# D Mixing at BaBar

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On Behalf of

BaBar Collaboration

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# Outline

- D Mixing
  - Introduction and CPV
  - SM predictions
- Babar
  - Detector and datasets
  - Reconstruction techniques
- Current results and analyses
  - $D \rightarrow K\pi$
  - $D \rightarrow K\pi\pi$
  - $D \rightarrow KK,\pi\pi$

# Introduction to D–Mixing

- The $D^0$ and $\bar{D}^0$ mesons are produced as flavor eigenstates but evolve as mixtures of the effective hamiltonian mass eigenstates $D_1$ and $D_2$:

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

- Mixing occurs when flavor and hamiltonian eigenstates differ that is when there is a non-zero mass difference $\Delta m = m_1 - m_2$ or lifetime difference $\Delta\Gamma = \Gamma_1 - \Gamma_2$
  - Base change: $$|D_{1,2}\rangle = p|D^0\rangle + q|\overline{D}^0\rangle$$
  - where $|p|^2 + |q|^2 = 1$
- The mixing parameters are defined as

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

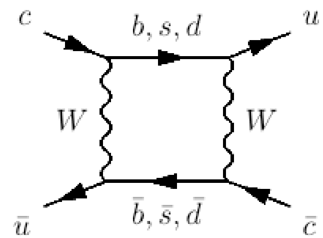
  - where $\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$
- More often you will find them expressed as x' and y'

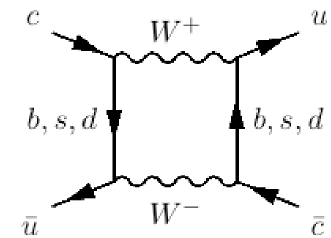
$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix}$$

- Where $\delta$ is the strong phase between the Cabibbo Favored and Doubly Cabibbo Suppressed decay amplitudes
- Mixing is well established in K, $B_d$, and $B_s$ mesons

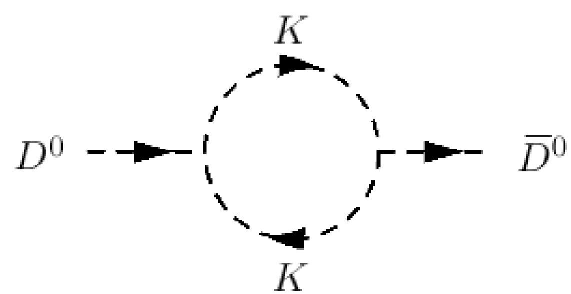
# SM Predictions

- Short distance contributions
  - SM predicts small mixing effect
  - b quark is CKM suppressed, s and d are GIM suppressed
  - Mainly contributes to mass difference ($x \sim O(10^{-5})$)




- Long distance contributions
  - Hadronic intermediate states dominant but still small
  - Non perturbative
  - Mainly affects the lifetime difference. Predictions give x and y in the range [0.001, 0.01], and |x| < |y|



# New Physics

- NP with new particles in loops
  - Sensitivity to NP through the mixing parameters
    - If |x|>>|y| or CPV ⇒ hint of NP
  - Requires direct measurement of x and y separately
    - $D^0 \to K^+\pi^-$ analysis measures $x'^2$ and $y'$ (strong phase rotated)
      - Relative $D^0$–$\overline{D}^0$ strong phase cannot be resolved at B factories in $D^0 \to K^+\pi^-$ decays
    - Decay modes like $D0 \to K_S h^+h^-$ where the final state can be accessed by both $D^0$ and $\overline{D}^0$ can resolve the strong phase via Dalitz analysis
  - Find CPV in SM is not expected with current sensitivity

# D-Mixing and CPV Analyses

- Mixing:
  - $D^0 \rightarrow K^+ \pi^-$
  - $D^0 \rightarrow K^+ K^-, \pi^+ \pi^-$
  - $D^0 \rightarrow K^+ \pi^- \pi^0$
  - $D^0 \rightarrow K^{(*)-} l^+ \nu$
  - $D^0 \rightarrow K_s \pi^+ \pi^-$

Measurement of mixing in time dependent suppressed hadronic decays.

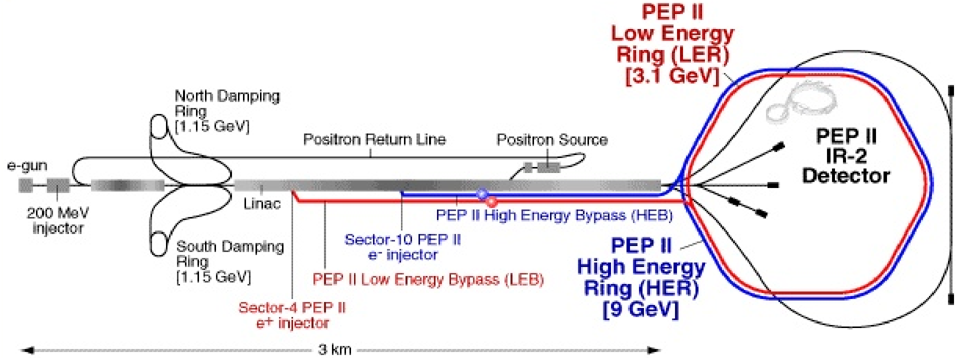
Measurement in time dependent semileptonic decays.

Dalitz time dependent analysis

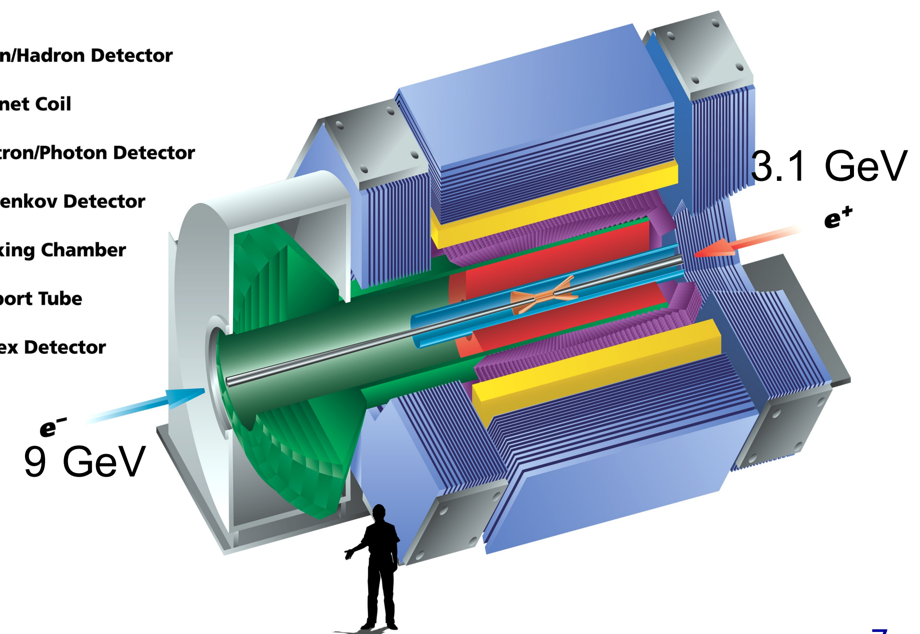
- CPV:
  - $D^0 \rightarrow K^+ K^-, \pi^+ \pi^-$
  - $D^0 \rightarrow \pi^+ \pi^- \pi^0$
  - $D^0 \rightarrow K^+ K^- \pi^0$

# PEP II and BaBar

- PEP II
  - Asymmetric
  - High Luminosity
  - On Y(4S) resonance
    - or 40MeV below for the off-peak
    - Final run also on Y(2S),Y(3S) and scan above Y(4S)




- BaBar
  - 1200 tons multipurpose detector
  - Wide angle coverage
  - 1.5T magnetic field

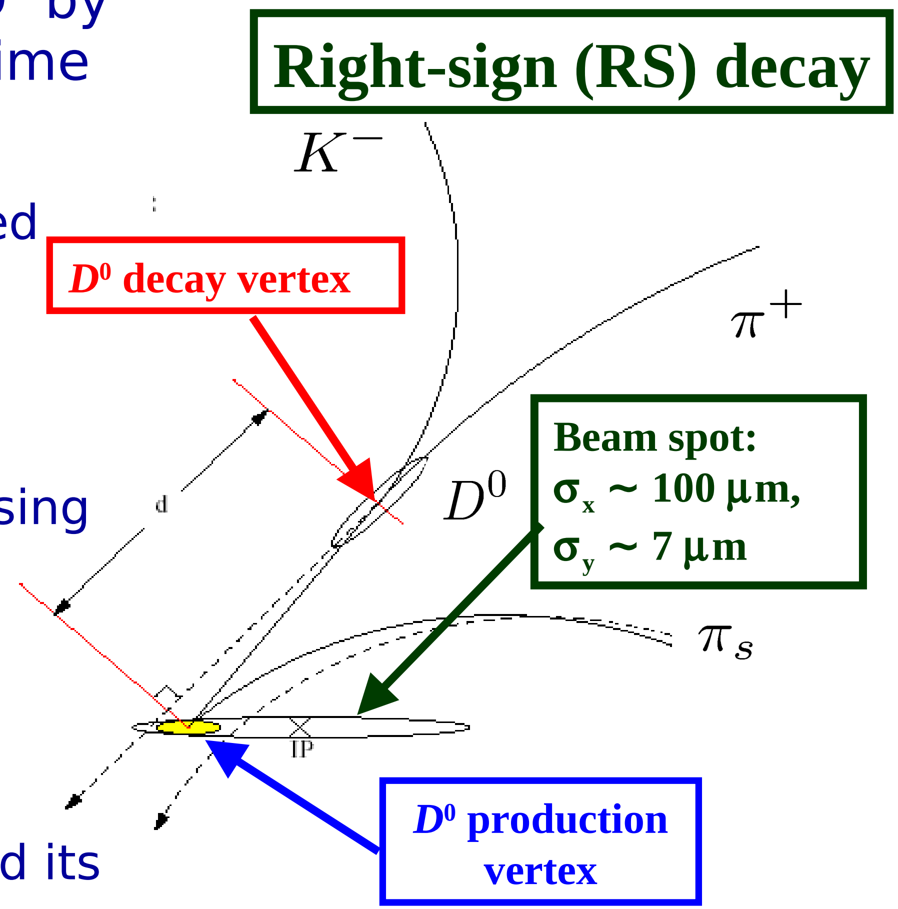



- A flavor factory
  - $\sigma_{b\bar{b}} = 1.10$ nb
  - $\sigma_{c\bar{c}} = 1.30$ nb
  - $\sigma_{\tau\tau} = 0.89$ nb
  - $\sigma_{uds} = 2.09$ nb

432/fb of $Y(4S)\rightarrow B\bar{B}$ events and 1.3 millions of $c\bar{c}$ events per fb

# D Production and Selection

- Select a clean sample of $D^0$ and $\overline{D}^0$ by tagging the flavor at production time using the decays $D^{*\pm} \rightarrow \pi^{\pm}_{s} D^0$
  - Select events around the expected $\Delta m = m(D^{*+}_{rec}) - m(D^0_{rec})$
  - The charge of the slow pion determines the flavor of the $D^0$
- Identify the $D^0$ flavor at decay time using the charge of the kaon
  - $D^0 \rightarrow K^- \pi^+$ right-sign (RS)
  - $D^0 \rightarrow K^+ \pi^-$ wrong-sign (WS)
- Vertices fit with beamspot constraint determines $m_{K\pi}$, $\Delta m$, proper time t and its error $\delta_t$




Typical $D^0$ flight length d~240μm
Average resolution $\sigma_d$~95μm

# Lifetime Measurement

- In absence of CPV, $D_1$ is CP-even and $D_2$ is CP-odd
- Lifetime $\tau$ measures for $D^0$ decays to CP-even and CP-odd final states result in a measure for $y_{CP}$:

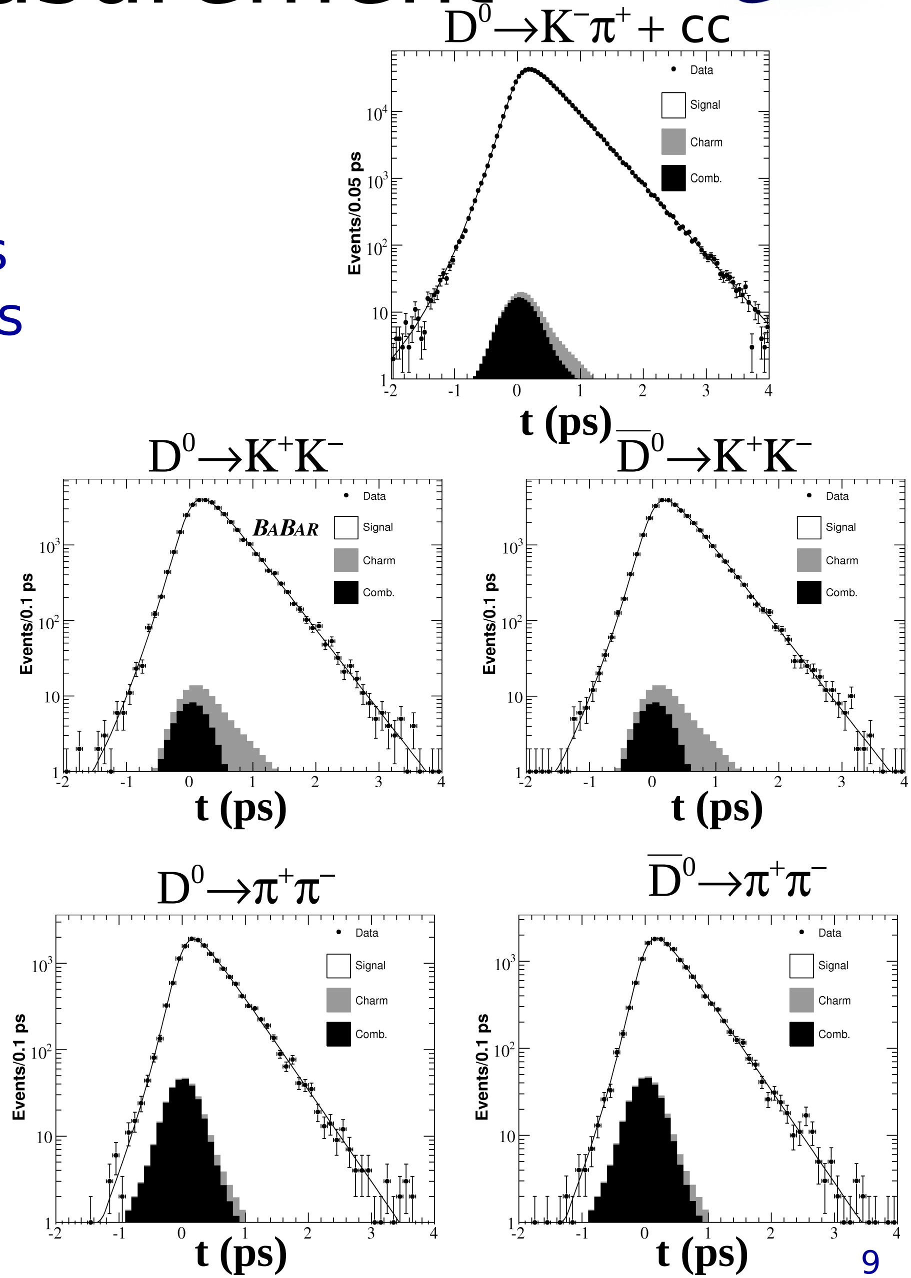
$$y_{CP} = \frac{\tau_{K\pi}}{\langle \tau_{hh} \rangle} - 1$$

- Allowing for CPV measure the $D^0$ and $\overline{D}^0$ asymmetry

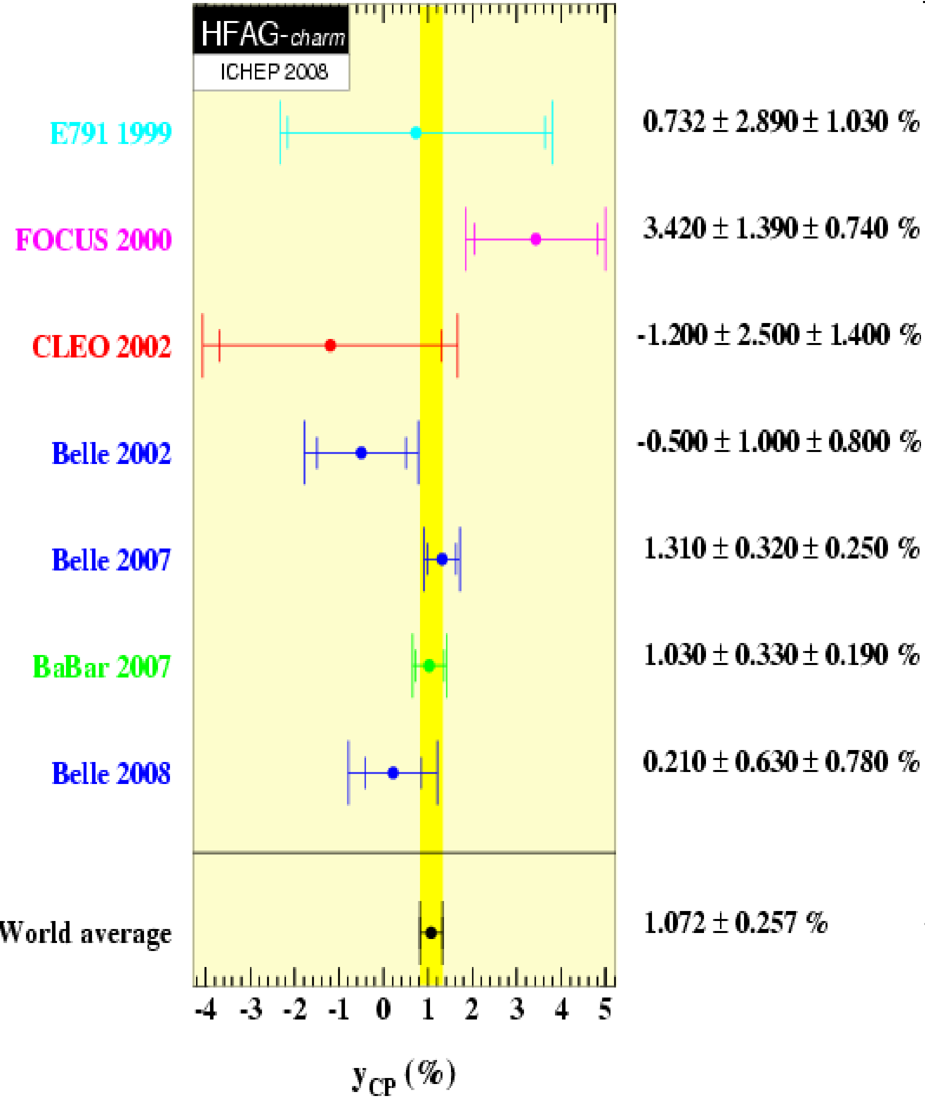
$$\Delta y = \frac{\tau_{K\pi}}{\langle \tau_{hh} \rangle} A_\tau$$

- where

$$\langle \tau_{hh} \rangle = \frac{\tau^+ + \tau^-}{2}, \qquad A_\tau = \frac{\tau^+ - \tau^-}{\tau^+ + \tau^-}$$



# Lifetime Results




Most recent result from BaBar

| Mode | $y_{CP}$ (%) | $\Delta Y = (1 - y_{CP}) A_\tau$ (%) |
|---|---|---|
| $K^+K^-$ | $1.60 \pm 0.46 \pm 0.17$ | $-0.40 \pm 0.44 \pm 0.12$ |
| $\pi^+\pi^-$ | $0.46 \pm 0.65 \pm 0.25$ | $0.05 \pm 0.64 \pm 0.32$ |
| Combined | $1.24 \pm 0.39 \pm 0.13$ | $-0.26 \pm 0.36 \pm 0.08$ |

**3.0 σ evidence - no *CPV***

**PRD 78 011105(R) (2008) 384 fb$^{-1}$**

Combining 384 /fb tagged and
91 /fb untagged (*BaBar*):
$y_{CP}$ = (1.03 ± 0.33(stat.) ± 0.19(syst.))%

HFAG World Average:
$y_{CP}$ = (1.072 ± 0.257 )%
arXiv 0808:1297 (2008)

# Mixing in WS $D^0 \to K^+\pi^-$

- The WS decays can occur via
  - Doubly Cabibbo-suppressed (DCS)
  - Mixing followed by the Cabibbo-Favored (CF) decay
- Two ways to reach the same final state: interference
  - The proper time evolution discriminates between the two
    - Assuming no CPV

$$\frac{d\Gamma}{dt}[|D^0(t)\rangle \to f] \propto e^{-\Gamma t}\left(R_{\rm D} + \sqrt{R_{\rm D}}y'\,\Gamma t + \frac{x'^2 + y'^2}{4}(\Gamma t)^2\right)$$

**DCS Decays** — **Interference between DCB and mixing** — **Mixing**

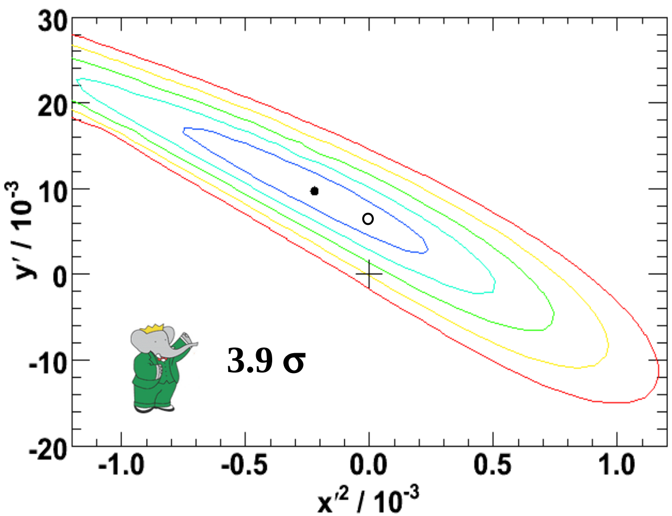
- $\delta_{K\pi}$ being the strong phase between CF and DCF decay amplitudes

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

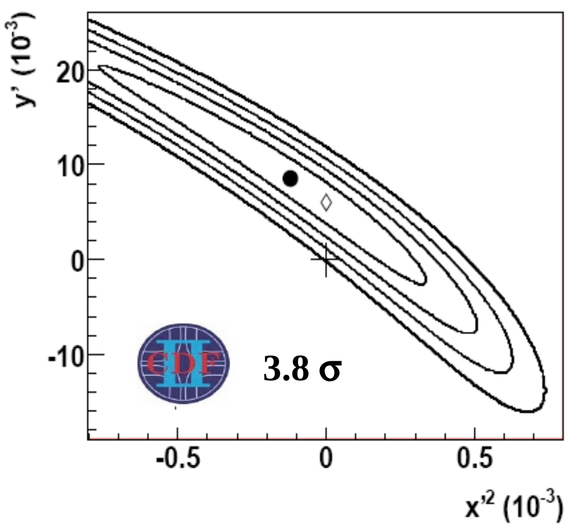
# Observation of Mixing in $D \to K^+\pi^-$

- Evidence of mixing from BaBar (3.9σ) confirmed by CDF (3.8σ)

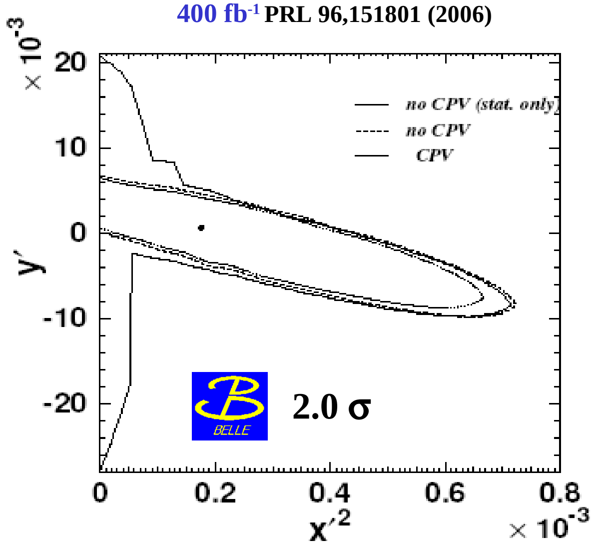
384 $fb^{-1}$ PRL 98,211802 (2007)




1.5 $fb^{-1}$ PRL 100,121802 (2008)




400 $fb^{-1}$ PRL 96,151801 (2006)




- ● Best fit
- ○ Best fit $x'^2 > 0$
- + No mixing

| Experiment | $R_D (10^{-3})$ | $y' (10^{-3})$ | $x'^2 (10^{-3})$ | Mixing Signif. |
|---|---|---|---|---|
| CDF | $3.04 \pm 0.55$ | $8.5 \pm 7.6$ | $-0.12 \pm 0.35$ | 3.8 |
| *BABAR* | $3.03 \pm 0.19$ | $9.7 \pm 5.4$ | $-0.22 \pm 0.37$ | 3.9 |
| Belle | $3.64 \pm 0.17$ | $0.6 + 4.0 - 3.9$ | $0.18 + 0.21 - 0.23$ | 2.0 |

# Mixing in WS $D^0 \to K^+\pi^-\pi^0$

- Analysis formally similar to the WS $D^0 \to K^+\pi^-$ analysis but the strong phase δ depends on the position on the Dalitz plot

$$\frac{dN_{\bar f}(s_{12}, s_{13}, t)}{ds_{12}ds_{13}dt} = e^{-\Gamma t}\{|A_{\bar f}|^2 + \quad \textbf{DCS Decays}$$

**Interference** $|A_{\bar f}||\bar A_{\bar f}|\left[y\cos\delta_{\bar f} - x\sin\delta_{\bar f}\right](\Gamma t) +$

**Mixing** $\frac{x^2+y^2}{4}|\bar A_{\bar f}|^2(\Gamma t)^2\}$

$$\bar A_{\bar f} = \bar A_{\bar f}(s_{12}, s_{13}) = \langle K^+\pi^-\pi^0 | H | \bar D^0\rangle$$

$$A_{\bar f} = A_{\bar f}(s_{12}, s_{13}) = \langle K^+\pi^-\pi^0 | H | D^0\rangle$$

$$s_{12} = m_{K^+\pi^-}$$

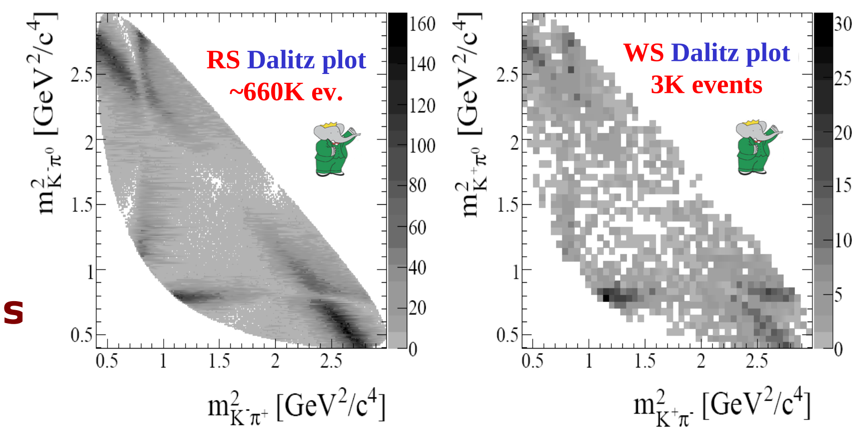
$$s_{13} = m_{K^+\pi^0}$$

- The mixing parameters are

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

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

**δ is the phase difference between DCS $D^0 \to \rho K^+$ and $\bar D^0 \to \rho K^+$ reference amplitudes and cannot be determined in this analysis**




signal box:
*0.1449<Δm<0.1459* GeV/c²
*1.8495<$m_{K\pi\pi}$<1.8795* GeV/c²

*RS* signal purity: 99%
*WS* signal purity: 50%

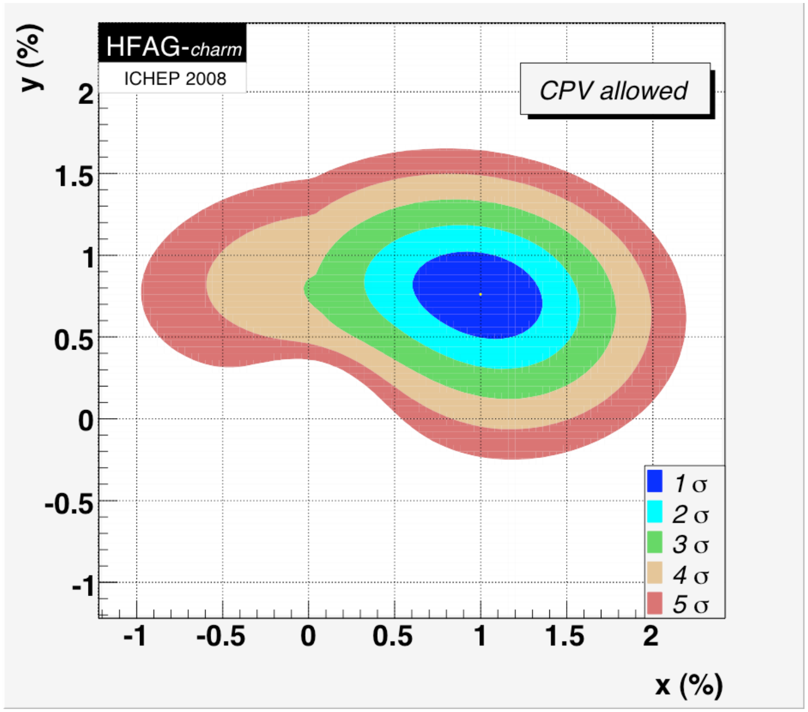
- Result: no evidence of CPV

384 fb-1 : arXiv:0807, 4544 [hep-ex], submitted to PRL

# Evidence of Mixing

| | | |
|---|---|---|
| *BABAR: PRL **98** 211802 (2007)* | $D^0 \to K^+\pi^-$ *decay time analysis* | $3.9\sigma$ |
| *BELLE: PRL **98** 211803 (2007)* | $D^0 \to K^+K^-, \pi^+\pi^-$ *vs* $K^+\pi^-$ *lifetime difference analysis* | $3.2\sigma$ |
| *BELLE: PRL **99** 131803 (2007)* | $D^0 \to K_s\pi^+\pi^-$ *time dependent amplitude analysis* | $2.2\sigma$ |
| *CDF: PRL **100**, 121802 (2008)* | $D^0 \to K^+\pi^-$ *decay time analysis* | $3.8\sigma$ |
| *BABAR: PRD **78**, 011105 R (2008)* | $D^0 \to K^+K^-, \pi^+\pi^-$ *vs* $K^+\pi^-$ *lifetime difference analysis* | $3\sigma$ |
| *BABAR*: arXiv:0807, 4544 *(2008)* | $D^0 \to K^+\pi^-\pi^0$ *time dependent amplitude analysis* | $3.1\sigma$ |
| | ***all mixing results combined by HFAG:*** | **$\sim 10\sigma$** |

- No-Mixing point excluded at 9.8σ
- No single mixing measurement exceeds 5σ but combined significance does.
- No evidence for CPV in mixing



# Time Integrated CPV

$$a_{CP}^{hh} = \frac{\Gamma(D^0 \to h^- h^+) - \Gamma(\bar{D}^0 \to h^+ h^-)}{\Gamma(D^0 \to h^- h^+) + \Gamma(\bar{D}^0 \to h^+ h^-)}$$

- Measures the time integrated CP asymmetries in CP-even final states
- SM predictions are very small ($10^{-(4-5)}$)
  - a 0.1% level observation would indicate NP
- Relative $\pi_s^+ - \pi_s^-$ tracking efficiencies are not equal
  - Use $D^0 \to K^- \pi^+$ tagged and untagged data to determine this systematic
  - Will scale down with luminosities
- Based on the measurement of the asymmetries of the partial decay widths
  - Due to $Z/\gamma$ interference and radiative corrections $D^0$ and $\overline{D}^0$ are produced with a forward backward asymmetry in the CM polar angle
    - Compute the $D^0$ – $\overline{D}^0$ flavor asymmetry vs $\cos\theta$ in the center of mass
    - Extract $A_{cp}$ and $A_{fb}$ by constructing even and odd functions of $\cos\theta$

$$a^{\pm}(\cos\theta) = \frac{N^{D^0}(\pm\cos\theta) - N^{\overline{D}^0}(\pm\cos\theta)}{N^{D^0}(\pm\cos\theta) + N^{\overline{D}^0}(\pm\cos\theta)}$$

+ : forward hemisphere

- : backward hemisphere

$$\frac{a^+(\cos\theta) + a^-(\cos\theta)}{2} \approx a_{CP}(\cos\theta)$$

$$\frac{a^+(\cos\theta) - a^-(\cos\theta)}{2} \approx a_{FB}(\cos\theta)$$

$0 \le \cos\theta \le 1$

# CP Asymmetries

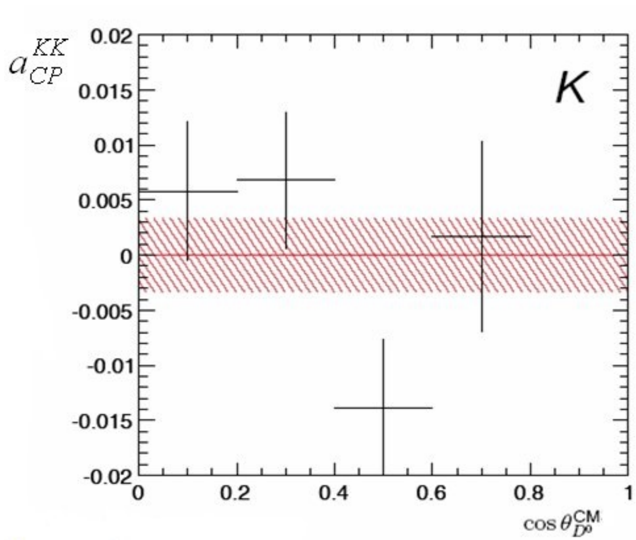
***Time integrated CP asymmetry***

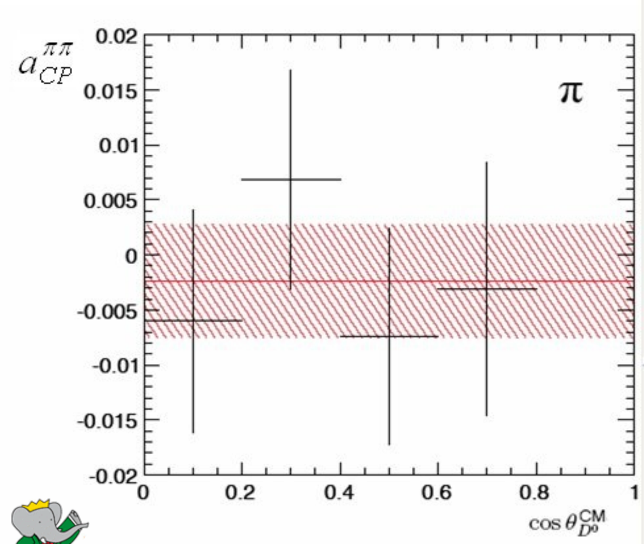
***PRL 100 061803 (2008), 384/fb***

***No evidence of CPV***

$$a_{CP}^{KK} = (0.00 \pm 0.34 \pm 0.13)\%$$

$$a_{CP}^{\pi\pi} = (-0.24 \pm 0.54 \pm 0.22)\%$$



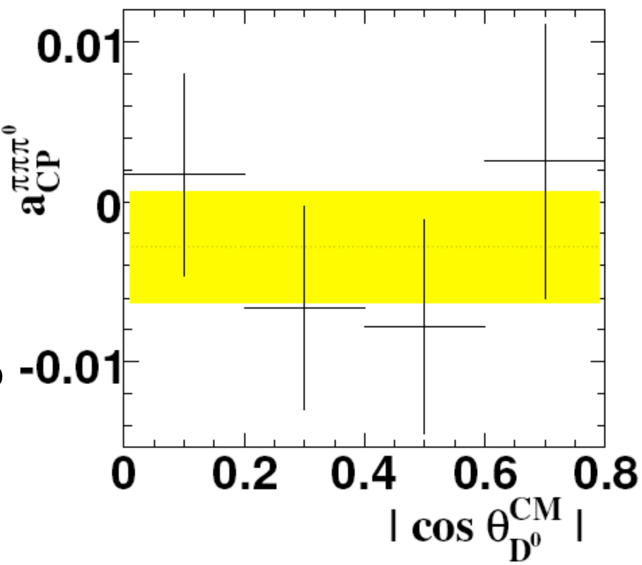

***Phase space integrated CP asymmetry***

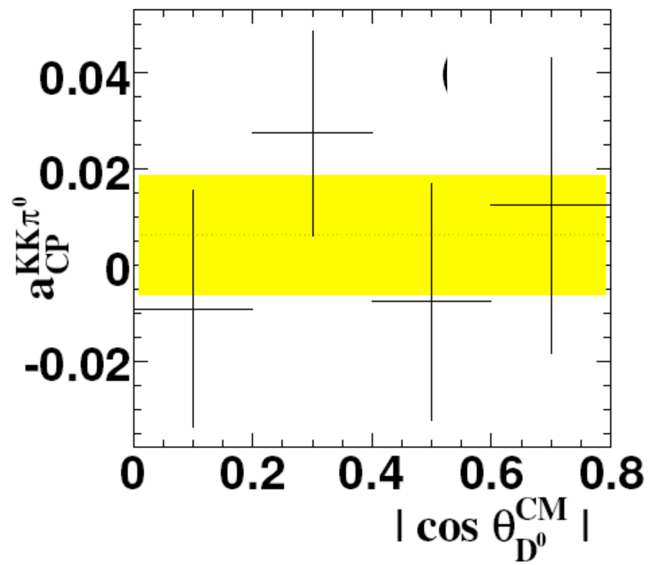
***Phys. Rev. D78 051102 (2008)***

***No evidence of CPV***

$$a_{CP}^{\pi\pi\pi^0} = (-0.31 \pm 0.41 \pm 0.17)\%$$

$$a_{CP}^{KK\pi^0} = (1.00 \pm 1.67 \pm 0.25)\%$$



# Summary

- Combined evidence for D-mixing
  - No-mixing point excluded at 10$\sigma$ (HFAG average)
  - No single measure exceeds 5$\sigma$
- Average values are still compatible with the SM
  - X~1%, y~0.8%
- No evidence of CP violation

# Backup

# Preview

- $D^0$ Dalitz decays ($D^0 \to K_s \pi^+ \pi^-$, $K_s K^+ K^-$, $D^0 \to \pi^+ \pi^- \pi^0$)
  - Since evolution of mass eigenstates is known, the time dependent amplitude is

$$\langle f|\mathcal{H}|D^0(t)\rangle = A_f\left(\frac{1+\chi}{2}e_1(t) + \frac{1-\chi}{2}e_2(t)\right)$$

  - Where

$$\tilde{A}_f = \langle f|\mathcal{H}|\tilde{D}^0\rangle = \tilde{A}_f(m^2_{K_s h^+}, m^2_{K_s h^-})$$

May implement CP violation in the mixing

$$\chi = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

May implement CP violation in the decay

  - What is relevant from these expressions is the fact that the phase space and the life time dependencies do not factorize.
    - This entanglement is exactly what provides sensitivity to the mixing parameters x and y, directly.
- Untagged lifetime ratio $D^0 \to KK(\pi\pi)$ / $D^0 \to K\pi$.
  - Update previous result with 384 $fb^{-1}$ of data.