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Measurement of the branching fraction of $D^+ \to \tau^+\nu_\tau$

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Abstract: By analyzing e^+e^- collision data with an integrated luminosity of $7.9\,\mathrm{fb}^{-1}$ collected with the BESIII detector at the center-of-mass energy of $3.773\,\mathrm{GeV}$, the branching fraction of $D^+ \to \tau^+\nu_\tau$ is determined as $\mathcal{B} = (9.9 \pm 1.1_{\mathrm{stat}} \pm 0.5_{\mathrm{syst}}) \times 10^{-4}$. Using the most precise result $\mathcal{B}(D^+ \to \mu^+\nu_\mu) = (3.981 \pm 0.079_{\mathrm{stat}} \pm 0.040_{\mathrm{syst}}) \times 10^{-4}$ [1], we determine $R_{\tau/\mu} = \Gamma(D^+ \to \tau^+\nu_\tau)/\Gamma(D^+ \to \mu^+\nu_\mu) = 2.49 \pm 0.31$, achieving a factor of two improvement in precision compared to the previous BESIII result. This measurement is in agreement with the standard model prediction of lepton flavor universality within one standard deviation.

Keywords: Branching fraction, Charm Physics, e^+-e^- Experiments, Flavour Physics

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1 Introduction

Lepton Flavor Universality (LFU), a fundamental assumption of the Standard Model (SM), asserts that leptons from different generations possess identical coupling to gauge bosons [2]. The leptonic decays of the D^+ meson present an excellent opportunity for testing $\mu - \tau$ LFU. Figure 1 shows the Feynman diagram of the $D^+ \to \ell^+\nu_\ell$ ($\ell = e, \mu, \tau$) decays at tree level, in which the c quark and the $\bar{d}$ quark annihilate, followed by a weak current connecting to the system of the lepton ℓ^+ and the corresponding flavored neutrino ν_ℓ. Throughout this paper, charge conjugate channels are implied.

Due to the isolation of the hadronic and leptonic systems, the partial decay width of $D^+ \to \ell^+\nu_\ell$ to the lowest order within the SM is proportional to the product of the decay constant f_{D^+} and the Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{cd}|$, given in a simple form [2–4]:

$$\Gamma(D^+ \to \ell^+\nu_\ell) = \frac{G_F^2 f_{D^+}^2}{8\pi}|V_{cd}|^2 M_{\ell^+}^2 M_{D^+}\left(1 - \frac{M_{\ell^+}^2}{M_{D^+}^2}\right)^2, \tag{1.1}$$

where M_ℓ and M_{D^+} are the masses of the lepton ℓ and the D^+ meson, respectively. The partial decay width is the branching fraction divided by the D^+ lifetime. G_F is the Fermi coupling constant, which is known to high precision. From eq. (1.1) and assuming LFU, the ratio of the branching fractions of $D^+ \to \tau^+\nu_\tau$ and $D^+ \to \mu^+\nu_\mu$ can be predicted with negligible uncertainty as

$$R_{\tau/\mu} = \frac{\Gamma(D^+ \to \tau^+\nu_\tau)}{\Gamma(D^+ \to \mu^+\nu_\mu)} = \frac{M_\tau^2\left(1 - \frac{M_\tau^2}{M_{D^+}^2}\right)^2}{M_\mu^2\left(1 - \frac{M_\mu^2}{M_{D^+}^2}\right)^2} = 2.67. \tag{1.2}$$

It is important to note that this expression is independent of G_F, $|V_{cd}|$ and f_{D^+}, while the uncertainties associated with the higher-order corrections and M_{ℓ/D^+} are negligible.

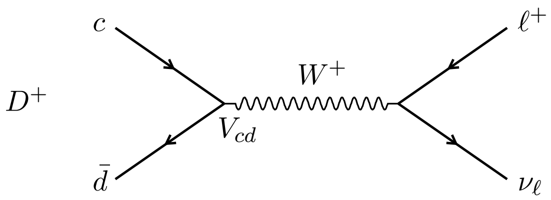


Figure 1. Tree level Feynman diagram of the leptonic decay of the D^+ meson. The CKM matrix element, V_{cd}, appears at the decay vertex.

Some new physics models, such as the two-Higgs-doublet model [5, 6], mediated via charged Higgs bosons, or the seesaw mechanism, which involves lepton mixing with Majorana neutrinos [7], may lead to LFU violation. LFU has been comprehensively tested in the B sector by the BaBar, LHCb, and Belle Collaborations [8–13]. However, tests of τ-μ LFU in the charm sector are still limited by the $\mathcal{B}(D^+ \to \tau^+\nu_\tau)$ measurement accuracy. Previously, BESIII reported the most precise measurement of the $D^+ \to \mu^+\nu_\mu$ branching fraction [1] and the observation of $D^+ \to \tau^+\nu_\tau$ [14] via $\tau^+ \to \pi^+\bar{\nu}_\tau$ based on $2.9\,\mathrm{fb}^{-1}$ [15] of e^+e^- collision data taken at $\sqrt{s} = 3.773\,\mathrm{GeV}$, resulting in a ratio $R_{\tau/\mu} = 3.21 \pm 0.64 \pm 0.43$. Improved measurements are essential to obtain better knowledge of this ratio and to enable more sensitive LFU tests. For D_s^+ leptonic decays, the ratio of $D_s^+ \to \tau^+\nu_\tau$ and $D_s^+ \to \mu^+\nu_\mu$ has been reported as $R_{\tau/\mu} = 9.72 \pm 0.37$ [16], which is in agreement with the SM prediction 9.75. Our analysis is complementary with the D_s^+ results in testing the effects of new physics, due to the symmetry of SU(3). Furthermore, the global fit that includes both D^+ and D_s^+ decays may impose more stringent constraints on new physics.

In this paper, we report an improved measurement of $\mathcal{B}(D^+ \to \tau^+\nu_\tau)$ and $R_{\tau/\mu}$, with an integrated luminosity of $7.9\,\mathrm{fb}^{-1}$ [17] data collected at $\sqrt{s} = 3.773\,\mathrm{GeV}$ with the BESIII detector in 2010, 2021 and 2022. The precision is improved by a factor of two compared with the previous BESIII result [14]. Furthermore, based on the measured partial decay width of $D^+ \to \ell^+\nu_\ell$,[1] we determine f_{D^+} by taking the $|V_{cd}|$ from the SM global fit [3], and also extract $|V_{cd}|$ taking as input f_{D^+} from lattice quantum chromodynamics (LQCD) calculations [18].

2 BESIII detector and Monte Carlo simulation

The BESIII detector [19] records symmetric e^+e^- collisions provided by the BEPCII storage ring [20] in the center-of-mass energy range from 1.85 to 4.95 GeV, with a peak luminosity of $1.1 \times 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ achieved at $\sqrt{s} = 3.773$ GeV. BESIII has collected large data samples in this energy region [21–23]. The cylindrical core of the BESIII detector covers 93% of the full solid angle and consists of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The solenoid is supported by an octagonal flux-return yoke with resistive plate counter muon identification modules interleaved with steel. The charged-particle momentum resolution

[1] The partial decay width is calculated as the measured branching fraction divided by the D^+ lifetime obtained through a global fit [3].

at 1 GeV/c is 0.5%, and the dE/dx resolution is 6% for electrons from Bhabha scattering. The EMC measures photon energies with a resolution of 2.5% (5%) at 1 GeV in the barrel (end-cap) region. The time resolution in the TOF barrel region is 68 ps, while that in the end-cap region was 110 ps. The end-cap TOF system was upgraded in 2015 using multigap resistive plate chamber technology, providing a time resolution of 60 ps, which benefits 63% of the data used in this analysis [24–26].

Monte Carlo (MC) simulated data samples produced with a GEANT4-based [27] software package, which includes the geometric description of the BESIII detector and the detector response, are used to determine detection efficiencies and to estimate backgrounds. The simulation models the beam-energy spread and initial-state radiation (ISR) in the e^+e^- annihilations with the generator KKMC [28, 29]. The inclusive MC sample includes the production of $D\bar{D}$ pairs (including quantum coherence for the neutral D channels), the non-$D\bar{D}$ decays of the $\psi(3770)$, the ISR production of the J/ψ and $\psi(3686)$ states, and the continuum processes incorporated in KKMC [28, 29]. All particle decays are modelled with EVTGEN [30, 31] using branching fractions either taken from the Particle Data Group [3], when available, or otherwise estimated with LUNDCHARM [32, 33]. Final-state radiation from charged final-state particles is incorporated using the PHOTOS package [34]. The leptonic decay $D^+ \to \tau^+\nu_\tau$ is simulated with the SLN model [30, 31].

3 Event selection and data analysis

The analysis uses the double-tag (DT) technique [35, 36]. All the selection criteria follow those adopted in the previous BESIII study [14]. On the single-tag (ST) side, the D^- mesons are reconstructed via the six hadronic decay modes $K^+\pi^-\pi^-$, $K^+\pi^-\pi^-\pi^0$, $K^0_S\pi^-$, $K^0_S\pi^-\pi^0$, and $K^0_S\pi^-\pi^-\pi^+$. On the signal side, the $\tau^+ \to \pi^+\bar{\nu}_\tau$ process is used to reconstruct $D^+ \to \tau^+\nu_\tau$ and thereby measure $R_{\tau/\mu}$.

On the ST side, to distinguish the D^- mesons from the combinatorial backgrounds, two variables, the beam-constrained mass $M_{\rm BC} \equiv \sqrt{E^2_{\rm beam} - |\vec{p}_{D^-}|^2}$ and energy difference $\Delta E \equiv E_{D^-} - E_{\rm beam}$ are defined, where $\vec{p}_{D^-}$ and E_{D^-} are the total reconstructed momentum and energy of the D^- candidate in the e^+e^- center-of-mass frame, and $E_{\rm beam}$ is the calibrated beam energy. For each ST decay mode, if more than one candidate satisfies the above requirements, the one with the smallest value of $|\Delta E|$ is kept for further analyses. The ST yields for data are obtained by a fit to the $M_{\rm BC}$ distributions with MC based signal shapes convolved with double Gaussian functions. The background shape is parametrized by an ARGUS function with free parameters, except for the endpoint, which is fixed at 1.8865 GeV corresponding to $E_{\rm beam}$. The fits are shown in figure 2. The ST efficiencies are determined by analyzing inclusive MC samples. Those candidates with $M_{\rm BC}$ lying within (1.863, 1.877) GeV/c^2 are retained for the subsequent analysis. The $|\Delta E|$ requirements, ST yields and the ST efficiencies are shown in table 1.

After the ST event is identified, the remaining tracks which have not been used in the ST-side reconstruction are used to select candidates for the signal process $D^+ \to \tau^+\nu_\tau$,$\tau^+ \to \pi^+\bar{\nu}_\tau$. Since the neutrinos are not detected, only one charged pion needs to be selected in a candidate event. Hence, we require that there must be only one additional track with opposite charge to the ST side. The selection criteria of the pions are identical to those of the ST side

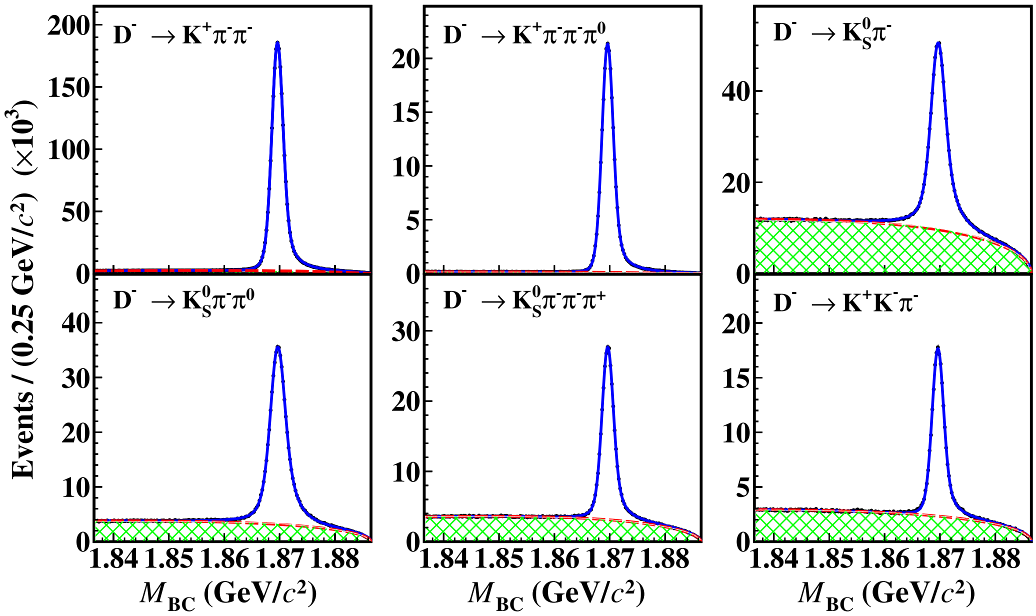


Figure 2. Fits to the $M_{\rm BC}$ distributions of the ST D^- candidates. The dots with error bars are data. The blue solid curves are the fit results. The red dashed curves are the fitted combinatorial backgrounds. The green hatched histograms are background events from the inclusive MC sample.

Tag mode	ΔE (MeV)	$N^{\rm ST}_{\rm tag}$	$\epsilon^{\rm ST}_{\rm tag}$(%)
$K^+\pi^-\pi^-$	(-25,24)	2164074±1571	51.17±0.01
$K^+\pi^-\pi^-\pi^0$	(-57,46)	689042±1172	25.50±0.01
$K^0_S\pi^-$	(-25,26)	250437±524	50.63±0.02
$K^0_S\pi^-\pi^0$	(-62,49)	558495±930	26.28±0.01
$K^0_S\pi^-\pi^-\pi^+$	(-28,27)	300519±669	28.97±0.01
$K^+K^-\pi^-$	(-24,23)	187379±541	41.06±0.02

Table 1. The ΔE requirements, ST yield ($N^{\rm ST}_{\rm tag}$) and ST efficiencies ($\epsilon^{\rm ST}_{\rm tag}$).

and have to match a shower in the EMC additionally. Since pions and muons are both charged particles with similar masses, the pion selection also accepts muon tracks with comparable efficiency (>90%). However, the deposited energy in the EMC ($E_{\rm EMC}$) of most muons is less than 300 MeV, which is used to separate muon from pion. To increase the signal significance, we partition the data into a π-like sample with $E_{\rm EMC} > 300$ MeV and a μ-like sample with $E_{\rm EMC} \leq 300$ MeV.

Four additional requirements are applied to further suppress background processes. These requirements are set from studies of MC data and the systematic uncertainties are assessed from studies of control samples in the data. (1) Processes with misidentified electrons backgrounds can contaminate our signal sample, for example the semileptonic decay $D^+ \to K^0_L e^+ \nu_e$ when the K^0_L is missed. The quantity $E_{\rm EMC}/p$ is distributed around unity for background processes in this category, where p is the momentum of the track reconstructed in the MDC. Therefore, we require $E_{\rm EMC}/p < 0.95$ for events in the π-like sample. (2) In order to suppress backgrounds with additional neutral particles, such as $D^+ \to \eta\pi^+$, we demand $E_{\gamma,\rm max} < 300\,\rm MeV$ for both samples, where $E_{\gamma,\rm max}$ is the maximum energy of all EMC showers not used in the reconstruction of either the ST or DT side. (3) We require $|\cos\theta_{\rm miss}| < 0.75(0.97)$ for the π-like (μ-like) sample to ensure that the missing track points to the active region of the detector, where $\cos\theta_{\rm miss}$ is the polar angle of the missing momentum. (4) In order to suppress background from $D^+ \to K_L^0\pi^+$ decays we impose $\alpha > 45°(25°)$ for the π-like (μ-like) sample, where α is the opening angle between the missing track and the most energetic unassigned shower.

4 Determination of the branching fraction

The quantity missing-mass squared ($M^2_{\rm miss}$) is defined to provide sensitivity to the missing neutrino:

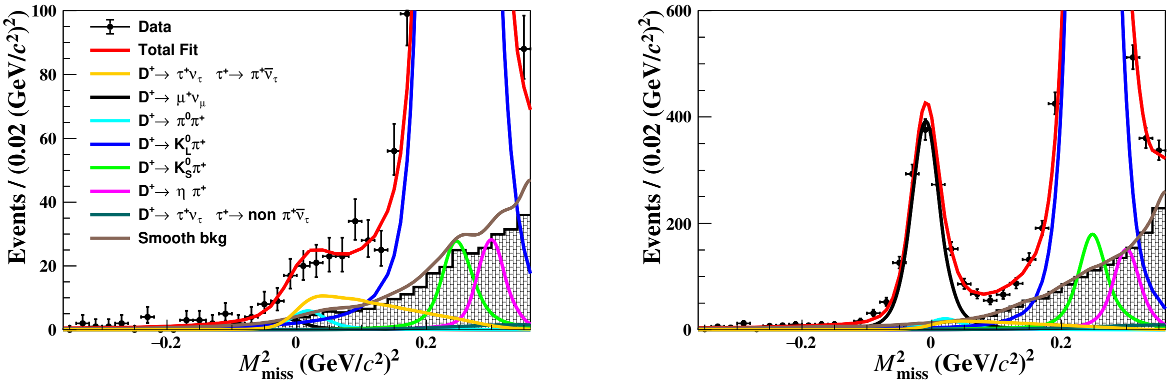
$$M^2_{\rm miss} = (E_{\rm cm} - E_{D^-} - E_\pi)^2 - (\vec{p}_{\rm cm} - \vec{p}_{D^-} - \vec{p}_\pi)^2, \tag{4.1}$$

where $E_{\rm cm}$ ($\vec{p}_{\rm cm}$) is the center-of-mass energy (momentum), E_π ($\vec{p}_\pi$) is the energy (momentum) of the pion, and E_{D^-} ($\vec{p}_{D^-}$) is the energy (momentum) of the D^- tag. An unbinned simultaneous maximum likelihood fit is performed on the $M^2_{\rm miss}$ distributions for both the π-like and μ-like samples, shown in figure 3, to obtain the yields. The branching fraction of signal process is a common parameter in the fit and is obtained through

$$\mathcal{B}(D^+ \to \tau^+\nu_\tau) = \frac{N_{\tau\nu}}{\sum_i N_i^{\rm ST}\epsilon^{\rm DT}_{i,\tau\nu}/\epsilon_i^{\rm ST}}, \tag{4.2}$$

where $N_{\tau\nu}$ is the DT yields for all tag modes, $\epsilon^{\rm DT}_{i,\tau\nu}$ is the signal selection efficiencies without $B(\tau^+ \to \pi^+\bar{\nu}_\tau)$ shown in table 2, $N_i^{\rm ST}$ and $\epsilon_i^{\rm ST}$ are the numbers of the ST events and ST efficiencies for the ST mode i. In extracting the DT yields for each tag mode the $D^+ \to \tau^+\nu_\tau$ ($\tau^+ \to \pi^+\bar{\nu}_\tau$) signal shape is taken from the MC sample. The peaking-background shapes of $D^+ \to \pi^0\pi^+$ and $D^+ \to K_L^0\pi^+$ are extracted from data-based control samples. All the other shapes are determined using inclusive MC simulation and constructed using kernel estimation PDF [37] in RooFit [38]. Additionally, the yields of the signal process $D^+ \to \tau^+\nu_\tau$ ($\tau^+ \to \pi^+\bar{\nu}_\tau$) and the significant peaking background $D^+ \to K_L^0\pi^+$ are floated in the fit. The other smaller peaking backgrounds, $D^+ \to \pi^0\pi^+$, $D^+ \to \eta\pi^+$, and $D^+ \to K_S^0\pi^+$ are fixed based on their known branching fractions quoted from the PDG [3] and $D^+ \to \mu^+\nu_\mu$ quoted from BESIII measurement [1]. The efficiencies obtained by the MC samples. The normalization of the remaining relatively smooth backgrounds is floated, but the relative ratio between π-like and μ-like samples is constrained, based on study of the inclusive MC sample. The $D^+ \to K_S^0\pi^+$ control sample is used to estimate the difference of data and MC to correct the ratio.

The signal yield is 283 ± 32 with a statistical significance of 6.5σ. The branching fraction of $D^+ \to \tau^+\nu_\tau$ is determined to be $\mathcal{B}(D^+ \to \tau^+\nu_\tau) = (9.9 \pm 1.1) \times 10^{-4}$, where the uncertainty is statistical only. As a cross check, we repeat the fit with the yields of $D^+ \to \mu^+\nu_\mu$ floated, and obtain $\mathcal{B}(D^+ \to \tau^+\nu_\tau) = (1.01 \pm 0.13) \times 10^{-3}$ and $\mathcal{B}(D^+ \to \mu^+\nu_\mu) = (3.89 \pm 0.12) \times 10^{-4}$. The latter is consistent with the PDG value of $(3.74 \pm 0.17) \times 10^{-4}$ [3].



(a) (b)

Figure 3. Fits to the distributions of M^2_{miss} for π-like (a) and μ-like (b) cases. All of the rest of the colored lines correspond to fits to background components.

Tag mode	ϵ_π (%)	ϵ_μ (%)
$D^- \to K^+\pi^-\pi^-$	39.54±0.23	25.00±0.19
$D^- \to K^0_S\pi^-$	40.48±0.24	25.60±0.19
$D^- \to K^+\pi^-\pi^-\pi^0$	38.94±0.33	25.45±0.25
$D^- \to K^0_S\pi^-\pi^0$	40.19±0.32	25.07±0.26
$D^- \to K^0_S\pi^-\pi^-\pi^+$	37.52±0.31	24.19±0.25
$D^- \to K^+K^-\pi^-$	37.74±0.26	23.14±0.20

Table 2. The signal efficiencies ($\epsilon_{\pi(\mu)} = \epsilon^{\mathrm{DT}}_{\pi(\mu)}/\epsilon^{\mathrm{ST}}_{\mathrm{tag}}$) for the $\pi(\mu)$-like selection. The branching fractions of the sub-particle ($\tau^+ \to \pi^+\nu_\tau$) decays are not included. The uncertainties are statistical only.

5 Systematic uncertainties

Benefiting from the DT technique, we assume that all systematic uncertainties due to the reconstruction of particles on the ST side largely cancel. The systematic uncertainties are dominated by the selection criteria on the DT side, the simultaneous fit, and the knowledge of $\mathcal{B}(D^+ \to \mu^+\nu_\mu)$. These are summarized in table 3.

The systematic uncertainties associated with the E_{EMC}, E_{EMC}/p and $E_{\gamma,\mathrm{max}}$ requirements are studied using a $D^+ \to K^0_S\pi^+$ control sample. Those associated with the $|\cos\theta_{\mathrm{miss}}|$ and missing cone α requirements are estimated by a control sample of $D^0 \to K^-e^+\nu_e$ decays. The difference in efficiency of each requirement between data and MC simulation is assigned to be the corresponding systematic uncertainty. To assess the uncertainty associated with the simultaneous fit, we change the MC components for example exclude the non-$D\bar{D}$ process to estimate the effect on the smooth background shapes. We also vary the E_{EMC} requirement by ±50 MeV to account for the difference in resolution between data and MC. We vary the normalizations of the small peaking backgrounds $D^+ \to K^0_S\pi^+$, $D^+ \to \pi^0\pi^+$ and $D^+ \to \eta\pi^+$ by $\pm1\sigma$ of their known branching fraction. The ratio of the smooth background contribution between π-like and μ-like samples in the M^2_{miss}fit has been corrected by $D^+ \to K^0_S\pi^+$ control

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Source	Sys. Uncertainty(%)
$E_{\rm EMC}$ requirement	1.1
Smooth background shape	1.8
π^+ tracking	1.0
π^+ PID	1.0
$N_{\rm ST}$	0.1
Requirement on $E_{\rm EMC}/p$	1.1
Requirement on $E_{\gamma,\rm max}$	1.2
Requirements on $\lvert\cos\theta_{\rm miss}\rvert$ and α	2.9
Tag bias	0.1
Normalizations of small peaking BKG	1.5
Relative size ratio of smooth BKG	1.5
Signal shape of $D^+ \to \tau^+\nu_\tau$	0.5
$\mathcal{B}(D^+ \to \mu^+\nu_\mu)$	2.1
$\mathcal{B}(\tau^+ \to \pi^+\bar{\nu}_\tau)$	0.5
Total	5.2

Table 3. Systematic uncertainties for the branching fraction measurement.

sample and the error is assumed as the systematic uncertainty. We vary the fixed branching fraction of $\mathcal{B}(D^+ \to \mu^+\nu_\mu)$ [1] by $\pm 1\sigma$ to estimate the corresponding systematic uncertainty.

6 Summary

Based on e^+e^- collision data corresponding to an integrated luminosity of 7.9 fb^{-1} collected with the BESIII detector at $\sqrt{s} = 3.773$ GeV, we measure $\mathcal{B}(D^+ \to \tau^+\nu_\tau) = (9.9 \pm 1.1_{\rm stat} \pm 0.5_{\rm syst}) \times 10^{-4}$, while fixing $\mathcal{B}(D^+ \to \mu^+\nu_\mu) = (3.981 \pm 0.079_{\rm stat} \pm 0.040_{\rm syst}) \times 10^{-4}$ [1]. This result is consistent with the previous BESIII measurement of $(1.20 \pm 0.24_{\rm stat} \pm 0.12_{\rm syst}) \times 10^{-3}$ [14] and is twice as precise. The ratio $R_{\tau/\mu}$ is determined to be 2.49 ± 0.31, which is consistent with the SM prediction of 2.67 within one standard deviation.

Combing the measured branching fraction with the world average value of G_F, m_ℓ, M_{D^+} and the D^+ lifetime (τ_{D^+}) shown in table 4, we obtain $f_{D^+}|V_{cd}| = (45.9 \pm 2.5_{\rm stat} \pm 1.2_{\rm syst} \pm 0.1_{\rm input})$ MeV. Here the third uncertainty arises from the knowledge of τ_{D^+} (0.2%). Taking the CKM matrix element $|V_{cd}| = 0.22486 \pm 0.00067$ from the global SM fit [3] we obtain $f_{D^+} = (204 \pm 11_{\rm stat} \pm 5_{\rm syst} \pm 1_{\rm input})$ MeV, which is in agreement with the value of $f_{D^+} = (212.1 \pm 0.7)$ MeV from recent LQCD calculations [18]. Alternatively, taking the LQCD value of the decay constant as input, we obtain $|V_{cd}| = (0.216 \pm 0.012_{\rm stat} \pm 0.006_{\rm syst} \pm 0.001_{\rm input})$, which is in agreement with the value from the global SM fit.

Parameter	Value
m_μ	0.10566(24) GeV
m_τ	1.77686(12) GeV
M_{D^+}	1.86966(5) GeV
G_F	$1.1663787(6) \times 10^{-5}\,\text{GeV}^{-2}$
τ_{D^+}	1.033(5) ps

Table 4. External input parameters with uncertainties.

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