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$D^0 - \overline{D}^0$ Mixing and CP Violation in $D^0 \to K^0_S hh$ Measurements

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In these proceedings, we give a summary of the experimental results from CLEO, Belle, BaBar and CDF collaboration about $D^0 - \overline{D}^0$ mixing and CP violation in self-conjugated-three-body decays $D^0 \to K^0_S hh$ (where h can be π or K). We report preliminary results of measurement of $D^0 - \overline{D}^0$ mixing and indirect CP violation in $D^0 \to K^0_S \pi^+\pi^-$ decays using full data sample collected by Belle detector at KEKB asymmetric-energy e^+e^- collider: give values for $x = (0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09})\%$, $y = (0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06})\%$, $|q/p| = 0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$ and $\arg(q/p) = -6 \pm 11^{+3+3}_{-3-4}(^\circ)$. We also report results of recent measurement searching for CP violation in $D^0 \to K^0_S \pi^+\pi^-$ decays by CDF collaboration using 6.0 fb^{-1} of data collected in $p\overline{p}$ collisions at Tevatron. The phase-space-integrated CP asymmetry is measured to be $A_{CP} = (-0.05 \pm 0.57 \pm 0.54)\%$ and the CP symmetry is also found to be conserved in all individual intermediate contributions.

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1 Introduction and Mixing formalism

The phenomenon of $D^0-\overline{D}^0$ mixing has been of great interest since Belle collaboration at KEK and BaBar collaboration at SLAC reported evidence for it in 2007 [1, 2]. This year LHCb collaboration reported first observation of the $D^0 - \overline{D}^0$ oscillations from a single measurement with significance corresponding to 9.1 standard deviations [3].

The two mass eigenstates D_1 and D_2, different to flavor eigenstates, are given by

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle \tag{1}$$

where $|p|^2 + |q|^2 = 1$ holds and CPT invariance has been assumed. The mixing parameters x and y in neutral D meson system are defined as

$$x \equiv \frac{M_2 - M_1}{\Gamma},\ y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}. \tag{2}$$

where $M_{1,2}$ and $\Gamma_{1,2}$ are the mass and width of $D_{1,2}$ and $\Gamma = (\Gamma_1 + \Gamma_2)/2$.

The proper time evolution of the mass eigenstates is $|D_{1,2}(t)\rangle = e_{1,2}(t)|D_{1,2}\rangle$, where $e_{1,2}(t) = e^{-i(M_{1,2}-(i\Gamma_{1,2}/2))t}$. A state, which is prepared as a flavor eigenstate $|D^0\rangle$ or $|\overline{D}^0\rangle$ at $t = 0$, will evolve according to

$$\begin{aligned} |D^0(t)\rangle &= \frac{1}{2p}[p(e_1(t) + e_2(t))|D^0\rangle + q(e_1(t) - e_2(t))|\overline{D}^0\rangle], \\ |\overline{D}^0(t)\rangle &= \frac{1}{2q}[p(e_1(t) - e_2(t))|D^0\rangle + q(e_1(t) + e_2(t))|\overline{D}^0\rangle]. \end{aligned} \tag{3}$$

The decay amplitude for three-body $D^0(\overline{D}^0) \to K_S^0 h^+ h^-$ decays, $\mathcal{A}(\overline{\mathcal{A}})(m_+^2, m_-^2)$, depends on two kinematic variables: $m_+^2 = m_{K_S^0\pi^+}$ and $m_-^2 = m_{K_S^0\pi^-}$. The time-dependent decay amplitude for initially produced D^0 or $\overline{D}^0$ meson is then given by

$$\begin{aligned} \mathcal{M}(m_+^2, m_-^2, t) &= \mathcal{A}(m_+^2, m_-^2)\frac{e_1(t) + e_2(t)}{2} + \frac{q}{p}\overline{\mathcal{A}}(m_-^2, m_+^2)\frac{e_1(t) - e_2(t)}{2}, \\ \overline{\mathcal{M}}(m_+^2, m_-^2, t) &= \overline{\mathcal{A}}(m_+^2, m_-^2)\frac{e_1(t) + e_2(t)}{2} + \frac{p}{q}\mathcal{A}(m_-^2, m_+^2)\frac{e_1(t) - e_2(t)}{2}. \end{aligned} \tag{4}$$

The decay rates as function of time are given by squaring the time-dependent amplitudes:

$$\begin{aligned} |\mathcal{M}|^2 &= |e_1(t)|^2|A_1|^2 + |e_2(t)|^2|A_2|^2 + 2\mathcal{R}[e_1(t)e_2^*(t)A_1A_2^*] \\ &= \left\{|A_1|^2e^{-yt} + |A_2|^2e^{yt} + 2\mathcal{R}[A_1A_2^*]\cos(xt) + 2\mathcal{I}[A_1A_2^*]\sin(xt)\right\}e^{-t}, \\ |\overline{\mathcal{M}}|^2 &= \left\{|\overline{A}_1|^2e^{-yt} + |\overline{A}_2|^2e^{yt} + 2\mathcal{R}[\overline{A}_1\overline{A}_2^*]\cos(xt) + 2\mathcal{I}[\overline{A}_1\overline{A}_2^*]\sin(xt)\right\}e^{-t}. \end{aligned} \tag{5}$$

Here t is in unit of D^0 lifetime. y modifies the lifetime of certain contributions to the Dalitz plot while x introduces a sinusoidal rate variation.

2 Measurement Summary

The $D^0 \to K_S^0 hh$ measurements from all experiments are shown in the Table 1. The Heavy Flavor Averaging Group gives $D^0 - \overline{D}^0$ Dalitz plot results assuming no CP violation: $x = (0.419 \pm 0.211)\%$ and $y = (0.456 \pm 0.186)\%$ [10].

Exp.	Year	Data	Channel	Results
CLEO	2005[5]	$9.0 fb^{-1}$	$h = \pi$	$x = (1.8^{+3.4}_{-3.2} \pm 0.4 \pm 0.4)\%$ $y = (-1.4^{+2.5}_{-2.4} \pm 0.8 \pm 0.4)\%$
Belle	2007[6]	$540 fb^{-1}$	$h = \pi$	$x = (0.80 \pm 0.29^{+0.09+0.10}_{-0.07-0.14})\%$ $y = (0.33 \pm 0.24^{+0.08+0.06}_{-0.12-0.08})\%$
				$\vert q/p \vert = 0.95^{+0.22+0.10}_{-0.20-0.09}$ $\arg(q/p) = -0.035^{+0.17}_{-0.19} \pm 0.09$
	2009[7]	$673 fb^{-1}$	$h = K$	$y_{CP} = (+0.11 \pm 0.61 \pm 0.52)\%$
BaBar	2010[8]	$469 fb^{-1}$	$h = \pi/K$	$x = (0.16 \pm 0.23 \pm 0.12 \pm 0.08)\%$ $y = (0.57 \pm 0.20 \pm 0.13 \pm 0.07)\%$
			$h = \pi$	$x = (+0.26 \pm 0.24)\%$ $y = (0.60 \pm 0.21)\%$
			$h = K$	$x = (-1.36 \pm 0.21)\%$ $y = (0.44 \pm 0.57)\%$
CDF	2012[9]	$6.0 fb^{-1}$	$h = \pi$	$A_{CP} = (-0.05 \pm 0.57 \pm 0.54)\%$

Table 1: Self-conjugated decay $D^0 \to K_S hh$ (here $h = K$ or π) published measurements from all experiments.

3 CP violation asymmetries measuremt at CDF

In the analysis of time-integrated CP violation asymmetries A_{CP} in $D^0/\overline{D}^0 \to K_S^0\pi^+\pi^-$ from CDF [9], they exploit a large sample of $D^*(2012)^\pm$ decays using CDF II data with 6.0 fb^{-1} of integrated luminosity produced in $p\overline{p}$ collision at $\sqrt{s} = 1.96 TeV$. The neutral D meson production flavor is determined by the charge of the pion in the $D^{*+}(2010) \to D^0\pi^+$ and $D^{*-}(2010) \to \overline{D}^0\pi^-$ decay (D^* tagging).

They use an artificial neural network to distinguish signal and background. The network uses five input variables: the transverse decay length of the D^0 candidate divided by its resolution $L_{xy}/\sigma_{L_{xy}}(D^0)$, the χ^2 quality of the D^{*+} vertex fit, the impact parameter of the pion from the D^{*+} decay divided by its uncertainty $d_0/\sigma_{d_0}(\pi_{D^{*+}})$, the transverse momentum of pion from D^{*+} decay $p_T(\pi_{D^{*+}})$ and the reconstructed mass of the K_S^0 candidate. The D^{*+} network training is based on the distribution of mass difference $\Delta M = M(K_S^0\pi^+\pi^-\pi^0) - M(K_S^0\pi^+\pi^-)$ in the range $140 < \Delta M <$

156 MeV/c^2. The final neural network output requirement is chosen to maximize $S/\sqrt{S+B}$ where $S(B)$ is the estimated number of signal(background) events in the signal region estimated from a fit to the $M(K_S^0\pi^+\pi^-)$ distribution. For the Dalitz plot studies, the analysis is restricted to candidates populating two mass range, $1.84 < M(K_S^0\pi^+\pi^-) < 1.89$ GeV/c^2 and $143.4 < \Delta M < 147.4$ MeV/c^2. The selected data sample contains approximately 3.5×10^5 signal events and consists of about 90% correctly D^*-tagged D^0 signal, 1% mistagged D^0 signal, and 9% background candidates.

The Dalitz plot of $D^0 \to K_S^0\pi^+\pi^-$ decay, shown in Figure 1, contains three types of intermediate states contribution: Cabibbo-favored, doubly-Cabibbo-suppressed and CP eigenstates. A measure for the overall integrated CP asymmetry is given by Eq. 6, where $\mathcal{M}$ is the matrix element used in isobar model for D^0 decay and $\overline{\mathcal{M}}$ the one for $\overline{D}^0$ decay.

$$A_{CP} = \frac{\int \frac{|\mathcal{M}|^2 - |\overline{\mathcal{M}}|^2}{|\mathcal{M}|^2 + |\overline{\mathcal{M}}|^2} dM^2_{K_S^0\pi^\pm(RS)} dM^2_{\pi^+\pi^-}}{\int dM^2_{K_S^0\pi^\pm(RS)} dM^2_{\pi^+\pi^-}} \tag{6}$$

$$\mathcal{M}(\overline{\mathcal{M}}) = a_0 e^{i\delta_0} + \sum_j a_j e^{i(\delta_j \pm \phi_j)}(1 \pm \frac{b_j}{a_j})\mathcal{A}_j. \tag{7}$$

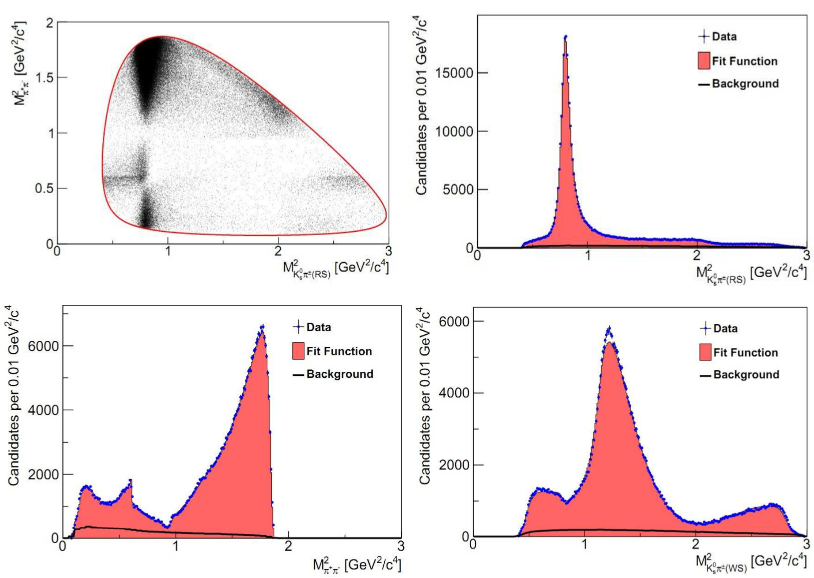

Figure 1: Dalitz plot of $D^0/\overline{D}^0 \to K_S^0\pi^+\pi^-$ and projections of Dalitz-plot fit on the invidual two-body masses.

All CP violation quantities are found to be consistent with zero. The results for the CP violation amplitudes and phase, defined in Eq. 7 and obtained from simultaneous fit to the D^0 and $\overline{D}^0$ Dalitz plots, are displayed in Table 2. None of these is significantly different from zero. The overall integrated CP asymmetry, defined in Eq. 6, is determined to be $A_{CP} = (-0.05 \pm 0.57(stat) \pm 0.54(syst))\%$, and the systematic uncertainties are shown in Table 3.

Resonance	Amplitude b	Phase $\phi[°]$
$K^*(892)^\pm$	$+0.004 \pm 0.004 \pm 0.011$	$-0.8 \pm 1.4 \pm 1.3$
$K_0^*(1430)^\pm$	$+0.044 \pm 0.028 \pm 0.041$	$-1.8 \pm 1.7 \pm 2.2$
$K_2^*(1430)^\pm$	$+0.018 \pm 0.024 \pm 0.023$	$-1.1 \pm 1.8 \pm 1.1$
$K^*(1410)^\pm$	$-0.010 \pm 0.037 \pm 0.021$	$-1.6 \pm 1.9 \pm 2.2$
$\rho(770)$	$-0.003 \pm 0.006 \pm 0.008$	$-0.5 \pm 1.5 \pm 1.4$
$\omega(782)$	$-0.003 \pm 0.002 \pm 0.000$	$-1.8 \pm 2.2 \pm 1.4$
$f_0(980)$	$-0.001 \pm 0.005 \pm 0.004$	$-0.1 \pm 1.3 \pm 1.1$
$f_2(1270)$	$-0.035 \pm 0.037 \pm 0.013$	$-2.0 \pm 1.9 \pm 2.1$
$f_0(1370)$	$-0.002 \pm 0.008 \pm 0.021$	$-0.1 \pm 1.7 \pm 2.8$
$\rho(1450)$	$-0.016 \pm 0.022 \pm 0.135$	$-1.7 \pm 1.7 \pm 3.9$
$f_0(600)$	$-0.012 \pm 0.017 \pm 0.025$	$-0.3 \pm 1.5 \pm 1.4$
σ_2	$-0.011 \pm 0.012 \pm 0.004$	$-0.2 \pm 2.9 \pm 1.1$
$K^*(892)^\pm$(DCS)	$+0.001 \pm 0.005 \pm 0.002$	$-3.8 \pm 2.3 \pm 1.2$
$K_0^*(1430)^\pm$(DCS)	$+0.022 \pm 0.024 \pm 0.035$	$-3.3 \pm 4.0 \pm 3.9$
$K_2^*(1430)^\pm$(DCS)	$-0.018 \pm 0.029 \pm 0.017$	$+4.2 \pm 5.3 \pm 3.0$

Table 2: Results of the simultaneous $D^0 - \overline{D}^0$ Dalitz-plot fit for the CP-violation amplitudes, b and phase, ϕ. The first uncertainties are statistical and the second systematic.

Effect	Uncertainty on $A_{CP}[10^{-2}]$
Efficiency	0.36
Background	0.09
Fit model	0.37
Trigger	0.05
Form factors	0.10
Total systematic	0.54
Statistical	0.57

Table 3: Uncertainties on the overall integrated CP asymmetry.

4 Updated measurement in $D^0 \to K_S\pi^+\pi^-$ at Belle

We report the updated measurement of $D^0 - \overline{D}^0$ mixing by time-dependent Dalitz analysis method using the 921 fb^{-1} of Υ(4S) and Υ(5S) full data collected by Belle detector at KEKB asymmetric-energy e^+e^- collider.

The decay chain $D^{*+} \to D^0\pi_s^+$, $D^0 \to K_S^0\pi^+\pi^-$, which is reconstructed from $c\bar{c}$ process, is used to distinguish between D^0 and $\overline{D}^0$ with the charge of the low-momentum pion π_s and to reduce the background. The D^0 decay time t and its uncertainty σ_t are obtained by projecting the flight length between D^0 decay and production vertices to momentum direction and then transforming it to the center-of-mass system(CMS). To suppress the combinatorial background and the events from B decays, we require D^{*+} momentum in CMS to be greater than 2.5 GeV/c and 3.1 GeV/c for Υ(4S) and Υ(5S) data respectively.

Two observable are used to determined the yield of signal and backgrounds: the invariant mass of D^0 daughter particles: $M = m_{K_S^0\pi^+\pi^-}$ and the energy released from D^{*+} decay: $Q = m_{K_S^0\pi^+\pi^-\pi_s} - m_{K_S^0\pi^+\pi^-} - m_{\pi_s}$. The M and Q distributions of selected candidates are shown in Figure 2. The Dalitz distribution of $D^0 \to K_S^0\pi^+\pi^-$

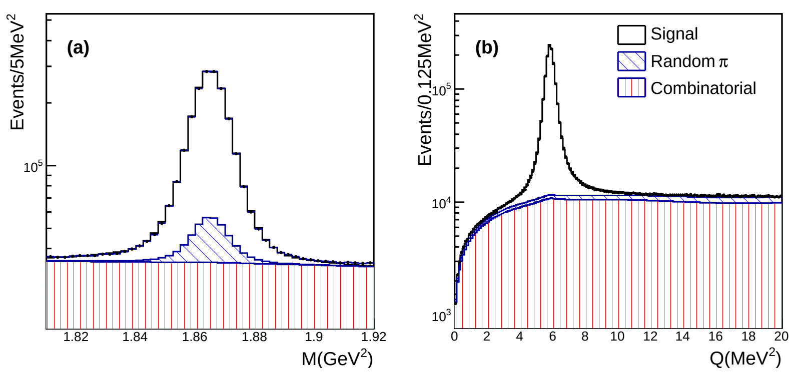

Figure 2: The projections of M and Q for MC data in region $1.81 < M < 1.92\ GeV/c^2$ and $0 < Q < 20\ MeV/c^2$, including signal, random π background and combinatorial background.

are expressed as a sum of quasi-two-body amplitudes. Different modes are used to describe the decay amplitude: Breit-Weigner model for the P- and D-wave with twelve intermediate resonances, K-matrix model for the $\pi\pi$ S-wave [11] and LASS model for $K_S^0\pi$ S-wave [8]. The final Dalitz plot parameterize is optimized according likelihood and χ^2 test.

We performe an unbinned maximum likelihood fit to extract the mixing parameters x and y. The distribution of combinatorial background is determined in

M sideband($30 < |M - m_{D^0}| < 50\ MeV/c^2$). Meanwhile the random π^+ background is mixture of true and mistagged D^0 with the fraction determined from Q sideband($3 < |Q - 5.85| < 14.15\ MeV/c^2$). In the final Dalitz fit with data sample, see Figure 3, we extract the mixing parameters $x = (0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09})\%$ and $y = (0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06})\%$, where the errors are statistical, experimental and model uncertainties respectively, see Table 4, and the D^0 mean lifetime $\tau = (410.3 \pm 0.4)fs$, see Figure 4, which is consistent with the world average.

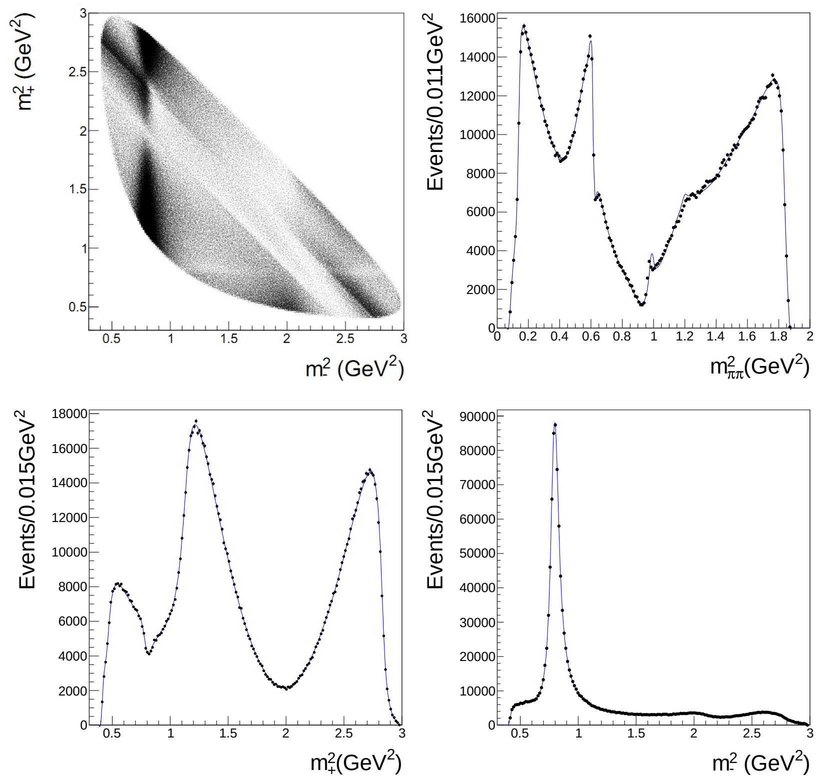

Figure 3: Dalitz plot distribution and Dalitz variables m_+^2, m_-^2 and $m_{\pi\pi}^2$ projections for experimental data with 2-dimensional χ^2 test over the Dalitz plot plane: $\chi^2/ndf = 1.207$ for $14264 - 42$ degrees of freedom.

We also search for CP violation in $D^0/\overline{D}^0 \to K_S^0\pi^+\pi^-$ decays. We obtain identical mixing parameters as fit result without CP violation and these CP violation parameters $|q/p| = 0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$ and $\arg(q/p)(^o) = -6 \pm 11^{+3+3}_{-3-4}$ which show no hint for indirect CP violation.

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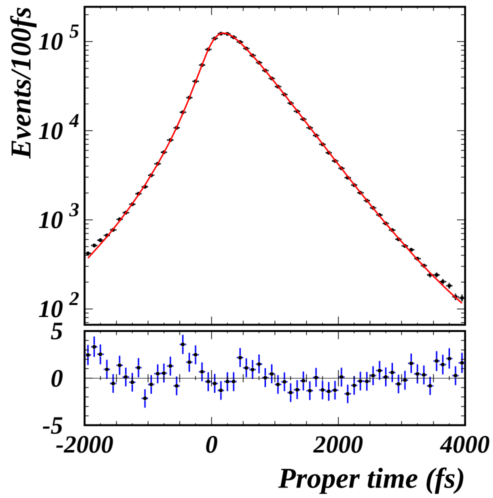

Figure 4: The proper time distribution for events in the signal region with $-2000 < t < 4000(fs)$(point) and fit projection for mixing fit(curve).

Source of systematic uncertainty	$(\Delta x)(\times 10^{-4})$	$(\Delta y)(\times 10^{-4})$
Best Candidate selection	$+1.05$	$+1.87$
Signal and backgrounds yields	± 0.30	± 0.27
Wrong tagged events' fraction	-0.67	-0.45
Time resolution of signal	-1.39	-0.92
Efficiency	-1.13	-2.09
Combinatorial's PDF	$^{+1.90}_{-4.82}$	$^{+2.28}_{-3.88}$
$K^*(892)$ DCS/CF reduced by 5%	-7.28	$+2.29$
$K^*(1430)$ DCS/CF reduced by 5%	$+1.71$	-0.67
Total uncertainty(experimental sys.)	$^{+2.78}_{-8.94}$	$^{+3.74}_{-4.58}$
Resonances' M and Γ error	± 1.40	± 1.21
Remove $K^*(1680)^+$	-1.78	-3.02
Remove $K^*(1410)^\pm$	-1.16	-3.62
Remove $\rho(1450)$	$+2.13$	$+0.30$
Form factors	$+4.05$	$+2.35$
$\Gamma(q^2)$ =constant	$+3.33$	-1.61
Angular dependence	-8.46	-3.86
K-matrix formalism	-2.16	$+1.79$
Total uncertainty(model sys.)	$^{+5.83}_{-9.09}$	$^{+3.21}_{-6.42}$

Table 4: The source of two kinds of systematic uncertainty.

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