

# A search for supersymmetry with jets and missing transverse energy at the Large Hadron Collider, and the performance of the ATLAS missing transverse energy trigger

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Thesis submitted in partial fulfilment of the requirements for the degree of  
Doctor of Philosophy at the University of Oxford

Hilary Term 2012

## Abstract

Attempting to find evidence for supersymmetry (SUSY) is one of the key aims of the ATLAS experiment at the Large Hadron Collider. This thesis is concerned with searching for supersymmetry in final states with 2-4 hadronic jets, missing transverse energy and no electrons or muons. In the first part, a search strategy is developed using  $1.04 \text{ fb}^{-1}$  of data from the first half of 2011. No excess over the Standard Model expectation is observed, so the data are used to set limits on two SUSY simplified models, in which pair-produced squarks or gluinos decay directly to neutralinos and jets. Good limits are achieved for scenarios where the neutralino is nearly as massive as the squark/gluino, compared to an earlier ATLAS analysis using the same dataset. For example, for pair-production of squarks decaying directly to neutralinos, all neutralino masses below 200 GeV are excluded at 95% confidence level when the squark mass is 300 GeV. Similarly, for pair-produced gluinos, neutralino masses below 300 GeV are excluded when the gluino mass is 400 GeV. The equivalent neutralino mass limits in the earlier analysis are 130 GeV and 240 GeV respectively. In the second part, the performance of the ATLAS missing transverse energy trigger is studied, and its suitability for use in the SUSY search is evaluated. The behaviour is found to be consistent with expectations, and the trigger strategy for 2010 data-taking is described.

To my family.

# Acknowledgements

Completing a doctorate is not a journey one makes alone, particularly it seems in the field of particle physics. Here I attempt to recall the names of everyone who has helped me along the way, and offer apologies to anyone I've forgotten!

Alan Barr has been, in many ways, the ideal supervisor. Happy to leave me to my own devices most of the year, but never short on time, goodwill or expertise on occasions when things started to unravel. A special mention must also go to Hugo Beauchemin, who effectively co-supervised me for the first 1.5 years or so. His philosophical style of supervision and infectious enthusiasm were invaluable in helping me to get started in particle physics.

All the past and present members of the Oxford ATLAS group have been a pleasure to work with, without exception. However, two individuals deserve to be singled out: James Ferrando for his infinite patience in teaching me how to use the ATLAS software, and Claire Gwenlan for expertly fielding endless queries about Monte Carlo samples.

The support staff at Oxford have always been friendly, and allowed me to focus on that which I came here to do. To the secretaries, Sue Geddes, Kim Proudfoot, Laura Nevay and Daniella Ellis, and to the computing support team, particularly Pete Gronbech and Ewan McMahon, I offer my gratitude.

During my studies I have benefited from working alongside many members of the ATLAS collaboration; here I name just a few. On the SUSY 0-lepton analysis team, Dan Tovey, Renaud Brunelierre, Mike Flowerdew, Simon Owen, Tanya Sandoval, George Redlinger, Valerio Consorti, Sascha Caron, Robin Van Der Leeuw, and Marija Vranjes Milosavljevic all gave helpful suggestions, feedback, or data at one time or another. Teng Jian Khoo and Kyle Cranmer were both tirelessly patient in helping me to understand statistics. On the trigger side, I am particular indebted to Diego Casadei, but also to George Lewis, Swagato Banerjee, Alan Watson, Allen Mincer, Venkat Kaushik, Attila Krasznahorkay, and Alexander Mann.

My thanks go to the STFC, for funding me so generously throughout my degree, and for making the transition to living at CERN so wonderfully painless that I barely had to look up from my work.

The other DPhil students at Oxford have made the last 3.5 years a joy. In particular, to Caterina, Chris, Dan, James, Phil and Sam, both for your physics expertise and your company, thank you. There isn't space to mention everybody here, but to those who I haven't named, I hope you know who you are.

Finally, I thank my parents and brother for, while never quite understanding what I do, being unrelentingly supportive and helping me to keep a sense of perspective!



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# Glossary

**BCID** Bunch-crossing identification (number)

**BSM** Beyond the Standard Model, i.e. new physics

**CDF** Cumulative distribution function

**CL** Confidence level (when preceded by a percentage, e.g. 95% CL)

**ECAL** Electromagnetic calorimeter

**EF** Event filter (level 3 trigger)

**EM** Electromagnetic

**EW** Electroweak

**FCAL** Forward calorimeter

**HCAL** Hadronic calorimeter

**HLT** High-level trigger (L2 + EF)

**ID** Inner detector

**ISR** Initial state radiation

**L1/2** Level 1/2 trigger

**LO** Leading order

**LSP** Lightest supersymmetric particle

**MC** Monte Carlo

**MS** Muon system

**MSSM** Minimal supersymmetric Standard Model

**NLO** Next-to-leading order

**PDF** Parton distribution function, *or* probability density function

**RMS** Root mean square

**SM** Standard Model (of particle physics)

**SUSY** Supersymmetry

# Introduction

The idea that nature is fundamentally supersymmetric has been popular in theoretical circles since the early 1970s. Now, with the completion of the Large Hadron Collider (LHC), we have the opportunity to put this idea to its most stringent experimental test so far. By considering quantum corrections to the mass of the (assumed) Higgs boson, there is reason to believe that supersymmetric particles will be accessible at LHC energies, should they exist. A discovery would herald an exciting new era in experimental particle physics, with a wealth of new particles to be investigated. On the other hand, should evidence of supersymmetry continue to be elusive, a revolution could well occur on the theoretical side of the field.

This thesis is concerned with a search for supersymmetry (SUSY) at the LHC, using data collected by the ATLAS detector in the first six months of 2011. The focus is on final states containing 2–4 hadronic jets, missing transverse momentum, and no electrons or muons. This search strategy can be motivated, briefly, as follows.

It is reasonable to expect that pair-production of squarks and gluinos would constitute the majority of SUSY particle production at the LHC, except in models where all the squarks and the gluino are very massive. It is also reasonable to expect that, in some cases, these squarks and gluinos would decay to the lightest supersymmetric particle (LSP) directly, rather than via a long cascade decay. If the LSP is stable and weakly interacting – and the existence of cosmological dark matter gives us reason to suppose that it might be both – then the LSP pair would escape the detector unseen, giving rise to a transverse momentum imbalance. The Standard Model decay products of the squarks and gluinos would be hadronic jets, most likely numbering 2–4.

Searches of this nature are particularly challenging owing to the potentially large background from QCD dijet/multijet events, where one or more of the jet energies is mismeasured. Offline cuts must be carefully selected in order to reduce the QCD background to a tractable level. Similarly, a trigger strategy must be devised which maintains a reasonable output rate while maintaining a satisfactory level of signal acceptance.

A brief outline of this thesis is as follows. Part I covers the necessary experimental and theoretical background, introducing the LHC, the ATLAS detector, the Standard Model, and supersymmetry. The SUSY search itself is described in detail in part II, including the estimation of the Standard Model backgrounds and the setting of limits on supersymmetric processes. Finally, part III comprises a detailed study of the ATLAS missing transverse energy ( $E_T^{\text{miss}}$ ) trigger, which is used to select the events for the analysis in part II.

The search presented in part II is loosely based on a similar example carried out by the ATLAS collaboration, with the participation of the author, and presented in [1]. In the original analysis, the author's contributions consisted of estimating the  $W$  + jets and top quark backgrounds (together with uncertainties), co-developing the  $W$  and top control region definitions, and cross-checking event counts with other analysers. Where definitions or data are taken from the earlier analysis, this is made clear in the text.

# Part I

## Experimental and theoretical background

# Chapter 1

## The Large Hadron Collider and the ATLAS experiment

### 1.1 The Large Hadron Collider (LHC)

#### 1.1.1 Introduction and design

The Large Hadron Collider [2] is the highest-energy particle accelerator in the world, colliding protons with protons at a centre-of-mass energy ( $\sqrt{s}$ ) of 7 TeV. The accelerator complex is located at the CERN laboratories near Geneva, on the Swiss-French border.

The LHC is of a synchrotron design, accelerating protons in opposite directions around a ring 27 km in circumference. The beams are kept on a circular path by 1232 superconducting dipole magnets, cooled using superfluid liquid helium, and capable of producing a field of up to 8 Tesla. Interspersed with the dipoles are 392 quadrupole magnets, used to focus the beams.

The LHC is housed in a tunnel originally constructed for the Large Electron-Positron Collider (LEP) between 1984 and 1989. The LEP accelerator ceased operation in 2000 to make way for the construction of the LHC, which was completed in 2008, seeing its

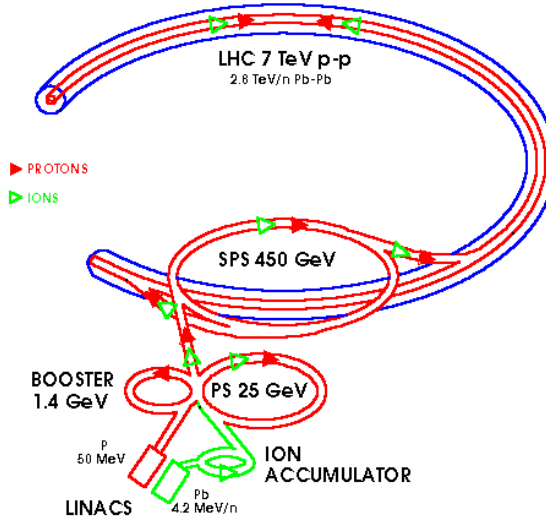


Figure 1.1: The LHC and its pre-accelerators at CERN, not to scale [5]. LINAC = linear accelerator, PS = Proton Synchrotron, SPS = Super Proton Synchrotron.

first proton-proton (p-p) collisions in September 2008. A mechanical failure caused by a faulty electrical connection between two magnets, 9 days after the first collisions, led to a long shutdown period in which the cause of the incident was determined, and the necessary modifications made [3, 4]. Collisions were resumed in November 2009, with the first collisions at  $\sqrt{s} = 7$  TeV in March 2010.

A series of smaller accelerators bring the protons up to an energy of 450 GeV before injection into the LHC itself. A schematic of the accelerator sequence is shown in figure 1.1, giving the energies achieved at each stage. The Super Proton Synchrotron, in its earlier guise as a proton-antiproton collider, was used to discover the  $W$  and  $Z$  bosons in the early 1980s. The LHC is also designed to collide lead nuclei (Pb-Pb) at  $\sqrt{s} = 2.76$  TeV per nucleon, and the pre-accelerators used to achieve this are also depicted in the figure (in green).

The two beams of the LHC are brought together at four interaction points arrayed around the ring. Large particle detectors have been built at each of these points to observe and record the resulting collisions. The ATLAS detector, where the studies presented in this thesis were carried out, is described in detail in the next section. It is a general-purpose experiment, intended to discover the Higgs boson – should it exist – and to observe any other new phenomena which may be present at TeV-scale energies. The other main detectors are:

a) CMS, another general-purpose experiment and counterpart to ATLAS, b) LHCb, which specialises in small-angle heavy-flavour physics, and c) ALICE, which is designed specifically for Pb-Pb collisions.

The proton beams are arranged in short bunches (up to 2808 per beam) which are timed to intersect at the interaction points, in events known as bunch crossings. There is one such crossing every 25 ns in ATLAS under the full quota of bunches, with 50 ns being used for the majority of 2011 data-taking [6].

### 1.1.2 Luminosity and pileup

The rate at which a given process (e.g.  $W$  production) occurs in a collider is a product of the fundamental cross-section,  $\sigma$ , and the luminosity\* at the interaction point,  $L$ . For a beam-on-beam collider such as the LHC,  $L$  is a function only of the beam parameters, such as the number of colliding particles per bunch and the spread of the particles in position and momentum space. The LHC is designed to reach a luminosity of  $1 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  at the ATLAS and CMS interaction points, with lower maximum values at LHCb and ALICE. The maximum values achieved at ATLAS in 2010 and 2011 were  $2 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$  and  $3.5 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  respectively [7]. The maximum so far in 2012 is  $6.8 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$ .

The luminosity may be raised in one of three ways: a) increasing the number of bunches per beam, b) increasing the number of protons per bunch, or c) squeezing the beams to reduce their cross-sectional area at the point where they intersect. The latter two give rise to additional proton-proton interactions in each bunch crossing, also known as in-time pileup. The first, by contrast, increases the out-of-time pileup, whereby electronic signals from collision events partially overlap inside a particle detector. Both phenomena require careful consideration of their effects on physics measurements.

An important related quantity is the integrated luminosity  $\mathcal{L}$  which is simply the luminosity integrated over time. It has dimensions of  $\text{area}^{-1}$ , typically expressed in units

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\*Sometimes referred to as the instantaneous luminosity, to avoid confusion with the integrated luminosity, introduced in next paragraph.



of inverse picobarns ( $\text{pb}^{-1}$ ) or inverse femtobarns ( $\text{fb}^{-1}$ ), of which the latter is the larger. The integrated luminosity is commonly used to express the size of a dataset. For example, the data recorded by ATLAS\* in 2010 totalled approximately  $45 \text{ pb}^{-1}$ , and in 2011 around  $5.2 \text{ fb}^{-1}$  [7]. The expected number of events due to a given process in a dataset is simply the product of the cross-section and the integrated luminosity.

## 1.2 The ATLAS detector

ATLAS is a general-purpose particle detector situated at interaction point 1 of the Large Hadron Collider [8]. “General-purpose” indicates that the experiment is designed to identify a wide range of new physics phenomena including, but not limited to, supersymmetry, extra spatial dimensions, and new fundamental forces [9]. This is achieved principally through direct production of new particles and analysis of their decay products, in contrast to experiments like LHCb, which predominantly identifies new sectors via their influence on decays of known particles. Another key aim of the experiment is to either discover the Standard Model Higgs boson, or exclude it at all theoretically viable masses.

ATLAS is the largest particle physics detector ever constructed, 44 m long and 25 m high, and weighing around 7000 tonnes. It follows a conventional layered design, with particle tracking detectors – collectively known as the inner detector – in the centre, calorimeters in the middle, and muon detectors on the outside. A solenoid magnet sits just inside the calorimeters, enabling the measurement of particle momenta via their track curvature in the inner detector. Another magnetic field, produced by a set of toroid magnets interleaved with the muon detectors, allows momentum measurements to be made on very energetic muons.

The inner detector is separated into the pixel detector, nearest the beamline, surrounded by the semiconductor tracker (SCT) and the transition radiation tracker (TRT). The calorimeter comprises the inner electromagnetic calorimeter (ECAL) and the outer hadronic calorime-

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\*These numbers are for data written to tape; the figures for raw integrated luminosity delivered by the LHC are slightly higher. A further complication is that the datasets used for physics analyses are usually slightly smaller than the recorded total, owing to data quality requirements.

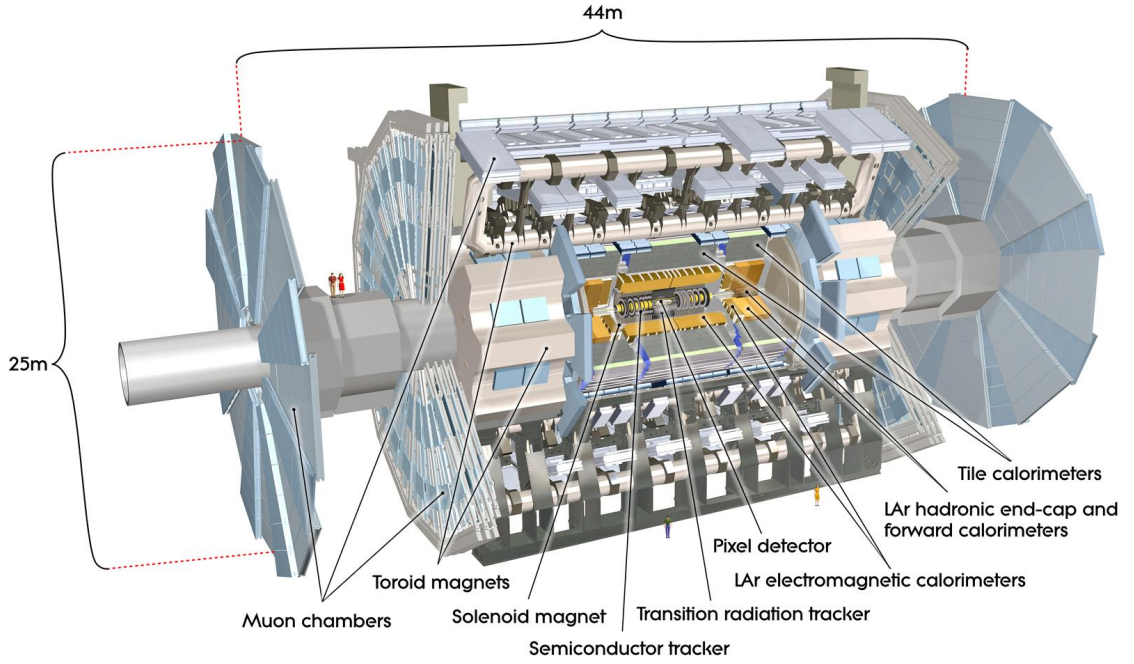


Figure 1.2: The layout and subdetectors of the ATLAS detector. Shown are: the inner detector components, the calorimeters, the muon system, and the magnets. The meaning of the ‘LAr’ and ‘tile’ calorimeters will be explained in section 1.2.3. Note humans for scale.

ter (HCAL), both of which are further subdivided into barrel and endcap components. A forward calorimeter (FCAL) provides energy measurement for particles emerging at small angles to the beams. The overall layout of the ATLAS detector is shown in figure 1.2. This figure, and all others for the remainder of this chapter, are taken from [8].

### 1.2.1 Coordinate definitions

The Cartesian axes are defined as follows:  $x$  is parallel to the ground, pointing towards the centre of the ring,  $y$  points vertically upwards and  $z$  is directed along the beamline. The  $x$ - $y$  plane is perpendicular to the beams and is referred to as the transverse plane.

For physics analyses, we more often use an  $r$ - $\eta$ - $\phi$  coordinate system, where  $r$  is the transverse distance from the beamline,  $\eta$  is the pseudorapidity and  $\phi$  is the angle relative to the  $x$ -axis in the transverse plane. The pseudorapidity is related to the polar angle with the

$z$ -axis,  $\theta$ , by the following relation:

$$\eta = -\ln[\tan(\theta/2)]. \quad (1.1)$$

This gives the value 0 anywhere in the  $z = 0$  plane and tends towards  $\pm\infty$  at very small angles to two incoming beams. The inner detector provides coverage up to  $\eta = \pm 2.5$  and the calorimeters up to around  $\eta = \pm 5$ . The pseudorapidity is an approximation to the physical rapidity of a particle  $y$ :

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}, \quad (1.2)$$

where  $E$  is the particle's energy and  $p_z$  its momentum along the  $z$ -axis. The rapidity and pseudorapidity of a particle are identical when the particle is massless, which is often a very good approximation in the high-energy collisions produced by the LHC, even for relatively massive particles such as muons.

The distance between two points in the  $\eta$ - $\phi$  plane,  $\Delta R$ , is defined simply as

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}. \quad (1.3)$$

This variable is used to define the widths of particle jets, and for deciding whether two detector objects (e.g. a muon and a jet) overlap.

### 1.2.2 Inner detector

The purpose of the inner detector (ID) is to reconstruct the paths, or tracks, taken by electrically-charged particles emerging from the collision area. These tracks can be used for particle identification, momentum measurement (in conjunction with the solenoid magnet), and to reconstruct the vertex from which a set of particles originate. The inner detector is composed of three layers: the pixel detector, the semiconductor tracker (SCT) and the transition radiation tracker (TRT). A cross-section of the ID barrel, together with radius values for the various layers, is shown in figure 1.3.

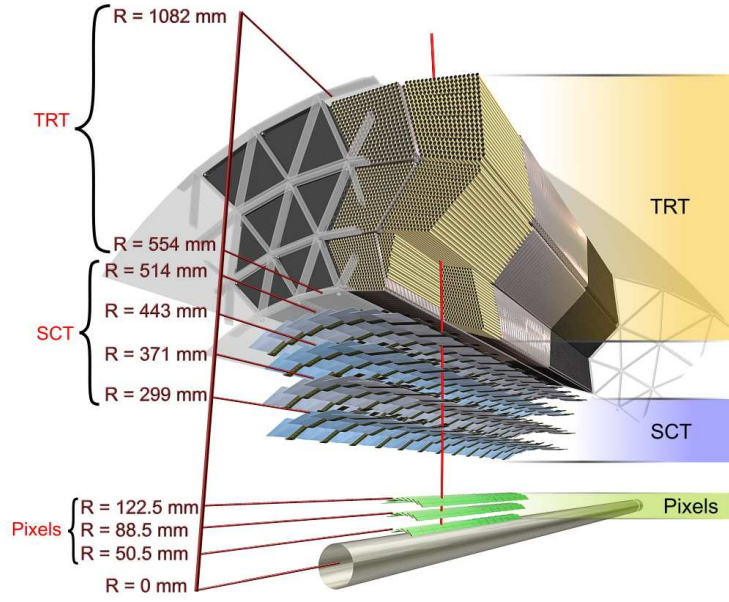


Figure 1.3: The structure of the inner detector barrel.

The pixel detector provides high-resolution tracking information in the region nearest the beams, using silicon pixels measuring  $50\ \mu\text{m}$  by  $400\ \mu\text{m}$ . It is subdivided into three cylindrical barrel layers and three circular endcap disks at either end, together giving coverage up to  $|\eta| = 2.5$ . The barrel layer nearest the interaction point is instrumental in obtaining precision tagging of  $b$ -quark decays, and as such is referred to as the  $b$ -layer. The SCT is essentially an upscaled continuation of the pixel detector, using long (12.8 cm in the barrel) silicon strips instead of pixels to cover a much greater surface area. It comprises four barrel layers and nine endcap disks, again providing continuous coverage up to  $|\eta| = 2.5$ .

The TRT serves as a further layer of tracking in the region  $|\eta| < 2$ , as well as contributing to electron identification by creating and detecting transition radiation (TR). It is composed of straws interleaved with a radiating material which produces abundant TR photons when crossed by an electron. Each straw comprises a hollow cathode 4 mm in diameter, surrounding a wire anode, and filled with a gas mixture. Charged particles are tracked by the pattern of straws in which they stimulate an ionisation, and electrons specifically are identified by the much stronger ionisation produced by the transition radiation that accompanies them.

|                     | ECAL/HCAL | $ \eta $ range          | Absorber        | Sampler      |
|---------------------|-----------|-------------------------|-----------------|--------------|
| Presampler          | E         | $0 \rightarrow 1.8$     | N/A             | LAr          |
| LAr EM barrel       | E         | $0 \rightarrow 1.475$   | Lead            | LAr          |
| LAr EM endcap       | E         | $1.375 \rightarrow 3.2$ | Lead            | LAr          |
| Tile barrel + ext.  | H         | $0 \rightarrow 1.7$     | Steel           | Scintillator |
| LAr hadronic endcap | H         | $1.5 \rightarrow 3.2$   | Copper          | LAr          |
| FCAL                | E+H       | $3.1 \rightarrow 4.9$   | Copper-tungsten | LAr          |

Table 1.1: Details of the various calorimeters of the ATLAS detector: whether they are part of the electromagnetic (E) or hadronic (H) calorimeter system, their pseudorapidity coverage, and the materials used as absorber/sampler.

### 1.2.3 Calorimetry

The purpose of the calorimeters is to measure the energies and  $\eta$ - $\phi$  positions of photons, electrons, and hadrons. This is achieved by alternately inducing showers of secondary particles in an absorbing medium and sampling the shower energy in a sampling medium. The loss of energy by the incoming particle to the shower takes place over a characteristic distance called the radiation length,  $X_0$ . Across all pseudorapidities, the total calorimeter thickness ranges from 10 to 40  $X_0$ , ensuring that, to very good approximation, all particles except muons and neutrinos are stopped.

The calorimeter system is divided into an inner electromagnetic layer (ECAL), an outer hadronic layer (HCAL) and a forward calorimeter at high  $|\eta|$  (FCAL), together covering the region  $|\eta| < 4.9$ . Electrons and photons deposit  $\sim 100\%$  of their energy in the ECAL, leaving only hadrons to progress to the HCAL. The ECAL, HCAL endcaps and FCAL use liquid argon (LAr) as the sampling medium with a variety of metal absorbers, and are referred to collectively as the LAr calorimeter. The HCAL barrel and extended barrel, also known as the tile calorimeter, combines a scintillator sampling medium with a steel absorber. An additional layer of argon inside the ECAL, called the presampler, measures the energy lost in the material in front of the calorimeters. The layout is summarised in figure 1.4 and table 1.1.

The liquid argon calorimeters are contained in three cryostats (one barrel, two endcap) that maintain the required low temperature. The solenoid magnet that curves the tracks in

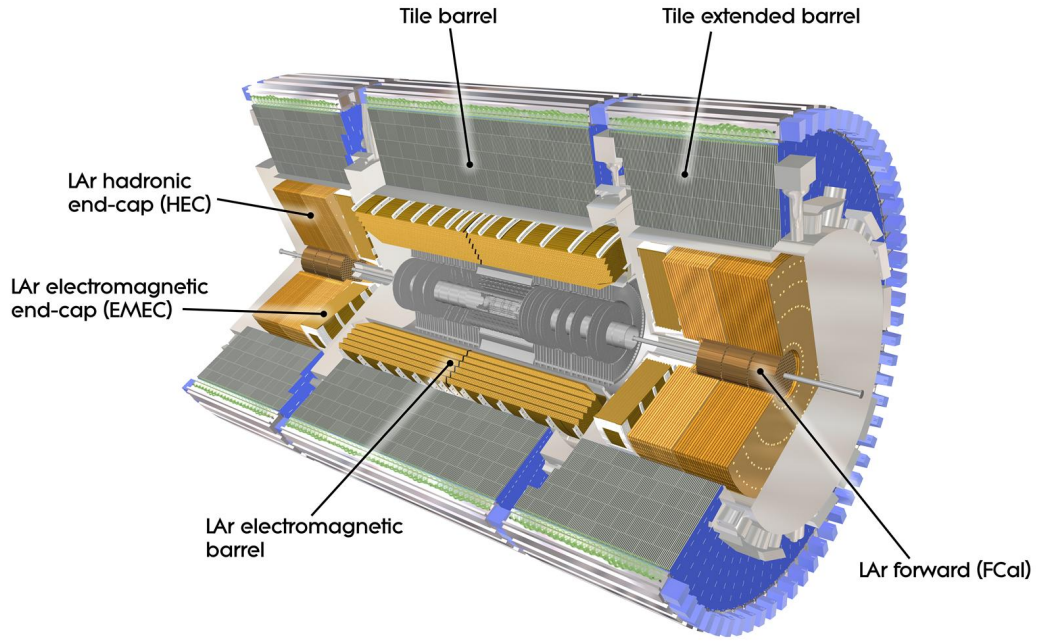


Figure 1.4: The structure of the ATLAS calorimeters. The inner detector is greyed-out in the centre.

the inner detector is housed in the central vacuum of the barrel cryostat.

### 1.2.4 Muon detection systems

Muons usually pass through the calorimeter system with relatively little energy loss, and subsequently interact with the muon detectors. That this property is not shared by any other stable particle allows muons to be easily identified and matched to tracks in the inner detector. The muon detectors serve two further purposes: 1) tracking, enabling a momentum measurement to be made in conjunction with the magnetic field produced by the toroid magnets and 2) triggering. Pseudorapidity coverage is up to  $|\eta| = 2.7$  for tracking and  $|\eta| = 2.4$  for triggering, although there are small gaps to accommodate a) power and data services to the inner region of the detector, and b) the detector support structures. These gaps result in reduced trigger and reconstruction efficiencies for muons at certain values of  $|\eta|$  and  $\phi$ .

The muon system comprises monitored drift tube chambers (MDTs), cathode strip cham-

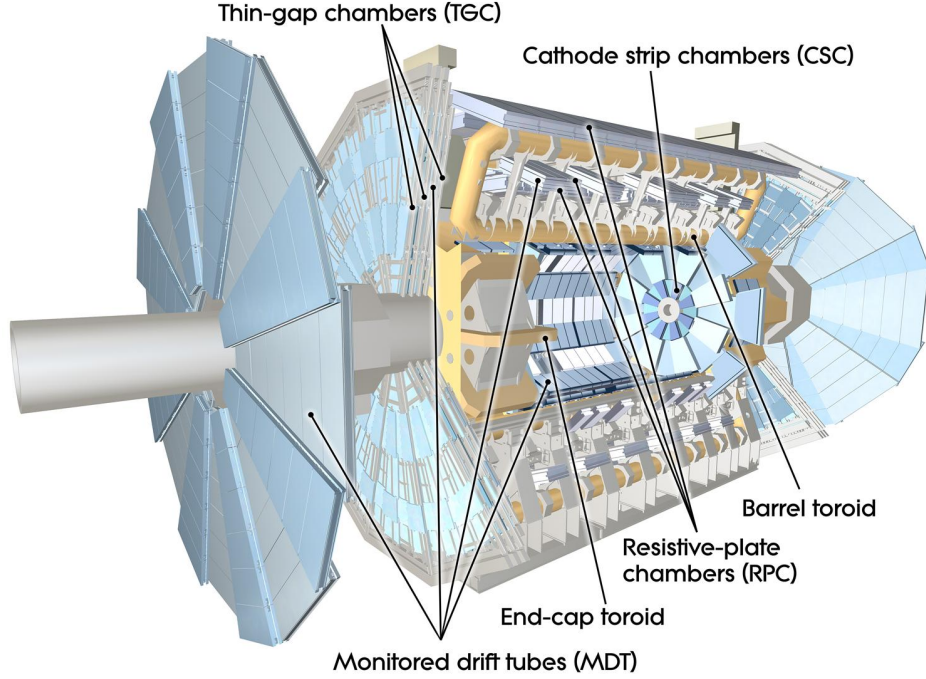


Figure 1.5: The structure of the ATLAS muon system.

bers (CSCs), resistive plate chambers (RPCs) and thin gap chambers (TGCs). The first two are used for their precision tracking ability, whereas the latter are employed primarily for triggering owing to their faster time response. The arrangement of the various chambers, along with the toroid magnets, is given in figure 1.5.

### 1.2.5 Trigger

The trigger system is used to select interesting events to be sent to long-term storage for offline analysis. The ATLAS trigger is divided into three levels, referred to as Level 1 (L1), Level 2 (L2), and Event Filter (EF). The latter pair constitute the high-level trigger, or HLT. The bunch crossing rate under full LHC design conditions is 40 MHz, which is reduced to around 75 kHz after L1, 3.5 kHz after L2 and 400 Hz after EF. In each case the limitation is imposed by the rate at which the upstream systems can process data. Assuming an event size of 1.3 megabytes, the EF rate implies a final data output rate of around  $520 \text{ MB s}^{-1}$ .

The L1 trigger uses in-cavern custom electronics to give the fastest possible decision, whereas the high-level triggers are software-based, and run on commercially-available com-



puter hardware situated above ground. The per-event time budget is approximately  $2.5 \mu\text{s}$  at L1, 40 ms at L2, and 4 seconds at EF.

The L1 trigger uses the calorimeters and muon detectors (RPCs/TGCs), at reduced granularity, to search for high- $p_T$  electrons, photons, jets, taus, and muons. The vector and scalar transverse energy sums are also calculated. The calorimeter is divided into  $\sim 7000$  trigger towers in  $\eta$ - $\phi$  space, of typical size  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ . Each tower produces an analogue energy measurement – separately for the electromagnetic and hadronic calorimeters – which is subsequently digitised and matched to an LHC bunch crossing. The results are passed to the jet/energy-sum processor (JEP), which builds hadronic jets and the global scalar/vector transverse energy sums, and the cluster processor (CP) which identifies electron, photon and tau candidates. The outputs from the L1 calorimeter trigger, along with information from the muon system, is sent to the L1 central trigger processor (CTP) where the various objects are combined and the decision is made.

If the CTP returns an “accept” decision, then regions of interest (ROIs) in  $\eta$ - $\phi$  space are defined and sent to L2, where they are used to seed the algorithms. The L2 trigger has access to the full detector granularity, using the ROIs to reduce the amount of data which has to be read out. The remainder of the data from the detector is sent to the readout system (ROS) where it is kept for use by the L2 trigger and event builder (see below), and for subsequent forwarding to offline storage if the event is accepted. An accept decision at L2 engages the event builder (EB), which assembles the data stored in the ROS to produce a complete event, using information from the full detector. The output from the EB is passed to the event filter, where offline-style reconstruction algorithms are used to make the final trigger decision. A schematic diagram of the ATLAS trigger system is shown in figure 1.6.

A trigger *chain* is defined by a set of sequential cuts at L1, L2 and EF. For example, the electron chain EF\_e20\_medium comprises  $p_T$  thresholds at 10, 20 and 20 GeV at L1, L2 and EF respectively, where “medium” denotes a set of quality cuts used to define good electrons at the HLT levels. At any stage in a chain, a *prescale* can be applied, which rejects a certain fraction of the events passing the threshold. Prescales allow events to be collected using



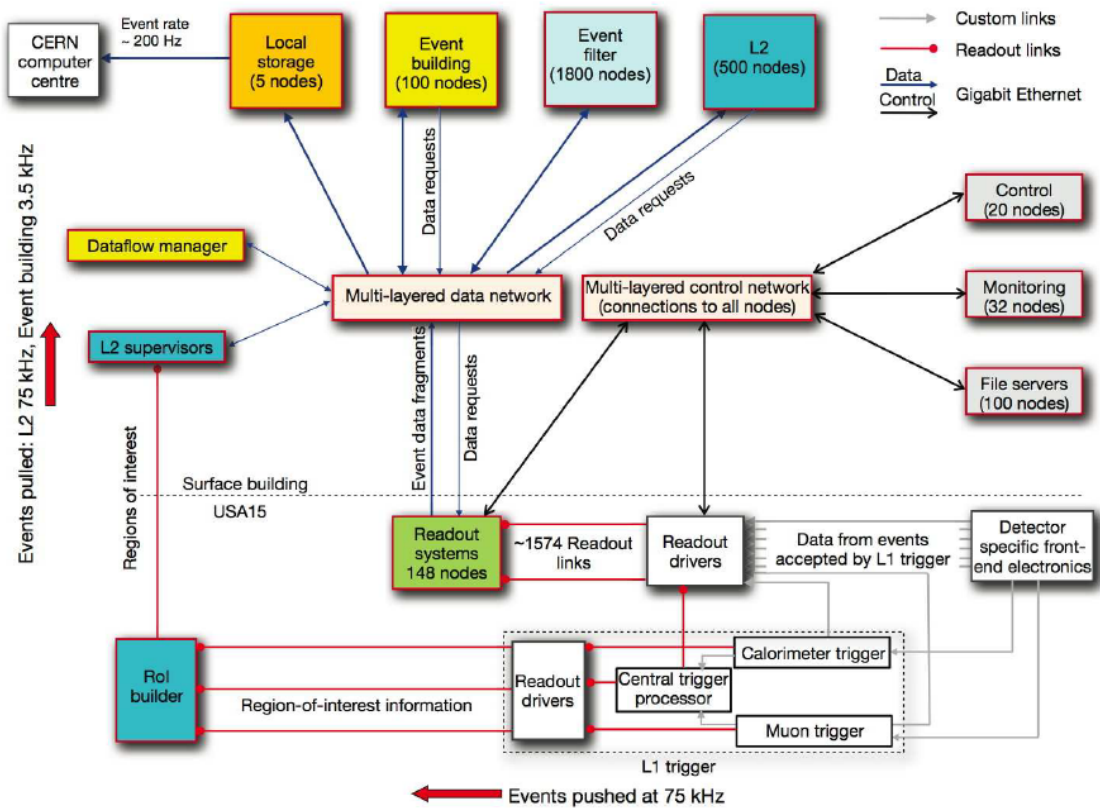


Figure 1.6: Schematic of the ATLAS trigger system. USA15, the area below the horizontal dotted line, is an off-detector area of the ATLAS cavern, which houses the detector readout systems and the L1 trigger electronics. The high-level trigger (L2 and EF) is top-centre, and reads data from the detector via the data and control networks in the centre of the diagram. The final destination of any data which passes all three trigger levels is the CERN computer centre, top-left.

chains whose rates would otherwise be unacceptably high, which can be useful for detector performance studies. The set of trigger chains running at ATLAS at any one time is referred to as the trigger *menu*.

## Physics objects

In the remainder of this chapter, we give a brief overview of the methods used to reconstruct electrons, muons, jets, and missing transverse energy. We also discuss the energy resolutions (and identification efficiencies where applicable) achievable for each of these objects.

### 1.2.6 Electrons

Electron candidates are seeded by energy clusters in the EM calorimeter, with an energy above 2.5 GeV, within a sliding window of size  $3 \times 5$  in units of  $0.025 \times 0.025$  in  $\Delta\eta \times \Delta\phi$ . If the cluster lies within the inner detector acceptance ( $|\eta| < 2.5$ ) then it must be matched to a track within  $\Delta\eta < 0.05$  and  $\Delta\phi < 0.1/0.05^*$ . The electron energy is then taken from a  $3 \times 7$  (barrel) or  $5 \times 5$  (endcaps) region of the calorimeter, with corrections for lateral and longitudinal leakage, and losses prior to entering the calorimeter. The energy resolution is therefore driven by the ECAL, for which  $\sigma_E/E \simeq 10\%/\sqrt{E} \oplus 0.7\%$  [8]. The  $\eta$  and  $\phi$  coordinates are nominally taken from the matched inner detector track, though they may also be derived from the cluster position if required.

Electrons within  $|\eta| = 2.5$  are identified using three sets of criteria – termed loose, medium, and tight – which offer increasing levels of rejection against hadronic jets and photons at the expense of lower efficiencies. The definitions are hierarchical, so a medium electron has to pass the loose selections and a tight electron the loose and medium selections. The full definitions may be found in [10], but may be summarised as follows.

- **Loose:** requirements on lateral shower shape and leakage into the HCAL.
- **Medium:** additional cuts on presampler shower shape, track quality and track-cluster

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\*The first/second numbers are on the outside/inside of the curved track.

matching.

- **Tight:** tighter track quality and calorimeter matching (including  $E_{\text{calo}}/p_{\text{track}}$ ), TRT cuts, veto on photon conversions.

The medium and tight efficiencies on electrons from  $W$  and  $Z$  decays have been measured in data to be around 94% and 79% respectively [10].

### 1.2.7 Muons

Muons are reconstructed [11] using one of two main algorithm families, Staco and Muid. Each family reconstructs muons in one of three different ways:

- **Standalone:** Muons reconstructed using tracks in the outer muon detectors only. The tracks are built and extrapolated back to the beamline using algorithms called Muonboy (Staco) and Moore (Muid). Muons may be reconstructed up to  $|\eta| = 2.7$  in this way.
- **Tagged:** Muons identified by extrapolating tracks outwards from the inner detector and searching for matched hits in the muon detectors. The matching is done using the MuTag algorithm for Staco muons, and MuGirl for Muid muons. Pseudorapidity coverage is reduced compared to the standalone method (2.5 rather than 2.7), but low- $p_T$  muons can be measured more reliably.
- **Combined:** Obtained by performing a  $\chi^2$  match between inner detector and muon detector tracks. The final four-momentum is constructed using slightly different methods for Staco and Muid, the former involving a straightforward combination of the two tracks and the latter starting with the inner detector track and then adding information from the muon detectors. Again, coverage is limited by the inner detector.

In the case of the Staco family, a muon may be either combined (the first choice) or tagged, but not both; with Muid there is some degree of overlap. The studies presented in this thesis will exclusively use Staco-family muons. The reconstruction efficiency for Staco muons, using a tag-and-probe method on  $Z$  decays, was measured to be around 92% for combined muons

and around 97% for combined + tagged muons in 2010 [12]. The transverse momentum resolution for the inner detector is  $\sigma_{p_T}/p_T \simeq 0.05\%p_T \oplus 1\%$  whereas that for the muon detectors is 10% at a  $p_T$  of 1 TeV [8].

### 1.2.8 Jets

Jets are produced when a quark or gluon, emerging from a particle interaction, fragments to form a number of hadrons whose momenta are correlated with that of the original parton. In experimental terms, jets are manifest as approximately conical regions of energy deposition in the electromagnetic and hadronic calorimeters. More formally, jets in ATLAS consist of topological clusters (topoclusters) in the calorimeters, which are assembled into jets by the anti- $k_t$  clustering algorithm [13]. The anti- $k_t$  algorithm is favoured because it is infrared and collinear safe, unlike the majority of cone-type algorithms, while producing jets that are neat and approximately conical, unlike the standard  $k_t$  algorithm.

The topoclusters are seeded by calorimeter cells with an energy content greater than four times the RMS noise for that cell ( $|E| > 4\sigma_{\text{noise}}$ ). The RMS noise is the square root of the mean energy-squared measured by that cell in the absence of any real energy deposition. All cells surrounding the seed in three dimensions are added to the cluster, with cells measuring  $|E| > 2\sigma_{\text{noise}}$  considered as secondary seeds. The procedure repeats with all the secondary seeds and the cluster grows until none of the cells surrounding it have  $|E| > 2\sigma_{\text{noise}}$ , at which point all these neighbouring cells are added, regardless of their energy.

The topoclusters are formed into jets by the anti- $k_t$  algorithm, which proceeds as follows. Firstly, we define the “distance” between two calorimeter objects  $i$  and  $j$ :

$$d_{ij} = \min(p_{T,i}^{-2}, p_{T,j}^{-2}) \frac{(\Delta R)^2}{(\Delta R_c)^2},$$

where  $\Delta R$  is as defined in equation 1.3 and  $R_c$  can be thought of as the jet width parameter (most commonly 0.4-0.6). The calorimeter objects in this case may be either topological

clusters, or protojets built out of them. We also define an absolute “distance” for  $i$ :

$$d_i = p_{T,i}^{-2}.$$

The jet reconstruction is done by looking for the smallest distance across all objects: if it is a  $d_{ij}$ , the objects  $i$  and  $j$  are combined; if it is a  $d_i$ , the object  $i$  is considered a jet and removed. This continues until all topological clusters are assembled into jets.

The calorimeters measure energy at the electromagnetic (EM) scale, with a pulse-height-to-energy calibration obtained using electron test beams. Jets therefore require an additional calibration to be applied which corrects the measured energy to the hadronic scale, and accounts for other effects such as pileup. The calibration may be performed either on individual calorimeter cells, prior to running the clustering algorithm, or on jets which have already been reconstructed at the EM scale [14]. For the studies presented in this thesis, the latter scheme is used. The calibration itself is done as a function of jet energy and pseudorapidity and is derived from comparisons between truth (particle-level) and reconstructed (detector-level) jets in simulated events. Prior to this, the expected energy contribution from pileup interactions is removed and the jet direction is corrected to point towards the primary vertex. The energy resolution for jets can be considered to equal that of the hadronic calorimeters, for which  $\sigma_E/E \simeq 50\%/\sqrt{E} \oplus 3\%$  in the barrel and endcap regions [8].

### 1.2.9 Missing transverse momentum and energy

The missing transverse momentum  $\vec{P}_T^{\text{miss}}$  is defined as the negative of the vector sum of all the visible activity in the transverse plane:

$$\vec{P}_T^{\text{miss}} = \begin{pmatrix} P_x^{\text{miss}} \\ P_y^{\text{miss}} \end{pmatrix} = - \left[ \sum_i^{\text{calo}} \begin{pmatrix} E_x^i \\ E_y^i \end{pmatrix} + \sum_j^{\text{muons}} \begin{pmatrix} p_x^j \\ p_y^j \end{pmatrix} \right], \quad (1.4)$$

where  $i$  represents a sum over calorimeter objects (most commonly cells) and  $j$  a sum over reconstructed muons. The energies in the  $x$  and  $y$  directions,  $E_x^i$  and  $E_y^i$ , are calculated

using the location of the object  $i$  in  $\theta$ - $\phi$  space as follows:

$$E_T^i = E_i \sin \theta_i, \quad (1.5)$$

$$E_x^i = E_T^i \cos \phi_i, \quad (1.6)$$

$$E_y^i = E_T^i \sin \phi_i. \quad (1.7)$$

It is conventional within ATLAS to refer to the magnitude of the missing transverse momentum as the missing transverse energy:

$$E_T^{\text{miss}} = |\vec{P}_T^{\text{miss}}| = \sqrt{(P_x^{\text{miss}})^2 + (P_y^{\text{miss}})^2}. \quad (1.8)$$

A large  $E_T^{\text{miss}}$  is a strong indicator of the presence of weakly interacting particles, such as neutrinos, which balance the visible momentum in the transverse plane. However, significant  $E_T^{\text{miss}}$  can also be created by jet energy mismeasurement, or simply by calorimeter noise.

For physics analyses, the  $E_T^{\text{miss}}$  is usually calculated using an object-based calibration. This means that the cell energies are calibrated differently depending on what sort of reconstructed object the cell belongs to: electron, photon, tau lepton or jet. Cells which are inside topoclusters but are not matched to an object also have their own calibration.

A related quantity is the total *visible* transverse energy

$$\text{Sum-}E_T = \sum_i^{\text{calo}} E_T^i, \quad (1.9)$$

where the  $E_T^i$  are defined in equation 1.5. The Sum- $E_T$  can in principle be used to search for highly energetic new physics phenomena, such as microscopic black holes, but in practice is too dominated by pileup and the underlying event to be a useful discriminant. More useful is the total transverse energy calculated from jets, usually referred to as  $H_T$ . However, the Sum- $E_T$  remains important because of its impact on the missing momentum resolution.

The relationship between the Sum- $E_T$  and the missing transverse momentum resolution

is sometimes approximated by

$$\sigma(P_{x,y}^{\text{miss}}) = k\sqrt{\text{Sum-}E_{\text{T}}}. \quad (1.10)$$

This model has been found to be reasonably accurate in data, with the constant  $k$  being measured at around 0.4–0.5 [15]. The missing transverse momentum resolution degrades with increasing  $\text{Sum-}E_{\text{T}}$ , on average, because larger measured energies are typically spread across a greater number of calorimeter cells. Each cell contributes an uncertainty to the missing transverse momentum sum, and so the larger the number of contributing cells, the poorer the overall resolution.

# Chapter 2

## Theoretical overview

### 2.1 The Standard Model

The Standard Model of particle physics (SM) is a highly successful theory of the interactions of elementary particles. The theory postulates twelve elementary fermions, representing matter, four vector bosons, which carry the fundamental forces, and a scalar Higgs boson. Each of these particles is identified with the excitations, or quanta, of a corresponding quantum field. The fermions are divided into three generations of four particles, each comprising an up-type quark, a down-type quark, a charged lepton and a neutrino. The vector bosons mediate three of the four known fundamental forces, namely the strong, electromagnetic and weak interactions. Gravity so far eludes a consistent description in the language of quantum field theory and is omitted from the SM.

The following gives a very short summary of the formalism of the Standard Model. For a more detailed overview, the reader may consult [16, 17, 18, 19, 20].

#### 2.1.1 Symmetries and gauge bosons

The Standard Model Lagrangian is symmetric under local transformations by the group  $SU(3) \times SU(2) \times U(1)$ , where  $SU(N)$  is the group of unitary  $N \times N$  matrices with unit



determinant, and  $U(1)$  is the group of complex numbers of unit magnitude. This *gauge invariance* depends on the existence of a number of vector (or gauge) fields,  $N^2 - 1$  for each of the  $SU(N)$  and one for the  $U(1)$ , each with an associated gauge boson. The numbers of fields come from group theory, and are equal to the number of *generators* of each subgroup. The eight  $SU(3)$  bosons are identified with the gluons, the carriers of the strong interaction. The  $SU(2)$  and  $U(1)$  bosons are not physical (i.e. detectable) but are mixed by spontaneous symmetry breaking (see below) to form the photon,  $W^\pm$  and  $Z$ . Prior to mixing, the fields are referred to as the  $W^i$  ( $i = 1, 2, 3$ ) for  $SU(2)$  and the  $B$  for  $U(1)$ .

The reason we cannot interpret the  $W^i$  and the  $B$  as the weak vector bosons and the photon is that none of the former has any mass, whereas we know from the short range of the weak force and from direct measurements that the  $W^\pm$  and  $Z$  are massive. Adding mass terms to the Lagrangian by hand is not a satisfactory solution as it destroys the gauge invariance. Hence we turn to spontaneous symmetry breaking to generate the vector boson masses.

Spontaneous symmetry breaking uses a complex scalar field  $\phi$  to destroy the invariance of the vacuum under the group  $G = SU(2) \times U(1)$ . This requires that a) there is a non-zero vacuum expectation value for the scalar field, i.e. the potential energy term  $V(\phi)$  is a minimum at  $\phi_{\min} \neq 0$ , and b) there exists a family of  $\phi_{\min}$ , which can be transformed into one another using the group  $G$ . Nature is forced to choose just one value for the actual vacuum, thereby breaking the  $G$  symmetry. This process gives rise to four new degrees of freedom: three Goldstone bosons and one Higgs boson. The Goldstones are absorbed into the gauge fields and give rise to the mass terms, while the massive Higgs boson remains physical, and can in principle be detected.

The massless  $W^{1,2,3}$ , and  $B$  fields are mixed by spontaneous symmetry breaking to produce four new fields which are eigenstates of mass and charge, whose quanta are the  $W^\pm$ , the  $Z$  and the photon ( $\gamma$ ). The vector boson content of the SM, after symmetry breaking, is summarised in table 2.1.

| Symmetry group      | No. generators | Bosons               | Boson mass |
|---------------------|----------------|----------------------|------------|
| SU(3)               | 8              | $g^i$ ( $i = 1..8$ ) | 0          |
| SU(2) $\times$ U(1) | 4              | $W^\pm$              | 80.4 GeV   |
|                     |                | $Z$                  | 91.2 GeV   |
|                     |                | $\gamma$             | 0          |

Table 2.1: Vector boson content of the SM, after spontaneous symmetry breaking. Masses are taken from [21].

### 2.1.2 Fermion content

The fermions in the Standard Model are chiral, meaning that their gauge interactions depend on whether they are *left-handed* or *right-handed*. The left and right-handed fields can be written as two-component *Weyl* spinors, which can be combined into a four-component Dirac spinor. Conversely, the chiral eigenstates may be obtained from the Dirac field by applying the projection operators  $P_L$  and  $P_R$ .

The interactions of the fermion fields are defined by their transformation properties under the SU(3), SU(2) and U(1) gauge groups. For example, all quarks fields transform as *triplets* under SU(3), which means that they can be written as three-component vectors which are rotated by the elements of the group. The three components are taken to represent the three “colour” charges of the strong force, known as red, green and blue. Physically, this is interpreted as meaning that a gluon interacts with a quark by transforming it into a quark of different colour. Similarly, the left-handed electron and electron neutrino fields form a two-component vector, or doublet, under SU(2). This means that  $W$  bosons turn left-handed electrons into left-handed electron neutrinos, and vice-versa. In contrast, a fermion field which transforms as a *singlet* under SU(3) or SU(2) is defined to have no interaction with the corresponding gauge field.

Since the elements of U(1) are, fundamentally, complex numbers rather than matrices, the interactions of fermions with a U(1) gauge field are defined simply by a quantum number, the weak hypercharge  $Y$ . Note that the more familiar electric charge,  $Q$ , can be derived by adding  $Y$  and the third component of weak isospin  $I_3$ , where  $I_3$  is  $\pm 1/2$  for the upper/lower

components of an  $SU(2)$  doublet and 0 for an  $SU(2)$  singlet. Table 2.2 summarises the gauge interactions of the fermions for a single (first) generation of the SM.

| Name                    | Notation                     | Gauge interactions<br>( $SU(3)$ , $SU(2)$ , $U_Y(1)$ ) |
|-------------------------|------------------------------|--------------------------------------------------------|
| Left-handed quark       | $Q_L = (u_L, d_L)^T$         | <b>3</b> , <b>2</b> , $+1/6$                           |
| Right-handed up quark   | $u_R$                        | <b>3</b> , <b>1</b> , $+2/3$                           |
| Right-handed down quark | $d_R$                        | <b>3</b> , <b>1</b> , $-1/3$                           |
| Left-handed lepton      | $L_L = (\nu_{e,L}, e_L^-)^T$ | <b>1</b> , <b>2</b> , $-1/2$                           |
| Right-handed electron   | $e_R^-$                      | <b>1</b> , <b>1</b> , $-1$                             |
| (Right-handed neutrino) | $\nu_{e,R}$                  | <b>1</b> , <b>1</b> , 0                                |

Table 2.2: Gauge interactions of the fermion fields in the Standard Model, for a single generation. A bold **3** indicates a triplet under  $SU(3)$  and **2** a doublet under  $SU(2)$ , with **1** indicating a singlet under either group.

The picture is simplified somewhat when considering the eigenstates of electric charge, since the electromagnetic interaction is blind to colour and to chirality. Table 2.3 shows the  $Q$  eigenstates across all three generations, together with the particle masses where these are well-measured. For each particle in the table there exists a corresponding antiparticle of equal mass and opposite electric charge.

| Type            | Q      | 1st gen |             | 2nd gen   |          | 3rd gen    |          |
|-----------------|--------|---------|-------------|-----------|----------|------------|----------|
| Up-type quark   | $+2/3$ | $u$     | 1.7–3.1 MeV | $c$       | 1.29 GeV | $t$        | 173 GeV  |
| Down-type quark | $-1/3$ | $d$     | 4.1–5.7 MeV | $s$       | 100 MeV  | $b$        | 4.19 GeV |
| Charged lepton  | $-1$   | $e$     | 0.511 MeV   | $\mu$     | 106 MeV  | $\tau$     | 1.78 GeV |
| Neutrino        | 0      | $\nu_e$ | –           | $\nu_\mu$ | –        | $\nu_\tau$ | –        |

Table 2.3: Fermion electric charge eigenstates of the Standard Model, together with their masses where appropriate. The neutrino masses are vanishingly small compared to that of the next lightest particle, the electron. Masses are taken from [21].

## 2.2 Supersymmetry (SUSY)

It is possible to add another symmetry to the SM, supersymmetry, that allows fermions to be transformed into bosons and vice-versa. The main phenomenological consequence of this

is the existence of a fermion *superpartner* for every boson in the theory, and vice-versa. If supersymmetry were exact, therefore, we would expect to have discovered a superpartner for every particle in the SM, in each case with identical mass and gauge interactions but differing in spin by half a unit. This not being the case we may assume that, if supersymmetry exists, it is broken and the superpartners are sufficiently massive to have eluded detection.

There are several reasons for believing supersymmetry to be a true symmetry of nature. Firstly, it provides an elegant solution to the hierarchy problem, i.e. the difficulty in explaining why the electroweak and gravitational (Planck) scales are so different. The issue arises because the Higgs mass receives large radiative corrections, of order  $m_{\text{Planck}} \sim 10^{19}$  GeV, from the particles that couple to it, whereas we know from experiment that  $m_H \sim 100$  GeV. In an exactly supersymmetric world, the problem disappears because the corrections from fermions precisely cancel those from their boson superpartners. Furthermore, supersymmetry improves the prospects for unifying the SM gauge forces into a single interaction and, if  $R$ -parity is conserved (see below), provides a natural candidate for dark matter.

For broken supersymmetry, we require  $m_{\text{SUSY}} \sim 1$  TeV in order to maintain a reasonable Higgs mass, which has obvious implications for physics at the LHC. This limit is driven primarily by the required cancellation between the radiative corrections of the top quark – the most massive particle in the SM – and its superpartner, the stop.

The material presented here is drawn primarily from [22] and [23], supplemented by [24] and the texts cited in the Standard Model section. The interested reader is encouraged to consult the comprehensive references listed in [22].

### 2.2.1 The minimal supersymmetric Standard Model (MSSM)

In the minimal form of supersymmetry, the SM and superpartner fields are grouped into chiral supermultiplets, containing a SM Weyl fermion, and a complex scalar superpartner, and gauge supermultiplets, containing a SM vector boson and a Weyl fermion superpartner.

For example:

$$\begin{pmatrix} u_L \\ \tilde{u}_L \end{pmatrix}, \begin{pmatrix} g \\ \tilde{g} \end{pmatrix}.$$

The superpartners of SM fermions are usually named by prefixing an ‘s’ (e.g. squark), and the superpartners of gauge bosons using an ‘ino’ suffix (e.g. gluino). The sfermions and gauginos are sometimes referred to collectively as *sparticles*. The symmetry requires that every superpartner has identical gauge interactions to those of its SM counterpart. Hence, for example, the  $\tilde{u}_L$  and  $\tilde{d}_L$  form a doublet under SU(2), whereas the  $\tilde{u}_R$  and  $\tilde{d}_R$  are singlets (recall table 2.2).

In the Higgs sector, supersymmetry requires the existence of five scalar bosons, as opposed to the one in the SM, for the following reason. The theory contains two complex scalar SU(2) doublets, one of which gives mass to the up-type quarks, and the other to the down-type quarks and charged leptons:

$$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}.$$

There are eight degrees of freedom in total, three of which are absorbed as masses for the  $W^\pm$  and  $Z$  (as in the SM), leaving five physical fields, two of which carry electric charge. These are denoted by  $H^0, A^0, h^0, H^+$  and  $H^-$ , and each has its own fermion superpartner.

The above formalism, which is exactly supersymmetric, can be encapsulated in a Lagrangian  $\mathcal{L}_{\text{SUSY}}$ . To make a model that is consistent with experiment, we must add terms which break supersymmetry, but in a way that does not reintroduce large radiative corrections to the Higgs mass. This requirement places restrictions on the sort of terms that are allowed, and results in so-called soft SUSY breaking:

$$\mathcal{L} = \mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{soft}}.$$

The soft-breaking part of the Lagrangian introduces a large number of theoretically-free parameters, around 120, which need to be measured experimentally. By contrast, the supersymmetric part requires just one additional mass term.

| Type        | Spin | Gauge eigenstates                                        | Mass eigenstates                                                         |
|-------------|------|----------------------------------------------------------|--------------------------------------------------------------------------|
| Higgs       | 0    | $H_u^0, H_u^+, H_d^0, H_d^-$                             | $H^0, A^0, h^0, H^\pm$                                                   |
| Squarks     | 0    | $(\tilde{u}_L, \tilde{d}_L), \tilde{u}_R, \tilde{d}_R$   | $\sim$ same                                                              |
|             |      | $(\tilde{c}_L, \tilde{s}_L), \tilde{c}_R, \tilde{s}_R$   | $\sim$ same                                                              |
|             |      | $(\tilde{t}_L, \tilde{b}_L), \tilde{t}_R, \tilde{b}_R$   | $\tilde{t}_1, \tilde{t}_2, \tilde{b}_1, \tilde{b}_2$                     |
| Sleptons    | 0    | $(\tilde{\nu}_{e,L}, \tilde{e}_L), \tilde{e}_R$          | $\sim$ same                                                              |
|             |      | $(\tilde{\nu}_{\mu,L}, \tilde{\mu}_L), \tilde{\mu}_R$    | $\sim$ same                                                              |
|             |      | $(\tilde{\nu}_{\tau,L}, \tilde{\tau}_L), \tilde{\tau}_R$ | $\tilde{\tau}_1, \tilde{\tau}_2, \tilde{\nu}_\tau$                       |
| Gluinos     | 1/2  | $\tilde{g}$                                              | same                                                                     |
| Charginos   | 1/2  | $\tilde{H}_u^+, \tilde{H}_d^-, \tilde{W}^\pm$            | $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$                                 |
| Neutralinos | 1/2  | $\tilde{H}_u^0, \tilde{H}_d^0, \tilde{W}^0, \tilde{B}$   | $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$ |

Table 2.4: The (non-SM) particle content of the minimal supersymmetric Standard Model, or MSSM.

The symmetry breaking must arise from a hidden sector (i.e. it cannot come from within the MSSM itself) and is communicated to the MSSM via one or more flavour-blind interactions. In gravity-mediated (or Planck-scale-mediated) supersymmetry breaking, the communication is done via the gravitational interaction. The principal alternative is gauge mediation, in which chiral supermultiplet messenger fields link the two sectors via the SM gauge interactions.

This supersymmetrised Standard Model, with added soft breaking terms, is titled the minimal supersymmetric Standard Model, or MSSM. In its various simplified forms, the MSSM is the favoured framework in which to conduct experimental searches for supersymmetry. Its particle content is summarised in table 2.4. Note that the soft breaking can mix mass and gauge eigenstates; the most significant mixings are indicated in the final column.

### 2.2.2 $R$ -parity and dark matter

It is possible to construct terms which are theoretically allowed in the MSSM, but which violate baryon and lepton number conservation. These would allow the proton to decay, with a mean lifetime several orders of magnitude below a second. In order to disallow this and

other unobserved processes, we introduce a new symmetry called  $R$ -parity, with conserved quantum number

$$P_R = (-1)^{3(B-L)+2S},$$

where  $B$  is baryon number,  $L$  is lepton number and  $S$  is the absolute spin. It so happens that  $P_R = +1$  for all particles in the SM (including the five Higgs scalars) and  $-1$  for all the superpartners. As a result, only interaction vertices with an even number of superpartners are possible, which implies that a) supersymmetric particles can only be produced in pairs, and b) the lightest supersymmetric particle (LSP) is stable.

If the LSP is weakly interacting, therefore, it becomes a viable candidate for cosmological dark matter. This gives three main options for the LSP: the lightest sneutrino, the lightest neutralino, and the gravitino, the superpartner of the hypothetical graviton (the gauge boson of gravity). The results of direct dark matter detection experiments make the sneutrino option somewhat unlikely, leaving the lightest neutralino and the gravitino. The gravitino is strongly favoured in gauge-mediated models, and in these cases is generally much lighter than the MSSM sparticles. In the absence of a light gravitino, the lightest neutralino is often supposed to be the LSP, on the basis that it alone provides a suitable candidate for dark matter. For this reason, many benchmark SUSY points and simplified models are chosen such that the LSP is a neutralino.

## Part II

# A search for supersymmetry with jets, missing transverse energy and no leptons



# Chapter 3

## Introduction to part II

Chapters 4-6 describe an analysis to search for supersymmetry at the LHC in the set of final states with missing transverse momentum, 2-4 jets and no leptons. In this short introduction we outline the motivation for this search in terms of the underlying interactions.

If supersymmetric particles do exist at energies of  $\mathcal{O}(100\text{--}1000\text{ GeV})$ , we can expect a varied phenomenology at the LHC. Assuming  $R$ -parity is conserved, and the LSP is weakly interacting, the most obvious sign of new physics would be an excess of events with large missing transverse momentum, caused by LSPs escaping the detector unseen. Beyond this one unifying feature, however, the range of possible signatures is huge. The best channel in which to search for SUSY is heavily dependent on the values of the large number of parameters in the soft-breaking part of the MSSM Lagrangian.

However, given that the LHC is a hadron collider, we may reasonably expect that the SUSY particles with the largest pair-production cross-sections would be those that carry colour charge. The exception would be if all the squarks and the gluino were very heavy relative to the electroweak gauginos and sleptons. There are three possibilities for strong production:  $\tilde{q}\tilde{q}$ ,  $\tilde{q}\tilde{g}$  and  $\tilde{g}\tilde{g}$ , where  $\tilde{q}$  is taken to represent a squark or an antisquark of arbitrary flavour and chirality. Some example LHC production diagrams are shown in figure 3.1.

The final state then depends on the subsequent decay sequence, which can potentially

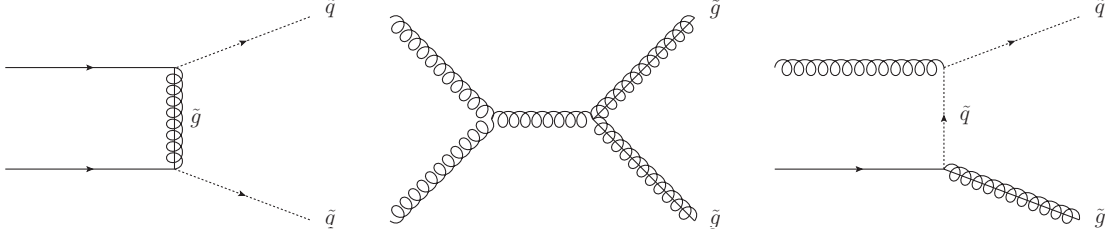


Figure 3.1: Examples of strong pair-production of supersymmetric particles at the LHC.

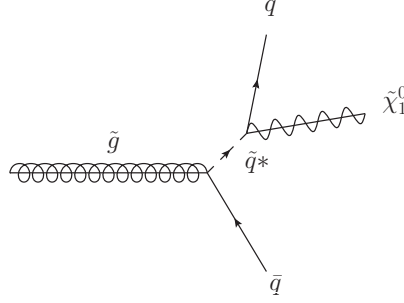


Figure 3.2: Gluino decay via a virtual squark.

contain a large number of intermediate SUSY particles. Broadly speaking, we can expect two weakly interacting LSPs plus  $n \geq 2$  Standard Model particles. At least two of the  $n$  need to be strongly interacting, in order to carry away the colour of the initial sparticle pair, typically yielding  $\geq 2$  jets after hadronisation. We therefore look for final states of the form:

$$E_{\text{T}}^{\text{miss}} + \geq 2 \text{ jets} + \geq 0 \text{ leptons}.$$

The simplest decay scheme sees both coloured sparticles decaying directly to the LSP:

$$\begin{aligned}\tilde{q} &\rightarrow q\tilde{\chi}, \\ \tilde{g} &\rightarrow q\bar{q}\tilde{\chi}.\end{aligned}$$

The squarks, being electroweakly interacting and having a non-zero Higgs coupling, can couple directly to the LSP, whereas the gluino decays via a virtual squark (figure 3.2). Assuming for simplicity that the squarks and quarks are first and second generation only, we expect final states with two  $(\tilde{q}\tilde{q})$ , three  $(\tilde{q}\tilde{g})$ , and four  $(\tilde{g}\tilde{g})$  jets\*, plus missing momentum and no leptons. In the following chapters, we focus on this set of signatures.

---

\*Assuming a  $1 \rightarrow 1$  correspondence between final-state partons and jets. In practice, of course, the number of jets can be lower or higher.

# Chapter 4

## Analysis setup

This chapter sets up all the basic tools and definitions for the 0-lepton SUSY search which is developed in chapters 5–6. The topics covered are: the dataset used, choice of trigger, event simulation, event cleaning, physics object definitions, and kinematic variable definitions. Finally, we define the four signal regions in which we will look for evidence of supersymmetry.

### 4.1 Preamble

All material presented in sections 4.2 to 4.6 inclusive is inherited from the ATLAS summer 2011 0-lepton SUSY search, in which the author participated. The author’s contribution consisted of estimating the  $W + \text{jets}$  and top backgrounds, confirming event counts in the control and signal regions with other analysers, and performing consistency checks on the final background fit results. This search was presented at the EPS 2011 conference [25] and in the paper [1] (with supporting documentation [26]). The two analyses begin to diverge from section 4.7 onwards, in the choice of signal regions, the background estimation methods used (chapter 5) and the statistical analysis applied to the results (chapter 6).

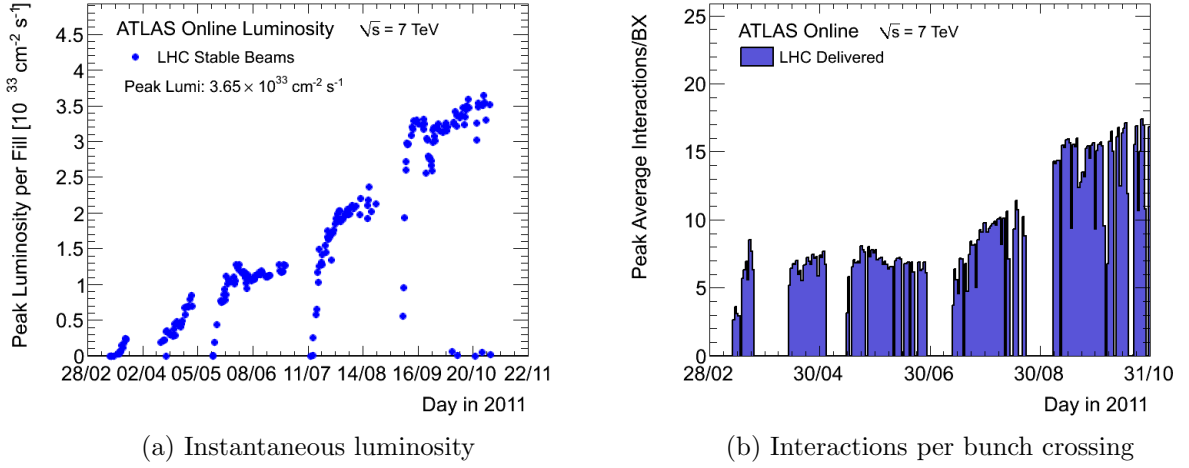


Figure 4.1: LHC beam characteristics at the ATLAS detector during 2011: instantaneous luminosity (left) and mean number of p-p interactions per bunch crossing (right) [7].

## 4.2 Dataset and trigger

The data were collected between 22 March and 28 June 2011 at a centre-of-mass energy of 7 TeV. After imposing requirements on data quality, detector and beam conditions, the total integrated luminosity is approximately  $1.04 \text{ fb}^{-1}$ . The maximum instantaneous luminosity in this dataset is approximately  $1.3 \times 10^{33} \text{ cm}^{-2} \text{ s}^{-1}$  and the maximum mean number of p-p interactions per bunch crossing is around eight (see figure 4.1).

Signal events are collected using a combined single-jet and  $E_{\text{T}}^{\text{miss}}$  trigger with EM-scale thresholds of 75 GeV (jet) and 45 GeV ( $E_{\text{T}}^{\text{miss}}$ ) at event filter. This trigger reaches approximately full efficiency at an offline jet  $p_{\text{T}}$  of  $\sim 130 \text{ GeV}$  and an offline  $E_{\text{T}}^{\text{miss}}$  of  $\sim 130 \text{ GeV}$  [26]. For this reason, the offline leading jet  $p_{\text{T}}$  and  $E_{\text{T}}^{\text{miss}}$  cuts for this analysis are both placed at 130 GeV (see section 4.7). The performance of the  $E_{\text{T}}^{\text{miss}}$  and combined jet +  $E_{\text{T}}^{\text{miss}}$  triggers is examined in detail in part III.

## 4.3 Simulated events

All simulated event samples used in this thesis were produced centrally by and for the ATLAS collaboration. The production process consists of several steps: a) Monte Carlo

| Process                           | Generator               | Hadronisation   | Underlying event |
|-----------------------------------|-------------------------|-----------------|------------------|
| $W/Z + \text{jets}$               | Alpgen [29]             | Herwig [30, 31] | Jimmy [32]       |
| $t\bar{t}$ , single top, $W$ -top | MC@NLO [33, 34, 35, 36] | Herwig          | Jimmy            |
| SUSY signal                       | Herwig++ [37]           | Herwig++        | Herwig++         |

Table 4.1: Summary of the simulated event samples used in this analysis.

(MC) generation of the desired hard process at the matrix-element level, b) hadronisation, in which all final-state partons are evolved into hadrons, c) the underlying event, which adds the contribution from the soft part of the p-p interaction, and d) simulation of the response of the ATLAS detector to all outgoing particles. The programs used for the generation, hadronisation and underlying event for the various background and signal processes are shown in table 4.1. The final step, d), is performed using the same GEANT4-based detector simulation in all cases [27, 28].

The  $W$ ,  $Z$  and signal samples are generated at leading order (LO), the  $t\bar{t}$  and single top at next-to-leading order (NLO). Different  $W$  and  $Z$  samples are generated according to the number of additional hard partons in the final state,  $N_p = 0-4$  and  $\geq 5$ , which allows for efficient production of large numbers of high- $n_{\text{jet}}$  events. Theoretical cross-sections, calculated at next-to-NLO ( $W/Z/\text{top}$ ) or NLO (signal), are used to fix the total cross-section for each process.

The distribution of incoming partons is determined using a particular set of parton distribution functions, or PDFs. The chosen PDF sets are: CTEQ6.6 for  $t\bar{t}$  and single top [38], CTEQ6L1 for  $W$  and  $Z$  [39], and MRST2007LO\* for the SUSY signal [40]. The first of these is derived at NLO and the others at LO, matching the orders of the respective generators.

## 4.4 Event cleaning

The purpose of event cleaning is to reject events where the jets and/or missing momentum do not originate from a proton beam collision. This non-collision background (NCB) can take several forms:

- Calorimeter noise, imitating real energy deposition.
- Cosmic ray events, in which an incoming muon radiates a photon.
- Beam halo events, in which a proton in the periphery of the beam passes through the detector longitudinally.
- Collisions between protons and gas molecules in the beam pipe.

Non-collision events are problematic because they can produce a jet-like energy deposition on just one side of the calorimeter, thus creating the illusion of missing momentum. When occurring in coincidence with a proton bunch crossing, a non-collision event can give a convincing imitation of our chosen signal.

To protect against NCB, we require that each event meet the following criteria:

- Passes the standard jet cleaning cuts, as defined by the jet performance group, designed to reject jets with features consistent with calorimeter noise.
- Has at least one reconstructed primary vertex, with at least five associated tracks.
- The energy-weighted mean time of the first  $N$  jets is less than  $|t| = 5$  ns, where  $t = 0$  is the time of the bunch crossing and  $N$  is the number of jets that define a given signal region ( $N = 2/3/4$ ).
- There are no jets among the first  $N$  with  $p_T > 100$  GeV,  $|\eta| < 2.0$ , and *charge fraction* less than 5%; the charge fraction is defined as the fraction of a jet's calorimeter energy which is reconstructed from tracks in the inner detector.
- The LAr calorimeter error flag is not set.

An additional complication that arose during part of 2011 was the appearance of a “hole” in the LAr calorimeter in the region  $-0.1 < \eta < 1.5$ ,  $-0.9 < \phi < 0.5$ , caused by a localised failure in the readout electronics. Jets measured in this region were found to have energies underestimated by around 30%. To minimise the effect of the hole on the  $E_T^{\text{miss}}$  measurement, we veto all events in which any of the four leading jets a) falls into the dead region, and b) has a (corrected)  $p_T$  over 40 GeV. The 40 GeV cut is chosen because it corresponds to the

minimum  $p_T$  required for a jet to contribute to the signal region jet multiplicity: see section 4.7 below.

## 4.5 Physics objects

**Jets** are reconstructed from topoclusters at EM scale, using the anti- $k_t$  algorithm with a width parameter of 0.4, and subsequently calibrated to the hadronic scale using a  $p_T$  and  $\eta$ -dependent scale factor (see section 1.2.8). They are required to have  $p_T > 20$  GeV after calibration, and  $|\eta| < 2.8$ . Jets entering the signal regions are required to pass more stringent  $p_T$  cuts (see section 4.7).

**Jets associated with  $b$ -quark decays** are identified using a neural network that combines information from the JetFitter (secondary vertex based) and IP3D (track impact parameter based) tagging algorithms. The combined weight is required to be greater than 2.0, which is designed to give a  $b$ -jet identification efficiency of 60% with a light-flavour rejection of approximately 400 [41].

For **electrons**, we use two separate definitions, referred to as the baseline and signal selections. Baseline electrons are required to have  $p_T > 20$  GeV and  $|\eta| < 2.47$ , to pass the “medium” identification criteria (see section 1.2.6) and to lie outside the LAr dead region (see section 4.4). Signal electrons are additionally required to be isolated, to have  $p_T > 25$  GeV and to pass the “tight” identification criteria.

**Muons** are likewise categorised into baseline and signal varieties. Baseline muons are combined or tagged, as defined within the Staco algorithm family (see section 1.2.7), have  $p_T > 10$  GeV and  $|\eta| < 2.4$ . Signal muons are additionally required to pass a higher  $p_T$  cut of 20 GeV and an isolation cut.

In order to remove non-hadronic jets associated with an electron, and leptons originating from heavy quark decays, we carry out the following **overlap removal** process on each event. Firstly, all jets reconstructed within  $\Delta R = 0.2$  of a baseline electron are discarded.

Subsequently, all baseline and signal leptons within  $\Delta R = 0.4$  of a surviving jet are also discarded.

The **missing transverse energy**,  $E_T^{\text{miss}}$ , is calculated from cells inside topoclusters. An object-based calibration is used, which means that a cell is calibrated differently depending on whether it is part of a hadronic jet, an electron, a photon, a tau, or not associated with a high- $p_T$  physics object at all. Topoclusters with  $|\eta| > 4.5$  are not included in the sum. A muon correction is applied using baseline muons, prior to overlap removal.

## 4.6 Kinematic variables

The *effective mass* ( $m_{\text{eff}}$ ) is a measure of the total transverse activity in a given event. Where a signal region is defined by a number of jets  $n_{\text{jet}}$ , the effective mass is given by the scalar sum

$$m_{\text{eff}}(n_{\text{jet}}) = E_T^{\text{miss}} + \sum_{i=1}^{n_{\text{jet}}} p_T^i, \quad (4.1)$$

where  $p_T^i$  is the transverse momentum of the  $i^{\text{th}}$  jet. The effective mass is correlated with the parton-parton centre-of-mass energy, so the observation of many events at large  $m_{\text{eff}}$  would be a strong indicator for new physics at high mass scales. It will be used as our primary discovery variable.

A related quantity is the ratio of the missing energy to the effective mass,  $E_T^{\text{miss}}/m_{\text{eff}}$ . This variable is useful for discriminating between high- $p_T$  QCD multijet events where the  $E_T^{\text{miss}}$  comes from jet energy mismeasurement, and electroweak or BSM processes with real missing energy. For the former, we expect  $E_T^{\text{miss}}/m_{\text{eff}} \ll 1$  in most cases, simply because small jet energy mismeasurements are more likely than large ones. For electroweak and BSM events, the ratio is less constrained.

Further protection against QCD processes can be gained by cutting on the minimum azimuthal angle between the missing momentum and the leading  $n$  jets,  $\Delta\phi_{\text{min}}$ , where  $n = 3$  for this analysis. If a jet is badly mismeasured, we expect the missing momentum will be



closely aligned with it. Hence we can reject the majority of such events by setting some minimum allowed value for  $\Delta\phi_{\min}$ .

Finally, we introduce the transverse mass between two massless particles:

$$M_T^2 = 2 \left( E_T^{(1)} E_T^{(2)} - \vec{p}_T^{(1)} \cdot \vec{p}_T^{(2)} \right), \quad (4.2)$$

where  $\vec{p}_T^{(i)}$  are the transverse momenta in the  $x$ - $y$  plane and  $(E_T^{(i)})^2 = |\vec{p}_T^{(i)}|^2$ . A particle  $X$  decaying into two massless particles 1 and 2 will have its mass bounded from below by  $M_T$ , in the limit of zero decay width and no detector smearing, i.e.  $M_T \leq M_X$ . The transverse mass is most commonly applied to  $W$  bosons decaying into a charged lepton and a neutrino, where lack of knowledge of the invisible momentum along the beam axis prevents the true mass being reconstructed.

## 4.7 Signal region definitions

Four signal regions are examined for this analysis, which are closely related to those used in [1]. The main difference is that instead of applying a final effective mass ( $m_{\text{eff}}$ ) cut and counting the events passing that cut (the so-called “cut-and-count” method), we use histograms binned in  $m_{\text{eff}}$ . This allows us to search for SUSY over a range of effective masses, which ought to increase sensitivity to near-degenerate SUSY points (those where the LSP mass is a substantial fraction of the squark/gluino mass) while maintaining sensitivity to high-mass splittings.

Note that, while no explicit cut is made on the effective mass, a de facto lower limit is imposed by the requirements on the  $E_T^{\text{miss}}$ , jet momenta, and jet multiplicity. While this limit could potentially affect the sensitivity to near-degenerate points, it is driven by the trigger and is therefore difficult to circumvent.

The cuts for the four signal regions are given in table 4.7. We assume that all events entering these regions pass the trigger (section 4.2) and event cleaning cuts (section 4.4),

| Signal region<br>Equivalent in [1]                                   | $\geq 2$ jets<br>A | $\geq 3$ jets<br>B | $\geq 4$ jets<br>C + D | $\geq 4$ jets incl.<br>E |
|----------------------------------------------------------------------|--------------------|--------------------|------------------------|--------------------------|
| $E_T^{\text{miss}}$ [GeV]                                            | $> 130$            | $> 130$            | $> 130$                | $> 130$                  |
| Leading jet $p_T$ [GeV]                                              | $> 130$            | $> 130$            | $> 130$                | $> 130$                  |
| Second jet $p_T$ [GeV]                                               | $> 40$             | $> 40$             | $> 40$                 | $> 80$                   |
| Third jet $p_T$ [GeV]                                                | –                  | $> 40$             | $> 40$                 | $> 80$                   |
| Fourth jet $p_T$ [GeV]                                               | –                  | –                  | $> 40$                 | $> 80$                   |
| $\Delta\phi(\text{jet}_i, E_T^{\text{miss}})_{\min} \ (i = 1, 2, 3)$ | $> 0.4$            | $> 0.4$            | $> 0.4$                | $> 0.4$                  |
| $E_T^{\text{miss}}/m_{\text{eff}}$                                   | $> 0.3$            | $> 0.25$           | $> 0.25$               | $> 0.2$                  |

Table 4.2: Signal regions for this analysis.

and contain no baseline electrons or muons after overlap removal (section 4.5). For both lepton flavours, the veto  $p_T$  threshold is 20 GeV. Note that, for muons, this is higher than the 10 GeV used for the baseline definition.

# Chapter 5

## Estimation of electroweak backgrounds using 1-lepton control regions

In this chapter, a data-driven method of estimating the  $Z + \text{jets}$ ,  $W + \text{jets}$  and top backgrounds to 0-lepton SUSY searches is presented. The total background from these sources is estimated in the four signal regions introduced at the end of the previous chapter, combined with an estimate of the QCD multijets background, and compared against the observed data.

### 5.1 Overview

The backgrounds to 0-lepton SUSY searches can be separated into two main categories: QCD multijets and electroweak. The electroweak part is defined by the presence of one or more real  $W/Z$  bosons, which decay invisibly or semi-invisibly, creating real missing momentum. This definition includes the various top quark backgrounds, since the top always produces a real  $W$  upon its decay. The QCD background is composed of events with mismeasured jets or a heavy-flavour quark decaying leptonically inside a jet, and so usually has the missing momentum closely aligned with one of the jets. This means that a cut on the azimuthal angle between the missing momentum and its nearest jet is very effective in reducing the QCD background; a cut on  $E_T^{\text{miss}}/m_{\text{eff}}$  reduces it still further, making it small with respect

to the various electroweak backgrounds.

We can subdivide the electroweak backgrounds into: a)  $Z + \text{jets}$  and  $W + \text{jets}$ , b)  $t\bar{t}$  and single top. The  $Z$  part of the background is mostly composed of  $Z \rightarrow \nu\nu + \text{jets}$ , with a smaller amount of  $Z \rightarrow \tau\tau$ . There is also a small contribution from diboson production, which is assumed to be negligible here (see the studies in [11]). This chapter focuses on estimating these backgrounds in a data-driven way, using  $W \rightarrow \ell\nu + \text{jets}$  and semi-leptonic  $t\bar{t}$  events in which the lepton is successfully reconstructed offline. The  $Z + \text{jets}$  and  $W + \text{jets}$  backgrounds are evaluated from a control sample dominated by  $W \rightarrow \ell\nu + \text{jets}$  events, and the top background from a control sample dominated by semi-leptonic  $t\bar{t}$  events.

The remainder of this chapter is structured as follows. In section 5.2 we discuss the use of a  $W \rightarrow \ell\nu$  control sample to estimate the irreducible  $Z \rightarrow \nu\nu + \text{jets}$  background, placing this method in context with the methods used in [1]. In sections 5.3 and 5.4 we generalise the method to include the  $W \rightarrow \ell\nu + \text{jets}$  and top backgrounds, and then in section 5.5 we examine the sources of systematic uncertainty affecting the estimate. Finally, we compare the observed control region distributions against simulation, and the signal region distributions against both simulation and the data-driven background prediction. In the next chapter, we use the background predictions to perform statistical tests on some simplified SUSY models.

## 5.2 Estimating $Z \rightarrow \nu\nu + \text{jets}$

### 5.2.1 Introduction

This section concerns the  $Z + \text{jets}$  background, where the  $Z$  decays invisibly to two neutrinos, one of the key backgrounds to 0-lepton + jets +  $E_{\text{T}}^{\text{miss}}$  new physics searches. In the following sections the method presented here will be generalised to the total electroweak background. The discussion of the  $Z \rightarrow \nu\nu$  background is given separately here to enable a clear exposition of the concepts, and to allow a comparison to be made with other  $Z \rightarrow \nu\nu$  estimation methods used in ATLAS. The remainder of this introduction will review these alternative methods.

The  $Z \rightarrow \nu\nu + \text{jets}$  background may be estimated using events where a  $Z$  decays to either electrons or muons. The  $Z \rightarrow \ell\ell$  method was proposed in [11] as the primary method of extracting the  $Z \rightarrow \nu\nu$  background. In this approach, the estimated  $Z \rightarrow \nu\nu$  background distribution is constructed by modelling the visible leptons from  $Z \rightarrow \ell\ell$  decays as neutrinos and then correcting for the control region acceptance:

$$N_{Z \rightarrow \nu\nu}(E_T^{\text{miss}}) = N_{Z \rightarrow \ell\ell}(p_T(\ell_1 + \ell_2)) \times c_{\text{Kin}}(p_T(Z)) \times c_{\text{Fidu}}(p_T(Z)) \times \frac{\text{BR}(Z \rightarrow \nu\nu)}{\text{BR}(Z \rightarrow \ell\ell)},$$

where  $c_{\text{Kin}}(p_T(Z))$  is the kinematic acceptance as a function of  $Z$  transverse momentum and  $c_{\text{Fidu}}(p_T(Z))$  is the fiducial acceptance. Corrections are also required to account for lepton trigger, reconstruction and identification efficiencies.

The only shortcoming of this method is that the branching ratio of  $Z \rightarrow \ell\ell$  ( $\ell = e$  or  $\mu$ ) is around one-sixth that of  $Z \rightarrow \nu\nu$ . This means that the estimate can be statistically limited in signal regions where the  $Z \rightarrow \nu\nu$  background is expected to be small. If the expected background is around ten events or fewer then it becomes likely that no control events will be seen at all.

Two solutions are proposed in [11] to counter this problem. The first is to make a fit to the observed  $Z \rightarrow \ell\ell$  distribution in a region with a larger number of events, and then to assume the fit parameters evolve smoothly as the signal region cuts are tightened. The second solution is to use the total number of events in the dileptonic control region to measure the overall normalisation, but then to use simulation for the distribution shape. The price paid in both of these approaches is the extra systematic uncertainty associated with the kinematic extrapolation.

An alternative method uses  $\gamma + \text{jets}$  events as a control sample for  $Z \rightarrow \nu\nu$ , and models the photon as missing momentum [42]. This method exploits the similar production mechanisms of  $Z \rightarrow \nu\nu + \text{jets}$  and  $\gamma + \text{jets}$  (see figure 5.1).

This method benefits from very large numbers of events (the cross-section for  $\gamma^* + \text{jets}$  production is roughly four times that of  $Z \rightarrow \nu\nu + \text{jets}$ ) but is more theoretically complex

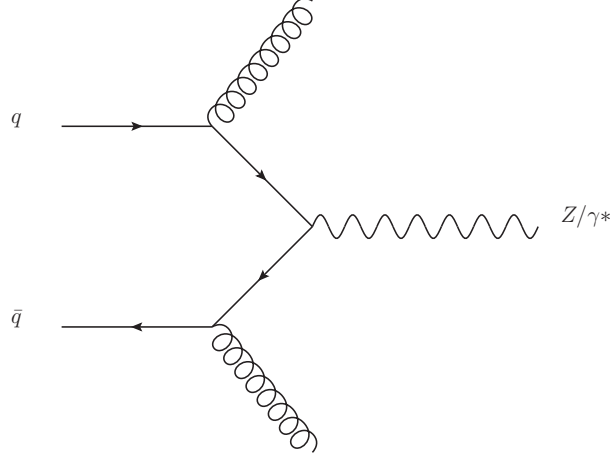


Figure 5.1: Typical tree-level production process for  $Z$  or  $\gamma^* + \text{jets}$  at the LHC.

than the  $Z \rightarrow \ell\ell$  method. While the ratio of the vertex couplings of  $Z$  and  $\gamma^*$  is a well-defined constant, the cross-section ratio gains a kinematic dependence from the finite mass of the  $Z$ . However, at very large vector boson  $p_T$ , the effect of the  $Z$  mass is relatively small, allowing a precise estimation of the ratio. The final theoretical uncertainty on the estimate can be as low as 7% [42]. The dilepton and photon methods were both used in [1] to produce statistically independent estimates of the  $Z \rightarrow \nu\nu + \text{jets}$  background.

Another potential approach – the one employed in this analysis – is to use  $W \rightarrow \ell\nu$  events. This has the advantage of using a control process which is very similar to the target process while benefitting from a much larger number of input events than the  $Z \rightarrow \ell\ell$  method. In effect, this method is a middle way between the simple but statistically limited  $Z \rightarrow \ell\ell$  approach and the events-rich but relatively complex photon method. The  $W \rightarrow \ell\nu$  method is the subject of the remainder of this section.

### 5.2.2 Control region definition

Each signal region (see table 4.7) has a parallel 1-lepton control region, designed to capture a large number of  $W \rightarrow \ell\nu + \text{jets}$  events, while keeping QCD and top quark contamination to a minimum. These are defined by the set of cuts shown in table 5.1; the baseline cuts for event cleaning, described in section 4.4, are also applied. The trigger names can be translated

| Cut                                                  | Electron                                                | Muon            |
|------------------------------------------------------|---------------------------------------------------------|-----------------|
| Trigger                                              | EF_e20_medium                                           | EF_mu18         |
| Lepton                                               | One signal electron                                     | One signal muon |
| Lepton veto                                          | No second baseline lepton ( $e$ or $\mu$ )              |                 |
| Transverse mass                                      | $30 < M_T < 100$ GeV                                    |                 |
| $b$ -jet veto                                        | No $b$ -tagged jets with $p_T > 40$ GeV                 |                 |
| Missing momentum                                     | Lepton added vectorially, $E_T^{\text{miss}} > 130$ GeV |                 |
| Jets, $E_T^{\text{miss}}/m_{\text{eff}}, \Delta\phi$ | As per signal regions                                   |                 |

Table 5.1: Definition of the 1-lepton control regions used to estimate  $Z \rightarrow \nu\nu + \text{jets}$ .

simply as “an electron trigger with a  $p_T$  threshold of 20 GeV at EF” and “a muon trigger with a  $p_T$  threshold of 18 GeV at EF”. All other object definitions are given in section 4.5, and  $M_T$  is defined in section 4.6.

The contamination from QCD is reduced primarily by the transverse mass ( $M_T$ ) and “signal lepton” cuts, the  $t\bar{t}$  by the  $b$ -jet veto and  $Z \rightarrow \ell\ell$  by the second lepton veto. The upper limit on the transverse mass is intended to reduce contamination from any new physics processes involving single leptons. The contributions from QCD and top will ultimately be estimated from data using modified versions of these control regions, while the  $Z \rightarrow \ell\ell$ , given its similarity to the target  $W \rightarrow \ell\nu$  process and low relative rate, can be folded into the control sample definition. These concerns will be discussed in much more detail in later sections.

### 5.2.3 Method overview

There is a useful correspondence between  $W$  and  $Z$  production at a hadron collider, namely that for every diagram producing a  $W$  boson, we can instead produce a  $Z$  by substituting an up-type quark for a down-type quark, or vice-versa. For example, the following parton interactions produce a  $W^+$  plus one final-state parton:

$$ug \rightarrow W^+d \quad u\bar{d} \rightarrow W^+g \quad \bar{d}g \rightarrow W^+\bar{u}.$$

The three interactions are arranged in order of decreasing importance for  $W + 1$  parton production at the LHC [43]. The corresponding interactions which produce a  $Z$  are:

$$dg \rightarrow Zd \quad u\bar{u} \rightarrow Zg \quad \bar{u}g \rightarrow Z\bar{u}.$$

Additionally, there are three leading-order processes which produce a  $W^-$ , and these also have counterparts in  $Z$  production. This mapping means that the cross-section *ratio*,  $\sigma_Z/\sigma_W$ , in some region of phase space, should be relatively stable against theoretical and experimental uncertainties, compared to the numerator or denominator alone [44, 45]. We might expect the ratio to remain sensitive to uncertainties in the parton distribution functions (PDFs) for up/down-type quarks and gluons in the proton. However, studies have shown that the sensitivity of the ratio to different choices of PDF set is relatively low [38].

The partial cross-section  $\tilde{\sigma}$  for  $Z \rightarrow \nu\nu$  production in a region of phase space  $X$  (e.g. 4-jets,  $m_{\text{eff}} > 1000$  GeV) may be obtained from the observed  $W \rightarrow \ell\nu$  cross-section as follows:

$$\tilde{\sigma}_{Z \rightarrow \nu\nu}^{\text{data}} = \tilde{\sigma}_{W \rightarrow \ell\nu}^{\text{data}}(\ell \rightarrow \nu) \cdot \frac{\tilde{\sigma}_{Z \rightarrow \nu\nu}^{\text{MC}}}{\tilde{\sigma}_{W \rightarrow \ell\nu}^{\text{MC}}(\ell \rightarrow \nu)}, \quad (5.1)$$

where  $\ell \rightarrow \nu$  indicates that the visible lepton is treated as a neutrino for the purposes of deciding whether a  $W$  event enters  $X$ . This is to ensure that we compare  $W$  and  $Z$  events which have comparable production topologies.

In practice, the total number of  $W$  events in  $X$  cannot be measured directly. Instead, it is accessed by way of the measured cross-section in a control region:

$$\tilde{\sigma}_{W \rightarrow \ell\nu}^{\text{data,CR}}(\ell \rightarrow \nu) = A \cdot \epsilon \cdot \tilde{\sigma}_{W \rightarrow \ell\nu}^{\text{data}}(\ell \rightarrow \nu). \quad (5.2)$$

The ratio of the measured and total cross-sections is given by  $A \cdot \epsilon$ , where  $A$  is the acceptance and  $\epsilon$  the efficiency. More specifically,  $A$  is the fraction of  $W$  events which meet the kinematic requirements of the control region selection cuts (e.g. transverse mass, lepton  $p_T$ ,  $|\eta|$ ), and  $\epsilon$  represents the fraction of accepted events which also pass the lepton reconstruction and identification requirements (including the trigger). In predicting the  $Z$  background, we can



account for these losses by substituting (5.2) into (5.1), giving

$$\tilde{\sigma}_{Z \rightarrow \nu\nu}^{\text{data}} = \frac{1}{A \cdot \epsilon} \cdot \tilde{\sigma}_{W \rightarrow \ell\nu}^{\text{data,CR}}(\ell \rightarrow \nu) \cdot \frac{\tilde{\sigma}_{Z \rightarrow \nu\nu}^{\text{MC}}}{\tilde{\sigma}_{W \rightarrow \ell\nu}^{\text{MC}}(\ell \rightarrow \nu)}.$$

Alternatively, we can define the simulated  $Z/W$  ratio in terms of the control region cross-section for  $W$ , i.e.

$$\tilde{\sigma}_{Z \rightarrow \nu\nu}^{\text{data}} = \tilde{\sigma}_{W \rightarrow \ell\nu}^{\text{data,CR}}(\ell \rightarrow \nu) \cdot \frac{\tilde{\sigma}_{Z \rightarrow \nu\nu}^{\text{MC}}}{\tilde{\sigma}_{W \rightarrow \ell\nu}^{\text{MC,CR}}(\ell \rightarrow \nu)}.$$

Here we have folded the acceptance and efficiency into the MC ratio, thus eliminating the need for separate estimates of these two quantities. In doing this, we must bear in mind that the lepton identification, reconstruction and trigger efficiencies in data are not necessarily well-modelled by the simulated samples (though by tuning of the detector model, the two are usually very close). These discrepancies can be compensated for by employing a set of scale factors, supplied by the ATLAS lepton performance groups (see section 5.5 for details).

The final step is to replace the observed  $W$  cross-section by the total cross-section in the control region, minus the contributions from top (pair-produced and single), QCD multijets faking a lepton,  $Z \rightarrow \ell\ell + \text{jets}$ , and diboson events. In practice, the  $Z \rightarrow \ell\ell$  and diboson contributions are small, giving

$$\tilde{\sigma}_{Z \rightarrow \nu\nu}^{\text{data}} = (\tilde{\sigma}_{\text{obs}}^{\text{data,CR}} - \tilde{\sigma}_{\text{top}}^{\text{data,CR}} - \tilde{\sigma}_{\text{QCD}}^{\text{data,CR}})(\ell \rightarrow \nu) \cdot \frac{\tilde{\sigma}_{Z \rightarrow \nu\nu}^{\text{MC}}}{\tilde{\sigma}_{W \rightarrow \ell\nu}^{\text{MC,CR}}(\ell \rightarrow \nu)}.$$

The top and QCD contributions may be estimated by defining control regions with slightly looser requirements than the main  $W$  control region. The extra events which are admitted by the loosened cuts are then used to estimate the numbers of non- $W$  events in the main control region, using the so-called matrix method. The matrix method, and its application, are described in detail in section 5.4.

### 5.2.4 The $Z/W$ differential ratio

For this analysis, the differential cross-section ratio

$$\frac{\tilde{\sigma}_{Z \rightarrow \nu\nu}^{\text{MC}}}{\tilde{\sigma}_{W \rightarrow \ell\nu}^{\text{MC,CR}}(\ell \rightarrow \nu)}$$

is calculated in bins of the discovery variable  $m_{\text{eff}}$ , i.e. the scalar sum of the jet transverse momenta and the missing transverse energy. We will refer to this binned ratio as a *transfer function*.

As described in section 4.7, this analysis uses four signal regions, with 2, 3 and 4 jets and one additional 4-jet region with a higher subleading jet cut. The effective mass is calculated using the first 2/3/4 jets in the 2/3/4-jet signal regions, and using all jets with  $p_{\text{T}} > 40$  GeV in the 4-jet inclusive signal region. We therefore require four transfer functions, each binned in a different effective mass variable. Figure 5.2 shows the transfer functions for each of the signal regions, computed from Alpgen  $W$  and  $Z$  samples. The figure also shows the choice of binning that will be used for this analysis. The ratio is shown with respectively: a) only  $W \rightarrow e\nu$  in the control region, b) only  $W \rightarrow \mu\nu$ , c) all  $W \rightarrow \text{lepton}$  contributions, including  $\tau$ . The reason for the  $W \rightarrow e\nu$  ratio being consistently below that of  $W \rightarrow \mu\nu$  is that the muon reconstruction – both at trigger level and offline – has a non-negligible inefficiency due to the presence of detector support structures and services in the muon system.

We use bins of increasing width in order to compensate for the lower event counts at high  $m_{\text{eff}}$ , both in the simulation and the data. Note that the final 1000–2000 GeV bins in each signal region are approximately equivalent to the event-counting regions A, B, D and E employed in [1]. The lower  $m_{\text{eff}}$  limits of 400–600 GeV are chosen so as to remove the turn-on region, where jet and missing momenta are close to their threshold values and where systematic uncertainties are potentially large.

The  $W$  and  $Z$  simulated samples have been reweighted to reflect the pileup conditions present during early 2011 data-taking. This procedure involves applying a weight to each simulated event according to the number of secondary interactions that were added during

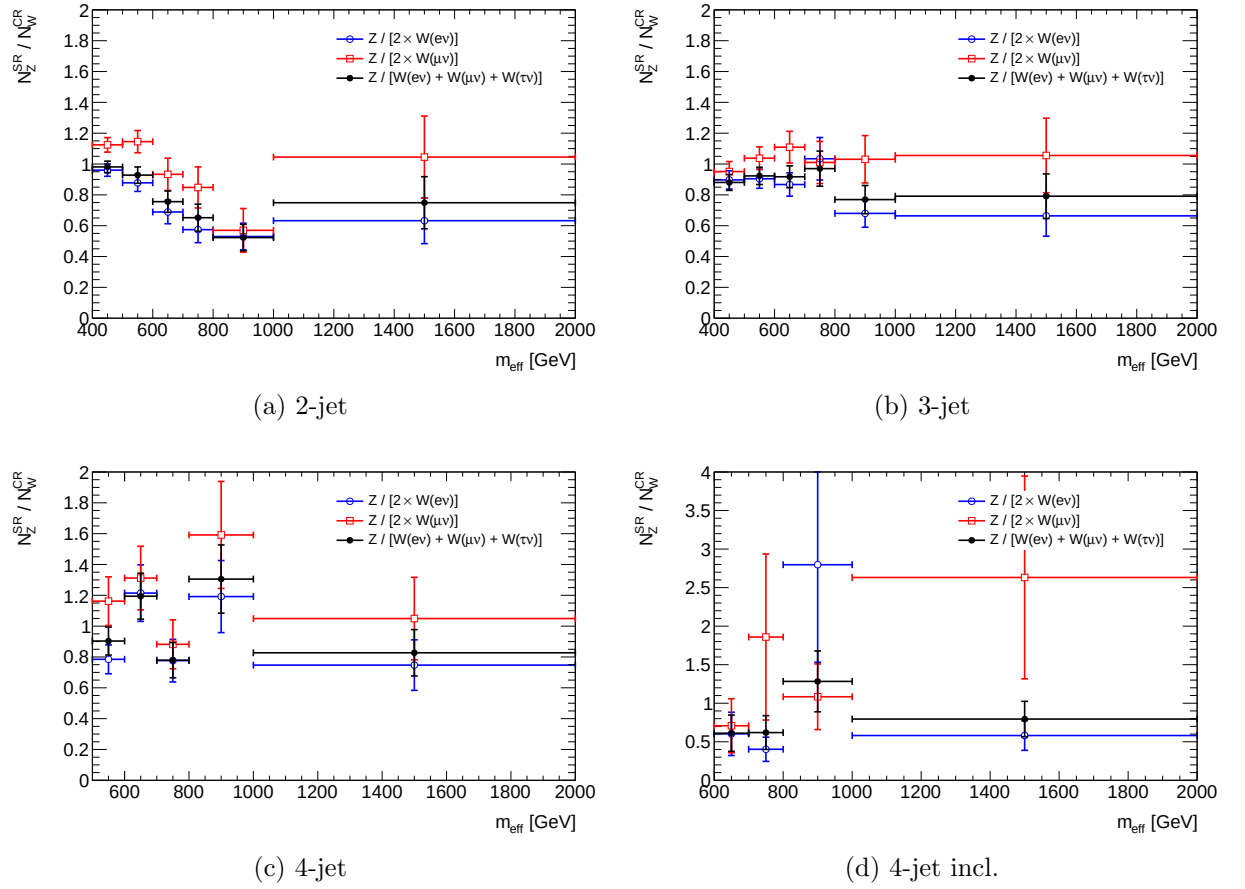


Figure 5.2: The simulated  $Z \rightarrow \nu\nu/W \rightarrow \ell\nu$  ratio in the four signal regions. The ratios for the  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  contributions to the control region are shown individually, with the  $W$  counts multiplied by two to facilitate comparison with the overall ratio. Also shown is the ratio with  $W \rightarrow e\nu$ ,  $W \rightarrow \mu\nu$  and  $W \rightarrow \tau\nu$  contributions combined.

simulation, in order that the reweighted distribution of the number of interactions is the same as in the data [46]. A side-effect of this process is that around half of the simulated events – those for which there are no events in the dataset with that amount of pileup – are weighted to zero, resulting in a loss of statistical power. This reweighting is largely responsible for the apparently discontinuous nature of some of the transfer functions; note the large statistical uncertainties. Prior to reweighting (plots not shown), the ratios appear smooth and continuous, as one would expect.

It is interesting to note that the pileup reweighting produces a statistically significant shift downwards in the  $Z/W$  ratio. This can be attributed to events with more secondary interactions having more jets and more diffuse calorimetric activity, resulting in a lower rate of leptons passing the isolation and overlap removal cuts. The shift is downwards because the simulated samples were produced with large numbers of secondary interactions; more, on average, than the data. Hence by reweighting to the data, we increase the rate at which leptons are successfully identified and thus the number of  $W$  events in the control region. All other pileup effects (e.g. secondary jets increasing the total jet multiplicity, decreased  $E_T^{\text{miss}}$  resolution) are expected to cancel between numerator and denominator.

In the next section we discuss generalising these transfer functions to incorporate the  $W + \text{jets}$  backgrounds in the signal region.

## 5.3 Estimating $W \rightarrow \ell\nu + \text{jets}$

### 5.3.1 Introduction

The  $Z \rightarrow \nu\nu$  background is particularly amenable to a 1-lepton control region technique. Once the lepton is added to the  $E_T^{\text{miss}}$ , the parallels between the control region and the target background are such that we require only well-understood and stable correction factors in order to move from one to the other. In particular, no kinematic extrapolation is required, which results in very small theoretical and experimental uncertainties. This section discusses

the application of the same control region to estimate the  $W \rightarrow \ell\nu + \text{jets}$  backgrounds and explores whether the same advantages can be exploited in this context.

### 5.3.2 Discussion

The  $W + \text{jets}$  backgrounds can be subcategorised into those that have a stable lepton in the final state ( $W \rightarrow e\nu$ ,  $W \rightarrow \mu\nu$ ,  $W \rightarrow \tau\nu \rightarrow [e/\mu]\nu\nu$ ) and those that do not ( $W \rightarrow \tau\nu \rightarrow \text{hadrons} + \nu\nu$ ). In the latter case, the event becomes background simply because there are no electrons or muons available to veto on. When an electron or muon is present, the event can enter the signal region through one of two routes: either the lepton fails the kinematic requirements that define an electron or muon (generally by going out of  $|\eta|$  acceptance) or it fails to meet the basic identification/reconstruction criteria.

It is reasonable to ask how closely our control region, which models leptons as missing momentum, approximates the behaviour of the various missed-lepton backgrounds:

**$W \rightarrow e\nu$  and  $W \rightarrow \tau\nu \rightarrow e\nu\nu$**  If an electron is not identified as such, it will generally be counted as a jet and hence will be seen as visible rather than missing transverse energy. If the electron is sufficiently energetic, the event may well end up in a signal region with a higher jet multiplicity requirement. If the electron goes out of acceptance, its behaviour will depend on the precise value of its pseudorapidity. If  $2.47 < |\eta_e| < 2.8$  – that is between the electron and jet upper limits – the electron will be treated as a jet. Beyond that, it will still be seen as visible energy (and hence correctly included in the  $E_T^{\text{miss}}$  calculation) but not as a jet. In any case, we see that modelling the lepton as missing momentum is not accurate in this case.

**$W \rightarrow \mu\nu$  and  $W \rightarrow \tau\nu \rightarrow \mu\nu\nu$**  A muon that is either out of acceptance or not identified will not, by definition, be accounted for in the  $E_T^{\text{miss}}$  calculation. This means that missed muons will always contribute additional missing momentum, and hence modelling them as such in the control region is entirely correct. There is potential for a muon to create visible energy in the calorimeters (by final state radiation or

bremsstrahlung) but this will be relatively rare, and result in a relatively small fraction of the muon’s energy being deposited.

**$W \rightarrow \tau\nu \rightarrow h\nu\nu$**  This component is irreducible and forms the largest single contribution to the  $W$  background. The presence of an additional neutrino means the modelling of the control region lepton as missing momentum is at least partially correct. However, there will evidently also be a jet-like contribution from the hadronic decay products. Neither the lepton  $\rightarrow E_{\text{T}}^{\text{miss}}$  nor the alternative lepton  $\rightarrow \text{jet}$  models are ideal in this case; the truth lies somewhere in between. The truly rigorous approach would be to redecay the leptons as taus via simulation, but this is beyond the scope of this study, and is discussed in detail elsewhere [47].

So overall the choice to model the lepton as missing momentum is reasonable, if not ideal. One alternative might be to model the lepton as a jet, which would be more appropriate for the electron component of the missed-lepton background, and may also be helpful in modelling  $W \rightarrow \tau\nu$  accurately. However, it would be difficult to use this control region alongside the original one, since the two would not be statistically independent: in a given  $n$ -jet channel, it is possible that the same event could enter both control regions. Keeping track of the dual events, and handling the associated statistical uncertainties, would not be trivial. Hence, for the sake of transparency and simplicity, we make the choice to always model leptons as missing momentum.

It is worth noting, at this point, that the electron part of the background – the only part for which the missing momentum description is manifestly wrong – represents only a small fraction of the missed-lepton total (see figure 5.3). The muon component is of roughly equal size, and the tau component is substantially larger.

### 5.3.3 Modified transfer functions

We now proceed to modify the transfer functions shown in figure 5.2 to include the  $W \rightarrow \ell\nu + \text{jets}$  backgrounds in the numerator; in other words, to predict the total vector boson +

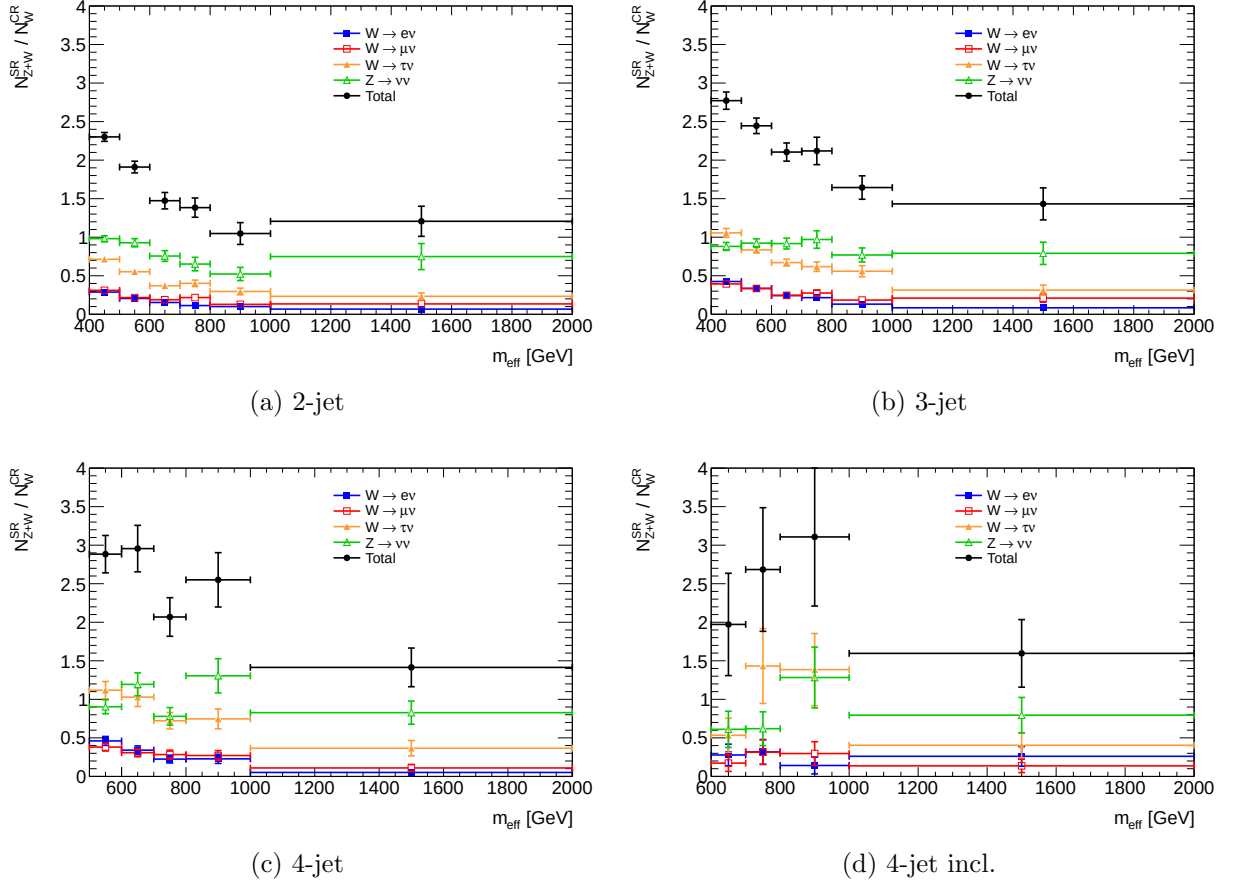


Figure 5.3: The simulated  $N(\text{signal})/N(\text{control})$  transfer functions in the four signal regions for  $W$  and  $Z$  events. The ratios for the  $W \rightarrow e\nu$ ,  $W \rightarrow \mu\nu$ ,  $W \rightarrow \tau\nu$  and  $Z \rightarrow \nu\nu$  contributions to the signal region are shown individually (the denominator is always the control region total). Also shown is the ratio with all signal region contributions combined.

jets background. The results are shown in figure 5.3. Overall, the background contributions from  $W$  and  $Z$  are seen to be approximately equal, though the relative amounts vary with the signal region and the value of the effective mass within a signal region.

In the next section, we add a further control region that will allow us to simultaneously estimate the top,  $W$  and  $Z$  backgrounds, thereby giving us a prediction of the total non-QCD background.

## 5.4 Estimating the total electroweak background

### 5.4.1 Introduction

A problem largely ignored in the preceding sections has been the presence of contaminants in the 1-lepton control regions used to estimate the  $W$  and  $Z$  backgrounds. The largest contaminant is semi-leptonic  $t\bar{t}$  with smaller contributions from dileptonic  $t\bar{t}$ , single top,  $W$ /top associated production and QCD multijets. We will first tackle the various top contaminants together, and return to the QCD question at the end of this section.

Ultimately, we will estimate the top contamination using a new control region which can itself be used to estimate the top background in the signal region. The original control region is then used to estimate the contamination from primary  $W$  + jets events in the top control region. Using the two control regions together will enable the simultaneous extraction of the top,  $W$  and  $Z$  backgrounds.

### 5.4.2 Method

A natural choice of control region for the top background uses the same cuts as the original 1-lepton control region (table 5.1) but with the  $b$ -jet veto reversed. That is, we require at least one jet with  $p_T > 40$  GeV which is tagged as a  $b$ -decay. This region should be dominated by top events, which almost invariably contain one or more real  $b$ -jets, with some small contribution from  $W$  +  $b$ -jet production,  $W$  + jets with a fake  $b$ -jet, and QCD heavy-flavour production (the last being ignored for the time being).

Let us assume that a fraction  $\epsilon_W$  of  $W$  + jets events (including  $W$  +  $b$ -jets) do not contain a reconstructed  $b$ -jet, thereby passing the  $b$ -jet veto. This number should be close to unity, since the cross-section for  $W$  +  $b$ -jets is substantially lower than that for  $W$  + light-flavour jets, and the rate of  $b$ -jet fakes is low. Let us also define the veto fraction  $\epsilon_t$  for top events ( $t\bar{t}$  + single top +  $Wt$ ). Then the number of events in the original control region,



which we may call CRW, is

$$N_{\text{CRW}} = \epsilon_W N_W + \epsilon_t N_t,$$

where  $N_W$  and  $N_t$  are defined to be the total number of  $W$  and top events with one identified lepton, but no  $b$ -jet tag or veto requirement. Likewise the number of events in the new  $b$ -tagged control region CRt is

$$N_{\text{CRt}} = (1 - \epsilon_W) N_W + (1 - \epsilon_t) N_t.$$

Solving these equations simultaneously gives us

$$\begin{aligned} N_W &= \frac{\epsilon_t N_{\text{CRt}} - (1 - \epsilon_t) N_{\text{CRW}}}{\epsilon_t - \epsilon_W}, \\ N_t &= \frac{\epsilon_W N_{\text{CRt}} - (1 - \epsilon_W) N_{\text{CRW}}}{\epsilon_W - \epsilon_t}, \end{aligned}$$

or equivalently

$$\begin{aligned} N_W^{\text{CRW}} &= \epsilon_W \frac{\epsilon_t N_{\text{CRt}} - (1 - \epsilon_t) N_{\text{CRW}}}{\epsilon_t - \epsilon_W}, \\ N_t^{\text{CRt}} &= (1 - \epsilon_t) \frac{\epsilon_W N_{\text{CRt}} - (1 - \epsilon_W) N_{\text{CRW}}}{\epsilon_W - \epsilon_t}. \end{aligned}$$

Now let us introduce two transfer factors,  $T_{WZ}$  and  $T_t$ , which map control region counts onto signal region background estimates:

$$T_{WZ} = \left. \frac{N_{W+Z}^{\text{SR}}}{N_W^{\text{CRW}}} \right|_{\text{MC}}, \quad (5.3)$$

$$T_t = \left. \frac{N_t^{\text{SR}}}{N_t^{\text{CRt}}} \right|_{\text{MC}}. \quad (5.4)$$

We can now express the estimated background in the signal region in terms of the control region counts and the two  $b$ -jet veto fractions:

$$N_{W+Z+t}^{\text{SR}} = T_{WZ} \epsilon_W \frac{\epsilon_t N_{\text{CRt}} - (1 - \epsilon_t) N_{\text{CRW}}}{\epsilon_t - \epsilon_W} + T_t (1 - \epsilon_t) \frac{\epsilon_W N_{\text{CRt}} - (1 - \epsilon_W) N_{\text{CRW}}}{\epsilon_W - \epsilon_t}.$$

Or, expressed in terms of the control region counts:

$$N_{W+Z+t}^{\text{SR}} = \alpha N_{\text{CRW}} + \beta N_{\text{CRt}}, \quad (5.5)$$

where

$$\begin{aligned} \alpha &= \frac{T_{WZ}\epsilon_W(1 - \epsilon_t) - T_t(1 - \epsilon_t)(1 - \epsilon_W)}{\epsilon_W - \epsilon_t}, \\ \beta &= \frac{T_t(1 - \epsilon_t)\epsilon_W - T_{WZ}\epsilon_W\epsilon_t}{\epsilon_W - \epsilon_t}. \end{aligned}$$

Equation 5.5 is the master equation for the signal region background prediction, and is applied to each  $m_{\text{eff}}$  bin in the four signal regions, where now  $N_{\text{CRW}}/N_{\text{CRt}}$  represent the binwise counts and  $T_{WZ}/T_t$  are the values of the transfer functions.

The only terms which have not already been discussed in detail are the efficiency factors  $\epsilon_W$  and  $\epsilon_t$ . These are calculated from simulation as follows:

$$\epsilon_i = \left. \frac{N_i^{\text{CRW}}}{N_i^{\text{CRW}} + N_i^{\text{CRt}}} \right|_{\text{MC}}. \quad (5.6)$$

Prior to calculating the ratio, the single-jet  $b$ -tagging efficiency (for real  $b$ -jets) and fake rate (other jets) are corrected to the values in data using scale factors supplied by the flavour-tagging performance group [48, 49]. We expect the efficiency to vary between signal regions, since the more jets are in the event, the higher the probability that one of them will be tagged as a  $b$ -jet, whether correctly or erroneously. However, we assume that within each signal region, the efficiencies are constant as a function of effective mass. This assumption is justified by figure 5.4, which shows the  $b$ -veto efficiency from simulation as a function of  $m_{\text{eff}}$  for each of the signal regions. The hatched uncertainty bands show the range of the  $m_{\text{eff}}$ -integrated veto efficiency when the  $b$ -tagging scale factors are varied within their ranges of uncertainty. That the binned efficiencies lie almost entirely within these envelopes demonstrates that our knowledge of the  $b$ -tagging efficiency in data is the limiting factor, and hence a pair of global efficiencies per signal region is adequate. The plots also demonstrate

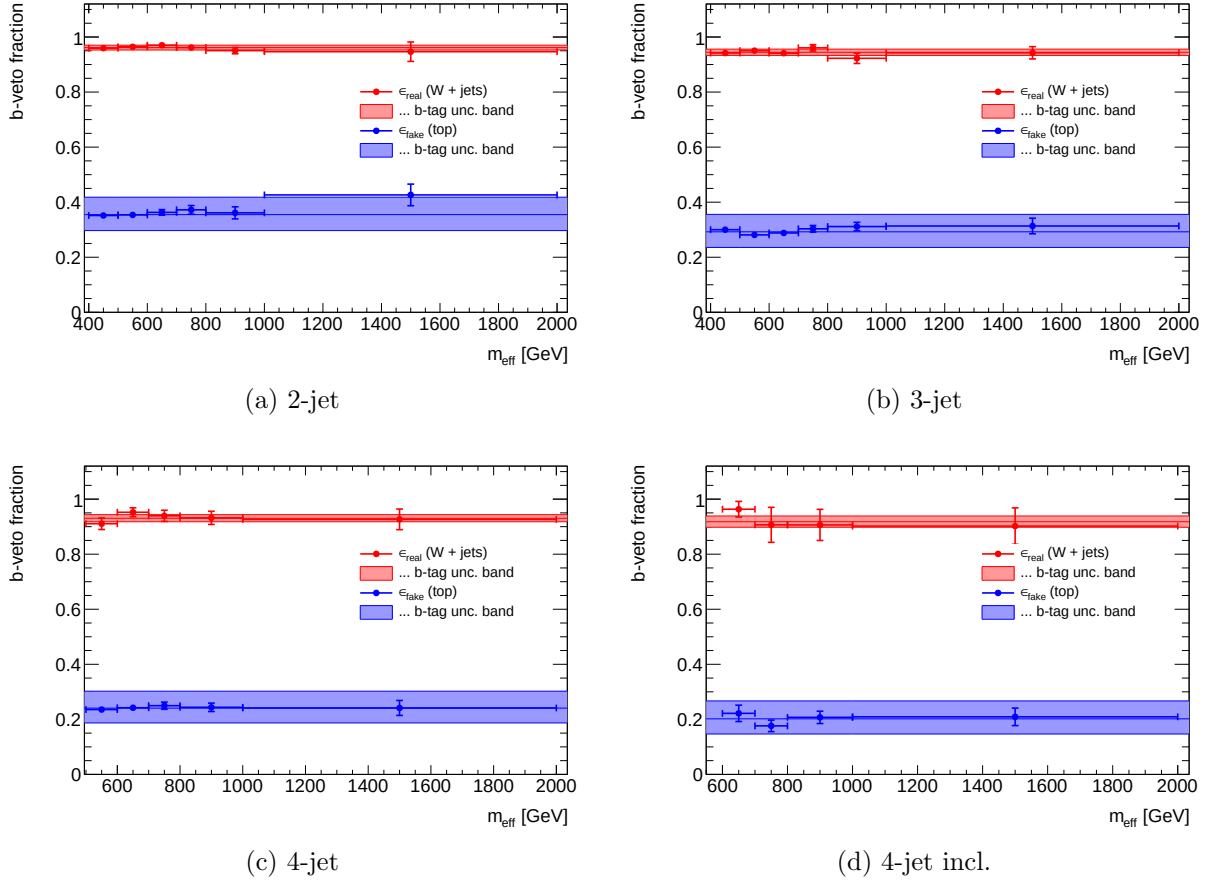


Figure 5.4: The efficiency of the  $b$ -jet veto for simulated  $W + \text{jets}$  and top events.

the dependence of the veto efficiency on the jet multiplicity.

It is useful to consider whether the efficiencies of equation 5.6 could feasibly be measured from data alone. The possibility rests on finding – without a  $b$ -tag or  $b$ -veto requirement – nearly pure samples of a)  $W + \text{jets}$  and b) top whose measured veto efficiencies would be representative of those in the signal regions. Obtaining pure samples is relatively easy: require 0–1 jets for  $W$ , two opposite-sign leptons for  $t\bar{t}$ . But the efficiencies obtained from these samples would not be representative of the signal regions, since the  $b$ -veto fraction is a function of the number of jets. This dependence could be corrected for, but this correction would require the use of simulated events, so the final result would be just as reliant on simulation as before.

| Flavour  | Tight cuts                                                      | Loose cuts                                         |
|----------|-----------------------------------------------------------------|----------------------------------------------------|
| Electron | Tight identification criteria<br>$p_T(\text{cone20})/p_T < 0.1$ | Medium identification criteria<br>No isolation cut |
| Muon     | $p_T(\text{cone20}) < 1.8 \text{ GeV}$                          | No isolation cut                                   |

Table 5.2: Changes made to the lepton selection criteria in order to estimate the QCD background in the 1-lepton control regions, where  $p_T(\text{cone20})$  denotes the total  $p_T$  of ID tracks within  $\Delta R = 0.2$  of the lepton track.

### 5.4.3 QCD background

In equation 5.5, we assume that the control regions are composed only of top and  $W$  events, whereas in reality there will be some contribution from QCD processes, both light and heavy-flavour. This contribution needs to be removed from  $N_{\text{CR}W}$  and  $N_{\text{CR}t}$  prior to applying equation 5.5. The removal is done using the “matrix method” [50, 51], which is fundamentally the same method as was used above to simultaneously extract the numbers of  $W$  and top events in their respective control regions (not to be confused with the “ABCD” control region technique, which is also sometimes known as the matrix method). The only difference is that now we compute the number of non-desired (QCD) events and subtract this number from the total, instead of calculating the number of desired events directly.

In the matrix method, we loosen the control region cuts so as to admit more QCD events, while keeping the number of events from the target process roughly constant. The specific cuts to be loosened are the lepton identification and isolation requirements, as laid out in table 5.2. The idea is that QCD events will contain predominantly low-quality and/or unisolated leptons. For example, an electron or muon from a  $b$ -quark decay will usually fall near a hadronic jet, and will therefore not be isolated. By contrast,  $W$  and top events should yield mostly high-quality and isolated leptons.

The method works as follows. Let us call the default control region cuts the “tight” selection, and the loosened cuts required by the matrix method the “loose” selection. Let us also define the target process (e.g.  $W + \text{jets}$ ) as “real” and the superfluous events (QCD)

as “fake”. Then we have

$$\begin{aligned} N_{\text{tight}} &= N_{\text{tight}}^{\text{real}} + N_{\text{tight}}^{\text{fake}}, \\ N_{\text{loose}} &= N_{\text{loose}}^{\text{real}} + N_{\text{loose}}^{\text{fake}}. \end{aligned}$$

Now let us define the efficiencies

$$\begin{aligned} \epsilon_{\text{real}} &= N_{\text{tight}}^{\text{real}} / N_{\text{loose}}^{\text{real}}, \\ \epsilon_{\text{fake}} &= N_{\text{tight}}^{\text{fake}} / N_{\text{loose}}^{\text{fake}}. \end{aligned}$$

We can now solve for  $N_{\text{tight}}^{\text{fake}}$ , the amount of background in the control region:

$$N_{\text{tight}}^{\text{fake}} = \frac{\epsilon_{\text{fake}}}{\epsilon_{\text{real}} - \epsilon_{\text{fake}}} \cdot (\epsilon_{\text{real}} N_{\text{fail}} - (1 - \epsilon_{\text{real}}) N_{\text{pass}}), \quad (5.7)$$

where  $N_{\text{pass}} = N_{\text{tight}}$  and  $N_{\text{fail}} = N_{\text{loose}} - N_{\text{tight}}$ . It should be clear from equation 5.7 that the method is most effective – least subject to statistical fluctuations – when  $\epsilon_{\text{real}} \gg \epsilon_{\text{fake}}$ .

The  $\epsilon_{\text{real,fake}}$  may be taken from data, in which case the method is entirely data-driven, or from simulation. If taken from data, two regions need to be defined in which  $\epsilon_{\text{real}}$  and  $\epsilon_{\text{fake}}$  can be measured. These regions must be such that either fake or real events are almost entirely dominant, and such that the derived  $\epsilon$  values are representative of those in the region where we intend to apply the matrix method. In reality, the measured values will not be exactly correct, but a limit can be set on the difference and included as a systematic uncertainty. If simulation is used, it is important that all the relevant lepton identification efficiencies are scaled to the data values, and the accompanying systematic uncertainties are properly accounted for.

For this analysis, the QCD contributions are estimated using the ATLAS software package “FakeLeptBkg”. The methods used to derive  $\epsilon_{\text{real}}$  and  $\epsilon_{\text{fake}}$  are documented in [50, 51]. The package also supplies statistical and systematic uncertainties on the estimate, which are propagated to the final results.

The differential fake lepton background estimations found using this method are shown in figures 5.5 ( $b$ -veto CR) and 5.6 ( $b$ -tag CR). The electron, muon and total estimates are shown along with the total (statistical  $\oplus$  systematic) uncertainties. The electron component is typically much larger since it is much easier for a jet to fake an electron than it is to fake a muon: jets and electrons are both primarily calorimeter objects, whereas muons are reconstructed in a different way altogether. In fact, it is likely that the majority of the muons seen here are not “fake” at all, but are real muons coming from heavy quark decay (but still referred to as fake for terminological convenience). Comparison with later figures will reveal that the relative contribution to the control regions from QCD is small, though not negligibly so. In several bins we get a negative estimate for the fake lepton background: we can see from equation 5.7 that this is not impossible. However, all negative predictions are compatible with zero within uncertainties, and so are used without alteration.

#### 5.4.4 Summary so far

We are now at a stage where we can estimate the total non-QCD 0-lepton background using our two 1-lepton control regions. The following summarises the procedure for obtaining this estimate, together with full statistical uncertainties, while also serving as a reminder of the methods described so far in this chapter. For each of the  $n$ -jet signal regions we:

1. Obtain the measured  $m_{\text{eff}}$  distributions in the two 1-lepton control regions, one requiring a tagged  $b$ -jet (for the top background) and the other with a  $b$ -jet veto (for the  $Z/W$  backgrounds). Before the effective mass is calculated, the lepton is added vectorially to the missing momentum. This substitution is suited to estimating the  $Z \rightarrow \nu\nu$  background in particular, but is also partially applicable to the  $W$  and top missed-lepton backgrounds.
2. Make two equivalent distributions with the lepton identification requirements relaxed, and use these to estimate the fake lepton background from QCD, via the matrix method, in each of the two control regions. Subtract it, and propagate the associated uncertainty to the new totals.

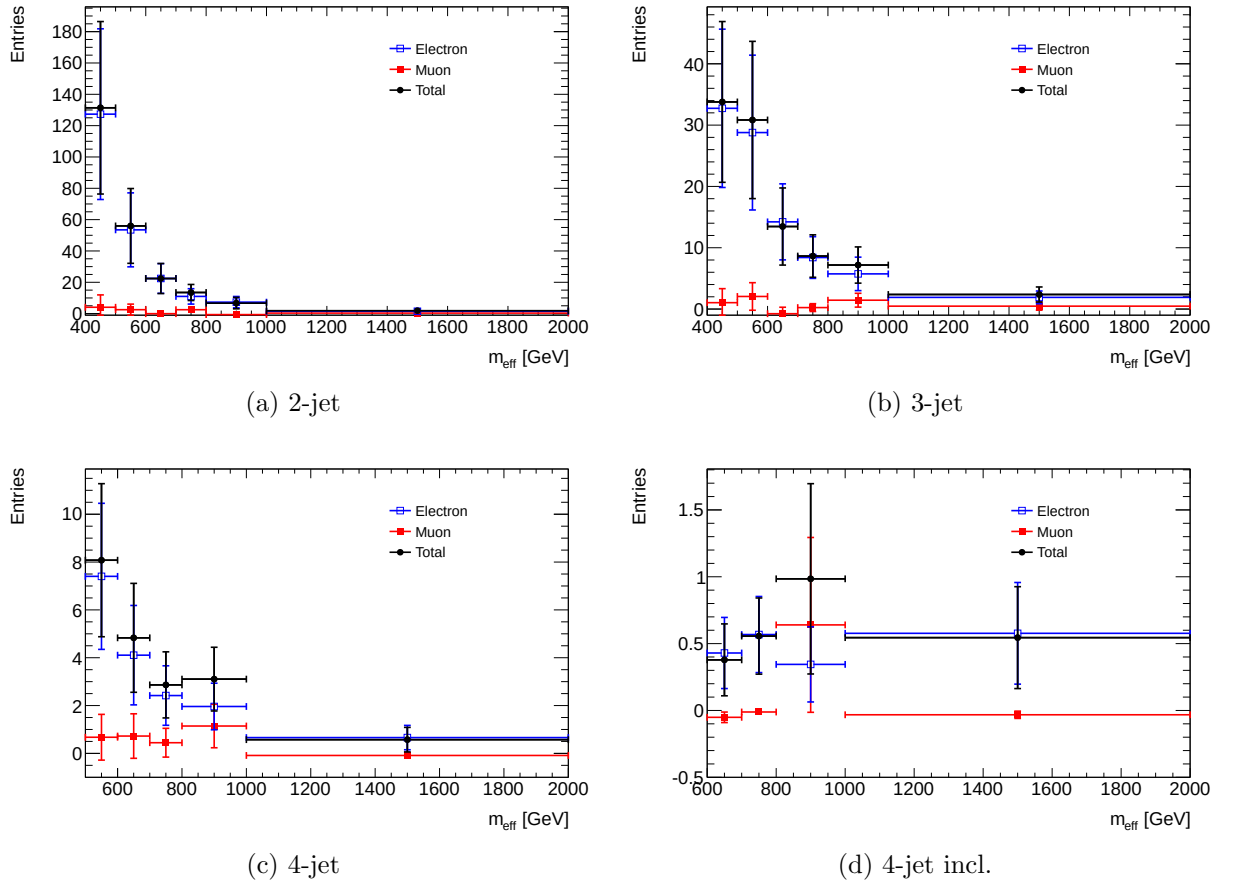


Figure 5.5: The QCD background prediction in the 1-lepton  $b$ -veto control region for the four main signal regions, estimated using the matrix method. Shown are the electron and muon contributions, and their sum. Uncertainties are systematic  $\oplus$  statistical, with the latter dominating.

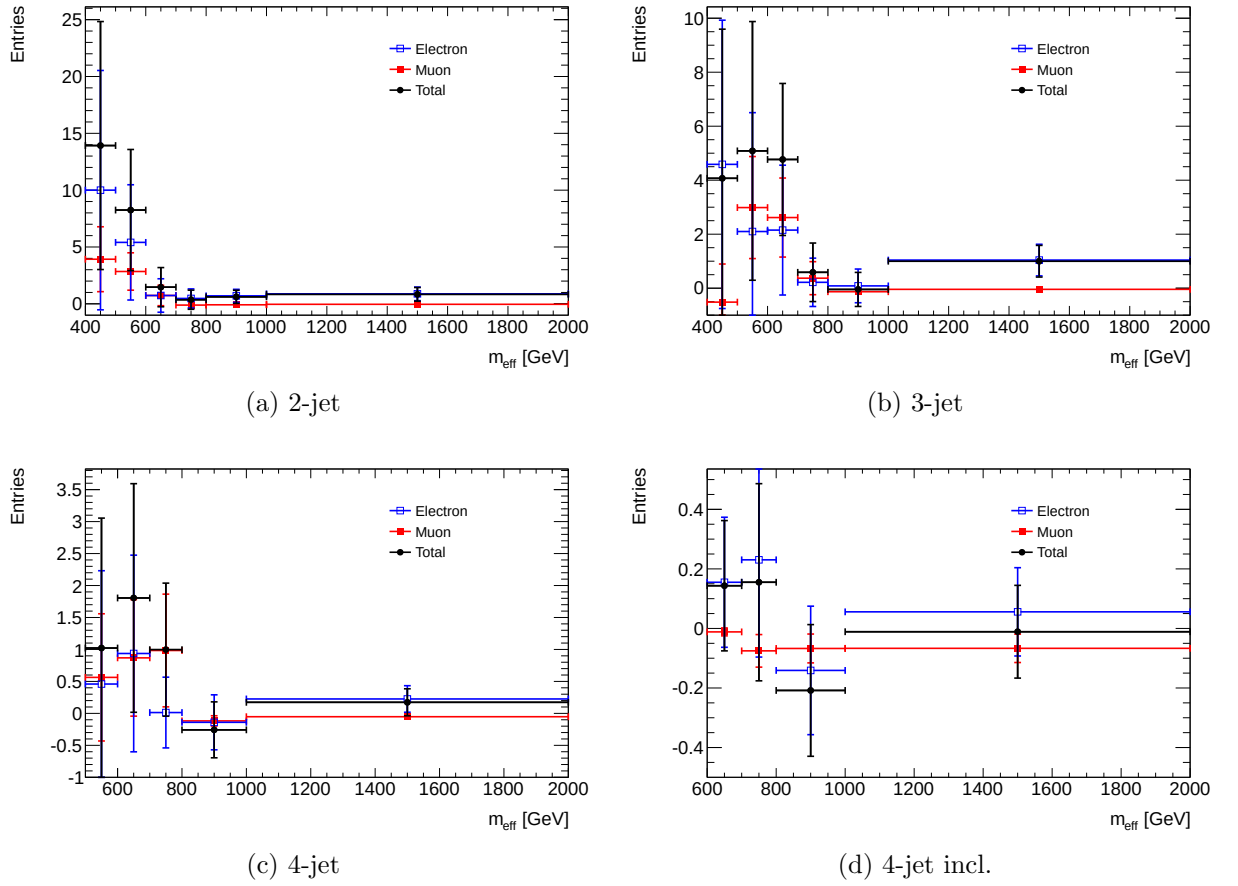


Figure 5.6: The QCD background prediction in the 1-lepton  $b$ -tag control region for the four main signal regions, estimated using the matrix method. Shown are the electron and muon contributions, and their sum. Uncertainties are systematic  $\oplus$  statistical, with the latter dominating.



3. Obtain the  $b$ -veto efficiency for 1-lepton  $W$  events and 1-lepton top events ( $t\bar{t}$  + single top) using simulation. Do this separately for each signal region to account for acceptance effects, but treat as a constant across  $m_{\text{eff}}$ .
4. Use the efficiencies found in step 3 to simultaneously estimate the number of  $W$  events in the  $b$ -veto control region and the number of top events in the  $b$ -tag control region. To put it another way, subtract the unwanted contribution from each control region.
5. Obtain two transfer functions from simulation, giving the ratios of a)  $Z \rightarrow \nu\nu$  and  $W \rightarrow \ell\nu$  in the signal region to  $W \rightarrow \ell\nu$  in the first control region, b) top in the signal region to top in the second control region.
6. Convolve the control regions distributions (backgrounds subtracted) with the transfer functions, to produce estimates for the  $Z \rightarrow \nu\nu$ ,  $W \rightarrow \ell\nu$ , and top backgrounds in the signal region.
7. Calculate the statistical uncertainty in each bin, taking into account the control region uncertainties (taken to be the square root of the bin contents), the uncertainties on  $N_{\text{fail}}$  used to estimate the QCD background, and the statistical uncertainties on the transfer functions.

This produces the central estimate, together with its statistical uncertainty. In the next section we discuss the systematic uncertainties affecting this analysis and how we propagate their effects to the final background estimate.

## 5.5 Systematic uncertainties

Systematic uncertainties affect both the transfer functions and the  $b$ -veto efficiencies. The QCD background estimate also has systematic uncertainties associated with it, being dominated by the difference between measurements of  $\epsilon_{\text{fake,real}}$  in various real and simulated control regions. These are handled separately by the FakeLeptBkg package and will not be considered further here.

Systematic uncertainties reflect an uncertainty in the modelling of reality by the simulation; they arise when the real-life value of some experimental parameter is not precisely known. Below we list the main uncertainties relevant to this analysis. All uncertainties associated with physics objects (jets, leptons,  $E_T^{\text{miss}}$ ) are generated by the relevant ATLAS performance group.

- The **jet energy scale** (JES) is the calibration whereby jet energies, measured at the EM scale in the ATLAS calorimeters, are corrected to the hadronic scale. The scale is derived primarily in simulation, by comparing the energies of truth-level and reconstructed jets as a function of  $p_T$  and  $\eta$ . Due to uncertainties in the event generation (e.g. the underlying event model) and the detector simulation (e.g. additional detector material), the calibration deduced using simulation may differ somewhat from that of the real detector. The jet energy scale uncertainty is a measure of how well this difference is constrained [52].
- A related concept is the **jet energy resolution** (JER), which characterises the spread of calibrated jet energies about the mean for a given true energy. The JER is measured using a combination of Monte Carlo truth information and data-driven techniques, including a dijet balance method. The data and simulation are found to be in agreement to within their own systematic uncertainties. An overall uncertainty is derived by comparing JER measurements made using simulation and data, and its potential impact evaluated by resmearing the simulated jet energies [53].
- The **electron energy scale** in data is measured and corrected using resonances such as  $J/\psi$  and  $Z$ , and the  $E/p$  ratio measured from  $W \rightarrow e\nu$  events. The systematic uncertainties on the correction come from a wide variety of sources, including the presence of dead material in front of the calorimeters, and limited knowledge of the presampler energy scale. The **electron energy resolution** is also measured in data, and used to smear the momenta of all simulated electrons [10].
- The **muon energy resolution** in simulation is corrected by smearing the transverse momenta of the simulated muons using the measured resolution in data. The muon

spectrometer and inner detector components of the momentum are smeared separately. The data measurement is done using the  $Z \rightarrow \mu\mu$  peak and also by comparing the ID and MS measurements in  $W \rightarrow \mu\nu$  and  $Z \rightarrow \mu\mu$  events. The systematic uncertainty here arises principally from multiple scattering in the inner detector, and alignment of the MS chambers [54].

- The **lepton identification, reconstruction and trigger efficiencies** in simulation are scaled to the data values using  $W \rightarrow \ell\nu$  and  $Z \rightarrow \ell\ell$  events. These scale factors are binned in pseudorapidity (and transverse energy for electrons only) and used to weight simulated events based on the kinematics of the identified lepton. The uncertainties in this case come from limited event counts (since the scale factors are binned) and systematic sources such as background subtraction [10, 12].
- The **effect of pileup** is evaluated using two different methods. The first, described in detail in section 5.2, applies pileup reweighting to the simulated events. The second method uses unweighted events to evaluate the transfer function shape, but scaling the transfer functions according to a pileup factor derived from the *total* number of events before and after pileup reweighting:

$$k_{\text{pu}} = \frac{(N_{\text{SR}}^{\text{tot}}/N_{\text{CR}}^{\text{tot}})_{\text{wgt}}}{(N_{\text{SR}}^{\text{tot}}/N_{\text{CR}}^{\text{tot}})_{\text{raw}}},$$

where the “wgt” and “raw” numbers are evaluated before and after pileup reweighting respectively. We might expect the two methods to give consistent results because we anticipate the effects of pileup to be limited to changing the lepton identification and overlap efficiencies, as discussed in section 5.2. There is no particular reason why this effect should be  $m_{\text{eff}}$ -dependent, so it seems reasonable that the transfer functions should change only by an overall factor. However, in certain bins (particularly in the middle range of the 2-jet signal region) these two methods give transfer functions which are not statistically consistent with each other. Given that the reasons for this are not understood\*, we take the two methods as delimiting the systematic uncertainty due to

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\*Several checks were performed to attempt to identify the source of the discrepancy: trigger, lepton identification, overlap removal,  $M_T$  cut, etc. However, there are too few events in the samples to identify a

pileup, with the central value being taken at their midpoint.

- The **missing transverse energy** is calculated using identified jets, electrons and muons. The calorimeter clusters associated with these objects are calibrated according to the nature of the object, to produce an estimate which is as close to the true  $E_T^{\text{miss}}$  as possible. In addition, the  $E_T^{\text{miss}}$  receives a contribution from clusters not associated with definite physics objects, the so-called **CellOut** term. A systematic uncertainty is associated with the energy scale and resolution of these clusters [15].
- The  $W$  and top control samples are differentiated by respectively **vetoing on, or requiring, a  $b$ -jet**. Similarly to the lepton identification efficiency, a scale factor is provided which corrects the value of the  $b$ -tagging efficiency in simulation to that measured in data. Additional scale factors are supplied which correct the light-flavour fake rate and the  $b$ -jet tagging inefficiency. The efficiencies and fake rates are measured in data using a wide array of techniques, including using a sample enriched in  $t\bar{t}$  events. The scale factor measurements have associated statistical and systematic uncertainties, which are then propagated through the analysis [41, 48, 49].
- The uncertainty from **parton distribution functions (PDFs)** is assessed in two ways. The first method compares the results obtained using leading order (LO) and next-to-leading order (NLO) PDF sets. The Alpgen  $W$  and  $Z$  samples used for this analysis were produced using the LO CTEQ6L1 PDF set [39]; the MC@NLO  $t\bar{t}$  and single top samples were generated using the CTEQ6.6 NLO PDF set [38]. The uncertainty is estimated by a) reweighting \* the Alpgen samples to use NLO PDFs, and b) reweighting the MC@NLO samples to use LO PDFs. In other words, the central value is defined using the default PDF sets, and the limits of the uncertainty using either all-LO or all-NLO PDFs. The uncertainty *within* a given PDF set is estimated using the CTEQ6.6 error PDFs, whereby the parameter space eigenvectors are varied

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single cause. It remains possible that there is simply a large statistical fluctuation that is correlated across the signal regions.

\*PDF reweighting is performed by calculating the probability density  $x_1 f(x_1, Q^2, q_1) \times x_2 f(x_2, Q^2, q_2)$  for the initial PDF set and the desired target PDF set and weighting each event by their ratio. Here the  $x_i$  are the proton momentum fractions for the two incoming partons,  $q_i$  their flavours and  $Q$  the momentum transfer between them. For this analysis, we use the LHAPDF libraries [55] to access the probability density functions for the various PDF sets.

up and down by their respective uncertainties (68% confidence level). The CTEQ6.6 set has 22 eigenvectors, each of which can be varied up or down to produce a total of 44 error PDFs. The uncertainty is assessed by reweighting to each of the error sets in turn, taking the central CTEQ6.6 PDF as the nominal.

- An estimate of the **theoretical uncertainty** is obtained by varying the parameters used to generate the Monte Carlo samples. Work has been done by others [56] to regenerate the Alpgen  $W$  and  $Z$  samples with one of the following variables shifted up or down: a) the renormalisation scale, which determines the strong coupling  $\alpha_s$ , b) the factorisation scale, which defines the cutoff between the collinear part of the interaction (the PDF) and the parton hard scatter, and c) the minimum  $p_T$  of partons which are matched to truth jets, used to decide whether a event enters a given  $N$ -parton sample. The scales are varied up and down (independently) by a factor of two, and the minimum  $p_T$  by  $\pm 5$  GeV from its default value of 15 GeV. Since the different  $N$ -parton samples are not identically affected by these variations, the distribution shape of the combined sample is distorted. The MC@NLO top samples are not generated according to numbers of partons, so this method cannot be used directly. However, the fractional shifts can be estimated using Alpgen  $t\bar{t}$ . The theoretical uncertainties are anticipated to be small for this analysis, so the numbers derived in this way, while only approximate, are sufficiently accurate for our purposes.

The *effects* of the systematic uncertainties are calculated by repeating all but the first two steps given in the procedure in section 5.4.4 but with one of the sources of uncertainty shifted up/down by one sigma. Steps 1–2 deal only with observed data, which is correct by definition. In this way, we derive a family of estimated background distributions, two per systematic uncertainty plus the central estimate, which can later be used as input to the limit-setting procedure.

## 5.6 Contributions from $Z \rightarrow \ell\ell$

So far in this analysis, the contribution from  $Z \rightarrow \ell\ell + \text{jets}$  ( $\ell = e/\mu/\tau$ ) has been ignored for the sake of simplicity. In reality, such events do make a non-negligible (though still small) impact in both the signal regions and the  $W$  control regions. In both cases the dominant component is  $Z \rightarrow \tau\tau$ , owing to the presence of real missing momentum and potentially electrons and muons.

When calculating the final background predictions shown in the next section,  $Z \rightarrow \ell\ell$  events are included in both numerator and denominator of the  $W + Z$  transfer functions (equation 5.3). This treatment is not perfect, since  $Z \rightarrow \tau\tau$  events will often have very different characteristics from  $Z \rightarrow \nu\nu$  and  $W \rightarrow \ell\nu$  events in the same signal region. For example, the missing momentum will be much more likely to lie in the direction of a jet. However, given that the fraction of  $Z \rightarrow \ell\ell$  events is small, this approach should be more than satisfactory.

## 5.7 Results

The observed control region distributions for the  $1.04 \text{ fb}^{-1}$  ATLAS summer 2011 dataset are compared with simulation in figures 5.7 and 5.8. The prediction from simulation is subdivided into  $W + \text{jets}$ ,  $Z + \text{jets}$ , and top contributions, where the first includes  $W + b\bar{b}$  production and the last includes single top. Also included in the histogram stack is the predicted background from QCD fake leptons, derived from data using the matrix method. The data/prediction ratio is shown in the lower panel of each subfigure, with the red hatched area representing the statistical uncertainty on the simulated events. Note that pileup reweighting has been applied to all simulated samples used in these figures.

We note that in figure 5.7(a)–(c) the simulation describes the data well in the lowest and highest regions of the  $m_{\text{eff}}$  range, but overestimates the data in the intermediate region. This is suspicious because we might expect any discrepancy, if it were due to imperfect

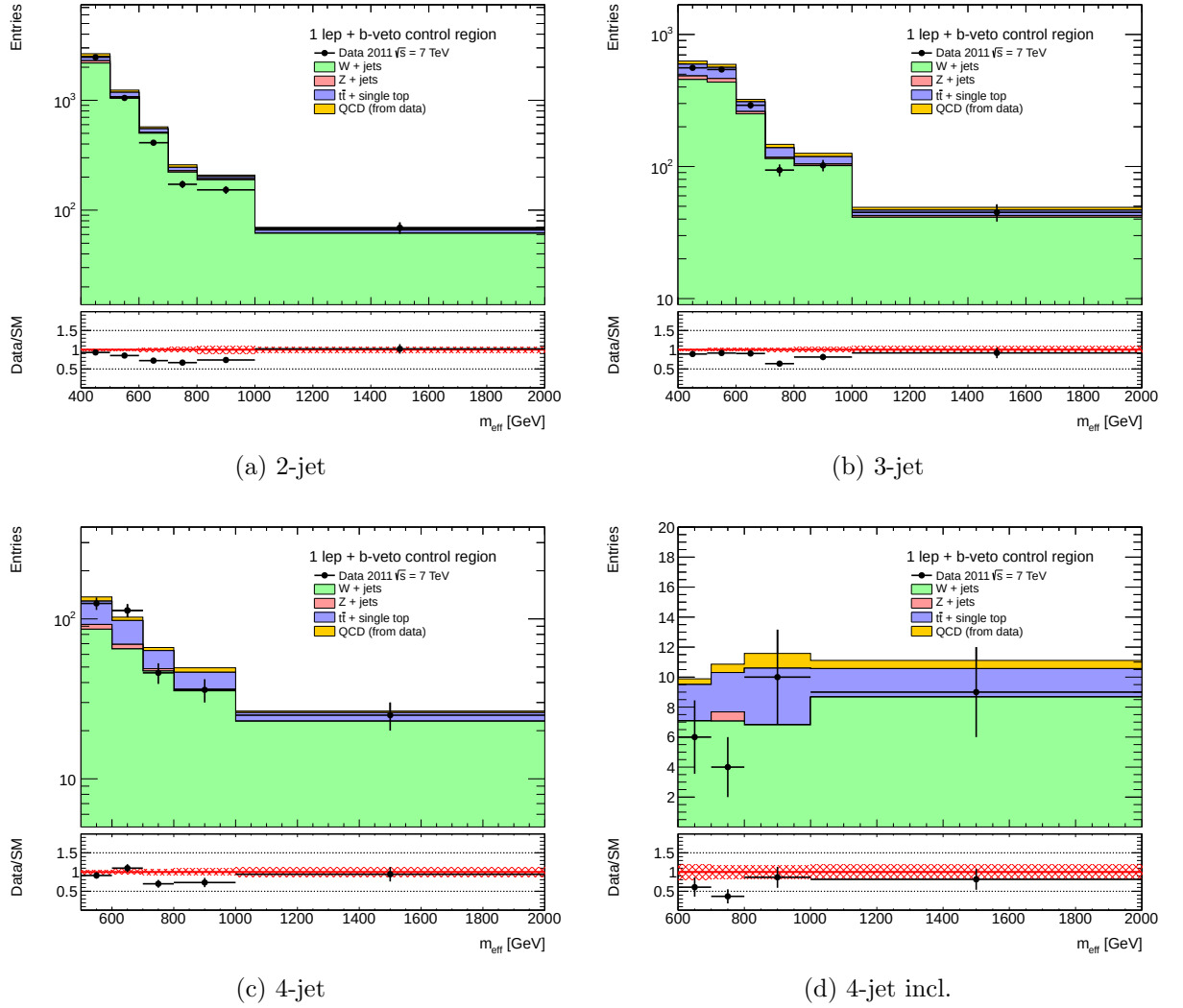


Figure 5.7: Observed  $m_{\text{eff}}$  distributions in the 1-lepton  $b$ -veto control regions for the four signal regions (black points) together with predictions from simulation (histograms). The red hatched area on the data/SM ratio subplot represents the statistical uncertainty on the simulated events.

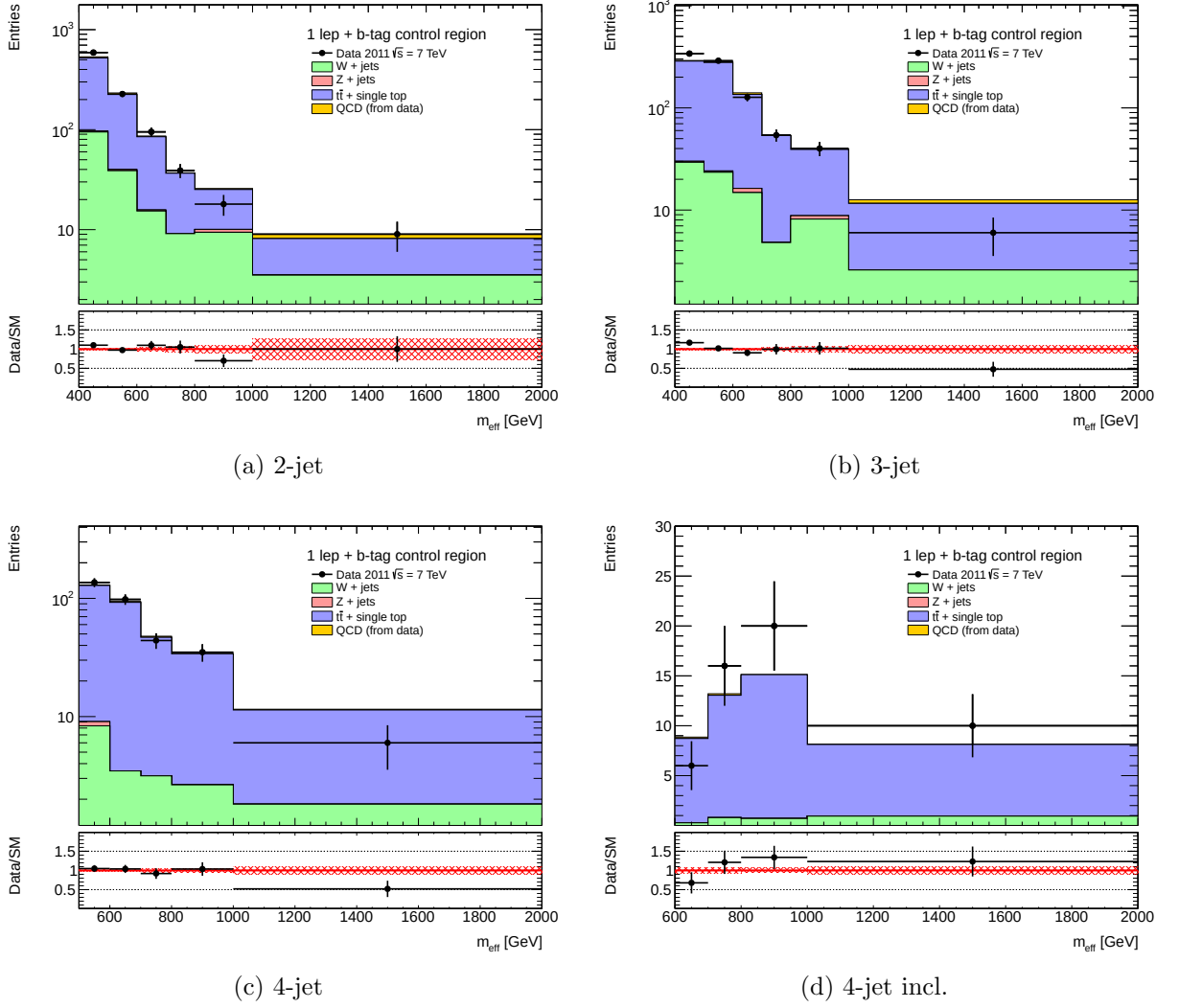


Figure 5.8: Observed  $m_{\text{eff}}$  distributions in the 1-lepton  $b$ -jet control regions for the four signal regions (black points) together with predictions from simulation (histograms). The red hatched area on the data/SM ratio subplot represents the statistical uncertainty on the simulated events.

modelling of very energetic and/or high-multiplicity events, to be largest in the highest  $m_{\text{eff}}$  bin. The difference is not consistent with any of the systematic uncertainties considered in this analysis, including the jet energy scale uncertainty. We shall see later that the feature is probably caused by a loss of efficiency in data in the muon control sample.

In figure 5.8 we see very close agreement between data and simulation in almost all bins, except the highest bins in the 3 and 4-jet signal regions, in which the simulation appears to overestimate the data. The number of events is rather low, however, so it is difficult to draw any definite conclusions.



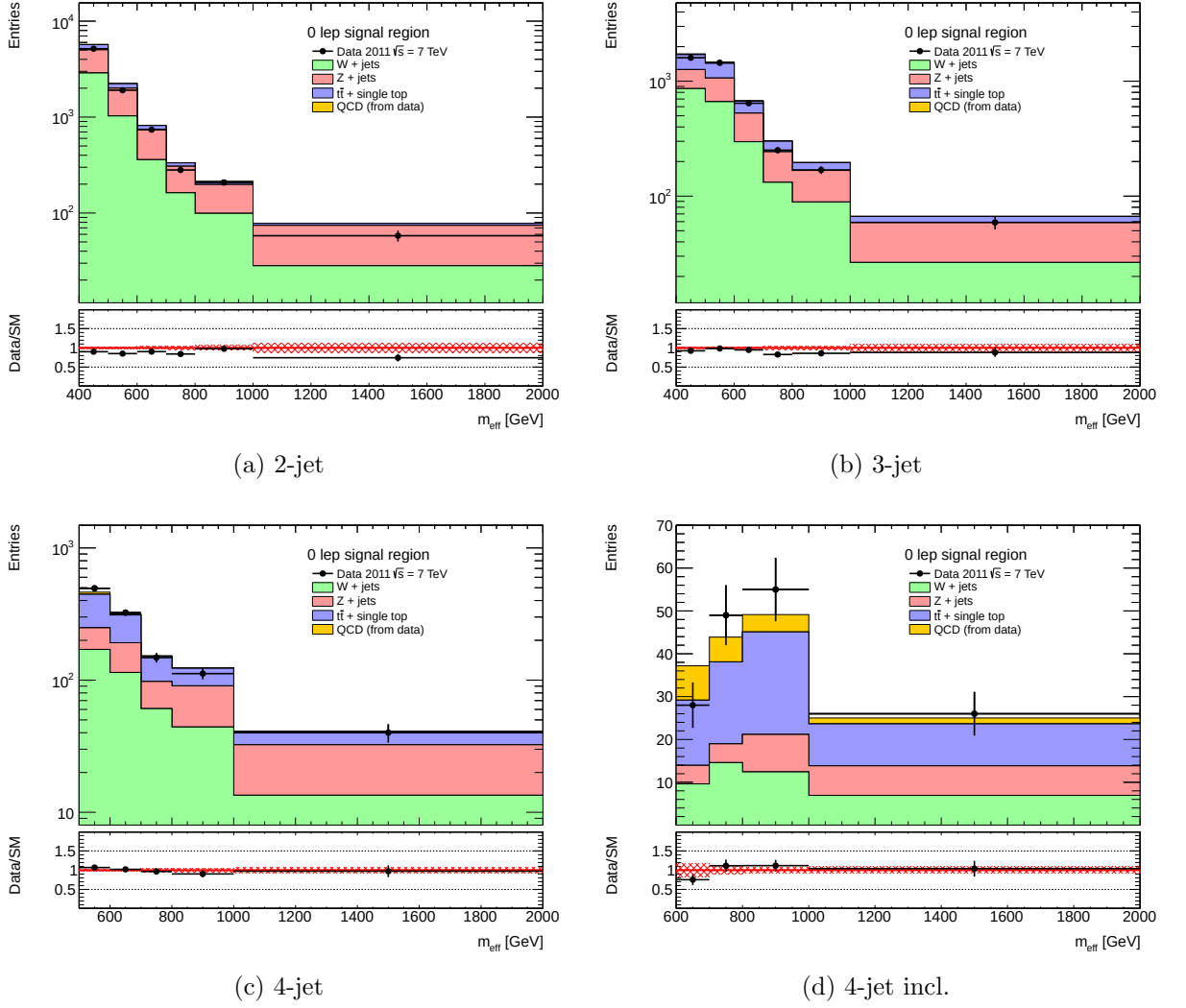


Figure 5.9: Observed  $m_{\text{eff}}$  distributions in the signal regions (black points) together with predictions from simulation (histograms). The red hatched area on the data/SM ratio subplot represents the statistical uncertainty on the simulated events.

Figure 5.9 compares the distributions in the signal regions. The QCD prediction is taken from [1], and is derived using a purely data-driven jet smearing method; full details can be found in [1] and [57]. There are no obvious “features” in the data which might correspond to a BSM signal. In fact, the agreement between data and simulation is remarkably good, considering the extremely energetic nature of the events being probed and the lack of Monte Carlo generator tuning in this area of parameter space.

Finally, figure 5.10 shows a comparison between the *data-driven* background estimate described in this chapter and the observed data in the signal regions. The predicted QCD background, calculated using the fully data-driven method, is added to the elec-

troweak prediction. Also shown is the deviation of the data from the prediction in units of  $\sigma_{\text{stat}} = \sqrt{\sigma_{\text{stat,data}}^2 + \sigma_{\text{stat,pred}}^2}$ .

The systematic uncertainties in any given  $m_{\text{eff}}$  bin are typically small compared to the statistical uncertainty. The most significant sources are pileup, the  $b$ -tagging efficiency, and the jet energy scale/resolution; see appendix A for the complete tables. The size of a systematic effect exceeds the statistical uncertainty only once, for pileup in the 800–1000 GeV bin of the 2-jet signal region, and effects larger than  $0.5\sigma_{\text{stat}}$  are rare. The statistical uncertainties themselves are dominated by the data control regions, with smaller contributions from the simulated transfer functions.

Each  $m_{\text{eff}}$  distribution has a region near 800 GeV where there is a statistically significant difference between the prediction and the data, in excess of  $2\sigma$ . These are difficult to explain in terms of the systematic uncertainties, which are typically too small to bridge the gap, and certainly not while retaining the good agreement seen elsewhere in  $m_{\text{eff}}$ .

The signal regions are not exclusive (i.e. they have events in common) and hence a statistical fluctuation that appears in one is likely to also affect the others. The consistent appearance of the features at roughly the same  $m_{\text{eff}}$  makes it plausible that they are the result of a single, large fluctuation. Nevertheless, we proceed by assuming that this is not the case.

## 5.8 Further investigations and cross-checks

The simplest cross-check to perform is to test if the feature is present using electron and muon control events separately. The transfer functions (equations 5.3–5.4) and  $b$ -veto efficiencies (equation 5.6) are correspondingly redefined to use only one lepton flavour at a time. The systematic uncertainties which are unique to each lepton sub-sample ( $e/\mu$  energy scale, resolution, identification and trigger efficiencies) are sufficiently small (of order 1%) that the two results should be statistically consistent. The results are shown in figures 5.11 (for electrons) and 5.12 (for muons).

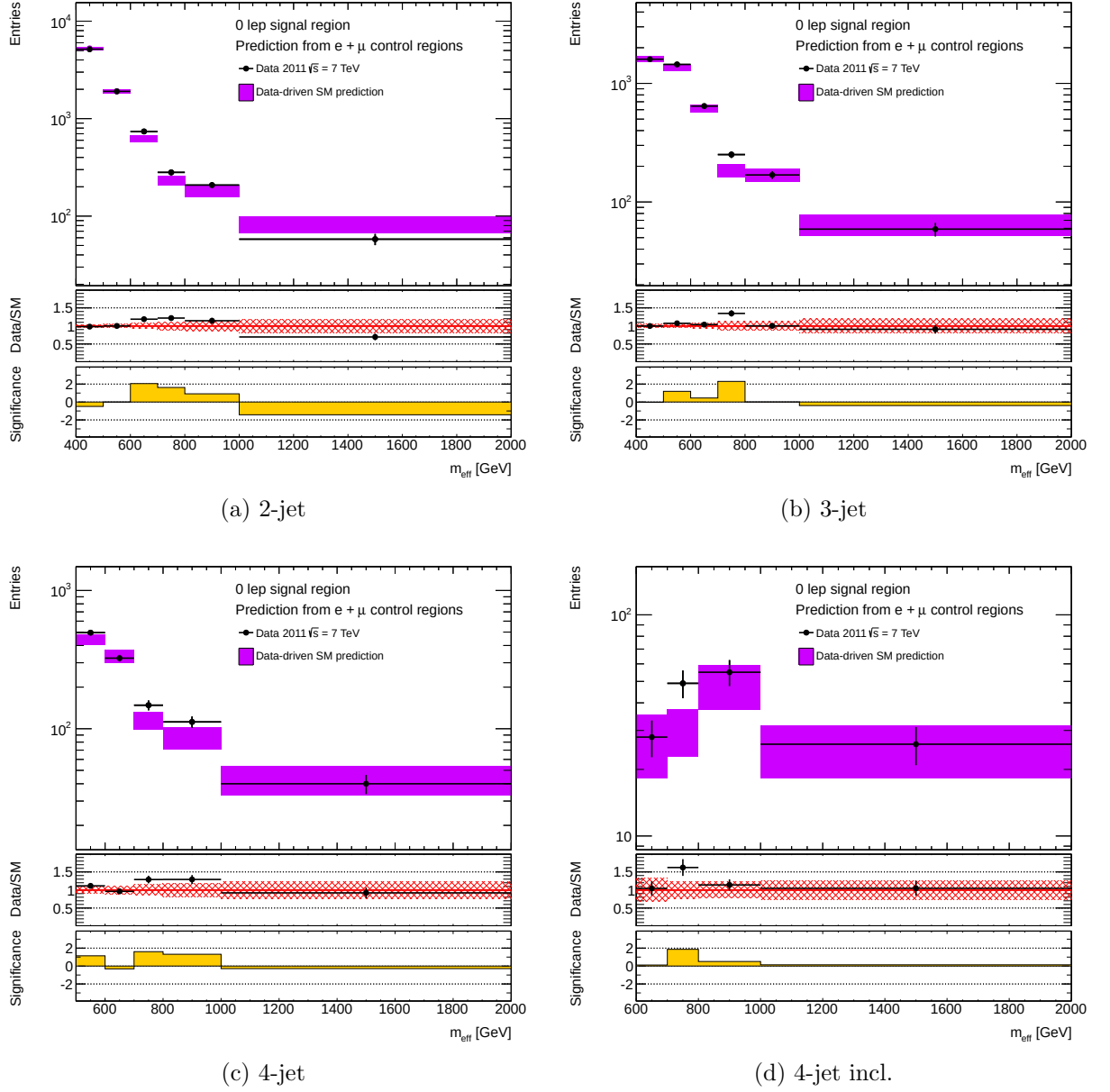


Figure 5.10: The total predicted background (Z + W + top + QCD) in the four signal regions, together with the observed distribution in data. The purple band shows the  $\pm 1\sigma$  range of the statistical uncertainty on the background prediction. The lower insets show the ratio of the observed data and the prediction, and the statistical significance (in  $\sigma_{\text{stat}}$ ) of the difference between them.

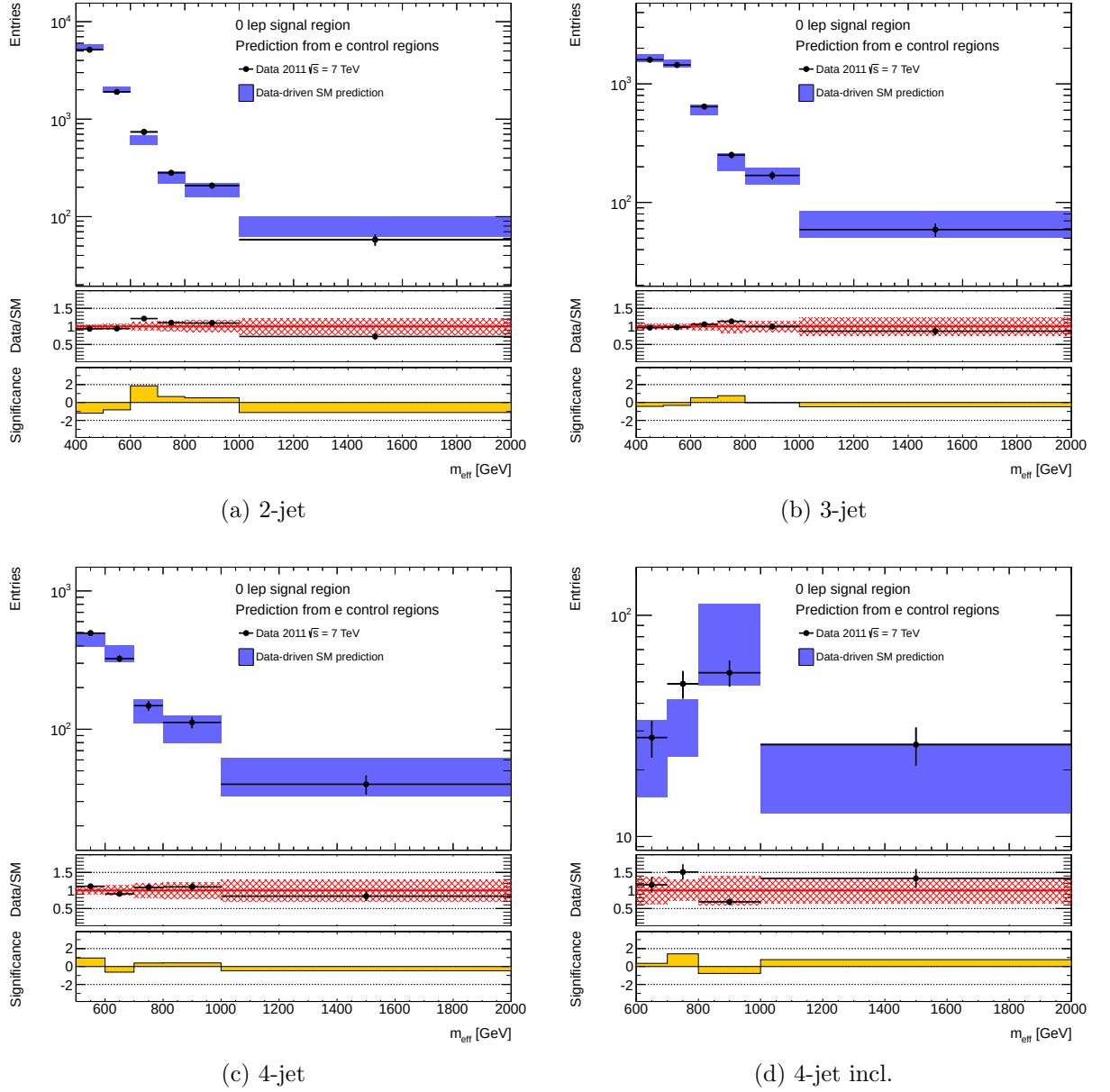


Figure 5.11: The total predicted background ( $Z + W + \text{top} + \text{QCD}$ ) in the four signal regions, estimated using electron control regions for the EW part, together with the observed distribution in data.

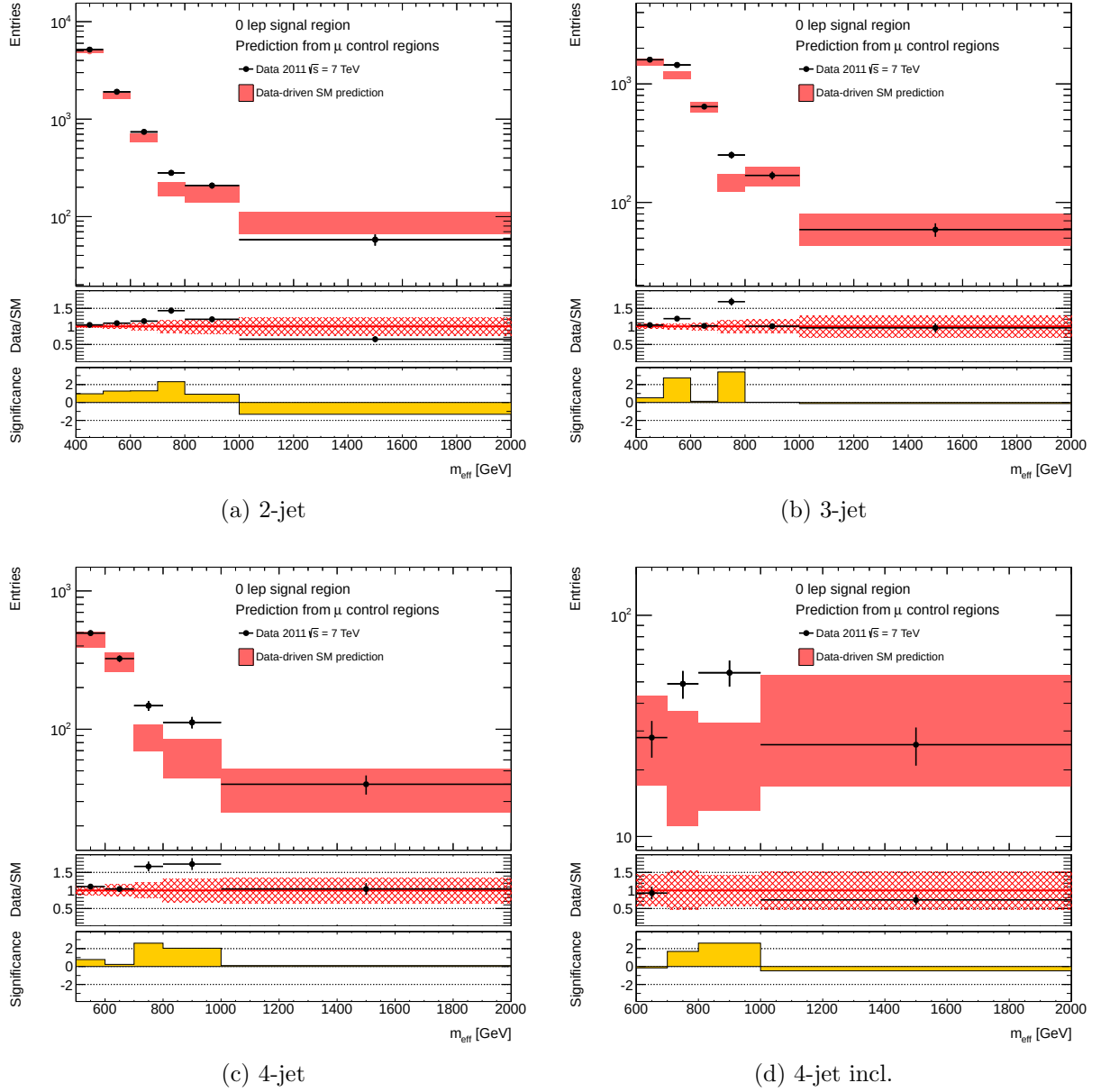


Figure 5.12: The total predicted background ( $Z + W + \text{top} + \text{QCD}$ ) in the four signal regions, estimated using muon control regions for the EW part, together with the observed distribution in data.

The difference is striking: using muons alone gives a background prediction which is well below the observed data at intermediate values of  $m_{\text{eff}}$ . Here “intermediate” can mean as low as 500 GeV and as high as 1000 GeV, depending on the signal region in question. By contrast, the electron estimate appears to match the data much more faithfully, with residual discrepancies that are consistent with statistical fluctuations. This evidence strongly suggests that a problem with the muon control sample, not a BSM signal, is responsible for the observed excesses.

The  $m_{\text{eff}}$  distributions in the  $b$ -veto control regions, using muon events alone, are shown in figure 5.13. We clearly see features corresponding to those in the signal regions, where the number of events in the parallel control region is well below what we would expect from simulation. There is an ambiguity about whether the observed event count is too low or the prediction too high, but the unusually rapid fall-off in the number of observed events suggests the former. Isolating the electron events instead of the muon events shows no unusual discrepancies, with the data/prediction ratio being flat or slowly-varying across the  $m_{\text{eff}}$  range.

A similar phenomenon was observed in the ATLAS 1-lepton SUSY search using the same dataset [58, 59], again for muons only, at approximately the same value of  $m_{\text{eff}}$  ( $\sim 800$  GeV). The reason the same feature was not noticed in [1] was probably that the  $W$  and top control regions treated the lepton as a jet rather than  $E_{\text{T}}^{\text{miss}}$ , meaning that the discrepancy was less apparent. Another factor could be the choice of signal regions, none of which would have been sensitive to a modest excess at intermediate  $m_{\text{eff}}$ .

Plotting the data/simulation ratio as a function of muon  $\eta$  or  $\phi$  does not reveal any regions where efficiency is obviously being lost. However, as a function of muon  $p_{\text{T}}$  we observe an apparent loss of events starting at 150–240 GeV, depending on the signal region (see figure 5.14). It is difficult to discern whether or not there are corresponding features in the  $b$ -jet control regions, given the very small numbers of events in this range of muon  $p_{\text{T}}$ .

There are many possible causes for this phenomenon; some can be ruled out relatively easily. For example, we do not recover the “lost” data events by relaxing the muon isolation

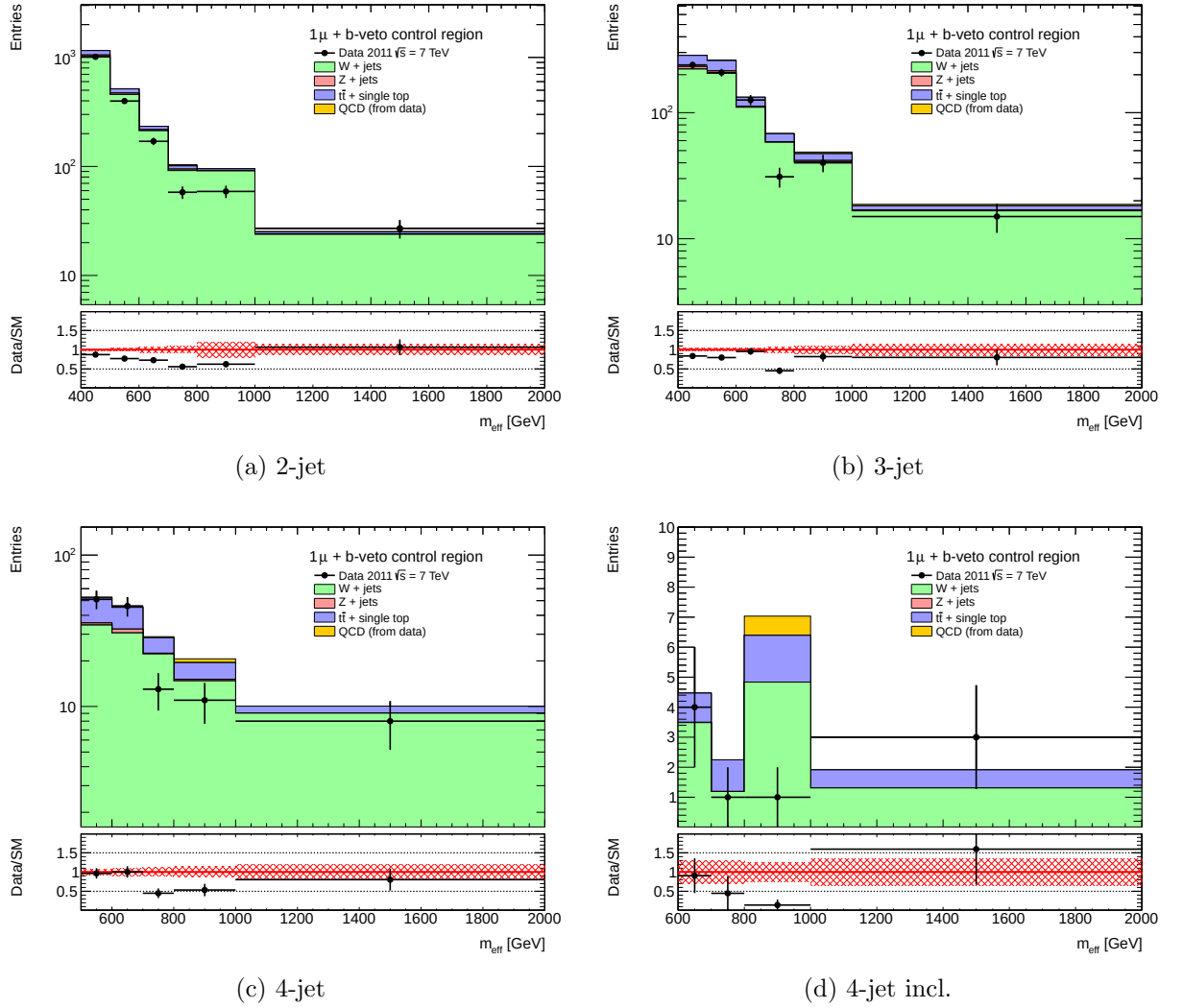


Figure 5.13: Observed  $m_{\text{eff}}$  distributions in the 1-lepton  $b$ -veto control regions, *using muons only*, for the four signal regions (black points) together with predictions from simulation (histograms). The red hatched area on the data/SM ratio subplot represents the statistical uncertainty on the simulated events.

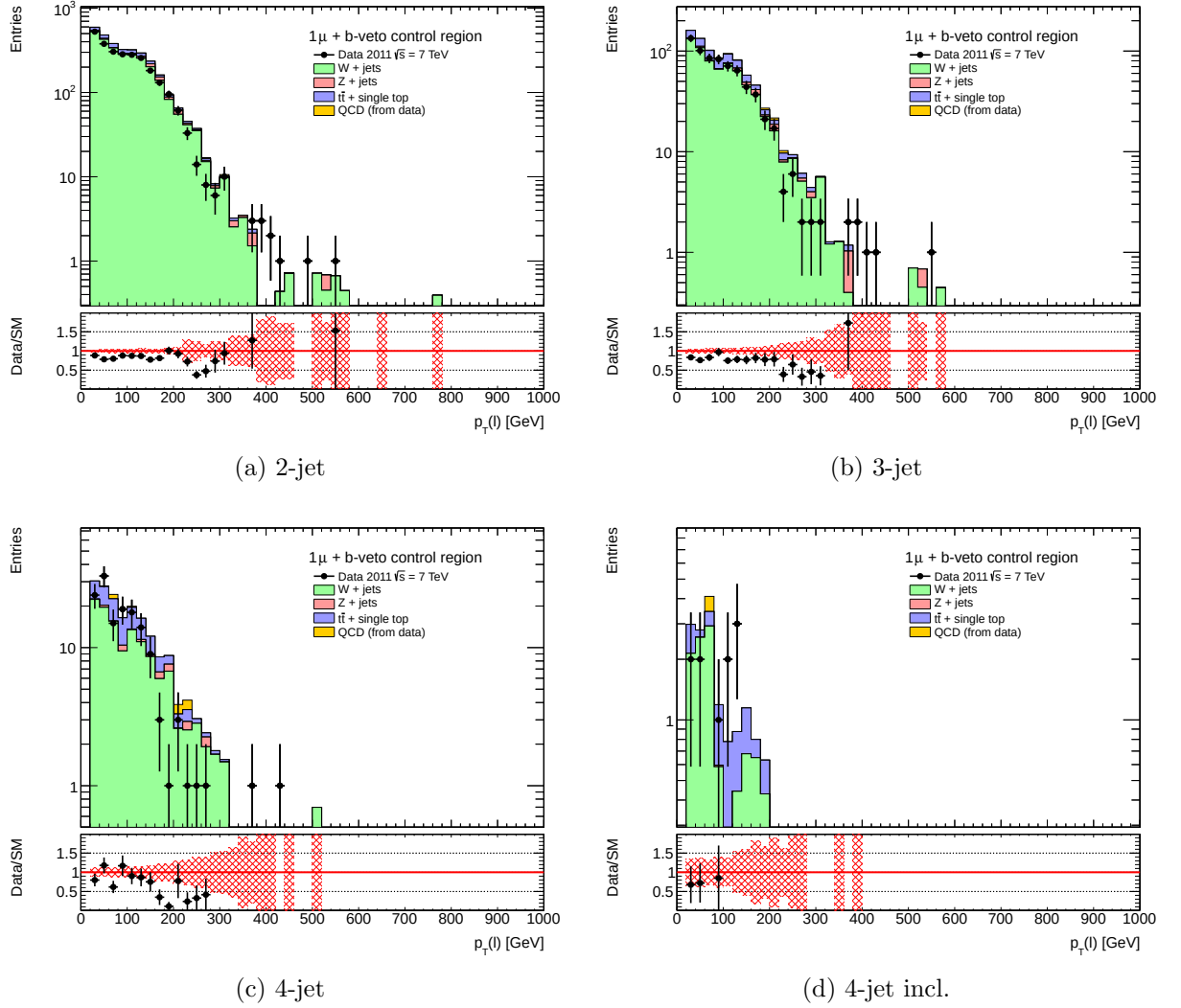


Figure 5.14: Observed muon  $p_T$  distributions in the 1-lepton  $b$ -veto control regions, for the four signal regions (black points) together with predictions from simulation (histograms). The red hatched area on the data/SM ratio subplot represents the statistical uncertainty on the simulated events.



cut, by allowing more than one lepton per event, or by removing the transverse mass cut. It is difficult to evaluate the effect of the trigger on the data, since events which did not pass the trigger are not guaranteed to have been recorded. Of course, it is possible (or probable) that there is no single cause, but several smaller effects acting in concert to produce the observed discrepancy.

Experts from the muon performance group were consulted and could not suggest a reason for the observed behaviour. They pointed out that the muon reconstruction and trigger efficiencies, measured using a  $Z$  tag-and-probe method, have only been evaluated up to  $p_T \simeq 100$  GeV, and in a low jet multiplicity environment. The high- $p_T$ , high- $n_{\text{jet}}$  region is unlikely to be accessible with  $Z$  events, but could be probed using  $W \rightarrow \mu\nu$  candidates, where a basic muon-like object has been identified and found to have a transverse mass consistent with  $M_W$ .

For the statistical tests that follow, we adopt an expedient solution, defining the control regions using electrons only. The anomalous muon behaviour, for the time being at least, remains as a curiosity that will hopefully inspire further study by others.

## 5.9 Summary

In this chapter, a method for estimating the electroweak backgrounds to 0-lepton SUSY searches was presented. The method is based around a pair of 1-lepton control regions per signal region, one with a tagged  $b$ -jet and the other with a veto on any such jets, to simultaneously estimate the top and vector boson + jets backgrounds. The predictions in the four signal regions, when added to estimates of the QCD background, give generally good agreement with the observed data. However, some unexplained features were found in the muon part of the  $W$  control regions, which suggest that further study is required.

## 5.10 Afterword: $W$ charge asymmetry

An effect which was not explicitly considered in the preceding analysis is the asymmetry between  $W^+$  and  $W^-$  at the LHC. This asymmetry arises from the different parton distribution functions (PDFs) for up and down-type quarks in the proton. Positive  $W$  bosons are produced in greater numbers than their negative counterparts, and with different kinematic distributions. For example, an ATLAS study using 2010 data showed a clear difference between positive and negative charges in the  $|\eta|$  distribution of muons from  $W$  decays [60].

Part of the asymmetry is due to the  $W$  polarisation, which affects the angular distributions of the  $W$  decay products. We expect the majority of  $W$  bosons at the LHC to be left-handed, since the  $W$  couples to left-handed quarks and right-handed antiquarks [43]. However, the exact fractions in each of the three polarisation states depend on the proton PDFs, and hence on the  $W$  charge. Studies carried out by ATLAS [61] and CMS [62] have found the polarisation fractions of  $W$  bosons at the LHC to be consistent with expectations.

Returning to the present analysis, it might seem reasonable that any mismodelling of the  $W$  charge asymmetry in the simulation would be accommodated by the systematic uncertainties on the proton PDFs. To test this, we plot the ratio  $N(\ell^+)/N(\ell^-)$  in each of the four 1-lepton  $W$  control regions for a) data, b) simulation using the default PDFs, and c) simulation using NLO instead of LO PDFs for the  $W$  and  $Z$  samples. The difference between b) and c) represents the largest contribution to the proton PDF uncertainty (see section 5.5). The results are shown in figure 5.15.

The figure appears to show a small but statistically significant difference between simulation and data, regardless of whether LO or NLO PDFs are chosen. However, switching to NLO PDFs does seem to produce a better agreement. A comparison was also made between LO PDF sets from the CTEQ (default) and MSTW [63] collaborations (plots not shown). Again, the difference between them is not sufficient to explain the discrepancy with the data.

To gauge the effect of this discrepancy on the analysis itself, we need to consider the  $WZ$  transfer functions ( $T_{WZ}$ ). Clearly it is not possible to plot charge-differentiated transfer

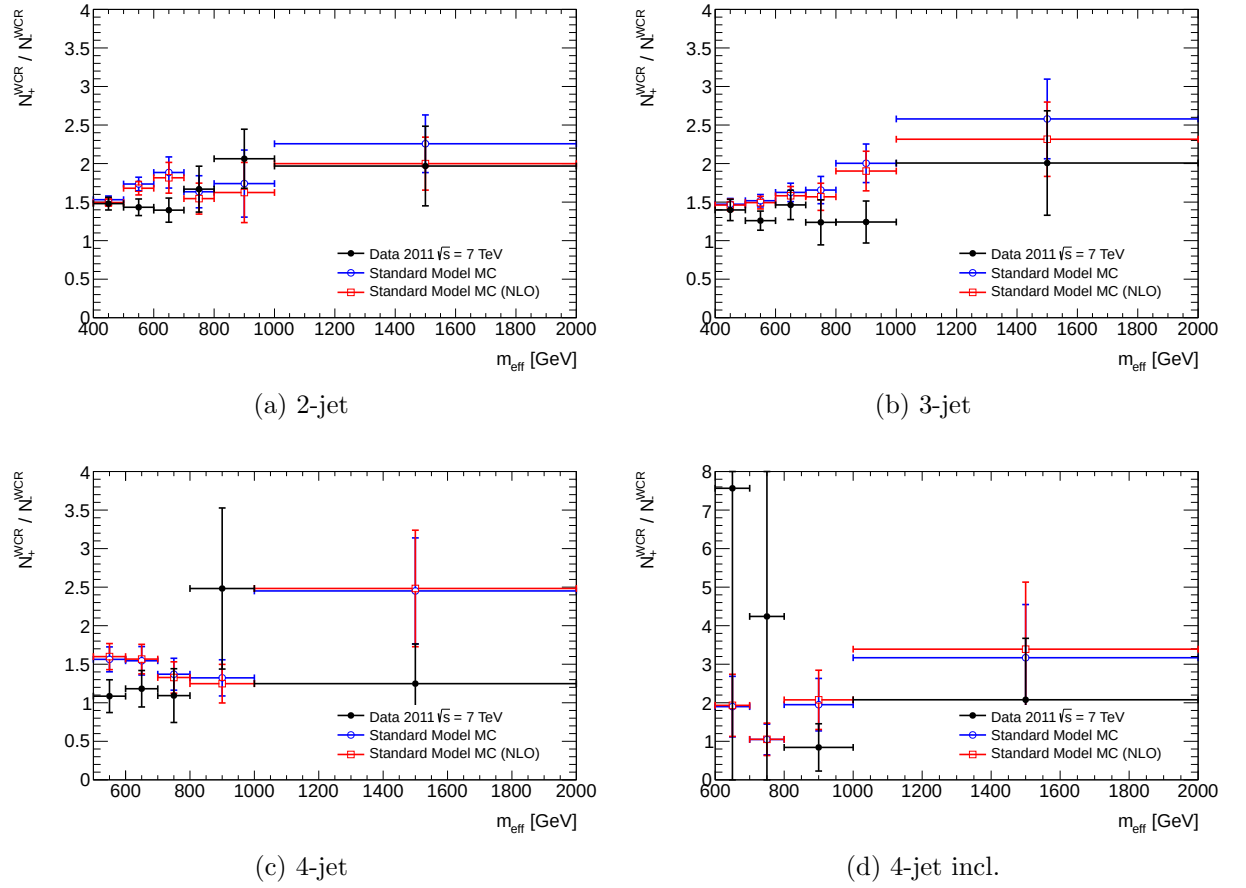


Figure 5.15: The lepton charge ratio in the  $W$  (i.e.  $b$ -veto) control regions for the four signal regions, comparing simulation with LO and NLO PDFs against data.

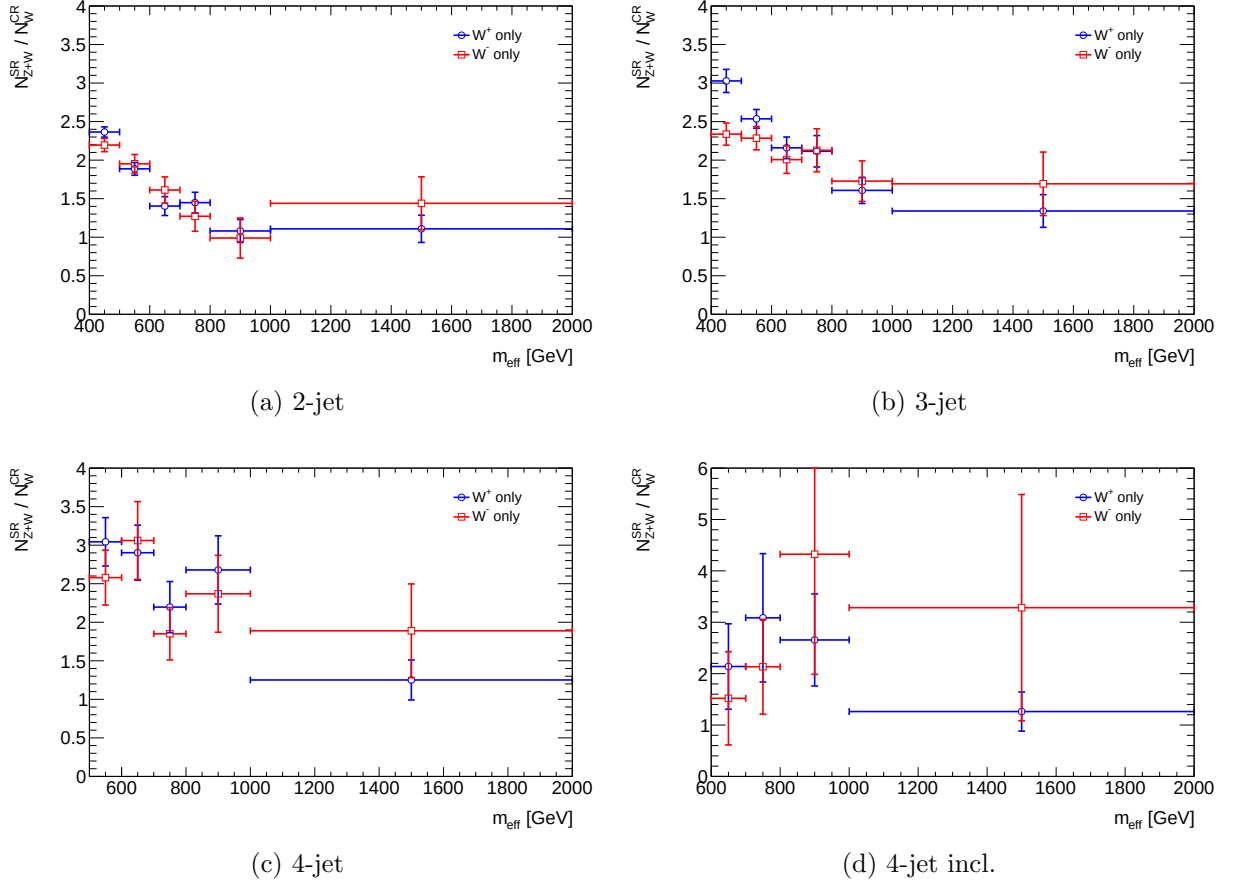


Figure 5.16: The  $WZ$  transfer functions ( $T_{WZ}$ ) for the four signal regions, plotted separately for  $W^+$  and  $W^-$ . In each case, the  $Z \rightarrow \nu\nu$  contribution is scaled by 0.5.

functions for the data itself, as the signal region events contain no leptons and hence no lepton charge information. However, we can obtain a rough estimate of the size of the effect using simulation alone. Figure 5.16 shows  $T_{WZ}$  calculated using a)  $W^+$  only and b)  $W^-$  only. In each case, the  $Z \rightarrow \nu\nu$  content in the signal region is scaled by 0.5 to keep it in proportion to the  $W$  contribution. As the difference is modest, even between these two extreme cases, we can reasonably conclude that the effect of any charge ratio mismodelling on the analysis would not be particularly large.

# Chapter 6

## Limits on SUSY simplified models

The data-driven background estimation method presented in the previous chapter is used to set exclusion limits in two relevant SUSY simplified model planes. The results are compared against those obtained using the baseline cut-and-count method and the same  $1.04 \text{ fb}^{-1}$  dataset.

### 6.1 Introduction

In the previous chapter we saw that, using electron-only control regions to estimate the electroweak backgrounds, no significant deviation from the Standard Model is observed. The apparent excesses seen when including muons in the control regions are ascribed to an unknown feature of the high- $p_T$  muon reconstruction and are hence assumed not to represent a real BSM signal. We may therefore use the data to set limits on new physics processes.

Given that broken supersymmetry has a very large number of free parameters (120 in the MSSM), it is unfortunately not practical to perform a scan across the entire model space. Instead we use simplified models, typically with just two degrees of freedom, to isolate the sorts of processes to which a given analysis is sensitive. An excluded region may then be found by a) generating a set of simulated signal samples across the plane defined by the two free parameters, and b) performing a statistical test at each point.

In this instance we will look at two simplified models in which colour-charged sparticles are pair-produced and decay to invisible LSPs plus Standard Model quarks. The two degrees

| Name              | $\tilde{\chi}$ mass | $\tilde{q}$ mass | $\tilde{g}$ mass | Other masses | Initial $\rightarrow$ final state                             |
|-------------------|---------------------|------------------|------------------|--------------|---------------------------------------------------------------|
| Squark-neutralino | Free                | Free             | 4.5 TeV          | 4.5 TeV      | $\tilde{q}\tilde{q} \rightarrow q\tilde{\chi}q\tilde{\chi}$   |
| Gluino-neutralino | Free                | 4.5 TeV          | Free             | 4.5 TeV      | $\tilde{g}\tilde{g} \rightarrow qq\tilde{\chi}qq\tilde{\chi}$ |

Table 6.1: The two simplified model grids used to set limits on new physics.

of freedom are the masses of the initial state sparticle and of the LSP, with the other SUSY particles assumed to be sufficiently massive as to have negligible production rates at the LHC. All other parameters (e.g. the  $\tilde{W}^0$  content of the  $\tilde{\chi}_1^0$ ) are rendered unimportant by the structure of the mass spectrum, which permits only a single decay sequence to take place.

The two models are summarised in table 6.1. The first assumes pair production of squarks, with each decaying to one SM quark and one neutralino. More precisely, the model includes production of  $\tilde{q} + \tilde{q}$  (dominant at high masses),  $\tilde{q} + \tilde{\bar{q}}$  (dominant at low masses), and  $\tilde{\bar{q}} + \tilde{q}$  (heavily suppressed by the proton PDFs). Here a “squark” is defined as being a squark or antisquark from one of the first two generations, with stops and sbottoms pushed to the high mass scale of 4.5 TeV along with the remaining superpartners. Similarly, a “quark” should be taken to mean a first or second generation quark or antiquark, whose quantum numbers match those of the parent squark. The second model assumes pair production of gluinos, each decaying via a virtual squark to two quarks and one neutralino. Both sets are generated with Herwig++, as outlined in section 4.3.

The production cross-sections are calculated at next-to-leading order (NLO) using Prospino [64, 65]. For the squark model, the squark-squark, squark-antisquark and antisquark-antisquark cross-sections have been calculated separately. In normalising to the data integrated luminosity, we weight each subprocess individually, i.e. we do not assume that the three subprocesses are generated in the correct ratio by Herwig++.

The 2-jet signal region is particularly well-suited to searching for processes of the squark-neutralino type, whereas the 4-jet and 4-jet inclusive regions should give better sensitivity to gluino-neutralino scenarios. The 3-jet signal region provides some useful redundancy in both cases, and may yield improved sensitivity in certain areas of the two mass planes.

Since the signal regions are defined in terms of inclusive jet multiplicities ( $\geq 2, 3, 4$  jets), the data in each one are not statistically independent. For example, an event containing four jets can potentially enter all four signal regions, albeit with a different  $m_{\text{eff}}$  in each one. For this reason, we always use a single signal region to test a given mass point; the method used to make the selection is described in more detail in section 6.10.

In sections 6.2–6.8 we give an overview of the statistical tools needed to set the limit. For a more detailed discussion, the reader is invited to consult [66], from which the majority of this material is drawn. We return to the SUSY study in section 6.9.

## 6.2 Limit-setting overview

For each mass point in the simplified model planes, our null hypothesis may be stated as follows: “the data are described by the Standard Model background prediction, together with the chosen SUSY signal at the nominal cross-section”. A p-value,  $p$ , may be calculated for this null hypothesis, whose interpretation is the probability of observing a deviation from the expected number of events at least as extreme as that actually observed in data. The smaller the p-value, the lower the compatibility between the data and the signal hypothesis. The threshold for rejecting the null is usually taken to be  $p < 0.05$ , at which point the model is said to be excluded at 95% confidence level.

Before we reach this stage, we first need to define a *test statistic*, a variable whose distribution can be used to calculate the p-value. A typical test statistic,  $T$ , will be small when the model is highly compatible with the data, and large when it is highly incompatible. The p-value is then defined as the integral of the test statistic distribution, assuming the null hypothesis, from the observed value to infinity.

In general, we can scale the nominal SUSY cross-section by a strength parameter  $\mu$ , where  $\mu = 1$  indicates the nominal value. The test statistic can then be considered as a function of this parameter,  $T \rightarrow T(\mu)$ . The value of  $\mu$  which best fits the data, called  $\hat{\mu}$ , is found where  $T(\mu)$  is a minimum. Where no excesses are observed, this value should be

compatible with zero.

The test statistic favoured by the ATLAS collaboration, and also used here, is the profile log likelihood ratio, or PLLR [11]. In addition to the signal strength parameter,  $\mu$ , we also define a set of nuisance parameters, represented by  $\boldsymbol{\alpha}$ . A nuisance parameter is a parameter which is not of primary interest, but whose value is not precisely known and must therefore be allowed to vary; the jet energy scale is one such example. In general, all sources of systematic uncertainty are associated with their own nuisance parameter. The PLLR for a hypothesised signal strength  $\mu$  is defined as follows:

$$\text{PLLR} = t_\mu = -2 \log \left( \frac{L(\mu, \hat{\boldsymbol{\alpha}}(\mu))}{L(\hat{\mu}, \hat{\boldsymbol{\alpha}})} \right). \quad (6.1)$$

Here  $L(x, \mathbf{y})$  denotes a likelihood, given the observed data, for a signal strength  $x$  and a set of nuisance parameters  $\mathbf{y}$ ; this takes the same value as the probability density function (PDF) for obtaining the observed data given the parameter set  $\{x, \mathbf{y}\}$ , which we can denote by  $\mathcal{P}(\text{data}|x, \mathbf{y})$ . The exact form of the PDF is discussed in more detail in the next section.

In equation 6.1,  $L(\hat{\mu}, \hat{\boldsymbol{\alpha}})$  represents the global maximum of the likelihood function  $L(\mu, \boldsymbol{\alpha})$ . In other words,  $\hat{\mu}$  and  $\hat{\boldsymbol{\alpha}}$  denote the overall *best-fit* values of the signal strength  $\mu$  and the nuisance parameter set  $\boldsymbol{\alpha}$ . The other instance of the likelihood function,  $L(\mu, \hat{\boldsymbol{\alpha}}(\mu))$ , is the conditional maximum likelihood for the hypothesised signal strength  $\mu$  but with the nuisance parameters allowed to vary. Hence  $\hat{\boldsymbol{\alpha}}(\mu)$  represents the best-fit value of the nuisance parameters with the signal strength fixed at  $\mu$ . Note that, by construction, the PLLR is zero at  $\mu = \hat{\mu}$  and positive everywhere else, which matches the behaviour of our archetypal test statistic  $T(\mu)$ .

As has already been alluded to, the target p-value is defined as the probability that the test statistic is at least as large as that obtained with the observed data, assuming the signal hypothesis is true. We therefore need to know the distribution of the PLLR, which we can denote by  $f(t_\mu|\mu')$ , where  $\mu'$  represents the *assumed* signal strength. When performing an exclusion, this is set equal to the hypothesised value  $\mu$ . If the observed PLLR is  $t_\mu^{\text{data}}$ , then



the p-value for a signal strength  $\mu$  is given by

$$p(\mu) = \int_{t_\mu^{\text{data}}}^{\infty} f(t_\mu|\mu) dt_\mu. \quad (6.2)$$

Formally,  $f(t_\mu|\mu')$  describes how  $t_\mu$  would be distributed if we repeated the analysis (with a new ATLAS detector) a large number of times, in a world with a real signal  $\mu'$ . It can be derived either by generating many random “toy” datasets and calculating  $t_\mu$  for each one or by using analytical formulae which are valid in the limit of large numbers of events. The latter method is used here.

## 6.3 Building a PDF

In this section, we discuss how to derive a probability density function which describes the data in terms of a background prediction, a signal model, and a set of nuisance parameters. The PDF is constructed as a workspace within the data modelling language RooFit [67] using the command line utility HistFactory [68], itself part of the RooStats project [69]. The workspace is then passed to a further set of RooStats tools which perform the necessary statistical analysis. The HistFactory utility constructs PDFs of the following general form:

$$\mathcal{P}(\mathbf{n}, \mathbf{a}|\boldsymbol{\nu}, \boldsymbol{\alpha}) = G(L_0|L, \Delta_L) \prod_{m=1}^M \text{Pois}(n_m|\nu_m) \prod_{i=1}^S N(a_i|\alpha_i, 1), \quad (6.3)$$

where the variables and functions are defined as follows:

- $\mathbf{n}$  = observed number of data events in each histogram bin (dimension =  $M$ ).
- $\boldsymbol{\nu}$  = expected number of events in each histogram bin (dimension =  $M$ ).
- $\boldsymbol{\alpha}$  = nuisance parameters corresponding to the various systematic uncertainties (dimension =  $S$ ).
- $\mathbf{a}$  = results of measurements that constrain the nuisance parameters (dimension =  $S$ ).
- $G(L_0|L, \Delta_L)$  = Gaussian function constraining the integrated luminosity, with mea-

sured value  $L_0$  and standard deviation  $\Delta_L$ .

- $\text{Pois}(n_m|\nu_m) = \text{Poisson function constraining the observed event count in bin } m$ .
- $N(a_i|\alpha_i, 1) = \text{function (usually Gaussian) constraining the nuisance parameter } \alpha_i$ .

A conspicuous absence from the above formula is that of the signal strength  $\mu$ . This enters via the expected number of events in each histogram bin  $\nu_m$ , via the relation:

$$\nu_m = \nu_m^{\text{bkg}}(\boldsymbol{\alpha}) + \mu \nu_m^{\text{sig}}(\boldsymbol{\alpha}),$$

where the expected number of events has been split into background and signal components. Both components depend on the values of the nuisance parameters  $\boldsymbol{\alpha}$ , which makes sense when we recall that the latter represent sources of systematic uncertainty. A convention is applied to the nuisance parameters whereby  $\alpha_i = 0$  corresponds to the nominal expected value (e.g. the best estimate of the JES), and  $\alpha_i = \pm 1$  correspond to the  $\pm 1\sigma$  variations in the parameter.

The  $\nu_m$  values are fed to the HistFactory application via an XML file, which itself points to a number of ROOT histograms. The bin contents of these histograms represent the  $\nu_m^{\text{bkg}}$  and  $\nu_m^{\text{sig}}$  quantities. The dependence on  $\boldsymbol{\alpha}$  is accounted for by supplying additional histograms for background and signal with the various systematics shifted up or down by one standard deviation. The full XML schema is described in detail in [68].

As mentioned in the previous section, when we consider the PDF (equation 6.3) as a function of the parameters  $\boldsymbol{\alpha}$  and  $\boldsymbol{\nu}$ , it becomes a likelihood function, given the observed data  $\{\boldsymbol{n}, \boldsymbol{a}\}$ . More precisely,

$$L(\boldsymbol{\nu}, \boldsymbol{\alpha}|\boldsymbol{n}, \boldsymbol{a}) = \mathcal{P}(\boldsymbol{n}, \boldsymbol{a}|\boldsymbol{\nu}, \boldsymbol{\alpha}).$$

Since  $\boldsymbol{\nu}$  is itself a function of the nuisance parameter set  $\boldsymbol{\alpha}$  and the parameter of interest  $\mu$ , we can transform the independent variables to make the dependence on the signal strength

explicit:

$$L(\boldsymbol{\nu}, \boldsymbol{\alpha} | \mathbf{n}, \mathbf{a}) \rightarrow L(\mu, \boldsymbol{\alpha} | \mathbf{n}, \mathbf{a}) \rightarrow L(\mu, \boldsymbol{\alpha}),$$

where in the last step we have hidden the dependence on the data observations, since these are fixed for a given analysis period. The likelihood is now in the form shown in equation 6.1, and we are ready to perform the statistical tests.

## 6.4 A better test statistic

Having established how to construct a PDF (equivalently, a likelihood), we can now return to the profile log likelihood and explore in more detail how to set a p-value for a given signal. Once again, the PLLR is defined by:

$$\text{PLLR} = t_\mu = -2 \log \left( \frac{L(\mu, \hat{\boldsymbol{\alpha}}(\mu))}{L(\hat{\mu}, \hat{\boldsymbol{\alpha}})} \right) = -2 \log \lambda(\mu).$$

Here we have defined a shorthand for the likelihood ratio:

$$\lambda(\mu) = \frac{L(\mu, \hat{\boldsymbol{\alpha}}(\mu))}{L(\hat{\mu}, \hat{\boldsymbol{\alpha}})}. \quad (6.4)$$

In line with ATLAS-wide recommendations, we will use a modified form of the PLLR which is adapted for the task of setting an upper limit on a hypothesised signal [11]. The change reflects the fact that we should only exclude signal mass points for which  $\hat{\mu} < 1$ . In other words, it doesn't make sense to exclude a given point if the best-fit value of the strength parameter is greater than unity, since this would strongly suggest the existence of a genuine signal; imagine excluding a model for which  $\hat{\mu} = 100$ , for example.

The modification to be made is a simple one. We set the test statistic equal to zero in the region  $\mu < \hat{\mu}$ :

$$t_\mu \rightarrow q_\mu = \begin{cases} -2 \log \lambda(\mu) & \mu > \hat{\mu} \\ 0 & \mu < \hat{\mu} \end{cases} \quad (6.5)$$

Now all  $\mu$  below the best-fit value are equally “allowed”; only those above are eligible for exclusion.

It is worth asking why this should make any difference to our result. After all, it is very unlikely that any of our signal hypotheses will yield  $\hat{\mu} > 1$  while also being incompatible with  $\mu = 1$ , otherwise we would be able to see a large excess in one or more of the signal regions. However, the redefinition of the test statistic also affects its distribution, i.e.  $f(q_\mu|\mu') \neq f(t_\mu|\mu')$ . This becomes important when we equate the value of the test statistic at  $\mu = 1$  with a p-value and use the latter to decide whether or not to reject the signal hypothesis (recall equation 6.2).

## 6.5 Distribution of the test statistic

In calculating the distribution  $f(q_\mu|\mu)$  we make use of Wilks’ theorem [70]. This is the statement that, in the limit where the number of expected events is large, the profile log likelihood ratio  $t_\mu$  follows a  $\chi^2$  distribution with one degree of freedom:

$$f(t_\mu|\mu) = \chi_1^2(t_\mu) = \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{t_\mu}} \exp(-t_\mu/2).$$

In this context, “large” is often taken to mean  $O(10)$  events, although it also depends on the size of the uncertainties in the model. With a 5% overall uncertainty, 10 events is sufficient for the asymptotic approximation to be valid, whereas with a 1% uncertainty it is not. A more precise way of expressing the condition is that the uncertainties must be large enough to smooth out the effects of discreteness in the Poisson distribution of the observed data. In the context of this analysis, we expect the asymptotic approximation to be a good one, since the expected number of events is very much larger than 10, and the uncertainty always greater than 5%.

Where the asymptotic approximation is not valid, it becomes necessary to build the distribution of the test statistic using toy simulated datasets. This technique involves creating

many (typically  $10^2 - 10^4$ ) pseudo-datasets sampled from the model PDF (equation 6.3), calculating the value of the test statistic for each one, and plotting the distribution of these values. This method is far more computationally expensive than using Wilks' theorem, but has the advantage of being universally applicable.

In moving to the one-sided form of the PLLR (equation 6.5), we have to modify the Wilks result slightly to account for the new asymmetry [66]. The result is a half- $\chi^2$  distribution with a  $\delta$ -function at the origin:

$$f(q_\mu|\mu) = \frac{1}{2}\delta(q_\mu) + \frac{1}{2}\chi_1^2(q_\mu). \quad (6.6)$$

The addition of a  $\delta$ -function shifts down the point at which the distribution integrates to 0.95, and hence the threshold value of the test statistic at which we consider a signal model to be excluded.

When the hypothesised ( $\mu$ ) and assumed ( $\mu'$ ) signal strengths are not the same, the distribution becomes somewhat more complex:

$$f(q_\mu|\mu') = \Phi\left(\frac{\mu - \mu'}{\sigma_A}\right) \delta(q_\mu) + \frac{1}{2} \frac{1}{\sqrt{2\pi}} \frac{1}{\sqrt{q_\mu}} \exp\left[-\frac{1}{2} \left(\sqrt{q_\mu} - \frac{\mu - \mu'}{\sigma_A}\right)^2\right]. \quad (6.7)$$

Here  $\Phi$  represents the Gaussian cumulative distribution (CDF) with a mean of zero and a standard deviation of one. Note that this reduces to equation 6.6 for  $\mu = \mu'$ , since  $\Phi(0) = 0.5$ . The method for deriving the standard deviation  $\sigma_A$ , which describes the scatter of  $\hat{\mu}$  around  $\mu'$ , will be discussed in section 6.7.

## 6.6 From p-values to CLs

We now have a recipe for calculating the exclusion p-value for a signal hypothesis with a cross-section multiplier  $\mu$  in the asymptotic limit:

$$\begin{aligned}
 p(\mu) &= \int_{q_\mu^{\text{data}}}^{\infty} f(q_\mu|\mu) dq_\mu \\
 &= \int_{q_\mu^{\text{data}}}^{\infty} \frac{1}{2} \delta(q_\mu) + \frac{1}{2} \chi_1^2(q_\mu) dq_\mu \\
 &= 1 - \Phi\left(\sqrt{q_\mu^{\text{data}}}\right).
 \end{aligned} \tag{6.8}$$

In the last step, we have exploited the relationship between the CDFs of the  $\chi^2$  and Gaussian distributions. To test the model at the nominal cross-section, we simply have to evaluate  $q_\mu^{\text{data}}$  at  $\mu = 1$ .

One further change will be required to make the hypothesis test as robust as possible [71]. Let's suppose that our signal model predicts a number of events much lower than the expected background:  $\nu_{\text{sig}} \ll \nu_{\text{bkg}}$ . Now if the data shows a large downward fluctuation relative to the signal + background expectation, there is a reasonable chance that the signal point will be excluded. However, since  $\nu_{\text{sig+bkg}} \simeq \nu_{\text{bkg}}$ , such a fluctuation would be almost equally contrary to the background-only hypothesis. In other words,  $p_{s+b} \simeq p_b$ , where both p-values are small. In such a situation, we are not strictly sensitive to the chosen signal. Even if it did exist, we would not be able to say so definitively, since the excess would be lost beneath the uncertainties on the expected background. Conversely, it does not really make sense to exclude such a signal either.

To protect against such spurious exclusions, we take the precaution of dividing the signal-plus-background p-value by the background-only equivalent:

$$p_{s+b} \rightarrow \text{CL}_s = \frac{p_{s+b}}{p_b}, \tag{6.9}$$

where  $p_{s+b}$  is calculated using equation 6.8. Now if  $p_{s+b}$  and  $p_b$  are of a similar magnitude, the overall “p-value”, called  $\text{CL}_s$ , will be large and the signal will not be rejected.

The background-only p-value is calculated in an analogous manner to equation 6.8, except that we replace  $f(q_\mu|\mu)$  by  $f(q_\mu|0)$ , the distribution of the test statistic  $q_\mu$  when the data contain only SM events. The form of  $f(q_\mu|0)$  may be deduced from equation 6.7.

## 6.7 The Asimov dataset and expected CLs values

In addition to calculating the observed  $CL_s$ , it is useful to calculate the expected value, assuming the observed data contain only background. In this way we can compare the excluded areas of the simplified model planes with what we would expect for the SM alone.

To do this, we construct an imaginary dataset called the Asimov dataset [66]. The Asimov dataset is defined such that the maximum likelihood estimator of every parameter (signal strength plus nuisance parameters) is equal to its assumed value, i.e. the nominal value defined by the simulation. As a corollary, the content of every histogram bin must exactly equal its expectation value with all parameters set to their nominal values. With  $\mu' = 0$ , this implies that the Asimov dataset corresponds exactly to the SM background expectation (including fractional events).

We can define a test statistic for the Asimov dataset just as we did for the observed data. For  $\mu > \hat{\mu}$ :

$$\begin{aligned} q_\mu^A &= -2 \log \left( \frac{L_A(\mu, \hat{\boldsymbol{\alpha}}(\mu))}{L_A(\hat{\mu}, \hat{\boldsymbol{\alpha}})} \right) \\ &= -2 \log \left( \frac{L_A(\mu, \hat{\boldsymbol{\alpha}}(\mu))}{L_A(\mu', \boldsymbol{\alpha}')} \right) \\ &= -2 \log \lambda_A(\mu). \end{aligned} \tag{6.10}$$

We have used the fact that, by definition,  $\hat{\mu} = \mu'$  and  $\hat{\boldsymbol{\alpha}} = \boldsymbol{\alpha}'$  for the Asimov dataset, where  $\boldsymbol{\alpha}'$  represents the assumed values of the nuisance parameters. Later we will be interested in the particular case of  $\mu' = 0$ , but for now we can keep the formulae general.

By seeing how  $q_\mu^A$  varies in the vicinity of  $\mu'$ , we can derive a characteristic width in  $\mu$ :

$$\sigma_A = \frac{|\mu - \mu'|}{\sqrt{q_\mu^A}}.$$

This can be used in the expression for the distribution of the test statistic  $q_\mu$  when  $\mu \neq \mu'$  (equation 6.7). It is now possible to express the observed  $\text{CL}_s$  (recall equation 6.9) in terms of the Gaussian CDF and the observed/Asimov values of the test statistic:

$$\begin{aligned} \text{CL}_s^{\text{obs}} &= \frac{\int_{q_\mu^{\text{data}}}^{\infty} f(q_\mu|\mu) dq_\mu}{\int_{q_\mu^{\text{data}}}^{\infty} f(q_\mu|0) dq_\mu} \\ &= \frac{1 - \Phi\left(\sqrt{q_\mu^{\text{data}}}\right)}{\Phi\left(\sqrt{q_\mu^A} - \sqrt{q_\mu^{\text{data}}}\right)}. \end{aligned} \quad (6.11)$$

We can adapt this formula to gives us the *expected*  $\text{CL}_s$  assuming the data consist of background only. To do this, we note that the Asimov dataset is identical to the expected background, and hence

$$\begin{aligned} \text{CL}_s^{\text{exp}} &= \frac{1 - \Phi(\sqrt{q_\mu^A})}{\Phi(\sqrt{q_\mu^A} - \sqrt{q_\mu^A})} \\ &= \frac{1 - \Phi(\sqrt{q_\mu^A})}{\Phi(0)} \\ &= 2 \left(1 - \Phi\left(\sqrt{q_\mu^A}\right)\right). \end{aligned} \quad (6.12)$$

Furthermore, we can calculate the standard deviation of this expectation. It should be clear from equation 6.11 that the  $\sqrt{q}$  quantities correspond to a significance, i.e. a number of sigma. So to get the  $\pm 1\sigma$  variations in  $\text{CL}_s^{\text{exp}}$ , we need simply increment the  $\sqrt{q_\mu^{\text{data}}}$  in equation 6.11 by  $\pm 1$  and again make the substitution  $q_\mu^{\text{data}} \rightarrow q_\mu^A$ , giving

$$\text{CL}_s^{\text{exp}}(\pm 1\sigma) = \frac{1 - \Phi(\sqrt{q_\mu^A} \pm 1)}{\Phi(\mp 1)}. \quad (6.13)$$

The relative sign between the left and right hand side is chosen to make  $\text{CL}_s^{\text{exp}}(+1\sigma)$  smaller



than  $\text{CL}_s^{\text{exp}}(-1\sigma)$  (and therefore more likely to reject the null hypothesis).

## 6.8 Summary so far

We now have all the necessary tools in place to find the excluded regions in the two simplified model planes. For each mass point we use equation 6.11 to find the observed  $\text{CL}_s$  value, and exclude the point if it is less than 0.05, corresponding to a confidence level of 95%. Equations 6.12 and 6.13 are used to find the expected  $\text{CL}_s$  value for the background-only model, together with its  $\pm 1\sigma$  variations. The  $q_\mu^{\text{data}}$  and  $q_\mu^A$ , the one-sided PLLR for the observed data and Asimov dataset respectively, are calculated by fitting the relevant data to the model, as depicted in equations 6.4, 6.5 and 6.10, where  $\mu = 1$  for our purposes. The code used to perform these tasks is based on the RooStats tutorial macro “StandardHypoTestInvDemo.C” [72], with the calculator type set to “asymptotic”.

## 6.9 Uncertainties and nuisance parameters

For the results that follow, a reduced set of systematic uncertainties is used for the background compared to that presented in section 5.5. This decreases the number of nuisance parameters which must be fitted and increases the chances of obtaining a successful convergence. A source of systematic uncertainty is neglected if it never produces a shift in the final background estimate greater than 0.2 of the statistical uncertainty in any  $m_{\text{eff}}$  bin. Applying this filter excludes the uncertainties due to electron energy resolution, the CellOut energy scale/resolution, the proton PDF, the factorisation scale, and anything that affects only muons (since we’re using the electron control sample only). The final set of nuisance parameters for the background estimate is therefore: jet energy scale, jet energy resolution,  $b$ -tagging efficiency, electron identification efficiency, electron energy scale, pileup, minimum  $p_T$  used in the Alpgen Monte Carlo generator, and renormalisation scale.

A different set is used for the signal. In common with the background, we retain the

uncertainties on jet energy scale and resolution. However, all nuisance parameters associated with leptons and  $b$ -jets are dropped as they have, at most, minimal impact in the signal regions. The uncertainties due to the factorisation scale and proton PDF are larger for signal than for background, since there is no cancellation between control and signal regions, and hence these are included. An uncertainty due to the value of the strong coupling  $\alpha_S$ , which is related to the renormalisation scale, has been calculated for the signal datasets and this is included by being added in quadrature to the PDF uncertainty. The nuisance parameter set for the signal is therefore: jet energy scale, jet energy resolution, factorisation scale, and PDF  $\oplus \alpha_S$ .

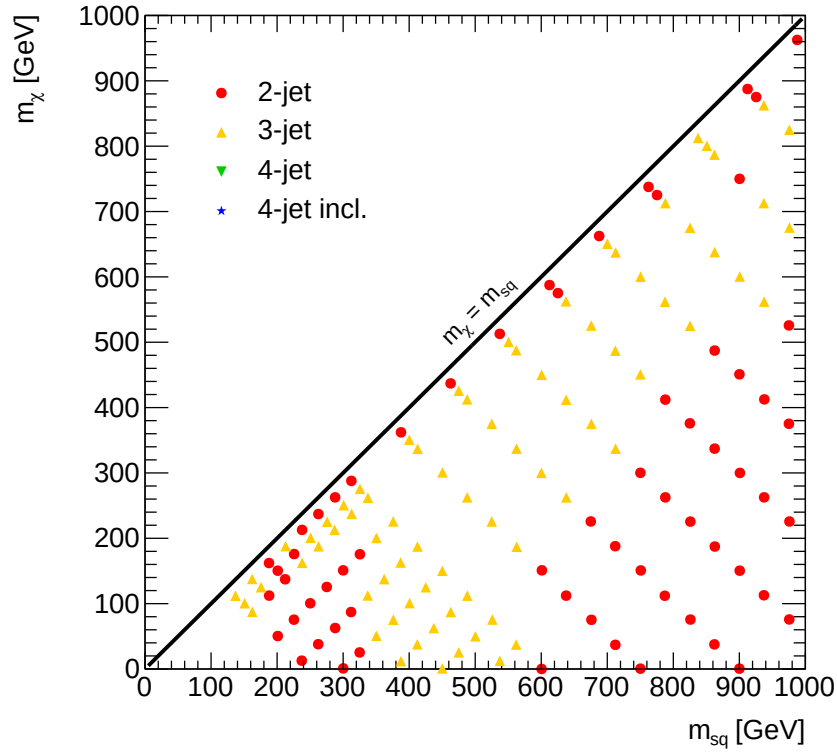
It should be noted that the factorisation scale and PDF  $\oplus \alpha_S$  uncertainties on the signal are global, meaning that they only affect the overall normalisation of the signal distribution. They do not, therefore, take into account migrations between bins, unlike the theoretical uncertainties on the background.

The statistical uncertainty is included via an additional nuisance parameter per  $m_{\text{eff}}$  bin, which represents the total uncertainty on the electroweak + QCD + signal prediction. In this way, we account for the fact that the contents of the bins are statistically independent.

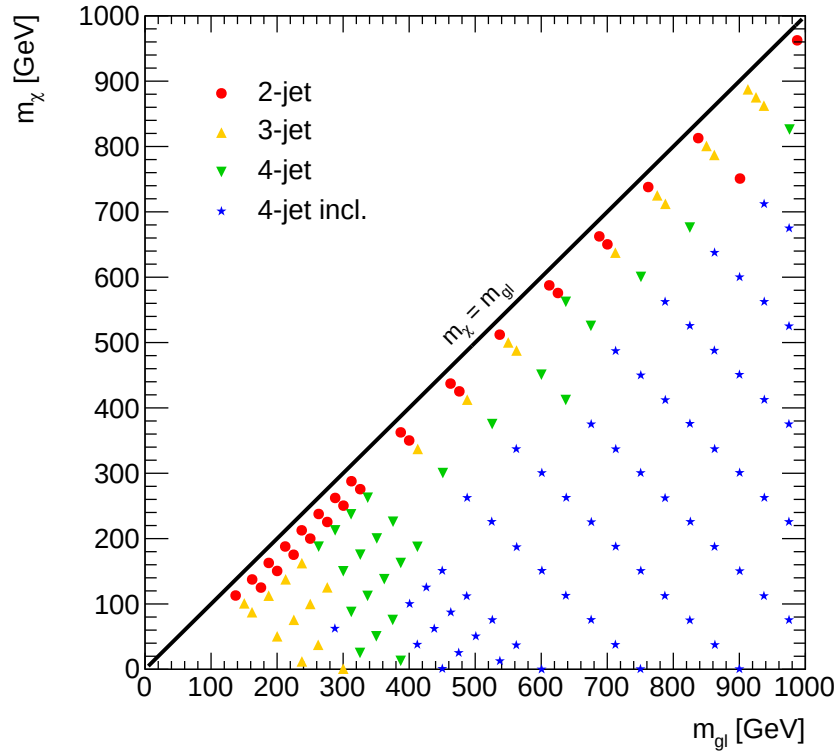
## 6.10 Results

As was mentioned in section 6.1, we use a single signal region to determine whether a given mass point is excluded at 95% confidence level. This relieves us from having to calculate the complex statistical effects that arise from using correlated signal regions.

The test signal region is taken to be that for which  $\text{CL}_s^{\text{exp}}$  is smallest at the nominal signal cross-section. That is, we use the signal region which has the best expected sensitivity to the chosen signal. This selection does not introduce any undue bias, since  $\text{CL}_s^{\text{exp}}$  is calculated independently of the observed data, using only the background estimate and the simulated signal model. This procedure is identical to that used to select signal regions in [1].



(a) Squark-neutralino



(b) Gluino-neutralino

Figure 6.1: The signal regions used to perform the hypothesis test for each mass point in the simplified models. The signal region indicated at each point is the one with the smallest  $CL_s^{\text{exp}}$  out of the four, and hence the most sensitive for that point.

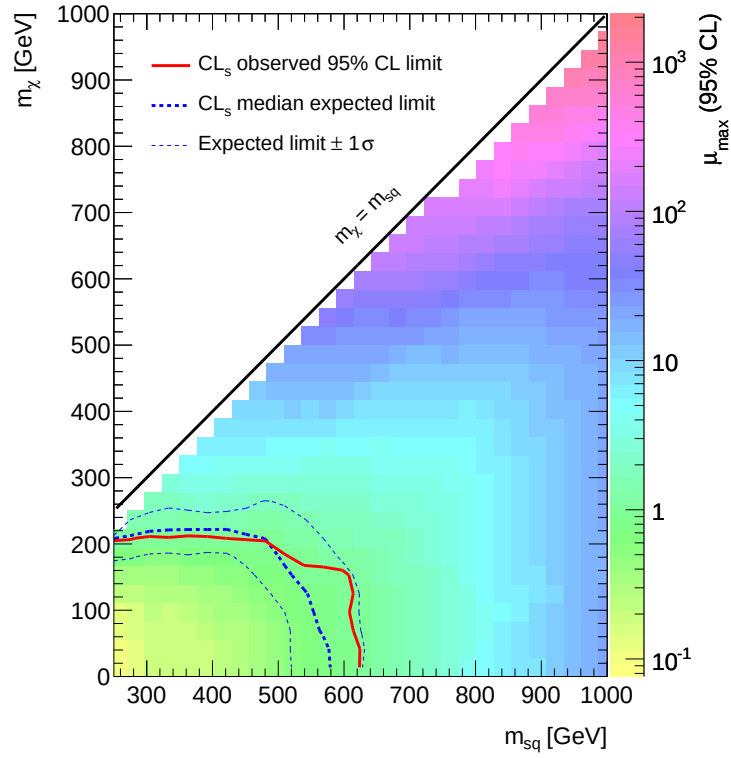
Figure 6.1 shows the signal region used for each mass point in the two simplified model planes. The figure also demonstrates the sampling of the sparticle masses, along lines of constant  $\Delta M$  and constant  $\sum M$ . The 2 and 3-jet signal regions monopolise the squark plane, as expected, but also make significant contributions in the gluino plane (perhaps surprisingly). In contrast, the two 4-jet signal regions contribute only to the gluino exclusion.

The overall trend is for the small and large  $n_{\text{jet}}$  signal regions to be respectively more sensitive at low and high mass splittings (i.e. small/large perpendicular distances from the diagonal). This can be understood as follows. When the neutralino is heavy, the quarks produced in the squark/gluino decay tend to have low  $p_T$ , which decreases the probability that they will form jets that pass the basic 40 GeV selection. Hence a digluino event decaying to four quarks may produce just two or three energetic jets, or maybe even fewer.

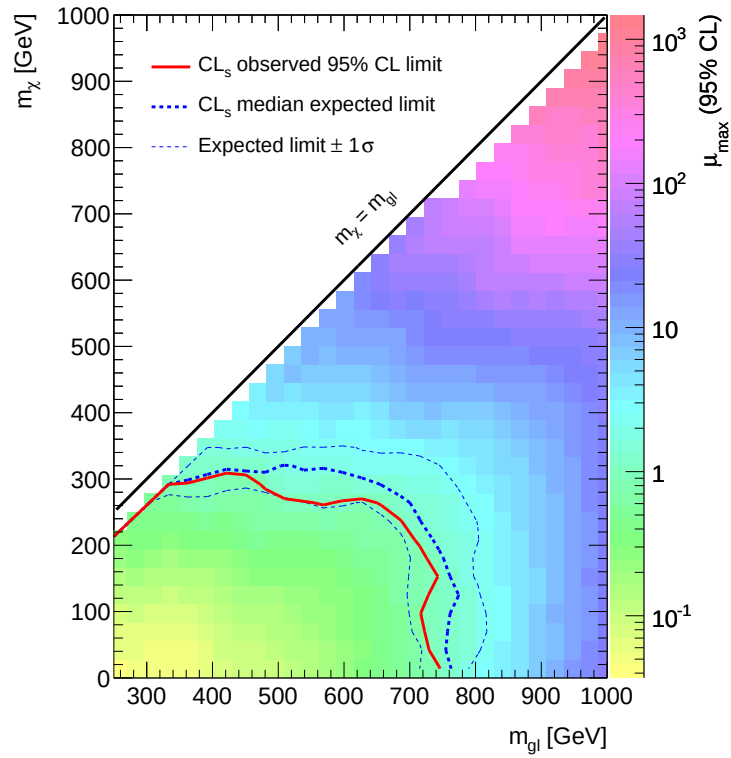
Other broad features of figure 6.1 are less clear-cut in terms of their physical origin, but can probably be ascribed to some combination of: a) the relative importance of primary quark jets and initial state radiation (ISR) jets, and b) variations in the effect of the nuisance parameters between signal regions and between  $m_{\text{eff}}$  bins. The distinction between primary and ISR jets is potentially very interesting, since the mean energies of the former are related to the mass splitting, the latter to the parton  $\sqrt{s}$  and hence the coloured sparticle mass [73]. For example, the transition that occurs at  $m_{\tilde{q}} \sim 340$  GeV in figure 6.1(a) may be due to additional ISR jets associated with the heavier squarks, giving a greater fraction of events with three or more jets.

Figure 6.2 shows the excluded regions in the squark and gluino planes, with the red line representing the observed limit and the blue the expected limit. The narrower blue lines show the limits obtained using  $\text{CL}_s^{\text{exp}}(\pm 1\sigma)$  instead of the central value. The coloured histograms show the observed upper limit on the cross-section parameter  $\mu$  at 95% confidence level, i.e. the estimated value of  $\mu$  for which  $\text{CL}_s^{\text{obs}} = 0.05$ . By definition, the region in which  $\mu_{\text{max}}^{95} < 1$  is the same as that delineated by the red line.

Some brief observations. Firstly, the observed limit always lies within the  $\pm 1\sigma$  range of the expected limit, which confirms that the observed data are consistent with the Standard



(a) Squark-neutralino



(b) Gluino-neutralino

Figure 6.2: The observed (red) and expected (blue) 95% CL exclusion limits in the squark (top) and gluino (bottom) simplified model planes, assuming NLO cross-sections calculated using Prospino. The histograms show the observed upper limit on the signal strength multiplier  $\mu$  at 95% CL. The red line encircles the region for which this is less than one.

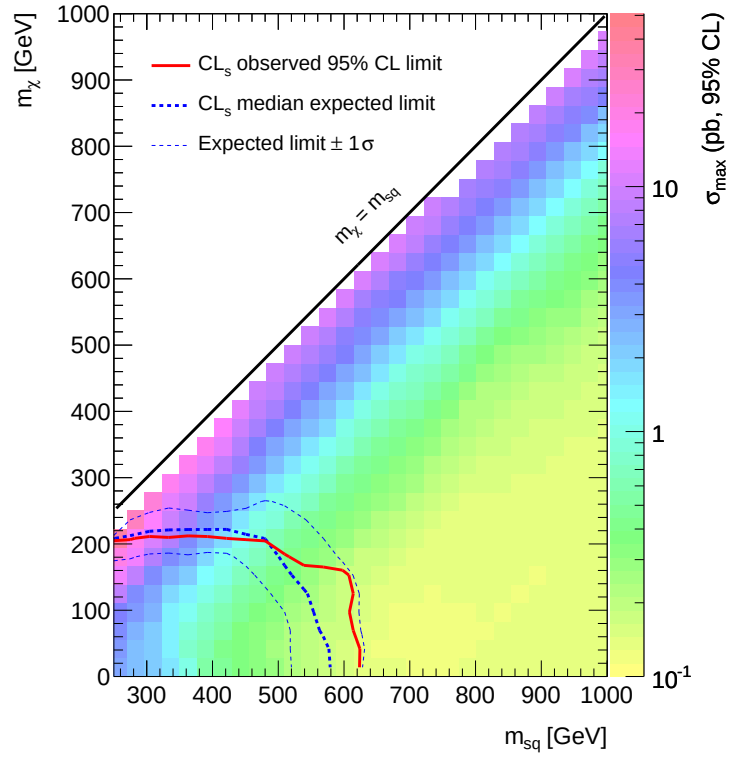
Model. There are two regions in which the observed limit approaches one standard deviation: a) at large  $m_{\tilde{q}}$  / small  $m_{\tilde{\chi}}$ , and b) at intermediate  $m_{\tilde{g}}$ . These can be explained, respectively, by the  $\mathcal{O}(1\sigma)$  underfluctuation in the data in the highest- $m_{\text{eff}}$  bin of the 2-jet signal region and the  $\mathcal{O}(1\sigma)$  overfluctuation in first/second bins of the 4-jet inclusive signal region. Secondly, the contours of constant  $\mu_{\text{max}}^{95}$  (i.e. regions of similar colour) follow a shape that arises from the interplay between the coloured sparticle mass (which drives the production cross-section) and the mass splitting (which drives the  $E_{\text{T}}^{\text{miss}}$  and the  $p_{\text{T}}$  of the jets). The two effects on their own would produce, respectively, approximately vertical and diagonal contours, but in combination they give the pattern seen here. Thirdly, we are able to exclude points for which the coloured sparticle and the LSP are very nearly degenerate in mass (the points are generated with  $\Delta M$  down to 25 GeV), provided the coloured sparticle is sufficiently light.

Figure 6.3 presents the information in a slightly different way. The limit lines are the same as before, but the histogram now shows the maximum signal *cross-section* at 95% confidence level\*, in picobarns. For comparison, the  $t\bar{t}$  production cross-section at ATLAS is approximately  $1.7 \times 10^2$  pb. The cross-section limit at each signal point is obtained by multiplying the value of  $\mu_{\text{max}}^{95}$  (see figure 6.2) by the Prospino-derived NLO production cross-section.

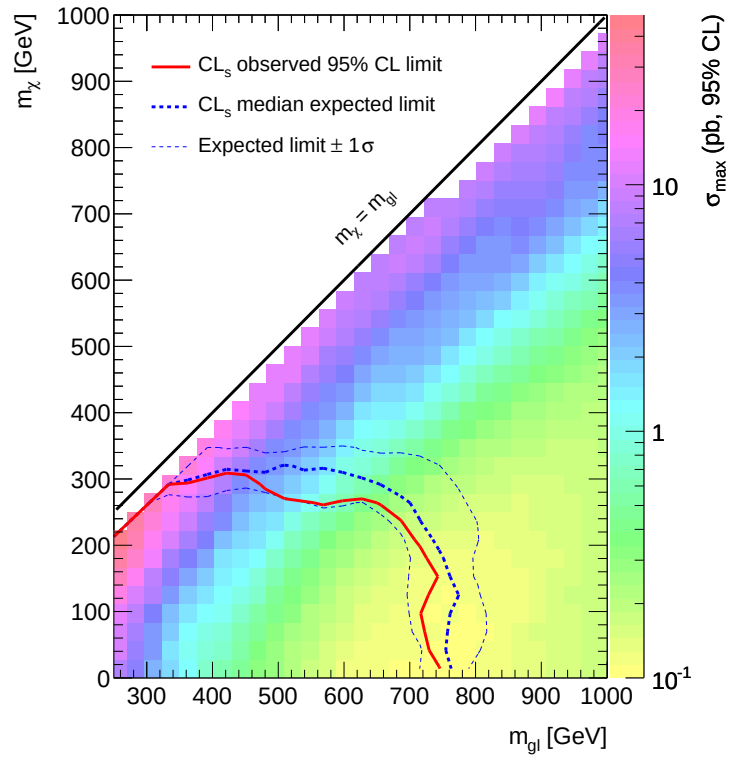
In some sense, this second representation is less model-dependent, since we no longer have to assume values for the squark-squark or gluino-gluino production cross-sections. Having said this, the cross-sections we use are determined only by the particles' mass and spin, so are already fairly model-independent. Nevertheless, we can imagine a scenario where, for example, the quark-like particles are fermions, giving a different production rate but preserving the shapes of the  $m_{\text{eff}}$  distributions. For example, some extra-dimensions models contain excitations of the SM particles with the same charges and spins, with a  $K$ -parity quantum number analogous to  $R$ -parity in SUSY [74]. In some scenarios the lightest extra-dimensional excitation is weakly interacting and a viable dark-matter candidate [75].

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\*Here cross-section is taken to mean  $\sigma_{\text{prod}} \times R$ , where  $R$  is the branching ratio to the chosen final state. To put it another way, we set a limit on the production cross-section assuming a branching ratio of unity to  $q(q)\tilde{\chi}$ .



(a) Squark-neutralino



(b) Gluino-neutralino

Figure 6.3: The observed (red) and expected (blue) 95% CL exclusion limits in the squark (top) and gluino (bottom) simplified model planes, assuming NLO cross-sections calculated using Prospino. The histograms show the observed upper limit on the cross-section ( $\sigma_{\text{prod}} \times R$ ) at 95% CL.

The lines of constant sensitivity follow a different pattern in figure 6.3 compared to figure 6.2. The dominant factor is now the mass splitting, which gives contours running approximately parallel to the diagonal. The absolute mass scale does still exert an influence, since with constant mass splitting we are able to exclude smaller cross-sections the more massive the particles. This is especially true for near-degenerate points: note the pink areas in the lower-left of each subfigure.

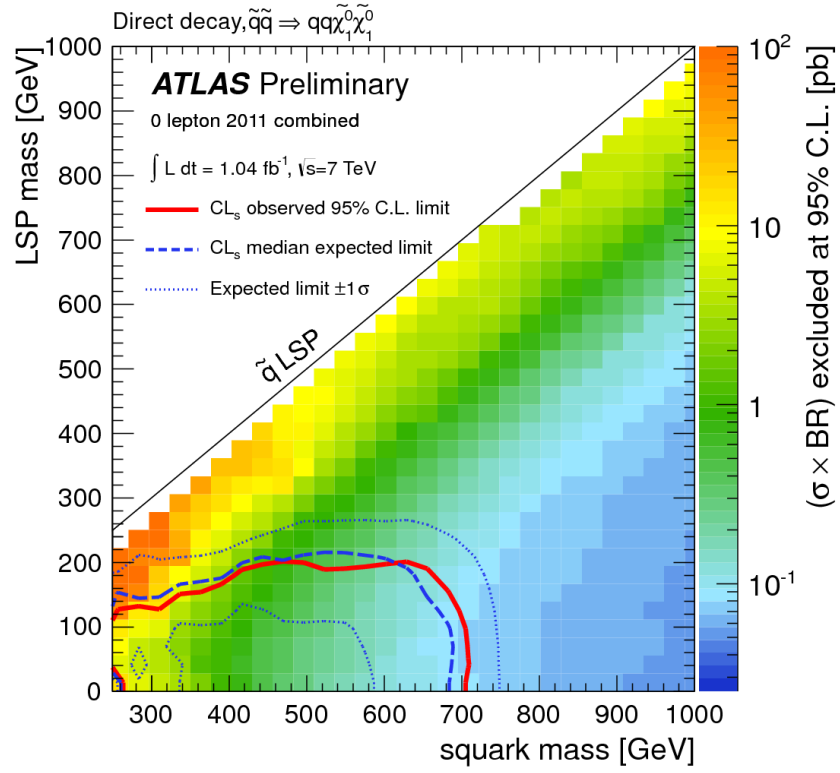
This may seem somewhat counterintuitive, since we might expect lighter pair-produced sparticles to typically have a larger back-to-back transverse boost, giving rise to higher- $p_T$  jets and larger  $E_T^{\text{miss}}$ . However, the dependence makes sense when we consider initial state radiation (ISR) from the incoming partons. The more massive the squarks or gluinos, the greater the typical energy of ISR jets, since the mean energy in ISR is proportional to the  $\sqrt{s}$  of the partons. The effects of this are to a) increase the number of high- $p_T$  jets in the event, and b) boost the di-particle system in the transverse plane, both of which are expected to increase sensitivity.

The region in which we are most sensitive to small cross-sections is where the squark/gluino mass and the mass splitting are both large. This is where the primary quark jets are the most energetic and where the largest missing transverse momenta are seen. In contrast, sensitivity to scenarios in which both the squark/gluino mass and the splitting are small requires large cross-sections; these points are excluded simply because their predicted cross-sections are so large.

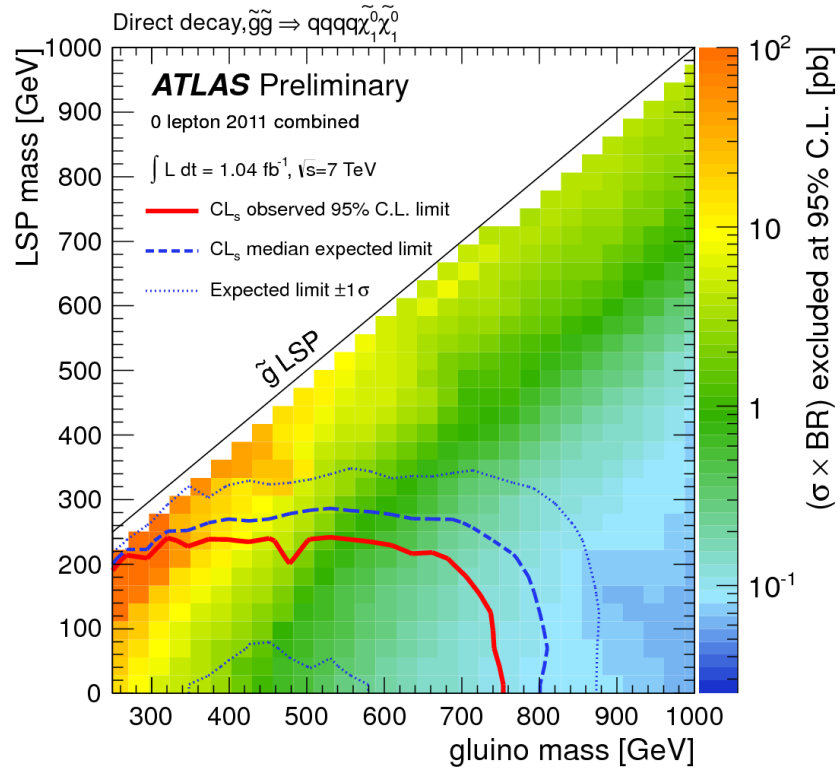
It is instructive to compare the results of this study with those obtained using the signal regions from the original ATLAS 0-lepton analysis [1] and the same dataset. For the earlier search,  $m_{\text{eff}}$  cuts were used to define five counting regions, whereas in this analysis we use histograms covering nearly the full  $m_{\text{eff}}$  range. The counting regions were as follows: 2-jet  $m_{\text{eff}} > 1000$  GeV, 3-jet  $m_{\text{eff}} > 1000$  GeV, 4-jet  $m_{\text{eff}} > 500$  GeV, 4-jet  $m_{\text{eff}} > 1000$  GeV, 4-jet inclusive  $m_{\text{eff}} > 1100$  GeV. The excluded regions and cross-section upper limits obtained using the counting method, taken from [76], are shown in figure 6.4.

The first thing to note is that, within the rather large range of uncertainty of the latter,





(a) Squark-neutralino



(b) Gluino-neutralino

Figure 6.4: The equivalent plots to figure 6.3 but using counting regions rather than histograms [76].

the excluded regions in figures 6.3 and 6.4 look to be broadly compatible. However, the fact that the two analyses have many systematic uncertainties, control and signal region events in common means that the two bands are likely to be correlated.

Secondly, the uncertainty band is much narrower in the present analysis; the limit is more highly constrained. It is reasonable to assume that this results from using the full distribution shapes to set the limit.

Thirdly, the present analysis is by far the more sensitive to near-degenerate scenarios. The exclusion limits (observed and expected) closely follow the diagonal up to around 240 GeV in  $m_{\tilde{q}}$  and 330 GeV in  $m_{\tilde{g}}$ , compared to  $\ll 250$  GeV and  $\lesssim 250$  GeV for the counting analysis. This is simple to understand in terms of the signal regions: for this analysis we perform the exclusion test using all events with  $m_{\text{eff}} > 400\text{--}600$  GeV (depending on the number of jets), which provides good sensitivity even when the jets are relatively soft and the  $E_{\text{T}}^{\text{miss}}$  is relatively low. By contrast, the counting analysis applies rather high  $m_{\text{eff}}$  cuts for most of its signal regions which, if the LSP is very massive, remove most of the signal events.

Fourthly, the maximum extent of the excluded region along the  $m_{\tilde{q}}$  axis is significantly different between the two analyses. Specifically, the present analysis only excludes squark masses up to around 580 GeV (expected), the counting analysis up to 680 GeV. In both cases, the limit in this part of the plane is determined by the 2-jet signal region, and one assumes that the mass splitting is sufficiently large that the highest  $m_{\text{eff}}$  bin (1000–2000 GeV) dominates the sensitivity in the present analysis\*. The difference is not caused by the addition of bins in the region  $m_{\text{eff}} < 1000$  GeV, since removing these bins from the present analysis does not increase the sensitivity at high  $m_{\tilde{q}}$ . Ultimately the cause of the discrepancy is not clear, but it should be noted that the two limits are consistent within the  $\pm 1\sigma$  uncertainty bands.

For completeness, we present the limits obtained using the four signal regions individually, in the squark (figure 6.5) and gluino (figure 6.6) planes. The results are consistent with the

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\*This hypothesis is supported by the fact that the observed limit  $\simeq$  the expected limit  $+ 1\sigma$  in this part of the plane, which is a result of the underfluctuation in the highest  $m_{\text{eff}}$  bin of the 2-jet signal region.

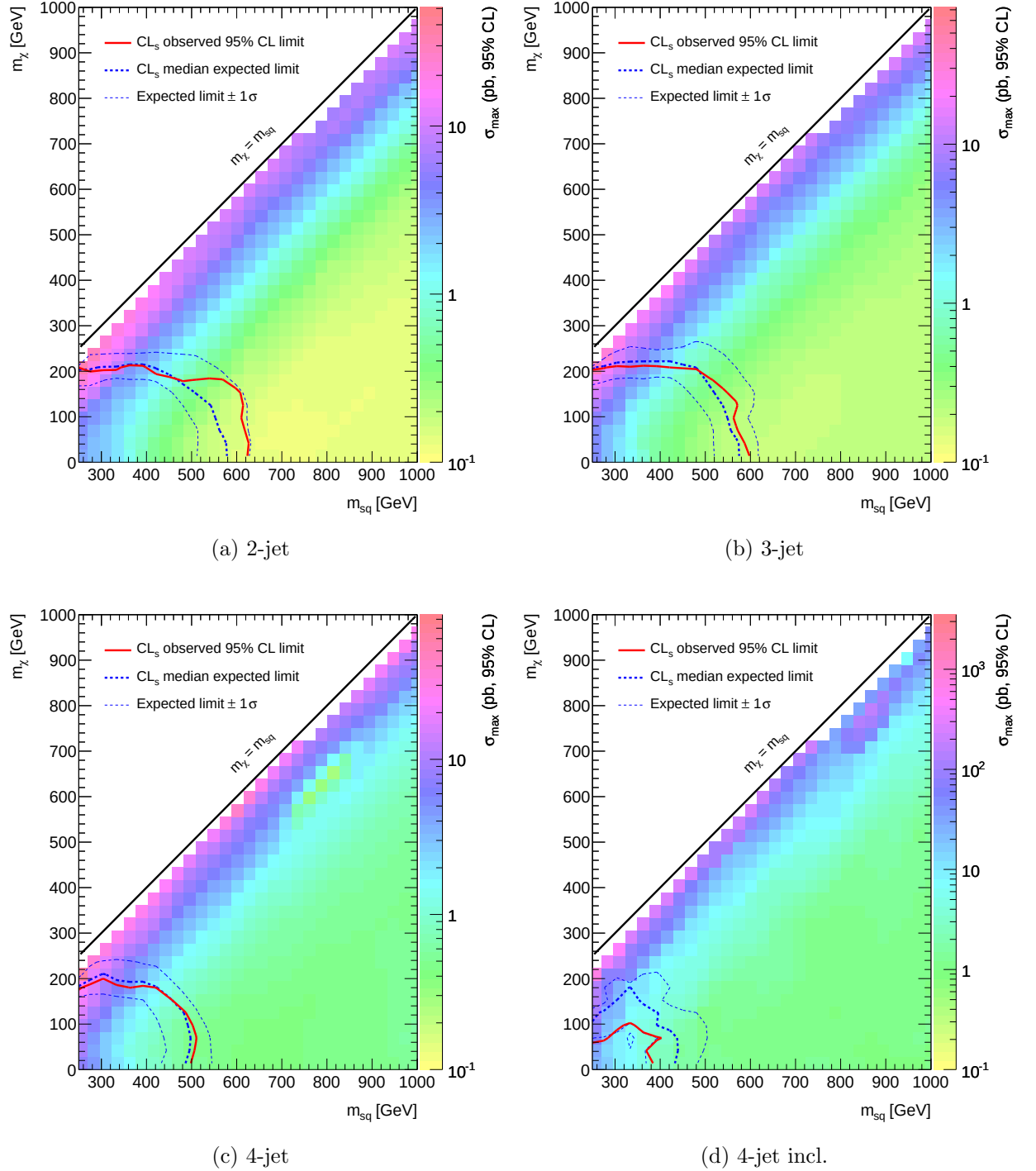


Figure 6.5: The observed (red) and expected (blue) 95% CL exclusion limits in the squark simplified model plane, for the four signal regions. The histograms show the observed upper limit on the cross-section ( $\sigma_{\text{prod}} \times R$ ) at 95% CL.

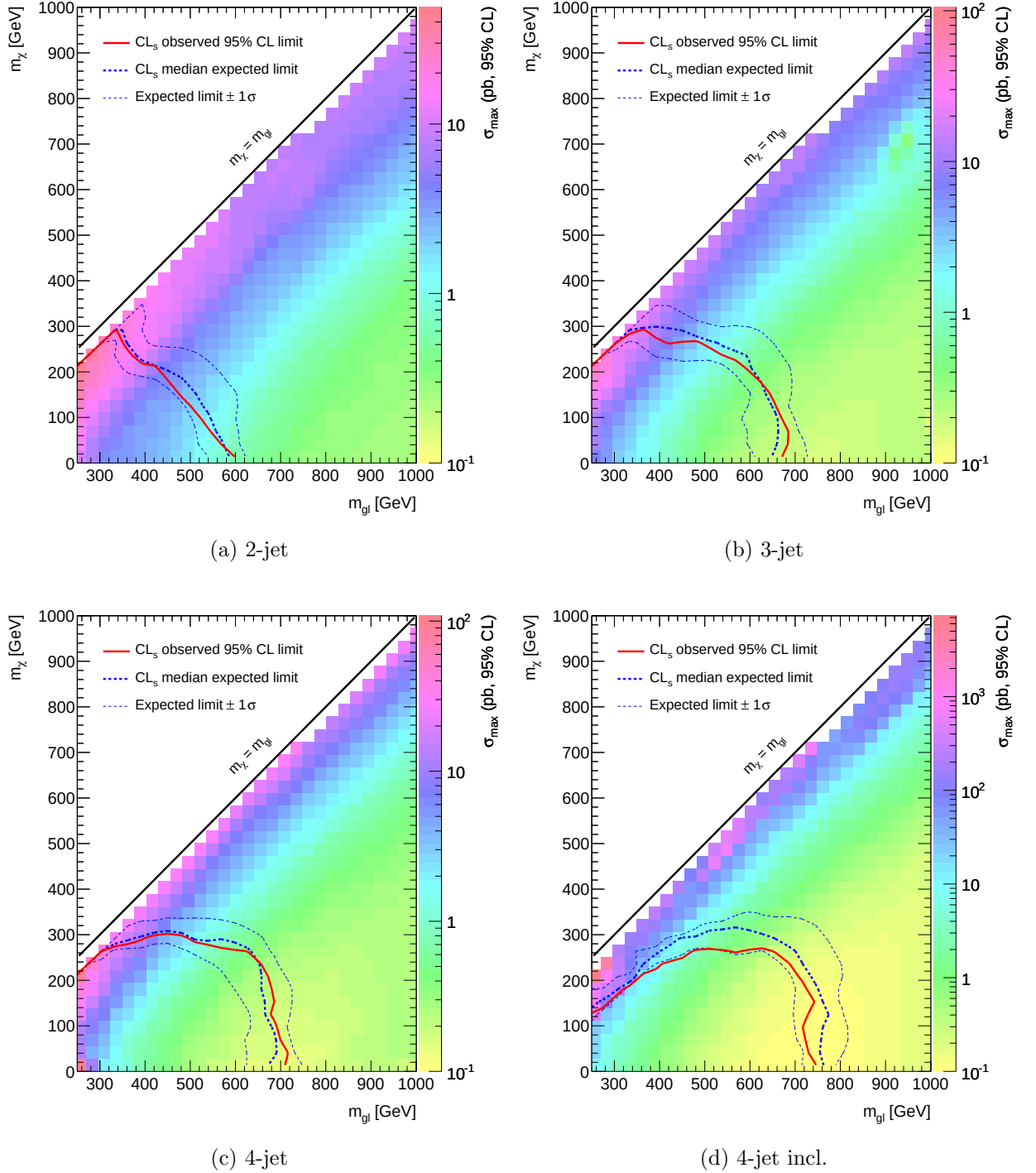


Figure 6.6: The observed (red) and expected (blue) 95% CL exclusion limits in the gluino simplified model plane, for the four signal regions. The histograms show the observed upper limit on the cross-section ( $\sigma_{\text{prod}} \times R$ ) at 95% CL.

results shown previously, insofar as:

- The 2 and 3-jet signal regions give the best overall performance with respect to the squark model.
- All four signal regions give substantial coverage in the gluino plane, with different signal regions making contributions in different areas of the plane.
- The 2 and 3-jet signal regions offer the best sensitivity in the region nearest the diagonal for both models. ISR can be assumed to dominate the jet production here.
- The 4-jet inclusive signal region performs the best at very high mass splittings in the gluino plane, where many very high- $p_T$  jets are expected.
- The 4-jet inclusive signal region is not very sensitive to disquark production, since the jet requirements remove almost all of the signal.
- However, the standard 4-jet signal region provides quite good sensitivity to disquarks, presumably helped by soft ISR.

## 6.11 Summary and conclusions

In this chapter we have used the data collected by the ATLAS detector in the first half of 2011 ( $1.04 \text{ fb}^{-1}$ ) to set limits on two SUSY simplified models, whereby coloured sparticles are pair produced and decay directly to jets plus invisible LSPs. By using binned signal regions which extend down to low  $m_{\text{eff}}$ , we have gained additional sensitivity in the near-degenerate area of parameter space, compared to the counting analysis with the same dataset [1, 76]. To the author's knowledge, and with the exception of the early  $35 \text{ pb}^{-1}$  analysis [57], this remains the only ATLAS study to probe the low- $m_{\text{eff}}$  region in the 2/3-jet + 0-lepton +  $E_T^{\text{miss}}$  channels.

## Part III

# Performance of the ATLAS missing transverse energy trigger

# Chapter 7

## Introduction to part III

A trigger based on missing transverse energy is a potentially useful tool in any search for  $R$ -parity-conserving supersymmetry. In channels with a relatively low number of jets and no leptons, it is indispensable, since a trigger based on jets alone offers little discrimination against Standard Model QCD interactions.

In this introduction, we give an overview of the implementation of the  $E_T^{\text{miss}}$  trigger [77], in preparation for the performance studies presented in the next two chapters. Chapter 8 is concerned with the general performance characteristics of the  $E_T^{\text{miss}}$  trigger, while chapter 9 concentrates on its use in 0-lepton SUSY searches.

A brief disclaimer is necessary at this point. The studies discussed in the following chapters were carried out on data taken during 2010, and so the implementation details given below are correct for that period. For updated information, the interested reader is encouraged to check [78].

In common with the majority of triggers in ATLAS, the  $E_T^{\text{miss}}$  trigger consists of three levels, referred to as Level 1 (L1), Level 2 (L2), and Event Filter (EF). For an overview of the ATLAS trigger system, see section 1.2.5.

At L1 the global energy sums,  $E_x$ ,  $E_y$  and  $\text{Sum-}E_T$ , are built in the jet/energy-sum processor (JEP) by adding the  $x/y/T$  energy measurements made by the  $\sim 7000$  L1 trigger towers

(see equations 1.5–1.7). Each tower makes an analogue transverse energy measurement, which is digitised into an eight-bit number from 0 to 255, where one count approximately equals 1 GeV. Towers with transverse energies below 1.0–1.3 GeV (depending on location in the calorimeter) are ignored, in order to reduce the contribution from random noise.

The JEP then compares the measured energy sums against a set of configurable thresholds, eight for  $E_T^{\text{miss}}$  and four for Sum- $E_T$ . In the case of the  $E_T^{\text{miss}}$  the comparison is not done directly (i.e. by computing  $\sqrt{E_x^2 + E_y^2}$ ), but rather via a look-up table (LUT) indexed by  $E_x$  and  $E_y$ . The results are output as an eight-bit and a four-bit binary number (where a ‘1’ denotes a threshold passed) and forwarded to the central trigger processor (CTP), where the L1 accept decision is made.

The L2  $E_T^{\text{miss}}$  trigger takes the  $E_{x,y}$  and Sum- $E_T$  computed at L1, optionally adds a muon correction, and calculates  $E_T^{\text{miss}} = \sqrt{E_x^2 + E_y^2}$ . In short, the L2 algorithm simply adds muon information to the calorimeter-only L1 quantities. If no muon correction is applied, as throughout 2010, then L2 is functionally identical to L1, modulo a small discrepancy due to the difference in the  $E_T^{\text{miss}}$  threshold comparison method (LUT vs direct evaluation).

At EF the  $E_T^{\text{miss}}$  and Sum- $E_T$  are calculated using all calorimeter cells which measure an energy over three times their expected RMS noise level. The noise threshold is one-sided, meaning that negative-energy contributions are not counted. Energies are measured at the EM scale, but the capability exists to apply a hadronic calibration, with up to 24 independent scale factors corresponding to different regions of the calorimeter system. As is the case at L2, a muon correction is available but was not used in 2010.

In this thesis, the following  $E_T^{\text{miss}}$  trigger naming conventions are used. Full chains are denoted by `xe $\star\star$ .noMu`, where  $\star\star$  gives the EF threshold (in GeV) and the “noMu” suffix indicates that no muon correction has been applied at L2/EF. Such chains effectively have only two levels, since the L1 and L2  $E_T^{\text{miss}}$  are almost identical in the absence of a muon correction. Single-level triggers at L1 and EF are denoted by `L1_XE $\star\star$`  and `EF_xe $\star\star$`  respectively. For example, the chain `xe40.noMu` is composed of the items `L1_XE30` and `EF_xe40`.



# Chapter 8

## Performance of the missing transverse energy trigger in 2010

This chapter examines the performance of the ATLAS missing transverse energy trigger during 2010 data-taking, covering almost exactly the same material as the ATLAS note [79]. The discussion presented here is intended to provide an analysis-neutral view of the trigger performance, with a focus on validation of the algorithms, and understanding of general behaviour and features. The next chapter will look at the use of  $E_T^{\text{miss}}$  and hybrid triggers in the specific context of 0-lepton SUSY searches. The trigger efficiencies for  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  events are studied, as are the effects of increasing pileup.

### 8.1 Introduction

The year 2010 represented an important commissioning period for the entire ATLAS detector. The credibility of the collaboration's physics results was dependent on the validation, using real p-p collision data, of the numerous detector subsystems. The trigger system was no exception.

The events examined here are taken from the latter third of the 2010 data-taking period, from 19 August to 29 October 2010. However, due to the rapidly increasing instantaneous luminosity throughout the year, this constitutes around 97% of the full 2010 dataset by integrated luminosity. In fact, more than half the total dataset was collected in the final five

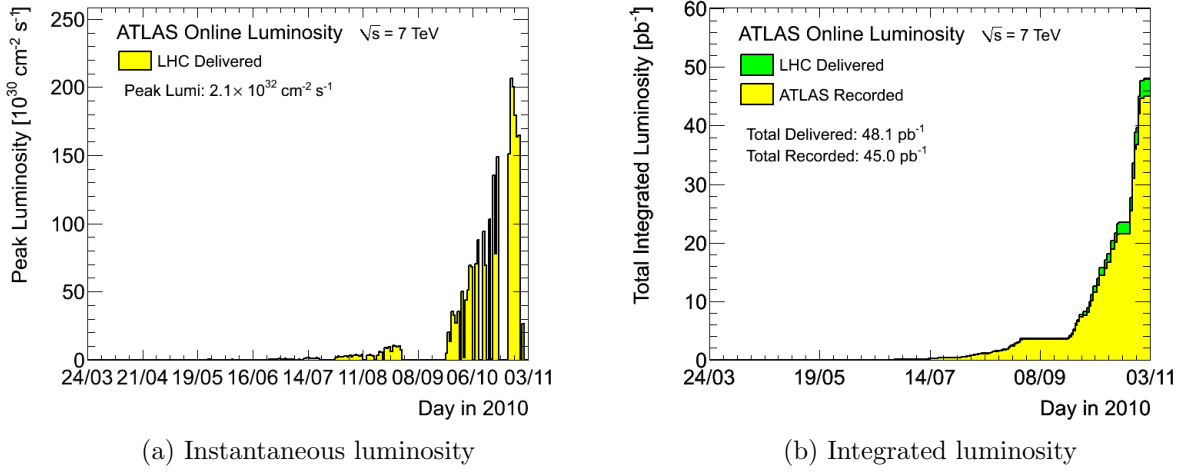


Figure 8.1: Instantaneous (left) and integrated (right) luminosity delivered to ATLAS in 2010 [7].

days of p-p operation; see figure 8.1.

The 97% sub-dataset considered here (henceforth “the dataset”) covers the data-taking periods F-I of 2010, with the remaining 3% coming from periods A-E. The data-taking periods are decided on the basis of reasonable uniformity in the detector and LHC machine conditions. Between periods F and I, the detector configuration, insofar as it affects the  $E_T^{\text{miss}}$  trigger, can be considered as unchanging, but on the LHC side there is a large variation in the instantaneous luminosity and number of p-p interactions per bunch crossing. The maximum instantaneous luminosity varies by more than an order of magnitude between period F and period I, and the maximum mean number of interactions per bunch crossing ( $\langle\mu\rangle$ ) approximately doubles. This variation will later be convenient for showing the effect of the LHC beam settings on the trigger performance (see section 8.4). Details of the different periods are shown in table 8.1.

The performance of the  $E_T^{\text{miss}}$  and Sum- $E_T$  triggers will be evaluated primarily using reference events collected via single-lepton triggers: EF\_e15\_medium for electrons and EF\_mu13 for muons. These require, respectively, an electron with  $p_T > 15$  GeV measured at EF level, and a muon with  $p_T > 13$  GeV. Both triggers have been shown to be near maximum efficiency at an offline lepton  $p_T$  of 20 GeV [80]. The advantage of using single-lepton triggers is that it is easy to construct a large sample of events containing large real  $E_T^{\text{miss}}$ , namely

| Period | Start date | End date | Int. lumi.<br>(pb <sup>-1</sup> ) | Peak lumi.<br>(cm <sup>-2</sup> s <sup>-1</sup> ) | Max $\langle\mu\rangle$ |
|--------|------------|----------|-----------------------------------|---------------------------------------------------|-------------------------|
| F      | 19 Aug     | 29 Aug   | 1.96                              | $1.0 \times 10^{31}$                              | 2.1                     |
| G      | 22 Sep     | 6 Oct    | 8.81                              | $7.1 \times 10^{31}$                              | 2.8                     |
| H      | 8 Oct      | 17 Oct   | 8.79                              | $1.5 \times 10^{32}$                              | 3.2                     |
| I      | 24 Oct     | 29 Oct   | 22.8                              | $2.1 \times 10^{32}$                              | 3.8                     |

Table 8.1: Details of the individual 2010 data-taking periods used to evaluate the  $E_T^{\text{miss}}$  trigger performance. The quantity  $\langle\mu\rangle$  (far right) is the mean number of p-p interactions per bunch-crossing.

$W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$ . Given that the purpose of the  $E_T^{\text{miss}}$  trigger is to collect events with real weakly interacting particles, this provides an ideal test sample.

We also examine events collected using the minimum bias trigger, which looks for activity in the minimum bias trigger scintillators (MBTS), mounted on the cryostats of the two endcap calorimeters. The scintillators are stimulated by a flux of charged particles in the forward regions of the detector, and at least one will fire on almost every collision event [80]. This means that events firing the MBTS are almost completely unbiased with respect to the set of all collision events, though the number recorded is considerably reduced by the MBTS trigger prescale, which was typically  $\mathcal{O}(10^4)$  at the time of these studies. There also exist entirely random (or zero bias) triggers, but these are prescaled too highly to be useful for detailed  $E_T^{\text{miss}}$  or Sum- $E_T$  trigger studies.

The offline reference variables against which we measure the trigger performance are the “MET-Topo”  $E_T^{\text{miss}}$  and Sum- $E_T$ , calculated using topological clusters at the EM scale (see section 1.2.8). This choice is intended to give a “fair” comparison with the trigger quantities (which are also measured at the EM scale) while sharing the basic topoclustering algorithm with the more sophisticated variables used in most physics analyses. No muon corrections are applied on the trigger or the offline quantities, in order to be consistent with the online trigger settings used in 2010 and 2011. Consequently, muons represent a source of  $E_T^{\text{miss}}$ , and do not contribute to the Sum- $E_T$ .

The remainder of this chapter is arranged as follows. In section 8.2 we compare the L1 and EF trigger variables ( $E_T^{\text{miss}}$  and Sum- $E_T$ ) with their offline equivalents for a sample of

electron-triggered events. We then discuss the correlations in terms of how the variables are built at the trigger level and offline. Section 8.3 is concerned with the efficiency of the  $E_T^{\text{miss}}$  trigger as a function of offline  $E_T^{\text{miss}}$ , and the offline values at which the triggers become fully efficient. Here we compare the results from electron and muon events, and attempt to explain these differences in terms of the underlying physics. Finally, in section 8.4, we examine the stability of the triggers between data-taking periods with respect to both rate and efficiency. This will give some insight into the effects of pileup.

## 8.2 Comparisons with offline quantities

In this section we compare the online  $E_T^{\text{miss}}$  and Sum- $E_T$  with their offline counterparts using two-dimensional histograms. We also compare the online quantities at L1 and EF. Such plots are instructive in deciding whether the triggers are operating as expected, and in looking for anomalous behaviour.

The histograms shown here use a sample of events collected using the electron trigger EF\_e15\_medium, with no further offline cuts on electron quality or event kinematics. In other words, no attempt has been made to increase the purity with respect to  $W \rightarrow e\nu$  or any other process. The events contain a mixture of real leptons from on-shell  $W$  production, real leptons from heavy-flavour quark decay and fakes from light-flavour QCD processes. We expect the first of these to dominate at high  $E_T^{\text{miss}}$ , and the last at low  $E_T^{\text{miss}}$ .

Figure 8.2 shows the correlations between L1, EF and offline  $E_T^{\text{miss}}$  ((a)–(c)) and the EF-offline correlation after preselection by the low-threshold L1 trigger L1\_XE10 (d). The black points indicate the profile of the distribution – the mean value of the  $y$ -axis variable in each  $x$ -axis bin – and are intended to show how the two quantities vary with respect to each other on average. The mean is calculated by taking the projection onto the  $y$ - $z$  plane for each bin in  $x$  and fitting a Gaussian function to the resulting one-dimensional histogram. The  $y$  error bars give the uncertainty on the fitted mean of the Gaussian, not the standard deviation  $\sigma$ .

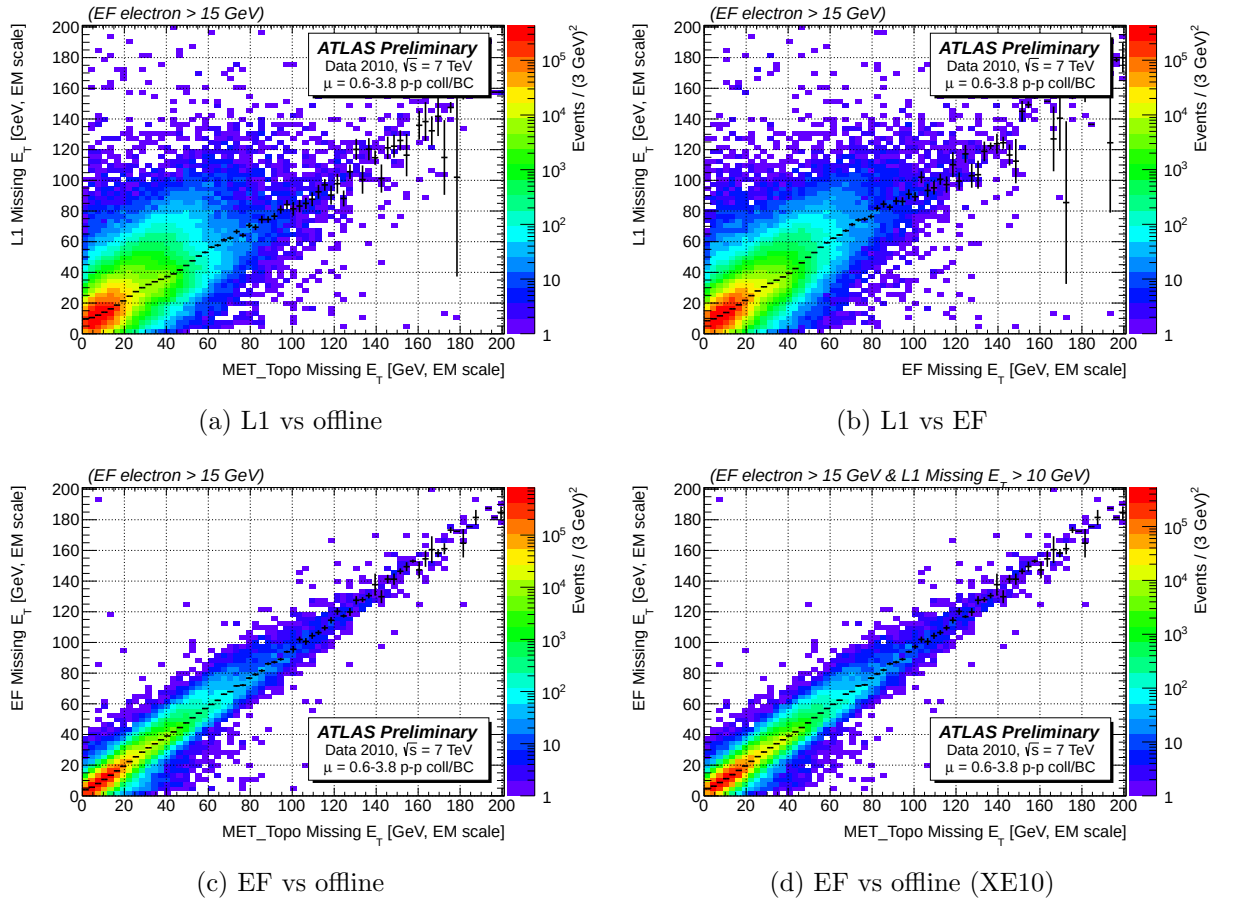


Figure 8.2: Correlations between online (L1/EF) and offline  $E_T^{\text{miss}}$  for electron-triggered events in 2010 data.

In figure 8.2(a) we see a relatively broad spread between the  $E_T^{\text{miss}}$  measured offline and at L1. This is a consequence of the different algorithms used. At L1 the  $E_T^{\text{miss}}$  is computed from trigger towers (in 2D  $\eta$ - $\phi$  space) which measure a transverse energy above a threshold. This setup is designed to yield a fast computation, enabling a quick ( $\mathcal{O}(\mu\text{s})$ ) decision to be made on whether an event should be passed to the HLT, at the cost of some accuracy and precision. In contrast, the offline algorithm operates at the calorimeter cell level (in 3D  $\eta$ - $\phi$ - $r$  space), using topoclusters to provide the noise suppression. The different noise suppression schemes mean that in some events, a given calorimeter cell contributes to the  $E_T^{\text{miss}}$  offline but not at L1, or at L1 but not offline. As we shall see from figure 8.3(a), the former is much more common. The difference between the tower-based and cell-based calculations is also apparent when comparing the  $E_T^{\text{miss}}$  calculated at L1 and EF (figure 8.2(b)).

In figure 8.2(c) we see that the  $E_T^{\text{miss}}$  at EF correlates strongly with that measured offline. This reflects the multi-level trigger structure: the EF algorithm has substantially more time available to reach a decision than the L1 has, of order  $\mathcal{O}(100 \text{ ms})$ . This additional time is used to calculate an  $E_T^{\text{miss}}$  which replicates the offline value as faithfully as possible. The EF algorithm, like the offline, loops over all calorimeter cells, albeit with a different method for deciding whether or not a given cell is included in the sum. The noise thresholds used are also rather similar:  $3\sigma_{\text{RMS}}$  (one-sided) at EF and 4/2/0 (two-sided) offline. The appearance of the distribution is not substantially altered by adding a low threshold at L1 (see figure 8.2(d)), an observation that is consistent with figures 8.2(a)–(b).

Figure 8.3 shows the equivalent distributions for the scalar transverse energy sum,  $\text{Sum-}E_T$ . Once again the final subfigure shows the EF-offline distribution after a L1 cut, this time on  $\text{Sum-}E_T$  at 50 GeV.

Figures 8.3(a)–(b) show that the  $\text{Sum-}E_T$  measured at L1 is consistently and substantially lower than that measured at EF or offline. This is a consequence of the high noise threshold applied to each trigger tower at L1 – typically around 1.2 GeV – which results in a majority of towers contributing nothing to the  $\text{Sum-}E_T$ . In contrast, the noise thresholds at EF and offline are relatively low and so a larger amount of soft (low- $p_T$ ) activity is included. The

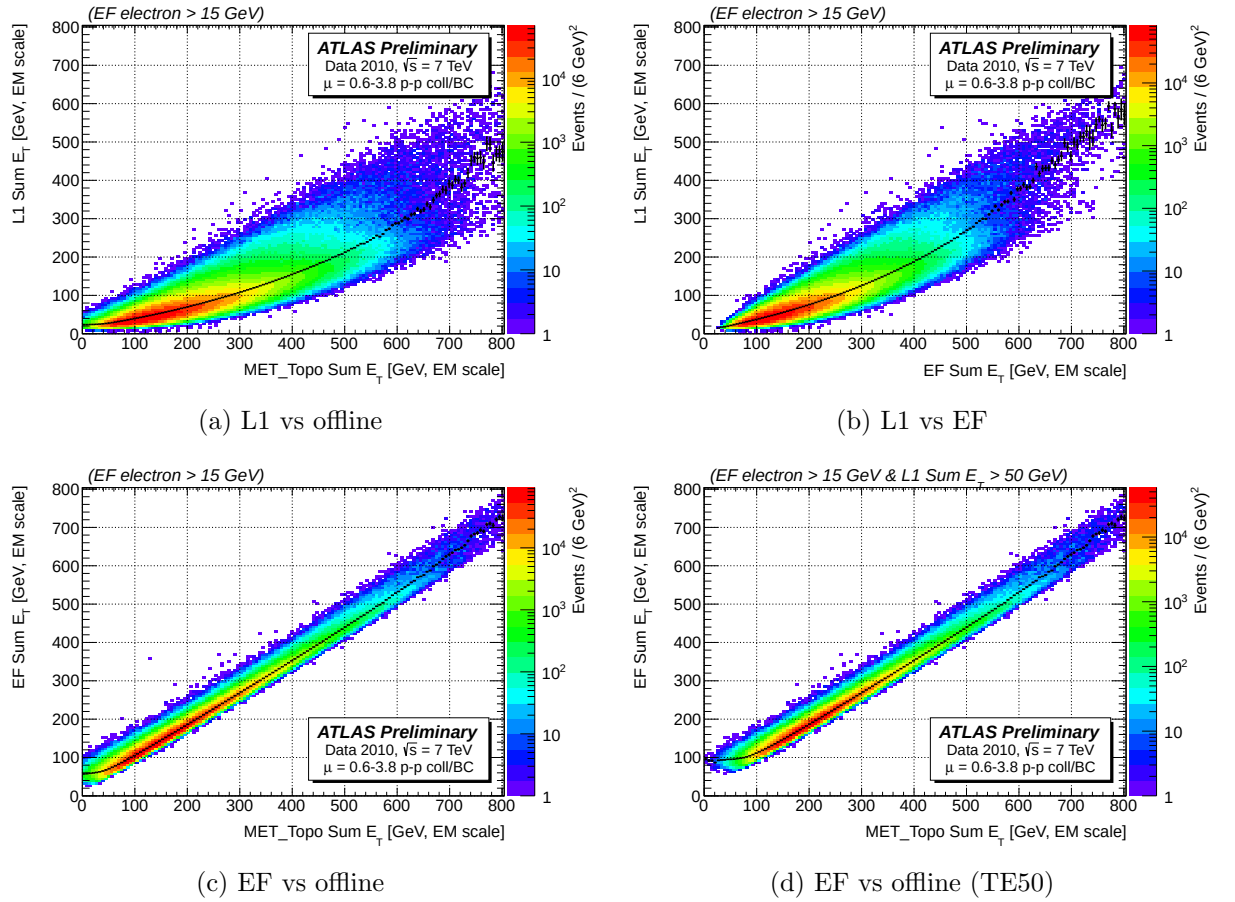


Figure 8.3: Correlations between online (L1/EF) and offline Sum- $E_T$  for electron-triggered events in 2010 data.

effect is not as extreme when examining the *missing* transverse energy because there we calculate a *vector* sum, so soft contributions from opposite sides of the detector will tend to cancel out.

The upward curve of the profile histograms can be explained along similar lines. When the total transverse energy in the event becomes very large, the thresholds used to reduce noise become less significant, and the L1 Sum- $E_T$  starts to converge with that measured at EF and offline.

Another noteworthy feature is the non-zero offset in the EF Sum- $E_T$  (figures 8.3(c)-(d)): there are very few events below 40 GeV at EF, and none below 20 GeV. This results from the one-sided noise cut that is applied at EF, which means that every transverse energy contribution is positive. Conversely, the offline noise cut (used to seed the topoclusters) is two-sided, giving both positive and negative energy contributions to the Sum- $E_T$ . Thus it is possible to see zero total transverse energy offline, even when we have a source of real energy, in the form of an electron.

In summary, the trigger-level  $E_T^{\text{miss}}$  and Sum- $E_T$  are seen to behave sensibly and in a way that is consistent with our knowledge of the L1, EF and offline algorithms. The features described here can be reproduced using simulated  $W \rightarrow e\nu$  events, which confirms that these are fundamental features of the algorithms and not just artifacts of the data. In the next section, we draw on the understanding gained here to look at the efficiency of the  $E_T^{\text{miss}}$  triggers, using the offline quantity as a reference variable.

## 8.3 Efficiency measurements

The efficiency of a trigger is defined as the fraction of some sample of events which are successfully passed. It is most commonly expressed as a function of a related offline variable, for example the offline  $E_T^{\text{miss}}$  in the case of the  $E_T^{\text{miss}}$  trigger. In this form the efficiency is used to decide where to place cuts on offline variables such that the trigger is fully efficient, or very nearly so. The penalty for not placing such cuts appropriately is that of potentially



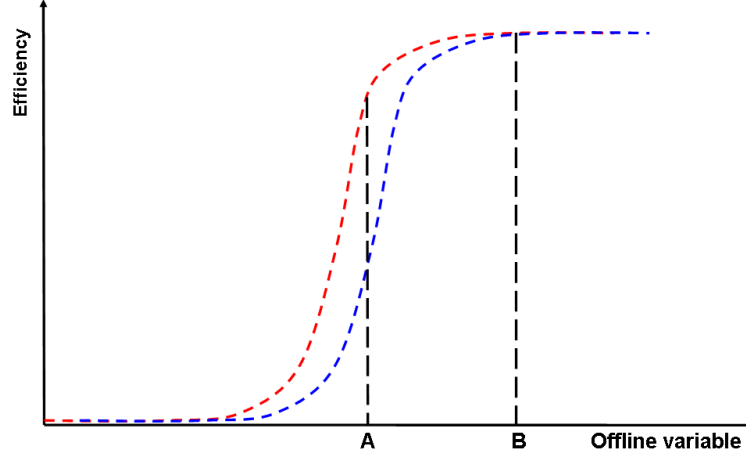


Figure 8.4: Example of efficiency turn-on curves and placing of offline cuts.

introducing a large systematic uncertainty from not knowing the exact centre and width of the efficiency turn-on region. As an example, consider the scenario shown in figure 8.4.

If the offline cut is placed at ‘A’, the number of events collected can potentially change by a factor of two with just a small change in the location of the turn-on region (indicated by the red and blue efficiency curves). The resulting uncertainty is so large because of the steepness of the efficiency curve in this region. On the other hand, if we cut at ‘B’ we do not suffer from this problem because the efficiency is near 100%. In general, the efficiency does not have to be exactly 100%, but the cut should be chosen such that the efficiency is slowly varying, and hence any uncertainty in the location of the turn-on region has only a small effect on the final event count.

For the following studies the offline reference variable will be the topocluster-based EM-scale  $E_T^{\text{miss}}$  described in the introduction to this chapter. The test samples will consist of electron and muon-triggered events with further offline cuts to increase the purity of  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  events respectively. For electron events, these cuts consist of a tight electron quality cut (see section 1.2.6),  $p_T > 20$  GeV,  $|\eta| < 2.47$  and a veto on electrons falling in the calorimeter barrel-endcap transition region ( $|\eta|$  not in range 1.37–1.52). Missing transverse energy and transverse mass cuts are *not* applied, since we wish to view the efficiency across the full range of  $E_T^{\text{miss}}$ . This leaves us somewhat vulnerable to fake-electron backgrounds from QCD, but these are heavily suppressed by the electron quality cut and should be confined to

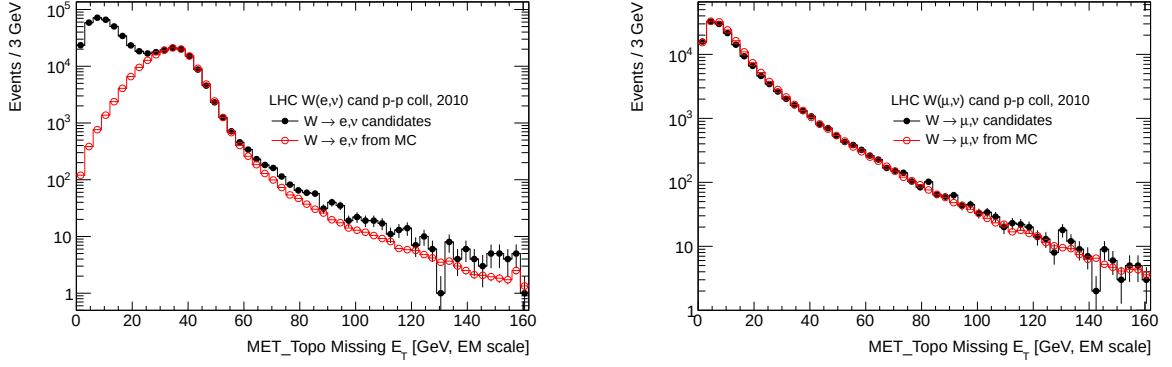


Figure 8.5: Offline  $E_T^{\text{miss}}$  distributions for  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  candidate events, compared with Pythia simulated samples.

the low- $E_T^{\text{miss}}$  region. In the muon channel, we require an isolated Staco combined muon (see section 1.2.7). We also apply a  $p_T$  cut at 20 GeV, an  $|\eta|$  cut at 2.4 and require  $M_T$  (see section 4.6) to be in the range 40–80 GeV. In the muon case the transverse mass cut does not severely suppress the low- $E_T^{\text{miss}}$  event count, since the  $E_T^{\text{miss}}$  used in the  $M_T$  calculation is corrected for the muon  $p_T$  whereas the offline reference variable is not muon-corrected. This reduces the correlation between the  $E_T^{\text{miss}}$  reference variable and the muon  $M_T$ . We therefore take advantage of the  $M_T$  cut in this instance to provide additional QCD background suppression.

Figure 8.5 shows how the electron (left) and muon (right) test samples are distributed as a function of offline  $E_T^{\text{miss}}$ . Also shown are the distributions from simulation of  $W \rightarrow e\nu$  and  $W \rightarrow \mu\nu$  events, normalised to the data in the region  $E_T^{\text{miss}} > 30$  GeV. The simulated samples are generated using Pythia [81] and are fully inclusive in jet multiplicity. Recall that the  $E_T^{\text{miss}}$  plotted here uses the calorimeter only (i.e. muons are effectively non-interacting for our purposes), which explains the very different appearance of the left and right plots. These comparisons are intended to show, from the similarity of the data and simulation distribution shapes, that the data collected are consistent with being dominated by  $W \rightarrow \ell\nu$  events. In the low- $E_T^{\text{miss}}$  region of the electron distribution we can also clearly identify a contribution from QCD fake electrons, whereas at high  $E_T^{\text{miss}}$  we see a feature consistent with  $t\bar{t}$  production (not included in the simulated distributions).

In figure 8.6 we see the efficiency of the L1  $E_T^{\text{miss}}$  trigger alone with no EF cut applied,

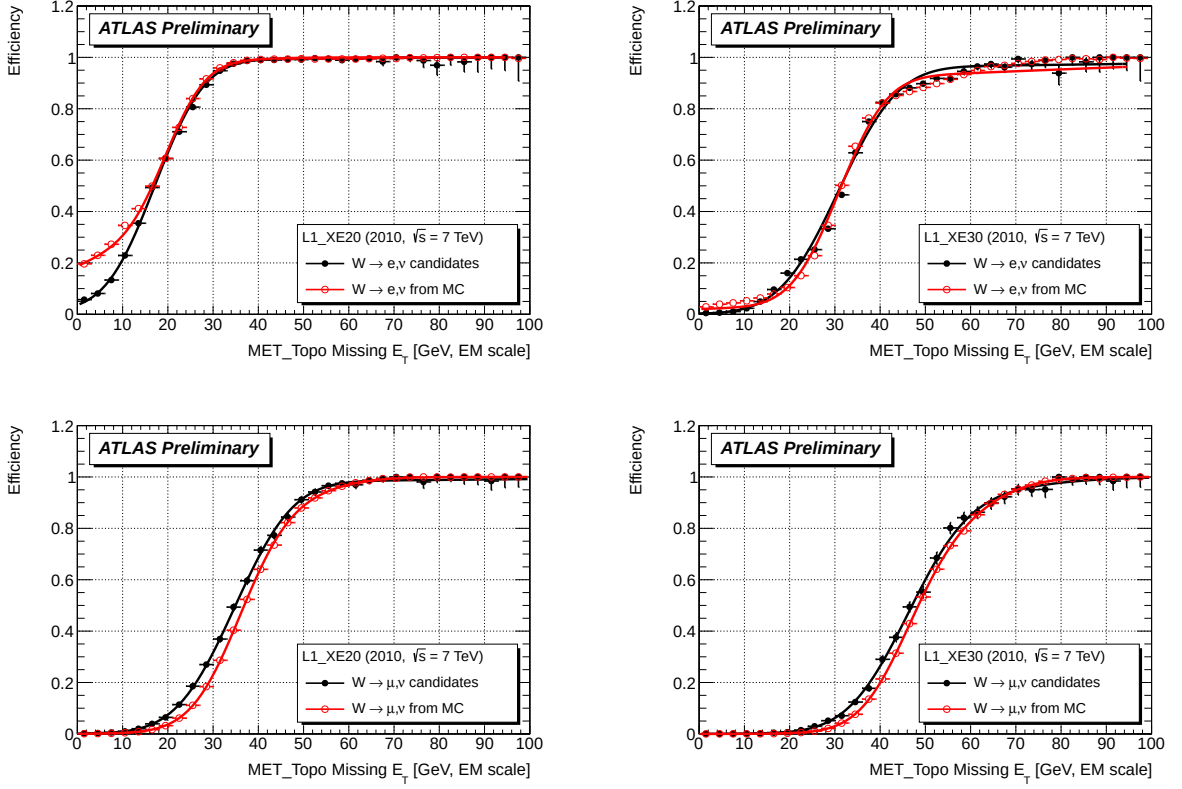


Figure 8.6: Efficiencies of some L1-only  $E_T^{\text{miss}}$  triggers for  $W \rightarrow e\nu$  (top) and  $W \rightarrow \mu\nu$  (bottom) candidate events. Left: L1\_XE20, right: L1\_XE30.

for both data and simulation. The upper and lower plots show the efficiencies for electron and muon events respectively. The two plots on the left place the L1 threshold at 20 GeV (L1\_XE20) and the plots on the right at 30 GeV (L1\_XE30). The thresholds are representative of those used during the bulk of 2010 data-taking: 20 GeV during earlier runs (until partway through period G) and 30 GeV towards the end of year.

The points are  $\chi^2$ -fitted using a Gaussian cumulative distribution function (CDF). The asymmetric error bars are evaluated using the “Bayesian” method of the TEfficiency class in ROOT, which is a class specifically written to handle efficiency calculations [82].

The agreement between the data and the prediction is good, which demonstrates that the performance of the L1  $E_T^{\text{miss}}$  trigger is well-understood in the context of events with real missing transverse energy. The one area where there is an appreciable difference is at low  $E_T^{\text{miss}}$  in the upper-left plot, which can be ascribed to contamination by QCD background events containing fake  $E_T^{\text{miss}}$ . This hypothesis is supported by the feature at low  $E_T^{\text{miss}}$  in

figure 8.5 (left plot), where the QCD contribution causes the data to deviate from the shape which would be expected for  $W$  events alone.

The muon events are notably much slower to reach full efficiency than the electron events. This may seem mysterious given the apparent similarities between the two samples, but it can easily be understood as follows. Recall that, in the muon sample, muons are effectively non-interacting, which means that a  $W$  produced at rest in the transverse plane will have zero measured  $E_T^{\text{miss}}$  – ignoring calorimeter resolution effects – with the transverse momentum of the neutrino cancelling that of the muon. By contrast, a  $W \rightarrow e\nu$  event with the  $W$  produced at rest can have  $E_T^{\text{miss}}$  up to 40 GeV (i.e.  $M_W/2$ ). To measure a  $W \rightarrow \mu\nu$  event with a large  $E_T^{\text{miss}}$  requires the  $W$  to be boosted such that the neutrino and muon momenta do not cancel out. This implies the presence of one or more high- $p_T$  jets in the event, to provide the necessary recoil. Here then is the essential difference between the electron and muon events: in the former case, the  $E_T^{\text{miss}}$  predominantly recoils against an electron, in the latter case, hadronic jets. This fundamental difference in event topologies gives rise to the observed difference in efficiency behaviour.

The recoil of the  $W$  against hadronic jets also explains why the efficiency for the muon events lags behind the L1 threshold, i.e. why the point of 50% efficiency is well beyond 20/30 GeV. It is well-established [80] that the energies of jets measured at L1 are well below those measured offline (even allowing for the offline hadronic calibration, which is typically  $\sim 1.5$  [52]). This means that, for example, an offline jet  $p_T$  cut is required at around 120 GeV for a L1 threshold of 55 GeV. The  $E_T^{\text{miss}}$  in the muon events is, to a good approximation, equal to the  $|p_T|$  of the recoiling jet, hence the  $E_T^{\text{miss}}$  at L1 is lower and the rise in the efficiency is delayed.

Figure 8.7 shows the efficiency of the EF  $E_T^{\text{miss}}$  trigger alone, with no L1 cut. Again we choose two thresholds which represent the primary triggers used during 2010, namely 30 and 40 GeV. The thresholds are higher than at L1 because of limitations on the rate of events being written to permanent storage, which is much lower than the number that can be processed by the event builder (recall section 1.2.5). As with L1, the simulation

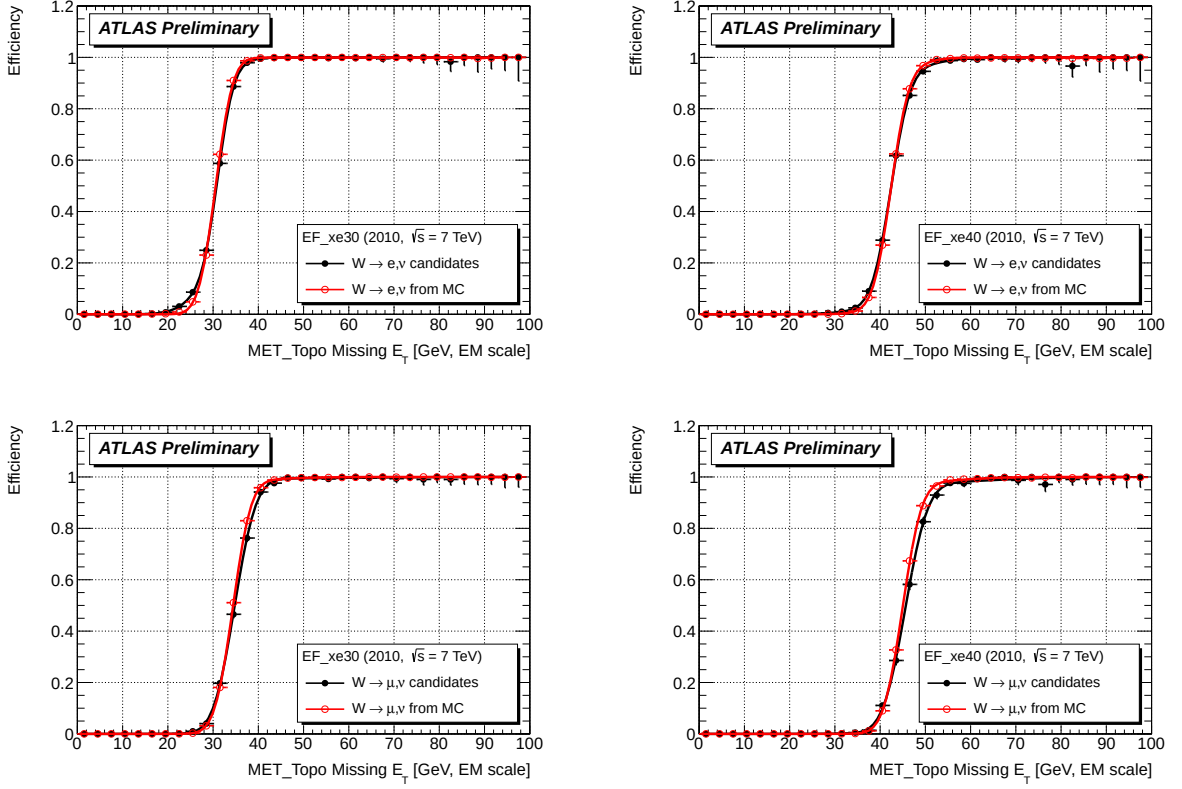


Figure 8.7: Efficiencies of some EF-only  $E_T^{\text{miss}}$  triggers for  $W \rightarrow e\nu$  (top) and  $W \rightarrow \mu\nu$  (bottom) candidate events. Left: EF\_xe30, right: EF\_xe40.

predicts the data well, this time with no noticeable effect from QCD background. Note that the turn-on is much sharper here than it was at L1, which reflects the strong correlation between offline and EF  $E_T^{\text{miss}}$  as shown in figure 8.2. For the same reason, the dependence on event topology is much smaller than at L1. Specifically, the performance on electron and muon events is much more similar than in figure 8.6, though with a small ( $\sim 5$  GeV) difference in the position of the turn-on region.

Finally, in figure 8.8 we show the efficiency for two full (L1+EF) chains, xe30\_noMu (L1\_XE20 + EF\_xe30) and xe40\_noMu (L1\_XE30 + EF\_xe40). All but the first of the subfigures display features of both the EF and L1 triggers, specifically the sharp initial turn-on (EF), followed by the slow rise to full efficiency (L1). The interplay between the two levels gives rise to a kink, which occurs when the EF trigger is nearly fully efficient but the L1 has some residual inefficiency. This double structure is fitted using a sum of two independent Gaussian CDFs, as opposed to the usual one, with their relative height treated as a free

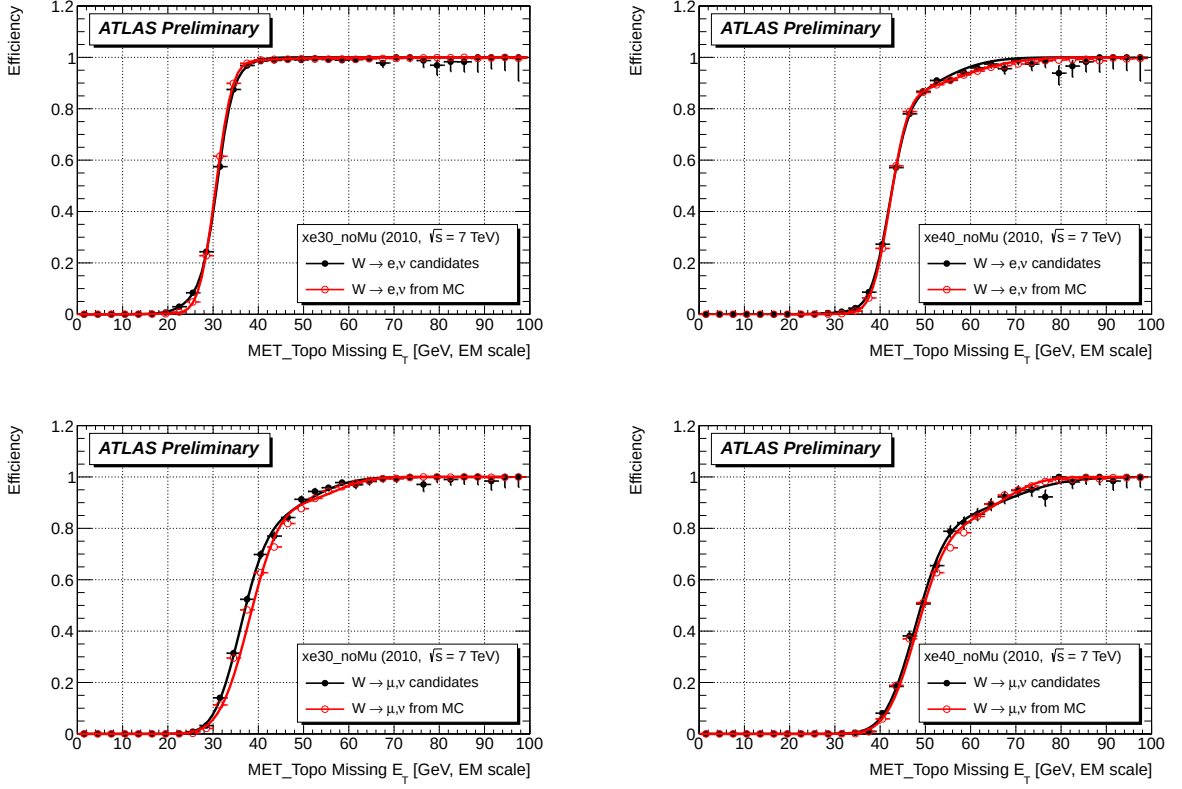


Figure 8.8: Efficiencies of some L1+EF  $E_T^{\text{miss}}$  triggers for  $W \rightarrow e\nu$  (top) and  $W \rightarrow \mu\nu$  (bottom) candidate events. Left: `xe30_noMu`, right: `xe40_noMu`.

parameter. In contrast, figure 8.8(a) shows an efficiency that is completely dominated by the EF trigger. Once again, we see good agreement between data and simulation.

In this section we have examined the efficiencies of the L1 and EF  $E_T^{\text{miss}}$  triggers, both separately and combined, on events containing real missing transverse energy. In comparing the data with the predictions, we have shown that the trigger performance is well-modelled in the simulation, thereby validating both the simulation and the online trigger algorithms themselves. We have also seen that the appearance and features of the efficiency curves are congruent with the nature of the data samples and our understanding of the triggers. This puts us in a strong position to start using these triggers for physics analyses.

## 8.4 Evolution of the triggers in 2010

In this section we look at how the performance of the trigger evolved between the 2010 data-taking periods F–I, with particular reference to the rate and the efficiency. In seeing which distributions change and which remain constant, we will gain understanding into the effects of pileup.

Increasing pileup (i.e. increasing number of secondary proton-proton interactions in each LHC bunch crossing) is expected to have a large effect on the acceptance rates of both the  $E_T^{\text{miss}}$  and Sum- $E_T$  triggers. The Sum- $E_T$  in a given event is strongly dependent on the mean number of interactions per bunch crossing,  $\langle\mu\rangle$ , and the  $E_T^{\text{miss}}$  is affected as well, via the resolution relation:

$$\sigma(E_{x,y}^{\text{miss}}) \simeq \text{const} \times \sqrt{(\text{Sum-}E_T)}$$

This formula, which has been verified with data [15], says that the more transverse activity the event has, the worse the  $E_T^{\text{miss}}$  resolution becomes. Given that the  $E_T^{\text{miss}}$  trigger rate is typically dominated by events containing no real missing transverse energy, this implies a dependence of the trigger rate on the number of pileup interactions. This means that the  $E_T^{\text{miss}}$  trigger output rate increases faster than would be expected from the rising instantaneous luminosity alone.

In figure 8.9 we see the unbiased  $E_T^{\text{miss}}$  (top) and Sum- $E_T$  (bottom) distributions at L1 (left) and EF (right) for the four data-taking periods F–I, where F has the lowest average pileup and I the highest. The four distributions in each subfigure are normalised to the same total area in order to emphasise the differences in shape. The data used in these plots are collected using the minimum bias trigger, and are therefore composed almost entirely of events with no real  $E_T^{\text{miss}}$ . Here we see a clear depiction of the effects of pileup, in that all four distributions become noticeably broader as we move towards larger  $\langle\mu\rangle$ . Beyond around 15 GeV in both the L1 and EF  $E_T^{\text{miss}}$  distributions, the rate for a given threshold increases by a factor of  $\sim 3$ , on a per-proton-interaction basis. However, this increase can be compensated for by a relatively modest change in the threshold: by moving 1-2 bins further

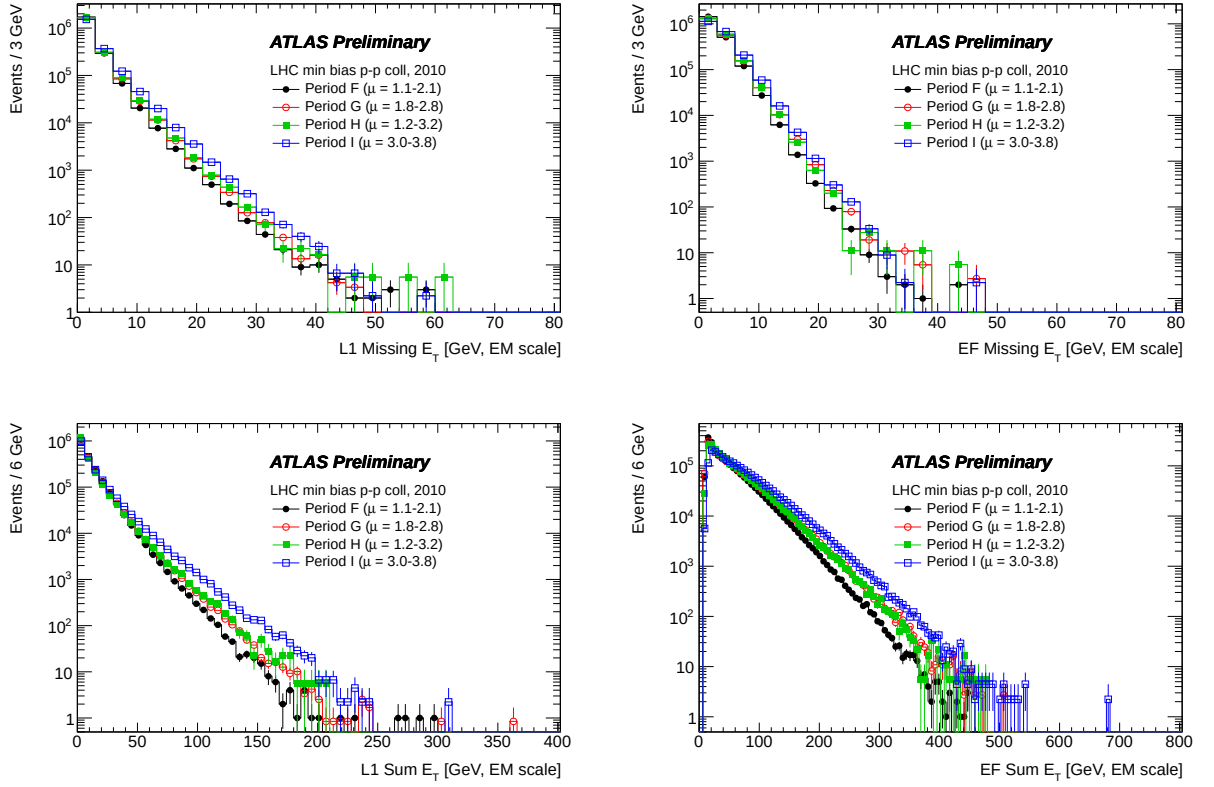


Figure 8.9: Unbiased  $E_T^{\text{miss}}$  (top) and Sum- $E_T$  (bottom) distributions for the L1 (left) and EF (right) triggers, comparing the last four data-taking periods of 2010.

to the right (an increase of 3–6 GeV) the same per-interaction rate can be maintained from period F to period I. The required increase is larger at L1 than at EF, demonstrating that L1 suffers more from the effects of pileup.

To check that the effect is really due to pileup and not some other cause, we reproduce the plots, this time requiring exactly one reconstructed primary vertex in each event; this cut effectively functions as a pileup veto. The results are shown in figure 8.10. Here the difference between the periods is minimal, which confirms our hypothesis, and also demonstrates the excellent stability of the triggers when pileup is factored out. Note also that the distributions are significantly steeper than those without the vertex cut.

Despite the rather dramatic changes to the rates, we would expect the efficiency on events with real  $E_T^{\text{miss}}$  to remain approximately constant from period to period. Where large real  $E_T^{\text{miss}}$  is present ( $E_T^{\text{miss}} \gg \sigma(E_{x,y}^{\text{miss}})$ ), the effects of degraded resolution should be much reduced. In figure 8.11 we plot the efficiency of the xe30\_noMu L1+EF trigger for



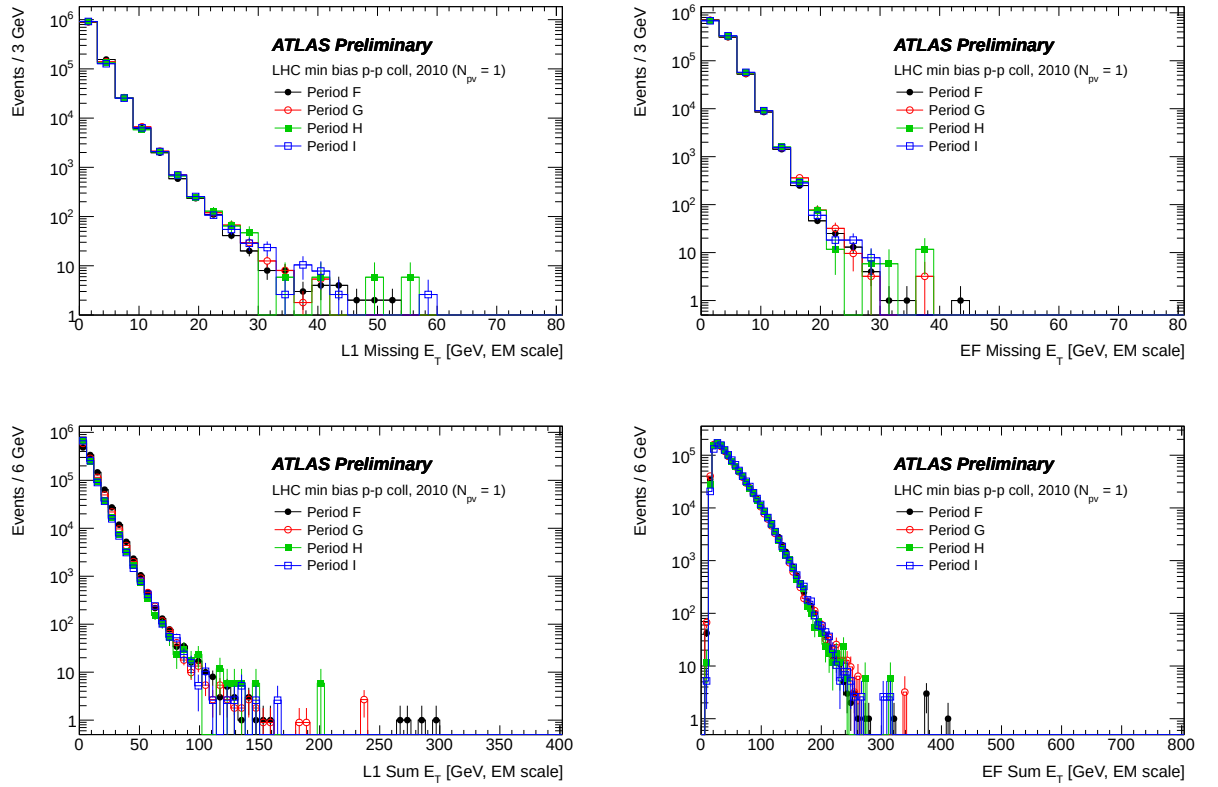


Figure 8.10: Unbiased  $E_T^{\text{miss}}$  (top) and Sum- $E_T$  (bottom) distributions for the L1 (left) and EF (right) triggers, comparing the last four data-taking periods of 2010. A cut is made requiring exactly one reconstructed primary vertex.

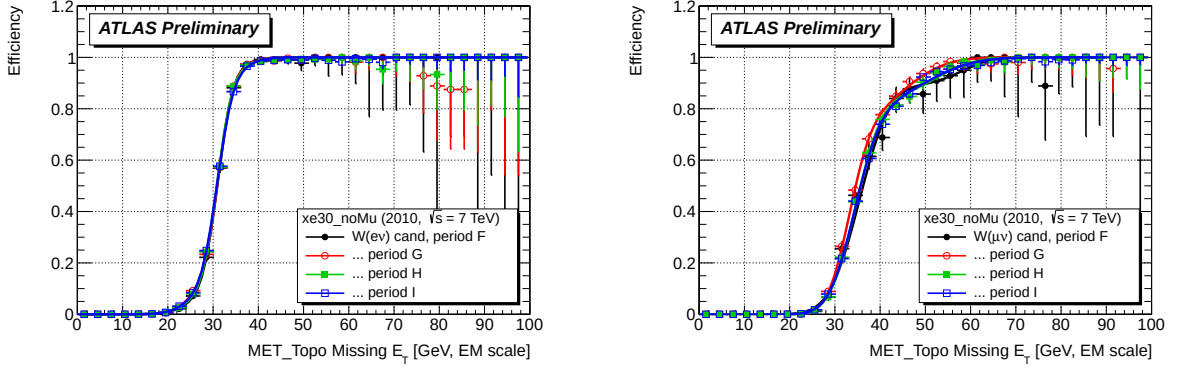


Figure 8.11: Variation – or lack thereof – in the efficiency of the xe30\_noMu trigger (L1\_XE20 + EF\_xe30) in 2010 data-taking, for  $W \rightarrow e\nu$  (left) and  $W \rightarrow \mu\nu$  (right) candidate events.

$W \rightarrow e\nu$  (left) and  $W \rightarrow \mu\nu$  (right) candidate events with the periods plotted separately. The efficiency curves are indeed compatible within uncertainties, as we expect. The stability of the efficiency is not only reassuring, it is convenient for physics analyses, as it allows a single efficiency to be assumed across the entire dataset, with no need for detailed event-by-event pileup corrections.

## 8.5 Conclusions

This chapter has examined, from several angles, the performance of the ATLAS missing transverse energy ( $E_T^{\text{miss}}$ ) and transverse energy sum (Sum- $E_T$ ) triggers during 2010 data-taking. Overall, the behaviour is seen to be compatible with expectations, and with simulation where applicable, with no major anomalies observed. The studies presented here allowed these triggers to be declared fully commissioned, and provided a strong foundation of understanding for physics analyses and for further studies using 2011 data. Of particular relevance to this thesis, we can be confident that a hypothetical new physics event containing sufficiently large  $E_T^{\text{miss}}$  will be passed by the trigger with  $> 98\%$  probability, and will thereby be made available for offline analysis.

# Chapter 9

## Use of missing transverse energy triggers for SUSY searches

In this chapter we consider the use of missing transverse energy ( $E_T^{\text{miss}}$ ) triggers for 0-lepton supersymmetry searches. In particular, we will be interested in the efficiencies of these triggers for events containing high- $p_T$  jets. Both inclusive (i.e.  $E_T^{\text{miss}}$  only) and combined jet +  $E_T^{\text{miss}}$  triggers will be considered, and their relative merits discussed. We conclude that a trigger seeded by jets at L1 and L2, with a cut on the missing transverse energy at event filter, is the best overall solution in terms of rates, efficiency, and understanding of the trigger behaviour. The discussion below is given in the context of the ATLAS 0-lepton search using 2010 data [57, 83] and uses the same dataset ( $35 \text{ pb}^{-1}$ ) and object definitions.

### 9.1 Introduction

In our search for  $R$ -parity-conserving SUSY, the events of interest are characterised by large  $E_T^{\text{miss}}$ , two or more energetic jets, and no reconstructed electrons or muons. The relevant triggers are therefore: a) jet, b)  $E_T^{\text{miss}}$ , c) Sum- $E_T$ , d) some combination of these. Of these, the Sum- $E_T$  suffers enormous contributions from the underlying event and pileup interactions, and so can safely be discarded for early searches. A jet trigger on its own – either single or dijet – is liable to be overwhelmed by QCD dijet events, which constitute the vast majority of the total hard interaction cross-section at the LHC. A high threshold is

invariably required in order to maintain a reasonable rate, which could harm the acceptance of SUSY events, particularly if the new particle masses are relatively low, or their mass splittings are small. We are therefore left with the  $E_T^{\text{miss}}$  trigger, or a combination of jet and  $E_T^{\text{miss}}$  triggers, as the most promising candidates.

For searches requiring higher jet multiplicities (e.g.  $\geq 6$  jets [84]), it becomes viable to use jet-only triggers, taking advantage of the large number of jets to keep thresholds low while still rejecting QCD events. However, we constrain ourselves here to topologies with only 2-3 jets, as per the ATLAS 2010 0-lepton SUSY search [57].

In what follows the  $m_{\text{eff}}$ ,  $M_{T2}$ ,  $\Delta\phi(\text{jet}, E_T^{\text{miss}})$  and  $E_T^{\text{miss}}/m_{\text{eff}}$  cuts described in [57] are not applied, so as to give the largest possible test samples. The  $E_T^{\text{miss}}$  cut is similarly omitted, in order that we can observe the behaviour of the  $E_T^{\text{miss}}$  trigger across the entire spectrum, and that we may keep an open mind about where the final offline cut should be placed. This reduces the four signal regions to a 2-jet and a 3-jet region, with cuts at 120 GeV on the leading jet and 40 GeV on the subleading jets, and no further kinematic cuts.

The offline  $E_T^{\text{miss}}$ , referred to by the shorthand “simplified MET\_RefFinal”, uses jets with  $p_T > 20$  GeV at the hadronic scale, and topoclusters not associated with physics objects at the EM scale. A muon correction is normally applied using Staco muons, but for these studies it is omitted, allowing a muon event sample to be used to evaluate the  $E_T^{\text{miss}}$  trigger efficiency.

## 9.2 Inclusive MET trigger

The lowest-threshold inclusive  $E_T^{\text{miss}}$  trigger which remained unrescaled throughout 2010 was `xe40_noMu`, with L1 and EF thresholds at 30 and 40 GeV respectively. We measure the efficiency of this trigger using two different event samples. The first is collected using a single jet trigger, `L1_J55 + L2_j70*`, which is approximately fully efficient at the leading jet  $p_T$  cut of 120 GeV [83]. This trigger was prescaled late in 2010, precluding its use for

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\*The EF jet trigger was not fully commissioned until 2011, and so was not used to reject events in 2010.

the main analysis, but it provides an adequately-sized data sample for evaluating the  $E_T^{\text{miss}}$  trigger performance. This sample is dominated by QCD dijet/multijet events with fake  $E_T^{\text{miss}}$  arising from jet energy mismeasurement. Note that while these events are predominantly QCD, in the signal regions the additional kinematic cuts mean that QCD is a relatively minor background.

The second sample used to measure efficiency is collected using the muon trigger EF\_mu13, and requiring at least one isolated combined/tagged Staco muon, with  $p_T > 20$  GeV and  $|\eta| < 2.4$ , reconstructed offline. The events captured here are more representative of the signal itself, being characterised by large real  $E_T^{\text{miss}}$ , enhanced by the contribution from the muon itself, and only hadronic activity in the calorimeter.

Figure 9.1 shows the efficiency of xe40\_noMu with respect to jet-triggered events for data, simulated QCD dijets and the SU4 SUSY model\*. The left and right subfigures are for 2 and 3 jets respectively. The data and the simulated QCD have a very broad turn-on region compared to the signal, and in fact seem never to reach full efficiency. The latter observation can be confirmed by plotting the efficiency as a function of EM-scale offline  $E_T^{\text{miss}}$ , which gives a very clear plateau at around 80% efficiency. From the close agreement between the data and the simulated QCD, and the extremely *poor* agreement with the simulated SUSY, we can deduce that the data are indeed dominated by QCD dijet events.

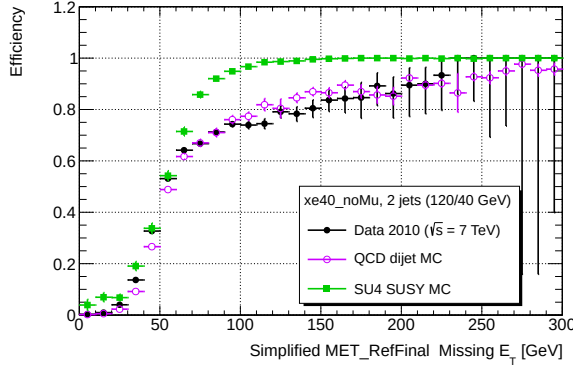
Figure 9.2 shows the efficiency for the L1 part of the chain. This demonstrates that the unusual behaviour seen in the full chain originates at L1: note the discontinuity at around 50 GeV, and the low plateau.

The implication of the low plateau is that QCD events can have arbitrarily large  $E_T^{\text{miss}}$ , but still fail to pass a 30 GeV threshold at L1. This is certainly plausible, given that the  $E_T^{\text{miss}}$  being measured is an artifact of the calorimeter energy measurement, and that the methods for measuring the energy are very different at L1 and offline<sup>†</sup>. Conversely, we can

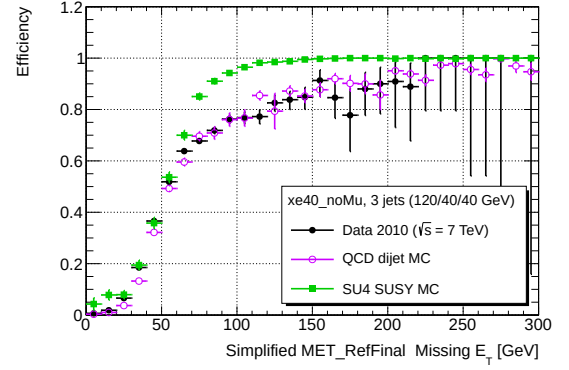
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\*SU4 is an ATLAS benchmark SUSY point, characterised by low sparticle masses and correspondingly high production cross-sections, lying just outside the Tevatron excluded region as of 2008 [11]. It contains a mixture of 0-lepton and leptonic events.

<sup>†</sup>Details of the L1 and offline  $E_T^{\text{miss}}$  algorithms may be found in previous chapters. Briefly, the main difference is that at L1 the  $E_T^{\text{miss}}$  is calculated from trigger towers (see chapter 7) whereas topological

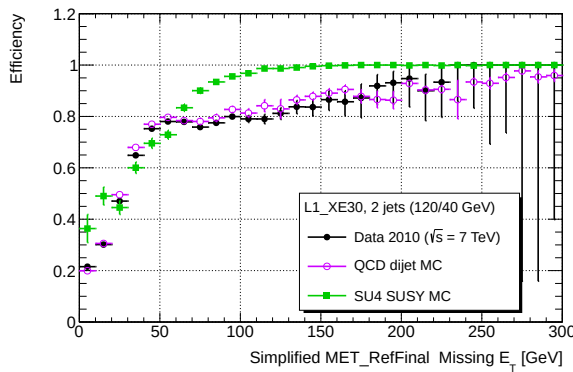


(a) 2-jet

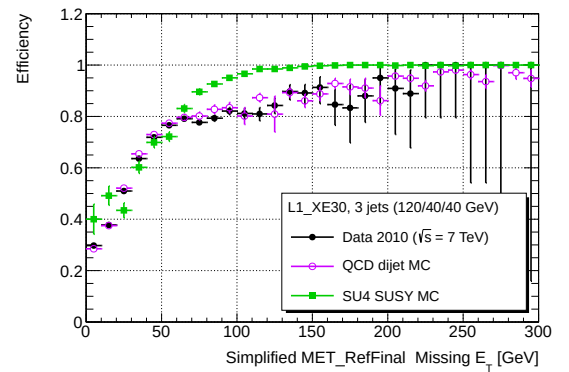


(b) 3-jet

Figure 9.1: Efficiency of the  $E_T^{\text{miss}}$  trigger xe40\_noMu for samples collected with the jet trigger L1\_J55 + L2\_j70 for events with  $\geq 2$  jets (left) and  $\geq 3$  jets (right). An offline cut on the  $p_T$  of the leading jet at 120 GeV ensures that the reference trigger is nearly fully efficient.



(a) 2-jet



(b) 3-jet

Figure 9.2: Efficiency of the  $E_T^{\text{miss}}$  trigger L1\_XE30 for samples collected with the jet trigger L1\_J55 + L2\_j70 for events with  $\geq 2$  jets (left) and  $\geq 3$  jets (right). An offline cut on the  $p_T$  of the leading jet at 120 GeV ensures that the reference trigger is nearly fully efficient.

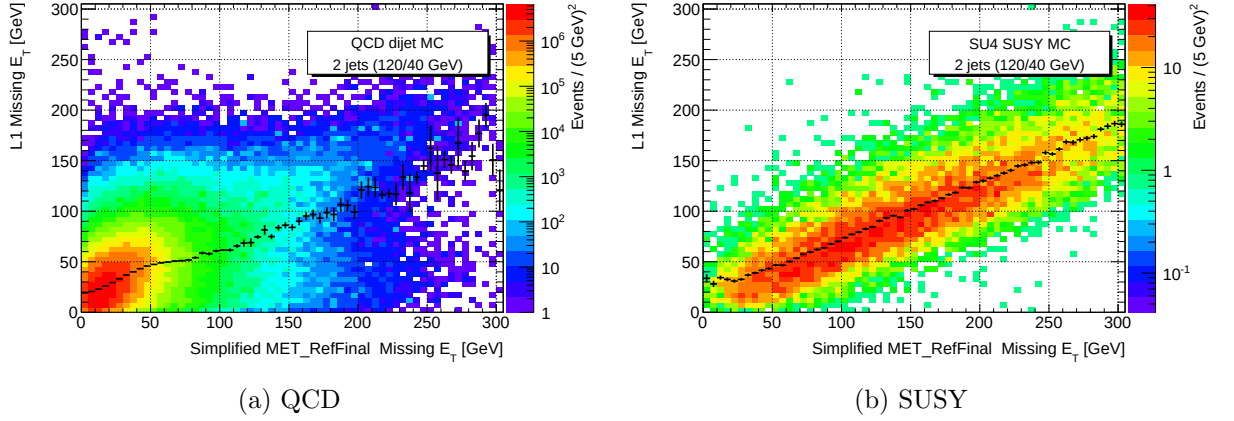


Figure 9.3: Correlation plot between L1 and offline  $E_T^{\text{miss}}$  for simulated QCD multijets (left) and SUSY (right), requiring 2 jets above 120 and 40 GeV.

reach full efficiency with signal events because here the  $E_T^{\text{miss}}$  is mostly real, meaning that the two algorithms are much more likely to agree.

Figure 9.3 shows the scatter between L1 and offline  $E_T^{\text{miss}}$  for simulated QCD events (left) and SUSY events (right) in the 2-jet channel. These plots show, from another perspective, the much stronger correlation between the online and offline quantities when the  $E_T^{\text{miss}}$  is real as opposed to fake.

It is now desirable to confirm that 100% efficiency can be attained for events containing real  $E_T^{\text{miss}}$  in data. To do this, we use the sample of muon-triggered events, which should be dominated by  $W \rightarrow \mu\nu + \text{jets}$  with smaller contributions from heavy-flavour QCD,  $Z \rightarrow \mu\mu + \text{jets}$ , and top quark production. The efficiency of the xe40\_noMu trigger for these events is shown in figure 9.4, comparing the data efficiency for different jet cuts (left), and comparing against simulation (right). The black points (corresponding to the baseline 120/40 GeV jet cuts) are the same in both plots. As expected, the efficiency seems to be much closer to that of the simulated signal than that of the QCD background.

Figure 9.4(a) demonstrates how the trigger is affected by increasing the amount of hard jet activity in the event. Fortunately, the effect is to *increase* efficiency at any given offline  $E_T^{\text{miss}}$ , so we need not be concerned about extremely energetic signal events failing to pass the trigger. Figure 9.4(b) shows that the observed efficiency is described well by the simulation, clusters are used offline (sections 1.2.8-1.2.9).

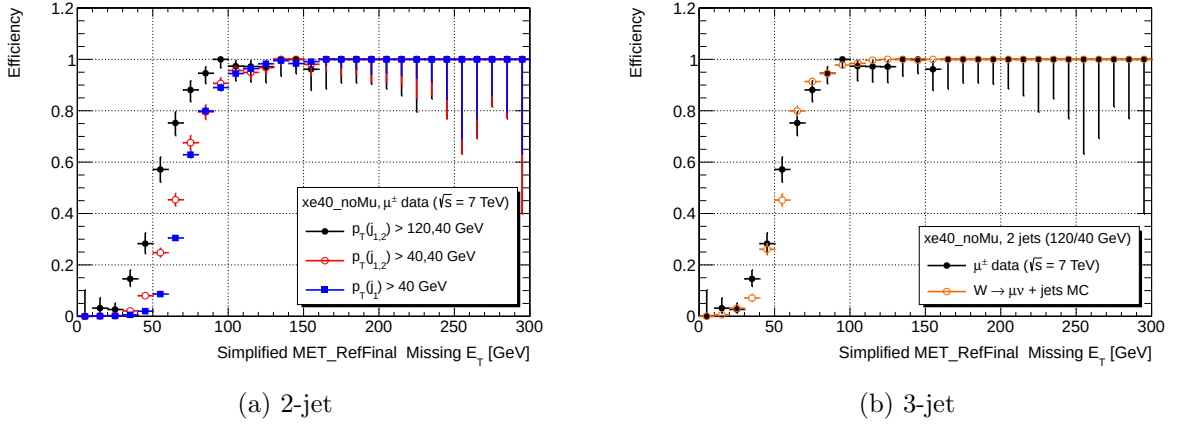


Figure 9.4: Efficiency of the  $E_T^{\text{miss}}$  trigger xe40\_noMu for muon events, showing data with different jet cuts (left) and data vs simulated  $W \rightarrow \mu\nu$  (right). In the left plot we require a) one jet with  $p_T > 40$  GeV, b) two jets, both with  $p_T > 40$  GeV, and c) the basic dijet cuts used in [57], i.e.  $p_T > 120/40$  GeV.

which is what we would have expected based on the results shown in the previous chapter.

In this section we have seen that the inclusive  $E_T^{\text{miss}}$  trigger, and in particular the L1 component, has the undesirable properties of a) behaving differently for real and fake  $E_T^{\text{miss}}$  events and b) not reaching full efficiency for the latter. These properties had the potential to introduce additional systematic uncertainties into the final analysis. In the next section we will introduce a new trigger which was used to circumvent the problematic L1  $E_T^{\text{miss}}$  trigger entirely.

## 9.3 Jet + $E_T^{\text{miss}}$ triggers

### 9.3.1 Introduction

Let us consider a trigger with a single jet threshold at L1 and L2 and a cut on  $E_T^{\text{miss}}$  at EF, i.e. L1\_JXX + L2\_jYY + EF\_xeZZ\*. No  $E_T^{\text{miss}}$  cut is applied at L1 or L2, thus avoiding the problems described in section 9.2.

Note that while combined jet- $E_T^{\text{miss}}$  triggers already existed in the trigger menu, they

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\*The reason we don't include a jet requirement at EF is that the algorithms were not validated at the time these studies were carried out.



all applied  $E_T^{\text{miss}}$  cuts at L1 and L2, thereby inheriting the same issues as the inclusive  $E_T^{\text{miss}}$  trigger. Furthermore, their efficiencies were somewhat difficult to measure owing to the difficulty in disentangling the jet and  $E_T^{\text{miss}}$  components of the chain. By contrast, the efficiency measurement for the new chains is straightforward.

### 9.3.2 History and development

The new trigger family was presented to the ATLAS trigger community by the author in September 2010, on behalf of the 0-lepton SUSY analysis team, and approved for immediate online use. The original proposal is summarised briefly here, as it gives some useful insight into the necessary considerations for designing and implementing a new trigger.

At the time of the initial proposal, the L2 jet trigger was not yet fully commissioned, so the prospective chains were in the form L1\_JXX + EF\_xeZZ. For the L1 jet trigger, the natural choice was L1\_J55, as this was the highest threshold that allowed the offline leading jet cut to be maintained at the established value of 120 GeV. In fact the 120 GeV cut was specifically chosen to be in the plateau of L1\_J55. The new trigger was designed to yield acceptable rates at an instantaneous luminosity of  $1 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ , the anticipated maximum for 2010 running (this maximum was eventually exceeded by a factor of two). At this luminosity, the predicted output rate of L1\_J55 was around 50 Hz, which represents roughly 0.1% of the total allowed bandwidth coming out of L1, and around 1.4% at L2, which was deemed acceptable.

The predicted rates from the chains L1\_J55 + EF\_xeZZ are shown in table 9.1, for  $ZZ = 20\text{-}35 \text{ GeV}$ . The inclusive (total) and exclusive (unique) rates are shown separately. The latter takes into account overlap with the inclusive  $E_T^{\text{miss}}$  trigger xe35\_noMu (anticipated to be the highest unrescaled  $E_T^{\text{miss}}$  trigger at  $1 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ ) and the jet trigger L1\_J75 (the lowest unrescaled jet trigger).

The total budget for combined jet- $E_T^{\text{miss}}$  triggers in ATLAS was intended to be around 8 Hz, so a choice was made to submit L1\_J55 + EF\_xe30 as the primary trigger, with

| EF $E_T^{\text{miss}}$ thr. | Incl. rate (Hz) | Excl. rate (Hz) | Notes                                   |
|-----------------------------|-----------------|-----------------|-----------------------------------------|
| xe20                        | 20              | 10              | -                                       |
| xe25                        | 13              | 5.5             | Unprescaled in 2010<br>Intended primary |
| xe30                        | 7.6             | 2.0             |                                         |
| xe35                        | 4.2             | 0.2             | -                                       |

Table 9.1: Predicted rate-to-tape of events passing L1\_J55 and the EF  $E_T^{\text{miss}}$  threshold shown, at  $1 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$  instantaneous luminosity. The exclusive rate removes overlap with xe35\_noMu and L1\_J75.

inclusive and exclusive rates of 7.6 Hz and 2.0 Hz respectively. Versions with lower and higher  $E_T^{\text{miss}}$  thresholds (20, 25, 35, 40 GeV) were also included in the menu as backup triggers, in case rates were lower or higher than predicted. As it transpired, the xe25 version remained unprescaled throughout 2010, despite the instantaneous luminosity being a factor of two higher than anticipated and the inclusive rate increasing to around 25 Hz.

Happily the L2 jet trigger was commissioned in time to be included in these chains before they were run online. A threshold of 70 GeV was chosen at L2, which reaches full efficiency at approximately the same offline jet  $p_T$  as L1\_J55 [80] while substantially reducing the rate going into EF.

### 9.3.3 Performance

As indicated above, the trigger used to select the final analysis sample consisted of the cuts L1\_J55 + L2\_j70 + EF\_xe25. The efficiency of this trigger may be expressed in terms of a jet part and an  $E_T^{\text{miss}}$  part:

$$P(E_T^{\text{miss}} \wedge \text{jet}) = P(E_T^{\text{miss}} | \text{jet}) \cdot P(\text{jet})$$

Here we focus on the  $E_T^{\text{miss}}$  part of the chain, i.e. the first probability on the right hand side; the efficiency of the jet part is described in detail elsewhere [80, 83].

The efficiency of the EF\_xe25 trigger for events collected with the jet trigger L1\_J55 + L2\_j70 is shown in figure 9.5, for 2-jet events (left) and 3-jet events (right). Note that while

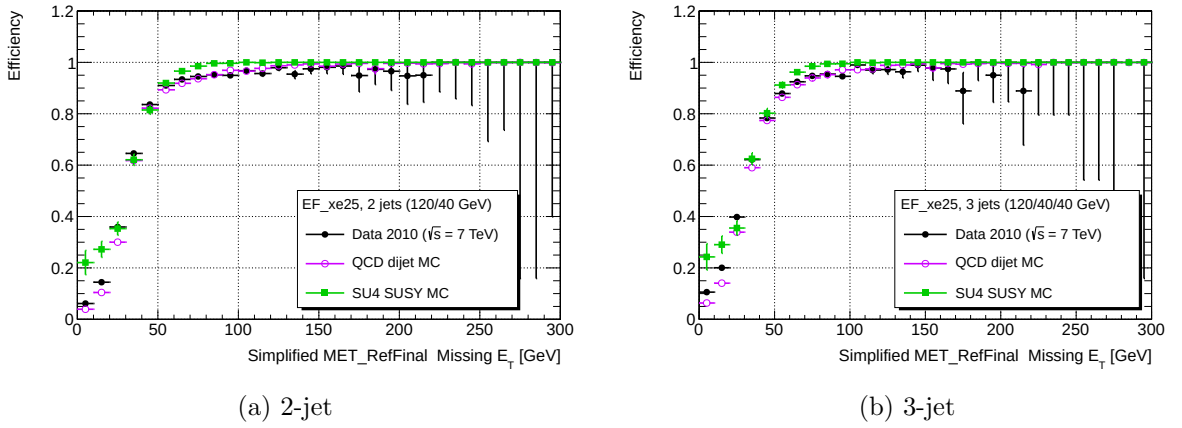


Figure 9.5: Efficiency of the  $E_T^{\text{miss}}$  trigger EF\_xe25 for events collected with the jet trigger L1\_J55 + L2\_j70 for events with  $\geq 2$  jets (left) and  $\geq 3$  jets (right). An offline cut on the  $p_T$  of the leading jet at 120 GeV ensures that the reference trigger is nearly fully efficient.

this jet trigger was prescaled for a substantial fraction of the data-taking period – if it wasn't we wouldn't require a  $E_T^{\text{miss}}$  cut at EF – the number of events collected is still sufficiently large to obtain quite precise efficiencies. Observe the much sharper (and earlier) rise in the efficiency compared to the inclusive  $E_T^{\text{miss}}$  trigger (figure 9.1), the fact that near-full efficiency is reached for QCD events, and the improved consistency between the signal and the QCD background. Also note that if the inclusive  $E_T^{\text{miss}}$  trigger had been used, the EF threshold would have been 40 GeV, whereas here it is only 25 GeV, allowing the use of a lower offline  $E_T^{\text{miss}}$  cut and giving potentially improved signal acceptance.

As before, we perform a cross-check using lepton-triggered events containing real  $E_T^{\text{miss}}$ . We use muon events, as previously, but this time we include an additional check on electron events, collected using the trigger EF\_e15\_medium and requiring a tight offline electron with  $p_T > 20$  GeV and  $|\eta| < 2.47$ . The results are shown in figure 9.6, for electrons on the left and muons on the right. The efficiencies are shown for three different sets of jet cuts (the jet matched to the electron is removed), with the black points representing the dijet cuts used for the search.

We see that the electron events are slower to reach full efficiency than the muon events. This occurs because the jets are calibrated to the hadronic scale in the offline  $E_T^{\text{miss}}$ , but not at EF, whereas the electron is measured at the EM scale in both cases. This leads to

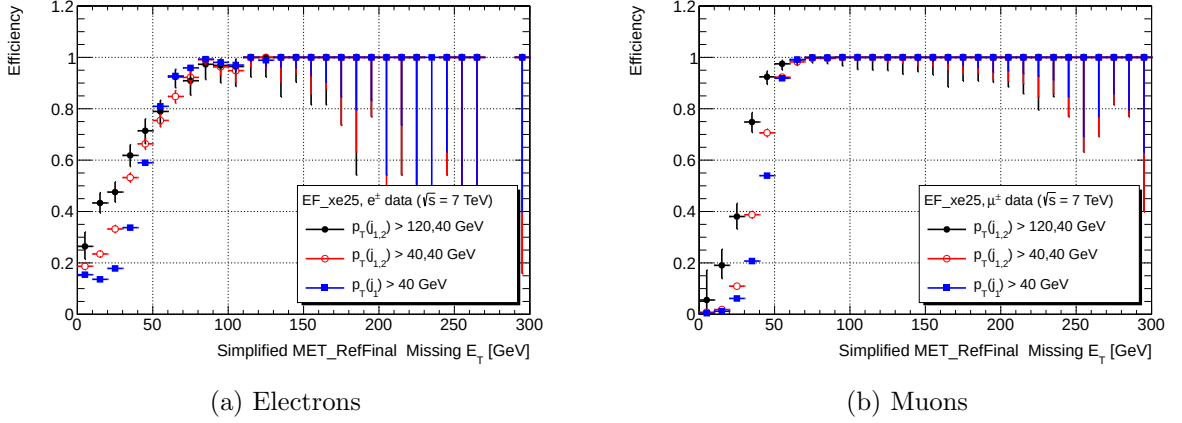


Figure 9.6: Efficiency of the  $E_T^{\text{miss}}$  trigger EF\_xe25 for events collected with the lepton triggers EF\_e15\_medium (left) and EF\_mu13 (right), including an offline lepton quality requirement. In each plot we require a) one jet with  $p_T > 40$  GeV, b) two jets, both with  $p_T > 40$  GeV, and c) the basic dijet cuts used in [57], i.e.  $p_T > 120/40$  GeV.

situations in which the visible transverse energy appears balanced at EF but not offline, or vice-versa.

There remains the question of where to place the offline  $E_T^{\text{miss}}$  cut for this analysis. Taking figures 9.5 and 9.6 together, we see that the initial choice of 100 GeV is a good one, giving the maximum achievable efficiency for all classes of events considered.

## 9.4 Systematic uncertainty from trigger efficiency

With a cut of 100 GeV on the offline  $E_T^{\text{miss}}$ , we can be confident that  $> 99\%$  of events with real  $E_T^{\text{miss}}$  will be successfully triggered. However, there remains a residual uncertainty on the QCD background, for which the final efficiency is not so precisely defined. To evaluate the size of the systematic uncertainty, we plot the *reverse-cumulative* efficiency\* for data events and simulated QCD events as a function of offline  $E_T^{\text{miss}}$  (figure 9.7).

We take the uncertainty to be the fractional difference between the data and predicted efficiency at 100 GeV, which is approximately 2% in both the 2 and 3-jet channels. Given that the efficiency is likely to be higher for the signal regions themselves (e.g. after  $m_{\text{eff}}$

\*Efficiency for events with  $E_T^{\text{miss}}$  in the range  $x \rightarrow \infty$ .

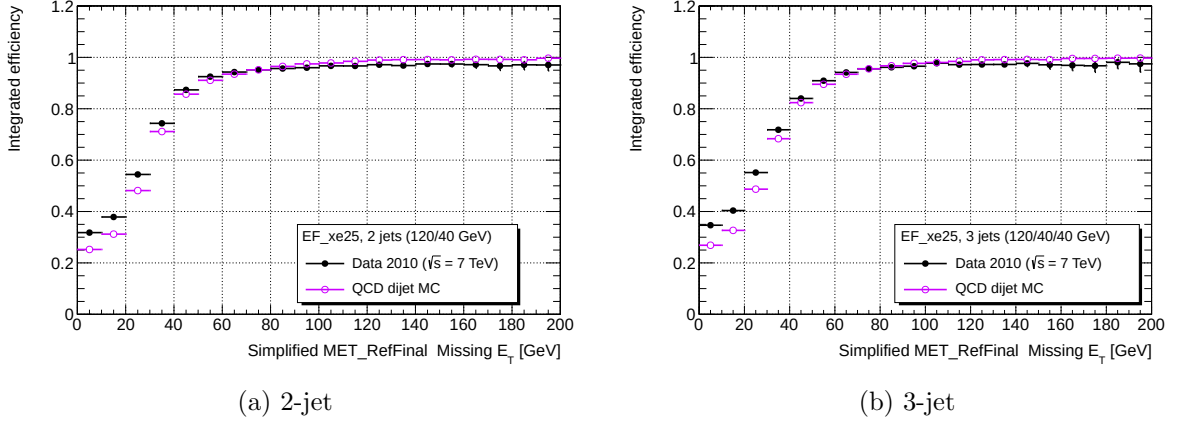


Figure 9.7: Reverse cumulative efficiency of the  $E_T^{\text{miss}}$  trigger EF\_xe25 for events collected with the jet trigger L1\_J55 + L2\_j70 for events with  $\geq 2$  jets (left) and  $\geq 3$  jets (right). An offline cut on the  $p_T$  of the leading jet at 120 GeV ensures that the reference trigger is nearly fully efficient.

cuts have been applied), and the QCD background is anticipated to make only a minor contribution to the total, we can take this number to represent a generous upper limit. We conclude that the final uncertainty is negligible compared to other sources such as the jet energy scale.

## 9.5 Conclusions and future developments

In this chapter, the case was made for adopting the L1/2 jet + EF  $E_T^{\text{miss}}$  triggers for the 2010 ATLAS 0-lepton SUSY search, and in particular their advantages over inclusive  $E_T^{\text{miss}}$  and inclusive jet triggers. The arguments presented here ultimately led to one of these chains being used as the primary trigger for the analysis.

In 2011, it was necessary to add a cut on  $E_T^{\text{miss}}$  at L1/2 to keep the rates manageable at the lower trigger levels. However, the cut was kept low relative to the EF threshold in order to minimise the undesirable effects from the L1  $E_T^{\text{miss}}$  trigger. Chains of the form EF\_j75\_xeZZ are still being used for the 0-lepton analysis at the time of writing (late 2011), with ZZ = 45–55 GeV. The situation for 2012 is not yet clear, but it is likely that the same trigger format will be used, with raised thresholds on  $E_T^{\text{miss}}$ , jets or both.

## Part IV

# Conclusion, appendices and bibliography

# Conclusion

This thesis has described a search for supersymmetry at the LHC, in channels with missing transverse momentum and hadronic jets, using 2011 data at  $\sqrt{s} = 7$  TeV. While no excess was observed, good limits were set on models where pair-produced squarks or gluinos decay directly to a pair of stable, weakly interacting LSPs. In the squark model, neutralino masses below 200 GeV are excluded (at 95% CL) for a squark mass of 300 GeV, and in the gluino model, neutralino masses below 300 GeV are excluded for a gluino mass of 400 GeV. The strong limits for cases such as these, where the LSP is massive compared to the strongly interacting parent, are achieved by using the full signal region distributions, instead of merely counting events in a single bin. In part III, the performance of the  $E_T^{\text{miss}}$  trigger was examined in detail. This trigger formed a crucial part of the early analysis strategy, and continues to be used today.

Since the completion of the studies in this thesis, numerous other searches for supersymmetry have been carried out by the ATLAS and CMS collaborations. At the time of writing, the first searches using 2012 data at  $\sqrt{s} = 8$  TeV are beginning to be made public [85]. Unfortunately, as yet, no significant deviation from the Standard Model has been observed. Future efforts will need to focus on some of the more difficult scenarios that nature may have chosen, including where the sparticle mass spectrum is very compressed. Needless to say, these new searches will require considerable ingenuity in terms of background estimation, background reduction, and triggering. However, there has already been some success in this area, particularly in the use of very soft leptons. The search continues.

## Appendix A

### Electroweak background estimation uncertainty tables



| Uncertainty                     | 400-500 GeV                  | 500-600 GeV                 | 600-700 GeV                | 700-800 GeV          | 800-1000 GeV                 | 1000-2000 GeV                |
|---------------------------------|------------------------------|-----------------------------|----------------------------|----------------------|------------------------------|------------------------------|
| Statistical                     | $\pm 0.037 (\pm 1.0)$        | $\pm 0.053 (\pm 1.0)$       | $\pm 0.08 (\pm 1.0)$       | $\pm 0.11 (\pm 1.0)$ | $\pm 0.14 (\pm 1.0)$         | $\pm 0.19 (\pm 1.0)$         |
| Jet-ES $\uparrow$               | $+0.015 (+0.4)$              | $+0.033 (+0.62)$            | $+0.0019 (+0.024)$         | $+0.043 (+0.38)$     | $-0.015 (-0.11)$             | $+0.019 (+0.099)$            |
| Jet-ES $\downarrow$             | $-0.0019 (-0.051)$           | $-0.019 (-0.35)$            | $-0.0039 (-0.049)$         | $-0.025 (-0.22)$     | $+0.12 (+0.84)$              | $-0.066 (-0.34)$             |
| Jet-ER                          | $+0.02 (+0.53)$              | $-0.00016 (-0.003)$         | $-0.0076 (-0.095)$         | $+0.028 (+0.25)$     | $-0.011 (-0.078)$            | $-0.012 (-0.063)$            |
| e-ES $\uparrow$                 | $-0.0028 (-0.074)$           | $-0.0075 (-0.14)$           | $-0.0089 (-0.11)$          | $-0.0079 (-0.07)$    | $-0.012 (-0.091)$            | $-0.011 (-0.054)$            |
| e-ES $\downarrow$               | $+0.0034 (+0.092)$           | $+0.004 (+0.076)$           | $+0.0049 (+0.061)$         | $+0.0045 (+0.04)$    | $+0.0066 (+0.048)$           | $+0.0054 (+0.028)$           |
| e-ER $\uparrow$                 | $-0.00032 (-0.0085)$         | $+0.00022 (+0.0042)$        | $-0.0023 (-0.028)$         | $+0.00068 (+0.006)$  | $-0.0052 (-0.038)$           | $-0.0011 (-0.0059)$          |
| e-ER $\downarrow$               | $-0.00055 (-0.015)$          | $-0.0027 (-0.051)$          | $+0.0011 (+0.014)$         | $+0.0015 (+0.013)$   | $-0.0019 (-0.014)$           | $+0.0027 (+0.014)$           |
| $\mu$ -ER (MS) $\uparrow$       | $+0.00014 (+0.0038)$         | $+8.8\text{e-}05 (+0.0017)$ | $-0.001 (-0.013)$          | $+0.0001 (+0.00092)$ | $-8.6\text{e-}05 (-0.00063)$ | $-0.00058 (-0.003)$          |
| $\mu$ -ER (MS) $\downarrow$     | $-0.00023 (-0.0061)$         | $+0.00038 (+0.0072)$        | $-0.00014 (-0.0017)$       | $-0.0016 (-0.014)$   | $+0.00056 (+0.0041)$         | $-0.0034 (-0.018)$           |
| $\mu$ -ER (ID) $\uparrow$       | $-0.00027 (-0.0073)$         | $+0.00092 (+0.017)$         | $-8.1\text{e-}05 (-0.001)$ | $-0.0038 (-0.033)$   | $+0.0018 (+0.013)$           | $-0.0032 (-0.017)$           |
| $\mu$ -ER (ID) $\downarrow$     | $-2.7\text{e-}05 (-0.00074)$ | $-0.00082 (-0.016)$         | $+0.0003 (+0.0037)$        | $-0.0012 (-0.01)$    | $-0.00036 (-0.0026)$         | $+0.0016 (+0.0084)$          |
| CellOut $\uparrow$              | 0.0 (0.0)                    | 0.0 (0.0)                   | 0.0 (0.0)                  | 0.0 (0.0)            | 0.0 (0.0)                    | 0.0 (0.0)                    |
| CellOut $\downarrow$            | 0.0 (0.0)                    | 0.0 (0.0)                   | 0.0 (0.0)                  | 0.0 (0.0)            | 0.0 (0.0)                    | 0.0 (0.0)                    |
| CellOut (smear)                 | $+6.6\text{e-}05 (+0.0018)$  | $+0.00027 (+0.0052)$        | $-0.0012 (-0.015)$         | $-0.0018 (-0.016)$   | $+0.00083 (+0.0061)$         | $+0.00026 (+0.0013)$         |
| e-id $\uparrow$                 | $-0.0086 (-0.23)$            | $-0.0089 (-0.17)$           | $-0.0091 (-0.11)$          | $-0.0091 (-0.08)$    | $-0.0086 (-0.063)$           | $-0.0094 (-0.048)$           |
| e-id $\downarrow$               | $+0.0087 (+0.23)$            | $+0.0091 (+0.17)$           | $+0.0093 (+0.12)$          | $+0.0092 (+0.081)$   | $+0.0088 (+0.064)$           | $+0.0096 (+0.049)$           |
| e-trig $\uparrow$               | $-0.0025 (-0.066)$           | $-0.0026 (-0.049)$          | $-0.0026 (-0.033)$         | $-0.0026 (-0.023)$   | $-0.0025 (-0.019)$           | $-0.0028 (-0.014)$           |
| e-trig $\downarrow$             | $+0.0025 (+0.066)$           | $+0.0026 (+0.049)$          | $+0.0026 (+0.033)$         | $+0.0027 (+0.023)$   | $+0.0025 (+0.019)$           | $+0.0028 (+0.014)$           |
| $\mu$ -id $\uparrow$            | $-0.0024 (-0.066)$           | $-0.0023 (-0.044)$          | $-0.0023 (-0.028)$         | $-0.0022 (-0.019)$   | $-0.0024 (-0.017)$           | $-0.0022 (-0.011)$           |
| $\mu$ -id $\downarrow$          | $+0.0025 (+0.066)$           | $+0.0023 (+0.044)$          | $+0.0023 (+0.028)$         | $+0.0022 (+0.019)$   | $+0.0024 (+0.018)$           | $+0.0022 (+0.011)$           |
| b-tag $\uparrow$                | $+0.019 (+0.5)$              | $+0.02 (+0.38)$             | $+0.019 (+0.24)$           | $+0.021 (+0.18)$     | $+0.013 (+0.096)$            | $+0.014 (+0.073)$            |
| b-tag $\downarrow$              | $-0.024 (-0.65)$             | $-0.025 (-0.48)$            | $-0.024 (-0.3)$            | $-0.026 (-0.23)$     | $-0.016 (-0.12)$             | $-0.018 (-0.091)$            |
| NLO PDF                         | $-0.0047 (-0.13)$            | $+0.002 (+0.038)$           | $-0.0029 (-0.037)$         | $-0.0023 (-0.02)$    | $+0.014 (+0.11)$             | $+0.0016 (+0.0084)$          |
| LO PDF                          | $-0.00014 (-0.0037)$         | $+0.0002 (+0.0038)$         | $+0.0011 (+0.014)$         | $+0.0025 (+0.022)$   | $+0.00097 (+0.0071)$         | $+2.8\text{e-}05 (+0.00014)$ |
| Pileup $\uparrow$               | $-0.021 (-0.57)$             | $+0.0024 (+0.045)$          | $+0.049 (+0.6)$            | $+0.042 (+0.37)$     | $+0.14 (+1.1)$               | $+0.023 (+0.12)$             |
| Pileup $\downarrow$             | $+0.021 (+0.57)$             | $-0.0024 (-0.045)$          | $-0.049 (-0.6)$            | $-0.042 (-0.37)$     | $-0.14 (-1.1)$               | $-0.023 (-0.12)$             |
| $p_T^{\text{min}}$ $\uparrow$   | $+0.002 (+0.055)$            | $-0.005 (-0.096)$           | $-0.037 (-0.47)$           | $-0.027 (-0.24)$     | $-0.076 (-0.56)$             | $-0.023 (-0.12)$             |
| $p_T^{\text{min}}$ $\downarrow$ | $-0.00092 (-0.025)$          | $+0.0038 (+0.073)$          | $+0.012 (+0.15)$           | $+0.0069 (+0.061)$   | $+0.027 (+0.2)$              | $+0.0017 (+0.0088)$          |
| Fact. scale $\uparrow$          | $+0.00058 (+0.016)$          | $+0.0008 (+0.015)$          | $-0.004 (-0.05)$           | $-0.0062 (-0.054)$   | $-0.0085 (-0.062)$           | $-0.0056 (-0.029)$           |
| Fact. scale $\downarrow$        | $-0.0012 (-0.032)$           | $+0.0027 (+0.052)$          | $+0.012 (+0.15)$           | $+0.0045 (+0.04)$    | $+0.027 (+0.19)$             | $-0.00044 (-0.0023)$         |
| Renorm. scale $\uparrow$        | $+0.0022 (+0.059)$           | $-0.0041 (-0.078)$          | $-0.029 (-0.36)$           | $-0.028 (-0.25)$     | $-0.059 (-0.43)$             | $-0.015 (-0.079)$            |
| Renorm. scale $\downarrow$      | $-0.00069 (-0.018)$          | $+0.0098 (+0.19)$           | $+0.039 (+0.49)$           | $+0.033 (+0.29)$     | $+0.082 (+0.6)$              | $+0.015 (+0.077)$            |

Table A.1: Relative statistical and systematic uncertainties for the electroweak background prediction in the 2-jet signal region. The values in parentheses represent the reduced uncertainties, i.e.  $\sigma/\sigma_{\text{stat}}$ . Abbreviations: ES = energy scale, ER = energy resolution, MS = muon system, ID = inner detector.

| Uncertainty                     | 400-500 GeV           | 500-600 GeV           | 600-700 GeV           | 700-800 GeV           | 800-1000 GeV         | 1000-2000 GeV        |
|---------------------------------|-----------------------|-----------------------|-----------------------|-----------------------|----------------------|----------------------|
| Statistical                     | $\pm 0.052 (\pm 1.0)$ | $\pm 0.055 (\pm 1.0)$ | $\pm 0.075 (\pm 1.0)$ | $\pm 0.13 (\pm 1.0)$  | $\pm 0.13 (\pm 1.0)$ | $\pm 0.2 (\pm 1.0)$  |
| Jet-ES $\uparrow$               | $+0.007 (+0.13)$      | $+0.0075 (+0.14)$     | $+0.045 (+0.59)$      | $-0.048 (-0.38)$      | $+0.044 (+0.35)$     | $+0.016 (+0.078)$    |
| Jet-ES $\downarrow$             | $-0.024 (-0.45)$      | $+0.0068 (+0.12)$     | $-0.029 (-0.39)$      | $-0.034 (-0.27)$      | $-0.01 (-0.08)$      | $+0.072 (+0.35)$     |
| Jet-ER                          | $+0.03 (+0.56)$       | $+0.014 (+0.26)$      | $-0.0059 (-0.078)$    | $-0.036 (-0.28)$      | $+0.033 (+0.26)$     | $+0.03 (+0.15)$      |
| e-ES $\uparrow$                 | $-0.0025 (-0.047)$    | $-0.0049 (-0.089)$    | $-0.0098 (-0.13)$     | $-0.0061 (-0.048)$    | $-0.008 (-0.063)$    | $-0.0035 (-0.017)$   |
| e-ES $\downarrow$               | $+0.0024 (+0.046)$    | $+0.0018 (+0.033)$    | $+0.006 (+0.081)$     | $+0.0061 (+0.048)$    | $+0.0074 (+0.059)$   | $+0.005 (+0.024)$    |
| e-ER $\uparrow$                 | $-0.0016 (-0.031)$    | $+0.0011 (+0.021)$    | $+0.00059 (+0.0079)$  | $-0.0022 (-0.017)$    | $-0.0012 (-0.0093)$  | $-0.0032 (-0.015)$   |
| e-ER $\downarrow$               | $-0.00049 (-0.0094)$  | $-0.0064 (-0.12)$     | $-0.0026 (-0.034)$    | $-0.0016 (-0.012)$    | $+0.00028 (+0.0022)$ | $+0.0065 (+0.032)$   |
| $\mu$ -ER (MS) $\uparrow$       | $-0.00077 (-0.015)$   | $+0.0002 (+0.0036)$   | $-0.00024 (-0.0032)$  | $-0.00044 (-0.0035)$  | $-0.0057 (-0.045)$   | $+0.004 (+0.02)$     |
| $\mu$ -ER (MS) $\downarrow$     | $-0.00057 (-0.011)$   | $-0.00013 (-0.0023)$  | $+0.0022 (+0.029)$    | $-0.00087 (-0.0069)$  | $-0.00079 (-0.0062)$ | $-0.005 (-0.024)$    |
| $\mu$ -ER (ID) $\uparrow$       | $+0.001 (+0.019)$     | $+0.00056 (+0.01)$    | $+0.0021 (+0.028)$    | $-0.00091 (-0.0072)$  | $-0.00094 (-0.0075)$ | $-0.0047 (-0.023)$   |
| $\mu$ -ER (ID) $\downarrow$     | $-0.00046 (-0.0087)$  | $-5.3e-05 (-0.00096)$ | $-0.00056 (-0.0074)$  | $+0.00031 (+0.0025)$  | $-0.006 (-0.047)$    | $+0.0042 (+0.02)$    |
| CellOut $\uparrow$              | $0.0 (0.0)$           | $0.0 (0.0)$           | $0.0 (0.0)$           | $0.0 (0.0)$           | $0.0 (0.0)$          | $0.0 (0.0)$          |
| CellOut $\downarrow$            | $0.0 (0.0)$           | $0.0 (0.0)$           | $0.0 (0.0)$           | $0.0 (0.0)$           | $0.0 (0.0)$          | $0.0 (0.0)$          |
| CellOut (smear)                 | $+0.0031 (+0.059)$    | $+0.0023 (+0.043)$    | $+0.00027 (+0.0036)$  | $+0.00094 (+0.0074)$  | $+0.0017 (+0.014)$   | $-0.003 (-0.015)$    |
| e-id $\uparrow$                 | $-0.0083 (-0.16)$     | $-0.0085 (-0.16)$     | $-0.0087 (-0.12)$     | $-0.0083 (-0.066)$    | $-0.0091 (-0.072)$   | $-0.0096 (-0.047)$   |
| e-id $\downarrow$               | $+0.0084 (+0.16)$     | $+0.0087 (+0.16)$     | $+0.0089 (+0.12)$     | $+0.0085 (+0.067)$    | $+0.0093 (+0.074)$   | $+0.0098 (+0.048)$   |
| e-trig $\uparrow$               | $-0.0024 (-0.045)$    | $-0.0024 (-0.044)$    | $-0.0025 (-0.034)$    | $-0.0024 (-0.019)$    | $-0.0027 (-0.021)$   | $-0.0027 (-0.013)$   |
| e-trig $\downarrow$             | $+0.0024 (+0.046)$    | $+0.0025 (+0.045)$    | $+0.0025 (+0.034)$    | $+0.0024 (+0.019)$    | $+0.0027 (+0.021)$   | $+0.0028 (+0.014)$   |
| $\mu$ -id $\uparrow$            | $-0.0025 (-0.048)$    | $-0.0024 (-0.044)$    | $-0.0024 (-0.032)$    | $-0.0025 (-0.019)$    | $-0.0022 (-0.018)$   | $-0.0021 (-0.01)$    |
| $\mu$ -id $\downarrow$          | $+0.0025 (+0.048)$    | $+0.0024 (+0.044)$    | $+0.0024 (+0.032)$    | $+0.0025 (+0.02)$     | $+0.0022 (+0.018)$   | $+0.0021 (+0.01)$    |
| b-tag $\uparrow$                | $+0.032 (+0.6)$       | $+0.031 (+0.56)$      | $+0.028 (+0.38)$      | $+0.037 (+0.29)$      | $+0.028 (+0.22)$     | $+0.013 (+0.063)$    |
| b-tag $\downarrow$              | $-0.042 (-0.8)$       | $-0.039 (-0.71)$      | $-0.036 (-0.48)$      | $-0.046 (-0.37)$      | $-0.035 (-0.28)$     | $-0.016 (-0.077)$    |
| NLO PDF                         | $-0.011 (-0.21)$      | $-0.004 (-0.072)$     | $-0.0025 (-0.033)$    | $-0.0068 (-0.054)$    | $-0.004 (-0.032)$    | $+0.021 (+0.1)$      |
| LO PDF                          | $-0.0023 (-0.045)$    | $-0.0012 (-0.022)$    | $+8.7e-05 (+0.0012)$  | $+0.0012 (+0.0098)$   | $+0.0019 (+0.015)$   | $+0.00069 (+0.0034)$ |
| Pileup $\uparrow$               | $-0.0013 (-0.025)$    | $-0.0012 (-0.022)$    | $+0.012 (+0.17)$      | $-0.054 (-0.43)$      | $+0.037 (+0.29)$     | $+0.065 (+0.32)$     |
| Pileup $\downarrow$             | $+0.0013 (+0.025)$    | $+0.0012 (+0.022)$    | $-0.012 (-0.17)$      | $+0.054 (+0.43)$      | $-0.037 (-0.29)$     | $-0.065 (-0.32)$     |
| $p_T^{\text{min}}$ $\uparrow$   | $+0.019 (+0.36)$      | $+0.0057 (+0.1)$      | $+0.0046 (+0.062)$    | $+5.9e-05 (+0.00046)$ | $+0.0028 (+0.022)$   | $-0.028 (-0.14)$     |
| $p_T^{\text{min}}$ $\downarrow$ | $-0.0061 (-0.12)$     | $-0.0013 (-0.023)$    | $+0.00065 (+0.0087)$  | $+0.0011 (+0.0083)$   | $+0.00051 (+0.004)$  | $+0.008 (+0.039)$    |
| Fact. scale $\uparrow$          | $-0.00097 (-0.018)$   | $+4.6e-05 (+0.00084)$ | $+0.0014 (+0.019)$    | $+0.001 (+0.0083)$    | $+0.00031 (+0.0025)$ | $-0.0033 (-0.016)$   |
| Fact. scale $\downarrow$        | $-0.0053 (-0.1)$      | $-0.0041 (-0.0075)$   | $-0.00084 (-0.011)$   | $+0.00017 (+0.0013)$  | $+0.001 (+0.0082)$   | $+0.0011 (+0.0053)$  |
| Renorm. scale $\uparrow$        | $+0.0049 (+0.093)$    | $+0.0025 (+0.045)$    | $+0.0037 (+0.05)$     | $+0.00018 (+0.0014)$  | $-0.0037 (-0.029)$   | $-0.015 (-0.073)$    |
| Renorm. scale $\downarrow$      | $-0.0037 (-0.07)$     | $+0.0011 (+0.019)$    | $-0.00091 (-0.012)$   | $+0.00065 (+0.0051)$  | $+0.012 (+0.099)$    | $+0.024 (+0.12)$     |

Table A.2: Relative statistical and systematic uncertainties for the electroweak backgrounds prediction in the 3-jet signal region. The values in parentheses represent the reduced uncertainties, i.e.  $\sigma/\sigma_{\text{stat}}$ . Abbreviations: ES = energy scale, ER = energy resolution, MS = muon system, ID = inner detector.

| Uncertainty                 | 500-600 GeV           | 600-700 GeV          | 700-800 GeV           | 800-1000 GeV         | 1000-2000 GeV        |
|-----------------------------|-----------------------|----------------------|-----------------------|----------------------|----------------------|
| Statistical                 | $\pm 0.088 (\pm 1.0)$ | $\pm 0.11 (\pm 1.0)$ | $\pm 0.15 (\pm 1.0)$  | $\pm 0.19 (\pm 1.0)$ | $\pm 0.24 (\pm 1.0)$ |
| Jet-ES $\uparrow$           | $+0.035 (+0.4)$       | $+0.011 (+0.097)$    | $+0.0024 (+0.016)$    | $+0.0056 (+0.03)$    | $-0.029 (-0.12)$     |
| Jet-ES $\downarrow$         | $+0.015 (+0.17)$      | $+0.014 (+0.13)$     | $+0.072 (+0.48)$      | $+0.057 (+0.3)$      | $+0.00062 (+0.0026)$ |
| Jet-ER                      | $+0.049 (+0.56)$      | $+0.028 (+0.25)$     | $+0.022 (+0.15)$      | $-0.02 (-0.11)$      | $-0.027 (-0.11)$     |
| $e$ -ES $\uparrow$          | $-0.003 (-0.034)$     | $+0.058 (+0.053)$    | $-0.013 (-0.091)$     | $-0.0042 (-0.023)$   | $-0.031 (-0.13)$     |
| $e$ -ES $\downarrow$        | $+0.01 (+0.12)$       | $+0.068 (+0.062)$    | $+0.0095 (+0.064)$    | $+0.0086 (+0.046)$   | $+0.0089 (+0.037)$   |
| $e$ -ER $\uparrow$          | $+0.0016 (+0.018)$    | $-0.00044 (-0.004)$  | $+4.6e-05 (+0.00031)$ | $-0.0037 (-0.02)$    | $-0.0034 (-0.014)$   |
| $e$ -ER $\downarrow$        | $-0.0012 (-0.013)$    | $-0.0062 (-0.056)$   | $-0.0074 (-0.05)$     | $-0.004 (-0.021)$    | $-0.002 (-0.0084)$   |
| $\mu$ -ER (MS) $\uparrow$   | $+0.0011 (+0.012)$    | $+0.0012 (+0.011)$   | $+0.0045 (+0.03)$     | $-0.00011 (-0.0006)$ | $-0.0077 (-0.032)$   |
| $\mu$ -ER (MS) $\downarrow$ | $+0.00048 (+0.0054)$  | $+0.0001 (+0.00091)$ | $+0.00027 (+0.0018)$  | $-0.0019 (-0.01)$    | $+0.00079 (+0.0033)$ |
| $\mu$ -ER (ID) $\uparrow$   | $+0.00069 (+0.0079)$  | $+0.00041 (+0.0037)$ | $-0.0002 (-0.0014)$   | $-0.0019 (-0.01)$    | $-0.00031 (-0.0013)$ |
| $\mu$ -ER (ID) $\downarrow$ | $+0.001 (+0.011)$     | $+0.00059 (+0.0054)$ | $-0.00055 (-0.0037)$  | $-0.00093 (-0.005)$  | $-0.0073 (-0.03)$    |
| CellOut $\uparrow$          | $0.0 (0.0)$           | $0.0 (0.0)$          | $0.0 (0.0)$           | $0.0 (0.0)$          | $0.0 (0.0)$          |
| CellOut $\downarrow$        | $0.0 (0.0)$           | $0.0 (0.0)$          | $0.0 (0.0)$           | $0.0 (0.0)$          | $0.0 (0.0)$          |
| CellOut (smear)             | $+0.0067 (+0.076)$    | $-0.0026 (-0.023)$   | $-0.0016 (-0.011)$    | $-0.001 (-0.0054)$   | $-0.0067 (-0.028)$   |
| $e$ -id $\uparrow$          | $-0.0089 (-0.1)$      | $-0.0087 (-0.079)$   | $-0.0088 (-0.059)$    | $-0.009 (-0.048)$    | $-0.0087 (-0.036)$   |
| $e$ -id $\downarrow$        | $+0.009 (+0.1)$       | $+0.0088 (+0.08)$    | $+0.009 (+0.06)$      | $+0.0091 (+0.049)$   | $+0.0088 (+0.037)$   |
| $e$ -trig $\uparrow$        | $-0.0025 (-0.029)$    | $-0.0025 (-0.023)$   | $-0.0026 (-0.017)$    | $-0.0026 (-0.014)$   | $-0.0026 (-0.011)$   |
| $e$ -trig $\downarrow$      | $+0.0025 (+0.029)$    | $+0.0025 (+0.023)$   | $+0.0026 (+0.017)$    | $+0.0026 (+0.014)$   | $+0.0026 (+0.011)$   |
| $\mu$ -id $\uparrow$        | $-0.0023 (-0.026)$    | $-0.0024 (-0.022)$   | $-0.0024 (-0.016)$    | $-0.0022 (-0.012)$   | $-0.0023 (-0.0098)$  |
| $\mu$ -id $\downarrow$      | $+0.0023 (+0.026)$    | $+0.0024 (+0.022)$   | $+0.0024 (+0.016)$    | $+0.0023 (+0.012)$   | $+0.0024 (+0.0098)$  |
| $b$ -tag $\uparrow$         | $+0.04 (+0.46)$       | $+0.043 (+0.39)$     | $+0.039 (+0.26)$      | $+0.054 (+0.29)$     | $+0.02 (+0.083)$     |
| $b$ -tag $\downarrow$       | $-0.053 (-0.61)$      | $-0.056 (-0.51)$     | $-0.05 (-0.34)$       | $-0.069 (-0.37)$     | $-0.024 (-0.098)$    |
| NLO PDF                     | $-0.0048 (-0.054)$    | $+0.018 (+0.16)$     | $+0.017 (+0.11)$      | $-0.0082 (-0.044)$   | $-0.0036 (-0.015)$   |
| LO PDF                      | $-0.0019 (-0.022)$    | $-0.0027 (-0.025)$   | $-0.0004 (-0.0027)$   | $+0.0021 (+0.011)$   | $+0.0024 (+0.01)$    |
| Pileup $\uparrow$           | $+0.017 (+0.2)$       | $-0.034 (-0.31)$     | $+0.016 (+0.11)$      | $-0.061 (-0.32)$     | $+0.14 (+0.6)$       |
| Pileup $\downarrow$         | $-0.017 (-0.2)$       | $+0.034 (+0.31)$     | $-0.016 (-0.11)$      | $+0.061 (+0.32)$     | $-0.14 (-0.6)$       |
| $p_T^{\min}$ $\uparrow$     | $+0.01 (+0.11)$       | $+0.016 (+0.15)$     | $+0.023 (+0.16)$      | $+0.019 (+0.099)$    | $+0.0013 (+0.0054)$  |
| $p_T^{\min}$ $\downarrow$   | $-0.0048 (-0.055)$    | $+0.002 (+0.018)$    | $-0.00085 (-0.0057)$  | $-0.00088 (-0.0047)$ | $+0.00019 (+0.0008)$ |
| Fact. scale $\uparrow$      | $-0.0015 (-0.017)$    | $+0.0039 (+0.035)$   | $+0.0047 (+0.032)$    | $+0.0059 (+0.032)$   | $-0.0013 (-0.0056)$  |
| Fact. scale $\downarrow$    | $-0.00083 (-0.0095)$  | $+0.00073 (+0.0067)$ | $-0.0036 (-0.025)$    | $+0.003 (+0.016)$    | $-0.0026 (-0.011)$   |
| Renorm. scale $\uparrow$    | $-0.0011 (-0.013)$    | $+0.0067 (+0.061)$   | $+0.018 (+0.12)$      | $+0.016 (+0.085)$    | $-0.0023 (-0.0094)$  |
| Renorm. scale $\downarrow$  | $+0.0017 (+0.02)$     | $+0.006 (+0.055)$    | $-0.012 (-0.084)$     | $-0.0077 (-0.041)$   | $+0.0041 (+0.017)$   |

Table A.3: Relative statistical and systematic uncertainties for the electroweak background prediction in the 4-jet signal region. The values in parentheses represent the reduced uncertainties, i.e.  $\sigma/\sigma_{\text{stat}}$ . Abbreviations: ES = energy scale, ER = energy resolution, MS = muon system, ID = inner detector.

| Uncertainty                     | 600-700 GeV              | 700-800 GeV              | 800-1000 GeV             | 1000-2000 GeV            |
|---------------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| Statistical                     | $\pm 0.35$ ( $\pm 1.0$ ) | $\pm 0.26$ ( $\pm 1.0$ ) | $\pm 0.25$ ( $\pm 1.0$ ) | $\pm 0.28$ ( $\pm 1.0$ ) |
| Jet-ES $\uparrow$               | -0.026 (-0.074)          | +0.033 (+0.12)           | +0.0041 (+0.017)         | +0.06 (+0.21)            |
| Jet-ES $\downarrow$             | -0.066 (-0.19)           | +0.1 (+0.39)             | -0.028 (-0.11)           | -0.054 (-0.19)           |
| Jet-ER                          | -0.087 (-0.25)           | +0.087 (+0.33)           | +0.021 (+0.084)          | +0.013 (+0.045)          |
| e-ES $\uparrow$                 | -0.0082 (-0.024)         | -0.0035 (-0.013)         | -0.018 (-0.072)          | -0.018 (-0.062)          |
| e-ES $\downarrow$               | -0.029 (-0.082)          | +0.0001 (+0.00039)       | +0.0031 (+0.012)         | -0.0033 (-0.012)         |
| e-ER $\uparrow$                 | +0.0018 (+0.0051)        | +0.002 (+0.0074)         | +0.0011 (+0.0043)        | -0.0028 (-0.0098)        |
| e-ER $\downarrow$               | -0.011 (-0.031)          | -0.004 (-0.015)          | -0.01 (-0.041)           | -0.0082 (-0.029)         |
| $\mu$ -ER (MS) $\uparrow$       | +0.00062 (+0.0018)       | +0.0024 (+0.0089)        | -0.00012 (-0.00047)      | +0.00088 (+0.0031)       |
| $\mu$ -ER (MS) $\downarrow$     | -6.7e-05 (-0.00019)      | -0.0002 (-0.00077)       | +0.00059 (+0.0024)       | -9e-05 (-0.00032)        |
| $\mu$ -ER (ID) $\uparrow$       | -0.00017 (-0.00049)      | +0.00087 (+0.0033)       | +0.00078 (+0.0032)       | +0.0014 (+0.0049)        |
| $\mu$ -ER (ID) $\downarrow$     | +0.00025 (+0.00072)      | +0.0015 (+0.0057)        | +0.0006 (+0.0024)        | +0.00088 (+0.0031)       |
| CellOut $\uparrow$              | 0.0 (0.0)                | 0.0 (0.0)                | 0.0 (0.0)                | 0.0 (0.0)                |
| CellOut $\downarrow$            | 0.0 (0.0)                | 0.0 (0.0)                | 0.0 (0.0)                | 0.0 (0.0)                |
| CellOut (smear)                 | -0.0039 (-0.011)         | -0.0056 (-0.021)         | -0.0061 (-0.025)         | -0.0068 (-0.024)         |
| e-id $\uparrow$                 | -0.009 (-0.026)          | -0.008 (-0.03)           | -0.0083 (-0.034)         | -0.01 (-0.037)           |
| e-id $\downarrow$               | +0.0092 (+0.026)         | +0.0081 (+0.031)         | +0.0085 (+0.034)         | +0.011 (+0.038)          |
| e-trig $\uparrow$               | -0.0025 (-0.0071)        | -0.0023 (-0.0087)        | -0.0024 (-0.0097)        | -0.0029 (-0.01)          |
| e-trig $\downarrow$             | +0.0025 (+0.0071)        | +0.0023 (+0.0087)        | +0.0024 (+0.0098)        | +0.003 (+0.011)          |
| $\mu$ -id $\uparrow$            | -0.0022 (-0.0063)        | -0.0024 (-0.0091)        | -0.0023 (-0.0095)        | -0.0017 (-0.0061)        |
| $\mu$ -id $\downarrow$          | +0.0022 (+0.0063)        | +0.0024 (+0.0091)        | +0.0023 (+0.0095)        | +0.0017 (+0.0061)        |
| b-tag $\uparrow$                | +0.015 (+0.042)          | +0.043 (+0.16)           | +0.044 (+0.18)           | +0.022 (+0.079)          |
| b-tag $\downarrow$              | -0.022 (-0.064)          | -0.062 (-0.23)           | -0.061 (-0.25)           | -0.028 (-0.1)            |
| NLO PDF                         | +0.011 (+0.032)          | -0.0013 (-0.0049)        | -0.01 (-0.041)           | -0.02 (-0.07)            |
| LO PDF                          | -0.0046 (-0.013)         | -0.014 (-0.053)          | +0.0032 (+0.013)         | +0.011 (+0.04)           |
| Pileup $\uparrow$               | +0.027 (+0.077)          | +0.042 (+0.16)           | -0.031 (-0.12)           | +0.038 (+0.13)           |
| Pileup $\downarrow$             | -0.027 (-0.077)          | -0.042 (-0.16)           | +0.031 (+0.12)           | -0.038 (-0.13)           |
| $p_T^{\text{min}}$ $\uparrow$   | +0.02 (+0.057)           | -0.0043 (-0.016)         | -0.0018 (-0.0071)        | -0.012 (-0.042)          |
| $p_T^{\text{min}}$ $\downarrow$ | -0.0038 (-0.011)         | +0.0014 (+0.0052)        | +0.0035 (+0.014)         | +0.0062 (+0.022)         |
| Fact. scale $\uparrow$          | -0.0024 (-0.0068)        | +0.0063 (+0.024)         | +0.025 (+0.1)            | -0.016 (-0.058)          |
| Fact. scale $\downarrow$        | -0.011 (-0.032)          | +0.015 (+0.055)          | +0.039 (+0.16)           | -0.0056 (-0.02)          |
| Renorm. scale $\uparrow$        | -0.005 (-0.014)          | -0.017 (-0.065)          | +0.065 (+0.26)           | -0.08 (-0.28)            |
| Renorm. scale $\downarrow$      | -0.0019 (-0.0055)        | +0.061 (+0.23)           | -0.03 (-0.12)            | +0.11 (+0.39)            |

Table A.4: Relative statistical and systematic uncertainties for the electroweak background prediction in the 4-jet incl. signal region. The values in parentheses represent the reduced uncertainties, i.e.  $\sigma/\sigma_{\text{stat}}$ . Abbreviations: ES = energy scale, ER = energy resolution, MS = muon system, ID = inner detector.

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