Charm CPV and Mixing at Belle

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for the Belle Collaboration

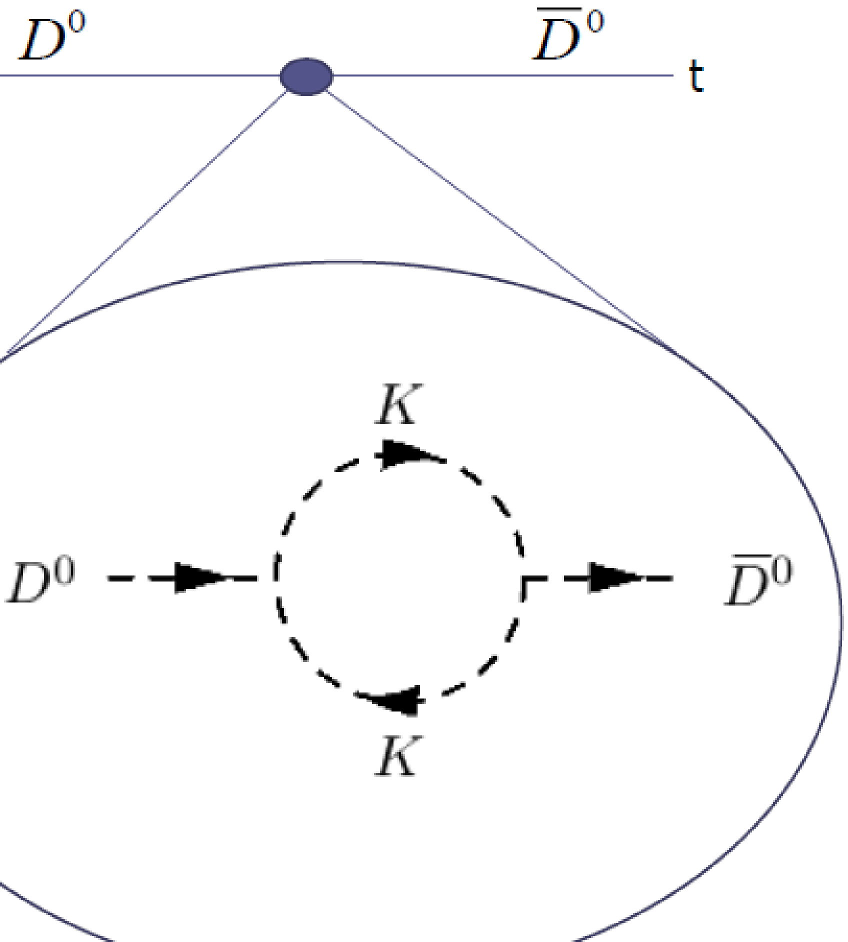
◦Introduction

- CPV in charm decays
  - Very small in the Standard Model (SM), <O(0.1%)
  - O(1%) CPV in charm decays would signal new physics

CP violation in charm decays provides a unique probe to search for beyond the SM

◦Introduction

- Charm mixing



- SM re-scattering dominates
→SM prediction of the mixing rate is quite difficult

Probe to search for BSM

- Independent observations of the mixing from LHCb, CDF and Belle

Contents

- Introduction

1)Mixing in $D^0 \to K^+\pi^-$

2)Mixing and indirect CPV in $D^0 \to K_S^0\pi^+\pi^-$

3)Time-integrated CPV in $D^0 \to \pi^0\pi^0$

(also update CPV in $D^0 \to K_S^0\pi^0$)

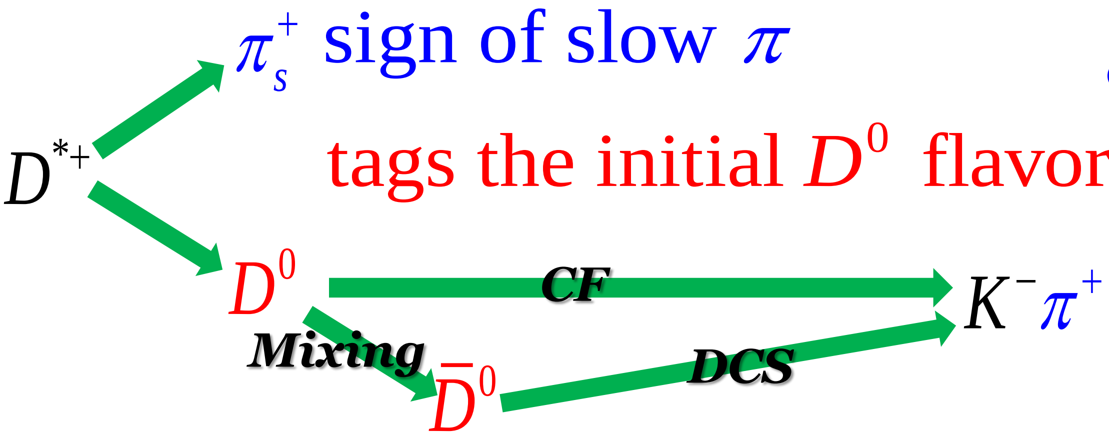
- Summary

1)Mixing in $D^0 \to K^+\pi^-$

-time-dependent ratio of $D^0 \to K^+\pi^-$(WS) to $D^0 \to K^-\pi^+$(RS) decay rates

(the role of RS : cancel most of experimental effects out)

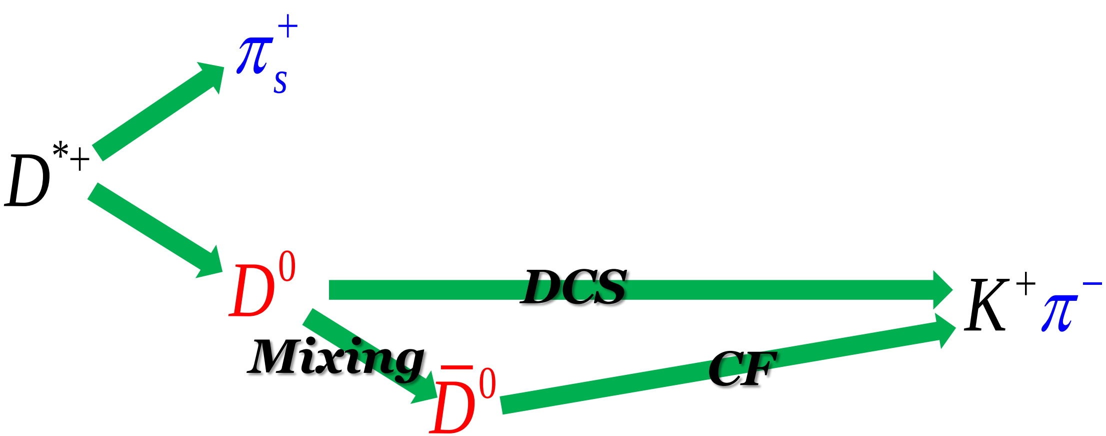
-have to use tagged D^0 from D^{*+} decay to identify WS and RS



- $\mathcal{A}_{RS} = \mathcal{A}_{CF} + \mathcal{A}_{DCS}\mathcal{A}_{Mixing} \approx \mathcal{A}_{CF}$

  : effectively CF decays

  $(\because \mathcal{A}_{CF} \gg \mathcal{A}_{DCS} \approx \mathcal{A}_{Mixing})$



- $\mathcal{A}_{WS} = \mathcal{A}_{DCS} + \mathcal{A}_{CF}\mathcal{A}_{Mixing}$

  $= \mathcal{A}_{CF}\left(\mathcal{A}_{DCS}/\mathcal{A}_{CF} + \mathcal{A}_{Mixing}\right)$

  : coherent sum of DCS and Mixing

1)Mixing in $D^0 \to K^+\pi^-$

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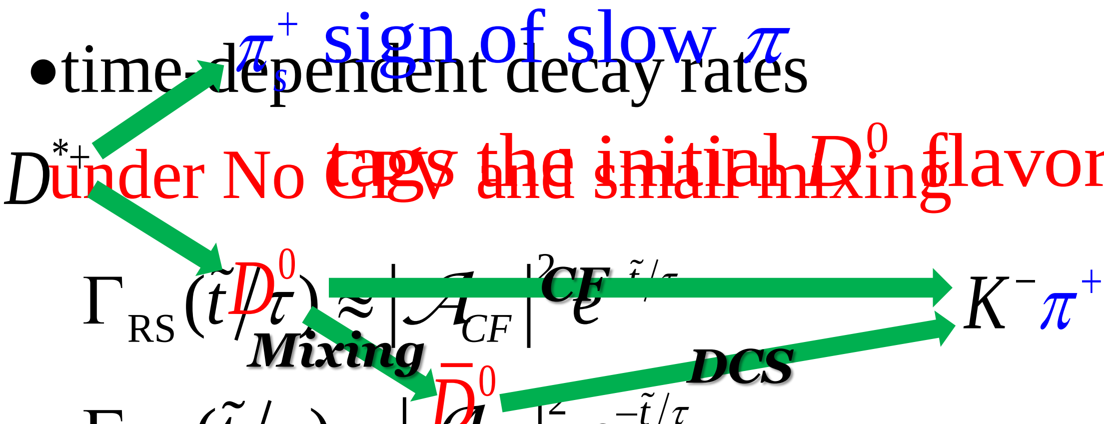
-have to use tagged D^0 from D^{*+} decay to identify WS and RS

π_s^+ sign of slow π tags the initial D^0 flavor

•time-dependent decay rates

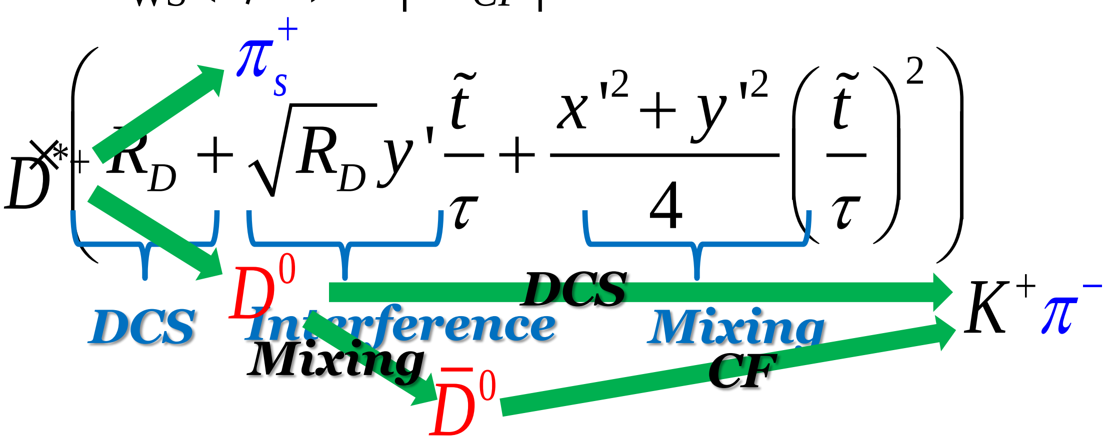
under No CPV and small mixing



$$\Gamma_{\rm RS}(\tilde{t}/\tau) \approx |\mathcal{A}_{CF}|^2 e^{-\tilde{t}/\tau}$$

$$\Gamma_{\rm WS}(\tilde{t}/\tau) \approx |\mathcal{A}_{CF}|^2 e^{-\tilde{t}/\tau}\left(R_D + \sqrt{R_D}\,y'\frac{\tilde{t}}{\tau} + \frac{x'^2+y'^2}{4}\left(\frac{\tilde{t}}{\tau}\right)^2\right)$$

DCS Interference Mixing



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$$\Gamma_{\mathrm{RS}}(\tilde{t}/\tau) \approx |\mathcal{A}_{CF}|^2 e^{-\tilde{t}/\tau}$$

$$\Gamma_{\mathrm{WS}}(\tilde{t}/\tau) \approx |\mathcal{A}_{CF}|^2 e^{-\tilde{t}/\tau} \times \left(R_D + \sqrt{R_D}\, y' \frac{\tilde{t}}{\tau} + \frac{x'^2 + y'^2}{4} \left(\frac{\tilde{t}}{\tau}\right)^2 \right)$$

DCS Interference Mixing

- $\mathcal{A}_{RS} = \mathcal{A}_{CF} + \mathcal{A}_{DCS}\mathcal{A}_{Mixing} \approx \mathcal{A}_{CF}$: effectively CF decays

$(\because |\mathcal{A}_{CF}|^2 \gg |\mathcal{A}_{DCS}|^2 \approx \mathcal{A}_{Mixing})$

- $\mathcal{A}_{WS} = \mathcal{A}_{DCS} + \mathcal{A}_{CF}\mathcal{A}_{Mixing} = \mathcal{A}_{CF}\left(\mathcal{A}_{DCS}/\mathcal{A}_{CF} + \mathcal{A}_{Mixing}\right)$: coherent sum of DCS and Mixing

$\tilde{t}$: decay time, τ : D^0 lifetime

$R_D = |\mathcal{A}_{DCS}|^2 / |\mathcal{A}_{CF}|^2$

$x' = x\cos\delta + y\sin\delta$

$y' = y\cos\delta - x\sin\delta$

$x = (m_1 - m_2)/\Gamma,\ y = (\Gamma_1 - \Gamma_2)/2\Gamma$

Mixing parameters

$\Gamma = 1/\tau$

δ : relative strong phase between $\mathcal{A}_{DCS}$ and $\mathcal{A}_{CF}$

1)Mixing in $D^0 \to K^+\pi^-$

- taking a ratio of the two decay rates

$$R(\tilde{t}/\tau) = \frac{\Gamma_{\mathrm{WS}}(\tilde{t}/\tau)}{\Gamma_{\mathrm{RS}}(\tilde{t}/\tau)} \approx R_D + \sqrt{R_D}\,y'\frac{\tilde{t}}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{\tilde{t}}{\tau}\right)^2$$

$*$ Note $e^{-\tilde{t}/\tau}$ cancel out

- extracting

R_D, y', and x'^2 from $R(\tilde{t}/\tau)$

$\to$ done by CDF and LHCb

1)Mixing in $D^0 \to K^+\pi^-$

PRL 112, 111801 (2014)

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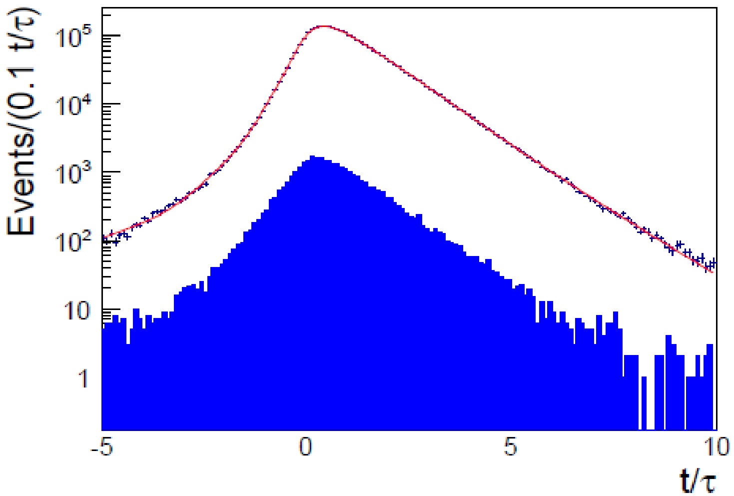
•extracting

R_D, y', and x'^2 from $R(\tilde{t}/\tau)$

→ done by CDF and LHCb

•RS decay time at Belle



t resolution : ~0.3 t/τ ~120 fs
most of events :~1.0 t/τ ~400 fs
take into account the t resolution using convolution

•the ratio with convolution

$$R(t/\tau) = \frac{\int_{-\infty}^{+\infty} \Gamma_{WS}(\tilde{t}/\tau)\mathcal{R}(t/\tau - \tilde{t}/\tau)d(\tilde{t}/\tau)}{\int_{-\infty}^{+\infty} \Gamma_{RS}(\tilde{t}/\tau)\mathcal{R}(t/\tau - \tilde{t}/\tau)d(\tilde{t}/\tau)}$$

∘$\mathcal{R}$: 4 Gaussians from RS decay time

∗ Note $e^{-\tilde{t}/\tau}$ does not cancel out

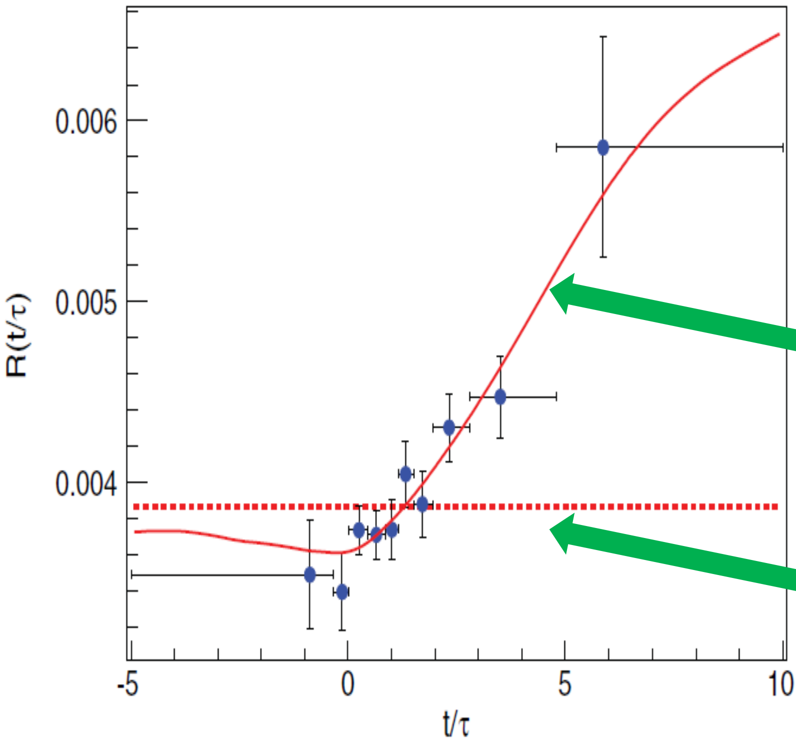
∗complicate functional form

•extracting R_D, y', and x'^2

from $R(t/\tau)$, not from $R(\tilde{t}/\tau)$ for Belle

1)Mixing in $D^0 \to K^+\pi^-$

PRL 112, 111801 (2014)



Test hypothesis (χ^2/DOF)	Parameters	Fit results (10^{-3})
Mixing (4.2/7)	R_D	3.53 ± 0.13
	y'	4.6 ± 3.4
	x'^2	0.09 ± 0.22
No mixing (33.5/9)	R_D	3.864 ± 0.059

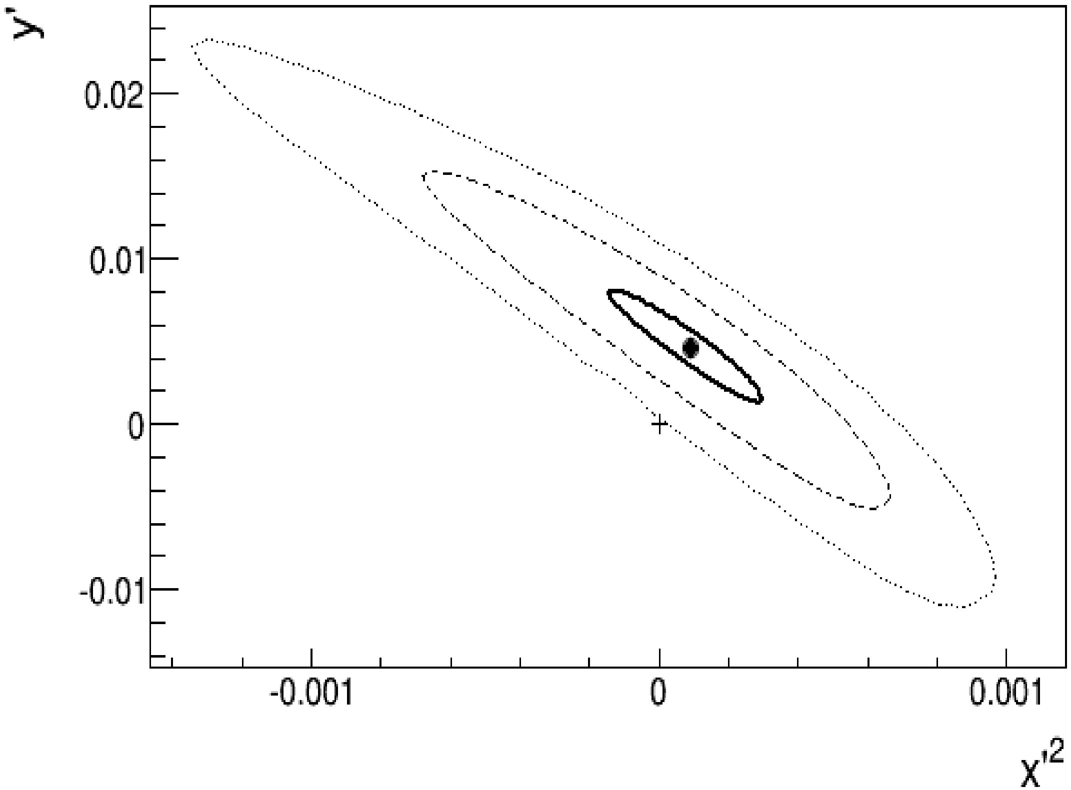
- $\Delta\chi^2 = \chi^2_{\text{Mixing}} - \chi^2_{\text{No Mixing}} = 29.3$

$\to$ 5.1 standard deviations from No mixing hypothesis

- First observation of $D^0 - \bar{D}^0$ mixing in e^+e^- collisions

1)Mixing in $D^0 \to K^+\pi^-$

PRL 112, 111801 (2014)



Correlation coefficient

R_D	y'	x'^2
1	−0.865	+0.737
	1	−0.948
		1

- 1 (line), 3 (dashed-line), and 5 (dots) standard deviations from the best fit (point)
- + : no mixing

the best fit (point) :
5σ away from No mixing

2)Mixing and indirect CPV in $D^0 \to K_S^0\pi^+\pi^-$

-time-dependent Dalitz fit

• time-dependent decay matrix elements

$$\mathcal{M}(m_+^2, m_-^2, t) = g_+(t)\mathcal{A}(m_+^2, m_-^2) + \frac{q}{p} g_-(t)\bar{\mathcal{A}}(m_+^2, m_-^2)$$

$$\bar{\mathcal{M}}(m_+^2, m_-^2, t) = g_+(t)\bar{\mathcal{A}}(m_+^2, m_-^2) + \frac{p}{q} g_-(t)\mathcal{A}(m_+^2, m_-^2)$$

$$\begin{cases} m_\pm^2 = m_{K_S^2\pi^\pm}^2 \\ \mathcal{M},\ \mathcal{A} \text{ for } D^0 \text{ decay} \\ \bar{\mathcal{M}},\ \bar{\mathcal{A}} \text{ for } \bar{D}^0 \text{ decay} \end{cases}$$

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∘ t-independent part

$$\mathcal{A}(m_+^2,m_-^2)=\sum a_j e^{i\delta_j} A_j(m_+^2,m_-^2)$$

$$\bar{\mathcal{A}}(m_+^2,m_-^2)=\sum \bar{a}_j e^{i\bar{\delta}_j} A_j(m_+^2,m_-^2)$$

a_j and δ_j from the fit

$A_j(m_+^2,m_-^2)$: known

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$$g_\pm(t) = \frac{1}{2}\left(e^{-i\lambda_1 t} \pm e^{-i\lambda_2 t}\right),$$

$$\lambda_i = m_i - \frac{i\Gamma_i}{2}$$

m_i and Γ_i : D_i mass and width

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- $\mathcal{M}^2$ (~decay rates) contains

$\left.\frac{q}{p} = \left|\frac{q}{p}\right| e^{i\phi}\right\}$ CPV parameters $\left|\frac{q}{p}\right|$ and $\phi = \arg\left(\frac{q}{p}\right)$

$$\left.\begin{array}{l} e^{-\Gamma t}\cos(x\Gamma t) \\ e^{-\Gamma t}\sin(x\Gamma t) \\ e^{[(-1\pm y)\Gamma t]} \end{array}\right\}$$ the mixing parameters x and y

–obtain them simultaneously

2)Mixing and indirect CPV in $D^0 \to K_S^0\pi^+\pi^-$

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•t-integrated Dalitz fits to D^0 and $\bar{D}^0$ separately $\Rightarrow$ $a_j \approx \bar{a}_j$ and $\delta_j \approx \bar{\delta}_j$

→assume No direct CPV, $\mathcal{A}(m_+^2, m_-^2) = \bar{\mathcal{A}}(m_+^2, m_-^2)$

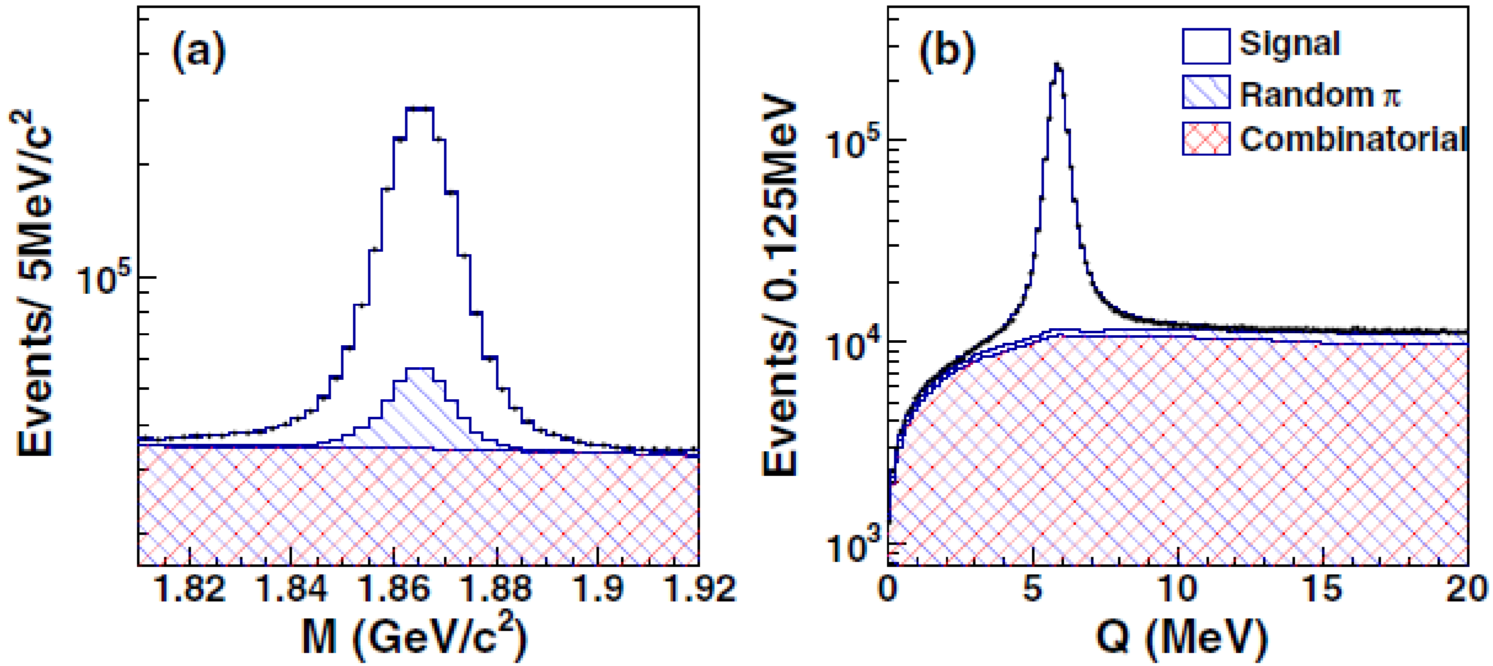
→ Search for indirect CPV

$|q/p| \neq 1$: CPV in mixing

$\arg(q/p) \neq 0$: CPV in the interference between mixing and decay

2)Mixing and indirect CPV in $D^0 \to K_S^0\pi^+\pi^-$

PRD 89, 091103 (2014)



- signal PDF: gaussian and asymmetric gaussian

- signal PDF: triple-gaussian $(M = M_{K_S^0\pi^+\pi^-})$ $(Q = M_{K_S^0\pi^+\pi^-\pi_s^+} - M_{K_S^0\pi^+\pi^-} - m_{\pi_s^+})$

  - signal region

    $|M - m_{D^0}| < 15$ MeV

    5.75 MeV$<Q<$5.95 MeV $\Rightarrow$

- ~1.2M signals
- ~96% purity

2)Mixing and indirect CPV in $D^0 \to K_S^0\pi^+\pi^-$

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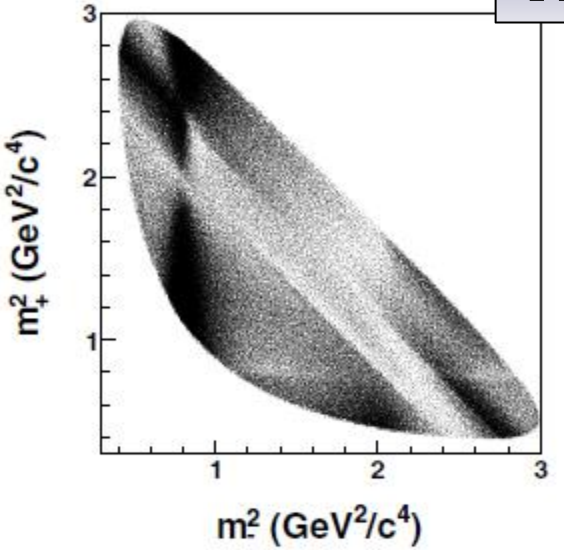

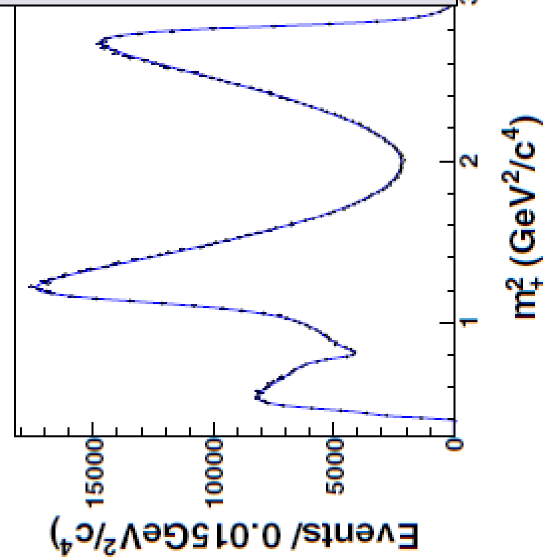

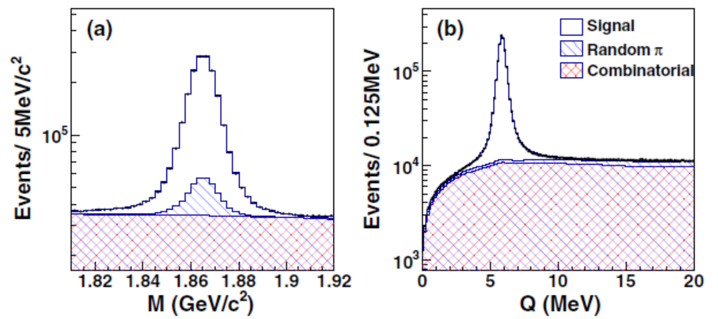

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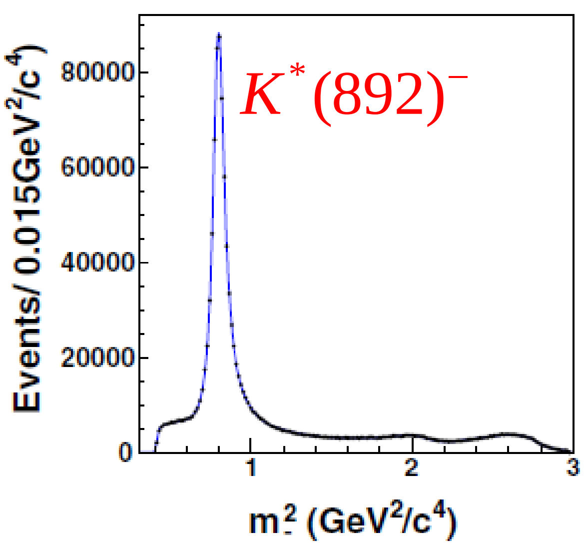

- best model found to be ;
  12 relativistic Breit-Wigner's
  (P- and D-waves)

+ K-matrix (ππ S-wave)
+ LASS (Kπ S-wave)
  without non-resonant decay

2)Mixing and indirect CPV in $D^0 \to K_S^0 \pi^+ \pi^-$

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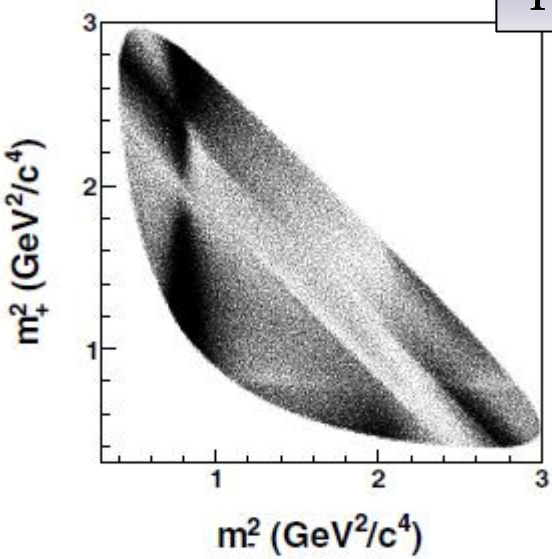

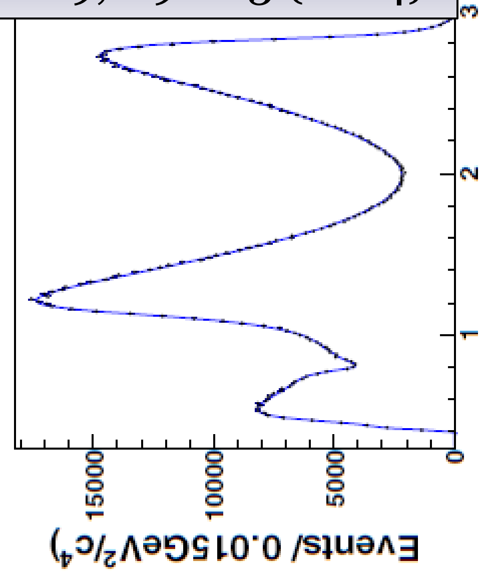

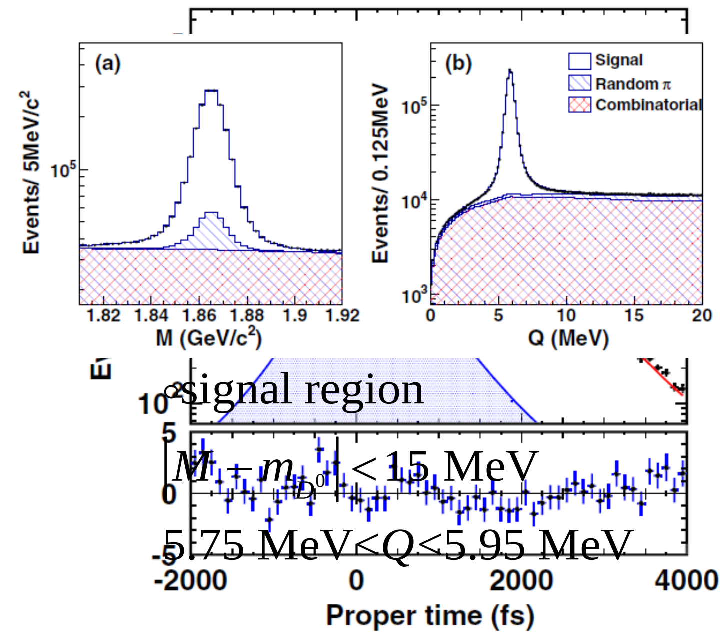

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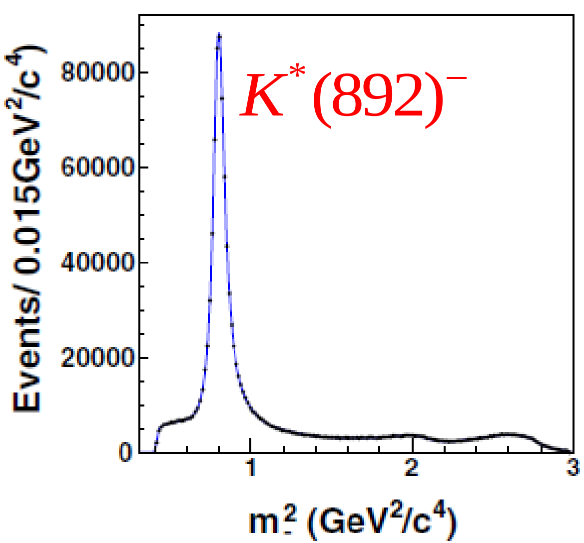

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  12 relativistic Breit-Wigner's (P- and D-waves)
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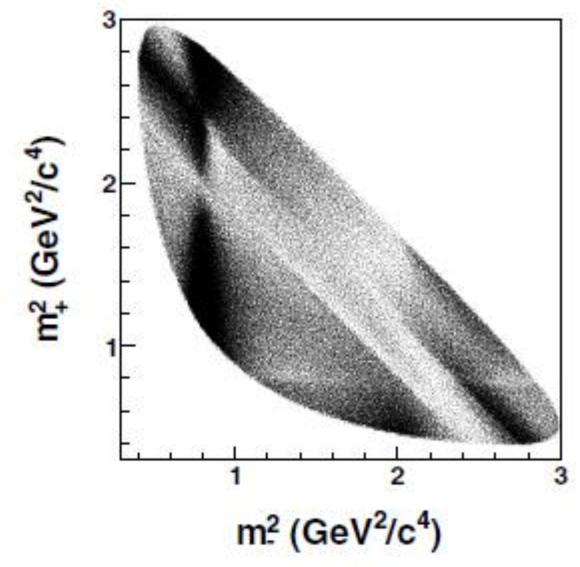
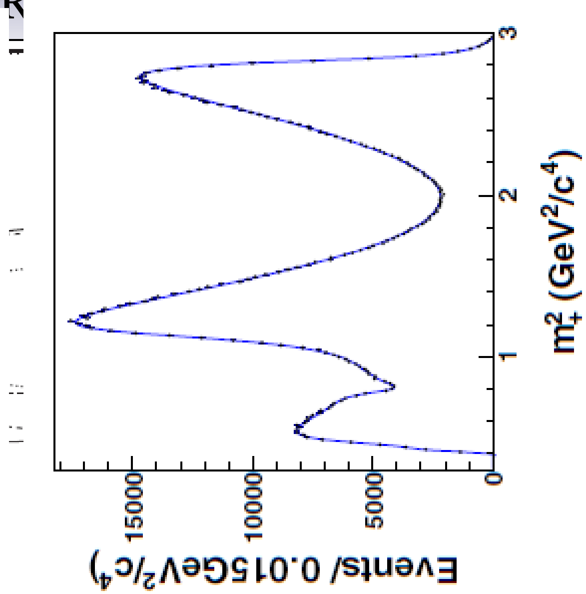
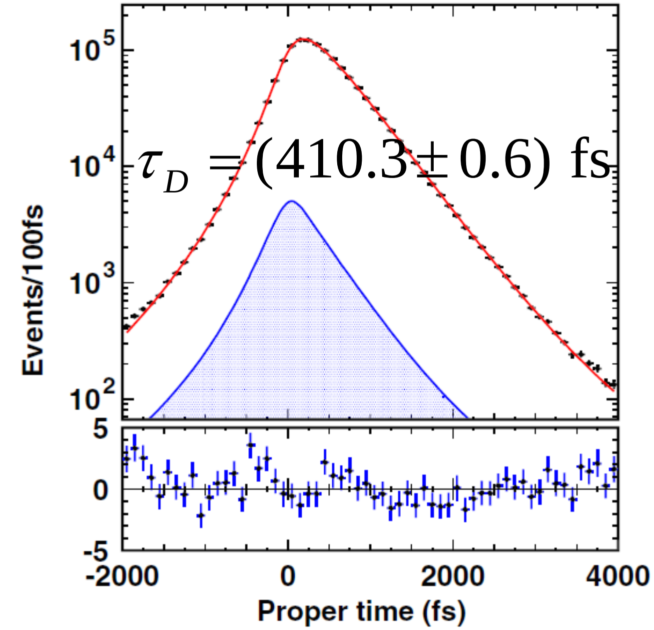
Fit type	Parameter	Fit result
No CPV	$x(\%)$	$0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06}$
CPV	$x(\%)$	$0.56 \pm 0.19^{+0.04+0.06}_{-0.08-0.08}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.07}$
	$\lvert q/p \rvert$	$0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$
	$\arg(q/p)(^\circ)$	$-6 \pm 11 \pm 3^{+3}_{-4}$

2)Mixing and indirect CPV in $D^0 \to K_S^0\pi^+\pi^-$

PRD







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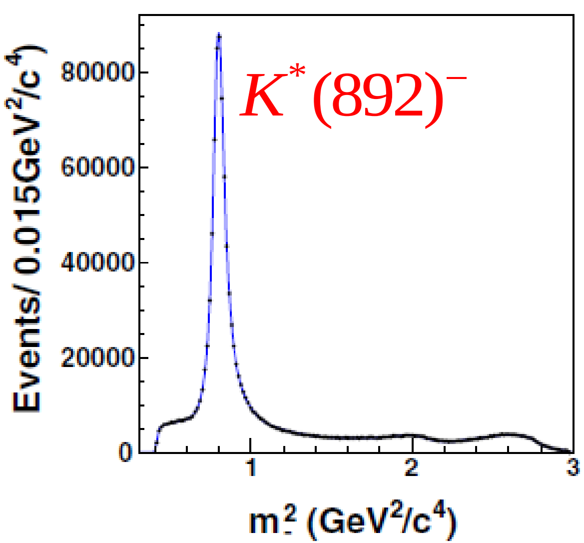

l fit

owed fit

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	$\|q/p\|$	$0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$
	$\arg(q/p)(^\circ)$	$-6 \pm 11 \pm 3^{+3}_{-4}$

3)Time-integrated CPV in $D^0 \to \pi^0\pi^0$

(also update CPV in $D^0 \to K_S^0\pi^0$)

- $A_{CP}^{D^0\to f} \equiv \dfrac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})}$, Γ : partial decay width
- $f \in \{\pi^0\pi^0, K_S^0\pi^0\}$: D^0 flavor from soft π in $D^{*+} \to D^0\pi_s^+$ decay
- $A_{rec}^{D^{*+}\to D^0\pi_s^+} = \dfrac{N_{rec}^{D^{*+}\to D^0\pi_s^+} - N_{rec}^{D^{*-}\to D^0\pi_s^-}}{N_{rec}^{D^{*+}\to D^0\pi_s^+} + N_{rec}^{D^{*-}\to D^0\pi_s^-}} \approx A_{CP}^{D^0\to f} + A_{\varepsilon}^{\pi_s^+} + A_{prod}^{D^{*+}}$ $(\because A_{\varepsilon}^{D^0} = 0)$

, $A_{CP}^{D\to f}$: CP asymmetry in $D \to f$

, $A_{\varepsilon}^{\pi_s^+}$: soft π detection asymmetry

, $A_{prod}^{D^{*+}}$: Forward-backward asymmetry, depending on $\cos\theta_{D^{*+}}^{*}$

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- $A_{CP}^{D^0\to f} \equiv \dfrac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})}$, Γ : partial decay width
- $f \in \{\pi^0\pi^0, K_S^0\pi^0\}$: D^0 flavor from soft π in $D^{*+} \to D^0\pi_s^+$ decay
- $A_{rec}^{D^{*+}\to D^0\pi_s^+} = \dfrac{N_{rec}^{D^{*+}\to D^0\pi_s^+} - N_{rec}^{D^{*-}\to D^0\pi_s^-}}{N_{rec}^{D^{*+}\to D^0\pi_s^+} + N_{rec}^{D^{*-}\to D^0\pi_s^-}} \approx A_{CP}^{D^0\to f} + A_\varepsilon^{\pi_s^+} + A_{prod}^{D^{*+}}$ $(\because A_\varepsilon^{D^0} = 0)$

, $A_{CP}^{D\to f}$: CP asymmetry in $D \to f$

, $A_\varepsilon^{\pi_s^+}$: soft π detection asymmetry

use the correction in PRL 106, 211801 (2011) from tagged and untagged $D^0 \to K^-\pi^+$ decays

, $A_{prod}^{D^{*+}}$: Forward-backward asymmetry, depending on $\cos\theta_{D^{*+}}^*$

decouple from $A_{CP}^{D^0\to f}$ using antisymmetry of $A_{FB}^{D^{*+}}$ in $\cos\theta_{D^{*+}}^*$

3)Time-integrated CPV in $D^0 \to \pi^0\pi^0$

(also update CPV in $D^0 \to K_S^0\pi^0$)

- $A_{CP}^{D^0\to f} \equiv \dfrac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to \bar{f})}$, Γ : partial decay width
- $f \in \{\pi^0\pi^0, K_S^0\pi^0\}$: D^0 flavor from soft π in $D^{*+} \to D^0\pi_s^+$ decay
- $A_{rec}^{D^{*+}\to D^0\pi_s^+} = \dfrac{N_{rec}^{D^{*+}\to D^0\pi_s^+} - N_{rec}^{D^{*-}\to D^0\pi_s^-}}{N_{rec}^{D^{*+}\to D^0\pi_s^+} + N_{rec}^{D^{*-}\to D^0\pi_s^-}} \approx A_{CP}^{D^0\to f} + A_\varepsilon^{\pi_s^+} + A_{prod}^{D^{*+}}$ $(\because A_\varepsilon^{D^0} = 0)$

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, $A_{prod}^{D^{*+}}$: Forward-backward asymmetry, depending on $\cos\theta_{D^{*+}}^*$

decouple from $A_{CP}^{D^0\to f}$ using antisymmetry of $A_{FB}^{D^{*+}}$ in $\cos\theta_{D^{*+}}^*$

- For $f = K_S^0\pi^0$

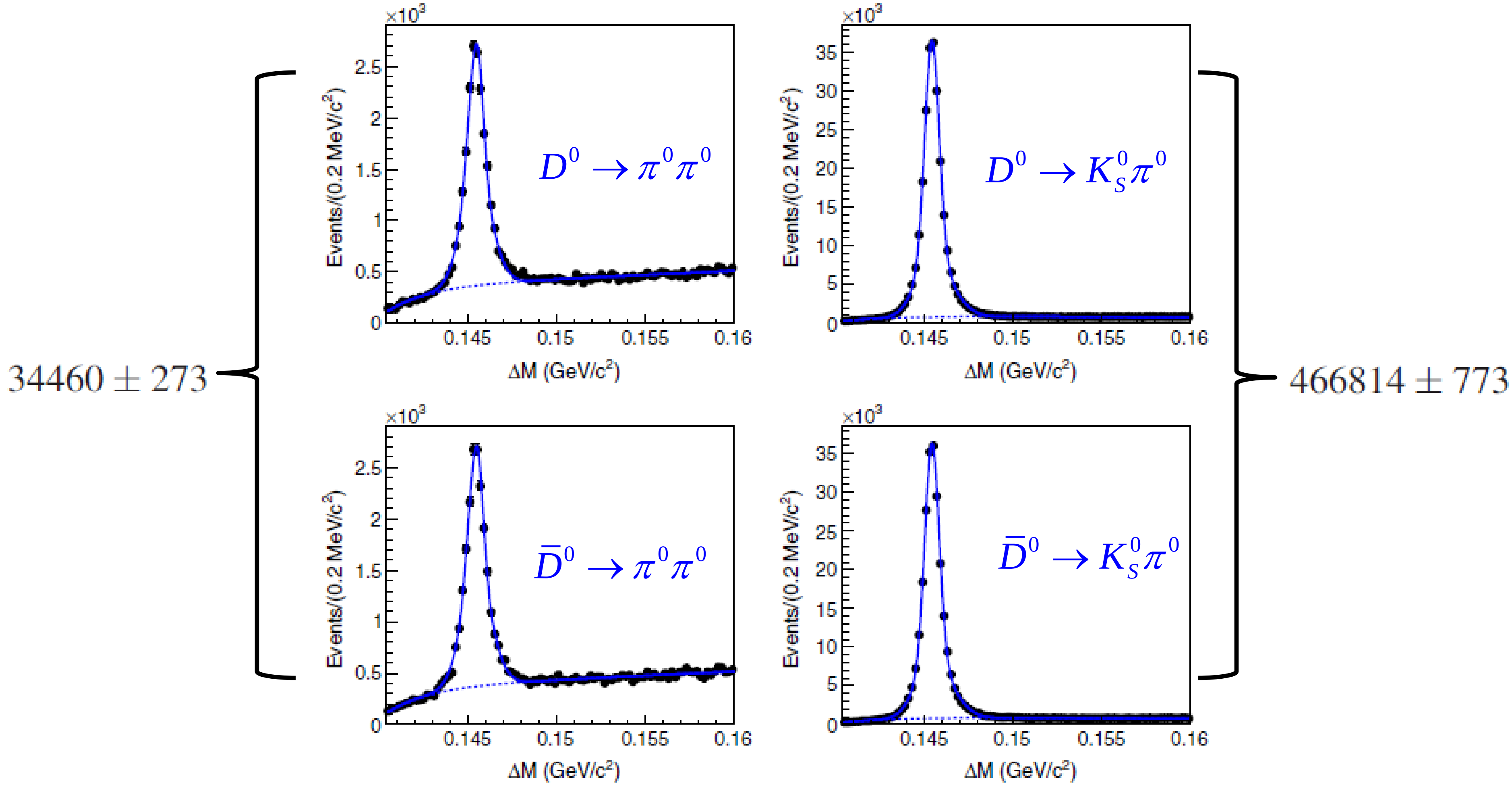
$A_\varepsilon^{\bar{K}^0}$ $(\sigma(\bar{K}^0\text{N}) \neq \sigma(K^0\text{N}))$ according to PRD 84, 111501 (2011)

$A_{CP}^{\bar{K}^0}$ (experiment dependent CPV in $\bar{K}^0$) according to JHEP, 04 (2012) 002

3)Time-integrated CPV in $D^0 \to \pi^0\pi^0$

PRL 112, 211601 (2014)

(also update CPV in $D^0 \to K_S^0\pi^0$)

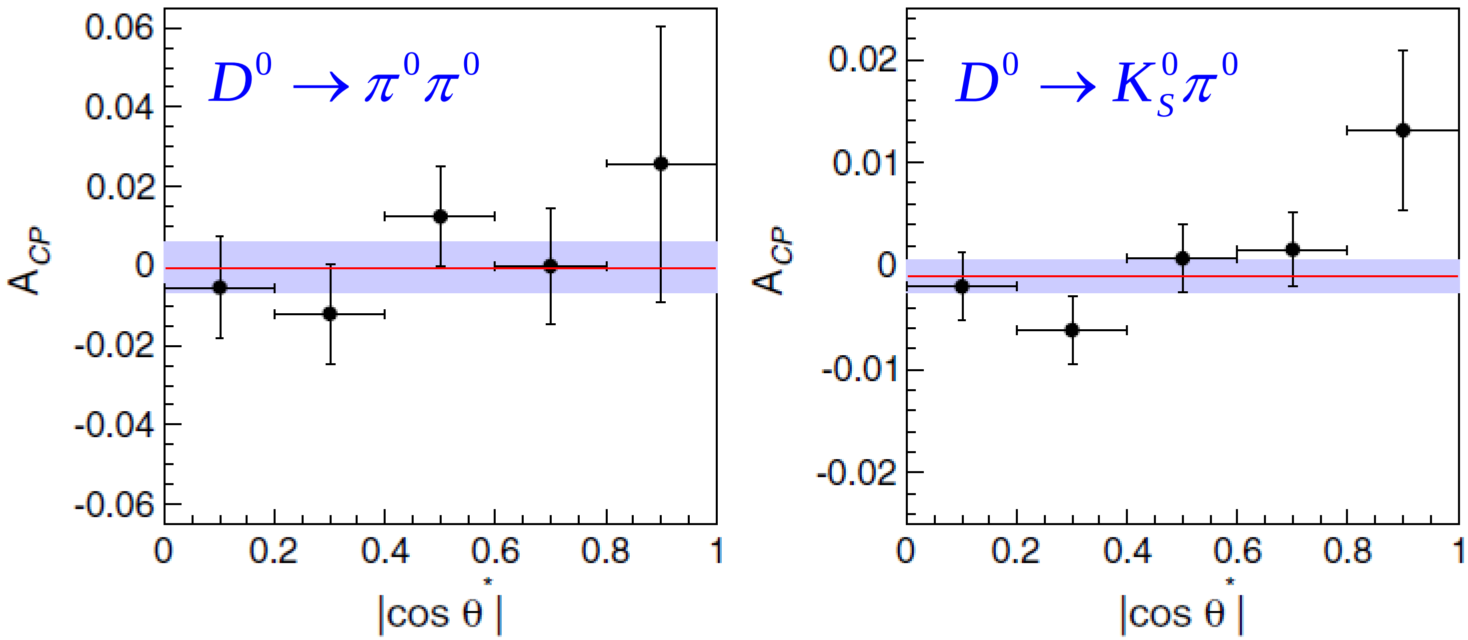


signal PDF:gaussian and asymmetric gaussian

3)Time-integrated CPV in $D^0 \to \pi^0\pi^0$

PRL 112, 211601 (2014)

(also update CPV in $D^0 \to K_S^0\pi^0$)



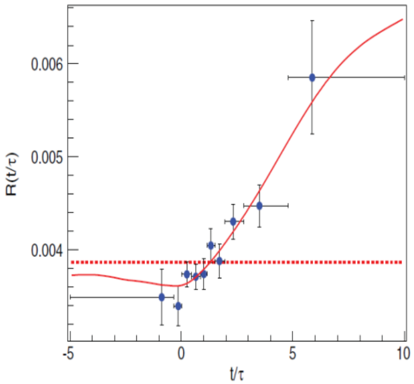
$$A_{CP}(D^0 \to \pi^0\pi^0) = (-0.03 \pm 0.64 \pm 0.10)\%$$

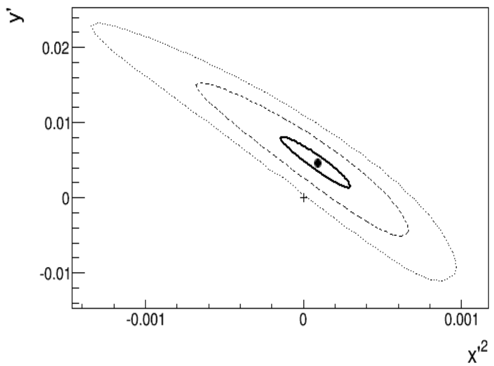
$$A_{CP}(D^0 \to K_S^0\pi^0) = (-0.21 \pm 0.16 \pm 0.07)\%$$

- consistent with No CPV
- most precise measurements to date

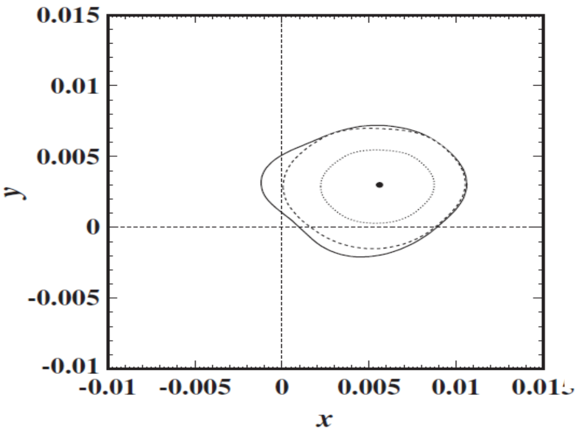
◦Summary

•Charm CPV and Mixing at Belle



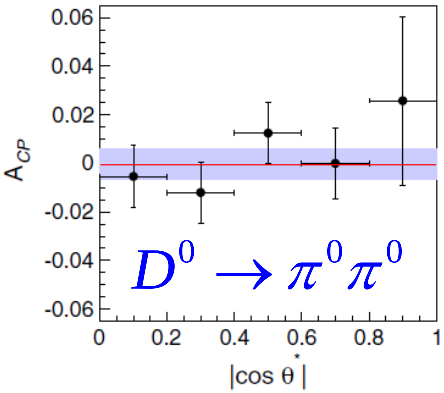


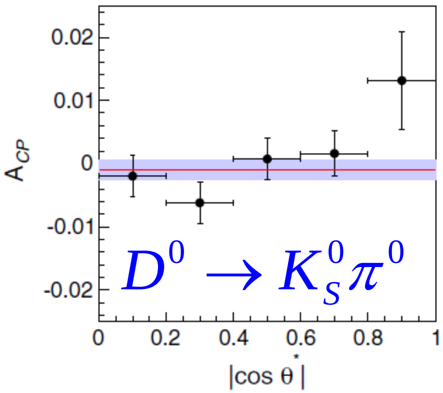
◦first observation in e^+e^- collisions



$x(\%)$	$0.56 \pm 0.19^{+0.04+0.06}_{-0.08-0.08}$
$y(\%)$	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.07}$
$\lvert q/p \rvert$	$0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$
$\arg(q/p)(°)$	$-6 \pm 11 \pm 3^{+3}_{-4}$

◦most precise in a single experiment





◦significantly improved A_{CP} in $D^0 \to \pi^0\pi^0$

BACKUP

$\bullet D^0 - \bar{D}^0$ Mixing

$$|D^0\rangle = \frac{1}{2p}\left(|D_1\rangle + |D_2\rangle\right)$$

$$|\bar{D}^0\rangle = \frac{1}{2q}\left(|D_1\rangle - |D_2\rangle\right)$$

$|D^0\rangle$ and $|\bar{D}^0\rangle$: flavor eigenstates, physical observable

$|D_1\rangle$ and $|D_2\rangle$: mass eigenstates, finite masses and widt

$p^2 + q^2 = 1$ under CPT symmetry

$p = q = 1/\sqrt{2}$ under CP symmetry

$$|D^0(t)\rangle = g_+(t)|D^0\rangle + \frac{q}{p}g_-(t)|\bar{D}^0\rangle$$

$$|\bar{D}^0(t)\rangle = g_+(t)|\bar{D}^0\rangle + \frac{p}{q}g_-(t)|D^0\rangle$$

$$g_\pm(t) = \frac{1}{2}\left(e^{-i\lambda_1 t} \pm e^{-i\lambda_2 t}\right),\ \lambda_i = m_i - \frac{i\Gamma_i}{2}$$

m_i and Γ_i : D_i mass and width

$\Rightarrow D^0 - \bar{D}^0$ Mixing

described by the mixing parameters

$$x = \frac{m_1 - m_2}{\Gamma} \text{ and } y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma},\ \Gamma = \frac{\Gamma_1 + \Gamma}{2}$$

•CP Violation

partial decay widths

$$\Gamma\left(D^0(t)\to f\right)=\left|\langle f|H|D^0(t)\rangle\right|^2 \qquad \langle f|H|D^0(t)\rangle = g_+(t)\langle f|H|D^0\rangle+\frac{q}{p}g_-(t)\langle f|H|\bar{D}^0\rangle$$

$$\Gamma\left(\bar{D}^0(t)\to \bar{f}\right)=\left|\langle \bar{f}|H|\bar{D}^0(t)\rangle\right|^2 \qquad \langle \bar{f}|H|\bar{D}^0(t)\rangle = g_+(t)\langle \bar{f}|H|\bar{D}^0\rangle+\frac{p}{q}g_-(t)\langle \bar{f}|H|D^0\rangle$$

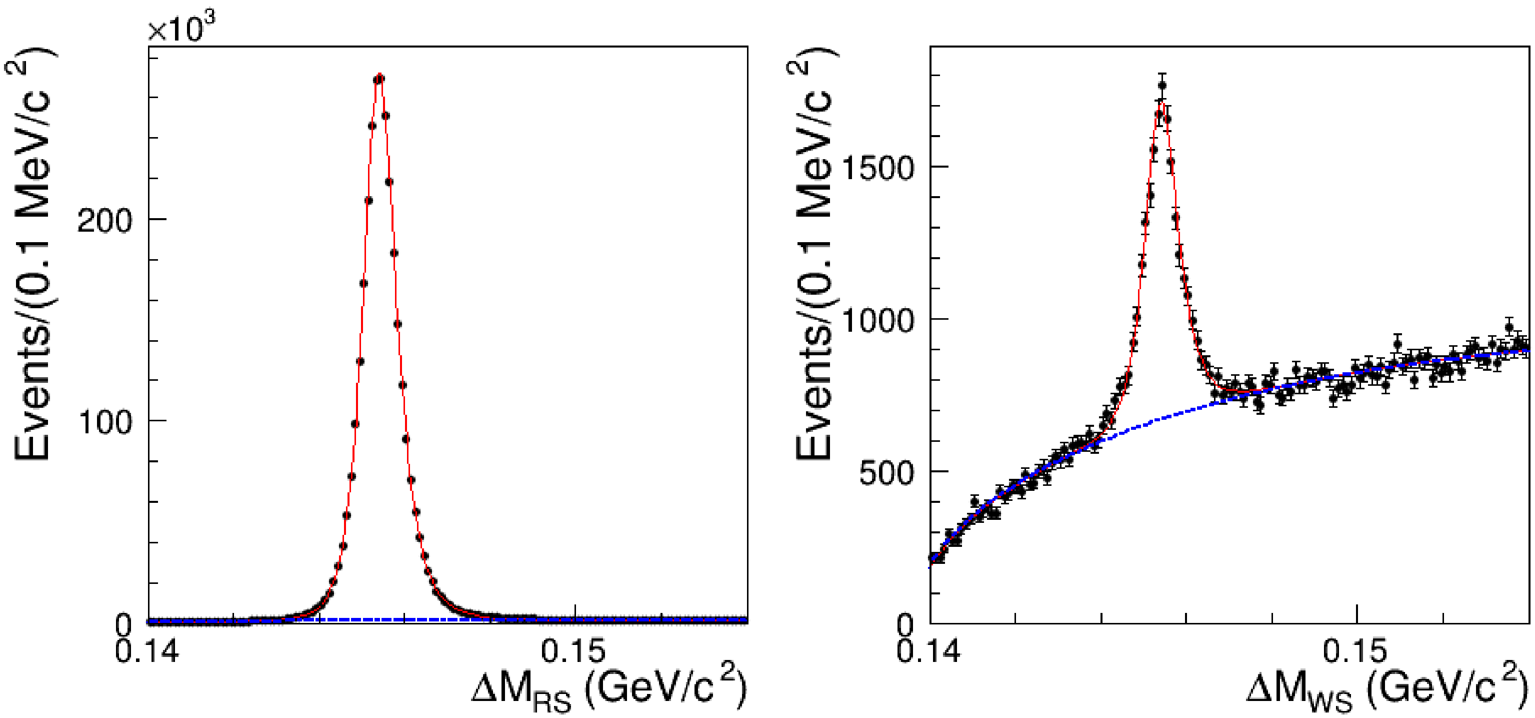
$\Gamma\left(D^0(t)\to f\right)\neq\Gamma\left(\bar{D}^0(t)\to \bar{f}\right)$ $\Rightarrow$ CP Violation

1) $\left|\langle f|H|D^0\rangle/\langle \bar{f}|H|\bar{D}^0\rangle\right|\neq 1$: different decay amplitudes

2) $|q/p|\neq 1$: different mixing rates

3) $\arg\left(q/p\right)\neq 0$: different interferences

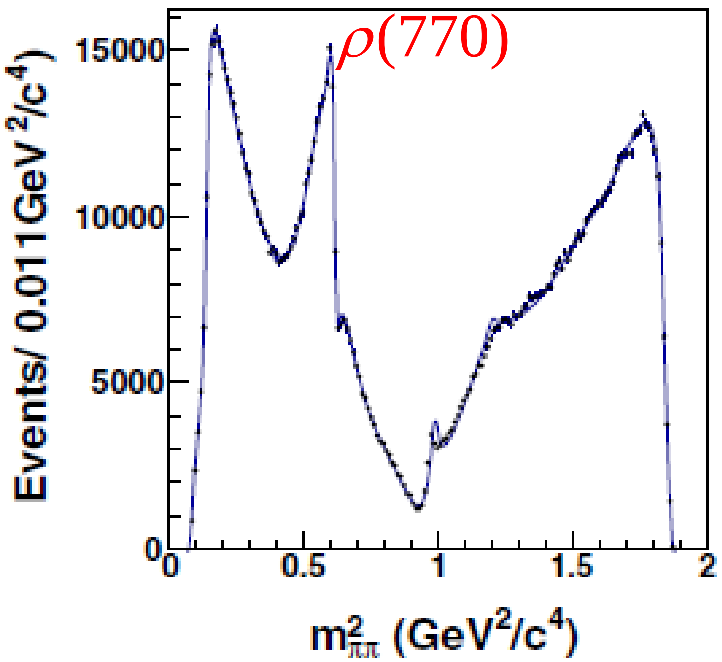
Time-integrated results



	nSIG (RS)	nSIG (WS)
data (976 fb^{-1})	2980710 ± 1885	11478 ± 177

$$R_{WS} = \left(3.851 \pm 0.059\right) \times 10^{-3}$$

Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.590 ± 0.003	131.8 ± 0.2	0.6045
$K_0^*(1430)^-$	2.059 ± 0.010	-194.6 ± 1.7	0.0702
$K_2^*(1430)^-$	1.150 ± 0.009	-41.5 ± 0.4	0.0221
$K^*(1410)^-$	0.496 ± 0.011	83.4 ± 0.9	0.0026
$K^*(1680)^-$	1.556 ± 0.097	-83.2 ± 1.2	0.0016
$K^*(892)^+$	0.139 ± 0.002	-42.1 ± 0.7	0.0046
$K_0^*(1430)^+$	0.176 ± 0.007	-102.3 ± 2.1	0.0005
$K_2^*(1430)^+$	0.077 ± 0.007	-32.2 ± 4.7	0.0001
$K^*(1410)^+$	0.248 ± 0.010	-145.7 ± 2.9	0.0007
$K^*(1680)^+$	1.407 ± 0.053	86.1 ± 2.7	0.0013
$\rho(770)$	1 (fixed)	0 (fixed)	0.2000
$\omega(782)$	0.0370 ± 0.0004	114.9 ± 0.6	0.0057
$f_2(1270)$	1.300 ± 0.013	-31.6 ± 0.5	0.0141
$\rho(1450)$	0.532 ± 0.027	80.8 ± 2.1	0.0012
$\pi\pi$ S wave			0.1288
β_1	4.23 ± 0.02	164.0 ± 0.2	
β_2	10.90 ± 0.02	15.6 ± 0.2	
β_3	37.4 ± 0.3	3.3 ± 0.4	
β_4	14.7 ± 0.1	-8.9 ± 0.3	
f_{11}^{prod}	12.76 ± 0.05	-161.1 ± 0.3	
f_{12}^{prod}	14.2 ± 0.2	-176.2 ± 0.6	
f_{13}^{prod}	10.0 ± 0.5	-124.7 ± 2.1	
$K\pi$ S wave	Parameters		
M (MeV/c^2)	1461.7 ± 0.8		
Γ (MeV/c^2)	268.3 ± 1.1		
F	0.4524 ± 0.005		
ϕ_F (rad)	0.248 ± 0.003		
R	1(fixed)		
ϕ_R (rad)	2.495 ± 0.009		
a (GeV/c^{-1})	0.172 ± 0.006		
r (GeV/c^{-1})	-20.6 ± 0.3		
$K^*(892)$	Parameters		
$M_{K^*(892)}$ (MeV/c^2)	893.68 ± 0.04		
$\Gamma_{K^*(892)}$ (MeV/c^2)	47.49 ± 0.06		



Correlation coefficient

	x	y	$\|q/p\|$	$\arg(q/p)$
x	1	0.054	-0.074	-0.031
y		1	0.034	-0.019
$\|q/p\|$			1	0.044
$\arg(q/p)$				1

TABLE III. Summary of the contributions to experimental systematic uncertainty on the mixing and *CPV* parameters. The positive and negative errors are added in quadrature separately.

	No *CPV*		*CPV*			
Source	$\Delta x/10^{-4}$	$\Delta y/10^{-4}$	$\Delta x/10^{-4}$	$\Delta y/10^{-4}$	$\lvert q/p\rvert/10^{-2}$	$\arg(q/p)/°$
Best candidate selection	+1.0	+1.9	+1.3	+2.0	−2.3	+2.2
Signal and background yields	±0.3	±0.3	±0.4	±0.4	±1.2	±0.8
Fraction of wrong-tagged events	−0.7	−0.4	−0.5	+0.4	+1.1	+0.8
Time resolution of signal	−1.4	−0.9	−1.2	−0.8	+0.8	−1.2
Efficiency	−1.1	−2.1	−1.4	−2.2	+3.1	+1.3
Combinatorial PDF	$^{+1.9}_{-4.8}$	$^{+2.3}_{-3.9}$	$^{+2.4}_{-4.1}$	$^{+2.0}_{-4.4}$	$^{+1.2}_{-2.9}$	$^{+2.8}_{-2.3}$
$K^*(892)$ DCS/CF reduced by 5%	−7.3	+2.3	−6.9	+3.1	+3.3	−1.4
$K_2^*(1430)$ DCS/CF reduced by 5%	+1.7	−0.7	+2.2	−0.2	+1.1	+0.4
Total	$^{+2.8}_{-8.9}$	$^{+3.7}_{-4.6}$	$^{+3.6}_{-8.3}$	$^{+4.3}_{-5.1}$	$^{+5.0}_{-4.0}$	$^{+3.3}_{-3.0}$

TABLE IV. Summary of contributions to the modeling systematic uncertainty on the mixing and *CPV* parameters. The positive and negative errors are added in quadrature separately.

	No *CPV*		*CPV*			
Source	$\Delta x/10^{-4}$	$\Delta y/10^{-4}$	$\Delta x/10^{-4}$	$\Delta y/10^{-4}$	$\lvert q/p\rvert/10^{-2}$	$\arg(q/p)/°$
Resonance M & Γ	±1.4	±1.2	±1.2	±1.3	±2.1	±1.0
$K^*(1680)^+$ removal	−1.8	−3.0	−2.2	−2.8	+2.1	−1.2
$K^*(1410)^\pm$ removal	−1.2	−3.6	−1.7	−3.9	−1.3	+1.4
$\rho(1450)$ removal	+2.1	+0.3	+2.1	+0.5	−1.9	+0.9
Form factors	+4.0	+2.4	+4.3	+2.0	−2.4	−1.0
$\Gamma(q^2)$ = constant	+3.3	−1.6	+4.1	−2.3	−1.6	+1.3
Angular dependence	−8.5	−3.9	−7.4	−3.6	+5.6	−3.2
K-matrix formalism	−2.2	+1.8	−3.5	+2.4	−3.6	+1.1
Total	$^{+5.8}_{-9.1}$	$^{+3.2}_{-6.4}$	$^{+6.4}_{-8.4}$	$^{+3.4}_{-6.9}$	$^{+6.4}_{-5.1}$	$^{+2.5}_{-3.7}$

- Obtaining A_{ε}^{f} from CPV free resonance data : depends on f
  - Assume the same A_{FB} for all charmed mesons

◦ soft charged π : $D^{*+} \rightarrow D^{0}\pi_{s}^{+} \rightarrow K^{-}\pi^{+}\pi_{s}^{+}$ and $D^{0} \rightarrow K^{-}\pi^{+}$

$$* \; A_{CP}^{D\rightarrow f} = \left\{ A_{rec}^{D\rightarrow f_{corr}}(\cos\theta_{D}^{*}) + A_{rec}^{D\rightarrow f_{corr}}(-\cos\theta_{D}^{*}) \right\} / 2$$

$$* \; A_{FB}^{D} = \left\{ A_{rec}^{D\rightarrow f_{corr}}(\cos\theta_{D}^{*}) - A_{rec}^{D\rightarrow f_{corr}}(-\cos\theta_{D}^{*}) \right\} / 2$$