

Search for new phenomena in final states with large jet multiplicities and missing transverse momentum with ATLAS using $\sqrt{s} = 13$ TeV proton–proton collisions

ATLAS Collaboration^{*}



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ABSTRACT

Results are reported of a search for new phenomena, such as supersymmetric particle production, that could be observed in high-energy proton–proton collisions. Events with large numbers of jets, together with missing transverse momentum from unobserved particles, are selected. The data analysed were recorded by the ATLAS experiment during 2015 using the 13 TeV centre-of-mass proton–proton collisions at the Large Hadron Collider, and correspond to an integrated luminosity of 3.2 fb^{-1} . The search selected events with various jet multiplicities from ≥ 7 to ≥ 10 jets, and with various b -jet multiplicity requirements to enhance sensitivity. No excess above Standard Model expectations is observed. The results are interpreted within two supersymmetry models, where gluino masses up to 1400 GeV are excluded at 95% confidence level, significantly extending previous limits.

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1. Introduction

New strongly interacting particles, if present at the TeV energy scale, may be produced in high-energy proton–proton (pp) collisions and decay to final states with large jet multiplicities. If their decay produces stable particles which only interact weakly, it will also result in a momentum imbalance in the plane transverse to the beam ($\vec{E}_T^{\text{miss}}$).

Such particles are present in supersymmetry (SUSY) [1–6], a theoretically favoured extension of the Standard Model (SM) that predicts partner fields for each of the SM particles. These fields combine into physical superpartners of the SM particles. The scalar partners of quarks and leptons are known as squarks ($\tilde{q}$) and sleptons ($\tilde{\ell}$). The fermionic partners of gauge and Higgs bosons are the gluinos ($\tilde{g}$), the charginos ($\tilde{\chi}_i^\pm$, with $i = 1, 2$) and the neutralinos ($\tilde{\chi}_i^0$ with $i = 1, 2, 3, 4$), with $\tilde{\chi}_i^\pm$ and $\tilde{\chi}_i^0$ being the mass eigenstates, ordered from the lightest to the heaviest, formed from the linear superpositions of the SUSY partners of the Higgs and electroweak gauge bosons.

Under the hypothesis of R -parity conservation [7], SUSY partners are produced in pairs and decay to the lightest supersymmetric particle (LSP), which is stable and in a large variety of models is assumed to be the lightest neutralino ($\tilde{\chi}_1^0$), which escapes detection. The undetected $\tilde{\chi}_1^0$ would result in missing transverse momentum, while the rest of the cascade can yield final states with

multiple jets and possibly leptons and/or photons. The strongly interacting gluinos and squarks can have large production cross-sections at the Large Hadron Collider (LHC), but no evidence of their existence has been observed to date.

This paper presents the results of a search for new phenomena, such as supersymmetry, in final states with large jet multiplicities (from ≥ 7 to ≥ 10 jets) in association with E_T^{miss} . This signature is exhibited, for example, by squark and gluino production followed by cascade decay chains, and/or decays to heavy SM particles, such as top quarks or W , Z or Higgs bosons, each of which can produce multiple jets in their decays. In contrast to many other searches for the production of strongly interacting SUSY particles, the requirement made here of large jet multiplicity means that the requirement on E_T^{miss} can be modest.

Previous searches [8–10] in similar final states have been performed by the ATLAS Collaboration at the lower centre-of-mass energies of $\sqrt{s} = 7$ TeV and 8 TeV, with integrated luminosities up to 20.3 fb^{-1} . The larger energy of the present dataset provides increased sensitivity, particularly to particles with higher masses. This paper closely follows the strategy of those previous studies. In particular, data are collected using an online selection relying only on high jet multiplicity and the signal regions (SR) are designed such that the dominant multijet background can be determined from the data using regions of lower E_T^{miss} and/or lower jet multiplicity.

The data were collected by the ATLAS detector [11] in pp collisions at the LHC at a centre-of-mass energy of 13 TeV, from 16th August to 3rd November 2015. The detector covers the

^{*} E-mail address: atlas.publications@cern.ch.

pseudorapidity¹ range of $|\eta| < 4.9$ and is hermetic in azimuth. It consists of an inner tracking detector surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters, and an external muon spectrometer incorporating large superconducting toroidal magnets. After applying beam-, data- and detector-quality criteria, the integrated luminosity was $3.2 \pm 0.2 \text{ fb}^{-1}$. The uncertainty was derived using beam-separation scans, following a methodology similar to that detailed in Ref. [12].

2. Physics object definition

Jets are reconstructed using the anti- k_t clustering algorithm [13, 14] with jet radius parameter $R = 0.4$ and starting from clusters of calorimeter cells [15]. The effects of coincident pp interactions ('pileup') on jet energies are accounted for by an event-by-event p_T -density correction [16]. The energy resolution of the jets is improved by using global sequential calibrations [17,18]. Events with jets originating from cosmic rays, beam background and detector noise are vetoed using the 'loose' requirements of Ref. [19]. Jets containing b -hadrons (b -jets) are identified using an algorithm exploiting the long lifetime, high decay multiplicity, hard fragmentation and large mass of b -hadrons [20]. The b -tagging algorithm tags b -jets with an efficiency of approximately 70% in simulated $t\bar{t}$ events, and mis-tags c -jets, τ -jets and light-quark or gluon jets with probabilities of approximately 10%, 4% and 0.2% respectively [21].

The primary vertex (PV) in each event is the vertex with the largest value of Σp_T^2 for all tracks associated with it. To reduce the effect of pileup, a jet having $20 \text{ GeV} < p_T < 50 \text{ GeV}$ and $|\eta| < 2.4$ is disregarded when the p_T -weighted sum of its associated tracks indicates that it originated from a pileup collision and not the PV, based on a jet vertex tagger as described in Ref. [16].

Electron candidates are identified according to the likelihood-based 'loose' criterion described in Ref. [22], formed from e.g. calorimeter shower shape and inner-detector track properties. Muon candidates are identified according to the 'medium' criterion described in Ref. [23], based on combined tracks from the inner detector and muon spectrometer. These candidates (which may cause an event to be rejected from the signal regions) are required to have $p_T > 10 \text{ GeV}$, $|\eta| < 2.47$ for e and $|\eta| < 2.5$ for μ .

To avoid double-counting of reconstructed objects, electron candidates sharing an inner-detector track with a muon candidate are removed. Next, jet candidates separated from an electron candidate by $\Delta R_y < 0.2$ are removed, where $\Delta R_y = \sqrt{(\Delta y)^2 + (\Delta \phi)^2}$. Jet candidates with fewer than three tracks and with $\Delta R_y < 0.4$ from a muon candidate are then removed. Following this, any lepton candidate separated from a surviving jet candidate by $\Delta R_y < 0.4$ is removed.

The missing transverse momentum, $\vec{E}_T^{\text{miss}}$, is the negative two-vector sum of the calibrated $\vec{p}_T$ of reconstructed jets with $p_T > 20 \text{ GeV}$ and $|\eta| < 4.5$, electrons, muons and photons [24]. It includes an additional contribution from inner-detector tracks, matched to the PV, that are not associated with these reconstructed objects. Photons are not considered beyond their contribution to the $\vec{E}_T^{\text{miss}}$ unless they are reconstructed as jets. To reduce the effect of pileup, jets do not contribute to the $\vec{E}_T^{\text{miss}}$ calculation when they are disregarded based on the jet vertex tagger as described above. Additionally, when a jet having $50 \text{ GeV} < p_T <$

70 GeV , $|\eta| < 2.0$ and azimuth relative to the missing momentum $\Delta\phi(\vec{p}_T, \vec{E}_T^{\text{miss}}) > 2.2$ meets the same vertex-tagging criterion, the event is discarded. Events in which the jet closest in ϕ to the $\vec{E}_T^{\text{miss}}$ is found in or near an inactive region in the hadronic calorimeter barrel (i.e. $-0.1 < \eta < 1.0$, $0.8 < \phi < 1.1$) are also discarded, in order to reduce the impact of this source of $\vec{E}_T^{\text{miss}}$ mismeasurement. These data-quality requirements reduce the expected acceptance of typical SUSY models by approximately 5%.

When defining leptons for control regions (Section 5), the candidates defined above are required to be isolated, to have a longitudinal impact parameter z_0 (with respect to the PV) satisfying $|z_0 \sin \theta| < 0.5 \text{ mm}$, and to have the significance of their transverse impact parameter $|d_0/\sigma(d_0)|$ (with respect to the measured beam position) be less than five for electrons and less than three for muons. Additionally, electrons must satisfy the 'tight' criterion of Ref. [22].

3. Event selection

The signal regions are defined using two jet multiplicity counts: either n_{50} , the number of jets having $p_T > 50 \text{ GeV}$ and $|\eta| < 2.0$, or n_{80} , the number of such jets which additionally satisfy the higher requirement $p_T > 80 \text{ GeV}$. The online selection (trigger) for n_{50} -based regions requires events to have at least six jets each with $p_T > 45 \text{ GeV}$ and $|\eta| < 2.4$, while that for n_{80} -based regions requires at least five jets each with $p_T > 70 \text{ GeV}$. The trigger efficiency is greater than 99.5% for events satisfying the signal selection described below. Jets with a looser definition – those having $p_T > 40 \text{ GeV}$ and $|\eta| < 2.8$ – are used to construct the scalar sum $H_T = \sum p_T^{\text{jet}}$, while those having $p_T > 40 \text{ GeV}$ and $|\eta| < 2.5$ are candidates for b -tagging, contributing to the number $n_{b\text{-jet}}$ of b -tagged jets.

The signal selection requires large jet multiplicity, which depends on the signal region (SR), as shown in Table 1. Fifteen different SRs are defined, providing wide-ranging sensitivity to models with different final states and mass spectra. There are three different triplets of regions defined in terms of the jet multiplicity n_{50} and two different triplets of regions defined in terms of n_{80} . Within each triplet, different requirements are made on $n_{b\text{-jet}}$, from no requirement to the requirement of at least two b -jets. In all cases the final selection is on the ratio of E_T^{miss} to $\sqrt{H_T}$, with the choice of a threshold at $4 \text{ GeV}^{1/2}$ being a good balance between background rejection and signal efficiency while maintaining the effectiveness of the background estimation. Events containing electron or muon candidates with $p_T > 10 \text{ GeV}$ are vetoed to reduce background from SM processes.

The SRs have events in common, for example all events in $9j50\text{-}1b$ also appear in $9j50$, which does not require the b -jet, and in $8j50$ and $8j50\text{-}1b$, which have a looser requirement on n_{50} . Events may also appear in both the n_{50} and the n_{80} categories.

4. Background and simulation

Standard Model processes contribute to the event counts in the SRs. The dominant background contributions are multijet production, including those from purely strong interaction processes and fully hadronic decays of $t\bar{t}$; partially leptonic decays of $t\bar{t}$; and leptonically decaying W or Z bosons produced in association with jets. Top-quark, W - and Z -boson decays that are not fully hadronic are collectively referred to as 'leptonic' backgrounds. They can contribute to the signal regions when no e or μ leptons are produced, for example $Z \rightarrow \nu\nu$ or hadronic $W \rightarrow \tau\nu$ decays, or when they are produced but are out of acceptance, lie within jets, or are not reconstructed.

¹ ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z -axis along the beam pipe. Cylindrical coordinates (r, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The transverse momentum of a four-momentum is $\vec{p}_T = (p_x, p_y)$, its rapidity is $y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$, and the pseudorapidity is defined in terms of the polar angle θ as $\eta = -\ln(\theta/2)$.

Table 1
Definition of the signal regions. The selection variables are described in Sections 2 and 3. A long dash ‘—’ indicates that no requirement is made. Events with leptons are vetoed.

(a) Signal regions using n_{50}									
	8j50	8j50-1b	8j50-2b	9j50	9j50-1b	9j50-2b	10j50	10j50-1b	10j50-2b
n_{50}	≥ 8			≥ 9			≥ 10		
$n_{b\text{-jet}}$	-	≥ 1	≥ 2	-	≥ 1	≥ 2	-	≥ 1	≥ 2
$E_{\text{T}}^{\text{miss}}/\sqrt{H_{\text{T}}}$	$> 4 \text{ GeV}^{1/2}$								

(b) Signal regions using n_{80}						
	7j80	7j80-1b	7j80-2b	8j80	8j80-1b	8j80-2b
n_{80}	≥ 7			≥ 8		
$n_{b\text{-jet}}$	-	≥ 1	≥ 2	-	≥ 1	≥ 2
$E_{\text{T}}^{\text{miss}}/\sqrt{H_{\text{T}}}$	$> 4 \text{ GeV}^{1/2}$					

The most significant leptonic backgrounds are $t\bar{t}$ and W boson production in association with jets. The contribution of these two backgrounds to the signal regions is determined from a combined fit as described later in Section 5. The yields for the other, generally subdominant, leptonic backgrounds are taken from the simulations as described below.

Monte Carlo simulations are used in the determination of the leptonic backgrounds and to assess sensitivity to specific SUSY signal models. All simulated events are overlaid with multiple pp collisions simulated with the soft QCD processes of PYTHIA 8.186 [25] using the A2 set of parameters (tune) [26] and the MSTW2008LO parton distribution functions (PDF) [27]. The simulations are weighted such that the pileup conditions match those of the data. The response of the detector to particles is modelled with an ATLAS detector simulation [28] based fully on GEANT4 [29], or using fast simulation based on a parameterisation of the performance of the ATLAS electromagnetic and hadronic calorimeters [30] and on GEANT4 elsewhere. Leptonic background samples use full simulation, while signal samples (described below) use the fast simulation option. Corrections are applied to the simulated samples to account for differences between data and simulation for the lepton identification and reconstruction efficiencies, and for the efficiency and misidentification rate of the b -tagging algorithm.

4.1. Leptonic background simulation

For the generation of $t\bar{t}$ and single top quarks in the Wt and s -channels [31] Powheg-Box v2 [32] is used with the CT10 PDF sets [33] in the matrix element calculations. Electroweak t -channel single-top-quark events are generated using Powheg-Box v1. This generator uses the four-flavour scheme for the next-to-leading order (NLO) matrix element calculations together with the fixed four-flavour PDF set CT10f4 [33]. For this process, the top quarks are decayed using MadSpin [34] preserving all spin correlations, while for all processes the parton shower, fragmentation, and the underlying event are simulated using PYTHIA v6.428 [35] with the CTEQ6L1 PDF sets [36] and the corresponding Perugia 2012 tune (P2012) [37]. The top quark mass is set to 172.5 GeV. The EvtGen v1.2.0 program [38] models the bottom and charm hadron decays, as it does for all non-SHERPA-simulated processes mentioned below. The $t\bar{t}$ simulation is normalised to the cross-section calculated to next-to-next-to-leading order (NNLO) in perturbative QCD, including soft-gluon resummation to next-to-next-to-leading-log (NNLL) accuracy [39].

Events containing $t\bar{t}$ and additional heavy particles – comprising three-top, four-top, $t\bar{t} + W$, $t\bar{t} + Z$ and $t\bar{t} + WW$ production [40] – are simulated at leading order in the strong coupling constant α_s , using MadGraph v2.2.2 [41] with up to two additional partons in the matrix element, interfaced to the PYTHIA 8.186

[25,35] parton shower model. The A14 tune of the PYTHIA parameters is used [42], together with the NNPDF2.3LO PDF set [43]. The predicted production cross-sections are calculated to NLO as described in Ref. [41] for all processes other than three-top, for which it is calculated to LO.

Events containing W bosons or Z bosons with associated jets [44] are likewise simulated using MadGraph, but with up to four additional final-state partons in the matrix element, and interfaced to PYTHIA, using the same tunes and particle decay programs. The $W + \text{jets}$ and $Z + \text{jets}$ events are normalised to NNLO cross-sections [45]. Diboson processes with at least one boson decaying leptonically [46] are simulated using the SHERPA v2.1.1 generator [47]. The matrix element calculations contain all diagrams with four electroweak vertices. They are calculated for up to one (for 4ℓ , $2\ell + 2\nu$, semileptonic ZZ) or no additional partons (for $3\ell + 1\nu$, other semileptonic processes) at NLO and up to three additional partons at LO using the Comix [48] and OpenLoops [49] matrix element generators and interfaced with the SHERPA parton shower [50] using the ME+PS@NLO prescription [51]. The CT10 PDF set is used in conjunction with dedicated parton shower tuning developed by the SHERPA authors.

Theoretical uncertainties are considered for all these simulated samples. Production of $t\bar{t}$ is by far the most important process simulated in this analysis and to evaluate the uncertainty on this background several samples are compared. Samples are produced with the factorisation and renormalisation scales varied coherently, along with variations of the resummation damping parameter and with more/less radiation tunes of the parton shower [52]. Additionally the nominal sample is compared to one with Powheg interfaced with Herwig++ [53] and SHERPA v2.1.1 samples with up to one additional jet at next-to-leading order using OpenLoops and up to four additional jets at leading order, to account for uncertainties in the parton shower and the generator respectively. The comparison with the SHERPA sample dominates the uncertainty in the signal region prediction.

4.2. SUSY signal models

Two classes of SUSY signal models are used when interpreting the results. The first is a simplified model, in which gluinos are pair-produced and then decay via the cascade

$$\begin{aligned}\tilde{g} &\rightarrow q + \bar{q}' + \tilde{\chi}_1^\pm \quad (q = u, d, s, c) \\ \tilde{\chi}_1^\pm &\rightarrow W^\pm + \tilde{\chi}_2^0 \\ \tilde{\chi}_2^0 &\rightarrow Z + \tilde{\chi}_1^0.\end{aligned}$$

The parameters of the model are the masses of the gluino, $m_{\tilde{g}}$, and the lightest neutralino, $m_{\tilde{\chi}_1^0}$. The mass of the $\tilde{\chi}_1^\pm$ is constrained to

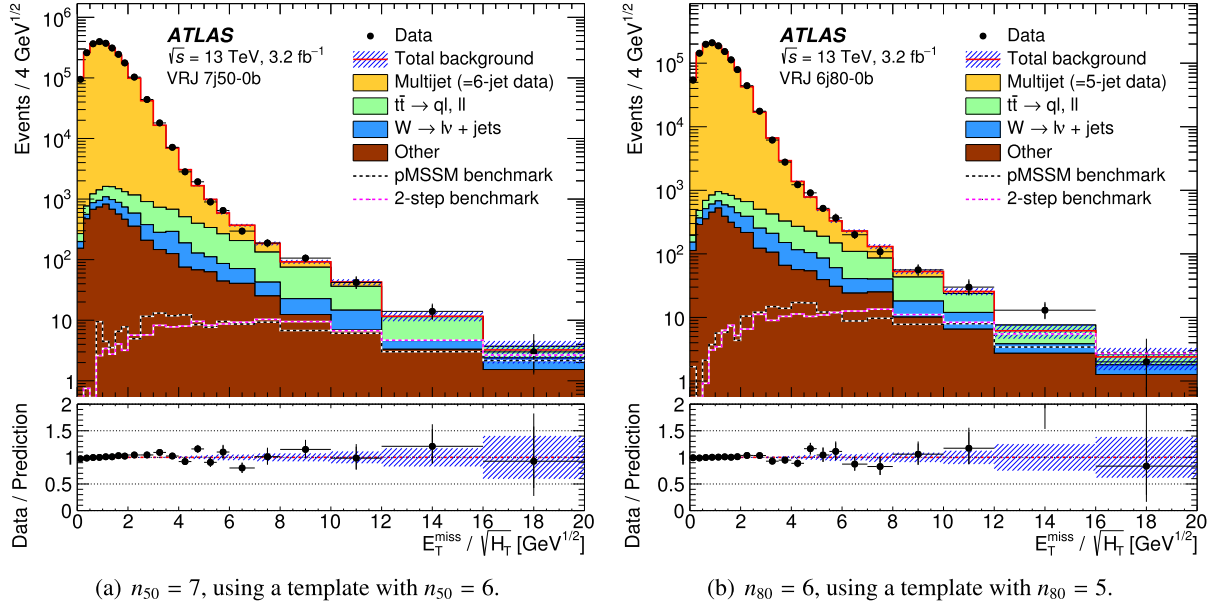


Fig. 1. Example distributions of the ratio $E_T^{\text{miss}}/\sqrt{H_T}$ in the validation region with jet multiplicities (a) $n_{50} = 7$, and (b) $n_{80} = 6$. The templates, which are in each case built from a jet multiplicity one smaller than that of the data, are normalised to the data in the region with $E_T^{\text{miss}}/\sqrt{H_T} < 1.5 \text{ GeV}^{1/2}$. The templates are weighted by H_T as described in the text. No requirement is made on $n_{b\text{-jet}}$. Variable bin sizes are used with bin widths (in units of $\text{GeV}^{1/2}$) of 0.25 (up to $E_T^{\text{miss}}/\sqrt{H_T} = 2$), 0.5 (from 2 to 6), 1 (from 6 to 8), 2 (from 8 to 12) and 4 thereafter, with the last bin additionally containing all events with $E_T^{\text{miss}}/\sqrt{H_T} > 20 \text{ GeV}^{1/2}$. The total background can lie below the leptonic background contribution in individual bins, since the template can give a negative contribution. The dashed lines labelled ‘pMSSM’ and ‘2-step’ show the (small) signal contamination from the example SUSY models described in Section 4.2 – a pMSSM slice model with $(m_{\tilde{g}}, m_{\tilde{\chi}_1^\pm}) = (1300, 200) \text{ GeV}$ and a cascade decay model with $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0}) = (1300, 200) \text{ GeV}$. The sub-plots show the ratio of the data to the SM prediction, with the blue hatched band showing the statistical uncertainty arising from a finite number of MC events and limited data in the templates and $E_T^{\text{miss}}/\sqrt{H_T} < 1.5$ normalisation regions.

be $\frac{1}{2}(m_{\tilde{g}} + m_{\tilde{\chi}_1^0})$ and the mass of the $\tilde{\chi}_2^0$ to be $\frac{1}{2}(m_{\tilde{\chi}_1^\pm} + m_{\tilde{\chi}_1^0})$. All other sparticles are kinematically inaccessible. This model is labelled in the following figures as ‘2-step’.

A second set of SUSY models is drawn from a two-dimensional subspace (a ‘slice’) of the 19-parameter phenomenological Minimal Supersymmetric Standard Model (pMSSM) [54,55]. The selection is motivated in part by models not previously excluded in the analysis presented in Ref. [56]. The models are selected to have a bino-dominated $\tilde{\chi}_1^0$, kinematically accessible gluinos, and a Higgsino-dominated multiplet at intermediate mass. The Higgsino multiplet contains two neutralinos (the $\tilde{\chi}_2^0$ and $\tilde{\chi}_3^0$) and a chargino (the $\tilde{\chi}_1^\pm$). The mass of these particles is varied by changing the soft SUSY-breaking parameters M_3 (for the gluino), M_1 (for the $\tilde{\chi}_1^0$, set to 60 GeV), and μ (for the Higgsinos). In order that other SUSY particles remain kinematically inaccessible, the other parameters, defined in Ref. [56], are set to $M_A = M_2 = 3 \text{ TeV}$, $A_\tau = 0$, $\tan\beta = 10$, $A_t = A_b = m_{\tilde{t}_{(1,2,3)}} = m_{(\tilde{e}, \tilde{\mu}, \tilde{\tau})} = m_{\tilde{Q}_{(1,2,3)}} = m_{(\tilde{u}, \tilde{c}, \tilde{t})} = m_{(\tilde{d}, \tilde{s}, \tilde{b})} = 5 \text{ TeV}$. Mass spectra with consistent electroweak symmetry breaking are generated using `softsusy` 3.4.0 [57]. The decay branching ratios are calculated with `SDECAY/HDECAY` 1.3b/3.4 [58], and when $m_{\tilde{\chi}_1^\pm} \lesssim 500 \text{ GeV}$ and $m_{\tilde{g}} \gtrsim 1200 \text{ GeV}$ the predominant decays are $\tilde{g} \rightarrow t + \bar{t} + \tilde{\chi}_{2,3}^0$ and $\tilde{g} \rightarrow t + \bar{b} + \tilde{\chi}_1^\pm$, with $\tilde{\chi}_{2,3}^0$ decaying to $Z/h + \tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$ to $W^\pm + \tilde{\chi}_1^0$ (numerical values are provided in Ref. [59]). When these decays dominate they lead to final states with many jets, several of which are b -jets, but relatively little E_T^{miss} . This renders this search particularly sensitive compared to most other SUSY searches, which tend to require high E_T^{miss} . At higher $m_{\tilde{\chi}_1^\pm}$ and lower $m_{\tilde{g}}$, the decay $\tilde{g} \rightarrow q + \bar{q} + \tilde{\chi}_1^0$ becomes dominant and this search starts to lose sensitivity. This model is labelled in the following figures as ‘pMSSM’.

The signal events are simulated using `MadGraph` v2.2.2 at LO interfaced to `PYTHIA` 8.186, as for those of $W + \text{jets}$ and $Z + \text{jets}$.

The signal cross-sections are calculated at NLO in the strong coupling constant, adding the resummation of soft gluon emission at next-to-leading-logarithmic (NLL) accuracy [60–64]. The nominal cross-section is taken from an envelope of cross-section predictions using different PDF sets and factorisation and renormalisation scales, as described in Ref. [65].

For the model points shown later in Figs. 1–3, with $m_{\tilde{g}} = 1300 \text{ GeV}$ slightly beyond the Run-1 exclusion limits, the SR selection efficiencies are around 8% in the SRs most sensitive to those models.

4.3. Multijet background

The signal regions were chosen such that the background from the multijet process can be determined from the data. The method relies on the observation [8] that where E_T^{miss} originates predominantly from calorimeter energy mismeasurement, as is the case for the multijet contributions, the distribution of the ratio $E_T^{\text{miss}}/\sqrt{H_T}$ is almost invariant under changes in jet multiplicity. This invariance, which is illustrated in Fig. 1, occurs because the calorimeter resolution that produces the momentum imbalance in these events is dominated by stochastic processes which have variance proportional to H_T , and is largely independent of the jet multiplicity.

The shape of the $E_T^{\text{miss}}/\sqrt{H_T}$ distribution is measured in control regions (CR) with lower jet multiplicities than the signal regions, and correspondingly much higher multijet contributions. For the n_{50} signal regions, the CR contains events with exactly six jets having $p_T > 50 \text{ GeV}$. For the n_{80} signal regions, the CR requires exactly five jets with $p_T > 80 \text{ GeV}$. For each SR jet selection, an appropriate $E_T^{\text{miss}}/\sqrt{H_T}$ distribution template is normalised to the data in a further CR having the same jet multiplicity as the SR but with $E_T^{\text{miss}}/\sqrt{H_T} < 1.5 \text{ GeV}^{1/2}$. That normalised template then provides the background prediction for the SR multiplicity in the region with $E_T^{\text{miss}}/\sqrt{H_T} > 4 \text{ GeV}^{1/2}$.

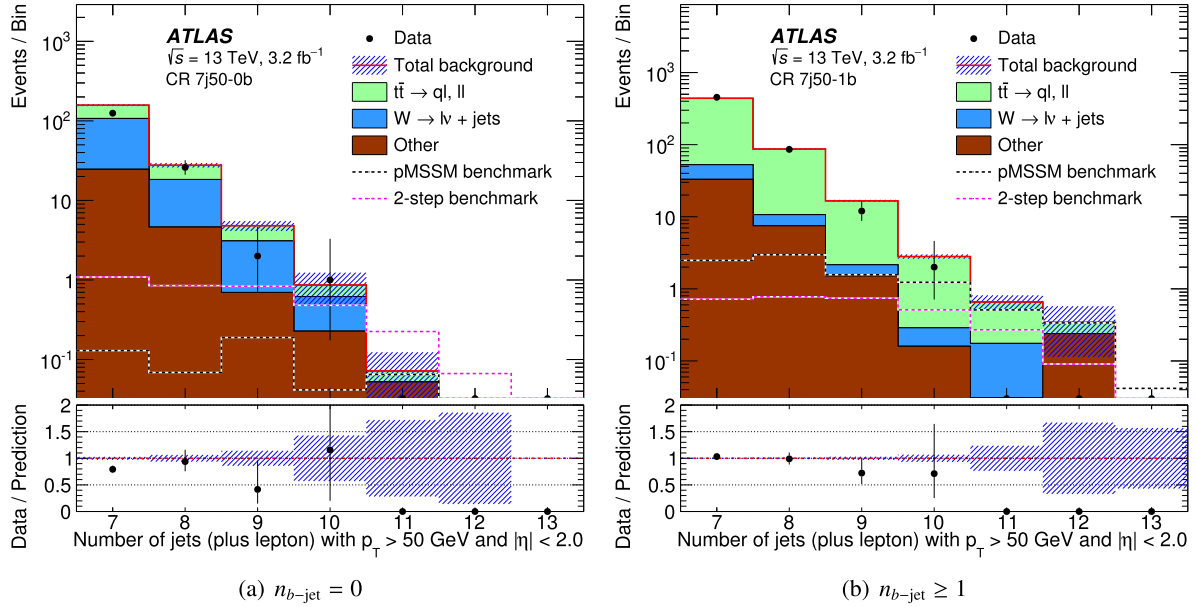


Fig. 2. Control regions – requiring one lepton – showing the n_{50} jet multiplicity distributions after all selections aside from n_{50} . That lepton is permitted to contribute to the jet multiplicity count and to H_T . The sub-plots show the ratio of the data to the Standard Model prediction. The blue hatched bands on those sub-plots show MC statistical uncertainties. The dashed lines labelled ‘pMSSM’ and ‘2-step’ refer to benchmark signal points – a pMSSM slice model with $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0}) = (1300, 200)$ GeV and a cascade decay model with $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0}) = (1300, 200)$ GeV. All backgrounds are normalised according to their theoretical (pre-fit) cross-sections. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Since semileptonic b -hadron decays can contribute to E_T^{miss} , these $E_T^{\text{miss}}/\sqrt{H_T}$ template distributions are built separately for each $n_{b\text{-jet}}$ requirement. For example, the multijet contribution to the 9j50-1b signal region is determined using a template built from events with exactly six jets with $p_T > 50$ GeV, and $n_{b\text{-jet}} \geq 1$. That template is normalised to 9j50-1b in the region with $E_T^{\text{miss}}/\sqrt{H_T} < 1.5$ GeV $^{1/2}$.

When constructing and normalising the $E_T^{\text{miss}}/\sqrt{H_T}$ templates, the same lepton veto is used as for the signal regions. However, some leptonic background contributions persist, and so the expected leptonic backgrounds to those templates (normalised according to their theoretical cross-sections, as described in Section 4.1) are subtracted from the data distributions. The uncertainties associated with the leptonic backgrounds are included in the systematic uncertainty in the prediction. Non-stochastic contributions to calorimeter resolution, which lead to a residual dependence of the $E_T^{\text{miss}}/\sqrt{H_T}$ distribution on H_T (at the $\mathcal{O}(10\%)$ level), are reduced by constructing the templates in four bins of H_T in the kinematic region of interest. Those proto-templates are combined with weights which reflect the H_T distribution of the CR with the same jet multiplicity as the target SR but with $E_T^{\text{miss}}/\sqrt{H_T} < 1.5$ GeV $^{1/2}$. The effect of changing the H_T binning is included in the systematic uncertainty.

The validity of assuming $E_T^{\text{miss}}/\sqrt{H_T}$ invariance is tested with data, using a series of validation regions (VR) with smaller jet multiplicities or smaller $E_T^{\text{miss}}/\sqrt{H_T}$ (between 1.5 GeV $^{1/2}$ and 3.5 GeV $^{1/2}$) than the SRs, or both. These VRs are found to be described by the templates, constructed as described above, mostly to within 10%–20%. However, for the tightest regions (with very few events) the discrepancy reaches 60%. The tests are performed separately for each of the three b -jet requirements, and the largest difference for each set, including VRs with jet multiplicity up to and including that of the SR in question, is included as an overall ‘closure’ systematic uncertainty associated with the method.

5. Statistical treatment and systematic uncertainties

Systematic uncertainties specific to the multijet and leptonic background contributions are described in Sections 4.3 and 4.1 respectively. Further uncertainties that apply to signal processes and all simulated backgrounds include those on the jet energy scale, jet resolution, integrated luminosity, the b -tagging efficiency (for correct and incorrect identifications of both the b - and non- b -jets), and the lepton identification efficiency and energy scale. They are in general small compared to the aforementioned ones, being at most one third the size of the largest of those.

The effect of the systematic uncertainties on the SM background calculations is reduced by constraining the normalisations of the $t\bar{t}$ and $W + \text{jets}$ backgrounds using dedicated control regions kinematically close to, but distinct from, the signal regions, as shown in Table 2. Each leptonic control region contains events with one electron or muon that meets the stricter requirements described in Section 2 and has transverse momentum $p_T^\ell > 20$ GeV. There must be no additional lepton candidates with $p_T^\ell > 10$ GeV. Each such region uses the same multijet trigger as its corresponding SR.

To reduce generic background from new particles which may decay to a final state with leptons and E_T^{miss} , a modest upper bound of 120 GeV is placed on the transverse mass $m_T = \left(2 E_T^{\text{miss}} p_T^\ell - 2 \vec{E}_T^{\text{miss}} \cdot \vec{p}_T^\ell\right)^{1/2}$. Since it is predominantly through hadronic τ decays that W bosons and $t\bar{t}$ pairs contribute to the signal regions, the corresponding control regions are created by recasting the muon or electron as a jet. If that lepton has sufficient p_T (without any additional calibration) it may contribute to the jet multiplicity count (denoted n_{50}^{CR} or n_{80}^{CR}), as well as to H_T and hence to $E_T^{\text{miss}}/\sqrt{H_T}$. In order to yield sufficient numbers of events in these CRs, the requirement on the jet multiplicity in each CR is one fewer than that in the corresponding SR, and a somewhat less stringent requirement is made on $E_T^{\text{miss}}/\sqrt{H_T}$ compared to the SRs.

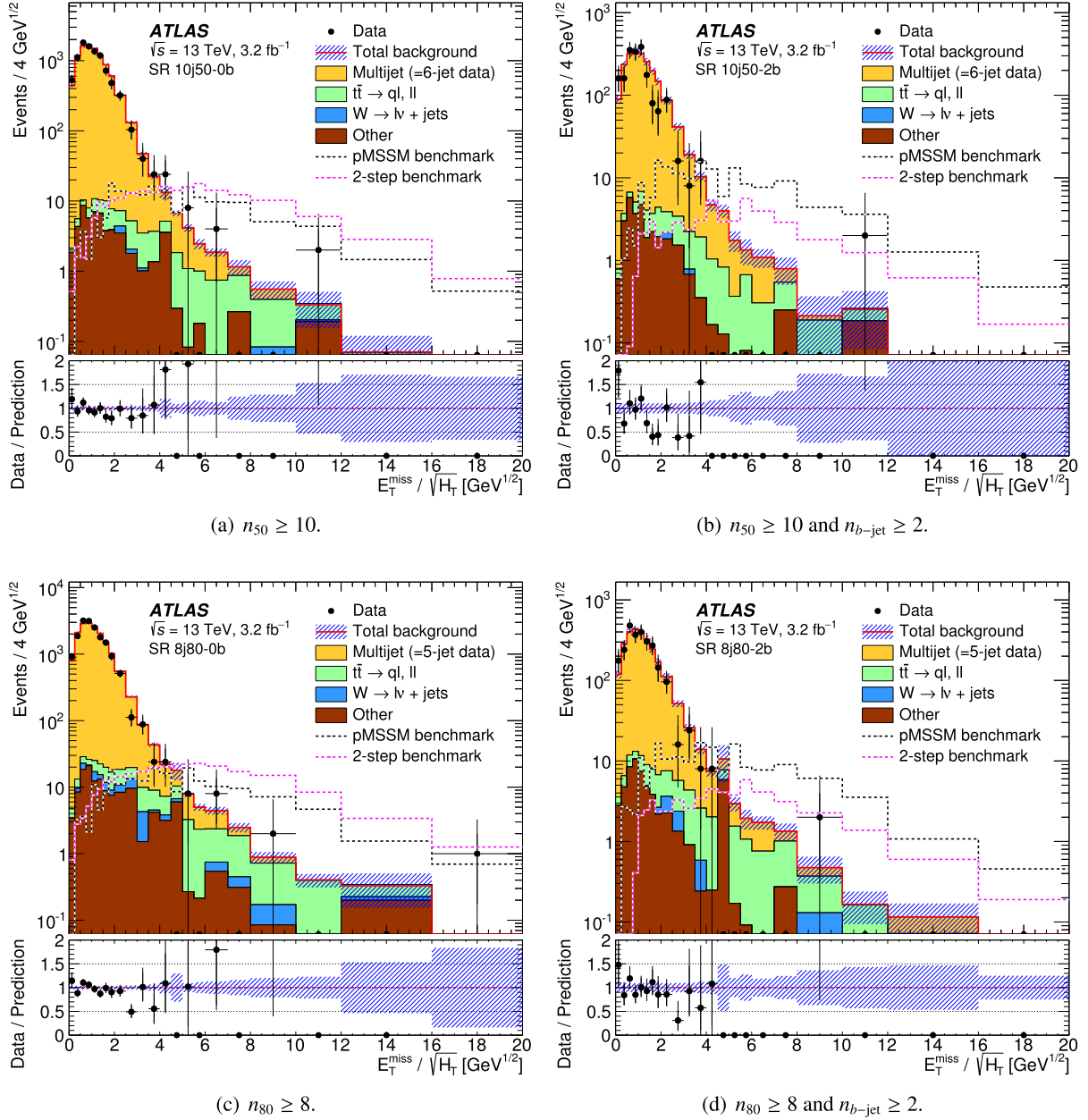


Fig. 3. Example distributions of the selection variable $E_T^{\text{miss}}/\sqrt{H_T}$, for the largest multiplicities required of the number of jets with p_T larger than 50 GeV (top) or 80 GeV (bottom). The plots on the left have no selection on the number of b -tagged jets, while those on the right are for events with $n_{b\text{-jet}} \geq 2$. W + jets and $t\bar{t}$ are normalised to their post-fit values, while the other leptonic backgrounds are normalised to their theoretical cross-sections. The multijet templates are normalised to data at lower jet multiplicities in the region $E_T^{\text{miss}}/\sqrt{H_T} < 1.5 \text{ GeV}^{1/2}$, in the manner described in Section 4.3. The SRs lie where $E_T^{\text{miss}}/\sqrt{H_T} > 4 \text{ GeV}^{1/2}$. The dashed lines labelled ‘pMSSM’ and ‘2-step’ refer to benchmark signal points – a pMSSM slice model with $(m_{\tilde{g}}, m_{\tilde{\chi}_1^\pm}) = (1300, 200) \text{ GeV}$ and a cascade decay model with $(m_{\tilde{g}}, m_{\tilde{\chi}_1^0}) = (1300, 200) \text{ GeV}$. Other details are as described in Fig. 1.

For each SR (regardless of its own requirement on $n_{b\text{-jet}}$) there are two CRs, which require either exactly zero or at least one b -jet. These help constrain the combination of $t\bar{t}$ and W + jets backgrounds, with the $t\bar{t}$ background being enhanced in the CR that requires a b -jet. Fig. 2 shows the resulting n_{50}^{CR} jet multiplicity distributions in these control regions.

For each signal region, a simultaneous fit is performed to the number of events found in the corresponding two CRs, using the HistFitter package [66]. For the purpose of exclusion, the simultaneous fit also includes data in the SR. In the fit the normalisations of the $t\bar{t}$ and W + jets background contributions are allowed to float, while the other leptonic backgrounds, which are generally subdominant, are determined directly from their yields using the

corresponding theoretical cross-sections. The event yields in each CR and SR are assumed to be Poisson distributed. The systematic uncertainties are treated as Gaussian-distributed nuisance parameters, and are assumed to be correlated within each fit. The multijet background yield in the SR is determined separately from the data using the methods described in Section 4.3.

The normalisations for the $t\bar{t}$ and W + jets backgrounds are generally found to be consistent with their corresponding theoretical predictions when uncertainties are considered. Systematic uncertainties are larger than statistical uncertainties for the regions with looser selection criteria, with the situation reversed for those with tighter selection criteria. The systematic uncertainties with the largest impact include theoretical uncertainties on the $t\bar{t}$ back-

Table 2

Leptonic control region definitions for each of the signal regions. In the names, the symbols n and $n-1$ refer to the corresponding jet multiplicity requirements. For example the three signal regions 9j50, 9j50-1b and 9j50-2b are each independently controlled by both the CR8j50-0b and CR8j50-1b control regions.

SR name	n_{j50} or n_{j50-1b} or n_{j50-2b}		n_{j80} or n_{j80-1b} or n_{j80-2b}	
CR name	CR($n-1$)j50-0b	CR($n-1$)j50-1b	CR($n-1$)j80-0b	CR($n-1$)j80-1b
p_T^ℓ ($\ell \in \{e, \mu\}$)			> 20 GeV	
m_T			< 120 GeV	
$E_T^{\text{miss}}/\sqrt{H_T}$			> 3 GeV $^{1/2}$	
n_{50}^{CR}	$\geq n_{50} - 1$		–	
n_{80}^{CR}	–		$\geq n_{80} - 1$	
$n_{b\text{-jet}}$	0	≥ 1	0	≥ 1

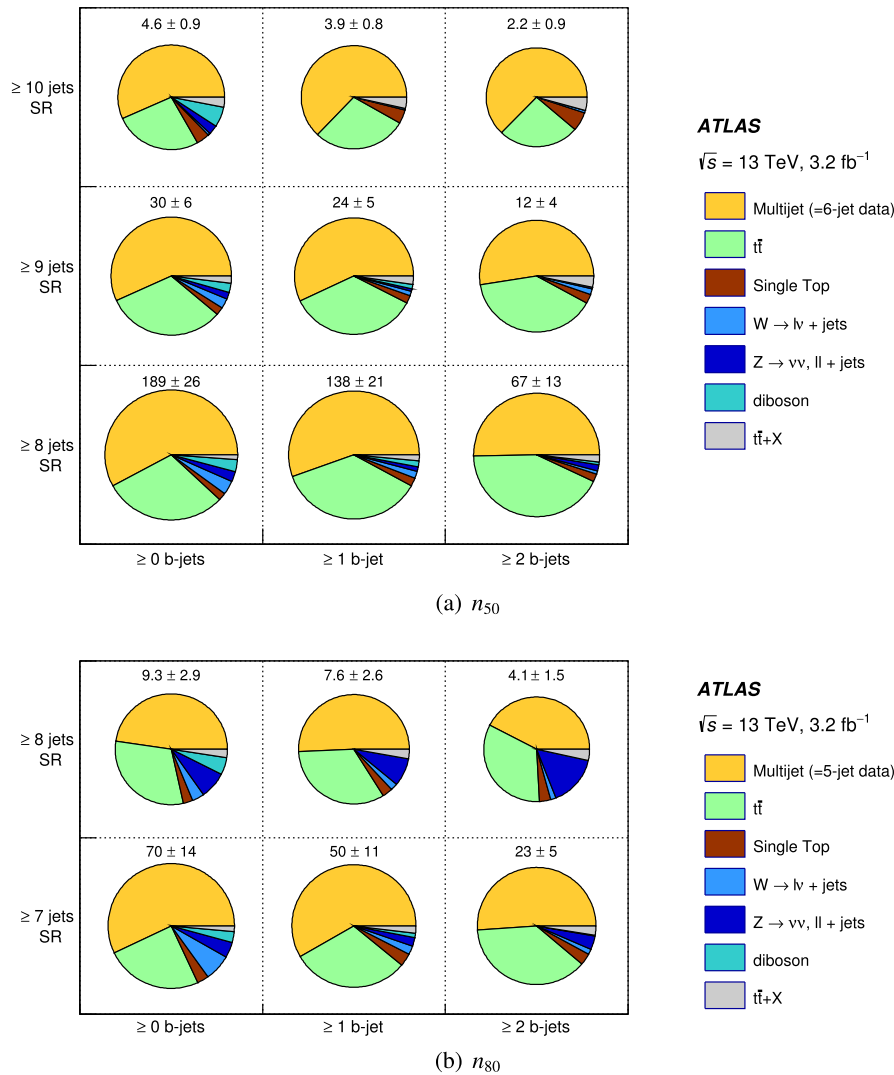


Fig. 4. Post-fit signal region compositions. The area of each pie chart is scaled to $\log_{10}$ of the total expected yield (as printed above each one).

ground, the impact of limited numbers of events in the control regions, the closure of the multijet background estimation method and the jet energy scale. The overall post-fit values range from 14% to 42% with the theoretical uncertainties on the $t\bar{t}$ backgrounds typically being the most significant contribution.

6. Results

Fig. 3 shows the post-fit $E_T^{\text{miss}}/\sqrt{H_T}$ distributions in the most sensitive signal regions (see below), while Fig. 4 shows the back-

ground composition in all fifteen SRs. The background is split between multijet and leptonic processes, with the latter being 60–90% $t\bar{t}$.

The yields in each of the 15 signal regions are reported in Table 3. No significant excess is observed above the SM expectations in any SR, and most have confidence levels for the background-only hypothesis larger than 10%, as shown in Table 4. The table also shows the model-independent limits – 95% confidence level (CL) limits on the maximum contribution of new physics processes

Table 3

For each signal region, the expected SM background (and separately the multi-jet and leptonic contributions) and the observed number of data events. The SM background normalisations are obtained from fits to the data in control regions, as described in Sections 4 and 5. The signal regions are as defined in Table 1.

Signal region	Fitted background			Obs events
	Multijet	Leptonic	Total	
8j50	109.3 ± 6.9	80 ± 25	189 ± 26	157
8j50-1b	76.7 ± 2.7	62 ± 21	138 ± 21	97
8j50-2b	33.8 ± 2.1	33 ± 13	67 ± 13	39
9j50	16.8 ± 1.3	12.8 ± 5.4	29.6 ± 5.6	29
9j50-1b	13.5 ± 2.0	10.2 ± 4.9	23.8 ± 5.3	21
9j50-2b	6.4 ± 1.6	5.8 ± 3.3	12.1 ± 3.6	9
10j50	2.61 ± 0.61	1.99 ± 0.62	4.60 ± 0.87	6
10j50-1b	2.42 ± 0.62	1.44 ± 0.49	3.86 ± 0.79	3
10j50-2b	1.40 ± 0.87	0.83 ± 0.37	2.23 ± 0.94	1
7j80	40.0 ± 5.3	30 ± 13	70 ± 14	70
7j80-1b	29.1 ± 3.4	20.8 ± 10	50 ± 11	42
7j80-2b	11.5 ± 1.6	11.0 ± 5.0	22.5 ± 5.2	19
8j80	4.5 ± 1.9	4.9 ± 2.2	9.3 ± 2.9	8
8j80-1b	3.9 ± 1.5	3.8 ± 2.1	7.6 ± 2.6	4
8j80-2b	1.72 ± 0.93	2.3 ± 1.1	4.1 ± 1.5	2

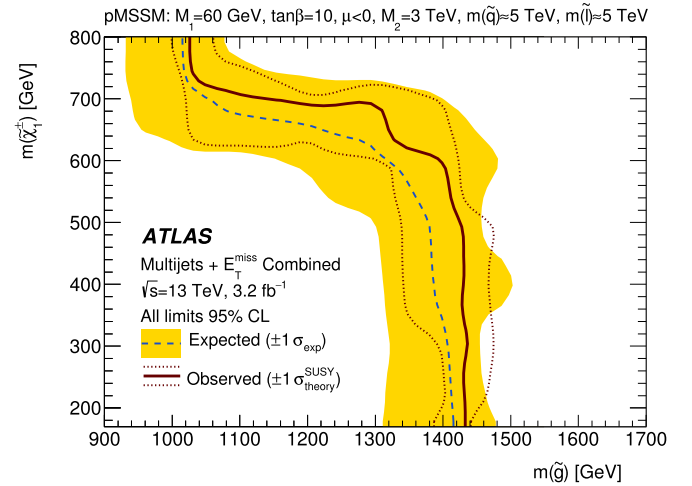
Table 4

The results of a fit to the control and signal region data, assuming no signal contamination in the control regions. Left to right: 95% CL upper limits on the visible cross-section ($(\epsilon\sigma)_{\text{obs}}^{95}$) and on the number of signal events (S_{obs}^{95}). Convergence and stability tests of the fits suggest uncertainties of order 5% on S_{obs}^{95} resulting from these effects. The third column (S_{exp}^{95}) shows the 95% CL upper limit on the number of signal events, given the expected number (and $\pm 1\sigma$ excursions on the expectation) of background events. The last two columns indicate the CL_B value, i.e. the confidence level observed for the background-only hypothesis, and the discovery p -value ($p(s=0)$). The test is one-sided, so the p -value is 0.50 when the observed number of events is smaller than the prediction. Yields are not statistically independent, since there are correlated systematic uncertainties and since signal regions overlap.

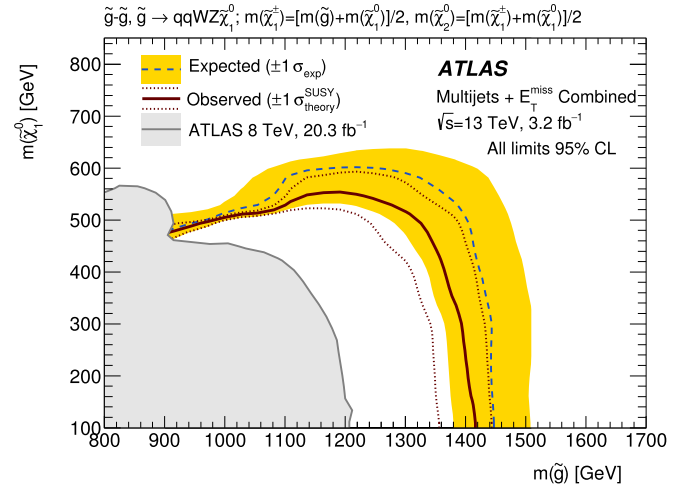
Signal region	$(\epsilon\sigma)_{\text{obs}}^{95}$ [fb]	S_{obs}^{95}	S_{exp}^{95}	CL_B	$p(s=0)$
8j50	11	36	49^{+19}_{-13}	0.14	0.50
8j50-1b	6.8	22	37^{+13}_{-10}	0.04	0.50
8j50-2b	3.8	12	22^{+8}_{-6}	0.03	0.50
9j50	5.8	19	19^{+4}_{-5}	0.49	0.50
9j50-1b	5	16	17^{+2}_{-2}	0.38	0.50
9j50-2b	2.6	8	10^{+3}_{-1}	0.31	0.50
10j50	2.5	8	6^{+3}_{-1}	0.74	0.26
10j50-1b	1.6	5	6^{+2}_{-1}	0.37	0.50
10j50-2b	1.1	4	4^{+2}_{-1}	0.27	0.50
7j80	10	32	32^{+11}_{-9}	0.51	0.50
7j80-1b	6.2	20	24^{+6}_{-5}	0.29	0.50
7j80-2b	4.2	14	14^{+6}_{-2}	0.33	0.50
8j80	3.2	10	11^{+2}_{-4}	0.41	0.50
8j80-1b	1.7	5	7^{+3}_{-2}	0.20	0.50
8j80-2b	1.4	4	5^{+2}_{-1}	0.24	0.50

to the event yields in the various SRs, assuming zero signal contamination in control regions.

The results are interpreted in the context of the two supersymmetric models described in Section 4.2. The limit for each signal region is obtained by comparing the observed event count with that expected from Standard Model background plus SUSY signal processes, with their contamination of the leptonic control regions, typically below 10% for points close to the exclusion contour, being accounted for. All uncertainties on the Standard Model expectation are considered, including those which are correlated between signal and background (for instance jet energy scale uncertainties)



(a) pMSSM slice



(b) Simplified cascade decay ('2-step') model

Fig. 5. 95% CL exclusion curve for the two supersymmetric models described in the text. The solid red and dashed blue curves show the 95% CL observed and expected limits, respectively, including all uncertainties except the theoretical signal cross-section uncertainty (PDF and scale). The dotted red lines bracketing the observed limit represent the result produced when moving the signal cross-section by $\pm 1\sigma$ (as defined by the PDF and scale uncertainties). The shaded yellow band around the expected limit shows the $\pm 1\sigma$ variation of the expected limit. The shaded grey area shows the observed exclusion from the combination of ATLAS $\sqrt{s} = 8$ TeV analyses performed in Ref. [68] (Fig. 25 therein). Excluded regions are below and to the left of the relevant lines. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

and all, except theoretical cross-section uncertainties (PDF and scale), on the signal expectation. The resulting exclusion regions, shown in Fig. 5, are obtained using the CL_s prescription [67]. For each signal model point, the signal region with the best expected limit is used. Signal regions defined by n_{50} and those defined by n_{80} both contribute to the best expected limit. The most sensitive signal regions are found to be those with no requirement on $n_{b\text{-jet}}$ for the simplified model decay. For the pMSSM slice, which has large branching ratios for gluinos to third-generation quarks, the best signal regions are those requiring either one or two b -jets. In both cases, gluino masses up to 1400 GeV are excluded at 95% confidence level, significantly extending previous limits for the simplified model decay.

7. Conclusions

A search is presented for new phenomena with large jet multiplicities (from ≥ 7 to ≥ 10) and missing transverse momentum. The search used 3.2 fb^{-1} of $\sqrt{s} = 13 \text{ TeV}$ pp collision data collected by the ATLAS experiment at the Large Hadron Collider. The increase in the LHC centre-of-mass energy provided increased sensitivity to higher-mass sparticles compared with previous searches. Further sensitivity was gained by considering separately final states with ≥ 0 , ≥ 1 and ≥ 2 b -tagged jets. The Standard Model predictions are found to be consistent with the data. The results are interpreted in the context of a simplified supersymmetry model, and a slice of the pMSSM, each of which predict cascade decays of supersymmetric particles and hence large jet multiplicities. The data exclude gluino masses up to 1400 GeV at the 95% CL in these models, significantly extending previous bounds. Model-independent limits were presented which allow reinterpretation of the results to cases of other models which also predict decays into multijet final states in association with invisible particles.

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G. Aad⁸⁶, B. Abbott¹¹³, J. Abdallah¹⁵¹, O. Abidinov¹¹, B. Abeloos¹¹⁷, R. Aben¹⁰⁷, M. Abolins⁹¹, O.S. AbouZeid¹³⁷, H. Abramowicz¹⁵³, H. Abreu¹⁵², R. Abreu¹¹⁶, Y. Abulaiti^{146a,146b}, B.S. Acharya^{163a,163b,a}, L. Adamczyk^{39a}, D.L. Adams²⁶, J. Adelman¹⁰⁸, S. Adomeit¹⁰⁰, T. Adye¹³¹, A.A. Affolder⁷⁵, T. Agatonovic-Jovin¹³, J. Agricola⁵⁵, J.A. Aguilar-Saavedra^{126a,126f}, S.P. Ahlen²³, F. Ahmadov^{66,b}, G. Aielli^{133a,133b}, H. Akerstedt^{146a,146b}, T.P.A. Åkesson⁸², A.V. Akimov⁹⁶, G.L. Alberghi^{21a,21b}, J. Albert¹⁶⁸, S. Albrand⁵⁶, M.J. Alconada Verzini⁷², M. Aleksa³¹, I.N. Aleksandrov⁶⁶, C. Alexa^{27b}, G. Alexander¹⁵³, T. Alexopoulos¹⁰, M. Alhroob¹¹³, G. Alimonti^{92a}, J. Alison³², S.P. Alkire³⁶, B.M.M. Allbrooke¹⁴⁹, B.W. Allen¹¹⁶, P.P. Allport¹⁸, A. Aloisio^{104a,104b}, A. Alonso³⁷, F. Alonso⁷², C. Alpigiani¹³⁸, B. Alvarez Gonzalez³¹, D. Álvarez Piqueras¹⁶⁶, M.G. Alviggi^{104a,104b}, B.T. Amadio¹⁵, K. Amako⁶⁷, Y. Amaral Coutinho^{25a}, C. Amelung²⁴, D. Amidei⁹⁰, S.P. Amor Dos Santos^{126a,126c}, A. Amorim^{126a,126b}, S. Amoroso³¹, N. Amram¹⁵³, G. Amundsen²⁴, C. Anastopoulos¹³⁹, L.S. Ancu⁵⁰, N. Andari¹⁰⁸, T. Andeen³², C.F. Anders^{59b}, G. Anders³¹, J.K. Anders⁷⁵, K.J. Anderson³², A. Andreazza^{92a,92b}, V. Andrei^{59a}, S. Angelidakis⁹, I. Angelozzi¹⁰⁷, P. Anger⁴⁵, A. Angerami³⁶, F. Anghinolfi³¹, A.V. Anisenkov^{109,c}, N. Anjos¹², A. Annovi^{124a,124b}, M. Antonelli⁴⁸, A. Antonov⁹⁸, J. Antos^{144b}, F. Anulli^{132a}, M. Aoki⁶⁷, L. Aperio Bella¹⁸, G. Arabidze⁹¹, Y. Arai⁶⁷, J.P. Araque^{126a}, A.T.H. Arce⁴⁶, F.A. Arduh⁷², J.-F. Arguin⁹⁵, S. Argyropoulos⁶⁴, M. Arik^{19a}, A.J. Armbruster³¹, L.J. Armitage⁷⁷, O. Arnaez³¹, H. Arnold⁴⁹, M. Arratia²⁹, O. Arslan²², A. Artamonov⁹⁷, G. Artoni¹²⁰, S. Artz⁸⁴, S. Asai¹⁵⁵, N. Asbah⁴³, A. Ashkenazi¹⁵³, B. Åsman^{146a,146b}, L. Asquith¹⁴⁹, K. Assamagan²⁶, R. Astalos^{144a}, M. Atkinson¹⁶⁵, N.B. Atlay¹⁴¹, K. Augsten¹²⁸, G. Avolio³¹, B. Axen¹⁵, M.K. Ayoub¹¹⁷, G. Azuelos^{95,d}, M.A. Baak³¹, A.E. Baas^{59a}, M.J. Baca¹⁸, H. Bachacou¹³⁶, K. Bachas^{74a,74b}, M. Backes³¹, M. Backhaus³¹, P. Bagiacchi^{132a,132b}, P. Bagnaia^{132a,132b}, Y. Bai^{34a}, J.T. Baines¹³¹, O.K. Baker¹⁷⁵,

E.M. Baldin^{109,c}, P. Balek¹²⁹, T. Balestri¹⁴⁸, F. Balli¹³⁶, W.K. Balunas¹²², E. Banas⁴⁰, Sw. Banerjee^{172,e}, A.A.E. Bannoura¹⁷⁴, L. Barak³¹, E.L. Barberio⁸⁹, D. Barberis^{51a,51b}, M. Barbero⁸⁶, T. Barillari¹⁰¹, M. Barisonzi^{163a,163b}, T. Barklow¹⁴³, N. Barlow²⁹, S.L. Barnes⁸⁵, B.M. Barnett¹³¹, R.M. Barnett¹⁵, Z. Barnovska⁵, A. Baroncelli^{134a}, G. Barone²⁴, A.J. Barr¹²⁰, L. Barranco Navarro¹⁶⁶, F. Barreiro⁸³, J. Barreiro Guimarães da Costa^{34a}, R. Bartoldus¹⁴³, A.E. Barton⁷³, P. Bartos^{144a}, A. Basalae¹²³, A. Bassalat¹¹⁷, A. Basye¹⁶⁵, R.L. Bates⁵⁴, S.J. Batista¹⁵⁸, J.R. Batley²⁹, M. Battaglia¹³⁷, M. Baue^{132a,132b}, F. Bauer¹³⁶, H.S. Bawa^{143,f}, J.B. Beacham¹¹¹, M.D. Beattie⁷³, T. Beau⁸¹, P.H. Beauchemin¹⁶¹, P. Bechtel²², H.P. Beck^{17,g}, K. Becker¹²⁰, M. Becker⁸⁴, M. Beckingham¹⁶⁹, C. Becot¹¹⁰, A.J. Beddall^{19e}, A. Beddall^{19b}, V.A. Bednyakov⁶⁶, M. Bedognetti¹⁰⁷, C.P. Bee¹⁴⁸, L.J. Beemster¹⁰⁷, T.A. Beermann³¹, M. Begel²⁶, J.K. Behr¹²⁰, C. Belanger-Champagne⁸⁸, A.S. Bell⁷⁹, G. Bella¹⁵³, L. Bellagamba^{21a}, A. Bellerive³⁰, M. Bellomo⁸⁷, K. Belotskiy⁹⁸, O. Beltramello³¹, N.L. Belyaev⁹⁸, O. Benary¹⁵³, D. Benchehrour^{135a}, M. Bender¹⁰⁰, K. Bendtz^{146a,146b}, N. Benekos¹⁰, Y. Benhammou¹⁵³, E. Benhar Noccioli¹⁷⁵, J. Benitez⁶⁴, J.A. Benitez Garcia^{159b}, D.P. Benjamin⁴⁶, J.R. Bensinger²⁴, S. Bentvelsen¹⁰⁷, L. Beresford¹²⁰, M. Beretta⁴⁸, D. Berge¹⁰⁷, E. Bergeaas Kuutmann¹⁶⁴, N. Berger⁵, F. Berghaus¹⁶⁸, J. Beringer¹⁵, S. Berlendis⁵⁶, N.R. Bernard⁸⁷, C. Bernius¹¹⁰, F.U. Bernlochner²², T. Berry⁷⁸, P. Berta¹²⁹, C. Bertella⁸⁴, G. Bertoli^{146a,146b}, F. Bertolucci^{124a,124b}, I.A. Bertram⁷³, C. Bertsche¹¹³, D. Bertsche¹¹³, G.J. Besjes³⁷, O. Bessidskaia Bylund^{146a,146b}, M. Bessner⁴³, N. Besson¹³⁶, C. Betancourt⁴⁹, S. Bethke¹⁰¹, A.J. Bevan⁷⁷, W. Bhimji¹⁵, R.M. Bianchi¹²⁵, L. Bianchini²⁴, M. Bianco³¹, O. Biebel¹⁰⁰, D. Biedermann¹⁶, R. Bielski⁸⁵, N.V. Biesuz^{124a,124b}, M. Biglietti^{134a}, J. Bilbao De Mendizabal⁵⁰, H. Bilokon⁴⁸, M. Bindi⁵⁵, S. Binet¹¹⁷, A. Bingul^{19b}, C. Bini^{132a,132b}, S. Biondi^{21a,21b}, D.M. Bjergaard⁴⁶, C.W. Black¹⁵⁰, J.E. Black¹⁴³, K.M. Black²³, D. Blackburn¹³⁸, R.E. Blair⁶, J.-B. Blanchard¹³⁶, J.E. Blanco⁷⁸, T. Blazek^{144a}, I. Bloch⁴³, C. Blocker²⁴, W. Blum^{84,*}, U. Blumenschein⁵⁵, S. Blunier^{33a}, G.J. Bobbink¹⁰⁷, V.S. Bobrovnikov^{109,c}, S.S. Bocchetta⁸², A. Bocci⁴⁶, C. Bock¹⁰⁰, M. Boehler⁴⁹, D. Boerner¹⁷⁴, J.A. Bogaerts³¹, D. Bogavac¹³, A.G. Bogdanchikov¹⁰⁹, C. Bohm^{146a}, V. Boisvert⁷⁸, T. Bold^{39a}, V. Boldea^{27b}, A.S. Boldyrev^{163a,163c}, M. Bomben⁸¹, M. Bona⁷⁷, M. Boonekamp¹³⁶, A. Borisov¹³⁰, G. Borissov⁷³, J. Bortfeldt¹⁰⁰, D. Bortoletto¹²⁰, V. Bortolotto^{61a,61b,61c}, K. Bos¹⁰⁷, D. Boscherini^{21a}, M. Bosman¹², J.D. Bossio Sola²⁸, J. Boudreau¹²⁵, J. Bouffard², E.V. Bouhova-Thacker⁷³, D. Boumediene³⁵, C. Bourdarios¹¹⁷, N. Bousson¹¹⁴, S.K. Boutle⁵⁴, A. Boveia³¹, J. Boyd³¹, I.R. Boyko⁶⁶, J. Bracinik¹⁸, A. Brandt⁸, G. Brandt⁵⁵, O. Brandt^{59a}, U. Bratzler¹⁵⁶, B. Brau⁸⁷, J.E. Brau¹¹⁶, H.M. Braun^{174,*}, W.D. Breaden Madden⁵⁴, K. Brendlinger¹²², A.J. Brennan⁸⁹, L. Brenner¹⁰⁷, R. Brenner¹⁶⁴, S. Bressler¹⁷¹, T.M. Bristow⁴⁷, D. Britton⁵⁴, D. Britzger⁴³, F.M. Brochu²⁹, I. Brock²², R. Brock⁹¹, G. Brooijmans³⁶, T. Brooks⁷⁸, W.K. Brooks^{33b}, J. Brosamer¹⁵, E. Brost¹¹⁶, J.H. Broughton¹⁸, P.A. Bruckman de Renstrom⁴⁰, D. Bruncko^{144b}, R. Bruneliere⁴⁹, A. Bruni^{21a}, G. Bruni^{21a}, B.H. Brunt²⁹, M. Bruschi^{21a}, N. Bruscino²², P. Bryant³², L. Bryngemark⁸², T. Buanes¹⁴, Q. Buat¹⁴², P. Buchholz¹⁴¹, A.G. Buckley⁵⁴, I.A. Budagov⁶⁶, F. Buehrer⁴⁹, M.K. Bugge¹¹⁹, O. Bulekov⁹⁸, D. Bullock⁸, H. Burckhart³¹, S. Burdin⁷⁵, C.D. Burgard⁴⁹, B. Burghgrave¹⁰⁸, K. Burka⁴⁰, S. Burke¹³¹, I. Burmeister⁴⁴, J.T.P. Burr¹²⁰, E. Busato³⁵, D. Büscher⁴⁹, V. Büscher⁸⁴, P. Bussey⁵⁴, J.M. Butler²³, A.I. Butt³, C.M. Buttar⁵⁴, J.M. Butterworth⁷⁹, P. Butti¹⁰⁷, W. Buttinger²⁶, A. Buzatu⁵⁴, A.R. Buzykaev^{109,c}, S. Cabrera Urbán¹⁶⁶, D. Caforio¹²⁸, V.M. Cairo^{38a,38b}, O. Cakir^{4a}, N. Calace⁵⁰, P. Calafiura¹⁵, A. Calandri⁸⁶, G. Calderini⁸¹, P. Calfayan¹⁰⁰, L.P. Caloba^{25a}, D. Calvet³⁵, S. Calvet³⁵, T.P. Calvet⁸⁶, R. Camacho Toro³², S. Camarda³¹, P. Camarri^{133a,133b}, D. Cameron¹¹⁹, R. Caminal Armadans¹⁶⁵, C. Camincher⁵⁶, S. Campana³¹, M. Campanelli⁷⁹, A. Campoverde¹⁴⁸, V. Canale^{104a,104b}, A. Canepa^{159a}, M. Cano Bret^{34e}, J. Cantero⁸³, R. Cantrill^{126a}, T. Cao⁴¹, M.D.M. Capeans Garrido³¹, I. Caprini^{27b}, M. Caprini^{27b}, M. Capua^{38a,38b}, R. Caputo⁸⁴, R.M. Carbone³⁶, R. Cardarelli^{133a}, F. Cardillo⁴⁹, T. Carli³¹, G. Carlino^{104a}, L. Carminati^{92a,92b}, S. Caron¹⁰⁶, E. Carquin^{33a}, G.D. Carrillo-Montoya³¹, J.R. Carter²⁹, J. Carvalho^{126a,126c}, D. Casadei⁷⁹, M.P. Casado^{12,h}, M. Casolino¹², D.W. Casper¹⁶², E. Castaneda-Miranda^{145a}, A. Castelli¹⁰⁷, V. Castillo Gimenez¹⁶⁶, N.F. Castro^{126a,i}, A. Catinaccio³¹, J.R. Catmore¹¹⁹, A. Cattai³¹, J. Caudron⁸⁴, V. Cavaliere¹⁶⁵, D. Cavalli^{92a}, M. Cavalli-Sforza¹², V. Cavasinni^{124a,124b}, F. Ceradini^{134a,134b}, L. Cerda Alberich¹⁶⁶, B.C. Cerio⁴⁶, A.S. Cerqueira^{25b}, A. Cerri¹⁴⁹, L. Cerrito⁷⁷, F. Cerutti¹⁵, M. Cerv³¹, A. Cervelli¹⁷, S.A. Cetin^{19d}, A. Chafaq^{135a}, D. Chakraborty¹⁰⁸, I. Chalupkova¹²⁹, S.K. Chan⁵⁸, Y.L. Chan^{61a}, P. Chang¹⁶⁵, J.D. Chapman²⁹, D.G. Charlton¹⁸, A. Chatterjee⁵⁰, C.C. Chau¹⁵⁸, C.A. Chavez Barajas¹⁴⁹, S. Che¹¹¹, S. Cheatham⁷³, A. Chegwidden⁹¹, S. Chekanov⁶, S.V. Chekulaev^{159a},

G.A. Chelkov^{66,j}, M.A. Chelstowska⁹⁰, C. Chen⁶⁵, H. Chen²⁶, K. Chen¹⁴⁸, S. Chen^{34c}, S. Chen¹⁵⁵, X. Chen^{34f}, Y. Chen⁶⁸, H.C. Cheng⁹⁰, H.J. Cheng^{34a}, Y. Cheng³², A. Cheplakov⁶⁶, E. Cheremushkina¹³⁰, R. Cherkaoui El Moursli^{135e}, V. Chernyatin^{26,*}, E. Cheu⁷, L. Chevalier¹³⁶, V. Chiarella⁴⁸, G. Chiarelli^{124a,124b}, G. Chiodini^{74a}, A.S. Chisholm¹⁸, A. Chitan^{27b}, M.V. Chizhov⁶⁶, K. Choi⁶², A.R. Chomont³⁵, S. Chouridou⁹, B.K.B. Chow¹⁰⁰, V. Christodoulou⁷⁹, D. Chromek-Burckhart³¹, J. Chudoba¹²⁷, A.J. Chuinard⁸⁸, J.J. Chwastowski⁴⁰, L. Chytka¹¹⁵, G. Ciapetti^{132a,132b}, A.K. Ciftci^{4a}, D. Cinca⁵⁴, V. Cindro⁷⁶, I.A. Cioara²², A. Ciocio¹⁵, F. Ciotto^{104a,104b}, Z.H. Citron¹⁷¹, M. Ciubancan^{27b}, A. Clark⁵⁰, B.L. Clark⁵⁸, P.J. Clark⁴⁷, R.N. Clarke¹⁵, C. Clement^{146a,146b}, Y. Coadou⁸⁶, M. Cobal^{163a,163c}, A. Coccaro⁵⁰, J. Cochran⁶⁵, L. Coffey²⁴, L. Colasurdo¹⁰⁶, B. Cole³⁶, S. Cole¹⁰⁸, A.P. Colijn¹⁰⁷, J. Collot⁵⁶, T. Colombo³¹, G. Compostella¹⁰¹, P. Conde Muiño^{126a,126b}, E. Coniavitis⁴⁹, S.H. Connell^{145b}, I.A. Connolly⁷⁸, V. Consorti⁴⁹, S. Constantinescu^{27b}, C. Conta^{121a,121b}, G. Conti³¹, F. Conventi^{104a,k}, M. Cooke¹⁵, B.D. Cooper⁷⁹, A.M. Cooper-Sarkar¹²⁰, T. Cornelissen¹⁷⁴, M. Corradi^{132a,132b}, F. Corriveau^{88,l}, A. Corso-Radu¹⁶², A. Cortes-Gonzalez¹², G. Cortiana¹⁰¹, G. Costa^{92a}, M.J. Costa¹⁶⁶, D. Costanzo¹³⁹, G. Cottin²⁹, G. Cowan⁷⁸, B.E. Cox⁸⁵, K. Cranmer¹¹⁰, S.J. Crawley⁵⁴, G. Cree³⁰, S. Crépé-Renaudin⁵⁶, F. Crescioli⁸¹, W.A. Cribbs^{146a,146b}, M. Crispin Ortuzar¹²⁰, M. Cristinziani²², V. Croft¹⁰⁶, G. Crosetti^{38a,38b}, T. Cuhadar Donszelmann¹³⁹, J. Cummings¹⁷⁵, M. Curatolo⁴⁸, J. Cúth⁸⁴, C. Cuthbert¹⁵⁰, H. Czirr¹⁴¹, P. Czodrowski³, S. D'Auria⁵⁴, M. D'Onofrio⁷⁵, M.J. Da Cunha Sargedas De Sousa^{126a,126b}, C. Da Via⁸⁵, W. Dabrowski^{39a}, T. Dai⁹⁰, O. Dale¹⁴, F. Dallaire⁹⁵, C. Dallapiccola⁸⁷, M. Dam³⁷, J.R. Dandoy³², N.P. Dang⁴⁹, A.C. Daniells¹⁸, N.S. Dann⁸⁵, M. Danninger¹⁶⁷, M. Dano Hoffmann¹³⁶, V. Dao⁴⁹, G. Darbo^{51a}, S. Darmora⁸, J. Dassoulas³, A. Dattagupta⁶², W. Davey²², C. David¹⁶⁸, T. Davidek¹²⁹, M. Davies¹⁵³, P. Davison⁷⁹, Y. Davygora^{59a}, E. Dawe⁸⁹, I. Dawson¹³⁹, R.K. Daya-Ishmukhametova⁸⁷, K. De⁸, R. de Asmundis^{104a}, A. De Benedetti¹¹³, S. De Castro^{21a,21b}, S. De Cecco⁸¹, N. De Groot¹⁰⁶, P. de Jong¹⁰⁷, H. De la Torre⁸³, F. De Lorenzi⁶⁵, D. De Pedis^{132a}, A. De Salvo^{132a}, U. De Sanctis¹⁴⁹, A. De Santo¹⁴⁹, J.B. De Vivie De Regie¹¹⁷, W.J. Dearnaley⁷³, R. Debbe²⁶, C. Debenedetti¹³⁷, D.V. Dedovich⁶⁶, I. Deigaard¹⁰⁷, J. Del Peso⁸³, T. Del Prete^{124a,124b}, D. Delgove¹¹⁷, F. Deliot¹³⁶, C.M. Delitzsch⁵⁰, M. Deliyergiyev⁷⁶, A. Dell'Acqua³¹, L. Dell'Asta²³, M. Dell'Orso^{124a,124b}, M. Della Pietra^{104a,k}, D. della Volpe⁵⁰, M. Delmastro⁵, P.A. Delsart⁵⁶, C. Deluca¹⁰⁷, D.A. DeMarco¹⁵⁸, S. Demers¹⁷⁵, M. Demichev⁶⁶, A. Demilly⁸¹, S.P. Denisov¹³⁰, D. Denysiuk¹³⁶, D. Derendarz⁴⁰, J.E. Derkaoui^{135d}, F. Derue⁸¹, P. Dervan⁷⁵, K. Desch²², C. Deterre⁴³, K. Dette⁴⁴, P.O. Deviveiros³¹, A. Dewhurst¹³¹, S. Dhaliwal²⁴, A. Di Ciaccio^{133a,133b}, L. Di Ciaccio⁵, W.K. Di Clemente¹²², C. Di Donato^{132a,132b}, A. Di Girolamo³¹, B. Di Girolamo³¹, B. Di Micco^{134a,134b}, R. Di Nardo⁴⁸, A. Di Simone⁴⁹, R. Di Sipio¹⁵⁸, D. Di Valentino³⁰, C. Diaconu⁸⁶, M. Diamond¹⁵⁸, F.A. Dias⁴⁷, M.A. Diaz^{33a}, E.B. Diehl⁹⁰, J. Dietrich¹⁶, S. Diglio⁸⁶, A. Dimitrievska¹³, J. Dingfelder²², P. Dita^{27b}, S. Dita^{27b}, F. Dittus³¹, F. Djama⁸⁶, T. Djobava^{52b}, J.I. Djuvsland^{59a}, M.A.B. do Vale^{25c}, D. Dobos³¹, M. Dobre^{27b}, C. Doglioni⁸², T. Dohmae¹⁵⁵, J. Dolejsi¹²⁹, Z. Dolezal¹²⁹, B.A. Dolgoshein^{98,*}, M. Donadelli^{25d}, S. Donati^{124a,124b}, P. Dondero^{121a,121b}, J. Donini³⁵, J. Dopke¹³¹, A. Doria^{104a}, M.T. Dova⁷², A.T. Doyle⁵⁴, E. Drechsler⁵⁵, M. Dris¹⁰, Y. Du^{34d}, J. Duarte-Camperros¹⁵³, E. Duchovni¹⁷¹, G. Duckeck¹⁰⁰, O.A. Ducu^{27b}, D. Duda¹⁰⁷, A. Dudarev³¹, L. Duflot¹¹⁷, L. Duguid⁷⁸, M. Dührssen³¹, M. Dunford^{59a}, H. Duran Yildiz^{4a}, M. Düren⁵³, A. Durglishvili^{52b}, D. Duschinger⁴⁵, B. Dutta⁴³, M. Dyndal^{39a}, C. Eckardt⁴³, K.M. Ecker¹⁰¹, R.C. Edgar⁹⁰, W. Edson², N.C. Edwards⁴⁷, T. Eifert³¹, G. Eigen¹⁴, K. Einsweiler¹⁵, T. Ekelof¹⁶⁴, M. El Kacimi^{135c}, V. Ellajosyula⁸⁶, M. Ellert¹⁶⁴, S. Elles⁵, F. Ellinghaus¹⁷⁴, A.A. Elliot¹⁶⁸, N. Ellis³¹, J. Elmsheuser¹⁰⁰, M. Elsing³¹, D. Emeliyanov¹³¹, Y. Enari¹⁵⁵, O.C. Endner⁸⁴, M. Endo¹¹⁸, J.S. Ennis¹⁶⁹, J. Erdmann⁴⁴, A. Ereditato¹⁷, G. Ernis¹⁷⁴, J. Ernst², M. Ernst²⁶, S. Errede¹⁶⁵, E. Ertel⁸⁴, M. Escalier¹¹⁷, H. Esch⁴⁴, C. Escobar¹²⁵, B. Esposito⁴⁸, A.I. Etienvre¹³⁶, E. Etzion¹⁵³, H. Evans⁶², A. Ezhilov¹²³, F. Fabbri^{21a,21b}, L. Fabbri^{21a,21b}, G. Facini³², R.M. Fakhruddinov¹³⁰, S. Falciano^{132a}, R.J. Falla⁷⁹, J. Faltova¹²⁹, Y. Fang^{34a}, M. Fanti^{92a,92b}, A. Farbin⁸, A. Farilla^{134a}, C. Farina¹²⁵, T. Farooque¹², S. Farrell¹⁵, S.M. Farrington¹⁶⁹, P. Farthouat³¹, F. Fassi^{135e}, P. Fassnacht³¹, D. Fassouliotis⁹, M. Faucci Giannelli⁷⁸, A. Favareto^{51a,51b}, W.J. Fawcett¹²⁰, L. Fayard¹¹⁷, O.L. Fedin^{123,m}, W. Fedorko¹⁶⁷, S. Feigl¹¹⁹, L. Feligioni⁸⁶, C. Feng^{34d}, E.J. Feng³¹, H. Feng⁹⁰, A.B. Fenyuk¹³⁰, L. Feremenga⁸, P. Fernandez Martinez¹⁶⁶, S. Fernandez Perez¹², J. Ferrando⁵⁴, A. Ferrari¹⁶⁴, P. Ferrari¹⁰⁷, R. Ferrari^{121a}, D.E. Ferreira de Lima⁵⁴, A. Ferrer¹⁶⁶, D. Ferrere⁵⁰, C. Ferretti⁹⁰, A. Ferretto Parodi^{51a,51b}, F. Fiedler⁸⁴, A. Filipčič⁷⁶, M. Filipuzzi⁴³, F. Filthaut¹⁰⁶,

M. Fincke-Keeler¹⁶⁸, K.D. Finelli¹⁵⁰, M.C.N. Fiolhais^{126a,126c}, L. Fiorini¹⁶⁶, A. Firan⁴¹, A. Fischer², C. Fischer¹², J. Fischer¹⁷⁴, W.C. Fisher⁹¹, N. Flaschel⁴³, I. Fleck¹⁴¹, P. Fleischmann⁹⁰, G.T. Fletcher¹³⁹, G. Fletcher⁷⁷, R.R.M. Fletcher¹²², T. Flick¹⁷⁴, A. Floderus⁸², L.R. Flores Castillo^{61a}, M.J. Flowerdew¹⁰¹, G.T. Forcolin⁸⁵, A. Formica¹³⁶, A. Forti⁸⁵, A.G. Foster¹⁸, D. Fournier¹¹⁷, H. Fox⁷³, S. Fracchia¹², P. Francavilla⁸¹, M. Franchini^{21a,21b}, D. Francis³¹, L. Franconi¹¹⁹, M. Franklin⁵⁸, M. Frate¹⁶², M. Fraternali^{121a,121b}, D. Freeborn⁷⁹, S.M. Fressard-Batraneanu³¹, F. Friedrich⁴⁵, D. Froidevaux³¹, J.A. Frost¹²⁰, C. Fukunaga¹⁵⁶, E. Fullana Torregrosa⁸⁴, T. Fusayasu¹⁰², J. Fuster¹⁶⁶, C. Gabaldon⁵⁶, O. Gabizon¹⁷⁴, A. Gabrielli^{21a,21b}, A. Gabrielli¹⁵, G.P. Gach^{39a}, S. Gadatsch³¹, S. Gadomski⁵⁰, G. Gagliardi^{51a,51b}, L.G. Gagnon⁹⁵, P. Gagnon⁶², C. Galea¹⁰⁶, B. Galhardo^{126a,126c}, E.J. Gallas¹²⁰, B.J. Gallop¹³¹, P. Gallus¹²⁸, G. Galster³⁷, K.K. Gan¹¹¹, J. Gao^{34b,86}, Y. Gao⁴⁷, Y.S. Gao^{143,f}, F.M. Garay Walls⁴⁷, C. García¹⁶⁶, J.E. García Navarro¹⁶⁶, M. Garcia-Sciveres¹⁵, R.W. Gardner³², N. Garelli¹⁴³, V. Garonne¹¹⁹, A. Gascon Bravo⁴³, C. Gatti⁴⁸, A. Gaudiello^{51a,51b}, G. Gaudio^{121a}, B. Gaur¹⁴¹, L. Gauthier⁹⁵, I.L. Gavrilenko⁹⁶, C. Gay¹⁶⁷, G. Gaycken²², E.N. Gazis¹⁰, Z. Gece¹⁶⁷, C.N.P. Gee¹³¹, Ch. Geich-Gimbel²², M.P. Geisler^{59a}, C. Gemme^{51a}, M.H. Genest⁵⁶, C. Geng^{34b,n}, S. Gentile^{132a,132b}, S. George⁷⁸, D. Gerbaudo¹⁶², A. Gershon¹⁵³, S. Ghasemi¹⁴¹, H. Ghazlane^{135b}, B. Giacobbe^{21a}, S. Giagu^{132a,132b}, P. Giannetti^{124a,124b}, B. Gibbard²⁶, S.M. Gibson⁷⁸, M. Gignac¹⁶⁷, M. Gilchriese¹⁵, T.P.S. Gillam²⁹, D. Gillberg³⁰, G. Gilles¹⁷⁴, D.M. Gingrich^{3,d}, N. Giokaris⁹, M.P. Giordani^{163a,163c}, F.M. Giorgi^{21a}, F.M. Giorgi¹⁶, P.F. Giraud¹³⁶, P. Giromini⁵⁸, D. Giugni^{92a}, C. Giuliani¹⁰¹, M. Giulini^{59b}, B.K. Gjelsten¹¹⁹, S. Gkaitatzis¹⁵⁴, I. Gkialas¹⁵⁴, E.L. Gkougkousis¹¹⁷, L.K. Gladilin⁹⁹, C. Glasman⁸³, J. Glatzer³¹, P.C.F. Glaysher⁴⁷, A. Glazov⁴³, M. Goblirsch-Kolb¹⁰¹, J. Godlewski⁴⁰, S. Goldfarb⁹⁰, T. Golling⁵⁰, D. Golubkov¹³⁰, A. Gomes^{126a,126b,126d}, R. Gonçalves^{126a}, J. Goncalves Pinto Firmino Da Costa¹³⁶, L. Gonella¹⁸, A. Gongadze⁶⁶, S. González de la Hoz¹⁶⁶, G. Gonzalez Parra¹², S. Gonzalez-Sevilla⁵⁰, L. Goossens³¹, P.A. Gorbounov⁹⁷, H.A. Gordon²⁶, I. Gorelov¹⁰⁵, B. Gorini³¹, E. Gorini^{74a,74b}, A. Gorišek⁷⁶, E. Gornicki⁴⁰, A.T. Goshaw⁴⁶, C. Gössling⁴⁴, M.I. Gostkin⁶⁶, C.R. Goudet¹¹⁷, D. Goujdami^{135c}, A.G. Goussiou¹³⁸, N. Govender^{145b}, E. Gozani¹⁵², L. Graber⁵⁵, I. Grabowska-Bold^{39a}, P.O.J. Gradin⁵⁶, P. Grafström^{21a,21b}, J. Gramling⁵⁰, E. Gramstad¹¹⁹, S. Grancagnolo¹⁶, V. Gratchev¹²³, H.M. Gray³¹, E. Graziani^{134a}, Z.D. Greenwood^{80,o}, C. Grefe²², K. Gregersen⁷⁹, I.M. Gregor⁴³, P. Grenier¹⁴³, K. Grevtsov⁵, J. Griffiths⁸, A.A. Grillo¹³⁷, K. Grimm⁷³, S. Grinstein^{12,p}, Ph. Gris³⁵, J.-F. Grivaz¹¹⁷, S. Groh⁸⁴, J.P. Grohs⁴⁵, E. Gross¹⁷¹, J. Grosse-Knetter⁵⁵, G.C. Grossi⁸⁰, Z.J. Grout¹⁴⁹, L. Guan⁹⁰, W. Guan¹⁷², J. Guenther¹²⁸, F. Guescini⁵⁰, D. Guest¹⁶², O. Gueta¹⁵³, E. Guido^{51a,51b}, T. Guillemin⁵, S. Guindon², U. Gul⁵⁴, C. Gumpert³¹, J. Guo^{34e}, Y. Guo^{34b,n}, S. Gupta¹²⁰, G. Gustavino^{132a,132b}, P. Gutierrez¹¹³, N.G. Gutierrez Ortiz⁷⁹, C. Gutsche⁴⁵, C. Guyot¹³⁶, C. Gwenlan¹²⁰, C.B. Gwilliam⁷⁵, A. Haas¹¹⁰, C. Haber¹⁵, H.K. Hadavand⁸, N. Haddad^{135e}, A. Hadeef⁸⁶, P. Haefner²², S. Hageböck²², Z. Hajduk⁴⁰, H. Hakobyan^{176,*}, M. Haleem⁴³, J. Haley¹¹⁴, D. Hall¹²⁰, G. Halladjian⁹¹, G.D. Hallewell⁸⁶, K. Hamacher¹⁷⁴, P. Hamal¹¹⁵, K. Hamano¹⁶⁸, A. Hamilton^{145a}, G.N. Hamity¹³⁹, P.G. Hamnett⁴³, L. Han^{34b}, K. Hanagaki^{67,q}, K. Hanawa¹⁵⁵, M. Hance¹³⁷, B. Haney¹²², P. Hanke^{59a}, R. Hanna¹³⁶, J.B. Hansen³⁷, J.D. Hansen³⁷, M.C. Hansen²², P.H. Hansen³⁷, K. Hara¹⁶⁰, A.S. Hard¹⁷², T. Harenberg¹⁷⁴, F. Hariiri¹¹⁷, S. Harkusha⁹³, R.D. Harrington⁴⁷, P.F. Harrison¹⁶⁹, F. Hartjes¹⁰⁷, M. Hasegawa⁶⁸, Y. Hasegawa¹⁴⁰, A. Hasib¹¹³, S. Hassani¹³⁶, S. Haug¹⁷, R. Hauser⁹¹, L. Hauswald⁴⁵, M. Havranek¹²⁷, C.M. Hawkes¹⁸, R.J. Hawkings³¹, A.D. Hawkins⁸², D. Hayden⁹¹, C.P. Hays¹²⁰, J.M. Hays⁷⁷, H.S. Hayward⁷⁵, S.J. Haywood¹³¹, S.J. Head¹⁸, T. Heck⁸⁴, V. Hedberg⁸², L. Heelan⁸, S. Heim¹²², T. Heim¹⁵, B. Heinemann¹⁵, J.J. Heinrich¹⁰⁰, L. Heinrich¹¹⁰, C. Heinz⁵³, J. Hejbal¹²⁷, L. Helary²³, S. Hellman^{146a,146b}, C. Helsens³¹, J. Henderson¹²⁰, R.C.W. Henderson⁷³, Y. Heng¹⁷², S. Henkelmann¹⁶⁷, A.M. Henriques Correia³¹, S. Henrot-Versille¹¹⁷, G.H. Herbert¹⁶, Y. Hernández Jiménez¹⁶⁶, G. Herten⁴⁹, R. Hertenberger¹⁰⁰, L. Hervas³¹, G.G. Hesketh⁷⁹, N.P. Hessey¹⁰⁷, J.W. Hetherly⁴¹, R. Hickling⁷⁷, E. Higón-Rodríguez¹⁶⁶, E. Hill¹⁶⁸, J.C. Hill²⁹, K.H. Hiller⁴³, S.J. Hillier¹⁸, I. Hinchliffe¹⁵, E. Hines¹²², R.R. Hinman¹⁵, M. Hirose¹⁵⁷, D. Hirschbuehl¹⁷⁴, J. Hobbs¹⁴⁸, N. Hod¹⁰⁷, M.C. Hodgkinson¹³⁹, P. Hodgson¹³⁹, A. Hoecker³¹, M.R. Hoferkamp¹⁰⁵, F. Hoenig¹⁰⁰, M. Hohlfield⁸⁴, D. Hohn²², T.R. Holmes¹⁵, M. Homann⁴⁴, T.M. Hong¹²⁵, B.H. Hooberman¹⁶⁵, W.H. Hopkins¹¹⁶, Y. Horii¹⁰³, A.J. Horton¹⁴², J.-Y. Hostachy⁵⁶, S. Hou¹⁵¹, A. Hoummada^{135a}, J. Howard¹²⁰, J. Howarth⁴³, M. Hrabovsky¹¹⁵, I. Hristova¹⁶, J. Hrivnac¹¹⁷, T. Hryn'ova⁵, A. Hrynevich⁹⁴, C. Hsu^{145c}, P.J. Hsu^{151,r}, S.-C. Hsu¹³⁸, D. Hu³⁶, Q. Hu^{34b}, Y. Huang⁴³, Z. Hubacek¹²⁸, F. Hubaut⁸⁶, F. Huegging²²,

T.B. Huffman¹²⁰, E.W. Hughes³⁶, G. Hughes⁷³, M. Huhtinen³¹, T.A. Hülsing⁸⁴, N. Huseynov^{66,b}, J. Huston⁹¹, J. Huth⁵⁸, G. Iacobucci⁵⁰, G. Iakovidis²⁶, I. Ibragimov¹⁴¹, L. Iconomidou-Fayard¹¹⁷, E. Ideal¹⁷⁵, Z. Idrissi^{135e}, P. Iengo³¹, O. Igonkina¹⁰⁷, T. Iizawa¹⁷⁰, Y. Ikegami⁶⁷, M. Ikeno⁶⁷, Y. Ilchenko^{32,s}, D. Iliadis¹⁵⁴, N. Ilic¹⁴³, T. Ince¹⁰¹, G. Introzzi^{121a,121b}, P. Ioannou^{9,*}, M. Iodice^{134a}, K. Iordanidou³⁶, V. Ippolito⁵⁸, A. Irles Quiles¹⁶⁶, C. Isaksson¹⁶⁴, M. Ishino⁶⁹, M. Ishitsuka¹⁵⁷, R. Ishmukhametov¹¹¹, C. Issever¹²⁰, S. Istin^{19a}, F. Ito¹⁶⁰, J.M. Iturbe Ponce⁸⁵, R. Iuppa^{133a,133b}, J. Ivarsson⁸², W. Iwanski⁴⁰, H. Iwasaki⁶⁷, J.M. Izen⁴², V. Izzo^{104a}, S. Jabbar³, B. Jackson¹²², M. Jackson⁷⁵, P. Jackson¹, V. Jain², K.B. Jakobi⁸⁴, K. Jakobs⁴⁹, S. Jakobsen³¹, T. Jakoubek¹²⁷, D.O. Jamin¹¹⁴, D.K. Jana⁸⁰, E. Jansen⁷⁹, R. Jansky⁶³, J. Janssen²², M. Janus⁵⁵, G. Jarlskog⁸², N. Javadov^{66,b}, T. Javůrek⁴⁹, F. Jeanneau¹³⁶, L. Jeanty¹⁵, J. Jejelava^{52a,t}, G.-Y. Jeng¹⁵⁰, D. Jennens⁸⁹, P. Jenni^{49,u}, J. Jentsch⁴⁴, C. Jeske¹⁶⁹, S. Jézéquel⁵, H. Ji¹⁷², J. Jia¹⁴⁸, H. Jiang⁶⁵, Y. Jiang^{34b}, S. Jiggins⁷⁹, J. Jimenez Pena¹⁶⁶, S. Jin^{34a}, A. Jinaru^{27b}, O. Jinnouchi¹⁵⁷, P. Johansson¹³⁹, K.A. Johns⁷, W.J. Johnson¹³⁸, K. Jon-And^{146a,146b}, G. Jones¹⁶⁹, R.W.L. Jones⁷³, S. Jones⁷, T.J. Jones⁷⁵, J. Jongmanns^{59a}, P.M. Jorge^{126a,126b}, J. Jovicevic^{159a}, X. Ju¹⁷², A. Juste Rozas^{12,p}, M.K. Köhler¹⁷¹, A. Kaczmarzka⁴⁰, M. Kado¹¹⁷, H. Kagan¹¹¹, M. Kagan¹⁴³, S.J. Kahn⁸⁶, E. Kajomovitz⁴⁶, C.W. Kalderon¹²⁰, A. Kaluza⁸⁴, S. Kama⁴¹, A. Kamenshchikov¹³⁰, N. Kanaya¹⁵⁵, S. Kaneti²⁹, V.A. Kantserov⁹⁸, J. Kanzaki⁶⁷, B. Kaplan¹¹⁰, L.S. Kaplan¹⁷², A. Kapliy³², D. Kar^{145c}, K. Karakostas¹⁰, A. Karamaoun³, N. Karastathis¹⁰, M.J. Kareem⁵⁵, E. Karentzos¹⁰, M. Karnevskiy⁸⁴, S.N. Karpov⁶⁶, Z.M. Karpova⁶⁶, K. Karthik¹¹⁰, V. Kartvelishvili⁷³, A.N. Karyukhin¹³⁰, K. Kasahara¹⁶⁰, L. Kashif¹⁷², R.D. Kass¹¹¹, A. Kastanas¹⁴, Y. Kataoka¹⁵⁵, C. Kato¹⁵⁵, A. Katre⁵⁰, J. Katzy⁴³, K. Kawagoe⁷¹, T. Kawamoto¹⁵⁵, G. Kawamura⁵⁵, S. Kazama¹⁵⁵, V.F. Kazanin^{109,c}, R. Keeler¹⁶⁸, R. Kehoe⁴¹, J.S. Keller⁴³, J.J. Kempster⁷⁸, K. Kentaro¹⁰³, H. Keoshkerian⁸⁵, O. Kepka¹²⁷, B.P. Kerševan⁷⁶, S. Kersten¹⁷⁴, R.A. Keyes⁸⁸, F. Khalil-zada¹¹, H. Khandanyan^{146a,146b}, A. Khanov¹¹⁴, A.G. Kharlamov^{109,c}, T.J. Khoo²⁹, V. Khovanskiy⁹⁷, E. Khramov⁶⁶, J. Khubua^{52b,v}, S. Kido⁶⁸, H.Y. Kim⁸, S.H. Kim¹⁶⁰, Y.K. Kim³², N. Kimura¹⁵⁴, O.M. Kind¹⁶, B.T. King⁷⁵, M. King¹⁶⁶, S.B. King¹⁶⁷, J. Kirk¹³¹, A.E. Kiryunin¹⁰¹, T. Kishimoto⁶⁸, D. Kisiielewska^{39a}, F. Kiss⁴⁹, K. Kiuchi¹⁶⁰, O. Kivernyk¹³⁶, E. Kladiva^{144b}, M.H. Klein³⁶, M. Klein⁷⁵, U. Klein⁷⁵, K. Kleinknecht⁸⁴, P. Klimek^{146a,146b}, A. Klimentov²⁶, R. Klingenberg⁴⁴, J.A. Klinger¹³⁹, T. Klioutchnikova³¹, E.-E. Kluge^{59a}, P. Kluit¹⁰⁷, S. Kluth¹⁰¹, J. Knapik⁴⁰, E. Kneringer⁶³, E.B.F.G. Knoops⁸⁶, A. Knue⁵⁴, A. Kobayashi¹⁵⁵, D. Kobayashi¹⁵⁷, T. Kobayashi¹⁵⁵, M. Kobel⁴⁵, M. Kocian¹⁴³, P. Kodys¹²⁹, T. Koffas³⁰, E. Koffeman¹⁰⁷, L.A. Kogan¹²⁰, T. Koi¹⁴³, H. Kolanoski¹⁶, M. Kolb^{59b}, I. Koletsou⁵, A.A. Komar^{96,*}, Y. Komori¹⁵⁵, T. Kondo⁶⁷, N. Kondrashova⁴³, K. Köneke⁴⁹, A.C. König¹⁰⁶, T. Kono^{67,w}, R. Konoplich^{110,x}, N. Konstantinidis⁷⁹, R. Kopeliansky⁶², S. Koperny^{39a}, L. Köpke⁸⁴, A.K. Kopp⁴⁹, K. Korcyl⁴⁰, K. Kordas¹⁵⁴, A. Korn⁷⁹, A.A. Korol^{109,c}, I. Korolkov¹², E.V. Korolkova¹³⁹, O. Kortner¹⁰¹, S. Kortner¹⁰¹, T. Kosek¹²⁹, V.V. Kostyukhin²², V.M. Kotov⁶⁶, A. Kotwal⁴⁶, A. Kourkouveli-Charalampidi¹⁵⁴, C. Kourkouvelis⁹, V. Kouskoura²⁶, A. Koutsman^{159a}, A.B. Kowalewska⁴⁰, R. Kowalewski¹⁶⁸, T.Z. Kowalski^{39a}, W. Kozanecki¹³⁶, A.S. Kozhin¹³⁰, V.A. Kramarenko⁹⁹, G. Kramberger⁷⁶, D. Krasnopevtsev⁹⁸, M.W. Krasny⁸¹, A. Krasznahorkay³¹, J.K. Kraus²², A. Kravchenko²⁶, M. Kretz^{59c}, J. Kretzschmar⁷⁵, K. Kreutzfeldt⁵³, P. Krieger¹⁵⁸, K. Krizka³², K. Kroeninger⁴⁴, H. Kroha¹⁰¹, J. Kroll¹²², J. Kroseberg²², J. Krstic¹³, U. Kruchonak⁶⁶, H. Krüger²², N. Krumnack⁶⁵, A. Kruse¹⁷², M.C. Kruse⁴⁶, M. Kruskal²³, T. Kubota⁸⁹, H. Kucuk⁷⁹, S. Kuday^{4b}, J.T. Kuechler¹⁷⁴, S. Kuehn⁴⁹, A. Kugel^{59c}, F. Kuger¹⁷³, A. Kuhl¹³⁷, T. Kuhl⁴³, V. Kukhtin⁶⁶, R. Kukla¹³⁶, Y. Kulchitsky⁹³, S. Kuleshov^{33b}, M. Kuna^{132a,132b}, T. Kunigo⁶⁹, A. Kupco¹²⁷, H. Kurashige⁶⁸, Y.A. Kurochkin⁹³, V. Kus¹²⁷, E.S. Kuwertz¹⁶⁸, M. Kuze¹⁵⁷, J. Kvita¹¹⁵, T. Kwan¹⁶⁸, D. Kyriazopoulos¹³⁹, A. La Rosa¹⁰¹, J.L. La Rosa Navarro^{25d}, L. La Rotonda^{38a,38b}, C. Lacasta¹⁶⁶, F. Lacava^{132a,132b}, J. Lacey³⁰, H. Lacker¹⁶, D. Lacour⁸¹, V.R. Lacuesta¹⁶⁶, E. Ladygin⁶⁶, R. Lafaye⁵, B. Laforge⁸¹, T. Lagouri¹⁷⁵, S. Lai⁵⁵, S. Lammers⁶², W. Lampl⁷, E. Lançon¹³⁶, U. Landgraf⁴⁹, M.P.J. Landon⁷⁷, V.S. Lang^{59a}, J.C. Lange¹², A.J. Lankford¹⁶², F. Lanni²⁶, K. Lantzsche²², A. Lanza^{121a}, S. Laplace⁸¹, C. Lapoire³¹, J.F. Laporte¹³⁶, T. Lari^{92a}, F. Lasagni Manghi^{21a,21b}, M. Lassnig³¹, P. Laurelli⁴⁸, W. Lavrijsen¹⁵, A.T. Law¹³⁷, P. Laycock⁷⁵, T. Lazovich⁵⁸, M. Lazzaroni^{92a,92b}, O. Le Dortz⁸¹, E. Le Guirriec⁸⁶, E. Le Menedeu¹², E.P. Le Quilleuc¹³⁶, M. LeBlanc¹⁶⁸, T. LeCompte⁶, F. Ledroit-Guillon⁵⁶, C.A. Lee²⁶, S.C. Lee¹⁵¹, L. Lee¹, G. Lefebvre⁸¹, M. Lefebvre¹⁶⁸, F. Legger¹⁰⁰, C. Leggett¹⁵, A. Lehan⁷⁵, G. Lehmann Miotto³¹, X. Lei⁷, W.A. Leight³⁰, A. Leisos^{154,y}, A.G. Leister¹⁷⁵, M.A.L. Leite^{25d}, R. Leitner¹²⁹, D. Lellouch¹⁷¹, B. Lemmer⁵⁵, K.J.C. Leney⁷⁹, T. Lenz²², B. Lenzi³¹, R. Leone⁷,

S. Leone^{124a,124b}, C. Leonidopoulos⁴⁷, S. Leontsinis¹⁰, G. Lerner¹⁴⁹, C. Leroy⁹⁵, A.A.J. Lesage¹³⁶, C.G. Lester²⁹, M. Levchenko¹²³, J. Levêque⁵, D. Levin⁹⁰, L.J. Levinson¹⁷¹, M. Levy¹⁸, A.M. Leyko²², M. Leyton⁴², B. Li^{34b,z}, H. Li¹⁴⁸, H.L. Li³², L. Li⁴⁶, L. Li^{34e}, Q. Li^{34a}, S. Li⁴⁶, X. Li⁸⁵, Y. Li¹⁴¹, Z. Liang¹³⁷, H. Liao³⁵, B. Liberti^{133a}, A. Liblong¹⁵⁸, P. Lichard³¹, K. Lie¹⁶⁵, J. Liebal²², W. Liebig¹⁴, C. Limbach²², A. Limosani¹⁵⁰, S.C. Lin^{151,aa}, T.H. Lin⁸⁴, B.E. Lindquist¹⁴⁸, E. Lipeles¹²², A. Lipniacka¹⁴, M. Lisovsky^{59b}, T.M. Liss¹⁶⁵, D. Lissauer²⁶, A. Lister¹⁶⁷, A.M. Litke¹³⁷, B. Liu^{151,ab}, D. Liu¹⁵¹, H. Liu⁹⁰, H. Liu²⁶, J. Liu⁸⁶, J.B. Liu^{34b}, K. Liu⁸⁶, L. Liu¹⁶⁵, M. Liu⁴⁶, M. Liu^{34b}, Y.L. Liu^{34b}, Y. Liu^{34b}, M. Livan^{121a,121b}, A. Lleres⁵⁶, J. Llorente Merino⁸³, S.L. Lloyd⁷⁷, F. Lo Sterzo¹⁵¹, E. Lobodzinska⁴³, P. Loch⁷, W.S. Lockman¹³⁷, F.K. Loebinger⁸⁵, A.E. Loevschall-Jensen³⁷, K.M. Loew²⁴, A. Loginov¹⁷⁵, T. Lohse¹⁶, K. Lohwasser⁴³, M. Lokajicek¹²⁷, B.A. Long²³, J.D. Long¹⁶⁵, R.E. Long⁷³, L. Longo^{74a,74b}, K.A. Looper¹¹¹, L. Lopes^{126a}, D. Lopez Mateos⁵⁸, B. Lopez Paredes¹³⁹, I. Lopez Paz¹², A. Lopez Solis⁸¹, J. Lorenz¹⁰⁰, N. Lorenzo Martinez⁶², M. Losada²⁰, P.J. Lösel¹⁰⁰, X. Lou^{34a}, A. Lounis¹¹⁷, J. Love⁶, P.A. Love⁷³, H. Lu^{61a}, N. Lu⁹⁰, H.J. Lubatti¹³⁸, C. Luci^{132a,132b}, A. Lucotte⁵⁶, C. Luedtke⁴⁹, F. Luehring⁶², W. Lukas⁶³, L. Luminari^{132a}, O. Lundberg^{146a,146b}, B. Lund-Jensen¹⁴⁷, D. Lynn²⁶, R. Lysak¹²⁷, E. Lytken⁸², V. Lyubushkin⁶⁶, H. Ma²⁶, L.L. Ma^{34d}, G. Maccarrone⁴⁸, A. Macchiolo¹⁰¹, C.M. Macdonald¹³⁹, B. Maček⁷⁶, J. Machado Miguens^{122,126b}, D. Madaffari⁸⁶, R. Madar³⁵, H.J. Maddocks¹⁶⁴, W.F. Mader⁴⁵, A. Madsen⁴³, J. Maeda⁶⁸, S. Maeland¹⁴, T. Maeno²⁶, A. Maevskiy⁹⁹, E. Magradze⁵⁵, J. Mahlstedt¹⁰⁷, C. Maiani¹¹⁷, C. Maidantchik^{25a}, A.A. Maier¹⁰¹, T. Maier¹⁰⁰, A. Maio^{126a,126b,126d}, S. Majewski¹¹⁶, Y. Makida⁶⁷, N. Makovec¹¹⁷, B. Malaescu⁸¹, Pa. Malecki⁴⁰, V.P. Maleev¹²³, F. Malek⁵⁶, U. Mallik⁶⁴, D. Malon⁶, C. Malone¹⁴³, S. Maltezos¹⁰, V.M. Malyshev¹⁰⁹, S. Malyukov³¹, J. Mamuzic⁴³, G. Mancini⁴⁸, B. Mandelli³¹, L. Mandelli^{92a}, I. Mandić⁷⁶, J. Maneira^{126a,126b}, L. Manhaes de Andrade Filho^{25b}, J. Manjarres Ramos^{159b}, A. Mann¹⁰⁰, B. Mansoulie¹³⁶, R. Mantifel⁸⁸, M. Mantoani⁵⁵, S. Manzoni^{92a,92b}, L. Mapelli³¹, G. Marceca²⁸, L. March⁵⁰, G. Marchiori⁸¹, M. Marcisovsky¹²⁷, M. Marjanovic¹³, D.E. Marley⁹⁰, F. Marroquim^{25a}, S.P. Marsden⁸⁵, Z. Marshall¹⁵, L.F. Marti¹⁷, S. Marti-Garcia¹⁶⁶, B. Martin⁹¹, T.A. Martin¹⁶⁹, V.J. Martin⁴⁷, B. Martin dit Latour¹⁴, M. Martinez^{12,p}, S. Martin-Haugh¹³¹, V.S. Martoiu^{27b}, A.C. Martyniuk⁷⁹, M. Marx¹³⁸, F. Marzano^{132a}, A. Marzin³¹, L. Masetti⁸⁴, T. Mashimo¹⁵⁵, R. Mashinistov⁹⁶, J. Masik⁸⁵, A.L. Maslennikov^{109,c}, I. Massa^{21a,21b}, L. Massa^{21a,21b}, P. Mastrandrea⁵, A. Mastroberardino^{38a,38b}, T. Masubuchi¹⁵⁵, P. Mättig¹⁷⁴, J. Mattmann⁸⁴, J. Maurer^{27b}, S.J. Maxfield⁷⁵, D.A. Maximov^{109,c}, R. Mazini¹⁵¹, S.M. Mazza^{92a,92b}, N.C. Mc Fadden¹⁰⁵, G. Mc Goldrick¹⁵⁸, S.P. Mc Kee⁹⁰, A. McCarn⁹⁰, R.L. McCarthy¹⁴⁸, T.G. McCarthy³⁰, L.I. McClymont⁷⁹, K.W. McFarlane^{57,*}, J.A. Mcfayden⁷⁹, G. Mchedlidze⁵⁵, S.J. McMahon¹³¹, R.A. McPherson^{168,l}, M. Medinnis⁴³, S. Meehan¹³⁸, S. Mehlhase¹⁰⁰, A. Mehta⁷⁵, K. Meier^{59a}, C. Meineck¹⁰⁰, B. Meirose⁴², B.R. Mellado Garcia^{145c}, F. Meloni¹⁷, A. Mengarelli^{21a,21b}, S. Menke¹⁰¹, E. Meoni¹⁶¹, K.M. Mercurio⁵⁸, S. Mergelmeyer¹⁶, P. Mermod⁵⁰, L. Merola^{104a,104b}, C. Meroni^{92a}, F.S. Merritt³², A. Messina^{132a,132b}, J. Metcalfe⁶, A.S. Mete¹⁶², C. Meyer⁸⁴, C. Meyer¹²², J-P. Meyer¹³⁶, J. Meyer¹⁰⁷, H. Meyer Zu Theenhausen^{59a}, R.P. Middleton¹³¹, S. Miglioranza^{163a,163c}, L. Mijović²², G. Mikenberg¹⁷¹, M. Mikestikova¹²⁷, M. Mikuž⁷⁶, M. Milesi⁸⁹, A. Milic³¹, D.W. Miller³², C. Mills⁴⁷, A. Milov¹⁷¹, D.A. Milstead^{146a,146b}, A.A. Minaenko¹³⁰, Y. Minami¹⁵⁵, I.A. Minashvili⁶⁶, A.I. Mincer¹¹⁰, B. Mindur^{39a}, M. Mineev⁶⁶, Y. Ming¹⁷², L.M. Mir¹², K.P. Mistry¹²², T. Mitani¹⁷⁰, J. Mitrevski¹⁰⁰, V.A. Mitsou¹⁶⁶, A. Miucci⁵⁰, P.S. Miyagawa¹³⁹, J.U. Mjörnmark⁸², T. Moa^{146a,146b}, K. Mochizuki⁸⁶, S. Mohapatra³⁶, W. Mohr⁴⁹, S. Molander^{146a,146b}, R. Moles-Valls²², R. Monden⁶⁹, M.C. Mondragon⁹¹, K. Mönig⁴³, J. Monk³⁷, E. Monnier⁸⁶, A. Montalbano¹⁴⁸, J. Montejo Berlingen³¹, F. Monticelli⁷², S. Monzani^{92a,92b}, R.W. Moore³, N. Morange¹¹⁷, D. Moreno²⁰, M. Moreno Llácer⁵⁵, P. Morettini^{51a}, D. Mori¹⁴², T. Mori¹⁵⁵, M. Morii⁵⁸, M. Morinaga¹⁵⁵, V. Morisbak¹¹⁹, S. Moritz⁸⁴, A.K. Morley¹⁵⁰, G. Mornacchi³¹, J.D. Morris⁷⁷, S.S. Mortensen³⁷, L. Morvaj¹⁴⁸, M. Mosidze^{52b}, J. Moss¹⁴³, K. Motohashi¹⁵⁷, R. Mount¹⁴³, E. Mountricha²⁶, S.V. Mouraviev^{96,*}, E.J.W. Moyse⁸⁷, S. Muanza⁸⁶, R.D. Mudd¹⁸, F. Mueller¹⁰¹, J. Mueller¹²⁵, R.S.P. Mueller¹⁰⁰, T. Mueller²⁹, D. Muenstermann⁷³, P. Mullen⁵⁴, G.A. Mullier¹⁷, F.J. Munoz Sanchez⁸⁵, J.A. Murillo Quijada¹⁸, W.J. Murray^{169,131}, H. Musheghyan⁵⁵, A.G. Myagkov^{130,ac}, M. Myska¹²⁸, B.P. Nachman¹⁴³, O. Nackenhorst⁵⁰, J. Nadal⁵⁵, K. Nagai¹²⁰, R. Nagai^{67,w}, Y. Nagai⁸⁶, K. Nagano⁶⁷, Y. Nagasaka⁶⁰, K. Nagata¹⁶⁰, M. Nagel¹⁰¹, E. Nagy⁸⁶, A.M. Nairz³¹, Y. Nakahama³¹, K. Nakamura⁶⁷, T. Nakamura¹⁵⁵, I. Nakano¹¹², H. Namasivayam⁴², R.F. Naranjo Garcia⁴³, R. Narayan³², D.I. Narrias Villar^{59a}, I. Naryshkin¹²³, T. Naumann⁴³, G. Navarro²⁰, R. Nayyar⁷, H.A. Neal⁹⁰,

P.Yu. Nechaeva⁹⁶, T.J. Neep⁸⁵, P.D. Nef¹⁴³, A. Negri^{121a,121b}, M. Negrini^{21a}, S. Nektarijevic¹⁰⁶, C. Nellist¹¹⁷, A. Nelson¹⁶², S. Nemecek¹²⁷, P. Nemethy¹¹⁰, A.A. Nepomuceno^{25a}, M. Nessi^{31,ad}, M.S. Neubauer¹⁶⁵, M. Neumann¹⁷⁴, R.M. Neves¹¹⁰, P. Nevski²⁶, P.R. Newman¹⁸, D.H. Nguyen⁶, R.B. Nickerson¹²⁰, R. Nicolaïdou¹³⁶, B. Nicquevert³¹, J. Nielsen¹³⁷, A. Nikiforov¹⁶, V. Nikolaenko^{130,ac}, I. Nikolic-Audit⁸¹, K. Nikolopoulos¹⁸, J.K. Nilsen¹¹⁹, P. Nilsson²⁶, Y. Ninomiya¹⁵⁵, A. Nisati^{132a}, R. Nisius¹⁰¹, T. Nobe¹⁵⁵, L. Nodulman⁶, M. Nomachi¹¹⁸, I. Nomidis³⁰, T. Nooney⁷⁷, S. Norberg¹¹³, M. Nordberg³¹, N. Norjoharuddeen¹²⁰, O. Novgorodova⁴⁵, S. Nowak¹⁰¹, M. Nozaki⁶⁷, L. Nozka¹¹⁵, K. Ntekas¹⁰, E. Nurse⁷⁹, F. Nuti⁸⁹, F. O'grady⁷, D.C. O'Neil¹⁴², A.A. O'Rourke⁴³, V. O'Shea⁵⁴, F.G. Oakham^{30,d}, H. Oberlack¹⁰¹, T. Obermann²², J. Ocariz⁸¹, A. Ochi⁶⁸, I. Ochoa³⁶, J.P. Ochoa-Ricoux^{33a}, S. Oda⁷¹, S. Odaka⁶⁷, H. Ogren⁶², A. Oh⁸⁵, S.H. Oh⁴⁶, C.C. Ohm¹⁵, H. Ohman¹⁶⁴, H. Oide³¹, H. Okawa¹⁶⁰, Y. Okumura³², T. Okuyama⁶⁷, A. Olariu^{27b}, L.F. Oleiro Seabra^{126a}, S.A. Olivares Pino⁴⁷, D. Oliveira Damazio²⁶, A. Olszewski⁴⁰, J. Olszowska⁴⁰, A. Onofre^{126a,126e}, K. Onogi¹⁰³, P.U.E. Onyisi^{32,s}, C.J. Oram^{159a}, M.J. Oreglia³², Y. Oren¹⁵³, D. Orestano^{134a,134b}, N. Orlando^{61b}, R.S. Orr¹⁵⁸, B. Osculati^{51a,51b}, R. Ospanov⁸⁵, G. Otero y Garzon²⁸, H. Otono⁷¹, M. Ouchrif^{135d}, F. Ould-Saada¹¹⁹, A. Ouraou¹³⁶, K.P. Oussoren¹⁰⁷, Q. Ouyang^{34a}, A. Ovcharova¹⁵, M. Owen⁵⁴, R.E. Owen¹⁸, V.E. Ozcan^{19a}, N. Ozturk⁸, K. Pachal¹⁴², A. Pacheco Pages¹², C. Padilla Aranda¹², M. Pagáčová⁴⁹, S. Pagan Griso¹⁵, F. Paige²⁶, P. Pais⁸⁷, K. Pajchel¹¹⁹, G. Palacino^{159b}, S. Palestini³¹, M. Palka^{39b}, D. Pallin³⁵, A. Palma^{126a,126b}, E.St. Panagiotopoulou¹⁰, C.E. Pandini⁸¹, J.G. Panduro Vazquez⁷⁸, P. Pani^{146a,146b}, S. Panitkin²⁶, D. Pantea^{27b}, L. Paolozzi⁵⁰, Th.D. Papadopoulou¹⁰, K. Papageorgiou¹⁵⁴, A. Paramonov⁶, D. Paredes Hernandez¹⁷⁵, M.A. Parker²⁹, K.A. Parker¹³⁹, F. Parodi^{51a,51b}, J.A. Parsons³⁶, U. Parzefall⁴⁹, V.R. Pascuzzi¹⁵⁸, E. Pasqualucci^{132a}, S. Passaggio^{51a}, F. Pastore^{134a,134b,*}, Fr. Pastore⁷⁸, G. Pásztor³⁰, S. Patariaia¹⁷⁴, N.D. Patel¹⁵⁰, J.R. Pater⁸⁵, T. Pauly³¹, J. Pearce¹⁶⁸, B. Pearson¹¹³, L.E. Pedersen³⁷, M. Pedersen¹¹⁹, S. Pedraza Lopez¹⁶⁶, R. Pedro^{126a,126b}, S.V. Peleganchuk^{109,c}, D. Pelikan¹⁶⁴, O. Penc¹²⁷, C. Peng^{34a}, H. Peng^{34b}, J. Penwell⁶², B.S. Peralva^{25b}, M.M. Perego¹³⁶, D.V. Perepelitsa²⁶, E. Perez Codina^{159a}, L. Perini^{92a,92b}, H. Pernegger³¹, S. Perrella^{104a,104b}, R. Peschke⁴³, V.D. Peshekhonov⁶⁶, K. Peters³¹, R.F.Y. Peters⁸⁵, B.A. Petersen³¹, T.C. Petersen³⁷, E. Petit⁵⁶, A. Petridis¹, C. Petridou¹⁵⁴, P. Petroff¹¹⁷, E. Petrolo^{132a}, M. Petrov¹²⁰, F. Petrucci^{134a,134b}, N.E. Pettersson¹⁵⁷, A. Peyaud¹³⁶, R. Pezoa^{33b}, P.W. Phillips¹³¹, G. Piacquadio¹⁴³, E. Pianori¹⁶⁹, A. Picazio⁸⁷, E. Piccaro⁷⁷, M. Piccinini^{21a,21b}, M.A. Pickering¹²⁰, R. Piegai²⁸, J.E. Pilcher³², A.D. Pilkington⁸⁵, A.W.J. Pin⁸⁵, J. Pina^{126a,126b,126d}, M. Pinamonti^{163a,163c,ae}, J.L. Pinfold³, A. Pingel³⁷, S. Pires⁸¹, H. Pirumov⁴³, M. Pitt¹⁷¹, L. Plazak^{144a}, M.-A. Pleier²⁶, V. Pleskot⁸⁴, E. Plotnikova⁶⁶, P. Plucinski^{146a,146b}, D. Pluth⁶⁵, R. Poettgen^{146a,146b}, L. Poggioli¹¹⁷, D. Pohl²², G. Polesello^{121a}, A. Poley⁴³, A. Policicchio^{38a,38b}, R. Polifka¹⁵⁸, A. Polini^{21a}, C.S. Pollard⁵⁴, V. Polychronakos²⁶, K. Pommès³¹, L. Pontecorvo^{132a}, B.G. Pope⁹¹, G.A. Popeneciu^{27c}, D.S. Popovic¹³, A. Poppleton³¹, S. Pospisil¹²⁸, K. Potamianos¹⁵, I.N. Potrap⁶⁶, C.J. Potter²⁹, C.T. Potter¹¹⁶, G. Poulard³¹, J. Poveda³¹, V. Pozdnyakov⁶⁶, M.E. Pozo Astigarraga³¹, P. Pralavorio⁸⁶, A. Pranko¹⁵, S. Prell⁶⁵, D. Price⁸⁵, L.E. Price⁶, M. Primavera^{74a}, S. Prince⁸⁸, M. Proissl⁴⁷, K. Prokofiev^{61c}, F. Prokoshin^{33b}, S. Protopopescu²⁶, J. Proudfoot⁶, M. Przybycien^{39a}, D. Puddu^{134a,134b}, D. Poldon¹⁴⁸, M. Purohit^{26,af}, P. Puzo¹¹⁷, J. Qian⁹⁰, G. Qin⁵⁴, Y. Qin⁸⁵, A. Quadt⁵⁵, W.B. Quayle^{163a,163b}, M. Queitsch-Maitland⁸⁵, D. Quilty⁵⁴, S. Raddum¹¹⁹, V. Radeka²⁶, V. Radescu^{59b}, S.K. Radhakrishnan¹⁴⁸, P. Radloff¹¹⁶, P. Rados⁸⁹, F. Ragusa^{92a,92b}, G. Rahal¹⁷⁷, S. Rajagopalan²⁶, M. Rammensee³¹, C. Rangel-Smith¹⁶⁴, M.G. Ratti^{92a,92b}, F. Rauscher¹⁰⁰, S. Rave⁸⁴, T. Ravenscroft⁵⁴, M. Raymond³¹, A.L. Read¹¹⁹, N.P. Readioff⁷⁵, D.M. Rebuzzi^{121a,121b}, A. Redelbach¹⁷³, G. Redlinger²⁶, R. Reece¹³⁷, K. Reeves⁴², L. Rehnisch¹⁶, J. Reichert¹²², H. Reisin²⁸, C. Rembser³¹, H. Ren^{34a}, M. Rescigno^{132a}, S. Resconi^{92a}, O.L. Rezanova^{109,c}, P. Reznicek¹²⁹, R. Rezvani⁹⁵, R. Richter¹⁰¹, S. Richter⁷⁹, E. Richter-Was^{39b}, O. Ricken²², M. Ridel⁸¹, P. Rieck¹⁶, C.J. Riegel¹⁷⁴, J. Rieger⁵⁵, O. Rifki¹¹³, M. Rijssenbeek¹⁴⁸, A. Rimoldi^{121a,121b}, L. Rinaldi^{21a}, B. Ristić⁵⁰, E. Ritsch³¹, I. Riu¹², F. Rizatdinova¹¹⁴, E. Rizvi⁷⁷, C. Rizzi¹², S.H. Robertson^{88,l}, A. Robichaud-Veronneau⁸⁸, D. Robinson²⁹, J.E.M. Robinson⁴³, A. Robson⁵⁴, C. Roda^{124a,124b}, Y. Rodina⁸⁶, A. Rodriguez Perez¹², D. Rodriguez Rodriguez¹⁶⁶, S. Roe³¹, C.S. Rogan⁵⁸, O. Röhne¹¹⁹, A. Romaniouk⁹⁸, M. Romano^{21a,21b}, S.M. Romano Saez³⁵, E. Romero Adam¹⁶⁶, N. Rompotis¹³⁸, M. Ronzani⁴⁹, L. Roos⁸¹, E. Ros¹⁶⁶, S. Rosati^{132a}, K. Rosbach⁴⁹, P. Rose¹³⁷, O. Rosenthal¹⁴¹, V. Rossetti^{146a,146b}, E. Rossi^{104a,104b}, L.P. Rossi^{51a}, J.H.N. Rosten²⁹, R. Rosten¹³⁸, M. Rotaru^{27b}, I. Roth¹⁷¹, J. Rothberg¹³⁸, D. Rousseau¹¹⁷,

C.R. Royon¹³⁶, A. Rozanov⁸⁶, Y. Rozen¹⁵², X. Ruan^{145c}, F. Rubbo¹⁴³, I. Rubinskiy⁴³, V.I. Rud⁹⁹, M.S. Rudolph¹⁵⁸, F. Rühr⁴⁹, A. Ruiz-Martinez³¹, Z. Rurikova⁴⁹, N.A. Rusakovich⁶⁶, A. Ruschke¹⁰⁰, H.L. Russell¹³⁸, J.P. Rutherford⁷, N. Ruthmann³¹, Y.F. Ryabov¹²³, M. Rybar¹⁶⁵, G. Rybkin¹¹⁷, S. Ryu⁶, A. Ryzhov¹³⁰, A.F. Saavedra¹⁵⁰, G. Sabato¹⁰⁷, S. Sacerdoti²⁸, H.F.-W. Sadrozinski¹³⁷, R. Sadykov⁶⁶, F. Safai Tehrani^{132a}, P. Saha¹⁰⁸, M. Sahinsoy^{59a}, M. Saimpert¹³⁶, T. Saito¹⁵⁵, H. Sakamoto¹⁵⁵, Y. Sakurai¹⁷⁰, G. Salamanna^{134a,134b}, A. Salamon^{133a,133b}, J.E. Salazar Loyola^{33b}, D. Salek¹⁰⁷, P.H. Sales De Bruin¹³⁸, D. Salihagic¹⁰¹, A. Salnikov¹⁴³, J. Salt¹⁶⁶, D. Salvatore^{38a,38b}, F. Salvatore¹⁴⁹, A. Salvucci^{61a}, A. Salzburger³¹, D. Sammel⁴⁹, D. Sampsonidis¹⁵⁴, A. Sanchez^{104a,104b}, J. Sánchez¹⁶⁶, V. Sanchez Martinez¹⁶⁶, H. Sandaker¹¹⁹, R.L. Sandbach⁷⁷, H.G. Sander⁸⁴, M.P. Sanders¹⁰⁰, M. Sandhoff¹⁷⁴, C. Sandoval²⁰, R. Sandstroem¹⁰¹, D.P.C. Sankey¹³¹, M. Sannino^{51a,51b}, A. Sansoni⁴⁸, C. Santoni³⁵, R. Santonico^{133a,133b}, H. Santos^{126a}, I. Santoyo Castillo¹⁴⁹, K. Sapp¹²⁵, A. Saponov⁶⁶, J.G. Saraiva^{126a,126d}, B. Sarrazin²², O. Sasaki⁶⁷, Y. Sasaki¹⁵⁵, K. Sato¹⁶⁰, G. Sauvage^{5,*}, E. Sauvan⁵, G. Savage⁷⁸, P. Savard^{158,d}, C. Sawyer¹³¹, L. Sawyer^{80,o}, J. Saxon³², C. Sbarra^{21a}, A. Sbrizzi^{21a,21b}, T. Scanlon⁷⁹, D.A. Scannicchio¹⁶², M. Scarcella¹⁵⁰, V. Scarfone^{38a,38b}, J. Schaarschmidt¹⁷¹, P. Schacht¹⁰¹, D. Schaefer³¹, R. Schaefer⁴³, J. Schaeffer⁸⁴, S. Schaepe²², S. Schaezel^{59b}, U. Schäfer⁸⁴, A.C. Schaffer¹¹⁷, D. Schaile¹⁰⁰, R.D. Schamberger¹⁴⁸, V. Scharf^{59a}, V.A. Schegelsky¹²³, D. Scheirich¹²⁹, M. Schernau¹⁶², C. Schiavi^{51a,51b}, C. Schillo⁴⁹, M. Schioppa^{38a,38b}, S. Schlenker³¹, K. Schmieden³¹, C. Schmitt⁸⁴, S. Schmitt⁴³, S. Schmitz⁸⁴, B. Schneider^{159a}, Y.J. Schnellbach⁷⁵, U. Schnoor⁴⁹, L. Schoeffel¹³⁶, A. Schoening^{59b}, B.D. Schoenrock⁹¹, E. Schopf²², A.L.S. Schorlemmer⁴⁴, M. Schott⁸⁴, D. Schouten^{159a}, J. Schovancova⁸, S. Schramm⁵⁰, M. Schreyer¹⁷³, N. Schuh⁸⁴, M.J. Schultens²², H.-C. Schultz-Coulon^{59a}, H. Schulz¹⁶, M. Schumacher⁴⁹, B.A. Schumm¹³⁷, Ph. Schune¹³⁶, C. Schwanenberger⁸⁵, A. Schwartzman¹⁴³, T.A. Schwarz⁹⁰, Ph. Schwegler¹⁰¹, H. Schweiger⁸⁵, Ph. Schwemling¹³⁶, R. Schwienhorst⁹¹, J. Schwindling¹³⁶, T. Schwindt²², G. Sciolla²⁴, F. Scuri^{124a,124b}, F. Scutti⁸⁹, J. Searcy⁹⁰, P. Seema²², S.C. Seidel¹⁰⁵, A. Seiden¹³⁷, F. Seifert¹²⁸, J.M. Seixas^{25a}, G. Sekhniaidze^{104a}, K. Sekhon⁹⁰, S.J. Sekula⁴¹, D.M. Seliverstov^{123,*}, N. Semprini-Cesari^{21a,21b}, C. Serfon¹¹⁹, L. Serin¹¹⁷, L. Serkin^{163a,163b}, M. Sessa^{134a,134b}, R. Seuster^{159a}, H. Severini¹¹³, T. Sfiligoj⁷⁶, F. Sforza³¹, A. Sfyrla⁵⁰, E. Shabalina⁵⁵, N.W. Shaikh^{146a,146b}, L.Y. Shan^{34a}, R. Shang¹⁶⁵, J.T. Shank²³, M. Shapiro¹⁵, P.B. Shatalov⁹⁷, K. Shaw^{163a,163b}, S.M. Shaw⁸⁵, A. Shcherbakova^{146a,146b}, C.Y. Shehu¹⁴⁹, P. Sherwood⁷⁹, L. Shi^{151,ag}, S. Shimizu⁶⁸, C.O. Shimmin¹⁶², M. Shimojima¹⁰², M. Shiyakova^{66,ah}, A. Shmeleva⁹⁶, D. Shoaleh Saadi⁹⁵, M.J. Shochet³², S. Shojaii^{92a,92b}, S. Shrestha¹¹¹, E. Shulga⁹⁸, M.A. Shupe⁷, P. Sicho¹²⁷, P.E. Sidebo¹⁴⁷, O. Sidiropoulou¹⁷³, D. Sidorov¹¹⁴, A. Sidoti^{21a,21b}, F. Siegert⁴⁵, Dj. Sijacki¹³, J. Silva^{126a,126d}, S.B. Silverstein^{146a}, V. Simak¹²⁸, O. Simard⁵, Lj. Simic¹³, S. Simion¹¹⁷, E. Simioni⁸⁴, B. Simmons⁷⁹, D. Simon³⁵, M. Simon⁸⁴, P. Sinervo¹⁵⁸, N.B. Sinev¹¹⁶, M. Sioli^{21a,21b}, G. Siragusa¹⁷³, S.Yu. Sivoklov⁹⁹, J. Sjölín^{146a,146b}, T.B. Sjursen¹⁴, M.B. Skinner⁷³, H.P. Skottowe⁵⁸, P. Skubic¹¹³, M. Slater¹⁸, T. Slavicek¹²⁸, M. Slawinska¹⁰⁷, K. Sliwa¹⁶¹, R. Slovak¹²⁹, V. Smakhtin¹⁷¹, B.H. Smart⁵, L. Smestad¹⁴, S.Yu. Smirnov⁹⁸, Y. Smirnov⁹⁸, L.N. Smirnova^{99,ai}, O. Smirnova⁸², M.N.K. Smith³⁶, R.W. Smith³⁶, M. Smizanska⁷³, K. Smolek¹²⁸, A.A. Snesarev⁹⁶, G. Snidero⁷⁷, S. Snyder²⁶, R. Sobie^{168,l}, F. Socher⁴⁵, A. Soffer¹⁵³, D.A. Soh^{151,ag}, G. Sokhrannyi⁷⁶, C.A. Solans Sanchez³¹, M. Solar¹²⁸, E.Yu. Soldatov⁹⁸, U. Soldevila¹⁶⁶, A.A. Solodkov¹³⁰, A. Soloshenko⁶⁶, O.V. Solovyanov¹³⁰, V. Solovyev¹²³, P. Sommer⁴⁹, H. Son¹⁶¹, H.Y. Song^{34b,z}, A. Sood¹⁵, A. Sopczak¹²⁸, V. Sopko¹²⁸, V. Sorin¹², D. Sosa^{59b}, C.L. Sotiropoulou^{124a,124b}, R. Soualah^{163a,163c}, A.M. Soukharev^{109,c}, D. South⁴³, B.C. Sowden⁷⁸, S. Spagnolo^{74a,74b}, M. Spalla^{124a,124b}, M. Spangenberg¹⁶⁹, F. Spanò⁷⁸, D. Sperlich¹⁶, F. Spettel¹⁰¹, R. Spighi^{21a}, G. Spigo³¹, L.A. Spiller⁸⁹, M. Spousta¹²⁹, R.D. St. Denis^{54,*}, A. Stabile^{92a}, J. Stahlman¹²², R. Stamen^{59a}, S. Stamm¹⁶, E. Stanecka⁴⁰, R.W. Stanek⁶, C. Stancu^{134a}, M. Stancu-Bellu⁴³, M.M. Stanitzki⁴³, S. Stapnes¹¹⁹, E.A. Starchenko¹³⁰, G.H. Stark³², J. Stark⁵⁶, P. Staroba¹²⁷, P. Starovoitov^{59a}, S. Stärz³¹, R. Staszewski⁴⁰, P. Steinberg²⁶, B. Stelzer¹⁴², H.J. Stelzer³¹, O. Stelzer-Chilton^{159a}, H. Stenzel⁵³, G.A. Stewart⁵⁴, J.A. Stillings²², M.C. Stockton⁸⁸, M. Stoebe⁸⁸, G. Stoicea^{27b}, P. Stolte⁵⁵, S. Stonjek¹⁰¹, A.R. Stradling⁸, A. Straessner⁴⁵, M.E. Stramaglia¹⁷, J. Strandberg¹⁴⁷, S. Strandberg^{146a,146b}, A. Strandlie¹¹⁹, M. Strauss¹¹³, P. Strizenec^{144b}, R. Ströhmer¹⁷³, D.M. Strom¹¹⁶, R. Stroynowski⁴¹, A. Strubig¹⁰⁶, S.A. Stucci¹⁷, B. Stugu¹⁴, N.A. Styles⁴³, D. Su¹⁴³, J. Su¹²⁵, R. Subramaniam⁸⁰, S. Suchek^{59a}, Y. Sugaya¹¹⁸, M. Suk¹²⁸, V.V. Sulín⁹⁶, S. Sultansoy^{4c}, T. Sumida⁶⁹, S. Sun⁵⁸, X. Sun^{34a}, J.E. Sundermann⁴⁹, K. Suruliz¹⁴⁹, G. Susinno^{38a,38b}, M.R. Sutton¹⁴⁹,

S. Suzuki⁶⁷, M. Svatos¹²⁷, M. Swiatlowski³², I. Sykora^{144a}, T. Sykora¹²⁹, D. Ta⁴⁹, C. Taccini^{134a,134b}, K. Tackmann⁴³, J. Taenzer¹⁵⁸, A. Taffard¹⁶², R. Tafirout^{159a}, N. Taiblum¹⁵³, H. Takai²⁶, R. Takashima⁷⁰, H. Takeda⁶⁸, T. Takeshita¹⁴⁰, Y. Takubo⁶⁷, M. Talby⁸⁶, A.A. Talyshev^{109,c}, J.Y.C. Tam¹⁷³, K.G. Tan⁸⁹, J. Tanaka¹⁵⁵, R. Tanaka¹¹⁷, S. Tanaka⁶⁷, B.B. Tannenwald¹¹¹, S. Tapia Araya^{33b}, S. Tapprogge⁸⁴, S. Tarem¹⁵², G.F. Tartarelli^{92a}, P. Tas¹²⁹, M. Tasevsky¹²⁷, T. Tashiro⁶⁹, E. Tassi^{38a,38b}, A. Tavares Delgado^{126a,126b}, Y. Tayalati^{135d}, A.C. Taylor¹⁰⁵, G.N. Taylor⁸⁹, P.T.E. Taylor⁸⁹, W. Taylor^{159b}, F.A. Teischinger³¹, P. Teixeira-Dias⁷⁸, K.K. Temming⁴⁹, D. Temple¹⁴², H. Ten Kate³¹, P.K. Teng¹⁵¹, J.J. Teoh¹¹⁸, F. Tepel¹⁷⁴, S. Terada⁶⁷, K. Terashi¹⁵⁵, J. Terron⁸³, S. Terzo¹⁰¹, M. Testa⁴⁸, R.J. Teuscher^{158,l}, T. Theveneaux-Pelzer⁸⁶, J.P. Thomas¹⁸, J. Thomas-Wilsker⁷⁸, E.N. Thompson³⁶, P.D. Thompson¹⁸, R.J. Thompson⁸⁵, A.S. Thompson⁵⁴, L.A. Thomsen¹⁷⁵, E. Thomson¹²², M. Thomson²⁹, M.J. Tibbetts¹⁵, R.E. Ticse Torres⁸⁶, V.O. Tikhomirov^{96,aj}, Yu.A. Tikhonov^{109,c}, S. Timoshenko⁹⁸, P. Tipton¹⁷⁵, S. Tisserant⁸⁶, K. Todome¹⁵⁷, T. Todorov^{5,*}, S. Todorova-Nova¹²⁹, J. Tojo⁷¹, S. Tokár^{144a}, K. Tokushuku⁶⁷, E. Tolley⁵⁸, L. Tomlinson⁸⁵, M. Tomoto¹⁰³, L. Tompkins^{143,ak}, K. Toms¹⁰⁵, B. Tong⁵⁸, E. Torrence¹¹⁶, H. Torres¹⁴², E. Torró Pastor¹³⁸, J. Toth^{86,al}, F. Touchard⁸⁶, D.R. Tovey¹³⁹, T. Trefzger¹⁷³, A. Tricoli³¹, I.M. Trigger^{159a}, S. Trincaz-Duvold⁸¹, M.F. Tripiana¹², W. Trischuk¹⁵⁸, B. Trocme⁵⁶, A. Trofymov⁴³, C. Troncon^{92a}, M. Trotter-McDonald¹⁵, M. Trovatelli¹⁶⁸, L. Truong^{163a,163b}, M. Trzebinski⁴⁰, A. Trzupek⁴⁰, J.C-L. Tseng¹²⁰, P.V. Tsiarehsha⁹³, G. Tsipolitis¹⁰, N. Tsirintanis⁹, S. Tsiskaridze¹², V. Tsiskaridze⁴⁹, E.G. Tskhadadze^{52a}, K.M. Tsui^{61a}, I.I. Tsukerman⁹⁷, V. Tsulaia¹⁵, S. Tsuno⁶⁷, D. Tsybychev¹⁴⁸, A. Tudorache^{27b}, V. Tudorache^{27b}, A.N. Tuna⁵⁸, S.A. Tupputi^{21a,21b}, S. Turchikhin^{99,ai}, D. Turecek¹²⁸, D. Turgeman¹⁷¹, R. Turra^{92a,92b}, A.J. Turvey⁴¹, P.M. Tuts³⁶, M. Tylmad^{146a,146b}, M. Tyndel¹³¹, G. Uccielli^{21a,21b}, I. Ueda¹⁵⁵, R. Ueno³⁰, M. Ughetto^{146a,146b}, F. Ukegawa¹⁶⁰, G. Unal³¹, A. Undrus²⁶, G. Unel¹⁶², F.C. Ungaro⁸⁹, Y. Unno⁶⁷, C. Unverdorben¹⁰⁰, J. Urban^{144b}, P. Urquijo⁸⁹, P. Urrejola⁸⁴, G. Usai⁸, A. Usanova⁶³, L. Vacavant⁸⁶, V. Vacek¹²⁸, B. Vachon⁸⁸, C. Valderanis⁸⁴, E. Valdes Santurio^{146a,146b}, N. Valencic¹⁰⁷, S. Valentinetti^{21a,21b}, A. Valero¹⁶⁶, L. Valery¹², S. Valkar¹²⁹, S. Vallecorsa⁵⁰, J.A. Valls Ferrer¹⁶⁶, W. Van Den Wollenberg¹⁰⁷, P.C. Van Der Deijl¹⁰⁷, R. van der Geer¹⁰⁷, H. van der Graaf¹⁰⁷, N. van Eldik¹⁵², P. van Gemmeren⁶, J. Van Nieuwkoop¹⁴², I. van Vulpen¹⁰⁷, M.C. van Woerden³¹, M. Vanadia^{132a,132b}, W. Vandelli³¹, R. Vanguri¹²², A. Vaniachine⁶, P. Vankov¹⁰⁷, G. Vardanyan¹⁷⁶, R. Vari^{132a}, E.W. Varnes⁷, T. Varol⁴¹, D. Varouchas⁸¹, A. Vartapetian⁸, K.E. Varvell¹⁵⁰, F. Vazeille³⁵, T. Vazquez Schroeder⁸⁸, J. Veatch⁷, L.M. Veloce¹⁵⁸, F. Veloso^{126a,126c}, S. Veneziano^{132a}, A. Ventura^{74a,74b}, M. Venturi¹⁶⁸, N. Venturi¹⁵⁸, A. Venturini²⁴, V. Vercesi^{121a}, M. Verducci^{132a,132b}, W. Verkerke¹⁰⁷, J.C. Vermeulen¹⁰⁷, A. Vest^{45,am}, M.C. Vetterli^{142,d}, O. Viazlo⁸², I. Vichou¹⁶⁵, T. Vickey¹³⁹, O.E. Vickey Boeriu¹³⁹, G.H.A. Viehhauser¹²⁰, S. Viel¹⁵, R. Vigne⁶³, M. Villa^{21a,21b}, M. Villaplana Perez^{92a,92b}, E. Vilucchi⁴⁸, M.G. Vincker³⁰, V.B. Vinogradov⁶⁶, C. Vittori^{21a,21b}, I. Vivarelli¹⁴⁹, S. Vlachos¹⁰, M. Vlasak¹²⁸, M. Vogel¹⁷⁴, P. Vokac¹²⁸, G. Volpi^{124a,124b}, M. Volpi⁸⁹, H. von der Schmitt¹⁰¹, E. von Toerne²², V. Vorobel¹²⁹, K. Vorobev⁹⁸, M. Vos¹⁶⁶, R. Voss³¹, J.H. Vosseveld⁷⁵, N. Vranjes¹³, M. Vranjes Milosavljevic¹³, V. Vrba¹²⁷, M. Vreeswijk¹⁰⁷, R. Vuillermet³¹, I. Vukotic³², Z. Vykydal¹²⁸, P. Wagner²², W. Wagner¹⁷⁴, H. Wahlberg⁷², S. Wahrmund⁴⁵, J. Wakabayashi¹⁰³, J. Walder⁷³, R. Walker¹⁰⁰, W. Walkowiak¹⁴¹, V. Wallangen^{146a,146b}, C. Wang¹⁵¹, C. Wang^{34d,86}, F. Wang¹⁷², H. Wang¹⁵, H. Wang⁴¹, J. Wang⁴³, J. Wang¹⁵⁰, K. Wang⁸⁸, R. Wang⁶, S.M. Wang¹⁵¹, T. Wang²², T. Wang³⁶, X. Wang¹⁷⁵, C. Wanotayaroj¹¹⁶, A. Warburton⁸⁸, C.P. Ward²⁹, D.R. Wardrope⁷⁹, A. Washbrook⁴⁷, P.M. Watkins¹⁸, A.T. Watson¹⁸, I.J. Watson¹⁵⁰, M.F. Watson¹⁸, G. Watts¹³⁸, S. Watts⁸⁵, B.M. Waugh⁷⁹, S. Webb⁸⁴, M.S. Weber¹⁷, S.W. Weber¹⁷³, J.S. Webster⁶, A.R. Weidberg¹²⁰, B. Weinert⁶², J. Weingarten⁵⁵, C. Weiser⁴⁹, H. Weits¹⁰⁷, P.S. Wells³¹, T. Wenaus²⁶, T. Wengler³¹, S. Wenig³¹, N. Wermes²², M. Werner⁴⁹, P. Werner³¹, M. Wessels^{59a}, J. Wetter¹⁶¹, K. Whalen¹¹⁶, N.L. Whallon¹³⁸, A.M. Wharton⁷³, A. White⁸, M.J. White¹, R. White^{33b}, S. White^{124a,124b}, D. Whiteson¹⁶², F.J. Wickens¹³¹, W. Wiedenmann¹⁷², M. Wielers¹³¹, P. Wienemann²², C. Wiglesworth³⁷, L.A.M. Wiik-Fuchs²², A. Wildauer¹⁰¹, H.G. Wilkens³¹, H.H. Williams¹²², S. Williams¹⁰⁷, C. Willis⁹¹, S. Willocq⁸⁷, J.A. Wilson¹⁸, I. Wingerter-Seez⁵, F. Winklmeier¹¹⁶, O.J. Winston¹⁴⁹, B.T. Winter²², M. Wittgen¹⁴³, J. Wittkowski¹⁰⁰, S.J. Wollstadt⁸⁴, M.W. Wolter⁴⁰, H. Wolters^{126a,126c}, B.K. Wosiek⁴⁰, J. Wotschack³¹, M.J. Woudstra⁸⁵, K.W. Wozniak⁴⁰, M. Wu⁵⁶, M. Wu³², S.L. Wu¹⁷², X. Wu⁵⁰, Y. Wu⁹⁰, T.R. Wyatt⁸⁵, B.M. Wynne⁴⁷, S. Xella³⁷, D. Xu^{34a}, L. Xu²⁶, B. Yabsley¹⁵⁰, S. Yacoob^{145a}, R. Yakabe⁶⁸,

D. Yamaguchi¹⁵⁷, Y. Yamaguchi¹¹⁸, A. Yamamoto⁶⁷, S. Yamamoto¹⁵⁵, T. Yamanaka¹⁵⁵, K. Yamauchi¹⁰³, Y. Yamazaki⁶⁸, Z. Yan²³, H. Yang^{34e}, H. Yang¹⁷², Y. Yang¹⁵¹, Z. Yang¹⁴, W.-M. Yao¹⁵, Y.C. Yap⁸¹, Y. Yasu⁶⁷, E. Yatsenko⁵, K.H. Yau Wong²², J. Ye⁴¹, S. Ye²⁶, I. Yeletsikh⁶⁶, A.L. Yen⁵⁸, E. Yildirim⁴³, K. Yorita¹⁷⁰, R. Yoshida⁶, K. Yoshihara¹²², C. Young¹⁴³, C.J.S. Young³¹, S. Youssef²³, D.R. Yu¹⁵, J. Yu⁸, J.M. Yu⁹⁰, J. Yu⁶⁵, L. Yuan⁶⁸, S.P.Y. Yuen²², I. Yusuff^{29,an}, B. Zabinski⁴⁰, R. Zaidan^{34d}, A.M. Zaitsev^{130,ac}, N. Zakharchuk⁴³, J. Zalieckas¹⁴, A. Zaman¹⁴⁸, S. Zambito⁵⁸, L. Zanello^{132a,132b}, D. Zanzi⁸⁹, C. Zeitnitz¹⁷⁴, M. Zeman¹²⁸, A. Zemla^{39a}, J.C. Zeng¹⁶⁵, Q. Zeng¹⁴³, K. Zengel²⁴, O. Zenin¹³⁰, T. Ženiš^{144a}, D. Zerwas¹¹⁷, D. Zhang⁹⁰, F. Zhang¹⁷², G. Zhang^{34b,z}, H. Zhang^{34c}, J. Zhang⁶, L. Zhang⁴⁹, R. Zhang²², R. Zhang^{34b,ao}, X. Zhang^{34d}, Z. Zhang¹¹⁷, X. Zhao⁴¹, Y. Zhao^{34d,117}, Z. Zhao^{34b}, A. Zhemchugov⁶⁶, J. Zhong¹²⁰, B. Zhou⁹⁰, C. Zhou⁴⁶, L. Zhou³⁶, L. Zhou⁴¹, M. Zhou¹⁴⁸, N. Zhou^{34f}, C.G. Zhu^{34d}, H. Zhu^{34a}, J. Zhu⁹⁰, Y. Zhu^{34b}, X. Zhuang^{34a}, K. Zhukov⁹⁶, A. Zibell¹⁷³, D. Zieminska⁶², N.I. Zimine⁶⁶, C. Zimmermann⁸⁴, S. Zimmermann⁴⁹, Z. Zinonos⁵⁵, M. Zinser⁸⁴, M. Ziolkowski¹⁴¹, L. Živković¹³, G. Zobernig¹⁷², A. Zoccoli^{21a,21b}, M. zur Nedden¹⁶, G. Zurzolo^{104a,104b}, L. Zwalinski³¹

¹ Department of Physics, University of Adelaide, Adelaide, Australia

² Physics Department, SUNY Albany, Albany NY, United States

³ Department of Physics, University of Alberta, Edmonton AB, Canada

⁴ (a) Department of Physics, Ankara University, Ankara; (b) Istanbul Aydin University, Istanbul; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey

⁵ LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France

⁶ High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States

⁷ Department of Physics, University of Arizona, Tucson AZ, United States

⁸ Department of Physics, The University of Texas at Arlington, Arlington TX, United States

⁹ Physics Department, University of Athens, Athens, Greece

¹⁰ Physics Department, National Technical University of Athens, Zografou, Greece

¹¹ Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

¹² Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Barcelona, Spain

¹³ Institute of Physics, University of Belgrade, Belgrade, Serbia

¹⁴ Department for Physics and Technology, University of Bergen, Bergen, Norway

¹⁵ Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States

¹⁶ Department of Physics, Humboldt University, Berlin, Germany

¹⁷ Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland

¹⁸ School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom

¹⁹ (a) Department of Physics, Bogazici University, Istanbul; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (d) Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey; (e) Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey

²⁰ Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

²¹ (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy

²² Physikalisches Institut, University of Bonn, Bonn, Germany

²³ Department of Physics, Boston University, Boston MA, United States

²⁴ Department of Physics, Brandeis University, Waltham MA, United States

²⁵ (a) Universidade Federal do Rio de Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil

²⁶ Physics Department, Brookhaven National Laboratory, Upton NY, United States

²⁷ (a) Transilvania University of Brasov, Brasov, Romania; (b) National Institute of Physics and Nuclear Engineering, Bucharest; (c) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca; (d) University Politehnica Bucharest, Bucharest; (e) West University in Timisoara, Timisoara, Romania

²⁸ Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

²⁹ Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom

³⁰ Department of Physics, Carleton University, Ottawa ON, Canada

³¹ CERN, Geneva, Switzerland

³² Enrico Fermi Institute, University of Chicago, Chicago IL, United States

³³ (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

³⁴ (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; (f) Physics Department, Tsinghua University, Beijing 100084, China

³⁵ Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France

³⁶ Nevis Laboratory, Columbia University, Irvington NY, United States

³⁷ Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

³⁸ (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy

³⁹ (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland

⁴⁰ Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland

⁴¹ Physics Department, Southern Methodist University, Dallas TX, United States

⁴² Physics Department, University of Texas at Dallas, Richardson TX, United States

⁴³ DESY, Hamburg and Zeuthen, Germany

⁴⁴ Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

⁴⁵ Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

⁴⁶ Department of Physics, Duke University, Durham NC, United States

⁴⁷ SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom

⁴⁸ INFN Laboratori Nazionali di Frascati, Frascati, Italy

⁴⁹ Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany

⁵⁰ Section de Physique, Université de Genève, Geneva, Switzerland

⁵¹ (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy

⁵² (a) E. Andronikashvili Institute of Physics, Iv. Javakishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

⁵³ II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

- ⁵⁴ SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
- ⁵⁵ II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
- ⁵⁶ Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
- ⁵⁷ Department of Physics, Hampton University, Hampton VA, United States
- ⁵⁸ Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States
- ⁵⁹ ^(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; ^(c) ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
- ⁶⁰ Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
- ⁶¹ ^(a) Department of Physics, The Chinese University of Hong Kong, Shatin, NT, Hong Kong; ^(b) Department of Physics, The University of Hong Kong, Hong Kong; ^(c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
- ⁶² Department of Physics, Indiana University, Bloomington IN, United States
- ⁶³ Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
- ⁶⁴ University of Iowa, Iowa City IA, United States
- ⁶⁵ Department of Physics and Astronomy, Iowa State University, Ames IA, United States
- ⁶⁶ Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
- ⁶⁷ KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
- ⁶⁸ Graduate School of Science, Kobe University, Kobe, Japan
- ⁶⁹ Faculty of Science, Kyoto University, Kyoto, Japan
- ⁷⁰ Kyoto University of Education, Kyoto, Japan
- ⁷¹ Department of Physics, Kyushu University, Fukuoka, Japan
- ⁷² Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
- ⁷³ Physics Department, Lancaster University, Lancaster, United Kingdom
- ⁷⁴ ^(a) INFN Sezione di Lecce; ^(b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
- ⁷⁵ Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
- ⁷⁶ Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
- ⁷⁷ School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
- ⁷⁸ Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
- ⁷⁹ Department of Physics and Astronomy, University College London, London, United Kingdom
- ⁸⁰ Louisiana Tech University, Ruston LA, United States
- ⁸¹ Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
- ⁸² Fysiska institutionen, Lunds universitet, Lund, Sweden
- ⁸³ Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain
- ⁸⁴ Institut für Physik, Universität Mainz, Mainz, Germany
- ⁸⁵ School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
- ⁸⁶ CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
- ⁸⁷ Department of Physics, University of Massachusetts, Amherst MA, United States
- ⁸⁸ Department of Physics, McGill University, Montreal QC, Canada
- ⁸⁹ School of Physics, University of Melbourne, Victoria, Australia
- ⁹⁰ Department of Physics, The University of Michigan, Ann Arbor MI, United States
- ⁹¹ Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States
- ⁹² ^(a) INFN Sezione di Milano; ^(b) Dipartimento di Fisica, Università di Milano, Milano, Italy
- ⁹³ B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
- ⁹⁴ National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
- ⁹⁵ Group of Particle Physics, University of Montreal, Montreal QC, Canada
- ⁹⁶ P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
- ⁹⁷ Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
- ⁹⁸ National Research Nuclear University MEPhI, Moscow, Russia
- ⁹⁹ D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
- ¹⁰⁰ Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
- ¹⁰¹ Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
- ¹⁰² Nagasaki Institute of Applied Science, Nagasaki, Japan
- ¹⁰³ Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
- ¹⁰⁴ ^(a) INFN Sezione di Napoli; ^(b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
- ¹⁰⁵ Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States
- ¹⁰⁶ Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
- ¹⁰⁷ Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands
- ¹⁰⁸ Department of Physics, Northern Illinois University, DeKalb IL, United States
- ¹⁰⁹ Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
- ¹¹⁰ Department of Physics, New York University, New York NY, United States
- ¹¹¹ Ohio State University, Columbus OH, United States
- ¹¹² Faculty of Science, Okayama University, Okayama, Japan
- ¹¹³ Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States
- ¹¹⁴ Department of Physics, Oklahoma State University, Stillwater OK, United States
- ¹¹⁵ Palacký University, RCPTM, Olomouc, Czech Republic
- ¹¹⁶ Center for High Energy Physics, University of Oregon, Eugene OR, United States
- ¹¹⁷ LAL, Univ. Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
- ¹¹⁸ Graduate School of Science, Osaka University, Osaka, Japan
- ¹¹⁹ Department of Physics, University of Oslo, Oslo, Norway
- ¹²⁰ Department of Physics, Oxford University, Oxford, United Kingdom
- ¹²¹ ^(a) INFN Sezione di Pavia; ^(b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
- ¹²² Department of Physics, University of Pennsylvania, Philadelphia PA, United States
- ¹²³ National Research Centre "Kurchatov Institute", B.P. Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
- ¹²⁴ ^(a) INFN Sezione di Pisa; ^(b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
- ¹²⁵ Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States
- ¹²⁶ ^(a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa; ^(b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; ^(c) Department of Physics, University of Coimbra, Coimbra; ^(d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; ^(e) Departamento de Física, Universidade do Minho, Braga; ^(f) Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); ^(g) Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- ¹²⁷ Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
- ¹²⁸ Czech Technical University in Prague, Praha, Czech Republic

- ¹²⁹ Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
- ¹³⁰ State Research Center Institute for High Energy Physics (Protvino), NRC KI, Russia
- ¹³¹ Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
- ¹³² ^(a) INFN Sezione di Roma; ^(b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- ¹³³ ^(a) INFN Sezione di Roma Tor Vergata; ^(b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
- ¹³⁴ ^(a) INFN Sezione di Roma Tre; ^(b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
- ¹³⁵ ^(a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; ^(b) Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; ^(c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; ^(d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; ^(e) Faculté des sciences, Université Mohammed V, Rabat, Morocco
- ¹³⁶ DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
- ¹³⁷ Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States
- ¹³⁸ Department of Physics, University of Washington, Seattle WA, United States
- ¹³⁹ Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom
- ¹⁴⁰ Department of Physics, Shinshu University, Nagano, Japan
- ¹⁴¹ Fachbereich Physik, Universität Siegen, Siegen, Germany
- ¹⁴² Department of Physics, Simon Fraser University, Burnaby BC, Canada
- ¹⁴³ SLAC National Accelerator Laboratory, Stanford CA, United States
- ¹⁴⁴ ^(a) Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; ^(b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
- ¹⁴⁵ ^(a) Department of Physics, University of Cape Town, Cape Town; ^(b) Department of Physics, University of Johannesburg, Johannesburg; ^(c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
- ¹⁴⁶ ^(a) Department of Physics, Stockholm University; ^(b) The Oskar Klein Centre, Stockholm, Sweden
- ¹⁴⁷ Physics Department, Royal Institute of Technology, Stockholm, Sweden
- ¹⁴⁸ Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States
- ¹⁴⁹ Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom
- ¹⁵⁰ School of Physics, University of Sydney, Sydney, Australia
- ¹⁵¹ Institute of Physics, Academia Sinica, Taipei, Taiwan
- ¹⁵² Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
- ¹⁵³ Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
- ¹⁵⁴ Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
- ¹⁵⁵ International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
- ¹⁵⁶ Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
- ¹⁵⁷ Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
- ¹⁵⁸ Department of Physics, University of Toronto, Toronto ON, Canada
- ¹⁵⁹ ^(a) TRIUMF, Vancouver BC; ^(b) Department of Physics and Astronomy, York University, Toronto ON, Canada
- ¹⁶⁰ Faculty of Pure and Applied Sciences, and Center for Integrated Research in Fundamental Science and Engineering, University of Tsukuba, Tsukuba, Japan
- ¹⁶¹ Department of Physics and Astronomy, Tufts University, Medford MA, United States
- ¹⁶² Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States
- ¹⁶³ ^(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; ^(b) ICTP, Trieste; ^(c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
- ¹⁶⁴ Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
- ¹⁶⁵ Department of Physics, University of Illinois, Urbana IL, United States
- ¹⁶⁶ Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
- ¹⁶⁷ Department of Physics, University of British Columbia, Vancouver BC, Canada
- ¹⁶⁸ Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
- ¹⁶⁹ Department of Physics, University of Warwick, Coventry, United Kingdom
- ¹⁷⁰ Waseda University, Tokyo, Japan
- ¹⁷¹ Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
- ¹⁷² Department of Physics, University of Wisconsin, Madison WI, United States
- ¹⁷³ Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
- ¹⁷⁴ Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
- ¹⁷⁵ Department of Physics, Yale University, New Haven CT, United States
- ¹⁷⁶ Yerevan Physics Institute, Yerevan, Armenia
- ¹⁷⁷ Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne, France

^a Also at Department of Physics, King's College London, London, United Kingdom.

^b Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

^c Also at Novosibirsk State University, Novosibirsk, Russia.

^d Also at TRIUMF, Vancouver, BC, Canada.

^e Also at Department of Physics & Astronomy, University of Louisville, Louisville, KY, United States.

^f Also at Department of Physics, California State University, Fresno, CA, United States.

^g Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.

^h Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.

ⁱ Also at Departamento de Física e Astronomia, Faculdade de Ciências, Universidade do Porto, Portugal.

^j Also at Tomsk State University, Tomsk, Russia.

^k Also at Università di Napoli Parthenope, Napoli, Italy.

^l Also at Institute of Particle Physics (IPP), Canada.

^m Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.

ⁿ Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States.

^o Also at Louisiana Tech University, Ruston, LA, United States.

^p Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.

^q Also at Graduate School of Science, Osaka University, Osaka, Japan.

^r Also at Department of Physics, National Tsing Hua University, Taiwan.

^s Also at Department of Physics, The University of Texas at Austin, Austin, TX, United States.

^t Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

^u Also at CERN, Geneva, Switzerland.

^v Also at Georgian Technical University (GTU), Tbilisi, Georgia.

^w Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.

^x Also at Manhattan College, New York, NY, United States.

^y Also at Hellenic Open University, Patras, Greece.

^z Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

^{aa} Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

^{ab} Also at School of Physics, Shandong University, Shandong, China.

^{ac} Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

^{ad} Also at Section de Physique, Université de Genève, Geneva, Switzerland.

^{ae} Also at International School for Advanced Studies (SISSA), Trieste, Italy.

^{af} Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States.

^{ag} Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.

^{ah} Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria.

^{ai} Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.

^{aj} Also at National Research Nuclear University MEPhI, Moscow, Russia.

^{ak} Also at Department of Physics, Stanford University, Stanford, CA, United States.

^{al} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

^{am} Also at Flensburg University of Applied Sciences, Flensburg, Germany.

^{an} Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.

^{ao} Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France.

^{ap} Also affiliated with PKU-CHEP.

* Deceased.