$D^0 - \bar{D}^0$ Mixing and T-Odd Asymmetry Search at BaBar

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for the BaBar collaboration

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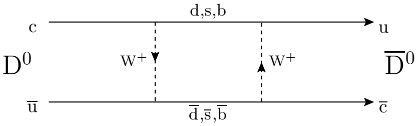
Outline

1. Overview
2. Measurements
   - Mixing parameters (x and y)
     - *PRELIMINARY...but just accepted to PRL!*
     - arXiv:1004.5053
   - Mixing parameter (y_{CP})
     - PhysRevD.80.071103
   - Search for T-odd correlations (CP-violation)
     - PhysRevD.81.111103
3. Summary

Overview

- Mixing
  - $K^0 - \bar{K}^0, B^0 - \bar{B}^0$
  - $D^0 - \bar{D}^0$
    - BaBar, 2007 PhysRevLett.98.211802
    - Belle, 2007 PhysRevLett.98.211803,PhysRevLett.99.131803
    - CDF, 2007 PhysRevLett.100.121802
  - Sensitive to *New Physics*



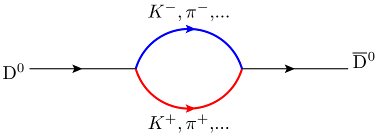


FIGURE: Examples of diagrams that contribute to mixing in the Standard Model.

$D^0 - \bar{D}^0$ MIXING

Flavour eigenstates	**Mass eigenstates**
$\|D^0(c\bar{u}\rangle)$	$\|D_1(M_1, \Gamma_1)\rangle$
$\|\bar{D}^0(\bar{c}u)\rangle$	$\|D_2(M_2, \Gamma_2)\rangle$

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Define some useful quantities:

$$M = \frac{M_1 + M_2}{2} \qquad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$
$$x = \frac{M_1 - M_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

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In the Standard Model :

Mixing parameters	$\sim$	10^{-2}
CP−violation	$<$	10^{-3}

First evidence for $D^0 - \bar{D}^0$ mixing

- First observation of $D^0 - \bar{D}^0$ mixing at 3.9σ (BaBar, 2007)
  10.1103/PhysRevLett.98.211802
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"Wrong" sign (WS)	$D^0 \rightarrow K^+\pi^-$	(Doubly Cabibbo suppressed (DCS))

- Tag charm meson flavor at $t = 0$ with $D^{*+} \rightarrow D^0\pi^+$ ($m_{D^{*+}} - m_{D^0} \approx 145\text{MeV}$)
  - Characteristic "slow" pion (π_s)

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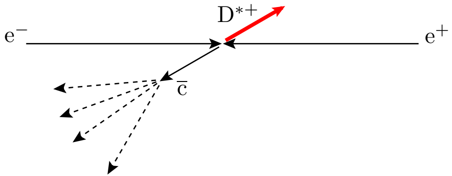

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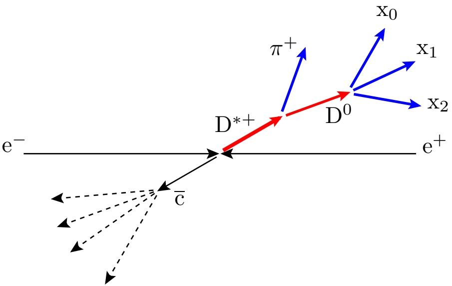

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- Tag flavor at $t = 0$ with $D^{*+} \to D^0\pi^+$ ($m_{D^{*+}} - m_{D^0} \approx 145$MeV)
  - Characteristic "slow" pion (π_s)
- Use **WS** events

$$D^0 \quad \to \quad K^+\pi^-$$
$$D^0 \to \mathbf{\bar{D}^0} \to K^+\pi^-$$

- Strong phase difference (D^0 or $\bar{D}^0$) in final state hadronization (δ_f) is significant for non-CP-conjugate decay modes.

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

$$|\mathcal{A}_{\bar{f}}(t)|^2 = e^{-\Gamma t}\cdot\left[\overbrace{|\mathcal{A}_{\bar{f}}|^2}^{\text{Direct(DCS)}} + \overbrace{\frac{(x^2+y^2)}{4}|\bar{\mathcal{A}}_{\bar{f}}|^2(\Gamma t)^2}^{\text{Mixing}} + \overbrace{((y\cos\delta_f - x\sin\delta_f)\ |\mathcal{A}_{\bar{f}}||\bar{\mathcal{A}}_{\bar{f}}|(\Gamma t))}^{\text{Interference}}\right]$$

DETERMINATION OF x AND y

- Measure x and y directly in self-conjugate final states.
- Analysis insensitive to strong phase, δ_f.
  - $D \to K_S^0 \pi^+ \pi^-$
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  - 609M $c\bar{c}$ pairs. (468.5 fb^{-1})

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- Perform time-dependent Dalitz plot analysis
  $s_+ = m^2(K^0_S h^+)$
  $s_- = m^2(K^0_S h^-)$
- If there is no CP-violation then
  $\mathcal{A}(s_+, s_-) = \bar{\mathcal{A}}(s_-, s_+)$
- x and y are common across both decay modes.
- Exploit time-dependence of mixing to observe changes in population of Dalitz plot.

- $D^0 \to K^0_S \pi^+ \pi^-$
  - 540,800±800 events (98.5% pure)
- Use "slow" pion to tag flavour. $D^{*+} \to D^0 \pi^+$
  $\Delta m = m_{D^{*+}} - m_{D^0}$

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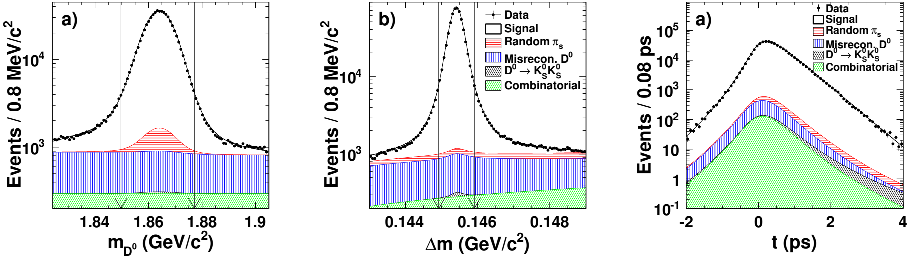

- $D^0 \to K^0_S K^+ K^-$
  - 79,900±300 events (99.2% pure)
- Use "slow" pion to tag flavour. $D^{*+} \to D^0\pi^+$
  $\Delta m = m_{D^{*+}} - m_{D^0}$

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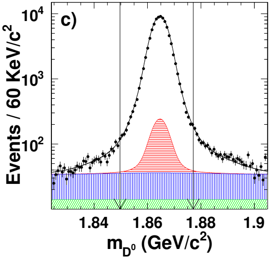

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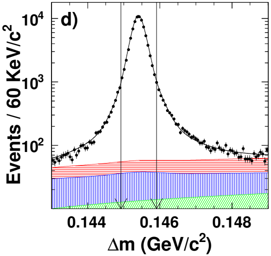

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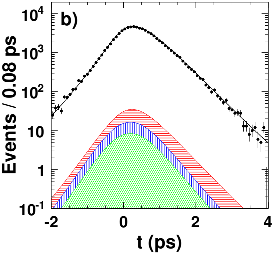
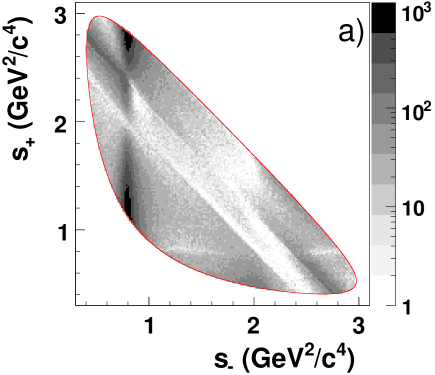


Determination of x and y

$$D^0 \rightarrow K^0_S \pi^+ \pi^-$$



Time integrated Dalitz plot.

DETERMINATION OF x AND y

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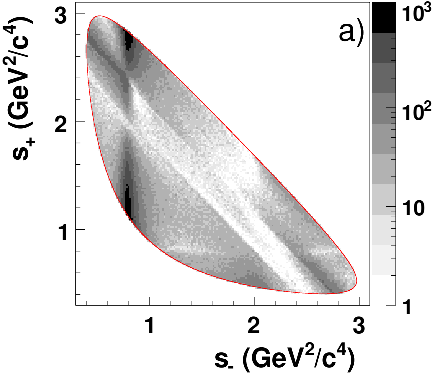

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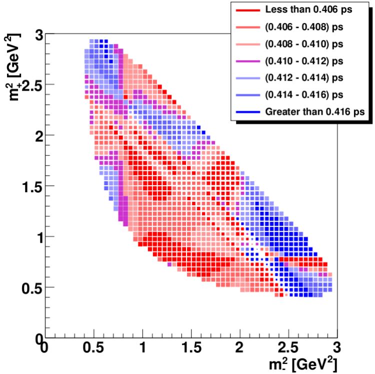

Average lifetime as function of position in Dalitz plot.
Monte Carlo
$x = y = 1\%$

Determination of x and y

- **PRELIMINARY...but just accepted to PRL!**
- $x = [1.6 \pm 2.3(\text{stat.}) \pm 1.2(\text{sys.}) \pm 0.8(\text{model})] \times 10^{-3}$
- $y = [5.7 \pm 2.0(\text{stat.}) \pm 1.3(\text{sys.}) \pm 0.7(\text{model})] \times 10^{-3}$
- Most precise single measurement of x.
- Assumes no CP-violation.

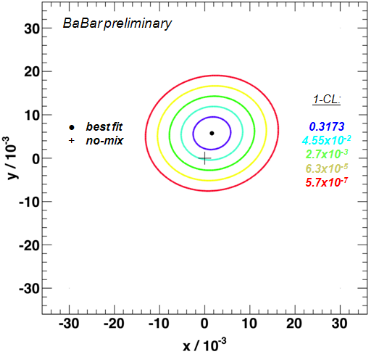

Figure 82: Contours for the combined $K^0_S\pi^+\pi^- + K^0_S K^+K^-$ fit results on data including the systematic errors due to the experimental analysis method and to the Dalitz model assumption. The marker at (0,0) represents the no mixing point, while the other ones represent the fit results.

Lifetime ratio

- Measure y_{CP}
- BaBar (2009) (PhysRevD.80.071103)
  - 500M $c\bar{c}$ pairs. (384 fb^{-1})
- Lifetime ratio using $D^0 \to K^+K^-, K^-\pi^+$
- Untagged (recoil charm meson is *not* reconstructed).
  - Results are later combined with a previous tagged analysis: recoil charm meson is reconstructed.
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\begin{aligned}
D_1 &\quad \text{is} \quad CP - \text{even} \\
D_2 &\quad \text{is} \quad CP - \text{odd} \\
y_{CP} &\approx y \\
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$$\begin{aligned} y_{CP} &= \frac{\langle \tau(\text{Mixed } CP \text{ final state}) \rangle}{\langle \tau(CP \text{ even final state}) \rangle} - 1 \\ &= \frac{\langle \tau(D^0 \to K^-\pi^+) \rangle}{\langle \tau(D^0 \to K^+K^-) \rangle} - 1 \end{aligned}$$

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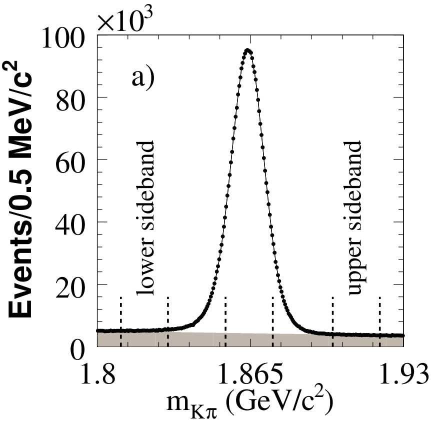
- $D^0 \to K^-\pi^+$
  - 2.7M signal yield
  - 94.2% purity



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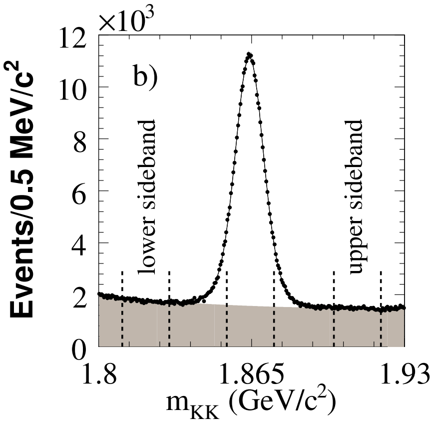
- $D^0 \to K^+K^-$
  - 0.26M signal yield
  - 80.9% purity



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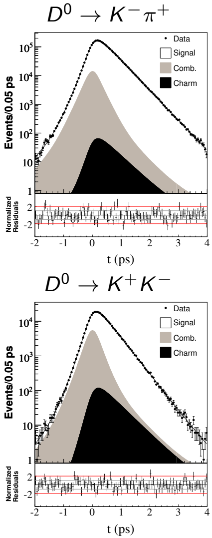
- $\tau_{K\pi} = 410.39 \pm 0.38(\text{stat.})\text{ps}$
- $\tau_{KK} = 405.85 \pm 1.00(\text{stat.})\text{ps}$



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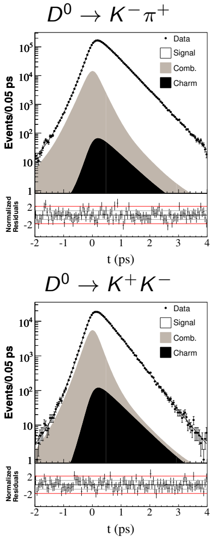

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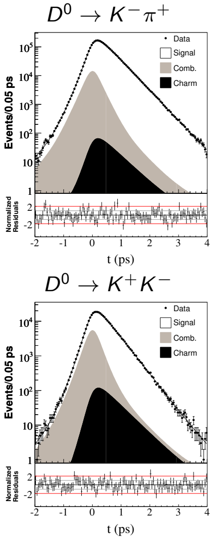
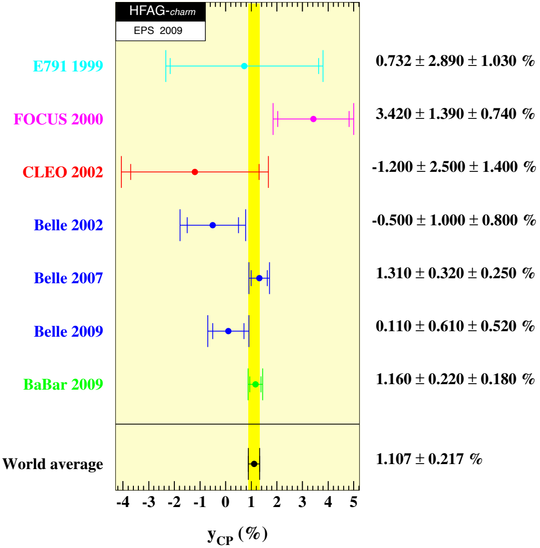
- Combining with previous tagged analysis
  - **PhysRevD.78.011105**
- $y_{CP} = [1.16 \pm 0.22(\text{stat.}) \pm 0.18(\text{syst.})]\%$
- No-mixing excluded at 4.1σ.



HFAG (World averages) y_{CP}



HFAG (World averages) x and y

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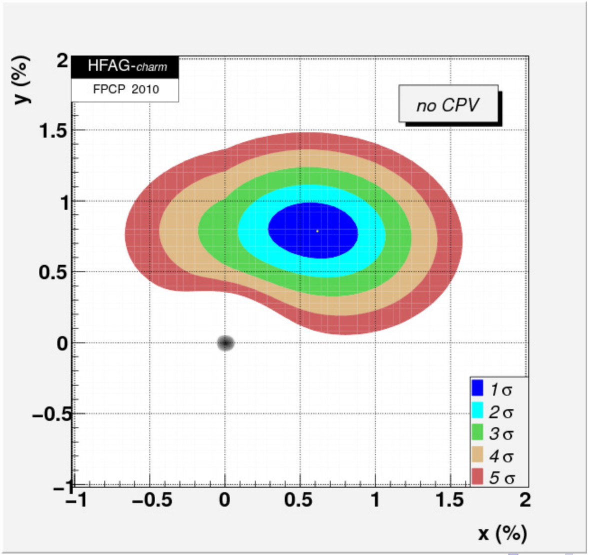

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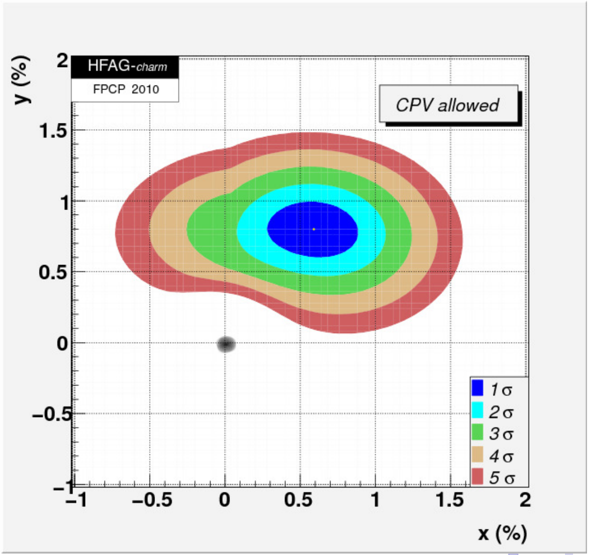

CP violation with *T*-odd correlations

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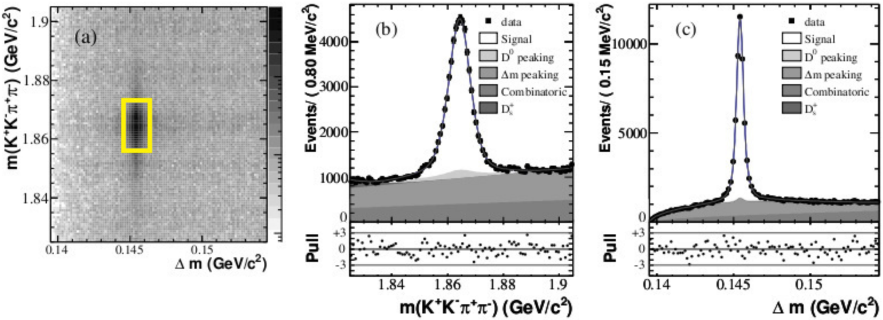
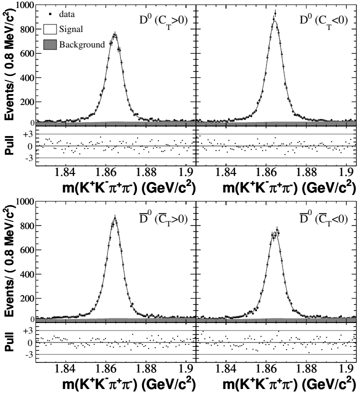
$$\mathcal{A}_T = \frac{1}{2}(A_T - \bar{A_T})$$

- Use "slow" pion to tag flavour.



- Count the yields

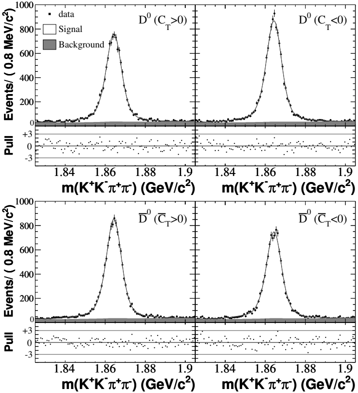
	Raw event yields from fit
$D^0, C_T > 0$	10974 ± 117
$D^0, C_T < 0$	12587 ± 125
$\bar{D}^0, \bar{C}_T > 0$	10749 ± 116
$\bar{D}^0, \bar{C}_T < 0$	12380 ± 124



- Count the yields

	Raw event yields from fit
$D^0, C_T > 0$	10974 ± 117
$D^0, C_T < 0$	12587 ± 125
$\bar{D}^0, \bar{C}_T > 0$	10749 ± 116
$\bar{D}^0, \bar{C}_T < 0$	12380 ± 124

- $A_T = [-68.5 \pm 7.3(\text{stat.}) \pm 5.8(\text{sys.})] \times 10^{-3}$
- $\bar{A}_T = [-70.5 \pm 7.3(\text{stat.}) \pm 3.9(\text{sys.})] \times 10^{-3}$
- $\mathcal{A}_T = [1.0 \pm 5.1(\text{stat.}) \pm 4.4(\text{sys.})] \times 10^{-3}$
  - *Consistent with no CP-violation.*



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  - $y_{CP} = [1.16 \pm 0.22(\text{stat.}) \pm 0.18(\text{syst.})]\%$
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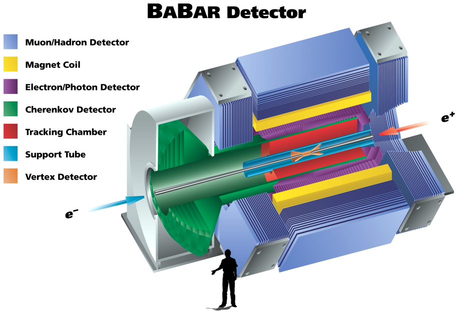
- **Thanks for your time!**

BACKUP SLIDES

- The B-factories
  - BaBar (SLAC)



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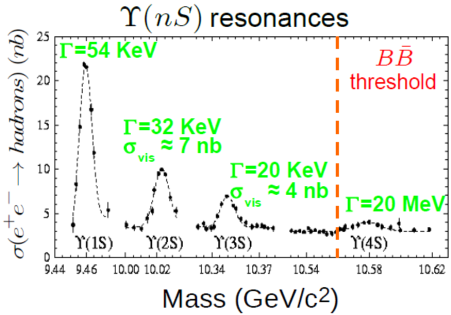

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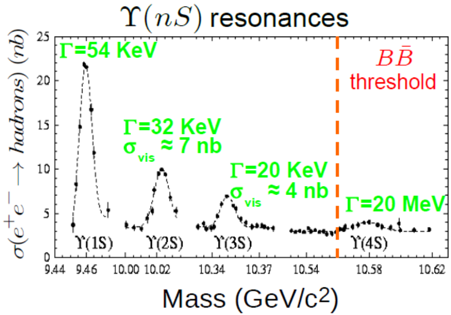
- Significant backgrounds under the resonance $(c\bar{c}, \tau^+\tau^-, ...)$



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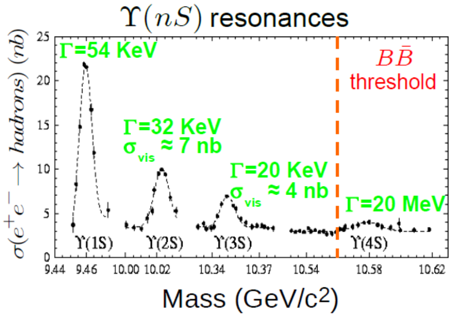
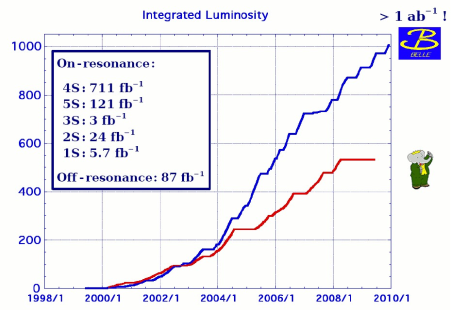
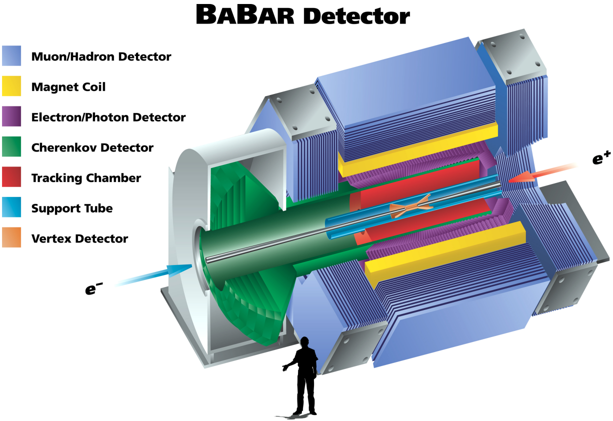


- The B-factories
  - BaBar (SLAC)
- Ran on $\Upsilon(4S)$ resonance.
- Significant backgrounds under the resonance $(c\bar{c}, \tau^+\tau^-, ...)$
- Wealth of *rich physics* under the resonance.
- High luminosity
- On the order of **1.5 billion $B\bar{B}$ pairs in the world's dataset!**



- BaBar
- 600 million $c\bar{c}$ pairs.



$D^0 - \bar{D}^0$ MIXING

Flavour eigenstates	**Mass eigenstates**
$\vert D^0(c\bar{u}\rangle)$	$\vert D_1(M_1, \Gamma_1)\rangle$
$\vert \bar{D}^0(\bar{c}u)\rangle$	$\vert D_2(M_2, \Gamma_2)\rangle$

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$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$$

$$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$$

$$|p|^2 + |q|^2 = 1 \qquad p = q = \frac{1}{\sqrt{2}} \mathrm{if there is no} \, CP-\mathrm{violation}$$

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$$i\frac{\partial}{\partial t}\begin{pmatrix}|D^0\rangle \\ |\bar{D}^0\rangle\end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{matrix}|D^0\rangle \\ |\bar{D}^0\rangle\end{matrix}$$

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Define some useful quantities:

$$M = \frac{M_1 + M_2}{2} \qquad \Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

$$x = \frac{M_1 - M_2}{\Gamma} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

Where do we go to measure this?

What is mixing

$$|D_1(t)\rangle = |D_1\rangle e^{-i(\Gamma_1/2+im_1)t}$$

$$|D_2(t)\rangle = |D_2\rangle e^{-i(\Gamma_2/2+im_2)t}$$

$$x = \frac{m_1 - m_2}{\Gamma}$$

$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

$$\left|\frac{p}{q}\right|$$

$$\psi_M = \mathrm{Arg}\left\{\frac{p}{q}\right\}$$

Determination of x and y

- Measure x and y directly in self-conjugate final states.
  - $D \to K^0_S \pi^+ \pi^-$
  - $D \to K^0_S K^+ K^-$
- Time-dependent Dalitz analysis

$$s_+ = m^2(K^0_S h^+)$$
$$s_- = m^2(K^0_S h^-)$$

- Decay amplitude

$$\mathcal{A}(s_+, s_-)$$

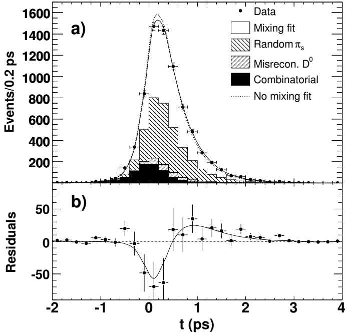
- If $CPV = 0$,
  $\mathcal{A}(s_+, s_-) = \bar{\mathcal{A}}(s_-, s_+)$

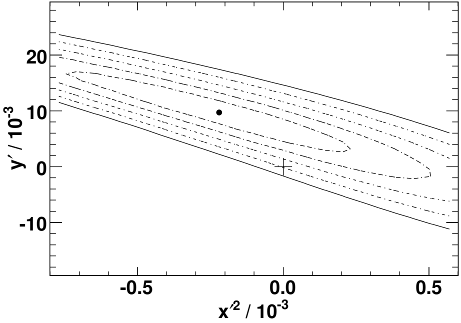
$g_\pm = \frac{1}{2}\left[e^{i(m_1 - i\Gamma_1/2)t} \pm e^{i(m_2 - i\Gamma_2/2)t}\right]$
Process is function of (s_-, s_+) and proportional to $\cosh(y\Gamma t)$, $\sinh(y\Gamma t)$, $\cos(x\Gamma t)$, $\sin(x\Gamma t)$, and modulated by $e^{-\Gamma t}$.
x and y are common across both topologies. Time dependance can be written as

$$\mathcal{M}(s_+, s_-, t) = \mathcal{A}(s_+, s_-)g_+(t) + \frac{q}{p}\mathcal{A}(s_-, s_+)g_-(t)$$
$$M(s_+, s_-, t) = \frac{q}{p}\overline{\mathcal{A}}(s_+, s_-)g_+(t) + \overline{\mathcal{A}}(s_-, s_+)g_-(t)$$

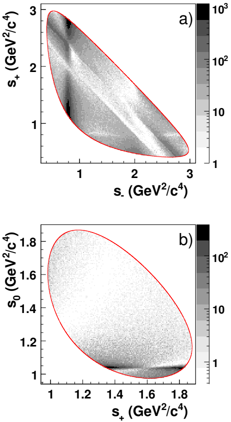
First evidence for $D^0 - \bar{D}^0$ mixing

- $x'^2 = [-0.22 \pm 0.30(\text{stat.}) \pm 0.21(\text{sys.})]$
- $y' = [9.7 \pm 4.4(\text{stat.}) \pm 3.1(\text{sys.})]$
- No-mixing excluded at 3.9σ.





- D^0 mixing in $K^0_S h^+ h^-$ $(h = K, \pi)$
- No strong phase: $\delta_{K\pi\pi} = 0$
    - CP-eigenstates in the final state.
    - This ties the phase of the D^0 and $\bar{D}^0$ decay amplitudes together. (ref Brian's ICHEP 2008)
    - Assume CPV=0
    - Can pull out x and y.
- Time dependent.
- $D^{*+} \to \pi^+ D^0$
    - "slow" π (π_s) tags flavour.
    - π_s and D^0 decay products are tracked back to a common origin for timing information.
        - $K^0_S \pi^+ \pi^-$: $\sigma_t = 0.2$ps
        - $K^0_S K^+ K^-$: $\sigma_t = 0.3$ps



Determination of x and y

- Measure x and y directly in self-conjugate final states.
  - $D \to K_S^0 \pi^+ \pi^-$
  - $D \to K_S^0 K^+ K^-$
- Time-dependent Dalitz analysis

$$s_+ = m^2(K_S^0 h^+) \qquad \text{If } CPV = 0,\ \mathcal{A}(s_+, s_-) = \bar{\mathcal{A}}(s_-, s_+)$$
$$s_- = m^2(K_S^0 h^-)$$

- Time dependence

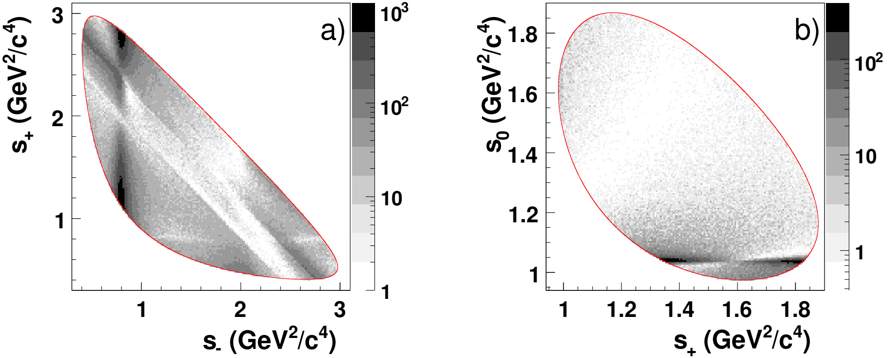
$$g_\pm = \frac{1}{2}\left[e^{i(m_1 - i\Gamma_1/2)t} \pm e^{i(m_2 - i\Gamma_2/2)t}\right]$$
$$\mathcal{M}(s_+, s_-, t) = \mathcal{A}(s_+, s_-)g_+(t) + \frac{q}{p}\mathcal{A}(s_-, s_+)g_-(t)$$
$$\overline{\mathcal{M}}(s_+, s_-, t) = \frac{q}{p}\overline{\mathcal{A}}(s_+, s_-)g_+(t) + \overline{\mathcal{A}}(s_-, s_+)g_-(t)$$

x and y are common across both topologies.

Determination of x and y

Time integrated Dalitz plots

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



Determination of x and y

- Measure x and y directly in self-conjugate final states.
  - $D \to K_S^0 \pi^+ \pi^-$
  - $D \to K_S^0 K^+ K^-$
- 600M $c\bar{c}$ pairs. (468.5 fb^{-1})
  - arXiv:1004.5053

- Time-dependent Dalitz plot analysis
  $s_+ = m^2(K_S^0 h^+)$
  $s_- = m^2(K_S^0 h^-)$
- If $CPV = 0$, $\mathcal{A}(s_+, s_-) = \bar{\mathcal{A}}(s_-, s_+)$
- Time dependence
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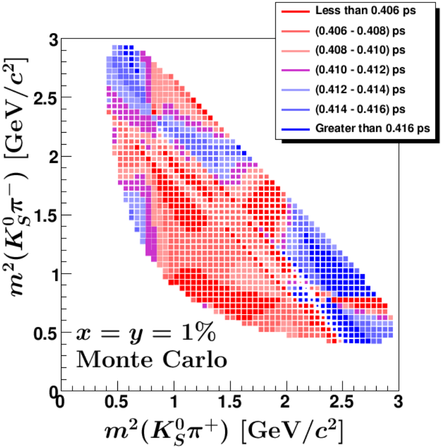
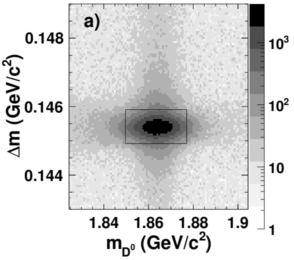
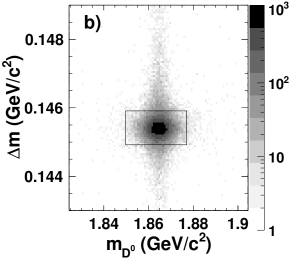


- D^0 and D^{*+} identification.
- ALSO INCLUDE PURITIES AND PERCENT OF BACKGROUND STUFF





HFAG (World averages) x and y