First Experimental Constraint on the Scalar Current in the $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$ Transition

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(Received 28 January 2026; revised 3 June 2026; accepted 10 July 2026; published 27 August 2026)

Using 20.3 fb^{-1} of e^+e^- collision data taken at the center-of-mass energy of $\sqrt{s} = 3.773$ GeV, we report the first experimental constraint on the scalar current in the $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$ transitions, based on a simultaneous fit to the first measured forward-backward asymmetries and precisely determined partial decay rates. The parameters of the scalar current are determined to be $\mathrm{Re}(c_S^\mu) = 0.017 \pm 0.008_{\mathrm{stat}} \pm 0.006_{\mathrm{syst}}$ and $\mathrm{Im}(c_S^\mu) = \pm(0.077 \pm 0.011_{\mathrm{stat}} \pm 0.009_{\mathrm{syst}})$, which deviates from the standard model by a significance of 2.3σ. The branching fractions of $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$, the hadronic form factor $f_+(0)$, and the modulus of the $c \to s$ Cabibbo-Kobayahsi-Maskawa matrix element $|V_{cs}|$ are also determined with improved precision. In addition, lepton flavor universality is tested via the ratios of the decay rates between semimuonic and semielectronic decays in the full momentum transfer range and in subranges.

DOI: 10.1103/2ygw-n5b1

In the standard model (SM), the couplings between the gauge bosons and the three families of leptons are expected to be the same, known as lepton flavor universality (LFU). Any observation of LFU violation indicates potential new physics (NP) effects beyond the SM. In recent years, several hints of lepton nonuniversal effects have been reported in the B meson semileptonic decays via $b \to c\tau^+\nu_\tau$ [1–5] and $b \to s\ell^+\ell^-$ ($\ell = e$, μ) [6–10] transitions. While some of these violations disappear after further update measurements, some anomalies remain. Various theoretical scenarios involving two-Higgs-doublet models [11,12] and leptoquark models [13,14], as well as model independent investigations [15], suggest that the violations could be attributed to a scalar current in the weak interaction. Given the weak interaction in the SM is only contributed by vector and axial-vector currents, such a scalar current would be a clear sign of NP. While constrained in B meson decays [10,15], its magnitude in charm decays remains virtually unexplored. References [16–20] state that the scalar current could also cause a deviation from the SM in the $c \to s\ell^+\nu_\ell$ transition. The partial decay rates ($d\Gamma/dq^2$) and the forward-backward asymmetries $A_{\mathrm{FB}}(q^2)$ of the semileptonic (SL) decays $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$ are sensitive to the scalar current contributions in the $c \to s\ell^+\nu_\ell$ transition. Therefore, experimental studies of these decays are important to explore the parameter space of the scalar current, which may reveal unknown scalar boson contributions beyond the SM [11–14].

In addition, precise measurements of the $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$ decay dynamics are critical to determine the hadronic transition form factor (FF) $f_+(0)$ and the modulus of the $c \to s$ Cabibbo-Kobayashi-Maskawa (CKM) matrix element $|V_{cs}|$. A precisely measured $f_+(0)$ allows for stringent tests of different theoretical predictions [21–31], and an accurately determined $|V_{cs}|$ is important for testing the CKM matrix unitarity. Also, the full and partial decay widths $\Delta\Gamma_{\ell=e,\mu}$ of $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$, measured with improved precision, provide an important test of the LFU via the ratio $\mathcal{R}_{\mu/e} \equiv (\Delta\Gamma_\mu/\Delta\Gamma_e)$.

Previously, the branching fraction (BF) and the decay dynamics of $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$ have been widely investigated by BES [32–34], *BABAR* [35], Belle [36], CLEO [37–40], and BESIII Collaborations [41–48]. However, no experimental study of the scalar current and the forward-backward asymmetry of $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$ has been reported yet. With 20.3 fb^{-1} of e^+e^- collision data taken at the center-of-mass energy of $\sqrt{s} = 3.773$ GeV with the BESIII detector, this Letter presents the first experimental constraint on the scalar current in the $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$ transition, based on a simultaneous fit to the first measured forward-backward asymmetries and precisely determined partial decay rates. The BFs of $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$, as well as the product of the FF $f_+(0)$ and the modulus of the CKM matrix element $|V_{cs}|$ are determined with improved precision. The results supersede those reported in Ref. [48], which was based on a portion of the data sample used in this Letter. Charge conjugate modes are implied throughout this Letter.

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Details about the design and performance of BESIII detector are given in Refs. [49,50]. The inclusive Monte Carlo (MC) samples, described in Refs. [51–56], are used to estimate the background in this analysis. The signal MC samples of $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$ are simulated with a specific two-parameter series expansion model [57] using parameters obtained in this Letter.

At $\sqrt{s} = 3.773$ GeV, the D and $\bar{D}$ mesons are produced in pairs without accompanying particles in the final state. This property allows us to study SL D decays with the double-tag (DT) method [58]. First, the single-tag (ST) $\bar{D}$ mesons are reconstructed with the hadronic decay modes $\bar{D}^0 \to K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^+$, $K^0_S\pi^+\pi^-$, $K^+\pi^-\pi^0\pi^0$, and $K^+\pi^-\pi^-\pi^+\pi^0$; $D^- \to K^+\pi^-\pi^-$, $K^0_S\pi^-$, $K^+\pi^-\pi^-\pi^0$, $K^0_S\pi^-\pi^0$, $K^0_S\pi^+\pi^-\pi^-$, and $K^+K^-\pi^-$. In the presence of the ST $\bar{D}$ mesons, candidates for the signal decays $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$ are selected to form DT events, in which $\bar{K}^0$ is reconstructed via $K^0_S \to \pi^+\pi^-$ and the lepton ℓ denotes the electron and muon. The BF of the signal decay is determined by

$$\mathcal{B}_{\rm sig} = \frac{N_{\rm DT}}{N^{\rm tot}_{\rm ST} \times \bar{\epsilon}_{\rm sig} \times \mathcal{B}_{\rm sub}}. \quad (1)$$

Here, $N^{\rm tot}_{\rm ST} = \sum_i N^i_{\rm ST}$ and $N_{\rm DT}$ are the total ST and DT yields after summing over all tag modes; $\bar{\epsilon}_{\rm sig} = \sum_i (N^i_{\rm ST}/N^{\rm tot}_{\rm ST})(\epsilon^i_{\rm DT}/\epsilon^i_{\rm ST})$ is the averaged signal efficiency of selecting $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$ in the presence of ST $\bar{D}$ mesons, where $\epsilon^i_{\rm ST}$ and $\epsilon^i_{\rm DT}$ are the ST and DT efficiencies for the ith tag mode, respectively; $\mathcal{B}_{\rm sub} = \mathcal{B}(\bar{K}^0 \to K^0_S, K^0_S \to \pi^+\pi^-)$ [59] for D^+ channels and $\mathcal{B}_{\rm sub} = 1$ for D^0 channels.

The selection criteria of $\pi^\pm, K^\pm, K^0_S, \gamma$, and π^0 candidates are the same as those in Ref. [60]. Two kinematic variables, the energy difference $\Delta E \equiv E_{\bar{D}} - E_{\rm beam}$ and the beam-constrained mass $M_{\rm BC} \equiv \sqrt{E^2_{\rm beam} - |\vec{p}_{\bar{D}}|^2}$, are used to distinguish the ST $\bar{D}$ mesons from combinatorial backgrounds, where $E_{\rm beam}$ is the beam energy and $(E_{\bar{D}}, \vec{p}_{\bar{D}})$ is the four momentum of the ST $\bar{D}$ in the e^+e^- rest frame. The combination with the smallest $|\Delta E|$ is chosen if there are multiple combinations in an event.

The ST candidates must satisfy tag mode requirements for ΔE, corresponding to about $\pm 3.5\sigma$ around the fitted peaks. The ST yields in data for each tag mode are obtained by fitting individual $M_{\rm BC}$ distributions. Candidates with $M_{\rm BC} \in [1.859, 1.873]$ GeV$/c^2$ for $\bar{D}^0$ and $M_{\rm BC} \in [1.863, 1.877]$ GeV$/c^2$ for D^- are retained for further analysis [61]. The ΔE requirements, the ST yields in data, and the ST efficiencies for different tag modes are provided in Ref. [60]. Summing over all the tag modes, $N^{\rm tot}_{\rm ST}$ is determined to be $(10646.9 \pm 3.8) \times 10^3$ for D^- and $(20226.3 \pm 5.5) \times 10^3$ for $\bar{D}^0$.

In the presence of the tagged $\bar{D}$, candidates for $D^0 \to K^-e^+\nu_e$, $D^0 \to K^-\mu^+\nu_\mu$, $D^+ \to \bar{K}^0 e^+\nu_e$, and $D^+ \to \bar{K}^0\mu^+\nu_\mu$ are selected from the residual tracks and showers, with the same selection criteria as those in Ref. [48] except that the $M_{\bar{K}\mu}$ requirements are optimized to $M_{K^-\mu^+} < 1.56$ GeV$/c^2$ for $D^0 \to K^-\mu^+\nu_\mu$ and $M_{K^0_S\mu^+} < 1.59$ GeV$/c^2$ for $D^+ \to \bar{K}^0\mu^+\nu_\mu$. The detailed descriptions are available in Ref. [60].

Since the neutrino is undetectable by the BESIII detector, its four momentum $(E_{\rm miss}, \vec{p}_{\rm miss})$ is obtained by calculating the missing energy and momentum, defined as $E_{\rm miss} \equiv E_{\rm beam} - E_{\bar{K}} - E_{\ell^+}$ and $\vec{p}_{\rm miss} \equiv \vec{p}_D - \vec{p}_{\bar{K}} - \vec{p}_{\ell^+}$, where $(E, \vec{p})$ is the four momentum of $\bar{K}$ or ℓ^+. A kinematic variable $U_{\rm miss} \equiv E_{\rm miss} - |\vec{p}_{\rm miss}|$ is defined to obtain the signal yield. To further improve the resolution of the neutrino, the momentum of the D meson is constrained as $\vec{p}_D = -\hat{p}_{\bar{D}}\sqrt{E^2_{\rm beam} - m^2_{\bar{D}}}$, where $\hat{p}_{\bar{D}}$ is the unit vector in the momentum direction of the ST $\bar{D}$ meson and $m_{\bar{D}}$ is the known $\bar{D}$ mass [59].

The signal yields of $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$ are determined from binned maximum likelihood fits to the $U_{\rm miss}$ distributions of the accepted candidates, as shown in Fig. 1. In the fits, the signals are modeled by the MC-simulated shape convolved with Gaussian resolution functions with free parameters to account for the difference between data and MC simulation. The peaking backgrounds $D \to \bar{K}\pi^+\pi^0$ for the $D \to \bar{K}\mu^+\nu_\mu$ are described with the simulated shape convolved with the same Gaussian functions with floating yields. The other background components are modeled by the inclusive MC sample. Both the yields of signal and backgrounds are floated in the fits. The fitted signal yields in data, the averaged signal efficiencies corrected for the data-MC

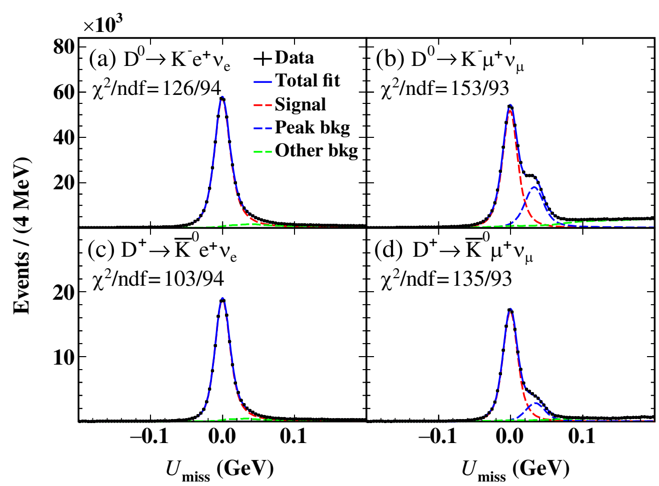

FIG. 1. Fits to the $U_{\rm miss}$ distributions of $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$. The points with error bars are data. The blue solid lines denote the total fits. The red, blue, and black dashed lines show the signal, peaking background, and other background contributions, respectively.

TABLE I. The fitted signal yields in data ($N_{\rm DT}$), the averaged signal efficiencies corrected for data-MC differences ($\bar{\epsilon}_{\rm sig}$), and the BFs ($\mathcal{B}_{\rm sig}$), where the first uncertainties are statistical and the second systematic.

Channel	$N_{\rm DT}$ ($\times 10^3$)	$\bar{\epsilon}_{\rm sig}$ (%)	$\mathcal{B}_{\rm sig}$(%)
$D^0 \to K^- e^+ \nu_e$	489.8 ± 0.8	68.25 ± 0.02	$3.548 \pm 0.006 \pm 0.017$
$D^0 \to K^- \mu^+ \nu_\mu$	403.9 ± 0.8	57.96 ± 0.02	$3.445 \pm 0.007 \pm 0.017$
$D^+ \to \bar{K}^0 e^+ \nu_e$	149.3 ± 0.4	45.39 ± 0.02	$8.928 \pm 0.025 \pm 0.050$
$D^+ \to \bar{K}^0 \mu^+ \nu_\mu$	125.1 ± 0.4	38.74 ± 0.02	$8.770 \pm 0.029 \pm 0.053$

differences [60] on tracking and particle identication (PID) efficiencies, and the BFs are summarized in Table I. Input and output checks have been performed with MC simulation to ensure the analysis workflow is correct. Based on these, we determine the ratios of the BFs between semimuonic and semielectronic D decays: $\mathcal{R}^{D^0}_{\mu/e} = 0.971 \pm 0.003_{\rm stat} \pm 0.004_{\rm syst}$ and $\mathcal{R}^{D^+}_{\mu/e} = 0.982 \pm 0.004_{\rm stat} \pm 0.002_{\rm syst}$, which are consistent with the LFU predicted value of 0.975 ± 0.001 [62] within 1.5σ.

The systematic uncertainties in the BF measurements include the uncertainties due to ST yields (0.3%), K^0_S reconstruction (0.4%), correction factors for data-MC differences on tracking (0.1%) and PID (0.1%) efficiencies, requirements on maximum energy of the extra photon (0.1%) and $M_{K\ell}$ (negligible), $U_{\rm miss}$ fit (0.08%–0.29%), quoted $\mathcal{B}_{\rm sub}$ (0.07%), MC statistics (0.04%), and MC model (0.04%–0.15%). The detailed descriptions and values are available in Ref. [60].

The q^2-binned partial decay rates in the ith q^2 interval $\Delta\Gamma_i = \int_{q^2_{\min(i)}}^{q^2_{\max(i)}} (d\Gamma/dq^2) dq^2$ are determined using $\Delta\Gamma_i = N^i_{\rm prd}/(\tau_D \cdot N^{\rm tot}_{\rm ST})$, where $N^i_{\rm prd}$ is the number of produced events in the ith q^2 interval and τ_D is the D lifetime [59]. $N^i_{\rm prd} = \sum_j (\epsilon^{-1}_{ij}) N^j_{\rm obs}$ is obtained by performing similar fits to the $U_{\rm miss}$ distributions in each q^2 interval to determine the numbers of observed events $N^j_{\rm obs}$ and then transforming them into the produced ones with the efficiency matrix ϵ_{ij}, based on MC simulation [60]. The systematic uncertainty studies are performed with similar approaches as those for the BF measurement with details shown in Ref. [60]. The measured partial decay rates of $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$ as well as the calculated ratios $\mathcal{R}_{\mu/e}$ are shown in the top and bottom panels of Fig. 2, respectively.

The q^2-binned forward-backward asymmetry in the ith q^2 interval,

$$A_{{\rm FB},i} = \int_{q^2_{\min(i)}}^{q^2_{\max(i)}} A_{\rm FB}(q^2) \frac{d\Gamma}{dq^2} dq^2 \Big/ \int_{q^2_{\min(i)}}^{q^2_{\max(i)}} \frac{d\Gamma}{dq^2} dq^2, \quad (2)$$

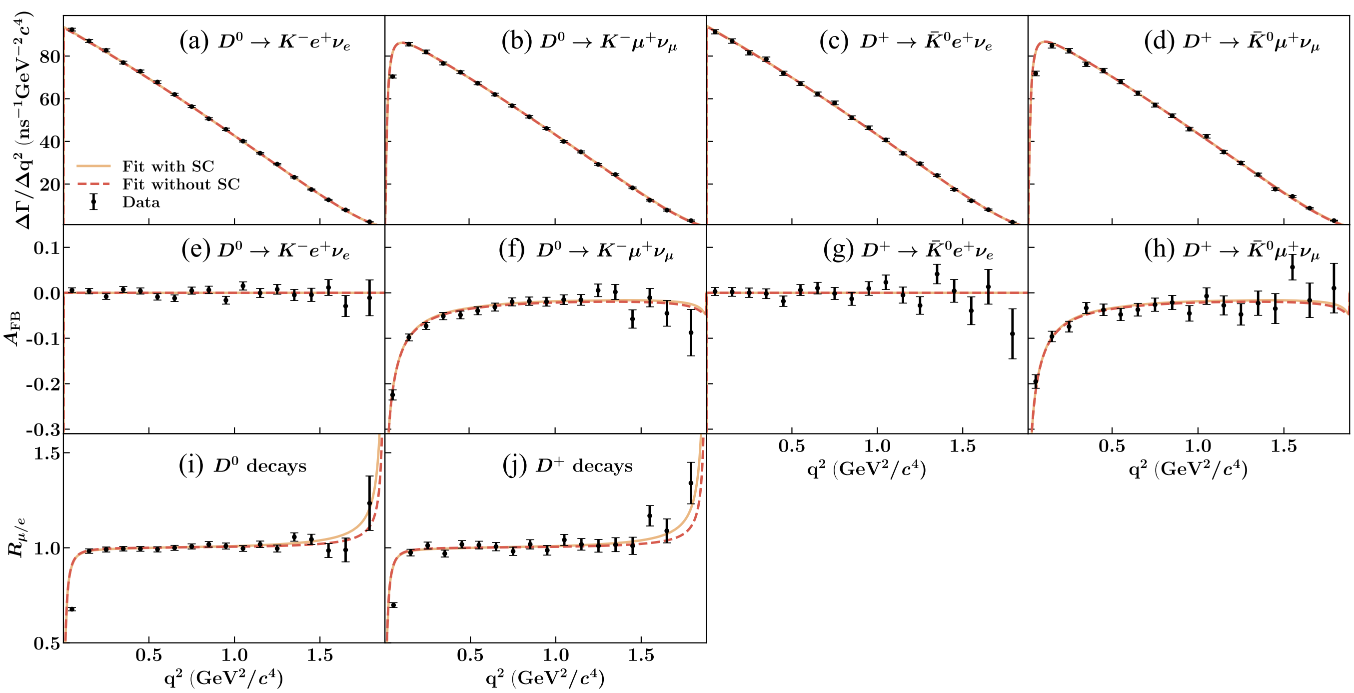

FIG. 2. Simultaneous fit to the measured partial decay rates (a) to (d), forward-backward asymmetries (e) to (h) of $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$, and the fit projections on the ratios of differential decay rates $\mathcal{R}_{\mu/e}$ (i) and (j). The black points with red error bars are data, the solid lines are the fit projections with scalar current (SC) contribution included, and the dashed lines are the fit projections without scalar current contribution.

is measured by $A_{\mathrm{FB},i} = [(N^i_{\mathrm{prd,f}} - N^i_{\mathrm{prd,b}})/(N^i_{\mathrm{prd,f}} + N^i_{\mathrm{prd,b}})]$, where $N^i_{\mathrm{prd,(f,b)}}$ is the number of produced forward ($\cos\theta_W > 0$) and backward ($\cos\theta_W < 0$) events in the ith q^2 interval obtained using the similar approach as that of partial decay rates, where θ_W is the angle between the flight direction of the lepton and opposite flight direction of D in the $\ell\nu_\ell$ rest frame. Some systematic uncertainties cancel, except for the U_{miss} fit $[(1-8)\times 10^{-4}]$, correction factors related to lepton (1×10^{-4}), requirements on $M_{K\ell}$ (negligible), and MC statistics ($< 7\times 10^{-4}$), where the values correspond to absolute uncertainties. The measured forward-backward asymmetries of $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$ are shown in Fig. 2.

The scalar current contribution is obtained via a simultaneous fit to the partial decay rates ($d\Gamma/dq^2$) and forward-backward asymmetries $A_{\mathrm{FB}}(q^2)$, the explicit expressions of which are written as [17,30]

$$\frac{d\Gamma}{dq^2} = \mathcal{N}(q^2)\left(1-\frac{m_\ell^2}{q^2}\right)^2\left[\left(1+\frac{m_\ell^2}{2q^2}\right)|h_0(q^2)|^2 + \frac{3m_\ell^2}{2q^2}|h_t(q^2)|^2\right], \tag{3}$$

and

$$A_{\mathrm{FB}}(q^2) = \frac{3\mathcal{N}(q^2)}{2}\frac{1}{d\Gamma^\ell/dq^2}\left(1-\frac{m_\ell^2}{q^2}\right)^2 \times \frac{m_\ell^2}{q^2}\mathrm{Re}\left(h_0(q^2)h_t^*(q^2)\right), \tag{4}$$

respectively. Here, $\mathcal{N}(q^2) = (G_F^2|V_{cs}|^2|\mathbf{q}|q^2/96\pi^3 m_D^2)$ is the factor including the Fermi coupling constant G_F, the CKM matrix element V_{cs}, and the mass of D meson m_D; q is the four momentum of the $\ell\nu_\ell$ system in the D rest frame, and $|\mathbf{q}|$ is the magnitude of the three momentum of q; m_ℓ is the mass of the lepton. With scalar currents included, the hadronic helicity amplitudes $h_{0(t)}(q^2)$ are modified as

$$h_0(q^2) = \frac{2m_D|\mathbf{q}|}{\sqrt{q^2}}f_+(q^2),$$
$$h_t(q^2) = \left(1 + c_S^\ell\frac{q^2}{m_\ell(m_s-m_c)}\right)\frac{m_D^2-m_K^2}{\sqrt{q^2}}f_0(q^2), \tag{5}$$

where $f_{+,0}(q^2)$ are the form factors; $c_S^\ell = c_R^\ell + c_L^\ell$ is the scalar combination of Wilson coefficients for the right- and left-handed scalar currents [17]; $m_c = 1.273\ \mathrm{GeV}/c^2$ and $m_s = 93.5\ \mathrm{MeV}/c^2$ [59] are the $\overline{\mathrm{MS}}$ masses at the energy scale $\mu = m_c$ and 2 GeV, respectively; m_K is the mass of kaon. The FF $f_+(q^2)$ is parametrized in the two-parameter series expansion approach [57] as

$$f_+(q^2) = \frac{1}{P(q^2)\Phi(q^2)}\frac{f_+(0)P(0)\Phi(0)}{1+r_1(t_0)z(0,t_0)} \times \{1 + r_1(t_0)[z(q^2,t_0)]\}, \tag{6}$$

where the parameters $r_1(t_0)$ and $f_+(0)$ are floated in the fit. The FF $f_0(q^2)$ is modeled with the one-parameter series expansion as

$$f_0(q^2) = \frac{1}{P(q^2)\Phi(q^2)}f_0(0)P(0)\Phi(0), \tag{7}$$

where the usual kinematic constraint $f_+(0) = f_0(0)$ [17] is used in this fit. The detailed definitions of variables shown in Eqs. (6) and (7) are given in Ref. [60]. The Wilson coefficient c_S^ℓ is generally allowed to be complex, thus two parameters $\mathrm{Re}(c_S^\mu)$ and $\mathrm{Im}(c_S^\mu)$ are introduced for the muon channels. For the positron one, the partial decay rates are only sensitive to the modulus $|c_S^e|$ and the forward-backward asymmetry is not sensitive to the scalar current contribution, thus only one parameter $|c_S^e|$ is considered.

The fit is performed by minimizing the χ^2 function constructed as

$$\chi^2 = \chi^2_{\Delta\Gamma} + \chi^2_{A_{\mathrm{FB}}}. \tag{8}$$

The decay rate part $\chi^2_{\Delta\Gamma}$ is defined as

$$\sum_{i,j}(\Delta\Gamma_i^{\mathrm{msr}} - \Delta\Gamma_i^{\mathrm{fit}})(C_{\Delta\Gamma}^{-1})_{ij}(\Delta\Gamma_j^{\mathrm{msr}} - \Delta\Gamma_j^{\mathrm{fit}}), \tag{9}$$

which sums over all four signal channels and takes the correlations between different q^2 intervals and signal channels into consideration with the sum of statistical and systematic covariance matrices $C_{ij} = C_{ij}^{\mathrm{stat}} + C_{ij}^{\mathrm{syst}}$. Here, $\Delta\Gamma^{\mathrm{msr}}$ and $\Delta\Gamma^{\mathrm{fit}}$ are the measured and fitted decay rates, respectively. The forward-backward asymmetry part $\chi^2_{A_{\mathrm{FB}}}$ is defined similarly as

$$\sum_{i,j}(A_{\mathrm{FB},i}^{\mathrm{msr}} - A_{\mathrm{FB},i}^{\mathrm{fit}})(C_{\mathrm{FB}}^{-1})_{ij}(A_{\mathrm{FB},j}^{\mathrm{msr}} - A_{\mathrm{FB},j}^{\mathrm{fit}}), \tag{10}$$

where the correlations between different signal channels are ignored, since the only correlated uncertainty caused by the correction factors of ℓ^+ is limited.

First, two different fits are performed with and without the scalar current contribution, with the c_S^ℓ shown in Eq. (5) allowed to float and fixed to zero, respectively. Corresponding fit projections are shown in Fig. 2, and the fitted parameters are summarized in Table II. No significant deviation from the SM is found in the positron channels with the fitted $|c_S^e|$ consistent with zero. For the muon channels, c_S^μ is found to deviate from zero as shown in Fig. 3(a), especially on its imaginary part.

TABLE II. Fitted parameters and overall quality of fits with and without a scalar current (SC) contribution, where the first uncertainties are statistical and the second are systematic.

Variable	With SC	Without SC
$f_+(0)\|V_{cs}\|$	$0.7193 \pm 0.0008 \pm 0.0014$	$0.7183 \pm 0.0007 \pm 0.0014$
r_1	$-2.23 \pm 0.04 \pm 0.02$	$-2.28 \pm 0.02 \pm 0.02$
$\|c_S^e\|$	$0.02 \pm 0.02 \pm 0.02$	
$\mathrm{Re}(c_S^\mu)$	$0.017 \pm 0.008 \pm 0.006$	
$\mathrm{Im}(c_S^\mu)$	$\pm(0.077 \pm 0.011 \pm 0.009)$	
χ^2/ndf	135.8/139	143.5/142

Since LFU may not hold for the scalar current, the coupling to muons may be significantly larger than that to positrons. Therefore, to estimate the significance of nonzero c_S^μ alone, a third fit is performed in which c_S^μ is float while $|c_S^e| = 0$ is fixed to zero; this fit serves as the alternative hypothesis and yields $\chi^2/\mathrm{ndf} = 135.9/140$. Comparing this with the null hypothesis, which assumes no scalar current and gives $\chi^2/\mathrm{ndf} = 143.5/142$, we obtained $\Delta\chi^2 = 7.6$ and $\Delta\mathrm{ndf} = 2$, corresponding to a significance of 2.3σ based on the Wilks's theorem.

Further constraints on the right- and left-handed components of the scalar current are obtained by combining with the decay rates of $D_s^+ \to \ell^+\nu_\ell$, which are sensitive to the pseudoscalar combination of Wilson coefficients $c_P^\ell = c_R^\ell - c_L^\ell$ as [17]

$$\mathcal{B}(D_s^+ \to \ell^+\nu_\ell) = \tau_{D_s}\frac{m_{D_s}}{8\pi}f_{D_s}^2\left(1-\frac{m_\ell^2}{m_{D_s}^2}\right)^2 G_F^2 \times |V_{cs}|^2 m_\ell^2 \left|1 - c_P^\ell \frac{m_{D_s}^2}{(m_c+m_s)m_\ell}\right|^2. \quad (11)$$

Here, the measured BFs $\mathcal{B}(D_s^+ \to \ell^+\nu_\ell)$ are taken from the Particle Data Group [59], and the inputs of $f_{D_s} = 249.9 \pm 0.5$ MeV from a lattice quantum chromodynamics (LQCD) calculation [63] and $|V_{cs}| = 0.97349 \pm 0.00016$ from the global SM fit [59] are used. Since the $D_s^+ \to \ell^+\nu_\ell$ decay cannot constrain the real and imaginary parts of c_P^ℓ simultaneously, the Wilson coefficient $c_{R(L)}^\ell$ is assumed to be real with T parity conserved here. As shown in Figs. 3(b) and 3(c), both the real parts of the right- and left-handed Wilson coefficients c_R^ℓ and c_L^ℓ are consistent with zero.

Furthermore, the simultaneous fit without a NP contribution gives the product of the FF $f_+(0)$ and the modulus of the CKM matrix element $|V_{cs}|$ to be $f_+(0)|V_{cs}| = 0.7183 \pm 0.0007_{\mathrm{stat}} \pm 0.0014_{\mathrm{syst}}$. Taking $|V_{cs}| = 0.97349 \pm 0.00016$ given by the Particle Data Group [59] as input, we determine $f_+(0) = 0.7378 \pm 0.0007_{\mathrm{stat}} \pm 0.0014_{\mathrm{syst}}$, which results in a stringent test of various theoretical calculations. Conversely, taking $f_+(0) = 0.7452 \pm 0.0031$ calculated with LQCD [26], we obtain $|V_{cs}| = 0.9639 \pm 0.0009_{\mathrm{stat}} \pm 0.0018_{\mathrm{syst}} \pm 0.0040_{\mathrm{LQCD}}$, which is important for testing the CKM matrix unitarity.

In summary, by analyzing 20.3 fb^{-1} of e^+e^- collision data taken at $\sqrt{s} = 3.773$ GeV by BESIII, we report the first measurement of the forward-backward asymmetries as well as the precise measurements of the partial decay rates of $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$. A simultaneous fit to these kinematic variables gives the first experimental constraint on the scalar current contribution in the $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$ transition ($\ell = e, \mu$). The complex Wilson coefficient is determined to be $\mathrm{Re}(c_S^\mu) = 0.017 \pm 0.008_{\mathrm{stat}} \pm 0.006_{\mathrm{syst}}$ and $\mathrm{Im}(c_S^\mu) = \pm(0.077 \pm 0.011_{\mathrm{stat}} \pm 0.009_{\mathrm{syst}})$, which deviates from the SM by 2.3σ. This result provides an important constraint on the scalar current contribution in

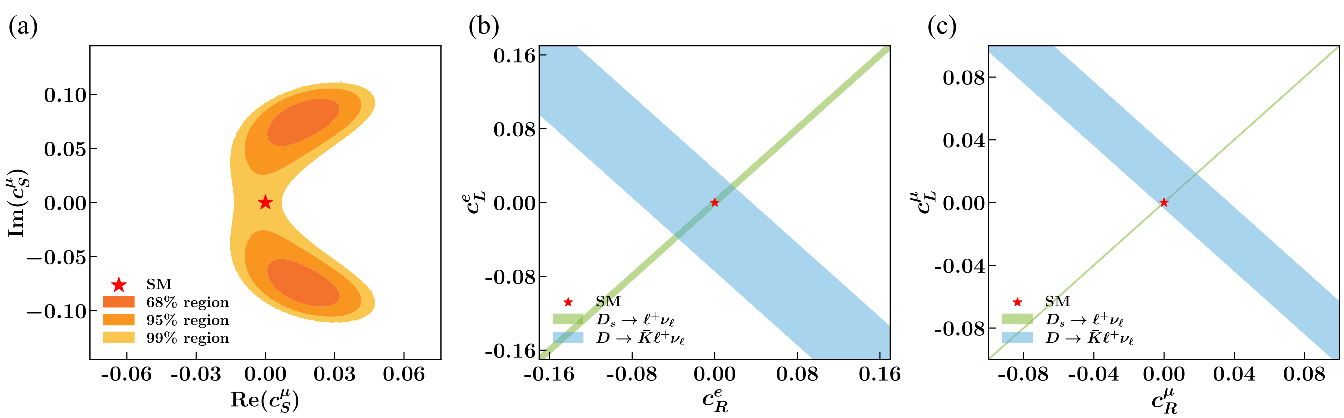

FIG. 3. The confidence regions of (a) the scalar combination of complex Wilson coefficients c_S^μ with probabilities of 68%, 95%, and 99% from $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$, as well as (b),(c) the right- and left-handed real Wilson coefficients c_R^ℓ and c_L^ℓ with probabilities of 95% by combining with the $D_s^+ \to \ell^+\nu_\ell$ decay rate. The red dot indicates the SM value.

the SL charmed meson decays, further provides new insights into the anomalies observed in the beauty sector [1–10], and facilitates the search for new scalar bosons beyond the standard model under various new-physics scenarios. Besides, the improved measurements of the BFs and tests of LFU in $D^{0(+)} \to \bar{K}\ell^+\nu_\ell$ decays, the hadronic transition FFs $f_+(0)$, as well as the CKM matrix element $|V_{cs}|$, which are in the highest precision to date, are also presented.

Acknowledgments—The BESIII Collaboration thanks the staff of BEPCII [64] and the IHEP computing center for their strong support. This work is supported in part by National Key R&D Program of China under Contracts No. 2023YFA1606000 and No. 2023YFA1606704; National Natural Science Foundation of China under Contracts No. 11635010, No. 11935015, No. 11935016, No. 11935018, No. 12025502, No. 12035009, No. 12035013, No. 12061131003, No. 12192260, No. 12192261, No. 12192262, No. 12192263, No. 12192264, No. 12192265, No. 12221005, No. 12225509, No. 12235017, No. 12342502, and No. 12361141819; the Chinese Academy of Sciences (CAS) Large-Scale Scientific Facility Program; the Strategic Priority Research Program of Chinese Academy of Sciences under Contract No. XDA0480600; CAS under Contract No. YSBR-101; 100 Talents Program of CAS; The Institute of Nuclear and Particle Physics and Shanghai Key Laboratory for Particle Physics and Cosmology; ERC under Contract No. 758462; German Research Foundation DFG under Contract No. FOR5327; Istituto Nazionale di Fisica Nucleare, Italy; Knut and Alice Wallenberg Foundation under Contracts No. 2021.0174, No. 2021.0299, and No. 2023.0315; Ministry of Development of Turkey under Contract No. DPT2006K-120470; National Research Foundation of Korea under Contract No. NRF-2022R1A2C1092335; National Science and Technology fund of Mongolia; Polish National Science Centre under Contract No. 2024/53/B/ST2/00975; STFC (United Kingdom); Swedish Research Council under Contract No. 2019.04595; and U.S. Department of Energy under Contract No. DE-FG02-05ER41374.

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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