Charm Meson Physics at BESIII

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Based on 2.93 fb^{-1} data taken at the center-of-mass energy of $\sqrt{s} = 3.773 \text{ GeV}$ with the BESIII detector at the BEPCII collider, we report the precise measurements of the decay constant f_{D^+} , the form factors of D semileptonic decays $D^0 \rightarrow K(\pi)^- e^+ \nu_e$ and $D^+ \rightarrow K^- \pi^+ e^+ \nu_e$, the Dalitz plot analysis of $D^+ \rightarrow K_S^0 \pi^+ \pi^0$, the strong phase measurement in $D^0 \rightarrow K^- \pi^+$ and the $D^0 \bar{D}^0$ mixing parameter y_{CP} .

1. Introduction

Precision measurements of charm decays provide rich information to better understand strong and weak effects. Firstly, the differential decay rates of the D leptonic and semileptonic decays can be simply functioned as decay constant f_{D^+} or form factors and CKM matrix element $|V_{cs(d)}|$. From analysis of the D leptonic and semileptonic decays, we can determine these elementary constants, thus calibrating the LQCD calculation on f_{D^+} and the form factors and testing the CKM matrix unitarity.

Secondly, studies of D hadronic decays are important due to several aspects. At $\psi(3770)$ resonance peak, the quantum correction property of D^0 meson production provides an access to CP asymmetry in $D^0 \bar{D}^0$ mixing and strong phase parameters which can be used to constrain γ/ϕ_3 and to further test the CKM matrix unitarity. Dalitz plot analysis of three-body decays can provide rich information about the parameters of sub-resonances and strong phases.

Thirdly, in the Standard Model (SM), the Flavor Changed Neutral Current (FCNC) process and the Leptonic Number Violation (LNV) process are highly suppressed. However, some new dynamics beyond the SM may enhance these kinds of processes to observable level at BESIII. So, search for these rare decays can be

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used to probe for new physics beyond the SM. Any evidence of rare decay and CP violation in charm decays or significant deviation of CKM unitarity may indicate new physics beyond the SM.

In this work, we report some results based on the studies of the leptonic, semileptonic and hadronic decays of D^0 and D^+ mesons at BESIII. These results are obtained by studying the 2.93 fb^{-1} data ¹ at $\sqrt{s} = 3.773 \text{ GeV}$ collected with the BESIII detector ². The charge conjugation is always implied.

2. D leptonic and semileptonic decay

In the Standard Model, the D^+ mesons decay into $\ell\nu_\ell$ via a virtual W^+ boson. The decay rate of the leptonic decays $D^+ \rightarrow \ell^+\nu_\ell$ can be parameterized by the D^+ decay constant f_{D^+} via

$$\Gamma(D^+ \rightarrow \ell^+\nu_\ell) = \frac{G_F^2}{8\pi} |V_{cd}|^2 f_{D^+}^2 m_\ell^2 m_{D^+} (1 - \frac{m_\ell^2}{m_{D^+}^2}), \quad (1)$$

where G_F is the Fermi coupling constant, $|V_{cd}|$ is the quark mixing matrix element, m_ℓ and m_{D^+} are the lepton and D^+ masses. To investigate the leptonic decay $D^+ \rightarrow \mu^+\nu_\mu$ ³, the singly tagged D^- mesons are reconstructed using 9 hadronic decays $K^+\pi^-\pi^-$, $K_S^0\pi^-$, $K_S^0K^-$, $K^+K^-\pi^-$, $K^+\pi^-\pi^-\pi^0$, $\pi^+\pi^-\pi^-$, $K_S^0\pi^-\pi^0$, $K^+\pi^+\pi^-\pi^-\pi^-$ and $K_S^0\pi^+\pi^-\pi^-$. From these, we accumulate $(170.31 \pm 0.34) \times 10^4$ singly tagged D^- mesons. Fig. 1 shows the M_{miss}^2 distribution of the $D^+ \rightarrow \mu^+\nu_\mu$ candidates, which are selected in the systems against the singly tagged D^- mesons. We obtain 409 ± 21 net $D^+ \rightarrow \mu^+\nu_\mu$ signals and measured the branching fraction $\mathcal{B}(D^+ \rightarrow \mu^+\nu_\mu) = (3.71 \pm 0.19_{\text{stat.}} \pm 0.06_{\text{sys.}}) \times 10^{-4}$. Using the measured $\mathcal{B}(D^+ \rightarrow \mu^+\nu_\mu)$ and the quark mixing matrix element $|V_{cd}|$ from a global Standard Model fit, we determine the D^+ decay constant $f_{D^+} = 203.2 \pm 5.3_{\text{stat.}} \pm 1.8_{\text{sys.}} \text{ MeV}$. The $\mathcal{B}(D^+ \rightarrow \mu^+\nu_\mu)$ and f_{D^+} measured at BESIII are consistent within errors with previous measurements, but with the best precision. By using the measured $\mathcal{B}(D^+ \rightarrow \mu^+\nu_\mu)$ and the LQCD calculation on f_{D^+} ⁴, we determine $|V_{cd}| = 0.2210 \pm 0.058_{\text{stat.}} \pm 0.047_{\text{sys.}}$, which has the best precision in the world to date.

On the other hand, the D semileptonic decays can be parameterized by the quark mixing matrix element and the form factor of hadronic weak current simply, thus providing an ideal window to probe for the weak and strong effects. For example, the differential decay rates of $D \rightarrow K(\pi)e^+\nu_e$ can be simply written as

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cs(d)}|^2 p_{K(\pi)}^3 |f_+^{K(\pi)}(q^2)|^2, \quad (2)$$

where G_F is the Fermi coupling constant, $|V_{cs(d)}|$ is the quark mixing matrix element, $p_{K(\pi)}$ is the kaon(pion) momentum in the D^0 rest frame, $f_+^{K(\pi)}(q^2)$ is the form factor of hadronic weak current depending on the square of the four momentum transfer $q = p_D - p_{K(\pi)}$. To investigate the semileptonic decays $D^0 \rightarrow K(\pi)^-e^+\nu_e$ ⁵, we reconstruct the singly tagged $\bar{D}^0$ mesons using 5 hadronic decays of $K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^-\pi^+$, $K^+\pi^-\pi^-\pi^+\pi^0$ and $K^+\pi^-\pi^0\pi^0$, which give

 Fig. 1. The M_{miss}^2 distribution of $D^+ \rightarrow \mu^+ \nu_\mu$.

 Fig. 2. Fits to the partial widths of (a) $D^0 \rightarrow K^- e^+ \nu_e$ and (b) $D^0 \rightarrow \pi^- e^+ \nu_e$.

$(279.33 \pm 0.37) \times 10^4$ singly tagged $\bar{D}^0$ mesons. Base on 70727 ± 278 $D^0 \rightarrow K^- e^+ \nu_e$ and 6297 ± 87 and $D^0 \rightarrow \pi^- e^+ \nu_e$ signals, we determine the branching fractions $\mathcal{B}(D^0 \rightarrow K^- e^+ \nu_e) = (3.505 \pm 0.014_{\text{stat.}} \pm 0.033_{\text{sys.}})\%$ and $\mathcal{B}(D^0 \rightarrow \pi^- e^+ \nu_e) = (0.2950 \pm 0.0041_{\text{stat.}} \pm 0.0026_{\text{sys.}})\%$, respectively. The branching fractions measured at BESIII are consistent within errors with previous measurements, but with the best precision. Fig. 2 shows the fits to the partial widths for $D^0 \rightarrow K^- e^+ \nu_e$ and $D^0 \rightarrow \pi^- e^+ \nu_e$ using the Simple Pole model, the Modified Pole model, the two-parameter series expansion (Series.2.Par.) and the three-parameter series expansion (Series.3.Par.). From the fits, we obtain the parameters of different models. With the extracted $f_+^{K(\pi)}(0)|V_{cs(d)}|$ based on two-parameter series mixing expansion and the expected $f_+^{K(\pi)}(0)$ by LQCD^{6,7}, we determine the quark mixing matrix elements $|V_{cs(d)}|$.

To study the semileptonic decays $D^+ \rightarrow K_L^0 e^+ \nu_e$, $D^+ \rightarrow K^- \pi^+ e^+ \nu_e$ and $D^+ \rightarrow \omega(\phi) e^+ \nu_e$, we use 6 hadronic decays of $K^+ \pi^- \pi^-$, $K^+ \pi^- \pi^- \pi^0$, $K_S^0 \pi^-$, $K_S^0 \pi^- \pi^0$, $K_S^0 \pi^+ \pi^- \pi^-$ and $K^+ K^- \pi^-$. With about 24 thousands of $D^+ \rightarrow K_L^0 e^+ \nu_e$ signals⁸, we make first measurement of the branching fraction $\mathcal{B}(D^+ \rightarrow K_L^0 e^+ \nu_e) = (4.482 \pm$

$0.027_{\text{stat.}} \pm 0.103_{\text{sys.}}\%$ and the CP asymmetry $A_{\text{CP}}^{D^+ \rightarrow K_L^0 e^+ \nu_e} = (-0.59 \pm 0.60_{\text{stat.}} \pm 1.50_{\text{sys.}})\%$, supporting that there is no CP asymmetry in this decay. In addition, we perform simultaneous fit to the event density $I(q^2)$ for different tag modes with the two-parameter series expansion and obtain the product of $f_+^K(0)|V_{cs}| = 0.728 \pm 0.006_{\text{stat.}} \pm 0.011_{\text{sys.}}$.

Using 18262 $D^+ \rightarrow K^- \pi^+ e^+ \nu_e$ candidates⁹ which is almost background free, we determine the branching fraction $\mathcal{B}(D^+ \rightarrow K^- \pi^+ e^+ \nu_e) = (3.77 \pm 0.03 \pm 0.08)\%$. A partial wave analysis (PWA) is performed on the selected candidates, with results shown in Fig. 3. The PWA results show that the dominant $\bar{K}^{*0}$ component is accompanied by an S -wave contribution accounting for $(6.05 \pm 0.22 \pm 0.18)\%$ of the total rate, and other components can be negligible. We obtain the mass and width of $\bar{K}^{*0}(892)$ $M_{\bar{K}^{*0}(892)} = (894.60 \pm 0.25 \pm 0.08) \text{ MeV}/c^2$ and $\Gamma_{\bar{K}^{*0}(892)} = (46.42 \pm 0.56 \pm 0.15) \text{ MeV}/c^2$, the Blatt-Weisskopf parameter $r_{\text{BW}} = 3.07 \pm 0.26 \pm 0.11 (\text{GeV}/c)^{-1}$, as well as the parameters of the hadronic form factors $r_V = \frac{V(0)}{A_1(0)} = 1.411 \pm 0.058 \pm 0.007$, $r_2 = \frac{A_2(0)}{A_1(0)} = 0.788 \pm 0.042 \pm 0.008$, $m_V = (1.81_{-0.17}^{+0.25} \pm 0.02) \text{ MeV}/c^2$, $m_A = (2.61_{-0.17}^{+0.22} \pm 0.03) \text{ MeV}/c^2$, $A_1(0) = 0.589 \pm 0.010 \pm 0.012$. In the above PWA process, the phase of the non-resonant background $\delta_S(m_{K\pi})$ is factorized by the LASS parameterizations, and the helicity form factors $H_+(q^2, m_{K\pi})$, $H_-(q^2, m_{K\pi})$ and $H_0(q^2, m_{K\pi})$ are parameterized by the spectroscopic pole dominance (SPD) model. We also make model-independent measurements of the $\delta_S(m_{K\pi})$, and the helicity form factors, respectively. The results are consistent with the expectations of the corresponding models and previous measurements.

Based on 491 ± 32 $D^+ \rightarrow \omega e^+ \nu_e$ signals¹⁰, we determine the branching fraction $\mathcal{B}(D^+ \rightarrow \omega e^+ \nu_e) = (1.63 \pm 0.11_{\text{stat.}} \pm 0.08_{\text{sys.}}) \times 10^{-3}$, which is consistent with previous measurements but with better precision. We perform amplitude analysis of $D^+ \rightarrow \omega e^+ \nu_e$ for the first time, and obtain the ratios of the hadronic form factors to be $r_V = \frac{V(0)}{A_1(0)} = 1.24 \pm 0.09_{\text{stat.}} \pm 0.06_{\text{sys.}}$ and $r_2 = \frac{A_2(0)}{A_1(0)} = 1.05 \pm 0.15_{\text{stat.}} \pm 0.05_{\text{sys.}}$. Also, we search for $D^+ \rightarrow \phi e^+ \nu_e$, but do not find obvious signal. So, we set the upper limit on the branching fraction for $D^+ \rightarrow \phi e^+ \nu_e$ to be 1.3×10^{-5} at 90% Confidence Level, which is significantly better than previous searches.

3. D hadronic decays

We perform Dalitz plot analysis on the 3-body decay $D^+ \rightarrow K_S^0 \pi^+ \pi^0$ ¹¹. Based on 166694 candidate events with a background of about 15%, we fit the distribution of data to a coherent sum of six intermediate resonances plus a nonresonant component with a low mass scalar resonance $\bar{\kappa}$ included. From the analysis, we obtain the partial branching fractions for each component combining with the fitted fractions and the world averaged branching fraction for $D^+ \rightarrow K_S^0 \pi^+ \pi^0$ of $(6.99 \pm 0.27)\%$ ¹².

We determine the $D^0 \bar{D}^0$ mixing parameter $y_{\text{CP}} = (-2.1 \pm 1.3_{\text{stat.}} \pm 0.7_{\text{sys.}})\%$, by analysis of $D^0 \rightarrow K^- \ell^+ \nu_\ell$ ($\ell = e$ and μ) using the CP even tags $K^+ K^-$, $\pi^+ \pi^-$ and $K_S^0 \pi^0 \pi^0$, and the CP odd tags $K_S^0 \pi^0$, $K_S^0 \eta$ and $K_S^0 \omega$ ¹³. This result is compatible

Fig. 3. Projections of the kinematic variables of PWA for $D^+ \rightarrow K^- \pi^+ e^+ \nu_e$, where $m_{K\pi}$ is the $K\pi$ mass, q^2 is the $e\nu_e$ mass square, θ_K is the angle between π and D momenta in the $K\pi$ rest frame, θ_e is the angle between ν_e and D momenta in the $e\nu_e$ rest frame and χ is the angle between the two decay planes. The dots with error bars are data, the blue curves are the weighted signal MC and the hatched histograms are the simulated backgrounds.

with the previous measurement with about two standard deviations. However, the precision is still statistically limited and less precise than the current world average.

Measurement of the strong phase difference between D^0 and $\bar{D}^0$ is important to relate to the $D^0 \bar{D}^0$ mixing parameters x and y from x' and y' . We measure the $D \rightarrow K^- \pi^+$ strong phase difference based on analysis of $D^0 \rightarrow K^- \pi^+$ and $K^+ \pi^-$ using the CP even tags $K^+ K^-$, $\pi^+ \pi^-$, $K_S^0 \pi^0 \pi^0$, $\pi^0 \pi^0$ and $\rho^0 \pi^0$, and the CP odd tags $K_S^0 \pi^0$, $K_S^0 \eta$ and $K_S^0 \omega$ ¹⁴. We determine the asymmetry of $\mathcal{A}_{K\pi}^{\text{CP}}$ of the branching fraction of $D \rightarrow K^- \pi^+$ in CP-odd and CP-even eigenstates to be $(12.7 \pm 1.3 \pm 0.7)\%$. With external inputs of $r^2 = (3.50 \pm 0.04) \times 10^{-3}$, $y = (6.7 \pm 0.9) \times 10^{-3}$ from HFAG¹⁵ and $R_{WS} = (3.80 \pm 0.05) \times 10^{-3}$ from PDG¹². The $\cos \delta_{K\pi}$ is determined to be $1.02 \pm 0.11_{\text{stat.}} \pm 0.06_{\text{sys.}} \pm 0.01_{\text{input.}}$

4. D rare decays

Search for the FCNC and LNV rare decays of charmed mesons can shed some lights on new physics beyond the SM. At BESIII, we have searched for the rare decays of $D^0 \rightarrow \gamma\gamma$ ¹⁶ and $D^+ \rightarrow K(\pi)^\pm e^\mp e^+$ ¹⁷ with double and single tag methods, respectively. No significant signals are observed, thus we set the upper limits of their branching fractions to be $\mathcal{B}(D^0 \rightarrow \gamma\gamma) < 3.8 \times 10^{-6}$, $\mathcal{B}(D^+ \rightarrow K^+ e^+ e^-) < 1.2 \times 10^{-6}$, $\mathcal{B}(D^+ \rightarrow K^- e^+ e^+) < 0.6 \times 10^{-6}$, $\mathcal{B}(D^+ \rightarrow K^+ e^+ e^-) < 0.3 \times 10^{-6}$,

$\mathcal{B}(D^+ \rightarrow K^- e^+ e^+) < 1.2 \times 10^{-6}$ at 90% confidence level. Some of them are improved compared to previous measurements.

5. Summary

In conclusion, by analyzing 2.93 fb^{-1} data taken at $\sqrt{s} = 3.773 \text{ GeV}$ with the BESIII detector, we report the precise measurements of the decay constant f_{D^+} , the form factors of D semileptonic decays, the Dalitz plot analysis of $D^+ \rightarrow K_S^0 \pi^+ \pi^0$, the strong phase measurement in $D^0 \rightarrow K^- \pi^+$, the $D^0 \bar{D}^0$ mixing parameter y_{CP} . These are important to test the LQCD calculations on f_{D^+} and the form factors of D semileptonic decays, to test the CKM matrix unitarity, to search for new physics beyond the SM. More interesting physics based on charmed mesons are hopefully achieved at BESIII in the near future.

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