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

K. M. Ecklund,[1] W. Love,[2] V. Savinov,[2] A. Lopez,[3] H. Mendez,[3] J. Ramirez,[3] J. Y. Ge,[4] D. H. Miller,[4] I. P. J. Shipsey,[4] B. Xin,[4] G. S. Adams,[5] M. Anderson,[5] J. P. Cummings,[5] I. Danko,[5] D. Hu,[5] B. Moziak,[5] J. Napolitano,[5] Q. He,[6] J. Insler,[6] H. Muramatsu,[6] C. S. Park,[6] E. H. Thorndike,[6] F. Yang,[6] M. Artuso,[7] S. Blusk,[7] S. Khalil,[7] J. Li,[7] R. Mountain,[7] S. Nisar,[7] K. Randrianarivony,[7] N. Sultana,[7] T. Skwarnicki,[7] S. Stone,[7] J. C. Wang,[7] L. M. Zhang,[7] G. Bonvicini,[8] D. Cinabro,[8] M. Dubrovin,[8] A. Lincoln,[8] J. Rademacker,[9] D. M. Asner,[10] K. W. Edwards,[10] P. Naik,[10] J. Reed,[10] R. A. Briere,[11] T. Ferguson,[11] G. Tatishvili,[11] H. Vogel,[11] M. E. Watkins,[11] J. L. Rosner,[12] J. P. Alexander,[13] D. G. Cassel,[13] J. E. Duboscq,[13] R. Ehrlich,[13] L. Fields,[13] L. Gibbons,[13] R. Gray,[13] S. W. Gray,[13] D. L. Hartill,[13] B. K. Heltsley,[13] D. Hertz,[13] C. D. Jones,[13] J. Kandaswamy,[13] D. L. Kreinick,[13] V. E. Kuznetsov,[13] H. Mahlke-Krüger,[13] D. Mohapatra,[13] P. U. E. Onyisi,[13] J. R. Patterson,[13] D. Peterson,[13] D. Riley,[13] A. Ryd,[13] A. J. Sadoff,[13] X. Shi,[13] S. Stroiney,[13] W. M. Sun,[13] T. Wilksen,[13] S. B. Athar,[14] R. Patel,[14] J. Yelton,[14] P. Rubin,[15] B. I. Eisenstein,[16] I. Karliner,[16] S. Mehrabyan,[16] N. Lowrey,[16] M. Selen,[16] E. J. White,[16] J. Wiss,[16] R. E. Mitchell,[17] M. R. Shepherd,[17] D. Besson,[18] T. K. Pedlar,[19] D. Cronin-Hennessy,[20] K. Y. Gao,[20] J. Hietala,[20] Y. Kubota,[20] T. Klein,[20] B. W. Lang,[20] R. Poling,[20] A. W. Scott,[20] P. Zweber,[20] S. Dobbs,[21] Z. Metreveli,[21] K. K. Seth,[21] A. Tomaradze,[21] J. Libby,[22] A. Powell,[22] and G. Wilkinson[22]

(CLEO Collaboration)

[1]*State University of New York at Buffalo, Buffalo, New York 14260, USA*
[2]*University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*
[3]*University of Puerto Rico, Mayaguez, Puerto Rico 00681*
[4]*Purdue University, West Lafayette, Indiana 47907, USA*
[5]*Rensselaer Polytechnic Institute, Troy, New York 12180, USA*
[6]*University of Rochester, Rochester, New York 14627, USA*
[7]*Syracuse University, Syracuse, New York 13244, USA*
[8]*Wayne State University, Detroit, Michigan 48202, USA*
[9]*University of Bristol, Bristol BS8 1TL, United Kingdom*
[10]*Carleton University, Ottawa, Ontario K1S 5B6, Canada*
[11]*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*
[12]*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*
[13]*Cornell University, Ithaca, New York 14853, USA*
[14]*University of Florida, Gainesville, Florida 32611, USA*
[15]*George Mason University, Fairfax, Virginia 22030, USA*
[16]*University of Illinois, Urbana-Champaign, Illinois 61801, USA*
[17]*Indiana University, Bloomington, Indiana 47405, USA*
[18]*University of Kansas, Lawrence, Kansas 66045, USA*
[19]*Luther College, Decorah, Iowa 52101, USA*
[20]*University of Minnesota, Minneapolis, Minnesota 55455, USA*
[21]*Northwestern University, Evanston, Illinois 60208, USA*
[22]*University of Oxford, Oxford OX1 3RH, United Kingdom*

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Using a sample of tagged D_s^+ decays collected near the $D_s^{*\pm} D_s^{\mp}$ peak production energy in e^+e^- collisions 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 $\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau) = (6.17 \pm 0.71 \pm 0.34)\%$, where the first error is statistical and the second systematic. Combining this result 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.

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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

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

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. Because no strong interactions are present in the leptonic final state $\ell^+ \nu_\ell$, such decays provide a clean way to probe the complex, strong interactions that bind the quark and antiquark within the initial-state meson. In these decays, strong interaction effects can be parametrized by a single quantity, f_P, the pseudoscalar meson decay constant. In the case of the D_s^+ meson, f_{D_s} describes the amplitude for the c- and $\bar{s}$-quarks within the D_s^+ to have zero separation, a condition necessary for them to annihilate into the virtual W^+ boson that produces the $\ell^+\nu_\ell$ pair.

The experimental determination of decay constants is one of the most important tests of calculations involving nonperturbative QCD. Such calculations have been performed using various models [1–4] or using lattice QCD [5,6] (LQCD). Trustworthy QCD calculations within the B-meson sector would enable the extraction of $|V_{td}|$ from measurements of $B^0-\bar{B}^0$ mixing, and $|V_{ub}|$ from (the very difficult [7,8]) measurements of $B^+\to\tau^+\nu_\tau$. Precision measurements of the decay constants f_D and f_{D_s} from charm meson decays are an attractive way to validate the QCD calculations used in the B-meson sector.

Physics beyond the SM might also affect leptonic decays of charmed mesons. Depending on the non-SM features, the ratio of $\Gamma(D^+\to\ell^+\nu_\ell)/\Gamma(D_s^+\to\ell^+\nu_\ell)$ could be affected [9], as could the ratio $\Gamma(D_s^+\to\tau^+\nu_\tau)/\Gamma(D_s^+\to\mu^+\nu_\mu)$ [10,11]. Any of the individual widths might be increased or decreased. In particular, a two-Higgs doublet model [9] predicts a reduction in $\Gamma(D_s^+\to\ell^+\nu_\ell)$.

Among the leptonic decays in the charm-quark sector, $D_s^+\to\ell^+\nu_\ell$ decays are the most accessible as they are Cabibbo favored ($|V_{cs}|\sim 1$). Furthermore, the large mass of the τ lepton removes the helicity suppression that is present in the decays to lighter leptons. The existence of multiple neutrinos in the final state, however, makes experimental measurement of this decay challenging.

In this Letter, we report the most precise measurement of the absolute branching fraction of the leptonic decay $D_s^+\to\tau^+\nu_\tau$, from which we extract the decay constant f_{D_s} using Eq. (1). We use a data sample of $e^+e^-\to D_s^{*\pm}D_s^\mp$ events collected by the CLEO-c detector [12–15] at the center-of-mass (CM) energy 4170 MeV, near $D_s^{*\pm}D_s^\mp$ peak production [16]. The data sample consists of an integrated luminosity of 298 pb^{-1} provided by the Cornell Electron Storage Ring (CESR). We have previously reported [17] 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.

From the interaction point (IP) out, the CLEO-c detector [12–15] 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 kaons and pions are identified based on information from the RICH detector and the specific ionization (dE/dx) measured by the drift chamber. Electron identification is based on a likelihood variable that combines the information from RICH detector, dE/dx, 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 [18] Monte Carlo (MC) simulation program. Physics events are generated by EvtGen [19], and final-state radiation (FSR) is modeled by the PHOTOS [20] program. The modeling of initial-state radiation (ISR) is based on cross sections for $D_s^{*\pm}D_s^\mp$ production at lower energies obtained from the CLEO-c energy scan [16] near the CM energy where we collect the sample.

The presence of two $D_s^\mp$ mesons in a $D_s^{*\pm}D_s^\mp$ event allows us to define a single-tag (ST) sample in which a $D_s^\mp$ is reconstructed in a hadronic decay mode and a further double-tagged (DT) subsample in which an additional $e^\pm$ is required as a signature of leptonic decay, the $e^\pm$ being the daughter of the $\tau^\pm$. The D_s^- reconstructed in the ST sample can either be primary or secondary from $D_s^{*-}\to D_s^-\gamma$ (or $D_s^{*-}\to\pi^0D_s^-$). (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 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.

Our double-tag (DT) sample is formed from events with only a single charged track, identified as a positron, in addition to an ST. The yield can be expressed as $n_{\text{DT}}=2N\mathcal{B}_{\text{ST}}\mathcal{B}_{\text{SG}}\epsilon_{\text{DT}}$, where $\mathcal{B}_{\text{SG}}$ is the signal decay (SG) branching fraction, ϵ_{DT} is the efficiency of finding the ST and the SG in the same event. From the ST and DT yield expressions, we obtain $\mathcal{B}_{\text{SG}}=(n_{\text{DT}}/n_{\text{ST}})\times(\epsilon_{\text{ST}}/\epsilon_{\text{DT}})=(n_{\text{DT}}/\epsilon)/n_{\text{ST}}$, where ϵ ($\equiv\epsilon_{\text{DT}}/\epsilon_{\text{ST}}$) is the effective signal efficiency. Since $\epsilon_{\text{DT}}\approx\epsilon_{\text{ST}}\epsilon_{\text{SG}}$ (where ϵ_{SG} is the SG efficiency), $\mathcal{B}_{\text{SG}}$ is nearly independent of the uncertainties in ϵ_{ST}.

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 $D_s^-\to K_S^0K^-$. 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 [21]. We require the resonance decay to satisfy the following mass windows around the nominal mass [21]: $\phi\to K^+K^-$ ($\pm$ 10 MeV) and $K^{*0}\to K^+\pi^-$ ($\pm$ 75 MeV). 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 an ST by using the invariant mass of the tag $M(D_s)$ and recoil mass against the tag $M_{\text{recoil}}(D_s)$. The recoil mass is defined as $M_{\text{recoil}}(D_s)\equiv[(E_{ee}-E_{D_s})^2-|\mathbf{p}_{ee}-\mathbf{p}_{D_s}|^2]^{1/2}$, 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 [21] of the D_s meson. We

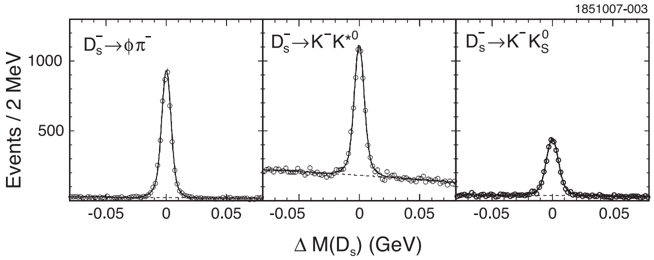

FIG. 1. The mass difference $\Delta M(D_s) \equiv M(D_s) - m_{D_s}$ distributions in each tag mode. We fit the $\Delta M(D_s)$ distribution (open circle) to the sum (solid curve) of signal (double Gaussian) plus background (second degree polynomial, dashed curve) functions.

require the recoil mass to be within 55 MeV of the D_s^* mass [21]. This loose window allows both primary and secondary D_s tags to be selected.

To estimate the backgrounds in our ST and DT yields from the wrong tag combinations, we use the tag invariant mass sidebands. We define the signal region as $-20\text{ MeV} \leq \Delta M(D_s) < +20\text{ MeV}$, and the sideband regions as $-55\text{ MeV} \leq \Delta M(D_s) < -35\text{ MeV}$ or $+35\text{ MeV} \leq \Delta M(D_s) < +55\text{ MeV}$, 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 ST $\Delta M(D_s)$ distributions to the sum of double-Gaussian signal plus second-degree polynomial background functions to get the sideband scaling factor, and use that scaling factor for DT events also. The invariant mass distributions of tag candidates for each tag mode are shown in Fig. 1.

The DT event should have an ST, a single positron ($p_e \geq 200$ MeV) with no other charged particles, and the net charge (Q_{net}) of the event is required to be zero. These DT events will contain the sought-after $D_s^+ \to \tau^+ \nu_\tau$ ($\tau^+ \to e^+ \nu_e \bar{\nu}_\tau$) events, but also some backgrounds. 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 quantity 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 $\Delta M(D_s)$. The sideband-subtracted E_{extra} distribution is used to obtain 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 and 200 MeV from $D_s^* \to \gamma D_s$ decays (and from $D_s^* \to \pi^0 D_s$, 5.8% branching fraction [21]). Also, there will be some events at lower energy when the photon from D_s^* decay escapes detection.

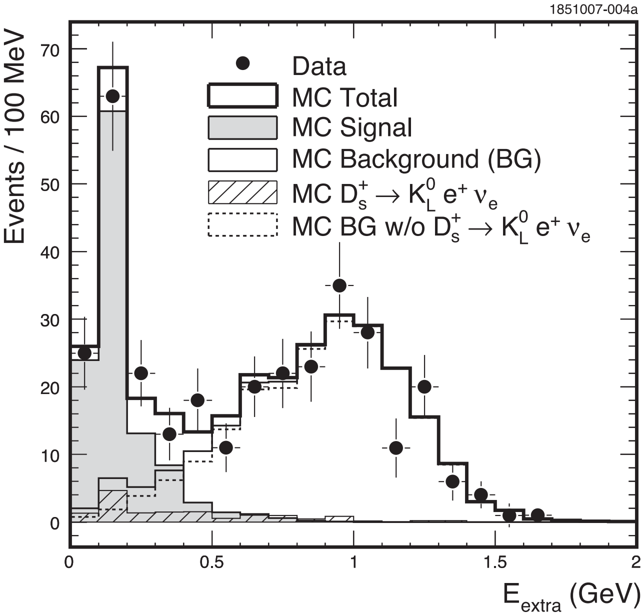

FIG. 2. Distribution of E_{extra} after $\Delta M(D_s)$ sideband subtraction. Filled circles are from data, and histograms are obtained from MC simulation. MC signal and the peaking background ($D_s^+ \to K_L^0 e^+ \nu_e$) components are normalized to our measured branching fractions.

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 [22] maximizes the signal significance. The number of nonpeaking 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, $b^{(l)}$, to the number of events in the sideband region, $b^{(h)}$. 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: $b = c_b b^{(h)}(\text{data}) + b(K_L^0 e^+ \nu_e)_{\text{MC}}$, where $b^{(h)}(\text{data})$ is the number of data events in the E_{extra} sideband region and $b(K_L^0 e^+ \nu_e)_{\text{MC}}$ is the number of background events due to $D_s^+ \to K_L^0 e^+ \nu_e$ as estimated from our MC simulation. The branching fraction for Cabibbo-suppressed decay $D_s^+ \to K_L^0 e^+ \nu_e$ has not yet been measured. We determine this quantity by measuring $\mathcal{B}(D_s^+ \to K_S^0 e^+ \nu_e) = (0.14 \pm 0.06 \pm 0.01)\%$ 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 with 400 MeV cut, and the number of estimated back-

TABLE I. Summary of ST yield ($n_{\rm ST}$), ST mass sideband scaling factor (s), DT yield ($n_{\rm DT}$) with 400 MeV cut, and the number of estimated backgrounds (b), where n^S is the yield in the ST mass signal region and n^B is the yield in the ST mass sideband.

Tag Mode	$n^S_{\rm ST}$	$n^B_{\rm ST}$	s	$n_{\rm ST}$	$n^S_{\rm DT}$	$n^B_{\rm DT}$	b	$n_{\rm DT}$
$D_s^- \to \phi\pi^-$	5243	391	0.997	4853.0 ± 75.1	49	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	8.6 ± 0.7	43.4 ± 7.6
$D_s^- \to K^- K_S^0$	3499	710	1.022	2773.1 ± 65.0	24	2	4.0 ± 0.4	18.0 ± 5.1

grounds events are summarized in Table I. We find $n_{\rm ST} = 12947 \pm 150$ and $n_{\rm DT} = 102 \pm 12$ integrated over all tag modes.

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 decay chain $D_s^+ \to \tau^+\nu_\tau \to e^+\nu_e\bar{\nu}_\tau\nu_\tau$. Using $\mathcal{B}(\tau^+ \to e^+\nu_e\bar{\nu}_\tau) = (17.84 \pm 0.05)\%$ [21], 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 nonpositron background in the signal positron sample is negligible (0.2%) due to the low probability (~ 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 nonpeaking background, and the fourth (with K_L^0) dominates the peaking background. Uncertainty in the signal yield due to nonpeaking background (0.5%) is assessed by varying the size of the dominant Cabibbo-favored semileptonic decays by the precision with which they are known [21]. Imperfect knowledge of $\mathcal{B}(D_s^+ \to K^0 e^+\nu_e)$ 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_L^0 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 $D^0 \to K_L^0\pi^+\pi^-$. When this uncertainty is combined in quadrature with the uncertainty in the determination of $\mathcal{B}(D_s^+ \to K_S^0 e^+\nu_e)$, 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 [21] of $G_F = 1.16637(1) \times 10^{-5}$ GeV^{-2}, $|V_{cs}| = 0.9738$ [23], $m_{D_s} = 1968.2(5)$ 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 [17] 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 $f_{D_s} = (294 \pm 27)$ MeV [21] and another recent measurement $f_{D_s} = (283 \pm 17 \pm 7 \pm 14)$ MeV [24]. These results are generally higher than recent LQCD calculations $f_{D_s} = (249 \pm 3 \pm 16)$ MeV [5] and $f_{D_s} = (241 \pm 3)$ MeV [6]. The predicted suppression [9] that would be caused by a charged Higgs seems to be incompatible with experimental measurements combined with LQCD calculations.

Combining with our previous measurement [17] 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 [17] 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 [10,11], as given in Eq. (1).

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