

First Measurement of the $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$ Decay

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We report the first measurement of the semileptonic decay $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$, using a sample of $e^+ e^-$ annihilation data corresponding to an integrated luminosity of 7.33 fb^{-1} collected at center-of-mass energies between 4.128 and 4.226 GeV with the BESIII detector at the BEPCII collider. The branching fraction of the decay is measured to be $\mathcal{B}(D_s^+ \rightarrow K^0 \mu^+ \nu_\mu) = (2.89 \pm 0.27_{\text{stat}} \pm 0.12_{\text{syst}}) \times 10^{-3}$, where the first uncertainty is statistical and the second is systematic. Based on a simultaneous fit to the partial decay rates in q^2 intervals measured in $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$ and $D_s^+ \rightarrow K^0 e^+ \nu_e$ decays, the product value of the form factor $f_+^{K^0}(0)$ and the Cabibbo-Kobayashi-Maskawa matrix element $|V_{cd}|$ is measured to be $f_+^{K^0}(0)|V_{cd}| = 0.140 \pm 0.008_{\text{stat}} \pm 0.003_{\text{syst}}$, which is the most precise determination to date. In addition, lepton flavor universality is tested for the first time with $D_s^+ \rightarrow K^0 \ell^+ \nu_\ell$ decays in full and separate q^2 intervals. No violation is found.

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In the standard model (SM), the semileptonic (SL) decays of D_s^+ mesons provide valuable information on the weak and strong interactions within hadrons composed of heavy quarks [1,2]. The partial decay rate is related to the product of hadronic form factor (FF) describing the strong interaction in the initial and final hadrons, and the Cabibbo-Kobayashi-Maskawa (CKM) matrix [3] element $|V_{cs(d)}|$ parametrizing the mixing between different flavors of quarks in the weak interaction. Therefore, the SL decay of D_s^+ mesons both allow determination of the CKM matrix element and provide rigorous tests on various nonperturbative theoretical calculations. In recent years, there has been a great deal of attention on the experimental studies of hadronic FFs in $D_s^+ \rightarrow P \ell^+ \nu_\ell$ decays [4], where P and ℓ refer to a pseudoscalar meson and a lepton, respectively. In particular, for $D_s^+ \rightarrow K^0$ transition, only $D_s^+ \rightarrow K^0 e^+ \nu_e$ has been experimentally reported [5,6]. It is also found that there are $\sim 2\sigma$ deviations between the $|V_{cd}|$ extracted in the $D_s^+ \rightarrow K^0 e^+ \nu_e$ decay and that in the $D \rightarrow \pi \ell \nu_\ell$ decays [7], as well as the one of the world average measurement [4]. Studying the dynamics in the $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$ decay will provide the necessary data to improve the precision of measuring $|V_{cd}|$ and help clarify the deviation.

Theoretical calculations on FFs in $D_s^+ \rightarrow K^0$ transition are extensively carried out by a series of nonperturbative

approaches [7–18], which are important in understanding the quantum-chromodynamics (QCD) theory in the charm sector. However, calculations referring to the value of FF at $q^2 = 0$, $f_+^{K^0}(0)$ differ significantly and vary in the range from 0.57–0.82 [7–18], which result in the predicted branching fraction (BF) varying from 0.20% to 0.39% [7–18]. In particular, for the $D_s^+ \rightarrow K^0$ transition, a recent Lattice QCD calculation shows $f_+^{K^0}(0) = 0.6307(20)$ [7], which provides the best precision among all known theoretical approaches. LQCD [19] also predicts that FFs have minimal dependence on the spectator-quark mass, with FF values in $D_s^+ \rightarrow K^0$ and $D^+ \rightarrow \pi^0$ transitions differing by less than 5%. The verification of the LQCD FF predictions at the few percent level in SL charm decays will be helpful for further applying the LQCD to SL B decays for precise determination of CKM matrix element $|V_{ub}|$ [19–21]. However, the precision of available FF measurement serving for these tests is still very limited.

The SL decays of $D_s^+ \rightarrow K^0 \ell^+ \nu_\ell$ also offer an excellent opportunity to test lepton flavor universality (LFU) predicted by the SM [22,23]. It is suggested that the observable LFU violation effects might appear in the SL decays mediated via $c \rightarrow d \ell^+ \nu_\ell$ [24]. In recent years, a great deal of theoretical models calculated the ratio of BFs between the μ and e modes, $R_{K^0}^{\mu/e} = [\mathcal{B}(D_s^+ \rightarrow K^0 \mu^+ \nu_\mu) / \mathcal{B}(D_s^+ \rightarrow K^0 e^+ \nu_e)]$, which is predicted to vary in the range 0.96–1.00 [8–17]. The experimental study of $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$ decay is still unavailable to date [4]. Hence it is important to measure the BF of $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$ and $R_{K^0}^{\mu/e}$ to distinguish among these theories and also test $\mu - e$ LFU.

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In this Letter, we report the first study of the $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$ decay, including a measurement of the absolute BF, the determination of the FF and the CKM element $|V_{cd}|$, as well as a LFU test via $D_s^+ \rightarrow K^0 \ell^+ \nu_\ell$ decays. Throughout this Letter, the charge-conjugate modes are implied unless explicitly noted. These measurements are performed using an e^+e^- annihilation data sample corresponding to an integrated luminosity of 7.33 fb^{-1} produced at center-of-mass energies between $\sqrt{s} = 4.128$ and 4.226 GeV with the BEPCII collider and collected by the BESIII detector [25,26].

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 inclusive MC sample includes the production of open charm processes, the initial state radiation (ISR) production of vector charmonium(like) states, and the continuum processes incorporated in KKMC [28]. All particle decays are modeled with EvtGen [29] using branching fractions either taken from the Particle Data Group [4], when available, or otherwise estimated with Lundcharm [30]. Final state radiation (FSR) from charged final state particles is incorporated using the Photos package [31]. The generation of signal $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$ incorporates knowledge of the FFs (using the z -series expansion model as mentioned below) obtained in this Letter.

The analysis presented in this analysis exploits the production of D_s mesons in $e^+e^- \rightarrow D_s^{*+} D_s^- + \text{c.c.}$ and uses both “single-tag” (ST) and “double-tag” (DT) samples of D_s decays [5,6]. The STs are D_s^- mesons reconstructed from their daughter particles in one of 14 hadronic decays as shown in Fig. 1, while the DTs are events with an ST and a D_s^+ meson reconstructed as $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$, with K^0 reconstructed via the $K^0 \rightarrow K_S^0 \rightarrow \pi^+ \pi^-$ decay. The BF for the SL decay is given by [32,33]

$$\mathcal{B}_{\text{SL}} = \frac{N_{\text{DT}}}{\sum_i N_{\text{ST}}^i (\epsilon_{\text{DT}}^i / \epsilon_{\text{ST}}^i)} = \frac{N_{\text{DT}}}{N_{\text{ST}} \epsilon_{\text{SL}}}, \quad (1)$$

where N_{DT} is the total yield of DT events, N_{ST} is the total ST yield, and $\epsilon_{\text{SL}} = (\sum_i N_{\text{ST}}^i \times \epsilon_{\text{DT}}^i / \epsilon_{\text{ST}}^i) / \sum_i N_{\text{ST}}^i$ is the average efficiency of reconstructing the SL decay in an ST event, weighted by the measured yields of tag modes in the data. Here, ϵ_{ST}^i and ϵ_{DT}^i are the efficiencies for finding the ST and the SL decay in the i th tag mode, respectively.

A detailed description of the selection criteria for $\pi^\pm$, $K^\pm$, and γ candidates is given in Refs. [32,33]. The π^0 , η , K_S^0 , ρ^- , η , and η' mesons are reconstructed using the same technique as described in Ref. [6]. For all events passing the ST selection criteria, we calculate the recoil mass against the tag with the following formula:

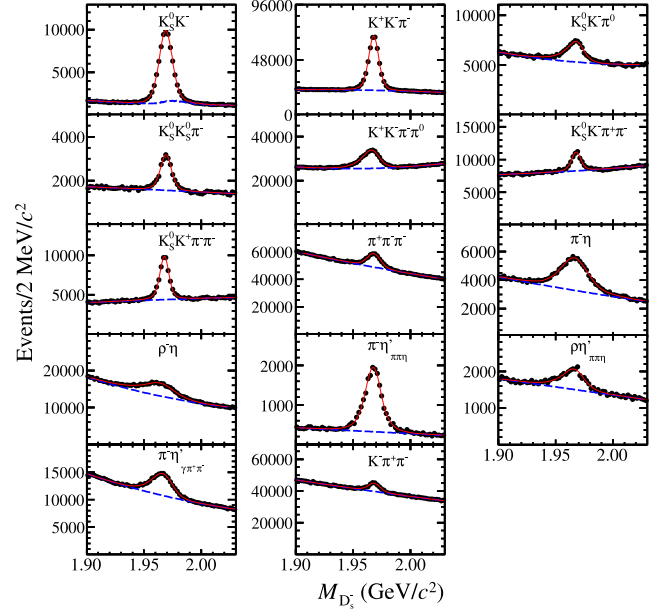


FIG. 1. Fits to $M_{D_s^-}$ distributions for the fourteen tag modes. Points with error bars are data, blue dashed curves are the fitted backgrounds and red solid curves are the total fits.

$$M_{\text{rec}} = \sqrt{(\sqrt{s} - \sqrt{|\vec{p}_{D_s^-}|^2 + m_{D_s}^2})^2 - |\vec{p}_{D_s^-}|^2},$$

where m_{D_s} and $\vec{p}_{D_s^-}$ are the known mass [4] and measured momentum of the tag D_s^- . In case of multiple candidates, only the candidate with M_{rec} closest to the known D_s^{*+} mass [4] is retained. To suppress other hadronic backgrounds from non- $D_s D_s^*$ processes, requirements on the kinematic variable $M_{\text{BC}} = \sqrt{(\sqrt{s}/2)^2 - |\vec{p}_{D_s^-}|^2}$ are applied. The detailed requirements on M_{BC} are described in Ref. [6], and they are chosen such that the tag D_s can come either directly from the production or from the $D_s^* \rightarrow D_s \gamma$ decay. To determine the mode-by-mode ST yields, we perform unbinned maximum likelihood fits to the distributions of the D_s^- invariant mass $M_{D_s^-}$, as shown in Fig. 1. Signals are modeled with the MC-derived signal shape convolved with a Gaussian function to account for the resolution differences between data and MC. For background description, due to misidentification of π^- as K^- , a sizable amount of the $D^- \rightarrow K_S^0 \pi^-$ background is responsible for the visible structure near the D_s^- known mass for the $K_S^0 K^-$ mode, and hence the background of this tag is described with the MC-derived shape. For other ST modes, the backgrounds are parameterized with second-order polynomial functions. For each tag mode, the ST yield is obtained by integrating the signal function over the D_s^- signal region specified by $1.94 < M_{D_s^-} < 1.99 \text{ GeV}/c^2$. The total ST yield summed over all 14 ST modes is $N_{\text{ST}} = (783.1 \pm 2.5) \times 10^3$, where the uncertainty is statistical only.

Candidates for the SL decay $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$ are selected from the remaining tracks recoiling against the ST D_s^- mesons. The $\bar{K}^0$ meson is reconstructed as a $K_S^0 \rightarrow \pi^+ \pi^-$ decay with the same selection criteria as on the ST side. Apart from the two charged tracks originating from K_S^0 decays, it is required that there be only one additional track with charge opposite to the tagged D_s^- meson. For muon identification, the dE/dx and TOF measurements are combined with shower properties from the electromagnetic calorimeter (EMC) to construct likelihoods for the electron, muon, and kaon hypotheses, $\mathcal{L}_e$, $\mathcal{L}_\mu$, and $\mathcal{L}_K$, respectively. The muon candidate must satisfy $\mathcal{L}_\mu > 0.001$, $\mathcal{L}_\mu > \mathcal{L}_e$, and $\mathcal{L}_\mu > \mathcal{L}_K$. Additionally, the deposited EMC energy (EMC_μ) of the muon candidate is required to be within $0.1 < \text{EMC}_\mu < 0.3$ GeV. The background from $D_s^+ \rightarrow K^0 \pi^+$ decay reconstructed as $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$ is rejected by requiring the $K^0 \mu^+$ invariant mass ($M_{K^0 \mu^+}$) to be less than 1.70 GeV/ c^2 . Backgrounds containing additional π^0 mesons are further suppressed by requiring the maximum energy of any unused photon ($E_{\gamma \text{max}}$) to be less than 0.15 GeV.

To identify a photon produced directly from $D_s^{\pm}$, a kinematic fit is performed by requiring the $D_s^\mp D_s^{\pm}$ pair to conserve energy and momentum in the center-of-mass frame [5], and the resultant χ^2 is required to satisfy $\chi^2 < 40$. We obtain information about the undetected neutrino with the missing-mass squared of an event, calculated by the energies and momenta of the tag ($E_{D_s^-}$, $\vec{p}_{D_s^-}$), transition photon (E_γ , $\vec{p}_\gamma$), and the detected SL products ($E_{\text{SL}} = E_{K^0} + E_{\mu^+}$, $\vec{p}_{\text{SL}} = \vec{p}_{K^0} + \vec{p}_{\mu^+}$) by

$$M_{\text{miss}}^2 = E_{\text{miss}}^2 - |\vec{p}_{\text{miss}}|^2,$$

where $E_{\text{miss}} = \sqrt{s} - E_{D_s^-} - E_\gamma - E_{\text{SL}}$, and $\vec{p}_{\text{miss}} = -(\vec{p}_{D_s^-} + \vec{p}_\gamma + \vec{p}_{\text{SL}})$.

Figure 2 shows the M_{miss}^2 distribution of the accepted candidate events for $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$ in data. The signal DT yield N_{DT} is obtained by performing an unbinned maximum likelihood fit to M_{miss}^2 . In the fit, the signal is described with an MC-derived signal shape convolved with a Gaussian, and the combinatorial background is described by a shape obtained from the inclusive MC sample. The residual peaking background from $D_s^+ \rightarrow K^0 \pi^+ \pi^0$ is simulated using the MC-derived shape, with its yield fixed to 27.2 based on the MC simulation. We obtain $N_{\text{DT}} = 147.1 \pm 13.9$ events for $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$, where the uncertainties are statistical only. No peaking backgrounds are observed in the K^0 mass sidebands. The average efficiency of reconstructing the SL decay ϵ_{SL} is estimated to be $(18.78 \pm 0.02)\%$, where the BF of $K^0 \rightarrow \pi^+ \pi^-$ is not included [34]. The BF of $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$ is determined by Eq. (1), and we obtain $\mathcal{B}(D_s^+ \rightarrow K^0 \mu^+ \nu_\mu) = (2.89 \pm 0.27) \times 10^{-3}$, where the uncertainty is statistical only.

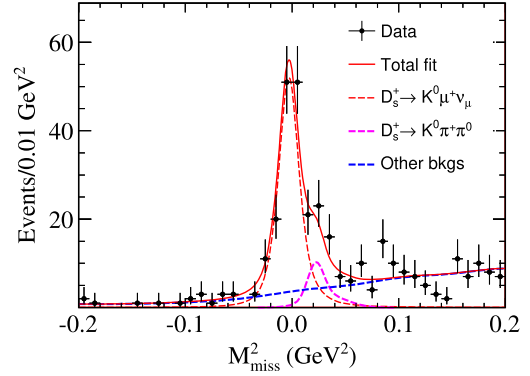


FIG. 2. Fits to the M_{miss}^2 distribution of SL candidate events. Dots with error bars are data, dot-dashed lines (blue) are the fitted combinatorial backgrounds, and solid curves (red) are the total fits. The long-dashed lines (pink) show the fitted background from $D_s^+ \rightarrow K^0 \pi^+ \pi^0$.

With the DT technique, the BF measurements are insensitive to the systematic uncertainties of the ST selection. The uncertainties of the μ^+ tracking and PID efficiency is 1.0% each studied with $e^+e^- \rightarrow \gamma \mu^+ \mu^-$ events, while the uncertainty due to the K^0 reconstruction is 1.5% using the control samples $J/\psi \rightarrow K^{*\mp} K^\pm$ and $J/\psi \rightarrow \phi K^0 K^\pm \pi^\mp$. The uncertainty associated with the M_{miss}^2 fit is estimated to be 1.2% by varying the fit ranges, the signal, and the background shapes. The uncertainty due to the selection of the γ is estimated to be 1.0% based on selecting the best photon candidate in a control sample of $e^+e^- \rightarrow D_s^{*\pm} D_s^\mp$ events with two hadronic tags, $D_s^+ \rightarrow K_S^0 K^+$ and $D_s^+ \rightarrow K^+ K^- \pi^+$. The systematic uncertainties due to the requirements of $E_{\gamma \text{max}}$ and χ^2 are estimated using the control samples $D_s^+ \rightarrow K_S^0 K^+$ and $D_s^+ \rightarrow K_S^0 K^+ \pi^0$. The differences of the acceptance efficiencies between data and MC simulation, 1.7% and 2.0%, are assigned as their systematic uncertainties. The uncertainties due to the $M_{K^0 \mu^+}$ requirement is estimated to be 1.1% by comparing the nominal BF with that measured with alternative requirement. The uncertainty due to the MC signal modeling is estimated to be 0.9% by varying the input FF parameter by $\pm 1\sigma$ measured in this Letter. We also consider the systematic uncertainties of N_{ST} (1.0%), evaluated by using alternative signal shapes when fitting the $M_{D_s^-}$ spectra, the quoted BF for $K_S^0 \rightarrow \pi^+ \pi^-$ (0.2%), and the MC statistics (0.8%). The uncertainty due to different tag dependencies between data and MC simulation is estimated to be 0.2%. Adding these contributions in quadrature gives total systematic uncertainty of 4.2% for the BF measurement. Finally, we determine the BF to be $\mathcal{B}(D_s^+ \rightarrow K^0 \mu^+ \nu_\mu) = (2.89 \pm 0.27_{\text{stat}} \pm 0.12_{\text{syst}}) \times 10^{-3}$.

To improve the experimental precision of the FF parameter in the $D_s^+ \rightarrow K^0$ transition, the candidates from $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$ and $D_s^+ \rightarrow K^0 e^+ \nu_e$ are analyzed simultaneously. The candidates of $D_s^+ \rightarrow K^0 e^+ \nu_e$ are selected as in

TABLE I. The measured partial decay rates for SL decays of $D_s^+ \rightarrow K^0 \ell^+ \nu_\ell$ in various q^2 bins, where the uncertainties are statistical only [37]. The systematic uncertainties of measuring $\Delta\Gamma_{K^0\mu^+\nu_\mu}^i$ ($\Delta\Gamma_{K^0e^+\nu_e}^i$) from lower to higher q^2 intervals are 4.2 (3.9)%, 4.3 (4.0)%, 4.4 (4.5)%, 4.2 (3.8) %, and 5.3 (6.0)%, respectively.

q^2 interval	$\Delta\Gamma_{K^0\mu^+\nu_\mu}^i$ (ns ⁻¹)	$\Delta\Gamma_{K^0e^+\nu_e}^i$ (ns ⁻¹)	$(\Delta\Gamma_{K^0\mu^+\nu_\mu}^i/\Delta q^2)$ (ns ⁻¹ GeV ⁻²)	$(\Delta\Gamma_{K^0e^+\nu_e}^i/\Delta q^2)$ (ns ⁻¹ GeV ⁻²)
$[m_\ell^2, 0.35)$	1.57 ± 0.31	1.63 ± 0.24	4.62 ± 0.90	4.65 ± 0.68
$[0.35, 0.70)$	1.09 ± 0.24	1.27 ± 0.22	3.12 ± 0.66	3.62 ± 0.62
$[0.70, 1.05)$	0.93 ± 0.23	1.18 ± 0.21	2.65 ± 0.62	3.38 ± 0.61
$[1.05, 1.40)$	1.24 ± 0.25	1.08 ± 0.19	3.55 ± 0.70	3.08 ± 0.56
$[1.40, q_{\max}^2)$	0.97 ± 0.23	0.84 ± 0.19	1.27 ± 0.30	1.10 ± 0.24

Ref. [6]. The partial decay rate of $D_s^+ \rightarrow K^0 \ell^+ \nu_\ell$ is measured by analyzing the $\ell^+ \nu_\ell$ mass-squared (q^2) distribution. The q^2 is defined as

$$q^2 = (E_\ell + E_\nu)^2 - |\vec{p}_\ell + \vec{p}_\nu|^2, \quad (2)$$

where E_ℓ and $\vec{p}_\ell$ are the measured energy and momentum of the lepton, and E_ν and $\vec{p}_\nu$ are the energy and momentum of the missing neutrino, with $E_\nu = E_{\text{miss}}$ and $\vec{p}_\nu = E_{\text{miss}} \hat{p}_{\text{miss}}$. The q^2 distributions of $D_s^+ \rightarrow K^0 \ell^+ \nu_\ell$ candidates are divided into seven bins, $[m_\ell^2, 0.35)$, $[0.35, 0.70)$, $[0.70, 1.05)$, $[1.05, 1.40)$ and $[1.40, q_{\max}^2)$ GeV²/c⁴, where $q_{\max}^2 = (m_{D_s} - m_\ell)^2$ and m_ℓ is the known mass of the lepton [4]. The measured partial decay rate in the i th q^2 bin, $\Delta\Gamma_{\text{meas}}^i$, is determined by

$$\Delta\Gamma_{\text{meas}}^i = \sum_{j=1}^{N_{\text{bins}}} (\epsilon^{-1})_{ij} N_{\text{DT}}^j / (\tau_{D_s} \times N_{\text{ST}}), \quad (3)$$

where $\tau_{D_s} = (501.2 \pm 2.2)$ fs is the lifetime of D_s^+ [4] and ϵ_{ij} is an efficiency matrix to describe the reconstruction efficiency of SL decays and migration effects across q^2 bins [35,36]. The SL signal yield observed in the j th q^2 bin, N_{DT}^j , is obtained from a fit to the corresponding M_{miss}^2 distribution. The measured partial decay rates $\Delta\Gamma_{\text{meas}}^i$, and the differential decay rates, $\Delta\Gamma_{\text{meas}}^i/\Delta q^2$, for SL decays $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$ and $D_s^+ \rightarrow K^0 e^+ \nu_e$, are summarized in Table I.

The expected differential decay rate in $D_s^+ \rightarrow K^0 \ell^+ \nu_\ell$ with respect to q^2 is expressed as [17]

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2 |V_{cd}|^2 |\vec{p}_{K^0}|}{96\pi^3 m_{D_s}^2} \lambda \left(1 - \frac{m_\ell^2}{q^2}\right)^2 |f_+^{K^0}(q^2)|^2 \left(1 + \frac{m_\ell^2}{2q^2}\right), \quad (4)$$

where G_F is the Fermi coupling constant, $\lambda = m_{D_s}^4 + m_{K^0}^4 + q^4 - 2(m_{D_s}^2 m_{K^0}^2 + m_{K^0}^2 q^2 + m_{D_s}^2 q^2)$, $|\vec{p}_{K^0}| = \lambda^{1/2}/(2m_{D_s})$ is the momentum of K^0 in the D_s^+ rest frame, m_{K^0} is the known mass of K^0 meson [4], and the $f_+^{K^0}(q^2)$ is

the hadronic FF in the $D_s^+ \rightarrow K^0$ transition. In Eq. (4), the short-distance electroweak corrections as described in Ref. [7] are not taken into account, which introduces $\sim 1\%$ systematic uncertainty for the $f_+^{K^0}(0)|V_{cd}|$ measured in this Letter.

To extract the FF parameter, a least- χ^2 fit is performed to the measured $\Delta\Gamma_{\text{meas}}^i$, and the theoretically expected $\Delta\Gamma_{\text{exp}}^i$, partial decay rates among q^2 intervals. The FF $f_+^{K^0}(q^2)$ in Eq. (4) is expressed using three theoretical parametrizations, which are the simple pole and modified pole models [38], as well as the z-series expansion [39]. The detailed FF parametrizations follow Ref. [40]. Taking into account the correlations of the measured partial decay rates among q^2 bins, the χ^2 to be minimized is defined by

$$\chi^2 = \sum_{i,j=1}^5 (\Delta\Gamma_{\text{meas}}^i - \Delta\Gamma_{\text{exp}}^i) C_{ij}^{-1} (\Delta\Gamma_{\text{meas}}^j - \Delta\Gamma_{\text{exp}}^j), \quad (5)$$

where $C_{ij} = C_{ij}^{\text{stat}} + C_{ij}^{\text{syst}}$ is the covariance matrix of the measured partial decay rates among q^2 intervals. The statistical covariance matrix is constructed as $C_{ij}^{\text{stat}} = [1/(\tau_{D_s} N_{\text{ST}})]^2 \sum_\alpha \epsilon_{i\alpha}^{-1} \epsilon_{j\alpha}^{-1} [\sigma(N_{\text{DT}}^\alpha)]^2$, where α labels the q^2 interval, and $\sigma(N_{\text{DT}}^\alpha)$ is the statistical uncertainty of DT yield observed in the α^{th} q^2 interval. The systematic covariance matrix is obtained by summing over the covariance matrix of each systematic uncertainty source, which takes the form as $C_{ij}^{\text{syst}} = \delta(\Delta\Gamma_{\text{meas}}^i) \delta(\Delta\Gamma_{\text{meas}}^j)$, where $\delta(\Delta\Gamma_{\text{meas}}^i)$ is the systematic uncertainty of the measured partial decay rate in the i^{th} q^2 interval.

We perform a simultaneous fit to the partial decay rates measured in SL decays $D_s^+ \rightarrow K^0 e^+ \nu_e$ and $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$, where the two SL decays share the same parameters for the hadronic FF $f_+^{K^0}(q^2)$. Figure 3 show the fits to the partial decay rates and the projections of the FF $f_+^{K^0}(q^2)$ for $D_s^+ \rightarrow K^0 e^+ \nu_e$ and $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$ decays. The numerical results of $f_+^{K^0}(0)|V_{cd}|$ from the χ^2 fit are summarized in Table II. Taking the $|V_{cd}| = 0.22487 \pm 0.00068$ [4] from the CKMfitter as an input, we also measure $f_+^{K^0}(0)$ as

TABLE II. Hadronic form factors of $D_s^+ \rightarrow K^0 \ell^+ \nu_\ell$, where the first uncertainties are statistical and the second systematic with 1% uncertainty due to short-distance electroweak correction also included. The correlation coefficient between the two fitted parameters is given in the fourth column. The $\chi^2/Nd.o.f.$ is the goodness of fit and Nd.o.f. is the number of degrees of freedom. The unit of M_{pole} is GeV/c^2 , while α and r_1 are dimensionless parameters.

Parametrization	$f_+^{K^0}(0) V_{cd} $	Parameter ($M_{\text{pole}}/\alpha/r_1$)	Coefficient	$\chi^2/Nd.o.f.$	$f_+^{K^0}(0)$
Simple pole [38]	$0.144 \pm 0.007 \pm 0.002$	$1.725 \pm 0.065 \pm 0.018$	0.74	5.2/8	$0.640 \pm 0.031 \pm 0.008$
Modified pole [38]	$0.140 \pm 0.008 \pm 0.003$	$0.636 \pm 0.198 \pm 0.056$	-0.83	5.6/8	$0.623 \pm 0.036 \pm 0.011$
z series (two par.) [39]	$0.140 \pm 0.008 \pm 0.003$	$-4.000 \pm 1.230 \pm 0.346$	0.87	5.8/8	$0.623 \pm 0.036 \pm 0.011$

summarized in the last column of Table II. The measured FF in $D_s^+ \rightarrow K^0$ transition at $q^2 = 0$ is consistent with $0.6307(20)$ as predicted by a LQCD calculation [7]. Figure 3(c) shows the projection of fits onto $f_+^{K^0}(q^2)$ for the $D_s^+ \rightarrow K^0 e^+ \nu_e$ and $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$ decays. The dots with error bars show the measured values of the FFs in i^{th} q^2 interval, $f_+^{K^0}(q_i^2)$, which is obtained with [40]

$$f_+^{K^0}(q_i^2) = \sqrt{\frac{\Delta\Gamma_i}{\Delta q_i^2} \cdot \frac{24\pi^3}{G_F^2 |V_{cd}|^2 p_{K^0}^3 \left(1 - \frac{m_\ell^2}{q^2}\right)^2 \left(1 + \frac{m_\ell^2}{2q^2}\right)}} \quad (6)$$

in which

$$p_{K^0}^3 = \frac{\int_{q_{\min}^2(i)}^{q_{\max}^2(i)} |\vec{p}_{K^0}|^3 |f_+^{K^0}(q^2)|^2 dq^2}{|f_+^{K^0}(q_i^2)|^2 [q_{\max}^2(i) - q_{\min}^2(i)]}, \quad (7)$$

where $f_+^{K^0}(q_i^2)$ and $f_+^{K^0}(q^2)$ are computed using three FF parametrizations with the measured parameters, and $q_{\max}^2(i)$ and $q_{\min}^2(i)$ are the upper and lower boundaries

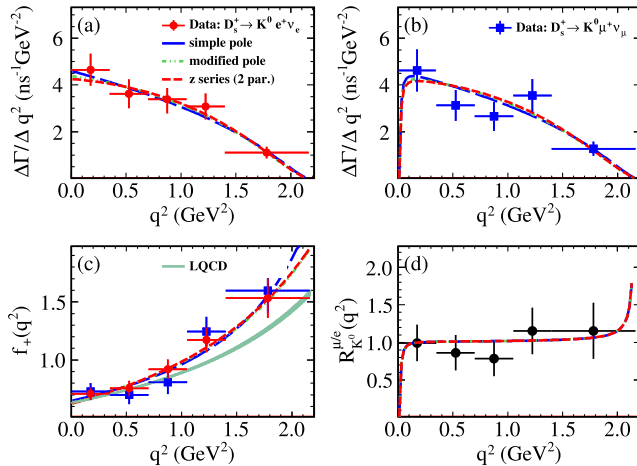


FIG. 3. Fits to the partial decay rates for (a) $D_s^+ \rightarrow K^0 e^+ \nu_e$ and (b) $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$. (c) Projection onto $f_+^{K^0}(q^2)$ for the two SL decays, while the hatched curves show the LQCD prediction in Ref. [7]. (d) The measured $\mathcal{R}_{K^0}^{\mu/e}(q^2)$ in various q^2 intervals. Dots with error bars are data, the curves show the fits with various FF parameterizations.

of the i^{th} q^2 interval. However, the dependence of the measured FF on q^2 shows roughly 2σ deviations with that from the LQCD calculation in the high- q^2 regions, as shown in Fig. 4. Comparisons of the measured $f_+^{K^0}(q^2)$ with other theoretical calculations are also shown in Fig. 4.

Combining $\mathcal{B}(D_s^+ \rightarrow K^0 e^+ \nu_e) = (2.98 \pm 0.23_{\text{stat}} \pm 0.12_{\text{syst}}) \times 10^{-3}$ measured in Ref. [6] and $\mathcal{B}(D_s^+ \rightarrow K^0 \mu^+ \nu_\mu) = (2.89 \pm 0.27_{\text{stat}} \pm 0.12_{\text{syst}}) \times 10^{-3}$ measured in this Letter, we obtain the relative ratio between μ and e modes to be

$$\mathcal{R}_{K^0}^{\mu/e} = 0.97 \pm 0.12_{\text{stat}} \pm 0.04_{\text{syst}},$$

which is consistent with $\mathcal{R}_{K^0}^{\mu/e} = 0.98099(10)^{\text{QCD}}[500]^{\text{QED}}$ from LQCD [7], and the SM predictions in Refs. [8–17]. In addition, with measurements shown in Table I, we measured the ratios of the differential decay rates, $\mathcal{R}_{K^0}^{\mu/e}(q^2) = [(\Delta\Gamma_{K^0 \mu^+ \nu_\mu}^i / \Delta q^2) / (\Delta\Gamma_{K^0 e^+ \nu_e}^i / \Delta q^2)]$, in various q^2 intervals. These results are shown in Fig. 3(d), which are also consistent with the SM predictions.

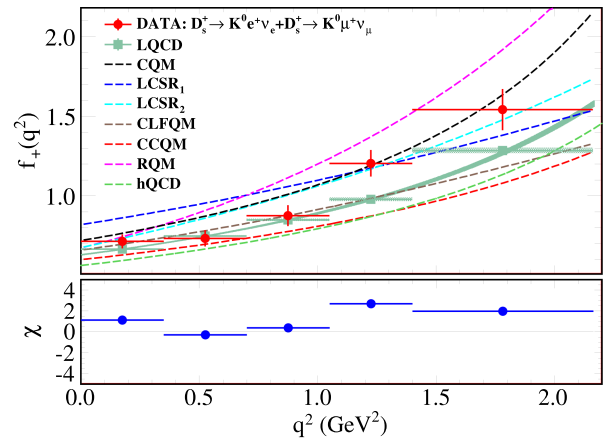


FIG. 4. (Top) Comparisons of $f_+^{K^0}(q^2)$ measured in this Letter with those calculated from the LQCD [7], CQM [8], LCSR₁ [9], LCSR₂ [10], CLFQM [13], CCQM [15], RQM [17], and the hQCD [18]. The square marker shows the average of the LQCD predicted FF in each q^2 interval. (bottom) Distribution of $\chi = [f_+^{\text{meas}}(q^2) - f_+^{\text{LQCD}}(q^2)] / [\sqrt{\sigma_{f_+^{\text{meas}}}^2(q^2) + \sigma_{f_+^{\text{LQCD}}}^2(q^2)}]$, calculated with the measured FFs and predicted FFs of the LQCD [7].

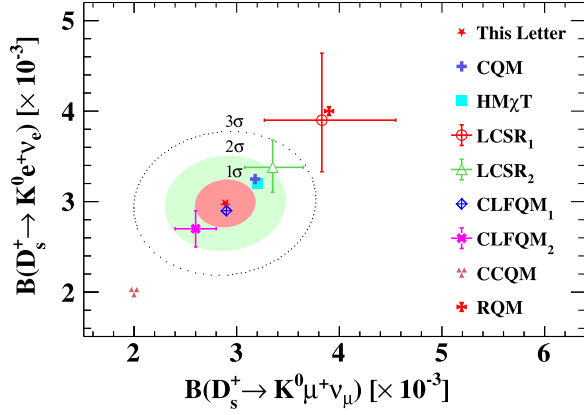


FIG. 5. Comparisons of measured BFs for $D_s^+ \rightarrow K^0 e^+ \nu_e$ [6] and $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$ with various theoretical calculations from the CQM [8], LCSR₁ [9], LCSR₂ [10], HM χ T [11], CLFQM₁ [12], CLFQM₂ [13,14], CCQM [15,16], and RQM [17]. The correlation coefficient between the measured BFs is 0.07.

To summarize, this Letter reports the first measurement of the SL decay $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$. The BF of the decay is measured to be $\mathcal{B}(D_s^+ \rightarrow K^0 \mu^+ \nu_\mu) = (2.89 \pm 0.27_{\text{stat}} \pm 0.12_{\text{syst}}) \times 10^{-3}$. Based on a simultaneous analysis on the differential rates in $D_s^+ \rightarrow K^0 \mu^+ \nu_\mu$ and $D_s^+ \rightarrow K^0 e^+ \nu_e$ decays, we report the most precise determination of the FF parameter in the $D_s^+ \rightarrow K^0$ transition and measure $f_+^{K^0}(0) = 0.623 \pm 0.036_{\text{stat}} \pm 0.011_{\text{syst}}$ at $q^2 = 0$ from the z -series expansion. In addition, taking $f_+^{K^0}(0) = 0.6307 \pm 0.0020$ from the LQCD [7] as an input and with $f_+^{K^0}(0)|V_{cd}|$ derived from the z -series expansion, we also obtain $|V_{cd}| = 0.222 \pm 0.013_{\text{stat}} \pm 0.005_{\text{syst}} \pm 0.001_{\text{LQCD}}$. The result is consistent in 1σ with $|V_{cd}| = 0.2238 \pm 0.0029$ [7] from the averaged measurements via $D \rightarrow \pi \ell \nu_\ell$ decays.

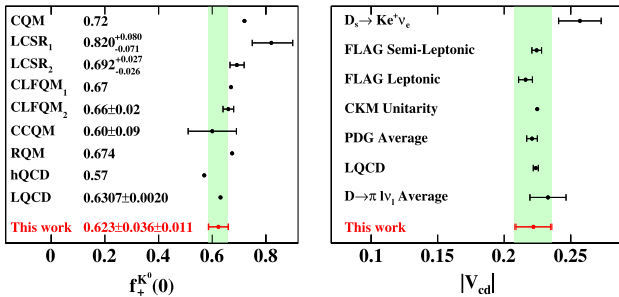


FIG. 6. (left) Comparisons of measured $f_+^{K^0}(0)$ with various theoretical calculations from the CQM [8], LCSR₁ [9], LCSR₂ [10], CLFQM₁ [12], CLFQM₂ [13,14], CCQM [15,16], RQM [17], hQCD [18], and the LQCD [7]. (right) Comparisons of measured $|V_{cd}|$ with various results from $D_s^+ \rightarrow K^0 e^+ \nu_e$ in Ref. [7], FLAG results with $N_f = 2 + 1 + 1$ [42], CKM global fit [4], PDG averaged results [4], LQCD via $D \rightarrow \pi \ell \nu_\ell$ decays [7], and averaged measurements via $D \rightarrow \pi \ell \nu_\ell$ decays [4].

The measured BF and FF presented in this Letter provide a stringent test on various theoretical models. Figures 5 and 6 show the comparisons of the measured BFs, FF and $|V_{cd}|$ with various results in the literature. At a confidence level of 95%, our measured BF disfavors the central values calculated with the CCQM [15,16] and RQM [17], and the measured FF disfavors the central value calculated with the CQM [8]. The LFU is also tested with $D_s^+ \rightarrow K^0 \ell^+ \nu_\ell$ in full and separate q^2 intervals, and no LFU violation is found. Combining the $f_+^{K^0}(0)|V_{cd}| = 0.1407 \pm 0.0025$ measured in $D^+ \rightarrow \pi^0 \ell \nu_\ell$ [4] and $f_+^{K^0}(0)|V_{cd}| = 0.140 \pm 0.008_{\text{stat}} \pm 0.003_{\text{syst}}$ measured in this Letter, we obtain $f_+^{K^0}(0)/f_+^{\pi^0}(0) = 0.995 \pm 0.061$, which is consistent with LQCD prediction [19–21] and the expectation of U -spin ($d \leftrightarrow s$) symmetry [41]. These measurements provide a unique test of the LQCD prediction that the FFs are insensitive to spectator quarks. However, as shown in Fig. 4, our measurements for $f_+^{K^0}(q^2)$ at high- q^2 regions show roughly 2σ deviations with theoretical calculations from the LQCD [7]. Comparisons of FFs measured at high- q^2 regions with predictions from the CLFQM [13], CCQM [15], RQM [17], and the hQCD [18] also show similar differences.

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Data availability—The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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