Results on $D^+ \rightarrow \ell^+\nu$ and $D^+_s \rightarrow \ell^+\nu$ decays at Charm factories

L.L. Jiang
Institute of High Energy Physics
No.918 P.O.X,Beijing,China

Proceedings of CKM 2012, the 7th International Workshop on the CKM Unitarity Triangle, University of Cincinnati, USA, 28 September - 2 October 2012

1 Introduction

In the Standard Model (SM) of particle physics, $D^+_{(s)}$ mesons can decay into $\ell^+\nu$ (where $\ell^+$ is $e$, $\mu$ or $\tau$) through a virtual $W^+$ boson. The virtual $W^+$ boson is produced in the annihilation of the $c$ and $\overline{d}(\overline{s})$ quarks. The decay rate of this process is determined by the wave-function overlap of the two quarks at the origin, and is parameterized by the $D^+_{(s)}$ decay constant, $f_{D^+_{(s)}}$. Figure 1 shows the decay diagram for the Cabibbo-suppressed purely leptonic decay of the $D^+_{(s)}$ meson. In this decay process, all strong interaction effects between the two quarks in initial state are absorbed into $f_{D^+_{(s)}}$. The decay width of $D^+_{(s)} \rightarrow \ell^+\nu$ is given by the formula $^1$

$$
\Gamma(D^+_{(s)} \rightarrow \ell^+\nu) = \frac{G_F^2 f^2_{D^+_{(s)}}}{8\pi} |V_{cd(s)}|^2 m^2_{\ell} m_{D^+_{(s)}} \left(1 - \frac{m^2_{\ell}}{m^2_{D^+_{(s)}}}\right)^2,
$$

Figure 1: The decay diagram for $D^+_{(s)} \rightarrow \ell^+\nu$.

$^1$throughout this manuscript, charge conjugation is implied
where $G_F$ is the Fermi coupling constant, $V_{cd(s)}$ is the $c \rightarrow d(s)$ Cabibbo-Kobayashi-Maskawa (CKM) matrix element \cite{2}, $m_\ell$ is the mass of the lepton, and $m_{D_\pm(s)}$ is the mass of the $D_\pm(s)$ meson. The ratios of decay rates for $D^+ \rightarrow \tau^+\nu_\tau$, $D^+ \rightarrow \mu^+\nu_\mu$ and $D^+ \rightarrow e^+\nu_e$ are expected by the well-known lepton-masses, which are

$$R = \frac{\Gamma(D^+ \rightarrow \tau^+\nu_\tau)}{\Gamma(D^+ \rightarrow \mu^+\nu_\mu)} : \frac{\Gamma(D^+ \rightarrow \mu^+\nu_\mu)}{\Gamma(D^+ \rightarrow e^+\nu_e)} = \frac{2.67}{1} : 2.35 \times 10^{-5}. \tag{2}$$

while the ratios of decay rates for $D_s^+ \rightarrow \tau^+\nu_\tau$, $D_s^+ \rightarrow \mu^+\nu_\mu$ and $D_s^+ \rightarrow e^+\nu_e$ are expected to be $9.8:1:2.4 \times 10^{-5}$. Any significant deviation of experimental results from theory expectation may indicate that there are New Physics (NP).

The pseudoscalar decay constants $f_{D_\pm(s)}$ are very important constants in heavy flavor physics. Within the context of the SM, measurement of the purely leptonic decay of the $D_\pm(s)$ meson provides a means of determining $f_{D_\pm(s)}$. As the decay constant is related to the annihilation probability of the heavy and the light quarks inside the meson, they play an important role both in characterizing the properties of confinement and as absolute normalization of numerous heavy-flavor transitions, including semileptonic decays and non-leptonic decays of the mesons as well as mixing of neutral and anti-neutral meson pairs. For example, $f_B$ relates the measurements of the $B\bar{B}$ mixing ratio to CKM matrix elements. At present it is impossible to precisely determine $f_{B^+}$ experimentally from the purely leptonic $B^+$ decay and is never possible to measure $f_{B^0}$ since $B^0_s$ does not have charge current leptonic decay, so theoretical calculations of the $f_{B^+}$ and $f_{B^0}$ have to be used. The ratios of $f_{D^+}/f_{B^+}$ and $f_{D_s^+}/f_{B_s^0}$ from LQCD calculations are determined with higher precision than the calculations of each of the decay constants. The LQCD calculations of $f_B$ can be used with some level of confidence given by the stringent tests from leptonic D decays on $f_{D^+}$ and $f_{D_s^+}$.

Conversely, taking the theoretical calculations of the decay constants as input, one can also determine the CKM matrix elements $|V_{cd}|$ and $|V_{cs}|$ by analyzing the $D^+$ and $D_s^+$ purely leptonic decays. Thanks to the unquenched LQCD calculations of $f_{D^+}$, which have reached a high precision of 2%, one can get more precisely experimental result of $|V_{cd}|$ than the one historically measured based on the $D \rightarrow \pi \ell^+\nu$ semileptonic decays.

\section{Methods}

The $D$ and $\bar{D}$ meson are produced in pairs near open-charm meson pair production energy thresholds in $e^+e^-$ experiments, which provides the cleanest experimental environment for studies of the leptonic decays of $D_\pm(s)$ meson. Taking advantage of the $D\bar{D}$ production, if a $D$ meson decay is fully reconstructed (this is called singly tagged
D meson), a $\bar{D}$ must exist in the system recoiling against the tagged $D$ meson. Based on the accumulated singly tagged $D$ meson sample, one can measure the absolute branching fraction of the leptonic decays of $D^+_s$. The neutrino in the final states of leptonic decays of $D^+_s$ can be reconstructed with the missing momentum and the missing energy of the events. If there is a neutrino in the recoil side of the singly tagged $D$ meson, the distribution of the missing mass squared, which is the missing energy square minus the missing momentum square, should characterize with a peak at zero.

3 Leptonic decays of $D^+$ meson

Historically MARK-III, BES-I, BES-II and CLEO-c experiments made measurements of $f_{D^+_s}$. Today’s running BES-III experiment focus on measurement of $f_{D^+}$.

3.1 Results at previous experiments

3.1.1 Search for $D^+ \rightarrow l^+ \nu$ decay at Mark-III experiment

In 1988, MARK III collaboration first searched for the decay of $D^+ \rightarrow \ell^+ \nu$ and got no signal event. They set an upper limit on the decay constant at 90% C.L. to be $f_{D^+} < 290$ MeV. [3].

3.1.2 First observed one candidate for $D^+ \rightarrow \ell^+ \nu$ at the BES-I experiments

In 1998, the BES collaboration observed one candidate event for $D^+ \rightarrow \ell^+ \nu$ in the recoil side of the 10082 singly tagged $D$ mesons, by analyzing 22.3 pb$^{-1}$ of data taken at 4.03 GeV. From this experiment, they measured the branching fraction for $D^+ \rightarrow \mu^+ \nu$ to be $(0.08^{+0.16}_{-0.06} \pm 0.05\%)$, corresponding to a value of decay constant of $f_{D^+} = (300^{+180}_{-150} \pm 80)\text{ MeV}$ [4].

3.1.3 First absolute measurements of $B(D^+ \rightarrow l^+\nu)$ and $f_{D^+}$ at the BES-II experiments

At the “04 Electroweak Interactions & Unified Theories” international meeting, the BES-II collaboration reported their analysis results of the leptonic decay of $D^+$ for the first time. With 33 pb$^{-1}$ of data taken in $e^+e^-$ annihilation with their upgraded BES-II detector at the BEPC collider, they accumulated $5321 \pm 149 \pm 160$ $D^-$ single tags and observed 3 candidates for $D^+ \rightarrow \mu^+ \nu$ decays in the recoil side of the single tags. With the 3 candidates, which contain 0.3 background events estimated from MC simulation and the accumulated $5321 \pm 149 \pm 160$ $D^-$ single tags, they measured
the branching fraction for $D^+ \rightarrow \mu^+ \nu$ decays to be $B(D^+ \rightarrow \mu^+ \nu) = (0.122^{+0.111}_{-0.053} \pm 0.010)\%$, corresponding to a value of the decay constant $f_{D^+} = (371^{+129}_{-119} \pm 25) \text{ MeV}$ [5]. Their analysis results were finally published in 2005. These are absolute measurements of the decay branching fraction and decay constant, which do not depend on the yield of $D^+$ meson production and do not depend on some branching fractions for $D^+$ meson decay into other modes.

3.1.4 Precise measurements of $B(D^+ \rightarrow l^+ \nu)$ and $f_{D^+}$ at CLEO-c experiments

CLEO-c published 3 papers to report their studies of the leptonic decay of $D^+$ mesons in 2004 [6], 2005 [7] and 2008 [8], respectively. Because the previous results are superseded by the most recent one, we here only discuss the results published in 2008. In that paper, the CLEO collaboration analyzed 818 pb$^{-1}$ of data taken at 3.773 GeV. They accumulated $460055 \pm 787 D^-$ tags with 6 hadronic decay modes of the $D^-$ meson and observed $149.7 \pm 12.0$ signal events for $D^+ \rightarrow \mu^+ \nu$. In the abstract and the summary in that paper, they presented the measured decay branching fraction of $B(D^+ \rightarrow \mu^+ \nu) = (3.82 \pm 0.32 \pm 0.09) \times 10^{-4}$ and the corresponding decay constant of $f_{D^+} = (205.8 \pm 8.5 \pm 2.5) \text{ MeV}$ [8].

3.2 New results at BES-III experiment

The BES-III collaboration has collected 2.9 fb$^{-1}$ of data at 3.773 GeV with BES-III detector [9] at the BEPC-II [10] during the time period from 2010 to 2011. In this section, we report measurements of the branching fraction for $D^+ \rightarrow \mu^+ \nu$ decay and the pseudoscalar decay constant $f_{D^+}$ obtained by analyzing this data sample.

Nine non-leptonic $D^-$ decay modes $K^+\pi^-\pi^-$, $K^0_s\pi^-$, $K^+K^-\pi^-$, $K^+\pi^-\pi^-\pi^0$, $\pi^+\pi^-\pi^-$, $K^0_s\pi^0$, $K^+\pi^-\pi^-\pi^+$, and $K^0_s\pi^-\pi^-\pi^+$ are used in accumulating the singly tagged $D^-$ mesons. The singly tagged $D^-$ mesons are fully reconstructed by requiring that the energy of the reconstructed candidate $D^-$ must be consistent with the beam energy, and then examine the beam energy constraint mass of the tagged $mKn\pi$ system,

$$M_B = \sqrt{E_{\text{beam}}^2 - |\vec{p}_{mKn\pi}|^2},$$

where $E_{\text{beam}}$ is the beam energy, and $|\vec{p}_{mKn\pi}|$ is the magnitude of the momentum of the daughter particle $mKn\pi$ system. The $M_B$ distributions and the maximum likelihood fit results for the $M_B$ distributions of the nine $D^-$ tag modes are shown in Fig. 2. The fits give a total of $1586056 \pm 2327 D^-$ tags. After subtracting 20103 double counting $D^-$ tags, BES-III reconstructed $1565953 \pm 2327 D^-$ tags which are used for further analysis of measuring the branching fraction for $D^+ \rightarrow \mu^+ \nu$ decays.

Candidate events for the decay $D^+ \rightarrow \mu^+ \nu$ are selected from the surviving charged tracks in the system recoiling against the singly tagged $D^-$ mesons.
Figure 2: Distributions of the beam energy constraint masses of the $mKn\pi$ combinations for the 9 single tag modes from the data; where (a), (b), (c), (d), (e), (f), (g), (h), (i) are for the modes of $D^- \rightarrow K^+\pi^\pm\pi^\mp$, $D^- \rightarrow K^0\pi^-$, $D^- \rightarrow K^0K^-$, $D^- \rightarrow K^0K^-\pi^-$, $D^- \rightarrow K^0\pi^-\pi^0$, $D^- \rightarrow \pi^+\pi^-\pi^0$, $D^- \rightarrow K^0\pi^-\pi^0$, $D^- \rightarrow K^+\pi^-\pi^-\pi^+$, and $D^- \rightarrow K^0\pi^-\pi^-\pi^+$, respectively.
Figure 3: Distributions of $M^2_{\text{miss}}$, where (a) and (b) are scatter plots of the identified muon momentum $p$ VS $M^2_{\text{miss}}$, and (c) is the distribution of $M^2_{\text{miss}}$. The insert shows the signal region for $D^+ \rightarrow \mu^+ \nu_\mu$ on a log scale, where dots with error bars are for the data, histograms are for the simulated backgrounds from $D^+ \rightarrow K_L^0 \pi^+$ (red), $D^+ \rightarrow \pi^0 \pi^+$ (green), $D^+ \rightarrow \pi^+ \nu_\tau$ (blue) and other decays of $D$ mesons (yellow) as well as from $e^+e^- \rightarrow \text{non-}D\overline{D}$ decays (pink).

the $D^+ \rightarrow \mu^+ \nu_\mu$ final states, there should be only one candidate charged track, which is identified as muon. At BES-III, the $\mu^+$ can be well identified with the Muon detector (MUC). Taking the difference of the passage lengths in MUC for difference types of the charged tracks, the candidate muon is required to have large passage length. Except for this, no extra good photon with energy greater than 300 MeV is allowed to be present.

Figures 3(a) and (b) show the scatter-plots of the momentum of the identified muon satisfying the requirement for selecting $D^+ \rightarrow \mu^+ \nu_\mu$ decay versus $M^2_{\text{miss}}$, where the blue box in Fig. 3(a) shows the signal region for $D^+ \rightarrow \mu^+ \nu_\mu$ decays. Within the signal region, there are 425 candidate events for $D^+ \rightarrow \mu^+ \nu_\mu$ decay. The two concentrated clusters out side of the signal region are from $D^+$ non-leptonic decays.
and some other background events. The events whose peak is around 0.25 GeV$^2$/c$^4$ in $M^2_{\text{miss}}$ are mainly from $D^+ \to K^0_L \pi^+$ decays, where $K^0_L$ is missing. Projecting the events for which the identified muon momentum being in the range from 0.8 to 1.1 GeV/c onto the horizontal scale yields the $M^2_{\text{miss}}$ distribution as shown in Fig.3(c). From this plot, we can see that the difficultly suppressed backgrounds from $D^+ \to K^0_L \pi^+$ decays in CLEO-c measurement \cite{8} are effectively suppressed due to that they use the MUC measurements to identify the muon. Detailed Monte Carlo studies show that there are 47.7 $\pm$ 2.3 $\pm$ 1.3 background events in 425 candidates for $D^+ \to \mu^+ \nu_\mu$ decays, where the first error is the MC statistical error and second is the systematic, which arises from uncertainties in the branching fractions or production cross sections for the source modes. After subtracting the number of background events, 377.3 $\pm$ 20.6 $\pm$ 2.6 signal events for $D^+ \to \mu^+ \nu_\mu$ decay are retained, where the first error is statistical and the second systematic arising from the uncertainty of the background estimation.

The overall efficiency for observing the decay $D^+ \to \mu^+ \nu_\mu$ is obtained by analyzing full MC simulated events of $D^+ \to \mu^+ \nu_\mu$ versus $D^-$ tags and combining with $\mu^+$ reconstruction efficiency of the MUC. The $\mu^+$ reconstruction efficiency of the MUC is measured with muon samples selected from the same data taken at 3.773 GeV. The overall efficiency is 0.6382 $\pm$ 0.0015.

With 1565953 singly tagged $D^-$ mesons, 377.3$\pm$20.6$\pm$2.6 $D^+ \to \mu^+ \nu_\mu$ decay events and with a reconstruction efficiency of 0.6382 $\pm$ 0.0015, the BES-III collaboration obtain the branching fraction

$$B(D^+ \to \mu^+ \nu_\mu) = (3.74 \pm 0.21 \pm 0.06) \times 10^{-4} \text{ (BESIII Preliminary)},$$

where the first error is statistical and the second systematic. This measured branching fraction is consistent within error with world average of $B(D^+ \to \mu^+ \nu_\mu) = (3.82 \pm 0.33) \times 10^{-4}$ \cite{2}, but with better precision.

The decay constant $f_{D^+}$ can be obtained by inserting the measured branching fraction, the mass of the muon, the mass of the $D^+$ meson, the CKM matrix element $|V_{cd}| = 0.2252 \pm 0.0007$ from the CKMFitter \cite{2}, $G_F$ and the lifetime of the $D^+$ meson \cite{2} Eq.(2), which yields

$$f_{D^+} = (203.91 \pm 5.72 \pm 1.97) \text{ MeV} \text{ (BESIII Preliminary)},$$

where the first error is statistical and the second is systematic, which arises mainly from the uncertainties in the measured branching fraction (1.7%), the CKM matrix element $|V_{cd}|$ (0.3%), and the lifetime of the $D^+$ meson (0.7%) \cite{2}. The total systematic error is 1.0%.
4 Leptonic decays of $D_s^+$ meson

The BES-I and CLEO-c experiments have published results on $f_{D^+}$ and BES-III will publish their experiment results of the purely leptonic decay of $D_s^+$ meson soon.

4.1 BES-I experiment near $D_s^+ D_s^-$ threshold

The first absolute measurements of decay branching fractions of $D_s^+ \rightarrow \mu^+\nu$, $D_s^+ \rightarrow \tau^+\nu$ and the decay constant were made by BES-I experiment in 1995. They found 3 events of both the $D_s^+ \rightarrow \tau^+\nu$ and $D_s^+ \rightarrow \mu^+\nu$ decays in the recoil side of 94.3 $\pm$ 12.5 singly tagged $D_s^-$ mesons by analyzing 22.3 pb$^{-1}$ of data taken at 4.03 GeV. They measured the decay branching fractions of $B(D_s^+ \rightarrow \tau^+\nu) = (15^{+13+3}_{-6-2})\%$ and $B(D_s^+ \rightarrow \mu^+\nu) = (1.5^{+1.3+0.3}_{-0.6-0.2})\%$, respectively, and the decay constant of $f_{D_s^+} = (430^{+150}_{-130} \pm 40)\text{ MeV}$ [11].

4.2 CLEO-c experiment near $D_s^+ D_s^*$ threshold

CLEO-c collected 600 pb$^{-1}$ of data at 4.17 GeV in $e^+ e^-$ annihilation. With this data sample, they published 3 papers to present the studies of the purely leptonic decays of $D_s^+$ by reconstructing the $D_s^+$ with various decay modes [12, 13, 14]. By averaging the results obtained by analyzing different leptonic decay modes of $D_s^+$ meson, CLEO-c gave $f_{D_s^+} = (259.0 \pm 6.2 \pm 3.0)\text{ MeV}$ [14].

5 Summary

Since the first attempt to search for the $D^+$ leptonic decay by the MARK-III experiment in 1988, many experiments have been making great efforts to search for and study the $D^+$ and $D_s^+$ leptonic decays. At present, the most precise measurements of the decay constant of $f_{D^+}$ is made by BES-III, which was first reported at Charm2012 [15]. They measured the branching fraction $B(D^+ \rightarrow \mu^+\nu) = (3.74 \pm 0.21 \pm 0.06) \times 10^{-4}$, $f_{D^+} = (203.9\pm 5.7\pm 2.0)\text{ MeV}$ and $|V_{cd}| = (0.222\pm 0.006\pm 0.005)$. In addition, more precise results on $D^+ \rightarrow \tau^+\nu$, $e^+\nu_e$ will be determined from the full BES-III data taken at 3.773 GeV in the near future, and results on $D_s^+ \rightarrow \tau^+\nu$, $\mu^+\nu_\mu$ will be reported from the BES-III recent selected data at 4.010 GeV soon.

Acknowledgement

I would like to thank the colleagues of BES-III collaboration, the staff of BEPCII and the computing center of IHEP for their hard efforts and excellent works. This work is partly supported by National Key Basic Research Program (973 by MOST).
and National Natural Science Foundation of China (NSFC) under Contract No. 10935007.

References

[1] Francis Halzen, Alan D. Martin, Quarks & Leptons (John Wiley & Sons, New York, Chichester, Brisbane, Toronto, Singapore, 1984).

[2] K. Nakamura et al. J. Phys. G 37, 075021 (2010).

[3] J. Adler et al. (The MARK III Collaboration), Phys. Rev. Lett. 60, 1375 (1998).

[4] J.Z. Bai et al. (BES Collaboration), Phys. Lett. B429, 188 (1998).

[5] G. Rong (for BES Collaboration), Proceeding of the XXXIXth RENCONTRES DE MORIOND, March 21–28, 2004, edited by J. Tran Thanh Van; M. Ablikim et al. (BES Collaboration), Phys. Lett. B610, 183 (2005).

[6] G. Bonvicini et al. (CLEO Collaboration), Phys. Rev. D 70, 112004 (2004).

[7] M. Artuso et al. (CLEO Collaboration), Phys. Rev. Lett. 95, 251801 (2005).

[8] B.I. Eisenstein et al. (CLEO Collaboration), Phys. Rev. D 78, 052003 (2008).

[9] M. Ablikim et al. (BESIII Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A A 614, 345 (2010)

[10] J. Z. Bai et al. (BES Collaboration), Nucl. Instrum. Methods Phys. Res. A 458, 627 (2001).

[11] J.Z. Bai et al. (BES Collaboration), Phys. Rev. Lett. 74, 4599 (1995).

[12] J.P. Alexander et al. (CLEO Collaboration), Phys. Rev. D 79, 052001 (2009).

[13] P.U.E. Onyisi et al. (CLEO Collaboration), Phys. Rev. D 79, 052002 (2009).

[14] P. Naik et al. (CLEO Collaboration), Phys. Rev. D 80, 112004 (2009).

[15] G. Rong (for BES-III Collaboration), arXiv:hep-ph/12090085.