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Measurement of the Absolute Branching Fraction of $D_s^+ \to \tau^+\nu_\tau$ Decay

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Abstract

Using a sample of tagged D_s^+ decays collected near the $D_s^{*\pm}D_s^{\mp}$ peak production energy with the CLEO-c detector, we study the leptonic decay $D_s^+ \to \tau^+\nu_\tau$ via the decay channel $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$. We measure $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (6.17 \pm 0.71 \pm 0.34)\%$. Combining with our measurements of $D_s^+ \to \mu^+\nu_\mu$ and $D_s^+ \to \tau^+\nu_\tau$ (via $\tau^+ \to \pi^+\bar{\nu}_\tau$), we determine $f_{D_s} = 274 \pm 10 \pm 5$ MeV.

Due to the absence of strong interactions in the final state, the leptonic decays of pseudoscalar mesons provide a theoretically clean way to probe the strong interactions that bind the quarks in the initial-state meson. All of the effects of the strong interaction can be parameterized as a single number called the decay constant f_P, which describes the probability for the quarks to have zero separation, necessary for them to annihilate into a virtual W^+ boson.

The decay constant can be calculated using various theoretical models [1–3] or using lattice QCD [4, 5] (LQCD). Thus experimental determination of decay constants is one of the most important tests of theoretical calculations involving non-perturbative QCD. The magnitude of a decay constant is also crucial to understand many interesting heavy-quark transitions, such as $B\bar{B}$ mixing.

In the Standard Model (SM), the decay rate of a pseudoscalar meson $P_{Q\bar{q}}$ to a lepton neutrino pair $\ell^+\nu_\ell$ is given by

$$\Gamma(P_{Q\bar{q}} \to \ell^+\nu_\ell) = \frac{G_F^2|V_{Qq}|^2 f_P^2}{8\pi} m_{Q\bar{q}} m_\ell^2 \left(1 - \frac{m_\ell^2}{m_{Q\bar{q}}^2}\right)^2, \tag{1}$$

where G_F is the Fermi coupling constant, V_{Qq} is the Cabibbo-Kobayashi-Maskawa (CKM) matrix element, $m_{Q\bar{q}}$ is the mass of the meson, and m_ℓ is the mass of the charged lepton.

Among the leptonic decays in the heavy-quark sector, $D_s^+ \to \ell^+\nu_\ell$ decays are the most accessible as they are Cabibbo favored ($|V_{cs}| \sim 1$). Furthermore, the inherent helicity suppression is broken in the case of $D_s^+ \to \tau^+\nu_\tau$. The existence of multiple neutrinos in the final state, however, makes experimental measurement of this decay challenging. While the B^+ meson decay constant is most relevant to important heavy-quark observables, the B^+ leptonic branching fraction is highly Cabibbo suppressed, because V_{ub} is small. This makes direct measurement of the decay constant f_B in B^+ meson decays [6, 7] less feasible, and precision measurements of decay constants f_D and f_{D_s} from charm meson decays are an attractive way to validate the QCD calculations that are used to predict f_B. Physics beyond the SM may also affect leptonic decays. In SM extensions, a charged Higgs ($H^\pm$) can mediate the leptonic decays and produce sizable modifications [8–10] to the SM-predicted decay rates of $B^+ \to \tau^+\nu_\tau$ as well as $D_s^+ \to \tau^+\nu_\tau$ ($\mu^+\nu_\mu$).

In this Letter, we report the most precise measurement of the absolute branching fraction of the leptonic decay $D_s^+ \to \tau^+\nu_\tau$ and a direct determination of the decay constant f_{D_s}. We use a data sample of $e^+e^- \to D_s^{*\pm}D_s^\mp$ events collected by the CLEO-c detector [11–14] at the center-of-mass (CM) energy 4170 MeV, near $D_s^{*\pm}D_s^\mp$ peak production [15]. The data sample consists of an integrated luminosity of 298 pb^{-1} provided by the Cornell Electron Storage Ring (CESR). We have previously reported [16] measurements of $D_s^+ \to \mu^+\nu_\mu$ and $D_s^+ \to \tau^+\nu_\tau$ (via $\tau^+ \to \pi^+\bar{\nu}_\tau$) with these data.

We use a double tagging technique. The D_s^- in the $e^+e^- \to D_s^{*\pm}D_s^\mp$ event is fully reconstructed to form a single-tag (ST) sample. (We also use charge-conjugate D_s^+ decays for the tag; in this Letter, mention of a particular charge also implies use of the opposite one.) The tagged D_s^- candidate can be either the primary D_s^- or the secondary D_s^- from the decay $D_s^{*-} \to \gamma D_s^-$ (or $D_s^{*-} \to \pi^0 D_s^-$), and the ST yield can be expressed as $n_{\text{ST}} = 2N\mathcal{B}_{\text{ST}}\epsilon_{\text{ST}}$, where N is the produced number of $D_s^{*\pm}D_s^\mp$ pairs, $\mathcal{B}_{\text{ST}}$ is the branching fraction of hadronic modes used in the ST sample, and ϵ_{ST} is the ST efficiency. For each ST event, we look at the system recoiling against the ST to search for signal resulting from the decay chain $D_s^+ \to \tau^+\nu_\tau$, $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$. Our double-tag (DT) sample is formed from events with only a single charged track, identified as a positron, in addition to a ST. The yield can be expressed as $n_{\rm DT} = 2N\mathcal{B}_{\rm ST}\mathcal{B}_{\rm SG}\epsilon_{\rm DT}$, where $\mathcal{B}_{\rm SG}$ is the signal decay (SG) branching fraction, $\epsilon_{\rm DT}$ is the efficiency of finding the ST and the SG in the same event. From the ST and DT yield expressions we obtain $\mathcal{B}_{\rm SG} = (n_{\rm DT}/n_{\rm ST}) \times (\epsilon_{\rm ST}/\epsilon_{\rm DT}) = (n_{\rm DT}/\epsilon)/n_{\rm ST}$, where ϵ ($\equiv \epsilon_{\rm DT}/\epsilon_{\rm ST}$) is the effective signal efficiency. Since $\epsilon_{\rm DT} \approx \epsilon_{\rm ST} \times \epsilon_{\rm SG}$ (where $\epsilon_{\rm SG}$ is the SG efficiency), $\mathcal{B}_{\rm SG}$ is nearly independent of the uncertainties in $\epsilon_{\rm ST}$.

From the interaction point (IP) out, the CLEO-c detector [11–14] consists of a six-layer vertex drift chamber, a 47-layer central drift chamber, a ring-imaging Cherenkov detector (RICH), and a CsI electromagnetic calorimeter, all operating in a 1.0 T magnetic field provided by a superconducting solenoidal magnet. The detector provides acceptance of 93% of the full 4π solid angle for both charged particles and photons. Charged particle identification is based on information from the RICH detector, the specific ionization (dE/dx) measured by the drift chamber, and the ratio of electromagnetic shower energy to track momentum (E/p). Background processes and the efficiency of signal-event selection are estimated with a GEANT-based [17] Monte Carlo (MC) simulation program. Physics events are generated by EvtGen [18], and final-state radiation (FSR) is modeled by the PHOTOS [19] program. The initial-state radiation (ISR) is modeled using cross sections for $D_s^{*\pm}D_s^{\mp}$ production at lower energies obtained from the CLEO-c energy scan [15] near the CM energy where we collect the sample.

To minimize systematic uncertainties, we tag using three two-body hadronic decay modes with only charged particles in the final state. The three ST modes are $D_s^- \to \phi\pi^-$, $D_s^- \to K^-K^{*0}$, and $D_s^- \to K_S^0 K^-$. The $K_S^0 \to \pi^+\pi^-$ decay is reconstructed by combining oppositely charged tracks that originate from a common vertex and that have an invariant mass within ± 12 MeV of the nominal mass [20]. We require the resonance decay to satisfy the following mass windows around the nominal mass [20]: $\phi \to K^+K^-$ (± 10 MeV) and $K^{*0} \to K^+\pi^-$ (± 75 MeV). Charged particles are reconstructed from well measured tracks that are consistent with coming from the IP. Charged kaons and pions are selected based on dE/dx and RICH information. We require the momenta of charged particles to be 100 MeV or greater to suppress the slow pion background from $D^*\bar{D}^*$ decays (through $D^* \to \pi D$). We identify a ST by using the invariant mass of the tag $M(D_s)$ and recoil mass against the tag $M_{\rm recoil}(D_s)$. The recoil mass is defined as $M_{\rm recoil}(D_s) \equiv [(E_{ee} - E_{D_s})^2 - |\mathbf{p}_{ee} - \mathbf{p}_{D_s}|^2]^{1/2}$, where $(E_{ee}, \mathbf{p}_{ee})$ is the net four-momentum of the e^+e^- beam, taking the finite beam crossing angle into account; $(E_{D_s}, \mathbf{p}_{D_s})$ is the four-momentum of the tag, with E_{D_s} computed from $\mathbf{p}_{D_s}$ and the nominal mass [20] of the D_s meson. We require the recoil mass to be within 55 MeV of the D_s^* mass [20]. This loose window allows both primary and secondary D_s tags to be selected.

The invariant mass distributions of tag candidates for each tag mode are shown in Fig. 1. To estimate the backgrounds in our positron yields from combinatorial backgrounds under the ST mass peaks, we use the ST invariant mass sidebands. We define the signal region as -20 MeV $\leq \Delta M(D_s) < +20$ MeV, and the sideband regions as -55 MeV $\leq \Delta M(D_s) < -35$ MeV or $+35$ MeV $\leq \Delta M(D_s) < +55$ MeV, where $\Delta M(D_s) \equiv M(D_s) - m_{D_s}$ is the difference between the tag mass and the nominal mass. We fit the $\Delta M(D_s)$ distributions to the sum of double-Gaussian signal plus second-degree polynomial background functions to get the sideband scaling factor.

For a given ST event, signal positron (or electron) candidates with momenta of at least 200 MeV are identified with a likelihood variable that combines E/p, dE/dx, and RICH information. The DT event should have a ST, a single positron with no other charged particles, and the net charge ($Q_{\rm net}$) of the event is required to be zero. Once a DT is found,

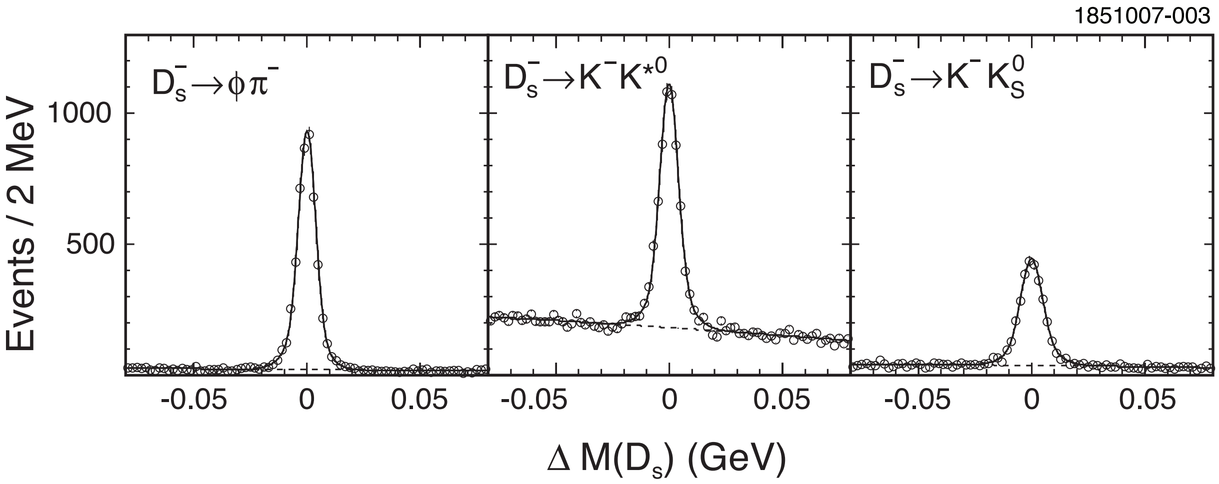

FIG. 1: The mass difference $\Delta M(D_s) \equiv M(D_s) - m_{D_s}$ distributions in each tag mode. We fit the $\Delta M(D_s)$ distribution (open circle) to the sum (solid curve) of signal (double Gaussian) plus background (second degree polynomial, dashed curve) functions.

the most effective discrimination variable that can separate signal from background events is the extra energy (E_{extra}) in the event, *i.e.* the total energy of the rest of the event. This is computed using the neutral shower energy in the calorimeter, counting all neutral clusters consistent with being photons above 30 MeV; these showers must not be associated with any of the ST decay tracks or the signal positron. We obtain E_{extra} in the signal and sideband regions of $\Delta M(D_s)$ and the scaled sideband subtracted E_{extra} distribution is used to get the DT yield.

The E_{extra} distribution obtained from data is compared to the MC expectation in Fig. 2. We have used the invariant mass sidebands, defined above, to subtract the combinatorial background. We expect that there will be a large peak between 100 MeV and 200 MeV from $D_s^* \to \gamma D_s$ decays (and from $D_s^* \to \pi^0 D_s$, 5.8% branching fraction [20]). Also, there will be some events at lower energy when the photon from D_s^* decay escapes detection.

After the $\Delta M(D_s)$ sideband subtraction, two significant components of background remain. One is from $D_s^+ \to K_L^0 e^+ \nu_e$. If the K_L^0 deposits little or no energy in the calorimeter, this decay mode has an E_{extra} distribution very similar to the signal, peaking well below 400 MeV. The second source, other semielectronic decays, rises smoothly with increasing E_{extra}, up to 1 GeV. Estimates of these backgrounds are also shown in Fig. 2. The optimal signal region in E_{extra} for DT yield extraction is predicted from an MC simulation study. Choosing E_{extra} less than 400 MeV [1] maximizes the signal significance. The number of non-peaking background events in the E_{extra} signal region is estimated from the number of events in the sideband region above 600 MeV scaled by the MC-determined ratio c_b of the number of background events in the signal region, $b^{(\mathrm{l})}$, to the number of events in the sideband region, $b^{(\mathrm{h})}$. The number of peaking background events due to the $D_s^+ \to K_L^0 e^+ \nu_e$ decay is determined by using the expected number from MC simulation. The overall expected number of background events in the E_{extra} signal region (b) is computed as follows: $b = c_b b^{(\mathrm{h})}(\mathrm{data}) + b(K_L^0 e^+ \nu_e)_{\mathrm{MC}}$, where $b^{(\mathrm{h})}(\mathrm{data})$ is the number of data events in the E_{extra}

[1] Note that with our chosen cut of $E_{\mathrm{extra}} < 400$ MeV, we are including $D_S^+ \to \tau^+ \nu_\tau \gamma$ as signal.

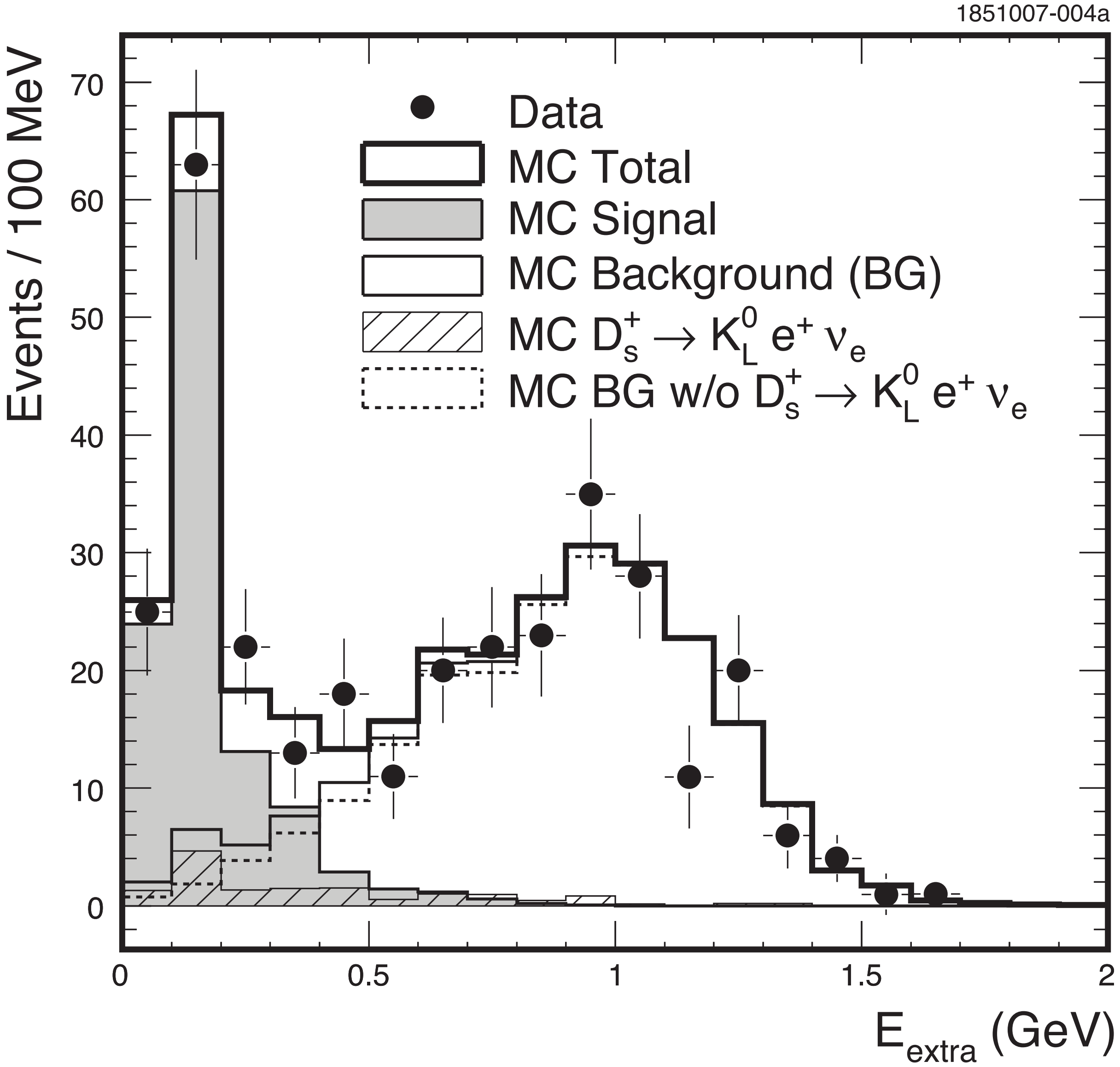

FIG. 2: The $\Delta M(D_s)$ sideband subtracted $E_{\rm extra}$ distribution. Filled circles are from data and histograms are obtained from MC simulation.

sideband region and $b(K_L^0 e^+\nu_e)_{\rm MC}$ is the number of background events due to $D_s^+ \to K_L^0 e^+\nu_e$ as estimated from our MC simulation. We ensure the correct value of the previously unmeasured Cabibbo-suppressed decay $D_s^+ \to K_L^0 e^+\nu_e$ by measuring $D_s^+ \to K_S^0 e^+\nu_e$. We find $\mathcal{B}(D_s^+ \to K^0 e^+\nu_e) = (0.28 \pm 0.11 \pm 0.03)\%$ (through $K_S^0 \to \pi^+\pi^-$ decay) using a sample of 38548 D_s^+ decays (more tag modes are used to increase statistics).

The ST yield, $\Delta M(D_s)$ sideband scaling factor, DT yield, and the number of estimated backgrounds events are summarized in Table I. We find $n_{\rm ST} = 12947 \pm 150$ and $n_{\rm DT} = 102 \pm 12$.

The signal efficiency determined by MC simulation has been corrected for a few small differences between data and MC simulation. We weight the mode-by-mode signal efficiencies by the ST yields in each mode to determine $\epsilon = (71.3 \pm 0.4)\%$ for the the decay chain

TABLE I: Summary of ST yield ($n_{\rm ST}$), ST mass sideband scaling factor (s), DT yield ($n_{\rm DT}$), and the number of estimated backgrounds (b), where $n(R)$ is the yield in the ST mass signal region, $n(B)$ is the yield in the ST mass sideband, and $n^{(0)}_{\rm DT}$ is the sideband subtracted DT yield before background correction.

Tag Mode	$n_{\rm ST}(R)$	$n_{\rm ST}(B)$	s	$n_{\rm ST}$	$n_{\rm DT}(R)$	$n_{\rm DT}(B)$	$n^{(0)}_{\rm DT}$	b	$n_{\rm DT}$
$D_s^- \to \phi\pi^-$	5243	391	0.997	4853.0 ± 75.1	49	0	49.0 ± 7.0	8.8 ± 0.6	40.2 ± 7.0
$D_s^- \to K^-K^{*0}$	9020	3661	1.010	5321.0 ± 112.8	55	3	52.0 ± 7.6	8.6 ± 0.7	43.4 ± 7.6
$D_s^- \to K^-K^0_S$	3499	710	1.022	2773.1 ± 65.0	24	2	22.0 ± 5.1	4.0 ± 0.4	18.0 ± 5.1

$D_s^+ \to \tau^+\nu_\tau \to e^+\nu_e\bar{\nu}_\tau\nu_\tau$. Using $\mathcal{B}(\tau^+ \to e^+\nu_e\bar{\nu}_\tau) = (17.84 \pm 0.05)\%$ [20] we obtain the leptonic decay branching fraction $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (6.17 \pm 0.71)\%$, where the error is statistical.

The non-positron background in the signal positron sample is negligible (0.2%) due to the low probability ($\sim$ 0.1% per track) that hadrons (π^+ or K^+) are misidentified as e^+. Uncertainty in these backgrounds produces a 0.2% uncertainty in the measurement of $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)$. The secondary positron backgrounds from charge symmetric processes, such as π^0 Dalitz decay ($\pi^0 \to e^+e^-\gamma$) and γ conversion ($\gamma \to e^+e^-$), are assessed by measuring the wrong-sign signal electron in events with $Q_{\rm net} = \pm 2$. The uncertainty in the measurement from this source is estimated to be 0.9%. Uncertainties in efficiency due to the extra energy cut (1.8%), extra track veto (0.9%), and $Q_{\rm net} = 0$ requirement (1.3%) are estimated using a sample in which both the D_s^+ and D_s^- in the event are tagged with any of the three hadronic ST modes.

We considered five semileptonic decays, $D_s^+ \to \phi e^+\nu_e$, $\eta e^+\nu_e$, $\eta' e^+\nu_e$, $K^0 e^+\nu_e$, and $K^{*0}e^+\nu_e$, as the major sources of background in the $E_{\rm extra}$ signal region. The first two dominate the non-peaking background, and the fourth (with K^0_L) dominates the peaking background. Uncertainty in the signal yield due to non-peaking background (0.5%) is assessed by varying the size of the dominant Cabibbo-favored semileptonic decays by the precision with which they are known [20]. Imperfect knowledge of $\mathcal{B}(D_s^+ \to K^0e^+\nu_e)$ gives rise to a systematic uncertainty in our estimate of the amount of peaking background in the signal region. This uncertainty comprises two parts. We estimate the K^0_L showering systematic uncertainty using $\psi(3770)$ events in which the $\bar{D}^0$ has been fully reconstructed in a hadronic mode and the D^0 decays as $D^0 \to K^0_L\pi^+\pi^-$. When this uncertainty is combined in quadrature with the uncertainty in the determination of $\mathcal{B}(D_s^+ \to K^0_S e^+\nu_e)$, the systematic uncertainty on $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)$ is 4.5%.

Other possible sources of systematic uncertainty include $n_{\rm ST}$ (0.8%), tracking efficiency (0.3%), positron identification efficiency (1%), and FSR (1%). Combining all contributions in quadrature, the total systematic uncertainty in the branching fraction measurement is estimated to be 5.5%.

In conclusion, using a sample of D_s^+ decays collected with the CLEO-c detector, we obtain a measurement of the absolute branching fraction, $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (6.17 \pm 0.71 \pm 0.34)\%$, where the first error is statistical and the second is systematic. This is the most precise measurement of this branching fraction and does not depend on measurements of other D_s branching fractions for normalization. The decay constant f_{D_s} can be computed using Eq. 1

with known values [20] of $G_F = 1.16637(1) \times 10^{-5}$ GeV^{-2}, $|V_{cs}| = 0.9738$ [2], $m_{D_s} = 1968.2(5)$ MeV, $m_\tau = 1776.99^{+0.29}_{-0.26}$ MeV, and the lifetime of $\tau_{D_s} = 500(7) \times 10^{-15}$ s (errors from these input parameters are negligible and ignored). We obtain $f_{D_s} = (273 \pm 16 \pm 8)$ MeV. Combining with our previous decay constant determination [16] of $f_{D_s} = (274 \pm 13 \pm 7)$ MeV, we obtain $f_{D_s} = (274 \pm 10 \pm 5)$ MeV. Our measured decay constant is consistent with the world average [20] and another recent measurement [21]. These results are generally higher than recent LQCD calculations [4, 5]. The predicted suppression [10] that would be caused by a charged Higgs seems to be incompatible with experimental measurements combined with LQCD calculations.

Combining with our previous measurement [16] of $D_s^+ \to \tau^+\nu_\tau$ ($\tau^+ \to \pi^+\bar{\nu}_\tau$), we obtain $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (6.47 \pm 0.61 \pm 0.26)\%$. Using this with our measurement [16] of $D_s^+ \to \mu^+\nu_\mu$, we obtain the branching fraction ratio $\frac{\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)}{\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)} = 11.0 \pm 1.4 \pm 0.6$. This is consistent with 9.72, the value predicted by the SM with lepton universality, as given in Eq. 1.

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