# $D^0$-$D^0$ Mixing

Amir Rahimi
The Ohio State University
BABAR Collaboration

APS 2007

## Outline

- Charm Meson Mixing
- Review of Recent Mixing Analysis
  - Mixing in Semileptonic Decays by Belle and BaBar
  - Quantum Correlation Analysis in CLEO-c
  - Mixing with t-dependent Dalitz Plot by Belle Using $D^0 \to K_s \pi^- \pi^+$
  - Evidence for Mixing from BaBar Using $D^0 \to K\pi^+$
  - Evidence for Mixing from Belle Using $D^0 \to KK$, $\pi\pi$, and $K\pi$
- Summary

# Brief History

- Neutral Charm meson is one of the four neutral mesons that can mix with its anti-particle
  - $K^0$, $B^0$ and $B_s^0$ are the other three
- $K^0$ mixing first observed in 1958
- $B^0$ mixing first observed by ARGUS experiment in 1987
- $B_s^0$ mixing rate first measured by CDF and D0 in 2006

# Brief History

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- $K^0$ mixing first observed in 1958
- $B^0$ mixing first observed by ARGUS experiment in 1987
- $B_s^0$ mixing rate first measured by CDF and D0 in 2006
- $D^0$ mixing was not observed until a few weeks ago

# Formalism

- Neutral mesons $D^0$ and $\bar{D}^0$ are flavor eigenstates produced via strong interactions
- Due to weak force, evolve into a mixture of $D^0$ and $\bar{D}^0$
  - Time evolution described by the weak Hamiltonian

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

$$m_{12} = m_1 - m_2$$
$$\Gamma_{12} = \Gamma_1 - \Gamma_2$$
$$m = \frac{m_1 + m_2}{2}$$
$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

- Mass eigenstates: $|D_{1,2}(t)\rangle = p|D^0(t)\rangle \pm q|\bar{D}^0(t)\rangle$
- Mixing is parameterized by x and y
  - $m_{1,2}$, and $\Gamma_{1,2}$ are $D_{1,2}$ mass and lifetimes

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

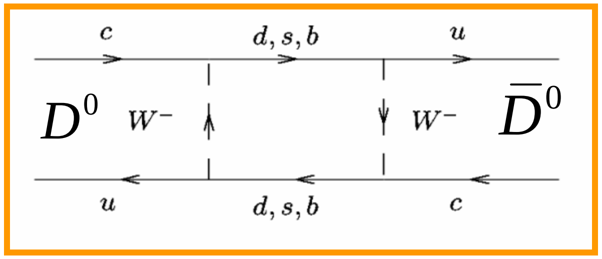
- Express time evolution of $D^0$ as:

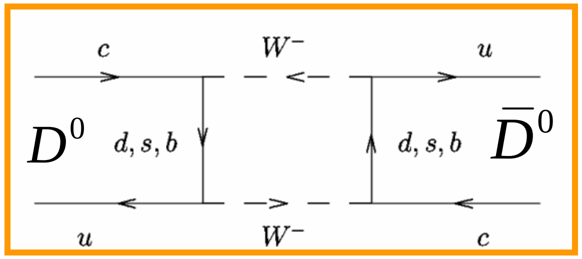
$$|D^0(t)\rangle = e^{-(im+\frac{\Gamma}{2})t}\left(|D^0\rangle \cosh\left[(y+ix)\Gamma t\right] + \frac{q}{p}|\bar{D}^0\rangle \sinh\left[(y+ix)\Gamma t\right]\right)$$

# Mixing Process

E.Golowitch, A.Petrov, Phys.Lett. B625 (2005) 53-62
A.Falk, Y.Grossman, Z.Ligeti, A.Pterov, Phys.Lett. B625 (2005) 53-62

- Box diagram Standard Model charm mixing rate naively expected to be very low (mainly contribute to x)
  - Cabibbo-Kobayashi-Maskawa and Glashow-Iliopoulus-Maiani suppressed

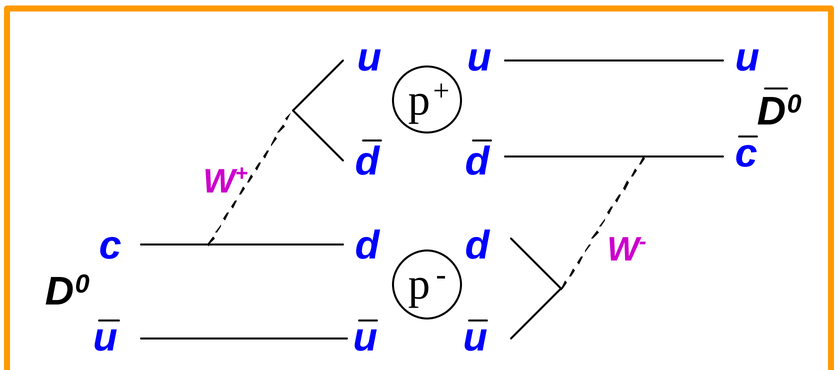



$$x \approx O(10^{-6}) - O(10^{-5})$$

Mass difference

- Long distance effects dominate (mainly contribute to y)




SM Mixing: a long-range contribution

Mass difference

$$x \le O(10^{-2})$$

$$y \le O(10^{-2})$$

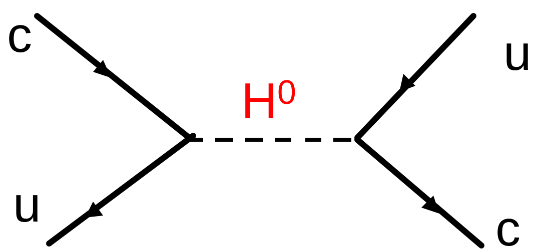
$$R_M = \frac{x^2 + y^2}{2} \le O(10^{-4})$$

Lifetime difference

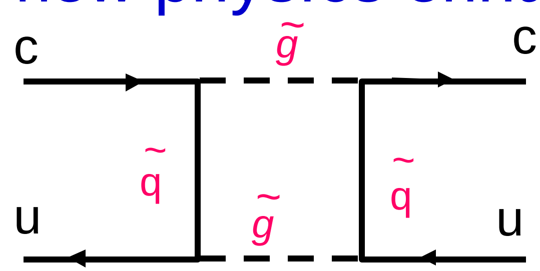
# New Physics Contribution to Charm Mixing

G.Burdman, I.Shipsey, Ann.Rev.Nucl.Part.Sci. 53 (2003) 431-499

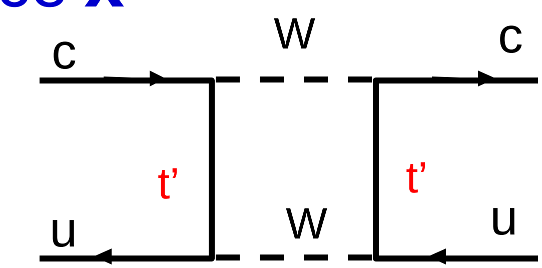
- Possible enhancements to mixing due to new physics
- Contributions from new physics enhance **x**




FCNC

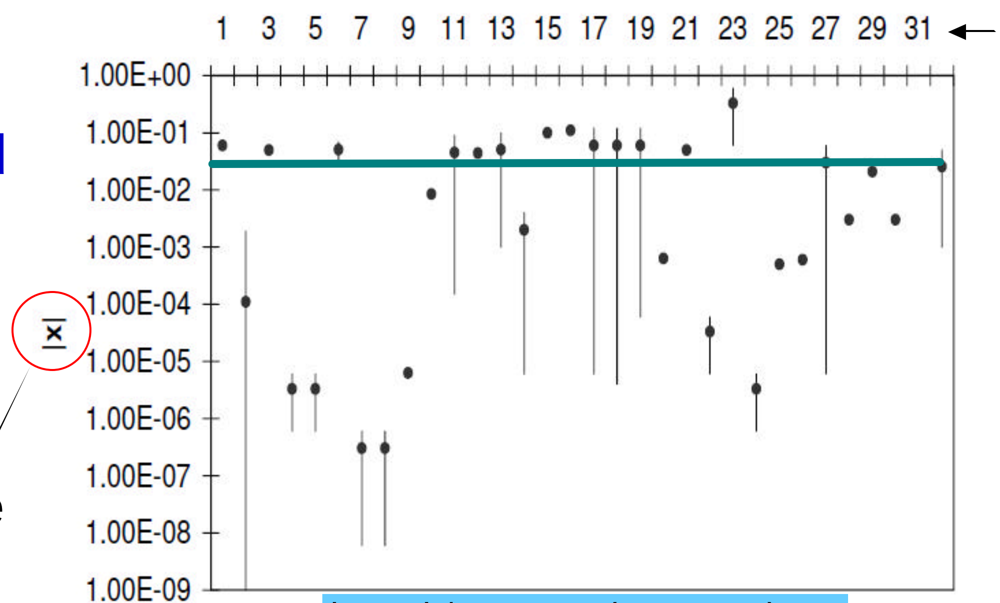



Supersymmetry




Fourth quark generation

- Indication of NP would be observation of CP-violation or $\Delta$(mass)>>$\Delta$(lifetime)




paper reference

Mass difference

hep-ph/0311371 (A. Petrov)

2006 upper limit

Already constraining New Physics models

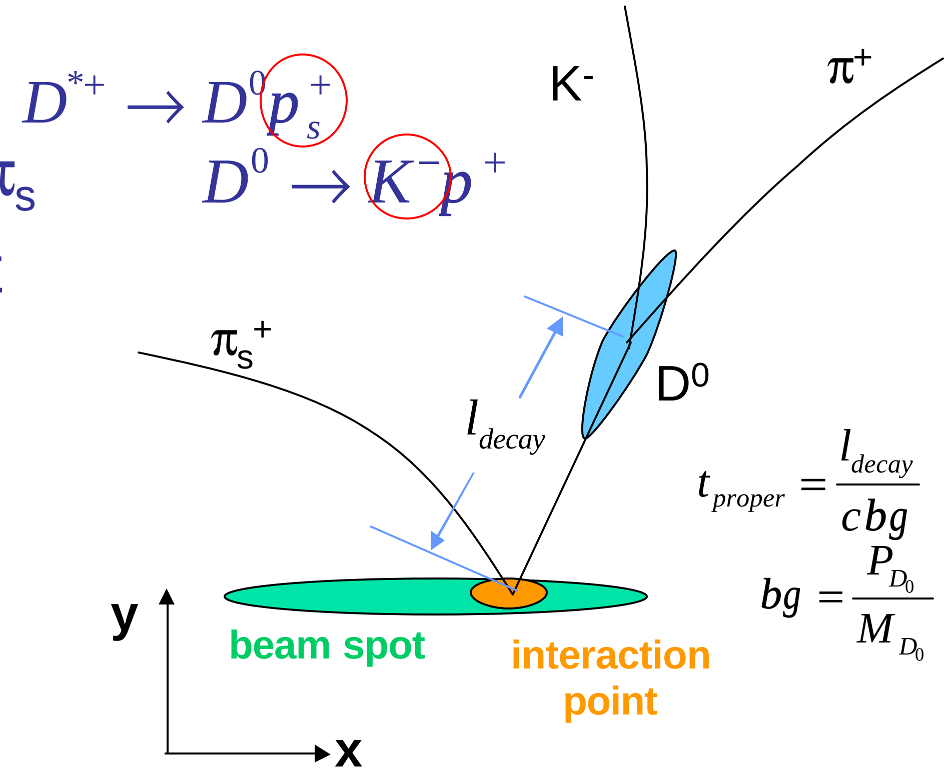
# $D^0$-$\bar{D}^0$ Mixing Parameters

- Mixing parameters and the quantities measured in the experiments (analyses which are most relevant to this talk):

| Analysis | Decay Modes | Time dependence | parameters |
|---|---|---|---|
| Wrong-Sign (**WS**) semileptonic decays | $D^0 \to K l \nu$, etc. | Time integrated | $R_M = \frac{x^2+y^2}{2} = \frac{N_{WS}}{N_{RS}}$ |
| WS hadronic decays | $D^0 \to K \pi$, etc. | Decay time analysis | $x'^2$, y' and r (Doubly Cabibbo Suppressed (DCS) Rate)<br>$x' = x\cos(d) + y\sin(d)$ → Strong phase<br>$y' = y\cos(d) - x\sin(d)$ |
| CP eigenstate lifetime differences | $D^0 \to KK$, $(\pi\pi)$, etc. | Decay time analysis | $y_{CP} = \frac{\Gamma(CP+) - \Gamma(CP-)}{\Gamma(CP+) + \Gamma(CP-)}$<br>If no CPV: $y_{CP} = y$ |
| Time dependent Dalitz plot analysis | $D^0 \to K_s\pi\pi$, etc. | Decay time analysis | x, y |
| Quantum Correlations<br>$e^+e^- \to \psi(3770) \to D\bar{D}$ | -flavored ($K^-\pi^+$)<br>-CP+ eigenstates ($K^-K^+$)<br>-CP- eignestates ($K_s\pi^0$)<br>-semileptonic ($Xe\nu$) | Time integrated | x, y, $\delta$, r |

# Several common event selection in B-Factories

- Flavor-tag using the charge $\pi_s$
- Proper lifetime measurement
- CM P*($D^0$) > 2.5 GeV/c
- Common background categories
  - Correct $D^0$, wrong $\pi_s$
  - Misreconstructed $D^0$
    - Partially reconstructed or double misid $D^0$
  - Combinatorial
  - Each tend to have distinct (M(Kπ), ΔM) distributions




- General Parameters of interest to measure mixing parameters
  - $D^0$ mass = m($D^o_{candidate}$)
  - $\Delta m$ = m($D^*_{candidate}$) – m ($D^o_{candidate}$)
  - $D^0$ proper decay time t

# Mixing with Semileptonic Modes From Belle and BaBar

**Belle: PRD (RC) 72, 071101 (2005)**

**BaBar: Moriond 2007**

**Previous analysis:**
**E.M. Aitala et al. (E791), PRL 77, 2384 (1996)**
**C. Cawlfield et al. (CLEO II), PRD 71, 077101 (2005)**
**B. Aubert et al. (BABAR), PRD 70, 091102 (2004)**

# $D^0 \rightarrow Ke\nu$ Results from Belle

- No DCS decays in semi-leptonic modes
- Simpler time dependence

$$\Gamma_{WS}(t) \approx \left[\exp\left(-t/t_{D^0}\right)\right]\left(\frac{t}{t_{D^0}}\right)^2\left(\frac{x^2+y^2}{4}\right)$$

$$D^{*+} \rightarrow D^0 \, p^+$$

**RS:** $D^0 \rightarrow K^- \ell^+ n$

**WS:** $D^0 \rightarrow K^+ \ell^- \overline{n}$

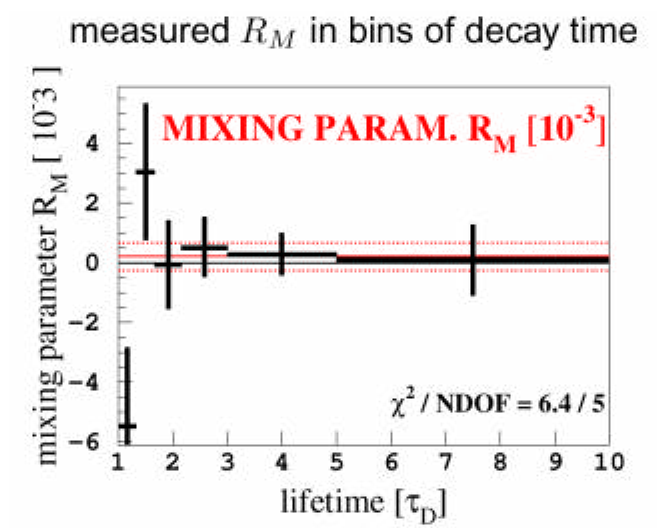
- In the limit of no CP violation measure time integrated mixing rate $$R_M = \frac{x^2+y^2}{2} = \frac{x'^2+y'^2}{2}$$

**253 fb$^{-1}$**

**PRD (RC) 72, 071101 (2005)**

- Observable: $\Delta M = M(\pi Ke\nu) - M(Ke\nu)$
- Fit of WS is performed in bins of lifetimes to increase sensitivity

***R*$_M$ < 1.2 x 10$^{-3}$ @95% CL**

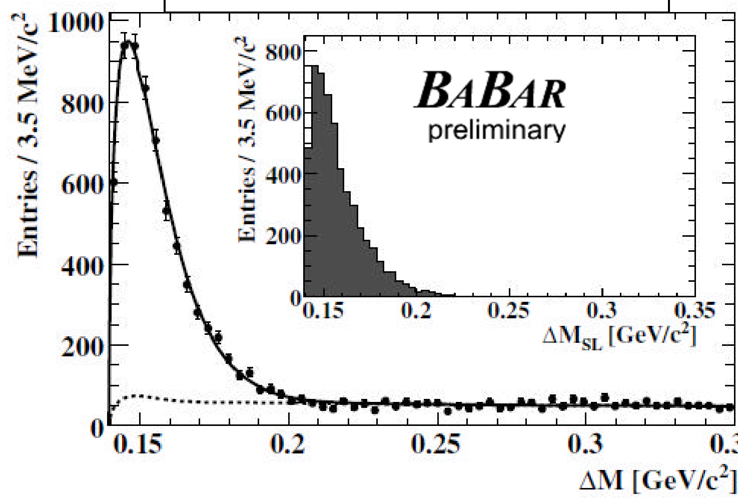


# $D^0 \to Ke\nu$ Results from BaBar

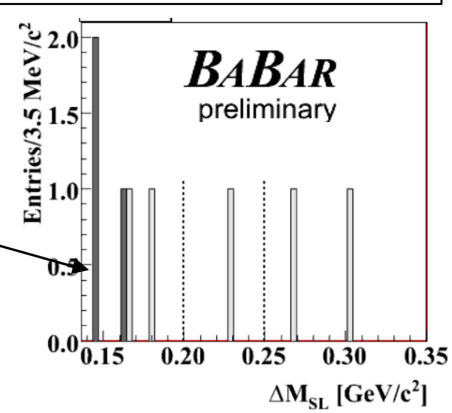
- Observable: $\Delta M = M(\pi Ke) - M(Ke)$, 344 $fb^{-1}$
- Double tag
  - $D^{*+} \to D^0 p_s^+$ in semileptonic
  - Five fully reconstructed hadronic tagging modes
- Unbinned maximum likelihood fit to RS *DM*
- Predict 2.85 background events, observe 3 (dark gray)

Presented at Moriond 2007

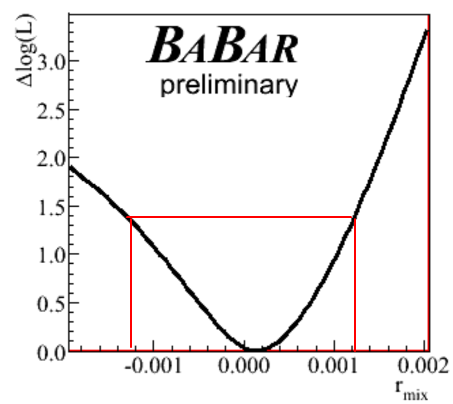
*DM* **RS distribution**




*DM* **WS distribution**




**Likelihood profile**




***$-1.3 \times 10^{-3} < R_M < 1.2 \times 10^{-3}$ @ 90% C. L.***

# CLEO-c

## $D^0D^0$ Quantum Correlations: Measuring x, y, r (DCS rate) and δ Simultaneously at CLEO-c

**Asner & Sun, PRD 73** 034024 (2006), [**hep-ph/0507238]**

CLEO-c

# Quantum-coherent $D^0D^0$ at CLEO-c

$e^+e^- \rightarrow \psi(3770) \rightarrow DD$

Pure $J^{PC} = 1^{--}$ initial state

$$e^+e^- \rightarrow g^* \rightarrow D^0\bar{D}^0 \quad C = -1$$

- Quantum-coherent $D^0D^0$ state provides time-integrated sensitivity for simultaneously measuring x, y, r, and $\delta$.

- Four types of final states considered:
  - flavored ($K^-\pi^+$)
  - CP+ eigenstates
  - CP- eignestates
  - semileptonic ($Xe\nu$)
- Reconstruct one (ST) or both (DT) D mesons
- Event yields can be expressed as a function of:
  - $D^0D^0$ pairs produced
  - Branching fractions
  - Mixing parameters y and $R_M = (x^2 + y^2)/2$
  - DCS rate *r* and the strong phase $-\delta$
- Fit to the yields to extract these parameters

# Preliminary Fit Results and Future Work at CLEO-c

CLEO-c

D.M. Asner et al, Int.J.Mod.Phys;5456-5659,2006

hep-ex/0607078

- Fit inputs: 6 ST, 14 hadronic DT, 10 semileptonic DT, efficiencies, crossfeeds, background branching fractions and efficiencies

- **Preliminary** fitted results when $r^2$ constrained (281 $pb^{-1}$ dataset)
  - **cosd = 1.08 ± 0.66 ± ?**
  - ***y* = -0.057 ± 0.066 ± ?**
- Final results on 281 $pb^{-1}$ dataset awaiting collaboration approval
  - Includes systematic errors and new modes $K_s\eta$, $K_s\omega$, and $K_L\pi^0$
  - First measurement of $\delta$
  - Expect $\sigma(y) \sim 0.015$ and $\sigma(\cos\delta_{K\pi}) \sim 0.3$
- Project 750 $pb^{-1}$ by 2008
  - Expect $\sigma(y) \sim 0.01$ and $\sigma(\cos\delta_{K\pi}) \sim 0.1\text{-}0.2$

$\chi 2 = 17.0$ for 19 d.o.f. (C.L. = 59%).

Uncertainties are statistical *only*

preliminary

| Parameter | Value |
|---|---|
| $N_{D^0\overline{D^0}}$ | $(1.09 \pm 0.04 \pm ?)\times 10^6$ |
| $y$ | $-0.057 \pm 0.066 \pm ?$ |
| $r^2$ | $-0.028 \pm 0.069 \pm ?$ |
| $r(2\cos\delta_{K\pi})$ | $0.130 \pm 0.082 \pm ?$ |
| $R_M$ | $(1.74 \pm 1.47 \pm ?)\times 10^{-3}$ |

**Q.C. technique very promising for future high-statistics experiments (BES III, "Super Flavor Factory")**

# Time–dependent Dalitz Plot Analysis of $D^0 \rightarrow K_s \pi^- \pi^+$ at Belle

arXiv:0704.1000v1 [hep-ex], Moriond EW/QCD 2007

**Previous analysis:**
**D. M. Asner et al. (CLEO), PRD 72, 012001 (2005)**
**H. Muramatsu et al. (CLEO), PRL 89, 251802 (2002)**

# Time-dependent Dalitz Plot Analysis of $D^0 \rightarrow K_s p^- p^+$

- Decay matrix element to a final state $|f\rangle$

Using the notation:

$$\mathcal{M}(m^2_{K^0_s p^-}, m^2_{K^0_s p^+}, t) \equiv \mathcal{M}(m^2_-, m^2_+, t)$$

$$\mathcal{M}(m^2_-, m^2_+, t) = \langle f | D^0(t) \rangle = \frac{1}{2}\mathcal{A}(m^2_-, m^2_+)\left[e^{-l_1 t} + e^{-l_2 t}\right] + \frac{1}{2}\frac{p}{q}\bar{\mathcal{A}}(m^2_+, m^2_-)\left[e^{-l_1 t} - e^{-l_2 t}\right]$$

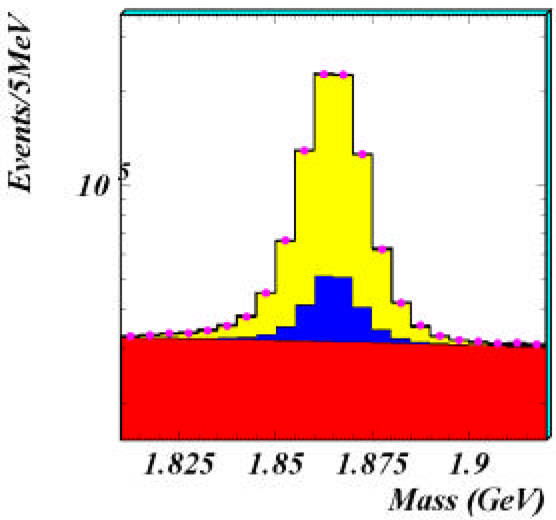
- Where: $l_{1,2} = i(m_{1,2} - \frac{i}{2}\Gamma_{1,2})$ (function of x and y)

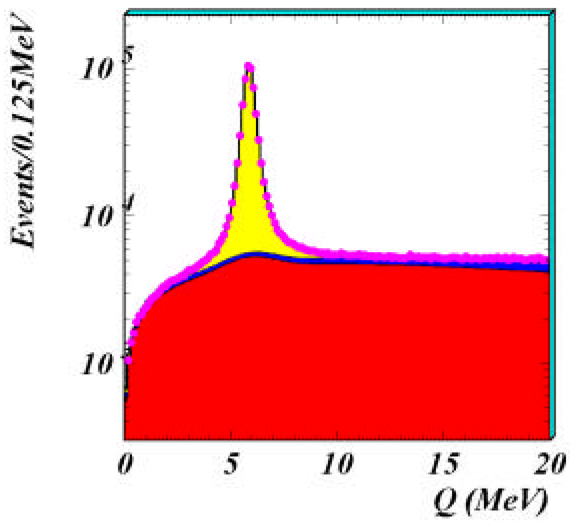
Analogous for $\bar{\mathcal{M}}$ and $\bar{D}^0(t)$

$$m_\pm = \begin{cases} m(K_s, p^\pm) & D^{*+} \to D^0 p^+ \\ m(K_s, p^\mp) & D^{*-} \to \bar{D}^0 p^- \end{cases}$$

- In the limit of CP conservation: $\left(\frac{p}{q} = 1, \mathcal{A} = \bar{\mathcal{A}}\right) \Rightarrow \mathcal{M} = \bar{\mathcal{M}}$
- Measurement directly sensitive to x and y

# Mass plots and Dalitz Fit for $D^0 \rightarrow K_s p^- p^+$




Belle preliminary, 540 $fb^{-1}$

**~700Million Charm Pairs**

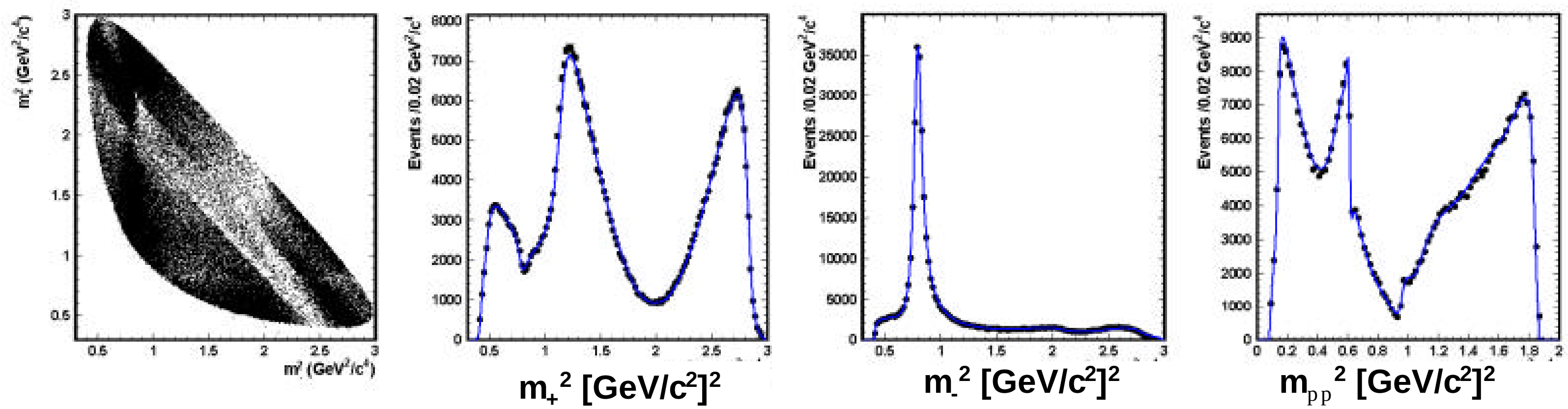
**M= M(K** p)

**Q** = **M($K_s p^+ p^- p_{slow}$)** - **M($K_s p^+ p^-$)** -M($p_{slow}$)

- $534 \times 10^3$ signal events
- purity 95%

- Dalitz model: 13 (BW) resonances, non-resonant, bkg.
- For scalar ππ, K-matrix formalism also used
- Results with refined model consistent with Belle $\phi_3$/g meas.

PRD73, 112009 (2006)



# Results of Time-dependent Dalitz Plot Analysis of $D^0 \rightarrow K_s\pi^-\pi^+$ at Belle

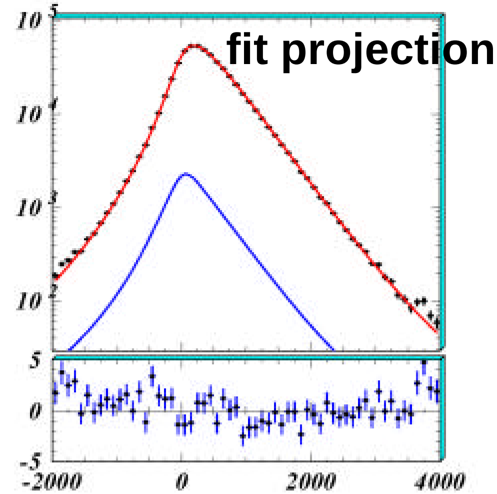
arXiv:0704.1000v1 [hep-ex], Moriond EW/QCD 2007

Results:

$x = 0.80 \pm 0.29 \pm 0.17$ %

$y = 0.33 \pm 0.24 \pm 0.15$ %

$\tau = 409.9 \pm 0.9$ fs




**Most sensitive measurement of x;**

(2.4 $\sigma$ 1-d significance)

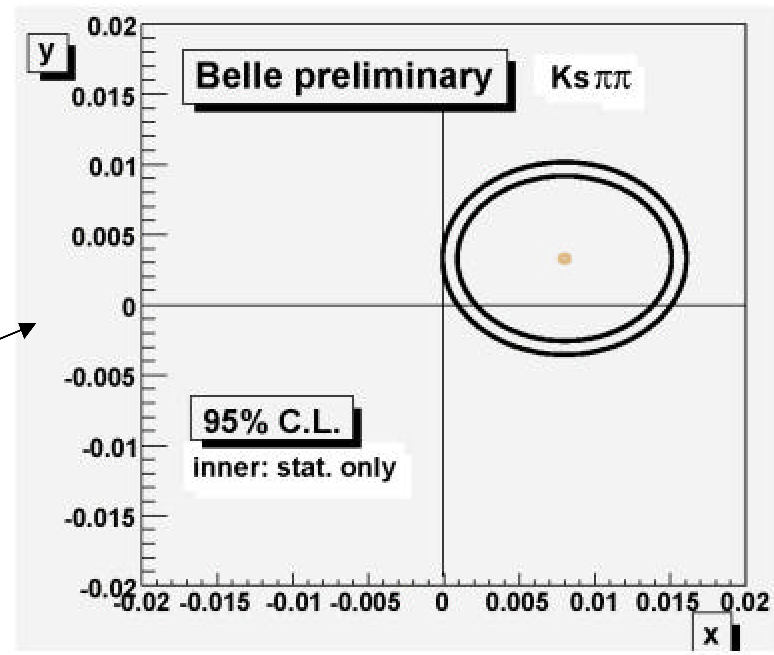
Cleo, PRD72, 012001 (2005)

$x = 1.8 \pm 3.4 \pm 0.6\%$

$y = -1.4 \pm 2.5 \pm 0.9\%$

95% C.L. contour;

(0,0) point has $-2\Delta\log(L)=7.3$
C.L. 2.6% (1.9 $\sigma$)



# Evidence For Mixing Using $D^0 \to K^- p^+$ at BaBar

**hep-ex/0703020**

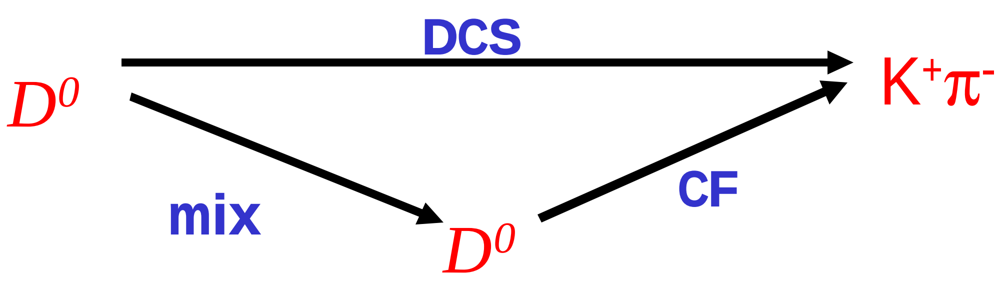
**Submitted To PRL**

**Previous analysis:**

**R. Godang et al. (CLEO), PRL 84, 5038 (2000)**
**J.M. Link et al. (FOCUS), PRL 86, 2955 (2001)**
**B. Aubert et al. (BABAR), PRL 91, 171801 (2003)**
**J.M. Link et al. (FOCUS), PLB 618, 23 (2005)**
**J. Li et al. (Belle), PRL 94, 071801 (2005)**
**L.M. Zhang et al. (Belle), PRL 96, 151801 (2006)**

# Time-dependent Mixing Analysis Using $D^0 \rightarrow K\pi$ at BaBar

**Hadronic wrong-sign (WS) decay**




**$|\text{DCS} + \text{mix} \,.\, \text{CF}|^2$**

- Separate DCS decays from the mixed decays using their different time evolution
- There is also interference effect
- Time evolution, assuming $|x| \ll 1$ and $|y| \ll 1$

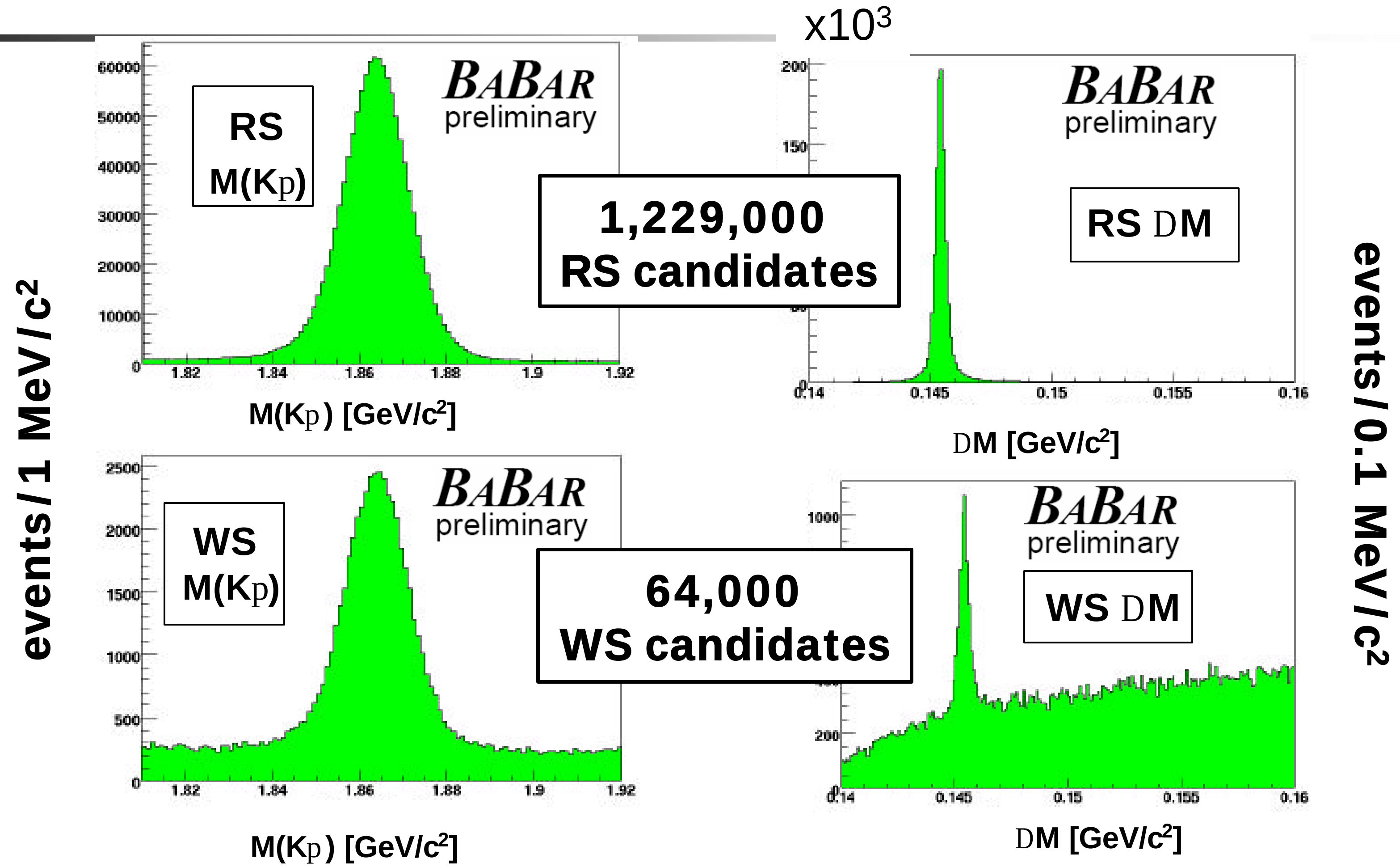
$$\Gamma_{WS}(t) = e^{-\Gamma t}\left(\underbrace{R_D}_{\text{DCS}} + \underbrace{y'\sqrt{R_D}(\Gamma t)}_{\text{Interference}} + \underbrace{\left(\frac{x'^2 + y'^2}{4}\right)(\Gamma t)^2}_{\text{Mixing}}\right)$$

$$x' = x\cos(d) + y\sin(d)$$
$$y' = y\cos(d) - x\sin(d)$$

d **is the phase difference between DCS and CF decays**

note: $x'^2 + y'^2 = x^2 + y^2$

# RS and WS Data Sets After Event Selection




- Fit M, ΔM and lifetime using unbinned maximum likelihood method

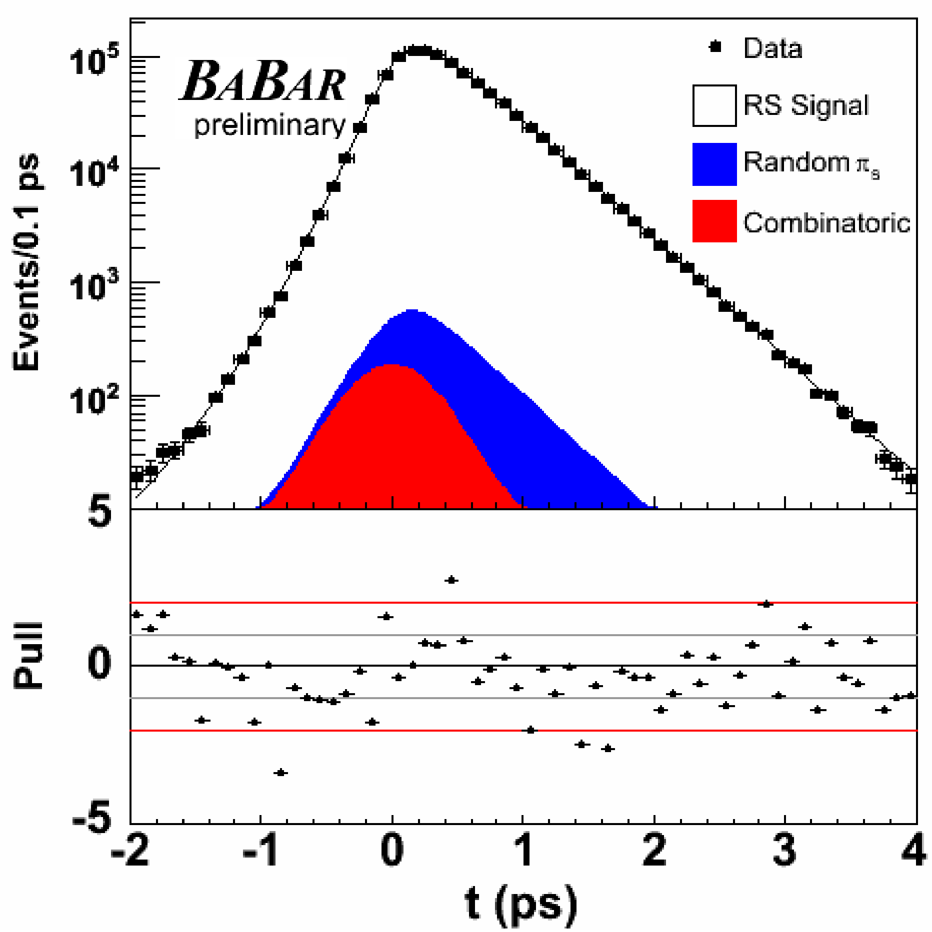
# RS Decay Time Fit

- $D^0$ lifetime and resolution function fitted in the RS sample

$\tau$ = (410.3 ± 0.6 (stat)) fs

- Consistent with PDG
  - 410.1 ± 1.5 fs

RS decay time, signal region

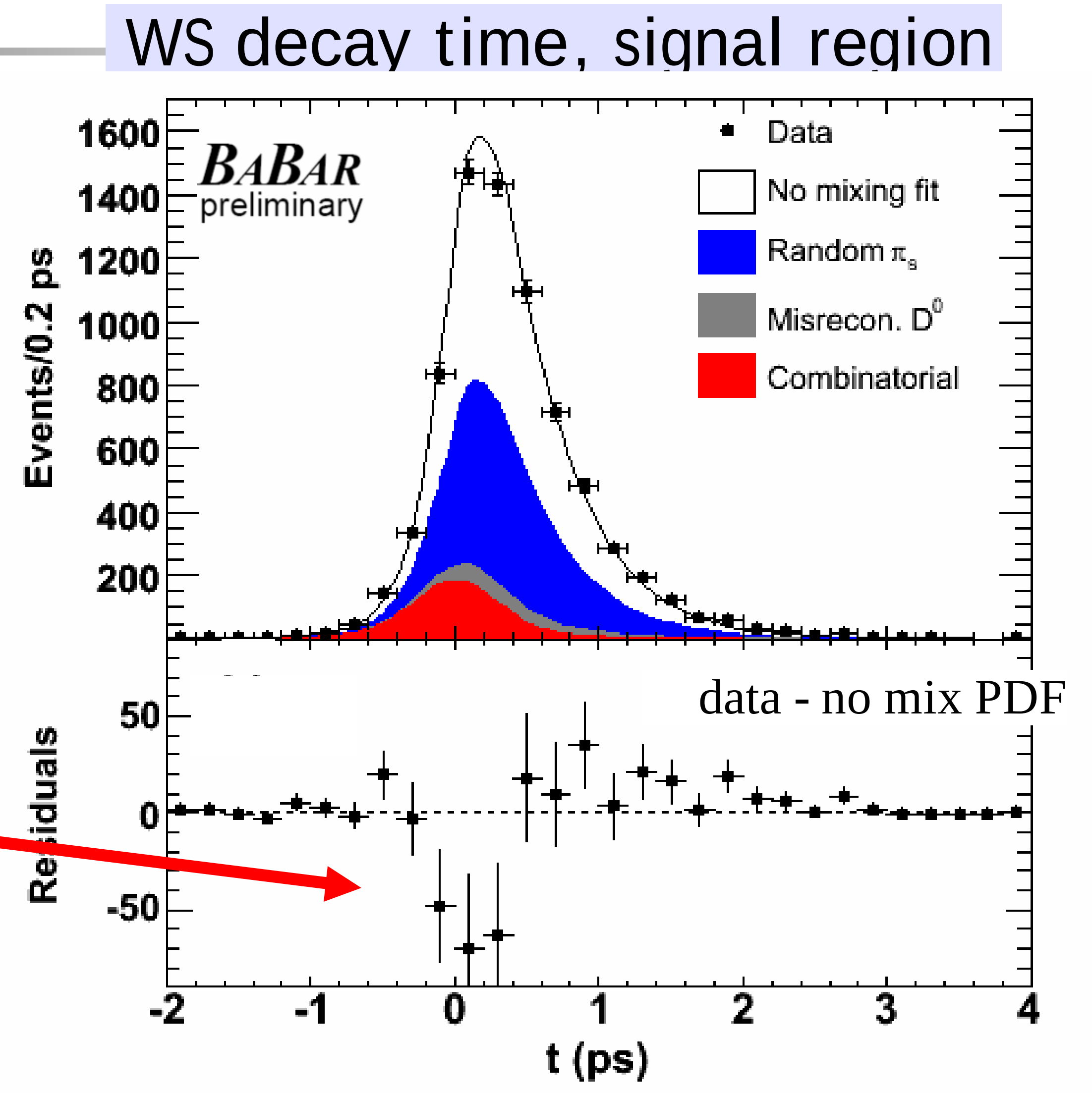



plot selection:
1.843<*m*<1.883 GeV/c²
0.1445<*Dm*< 0.1465 GeV/c²

# WS Fit With no Mixing

- Fit results assuming no mixing

- Poor residuals in the signal region
  - $\chi^2$/bin = 49.7/28




plot signal region:

1.843<*m*<1.883 GeV/c$^2$

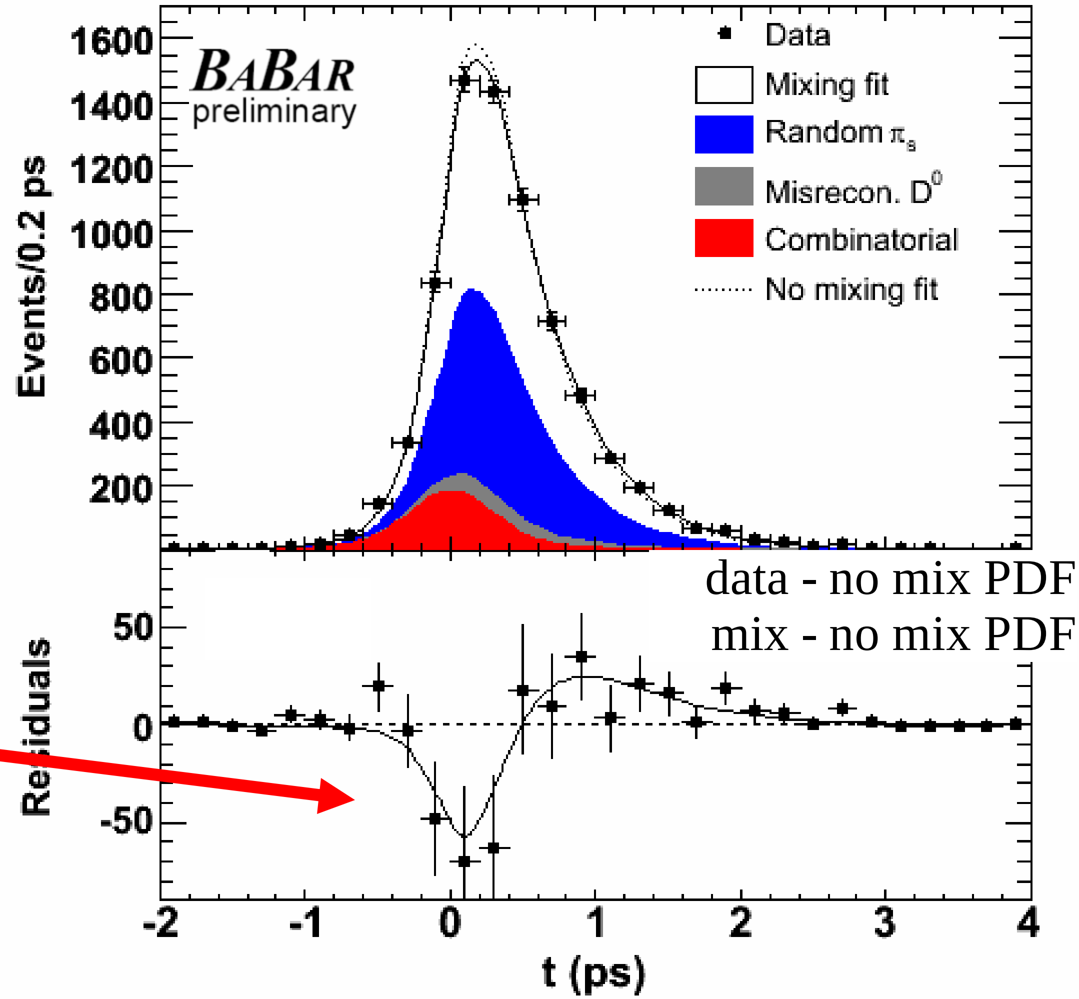
0.1445<*Dm*< 0.1465 GeV/c$^2$

# WS Fit with Mixing

Fit results allowing mixing:

- $R_D$= (3.03±0.16±0.10)x10-3
- $x'^2$ = (-0.22±0.30±0.21)x10-3
- $y'$ = (9.7±4.4±3.1)x10-3
  - $x'^2$ and $y'$ correlation = -0.94
- Mixing fit describes data better
  - $\chi^2$/bin = 31/28

WS decay time, signal region

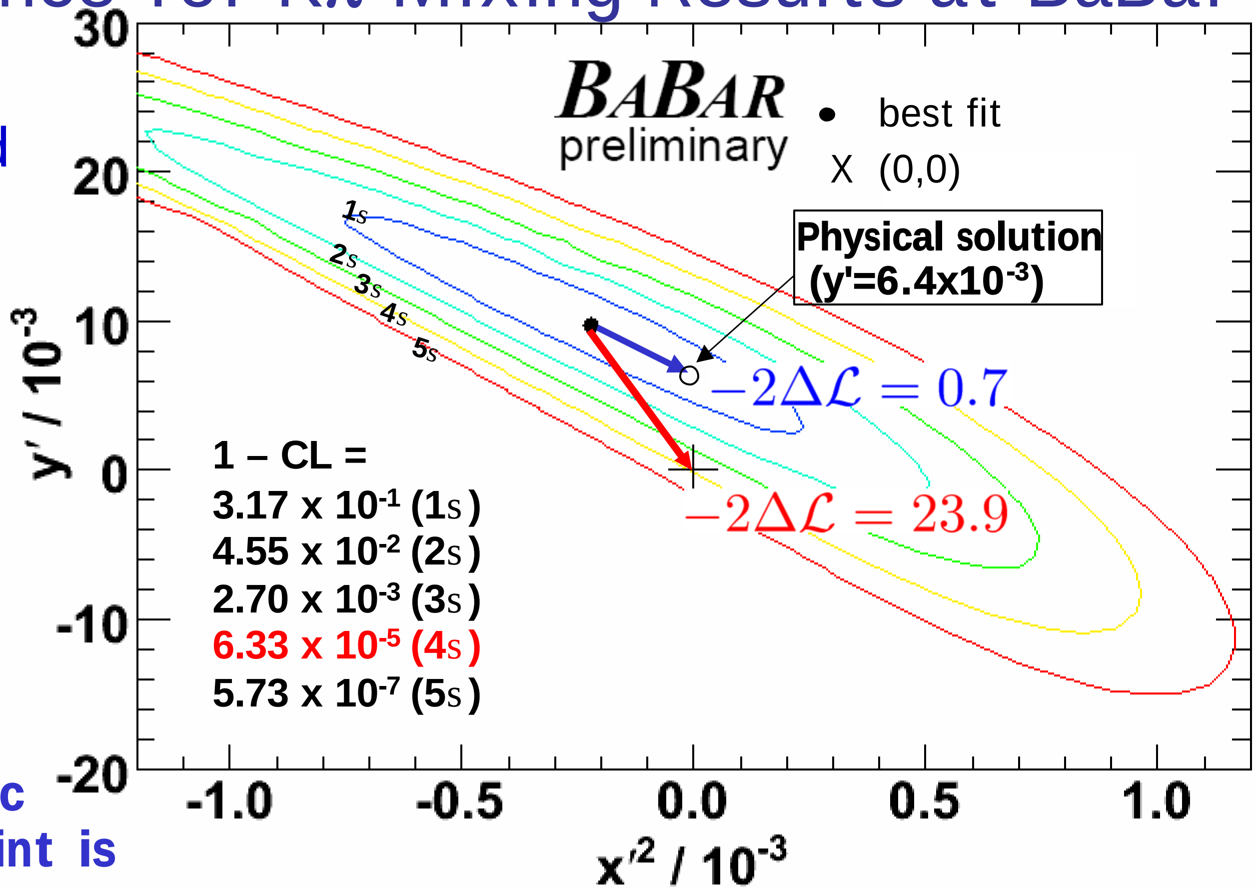



plot signal region:
1.843<$m$<1.883 GeV/$c^2$
0.1445<$Dm$< 0.1465 GeV/$c^2$

What is the significance of the signal?

# Signal Significance for Kπ Mixing Results at BaBar

- y', $x'^2$ contours computed by change in log lilkelihood
  - Best-fit point in non-physical region $x'^2 < 0$, but 1-sigma contour extends into physical region
- Contours include systematic errors
- **Accounting for systematic errors, the no-mixing point is at 3.9-sigma contour**
- **→ clear evidence for $D^0\bar{D}^0$ mixing**




**$R_D$: $(3.03 \pm 0.16 \pm 0.10) \times 10^{-3}$**

**$x'^2$: $(-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$**

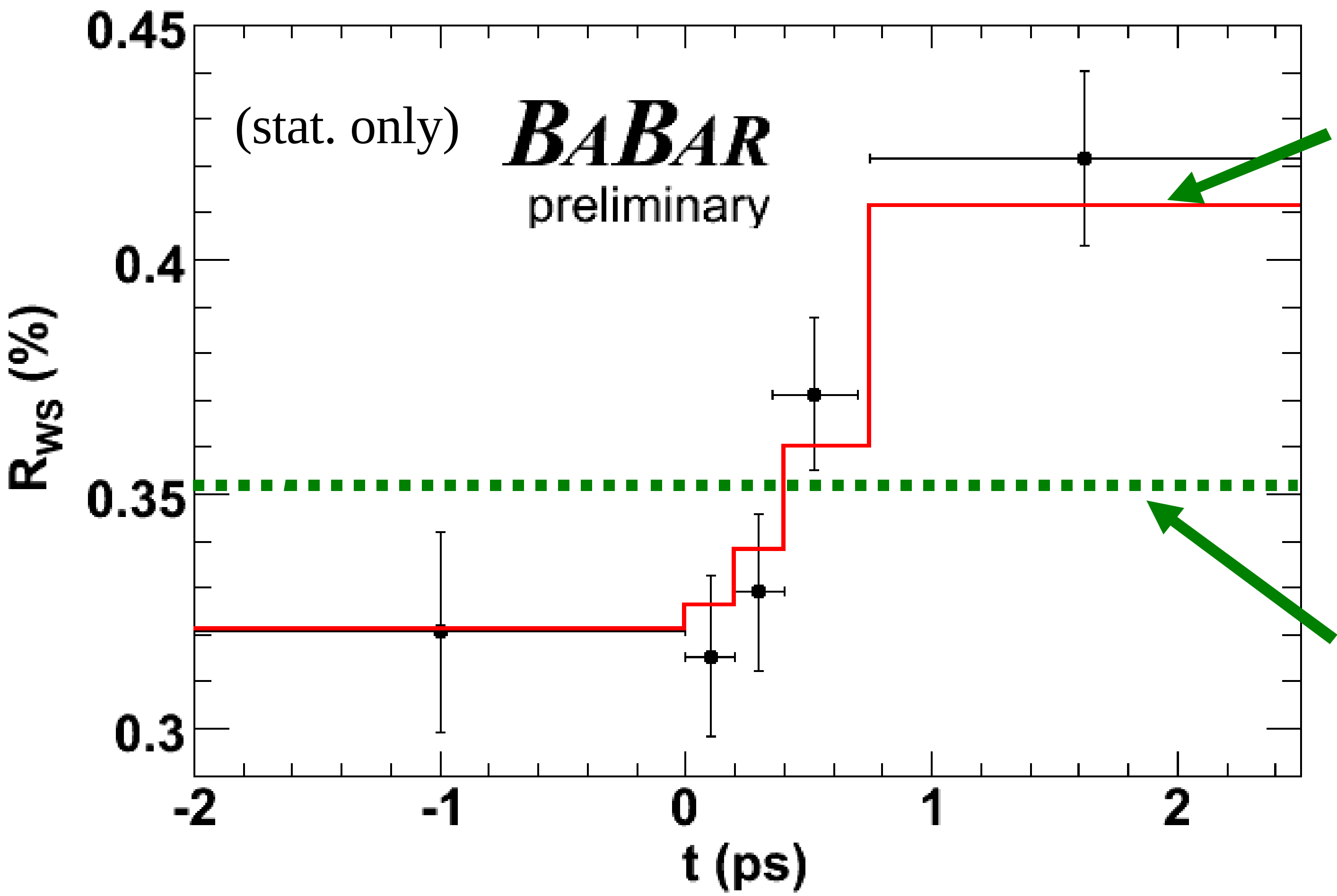
**y': $(9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$**

No evidence for CP violation found

hep-ex/0703020
Submitted To PRL

# Validation: Alternative Fit Strategy

- Fit $\Delta M$ and $M(K\pi)$ in bins of lifetime
  - If no mixing the ratio of WS to RS signal should be constant
  - No assumptions made in resolution model and the time evolution of background
  - Each time bin is fit independently




Consistent with prediction based on resolution model and mixing parameters from full likelihood fit

$\chi^2=1.5$

Inconsistent with no-mixing hypothesis

$\chi^2=24$

# Evidence For Mixing From Belle Using CP modes KK and ππ and flavor mode Kπ

hep-ex/0703036v1

Submitted to PRL

**Previous analysis:**
**E791, PRL 83, 32 (1999)**
**FOCUS, PLB 485, 62 (2000)**
**CLEO, PRD 65, 092001 (2002)**
**Belle, PRL 88, 162001 (2002)**
**BABAR, PRL 91, 121801 (2003)**
**Belle, Lepton Photon 2004**

# Mixing with CP Lifetimes at Belle

- Mixing alters the decay time distribution of $D^0$ $D^0$ decaying into CP states.
- The CP lifetime difference can be expressed as:

$$y_{CP} = \frac{t^{0}}{\langle t \rangle} - 1 \quad \text{where} \quad \langle t \rangle = \frac{(t^{+} + t^{-})}{2}$$

- $t^{0}$ is Kπ lifetime
- $t^{+}$ ($t^{-}$) is lifetime for CP+ final states of $D^0$ ($D^0$)
  - KK and ππ
- Mixing (and CPV) studied with $K^-\pi^+$, $K^+K^-$ and $\pi^-\pi^+$ at Belle:

$$y_{CP} \equiv \frac{t\,(K^{-}p^{+})}{t\,(K^{-}K^{+})} - 1 \underset{no\;CPV}{=} y = \frac{\Delta\Gamma}{2\Gamma}$$

Same for ππ

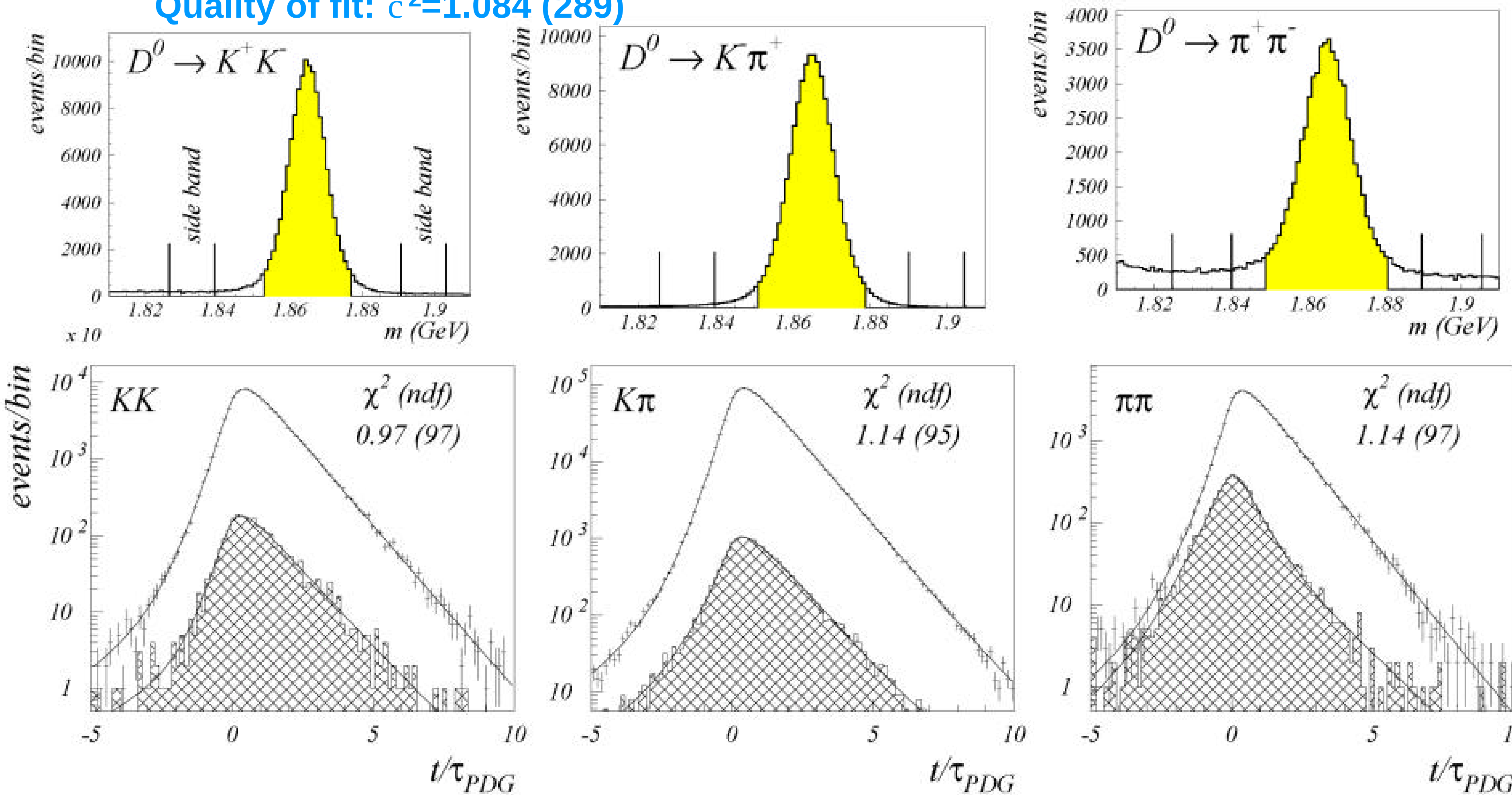
$$CPV : A_{\Gamma} = \frac{\Gamma(D^{0} \to K^{-}K^{+}) - \Gamma(\overline{D}^{0} \to K^{-}K^{+})}{\Gamma(D^{0} \to K^{-}K^{+}) + \Gamma(\overline{D}^{0} \to K^{-}K^{+})}$$

# Decay Time Fit

- Simultaneous binned likelihood fit to KK/Kπ/ππ final states
  - Parameters to vary include $\tau_{D0}$, $y_{cp}$, some of the resolution func. parameters and the normalizations

| channel | $KK$ | $K\pi$ | $\pi\pi$ |
|---|---|---|---|
| signal purity | 110K 98% | 1.2M 99% | 50K 92% |

**Quality of fit: $\chi^2$=1.084 (289)**



# Mixing Results with $K^-\pi^+$, $K^+K^-$ and $\pi^-\pi^+$ at Belle

## Results

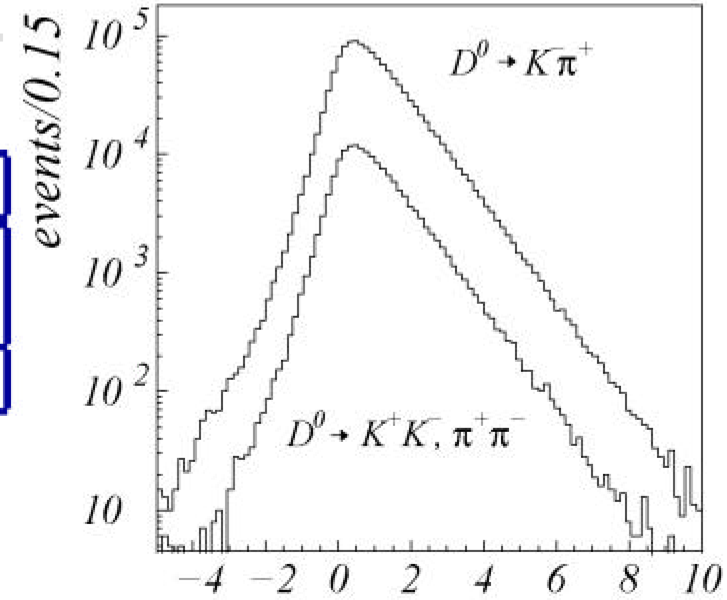
Belle preliminary, 540 fb$^{-1}$

| | $y_{CP}$ (%) | $A_\Gamma$ (%) |
|---|---|---|
| $KK$ | 1.25±0.39±0.28 | 0.15±0.34±0.16 |
| $\pi\pi$ | 1.44±0.57±0.42 | -0.28±0.52±0.30 |
| $KK+\pi\pi$ | 1.31±0.32±0.25 | 0.01±0.30±0.15 |

$y_{CP}$ = 1.31 ± 0.32 ± 0.25 %

3.2 σ (stat.+syst.)
4.1 σ (stat.)

Clear evidence for $D^0$-$\overline{D}^0$ mixing



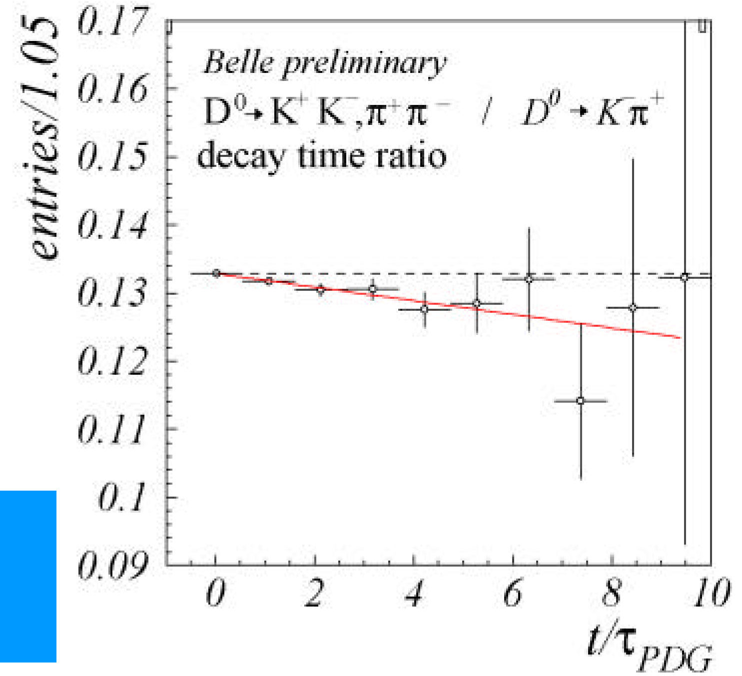

To measure CPV, fit for $\tau_D$ of D0 and D0 separately:

$A_G$ = 0.01 ± 0.30 ± 0.15 %

Consistent with no CPV

hep-ex/0703036

Submitted to PRL



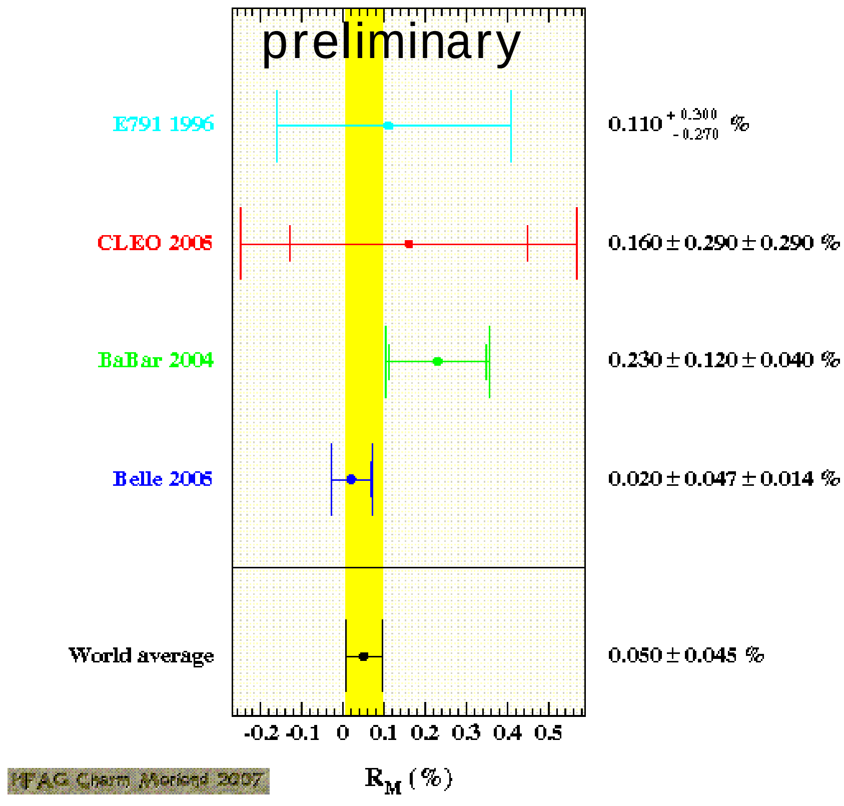
# Summary I: $R_M$ and $Y_{cp}$

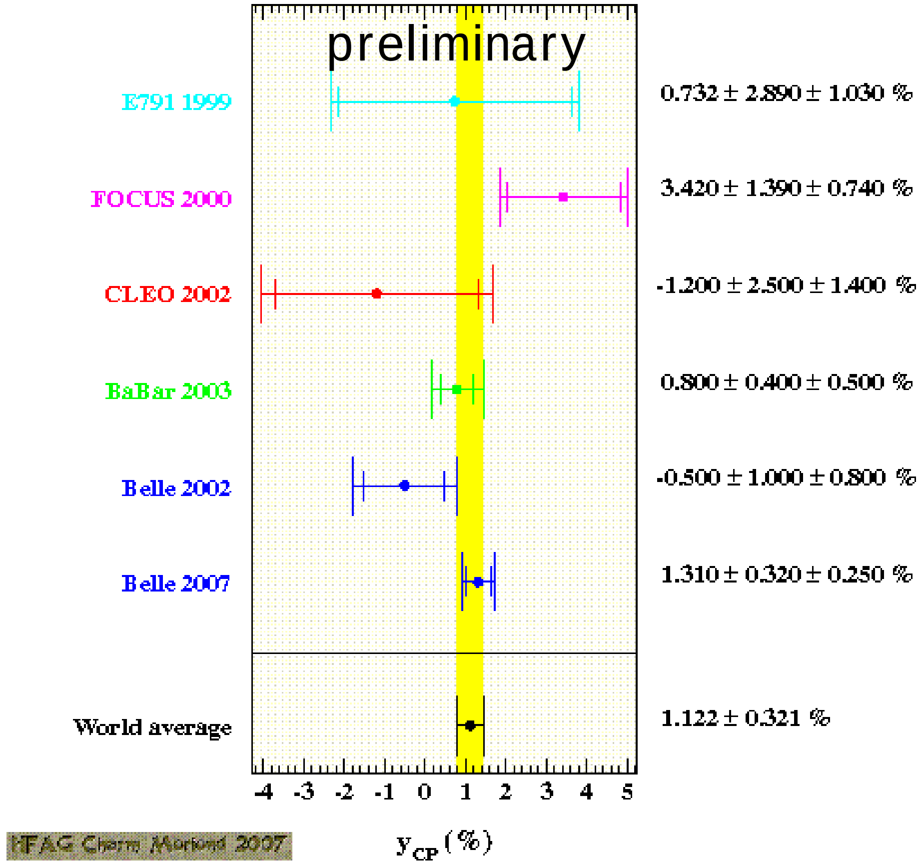
E791, PRL 83, 32 (1999)
FOCUS, PLB 485, 62 (2000)
CLEO, PRD 65, 092001 (2002)
Belle, PRL 88, 162001 (2002)
BABAR, PRL 91, 121801 (2003)
Belle, hepx-ex/0703036

E.M. Aitala et al. (E791), PRL 77, 2384 (1996)
C. Cawlfield et al. (CLEO II), PRD 71, 077101 (2005)
B. Aubert et al. (BABAR), PRD 70, 091102 (2004)
K. Able et al. (Belle), PRD 72, 071101, 2005

- Statistical and systematic errors assumed uncorrelated

- Symmetrized statistical, systematic errros
- stat. errors for two Belle analysis have correlation=0.0165
- all systematic errors assumed uncorrelated



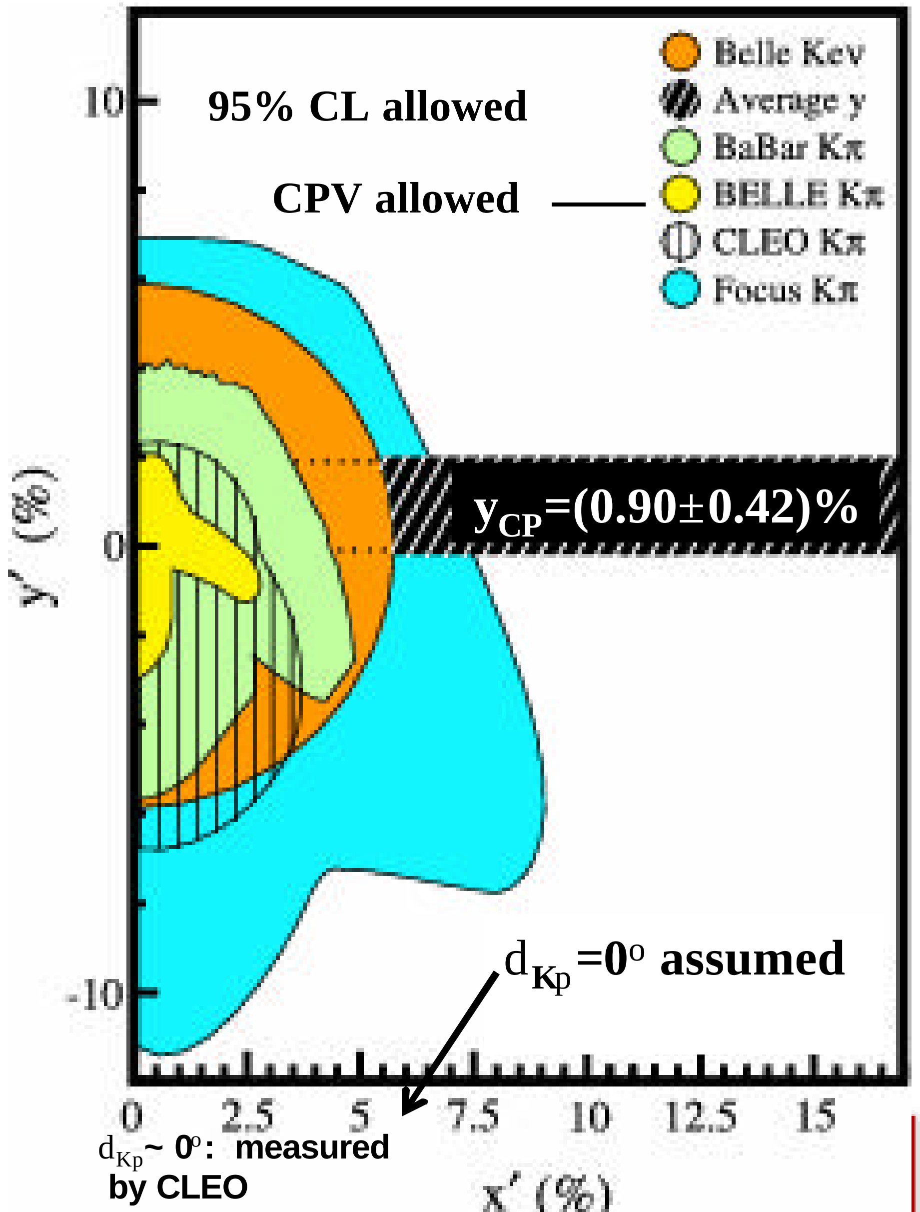




Many Thanks to Heavy Flavor Averaging Group (HFAG) 2007

# Summary II

- Mixing contours from 2006 PDG
  - $K\pi$ decay the dominant mode in the search for mixing
  - CP lifetimes sensitive to measuring y
  - Semileptonic sensitive to $R_M = (x^2 + y^2)/2$

PDG 2006




d<sub></sub>$d_{Kp}$~ 0°: measured by CLEO

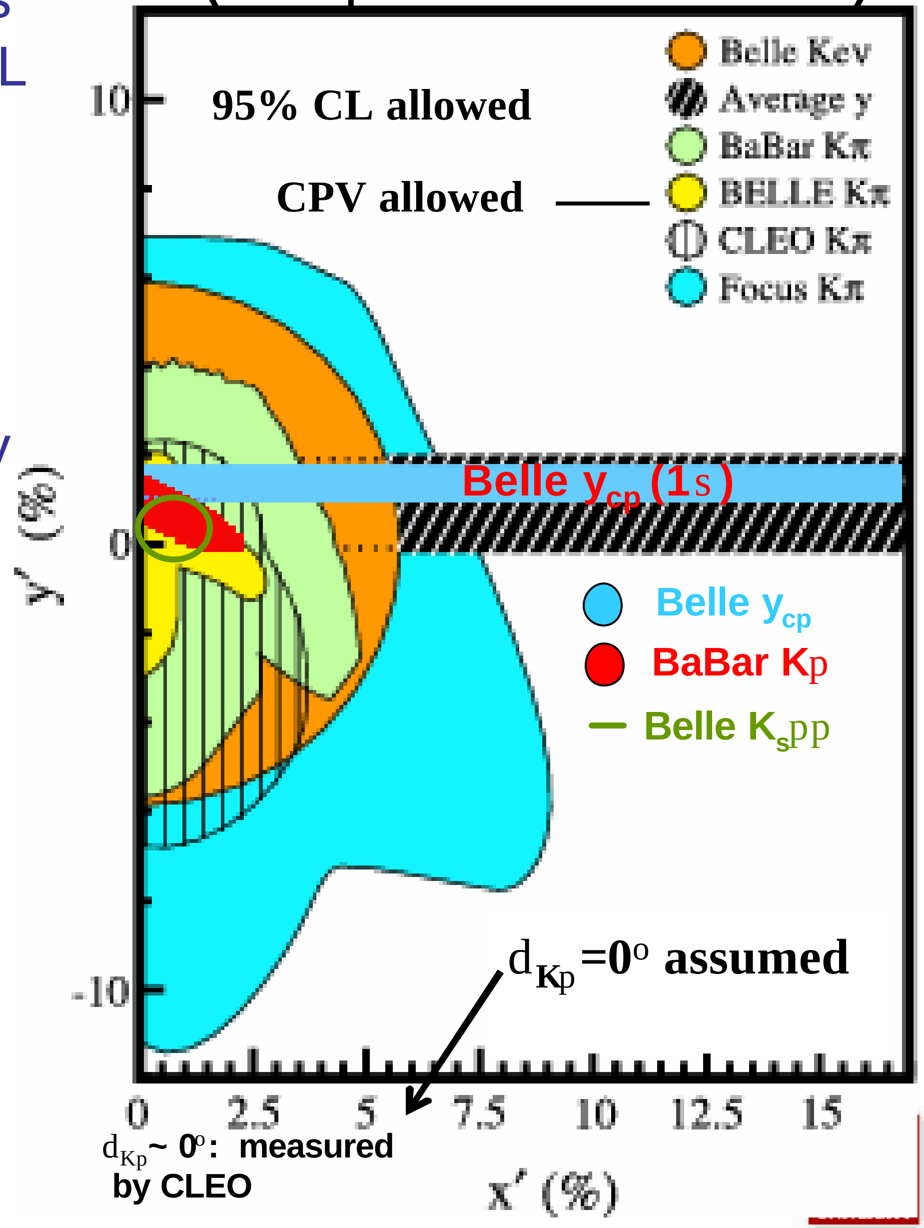
# Summary II

hep-ex/0703036 Submitted To PRL(Belle)
hep-ex/0703020 Submitted To PRL (BaBar)
0704.1000v1 [hep-ex], Moriond EW/QCD 2007(Belle)

**Updated with new results for this talk**

**(HFAG plots will be available soon)**

- Assuming CP conservation BaBar has found evidence for mixing at 3.9σ CL using $D^0 \rightarrow K\pi$ decay mode (384 $fb^{-1}$)
- $y_{cp}$ by Belle also evidence for mixing at 3.2σ CL (540 $fb^{-1}$)
  - **Mixing is observed**
- Most sensitive measurement of x by Belle ($D^0 \rightarrow K_s\pi\pi$)
- A precision measurement of cosδ needed to express mixing in x and y
  - CLEO-c quantum correlation
  - BaBar and Belle B-factories
    - Are also charm factories
- Searches for CP violation
  - Improved techniques
  - More data



# Recent Theoretical Work

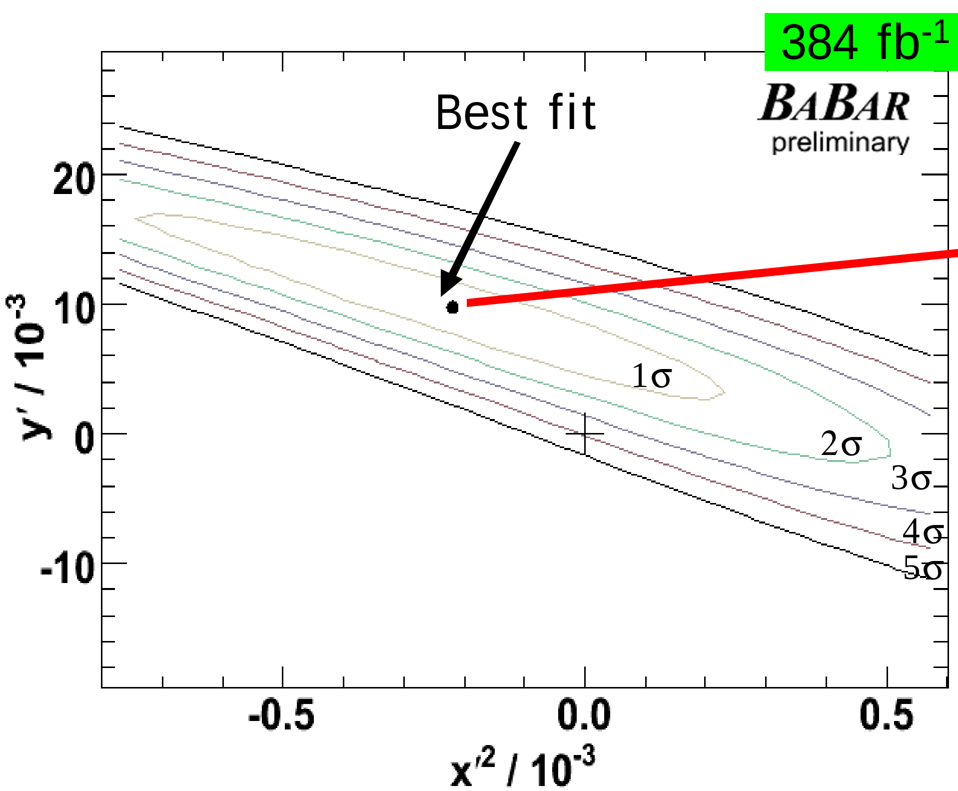
- D-Dbar Mixing And New Physics: General Considerations and Constraints on the MSSN (M. Ciuchini et al)
  - hep-ph/0703204v1
- Lessons from BaBar and Belle measurements of D0-D0bar mixing parameters, (Y. Nir)
  - hep-ph/0703235v1
- Littlest Higgs Model with T-Parity Confronting the New Data on D0-D0bar Mixing,(M. Blanke et al)
  - hep-ph/0703254v1
- Basics of D0-D0bar Mixing, (P. Ball)
  - hep-ph/0703245v1

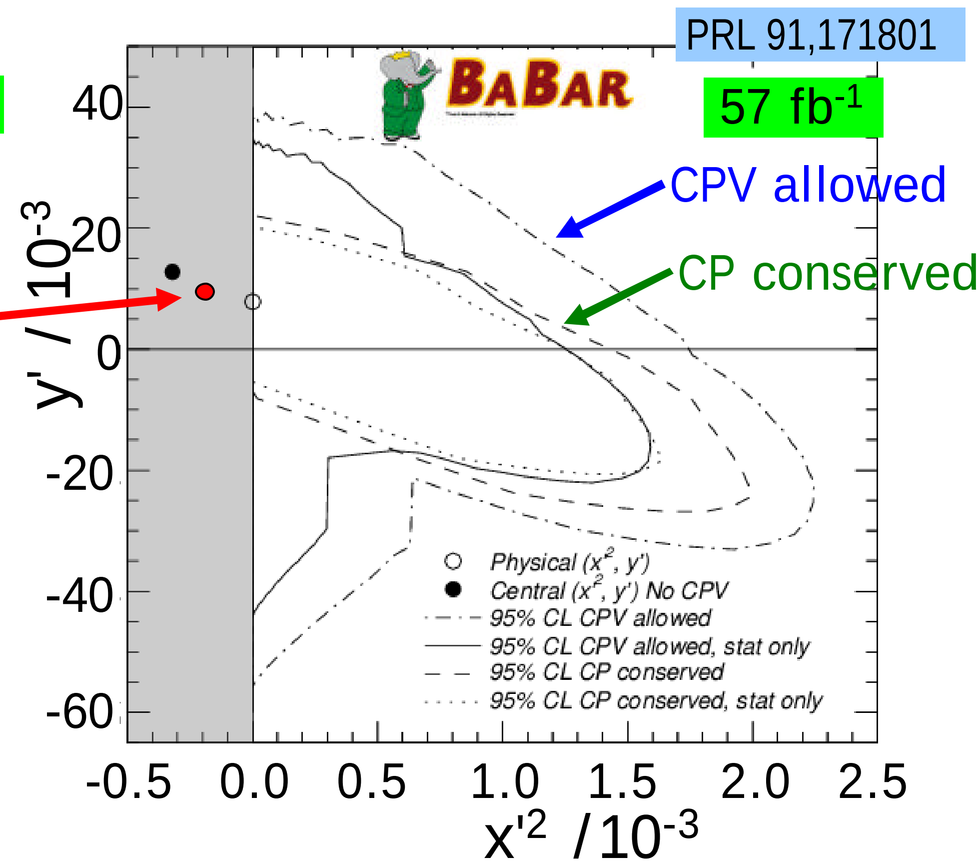
# Extra Slides

# Comparison of Results

# Previous BaBar Kπ Analysis

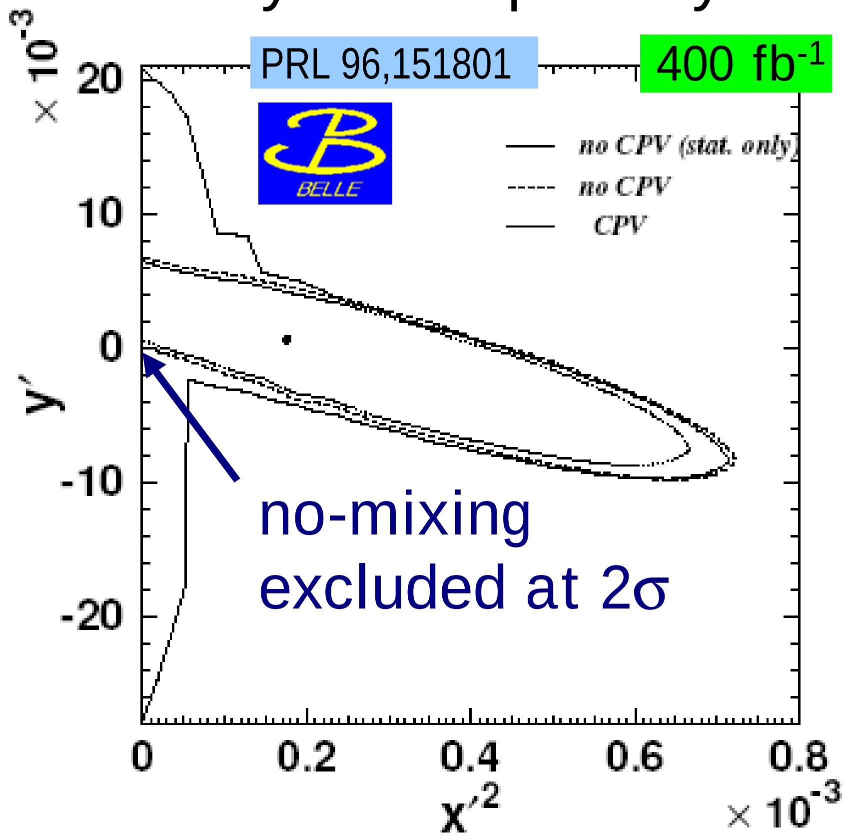
Fully consistent with previous BaBar analysis



# Kπ Analysis from Belle

Last year Belle published analysis of Kp decays:



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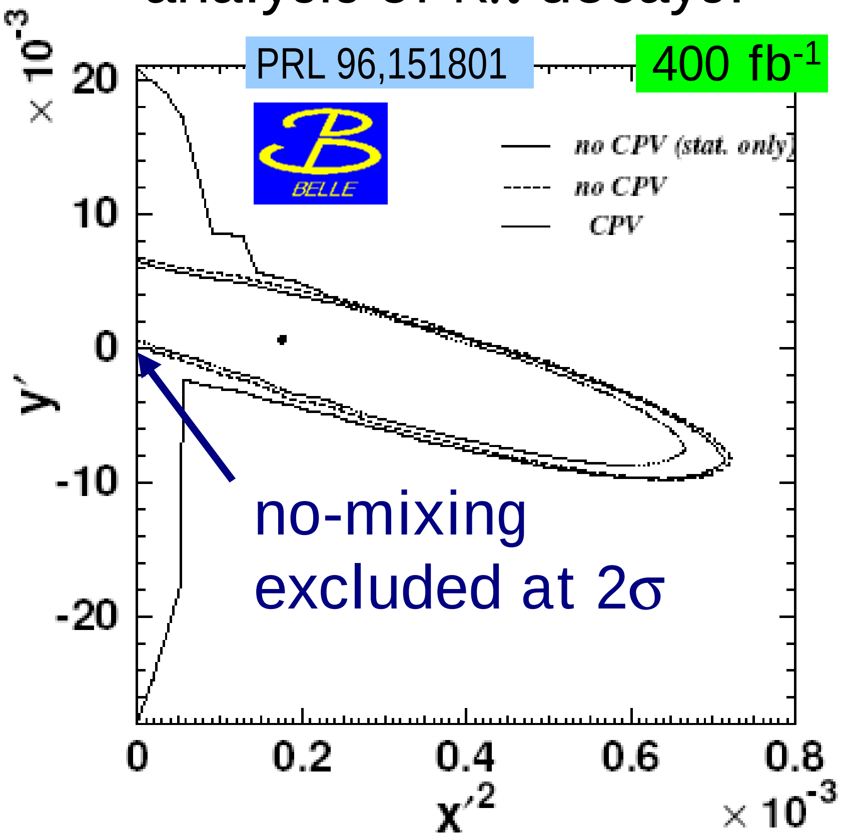
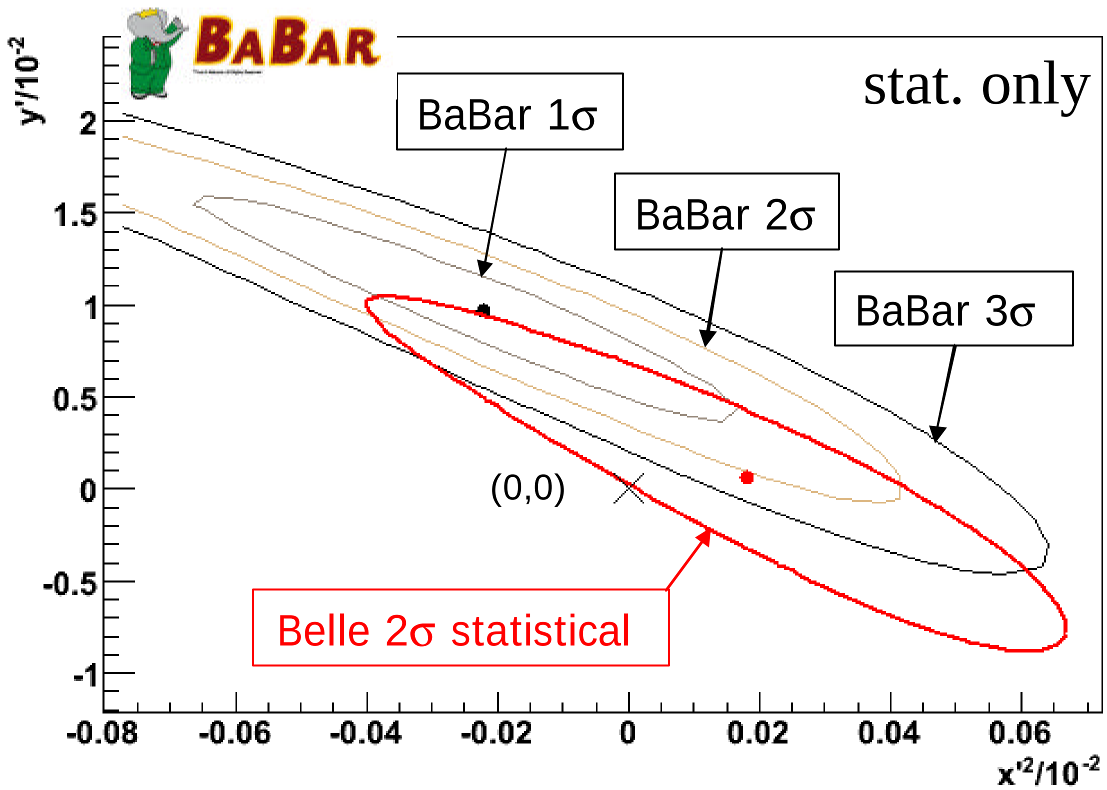


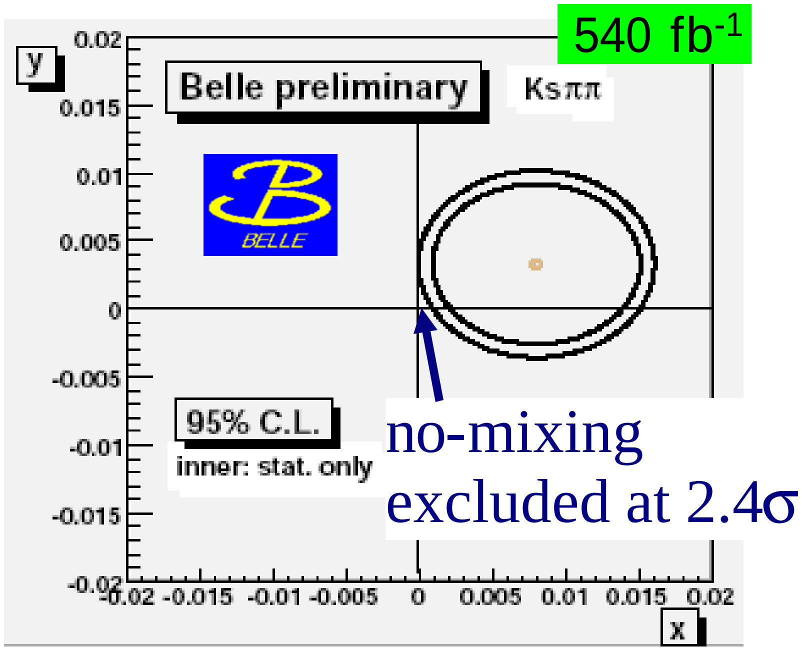

Results consistent within 2σ:



# Belle Results from Moriond

Belle presented two new mixing results at Moriond EW:

Dalitz analysis of $D^0 ® K_s pp$



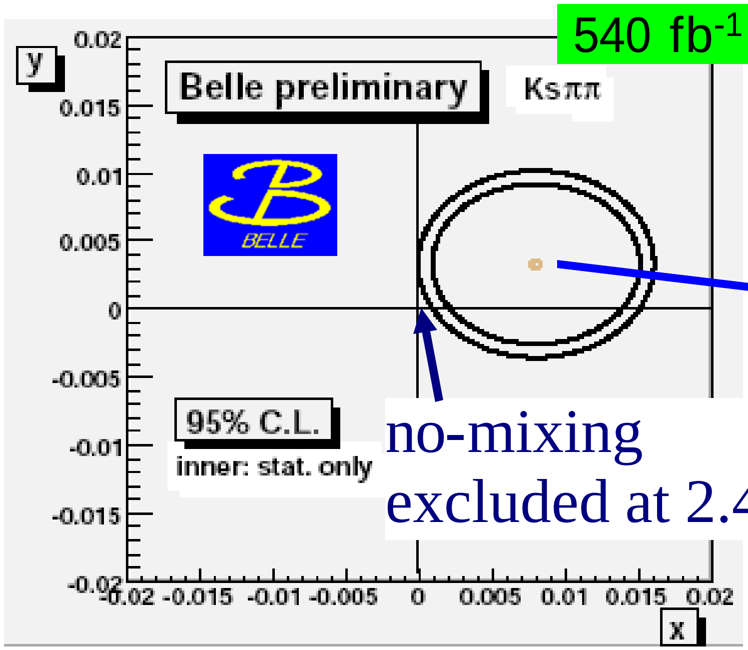

$$x = 0.80 \pm 0.29 \pm 0.17\ \%$$

$$y = 0.33 \pm 0.24 \pm 0.15\ \%$$

# Belle Results from Moriond

Belle presented two new mixing results yesterday at Moriond EW:

Dalitz analysis of $D^0 ® K_s pp$

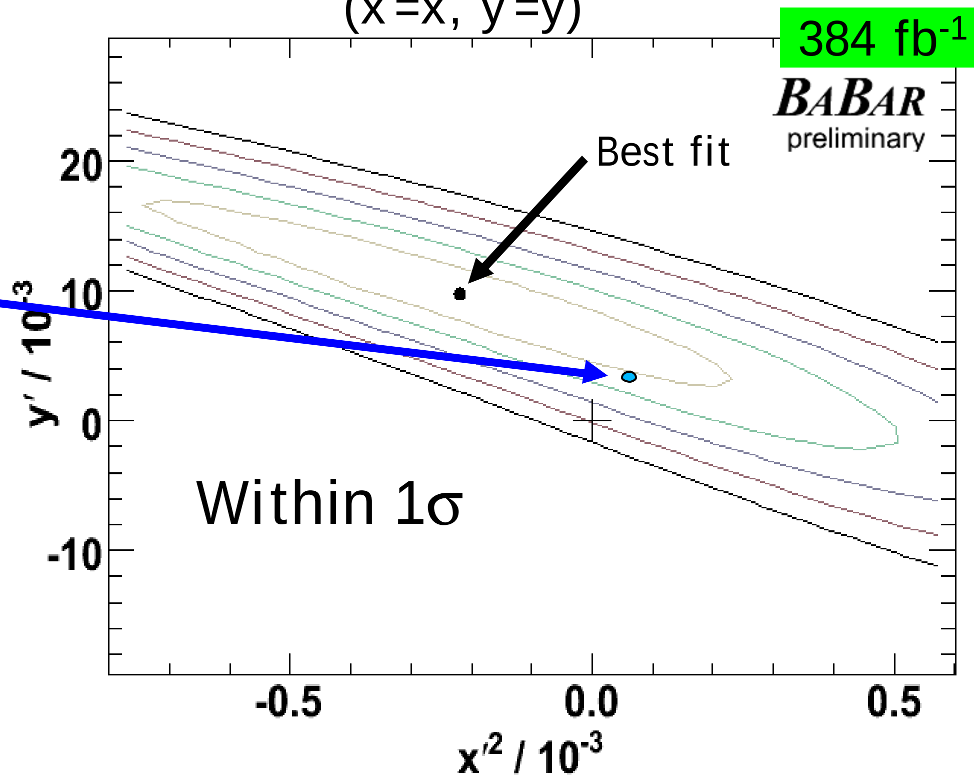



$$x = 0.80 \pm 0.29 \pm 0.17\ \%$$

$$y = 0.33 \pm 0.24 \pm 0.15\ \%$$

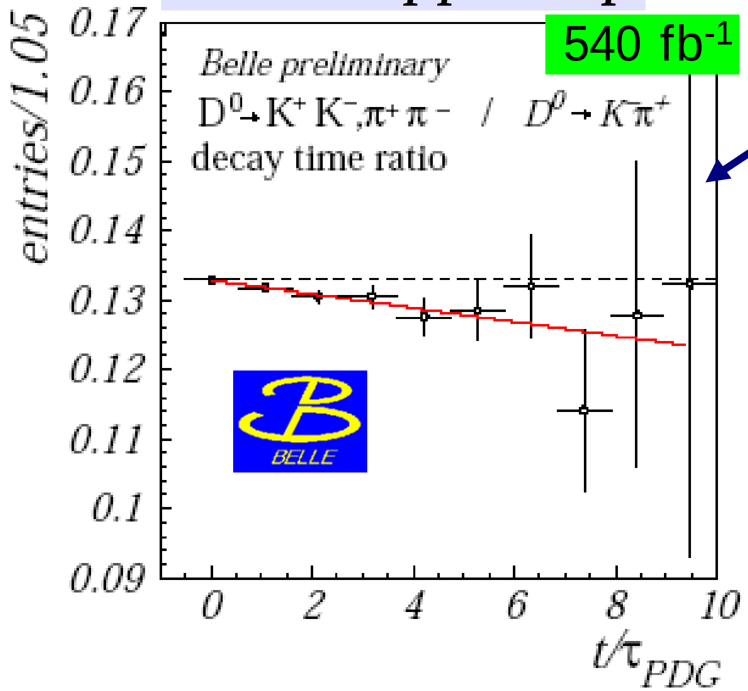
Compare assuming δ=0:

(x'=x, y'=y)



# Belle Results from Moriond

Lifetime ratio in
$D^0$ ® *KK/pp* to *Kp*




$K^+K^-/\pi^+\pi^-$ are CP-even eigenstates

If no CP violation, directly measures lifetime of mass eigenstate

$y_{CP} = 1.31 \pm 0.32 \pm 0.25$ %

$> 3\sigma$ above zero
($4.1\sigma$ stat. only)

Also evidence of $D^0$ mixing!

# Belle Results from Moriond

Lifetime ratio in
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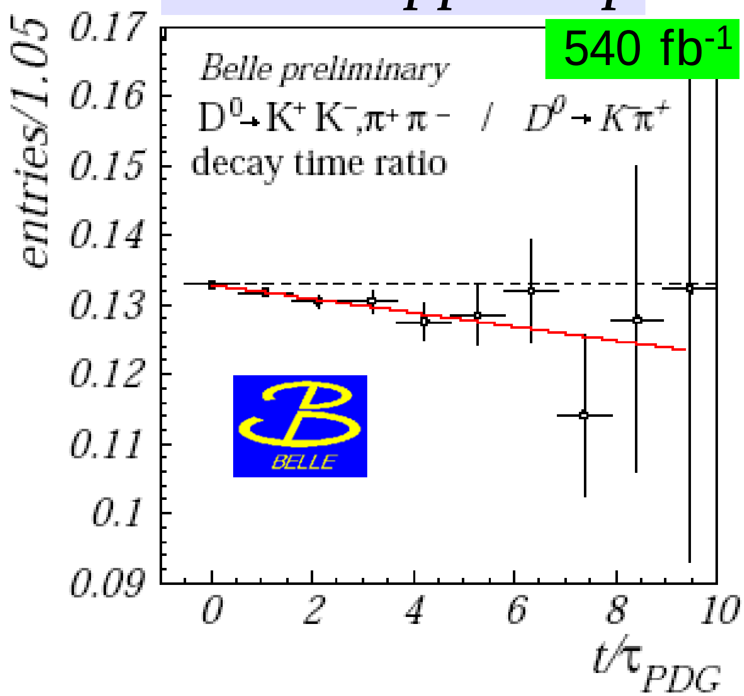


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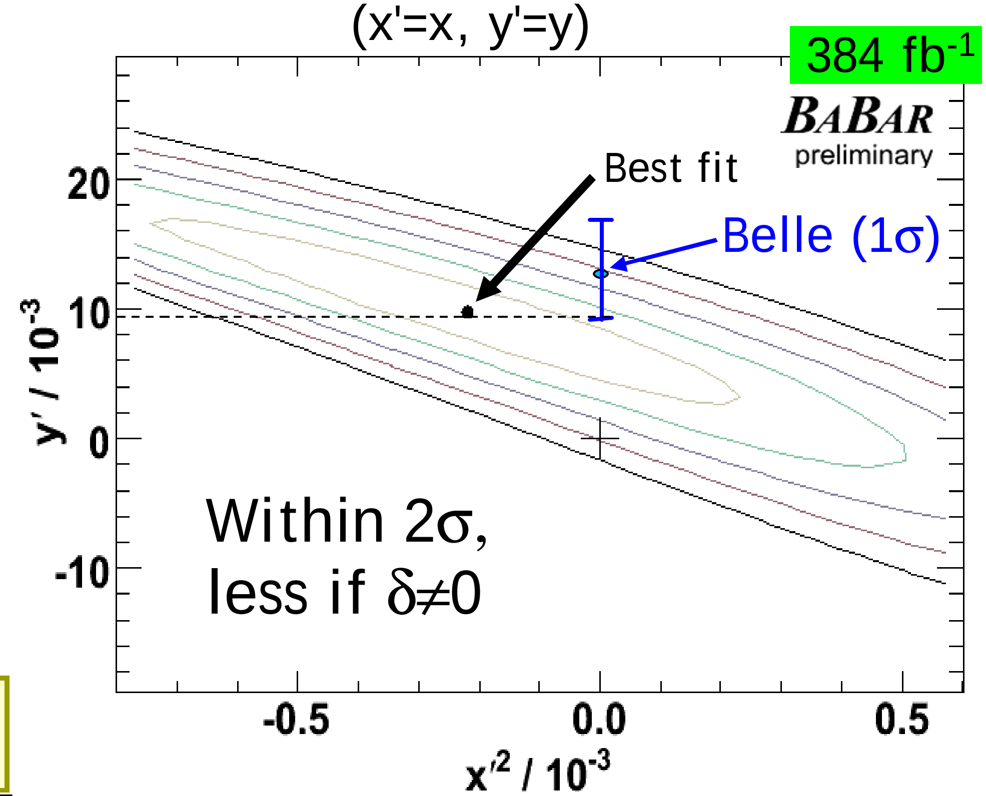


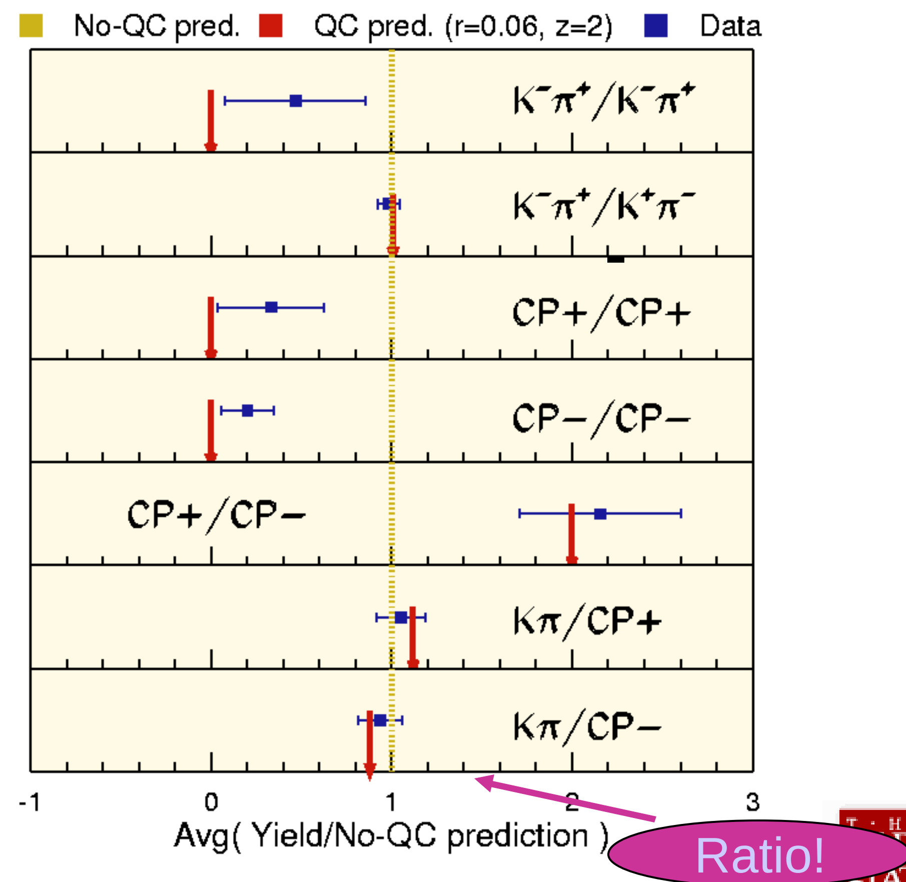
# Single-tag and Double-tag rates

**CLEO-c**

- Hadronic rates (flavored and *CP* eigenstates) depend on mixing/DCSD.
- Semileptonic modes ($r = \delta = 0$) resolve mixing and DCSD.
- Also measure BF's simulatenously
- Rate enhancement factors, to leading order in $x$, $y$ and $r^2$:

| | $f$ | $l+$ | $CP+$ | $CP-$ |
|---|---|---|---|---|
| $f$ | $R_M/r^2$ | | | |
| $\bar{f}$ | $1+r^2(2-(2\cos d)^2)$ | | | |
| $l-$ | 1 | 1 | | |
| $CP+$ | $1+r\ (2\cos d)$ | 1 | 0 | |
| $CP-$ | $1-r\ (2\cos d)$ | 1 | 2 | 0 |
| $X$ | $1+ ry\ (2\cos d)$ | 1 | $1-y$ | $1+y$ |

Data clearly favors QC interpretation showing constructive and destructive interference and no effect as predicted

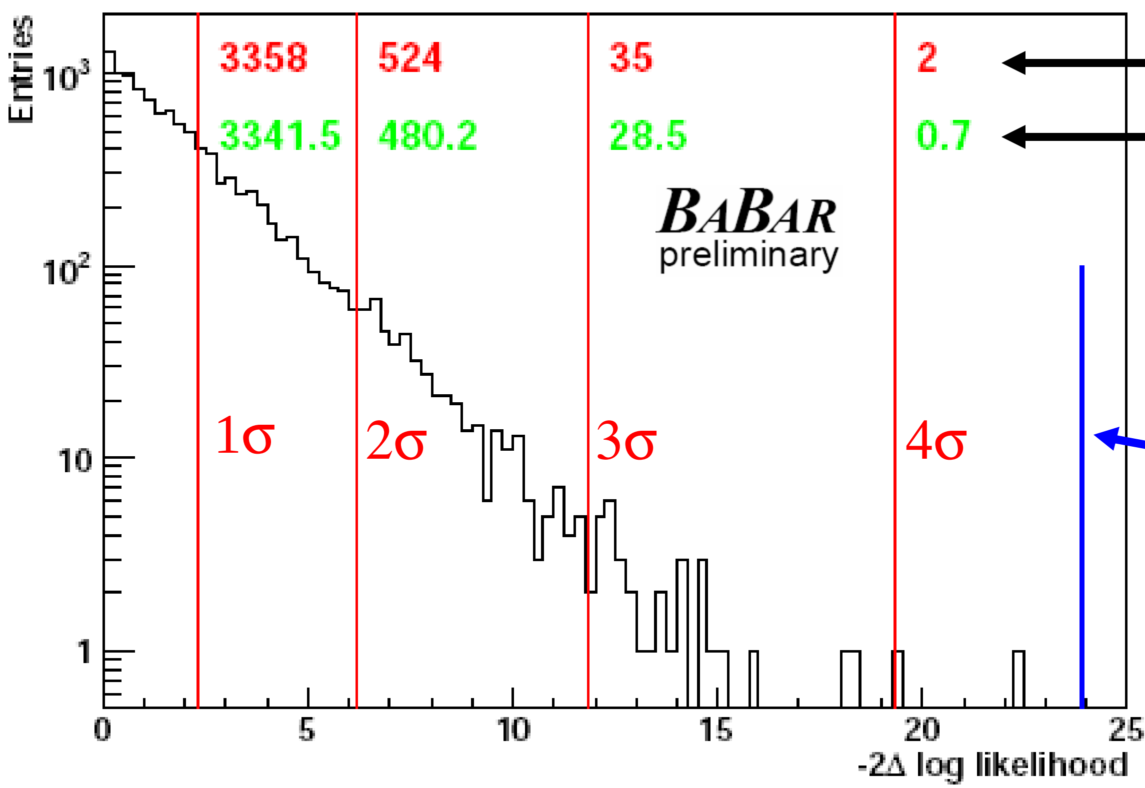


# Several Other Validation Studies

- Fit to MC with no mixing
  - No signal found
  - → Fit not biased
- Fit to MC with mixing
  - Fit reproduces the signal
  - → Fit not biased
- Fit RS data for mixing
  - No signal found
  - → $D^0$ decay time distribution is described properly
- Tested the coverage of $-2\Delta\text{Log}\mathcal{L}$
  - Generated >10000 toys without mixing to test coverage
  - Toys expected consistent with number observed
  - → $\Delta$LL is $\chi^2$ distributed for 2-DOF
  - → $-2\Delta\ln\mathcal{L}$ gives correct frequentist coverage

# Validation: Coverage of $-2\Delta\mathrm{Log}\mathcal{L}$

- Generated >10000 toys without mixing to test coverage
  - $-2\Delta\ln\mathcal{L}$ gives correct frequentist coverage




# toys to the greater than line

# toys expected greater than line, if ΔLL is distributed as a $\chi^2$ for 2 DOF

$-2\Delta\mathcal{L} = 23.9$ observed in data

# CPV Allowed Contours

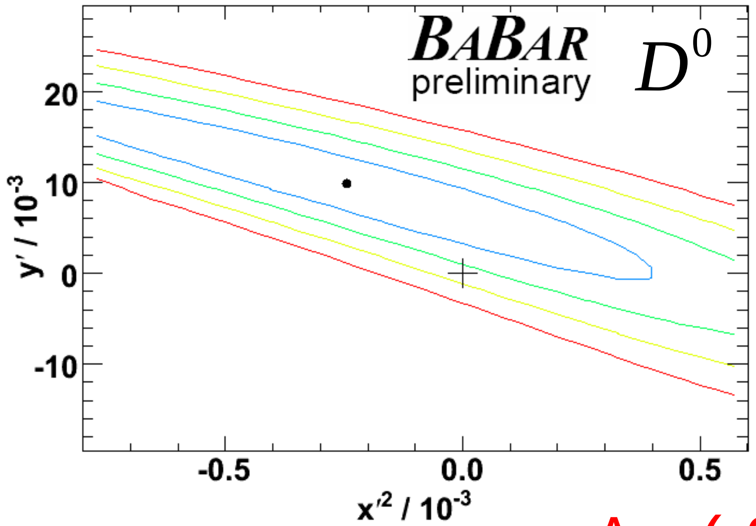
- Fit $D^0$ and $\bar{D}^0$ separately:

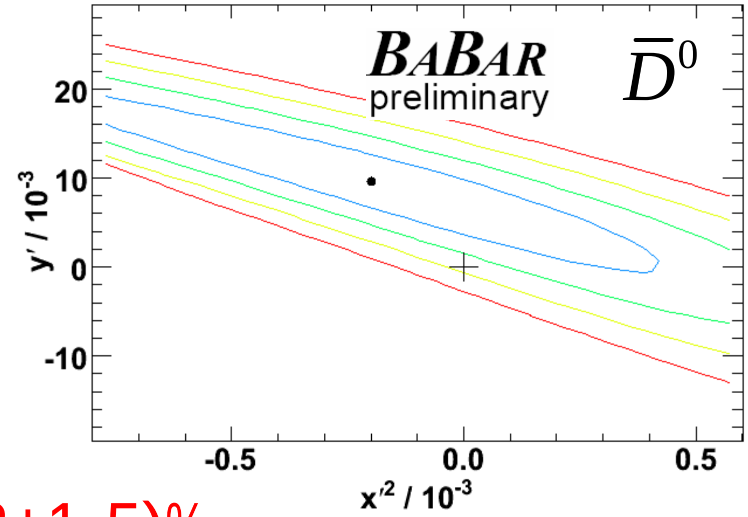
$x'^{+2}$: $(-0.24\pm0.43\pm0.30)\times10^{-3}$

$y'^{+}$: $(9.8\pm6.4\pm4.5)\times10^{-3}$

$x'^{-2}$: $(-0.20\pm0.41\pm0.29)\times10^{-3}$

$y'^{-}$: $(9.6\pm6.1\pm4.3)\times10^{-3}$




$A_D=(-2.1\pm5.2\pm1.5)\%$

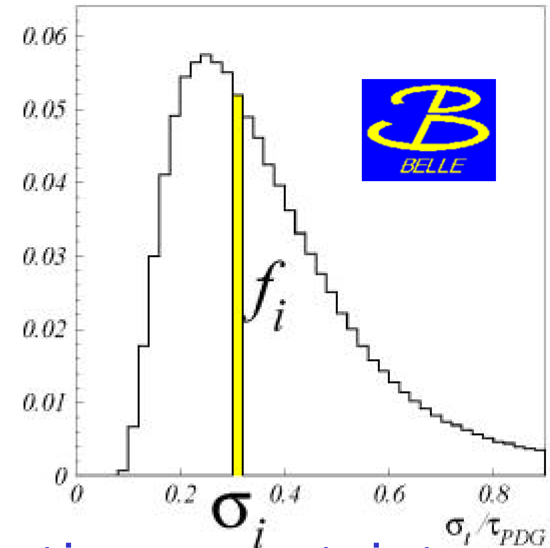
A significant difference in (+), (-) fits would suggest CP violation

→ No evidence for CP violation found

# Decay Time Fit

Belle preliminary, 540 fb$^{-1}$

$\sigma_t$ distribution




- Lifetime distribution

$$dN/dt = \frac{N_{\rm sig}}{\tau}\int e^{-t'/\tau}\, R(t-t')\, dt' + B(t).$$

Resolution fucn. Background term

- Resolution function:
  - from normalized distribution of event proper time uncertainty $\sigma_t$
  - ideally, each $\sigma_i$ represents Gaussian p.d.f.
  - distribution of pulls ? p.d.f. = sum of 3 Gaussians for each $\sigma_i$

$$R(t) = \sum_{i=1}^{n} f_i \sum_{k=1}^{3} w_k G(t;\sigma_{ik}, t_0), \qquad \sigma_{ik} = s_k \sigma_k^{pull} \sigma_i$$

Common offset Scale factor

- R(t) studied in details with $D^0$ ? $K^-\pi^+$ and dedicated MC samples, including slight changes in running conditions (two SVD detectors, small misalignments)