Charm and tau decays at B factories

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We discuss recent results on charm and tau physics obtained by the Belle and BaBar collaborations. In the charm section we present measurements of D^0 – $\bar{D}^0$ mixing parameters, measurements searches for CP violation in D^0 decays and a measurement of D_s meson decay constant. In the tau section the recent results on lepton flavor violation in tau decays to three leptons or a lepton and a vector meson are discussed.

1 Introduction

The cross-sections for $c\bar{c}$ and τ pair production are very similar to the $b\bar{b}$ production cross-section at the B factories. The Belle [1] and BaBar [2] detectors at the KEKB [3] and PEP-II colliders have accumulated together over 1 ab^{-1} of data and therefore provide large samples and an excellent environment to study charm and τ decays.

2 $D^0 - \overline{D}^0$ mixing and search for CP violation in D^0 decays

Particle-antiparticle mixing has been observed in several systems of neutral mesons: neutral kaons, B_d and B_s mesons. Last year at this conference the first evidence for $D^0 - \overline{D}^0$ mixing [4,5] was presented by both Belle and BaBar collaborations. As in the kaon and B-meson systems, the $D^0 - \overline{D}^0$ are produced in flavor eigenstates. The mixing occurs through weak interactions between the quarks and gives rise to two different mass eigenstates

$$|D_{1,2}\!>= p|D^0\!> \pm q|\bar{D}^0\!>, \tag{1}$$

where $|p|^2 + |q|^2 = 1$. The time evolution of flavor eigenstate is then given by

$$|D^0(t)\!>= \left[|D^0\!> \cosh\left(\frac{ix+y}{2}t\right) + \frac{q}{p}|\bar{D}^0\!> \sinh\left(\frac{ix+y}{2}t\right)\right] \times e^{-\frac{1}{2}(1+\frac{im}{\Gamma})t}, \tag{2}$$

Table 1: The mixing parameter y_{CP} and CP violating parameter ΔY measured by BaBar using the ratios of lifetimes for the decays of D^0 mesons to K^-K^+, $\pi^-\pi^+$ and $K^-\pi^+$.

Sample	y_{CP}	ΔY
K^-K^+	$(+1.60 \pm 0.46 \pm 0.17)\%$	$(-0.40 \pm 0.44 \pm 0.12)\%$
$\pi^-\pi^+$	$(+0.46 \pm 0.65 \pm 0.25)\%$	$(+0.05 \pm 0.64 \pm 0.32)\%$
Combined	$(+1.24 \pm 0.39 \pm 0.13)\%$	$(-0.26 \pm 0.36 \pm 0.08)\%$

where the two parameters that describe the $D^0 - \overline{D}^0$ mixing x and y,

$$x = \frac{m_1 - m_2}{\Gamma}, \tag{3}$$

$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}, \tag{4}$$

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2} \tag{5}$$

are the mass and width difference of the two mass eigenstates. In the Standard Model (SM), $D^0 - \overline{D}^0$ mixing is strongly GIM and CKM suppressed, and is dominated by long distance effects[6]. As the mixing rate is expected to be small within the SM, it is sensitive to the contribution of new, as of now unobserved processes and particles. The largest SM predictions for the parameters x and y, which include the impact of long distance dynamics, are of order 1% [6].

CP violating effects in decays of neutral D meson system would appear as a difference in the partial decay widths of D^0 and $\overline{D}^0$ mesons decaying to a CP eigenstate f

$$A_{CP} = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})}. \tag{6}$$

The contribution to the time-integrated asymmetry in neutral D meson decays can be separated into three parts: direct CP violation in decays to specific states, indirect CP violation in $D^0 - \overline{D}^0$ mixing, and indirect CP violation in interference between mixing and decay. Indirect CP violation is to a good approximation predicted to be universal for amplitudes with final CP eigenstates, but direct CP violation can be non-universal depending on the specifics of the new physics. Within the SM the expected level of CP violation is below the current experimental sensitivity [7], therefore any positive signal would indicate physics beyond the SM.

BaBar measured $D^0 - \overline{D}^0$ mixing parameters using the ratios of lifetimes for the decays of neutral D mesons to CP even eigenstates K^-K^+ and $\pi^-\pi^+$ to the mixed-CP state $K^-\pi^+$ [8]. The ratio of lifetimes

$$y_{CP} = \frac{\tau_{K\pi}}{\tau_{hh}} - 1, \quad h = K, \pi, \tag{7}$$

corresponds in the limit of conserved CP symmetry to the mixing parameter y defined above. By measuring the lifetime difference of D^0 and $\overline{D}^0$ mesons decaying to CP eigenstates the CP violating parameter

$$\Delta Y = \frac{\tau_{K\pi}}{<\tau_{hh}>} A_\Gamma, \quad A_\Gamma = \frac{\tau_{hh}(D^0) - \tau_{hh}(\overline{D}^0)}{\tau_{hh}(D^0) + \tau_{hh}(\overline{D}^0)} \tag{8}$$

is measured. In the limit of CP conservation $\Delta Y = 0$.

The D^0 meson is required to be produced in a $D^{*+} \to D^0\pi^+$ decay [a]. This requirement suppresses the background and tags the flavor of neutral D meson at the production with the charge of the pion. The D^0 lifetime is determined from an unbinned likelihood fit to the

[a] Charge conjugation is implied throughout this paper.

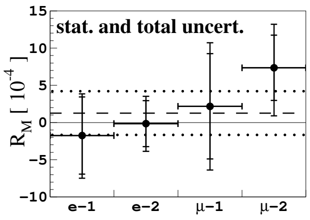

Figure 1: The R_M values of the four subsamples (e and μ, each for two different Belle detector configurations). Fit result to this four values is shown with dashed line, the dotted lines represent $\pm\sigma$ interval, and the solid line corresponds to no mixing.

reconstructed decay time and its estimated error, determined by a vertex-constrained combined fit to the D^0 decay and production vertices. The obtained value of y_{CP} given in Table 1, combined for both decay modes, represent evidence of $D^0 - \overline{D}^0$ mixing at the 3σ level. It confirms the lifetime ratio measurement made by Belle [4]. The comparison of measured lifetimes for D^0 and $\overline{D}^0$ decaying to CP eigenstates K^-K^+, $\pi^-\pi^+$ shows now evidence for CP violation (Table 1).

Belle performed an improved search for $D^0 - \overline{D}^0$ mixing using semileptonic $D^0 \to K^{(*)-}\ell^+\nu_\ell$ decays [9], where the lepton is either an electron or a muon. Neutral D mesons from $D^{*+} \to D^0\pi^+$ decays are used and tagged at production by the charge of the pion. The mixing parameter,

$$R_M \simeq \frac{x^2+y^2}{2} = \frac{N_{\rm WS}}{N_{\rm RS}}, \tag{9}$$

is determined by measuring the numbers of reconstructed wrong (WS) and right sign (RS) events. The non-mixed decay results in a charge combination $\pi^+K^-\ell^+$ referred to as the RS charge combination while the mixing process results in a charge combination $\pi^+K^+\ell^-$ and is referred to as the WS charge combination. The reconstructed masses of D^0 and D^{*+} candidates are smeared since the neutrino is not directly reconstructed. The RS and WS yields are determined from the fits to the RS and WS distributions of mass difference $\Delta M = M(K\ell\nu\pi) - M(K\ell\nu)$, in which the uncertainty due to the neutrino four momentum cancels to a large extent. No significant WS signal is found in either the electron or muon samples and the most stringent experimental limit, obtained from semileptonic decays, on time time integrated mixing rate is given, $R_M < 6.1 \times 10^{-4}$ at 90% C.L. The R_M values obtained for each subsample, e and μ, are shown on Fig. 1.

The Belle and BaBar collaborations performed measurements searching for CP violation in decays of neutral D mesons to K^-K^+, $\pi^-\pi^+$ [10], $\pi^-\pi^+\pi^0$ [11,12] and $K^+K^-\pi^0$ [12]. The main experimental challenge in these analyses is precise tagging of a neutral D meson decaying to a CP eigenstate. The flavor of the D^0 meson at production is tagged, as in the mixing analyses described above, by reconstructing $D^{*+} \to D^0\pi^+$ decays. Beside the intrinsic asymmetry A_{CP}, defined by Eq. 6, there are two other contributions that create a difference in the numbers of reconstructed D^0 and $\overline{D}^0$ events. The first one is the forward-backward (FB) asymmetry in the production of D^{*+} in $e^+e^- \to c\bar{c}$ arising from γ–Z interference and higher order QED effects and is an odd function of the cosine of the D^{*+} production polar angle in the center-of-mass system (CMS) [13]. The second one is the asymmetry in the reconstruction efficiencies of oppositely charged pions from D^{*+} decays. The effect of the latter is evaluated and corrected for by measuring the relative detection efficiency for tagging pions using the $D^0 \to K^-\pi^+$ decays with and without flavor tag. CP violation would appear as an asymmetry in the $D^0 - \overline{D}^0$ yields independent of any kinematic variable. However, the reconstruction efficiency of the tagging pion is polar angle dependent, therefore the CP asymmetry, $A_{CP} = \frac{N_{\overline{D}^0} - N_{D^0}}{N_{\overline{D}^0} + N_{D^0}}$, is measured

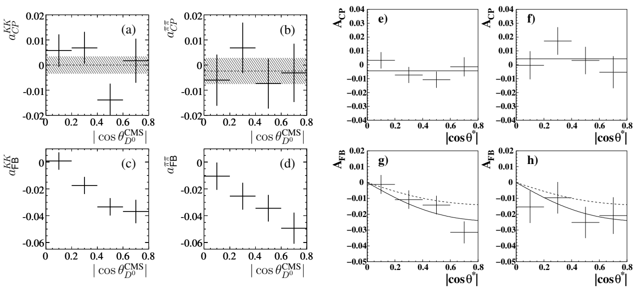

Figure 2: CP-violating asymmetries in KK (BaBar (a) and Belle (e)) and $\pi\pi$ (BaBar (b) and Belle (f)), and forward-backward asymmetries in KK (BaBar (c) and Belle (g)) and $\pi\pi$ (BaBar (d) and Belle (h)). In (a), (b), (e), and (f) the horizontal lines represent the central values.

Table 2: Measured CP asymmetry by the BaBar and Belle Collaborations in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays.

A^{hh}_{CP}	BaBar	Belle
K^+K^-	$(\ 0.00 \pm 0.34(\text{stat}) \pm 0.13(\text{syst}))\%$	$(-0.43 \pm 0.30(\text{stat}) \pm 0.11(\text{syst}))\%$
$\pi^+\pi^-$	$(-0.24 \pm 0.52(\text{stat}) \pm 0.22(\text{syst}))\%$	$(+0.43 \pm 0.52(\text{stat}) \pm 0.12(\text{syst}))\%$

in intervals of the cosine of the polar angle in the CMS. Any forward-backward asymmetry is canceled by averaging over symmetric intervals in the cosine of the polar angle in the CMS.

In Table 2 the measured CP asymmetry by the BaBar and Belle Collaborations in $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ decays is given. No CP violation is observed in either of the decay modes. The measurements are statistically limited. The main source of the systematic uncertainty is the statistics of the $D^0 \to K^-\pi^+$ samples, used to correct the charged pion reconstruction efficiency asymmetry and will thus also reduce with larger data samples.

The three-body decays $D^0 \to \pi^-\pi^+\pi^0$, $K^-K^+\pi^0$ proceed both via CP eigenstates and flavor states, making it possible to probe CP violation in both types of amplitudes and in the interference between them. Measuring interference effects in a Dalitz plot probes asymmetries in both the magnitudes and phases of the amplitudes, not simply in the overall decay rates. Belle measured time- and phase-space integrated CP asymmetry (Eq. 6) in $D^0 \to \pi^-\pi^+\pi^0$ decays and BaBar measured it in $D^0 \to \pi^-\pi^+\pi^0$ and $D^0 \to K^-K^+\pi^0$ decays. Measured asymmetries are given in Table 3. The asymmetry in reconstruction efficiency of tagging pions from D^{*+} decays was evaluated using independent $D^{*+} \to D^0(K_S\pi^0)\pi^+$ data and Monte Carlo simulated samples at Belle, while in BaBar's measurement it was evaluated using tagged and untagged data samples of $D^0 \to K^-\pi^+$ decays as described above. This difference explains the larger systematic uncertainty on measured CP asymmetry from Belle. The phase-space integrated CP asymmetry is insensitive to differences in the Dalitz plot shapes, so BaBar adopted three other approaches to search for CP violation in $D^0 \to \pi - \pi^+\pi^0$, $K^-K^+\pi^0$ decays. First they quantified differences between the D^0 and $\overline{D}^0$ Dalitz plots in two dimensions by ploting normalized residuals (shown in Figure 3)

$$\Delta = (n_{\overline{D}^0} - Rn_{D^0})/\sqrt{\sigma^2_{n_{\overline{D}^0}} + R^2\sigma^2_{n_{D^0}}} \tag{10}$$

in the Dalitz plot area elements, and where n denotes the number of events, σ its uncertainty and R is the efficiency corrected ratio. From the calculated $\chi^2/\nu = (\sum_{DP}\Delta^2)/\nu$ value, where ν is the number of Dalitz plot elements, the one-sided Gaussian confidence levels for consistency with no CP violation are obtained: 32.8% for $\pi^-\pi^+\pi^0$ and 16.6% for $K^-K^+\pi^0$. In BaBar's second approach differences in the angular moments of the D^0 and $\overline{D}^0$ intensity distributions

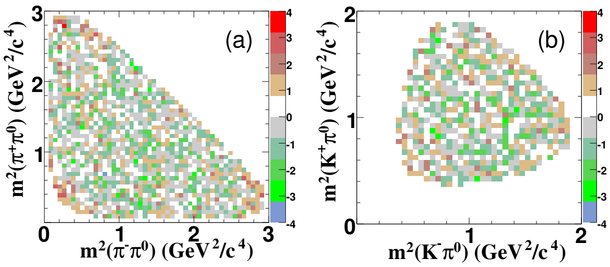

Figure 3: Normalized residuals Δ for $D^0 \to \pi - \pi^+\pi^0$ (left) and $D^0 \to K^-K^+\pi^0$ (right) decays.

Table 3: Measured CP asymmetry by the Belle and BaBar Collaborations in $D^0 \to \pi^-\pi^+\pi^0$ and $D^0 \to K^-K^+\pi^0$ decays.

$A_{CP}^{f_{CP}}$	Belle	BaBar
$\pi^+\pi^-\pi^0$	$(0.43 \pm 0.41(\text{stat}) \pm 1.23(\text{syst}))\%$	$(-0.31 \pm 0.41(\text{stat}) \pm 0.17(\text{syst}))\%$
$K^+K^-\pi^0$	-	$(+1.00 \pm 1.67(\text{stat}) \pm 0.25(\text{syst}))\%$

are looked for. The angular moments of the cosine of the helicity angle of the D^0 meson decay products reflect the spin and mass structure of intermediate resonant and nonresonant amplitudes. Similarly to the previous approach the one sided Gaussian confidence levels for consistency with no CP violation are obtained: 28.2% for the $\pi^+\pi^-$, 28.4% for the $\pi^+\pi^0$, 63.1% for the K^+K^-, and 23.8% for the $K^+\pi^0$ subsystems. In the third, model dependent approach, BaBar searched for CP violation in the amplitudes describing intermediate states in the D^0 and $\overline{D}^0$ decays. The Dalitz plot amplitude $\mathcal{A}$ can be parametrized as a sum of amplitudes $A_r(s_+, s_-)$ for all relevant intermediate states r, each with a complex coefficient, i.e., $\mathcal{A} = \sum_r a_r e^{i\phi_r} A_r(s_+, s_-)$, where a_r and ϕ_r are real and s_+ and s_- are the squared invariant masses of the pair of final state particles with $+1$ and -1 net charge. In the absence of CP violation the values of a_r and ϕ_r are expected to be identical for D^0 and $\overline{D}^0$ decay. Comparison of amplitudes and relative phases, $a_r$and ϕ_r, obtained for D^0 and $\overline{D}^0$ decays showed, that the CP asymmetry in any amplitude, relative to that of the whole decay, is no larger than a few percent.

3 Measurement of $\mathcal{B}(D_s^+ \to \mu^+\nu_\mu)$

One of the more important goals of particle physics is the precise measurement and understanding of the CKM matrix. To interpret results on B meson decays, theoretical calculations of form factors and decay constants are often needed (usually based on lattice gauge theory [14]). Decays of charmed hadrons in turn enable tests of the predictions for analogous quantities in the charm sector. It is necessary to have accurate measurements in the charm sector to check theoretical methods and predictions. In the SM the leptonic decays of mesons are mediated by a single virtual $W^\pm$ boson. The decay rate for e.g. $D_s^+ \to \ell^+\nu_\ell$ is given by

$$\Gamma(D_s^+ \to \ell^+\nu_\ell) = \frac{G_F^2}{8\pi} f_{D_s}^2 m_\ell^2 m_{D_s} (1 - \frac{m_\ell^2}{m_{D_s}^2})^2 |V_{cs}|^2, \tag{11}$$

where G_F is the Fermi coupling constant, V_{cs} is the corresponding CKM matrix element, m_ℓ and m_{D_s} are the masses of the lepton and D_s meson, respectively. The effects of the strong interaction are accounted for by the decay constant f_{D_s}. Since the decay rate is very small for

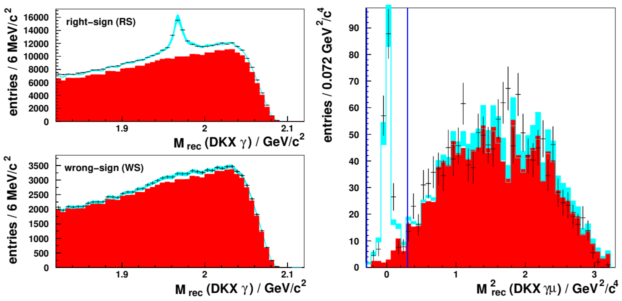

Figure 4: Recoil mass spectrum for D_s-tags for right-sign (left top) and wrong sign (left bottom) charge combinations of the D meson and kaon. (Right) Spectrum of missing mass squared for $D_s^+ \to \mu^+\nu_\mu$ candidates. The signal peaks at zero, the background shape in red is obtained by reconstructing $D_s^+ \to e^+\nu_e$ decays, where no signal is expected due to helicity suppression.

electrons due to helicity suppression and detection of τ's involves additional neutrinos, the muon mode is experimentally the most accessible one.

The analysis performed at Belle uses events of the type $e^+e^- \to D_s^* D^{\pm,0} K^{\pm,0} X$, where X can be any number of pions and up to one photon [15]. The particles in the final state are divided into a tag and signal side. The tag side consists of a D meson and a kaon in any charge combination and tags the flavor of the D_s meson. The signal side is a D_s^* decaying to $D_s\gamma$. Reconstructing the tag side, and allowing for any possible set of particles in X, the signal side is identified by reconstruction of the recoil mass as shown in Figure 4. Within this sample of tagged inclusive D_s decays, decays of D_s meson to muon and neutrino are selected by requiring another charged track that is identified as a muon and has the same charge as the D_s candidate. The number of reconstructed $D_s^+ \to \mu^+\nu_\mu$ decays is then determined from the fit to the recoil mass squared against all reconstructed particles, including the muon, as shown in Figure 4. Normalizing the number of reconstructed $D_s^+ \to \mu^+\nu_\mu$ decays to the number of reconstructed tagged inclusive D_s decays an absolute branching ratio is measured

$$\mathcal{B}(D_s^+ \to \mu^+\nu_\mu) = [6.44 \pm 0.76(\mathrm{stat}) \pm 0.57(\mathrm{syst})] \times 10^{-3}, \tag{12}$$

which is consistent with the world average [16] and Babar's [17] and Cleo-c's [18] measurements. The obtained value of f_{D_s} using Eq. 11 is

$$f_{D_s} = (275 \pm 16(\mathrm{stat}) \pm 12(\mathrm{syst}))\ \mathrm{MeV}. \tag{13}$$

A simple average of the D_s meson decay constant obtained from the cited measurements has an uncertainty of 11 MeV. Recently a lattice QCD calculation of significantly improved precision was performed, with preliminary result $f_{D_s} = (241 \pm 3)$ MeV [19]. This value is somewhat lower than the experimental average and if it proves to be stable the comparison with the experimental results may point to some inconsistency between the two. More precise measurements are needed for a firm conclusion.

4 Search for lepton flavor violating τ decays

One of the currently most interesting questions in τ physics is whether there is a sizable lepton flavor violation (LFV) or not. LFV decays are expected even in the SM extended with the massive neutrinos [20], but the expected rate is very small and far beyond the reach of B factories. Many extensions of the SM however, predict LFV $\tau \to \ell\ell\ell$ decays at the level of $10^{-10} - 10^{-7}$ [21], which can be already probed at B factories with the current accumulated data. B factories provide very clean environment for measurements searching for LFV τ decays. Candidate signal events are required to have 1-3 topology, where the τ on the signal side yields three charged

Table 4: Improved 90% C.L. upper limits (UL) on $\mathcal{B}(\tau \to \ell\ell\ell)$.

Mode	Belle $\mathcal{B}^{90}_{\rm UL}(\times 10^{-8})$	BaBar $\mathcal{B}^{90}_{\rm UL}(\times 10^{-8})$
$\tau^- \to e^-e^+e^-$	3.6	4.3
$\tau^- \to \mu^-\mu^+\mu^-$	3.2	5.3
$\tau^- \to e^-\mu^+\mu^-$	4.1	3.7
$\tau^- \to \mu^-e^+e^-$	2.7	8.0
$\tau^- \to e^+\mu^-\mu^-$	2.3	5.6
$\tau^- \to \mu^+e^-e^-$	2.0	5.8
$\mathcal{L}$ (fb^{-1})	535	376

Table 5: Improved 90% C.L. upper limits (UL) on $\mathcal{B}(\tau \to \ell V^0)$.

Mode	Belle $\mathcal{B}_{90}(\times 10^{-8})$	BaBar $\mathcal{B}_{90}(\times 10^{-8})$	Mode	Belle $\mathcal{B}^{90}_{\rm UL}(\times 10^{-8})$	BaBar $\mathcal{B}^{90}_{\rm UL}(\times 10^{-8})$
$\tau^- \to e^-\phi$	7.3	–	$\tau^- \to \mu^-\phi$	13	–
$\tau^- \to e^-\omega$	18	11	$\tau^- \to \mu^-\omega$	8.9	10
$\tau^- \to e^-K^{*0}$	7.8	–	$\tau^- \to \mu^-K^{*0}$	5.9	–
$\tau^- \to e^-\bar{K}^{*0}$	7.7	–	$\tau^- \to \mu^-\bar{K}^{*0}$	10	–
$\tau^- \to e^-\rho^0$	6.3	–	$\tau^- \to \mu^-\rho^0$	6.8	–
$\mathcal{L}$ (fb^{-1})	543	384	$\mathcal{L}$ (fb^{-1})	543	384

particles, while the second τ on the tag side yields one charged track. The event is easily divided into two hemispheres in the CMS. The signal side does not include any neutrinos in the final state, therefore signal events should peak at the nominal mass of the tau and at zero in the two dimensional distribution of the invariant mass versus energy difference.

Belle and BaBar reported improved upper limits on $\tau \to \ell\ell\ell$ branching ratios [22,23], where leptons in the final state are either electrons or muons, leading to six distinct decay modes: $e^-e^+e^-$, $\mu^+e^-e^-$, $\mu^-e^+e^-$, $e^+\mu^-\mu^-$, $e^-\mu^+\mu^-$ and $\mu^-\mu^+\mu^-$. In all cases the observed number of events in the signal region is consistent with the expected background. The improved upper limits on branching ratios, given in Table 4, are of order of 10^{-8} and they already restrict the parameter space of some beyond the SM models.

Belle reported improved upper limits on LFV τ decays to a lepton and vector meson, where the lepton is either an electron or a muon and vector meson is either ϕ, K^{*0}, $\overline{K}^{*0}$ or ρ^0 [24]. For the first same a search for $\tau \to \ell\omega$ ($\ell = e, \mu$) decays was performed by Belle and BaBar [24,25]. No significant signal was observed in any of the studied decay modes. The improved upper limits on $\mathcal{B}(\tau \to \ell V^0)$ range from 5.9–10$\times 10^{-8}$ and are given in Table 5.

5 Conclusions

Only one year after the first observation of $D^0 - \overline{D}^0$ mixing, the mixing parameter y_{CP} is known with relatively high precision. The current world averages of the mixing parameters x and y [26] lie at the upper edge of still uncertain theoretical expectations, at the level of 1%, therefore making it impossible to conclude whether $D^0 - \overline{D}^0$ mixing is a purely SM effect or receives contributions from new physics. CP violation is expected to be small in the D meson system, below the sensitivity of current experimental data. If large CP violating phases are present in yet unknown processes the asymmetries could be increased to $\sim 1\%$. All measured CP asymmetries in D^0 decays observe no CP violation.

Further measurements of the D_s meson decay constant are needed to resolve the discrepancy between the latest lattice QCD calculations and the experimental value.

The measurements searching for LFV tau decays are approaching the 10^{-8} level and already restrict the parameter space of many beyond the SM models.

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