Relevance of $D^0\bar{D}^0$ threshold data for mixing and CPV measurements

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Workshop on Charm Physics at threshold
IHEP, Beijing 21-23 October 2011

Outline

- Introduction
- Mixing and CP violation measurements at the B Factories
- Sensitivity projections at SuperB
  - with 75 ab^{-1} of data at $\Upsilon(4S)$
  - with additional 500 fb^{-1} of $\psi(3770)$ data
- Possible approaches for improving sensitivity on mixing and CPV using threshold data:
  - model independent approaches
  - time-dependent measurements at threshold
- Summary

Introduction

- Flavor mixing occurs when flavor eigenstates differ from mass eigenstates: well established phenomena in neutral K, B_d, B_s systems.

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

- Mixing parameters are expressed in terms of *x*, *y* parameters, proportional to the mass and decay width differences of the mass eigenstates:

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

Three types of CP violation

$$\langle f|H|D^0\rangle = A_f \qquad \langle f|H|\overline{D}^0\rangle = \overline{A}_f$$

1. in the decay (direct):

$$\boxed{\left|\frac{\overline{A}_{\overline{f}}}{A_f}\right| \neq 1} \quad \Longrightarrow \quad \text{CPV}$$

2. in mixing (indirect):

$$r_m = \boxed{\left|\frac{q}{p}\right| \neq 1} \quad \Longrightarrow \quad \text{CPV}$$

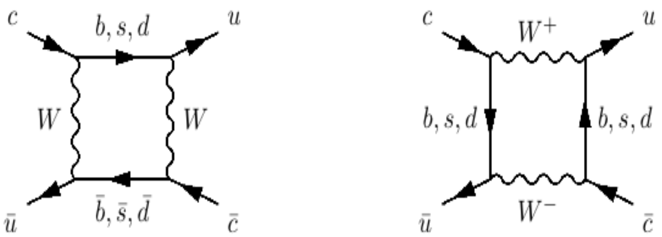
3. in the interference between mixing and decay:

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f} = r_m \left|\frac{\overline{A}_f}{A_f}\right| e^{i(\delta_f + \varphi_f)} \qquad \boxed{\varphi_f \neq 0} \quad \Longrightarrow \quad \text{CPV}$$

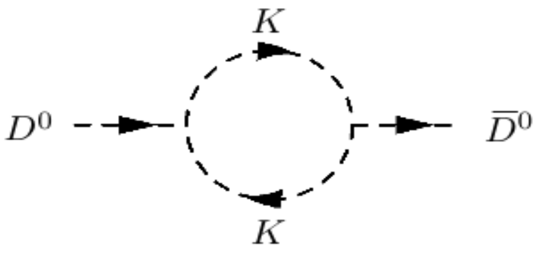
strong phase　weak phase

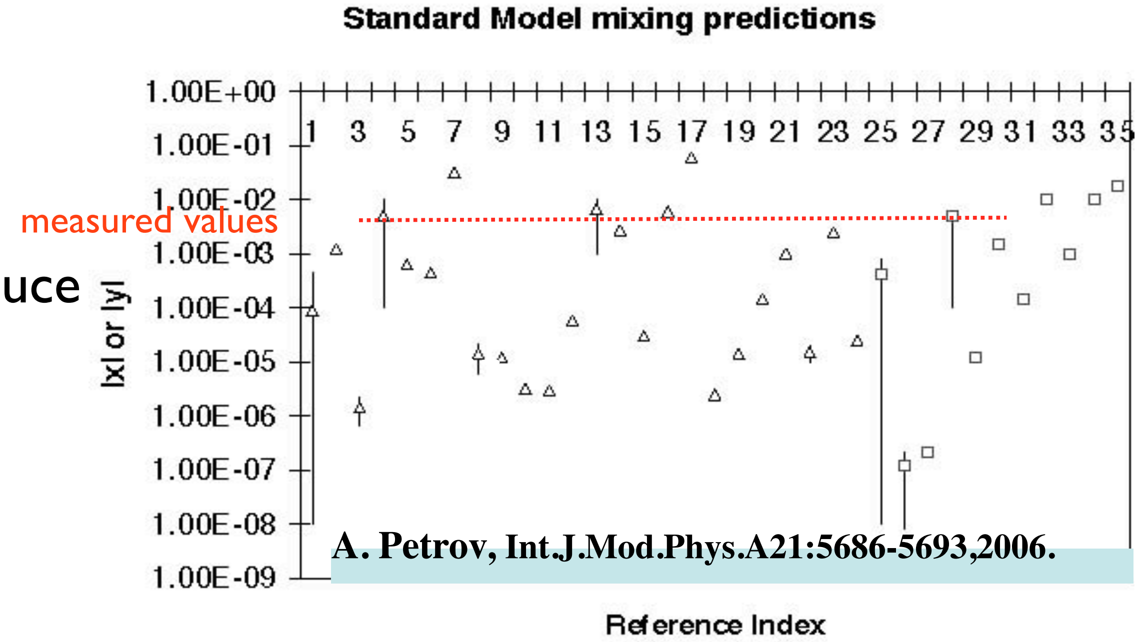
Standard Model predictions

- Short-distance contributions $|\Delta F_{charm}=2|$ from mixing box diagrams in the Standard Model are expected to be small :
  - *b* quark is CKM-suppressed;
  - *s* and *d* quarks are GIM suppressed;



- Long-distance contributions (via $|\Delta F_{charm}=1|$ interactions) expected to dominate, still small effect, hard to estimate precisely.

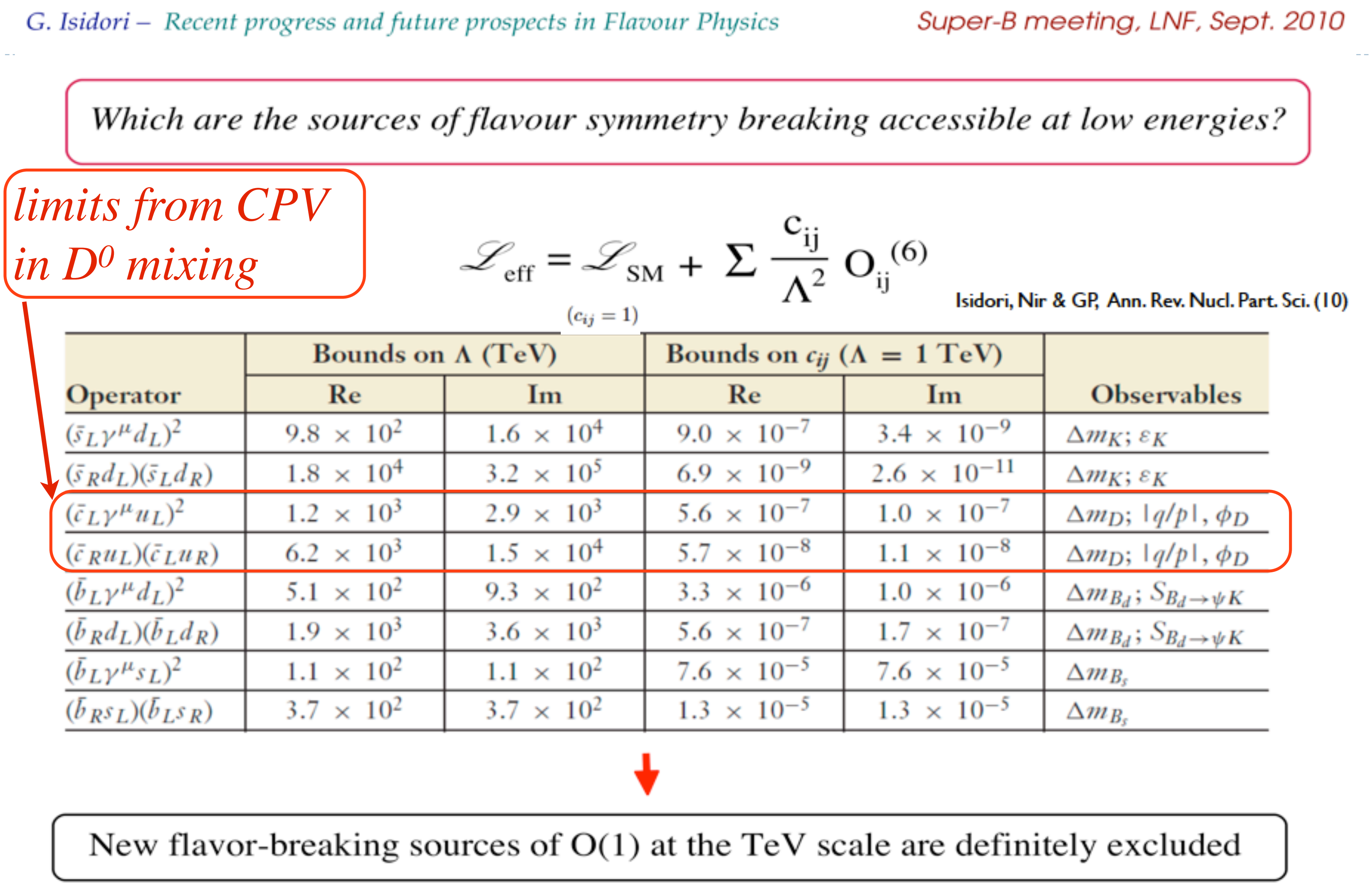




A. Petrov, Int.J.Mod.Phys.A21:5686-5693,2006.

- New Physics (NP) could introduce new particles in loops, enhancing mixing effects.

- Large CP violation would be a sign of new physics.



G. Isidori – *Recent progress and future prospects in Flavour Physics*

Super-B meeting, LNF, Sept. 2010

Which are the sources of flavour symmetry breaking accessible at low energies?

limits from CPV in D^0 mixing

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \sum \frac{c_{ij}}{\Lambda^2} O_{ij}^{(6)}$$

Isidori, Nir & GP, Ann. Rev. Nucl. Part. Sci. (10)

($c_{ij} = 1$)

	Bounds on Λ (TeV)		Bounds on c_{ij} (Λ = 1 TeV)		
Operator	Re	Im	Re	Im	Observables
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ε_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ε_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert, \phi_D$
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2	1.1×10^2	7.6×10^{-5}	7.6×10^{-5}	Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2	3.7×10^2	1.3×10^{-5}	1.3×10^{-5}	Δm_{B_s}

New flavor-breaking sources of O(1) at the TeV scale are definitely excluded

Mixing and CPV analyses at the B Factories

Time-dependent analyses

		Note:
$D^0 \to K^+\pi^-$	★ BELLE ★ CDF	*Mixing (x',y') and CPV*
$D^0 \to K^+K^-, \pi^+\pi^-$	★ ★ BELLE	*Mixing (y_{CP}) and CPV*
$D^0 \to K^+\pi^-\pi^0$	★	*Dalitz plot analysis. Mixing (x",y") and CPV*
$D^0 \to K^0_S\pi^+\pi^-$	BELLE	*Dalitz plot analyses. Mixing (x,y) and indirect CPV (|q/p|, φ)*
$D^0 \to K^0_S K^+K^-$		
$D^0 \to K^0_S\phi$	BELLE	*Mixing (y_{CP})*

In time-dependent analyses we can distinguish the three different contributions to CP violation: decay, mixing and interference between mixing and decay.

Legend: ★ = mixing evidence $> 3\sigma$

Time-integrated analyses

		Note:
$D^0 \rightarrow K^+K^-, \pi^+\pi^-$		*Search for CPV*
$D^0 \rightarrow \pi^+\pi^-\pi^0$		*Search for CPV (phase space integrated and in Dalitz plot regions)*
$D^0 \rightarrow K^+K^-\pi^0$		*Search for CPV*
$D^0 \rightarrow K^+K^-\pi^+\pi^-$		*Search for CP violation using T-odd correlations (assuming CPT conserved)*
$D^0 \rightarrow K_S^0\pi^0, K_S^0\eta, K_S^0\eta'$		*Search for CPV*
$D^0 \rightarrow K^+\pi^-\pi^0, K^+\pi^-\pi^+\pi^-$		*Search for CPV*
$D^0 \rightarrow K^{(*)}l\nu$		*Mixing (x^2+y^2)*

In time-integrated analyses we cannot trivially distinguish among the three different contributions to CP violation.

Mixing and CPV measurements at B factories

- Here I will report only few examples among the most significant measurements for mixing and CP violation performed at BaBar:
  - $D^0 \rightarrow K^+\pi^-$ WS - Pro: in wrong sign (WS) decays the effect of mixing is a relatively large effect, evidence for mixing at 3.9σ level. Cons: not possible to determine the mixing parameters x, y without external input for $\delta_{K\pi}$;
  - $D^0 \rightarrow K_S\pi^+\pi^-, K_SK^+K^-$ - Pro: direct measurement of x and y. Cons: Dalitz model dependent approach. Assumptions: CP conservation in the decay, neglecting CP violation in the $K^0 - \bar{K}^0$ mixing;
  - $D^0 \rightarrow K^+\pi^-\pi^0$ WS - Pro: evidence for mixing at 3.2σ level. Cons: Dalitz model dependent approach, not possible to determine the mixing parameters x, y directly.

At SuperB we should aim for model independent measurement without any CP conservation assumption.

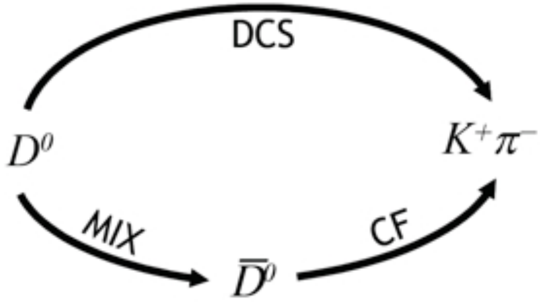
First evidence for D^0-$\bar{D}^0$ mixing in wrong sign $D^0 \to K^+\pi^-$ decays

***Phys. Rev. Lett.* 98:211802,2007** *(384 fb^{-1})*

- Wrong Sign (WS) final states from 2 sources: via double-Cabibbo-suppressed (DCS) decays or via mixing followed by Cabibbo-favored (CF) decays.

Time evolution $(|x| \ll 1, |y| \ll 1)$:

$$\frac{dN_{WS}}{dt} \propto e^{-\Gamma t}\left(\underbrace{R_D}_{\substack{\text{DCS}\\ 0.05\times 0.05}} + \underbrace{y'\sqrt{R_D}(\Gamma t)}_{\substack{\text{Interference}\\ 0.01\times 0.05}} + \underbrace{\frac{x'^2+y'^2}{4}(\Gamma t)^2}_{\text{Mixing}}\right)$$



$$R_D = \frac{\mathrm{B}(D^0 \to K^+\pi^-)}{\mathrm{B}(D^0 \to K^-\pi^+)} \simeq 3\cdot 10^{-3}$$

phase between D^0 and $\bar{D}^0$ decays not directly measurable at B Factories

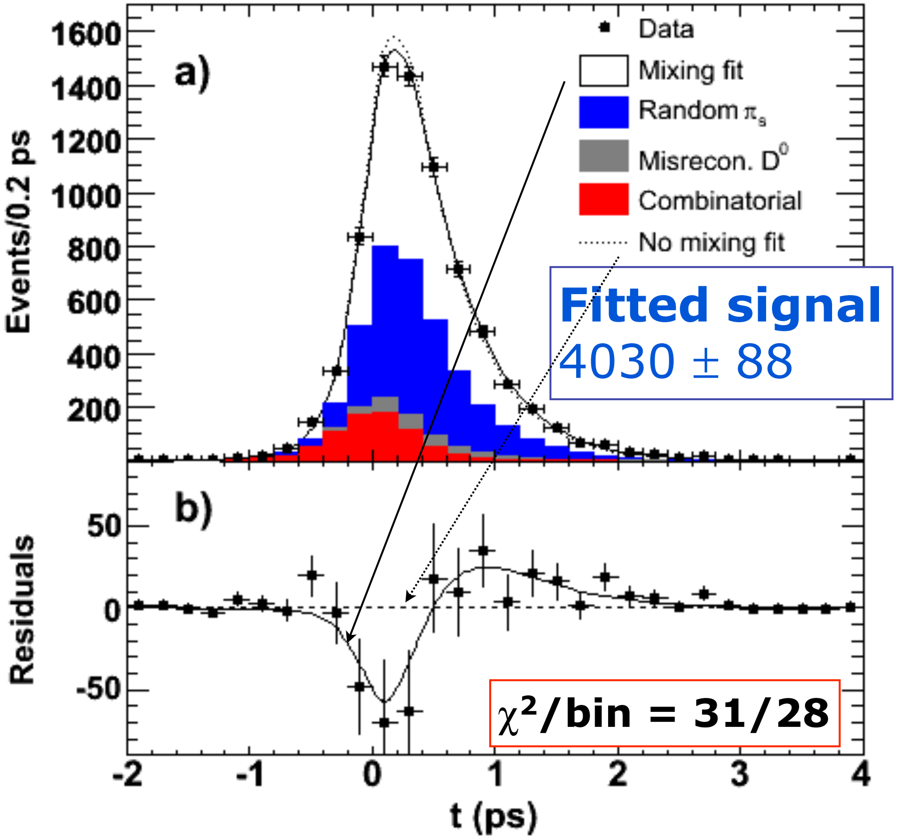
$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$$

$$y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi}$$

Analysis of the proper time distribution of WS events permits extraction of D^0 mixing parameters y', x'^{2}.

WS time fit: evidence of mixing at 3.9σ

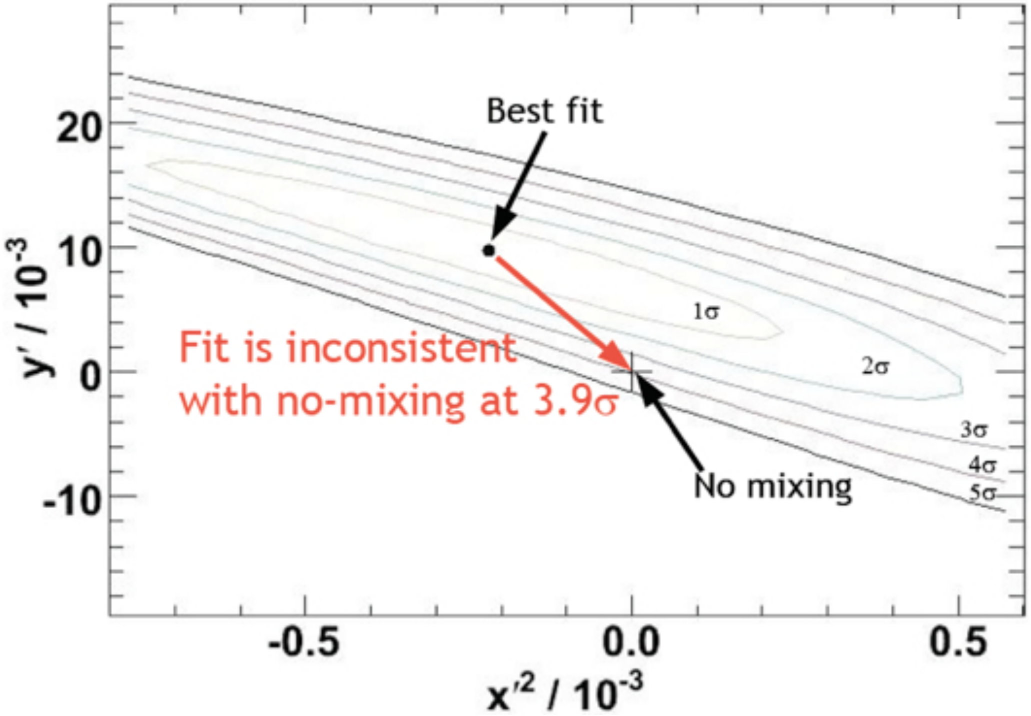
Phys. Rev. Lett. 98:211802,2007 (384 fb^{-1})



Fitted signal
4030 ± 88

χ^2/bin = 31/28

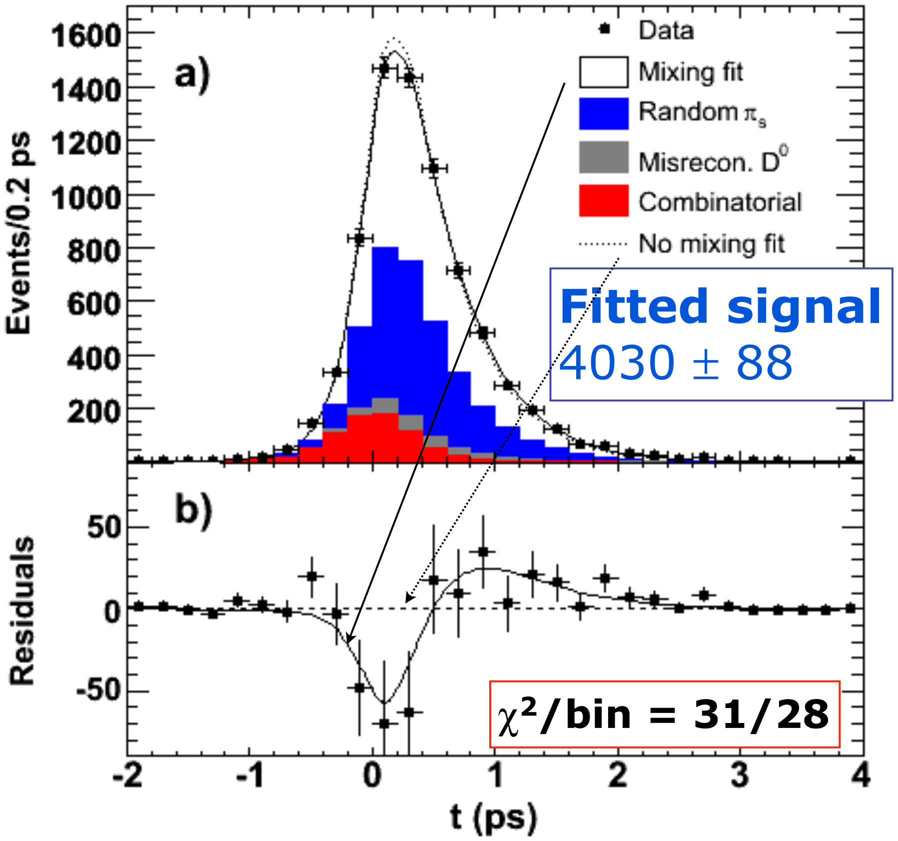
No CP violation fit



Fit is inconsistent with no-mixing at 3.9σ

WS time fit: evidence of mixing at 3.9σ

Phys. Rev. Lett. 98:211802,2007 *(384 fb^{-1})*



Fitted signal
4030 ± 88

χ^2/bin = 31/28

Results from different fits

Fit type	Parameter	Fit Results ($/10^{-3}$)
No *CP* viol. or mixing	R_D	$3.53 \pm 0.08 \pm 0.04$
No *CP* violation	R_D	$3.03 \pm 0.16 \pm 0.10$
	x'^2	$-0.22 \pm 0.30 \pm 0.21$
	y'	$9.7 \pm 4.4 \pm 3.1$
CP violation allowed	R_D	$3.03 \pm 0.16 \pm 0.10$
	A_D	$-21 \pm 52 \pm 15$
	x'^{2+}	$-0.24 \pm 0.43 \pm 0.30$
	y'^+	$9.8 \pm 6.4 \pm 4.5$
	x'^{2-}	$-0.20 \pm 0.41 \pm 0.29$
	y'^-	$9.6 \pm 6.1 \pm 4.3$

Fit separately D^0 (+) and $\overline{D}^0$ (-):

$$T^{\pm}_{WS}(t) = e^{-\Gamma t}\left(R^{\pm}_D + \sqrt{R^{\pm}_D} y'^{\pm}\,\Gamma t + \frac{x'^{\pm 2} + y'^{\pm 2}}{4}(\Gamma t)^2\right)$$

$$\boxed{A_D = \frac{R^+_D - R^-_D}{R^+_D + R^-_D}} \qquad R_D = \sqrt{R^+_D R^-_D}$$

Sensitive to CP violation in mixing and decay.

No evidence for CP violation was found.

Study event distribution as a function of Dalitz plot position and time

$$\frac{dN_f(s_{12},s_{13},t)}{ds_{12}ds_{13}dt} \propto e^{-\Gamma t}\left\{|A_f|^2 + \left[y\underbrace{\boxed{\mathrm{Re}(A_f^*\bar{A}_f)}}-x\underbrace{\boxed{\mathrm{Im}(A_f^*\bar{A}_f)}}\right](\Gamma t) + \frac{x^2+y^2}{4}(\Gamma t)^2|\bar{A}_f|^2\right\}$$

Model dependent approach. Requires parameterization of the D^0 decay amplitude in the Dalitz plot.

$A_f = A(s_{12}, s_{13})$ $\quad \bar{A}_f = \bar{A}(s_{12}, s_{13})$ and $(s_{12}, s_{13}) = \text{Dalitz plot location}$

- if f and $\bar{f}$ belong to the same Dalitz plot $\boxed{\text{(e.g. } K_S^0\pi^+\pi^-)}$ by $\boxed{\text{assuming CP conservation}}$ in decay $(\bar{A}_f = A_{\bar{f}})$ is possible to extract directly x, y mixing parameters, without $D^0 - \overline{D}^0$ relative strong phase uncertainty.

Method pioneered by CLEO Collaboration: D.Asner *et. al. Phys.Rev.D72:012001,2005*.

- if f and $\bar{f}$ do not belong to the same Dalitz plot $\boxed{\text{(e.g } K^+\pi^-\pi^0)}$ the relative strong phase is not directly measurable at B Factories and we can extract effective mixing parameters, as for example:

$$\boxed{x'' = x\cos\delta_{K\pi\pi^0} + y\sin\delta_{K\pi\pi^0} \qquad y'' = -x\sin\delta_{K\pi\pi^0} + y\cos\delta_{K\pi\pi^0}}$$

$$\delta_{K\pi\pi^0} = \arg\left(\frac{A(D^0 \to K^+\rho^-)}{A(\overline{D}^0 \to K^+\rho^-)}\right)$$

Method pioneered by BaBar Collaboration: *Phys.Rev.Lett.103:211801,2009*

$D^0(t)\to K^+\pi^-\pi^0$ (WS) mixing fit

Phys. Rev. Lett. 103:211801,2009 ($384\ \mathrm{fb}^{-1}$)

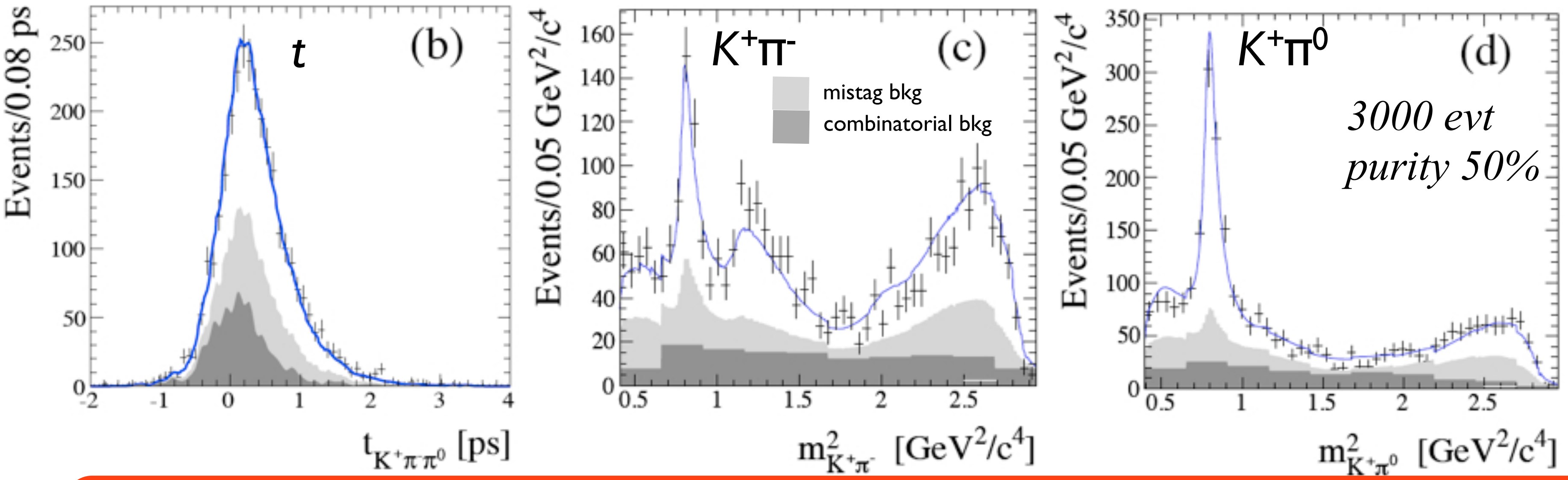
The *WS time-evolution* *function contains both* *DCS* (A_f) *and* *CF* *amplitudes* $(\bar{A}_f)$.
The *CF amplitudes* *are determined in a time-independent Dalitz plot fit to the* *RS sample* *(~660K evt) and* *fixed in the WS time-dependent Dalitz plot mixing fit* *(~3000 evt).*

DCS=Doubly Cabibbo Suppressed
WS = Wrong Sign, $D^0 \to K^+\pi^-\pi^0$

CF = Cabibbo Favored
RS = Right Sign, $D^0 \to K^-\pi^+\pi^0$

Dalitz plot model:

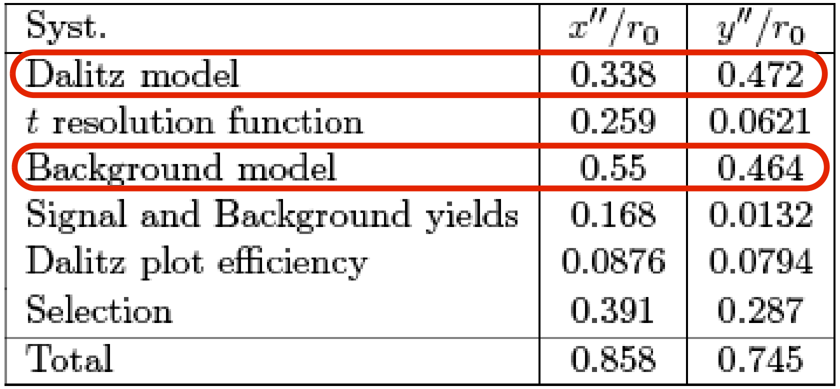
Use Breit-Wigner functions for DCS and CF D^0 decay amplitudes. ***D. Aston et al., Nucl. Phys. B 296, 493 (1988);***
$K\pi$ S-wave amplitude use BW together with effective range non-resonant component.



$$x'' = \left[2.61^{+0.57}_{-0.68}(\text{stat.}) \pm 0.39(\text{syst.})\right]\ \% \qquad y'' = \left[-0.06^{+0.55}_{-0.64}(\text{stat.}) \pm 0.34(\text{syst.})\right]\ \%$$

Evidence for mixing at 3.2σ level. No evidence for CPV.

$D^0(t)\to K^+\pi^-\pi^0$ (WS): systematic errors



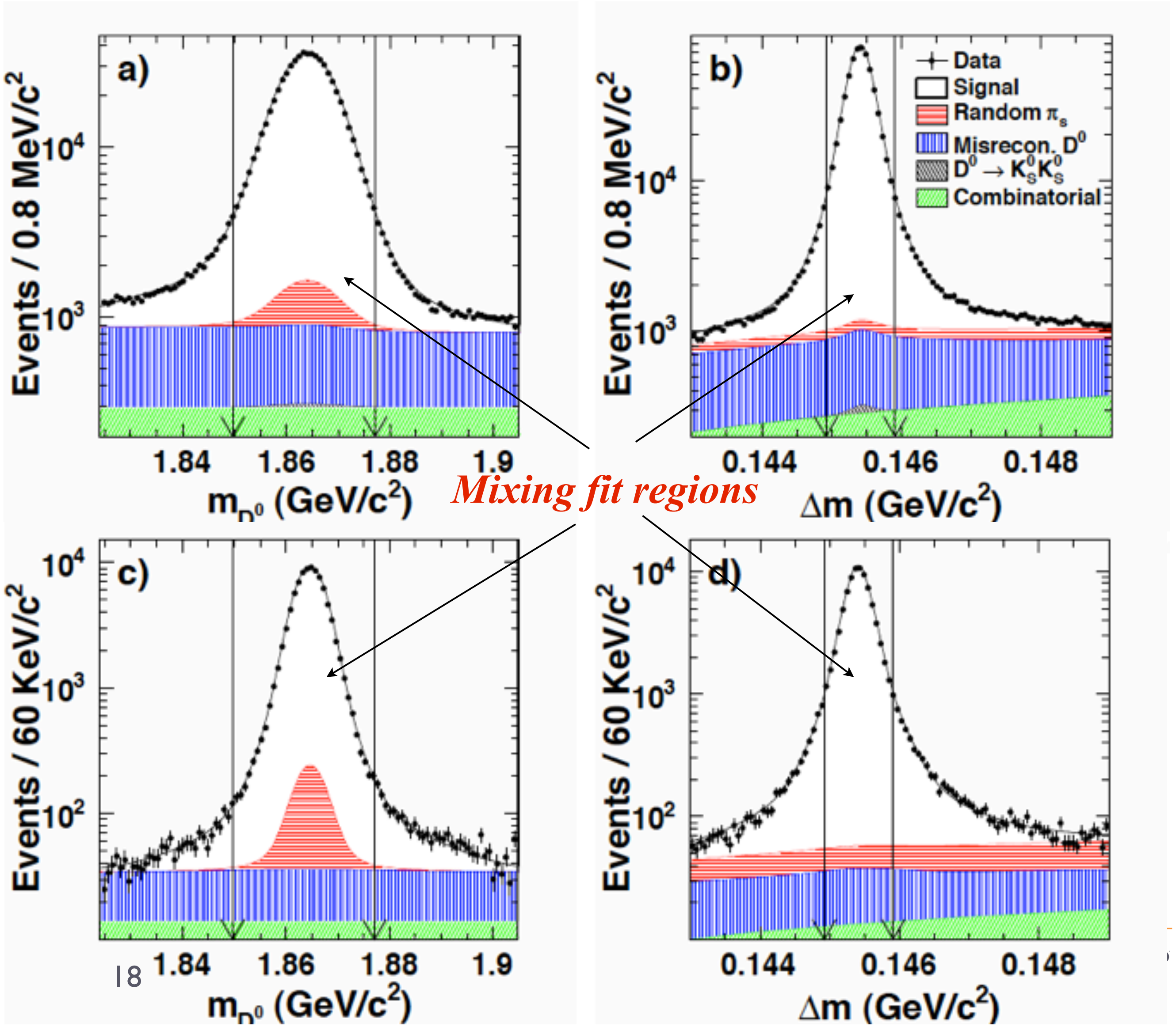
Syst.	x''/r_0	y''/r_0
Dalitz model	0.338	0.472
t resolution function	0.259	0.0621
Background model	0.55	0.464
Signal and Background yields	0.168	0.0132
Dalitz plot efficiency	0.0876	0.0794
Selection	0.391	0.287
Total	0.858	0.745

Dalitz plot model and background model uncertainties represent the most relevant systematic errors for mixing parameters at B factories.

$D^0(t)\rightarrow K_S\pi^+\pi^-$ + $K_SK^+K^-$ analysis

Phys. Rev. Lett. 105, 081803 (2010) 468.5 fb^{-1} data

- Select $D^{*+}\rightarrow D^0\pi^+$ events with high purity



Mixing fit regions

$K_S\pi^+\pi^-$

N_{sig}= (540.8±0.8)x10^3
Purity= 98.5%

$K_SK^+K^-$

N_{sig}= (79.9±0.3)x10^3
Purity= 99.2%

Mixing time-dependent Dalitz plot fit

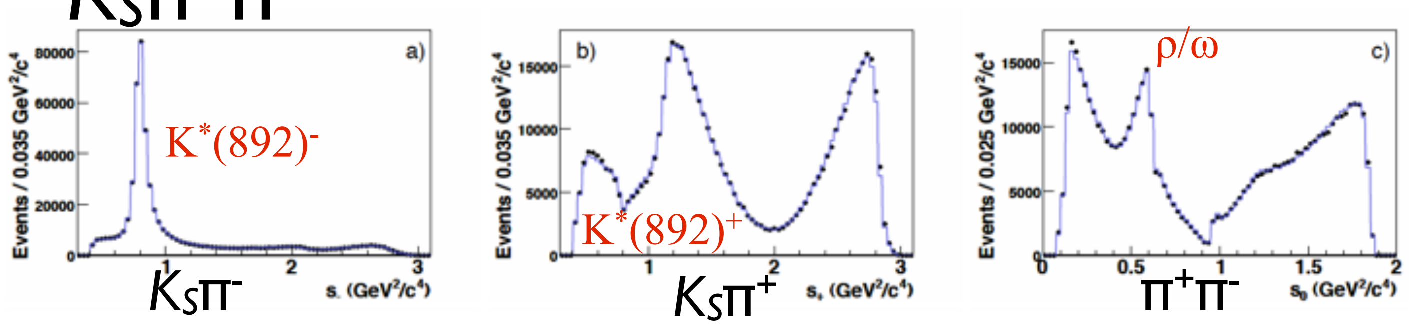
D^0 decay amplitude phenomenological parameterization:

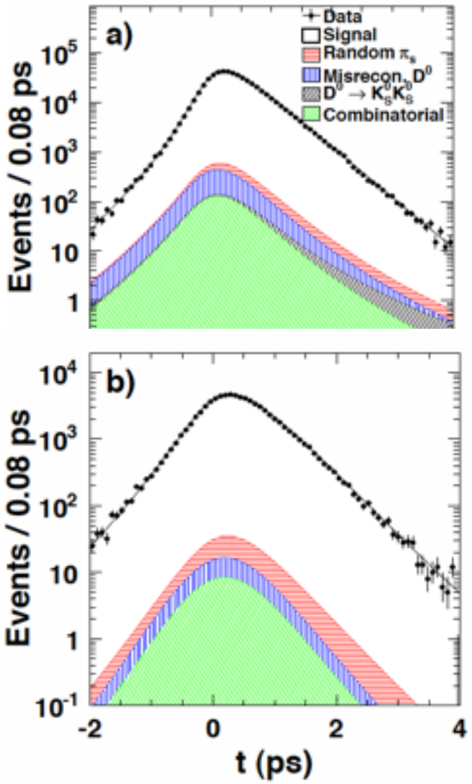
- for P- and D-wave amplitudes use Breit-Wigner (BW) model
- $\pi^+\pi^-$ S-wave dynamics use K-matrix formalism *V. V. Anisovich, A. V. Sarantsev, Eur. Phys. J. A 16 (2003) 229*
- $K\pi$ S-wave amplitude use BW with coherent non-resonant contribution *D. Aston et al., Nucl. Phys. B 296, 493 (1988); W. Dunwoodie, private communication.*
- K^+K^- S-wave use a coupled-channel BW for the $a_0(980)$ contribution.

$K_S\pi^+\pi^-$. DCS: $K^*(892)^+$, $K^*_0(1430)^+$, $K^*_2(1430)^+$.
CP eigenstates: $K_S\rho^0$ (CP=-1)

$K_SK^+K^-$. CP eigenstates: $K_S\phi$ (CP=-1), $K_Sa_0(980)$ (CP=+1).

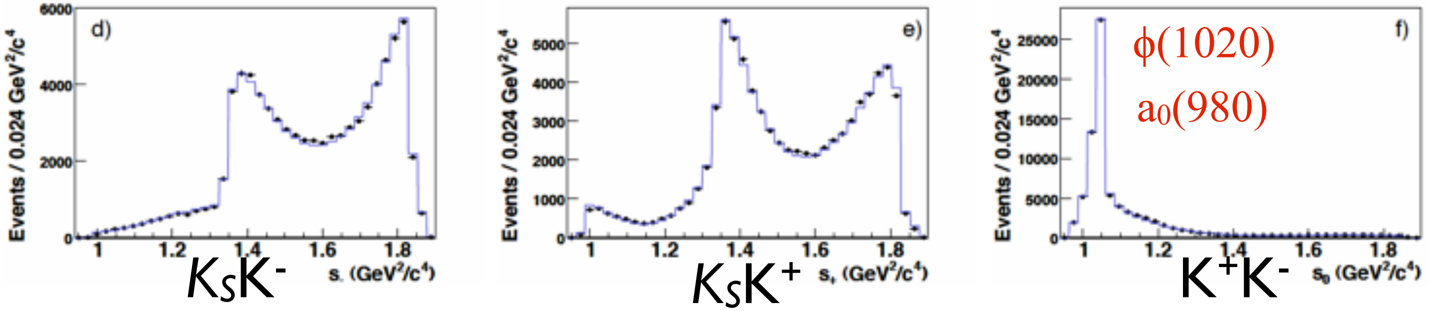
$K_S\pi^+\pi^-$





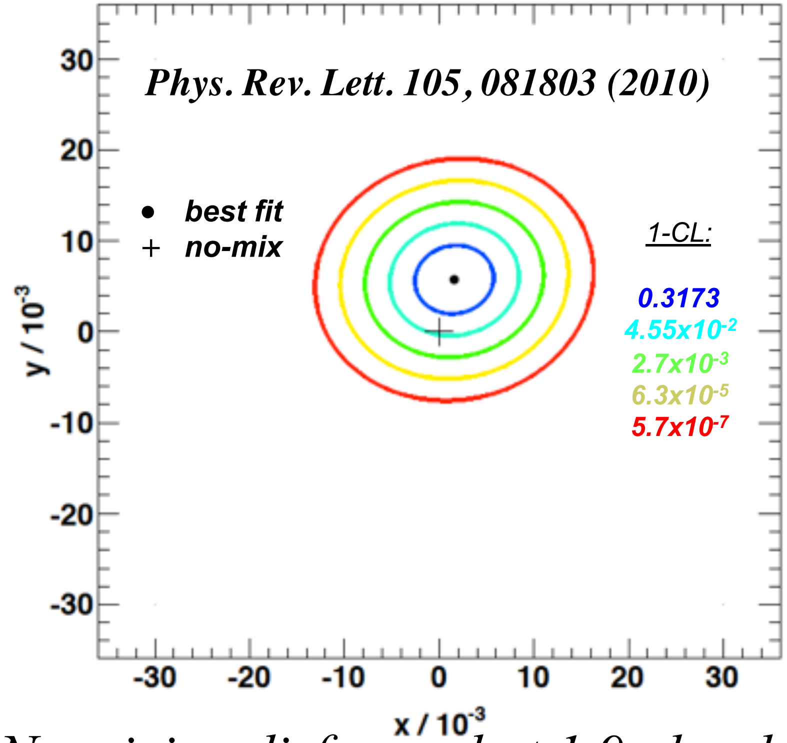
$K_SK^+K^-$

$$\chi^2/ndof = 1.28 \text{ with } (1195\text{-}17) \text{ ndof}$$



Mixing fit results

Combined $K_S\pi^+\pi^-$ + $K_SK^+K^-$ fit



No mixing disfavored at 1.9σ level

Experimental systematics

Source	$x[\%]$	$y[\%]$
SVT misalignment	0.0279	0.0826
Fit bias	0.0745	0.0662
Charge-flavor correlation (mistagging)	0.0487	0.0398
Event selection	0.0395	0.0508
Efficiency map	0.0367	0.0175
Background Dalitz-plot distribution	0.0331	0.0142
D^0 mass window	0.0250	0.0250
Proper lifetime PDF	0.0134	0.0128
Signal and background yields	0.0109	0.0069
Mixing in background	0.0103	0.0082
Dalitz-plot normalization	0.0106	0.0053
Proper lifetime error PDF	0.0058	0.0087
Experimental systematics	0.1177	0.1302

D^0 decay amplitude model systematics

Dominated by uncertainty on K*(892), K-matrix, Kπ Lass parameters	0.0678	0.0532
Total	0.0830	0.0685

Combined $K_S\pi^+\pi^-$ + $K_SK^+K^-$ fit results assuming CP conservation:

$$x = [0.16 \pm 0.23(\text{stat.}) \pm 0.12(\text{syst.}) \pm 0.08(\text{model})]\,\%$$

$$y = [0.57 \pm 0.20(\text{stat.}) \pm 0.13(\text{syst.}) \pm 0.07(\text{model})]\,\%$$

Mixing and CPV: sensitivity projections at SuperB

Based on material found in the
SuperB Progress Report: Physics
arXiv:1008.1541v1 (August 2010)

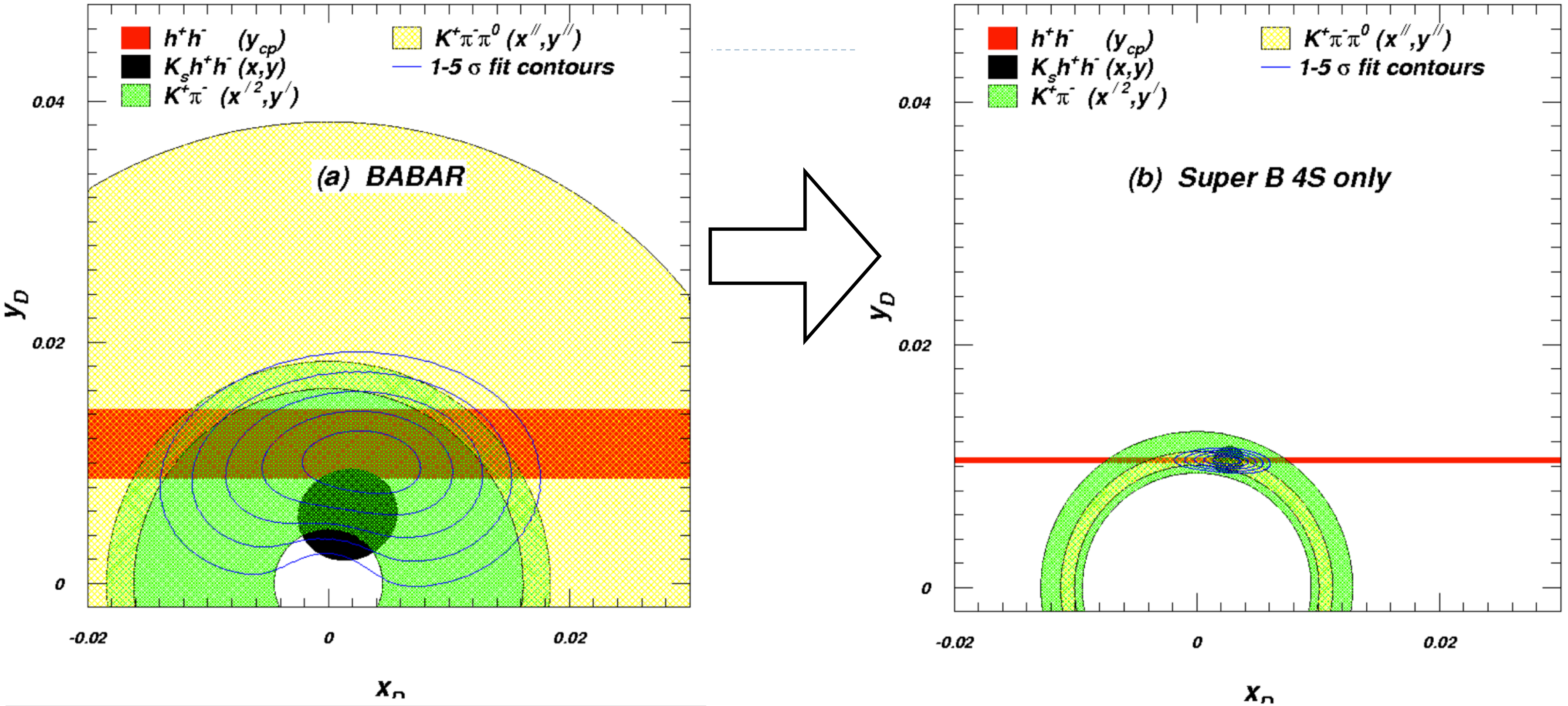
Sensitivity projections for mixing

- ✓ Realistic estimates using BaBar's results with 482 fb^{-1} of data at $\Upsilon(4S)$ and projecting to 75 ab^{-1}.
- ✓ Statistical error scales as $\sqrt{\text{integrated luminosity}}$.

- ✓ Same for systematic errors:
  - mostly determined directly from data and control samples.
  - Except for:

$D^0 \rightarrow K_S\pi^+\pi^-$ analysis has "irreducible" uncertainty in x_D and in y_D of order 1×10^{-3} due to uncertainty in Dalitz model.

Sensitivity projections with 75 ab^{-1} at $\Upsilon(4S)$



Fit	$x\times10^3$	$y\times10^3$	$\delta^{\circ}_{K^+\pi^-}$	$\delta^{\circ}_{K^+\pi^-\pi^0}$
(a)	$3.01\boxed{^{+3.12}_{-3.39}}$	$10.10\boxed{^{+1.69}_{-1.72}}$	$41.3^{+22.0}_{-24.0}$	43.8 ± 26.4
Stat.	(2.76)	(1.36)	(18.8)	(22.4)

Fit	$x\times10^3$	$y\times10^3$	$\delta^{\circ}_{K^+\pi^-}$	$\delta^{\circ}_{K^+\pi^-\pi^0}$
(b)	$xxx\boxed{^{+0.72}_{-0.75}}$	$xxx\boxed{\pm0.19}$	$xxx^{+3.7}_{-3.4}$	$xxx^{+4.6}_{-4.5}$
Stat.	(0.18)	(0.11)	(1.3)	(2.9)

Uncertainties shrink:

$x_D \rightarrow x_D/4$; $y_D \rightarrow y_D/10$

Precision in x_D is limited by Dalitz plot model.

Using $D\bar{D}$ threshold data

✓ Data taken at $D\bar{D}$ threshold provide measurements of strong phases $\delta_{K\pi}$ and $\delta_{K\pi\pi0}$.

✓ Also provide measurement of δ as a function of Dalitz plot position:

- this can be used to significantly reduce the Dalitz model uncertainties for the three-body decay modes Ksh^+h^-.

✓ As a basis for projection, we take results from CLEO-c:

-N. Lowrey et al, PRD80, 031105 (2009), 0903.4853

-D. M. Asner et al., Phys. Rev. D78, 012001(2008), 0802.2268.

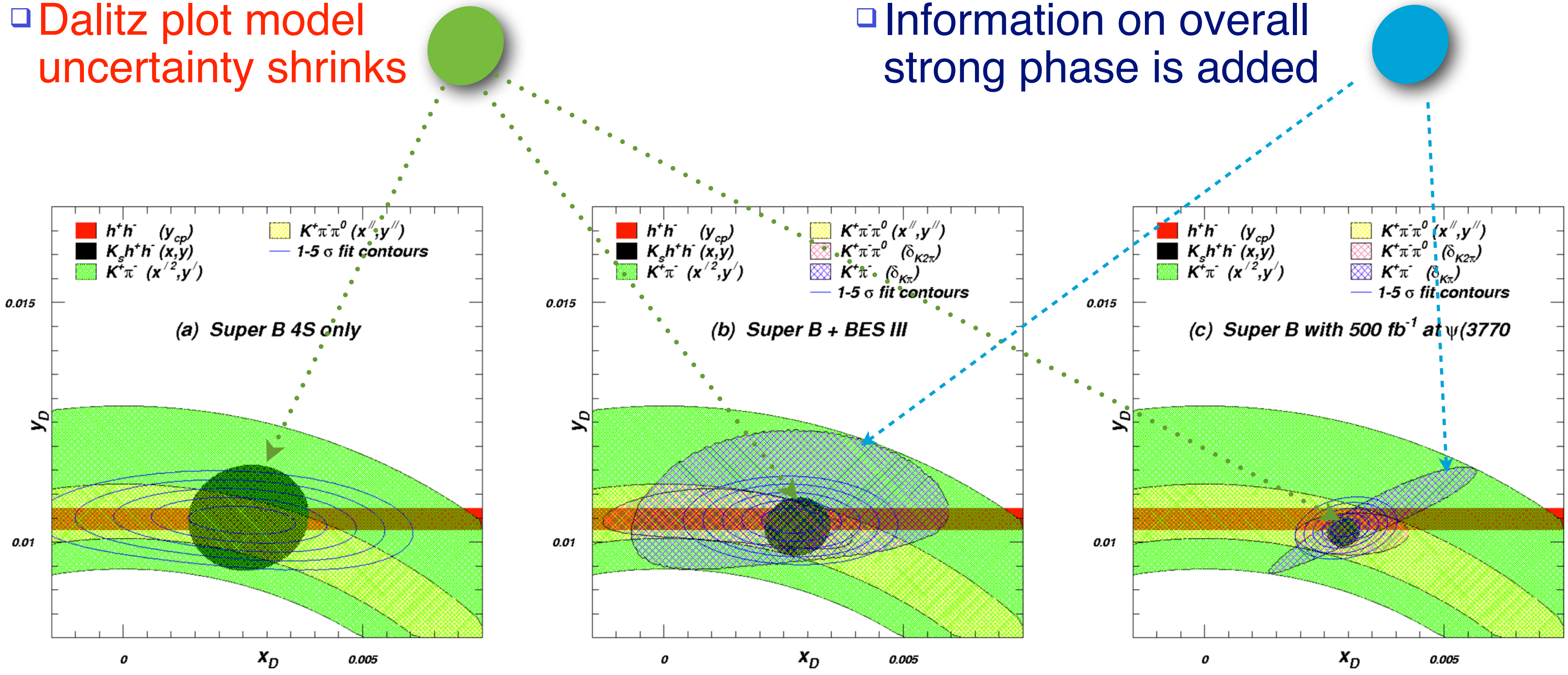
✓ We assume that new data from threshold will reduce the uncertainties in model uncertainty:

- BES III – ~factor 3 improvement in model uncertainty
- Super B 500 fb^{-1} $D\bar{D}$ threshold run – ~factor 10 improvement.

Two improvements in mixing precision come from threshold data:

- Dalitz plot model uncertainty shrinks

- Information on overall strong phase is added



Fit	$x \times 10^3$	$y \times 10^3$	$\delta^\circ_{K^+\pi^-}$	$\delta^\circ_{K^+\pi^-\pi^0}$
(b)	$xxx^{+0.72}_{-0.75}$	$xxx \pm 0.19$	$xxx^{+3.7}_{-3.4}$	$xxx^{+4.6}_{-4.5}$
Stat.	(0.18)	(0.11)	(1.3)	(2.9)

Fit	$x \times 10^3$	$y \times 10^3$	$\delta^\circ_{K^+\pi^-}$	$\delta^\circ_{K^+\pi^-\pi^0}$
(c)	$xxx \pm 0.42$	$xxx \pm 0.17$	$xxx \pm 2.2$	$xxx^{+3.3}_{-3.4}$
Stat.	(0.18)	(0.11)	(1.3)	(2.7)

Fit	$x \times 10^3$	$y \times 10^3$	$\delta^\circ_{K^+\pi^-}$	$\delta^\circ_{K^+\pi^-\pi^0}$
(d)	$xxx \pm 0.20$	$xxx \pm 0.12$	$xxx \pm 1.0$	$xxx \pm 1.1$
Stat.	(0.17)	(0.10)	(0.9)	(1.1)

Uncertainty in x_D improves more than that of y_D

Possible approaches for improving sensitivity on mixing and CPV using threshold data

Model independent approach for 3-body decays

- *A. Bondar, A. Poluektov, V. Vorobiev* have proposed a model independent analysis of 3-body D^0 decays for mixing and CPV. See **Phys. Rev. D 82, 034033 (2010)**

Sensitivity relies on the variation of the yields in different regions of the Dalitz plot along the time. No amplitude analysis is required.

$$\begin{aligned}\frac{d\Gamma_i[D^0_{\rm phys}\to f]/dt}{e^{-\Gamma t}\mathcal{N}_f} = & \Big[\Big(T_i+|\frac{q}{p}|^2\bar{T}_i\Big)\cosh(\Gamma y t)+\Big(T_i-|\frac{q}{p}|^2\bar{T}_i\Big)\cos(\Gamma x t)\\ & + 2\Big(c_i\sqrt{T_i\bar{T}_i}\Big|\frac{q}{p}\Big|\cos\phi - s_i\sqrt{T_i\bar{T}_i}\Big|\frac{q}{p}\Big|\sin\phi\Big)\sinh(\Gamma y t)\\ & - 2\Big(c_i\sqrt{T_i\bar{T}_i}\Big|\frac{q}{p}\Big|\sin\phi + s_i\sqrt{T_i\bar{T}_i}\Big|\frac{q}{p}\Big|\cos\phi\Big)\sin(\Gamma x t)\Big]\end{aligned}$$

Time dependence for flavor tagged decays (i.e. D* tagged at ϒ(4S))

where: i = region of Dalitz plot

$$A_f=|A_f|e^{i\delta_f} \qquad \bar{A}_f=|\bar{A}_f|e^{i\bar{\delta}_f}$$

$$\int_i |A_f|^2 d\mathcal{P} = \boxed{T_i} \qquad \int_i |\bar{A}_f|^2 d\mathcal{P} = \boxed{\bar{T}_i}$$

proportional to number of events in bin i
Can be measured at ϒ(4S) or at ψ(3770)

$$\frac{\int_i \mathcal{R}e(A_f^*\bar{A}_f)d\mathcal{P}}{\sqrt{T_i\bar{T}_i}} = \frac{\int_i |A_f||\bar{A}_f|\cos(\boxed{\bar{\delta}_f-\delta_f})d\mathcal{P}}{\sqrt{T_i\bar{T}_i}} = c_i$$

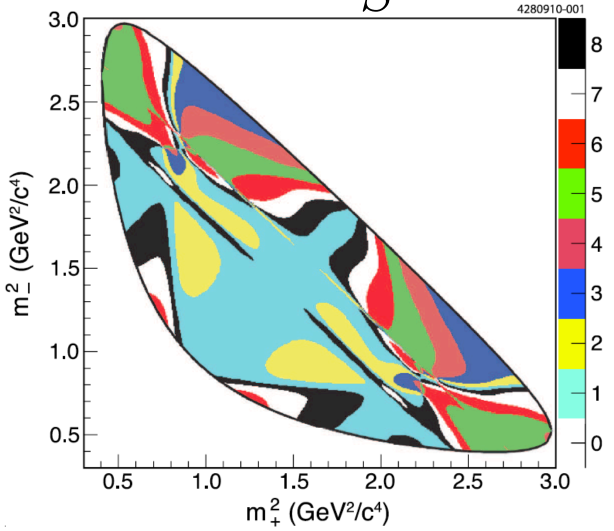
$$\frac{\int_i \mathcal{I}m(A_f^*\bar{A}_f)d\mathcal{P}}{\sqrt{T_i\bar{T}_i}} = \frac{\int_i |A_f||\bar{A}_f|\sin(\boxed{\bar{\delta}_f-\delta_f})d\mathcal{P}}{\sqrt{T_i\bar{T}_i}} = s_i$$

$D^0-\bar{D}^0$ relative phase.
Accessible at ψ(3770)

Determination of Dalitz plot parameters: T_i, c_i, s_i

- c_i, s_i determination requires $D\overline{D}$ coherent production. The method has been proved to work well by CLEO-c. See **Phys. Rev. D 82, 112006 (2010).**
- c_i, s_i from time integrated analysis of ψ(3770) data is affected by $\mathcal{O}(x^2, y^2)$ approximations (relatively small).
- c_i, s_i extraction: no CP conservation assumption required if doubling number of bins in the Dalitz plot.

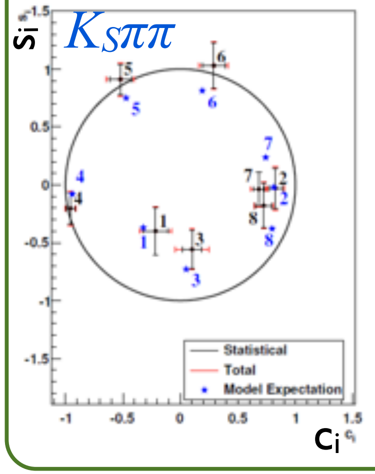
$$D^0 \to K_S^0 \pi^+ \pi^-$$



the i^{th} bin is defined by the condition

$$2\pi(i - 3/2)/\mathcal{N} < \Delta\delta_D(m_+^2, m_-^2) < 2\pi(i - 1/2)/\mathcal{N},$$

Good agreement between BaBar/Belle Dalitz model expectation and CLEO-c model independent determination of D^0-$\overline{D}^0$ relative phases.



Modified optimal BABAR 2008

χ^2/DOF = 13.8/16

from Stefania Ricciardi talk at CKM 2010.

- T_i, $\overline{T}_i$ can be measured at ψ(3770) with a time-integrated analysis and then fixed in the time-dependent mixing analysis at the ϒ(4S).
- T_i, $\overline{T}_i$ can also be determined simultaneously in the time-dependent mixing analysis at the ϒ(4S) if helpful for reducing systematic errors (different efficiencies, resolutions, etc.)

Sensitivity results for mixing and CPV parameters for $D^0 \to K_S \pi^+ \pi^-$

- Sensitivity studies for mixing and CPV with model independent approach. From **Phys.Rev.D82, 034033 (2010):**
  - assume perfect proper time resolution and no bkg;
  - assume very precise determination of c_i, s_i (considering 2×10^6 flavor tagged $D^0 \to K_S \pi^+ \pi^-$ decays at $\Psi(3770)$).

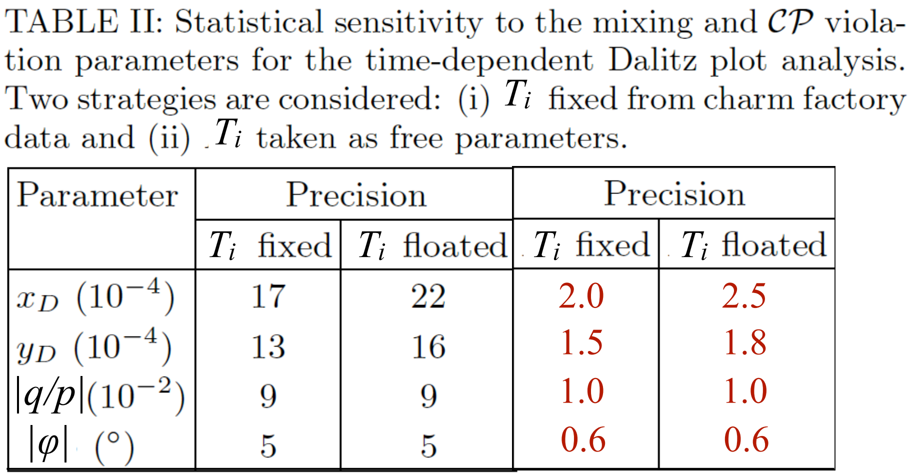


TABLE II: Statistical sensitivity to the mixing and $\mathcal{CP}$ violation parameters for the time-dependent Dalitz plot analysis. Two strategies are considered: (i) T_i fixed from charm factory data and (ii) T_i taken as free parameters.

Parameter	Precision		Precision	
	T_i fixed	T_i floated	T_i fixed	T_i floated
x_D (10^{-4})	17	22	2.0	2.5
y_D (10^{-4})	13	16	1.5	1.8
$\lvert q/p \rvert (10^{-2})$	9	9	1.0	1.0
$\lvert \varphi \rvert$ (°)	5	5	0.6	0.6

B Factories
1M signal events

SuperB
75 M signal events

- Similar approach is valid also for $D^0 \to K^+ \pi^- \pi^0$. Using a model independent approach is possible to extract mixing parameters x, y directly also in this case.

Time-dependent measurements at $D\bar{D}$ threshold: preamble

- SuperB will have the possibility to operate with energy asymmetric beams also at the ψ(3770) allowing time-dependent measurement of $D\bar{D}$ quantum coherent pairs.
- This is a unique feature of the SuperB machine to be studied and possibly exploited:
  - additional tag states (e.g. CP tag), other than flavor eigenstates, will be available at threshold thanks to the quantum coherence;
  - background free time-dependent measurements (e.g. $D^0 \rightarrow K^+\pi^-\pi^0$)
  - access to the mixing and CP violation parameters along with relative D^0-$\bar{D}^0$ relative phases from the same data;
  - possibility of time-dependent CPT tests exploiting using quantum coherence as for the Kaon and B meson systems;
  - possibility to double check a possible discovery of CP violation in the charm sector in different energy regimes and experimental environments with different systematic errors.

Time-dependent measurements at $D\bar{D}$ threshold: general considerations

- At $\Upsilon(4S)$
  - Flavor tagged D^0 through $D^{*+} \rightarrow D^0\pi^+$ decay. Flavor mistag ≈ 0.2%
  - We denote the D* flavor tag with label *l*X
  - D^0 can be reconstructed in flavor *l*X, CP, Kπ and multibody (e.g. Ksππ) final states. Relatively high purity due to $m(D^0)$ and $\Delta m = m(D^{*+}) - m(D^0)$
  - Proper time resolution is about $\tau(D^0)/4 \approx 0.1$ ps
- At $\psi(3770)$
  - Coherent $D^0\bar{D}^0$ production
  - Both D mesons can be reconstructed in *l*X, CP, Kπ and Ksππ final states, with very low background
  - Flavor mistag ≈ 0.2% with eX, but ≈ 2% with μX (large μ misid @ low p)
  - Time-dependent measurements require larger CM boost compared to the $\Upsilon(4S)$ case to achieve time resolution, but reconstruction efficiency decreases with large CM boost. Need to determine the optimal boost value.

Double tags @ $\Psi(3770)$

Modes with D* tag @ $\Upsilon(4S)$

	CP–	Kπ	*l*X	Ksππ
CP+	X	X	XX	X
CP–		X	XX	X
Kπ		X	XX	X
*l*X			XX	XX
Ksππ				X

Time-dependent measurements at $D\bar{D}$ threshold: to do list

See Matteo Rama's talk.

- Consider for the time being 500 fb^{-1} of $\psi(3770)$ data at SuperB;
  - Determine adequate center of mass boost value for time-dependent studies at $\psi(3770)$ and detector specifications/configuration (e.g. magnetic field value, inner layer silicon detector technology, IP position);
- 2-body decays:
  - study sensitivity for mixing and CPV parameters exploiting quantum coherence and with additional CP tagged D^0 decays;
  - compare sensitivities of time-dependent vs time-integrated measurements;
- 3-body decays:
  - determination of c_i, s_i at SuperB. Sensitivity projections and systematic errors;
  - Time-dependent (Dalitz model independent) measurement of mixing and CPV at $\psi(3770)$ and at $\Upsilon(4S)$.

work in progress

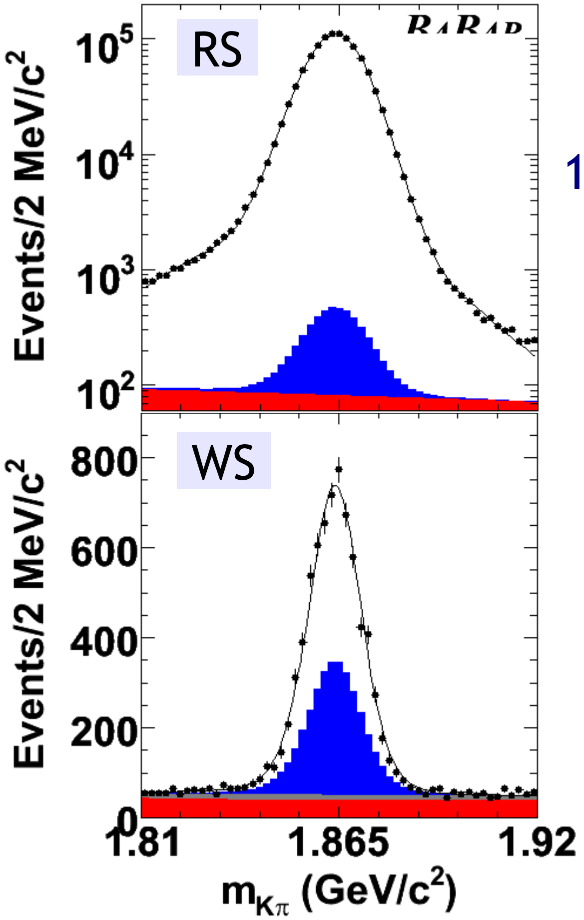
Summary

- Charm physics provides a unique opportunity to search for New Physics at SuperB.
- Precision measurements for mixing and CPV would benefit of $D^0\bar{D}^0$ threshold data for improving sensitivities and reducing systematic errors.
- Expected sensitivities at SuperB including threshold data:
  - error on x, y at 10^{-4} level
  - error on |q/p| at 10^{-2} level, error on φ at 1 degree level.
- Time-dependent measurements at threshold are a unique feature of SuperB that we are currently studying.

Backup slides

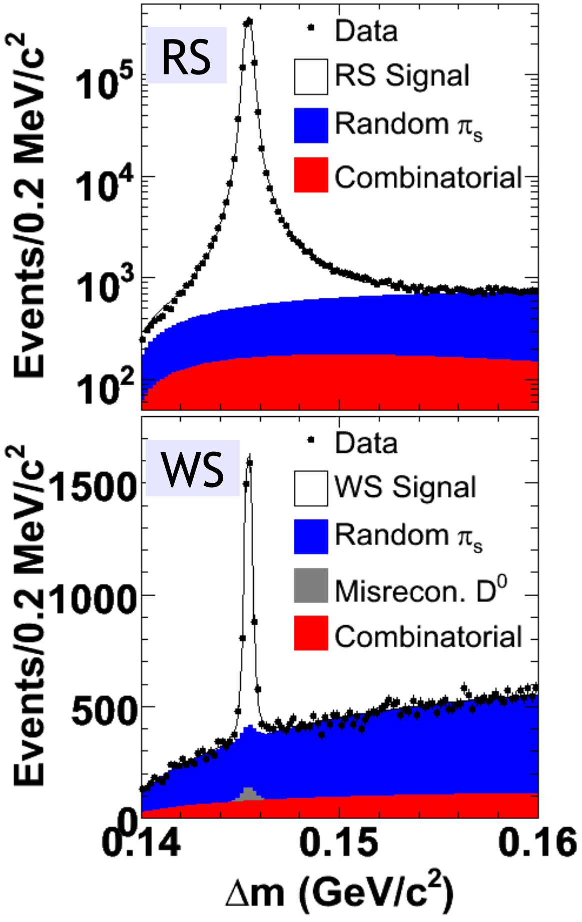
Selection of RS and WS decays

RS = Right Sign
WS = Wrong Sign



RS signal:
1,141,500±1200
combinations

WS signal:
4,030±90
combinations



RS sample is very useful!

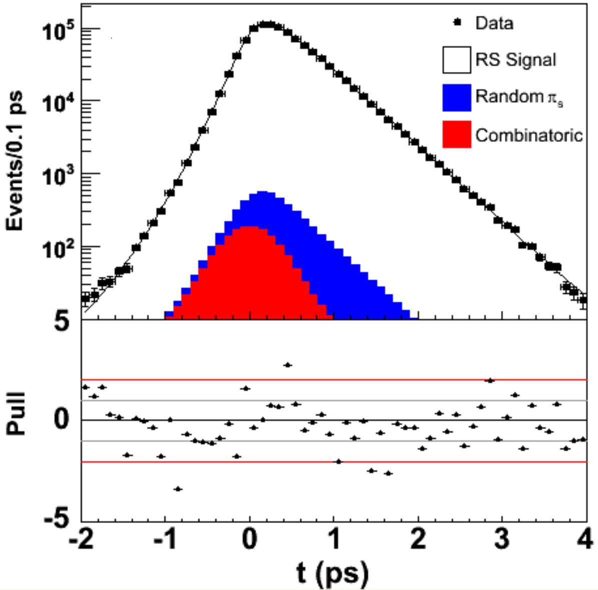
✓ D^0 lifetime and resolution function fitted in RS sample

Good Idea

τ=(410.3±0.6(stat.)) fs

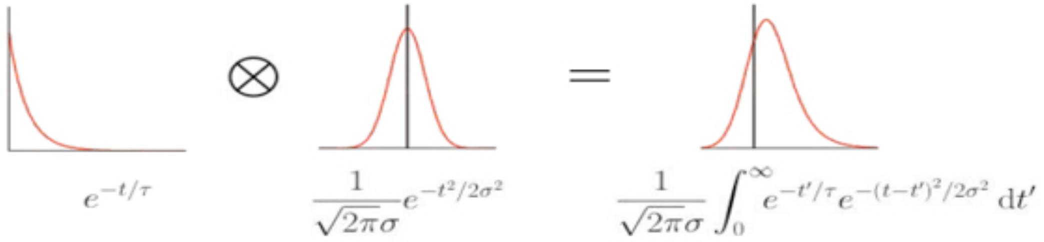
Consistent with PDG
(410.1±1.5 fs)

RS decay time, signal region



Signal resolution function described by sum of 3 Gaussians (core, tail, outliers):

- Mean of Gaussian allowed to be non-zero *(Small vertex detector misalignment);*
- Use per-event-error for all 3 Gaussian components

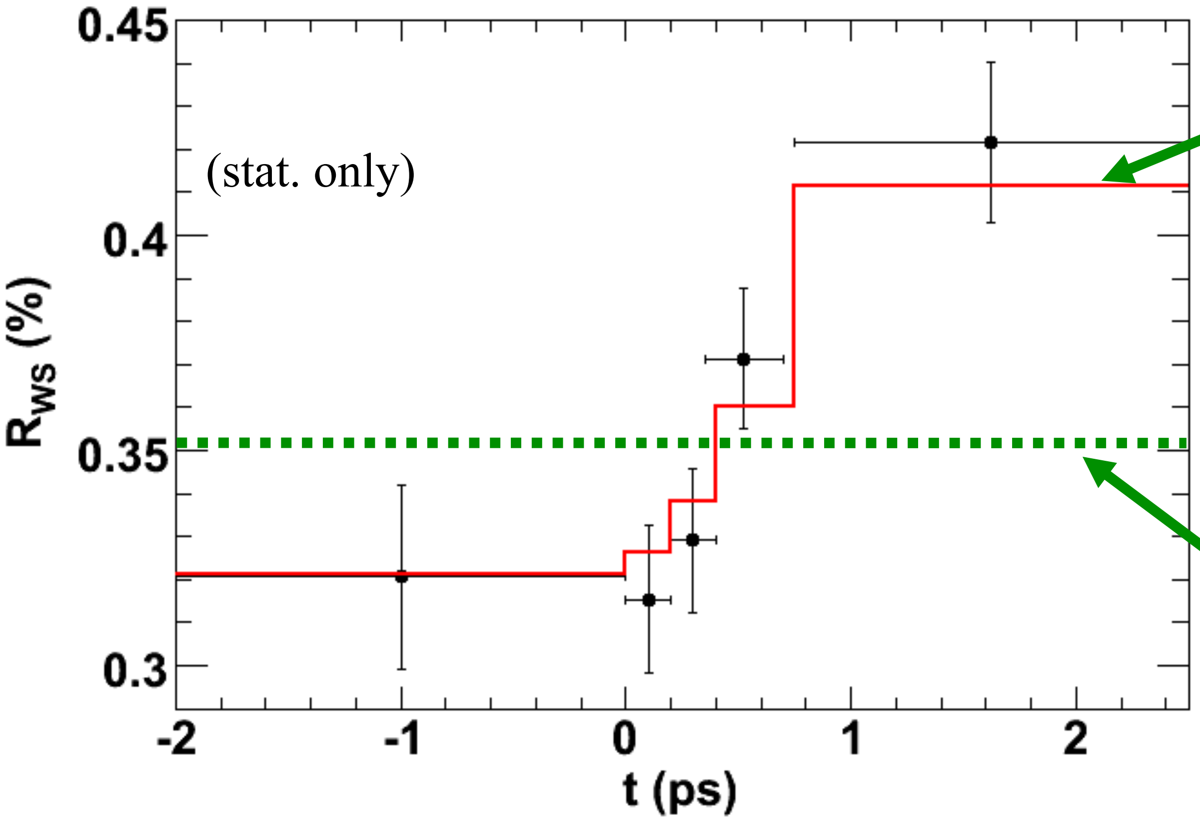


$$e^{-t/\tau} \otimes \frac{1}{\sqrt{2\pi}\sigma}e^{-t^2/2\sigma^2} = \frac{1}{\sqrt{2\pi}\sigma}\int_0^{\infty} e^{-t'/\tau}e^{-(t-t')^2/2\sigma^2}\,dt'$$

Rate of WS events clearly increases with time

Good Idea

Validation test: independent of the proper time resolution function



Consistent with prediction from full likelihood fit

$\chi^2=1.5$

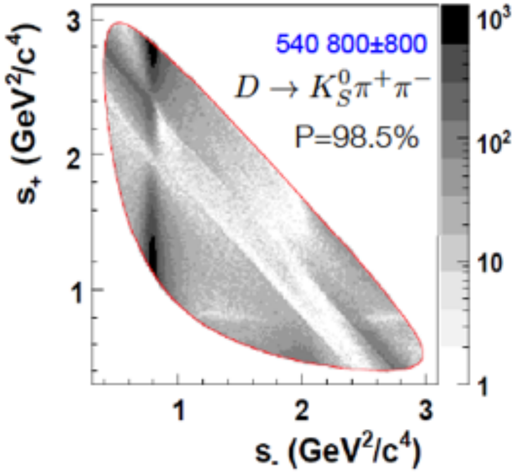
Inconsistent with no-mixing hypothesis

$\chi^2=24$

- Extract D^0 decay amplitude from independent high statistics sample of flavor tagged D^0 mesons ($D^{*+} \rightarrow D^0\pi^+$). The so called "Dalitz model".
- Model independent approach has been proposed by Bondar et. al. Requires also charm threshold results. **Phys. Rev. D 82, 034033 (2010)**

Good fit quality taking into account statistical, experimental and model uncertanties

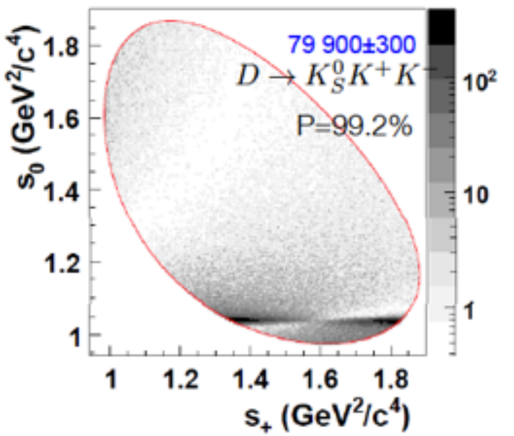
$\chi^2/ndof = 1.21$ with (8626-41) ndof



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

Wave	Parameterization
ππ S-wave	K-matrix
KSπ S-wave	K-matrix (LASS)
ππ P-wave	BW: ω(782), G.S. ρ(770)
KSπ P-wave	BW: CA and DCS K*(892), CA K*(1680)
ππ D-wave	BW $f_2(1270)^0$
KSπ D-wave	BW: CA and DCS $K_2^*(1430)$

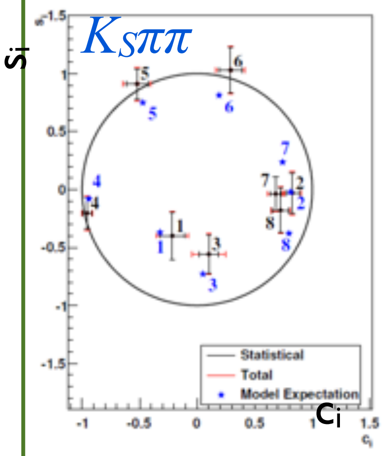
$\chi^2/ndof = 1.28$ with (1195-17) ndof



$D \rightarrow K_S^0K^+K^-$

KKS S-wave	BW: CA and DCS $a_0(980)$, CA $a_0(1450)$
KK S-wave	Flatte $a_0(980)$, BW $a_0(1450)$, $f_0(1370)$
KK P-wave	BW ϕ(1020)
KK D-wave	BW $f_2(1270)^0$

Good agreement between BaBar/Belle Dalitz model expectation and CLEO-c model independent determination of D^0-$\overline{D}^0$ relative phases.



Modified optimal BABAR 2008

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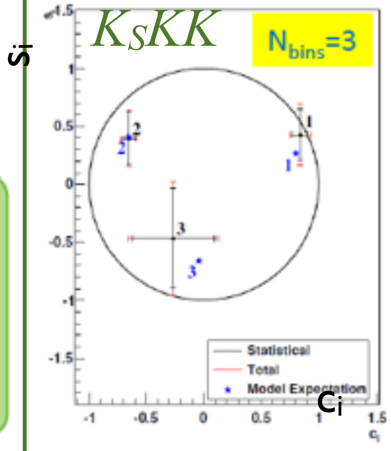

from Stefania Ricciardi talk at CKM 2010.

- c_i and s_i are weighted averages of the cosine and sine of the phase-difference between D^0 and $\overline{D}^0$ in bin i