PROCEEDINGS OF SCIENCE

(Semi-)leptonic D$_{(s)}$ decays at BESIII

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BESIII has collected 2.93 and 6.32 fb^{-1} of e$^+$e$^-$ collision data samples at 3.773 and 4.178-4.226 GeV, respectively. We will report precision measurements of $f_{D_{(s)}}$, $|V_{cs}|$, and test of lepton flavor universality by studying the leptonic decays of $D_s^+ \to l\nu$ with $\tau^+ \to \rho^+\nu$, $\pi^+\nu$, and $e^+\nu\nu$. We will also report the observation of semileptonic decay of $D^0 \to \rho^-\mu^+\nu$ and lepton flavor universality test, and the studies of some other semileptonic decays, such as $D_s^+ \to \pi^0\pi^0 e^+\nu$ and $D_s^+ \to K_s^0 K_s^0 e^+\nu$.

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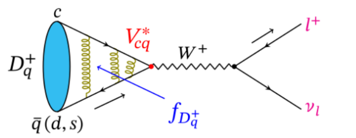
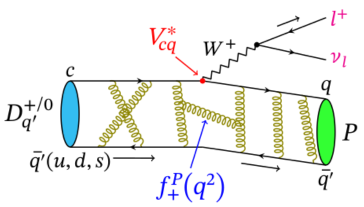
1. Introduction

A very good environment to study strong and electroweak interactions is the one of the leptonic and semi-leptonic decays of heavy-flavoured mesons. In fact, from the decay amplitude of these two processes, it is possible to access to the product of the decay constant with the Cabibbo-Kobayashi-Maskawa (CKM) matrix element. These processes are described in Figure 1.



$$\Gamma(D_{(s)}^+ \to l^+\nu) = \frac{G_F^2}{8\pi} f_{D_{(s)}^+}^2 \left|V_{cd(s)}\right|^2 m_l^2 m_{D_{(s)}^+} \left(1 - \frac{m_l^2}{m_{D_{(s)}^+}^2}\right)^2$$



$$\frac{d\Gamma}{dq^2} = X \frac{G_F^2 p^3}{24\pi^3} \left|f_+(q^2)\right|^2 \left|V_{cd(s)}\right|^2$$

Figure 1: (Top) Leptonic Decay; (Btm) Semi-Leptonic Decay

In the BESIII environment, focusing on the cases of D and D_s^+, it is possible to access the two terms of the decay constant directly, $f^2_{D^+_{(s)}}$ and $f_+^2(q^2)$, and also the two CKM matrix elements, $|V_{cd}|^2$ and $|V_{cs}|^2$. Improving the knowledge on these parameters opens the room to different field studies like testing the unitarity triangle with precise measurements of its element and testing lattice QCD [1] predictions. Moreover, it may be possible to look for evidence of Lepton Flavour Universality (LFU) violation in D decays, such as the one shown in B semileptionic decay [2–4]. It is worth mentioning that from these results it is possible to understand if New Physics may arise.

The Institute of High Energy Physics of Beijing hosts the Beijing Electron Positron Collider II (BEPCII) that works in the center-of-mass energy range from 2 GeV to 4.9 GeV, and that reached, in 2016, the peak luminosity of $\mathcal{L} = 10^{33} cm^{-2} s^{-1}$ at the $\psi(3770)$ energy threshold. On its only interaction point, there is the BEijing Spectrometer III (BESIII). It is an experiment, at its third generation, with a central geometry around the interaction point to cover 93% of the total 4π solid angle, and operating in a 1 T magnetic field, that allows the studies to be focused on flavour physics. The detector is composed, from the interaction point outward, of a Main Drift Chamber (MDC), a Time-of-Flight (TOF) detector, a CsI(Tl) electromagnetic calorimeter (EMC) and Resistive Plate Chambers as Muon Chambers (MUC). The detailed schematic and their performance parameters can be found in Ref [5].

Such an environment is suitable to tune the collision energy at the threshold opening of charmed mesons, working with a reduced hadronic background and consequently a simpler kinematics. BESIII uses a technique called *double-tag*: at first one D_s is reconstructed via well-studied hadronic decay modes as *tag* and then information on the signal side is extracted. In these analyses with (semi-)leptonic decays the missing mass due to the neutrino in the final state is calculated. The important variables in this process are the energy difference between the beam and the reconstructed candidate $\Delta E = E_{candidate} - E_{beam}$, to be sure that the right side of the decay is under study, and the mass constrained to the energy of the beam $M_{bc} = \sqrt{E^2_{beam} - p^2_{candidate}}$.

2. Leptonic Decays

2.1 $D_s^+ \to \tau^+\nu_\tau$ *via* $\tau^+ \to \pi^+\bar{\nu}_\tau$ *and* $D_s^+ \to \mu^+\nu_\mu$

These two decays are considered together due to pion and muon's similar masses: the selection to distinguish them is made from the energy-deposit in the EMC. Muons are the candidates with $E_{EMC} \leq 300\,\text{MeV}$ while the rest are identified as pions. Figure 2 shows the distributions of the invariant mass of the fully reconstructed D_s^- and the missing mass square (MM^2), where an unbinned maximum-likelihood fit is performed. The signal yield for $D_s^+ \to \tau^+\nu_\tau$ is (946^{+46}_{-45}) and for $D_s^+ \to \mu^+\nu_\mu$ is (2198 ± 55), where the uncertainties are only statistical. The branching fractions (BFs) measured are: $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.21 \pm 0.25 \pm 0.17) \times 10^{-2}$ and $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = (5.35 \pm 0.13 \pm 0.16) \times 10^{-3}$ [6]. To date, the result obtained for the $D_s^+ \to \mu^+\nu_\mu$ is the most precise measurement performed.

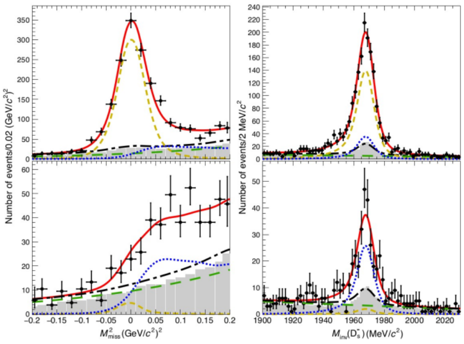


Figure 2: (Top) $D_s^+ \to \mu^+\nu_\mu$; (Btm) $D_s^+ \to \tau^+\nu_\tau$; (Left) MM^2; (Right) Tag Invariant Mass. Signal events: (Yellow) $D_s \to \mu\nu$; (Blue) $D_s \to \tau\nu$.

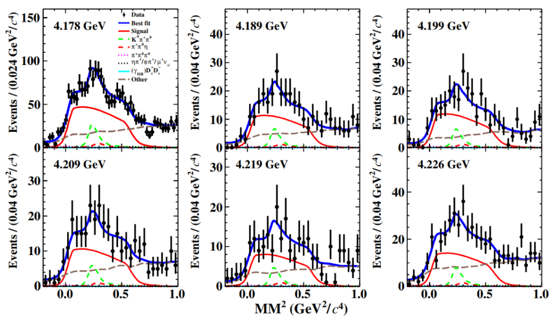


Figure 3: MM^2 for $D_s^+ \to \tau^+\nu_\tau$at different center-of-mass energies. The signal is the green dashed line.

2.2 $D_s^+ \to \tau^+\nu_\tau$ *via* $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$

This process is investigated by means of a simultaneous fit to MM^2 for the data samples at $\sqrt{s} = 4.178 - 4.226\,\text{GeV}$. The samples at different $\sqrt{s}$ share the common BF, knowing that the missing part is represented by the neutrinos that went undetected. Figure 3 shows the results where the signal yield is estimated to be (1745 ± 84) and the common leptonic decay BF is $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.29 \pm 0.25_{stat} \pm 0.20_{syst}) \times 10^{-2}$ [7].

2.3 $D_s^+ \to \tau^+\nu_\tau$ *via* $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$

This process is studied at the center-of-mass energies $\sqrt{s} = 4.178 - 4.226\,\text{GeV}$ with a sample corresponding to $6.32\,\text{fb}^{-1}$. The variable E^{tot}_{extra}, the total energy of the good electromagnetic showers, is used in this case, as shown in Figure 4, to overcome the fact that three massless neutrinos go undetected. The good showers are selected by excluding the showers associated with the fully reconstructed D_s^- candidate and those within 5° of the initial direction of the position. The amount of background is inferred by studying the sideband corresponding to $E^{tot}_{extra} > 0.6\,\text{GeV}$. Afterwards, it is subtracted from the signal region corresponding to $E^{tot}_{extra} < 0.4\,\text{GeV}$. The obtained signal yield is then converted into the BF: $\mathcal{B}(D_s^+ \to \tau^+\nu_\tau) = (5.27 \pm 0.10 \pm 0.12)\%$. To date, this is the most precise determination of this quantity [8].

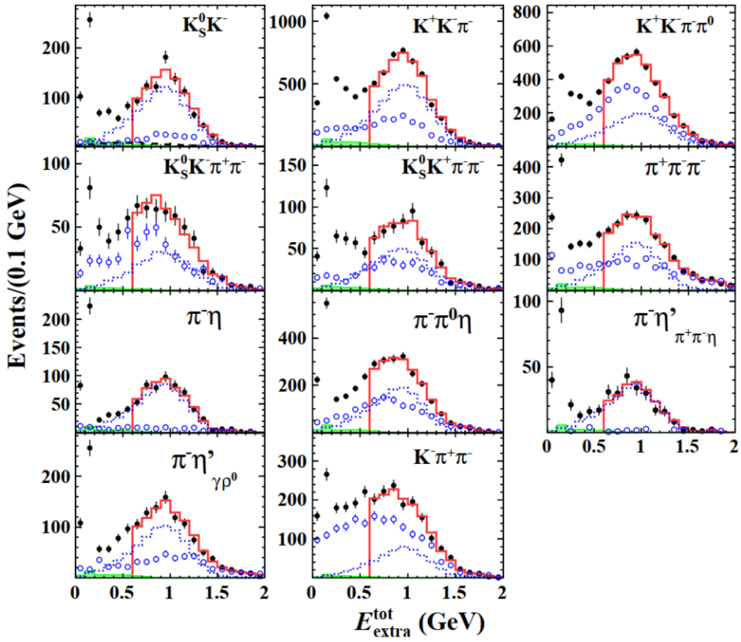


Figure 4: E_{extra}^{tot} distribution for different tag modes in $\tau e \nu_e \bar{\nu_\tau}$

2.4 LFU test, CKM matrix element and $f_{D_s^+}$ extraction

The combined results presented in this section, together with the world average values [9] allow $R = \frac{\mathcal{B}(D_s^+ \to \tau^+ \nu_\tau)}{\mathcal{B}(D_s^+ \to \mu^+ \nu_\mu)} = 9.67 \pm 0.34$ to be measured, finding it consistent with the SM prediction $R = 9.75 \pm 0.01$. No violation of the LFU is observed within the reported precision.
Moreover, with the values from the global SM fit [9] for the CKM matrix element ($|V_{cs}| = 0.97320 \pm 0.00011$) it is possible to extract the value $f_{D_s^+}$. Figure 5 presents the result compared to previous determinations of this quantity from other experiments.
The same procedure can be applied to determine $|V_{cs}|$, using as input the theoretical value $f_{D_s^+} = 149.9 \pm 0.5$ MeV from the Lattice QCD calculation. Figure 6 shows the obtained value and compare it with previous determinations from other experiments.

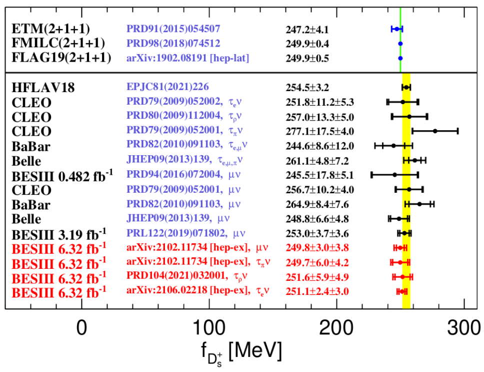


Figure 5: $f_{D_s^+}$ comparison between BESIII measurements and other results

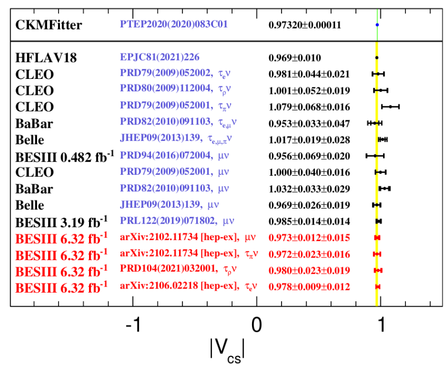


Figure 6: $|V_{cs}|$ comparison between BESIII measurements and other results

3. Semi-leptonic Decays

3.1 $D_0 \to \rho^- \mu^+ \nu_\mu$

The observation of this process is performed for the first time [11], determining $\mathcal{B}(D^0 \to \rho^- \mu^+ \nu_\mu) = (1.35 \pm 0.09_{syst} \pm 0.09_{stat}) \times 10^{-3}$, despite a large contribution from peaking background (Figure 7). Also in this case it is possible to extract the value $|V_{cs}| = (0.204 \pm 0.007_{syst} \pm 0.007_{stat} \pm 0.014_{theory})$ using theoretical inputs. Moreover, using the world average value of $\mathcal{B}(D^0 \to \rho^- e^+ \nu_e)$ [9], the ratio $\frac{\mathcal{B}(D^0 \to \rho^- \mu^+ \nu_\mu)}{\mathcal{B}(D^0 \to \rho^- e^+ \nu_e)} = (0.90 \pm 0.11)$ is obtained, without finding any evidence of LFU violation. Additional information can be obtained using the ratio $\frac{\Gamma_{D^+ \to \rho^0 \mu^+ \nu_\mu}}{2\Gamma_{D^0 \to \rho^- \mu^+ \nu_\mu}} = 0.71 \pm 0.14$ which, within 2.1 σ, is consistent with the isospin symmetry expectation of one.

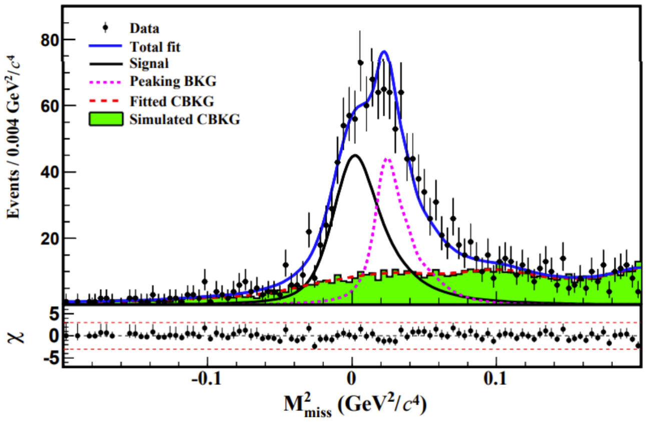


Figure 7: MM^2 for $D^0 \to \rho^- \mu^+ \nu_\mu$ data. The black line is the semileptonic signal, the pink line is the peaking background of $D^0 \to \pi^+ \pi^- \pi^0 \pi^0$.

3.2 $D_s^+ \to \pi^0 \pi^0 e^+ \nu_e$ and $D_s^+ \to K_s^0 K_s^0 e^+ \nu_e$

The data analysed for this result correspond to an integrated luminosity of 6.32 fb^{-1} at the center-of-mass energies $\sqrt{s} = 4.178 - 4.226$ GeV. The distributions of the invariant masses are presented in Figures 8 and 9. The measured quantity [12] $\mathcal{B}(D_s^+ \to f_0 e^+ \nu_e, f_0 \to \pi^0 \pi^0) = (7.9 \pm 0.4_{syst} \pm 1.4_{stat}) \times 10^{-4}$, according to $\frac{\mathcal{B}(f_0 \to \pi^0 \pi^0)}{\mathcal{B}(f_0 \to \pi^+ \pi^-)} = 0.5$ expectation, has been proved to be consistent with the previous measurement from the CLEO collaboration [13]. In the same work, an upper limit is calculated for $\mathcal{B}(D_s^+ \to \sigma (\to \pi^0 \pi^0) e^+ \nu_e) < 7.3 \times 10^{-4}$ with 90% C.L. and this result follows, for f_0 and σ_0 mesons, the four-quark structure or meson-meson interaction hypothesis. However, due to large uncertainties on the σ parametrization, the results are still not conclusive. Finally, the upper limit for $\mathcal{B}(D_s^+ \to f_0 e^+ \nu_e, f_0 \to K_s^0 K_s^0)$ is set to be 3.8×10^{-4} at 90% C.L.. Such a result indicates that its contribution is negligible with respect to $\mathcal{B}(f_0 \to \pi^0 \pi^0)$. Running under the hypothesis that $\mathcal{B}(f_0 \to \pi^0 \pi^0)$ contributes 1/3 of the f_0 decays, the result $\mathcal{B}(D_s^+ \to f_0(980) e^+ \nu_e) = (2.4 \pm 0.4) \times 10^{-3}$ is consistent with the hypothesis [14, 15] of $f_0(980)$ being an admixture of $s\bar{s}$ and other light quark-antiquark pairs.

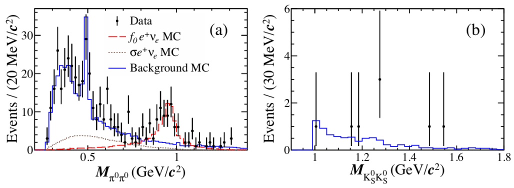


Figure 8: Pseudoscalar (P) pairs invariant mass in $D_s^+ \to PPe\nu$. (Left) $\pi^0\pi^0$ invariant mass; (Right) $K_s^0K_s^0$ invariant mass.

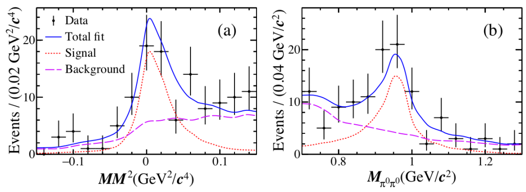


Figure 9: Zoom for the $f_0(980)$ signal extraction in $D_s^+ \to \pi^0\pi^0 e\nu_e$. The signal is represented by the red line. (Left) MM^2; (Right) Invariant mass of $\pi^0\pi^0$, that peaks at $f_0(980)$ mass

4. Conclusions

BESIII has proven capable of measuring with high precision (semi-)leptonic $D_{(s)}$ decays thanks to the clean environment provided by e^+e^- collisions at threshold. At present time, the BESIII measurements are either the first or the most precise ones for many final states. In the future, with 20 fb^{-1} at 3.773 GeV and further data above 4.178 GeV, BESIII will continue the exploration of these decays to search for LFU violation, to measure CKM matrix elements, and to test Lattice QCD calculations.

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