Measurement of $y_{CP}$ in $D$ meson decays to $CP$ eigenstates

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We present a measurement of the $D^0\overline{D}^0$ mixing parameter $y_{CP}$ using a flavor-untagged sample of $D^0 \rightarrow K^0_S K^+ K^−$ decays. The measurement is based on a 673 fb$^{-1}$ data sample recorded by the Belle detector at the KEKB asymmetric-energy $e^+e^−$ collider. We find $y_{CP} = (0.21 ± 0.63(\text{stat.}) ± 0.78(\text{syst.}) ± 0.01(\text{model}))%$.

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Particle-antiparticle mixing has been observed in several systems of neutral mesons: neutral kaons, $B_d$ and $B_s$ mesons. As in the kaon and $B$-meson systems, the $D^0 - \bar{D}^0$ are produced in flavor eigenstates. The mixing occurs through weak interactions between the quarks and gives rise to two different mass eigenstates $|D_{1,2}^0\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$, where $p$ and $q$ are complex coefficients satisfying $|p|^2 + |q|^2 = 1$. The time evolution of flavor eigenstates, $D^0$ and $\bar{D}^0$, is governed by the mixing parameters $x = (m_1 - m_2)/\Gamma$ and $y = (\Gamma_1 - \Gamma_2)/2\Gamma$, where $m_{1,2}$ and $\Gamma_{1,2}$ are the masses and widths of the two mass eigenstates $D_{1,2}$, and $\Gamma = (\Gamma_1 + \Gamma_2)/2$. In the Standard Model (SM), $D^0 - \bar{D}^0$ mixing is strongly GIM suppressed for $d$ and $s$ quarks and CKM suppressed for $b$ quark box diagrams, and is dominated by long distance effects [1]. As the mixing rate is expected to be small within the SM, it is sensitive to the contribution of new, as yet 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% [1]. Various $D^0$ decay modes have been used to measure or constrain $x$ and $y$ [2]. Evidence for $D^0 - \bar{D}^0$ has been found in $D^0 \rightarrow K^+K^-/\pi^+\pi^- [3,4]$, $D^0 \rightarrow K^+\pi^- [5,6]$ and $D^0 \rightarrow K^+\pi^- \pi^0 [7]$ decays. The world average [8, 9] of $D^0$ mixing parameter $y_{CP}$ measured in $D^0 \rightarrow K^+K^-/\pi^+\pi^-$ decays is $y_{CP} = (1.132 \pm 0.266)\%$, where $y_{CP} = y$ if $CP$ is conserved. Here we study the self-conjugate decay $D^0 \rightarrow K_S^0 K^+ K^-$ [10].

The time dependent decay rate of an initially produced $D^0$ or $\bar{D}^0$ can be expressed as

\[
|M(s_0, s_+, t)|^2 = |A_1(s_0, s_+)|^2 e^{-\frac{(1+|y|)}{\tau} t} + |A_2(s_0, s_+)|^2 e^{-\frac{(1-|y|)}{\tau} t} \\
+ 2\text{Re}[A_1(s_0, s_+)A_2^*(s_0, s_+)]\cos\left(\frac{xt}{\tau}\right)e^{-\frac{t}{\tau}} \\
+ 2\text{Im}[A_1(s_0, s_+)A_2^*(s_0, s_+)]\sin\left(\frac{xt}{\tau}\right)e^{-\frac{t}{\tau}}
\]

(1)

\[
|\bar{M}(s_0, s_+, t)|^2 = |\bar{A}_1(s_0, s_+)|^2 e^{-\frac{(1-|y|)}{\tau} t} + |\bar{A}_2(s_0, s_+)|^2 e^{-\frac{(1+|y|)}{\tau} t} \\
+ 2\text{Re}[\bar{A}_1(s_0, s_+)\bar{A}_2^*(s_0, s_+)]\cos\left(\frac{xt}{\tau}\right)e^{-\frac{t}{\tau}} \\
+ 2\text{Im}[\bar{A}_1(s_0, s_+)\bar{A}_2^*(s_0, s_+)]\sin\left(\frac{xt}{\tau}\right)e^{-\frac{t}{\tau}},
\]

(2)

where $\tau = 1/\Gamma$ is the $D^0$ lifetime, $s_0$ and $s_+$ are invariant masses squared of $K^+K^-$ and $K_S^0K^+$ pairs, respectively. The decay amplitudes $A_1$ and $A_2$ can be expressed with $D^0$ and $\bar{D}^0$ decay amplitudes $A$ and $\bar{A}$ as

\[
A(s_0, s_+) = \sum_r a_r e^{i\phi_r} A_r(s_0, s_+)
\]

(3)

\[
\bar{A}(s_0, s_+) = \sum_r \bar{a}_r e^{i\phi_r} \bar{A}_r(s_0, s_+)
\]

(4)

\[
A_1(s_0, s_+) = \frac{1}{2} \left( A(s_0, s_+) + \bar{A}(s_0, s_+) \right) = \sum \text{CP} = +1 \text{ and flavor eigenstates}
\]

(5)

\[
A_2(s_0, s_+) = \frac{1}{2} \left( A(s_0, s_+) - \bar{A}(s_0, s_+) \right) = \sum \text{CP} = -1 \text{ and flavor eigenstates},
\]

(6)

where $A$ and $\bar{A}$ are summed over resonant contributions $r$ found in $D^0 \rightarrow K_S^0 K^+ K^-$ decays. In the limit of $CP$ conservation $a_r = \bar{a}_r$, $\phi_r = \phi_r$ and $\bar{A}(s_0, s_+) = A(s_0, s_+)$. The existing Dalitz plot analyses of $D^0 \rightarrow K_S^0 K^+ K^-$ decays [13, 14] observed contribution of
FIG. 1: $s_0$ (left) and $s_+$ (right) Dalitz plot projections of $|\mathcal{M}(s_0, s_+)|^2$ (black line), $|\mathcal{A}_1(s_0, s_+)|^2$ (blue line), $|\mathcal{A}_2(s_0, s_+)|^2$ (red line), $2Re[\mathcal{A}_1(s_0, s_+)\mathcal{A}_2^*(s_0, s_+)]$ (green solid line), and $2Im[\mathcal{A}_1(s_0, s_+)\mathcal{A}_2^*(s_0, s_+)]$ (green dashed line) for Dalitz model given in [14].

$CP (K^0_S a_0(980)^0, K^0_S \phi(1020), K^0_S f_0(1370), K^0_S f_2(1270), K^0_S a_0(1450)^0, K^0_S f_0(980))$, Cabbibo-allowed $(K^- a_0(980)^+, K^- a_0(1450)^+)$ and doubly Cabbibo-suppressed $(K^+ a_0(980)^-)$ flavor eigenstates. Figure 1 shows time integrated $s_0$ and $s_+$ projections of $|\mathcal{M}(s_0, s_+)|^2$, $|\mathcal{A}_1(s_0, s_+)|^2$, $|\mathcal{A}_2(s_0, s_+)|^2$, $2Re[\mathcal{A}_1(s_0, s_+)\mathcal{A}_2^*(s_0, s_+)]$ and $2Im[\mathcal{A}_1(s_0, s_+)\mathcal{A}_2^*(s_0, s_+)]$ obtained by Dalitz model given in Ref. [14]. The integral of $2Re[\mathcal{A}_1(s_0, s_+)\mathcal{A}_2^*(s_0, s_+)]$ and $2Im[\mathcal{A}_1(s_0, s_+)\mathcal{A}_2^*(s_0, s_+)]$ over $s_+$ yields 0.

The $|\mathcal{A}_1|^2$ and $|\mathcal{A}_2|^2$ parts of the decay rate have different time dependence (Eq. 1 and 2) and also very different dependence in the $s_0$ (Fig. 1 (left)). In any given $s_0$ region the lifetime of $D^0$ candidates is given by

$$\tau' = f_1 \tau \left( \frac{1}{1 + y_{CP}} + (1 - f_1) \frac{1}{1 - y_{CP}} \right),$$

where $\tau$ is the mean $D^0$ lifetime $1/\Gamma$, $f_1 = \frac{1}{2} |\mathcal{A}_1|^2 / \frac{1}{2} (|\mathcal{A}_1|^2 + |\mathcal{A}_2|^2)$ and $CP$ conservation is assumed. The lifetime difference of $D^0$ candidates in two different regions is then proportional to the mixing parameter $y_{CP}$

$$\Delta \tau = \frac{\tau' - \tau''}{\tau' + \tau''} = y_{CP} \left( f_1'' - f_1' \right) \left( 1 + y_{CP} \right) \approx y_{CP} (f_1'' - f_1').$$

The best $m(K^+K^-)$ intervals from which $D^0$ lifetimes are measured and compared are those that minimize the statistical uncertainty on $y_{CP}$ and are found to be: region around $\phi(1020)$ peak $m(K^+K^-) \in [1.015, 1.025]$ GeV/c$^2$ (denoted as ON) and intervals $m(K^+K^-) \in [2m_{K^\pm}, 1.010]$ GeV/c$^2$ and $m(K^+K^-) \in [1.033, 1.100]$ GeV/c$^2$ (the union of this two intervals is denoted as OFF), where $m_{K^\pm}$ is the nominal $K^\pm$ mass.

The data were recorded by the Belle detector at the KEKB asymmetric-energy collider [15]. The Belle detector is a large-solid-angle magnetic spectrometer that consists of a silicon vertex detector (SVD), a 50-layer central drift chamber (CDC), an array of aerogel threshold Cherenkov counters (ACC), a barrel-like arrangement of time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter (ECL) comprised of CsI(Tl) crystals located inside a superconducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect $K_L^0$ mesons and to identify muons (KLM). The detector is described in detail elsewhere [16]. Two inner detector configurations were used. A 2.0 cm beampipe and a 3-layer silicon vertex detector was used for the first
FIG. 2: The distribution of $m(K_S)$ with $m(K_S^0K^+K^-) \in [1.85, 1.88]$ GeV/$c^2$ (left) and $m(K_S^0K^+K^-)$ with $m(K_S) \in [0.490, 0.505]$ GeV/$c^2$ (right). Superimposed on the data (points with error bars) are projections of the $m(K_S) - m(K_S^0K^+K^-)$ fit (result from the fit (solid blue line), signal contribution (solid green line), true $K_S^0$ (solid black line) and rest of the background (solid red line)).

sample of 156 fb$^{-1}$, while a 1.5 cm beampipe, a 4-layer silicon detector and a small-cell inner drift chamber were used to record the remaining 517 fb$^{-1}$ of data.

The $K_S^0$ candidates are reconstructed in the $\pi^+\pi^-$ final state; we require that the pion candidates form a common vertex at least 0.9 mm from the $e^+e^-$ interaction point (IP) in plane perpendicular to the beam axis and have an invariant mass within $\pm 30$ MeV/$c^2$ of $K_S^0$ nominal mass. We reconstruct $D^0$ candidates by combining the $K_S^0$ candidate with two oppositely charged tracks assigned as kaons. These tracks are required to have at least one SVD hit in both $r-\phi$ and $z$ coordinates. A $D^0$ momentum greater than 2.55 GeV/$c$ in the $e^+e^-$ center-of-mass (CM) frame is required to reject $D$ mesons produced in $B$ mesons decays and to suppress combinatorial background.

The decay point of $D^0$ candidate is determined by refitting one of the charged kaons and $K_S^0$ candidate to a common vertex [18]; confidence levels exceeding $10^{-3}$ are required for the both fits. Out of two possibilities the one with lowest $\chi^2$ value of the fit is used. In addition we require that $K_S^0K^+K^-$ and $K^+K^-$ combinations originate from the common vertex by rejecting candidates of this two fits with confidence levels lower than $10^{-3}$. The $D^0$ production point is taken to be the intersection of the $D^0$ momentum vector with the IP. The proper decay time of the $D^0$ candidate is then calculated from the projection of the vector joining the production and decay points, $\vec{L}$, onto the $D^0$ momentum vector, $t = (m_{D^0}/p_{D^0})\vec{L} \cdot (\vec{p}_{D^0}/p_{D^0})$, where $m_{D^0}$ is the nominal $D^0$ mass. The decay time uncertainty $\sigma_t$ is evaluated event-by-event, and we require $\sigma_t < 600 \text{ fs}$ (the maximum of $\sigma_t$ distribution is at $\sim 230 \text{ fs}$).

The signal and background yields are determined from a two-dimensional fit to the in-
The lifetime of signal events is obtained in the following way. For each event category where $\sigma$ masses, functions. The $m$ in the MC event-by-event in order to achieve better agreement in fit is performed to obtain scaling factors for the background fractions, and then tune them from $K_S^0$ decay. These events are peaking in $m(K_S^0 K^+ K^-)$, but not in $m(K_S^0)$. The projections of $m(K_S^0 K^+ K^-)$ for events in $m(K_S^0)$ sidebands are checked for possible contribution of $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ decays. We find no contribution of $D^0 \rightarrow K^+ K^- \pi^+ \pi^-$ decays. The fit is performed to obtain scaling factors for the background fractions, and then tune them in the MC event-by-event in order to achieve better agreement in $m(K_S^0)$ and $m(K_S^0 K^+ K^-)$ distributions between MC and data events.

The sample of events for the lifetime measurement is selected using $|m'(K_S^0)|$ and $|m'(K_S^0 K^+ K^-)|$, where $m'(K_S^0)$ and $m'(K_S^0 K^+ K^-)$ are rotated $K_S^0$ and $D^0$ candidate masses according to

$$m'(K_S^0) = \frac{m(K_S^0) - m_{K_S^0}}{\sigma(K_S^0)}$$

$$m'(K_S^0 K^+ K^-) = \frac{m(K_S^0) - m_{K_S^0}}{\sigma(K_S^0) \sqrt{1 - \rho^2}} - \frac{m(K_S^0 K^+ K^-) - m_{D^0}}{\sigma(K_S^0 K^+ K^-) \sqrt{1 - \rho^2}},$$

where $m_{K_S^0} = 497.57 \pm 0.01$ MeV/$c^2$ and $m_{D^0} = 1864.96 \pm 0.01$ MeV/$c^2$ are fitted $K_S^0$ and $D^0$ masses, $\sigma(K_S^0) = 1.826 \pm 0.006$ MeV/$c^2$ and $\sigma(K_S^0 K^+ K^-) = 2.915 \pm 0.009$ MeV/$c^2$ are widths of the core Gaussian function and $\rho = 0.602 \pm 0.002$ is the correlation coefficient. The above uncertainties are statistical only. We define the signal box in the plane of rotated masses $m'(K_S^0)$ and $m'(K_S^0 K^+ K^-)$ in order to minimize correlations. Signal window in $|m'(K_S^0)|$ and $|m'(K_S^0 K^+ K^-)|$ is chosen to minimize the expected statistical error on $y_{CP}$, using the tuned MC: we require $|m'(K_S^0)| < 3.9$ and $|m'(K_S^0 K^+ K^-)| < 2.2$. The selection criteria on $\sigma$, $K_S$ and $K_S^0$ candidate flight distance in $r - \phi$ plane, given above, are determined in the same way. We find $139 \times 10^3$ signal events with purity of 94%.

The lifetime difference $\Delta_r$ (Eq. 5) is determined from $D^0 \rightarrow K_S^0 K^+ K^-$ proper decay time distributions by measuring lifetime of signal events in ON and OFF $m(K^+ K^-)$ regions. The lifetime of signal events is obtained in the following way. For each event category $i$ the proper decay time distribution $P_i(t)$ is assumed to be either exponential or a delta function, convoluted with a resolution function $R_i(t)$. The distribution for all event categories is then

$$P(t) = \sum_i p_i P_i(t) \otimes R_i(t),$$

where $p_i = N_i / \sum_j N_j$ is a fraction of the category $i$. By grouping the events into the signal and background one can also write

$$P(t) = p \frac{1}{\tau_s} e^{-t/\tau_s} \otimes R_s(t) + (1 - p) B(t),$$

where $\tau_s$ is the signal decay constant and $B(t)$ is the background distribution.
where the first term represents the measured distribution of a signal with lifetime $\tau_s$, $R_s(t)$ is a signal resolution function and $p = N_s/(N_s + N_b)$ is a fraction of signal events. The last term represents the distribution of background events. The mean of the above distribution (Eq. 12) is

$$< t > = p(\tau_s + t_0) + (1 - p) < t >_b, \quad (13)$$

where $t_0$ is the mean of the signal resolution function $R_s(t)$ and $< t >_b$ is the mean lifetime of the background. The lifetime of signal events, shifted for the resolution function offset, can be calculated from Eq. (13)

$$\tau_s + t_0 = \frac{< t > - (1 - p) < t >_b}{p}. \quad (14)$$

with uncertainty

$$\sigma^2_{\tau_s} = \left(\frac{1}{p}\right)^2 + \left(\frac{1 - p}{p}\sigma_b\right)^2 + \left(\frac{< t > - < t >_b}{p^2\sigma_p}\right)^2, \quad (15)$$

where $\sigma$, $\sigma_b$ and $\sigma_p$ are determined from the proper decay time distributions of all events $P(t)$ and background events $B(t)$ in the following way

$$\sigma = \frac{\text{rms}(P)}{\sqrt{N}}, \quad \sigma_b = \frac{\text{rms}(B)}{\sqrt{N_b}} \quad \text{and} \quad \sigma_p = \sqrt{\frac{p(1-p)}{N}}.$$ 

The $B(t)$ distribution of background events populating the signal window is approximated by the proper decay time distribution of events taken from $m'(K^0_SK^+K^-)$ sideband of equal size as signal window. No scaling factor is needed, since the background events are linearly distributed in $m'(K^0_SK^+K^-)$. The tuned MC is used to select the sideband region that best reproduces the timing distribution of background events in $m'(K^0_SK^+K^-)$ signal window, which is chosen to be $9.7 < |m'(K^0_SK^+K^-)| < 11.9$.

In Table I the numbers of reconstructed events in the signal window $N_{sw}$ and sideband $N_{sb}$, mean proper decay times of events in the signal window $< t >_{sw}$ and $< t >_{sb}$, fraction of signal events in the signal window $p = 1 - N_{sb}/N_{sw}$ and reconstructed lifetime $\tau_s + t_0$ (Eq. 14) shifted for resolution function offset obtained on real data sample are given for 3 different regions: OFF left ($m(K^+K^-) < 1.010$ GeV/$c^2$), ON ($1.015 < m(K^+K^-) < 1.025$ GeV/$c^2$) and OFF right ($1.033 < m(K^+K^-) < 1.100$ GeV/$c^2$). Figure [3] shows proper decay time distributions for events populating OFF left, ON and OFF right $m(K^+K^-)$ regions.

| $m(K^+K^-)$ | $N_{sw}$ | $N_{sb}$ | $< t >_{sw}$ [fs] | $< t >_{sb}$ [fs] | $p$ [%] | $\tau_s + t_0$ [fs] |
|-------------|---------|---------|-----------------|-----------------|--------|-----------------|
| OFF left    | 19618   | 763     | 400.2 ± 4.5     | 121.2 ± 27.7    | 96.11 ± 0.14 | 411.5 ± 4.8 |
| ON          | 66112   | 2104    | 403.0 ± 2.4     | 41.2 ± 13.8     | 96.82 ± 0.07 | 414.9 ± 2.6 |
| OFF right   | 40634   | 4879    | 381.6 ± 3.2     | 138.6 ± 10.2    | 87.99 ± 0.16 | 414.7 ± 3.9 |
FIG. 3: Proper decay time distributions for events populating \(m(K^+K^-) < 1.010\) GeV/\(c^2\) (left), 1.015 < \(m(K^+K^-) < 1.025\) GeV/\(c^2\) (middle) and 1.033 < \(m(K^+K^-) < 1.100\) GeV/\(c^2\) (right). The hatched area histograms show the contribution of events populating the \(m'(K_S^0K^+K^-)\) sideband. The free parameters of the fit are also the coupling constant \(\chi\) and the fraction difference \(\phi(1020)\) resonance and the mass and width of the \(\phi(1020)\) resonance. In Table II fractions \(f_{1s}^{ON}\) and \(f_{1s}^{OFF}\) are given for both Dalitz models. In Table II fractions \(f_{1s}^{ON}\) and \(f_{1s}^{OFF}\) are given for both Dalitz models. The reconstructed lifetimes shifted for the resolution function \(\tau_s + t_0\) of \(D^0\) candidates in ON and OFF regions are 414.9 ± 2.6 fs and 413.6 ± 3.1 fs, respectively, from which \(\Delta t = (0.16 ± 0.48)\%\) is obtained. We assumed that the resolution function offset, \(t_0\), is equal for the events populating the ON and OFF regions and much smaller than \(D^0\) lifetime.
FIG. 4: \(s_0\) distribution of \(D^0 \to K_S^0 K^+ K^-\) decays with superimposed fit results with Dalitz model given in Ref. [14] (right). The blue solid line is the overall fitted function and the red line is the background contribution.

| Model | Nominal \(f_{ON}^1\) | Fitted \(f_{ON}^1\) | \(f_{ON}^1 - f_{OFF}^1\) | Nominal \(f_{ON}^1 - f_{OFF}^1\) | Fitted \(f_{ON}^1 - f_{OFF}^1\) |
|-------|----------------------|------------------|----------------|------------------|------------------|
| 4 res. [13] | 0.117 0.847 -0.730 ± 0.031 | 0.113 0.844 -0.732 ± 0.003 |
| 8 res. [14] | 0.124 0.877 -0.753 ± 0.004 | 0.111 0.880 -0.769 ± 0.005 |

TABLE II: Fractions \(f_{ON}^1\) and \(f_{OFF}^1\) \((f_{ON/Off}^1)^2 = f_{ON/Off}^1 |A_1|^2 / f_{ON/Off}^1(|A_1|^2 + |A_2|^2)\) and the fraction difference \(f_{ON}^1 - f_{OFF}^1\) for the two Dalitz models Ref. [13, 14]. The nominal values are calculated using the given Dalitz models in Ref. [13, 14] and fitted values using the obtained values of free parameters of the fit to the \(s_0\) distribution. Uncertainties on \(f_{ON}^1 - f_{OFF}^1\) were calculated using the statistical errors of amplitudes and phases given for each model, without taking into account any correlation between the amplitudes and phases.

Using the Eq. 8 and the fraction difference \(f_{ON}^1 - f_{OFF}^1 = -0.769\), obtained by fitting \(s_0\) distribution with Dalitz model given in Ref. [14], yields \(y_{CP} = (0.21 ± 0.63(\text{stat.}))\%\).

We consider systematic uncertainties arising from both experimental sources and from the \(D^0 \to K^0_S K^+ K^-\) model. First, we check on the MC sample if the resolution function offsets, \(t_0^0\) and \(t_0^{\text{OFF}}\) are equal. They are in agreement within the statistical uncertainty and small \((t_0 = 0.7\% \cdot \tau_{D^0})\). Next, we vary the sideband in \(m'(K_S^0 K^+ K^-)\) used to describe the background populating the signal window and measure for each sideband the \(\Delta_\tau\). For different sidebands used the obtained \(\Delta_\tau\) values are in agreement. The maximal difference in \(\Delta_\tau\) was taken to estimate the systematic uncertainty. Finally, possible systematic effects
of selection criteria were studied by varying the signal box sizes, and cut values on $\sigma_t$ and $K_0^S$ flight distance in $r-\phi$ plane. Again no statistical significant deviation was observed and the maximal difference in $\Delta_{\tau}$ was taken to estimate the systematic uncertainty. We add all different sources in quadrature to obtain the overall experimental systematic uncertainty summarized in Table III.

The systematic uncertainty due to our choice of $D^0 \to K_0^S K^+ K^-$ decay model is evaluated as follows. First, we compare the fraction difference $f_{1\text{ON}} - f_{1\text{OFF}}$ obtained using the Dalitz Models in Ref. [13, 14]. Despite the differences between the two models in terms of the resonant structure [19], the fraction differences $f_{1\text{ON}} - f_{1\text{OFF}}$ (given in Tab. II) are in agreement. We assign 3% relative error for measured $y_{CP}$ due to small difference in the above fractions. An additional 2% relative error for measured $y_{CP}$ is assigned due to the small difference between fitted and nominal values of fraction difference $f_{1\text{ON}} - f_{1\text{OFF}}$ (given in Tab. II). The real and imaginary part of the interference term $A_1 A_2^*$ in the decay rate (Eq. 1) are zero after integrating over the $s_\pi$. Since the reconstruction efficiency is not constant in $s_\pi$, this is not entirely true. However, even if the observed $s_\pi$ reconstruction efficiency is taken into account this has negligible effect and Eq. 8 still holds. This was also verified by MC with non-zero $x$ and $y$ values of mixing parameters, where the detector response was simply simulated by randomly rejecting events according to the observed dependence of efficiency in $s_\pi$. The difference between the obtained $\Delta_{\tau}$ values (with and without taking into account the efficiency in $s_\pi$) are in agreement within statistical uncertainty, so no additional systematical uncertainty is assigned. Adding all variations in quadrature, the obtained relative model systematic uncertainty is 4%.

In summary, we determine $y_{CP}$ by measuring the difference in lifetimes between $D^0$ mesons decaying to $K_0^S K^+ K^-$ in two different $m(K^+ K^-)$ regions with different contributions of $CP$ even and odd eigenstates to be

$$y_{CP} = (0.21 \pm 0.63(\text{stat.}) \pm 0.78(\text{syst.}) \pm 0.01(\text{model}))\%.$$  

The result is in agreement with world average of $y_{CP}$ of previous measurements [8, 9].

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