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Experimental status of $|V_{cs}|$ and $|V_{cd}|$ at BESIII

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Using 20.3 fb^{-1}, 7.93 fb^{-1}, and 10.64 fb^{-1} of e^+e^- collision data collected at the center-of-mass energies of 3.773, 4.128-4.226, and 4.237-4.669 GeV with the BESIII detector, the CKM matrix elements $|V_{cs}|$ and $|V_{cd}|$ are extracted with the (semi-)leptonic decays $D_{(s)} \to \ell\nu_\ell$ and $D_{(s)} \to \bar{K}(\pi)\ell\nu_\ell$.

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1. Introduction

The elements of the Cabibbo-Kobayashi-Maskawa (CKM) matrix are crucial parameters within the Standard Model (SM) of particle physics. Accurate determination of these elements is vital for exploring potential new physics beyond the SM. Recent advancements in experimental techniques and theoretical methodologies have significantly enhanced our understanding of CKM unitarity, imposing tighter constraints on models that predict novel phenomena. Among the CKM elements, $|V_{cs}|$ and $|V_{cd}|$ have a relatively small impact on the unitarity condition of the second row, underscoring the importance of precise experimental measurements for these elements.

Charm decay modes, such as $D_{(s)} \to \ell\nu_\ell$ and $D_{(s)} \to K(\pi)\ell\nu_\ell$, play a vital role in the precise determination of the elements $|V_{cs(d)}|$. In the SM, the purely leptonic decays of $D_{(s)}$ mesons can be factorized into a function of the CKM matrix elements, the decay constants $f_{D_{(s)}}$, which parameterize the overlap of the wave functions of the constituent quarks and antiquarks, and known kinematic factors. The decay width for the process $D_{(s)} \to \ell\nu_\ell$ can be expressed as [1]

$$\Gamma_{D^+_{(s)}\to\ell^+\nu_\ell} = \frac{G_F^2}{8\pi} f^2_{D_{(s)}} \left|V_{cs(d)}\right|^2 m_{D_{(s)}} m_\ell^2 \left(1 - \frac{m_\ell^2}{m^2_{D_{(s)}}}\right)^2, \tag{1}$$

where G_F is the Fermi coupling constant, $m_{D_{(s)}}$ is the mass of the $D_{(s)}$ meson, and m_ℓ is the mass of the charged lepton.

Semileptonic decays of $D_{(s)} \to K(\pi)\ell\nu_\ell$, which involve the interaction of a leptonic current with a hadronic current, can be parametrized using form factors. The differential decay rate can be written as [2–6]

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}q^2} = \frac{G_F^2|V_{cs(d)}|^2|\mathbf{q}|q^2}{96\pi^3 m^2_{D_{(s)}}}\left[\left(1+\frac{m_\ell^2}{2q^2}\right)\left|\mathcal{H}_0(q^2)\right|^2 + \frac{3m_\ell^2}{8q^2}\left|\mathcal{H}_t(q^2)\right|^2\right]. \tag{2}$$

Here, $\mathcal{H}_0(q^2) = \frac{2m_{D_{(s)}}|\mathbf{q}|}{\sqrt{q^2}} f_+^{D_{(s)}\to P}(q^2)$ and $\mathcal{H}_t(q^2) = \frac{m^2_{D_{(s)}} - m_P^2}{\sqrt{q^2}} f_0^{D\to P}(q^2)$, where q is the four-momentum of the $\ell\nu_\ell$ system in the rest frame of the $D_{(s)}$ meson and P is the pseudoscalar meson in the final state. The functions $f_+^{D_{(s)}\to P}(q^2)$ and $f_0^{D_{(s)}\to P}(q^2)$ are the vector and scalar form factors, respectively.

Experimental measurements of decay rates, combined with non-perturbative calculations of $f_{D_{(s)}}$ using lattice QCD, allow for a determination of $|V_{cs}|$ and $|V_{cd}|$. Recently, the BESIII experiment has accumulated the largest charm dataset from the $\psi(3770)$ at 3.773 GeV, with an integrated luminosity of 20.3 fb^{-1}, yielding samples of approximately $\bar{D}^0 \sim 1.69\times10^7$ and $D^- \sim 1.10\times10^7$ events. Additionally, the BESIII detector collected 7.33 fb^{-1} data for the process $e^+e^- \to D_s^\pm D_s^{*\mp}$ at $\sqrt{s}$ =4.128-4.226 GeV, contributed about $D_s^- \sim 1.10\times10^7$ events. Furthermore, $e^+e^- \to D_s^{*+}D_s^{*-}$ at $\sqrt{s}$ = 4.237-4.669 GeV provides additional $D_s^- \sim 0.12\times10^6$ events. These efforts have led to a substantial increase in the precision of measurements. Concurrently, advancements in lattice QCD calculations have refined theoretical predictions for hadronic form factors. The combination of high-quality experimental data and enhanced computational techniques provides crucial constraints on the CKM matrix and could potentially reveal new physics phenomena.

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2. Status of the $|V_{cs}|$

With the world's largest $D\bar{D}$ data samples collected near threshold by the BESIII detector, the CKM matrix element $|V_{cs}|$ is determined using the decays $D_s \to \ell\nu_\ell$ and $D \to \bar{K}\ell\nu_\ell$. Measurements of $|V_{cs}|$ have been conducted through leptonic decays $D_s \to \mu\nu_\mu$ in 2023 and 2024, based on data from the processes $e^+e^- \to D_s^\pm D_s^{*\mp}$ and $e^+e^- \to D_s^{*+}D_s^{*-}$ [7, 8]. Additionally, $|V_{cs}|$ is measured from $D_s \to \tau\nu$ decays using various τ decay channels, including $\tau \to \pi\pi^0\bar{\nu}_\tau$, $\tau \to \pi\bar{\nu}_\tau$, $\tau \to e\nu_e\bar{\nu}_\tau$, and $\tau \to \mu\nu_\mu\bar{\nu}_\tau$, facilitated by the $e^+e^- \to D_s^\pm D_s^{*\mp}$ process [9–13]. Furthermore, $|V_{cs}|$ is extracted under the constraint of the same branching fraction for the four channels mentioned earlier, utilizing 10.64 fb^{-1} of data at a center-of-mass energy of 4.237-4.669 GeV [8]. By weighting the results from $D_s \to \tau\nu_\tau$, the determined value of $|V_{cs}|$ is $0.9892 \pm 0.0060 \pm 0.0071$. Overall, the CKM matrix element $|V_{cs}|$ is obtained as $0.9820 \pm 0.0052 \pm 0.0071$, incorporating results from all measured $D_s \to \ell\nu_\ell$ channels reported by the BESIII collaboration. The most precise determination of $|V_{cs}|$ is obtained from the four semileptonic decays $D \to \bar{K}\ell\nu_\ell$, utilizing a simultaneous fit method for the differential partial decay width [14] with 7.93fb^{-1} of data from the $\psi(3770)$. The result is $|V_{cs}| = 0.9623 \pm 0.0015 \pm 0.0017$, corresponding to a precision of 0.23%.

3. Status of the $|V_{cd}|$

The CKM matrix element $|V_{cd}|$ has been determined from the purely leptonic decay $D \to \mu\nu_\mu$, yielding a result of $0.2265\pm0.0023\pm0.0011$, which represents the highest precision measurement to date with an accuracy of 1.2%, based on a dataset of 20.3 fb^{-1} collected at the center-of-mass energy of 3.773 GeV [15]. It also accounts for the radiative correction $(1+\frac{\alpha}{\pi}C_p)$, which includes structure-dependent bremsstrahlung, as well as short-distance and long-distance electroweak corrections. Additionally, the BESIII collaboration also measured $|V_{cd}| = 0.216 \pm 0.012 \pm 0.006$ using the purely leptonic decay $D \to \tau\nu_\tau$ (with $\tau \to \pi\bar{\nu}_\tau$), utilizing 7.93 fb^{-1} of data collected from the $\psi(3773)$ resonance [16]. Furthermore, $|V_{cd}|$ is extracted with the semileptonic decay $D \to \pi e\nu_e$ previously with 2.93 fb^{-1} data taken at $\sqrt{s}$ =3.773 GeV [17, 18].

4. Summary

Measurements of charm (semi-)leptonic decays are crucial to validate Lattice QCD calculations of the hadronic effects involved in these decays. The experimental effort in the past few years has been remarkable. There are many results from several experiments working at different energy and using different techniques resulting in accurate measurements of the CKM matrix elements $|V_{cs}|$ and $|V_{cd}|$. They have reached precision of 0.23% and 1.2%, respectively, as shown in Fig. 1. In addition, there are still room for improvements with 20.3 fb^{-1} data taken at $\sqrt{s}$ = 3.773 GeV with the BESIII detector..

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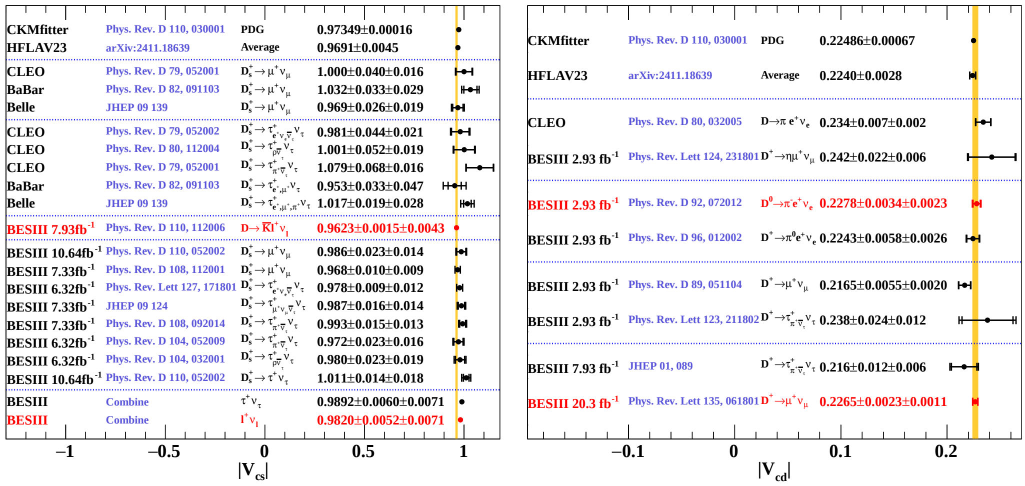

Figure 1: Comparesion of the results for the CKM elements $|V_{cs}|$ and $|V_{cd}|$.

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