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Charm physics at B-factories: rare, mixing and CPV

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In this proceeding, we give a summary of the experimental results on charm physics studies at two experiments at B-factories: Belle and BABAR. It includes three parts: (1) D^0-$\bar{D}^0$ mixing and Charge-Parity(CP) violation in different physics processes: CP-eigenstate decays, wrong-sign(WS) two-body decays, WS or self-conjugated three-body decays; (2) direct CP violation in neutral and charged charmed meson decays; (3) rare or radiative charm decays: for $D^0 \to \gamma\gamma$ decay, using 832 fb^{-1} of data, Belle gave the upper limit on the branching fraction $Br < 8.5\times10^{-7}$ at 90% confidence level which is most restrictive limit to date; For the branching fractions of $D^0 \to V\gamma$, where $V = \phi$, $\bar{K}^{*0}$, or ρ^0, based on 943 fb^{-1} data, Belle obtianed two improved measurements of branching ratio: $Br(D^0 \to \phi\gamma) = (2.76\pm0.20\pm0.08)\times10^{-5}$ and $Br(D^0 \to \bar{K}^{*0}\gamma) = (4.66\pm0.21\pm0.18)\times10^{-4}$, and the first observation of $D^0 \to \rho^0\gamma$ with $(1.77\pm0.30\pm0.08)\times10^{-5}$. Belle obtianed the first measurements of CP asymmetry: $A_{CP}^{\phi\gamma} = -0.094\pm0.066\pm0.001$, $A_{CP}^{\bar{K}^{*0}\gamma} = -0.003\pm0.020\pm0.000$ and $A_{CP}^{\rho^0\gamma} = +0.056\pm0.151\pm0.006$.

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1. Introduction

Belle experiment at KEKB and BABAR experiment at PEP-II have together collected integrated luminosity of about 1.5 ab^{-1} mainly at the energy of $\Upsilon(4S)$ resonance with asymmetric e^+e^- energy collisions. $\Upsilon(4S)$ decays to the $B\bar{B}$ pairs (so-called B-factories). These two detectors have good momentum resolution and vertex resolution. A detailed description of Belle and BABAR detectors is available in Ref. [1].

2. D^0-$\bar{D}^0$ mixing and CP violation

Since D^0-$\bar{D}^0$ mixing, as the only up-type quark meson mixing, has already been observed with the confidence level of more than 5σ in single wrong-sign(WS) decay channel [2, 3] in recent years, all open-flavored neutral meson mixing phenomena, which originate from the difference between the flavor and mass eigenstates of the meson-anti-meson system, are well established. The two mass eigenstates D_1 and D_2 of the effective Hamiltonian matrix $\mathscr{H} = (M - \frac{i}{2}\Gamma)$ are given by the mixture of flavor-eigenstates: $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$, here $|p|^2 + |q|^2 = 1$ for CPT conservation and we assume $CP|D^0\rangle = |\bar{D}^0\rangle$. $|D_1\rangle$ is the positive-CP eigenstate and $|D_2\rangle$ is the negative-CP eigenstate assuming no CP violation. The mixing parameters, $x = \Delta m/\bar{\Gamma}$ and $y = \Delta\Gamma/(2\bar{\Gamma})$, are related to the mass and the width differences Δm and $\Delta\Gamma$ between the two mass eigenstates and $\bar{\Gamma}$ is the average decay width of the mass eigenstates. The mixing parameters x and y are difficult to calculate. The Standard Model (SM) predicts that D^0-$\bar{D}^0$ mixing can occur via short distance effects and long distance effects and is strongly suppressed to $\sim 1\%$.

There are three types of CP violation (CPV) according to their different sources: (1) in the mixing (indirect CPV): $r_m = |q/p| \neq 1$; (2) in the decay (direct CPV): $|\bar{A}_{\bar{f}}/A_f| \neq 1$, Here the amplitudes of D^0 decays are defined as: $\langle f|\mathscr{H}|D^0\rangle = A_f$, $\langle \bar{f}|\mathscr{H}|\bar{D}^0\rangle = \bar{A}_{\bar{f}}$; (3) in the interference between mixing and decay: $\arg(q/p) \neq 0$.

The status of some experiments from charm factories, B-factories and hadron colliders are available in Heavy Flavor Averaging Group (HFAG) [4]. These measurements have excluded the no-mixing hypothesis with more than 11.5σ confidence level assuming CPV is allowed. Many of them are given by the Belle and BABAR experiments at B-factories. Only one or three decays have reached the observation or evidence confidence level. More decay channels or larger samples need to be studied at different experiments.

At B-factories, we usually use the D^0 tagged sample via the charge of slow pions from D^* decays. After vetoing signals from B decays by D^* momentum requirement in the center mass frame (p>2.5 (3.1) GeV/c for data below (at) Υ(5S) mass energy), we extract signal and background fractions across Dalitz plot by M-Q two-dimensional fit, where M is the invariant mass of reconstructed D^0, and Q is the release energy of D^* decay. The D^0 proper lifetime is obtained by the D^0 flight vector projection onto D^0 momentum unit vector, and lifetime uncertainty is calculated by the error matrices of the D^0 production and decay vertices. For different physical process, we choose the respective method to extract the mixing parameters. Some examples:

(1) for CP eigenstates $D^0 \to K^+K^-$, $\pi^+\pi^-$, we analyse D^0 lifetime relative to non-CP eigenstates,

$$y_{cp} = \frac{\tau_{K\pi}}{< \tau_{hh} >} - 1; \quad A_\Gamma = \frac{\tau(\bar{D}^0 \to h^- h^+) - \tau(D^0 \to h^+ h^-)}{\tau(\bar{D}^0 \to h^- h^+) + \tau(D^0 \to h^+ h^-)} \tag{2.1}$$

Belle recently published result [5] with full dataset (976 fb^{-1}) which is twice than the first evidence measurement [6]. With the asymmetric time resolution function depending on the D^* polar angle in center of mass system and different configuration for 3(4)-layer silicon vertex detector, Belle obtained $y_{CP} = (1.11 \pm 0.22 \pm 0.09)\%$ with 4.7σ confidence level and $A_\Gamma = (-0.03 \pm 0.20 \pm 0.07)\%$. BABAR gave the measurement [7] with full dataset (468 fb^{-1}) using both tagged and untagged samples for KK and $K\pi$ channels, but only tagged for $\pi\pi$ channel because of the poor signal-to-background ratio in untagged sample: $y_{CP} = (0.72 \pm 0.18 \pm 0.12)\%$ and $\Delta Y = -A_\Gamma/2 = (0.09 \pm 0.26 \pm 0.06)\%$ which is more precise than previous measurement with tagged or untagged sample separately [8].

(2) for two-body WS decay $D^0 \to K^+\pi^-$, we analyse WS-to-RS decay rate ratio under CP conservation,

$$R_{WS}(t) = R_D + y'\sqrt{R_D}\Gamma t + \frac{x'^2 + y'^2}{4}\Gamma^2 t^2 \tag{2.2}$$

which is related to the effective mixing parameters $x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$, $y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$. BABAR gave the first evidence (3.9σ) for D^0-$\bar{D}^0$ mixing in this decay in 2007 [9] by fitting D^0 proper-time distribution based on 384 fb^{-1} of data: $x'^2 = (-0.22 \pm 0.30 \pm 0.21) \times 10^{-2}$ and $y' = (9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$ with correlation factor -0.95. Belle recently obtained the first observation (5.1σ) [3] in e^+e^- collisions by fitting time-dependent ratio of WS-to-RS decay rates based on 976 fb^{-1} of data: $x'^2 = (0.09 \pm 0.22(stat.+syst.)) \times 10^{-2}$ and $y' = (4.6 \pm 3.4(stat.+syst.)) \times 10^{-3}$ with correlation factor -0.948.

(3) for three-body decays, the Dalitz amplitude analysis, which can well describe the interference between quasi-two-body process, is widely used to study the time evolution of amplitude as follows.

$$\begin{aligned} |M(f,t)|^2 =& e^{-\Gamma t}\Big\{(|A_f|^2 + |\frac{q}{p}|^2|A_{\bar{f}}|^2)\cosh(\Gamma yt) - 2\Re(\frac{q}{p}A_{\bar{f}}A_f^*)\sin(\Gamma yt) \\ & + (|A_f|^2 - |\frac{q}{p}|^2|A_{\bar{f}}|^2)\cos(\Gamma xt) + 2\Im(\frac{q}{p}A_{\bar{f}}A_f^*)\sin(\Gamma xt)\Big\}. \end{aligned} \tag{2.3}$$

The Dalitz model is optimized by the time-integrated Dalitz fitting of experimental data.

For WS three-body decay $D^0 \to K^+\pi^-\pi^0$, the amplitude includes two processes: doubly Cabibbo suppressed (DCS) decay; the mixing process followed Cabibbo favored (CF) decay, which amplitude can be obtained from right-sign time-independent Dalitz fit. Through studying the amplitude evolution assuming $|x|, |y| \ll 1$, we extract the effective mixing parameters $x' = x\cos\delta_f + y\sin\delta_f$ and $y' = y\cos\delta_f - x\sin\delta_f$. Under the definitions $c_x = x'/r_0$ and $c_y = y'/r_0$, $r_0^2 = \int |A_f|^2 ds_{12}ds_{13} / \int |\bar{A}_f|^2 ds_{12}ds_{13}$, we have

$$\mathscr{M}(s_{12}, s_{13}, t) = e^{-\Gamma t} r_0^2[|A_f^{DCS}|^2 + |A_f^{DCS}||A_f^{CF}|c_y\Gamma t + \frac{c_x^2 + c_y^2}{4}|A_f^{CF}|^2(\Gamma t)^2] \tag{2.4}$$

BABAR gave the evidence of D^0-$\bar{D}^0$ mixing using above time-dependent amplitude analysis of this decay based on 384 fb^{-1} of data: $x'_{K\pi\pi^0} = (2.61^{+0.57}_{-0.68} \pm 0.39)\%$ and $y'_{K\pi\pi^0} = (-0.06^{+0.55}_{-0.64} \pm 0.34)\%$ assuming no CPV which is inconsistent with no-mixing hypothesis with a significance of 3.2σ.

For self-conjugated decay the situation is different, such decays can provide a direct measurement of x and y, and also enable a search for direct or indirect CP violation. Assuming no CPV, the amplitude of D^0 and $\bar{D}^0$ have the same formalism so that we don't need to separate the final states into flavor or CP eigenstates.

$$|M(t)|^2 = \left\{|A_1|^2 e^{-y\Gamma t} + |A_2|^2 e^{y\Gamma t} + 2\Re[A_1 A_2^*]\cos(x\Gamma t) + 2\Im[A_1 A_2^*]\sin(x\Gamma t)\right\} e^{-\Gamma t} \qquad (2.5)$$
$$|\bar{M}(t)|^2 = \left\{|\bar{A}_1|^2 e^{-y\Gamma t} + |\bar{A}_2|^2 e^{y\Gamma t} + 2\Re[\bar{A}_1 \bar{A}_2^*]\cos(x\Gamma t) + 2\Im[\bar{A}_1 \bar{A}_2^*]\sin(x\Gamma t)\right\} e^{-\Gamma t} \qquad (2.6)$$

$D^0 \to K_S^0 \pi^+\pi^-$, regarded as the Golden channel for D^0-$\bar{D}^0$ mixing and CP violation measurement, is a sum of quasi-two-body amplitudes including CF, DCS, and CP-eigenstate decays like $K^{*\mp}\pi^{\pm}$, ρK_S^0 etc. Belle recently gave the time-dependent amplitude analysis using the Isobar mode with Blatt-Weisskopt form factor and Zemach tensor angular dependence [10]. Based on 921 fb^{-1} of data, Belle obtains $x = (0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09})\%$ and $y = (0.30 \pm 0.15^{+0.04+0.06}_{-0.05-0.06})\%$ with 2.5σ confidence level to exclude the no-mixing hypothesis under no CP violation. For indirect CP violation allowed, the CP violation parameters are measured $|q/p| = 0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$ and $\arg(q/p) = (-6 \pm 11 \pm 3^{+3}_{-4})^o$ consistent with conservation of CP asymmetry. BABAR gives a combined measurement [11] of $D^0 \to K_S^0\pi^+\pi^-$ and $D^0 \to K_S^0 K^+K^-$ based on 468.5 fb^{-1} of data: $x = (1.6 \pm 2.3 \pm 1.2 \pm 0.8) \times 10^{-3}$ and $y = (5.7 \pm 2.0 \pm 1.3 \pm 0.7) \times 10^{-3}$.

3. direct CP violation in charm decays

Here we firstly present a measurement of the time-integrated CP violating asymmetry in $D^0 \to \pi^0\pi^0$ decay using Belle's 966 fb^{-1} full data sample [12]. The SM predicts a nonzero CP asymmetry in final states containing a neutral kaon due to $K^0 - \bar{K}^0$ mixing even if no CP-violating phase exist in the charm decay amplitudes. The signal yield is 34460 ± 273 events and $A_{rec} = (+0.29 \pm 0.64)\%$ for $D^0 \to \pi^0\pi^0$, and 466814 ± 773 events and $A_{rec} = (+0.29 \pm 0.15)\%$ for $D^0 \to K_S^0\pi^0$ shown in Fig. 1(a) and (b). Then the data samples are divided into ten bins of the cosine of the D^{*+} polar angle θ^* in the center of mass system where

$$A_{CP/FB} = [A^{cor}_{rec}(\cos\theta^*) \pm A^{cor}_{rec}(-\cos\theta^*)]/2 \qquad (3.1)$$

For each 3-dimensional bin[1], a simultaneous fit analogous to the one used for the full sample is performed. Fig. 1(c) and (d) show A_{CP} and A_{FB} as a function of $|\cos\theta^*|$ obtained for two data samples. From the weighted average over the $|\cos\theta^*|$ bins, we obtain $A_{CP}(\pi^0\pi^0) = (-0.03 \pm 0.64)\%$ and $A_{CP}(K_S^0\pi^0) = (-0.10 \pm 0.16)\%$. The former has an order of magnitude improvement better precision than previous result and shows no evidence for CP violation.

In recent years, no new measurements of direct CPV measurements in charged charmed meson decays have been performed. We give a summary table of the measurements from Belle and BABAR: Tab. 1. All these measurements are under the limit of statistics for CPV in charm sys-

[1] data samples are divided into bins of $\cos\theta^*$, transverse momentum of π_s and polar angle of π_s

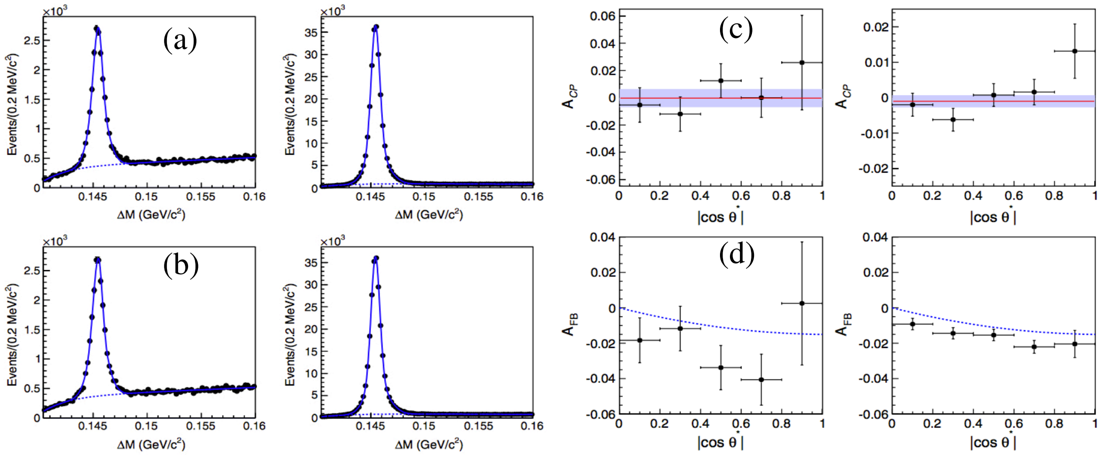

Figure 1: Distributions of the mass difference ΔM for $\pi^0\pi^0$(top) and $K_S^0\pi^0$(bottom) final states for (a) D^{*+} or (b) D^{*-} sample. (c) and (d) are the CPV asymmetry A_{CP} and forward-backward asymmetry A_{FB} respectively as a function of $|\cos\theta^*|$ of $\pi^0\pi^0$(left) and $K_S^0\pi^0$(right).

tem. The CP asymmetry measurement in $D^+ \to K_S^0\pi^+$ gives the 3.2σ confidence level [13] but this evidence result is consistent with the expected CPV $(-0.345\pm0.008)\%$ due to K^0-mixing.

Table 1: Summary of direct CP violation A_{CP} measurements in charged charmed meson decays.

meson	final	$\mathscr{L}(fb^{-1})$	$A_{CP}(\%)$	experiment	references
$D^+ \to$	$\phi\pi^+$	955	$+0.51\pm0.28\pm0.05$	Belle	PRL **108**, 071801 (2012)
	$\eta\pi^+$	791	$+1.74\pm1.13\pm0.19$	Belle	PRL **107**, 221801 (2011)
	$\eta'\pi^+$	791	$-0.12\pm1.12\pm0.17$	Belle	PRL **107**, 221801 (2011)
	$K_S^0\pi^+$	977	$-0.36\pm0.09\pm0.07$	Belle	PRL **109**, 021601 (2012)
	$K_S^0\pi^+$	469	$-0.44\pm0.13\pm0.10$	BABAR	PRD **83**, 071103 (2011)
	$K_S^0K^+$	977	$-0.25\pm0.28\pm0.14$	Belle	JHEP **02**, 98 (2013)
	$K_S^0K^+$	469	$+0.13\pm0.36\pm0.25$	BABAR	PRD **87**, 052012 (2013)
	$K_S^0\pi^+\pi^0$	476	$+0.51\pm0.28\pm0.05$	BABAR	PRD **87**, 052010 (2013)
$D_s^+ \to$	$K_S^0\pi^+$	673	$+5.45\pm2.50\pm0.33$	Belle	PRL **104**, 181602 (2010)
	$K_S^0\pi^+$	469	$+5.45\pm2.50\pm0.33$	BABAR	PRD **87**, 052012 (2013)
	$K_S^0K^+$	673	$+0.12\pm0.36\pm0.22$	Belle	PRL **104**, 181602 (2010)
	$K_S^0K^+$	469	$+0.12\pm0.36\pm0.22$	BABAR	PRD **87**, 052012 (2013)

4. rare or radiative charm decays

4.1 Analysis of $D^0 \to V\gamma$

The radiative decays $D^0 \to V\gamma$ where V is a vector meson, are dominated by long-range contribution. These decays could be sensitive to New Physics. Belle presents a measurement of branching fractions and CP asymmetries in these decays based on 943 fb^{-1} of data [14]. The D^0s are required to originate from the decay $D^* \to D^0\pi^+$ in order to tag D^0 and to suppress combinatorial background. The signal decays are reconstructed in $\phi \to K^+K^-$, $\bar{K}^* \to K^-\pi^+$ and $\rho^0 \to \pi^+\pi^-$ respectively. The selection criteria are optimized to maximize the figure of merit $N_{sig}/\sqrt{N_{sig}+N_{bkg}}$ where $N_{sig}(N_{bkg})$ is the number of signal (background) events. Both the branching fraction B and

CP asymmetry A_{CP} are obtained via normalization to other channels. The signal branching fraction is given by

$$B_{sig} = B_{norm} \times \frac{N_{sig}}{N_{norm}} \times \frac{\varepsilon_{norm}}{\varepsilon_{sig}}. \tag{4.1}$$

We obtain three branching fractions $B(D^0 \to \phi\gamma) = (2.76 \pm 0.20 \pm 0.08) \times 10^{-5}$ which is much more precise than Belle's previous result [15], $B(D^0 \to \bar{K}^{*0}\gamma) = (4.66 \pm 0.21 \pm 0.18) \times 10^{-4}$ which is 3.3σ away from BABAR result [16] and $B(D^0 \to \rho^0\gamma) = (1.77 \pm 0.30 \pm 0.08) \times 10^{-5}$ which is the first observation and branching fraction measurement of the decay $D^0 \to \rho^0\gamma$.

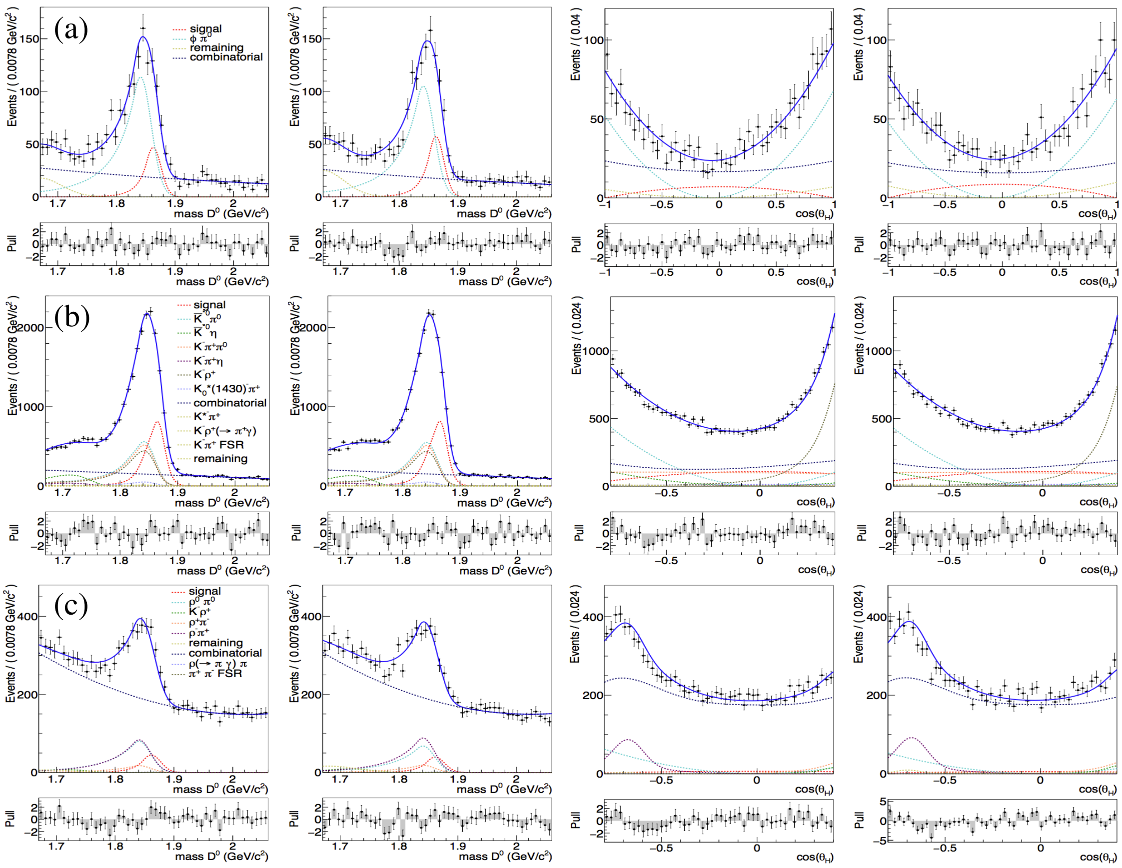

Figure 2: Distributions from left to right respectively in invariant mass of D^0 and $\bar{D}^0$ and the cosine of helicity angle for D^0 and $\bar{D}^0$ of the (a) ϕ, (b) $\bar{K}^{*0}$, (c) ρ^0 mode respectively from top to bottom.

Belle gave the first measurement of CP asymmetry in these radiative decays [14]. The raw asymmetry is obtained by

$$A_{raw} = \frac{N(D^0) - N(\bar{D}^0)}{N(D^0) + N(\bar{D}^0)} = A_{CP} + A_{FB} + A_{\varepsilon}^{\pm} \tag{4.2}$$

where A_{FB} and $A_{\varepsilon}^{\pm}$ can be eliminated through a relative measurement of A_{CP}, so $A_{CP}^{sig} = A_{raw}^{sig} - A_{raw}^{norm} + A_{CP}^{norm}$. From the D^0 and $\bar{D}^0$ separate fitting result, we obtain CP asymmetry in these three channels: $A_{CP}^{\phi\gamma} = -0.094 \pm 0.066 \pm 0.001$, $A_{CP}^{\bar{K}^{*0}\gamma} = -0.003 \pm 0.020 \pm 0.000$ and $A_{CP}^{\rho^0\gamma} = +0.056 \pm 0.151 \pm 0.006$.

4.2 Analysis of $D^0 \to \gamma\gamma$

The D^0 samples are obtained from $D^{*+} \to D^0\pi^+$ in order to suppress combinatorial background. The branching fraction is calculated with normalisation to the decay $D^0 \to K_S^0\pi^0$. BABAR used 470.5 fb^{-1} of data to extract the signal events after measuring the main background as well $D^0 \to \pi^0\pi^0$ [17] BABAR gives the upper limit on branching ratio: $Br(D^0 \to \gamma\gamma) < 2.2 \times 10^{-6}$ [17].

Based on 832 fb^{-1} of data collected near the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances, a two-dimensional unbinned extended maximum likelihood fit in M(D^0) and the mass difference ΔM between the D^* and D^0 are preformed [18]. After thinking of the correlation between M and ΔM in the peak background, Belle finds 4 ± 15 signal with efficiency $(7.34 \pm 0.05)\%$ of $D^0 \to \gamma\gamma$ and obtains a signal yield of 343050 ± 673 events with efficiency $(7.18 \pm 0.05)\%$ in $D^0 \to K_S^0\pi^0$. After systematic uncertainties see Ref. [18], Belle gives the most stringent upper limit to date at 90% confidence level: $< 8.5 \times 10^{-7}$ which is approaching SM prediction.

References

[1] Ed. A.J. Bevan, B. Golob, Th. Mannel, S. Prell, and B.D. Yabsley, *Eur. Phys. J.* C**74** (2014) 3026, SLAC-PUB-15968, KEK Preprint 2014-3.

[2] R. Aaij *et al.* (LHCb Collaboration), Phys. Rev. Lett. **110**, 101802 (2013); Phys. Rev. Lett. **111**, 251801 (2013); T. Aaltonen *et al.* (CDF Collaboration), Phys. Rev. Lett. **111**, 231802 (2013);

[3] B. R. Ko *et al.* (Belle Collaboration), Phys. Rev. Lett. **112**, 111801 (2014).

[4] HFAG: Charm Physics Paramters, http://www.slac.stanford.edu/xorg/hfag/charm

[5] M. Staric *et al.* (Belle Collaboration), Phys. Lett. B **753** (2016) 412-418.

[6] M. Staric *et al.* (Belle Collaboration), Phys. Rev. Lett. **98**, 211803 (2007).

[7] J.P. Lees *et al.* (BABAR Collaboration), Phys. Rev. D **87**, 012004 (2013).

[8] B. Aubert *et al.* (BABAR Collaboration), Phys. Rev. D **78**, 011105(R) (2008); B. Aubert *et al.* (BABAR Collaboration), Phys. Rev. D **80**, 071103(R) (2009).

[9] B. Aubert *et al.* (BABAR Collaboration), Phys. Rev. Lett. **98**, 211802 (2007).

[10] T. Peng *et al.* (Belle Collaboration), Phys. Rev. D **89**, 091103(R) (2014).

[11] P. del Amo Sanchez *et al.* (BABAR Collaboration), Phys. Rev. Lett. **105**, 081803 (2010).

[12] N.K. Nisar *et al.* (Belle Collaboration), Phys. Rev. Lett. **112**, 211601 (2014).

[13] B.R. Ko *et al.* (Belle Collaboration), Phys. Rev. Lett. **109**, 119903 (2012).

[14] T. Nanut *et al.* (Belle Collaboration), arXiv:1603.03257 [hep-ex].

[15] O. Tajima *et al.* (Belle Collaboration), Phys. Rev. Lett. **92**, 101803 (2004).

[16] B. Aubert *et al.* (BABAR Collaboration), Phys. Rev. D **78**, 071101(R) (2008).

[17] J.P. Lees *et al.* (BABAR Collaboration), Phys. Rev. D **85**, 091107(R) (2012).

[18] N.K. Nisar *et al.* (Belle Collaboration), Phys. Rev. D **93**, 051102(R) (2016).