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Semi-leptonic and leptonic $D^{0(+)}$ and D_s decays at BESIII

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Precision measurements of the $|V_{cs}|$ matrix element are crucial to test the unitarity of the CKM matrix. D and D_s decays are one of the best environments to perform such measurements. Moreover, an improved knowledge of the D/D_s decay can help to calibrate the LQCD calculations. The BESIII Experiment at Beijing Electron Positron Collider II (BEPC-II) has accumulated the world′s largest e^+e^- collision samples at 3.773 and 4.178 GeV. In this presentation, we report the measurement of leptonic and semileptonic $D^{0(+)}$ and D_s decay at BESIII, with focus on $|V_{cs}|$ determination, form factor and decay constant estimations. In addition, we report the LFU test in $D \to \pi l \nu$ decays.

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1. Physics motivation

During the last years, leptonic and semi-leptonic decays of heavy-flavor mesons are the ideal laboratory to test the knowledge of strong and electroweak interactions. Two examples of the Feynman diagram that are used to describes such processes can be found in Fig. 1.

Figure 1: Example of Feynman diagram: (left) D_s^+ meson leptonic decay; (right) D meson semileptonic decay to pseudoscalar meson-electron-neutrino.

Indeed, the branching ratio of these decays can be easily factorized by a product of the two interactions and later, with an external output from the theory, test the parameter of interest. A typical example of a differential decay rate of a semileptonic decay is expressed by the following formula:

$$\frac{d\Gamma}{dq^2} = X\frac{G_F^2}{24\pi^3}|V_{CKM}|^2 p^3 |f(q^2)|^2, \tag{1.1}$$

where X represents the products of other terms, G_F is the Fermi constant, V_{CKM} is the Cabibbo-Maskawa-Kobayashi matrix element, and $f(q^2)$ is the hadronic form factor and q is the transferred 4-momentum. For the case of leptonic decay, the hadronic form factor is missing, since there are no hadrons in the final state.

In particular, for the case of D and D_s mesons, it is possible to access to the $|V_{cd}|$ and $|V_{cs}|$ matrix elements. A precise knowledge of these element can help test the unitary of the CKM triangle. On the other hand, it is possible to test the Lattice QCD [1] predictions and tuning the result by extracting the new or more precise form factors or decay constants. Moreover, recent results [2, 3, 4] shows an evidence of Lepton Flavour Universality (LFU) violation in B semileptonic decay. In addition to study more precisely the B decays, it is possible to search for such violation in D decays, to understand if some New Physics may arise from these results.

2. BESIII @ BEPCII

BEijing Spectrometer III (BESIII) is the third upgrade of a detector hosted at the Beijing Electron Positron Collider II (BEPCII), at the Institute of High Energy Physics of Beijing, PRC. The BEPCII collider can provide collisions in center of mass energy range from 2 to 4.6 GeV with a peak luminosity at $\psi(3770)$ of $\mathscr{L} = 10^{33} cm^{-2} s^{-1}$, that was reached during the 2016 data taking. The design of the detector follows the principle for central detector optimized for flavour physics. It is divided in a barrel and two endcap to cover a total solid angle of 93% of 4π. The main drift chambers (MDC) associated with the 1 T magnetic field allows to measure the charged particle charge, position, and momentum with spatial resolution for single wire of $\sigma_{wire} = 130\,\mu$m and momentum resolution of $\sigma_{p_T}/p_T = 0.5\%$ for 1 GeV/c particles. Time-of-Flight (TOF) detectors participate to the particle identification with a time resolution of 90 ps and 68 ps in the barrel and in the endcap part respectively. A CsI(Tl) electromagnetic calorimeter is used to measure the energy of neutral and charged particle with a energy resolution of $dE/\sqrt{E} = 2.5\%$ for 1 GeV particles. Last, Resistive Plate Chambers operates as Muon Chambers (MUC), that guarantees the muon identification down to momenta equal to 0.4 GeV with good position resolution ($\delta_{r\phi} = 1.4 - 1.7\,\mathrm{cm}$). More details can be found in Ref. [5].

2.1 Charmed meson analyses at BESIII

BEPCII can shift the center of mass energy in the whole energy range available. For the study of charmed mesons it is possible to tune the collisions energy to be exactly at the threshold opening of charmed mesons. This allows to reduce largely the hadronic background and the kinematics is quite simple. On the other hand, this proves also to be a challenge for the detector, since the decay products may have low momenta and thus be much more complicated to be reconstructed.

Thanks to the fact that charmed mesons are produced in pairs at threshold, and since the neutrino cannot be reconstructed, at BESIII it is possible to analyse the data in the so-called *double-tag* mode: first one side of the decay is reconstructed with the hadronic decays; later, from the all the remaining events, the (semi-)leptonic decay is searched by studying the missing mass, that shall peak at zero. Two important variables can be defined: $\Delta E = E_{candidate} - E_{beam}$, that is the energy difference between the beam and the reconstructed candidate and it used to be sure that the reconstructed tracks belong to the proper side of the decay; $M_{bc} = \sqrt{E_{beam}^2 - p_{candidate}^2}$, that is the mass constrained to the energy of the beam.

3. D meson decay

BESIII has collected the world's largest sample of $\psi(3770)$ to perform measurements on D mesons decays. The $2.93\,\mathrm{fb}^{-1}$ data sample corresponds to 21 millions D^0 pairs and 16 millions charged D pairs.

3.1 Measurement of $D^+ \to \bar{K}^0/\pi^0 e^+\nu_e$

The study of $D \to Pe^+\nu_e$, where P can be π^0 or $\bar{K}^0$ can be described with Eq. 1, where X represents a correction for the isospin, and it is equal to 1 and 1/2 for the decay that includes the $\bar{K}^0$ and the π^0 respectively. In this work [6], the D^- tag were reconstructed in nine hadronic decay modes following the criteria described in Ref. [7]. The total of $N_{tag} = 1703054 \pm 3405$ events were tagged. The semileptonic decays were searched then in this sample of events. The distribution of the missing mass resulting from the selections is shown in Fig. 2.

The background shape is extracted from the MC simulation to properly extract the number of events. The branching ration are then extracted using the following formula

$$B(D^+ \to Pe^+\nu_e) = \frac{N_{obs}(D^+ \to Pe^+\nu_e)}{N_{tag}\varepsilon(D^+ \to Pe^+\nu_e)}$$

where $N_{obs}(D^+ \to Pe^+\nu_e)$ is the fitted number of events and $\varepsilon(D^+ \to Pe^+\nu_e)$ is the efficiency of the selections. The branching ratio are found to be $B(D^+ \to \bar{K}^0 e^+\nu_e) = (8.60 \pm 0.06 \pm 0.15) \times 10^{-2}$ and $B(D^+ \to \pi^0 e^+\nu_e) = (3.63 \pm 0.08 \pm 0.05) \times 10^{-3}$, where the first errors are statistical and the

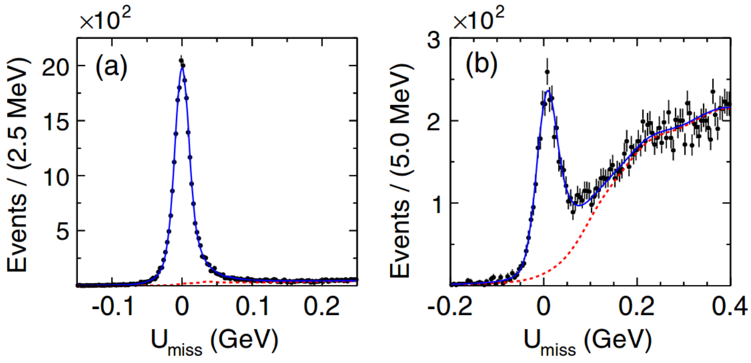

Figure 2: Missing mass distribution for the processes $D^+ \to \bar{K}^0 e^+ \nu_e$ and $D^+ \to \pi^0 e^+ \nu_e$ on the left and on the right plot respectively. The red dashed lines represent the background shape.

second systematic uncertainties. the value found are in good agreement with the isospin symmetry expectations. Both results are the world's most precise results to date.

By dividing the number of events in $q^2 = (E_{e^+} + E_{\nu_e})^2/c^4 - (\overrightarrow{p}_{e^+} + \overrightarrow{p}_{\nu_e})^2/c^2$ is possible to extract the $f_+(0)V_{cs(d)}$ term. The form factor is parametrized following the *series expansion* [8]. The q^2 is mapped through a new variable z following:

$$z(q^2,t_0) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}, \tag{3.1}$$

with $t_\pm = (m_{D*} \pm m_p)^2$ and $t_0 = t_+(1 - \sqrt{1 - t_-/t_+})$. The series is truncated at the second order. The form factor is then fitted to the q^2 bins using χ^2 minimizations. All the details can be found in the original paper [6]. The resulting values from the fit are shown in Tab. 1.

Decay mode	$f_+(0)\lvert V_{Ca}\rvert$
$D^+ \to \bar{K}^0 e^+ \nu_e$	$0.7053 \pm 0.0040 \pm 0.0112$
$D^+ \to \pi^0 e^+ \nu_e$	$0.1400 \pm 0.0026 \pm 0.0007$

Table 1: Result to the q^2 bin using series expansion at the second order.

3.2 Measurements of $D^0 \to \pi^- \mu^+ \nu_\mu$ and first measurement of $D^+ \to \pi^- \mu^+ \nu_\mu$

One of the most promising fields into the search of New Physics beyond the Standard Model is the study of Lepton Universality in semi-leptonic decay of pseudoscalar mesons. While in b quark sector the decay can be mediated either via Cabibbo-suppressed (CS) transition $b \to c$ or via flavour-changing-neutral-current (FCNC) transitions, in D meson decay the FCNC are highly suppressed by Glashow-Iliopoulos-Maiani mechanism and the CS semi-tauonic decays are kinematically forbidden. The most simplest decay to prove LU in D meson is then $D^{0(+)} \to \pi^{-(0)} l^+ \nu_l$, where l can be either an electron or a muon. Additionally, in the Standard Model the ratio $R_{LU}^{0(+)} = B_{\pi\mu\nu}^{0(+)}/B_{\pi e\nu}^{0(+)}$, where $B_{\pi\mu\nu}^{0(+)}$ is the branching ratio of $D^0 \to \pi^- \mu^+ \nu_\mu$ and $B_{\pi e\nu}^{0(+)}$ is the semi-electronic decay, is predicted to be $R_{LU}^{0(+)} = 0.97$. Recently BESIII has reported the measurement of the semi-electronic decay (see Sec. 3.1), while in the PDG [9] the measurement of the semi-muonic has an uncertainty of 10%, and the charged D decay has not yet been measured.

In this work [10] BESIII has reported the improved measurement of $B^0_{\pi\mu\nu}$ and the first measurement of $B^+_{\pi\mu\nu}$. The single tag measurements are different for the neutral and the charged D study. In the case of the D^0 decay, three $\bar{D}^0$ decay mode were reconstructed, while for the case of the D^- six decays mode are selected. The semi-leptonic decays are then searched as peak in the missing mass. Figure 3 shows the squared missing mass distributions for neutral and charged D meson decay on top and bottom respectively.

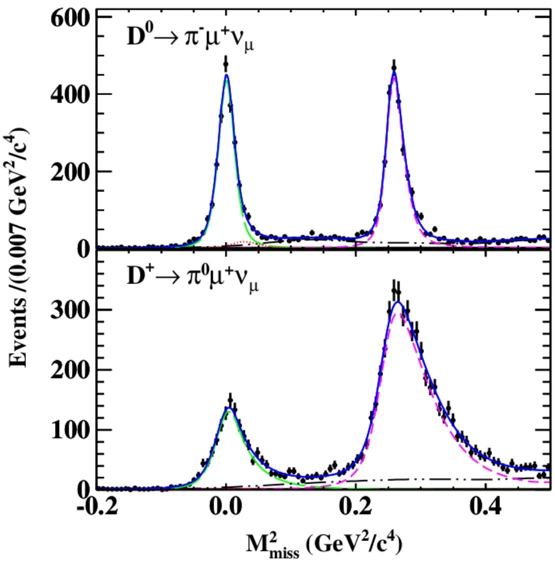

Figure 3: Squared missing mass distributions for the neutral and the charged D meson on top and bottom respectively. The second peaks represent the peaking $D^{0(+)} \to \pi^{-(0)}\pi^+\bar{K}^0$ background.

The second peaks in Fig. 3 represent $D^{0(+)} \to \pi^{-(0)}\pi^+\bar{K}^0$. To extract the proper number of events other background sources are taken in account: other peaking background (from MC studies $D^0 \to K\cdot\pi^+$, $D^{0(+)} \to \pi^{-(0)}\pi^+$ and $D^{0(+)} \to \pi^{-(0)}\pi^+\pi^0$ are expected to peak around $0.02\,\mathrm{GeV}^2/c^4$ just under the right of the signal) and non-peaking background. All the background are parametrized by the respective MC-simulated shapes. The signal-to-background ratio is fixed, except for the $D^{0(+)} \to \pi^{-(0)}\pi^+\pi^0$ that is well separated from the signal.

The final branching ratio are extracted using the following formula:

$$B^{0(+)}_{\pi\mu\nu} = N^{0(+)}_{DT}/(N^{0(+)}_{ST}\,\bar{\varepsilon}^{0(+)}_{\pi\mu\nu}),$$

where $N^{0(+)}_{DT}$ and $N^{0(+)}_{ST}$ are respectively the single tag and double tag yields, $\bar{\varepsilon}^{0(+)}_{\pi\mu\nu}$ is the single tag yield weighted average efficiency

$$\bar{\varepsilon}^{0(+)}_{\pi\mu\nu} = \sum_i (N^{0(+)}_{ST,i}\,\varepsilon^{0(+)}_{\pi\mu\nu,i}/N^{0(+)}_{ST,i},$$

where $\varepsilon^{0(+)}_{\pi\mu\nu,i} = \varepsilon^0(+)_{DT,i}/\varepsilon^0(+)_{ST,i}$, $\varepsilon^0(+)_{ST,i}$ is the efficiency of selecting the i-th tag mode and $\varepsilon^0(+)_{DT,i}$ is the efficiency of reconstructing both the signal and the i-th tag mode simultaneously. The resulting branching ratio are

$B^0_{\pi\mu\nu} = (0.267 \pm 0.007_{stat} \pm 0.007_{syst})\%$ and $B^+_{\pi\mu\nu} = (0.342 \pm 0.011_{stat} \pm 0.010_{syst})\%$. The $B^0_{\pi\mu\nu}$ result is consistent with the world average result, but with much better improvement, while $B^+_{\pi\mu\nu}$ is measured for the first time.

Combining these results with the previous BESIII measurement [11, 6] $B^0_{\pi e\nu} = (0.295 \pm 0.004_{stat} \pm 0.003_{syst})\%$ and $B^+_{\pi e\nu} = (0.363 \pm 0.008_{stat} \pm 0.005_{syst})\%$, it is possible to obtain

$$R^0_{LU} = (0.905 \pm 0.027_{stat} \pm 0.023_{syst})$$

and

$$R^+_{LU} = (0.942 \pm 0.037_{stat} \pm 0.027_{syst}).$$

These results agree with the theoretical expectation of 0.97 within $1.9\sigma(0.6\sigma)$. These are the first searches for LU violation in D decays.

4. D_s decays

BESIII has collected two data samples for D_s studies: one directly at $D_s\bar{D}_s$ threshold and one at $D^*_s\bar{D}_s$ threshold. The latter provides a much larger statistics with respect to the former, since the production cross section is higher: moreover $B(D^*_s \to \gamma D_s) = (93.5 \pm 0.7)\%$, so it can be easily reconstructed.

4.1 Measurement of $D^+_s \to l^+\nu_l$

This analysis [12] is performed with the $482\,\mathrm{pb}^{-1}$ sample at 4.009 GeV, *i.e.* the threshold for $D_s\bar{D}_s$ production. It is an example of W-annihilation process that can be easily calculated both experimentally and theoretically. The decay rate is predicted [13] to be

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

where $m_{D^+_s}$ is the D^+_s mass, G_F is the Fermi coupling constant, and $f_{D^+_s}$ is the decay constant. Due to chirality conservation, the process is much more suppressed for lighter leptons that for the heavier, so that the ratio is expected to be $e^+\nu_e : \mu^+\nu_\mu : \tau^+\nu_\tau = 2 \times 10^{-5} : 1 : 10$. In this analysis the decays to $\mu^+\nu_\mu$ and $\tau^+\nu_\tau$ are measured. Moreover, based on PDG averages [9], there is a discrepancy between the experimental $f_{D^+_s} = (257.5 \pm 4.6)\,\mathrm{MeV}$ and the one extracted from the combination of (2+1)- and (2+1+1)-flavour lattice QCD results $f^{LQCD}_{D^+_s} = (249.0 \pm 1.2)\,\mathrm{MeV}$ [1]. BESIII can update the experimental measurement in order to test this discrepancy.

Nine hadronic decay modes are selected in the $\bar{D}^-_s$ tag side. The total overall number of tag side events is $N_{ST} = 15127 \pm 321$. The τ leptons are reconstructed via the process $\tau \to \pi^+\bar{\nu}_\tau$ so that in the final events there will be two missing neutrinos. It is possible to fit the signal events with two possible hypotheses. First, the relative number of events are fixed to the Standard Model ratio:

$$R \equiv \frac{\Gamma(D^+_s \to \tau^+\nu_\tau)}{\Gamma(D^+_s \to \mu^+\nu_\mu)} = \frac{m^2_{\tau^+}\left(1 - \frac{m^2_{\tau^+}}{m^2_{D^+_s}}\right)}{m^2_{\mu^+}\left(1 - \frac{m^2_{\mu^+}}{m^2_{D^+_s}}\right)} = 9.76.$$

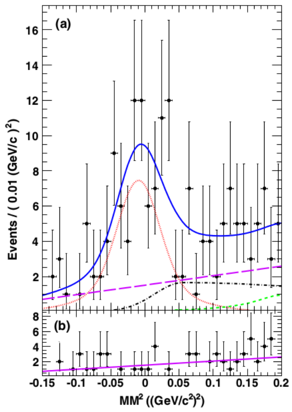

Figure 4: Standard Model constrained fit to squared missing mass. The blue line is the total fit, while the red dotted and black dash-dotted lines represent the $\mu\nu_\mu$ and the $\tau\nu_\tau$ final state respectively. The background is extracted from the simultaneous fit to the sideband, shown in the bottom part of the plot.

The fit is shown in Fig. 4, and the results are $B(D_s^+ \to \tau^+\nu_\tau) = (4.83 \pm 0.65 \pm 0.26)\%$ and $B(D_s^+ \to \mu^+\nu_\mu) = (0.495 \pm 0.067 \pm 0.026)\%$.

To test if any possible LU violation may arise, a simultaneous fit to three separated sample based on MUC and EMC information. The fit is performed by leaving floating the ratio between the two leptonic decay, but constraining the relative samples in the three samples by looking at the relative distribution of pions and muons in $e^+e^- \to \mu^+\mu^-$ and $\psi(2S) \to \pi^+\pi^- J/\psi(J/\psi \to \rho\pi)$. The result of this fit are $B(D_s^+ \to \tau^+\nu_\tau) = (3.28 \pm 1.83 \pm 0.37)\%$ and $B(D_s^+ \to \mu^+\nu_\mu) = (0.517 \pm 0.075 \pm 0.021)\%$. The branching ratio of $D_s^+ \to \tau^+\nu_\tau$ is 1.5σ larger than in the PDG. By taking the Standard model fit is possible to extract $f_{D_s^+} = (241.0 \pm 16.3 \pm 6.6)$ MeV, in good agreement with lattice QCD calculation.

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