D^0 - $\overline{D^0}$ mixing results from Belle

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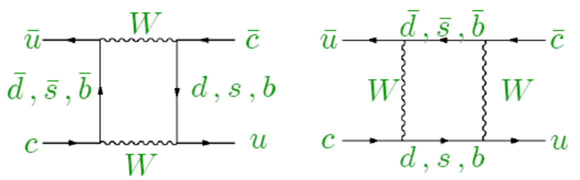
Outline:

- **Introduction**
  - **D^0 Mixing formalism**
  - **Experimental method**
- **Lifetime difference measurement in $D^0 \rightarrow K^+K^-$, $\pi^+\pi^-$**
- **Time-dependent Dalitz analysis of $D^0 \rightarrow K_S\pi^+\pi^-$**
- **Summary**

Introduction: Mixing formalism

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathrm{M} - \frac{i}{2}\Gamma\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$



- Mass eigenstate ≠ Flavor eigenstate

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

- Time dependent decay rate of **$D^0 \rightarrow$ f**: (|x|,|y| <<1)

$$\frac{dN_{D^0 \to f}}{dt} \propto |\langle f|\mathcal{H}|D^0(t)\rangle|^2 = e^{-\Gamma t}\left|\langle f|\mathcal{H}|D^0\rangle + \frac{q}{p}\left(\frac{y+ix}{2}\Gamma t\right)\langle f|\mathcal{H}|\overline{D}^0\rangle\right|^2$$

- Exponential decay modulates with mixing parameters x,y

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

$M_{1,2}$ and Γ_{12} are the masses and widths of mass eigenstates, respectively.

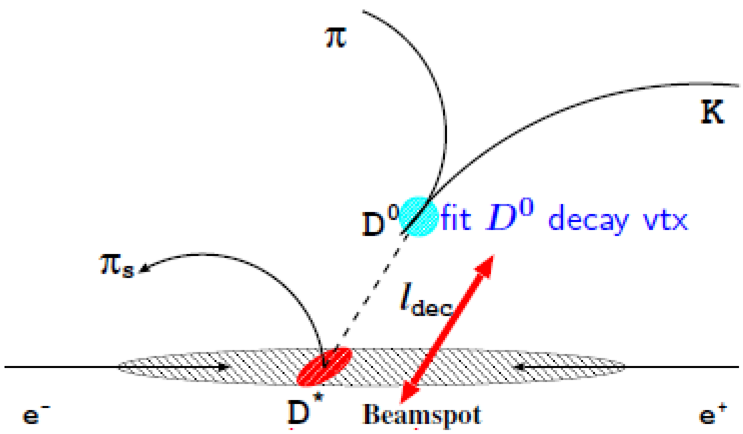
➢ x,y can be obtained from time-dependent decay rates studies

- Different final states sensitive to different combinations of x and y.

Experimental method

- Use D^0 from $D^{*+} \rightarrow D^0 \pi^+_s$
  - Tagging $\mathbf{D^0}$ flavor from π_s charge
  - Background suppression
- $\mathbf{D^0}$ proper decay time measurement

$$t = \frac{l_{dec}}{c\beta\gamma}, \quad \beta\gamma = \frac{p_{D^0}}{M_{D^0}}$$



- Reject D^{*+} from B decays:

$p^{CM}_{D^{*+}} \geq 2.5(3.1)\,\mathrm{GeV}$ for Y(4S) and Y(5S) data

- Observables

M: invariant mass of $\mathbf{D^0}$ daughters

$Q = M_{D^{*+}} - M - m_{\pi^+_s}$

- 3-layer SVD (SVD1) and 4-layer SVD (SVD2)

Decays to CP eigenstates $D^0 \to K^+K^-, \pi^+\pi^-$

- Measurement of lifetime difference btw. $D^0 \to K^- \pi^+$ and $D^0 \to K^+K^-, \pi^+\pi^-$
- Time distribution are exponential(CP conserved)
  - Mixing parameters
    $$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1$$
  - If CP conserved: $y_{CP} = y$
- If CP violated $\to$ difference in lifetime of $D^0/\overline{D^0} \to K^+K^-, \pi^+\pi^-$
  - Lifetime asymmetry:
    $$A_\Gamma = \frac{\tau(\overline{D}^0 \to K^-K^+) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^-K^+) + \tau(D^0 \to K^+K^-)}$$
- Relation with mixing and CP violating parameters

$$\begin{aligned} y_{CP} &= y\cos\phi - \tfrac{1}{2}A_M x \sin\phi \\ A_\Gamma &= \tfrac{1}{2}A_M y \cos\phi - x\sin\phi \end{aligned}$$

$$\phi = \arg\left(\frac{q}{p}\right)$$

$D^0 \to K^+K^-$, $\pi^+\pi^-$（updated with 976 fb-1）

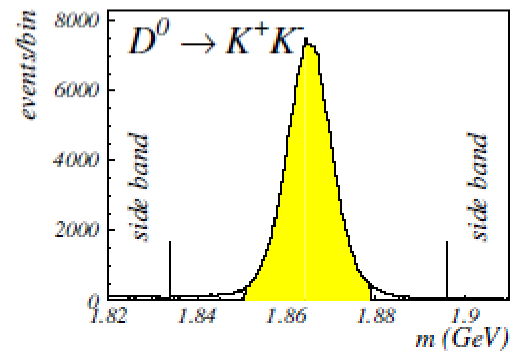
- Signal yield(purities)

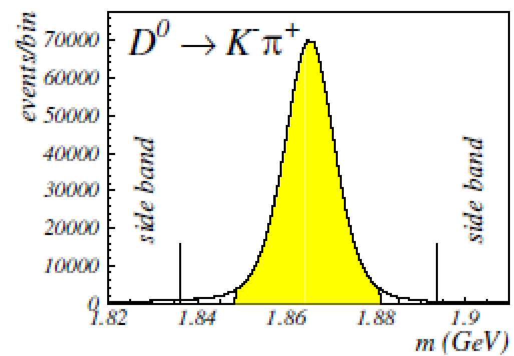
	KK	Kπ	ππ
Yield	242k	2.61M	114k
Purity	98.0%	99.7%	92.9%

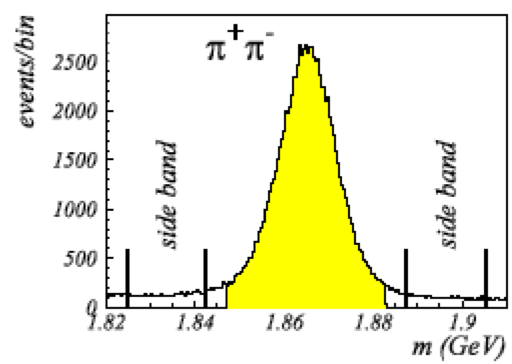
- Background estimated from sidebands
- Fitting Proper decay time distribution

$$f(t) = \frac{N}{\tau} \int e^{-t'/\tau(ycp, A_\Gamma)} R(t-t') + B(t)$$

- Resolution function for each bin of timing resolution (σ_t)
- PDF parameters determined in bins of ***D**$^{*+}$* polar angle in CMS (cos θ^*)
  - mean proper time of $\mathbf{D^0 \to K^- \pi^+}$ as a function of cos θ^*



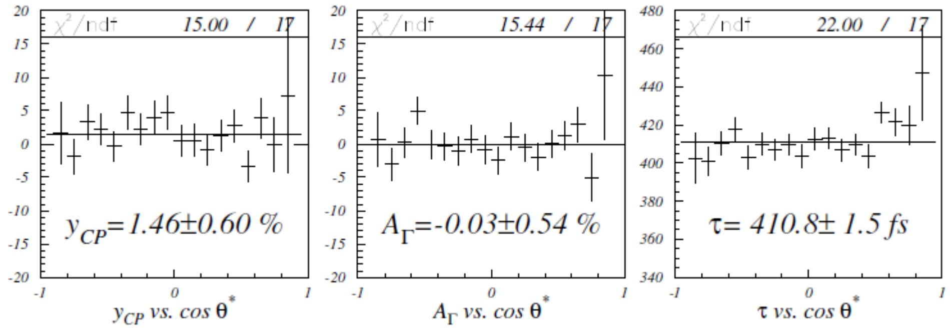




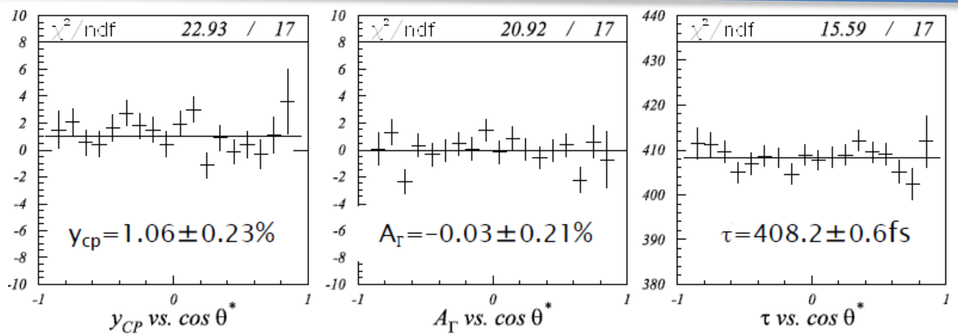
$D^0 \to K^+K^-, \pi^+\pi^-$ (updated with 976 fb-1)

Results (preliminary)

SVD 1



SVD 2



$$y_{CP} = (+1.11 \pm 0.22 \pm 0.11)\%$$
$$A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\%$$

- y_{CP} is at 4.5 σ from zero when both errors are combined and at 5.1 σ if only statistical error is considered.
- A_Γ is consistent with zero.

D^0 self-conjugated decays

- For D^0 3 body self-conjugated decays, Dalitz analysis can be performed:

  e.g. in $D^0 \to K_S\pi^+\pi^-$, decay amplitude : $\mathcal{A}(m_-^2, m_+^2)$

  where $m_-^2 \equiv m_{K_S^0\pi^-}, m_+^2 \equiv m_{K_S^0\pi^+}$

- In CP conservation assumption, $A = \overline{A}$ and $q/p = 1$
- Decay rate as function of time: $(\mathcal{A}_{1,2} = \frac{1}{2}(\mathcal{A} \pm \bar{\mathcal{A}}))$

$$\mathcal{M}(m_-^2, m_+^2, t) = \left\{|A_1|^2 e^{-yt} + |A_2|^2 e^{yt} + 2\mathcal{R}[A_1 A_2^*]\cos(xt) + 2\mathcal{I}[A_1 A_2^*]\sin(xt)\right\} e^{-t}$$

Simultaneous determination of x and y!

$D^0 \to K_S\pi^+\pi^-$ t-dependent Dalitz analysis

Event Reconstruction: $D^{*+} \to D^0\pi^+_s,\ D^0 \to K_S\pi^+\pi^-$

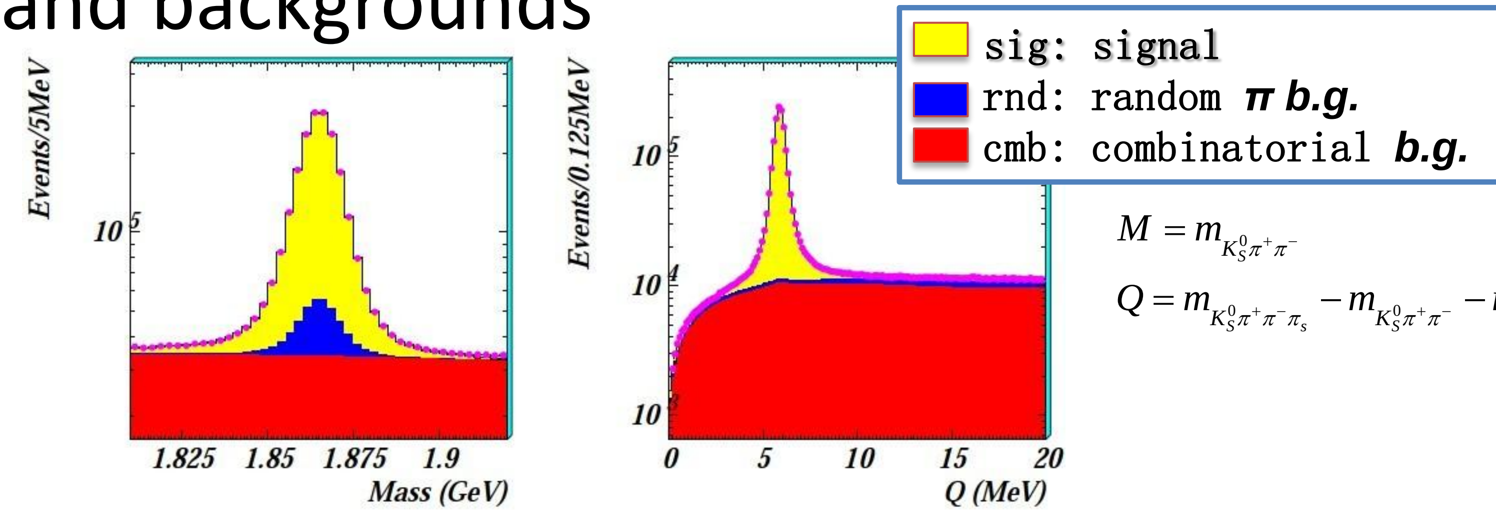
- K_S selection ($\pi^+\pi^-$ *final state*):
  - Common vertex separated from the interaction region.
  - $|M_{\pi^+\pi^-} - m_{K_S}| < 10$ MeV/c²
- For each π from D^0: at least 4 hits on SVD.
  - To improve decay vertex resolution
- Decay vertex :reconstructed with charged π tracks **only.**

Selection criteria:

- $\Sigma\,\chi^2 < 100$ (vertex fit constraint)
- $\sigma_t < 1000$ fs
  - half of D^0 life time on average

$D^0 \to K_S\pi^+\pi^-$ t-dependent Dalitz analysis

Signal and backgrounds



$$M = m_{K_S^0\pi^+\pi^-}$$

$$Q = m_{K_S^0\pi^+\pi^-\pi_s} - m_{K_S^0\pi^+\pi^-} - m_\pi$$

- Signal yield and purity:
  - ϒ(4S), ϒ(5S) full dataset, **920 fb^{-1}**

	Yield	Putiry
Signal	1.23M	95.6%

  - Compared with belle's 2007 analysis:

	Belle (2007)	New	Ratio
Luminosity(fb^{-1})	540	920	1.7
Signal yield	534K	1231K	2.3

improve efficiency from new reprocess with new tracking.

$D^0 \to K_S\pi^+\pi^-$ t-dependent Dalitz analysis

Unbinned time-dependent Dalitz fit

•The logarithm of the likelihood function:

$$2\ln\mathcal{L} = 2\sum_{i=1}^{n}\ln\left[f_{\rm sig}^{i}p_{\rm sig}(m_{-,i}^2, m_{+,i}^2) + f_{\rm rnd}^{i}p_{\rm rnd}(m_{-,i}^2, m_{+,i}^2) + f_{\rm cmb}^{i}p_{\rm cmb}(m_{-,i}^2, m_{+,i}^2)\right]$$

•The normalized signal PDF :

$$p_{\rm sig}(m_{-,i}^2, m_{+,i}^2, t_i) = \frac{\int_0^{+\infty} dt'\ R_{\rm sig}(t_i - t')|\mathcal{M}(m_{-,i}^2, m_{+,i}^2, t')|^2\epsilon(m_{-,i}^2, m_{+,i}^2)}{\int_0^{+\infty} dt \int_D dm_-^2 dm_+^2\ |\mathcal{M}(m_-^2, m_+^2, t)|^2\epsilon(m_-^2, m_+^2)}$$

•Event-by-event fraction $\boldsymbol{f^{i}_{x}}$ determined by 2D M-Q fit

•DP Efficiency function $\epsilon(m_-^2, m_+^2)$ estimated from MC, parameterized by 3rd order polynomial.

•Background estimated from sideband.

•Convolved by resolution function

$D^0 \rightarrow K_S\pi^+\pi^-$ t-dependent Dalitz analysis

Dalitz model:

$$\mathcal{A}(m_-^2, m_+^2) = B_{r\neq\ \mathrm{S-wave}} + K_{\pi\pi\ \mathrm{S-wave}} + L_{K\pi\ \mathrm{S-wave}}.$$

- **P,D wave : Breit Wigner model(12 resonances)**

$$B_{r\neq\ \mathrm{S-wave}} = \sum_{r\neq\ \mathrm{S-wave}} a_r e^{i\phi_r} \mathcal{A}_r(m_-^2, m_+^2)$$

- **$\pi^+\pi^-$ S wave: K-matrix model**

$$F_1(s) = \sum_j [I - iK(s)\rho(s)]_{1j}^{-1} P_j(s) .$$

- **K π S wave: LASS model**

$$T = \sin\delta_B e^{\delta_B} + \sin\delta_R e^{\delta_R} e^{2i\delta_B}$$

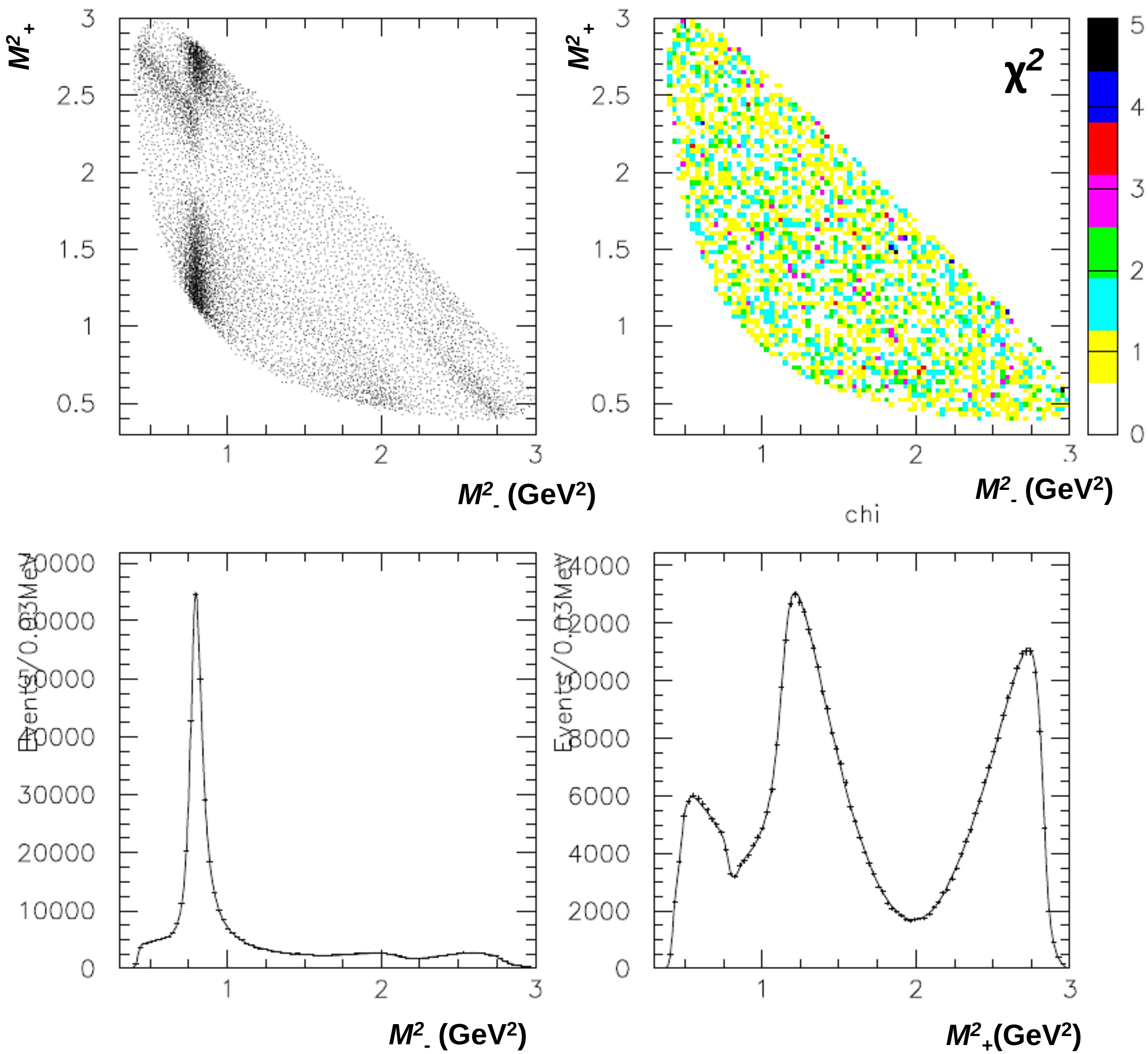
$$\tan\delta_R = \frac{m_R\Gamma(s)}{m_R^2 - m_{K\pi}^2}$$

$$\cot\delta_B = \frac{1}{ap} + \frac{rp}{2}$$

$D^0 \to K_S\pi^+\pi^-$ t-dependent Dalitz analysis

- DP projections of $D^0 \to K_S\pi^+\pi^-$ t-integrated Dalitz fit.
- Several DP models tested, the best description shown.

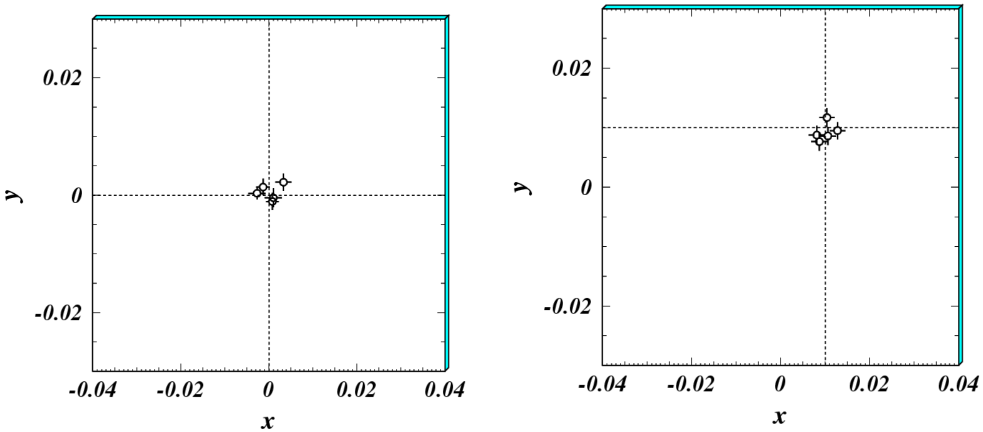
χ^2 **/ndf**= 1.246 for (3653-49) ndof



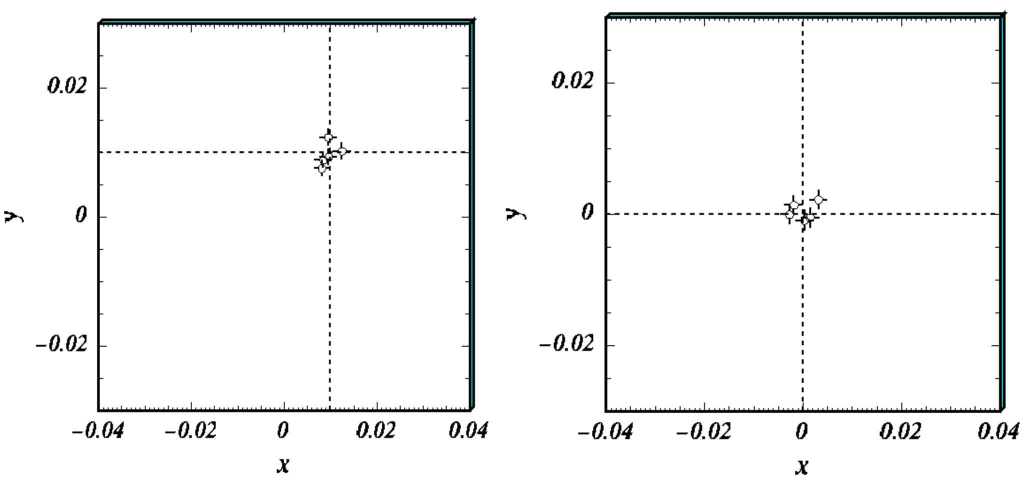
$D^0 \rightarrow K_s\pi^+\pi^-$ t-dependent Dalitz analysis

- The MC tests of t-dependent Dalitz fit

Pure signal MC tests



Background included MC tests



Background included fit results:

Input x,y(%)	Mean of outputs(%)
(0,0)	(0.023±0.078, 0. 049±0. 063)
(1,1)	(1.014±0.080, 0. 925±0.068)

x,y outputs consistent with true value.

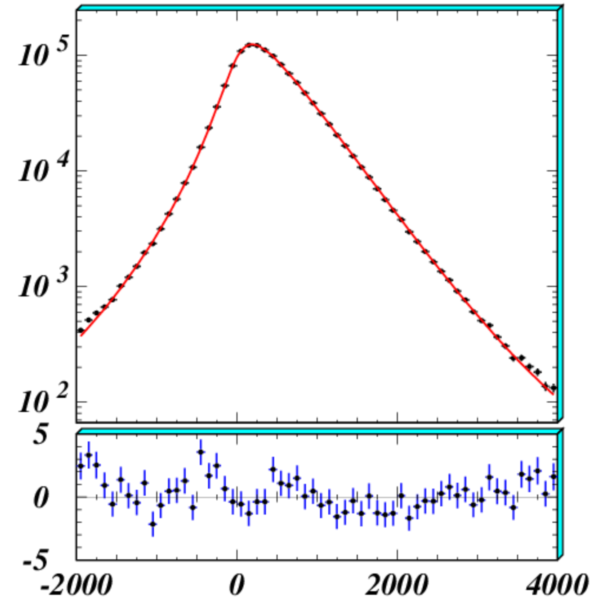
$D^0 \rightarrow K_S\pi^+\pi^-$ t-dependent Dalitz analysis

Results (preliminary):

- Result for the mixing parameters:

No CPV

	Fit result	95% C.L interval (stat. only)
X(%)	0.56 ± 0.19	(0.09,1.03)
Y(%)	0.30 ± 0.15	(-0.08,0.68)



χ2=97./60bins

- D^0 lifetime

  - τ=410.3 $\pm$ 0.4 fs
  - PDG Mean life $\tau = (410.1 \pm 1.5) \times 10^{-15}$ s

$D^0 \to K_s\pi^+\pi^-$ t-dependent Dalitz analysis

Systematics

Experimental Systematics

Source	$(\Delta x)(\times 10^{-4})$	$(\Delta y)(\times 10^{-4})$
Time resolution of signal	-1.39	-0.92
CMB t PDF(diff. sideband)	+1.74	+1.65
Error on CMB t parameters	$\pm$0.77	$\pm$1.57
BG Dalitz dep t	-4.76	-3.55
f_w float	-0.67	-0.45
Efficiency	-1.13	-2.09
Best Candidate selection	+1.05	+1.87
$K^*(892)$ DCS/CF reduced by 5%	-7.28	+2.29
$K_2^*(1430)$ DCS/CF reduced by 5%	+1.71	-0.67
Rnd N	$\pm$0.27	$\pm$0.13
CMB N	$\pm$0.13	$\pm$0.24
Total	${}^{+2.78}_{-8.94}$	${}^{+3.74}_{-4.58}$

Model Systematics

Fit model	$(\Delta x)(\times 10^{-4})$	$(\Delta y)(\times 10^{-4})$
$F_r = F_D = 1$	+4.05	+2.35
$\Gamma(q^2) =$ constant	+3.33	-1.61
No $K^*(1680)^+$	-1.78	-3.02
No $K^*(1410)\pm$	-1.16	-3.62
No $\rho(1450)$	+2.13	+0.30
K-matrix	-2.16	+1.79
Angular dependence	-8.46.	-3.86
M & Γ error	$\pm$1.40	$\pm$1.21
Total	${}^{+5.83}_{-9.09}$	${}^{+3.21}_{-6.42}$

Consistent with MC estimations.

Result (preliminary):

$$x = (0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09})\%, \; y = (0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06})\%$$

$D^0 \to K_S\pi^+\pi^-$ t-dependent Dalitz analysis

Result compared with previous analysis:

- Assuming CP conservation,

	x(%)	y(%)	
Belle 2007@540 fb^{-1}	$0.80 \pm 0.29^{+0.09+0.10}_{-0.07-0.14}$	$0.33 \pm 0.24^{+0.08+0.06}_{-0.12-0.08}$	*PRL. 99, 131803 (2007)*
Babar 2010	$0.16 \pm 0.23 \pm 0.12 \pm 0.08$	$0.57 \pm 0.20 \pm 0.13 \pm 0.07$	*PRL.105, 081803 (2010)*
	0.26 ± 0.24	0.60 ± 0.21	***$D^0 \to K_S\pi^+\pi^-$ (only)***
New@920 fb^{-1}	$0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09}$	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06}$	

Most precise determination of x,y to date.

Summary

- ***D⁰*** mixing measurements updated with full Belle data(**~ 1 ab⁻**)
  - $D^0 \to K^+K^-, \pi^+\pi^-$ lifetime difference measurement

$$y_{CP} = (+1.11 \pm 0.22 \pm 0.11)\% \qquad \text{4.5 σ from zero}$$

$$A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\% \qquad \text{No indirect CPV}$$

  - $D^0 \to K_S\pi^+\pi^-$ time-dependent DP analysis

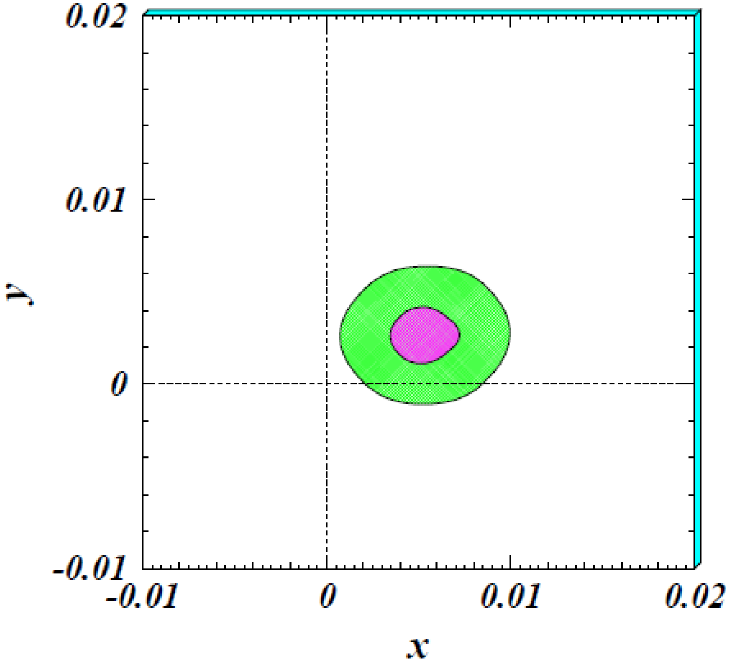
$$x = (0.56 \pm 0.19^{+0.03}_{-0.09}{}^{+0.06}_{-0.09})\%,\ y = (0.30 \pm 0.15^{+0.04}_{-0.05}{}^{+0.03}_{-0.06})\%$$

most precise measurements of x and y to date.

Backups

$D^0 \to K_S\pi^+\pi^-$ t-dependent Dalitz analysis

Results (preliminary):



Contours for 1 σ and 95% C.L.(statistical only)

	Fit result	95% C.L interval (stat. only)
X(%)	0.56±0.19	(0.09,1.03)
Y(%)	0.30±0.15	(-0.08,0.68)

Consistent with previous measurement.

$D^0 \to K_S\pi^+\pi^-$ DP model optimization

	P,D-wave	$\pi\pi$ S-wave	$K\pi$ S-wave	NR	-2Δlnς	χ2
Belle(2007)	BW(12Res.)	BW	BW	$a_{\mathrm{NR}}e^{i\phi_{\mathrm{NR}}}$	0(default)	1.758
Fit 2	BW(12)	K-matrix(I)	BW	0	620	1.776
Fit 3	BW(12)	K-matrix(II)	BW	0	261	
Fit 4	BW(12)	BW	LASS	0	-1707	
Fit 5	BW(12)	BW	LASS	$a_{\mathrm{NR}}e^{i\phi_{\mathrm{NR}}}$	-2021	1.252
Babar2010	BW(8)	K-matrix(II)	LASS	0	-1468	
Fit 7	BW(12)	K-matrix(II)	LASS	0	-1886	1.246

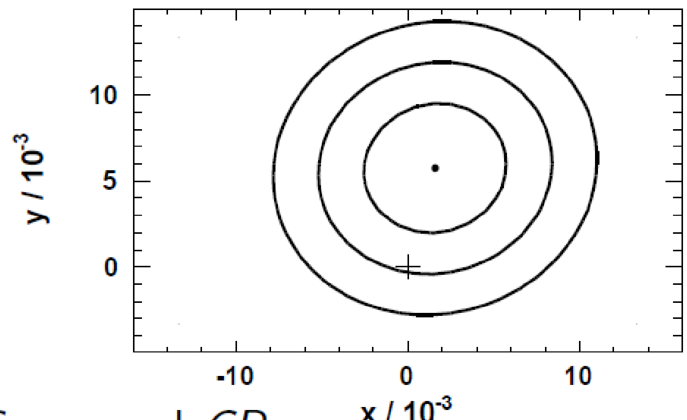
- For the ππ-S wave, BW and K-matrix model tested
- For the Kπ-S wave, BW and LASS model tested

Mixing and CPV in $D^0 \to K_S\pi^+\pi^-, D^0 \to K_S K^+ K^-$

BaBar@469 fb^{-1} [PRL105,081803]

$D^0 \to K_S^0\pi^+\pi^-$ and $D^0 \to K_S^0 K^+ K^-$

68%, 95% and 99.9% confidence level contours



Conserved CP symmetry ($|q/p| = 1$ & $\phi = 0$)

$$\mathbf{x = (0.16 \pm 0.23 \pm 0.14)\%}$$
$$\mathbf{y = (0.57 \pm 0.20 \pm 0.15)\%}$$

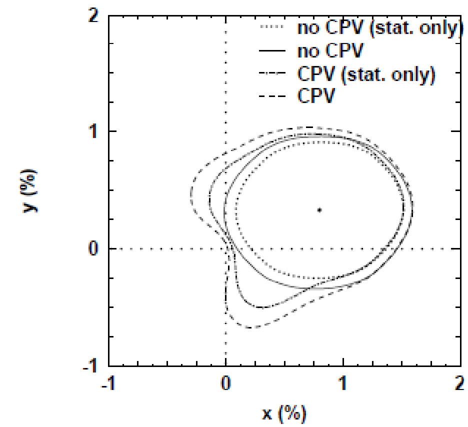
Most accurate determinations of x and y!

1.9 standard deviation from no-mixing hypothesis

Belle@540 fb^{-1} [PRL99,131803]

$D^0 \to K_S^0\pi^+\pi^-$

95% confidence level contours



Conserved CP symmetry ($|q/p| = 1$ & $\phi = 0$)

$$\mathbf{x = (0.80 \pm 0.29^{+0.13}_{-0.16})\%}$$
$$\mathbf{y = (0.33 \pm 0.24^{+0.10}_{-0.14})\%}$$

CPV allowed ($|q/p|$ & ϕ free parameters of the fit)

$$\mathbf{|q/p| = 0.86 \pm 0.30 \pm 0.09}$$
$$\mathbf{\phi = -0.24 \pm 0.30 \pm 0.09}$$

Consistent with no CPV!

2.2 standard deviation from no-mixing hypothesis