A possible signature of new physics at BES-III *

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Abstract The recent observations of the purely leptonic decay $D_s^+\to\mu^+\nu_\mu$ and $\tau^+\nu_\tau$ at CLEO-c and B factory may allow a possible contribution from a charged Higgs boson. One such measurement of the decay constant f_{D_s} differs from the most precise unquenched lattice QCD calculation by a level of 4 σ. Meanwhile, the measured ratio, $\mathcal{BR}(D_s^+\to\mu^+\nu_\mu)/\mathcal{BR}(D^+\to\mu^+\nu_\mu)$, is larger than the standard model prediction at a 2.0σ level. We discuss that the precise measurement of the ratio $\mathcal{BR}(D_s^+\to\mu^+\nu_\mu)/\mathcal{BR}(D^+\to\mu^+\nu_\mu)$ at BES-III will shed light on the presence of new intermediate particles by comparing the data with the theoretical predictions, especially, the predictions of high precise unquenched lattice QCD calculations.

Key words BES-III, decay constant, QCD, leptonic decay

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1 Introduction

Purely leptonic decays of heavy mesons are of great interest both theoretically and experimentally. Measurements of the decays $B^+\to l^+\nu$, $D_s^+\to l^+\nu$ and $D^+\to l^+\nu$, provide an experimental determination of the product of CKM elements and decay constants. If the CKM element is measured from other reactions, the leptonic decays can access the decay constants, which can be used to test lattice QCD predictions for heavy quark systems.

In the Standard Model (SM) the purely leptonic decays $B^+\to l^+\nu$ and $D_s^+\to l^+\nu$ proceed via annihilation of the heavy meson into a W^*. Akeroyd and Chen [1] pointed out that the leptonic decay widths are modified by new physics. For the D^+ and D_s^+, the two $SU(2)_L\times U(1)_Y$ Higgs doublets with hypercharge $Y=1$ (2HDM) would contribute to these decays[1]. The tree level partial width in the 2HDM is given by[1]

$$\Gamma(D_s^+\to l^+\nu)=\frac{G_F^2 m_{D_s^+} m_l^2 f_{D_s^+}^2}{8\pi}|V_{cs}|^2\left(1-\frac{m_l^2}{m_{D_s^+}^2}\right)^2 r_s, \tag{1}$$

where $G_F=1.16639\times10^{-5}$ GeV^{-2} is the Fermi constant, m_l is the mass of the lepton, $m_{D_s^+}$ is the mass of the D_s^+ meson, V_{cs} is the Cabibbo-Kobayashi-Maskawa (CKM) matrix element, and $f_{D_s^+}$ is the decay constant. In the 2HDM (model II type Yukawa couplings), at tree level, the scaling factor r_s is given by[1]

$$r_s=\left[1-m_{D_s^+}^2\frac{\tan^2\beta}{m_{H^\pm}^2}\left(\frac{m_s}{m_c+m_s}\right)\right]^2=\left[1-m_{D_s^+}^2R^2\left(\frac{m_s}{m_c+m_s}\right)\right]^2, \tag{2}$$

where $m_{H^\pm}$ is the charged Higgs mass, m_c is the charm quark mass, m_s is the strange quark mass (for D^+ decays, it is the light d-quark mass), $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs doublets, and the $H^\pm$ contribution to the decay rate depends on $R=\frac{\tan\beta}{m_{H^\pm}}$. The contribution from the $H^\pm$ interferes destructively with the $W^\pm$ mediated SM diagram. As discussed in Ref. [2], the recent experimental measurements of $\mathcal{BR}(B^\pm\to\tau^\pm\nu_\tau)$[3, 4] provide an upper limit of $R<0.29$ GeV^{-1} at 90% C.L. For values of R in the interval $0.20<R<0.30$ GeV^{-1}, the charged Higgs contribution could have a sizable ef-

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fect on the D_s^+ leptonic decay rate[1, 2]. For the quark masses m_s and m_c the range of $0.03 < m_s/(m_c+m_s) < 0.15$ is used in the following discussions based on the Particle Data Group values[1, 5].

For the D^+, $m_d \ll m_c$, the modification is negligible, and thus the scaling factor $r_d \approx 1$. However, in the case of the D_s^+, the scaling factor r_s may be sizable due to the non-negligible m_s/m_c. Although the contribution of the new physics to the rate is small in comparison to the SM rate for $D_s^+ \to l^+\nu$ decays, measureable effects may be accessible since the decay rate for $D_s^+ \to \mu^+\nu_\mu$ is much larger than that for B leptonic decays, and can be measured with good precision.

2 Recent measurements and constraints

The most precise measurement of the branching fraction for the $D^+ \to \mu\nu_\mu$ is from CLEO-c based on 281 pb^{-1} of data taken on the $\psi(3770)$ peak. The measured decay rate of the $D^+ \to \mu\nu_\mu$ is $(4.40\pm0.66^{+0.09}_{-0.12})\times10^{-4}$ [6]. In the context of the SM, using the well measured D^+ lifetime of 1.040 ± 0.007 ps and assuming $|V_{cd}| = |V_{us}| = 0.2238(29)$, they determine[6]

$$(f_{D^+})_{\text{CLEO-c}} = (222.6\pm16.7^{+2.8}_{-3.4})\ \text{MeV}. \tag{3}$$

Recently, measurements of $D_s^+ \to l^+\nu$ decays with precision levels comparable to that for $D^+ \to \mu^+\nu$ decays have been reported by CLEO-c[7, 8], BaBar[9] and Belle[2, 10]. For the $D_s^+ \to \mu\nu_\mu$ decay mode, the combined decay rate from the CLEO-c, Belle and BaBar experiments is $(6.26\pm0.43\pm0.25)\times10^{-3}$. For the $D_s^+ \to \tau^+\nu_\tau$ decay mode, combining the two τ decay channels ($\tau^+ \to \pi^-\bar{\nu}_\tau$ and $e^+\nu_e\bar{\nu}_\tau$) from CLEO-c[8], one obtains $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (6.47\pm0.61\pm0.26)\%$. Using the D_s^+ lifetime of 0.50 ps and $|V_{cs}| = 0.9737$[5] in the SM relation, one determines the decay constant $f_{D_s^+}$ from the $D_s^+ \to \mu^+\nu_\mu$ mode to be

$$(f_{D_s^+})^{\mu}_{\text{exp}} = (272\pm11)\ \text{MeV}, \tag{4}$$

and that from $D_s^+ \to \tau^+\nu_\tau$ decay mode to be

$$(f_{D_s^+})^{\tau}_{\text{exp}} = (285\pm15)\ \text{MeV}. \tag{5}$$

The average of $\tau\nu_\tau$ and $\mu\nu_\mu$ values is

$$(f_{D_s^+})_{\text{exp}} = (276\pm9)\ \text{MeV}. \tag{6}$$

Recently, the HPQCD+UKQCD collaboration claims better than 2% precision for their unquenched calculations[11]

$$\begin{aligned}(f_{D^+})_{\text{QCD}} &= (208\pm4)\ \text{MeV},\\ (f_{D_s^+})_{\text{QCD}} &= (241\pm3)\ \text{MeV},\end{aligned} \tag{7}$$

which is four times better than the experiment and previous theory[12—15]. As pointed out in Ref. [16], there is a 15% (3.8σ) discrepancy between the experimental and lattice QCD values of $f_{D_s^+}$ (Eqs. (6) and (7)). The discrepancy is seen in both the $\tau\nu_\tau$ mode, where it is 18% (2.9σ), and the $\mu\nu_\mu$ where it is 13% (2.7σ).

Equation (1) shows that the charged Higgs would lower the D_s^+ decay rate relative to the SM prediction. However, the LQCD predicted value (Eq. (7)) is below the measured value by more than 3σ. This indicates that there is no value of m_{H^+} in the 2HDM that can accommodate the measured f_{D_s} value[2]. If we take the discrepancy seriously, there must be new physics that enhances the predicted leptonic decay rate.

Measurements of $f_{D_s^+}$ (a detailed summary in Ref. [2]) and its world average are shown in Fig. 1 together with the LQCD prediction. With 20 fb^{-1} at $E_{CM} = 4170$ MeV, the BES-III sensitivity for the measurement of the leptonic D_s^+ decay branching fraction would be about 2%[17], which corresponds to a 1.0% uncertainty level for $f_{D_s^+}$, as indicated in Fig. 1. Assuming that the central value for the combined experimental $f_{D_s^+}$ result persists, the discrepancy between the SM prediction and a BES-III measurement would be more than 8σ, and a signal for new physics beyond the SM.

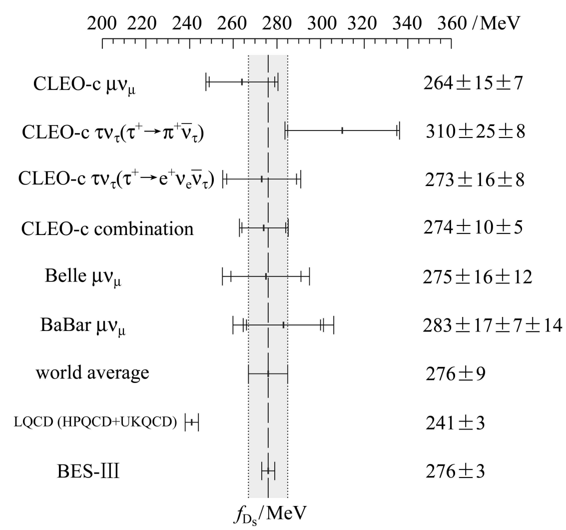

Fig. 1. Values of $f_{D_s^+}$ extracted from different experiments in the context of the SM (a detailed summary in Ref. [2]). The world average is $f_{D_s^+} = 276\pm9$ MeV, with an uncertainty of about 3.3%. The 1% BES-III sensitivity to $f_{D_s^+}$ is indicated with the assumption that the current world average central value persists.

Another, more conservative approach, is to use the LQCD prediction for the ratio $f_{D_s^+}/f_{D^+}$, which is inherently more precise than those for the individual

$f_{\rm D}$ values. A significant deviation of this ratio from the SM prediction would be a very robust sign of new physics beyond the SM.

Experimentally, the ratio $f_{\rm D_s^+}/f_{\rm D^+}$ can be extracted from the measured ratio $\mathcal{R}_\mu$ of the leptonic decay rates of the $\rm D_s^+$ and the $\rm D^+$. In the SM, one has[1]:

$$\mathcal{R}_\mu \equiv \frac{\mathcal{BR}(\mathrm{D_s^+}\to\mu^+\nu)}{\mathcal{BR}(\mathrm{D^+}\to\mu^+\nu)} = \left|\frac{f_{\rm D_s^+}}{f_{\rm D^+}}\right|^2 \left|\frac{V_{\rm cs}}{V_{\rm cd}}\right|^2 \frac{m_{\rm D_s^+}}{m_{\rm D^+}} \times \left(\frac{1-m_\mu^2/m_{\rm D_s^+}^2}{1-m_\mu^2/m_{\rm D^+}^2}\right) \times \frac{\tau_{\rm D_s^+}}{\tau_{\rm D^+}}. \tag{8}$$

In the case of the 2HDM, new physics only modifies the decay of $\rm D_s^+$, and the ratio $\mathcal{R}_\mu$ in Eq. (8) is corrected by a factor $r_{\rm s}$ defined in Eq. (2).

Using only CLEOc measurements and the SM relation, the experimental value for the $f_{\rm D_s^+}/f_{\rm D^+}$ ratio is[2]

$$r_{\rm D_s^+/D^+} \equiv \frac{f_{\rm D_s^+}}{f_{\rm D^+}} = 1.23\pm 0.10, \tag{9}$$

The most precise prediction of the ratio from LQCD[11] is $f_{\rm D_s^+}/f_{\rm D^+} = 1.164\pm 0.011$, which has a claimed precision that is better than 1%, and an order of magnitude better than the existing experimental determination. The discrepancy is about 1.0 σ between the current experimental determination and the LQCD calculations.

In Fig. 2, $\mathcal{R}_\mu$ is plotted as a function of $R = \tan\beta/m_{\rm H^\pm}$ for the case of the 2HDM, using $m_{\rm sc} = m_{\rm s}/(m_{\rm s}+m_{\rm c}) = 0.08$ and $f_{\rm D_s^+}/f_{\rm D^+} = 1.164\pm 0.011$ from the LQCD calculation (detailed discussion on 2HDM in Ref. [1]). The SM prediction for $\mathcal{R}_\mu$ is (12.99±0.25), where the error is from the uncertainty on the LCQCD prediction for $f_{\rm D_s^+}/f_{\rm D^+}$. Compared to the measured value $\mathcal{R}_\mu = 14.2\pm 0.7$, we see that the SM prediction is almost 2 standard deviations lower. If the LQCD calculation is reliable, this indicates that we need a modification to the SM that has constructive interference to accommodate the discrepancy[16]. It may be concluded that the 2HDM discussed in Ref. [1] is disfavored by the current data. It would be very interesting if the experimental precision on $\mathcal{R}_\mu$ ratio could be improved to match the one percent level of the theoretical errors in the near future. As discussed below in Table 3, the sensitivity of the measurement of the ratio at BES-III is about 2.6% with 20 fb^{-1} at $E_{\rm CM} = 4170$ MeV[17]. This results in a 1.0% uncertainty on the ratio of $f_{\rm D_s^+}/f_{\rm D^+}$.

Beginning in mid-2008, the BEPC-Ⅱ/BES-III will be operated at center-of-mass (CM) energies corresponding to $\sqrt{s} = 2.0-4.6$ GeV. The designed luminosity over this energy region will range from 1×10^{33} cm$^{-2}\cdot$s^{-1} down to about 0.6×10^{33} cm$^{-2}\cdot$s^{-1}[18], yielding around 5 fb^{-1} each at ψ(3770) and at $\sqrt{s} = 4170$ MeV[18] above $\rm D_s^+D_s^-$ threshold and 3 fb^{-1} at J/ψ peak in one year's running with full luminosity[18]. These integrated luminosities correspond to samples of 2.0 million $\rm D_s^+D_s^-$, 30 million $\rm D\overline{D}$ pairs and 10×10^9 J/ψ decays. Table 1 summarizes the data set per year at BES-III. In this paper, the sensitivity studies are based on 20 fb^{-1} luminosity at ψ(3770) peak for D physics, the same luminosity also for $\rm D_s$ physics at $\sqrt{s} = 4170$ MeV.

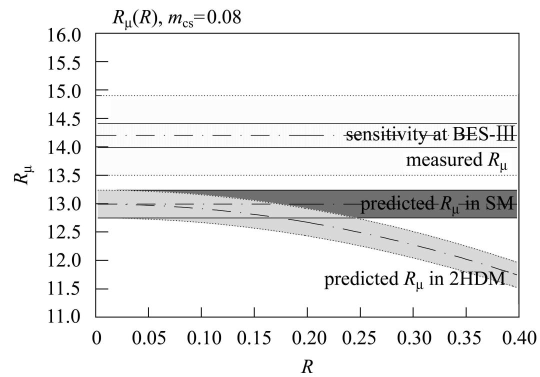

Fig. 2. $\mathcal{R}_\mu$ as a function of $R = \tan\beta/m_{\rm H^\pm}$ for $m_{\rm sc} = m_{\rm s}/(m_{\rm s}+m_{\rm c}) = 0.08$ and $f_{\rm D_s^+}/f_{\rm D^+} = 1.164\pm0.011$ from LQCD calculations. The uncertainty on the theoretical prediction of $\mathcal{R}_\mu$ is shown as the gray band, and a detailed discussion can be found in Ref. [1]. The expected $\pm1\sigma$ BES-III uncertainty experimental range of $\mathcal{R}_\mu$ is indiated by the yellow band. The sensitivity for the measurement of the ratio $\mathcal{R}$ at BES-III is about 2.6% level is also shown with the assumption that the current central value for $\mathcal{R}_\mu$ persists.

Table 1. τ-charm productions at BEPC-Ⅱ in one year's running (10^7 s)[17].

data sample	central-of-mass /MeV	#events per year
J/ψ	3097	10×10^9
$\tau^+\tau^-$	3670	12×10^6
ψ(2S)	3686	3.0×10^9
$\rm D^0\overline{D}^0$	3770	18×10^6
$\rm D^+D^-$	3770	14×10^6
$\rm D_s^+D_s^-$	4030	1.0×10^6
$\rm D_s^+D_s^-$	4170	2.0×10^6

According to the recent energy scan above the threshold of $\rm D_s^+D_s^-$ pair from CLEO-c[19], the production cross section of $\rm D_s^{*+}D_s^- + D_s^+D_s^{*-}$ is about 1.0 nb at 4170 MeV, which is 3 times higher than the cross section of $\rm D_s^+D_s^+$ at 4030 MeV. The scan succeeded in identifying a $\rm D_s^+$ "minifactory" at $E_{\rm CM} = 4170$ MeV. At this energy the $\rm e^+e^-$ annihilation cross sections into $\rm D_{(s)}^{(*)}$ pairs are estimated from the scan of CLEO-c and summarized in Table 2.

Table 2. The preliminary results for the cross sections of the $D^{(*)}_{(s)}$ pairs at $E_{CM}=4016$ MeV and $E_{CM} = 4170$ MeV, respectively, from CLEO-c experiment[19].

decay modes	4016 MeV $D^*\bar{D}^*$ threshold in nb	4170 MeV in nb
$\sigma(D_s^+D_s^-)$	0.25	<0.05
$\sigma(D_s^{*+}D_s^-+D_s^+D_s^{*-})$	–	1.0
$\sigma(D\bar{D}^*)+D^*\bar{D})$	7.0	2.0
$\sigma(D^*\bar{D}^*)$	3.0	5.1

3 Decay constants at BES-Ⅲ

Measurements of leptonic decays at the BES-III will benefit from the fully tagged D^+ and D_s^- decays available at the $\psi(3770)$ and at $\sqrt{s}\sim 4170$ MeV. The leptonic decay of $D_s^+(D^+)\to\mu^+\nu$ is detected by using this kind of "double-tag" techniques in which one D^+ or D_s^+ is fully reconstructed and the rest of the event is examined without bias but with substantial kinematic constraints[20]. For the decay of $D^+\to\mu^+\nu_\mu$ at $\psi(3770)$ peak, the pure $D\overline{D}$ pair in the initial state and cleanliness of the full tag reconstruction make this measurement essentially background-free at CLEO-c and BES-III[6, 17]. The leptonic decay rate for D^+ can be measured with a precision of 1%—2% level at the BES-III experiment. This will allow the validation of theoretical calculations of the decay constants at the 1% level. Table 3 summarizes the expected precision in the decay constant measurements.

Table 3. Expected errors on the branching fractions for leptonic decays and decay constants at the BES-III with 20 fb^{-1} at $\psi(3770)$ peak and $E_{CM}=4170$ MeV, respectively.

observable	error	measurement	error
$\mathcal{BR}(D^+\to\mu^+\nu)$	2.0%	$f_D\lvert V_{cd}\rvert$	1.1%
$\mathcal{BR}(D_s^+\to\mu^+\nu)$	2.0%	$f_{D_s}\lvert V_{cs}\rvert$	1.0%
$\dfrac{\mathcal{BR}(D_s^+\to\mu^+\nu)}{\mathcal{BR}(D^+\to\mu^+\nu)}$	2.6%	$\left\lvert\dfrac{V_{cs}f_{D_s}}{V_{cd}f_D}\right\rvert$	1.3%

For the decay of $D_s^+\to\mu\nu_\mu$ at $E_{CM}=4170$ MeV, to select the sample of single tag events, one has to fully reconstruct one of D_s by using the decay modes, such as $D_s^+\to K^+K^-\pi^+$, K_sK^+, $\eta(\eta')\pi^+$, $\pi^+\pi^-\pi^+$ and $K^{*+}K^{*0}$ as described in Ref. [21] in the CLEO-c experiment. Then one can find another photon to reconstruct the $D_s^*\to D_s\gamma$ decay. For the $D_s^*D_s$ candidates, the missing mass-squared, MM^{*2}, recoiling against the photon and the D_s tag should peak at the D_s mass-squared, one obtains:

$$MM^{*2}=(E_{CM}-E_{D_s}-E_\gamma)^2-(\boldsymbol{p}_{CM}-\boldsymbol{p}_{D_s}-\boldsymbol{p}_\gamma)^2,$$

where E_{CM} ($\boldsymbol{p}_{CM}$) is the center-of-mass energy (momentum), E_{D_s} ($\boldsymbol{p}_{D_s}$) is the energy (momentum) of the fully reconstructed D_s^+ tag, and E_γ ($\boldsymbol{p}_\gamma$) is the energy (momentum) of the additional photon.

Candidates $D_s^+\to\mu^+\nu$ events are reconstructed by selecting events with only a single extra muon with opposite sign of charge to the tag side. Thus, the undetected energy and momentum is interpreted as the neutrino four-vector, the missing mass squared, MM^2, evaluated by taking into account the seen muon, D_s^+, and the photon should peak at zero, and is given by

$$MM^2 = (E_{CM}-E_{D_s}-E_\gamma-E_\mu)^2- (\boldsymbol{p}_{CM}-\boldsymbol{p}_{D_s}-\boldsymbol{p}_\gamma-\boldsymbol{p}_\mu)^2, \qquad (10)$$

where E_μ ($\boldsymbol{p}_\mu$) is the energy (momentum) of the candidate muon. The missing mass resolution is about one pion mass[20]. These techniques pioneered by Mark-III and well developed by the CLEO-c[22] allow precise absolute branching fraction determination. Backgrounds can be highly suppressed and the statistical errors and systematic errors can be minimized[20].

At BES-III, in order to measure the branching fractions of the pure leptonic decays at 2% level or below, one has to pay more attention to the systematic uncertainties due to the dilution to the signal region from irreducible backgrounds. The main backgrounds are from $D_s^+\to\pi^+\pi^0$, $D_s^+\to\pi^+\eta$, and $D_s^+\to\pi^+K_L$ in which the neutral particles in the final states are not detected and only a charged pion left. To suppress the background with only a detected charged pion, at BES-III, both calorimeter and muon counters can be used to distinguish the muon from the pion. Since the typical momentum of muon and pion from D_s^+ decays are above 700 MeV, according to the design of BES-III[18], the detection efficiency of muon in the muon counters is above 97%, and the rate of contamination from pion is less than 5%. Thus, if we take the estimated 90% upper limit for the $D_s^+\to\pi^+\pi^0$ decay as 1.1×10^{-3}, and find zero expected background under the signal peak. Another dangerous background is from the radiative decay $D_s^+\to\mu^+\nu_\mu\gamma$. For $D_s^+\to\mu^+\nu$ radiative corrections had been estimated and found that it is genuinely of order α[23]. In the analysis of CLEO-c[21], a cut $E_\gamma<300$ MeV is used to remove the dilution from radiative decay, and one finds that the radiative rate is less than 1% which can be neglected with current statistics.

4 Summary

In summary, following the work of Rosner[2] and Dobrescu et al.[16], we have reviewed the most recent determinations of the decay constant $f_{D_s^+}$ from different experiments. We find that the current experimental determination in the SM differs from the most precise unquenched lattice QCD calculation at the 4σ level. Meanwhile, the measured ratio, $\mathcal{BR}(D_s^+ \to \mu^+\nu_\mu)/\mathcal{BR}(D^+ \to \mu^+\nu_\mu)$, is larger than the standard model prediction at the 2.0σ level. With current data, the occurrence of new physics, in the case of the 2HDM[1], is disfavored. The measured ratio, $\mathcal{BR}(D_s^+ \to \mu^+\nu_\mu)/\mathcal{BR}(D^+ \to \mu^+\nu_\mu)$, suggests that we need a new physics contribution with constructive interference. we discuss that the precise measurement of the ratio $\mathcal{BR}(D_s^+ \to \mu^+\nu_\mu)/\mathcal{BR}(D^+ \to \mu^+\nu_\mu)$ at BES-III will shed light on the presence of new intermediate particles by comparing with the theoretical predictions, especially, the predictions of high precise unquenched lattice QCD calculation.

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