Leptonic Decays of Charm

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We present results of various searches for leptonic decays of charm mesons performed with the Belle detector. Also discussed are $D^0 \to \gamma\gamma$ decays.

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1 Introduction

Leptonic decays of charm mesons are suppressed in Standard Model (SM) and are therefore a convenient place to search for New Physics (NP). B factories provide a copious source of charm because at $\Upsilon(4S)$ the cross section of $c\bar{c}$ production is $\sim 1.1$ nb, so each $fb^{-1}$ brings $\sim 10^6$ events and with their huge integrated luminosities the B factories produce inclusively a huge amount of $c\bar{c}$ pairs. At lower energy, $\psi(3770)$ is a factory of $D^+D^-$, $D^0\bar{D}^0$ while at $\sqrt{s} \sim 4.17$ GeV $D^+D^-$ pairs are copiously produced.

The branching fraction of $D_s$ leptonic decay (see the Feynman diagram in Fig. 1) is given by the following expression

$$\mathcal{B}(D^+_s \rightarrow \ell^+\nu_\ell) = \frac{\tau_{D_s} m_{D_s}}{8\pi} f_{D_s}^2 G_F^2 |V_{cs}|^2 m_\ell^2 \left(1 - \frac{m_\ell^2}{m_{D_s}^2}\right)^2.$$

Here, $m_{D_s}$ is the $D_s^+$ meson mass, $\tau_{D_s}$ is its lifetime, $m_\ell$ is the lepton mass, $V_{cs}$ is the relevant CKM matrix element, and $G_F$ is the Fermi coupling constant. The parameter $f_{D_s}$ is the $D_s$ meson decay constant related to the wave-function overlap of the meson’s constituent quark and antiquark. The leptonic decays of pseudoscalar mesons are helicity suppressed with $\Gamma(\ell^+\nu_\ell) \propto m_\ell^2$, so that $\Gamma(e^+\nu_e) \ll \Gamma(\mu^+\nu_\mu) \ll \Gamma(\tau^+\nu_\tau)$, $R^{D^+}_{\tau/\mu} \equiv \mathcal{B}(D^+_s \rightarrow \tau^+\nu_\tau)/\mathcal{B}(D^+_s \rightarrow \mu^+\nu_\mu) = m_\tau^2/m_\mu^2 (1 - m_\tau^2/m_{D_s}^2)^2/(1 - m_\mu^2/m_{D_s}^2)^2 = 9.762 \pm 0.031$, $R^{D^+}_{\tau/\mu} \equiv \mathcal{B}(D^+ \rightarrow \tau^+\nu_\tau)/\mathcal{B}(D^+ \rightarrow \mu^+\nu_\mu) = 2.67 \pm 0.01$. A study of
such decays not only tests SM and searches for NP, e.g., a charged Higgs, but also provides a test of lepton flavor universality in decays with \( \mu \) and \( \tau \) (decays to \( e^+\nu_e \) are extremely rare and hardly observable).

2 \( D_s^+ \to \ell^+\nu_\ell \) at Belle

Recently Belle studied \( D_s^+ \to \ell^+\nu_\ell \) with 913 fb\(^{-1}\) at \( \Upsilon(4S) \) and \( \Upsilon(5S) \) \( \text{[1]} \). The \( e^+e^- \to \ell^+\nu_\ell \) events that contain \( D_s^+ \) mesons are reconstructed in two steps. First, one of the two charm quarks that hadronizes into a \( D_s^{*+} \) meson, is searched for. Then the other, a tagging charm hadron, \( D_{\text{tag}} \) (\( D^0, D^-, \Lambda^c, D^{*-}, D^{*0} \)), is reconstructed. The strangeness of the event is conserved by requiring an additional kaon, denoted \( K_{\text{frag}} \), to be produced in the fragmentation process; \( K_{\text{frag}} \) is either \( K^+ \) or \( K^0_S \). In events where \( D_{\text{tag}} \) is the tagging charm hadron, the baryon number of the event is conserved by requiring an antiproton. Since Belle collected data at energies well above the \( D_s^{*+}K_{\text{frag}}D_s^{*-} \) threshold, additional particles can be produced in the course of hadronization. These particles are denoted as \( X_{\text{frag}} \) and consist of an even number of kaons plus any number of pions or photons. In this measurement, only pions are considered when reconstructing the fragmentation system. The number of inclusively reconstructed \( D_s^+ \) mesons is extracted from the distribution of events in the missing mass, \( M_{\text{miss}}(D_{\text{frag}}X_{\text{frag}}\gamma) \), recoiling against the \( D_{\text{frag}}X_{\text{frag}}\gamma \) system

\[
M_{\text{miss}}(D_{\text{tag}}K_{\text{frag}}X_{\text{frag}}\gamma) = \sqrt{p_{\text{miss}}(D_{\text{tag}}K_{\text{frag}}X_{\text{frag}}\gamma)^2}, \tag{1}
\]

where \( p_{\text{miss}} \) is the missing four-momentum in the event

\[
p_{\text{miss}}(D_{\text{tag}}K_{\text{frag}}X_{\text{frag}}\gamma) = p_{\ell^+} + p_{\ell^-} - p_{D_{\text{tag}}} - p_{K_{\text{frag}}} - p_{X_{\text{frag}}} - p_{\gamma}. \tag{2}
\]

Here, \( p_{D_{\text{tag}}} \), \( p_{K_{\text{frag}}} \), \( p_{X_{\text{frag}}} \), and \( p_{\gamma} \) are the measured four-momenta of the reconstructed \( D_{\text{tag}} \), strangeness-conserving kaon, fragmentation system and the photon from \( D_s^{*+} \to D_s^+\gamma \). Correctly reconstructed events produce a peak in the \( M_{\text{miss}}(D_{\text{frag}}X_{\text{frag}}\gamma) \) at the nominal \( D_s^+ \) meson mass.

18 modes of \( D_{\text{tag}} \) were considered in total. Six modes of \( D^0 \) (the total branching of 38.4\%): \( K^-\pi^+ \), \( K^-\pi^+\pi^0 \), \( K^-\pi^+\pi^0 \), \( K^-\pi^+\pi^-\pi^0 \), \( K^0\pi^+\pi^-\pi^0 \), \( K^0\pi^+\pi^-\pi^0 \), six modes of \( D^+ \) (28.0\%): \( K^-\pi^+\pi^0 \), \( K^-\pi^+\pi^0 \), \( K^0\pi^+\pi^0 \), \( K^0\pi^+\pi^0 \), \( K^0\pi^+\pi^0 \), \( K^0\pi^+\pi^0 \), \( K^+K^-\pi^+ \), and six modes of \( \Lambda^c_+ \) (16.8\%): \( pK^-\pi^+ \), \( pK^-\pi^+\pi^0 \), \( pK^0_S \), \( \Lambda\pi^+ \), \( \Lambda\pi^+\pi^0 \), \( \Lambda\pi^+\pi^0 \).

There were seven \( X_{\text{frag}} \) modes of pions only: nothing, \( \pi^\pm \), \( \pi^0 \), \( \pi^\pm\pi^0 \), \( \pi^\pm\pi^0 \), \( \pi^\pm\pi^0 \), \( \pi^\pm\pi^0 \), \( \pi^\pm\pi^0 \). With these conditions 94360 ± 1310 events were selected.

Results of a search for \( D_s^+ \to \mu^+\nu_\mu \) are shown in Fig. \( \text{[2]} \).

In \( D_s^+ \to \tau^+\nu_\tau \) decay, because of extra \( \nu \)'s there is no peak in \( M_{\text{miss}} \), so small \( E_{ECL} \) is used instead, see Fig. \( \text{[2]} \), where three different decay modes of the \( \tau^+ \) are used.

Results of the fits are shown in Table \( \text{[1]} \). Since different \( \tau \) decay modes give consistent values of the branching fractions, they are combined in the Table.

2
Figure 2: Results of the fit for $D_s^+ \rightarrow \mu^+ \nu_\mu$.

| $D_s^+$ decay mode | Signal yield $f_{\text{bias}} \cdot \varepsilon$ [%] | $\mathcal{B}$ [%] |
|---------------------|-----------------|------------------|
| $\mu^+ \nu_\mu$     | $492 \pm 26$    | $98.2$           |
| $\tau^+ \nu_\tau$ (e mode) | $952 \pm 59$ | $18.8$          |
| $\tau^+ \nu_\tau$ (µ mode) | $758 \pm 48$ | $13.7$         |
| $\tau^+ \nu_\tau$ (π mode) | $496 \pm 35$ | $8.7$          |
| $\tau^+ \nu_\tau$ (combined) | $2217 \pm 83$ | $41.2$       |

Table 1: Results of data selection for the $\mu^+ \nu_\mu$ and $\tau^+ \nu_\tau$ decay modes

The obtained value of the branching fraction for the muon decay mode of $D_s$

$$\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu_\mu) = (5.31 \pm 0.28(\text{stat.}) \pm 0.20(\text{syst.})) \times 10^{-3}$$  (3)

is consistent with and much more precise than the previous Belle one [2]:

$$\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu_\mu) = (6.44 \pm 0.76(\text{stat.}) \pm 0.57(\text{syst.})) \times 10^{-3}.$$  (4)

Comparison with measurements of the other groups is performed in Table 2.

For the $\tau$ lepton decay mode Belle obtains

$$\mathcal{B}(D_s^+ \rightarrow \tau^+ \nu_\tau) = (5.70 \pm 0.21(\text{stat.}) \pm 0.31(\text{syst.})) \times 10^{-2},$$  (5)

doubling the total statistics of the previous experiments and consistent with the PDG2012 $(5.43 \pm 0.31) \times 10^{-2}$ [3]. Comparison with other measurements is presented in Table 3.

| $\mathcal{B}(D_s^+ \rightarrow \mu^+ \nu_\mu)$, $10^{-3}$ | $N_{\text{ev}}$ | Group |
|----------------|----------------|--------|
| $5.31 \pm 0.28 \pm 0.20$ | $492 \pm 26$ | Belle [1] |
| $6.02 \pm 0.38 \pm 0.34$ | $275 \pm 17$ | BaBar [4] |
| $5.65 \pm 0.45 \pm 0.17$ | $235 \pm 14$ | CLEO [5] |
| $5.56 \pm 0.25$ | $-$ | Average |

Table 2: Summary of $D_s^+ \rightarrow \mu^+ \nu_\mu$ measurements
Figure 3: Results of the fit for $D_s^+ \rightarrow \tau^+ \nu_\tau$
They also perform a test of lepton flavor universality,

\[ R_{\tau/\mu}^{D_s} = 10.73 \pm 0.69 \text{(stat.)}^{+0.56}_{-0.53} \text{(syst.)}, \]  

in agreement with the SM value of 9.762 ± 0.031.

As expected, a study of \( D_s^+ \to e^+\nu_e \) decay does not show any signal and they set an upper limit for the branching fraction

\[ \mathcal{B}(D_s^+ \to e^+\nu_e) < 0.83 \times 10^{-4} \text{ at 90}\% CL \]  

compared to the best previous limit < 1.2 × 10^{-4} from CLEO with 600 pb\(^{-1}\) at 4.17 GeV [5].

The results for the branching fractions can be used for a determination of \( f_{D_s} \) from the relation

\[ f_{D_s} = \frac{1}{G_F m_\ell \left( 1 - \frac{m_\ell^2}{m_{D_s}} \right) |V_{cs}| \sqrt{8\pi \mathcal{B}(D_s^+ \to \ell^+\nu_\ell) m_{D_s} \tau_{D_s}}} \]  

From \( |V_{ud}| = 0.97425 \pm 0.00022 \) and \( |V_{cb}| = (40.9 \pm 1.1) \times 10^{-3} \) and using the relation \( |V_{cs}| = |V_{ud}| - |V_{cb}|^2 / 2 \) one obtains the following results, see Table 4.

The combined result from the two decay modes is consistent with the most precise value from lattice QCD 248.0 ± 2.5 MeV [8].

| \( D_s^+ \) decay | \( f_{D_s} \) [MeV] |
|-------------------|------------------|
| \( \mu^+\nu_\mu \) | 249.8 ± 6.6(stat.) ± 4.7(syst.) ± 1.7(\( \tau_{D_s} \)) |
| \( \tau^+\nu_\tau \) | 261.9 ± 4.9(stat.) ± 7.0(syst.) ± 1.8(\( \tau_{D_s} \)) |
| Combination | 255.5 ± 4.2(stat.) ± 4.8(syst.) ± 1.8(\( \tau_{D_s} \)) |

Table 4: Determination of \( f_{D_s} \) at Belle
3 \( D^0 \rightarrow \gamma\gamma \) and \( D^0 \rightarrow \ell^+\ell^- \) Decays

In SM, flavor-changing neutral current (FCNC) decays are suppressed by the GIM mechanism, so that the expected branching fractions for \( D^0 \rightarrow \gamma\gamma \) decays are small

\[
\mathcal{B} \sim (1 - 3) \cdot 10^{-8}. \tag{9}
\]

In MSSM, gluino exchange enhances \( \mathcal{B} \) to \( 6 \cdot 10^{-6} \), therefore searches for NP can be performed. The current sensitivity of such searches is at the level of a few units of \( 10^{-6} \) and the achieved upper limits are shown in Table 5.

In SM, the FCNC \( D^0 \rightarrow \ell^+\ell^- \) decays are additionally suppressed by helicity,

\[
\mathcal{B} \sim 2.7 \cdot 10^{-5} \mathcal{B}(D^0 \rightarrow \gamma\gamma) \tag{10}
\]

or \( \sim 10^{-13} \). Extensions of SM, e.g., models with R-parity violating SUSY, large extra dimensions or leptoquarks enhance the branchings to \( \sim 10^{-8} \). Even smaller in SM are expected branchings for lepton-flavor-violating decays. The results of searches for such decays are presented in Table 6.

4 Conclusions

Leptonic decays of \( D^0, D^+, D^+_s \) are very convenient to search for effects of New Physics. Recently there has been significant experimental progress due to CLEO, BESIII, BaBar, Belle and LHCb. LHCb has strong advantage for decays accessible
to it because of large data samples at high energy. Experience of CLEOc and BESIII shows advantages of exclusive measurements with $e^+e^- \rightarrow D^+D^-, \ D^0\bar{D}^0, \ D_s^+D_s^-$. Future progress is related to LHCb, BelleII and hopefully Super-c-τ.

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