Study of $D_s^{\pm} \to \mu^{\pm}\nu_{\mu}$ at Belle

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Abstract We present a preliminary measurement of the $\mathcal{B}(D_s \to \mu\nu_{\mu})$ with the Belle experiment at the KEKB collider. We select $D_s \to \mu\nu_{\mu}$ decays with a method that provides a high-purity of the selected sample and an absolute measurement of the branching fraction. The results are based on a data sample of 550 fb^{-1} and are compared to similar measurements by other experiments as well as to the predictions of LQCD. We conclude with short prospects for improvements in the accuracy of the measurement.

Key words meson decays, leptonic decays, decay constant, lattice QCD

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Beside being a standalone field of different Standard Model (SM) tests and searches for New physics (e.g. searches for CP-violation in charmed hadron decays) the charm sector provides also for important tests of theoretical predictions, most notably of the lattice QCD (LQCD). In order to interpret abundant B-physics experimental results in terms of the Cabibbo-Kobayashi-Maskawa (CKM) matrix elements one needs to rely upon the predictions of form factors, decay constants and other quantities describing the QCD effects. They are calculable within the LQCD; the appropriateness of the theoretical methods, however, must be independently tested. B factories are a perfect source of charmed hadrons[2)]. Decays of these hadrons, in turn, enable measurement of analogous quantities in charm sector and comparison of those to the LQCD predictions. To illustrate this, Fig. 1 (top) shows the recent average of measurements of CKM elements as given in Ref. [1]. In comparison, an expected average is shown in the bottom plot[2], with an assumed accuracy arising from the 500 fb^{-1} of data accumulated at B factories and LQCD calculations precise enough to contribute 2%, 2%, 3%, 5%, 5% and 5% uncertainty on V_{cd}, V_{cs}, V_{cb}, V_{ub}, V_{td}, and V_{ts}, respectively. Improvement is obvious, but measurements in the charm sector with an accuracy similar to that of the LQCD predictions are expected in order to test those.

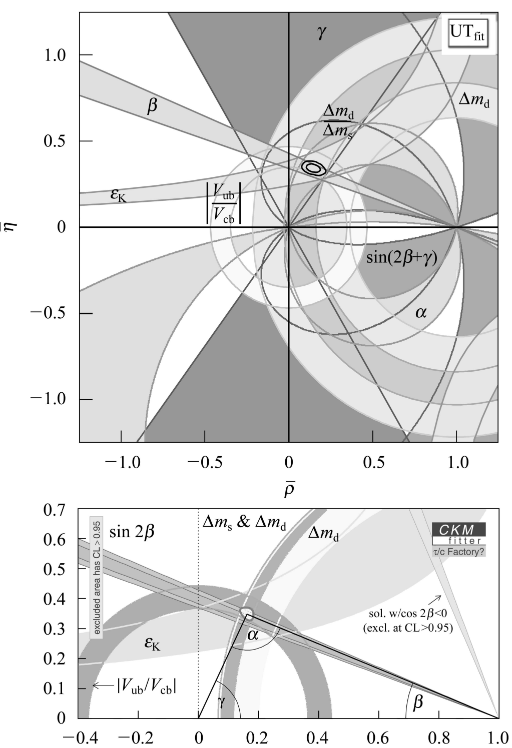

Fig. 1. Top: Recent average of measurements related to the CKM unitarity triangle[1]. Bottom: Expected accuracy of the measurements with assumptions described in the text, mainly the improved accuracy of LQCD calculations[2]. Note different scales.

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2) Cross section for $e^+e^- \to c\bar{c}$ at $\Upsilon(4S)$ amounts to around 1.3 nb, corresponding to approximately 900×10^6 produced charmed hadron pairs at the integrated luminosity reached by the KEKB.

In pseudoscalar meson decays to a purely leptonic final state the effects of QCD (i.e. of the wave function of the constituent quarks) are parametrized by a single decay constant. The decays are mediated by a single weak boson as shown in Fig. 2.

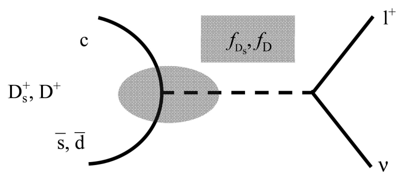

Fig. 2. Feynman diagram for D_s^+ or D^+ meson leptonic decay. The QCD effects are parametrized by decay constants f_{D_s} or f_D.

Within the SM the partial width for such leptonic decays is written in the form

$$\Gamma(D_q^+ \to l^+\nu_l) = \frac{G_F^2}{8\pi} f_{D_q}^2 m_l^2 m_{D_q} \left(1 - \frac{m_l^2}{m_{D_q}^2}\right) |V_{cq}|^2 , \quad (1)$$

where m_l and m_{D_q} are the masses of the lepton and the meson, respectively, G_F is the Fermi constant, V_{cq} is the corresponding CKM matrix element and f_{D_q} the decay constant. The m_l^2 factor arises due to the helicity suppression and causes the rate of decays with electrons in the final state to be tiny. Since in the decays with τ's one has additional unreconstructed neutrinos in the final state, the muon decay mode is most readily accessible for the measurement of the decay rate.

This paper describes a measurement of $\mathcal{B}(D_s \to \mu\nu_\mu)$ performed by the Belle experiment[3] using the data corresponding to an integrated luminosity of 548 fb^{-1}. The method used was first applied in the measurement of semileptonic D^0 decays[4]. Events of the type $e^+e^- \to D_s^* D^{\pm,0} K^{\pm,0} X$ are used, where X can be any number of additional pions from fragmentation, and up to one photon. The principle of reconstruction is sketched in Fig. 3 (details of the method are described in Ref. [5]). An event is divided into a tag side, where a full reconstruction of D and primary K meson is performed, and a signal side where the decay chain $D_s^{*+} \to D_s^+\gamma$, $D_s^+ \to \mu^+\nu_\mu$ is searched for[1]. Tag side charged and neutral D mesons are reconstructed in $D \to K n\pi$ decays with $n = 1, 2, 3$. Charged kaons are identified using the standard Belle particle identification[6]. For all possible combinations of particles in X, the signal side D_s^{*+} meson is identified by reconstruction of the recoil mass $M_{rec}(DKX)$, using the known beam momentum and four-momentum conservation. The recoil mass $M_{rec}(Y)$ is calculated as the magnitude of the four-momentum $p_{beams} - p_Y$.

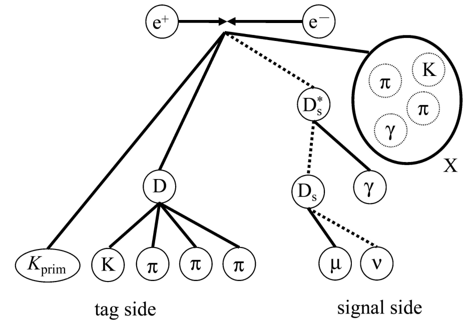

Fig. 3. Illustration of an event reconstruction. Full lines represent fully reconstructed particles. Dashed lines represent particles reconstructed in the recoil.

The next step in the event reconstruction is a search for a photon for which the recoil mass $M_{rec}(DKX\gamma)$ is consistent with the nominal mass of D_s^+. The spectrum of $M_{rec}(DKX\gamma)$ is shown in Fig. 4 (top).

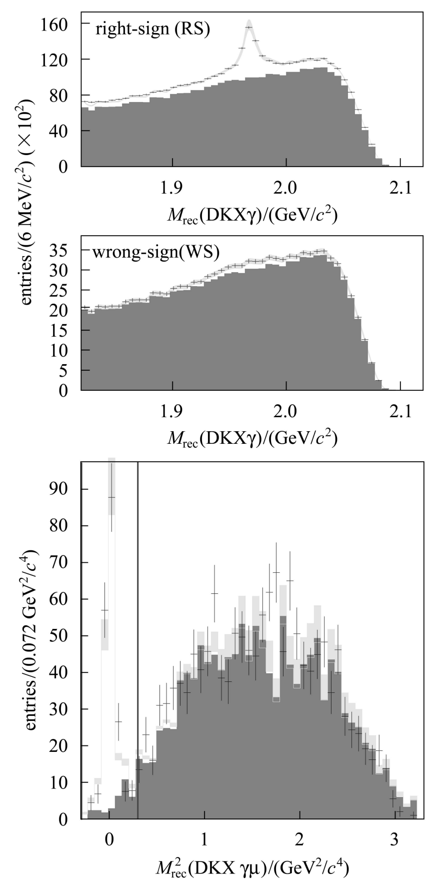

Fig. 4. Top: Spectrum of $M_{rec}(DKX\gamma)$ for the RS and WS event sample. Data with statistical errors are represented by the error bars. The light shaded band shows the result of the fit described in the text, with the systematic uncertainties. The dark shaded histogram represents the background contribution. Bottom: $M_{rec}^2(DKX\gamma\mu)$ for selected $D_s \to \mu\nu_\mu$ decays. The notation is the same as for the upper plots.

1) The charge conjugated processes are implied throughout the paper unless explicitly noted otherwise.

For a reliable description of the background in this sample of reconstructed inclusive D_s decays, the sample is divided into the right- and wrong-sign charge combinations (RS and WS, respectively) based on the charge of the primary kaon, flavor of the tag side D meson and charge of the reconstructed D_s^{*} 1). D_s candidates in the RS sample represent a normalization for the estimation of the $Br(D_s \to \mu\nu_\mu)$ and are used for further analysis.

If a positively identified muon[6] is found among the tracks so far not used in the reconstruction, the square of the recoil mass $M^2_{\rm rec}(\rm DKX\gamma\mu)$ is calculated. For $D_s \to \mu\nu_\mu$ decays this mass corresponds to the mass of the final state neutrino. At this step of reconstruction no remaining charged tracks are allowed in the event. If there are remaining neutral particles the sum of their energies should not exceed $1.0/m$ GeV, where m is the number of such neutrals. The resulting $M^2_{\rm rec}(\rm DKX\gamma\mu)$ distribution is shown in Fig. 4 (bottom), where a prominent peak around zero, corresponding to the signal of $D_s \to \mu\nu_\mu$ decays, can be observed.

Efficiency of the described reconstruction strongly depends on the number of primary particles (n_X) present in the event (beside the tag side D and K mesons and the signal side γ). Since there are significant differences observed between the simulated and measured n_X distributions the yield of inclusive D_s as well as of the $D_s \to \mu\nu_\mu$ decays must be obtained as a function of n_X.

Two-dimensional histogram of $M_{\rm rec}(\rm DKX\gamma)$ vs. n_X is fitted to the expected distribution. The signal $M_{\rm rec}(\rm DKX\gamma)$ shape in each n_X interval is parametrized as a sum of Monte-Carlo (MC) simulated distributions in bins of generated n_X. The normalizations of MC terms $w_i^{D_s}$ are free parameters of the fit. The background is described by the WS sample of inclusive D_s decays, taking into account a small fraction of signal events in the WS sample. Results of the fit are superimposed in Fig. 4 (top). The yield of inclusive D_s decays is calculated as

$$N^{\rm inc}_{D_s} = \sum_i w_i^{D_s} N^{{\rm MC},i}_{D_s} \quad , \tag{2}$$

with $N^{{\rm MC},i}_{D_s}$ denoting the number of reconstructed MC events in i-th bin of generated n_X. We find $N^{\rm inc}_{D_s} = 32100 \pm 870({\rm stat}) \pm 1210({\rm syst})$.

A similar fit is performed to the two-dimensional distribution of $M^2_{\rm rec}(\rm DKX\gamma\mu)$ vs. n_X to obtain the number of $D_s \to \mu\nu_\mu$ decays. Also here the signal is modelled by the simulated distribution. The background can be described by $D_s \to e\nu_e$ decays reconstructed with the same method as the $D_s \to \mu\nu_\mu$ and corrected for the efficiency and kinematic differences. Normalization constants which are free parameters of the fit are denoted $w_i^{\mu\nu}$. Results are superimposed to the measured $M^2_{\rm rec}(\rm DKX\gamma\mu)$ distribution in Fig. 4 (bottom). The signal yield,

$$N^{\mu\nu}_{D_s} = \sum_i w_i^{\mu\nu} N^{{\rm MC},i}_{\mu\nu} \ , \tag{3}$$

where $N^{{\rm MC},i}_{\mu\nu}$ is the number of reconstructed signal MC events in i-th bin of generated n_X, is found to be $N^{\mu\nu}_{D_s} = 169 \pm 16({\rm stat}) \pm 8({\rm syst})$.

The efficiency for the reconstruction of inclusive D_s decays cancels in the estimation of the branching fraction. The latter is obtained as

$$\mathcal{B}(D_s \to \mu\nu_\mu) = \frac{N^{\mu\nu}_{D_s}}{\bar{\epsilon}_{\mu\nu} N^{\rm inc}_{D_s}} \ , \tag{4}$$

with the average efficiency for selection of $D_s \to \mu\nu_\mu$ decays among the inclusive D_s decays defined as

$$\bar{\epsilon}_{\mu\nu} = \sum_i (w_i^{D_s} N^{{\rm MC},i}_{\mu\nu}) / \sum_i (w_i^{D_s} N^{{\rm MC},i}_{\mu\nu}/\epsilon_i). \tag{5}$$

The result is

$$\mathcal{B}(D_s \to \mu\nu_\mu) = (6.44 \pm 0.76({\rm stat}) \pm 0.57({\rm syst})) \cdot 10^{-3} \ . \tag{6}$$

Statistical uncertainty is obtained by varying the bin content of data histograms and repeating the fits. By that the correlations among fitted weights are taken into account. Systematic error includes uncertainty due to the finite background samples used in the fits, uncertainty of $\bar{\epsilon}_{\mu\nu}$ and possible differences between data and simulated samples in the relative rates of individual D_s decay modes.

The D_s meson decay constant can be calculated using Eq. (1) and the value of $|V_{cs}| = 0.9730$[7] arising from the overall fit to the CKM matrix elements imposing the unitarity constraint:

$$f_{D_s} = (275 \pm 16({\rm stat}) \pm 12({\rm syst}))\ {\rm MeV}. \tag{7}$$

The measured branching fraction is in good agreement with similar measurements performed by Cleo-c[8] and BaBar experiments[9]. The results are compared in Fig. 5[10]. A simple weighted average of these measurements has an accuracy of around 10 MeV.

Recently new preliminary LQCD calculation of D_s decay constant with significantly improved precision became available[11]. The relative accuracy of the result is quoted to be 1%—2%, significantly better than the current experimental sensitivity (see Fig. 5). This result deviates from a simple average of experimental values by around 2.5 standard deviations. Two tasks should be accomplished before any firm conclusion on the comparison can be reached: confirmation of the LQCD result and especially its accuracy, and

1) Different RS and WS combinations are considered; for example, $K^+D^+D_s^{*-}$ is a RS and $K^+\overline{D}^0 D_s^{*-}$ a WS combination.

measurements with an even higher precision than the current to be performed.

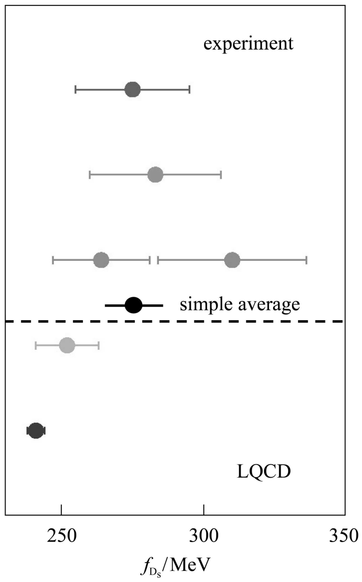

Fig. 5. Decay constant f_{D_s} as obtained (from top to bottom) in the present measurement, by the BaBar[9] and Cleo-c[8] experiment. The plot is adopted from Ref. [10]. In the fourth row a simple weighted average of these measurements is shown. The dashed line separates experimental determinations and LQCD calculations from Refs. [11,12]. The difference between the result of Ref. [11] and the experimental average is around 2.5 standard deviations.

In Fig. 6 an estimate of the projected accuracy on f_{D_s} for the measurements based on the method described in this paper and the one used in Ref. [8] is shown. With approximately 2 ab^{-1} of data available from the B factories and 1 fb^{-1} from the charm factories the relative precision of individual measurements would reach 4%, and that of an experimental average around 2%. This would match the precision of the LQCD calculations and enable a precise test of their accuracy.

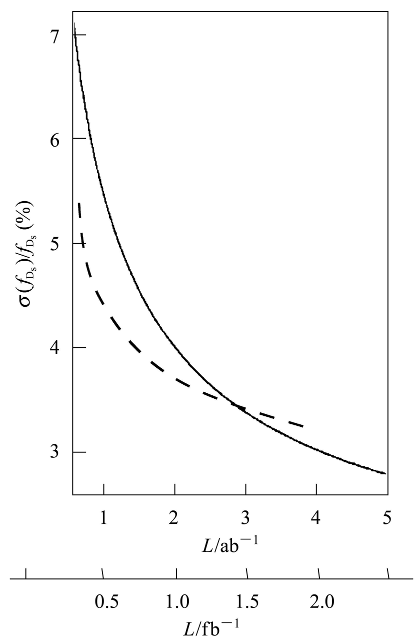

Fig. 6. Approximate projection of the accuracy of f_{D_s} measurements based on the method described in this paper (solid line) and on the method of charm factory (dashed line). The upper horizontal axis is the integrated luminosity of B factory and the lower one the luminosity of the charm factory.

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