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Leptonic $D_s$ decays at $B$-factories

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We review recent measurements of leptonic $D_s$-meson decays performed by Belle and BaBar collaborations. Described measurements enable experimental extraction of the $D_s$-meson decay constant which can be compared with lattice QCD calculations.

1 Introduction

The leptonic decays of mesons provide access to experimentally clean measurements of the meson decay constants or the relevant Cabibbo-Kobayashi-Maskawa matrix elements. In the Standard Model (SM) the branching fraction for a leptonic decay of a charged pseudoscalar meson, such as $D_s^+$, is given by \[1, 2\]:

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

where $M_{D_s}$ is the $D_s$ mass, $\tau_{D_s}$ is its lifetime, $m_\ell$ is the lepton mass, $V_{cs}$ is the Cabibbo-Kobayashi-Maskawa (CKM) matrix element between the $D_s$ constituent quarks $c$ and $s$, and $G_F$ is the Fermi coupling constant. The parameter $f_{D_s}$ is the decay constant, and is related to the wave-function overlap of the quark and anti-quark. The magnitude of the relevant CKM matrix element, $|V_{cs}|$, can be obtained from the very well measured $|V_{ud}| = 0.97425(22)$ and $|V_{cb}| = 0.04$ from an average of exclusive and inclusive semileptonic B decay results as discussed in Ref. \[3\] by using the following relation, $|V_{cs}| = |V_{ud}| - \frac{1}{2}|V_{cb}|^2$. Measurements of leptonic branching fraction of a pseudoscalar meson thus provide a clean probe of the decay constant which can than be compared with precise lattice QCD calculations \[3\].

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2 Absolute branching fraction measurement

The methods of absolute branching fraction measurement of $D_s^- \to \ell^- \nu_\ell$ decays used recently by Belle [4] and before by the BaBar [5] are similar. Both collaborations study $e^+e^- \to \ell\bar{\ell}$ events which contain $D_s^-$ mesons produced through the following reactions:

$$e^+e^- \to \ell\bar{\ell} \to D_{\text{tag}} K X_{\text{frag}} D_s^{*-}, \quad D_s^- \to D_s^* \gamma.$$  \hfill (2)

In these events one of the two charm quarks hadronizes into a $D_s^*$ meson while the other quark hadronizes into a charm hadron denoted as $D_{\text{tag}}$ (tagging charm hadron). The above events are reconstructed fully in two steps: in the first step $D_s$ mesons are reconstructed inclusively while in the second step $D_s \to \ell\nu_\ell$ decays are reconstructed within the inclusive sample. The tagging charm hadron is reconstructed as $D^0, D^+, \Lambda^+_c$ in 18 (15) hadronic decay modes by Belle (BaBar). In addition $D^{*+}$ or $D^{*0}$ are reconstructed in order to clean up the event. The strangeness of the event is conserved by requiring additional kaon, denoted as $K$, which can be either $K^+$ or $K^0_S$. Since $B$-factories collected data at energies well above $D_s^*(s)D_s^*\gamma$ threshold additional particles can be produced in the process of hadronization. These particles are denoted as $X_{\text{frag}}$ and can be: even number of kaons and or any number of pions or photons. Both Belle and BaBar reconstruct $X_{\text{frag}}$ modes with up to three pions in order to keep background at reasonable level. $D_s^-$ mesons are required to be produced in a $D_s^{*-} \to D_s^- \gamma$ decays which provide powerful kinematic constraint ($D_s^*$ mass, or mass difference between $D_s^*$ and $D_s$) that improves the resolution of the missing mass (defined below) and suppresses the combinatorial background.

In the first step of the measurement no requirements are placed on the daughters of the signal $D_s^-$ meson in order to obtain a fully inclusive sample of $D_s^-$ events which is used for normalization in the calculation of the branching fractions. The number of inclusively reconstructed $D_s$ mesons is extracted from the distribution of events in the missing mass, $M_{\text{miss}}(D_{\text{tag}} K X_{\text{frag}} \gamma)$, recoiling against the $D_{\text{tag}} K X_{\text{frag}} \gamma$ system:

$$M_{\text{miss}}(D_{\text{tag}} K X_{\text{frag}} \gamma) = \sqrt{p_{\text{miss}}(D_{\text{tag}} K X_{\text{frag}} \gamma)^2}, \quad (3)$$

where $p_{\text{miss}}$ is the missing momentum in the event:

$$p_{\text{miss}}(D_{\text{tag}} K X_{\text{frag}} \gamma) = p_{e^+} + p_{e^-} - p_{D_{\text{tag}}} - p_K - p_{X_{\text{frag}}} - p_\gamma. \quad (4)$$

Here, $p_{e^+}$ and $p_{e^-}$ are the momenta of the colliding positron and electron beams, respectively, and the $p_{D_{\text{tag}}}, p_K, p_{X_{\text{frag}}}$, and $p_\gamma$ are the measured momenta of the reconstructed $D_{\text{tag}}$, kaon, fragmentation system and the photon from $D_s^* \to D_s \gamma$ decay, respectively. Correctly reconstructed events given in the Eq. 2 produce a peak

\hfill \footnote{In events where $\Lambda_c^+$ is reconstructed as tagging charm hadron additional $\bar{p}$ is reconstructed in order to conserve the total baryon number.
in the $M_{\text{miss}}(D_{\text{tag}}K_{\text{frag}}\gamma) = m_r(DKX\gamma)$ at nominal $D_s$ meson mass as shown in Fig. 1. Belle finds $94400 \pm 1900$ correctly reconstructed inclusive $D_s$ candidates in a data sample corresponding to 913 fb$^{-1}$, while BaBar finds $108900 \pm 2400$ events$^3$ containing $D_s$ meson in a data sample corresponding to 521 fb$^{-1}$.

In the second step Belle and BaBar search for the purely leptonic $D_s^+ \to \mu^+\nu_\mu$ and $D_s^+ \to \tau^+\nu_\tau$ decays within the inclusive $D_s^+$ sample by requiring that there be exactly one additional charged track identified as an electron, muon or charged pion present in the rest of the event. In case of $D_s^+ \to \tau^+\nu_\tau$ decays the electron, muon or charged pion track identifies the subsequent $\tau^+$ decay to $e^+\nu_e\bar{\nu}_e$, $\mu^+\nu_\mu\bar{\nu}_\mu$ or $\pi^+\nu_\pi$.

The $D_s^+ \to \mu^+\nu_\mu$ decays are identified as a peak at zero in the missing mass squared distribution, $M_{\text{miss}}^2(D_{\text{tag}}K_{\text{frag}}\gamma\mu) = p_{\text{miss}}^2(D_{\text{tag}}K_{\text{frag}}\gamma\mu)$ shown in Fig. 2.

Due to multiple neutrinos in the final state the $D_s \to \tau\nu_\tau$ decays don’t peak in the $M_{\text{miss}}^2$ distribution. Instead, Belle and BaBar use extra neutral energy in the calorimeter$^4$, $E_{\text{ECL}}$, to extract the signal yields of $D_s \to \tau\nu_\tau$ decays. These are expected to peak towards zero in $E_{\text{ECL}}$, while the backgrounds extend over a wide range as shown in Fig. 3 for $D_s \to \tau\nu_\tau$ candidates when $\tau$ lepton is reconstructed in its leptonic decay to a muon.

Table 1 summarizes the signal yields and measured absolute branching fractions of leptonic $D_s$-meson decays at Belle and BaBar. The latter are found to be consistent within uncertainties.

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$^3$ Note that Belle quotes number of correctly reconstructed candidates while BaBar number of events. It is subtle but important difference that reader should be aware of.

$^4$ The $E_{\text{ECL}} (E_{\text{extra}})$ at Belle (BaBar) is defined as a sum over all energy deposits in the calorimeter with individual energy greater than 50 (30) MeV and which are not associated to the tracks or neutrals used in inclusive reconstruction of $D_s$ candidates nor the $D_s \to \tau\nu_\tau$ decays.
3 Extraction of $f_{D_s}$ and Conclusions

The value of $f_{D_s}$ is determined from measured branching fractions of leptonic $D_s$ decays by inverting Eq. [1]. The external inputs needed in the extraction of $f_{D_s}$ are all very precisely measured and do not introduce additional uncertainties except the $D_s$ lifetime, $\tau_{D_s}$, which introduces an 0.70% relative uncertainty on $f_{D_s}$.

An error-weighted average\footnote{Average of the decay constants extracted from measured $B(D_s^+ \to \mu^+\nu_\mu)$ and $B(D_s^+ \to \tau^+\nu_\tau)$.} of $D_s$-meson decay constant, $f_{D_s}$, are found by Belle and BaBar to be

$$f_{D_s}^{\text{Belle}} = (255.0 \pm 4.2(\text{stat.}) \pm 4.7(\text{syst.}) \pm 1.8(\tau_{D_s})) \text{ MeV} \quad (5)$$
$$f_{D_s}^{\text{BaBar}} = (258.6 \pm 6.4(\text{stat.}) \pm 7.3(\text{syst.}) \pm 1.8(\tau_{D_s})) \text{ MeV.} \quad (6)$$
Table 1: Signal yields and measured branching fractions for $D_s^+ \to \ell^+ \nu_\ell$ decays by Belle and BaBar. The first uncertainty is statistical and the second is systematic. Results from Belle are preliminary.

Preliminary results from Belle represent the most precise measurement of $f_{D_s}$ up to date at single experiment.

Averaging measurements of $f_{D_s}$ from $B$-factories with the one performed by CLEO-c experiment [7], $f_{D_s}^{\text{CLEO-c}} = (259.0 \pm 6.2(\text{stat.}) \pm 2.4(\text{syst.}) \pm 1.8(\tau_{D_s}))$ MeV, gives an experimental world average,

$$f_{D_s}^{\text{WA}} = (257.2 \pm 4.5) \text{ MeV},$$

which is found to be within $2\sigma$ consistent with currently most precise lattice QCD calculation from HPQCD collaboration [8, 3], $f_{D_s}^{\text{HPQCD}} = (246.0 \pm 3.6) \text{ MeV}$.

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