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Charm states at the BESIII experiment

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We present recent BESIII results about the study of mesons and baryons which contain at least one charm quark. We determined the $D^+_{(s)}$ decay constants, the form factors of D semi-leptonic decays, the CKM matrix elements $|V_{cs(d)}|$, the $D^+_{(s)}$ hadronic decays, and the search for charm rare decays. We measured the absolute branching fractions of Λ_c^+ baryon with a double tag technique, and the measured branching fractions for hadronic decays and semi-leptonic decays of Λ_c^+ are significantly improved.

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1. Introduction

The study of mesons and baryons which contain at least one charm quark is referred to as open charm physics. It offers the possibility to study up-type quark transitions. Since the c quark cannot be treated in any mass limit, theoretical predictions are difficult and experimental input is crucial. The at-threshold decay topology offers special opportunities to study open charm decays.

The BESIII is a magnetic spectrometer working at a double-ring e^+e^- collider operating at center-of-mass energy between 2.0 GeV and 4.6 GeV, located at the Institute of High Energy Physics (IHEP) in Beijing. The maximum luminosity of the BEPCII at 3.773 GeV is $1\times 10^{33}\text{cm}^{-2}\text{s}^{-1}$ [1]. The samples of interest for the analysis described in the following were taken at the $D\bar{D}$ threshold (3.773 GeV), $D_s^+D_s^-$ threshold (4.009 GeV) and $\Lambda_c^+\Lambda_c^-$ threshold (4.599 GeV) with integrated luminosities of 2.93 fb^{-1}, 0.482 fb^{-1} and 0.567 fb^{-1}, respectively. Throughout in the following, charge conjugate is implied.

2. Pure leptonic $D_{(s)}$ decays

The pure leptonic decay of charged $D^+_{(s)}$ mesons proceeds via the annihilation of the c quark and the anti-d (anti-s) quark to a virtual $W^{\pm}$ boson and its decay to $\ell^+\nu_\ell$. The decay rate can be parameterized as:

$$\Gamma(D^+_{(s)}\to\ell^+\nu_\ell)=\frac{G_F^2}{8\pi}f^2_{D_{(s)}}m_\ell^2 m_{D_{(s)}}(1-\frac{m_\ell^2}{m^2_{D_{(s)}}})^2|V_{cd(s)}|^2, \tag{2.1}$$

where G_F is the Fermi coupling constant, m_ℓ and $m_{D_{(s)}}$ are the masses of the lepton and the $D_{(s)}$ meson in the final state, respectively.

2.1 $D^+\to\mu^+\nu_\mu$

By analyzing the data sample accumulated at 3.773 GeV, we first selected the D^- meson sample from its hadronic decay modes, which is called singly tagged (ST) D^-. The $D^+\to\mu^+\nu_\mu$ decays are selected in the recoil side of the ST D^-. To select the leptonic D^+ decay with a missing neutrino, we calculated $U_{\text{miss}}=E_{\text{miss}}-p_{\text{miss}}$ or $M^2_{\text{miss}}=E^2_{\text{miss}}-p^2_{\text{miss}}$, where E_{miss} and p_{miss} are the missing energy and missing momentum of the event. Figure 1 shows the distribution of M^2_{miss}. After subtracting the backgrounds, 409.0 ± 21.2 signal events are retained and the branching fraction (BF) is measured to be $BF(D^+\to\mu^+\nu_\mu)=(3.71\pm0.19_{stat}\pm0.06_{syst})\times10^{-4}$, which is the most precise measurement to date. Combining this BF measurement and the Particle Data Group (PDG) [2] values of D^+ lifetime, m_{D^+}, m_μ and magnitude of $|V_{cd}|$ determined from the global Standard Model (SM) fit, the decay constant is determined to be $f_D=(203.2\pm5.3_{stat}\pm1.8_{syst})$ MeV. Alternatively, the magnitude of CKM matrix element V_{cd} is extracted to be $V_{cd}=0.2210\pm0.0058_{stat}\pm0.0047_{syst}$ [3].

2.2 Search for $D^+\to\gamma e^+\nu_e$ decays

We present the first search for the radiative leptonic decay $D^+\to\gamma e^+\nu_e$ using a data sample collected at $\sqrt{s}=3.773$ GeV. We search for the $D^+\to\gamma e^+\nu_e$ signal in the remaining charged tracks and showers recoiling against the ST D^- mesons. Figure 2 shows the distributions of U_{miss}. No

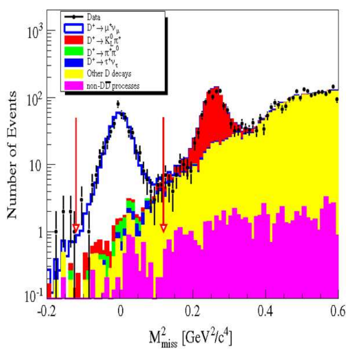

Figure 1: The $M^2_{\rm miss}$ distributions of the $D^+ \to \mu^+\nu_\mu$ candidates, where two arrows denote the signal region.

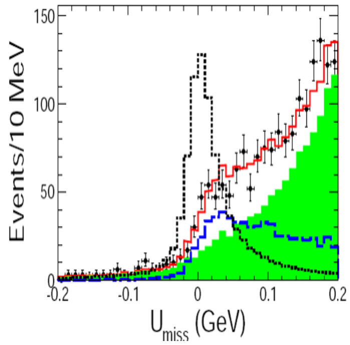

Figure 2: The $U_{\rm miss}$ distribution of the $D^+ \to \gamma e^+\nu_e$ candidates.

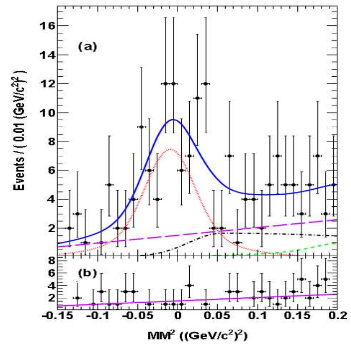

Figure 3: The $M^2_{\rm miss}$ distributions of the signal are (a), and the side-band region (b).

significant $D^+ \to \gamma e^+\nu_e$ signal is observed. With a 10 MeV cutoff on the radiative photon energy, the upper limit of the decay BF for $D^+ \to \gamma e^+\nu_e$ is $BF(D^+ \to \gamma e^+\nu_e) < 3.0\times 10^{-5}$ at the 90% C.L. [4]. The result approaches the theoretical predictions.

2.3 $D_s^+ \to \mu^+\nu_\mu$ and $D_s^+ \to \tau^+\nu_\tau$

By analyzing the data taken at 4.009 GeV, we also studied the leptonic D_s^+ decays. From nine D_s^- hadronic decay modes, 15127 ± 321 ST D_s^- mesons were accumulated. In the system recoiling against the ST D_s^-, the signal events of $D_s^+ \to \ell^+\nu_\ell$ ($\ell = \mu$, or τ) decays were selected. We obtained 69.3 ± 9.3 $D_s^+ \to \mu^+\nu_\mu$ and 32.5 ± 4.3 $D_s^+ \to \tau^+\nu_\tau$ events. The distribution of $M^2_{\rm miss}$ is shown in Fig. 3.

The results of BFs are determined to be $BF(D_s^+ \to \mu^+\nu_\mu) = (0.495\pm 0.067_{stat}\pm 0.026_{syst})\%$, $BF(D_s^+ \to \tau^+\nu_\tau) = (4.83\pm 0.65_{stat}\pm 0.26_{syst})\%$, and the decay constant $f_{D_s} = (241.0\pm 16.3_{stat}\pm 6.6_{syst})$ MeV [5].

3. Semi-leptonic $D_{(s)}$ decays

3.1 $D^{0(+)} \to Pe^+\nu_e$ ($P = K^-, \pi^-, K^0, \pi^0$)

In the SM, neglecting the lepton mass, the differential decay rate for $D^{0(+)} \to Pe^+\nu_e$ ($P = K^-, \pi^-, K^0$ or π^0) is given by

$$\frac{d\Gamma}{dq^2} = X\frac{G_F^2}{24\pi^3}|V_{\rm cd(s)}|^2 p^3 |f_+^P(q^2)|^2, \tag{3.1}$$

where X is a multiplicative factor due to isospin, which equals to 1 for modes $D^0 \to K^- e^+\nu_e$, $D^0 \to \pi^- e^+\nu_e$, $D^+ \to K^0 e^+\nu_e$, and 1/2 for mode $D^+ \to \pi^0 e^+\nu_e$, p is the momentum of the pseudo-scalar meson P in the rest frame of the D meson, q^2 is the squared four momentum transfer, i.e., the invariant mass of the electron and neutrino system, $f_+^P(q^2)$ is the form factor which describes the strong interaction between the final state quarks and is usually parameterized in data analysis.

Based on the data taken at 3.773 GeV, BESIII studies the dynamics of the $D^0 \to K^- e^+ \nu_e$ and $D^0 \to \pi^- e^+ \nu_e$ decays. The BFs are measured to be $BF(D^0 \to K^- e^+ \nu_e) = (3.505 \pm 0.014_{stat} \pm 0.033_{syst})\%$ and $BF(D^0 \to \pi^- e^+ \nu_e) = (0.295 \pm 0.004_{stat} \pm 0.003_{syst})\%$ [6]. Similarly, the BFs are measured to be $BF(D^+ \to \bar{K}^0 e^+ \nu_e) = (8.60 \pm 0.06_{stat} \pm 0.15_{syst})\%$ and $BF(D^+ \to \pi^0 e^+ \nu_e) = (0.363 \pm 0.008_{stat} \pm 0.005_{syst})\%$ [7].

We also studied the differential decay rates of these two processes. Figures 4 and 5 show the fit results. We extract the product $f_+(0)|V_{cs(d)}|$ and other form factor parameters. Using the values for $f_+^{K(\pi)}(0)|V_{cs(d)}|$ from the two-parameter z-series expansion fits and with $f_+^K(0) = 0.747 \pm 0.011 \pm 0.015$ [8] and $f_+^\pi(0) = 0.666 \pm 0.020 \pm 0.021$ [9] calculated in LQCD, $|V_{cs}|$ is obtained to be $0.9601 \pm 0.0033 \pm 0.0047 \pm 0.0239$ ($|V_{cd}| = 0.2155 \pm 0.0027 \pm 0.0014 \pm 0.0094$), where the first uncertainties are statistical, the second ones systematic, and the third ones are due to the theoretical uncertainties in the form factor calculations. The BESIII results are in good agreement with the previous measurements, and with the best precision to date.

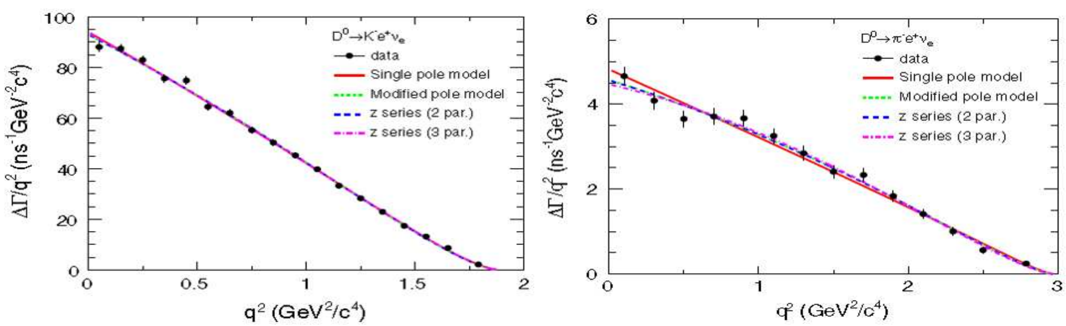

Figure 4: Fits to partial decay widths of $D^0 \to K^- e^+ \nu_e$ (left) and $D^0 \to \pi^- e^+ \nu_e$ (right).

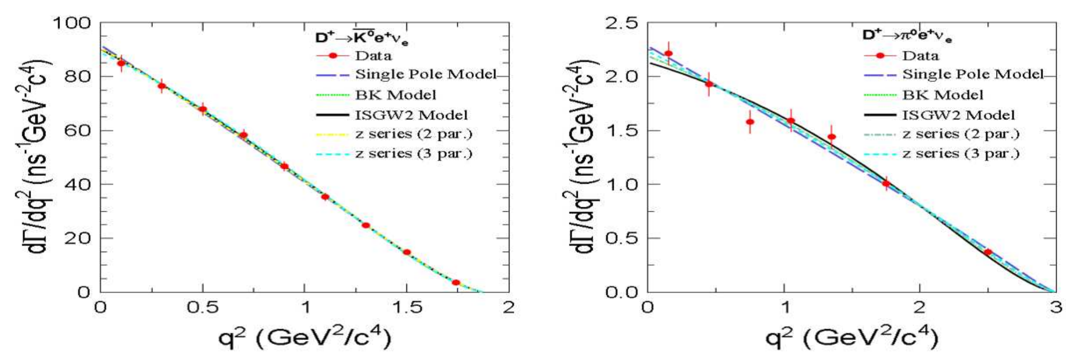

Figure 5: Fits to partial decay widths of $D^+ \to \bar{K}^0 e^+ \nu_e$ (left) and $D^+ \to \pi^0 e^+ \nu_e$ (right).

3.2 $D_s^+ \to \eta(\eta') e^+ \nu_e$

By analyzing the data taken at 4.009 GeV, BESIII studied the semi-leptonic $D_s^+ \to \eta(\eta') e^+ \nu_e$ decays [10]. The information of the signal candidate is inferred from the variable U_{miss}. Figure 6 shows the distributions of U_{miss}.

After subtracting the backgrounds, 58.5 ± 8.0 $D_s^+ \to \eta e^+ \nu_e$ candidates, 3.8 ± 2.0 $D_s^+ \to \eta'(\eta\pi^+\pi^-)e^+\nu_e$ candidates and 8.2 ± 3.2 $D_s^+ \to \eta'(\gamma\rho^0)e^+\nu_e$ candidates are retained, respectively. The BFs are determined to be $BF(D_s^+ \to \eta e^+ \nu_e) = (2.30 \pm 0.31_{stat} \pm 0.08_{syst})\%$ and $BF(D_s^+ \to \eta' e^+ \nu_e) = (0.93 \pm 0.30_{stat} \pm 0.05_{syst})\%$, which are consistent with previous measurements within uncertainties. Combining the BF measurements, we obtain the ratio $BF(D_s^+ \to \eta' e^+ \nu_e)/BF(D_s^+ \to \eta e^+ \nu_e) = 0.40 \pm 0.14_{stat} \pm 0.02_{syst}$, which provides complementary information to understand η-η' mixing.

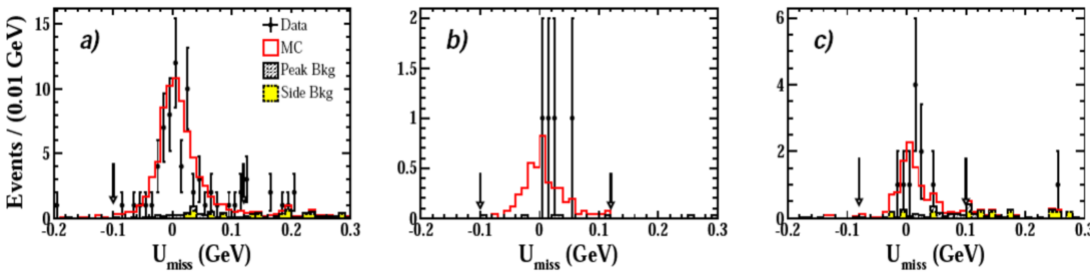

Figure 6: The $U_{\rm miss}$ distributions of the (a) $D^+ \to \mu^+ \nu_\mu$, (b) $D_s^+ \to \eta'(\eta\pi^+\pi^-)e^+\nu_e$ and (c) $D_s^+ \to \eta'(\gamma\rho^0)e^+\nu_e$ candidates. The arrows denote the signal region.

4. Hadronic D decays

An amplitude analysis of the decay $D^0 \to K^-\pi^+\pi^+\pi-$ has been performed with the data at $\sqrt{s} = 3.773$ GeV. With a nearly background free sample of about 16000 events, we investigate the substructure of the decay and determine the relative fractions and the phases among the different intermediate processes. Our amplitude model includes the two-body decays $D^0 \to \bar{K}^{*0}\rho^0$, $D^0 \to K^- a_1^+(1260)$ and $D^0 \to K_1^-(1270)\pi^+$, the three-body decays $D^0 \to \bar{K}^{*0}\pi^+\pi^-$, $D^0 \to K^-\pi^+\rho^0$, as well as the four-body non-resonant decay $D^0 \to K^-\pi^+\pi^+\pi-$. The dominant intermediate process is $D^0 \to K^- a_1^+(1260)$, accounting for a fit fraction of 54.6%. By using the inclusive BF $BF(D^0 \to K^-\pi^+\pi^+\pi-) = (8.07 \pm 0.23)\%$, taken from the PDG and the fit fraction for the different components $FF(n)$ obtained in this analysis, we calculate the exclusive absolute BFs for the individual components with $BF(n) = BF(D^0 \to K^-\pi^+\pi^+\pi-) \times FF(n)$ [11].

5. Λ_c^+ decays

The electromagnetic structure of hadrons, parameterized in terms of electromagnetic form factors (EMFFs), provides a key to understand the strong interaction. Previously, the Belle collaboration measured the cross section of $e^+e^- \to \Lambda_c^+\Lambda_c^-$ using initial-state-radiation (ISR) technique [12], but the results suffered from significant uncertainties in center-of-mass (CM) energy and cross section. Therefor, near $\Lambda_c^+\Lambda_c^-$ threshold, precise measurements of the EMFF ratios are highly needed.

5.1 Λ_c^+ semi-leptonic decays

Based on the data sample collected at $\sqrt{s} = 4.599$ GeV, we apply a tag technique to study the semi-leptonic decay of Λ_c^+. To identify the $\Lambda_c^+\Lambda_c^-$ signal candidates, we firstly reconstruct one

Λ_c^- baryon, called ST Λ_c^-, through the final states of any of ST modes. The signal candidates for $\Lambda_c^+ \to \Lambda l \nu_l$, where $l = e, \mu$, are selected from the remaining tracks recoiling against the ST Λ_c^-. As the neutrinos is missing, we employ U_{miss} to obtain information for the neutrino.

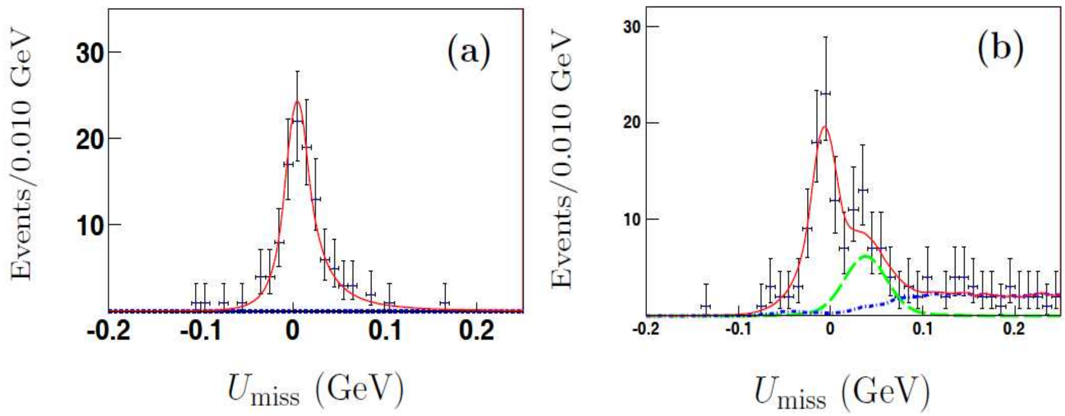

Figure 7: The $U_{\rm miss}$ distributions of the (a) $\Lambda_c^+ \to \Lambda e^+ \nu_e$, (b) $\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$. The green-dashed line in the right sub-figure denotes the MC-driven background shapes.

Figure 7 shows the distributions of $U_{\rm miss}$. From the fits, after subtracting all the backgrounds, we determine the number of signal events for $\Lambda_c^+ \to \Lambda e^+ \nu_e$ to be 103.5 ± 10.9. The absolute BF for $\Lambda_c^+ \to \Lambda e^+ \nu_e$ is determined to be $BF(\Lambda_c^+ \to \Lambda e^+ \nu_e) = (3.63 \pm 0.38(stat.) \pm 0.20(sys.)\%$ [13]. Similarly, we determined the absolute BF for decay $\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$ to be $(3.49 \pm 0.46 \pm 0.26)\%$. The ratio $BF(\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu)/BF(\Lambda_c^+ \to \Lambda e^+ \nu_e)$ is found to be $(0.96 \pm 0.16 \pm 0.04)\%$ [14].

5.2 Λ_c^+ hadronic decays

Mode	This work (%)	PDG (%)
pK_S^0	$1.52 \pm 0.08 \pm 0.03$	1.15 ± 0.30
$pK^-\pi^+$	$5.84 \pm 0.27 \pm 0.23$	5.0 ± 1.3
$pK_S^0\pi^0$	$1.87 \pm 0.13 \pm 0.05$	1.65 ± 0.50
$pK_S^0\pi^+\pi^-$	$1.53 \pm 0.11 \pm 0.09$	1.30 ± 0.35
$pK_S^0\pi^+\pi^0$	$4.53 \pm 0.23 \pm 0.30$	3.4 ± 1.0
$\Lambda\pi^+$	$1.24 \pm 0.07 \pm 0.03$	1.07 ± 0.28
$\Lambda\pi^+\pi^0$	$7.01 \pm 0.37 \pm 0.19$	3.6 ± 1.3
$\Lambda\pi^+\pi^-\pi^+$	$3.81 \pm 0.24 \pm 0.18$	2.6 ± 0.7
$\Sigma^0\pi^+$	$1.27 \pm 0.08 \pm 0.03$	1.05 ± 0.28
$\Sigma^+\pi^0$	$1.18 \pm 0.10 \pm 0.03$	1.00 ± 0.34
$\Sigma^+\pi^+\pi^-$	$4.25 \pm 0.24 \pm 0.20$	3.6 ± 1.0
$\Sigma^+\omega$	$1.56 \pm 0.20 \pm 0.07$	2.7 ± 1.0

Table 1: Comparison of the measured BFs with previous results from PDG.

We apply a double tag (DT) technique pioneered by the MARK-III Collaboration [15] to study the hadronic decay of Λ_c^+. The DT Λ_c^+ for all of tag modes are selected from the remaining tracks recoiling against the ST Λ_c^-. By analyzing the data sample taken at the $\Lambda_c^+\Lambda_c^-$ threshold (4.599 GeV), we simultaneously reconstruct ST Λ_c^- and DT Λ_c^+ candidates for the $\Lambda_c^+\Lambda_c^-$ decays. We use a least-squares fitter, which considers statistical and systematic correlations among the different hadronic modes, to obtain the BFs of the twelve Λ_c^+ decays. The extracted absolute BFs of Λ_c^+ hadronic decays are listed in Table 1. The total number of $\Lambda_c^+\Lambda_c^-$ pairs produced is obtained to be $(105.9 \pm 4.8 \pm 0.5) \times 10^3$ and the goodness of fit is evaluated as χ^2/ndf=0.9 [16].

6. Summary

We present a selection of recent BESIII charm results based on the data sets collected by BESIII detector near the $D\bar{D}$ threshold (3.773 GeV), $D_s^+D_s^-$ threshold (4.009 GeV) and $\Lambda_c^+\Lambda_c^-$ threshold (4.599 GeV) with integrated luminosities of 2.93 fb^{-1}, 0.482 fb^{-1} and 0.567 fb^{-1}, respectively. From the leptonic $D_{(s)}$ pure leptonic and semi-leptonic decays we determined the most precise values for the decay constant f_{D^+}, the hadronic form factors $f_+^{K(\pi)}(0)$, and the form factor shape $f_+^{K(\pi)}(q^2)$ which provide important test to LQCD calculations, and CKM matrix unitary. Using the tag technique on the threshold data set, BESIII firstly measured the absolute hadronic BFs of twelve Cabibbo-favored decays of Λ_c^+ baryon. The study of charmed meson and charmed baryon hadronic decays is given with significant improved precision. BESIII also presented the first model-independent measurement of the BFs of Λ_c^+ semi-leptonic decay $\Lambda_c^+ \to \Lambda e^+ \nu_e$ and $\Lambda_c^+ \to \Lambda \mu^+ \nu_\mu$. BESIII have taken more than 3 fb^{-1} $D_sD_s^*$ data at $\sqrt{s} = 4.180$ GeV, many more results are expected.

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