Evidence for D^0-$\overline{D}^0$ Mixing

(hep-ex/0703020, submitted to PRL)

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for the *BABAR* collaboration

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Outline

- Neutral meson mixing
- Charm meson mixing
- The *BaBar* experiment
- Mixing in $D^0 \to K\pi$ decays
- Comparison with other results

Neutral Meson Mixing

Neutral Meson Mixing

Mixing can occur in four neutral mesons:

$$|K^0\rangle = |d\bar{s}\rangle, \quad |\overline{K}^0\rangle = |\bar{d}s\rangle$$ Mass: ~0.5 GeV/c^2

$$|D^0\rangle = |c\bar{u}\rangle, \quad |\overline{D}^0\rangle = |\bar{c}u\rangle$$ Mass: ~1.9 GeV/c^2

$$|B^0\rangle = |d\bar{b}\rangle, \quad |\overline{B}^0\rangle = |\bar{d}b\rangle$$ Mass: ~5.3 GeV/c^2

$$|B_s^0\rangle = |s\bar{b}\rangle, \quad |\overline{B}_s^0\rangle = |\bar{s}b\rangle$$ Mass: ~5.4 GeV/c^2

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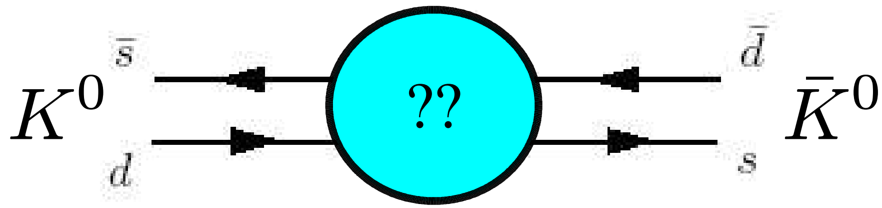
Will present mixing measurement for D^0 meson

Note: D^0 meson first discovered at SLAC

Mark-I, PRL 37, 255 (1976)

Meson Mixing

Neutral mesons have no conserved quantum number – can have mixing between $|M^0\rangle$ and $|\overline{M}^0\rangle$



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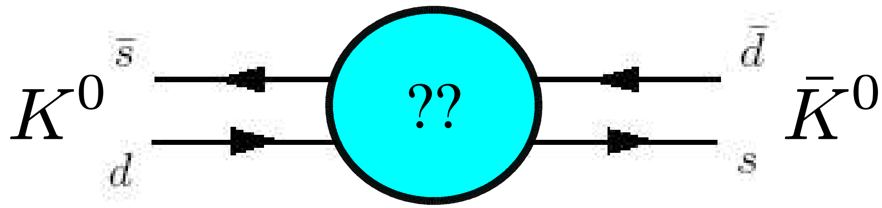

Time evolution by Schrödinger eq.:

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

2x2 hermitian matrices

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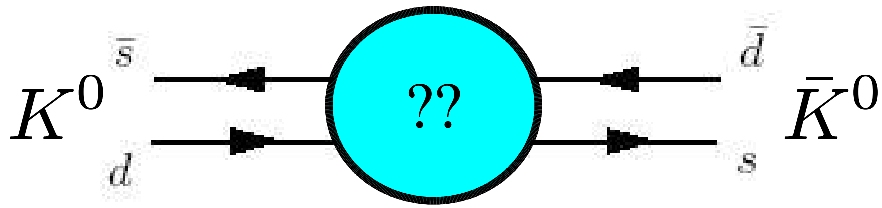

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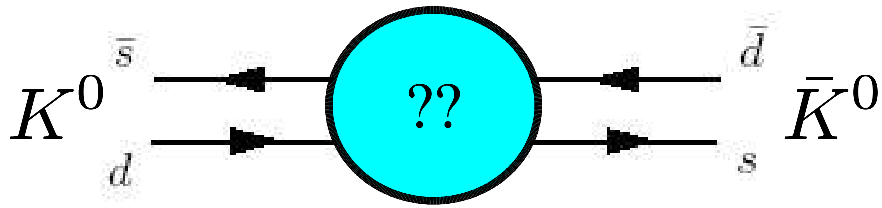

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Mesons decay!

Mass eigenstates:

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

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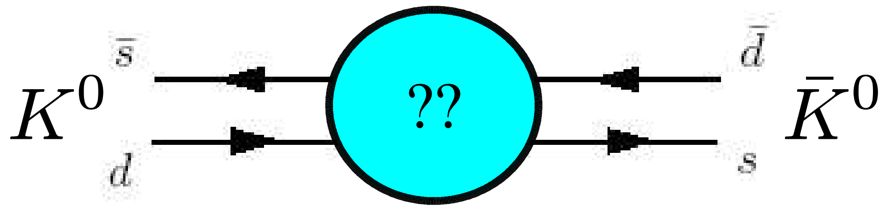

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Mesons decay!

Mass eigenstates:

$$|M_{1,2}\rangle = p|M^0\rangle \pm q|\overline{M}^0\rangle$$

Propagate with separate mass $m_{1,2}$ and width $\Gamma_{1,2}$:

$$|M_{1,2}(t)\rangle = e^{-i(m_{1,2}-i\Gamma_{1,2}/2)t}|M_{1,2}(t=0)\rangle$$

Meson Mixing

Time evolution of $|M^0\rangle$ state is described by

$$\begin{cases} x = \dfrac{m_2 - m_1}{\Gamma} \\ y = \dfrac{\Gamma_2 - \Gamma_1}{2\Gamma} \end{cases} \qquad \Gamma = \frac{\Gamma_2 + \Gamma_1}{2}$$

General time evolution equation:

$$|M^0(t)\rangle = e^{-\bar{\gamma}t/2}\left(\cosh(\Delta\gamma t/2)|M^0\rangle - \frac{q}{p}\sinh(\Delta\gamma t/2)|\overline{M}^0\rangle\right)$$

Where $\Delta\gamma = (y + ix)\Gamma \qquad \bar{\gamma} = (\Gamma_1 + \Gamma_2)/2 - i(m_1 + m_2)$

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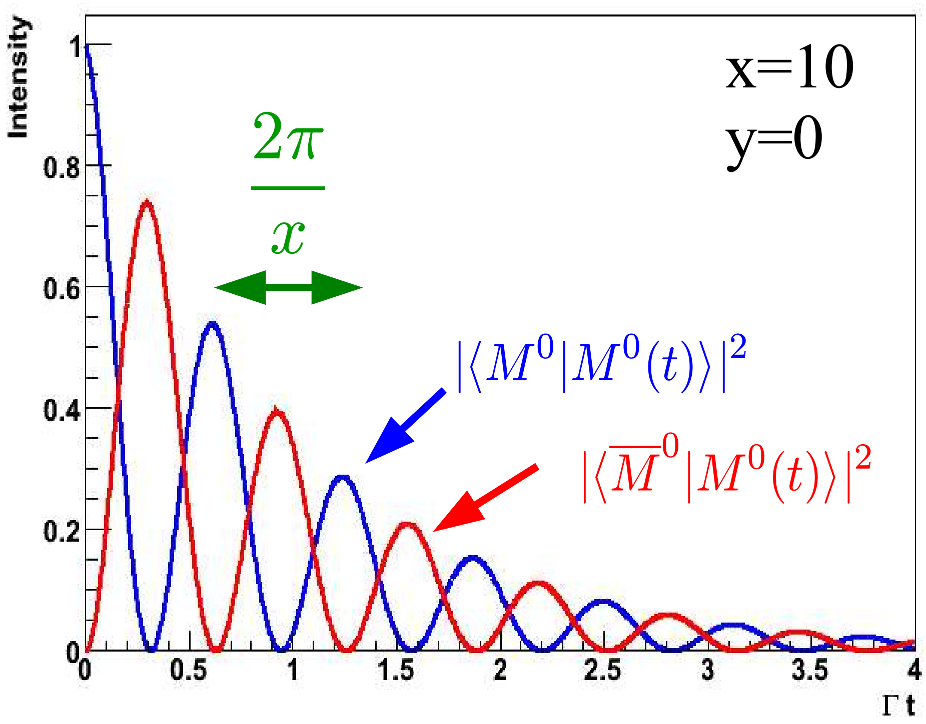

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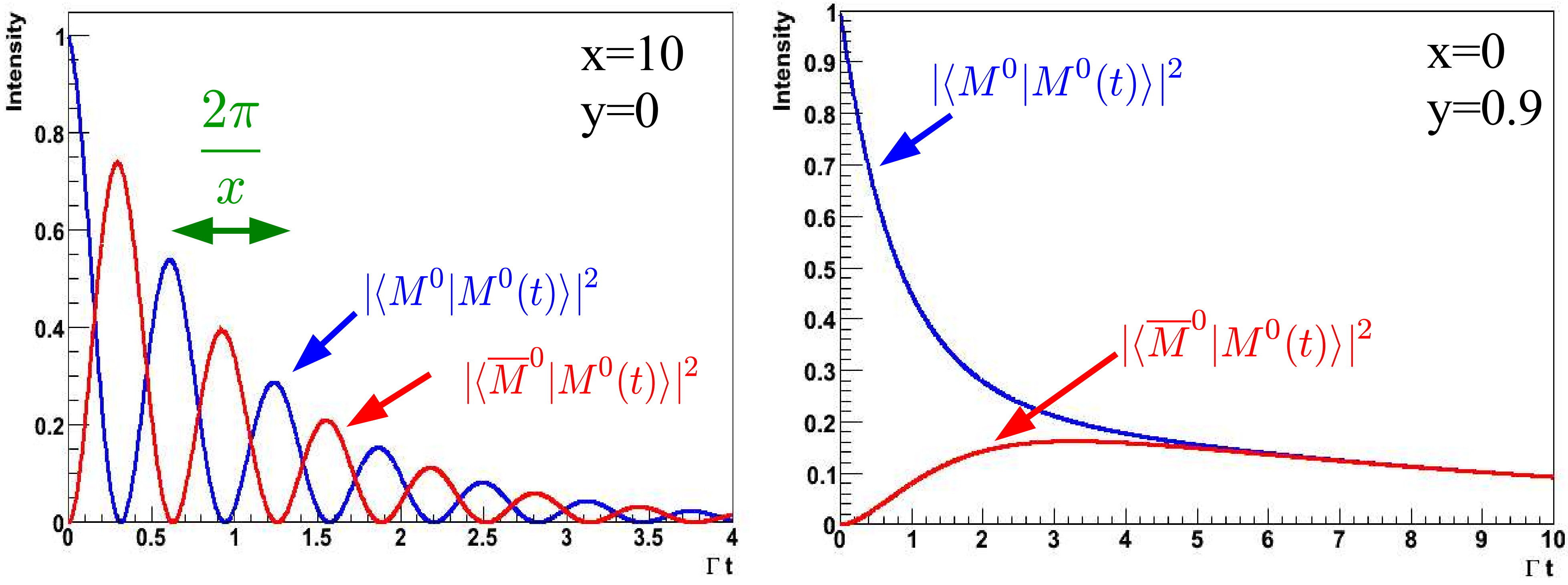
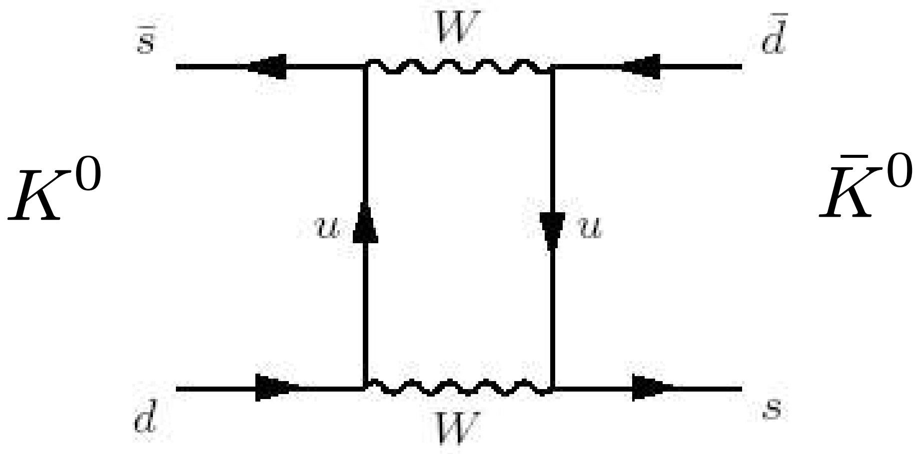


Mixing Sources

In Standard Model, only charged weak interaction change quark flavor:

Mixing through box diagram:



Box diagrams mainly contribute to x

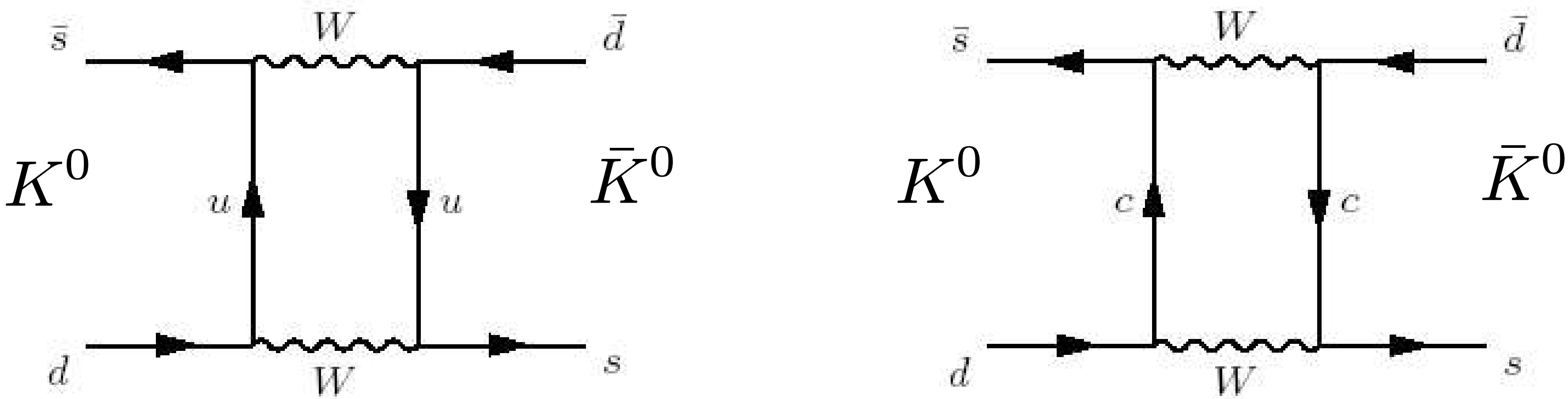
In SM, there are no tree-level flavor-changing neutral currents (FCNC)

GIM Suppression

Glashow, Iliopoulus and Maiani (1970):

FCNC calculated from single quark loop still too large

Introduce additional loop with new c quark

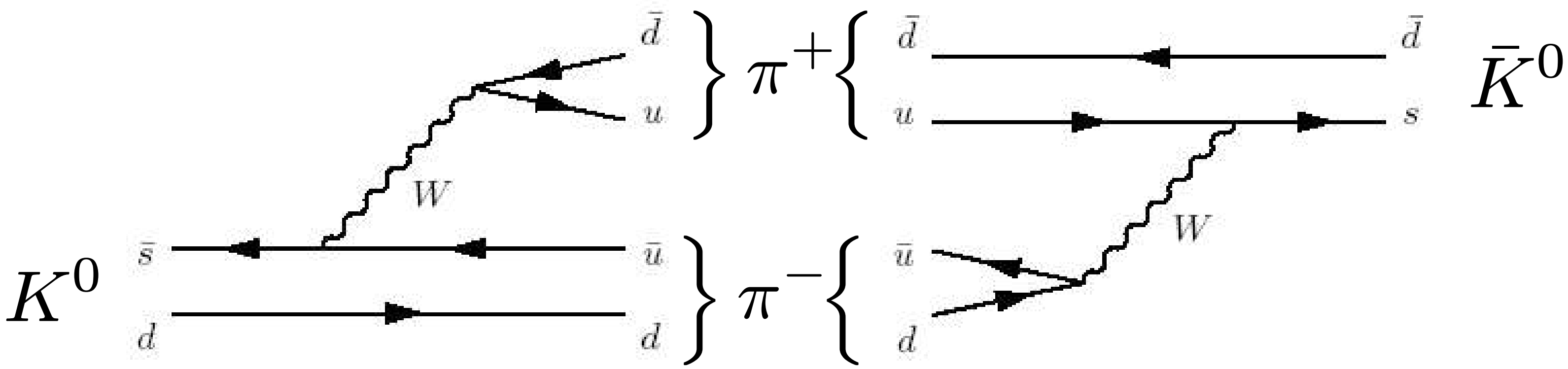


In limit of degenerate quarks, loops will cancel each other – mass difference between quarks will give a small x

GIM predicted charm quark 4 years before observation

Long-distance Effects

Additional contribution from intermediate hadronic states common to K^0 and $\overline{K}^0$:



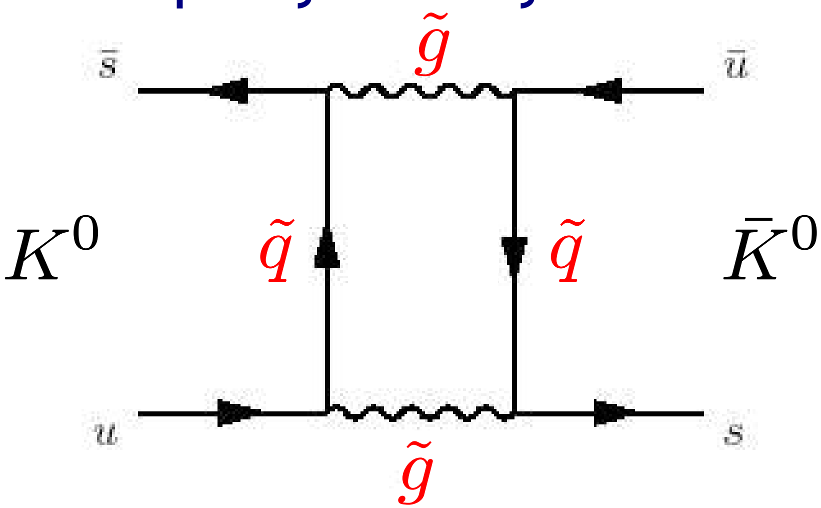
Mainly gives lifetime difference y

Oscillations from New Physics

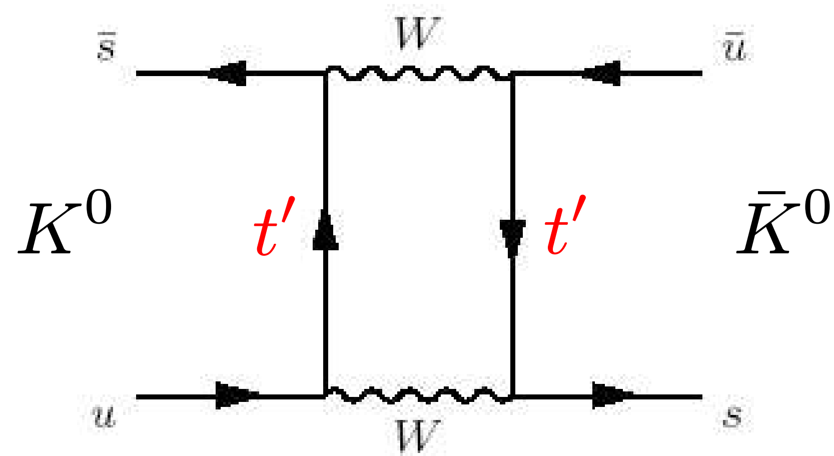
New physics can break GIM suppression

Examples:

Supersymmetry:



Fourth quark generation:



Differences between measured and predicted mixing rates would be signal for new physics

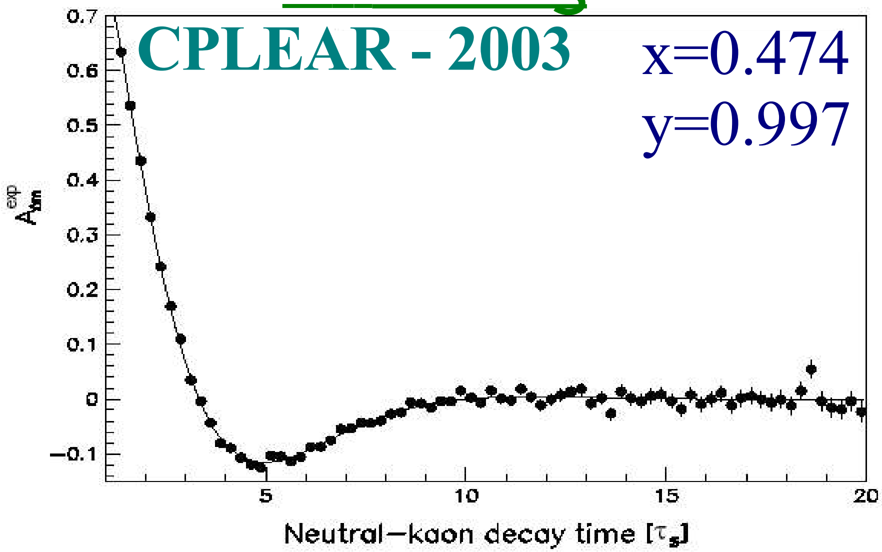
The good agreement in K and B systems with SM constrains any new physics model

Status of Neutral Meson Mixing

K^0 mixing

CPLEAR - 2003

x=0.474
y=0.997



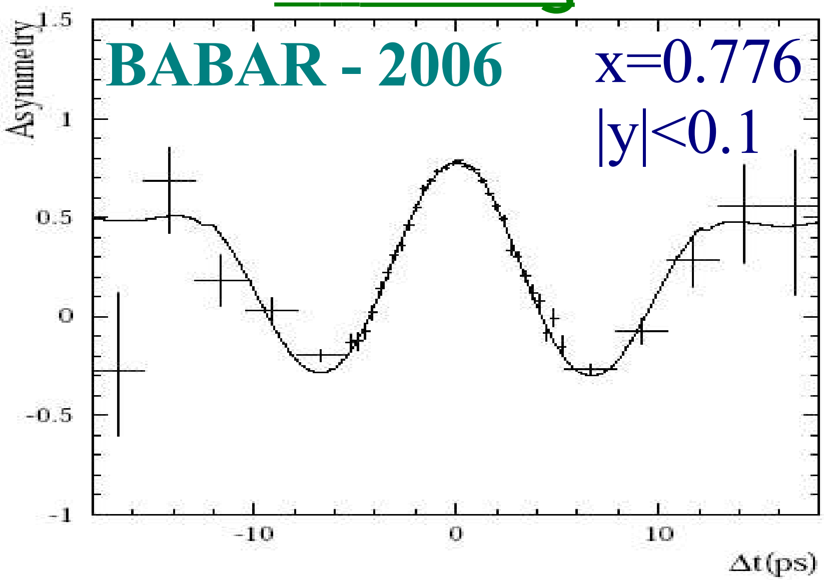
D^0 mixing

?

B^0 mixing

BABAR - 2006

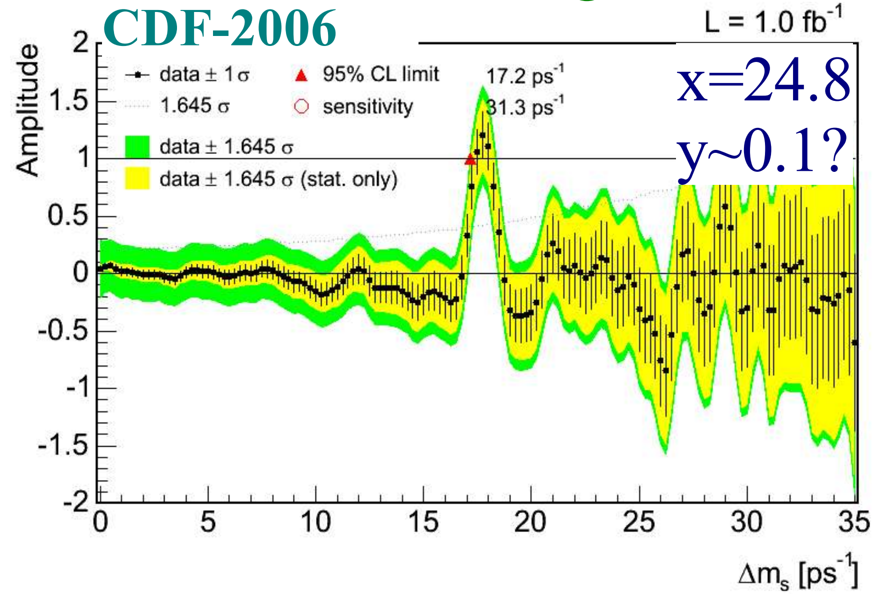
x=0.776
|y|<0.1



B_s^0 mixing

CDF-2006

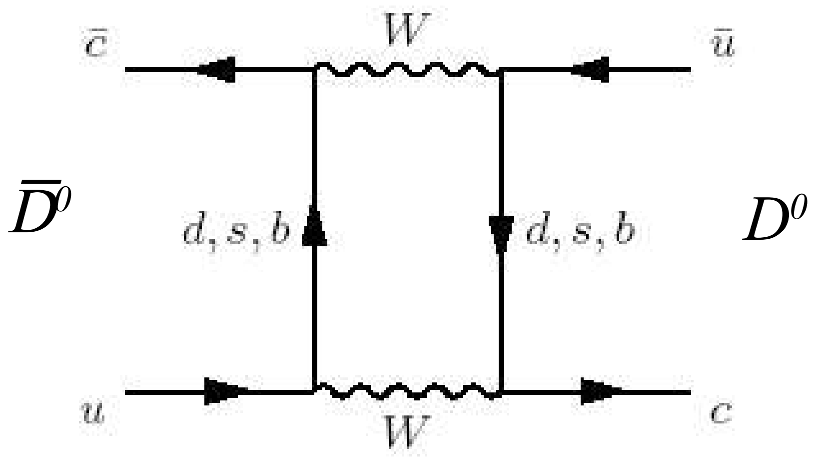
x=24.8
y~0.1?



Mixing in Charm?

Charm Mixing

SM charm mixing box has down-type quarks in loop



Effective GIM suppression:

$$x \propto \frac{(m_s^2 - m_d^2)^2}{m_c^2}$$

→ $x \sim 10^{-5}$ Tiny!

Charm Mixing

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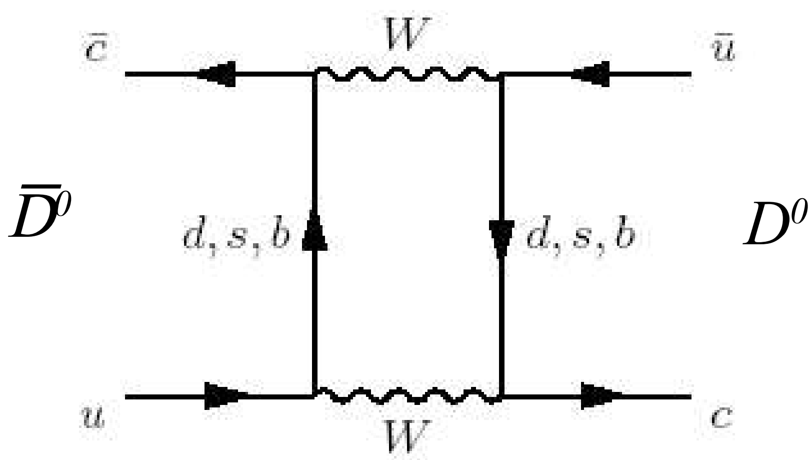

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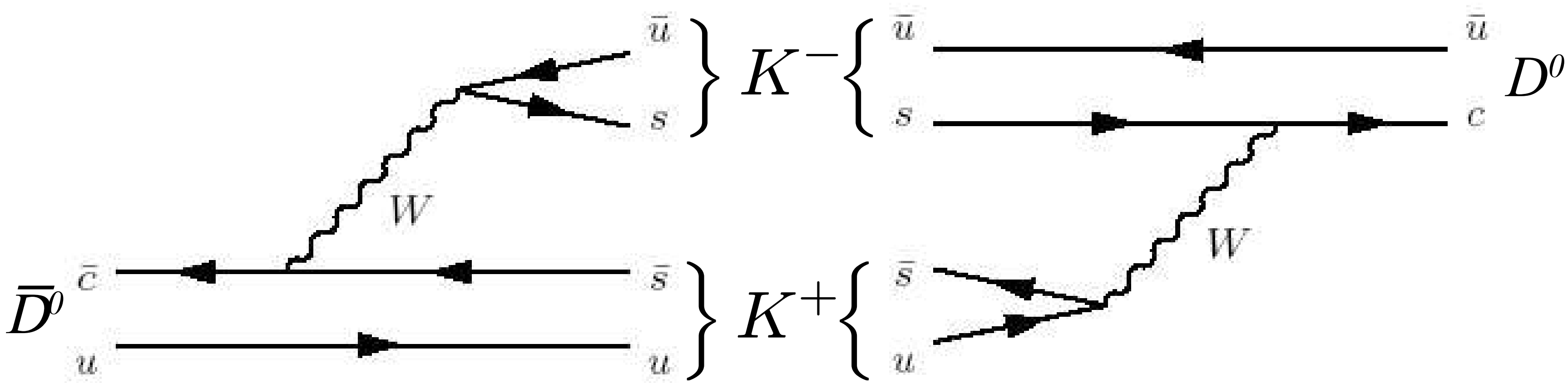
Expect hadronic intermediate states to dominate:



Makes it difficult to predict SM expectation

Charm Mixing Predictions

Most predictions give x,y~0.001-0.01
and in most cases |x|<|y|

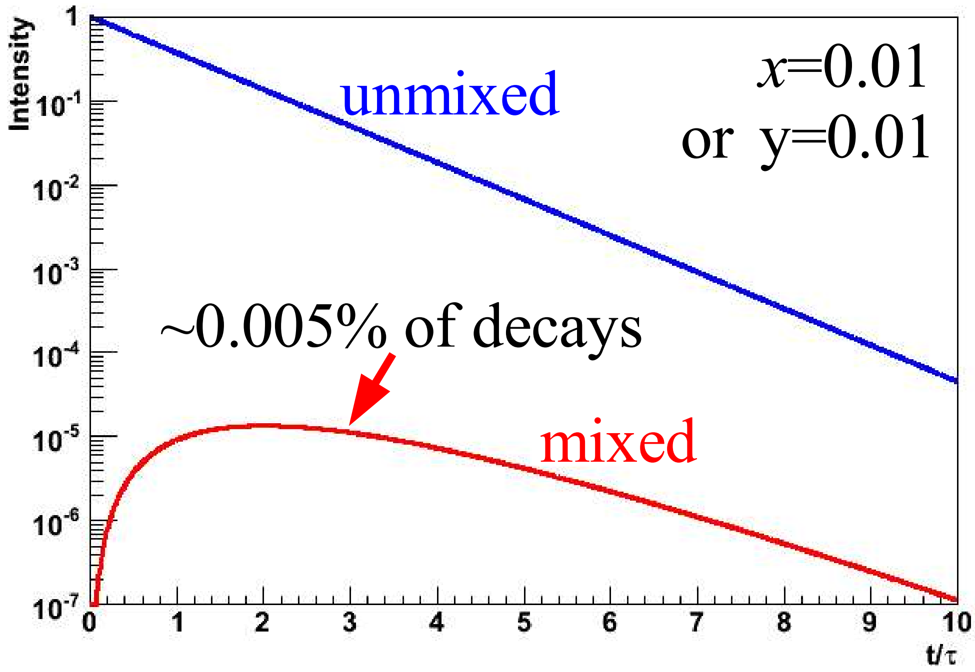
$$x = \frac{m_2 - m_1}{\Gamma}$$

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

Latest estimations:

$|y| \leq 0.01$ — PRD 65 054034 (2002), Falk, Grossman, Ligeti and Petrov

$|x| \sim (0.1 \text{ to } 1) \cdot |y|$ — PRD 69 114021 (2004), Falk, Grossman, Ligeti, Nir and Petrov

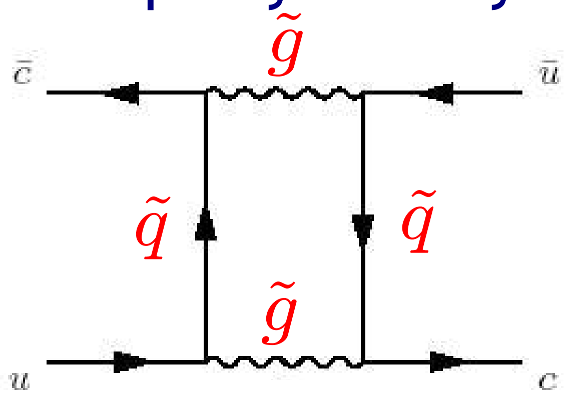


Very low rate makes measurement difficult

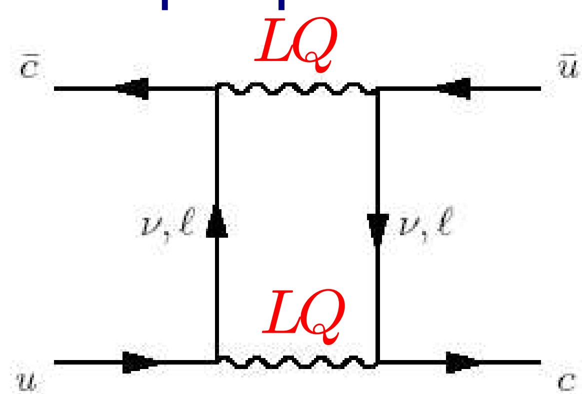
New Physics in Charm Mixing

Charm mixing could have New Physics contribution

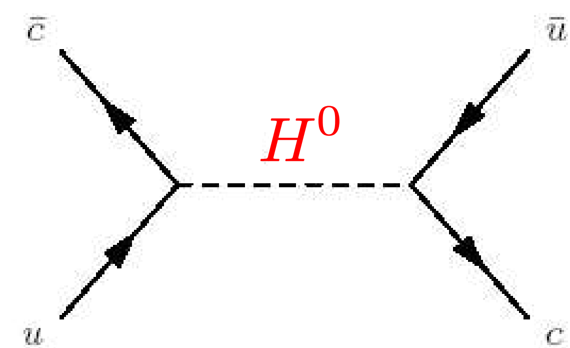
Supersymmetry:



Leptoquarks:



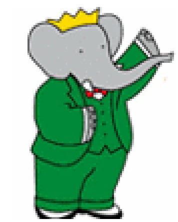
Extended Higgs:



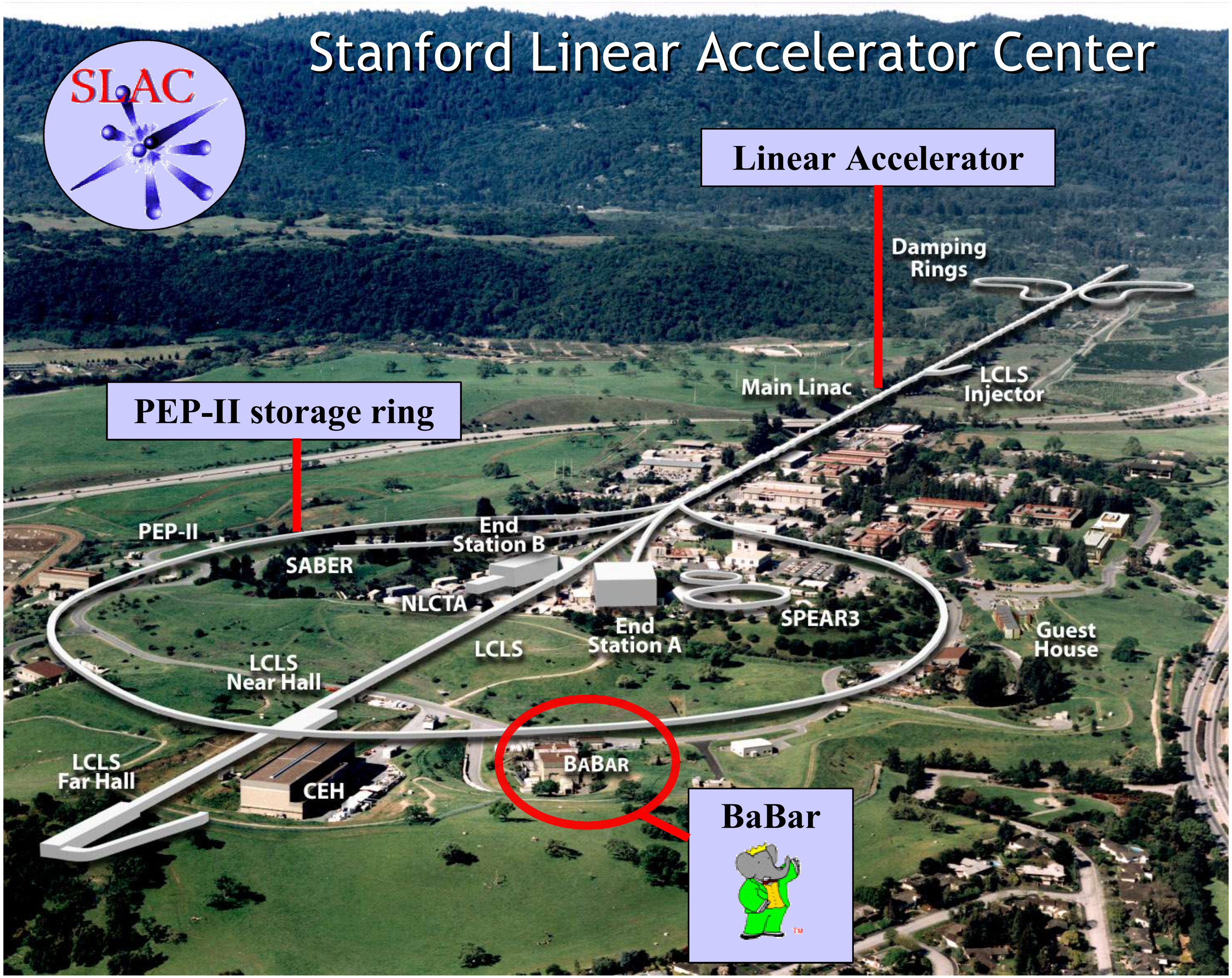
Charm mixing complements K^0 and B^0 mixing measurements

- Sensitive to up-type quarks instead of down-type quarks

Some models avoid K^0 and B^0 mixing signals by having large charm mixing

The BaBar  Experiment

PEP-II, a B-Factory (and Charm)



High-luminosity asymmetric energy e^+e^- collider at $\Upsilon(4S)$ resonance

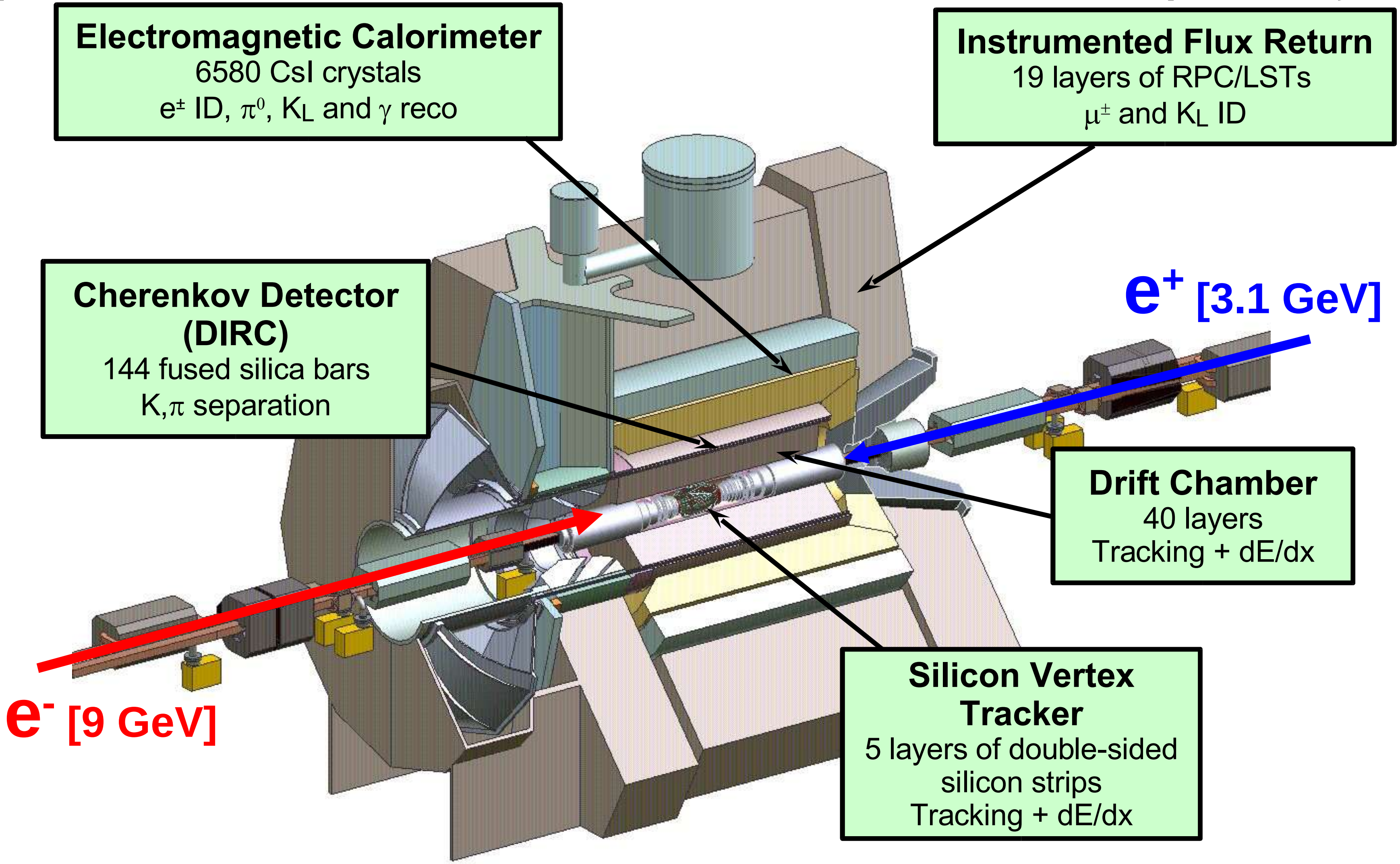
B-Factory built for study of CP-violation and other CKM-physics in B meson decays

~10 Hz of $B\overline{B}$

The BaBar Experiment

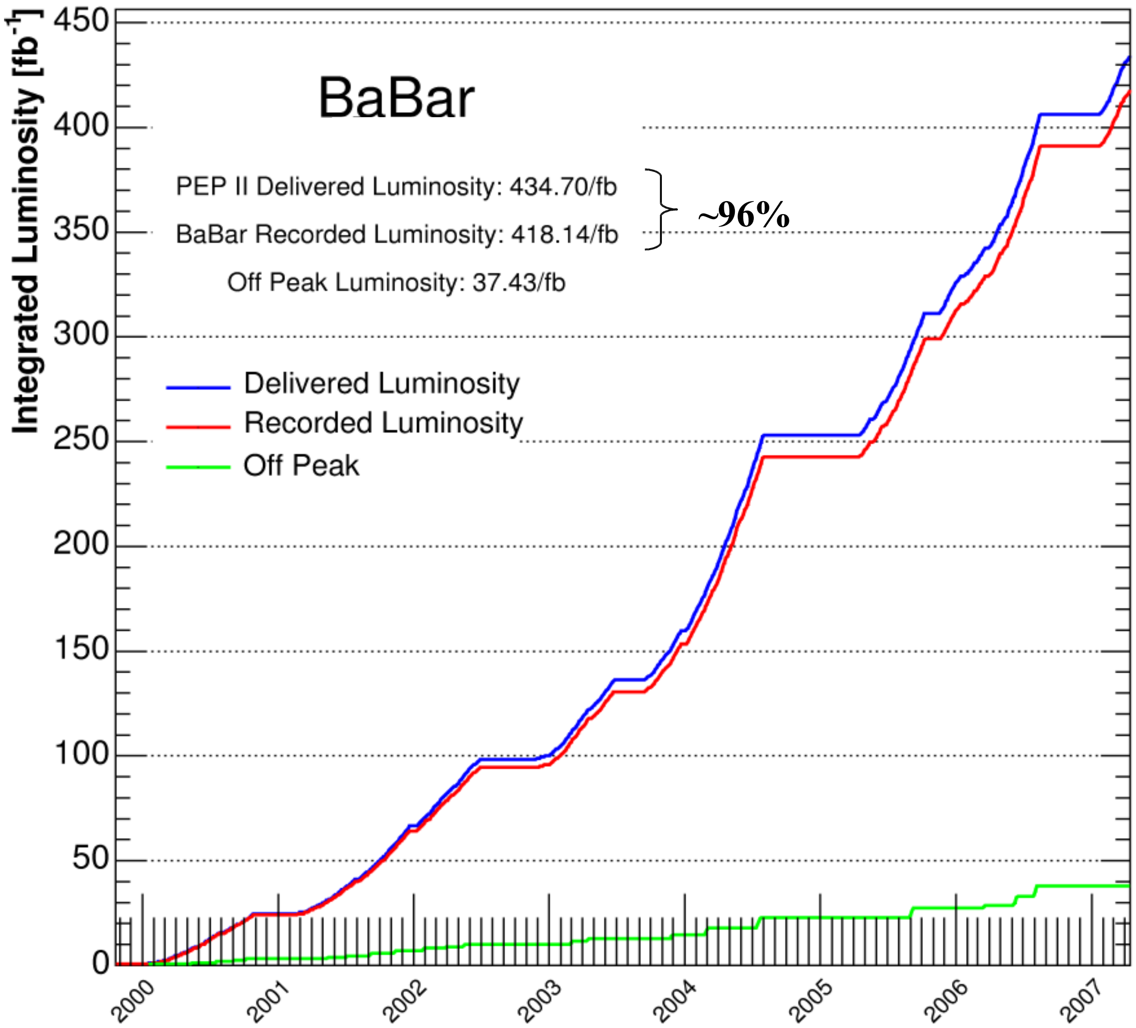
The BaBar Experiment

BaBar is a large acceptance experiment with excellent particle reconstruction and identification capability



B-Factory: High Luminosity

High luminosity recorded efficiently



$\sigma_{eff}(b\bar{b})$=1.1 nb
$\sigma(c\bar{c})$=1.3 nb

Recorded >400M $B\bar{B}$ events, and >500M $c\bar{c}$ events

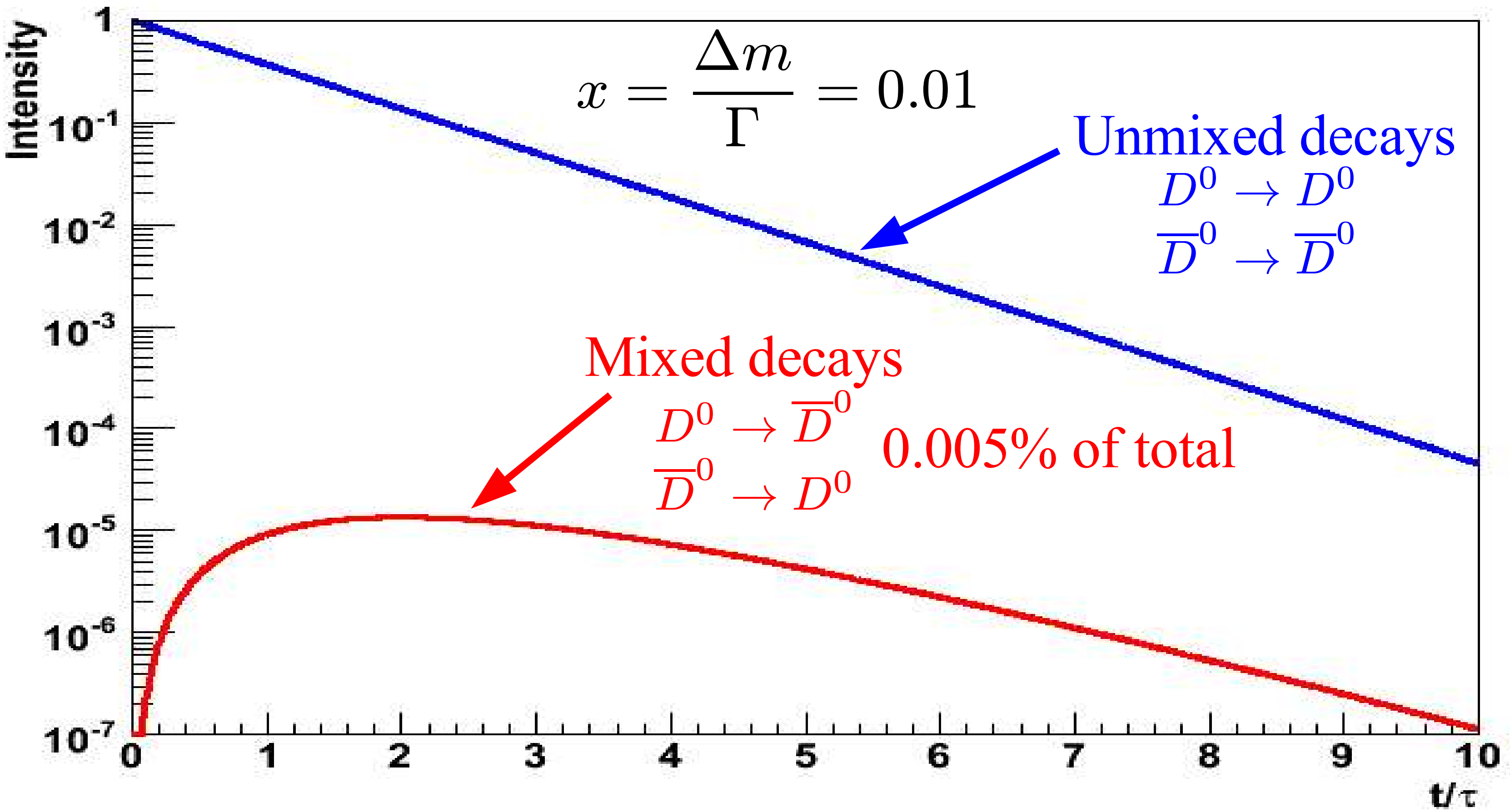
Add ~1M $c\bar{c}$ each day

Excellent sample to search for charm mixing

Charm Mixing in $D^0 \rightarrow K\pi$ Decay at BaBar

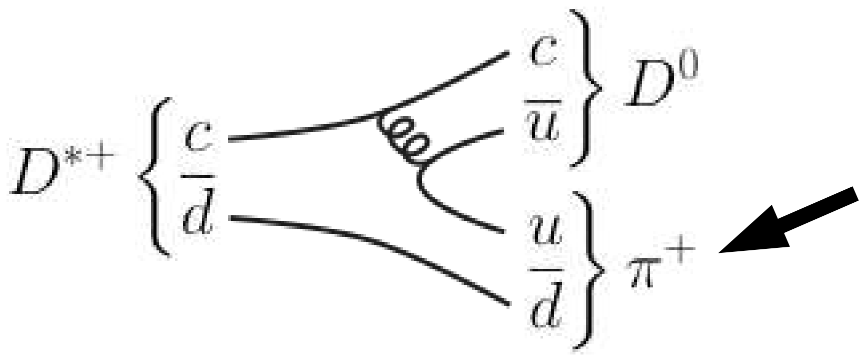
Principle of Mixing Measurement

- Produce clean sample of D^0 and $\bar{D}^0$
- Identify flavor (D^0 or $\bar{D}^0$?) at decay time
- Measure rate of mixed decays as function of time



Production Flavor

Use D^0 from $D^{*+} \rightarrow D^0 \pi^+$ decays:



Charge of pion "tags" initial flavor as D^0 or $\bar{D}^0$

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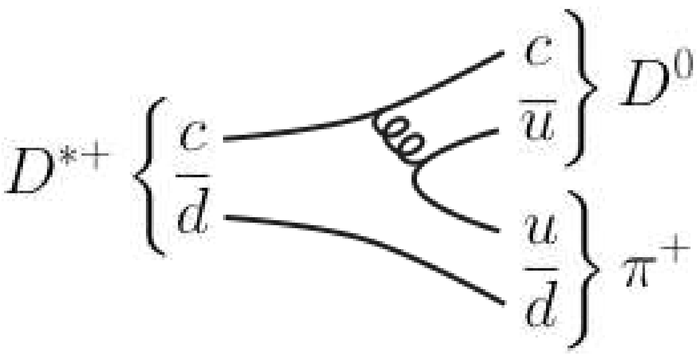

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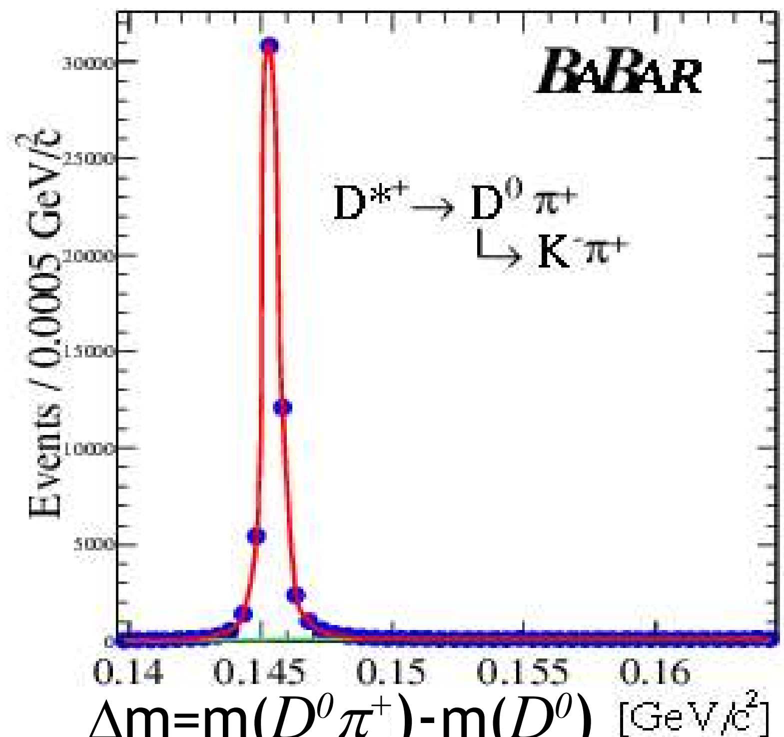
<u>Additional benefit: small Q</u>

$$Q = m(D^{*+}) - m(D^0) - m(\pi^+) \approx 6\,\mathrm{MeV}/c^2$$

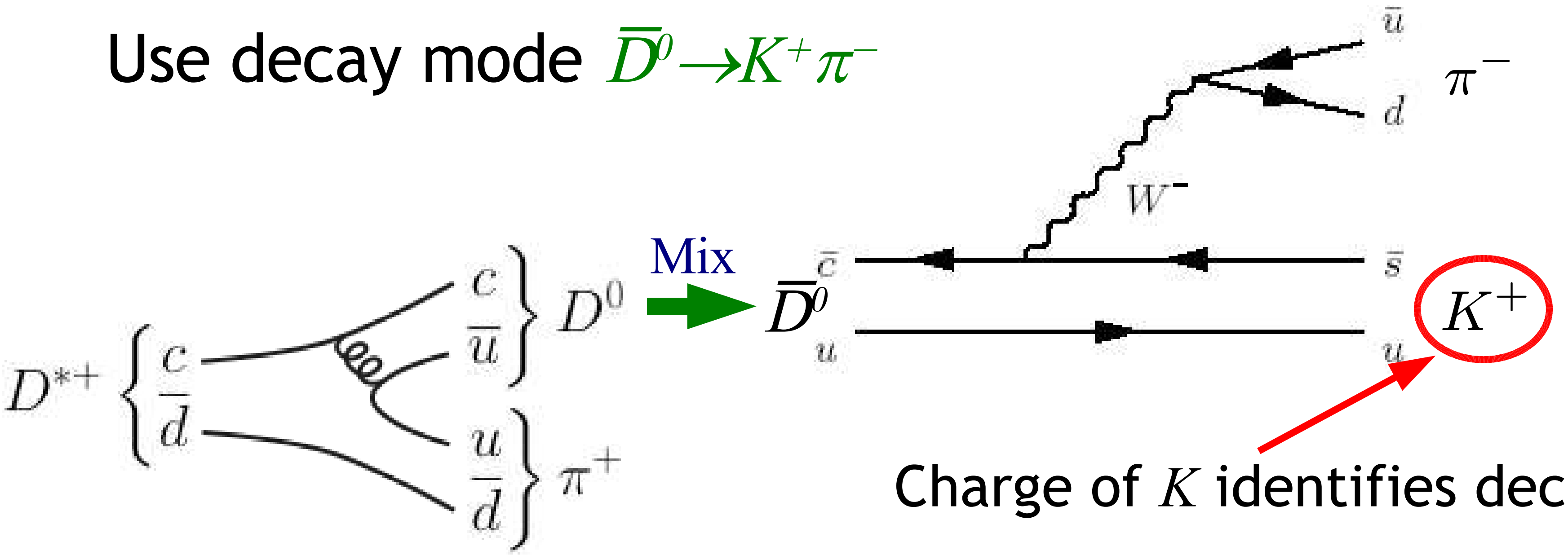
Gives narrow mass peak

Excellent background suppression



Flavor at Decay

Use decay mode $\overline{D}^0 \rightarrow K^+ \pi^-$



Charge of K identifies decay flavor

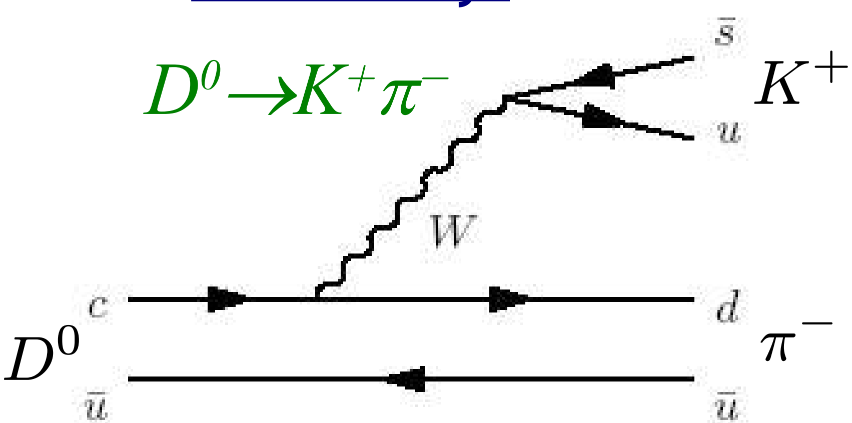
If opposite flavor: Wrong-sign (WS) event – mixing occurred
If same flavor: Right-sign (RS) events – unmixed decay

Doubly-Cabibbo Suppressed Decays

Hadronic decays do not uniquely identify decay flavor

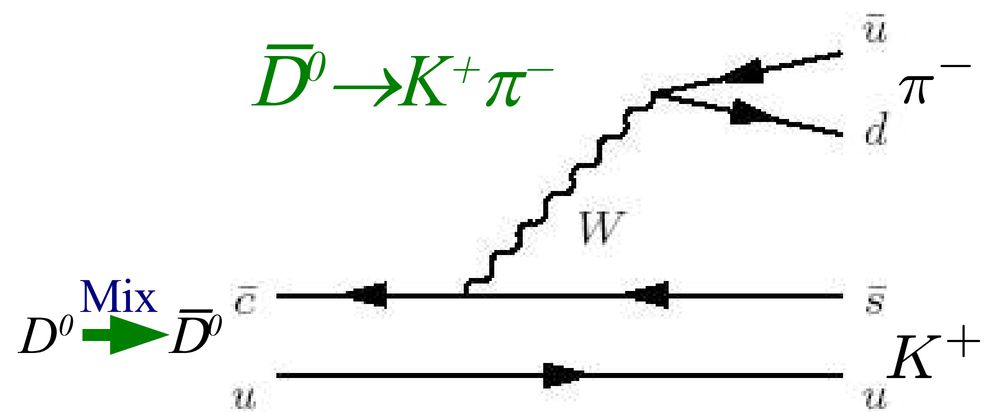
Get unmixed wrong-sign decays from DCS decays

DCS decay:



Relative rate ~0.3%

Mixed decay:

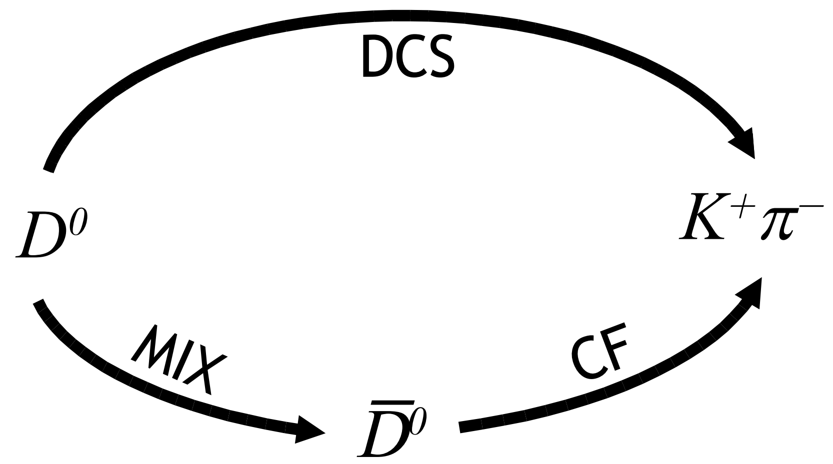


Relative rate: 0.005% (for x=0.01)

Time-Evolution of $D^0 \to K\pi$ Decays

Discriminate DCS and mixing by their different time evolution

Also have interference effect:



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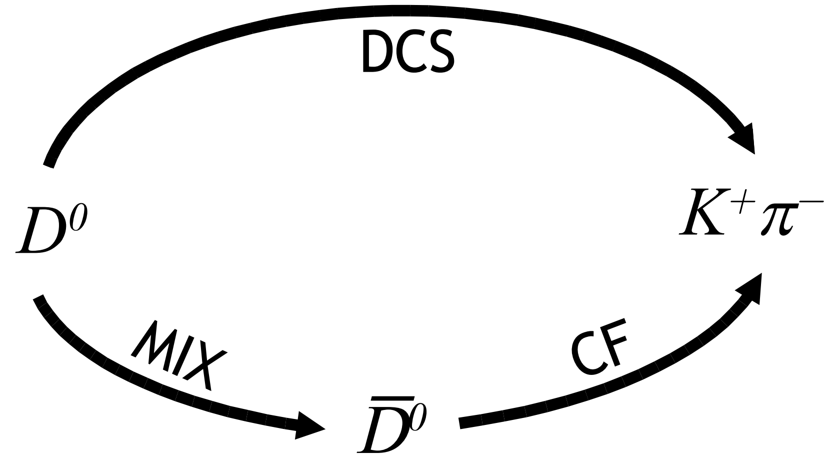


Time evolution: $(|x| \ll 1, |y| \ll 1)$

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

$$y' = y\cos\delta - x\sin\delta$$
$$x' = y\cos\delta + x\sin\delta$$

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

δ is phase difference between DCS and CF decays

Event Selection

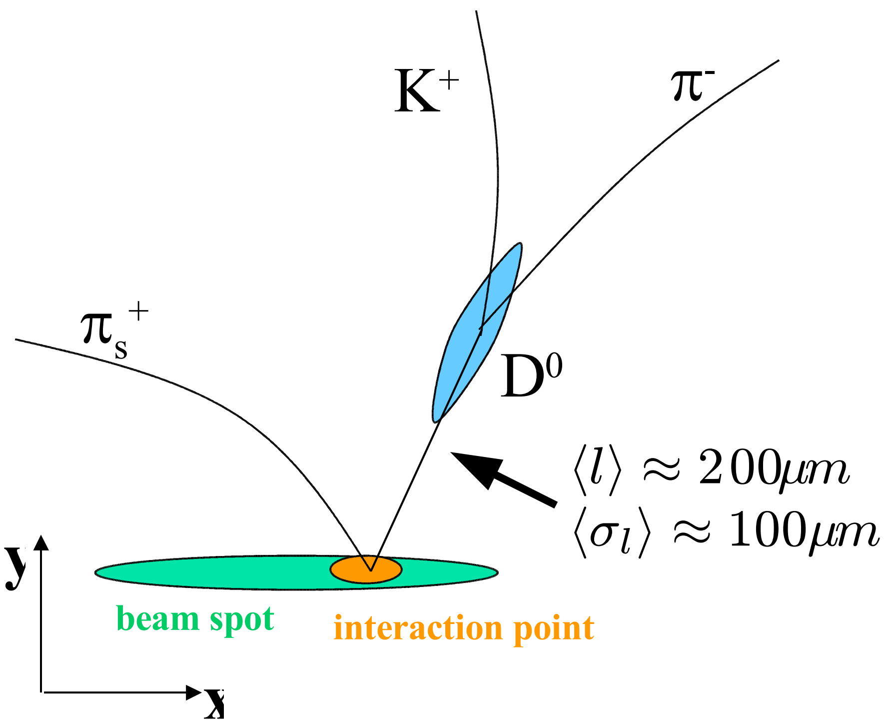
D^0 selection:

- Identified K and π
- $p^*(D^0)$> 2.5 GeV/c
- 1.81<m($K\pi$)<1.92 GeV/c^2

Slow π selection:

- $p^*(\pi_s)$< 0.45 GeV/c
- $p_{lab}(\pi_s)$> 0.1 GeV/c
- 0.14<Δm<0.16 GeV/c^2

  $\Delta m = m(K\pi\pi_s) - m(K\pi)$

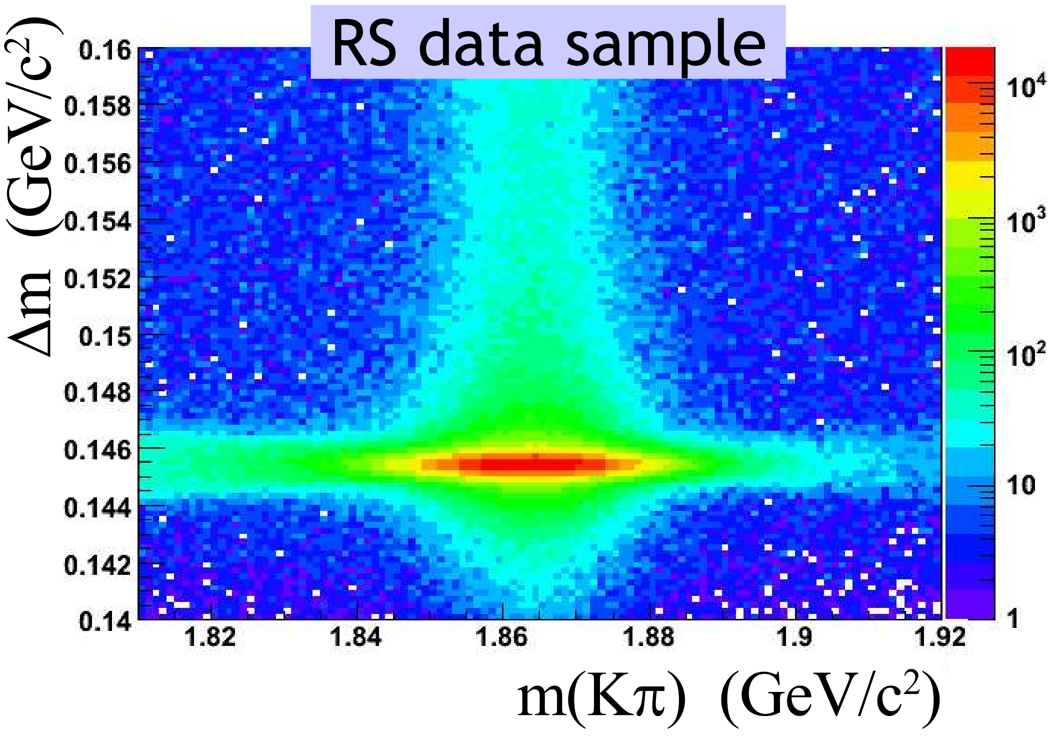


Vertexing:

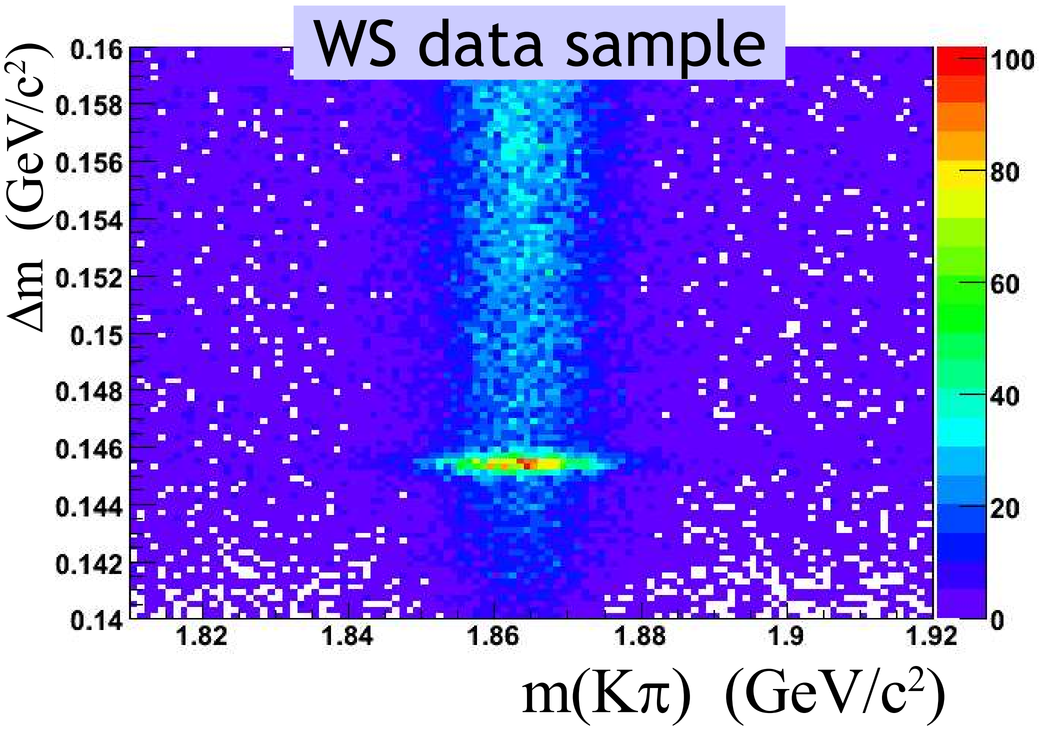
- D^0 and π_s constrained to luminous region
- Fit probability > 0.1%
- Reconstructed decay time, t: -2<t<4 ps
- Estimated decay time error, δt<0.5 ps

Selected Events

1,229,000 RS events



64,000 WS events



Separate signal from background using m(Kπ) and Δm

Fit Procedure

Unbinned maximum likelihood fit in several steps

(fitting 1+ million events takes a long time)

Fit to m(Kπ) and Δm distribution:

- RS and WS samples fit simultaneously
- Signal and some background parameters shared
- All parameters determined in fit to data, not MC

Fit RS decay time distribution:

- Determines D^0 lifetime and resolution function
- Include event-by-event decay time error δt in resolution
- Use m(Kπ) and Δm to separate signal/bkgd (fixed shapes)

Fit WS decay time distribution:

- Use D^0 lifetime and resolution function from RS fit
- Compare fit with and without mixing (and CP violation)

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Signal and Background Components

Signal:

- Correct $D^{*+} \to D^0\pi^+$
- Peaks in m($K\pi$) and Δm

Random π_s:

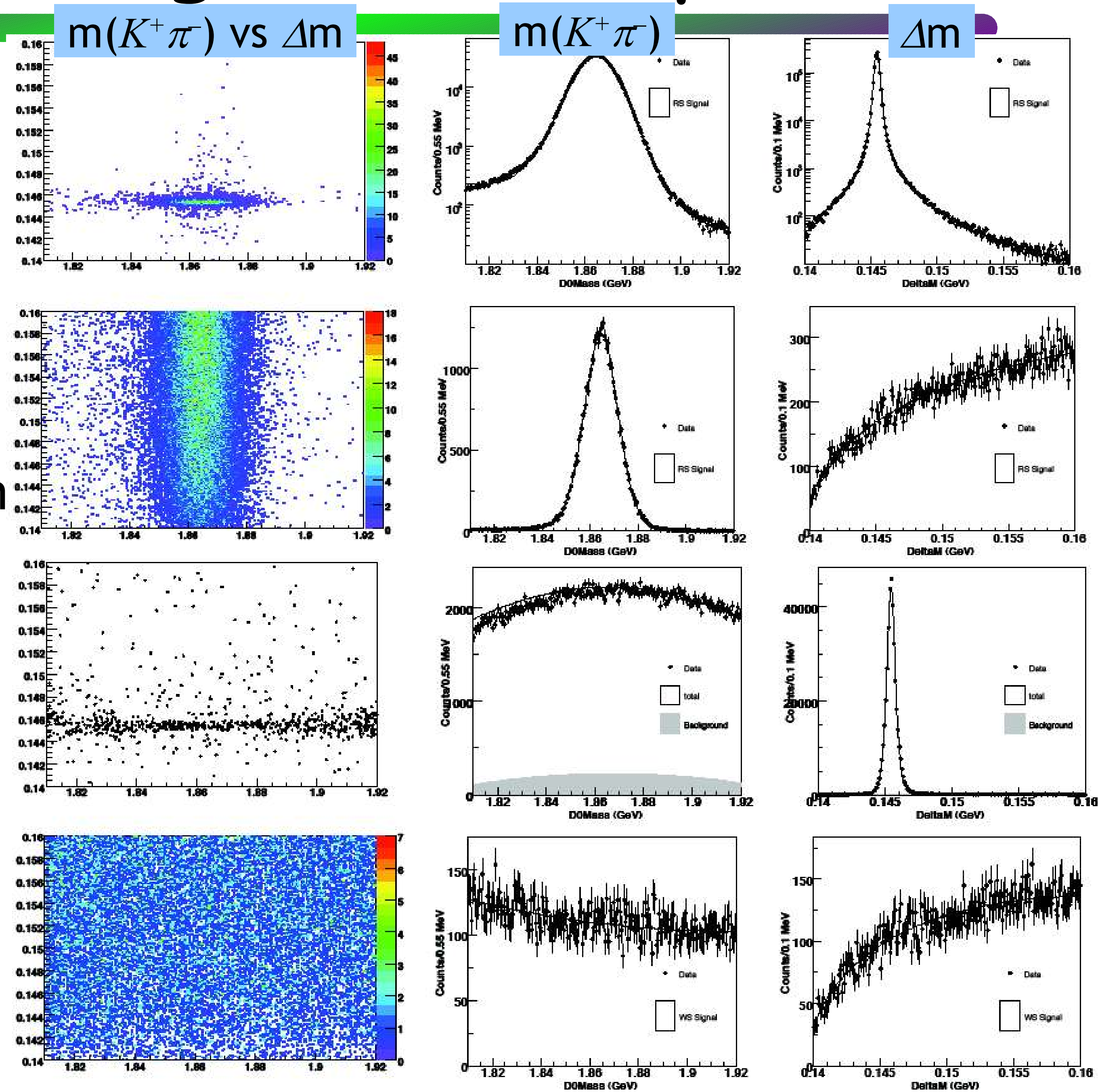
- Correct D^0, wrong π_s
- Peaks in m($K\pi$), not Δm

Misreconstructed D^0:

- Real $D^{*+} \to D^0\pi^+$
- $D^0 \to K^-\mu^+\nu$
- Double misid $D^0 \to K^-\pi^+$ (WS events only)

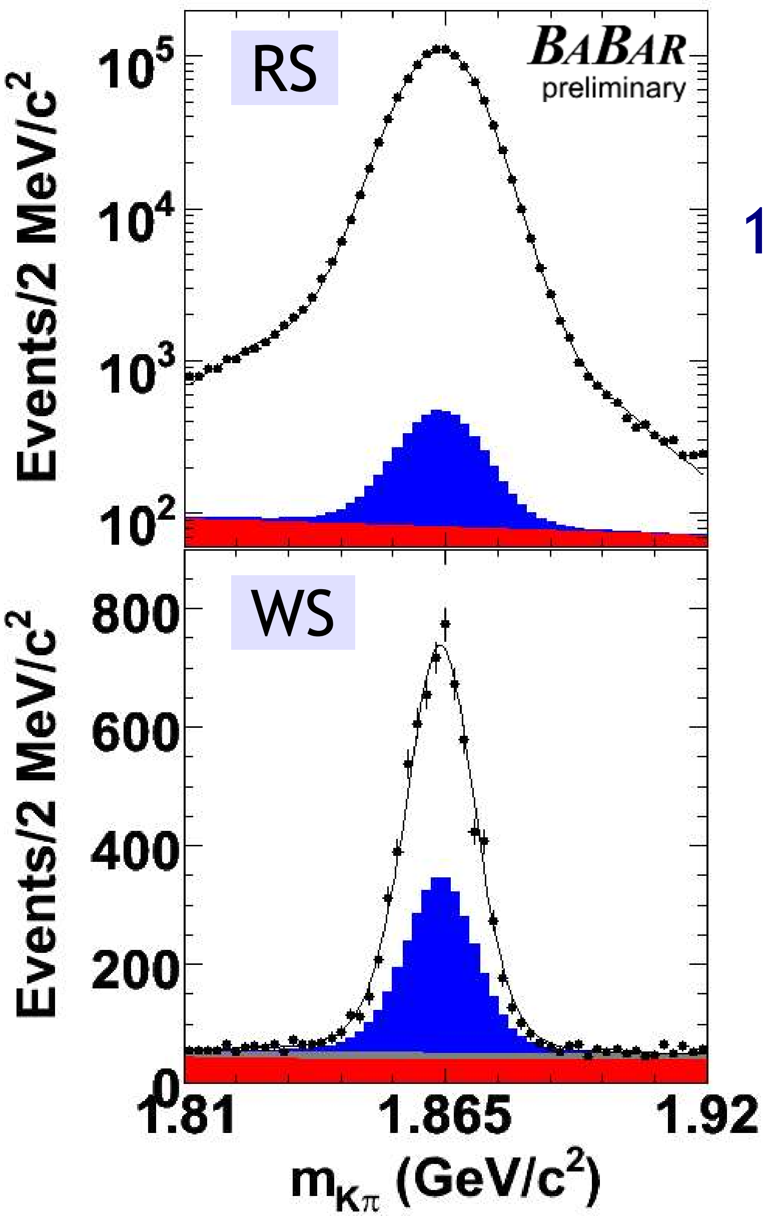
Combinatoric:

- Random tracks



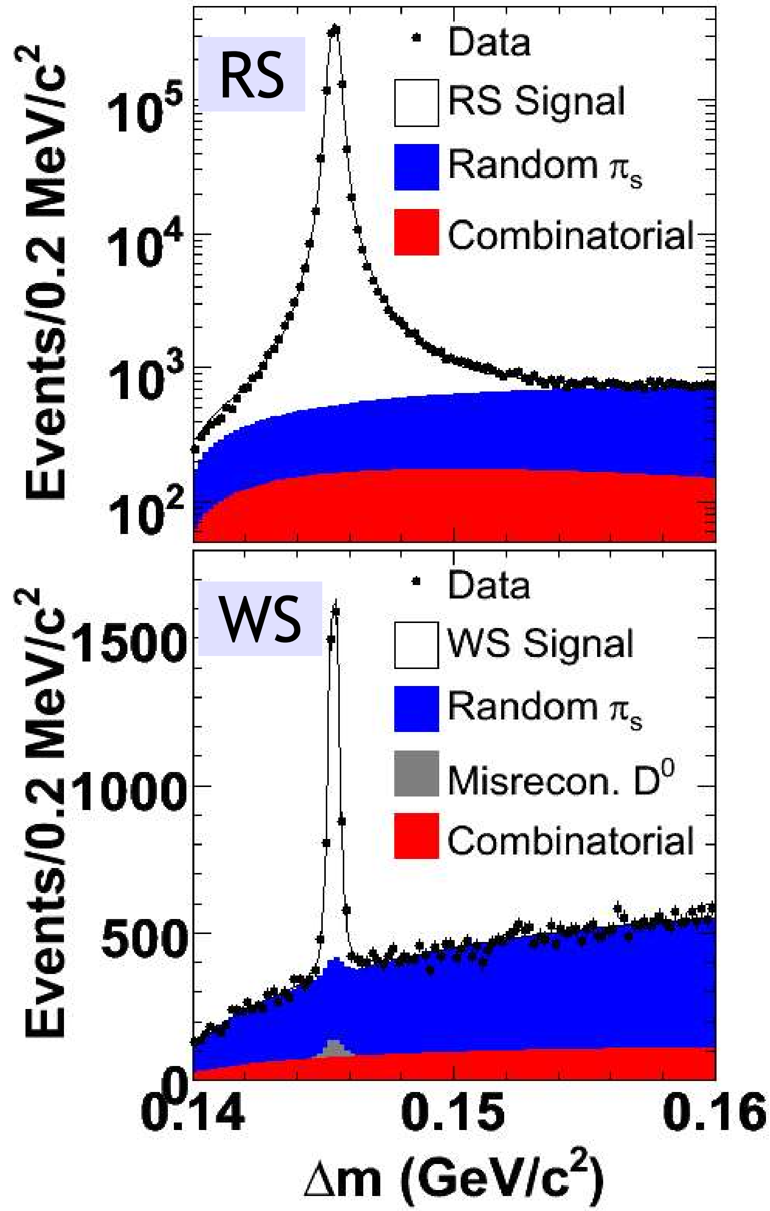
Brian Petersen

m(Kπ)-Δm Fit Results



RS signal:
1,141,500±1200
combinations

WS signal:
4,030±90
combinations



Fit Procedure

Unbinned maximum likelihood fit in several steps
(fitting 1+ million events takes a long time)

Fit to m(Kπ) and Δm distribution:

- RS and WS samples fit simultaneously
- Signal and some background parameters shared
- All parameters determined in fit to data, not MC

Fit RS decay time distribution:

- Determines D^0 lifetime and resolution function
- Include event-by-event decay time error δt in resolution
- Use m(Kπ) and Δm to separate signal/bkgd (fixed shapes)

Fit WS decay time distribution:

- Use D^0 lifetime and resolution function from RS fit
- Compare fit with and without mixing (and CP violation)

Decay Time Resolution

Average D^0 flight length only twice average resolution

- Resolution function described by sum of 3 Gaussians
- Resolution widths scales with δt
- Mean of core Gaussian allowed to be non-zero

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

For combinatorial background, use Gaussians and power-law "tail" for small long-lived component

RS Decay Time Fit

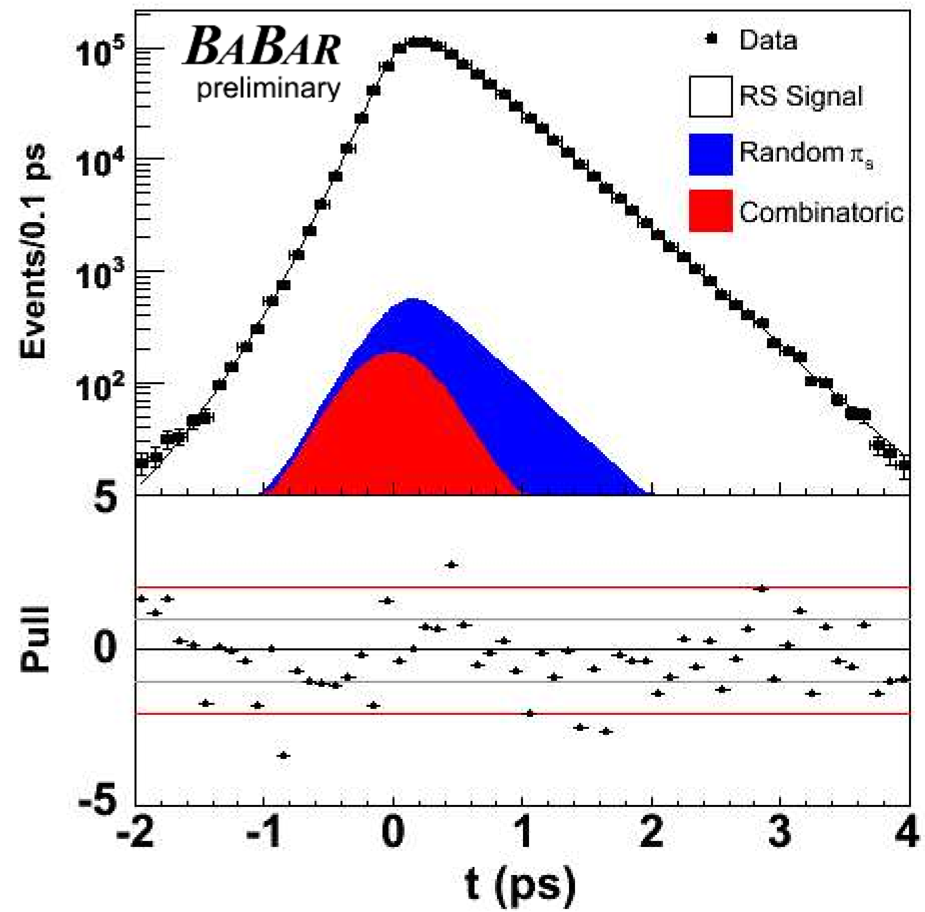
D^0 lifetime and resolution function fitted in RS sample

τ=(410.3±0.6(stat.)) fs

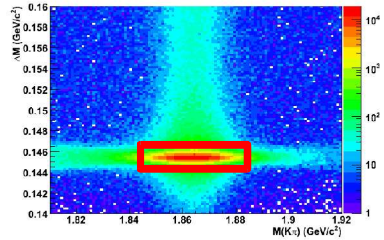
Consistent with PDG
(410.1±1.5 fs)

Systematics dominated by resolution function

RS decay time, signal region



plot selection:
1.843<m<1.883 GeV/c^2
0.1445<Δm< 0.1465 GeV/c^2



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Fit WS decay time distribution:

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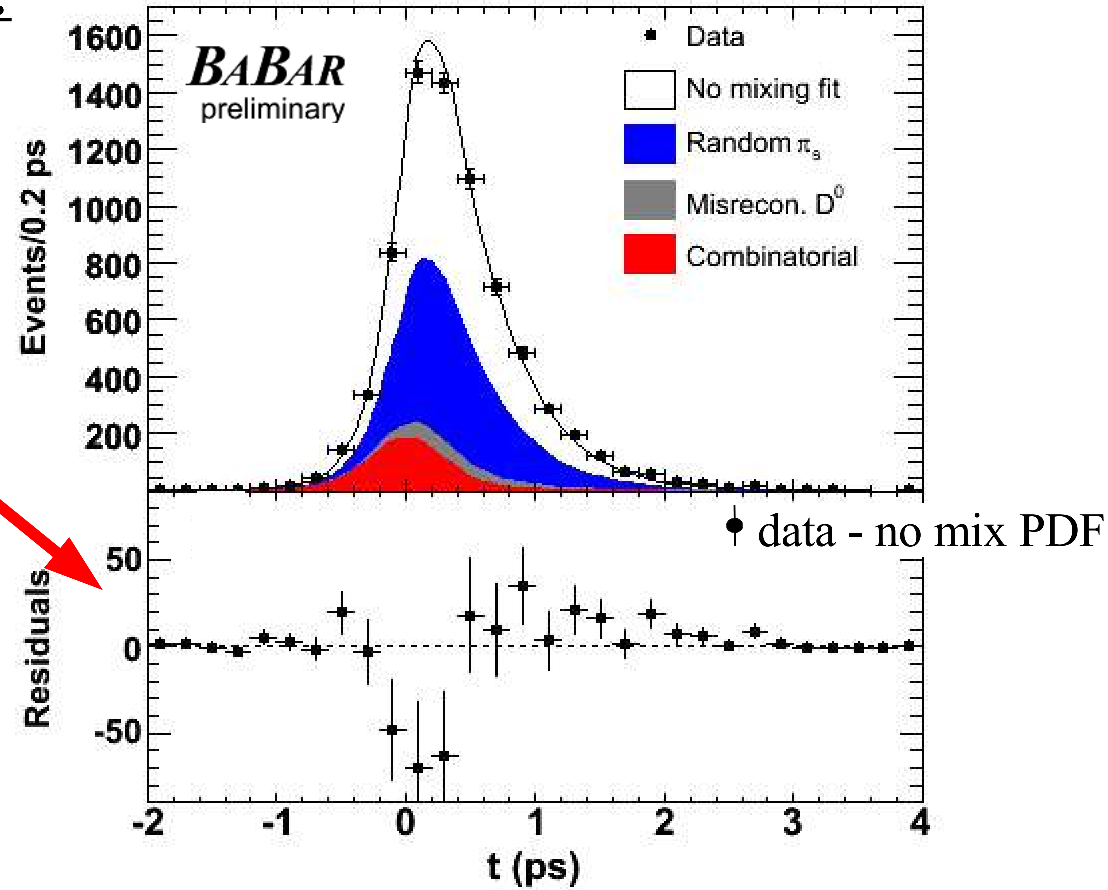
WS Fit with no Mixing

WS decay time, signal region



<u>Fit results assuming no mixing:</u>

R_D: $(3.53 \pm 0.08 \pm 0.04) \times 10^{-3}$

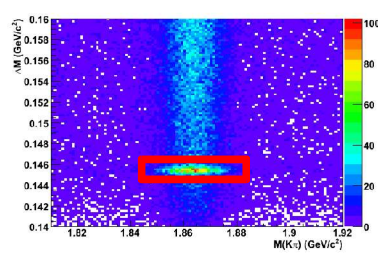
However, residuals in signal region are not good

$\chi^2/bin = 49.7/28$

plot signal region:

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

$0.1445 < \Delta m < 0.1465$ GeV/c^2



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WS Fit with Mixing

Fit results allowing 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': $(9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$

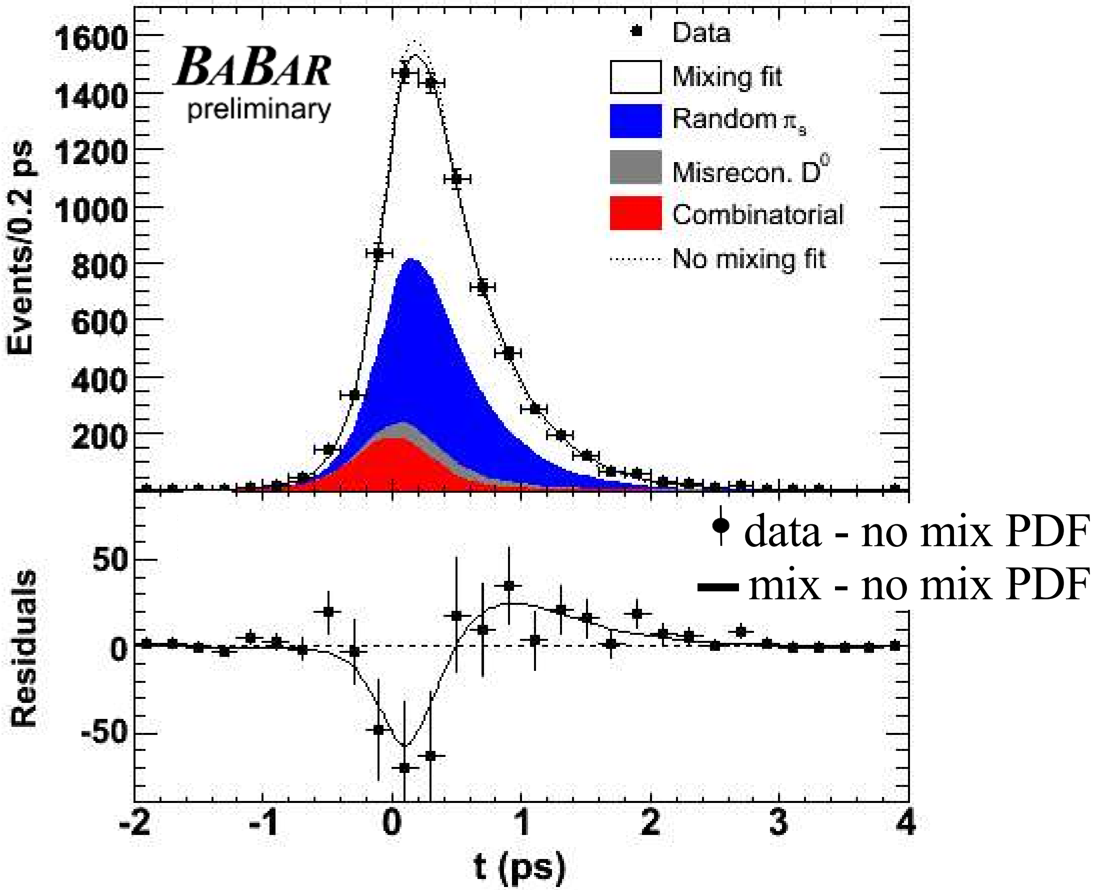
x'^2, y' correlation: -0.94

Fit with gives better description of data

$\chi^2/bin = 31/28$

How significant?

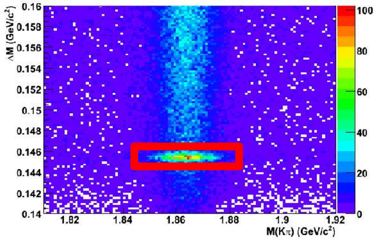
WS decay time, signal region



plot signal region:

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

$0.1445 < \Delta m < 0.1465$ GeV/c^2



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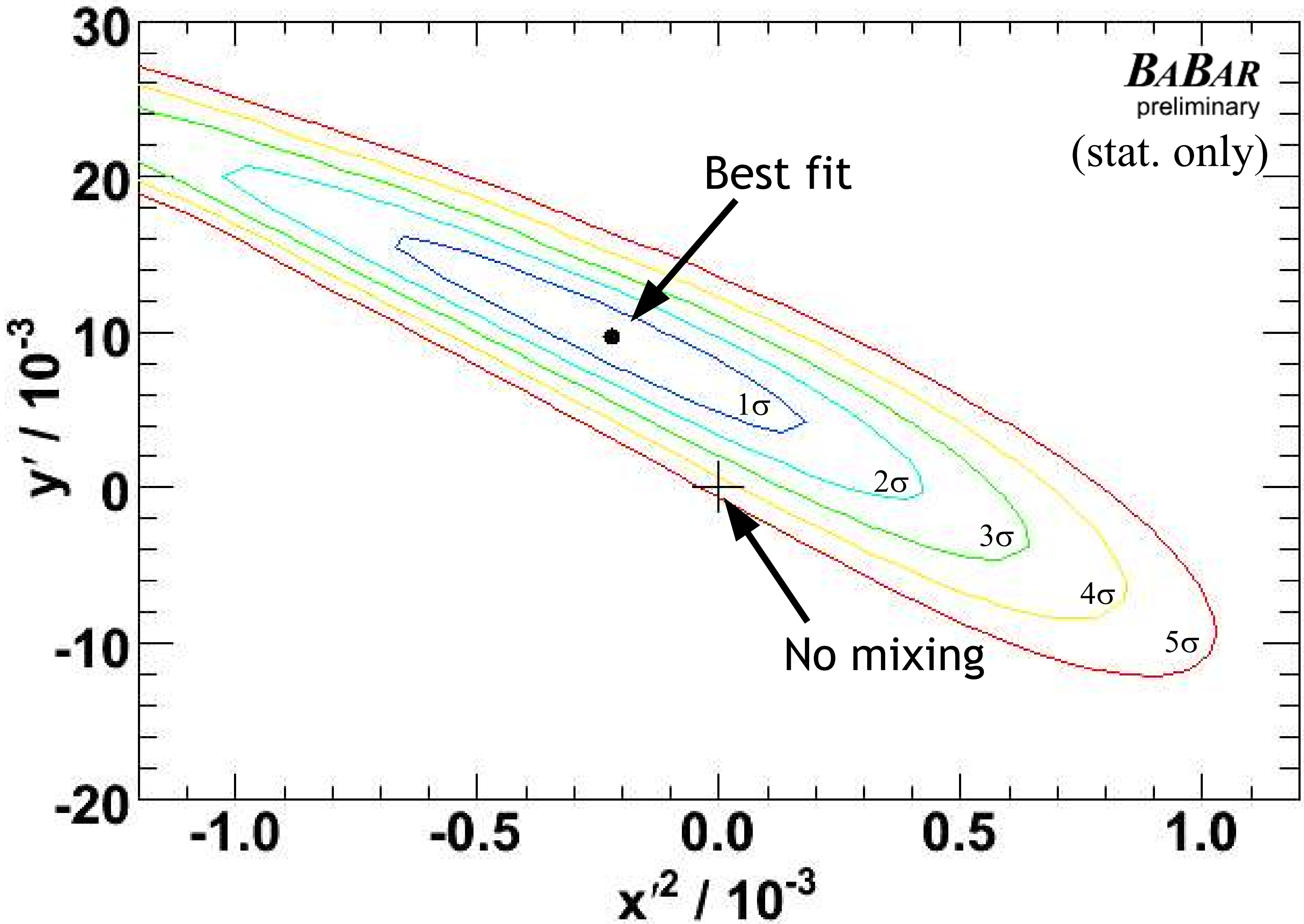
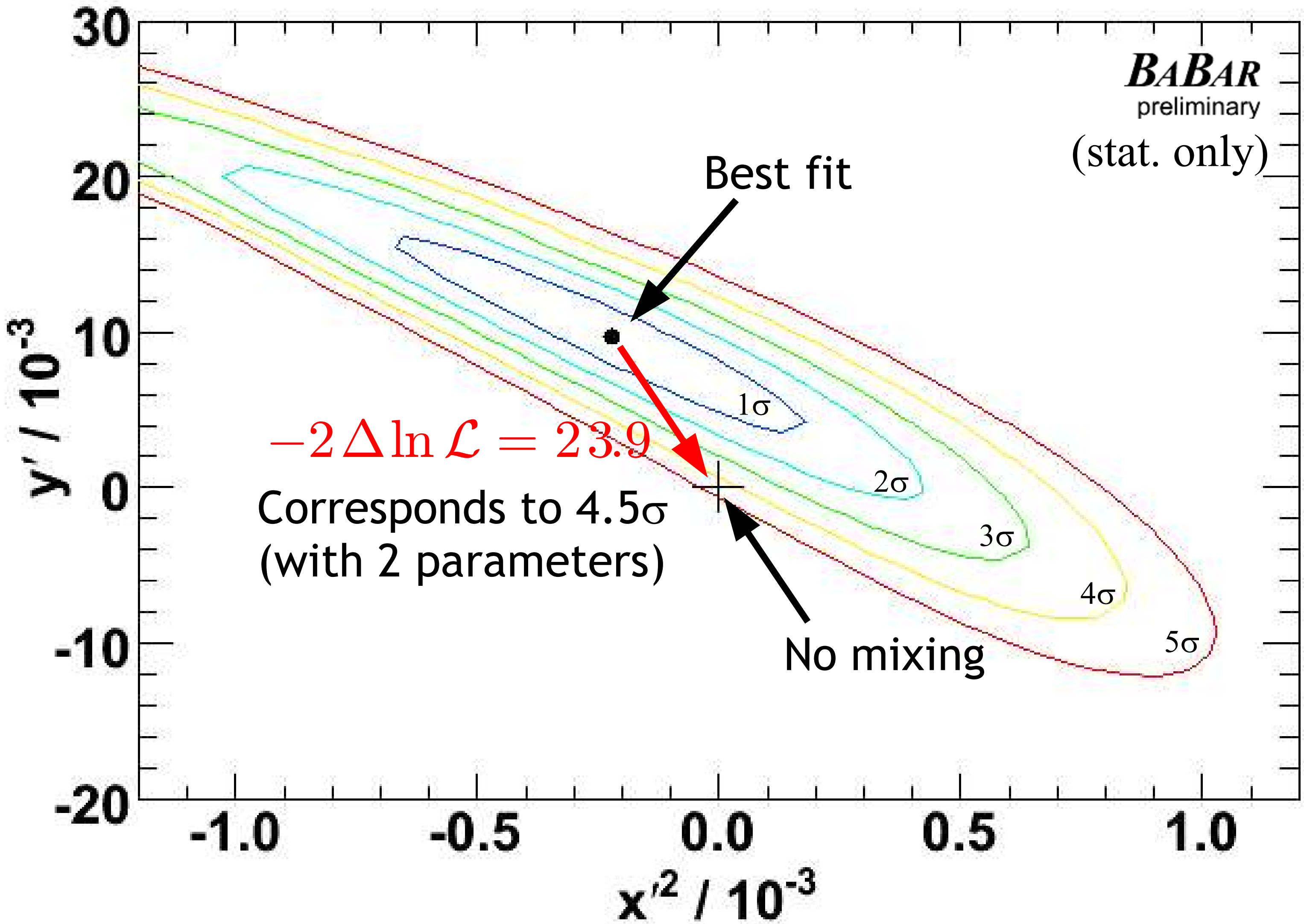
Signal Significance

Significance calculated from change in log likelihood:



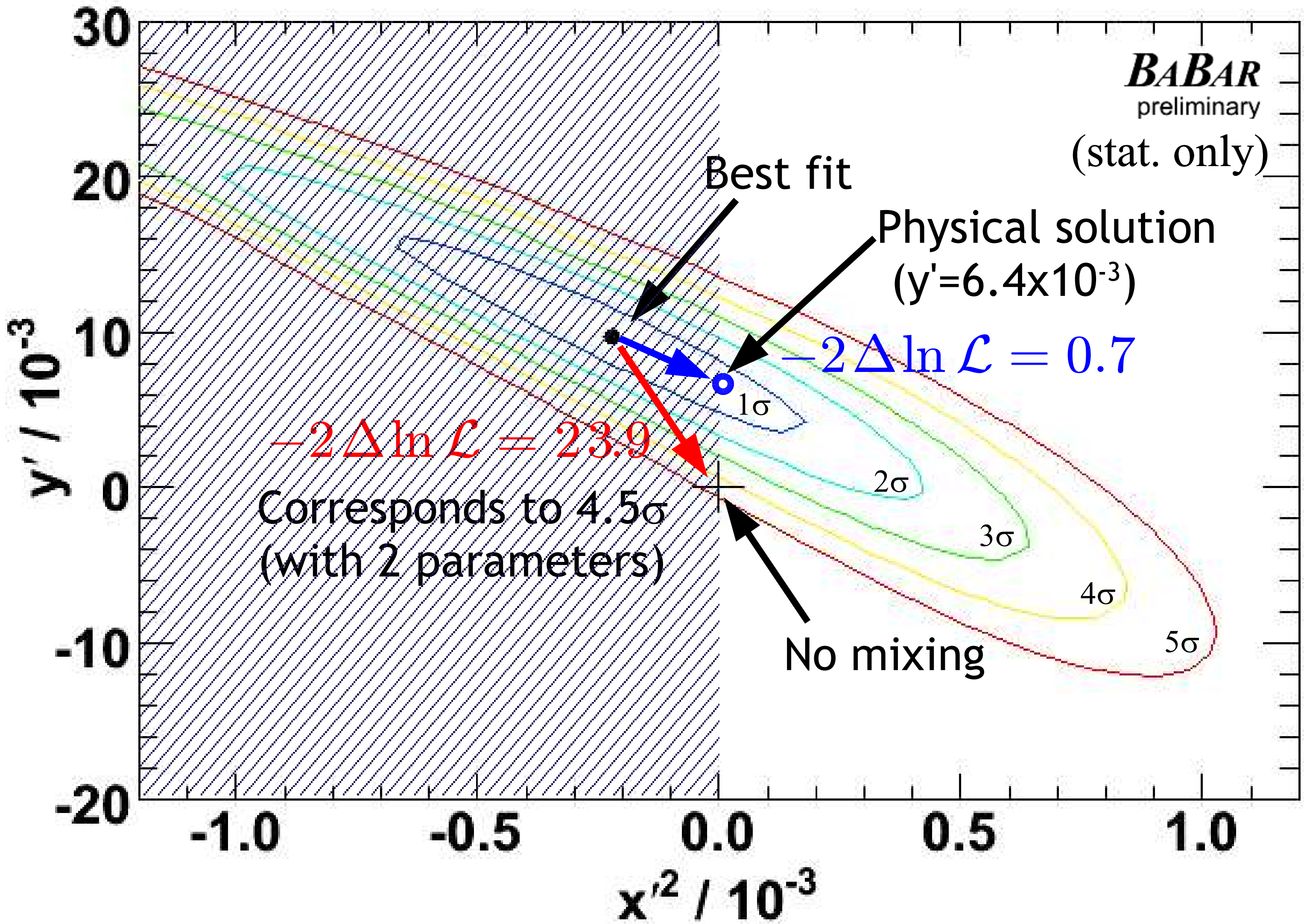
Signal Significance

Significance calculated from change in log likelihood:



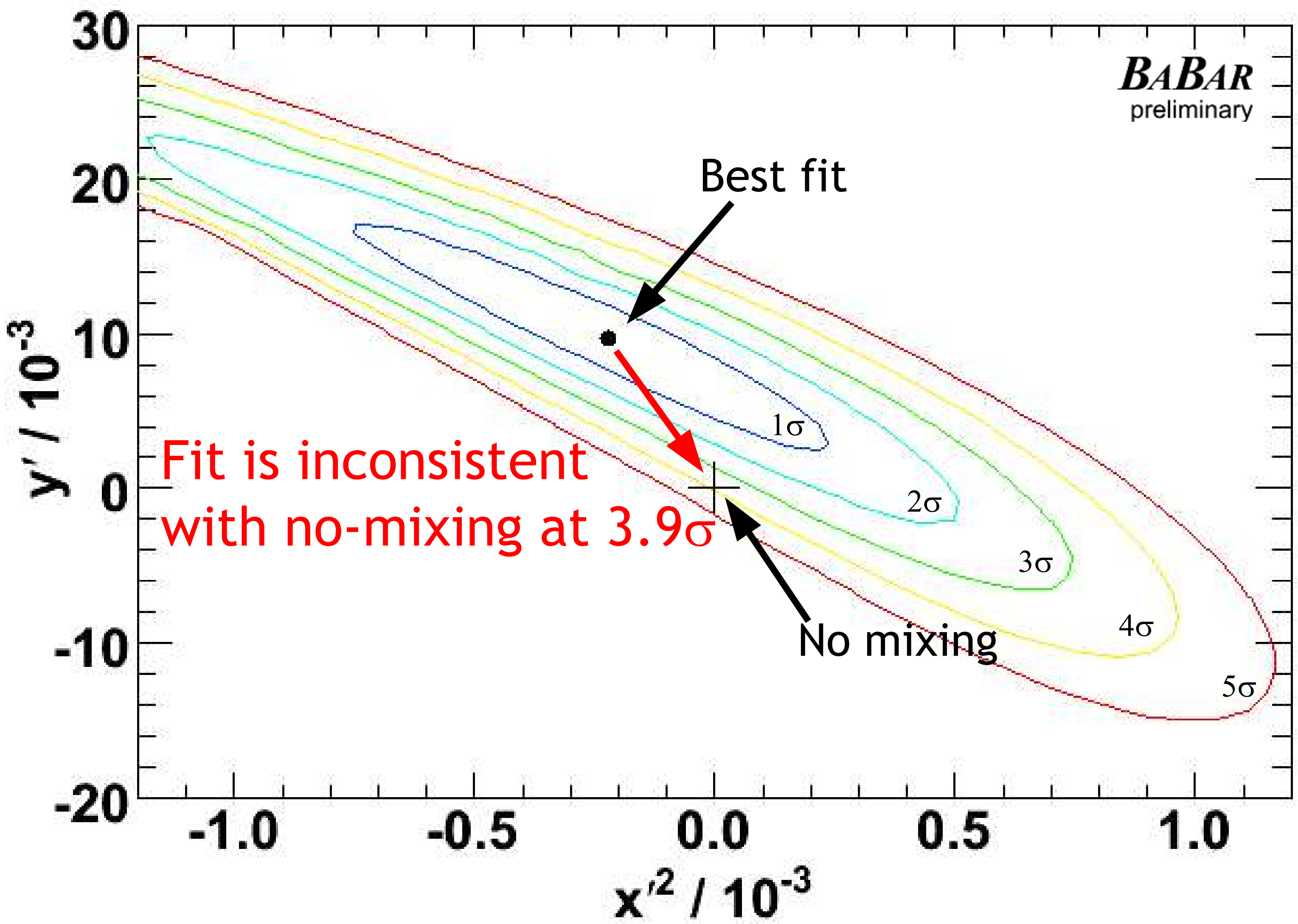
Signal Significance

Best fit is in unphysical region ($x'^2<0$)



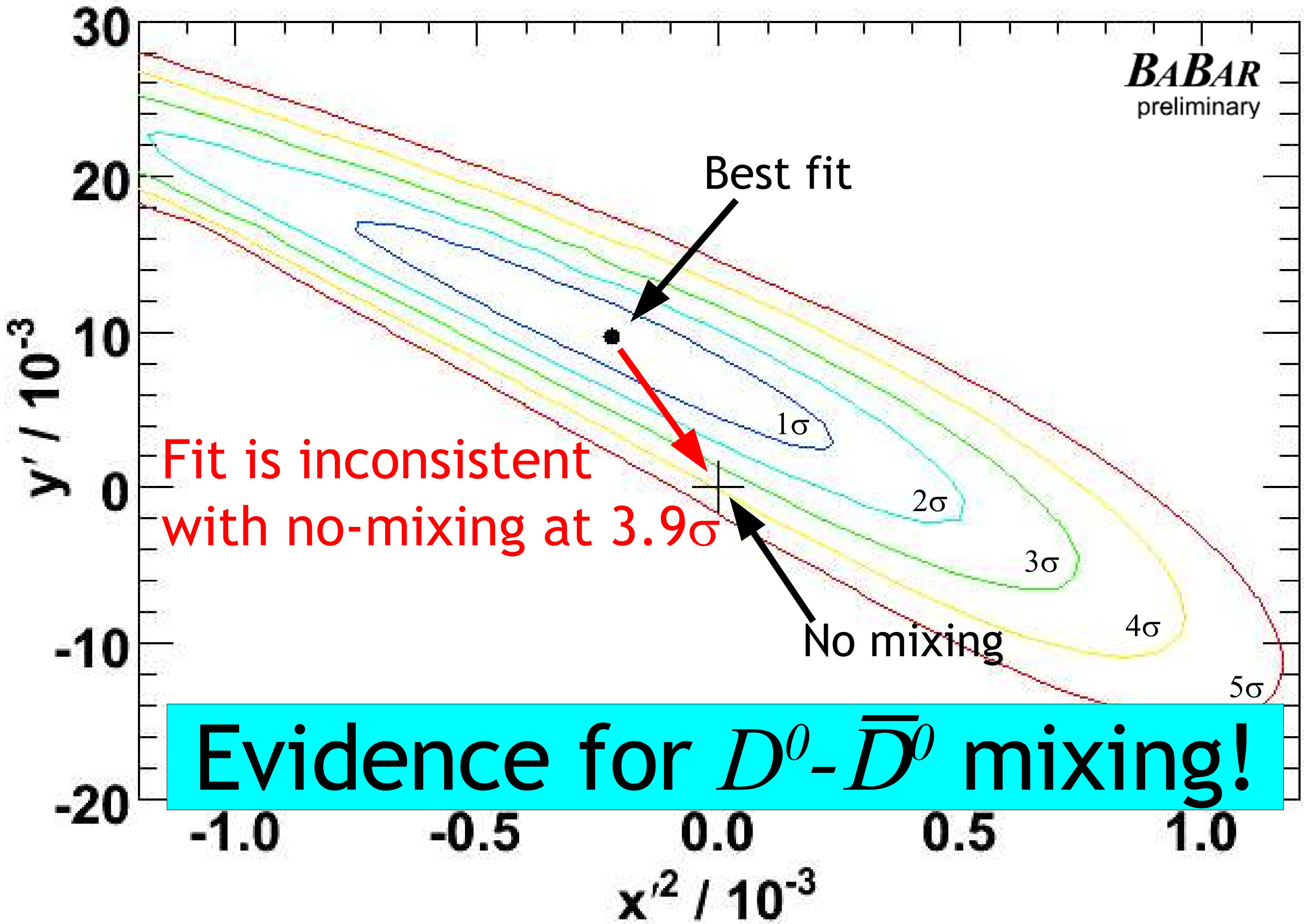
Signal Significance with Systematics

Including systematics decreases signal significance



Signal Significance with Systematics

Including systematics decreases signal significance



Evidence for D^0-$\bar{D}^0$ mixing!

Validation Studies

Performed extensive checks of mixing signal:

- Could something fake signal?
- Is significance estimated correctly?
- Are mixing parameters unbiased?

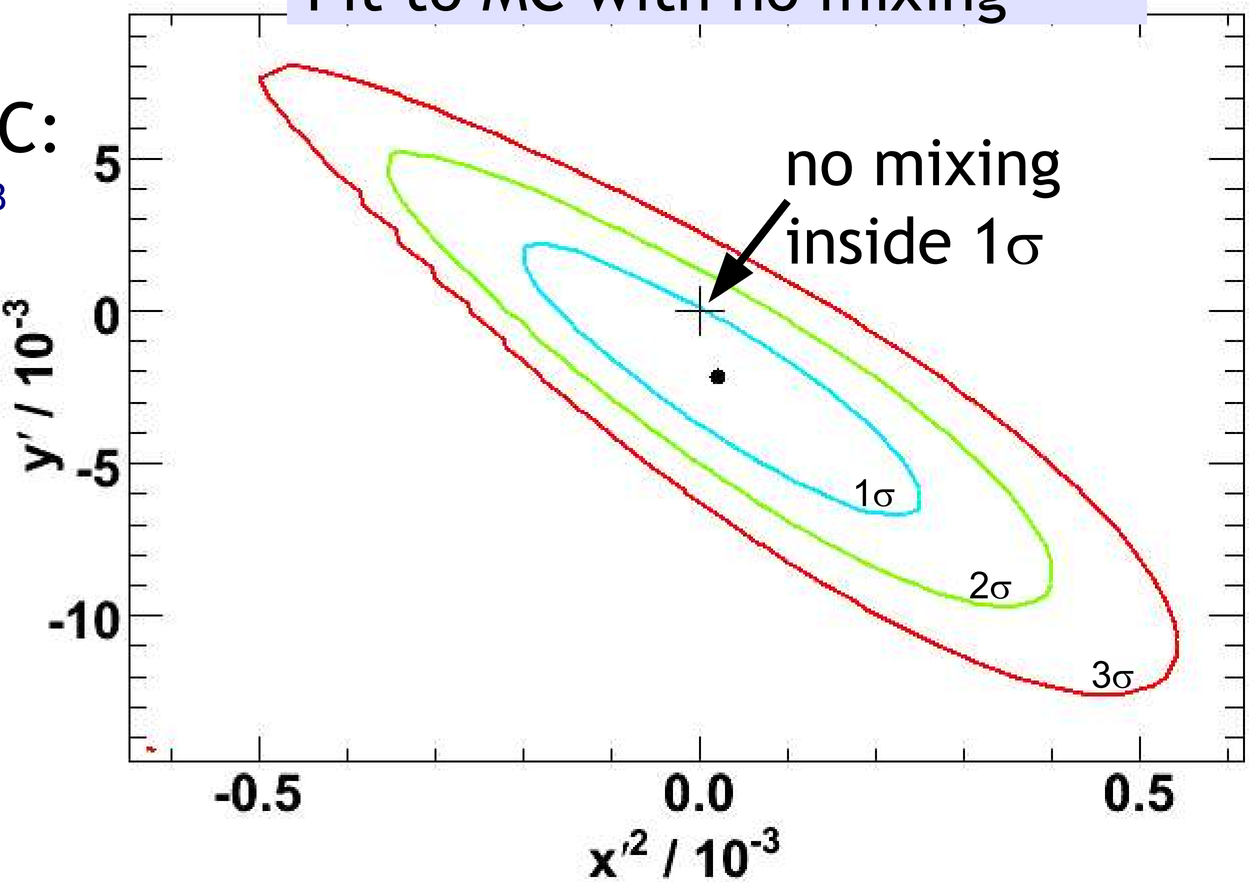
Fit to MC with no mixing

No signal found in MC:

x'^2: $(-0.02\pm0.18)\times10^{-3}$

y': $(-2.2\pm3.0)\times10^{-3}$

In MC with signal,
fit reproduces signal
 - no intrinsic bias



Validation: WS/RS Yield vs Time

RS events:

WS events:

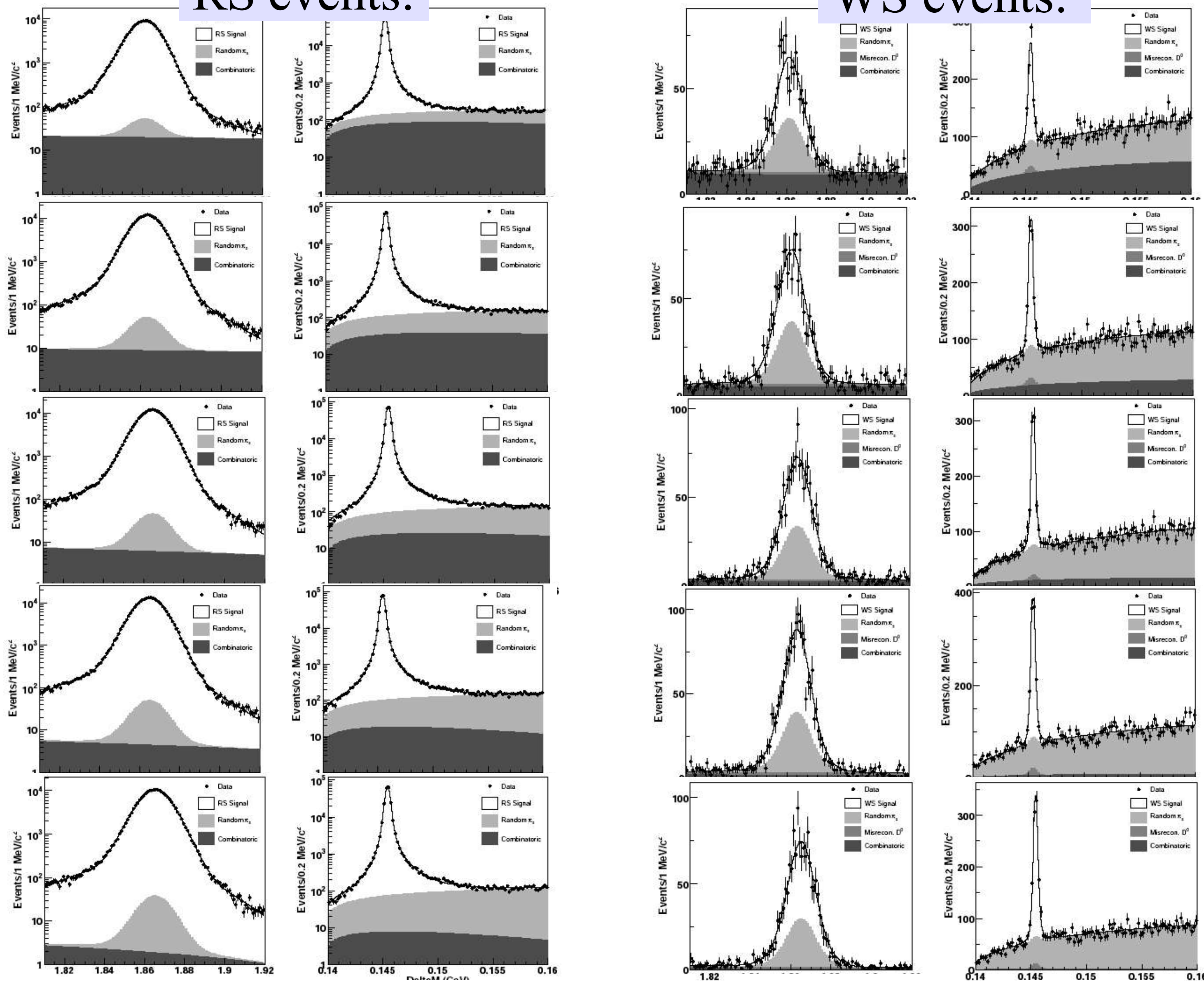
-2<t<0 ps

0<t<0.2 ps

0.2<t<0.4 ps

0.4<t<0.75 ps

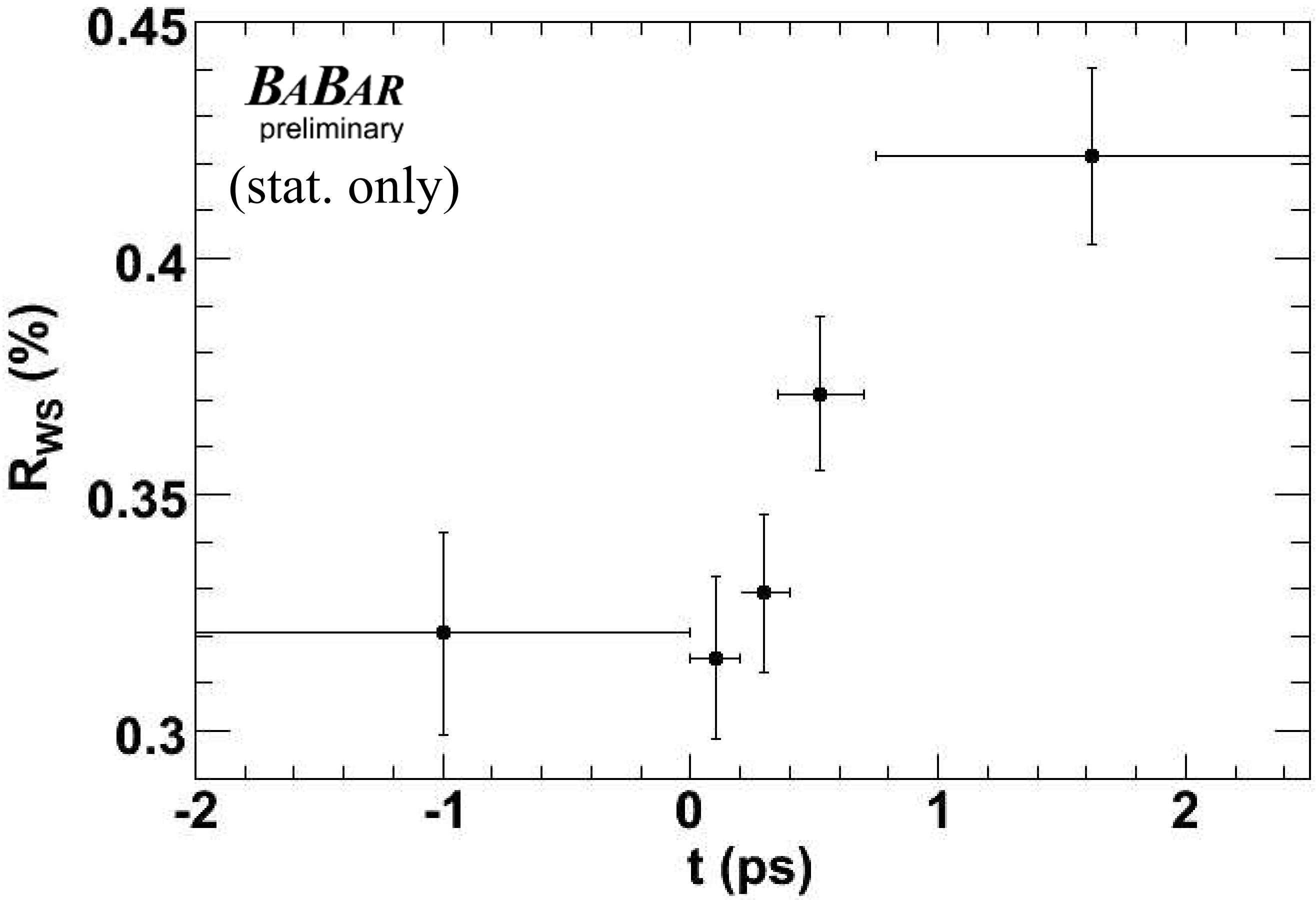
0.75<t<2.5 ps



m($K^+\pi^-$) Δm m($K^+\pi^-$) Δm

Validation: WS/RS Yield vs Time

Rate of WS events clearly increase with time:



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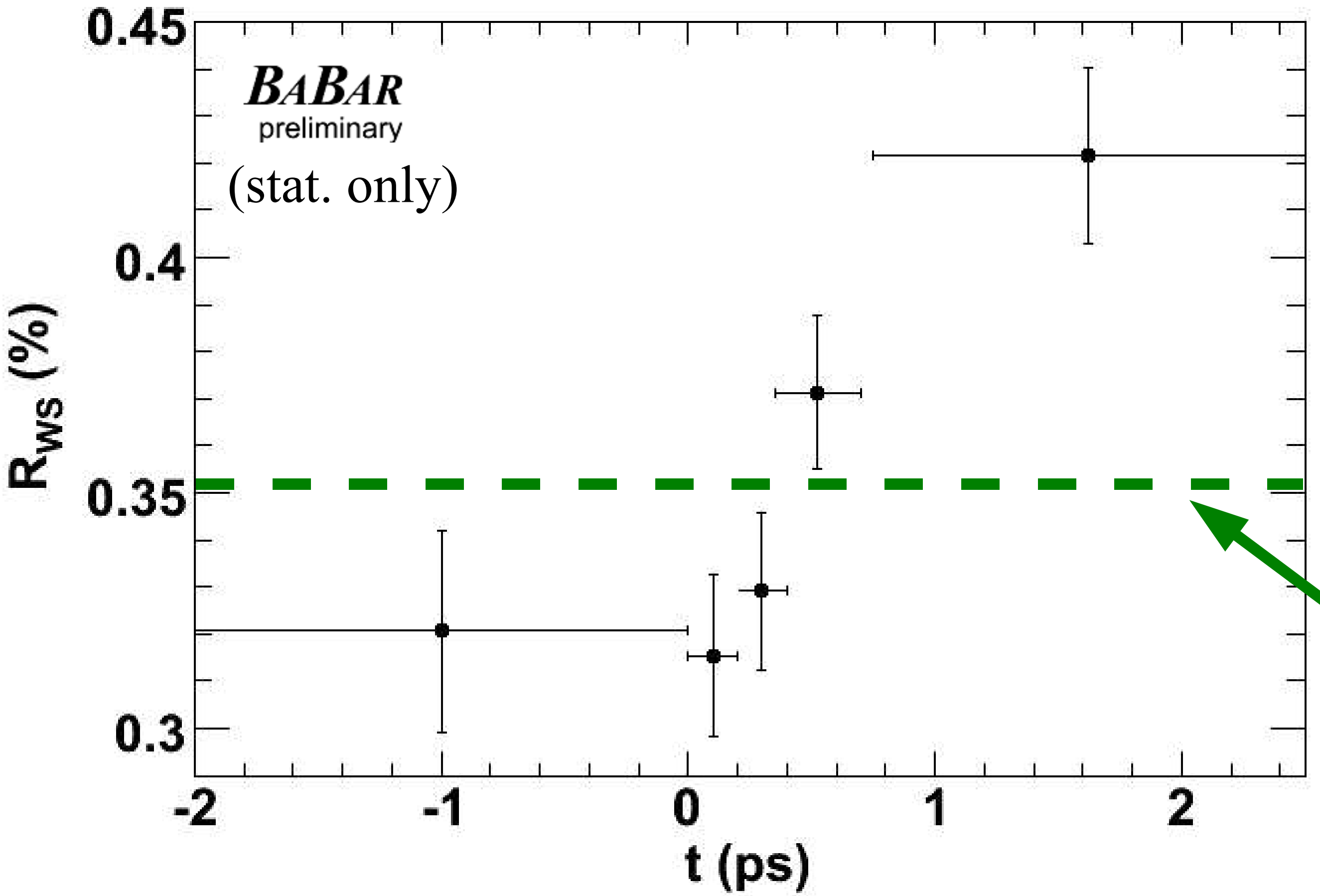
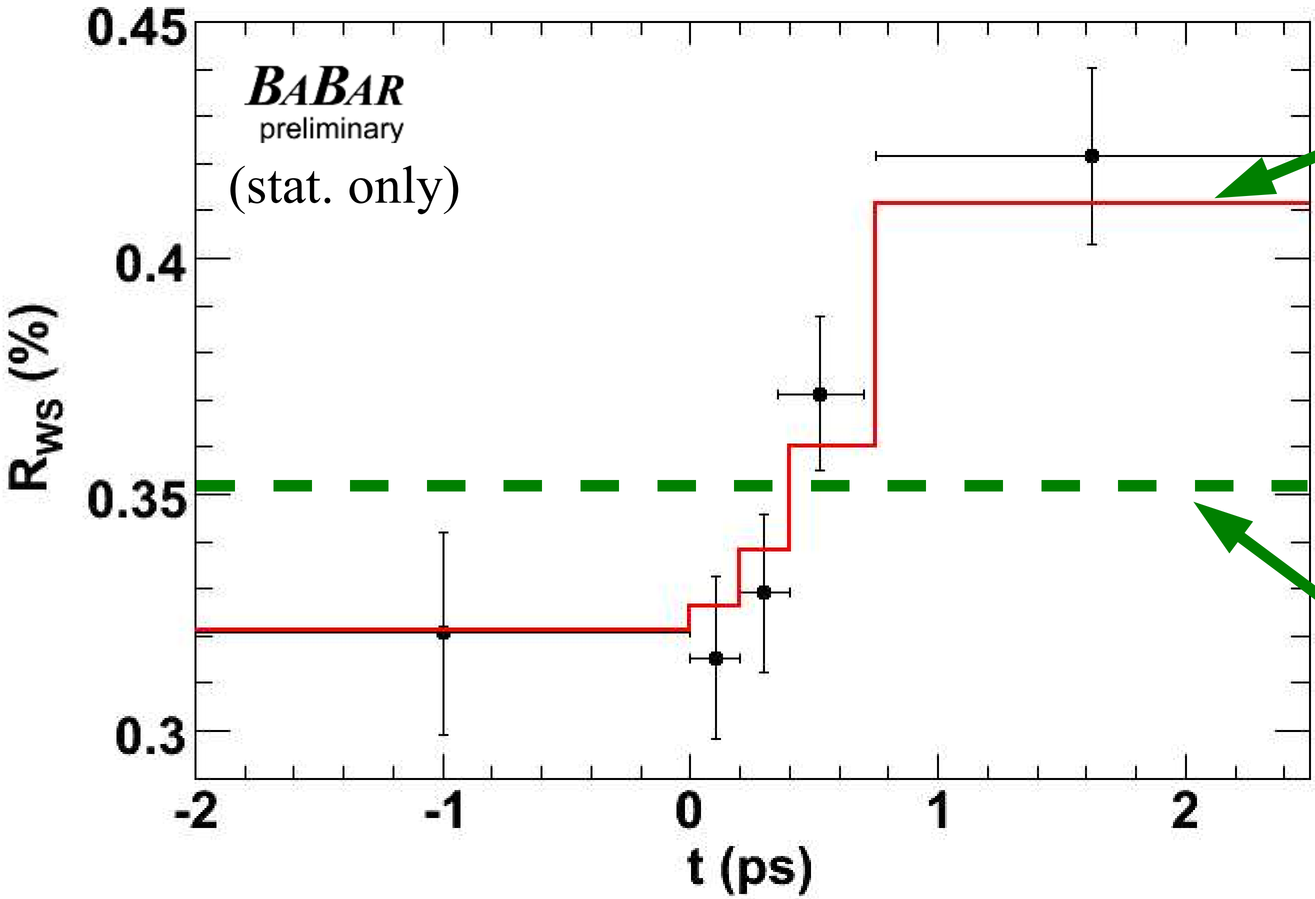


Inconsistent with no-mixing hypothesis

χ^2=24

Validation: WS/RS Yield vs Time

Rate of WS events clearly increase with time:



Consistent with prediction from full likelihood fit
χ^2=1.5

Inconsistent with no-mixing hypothesis
χ^2=24

Validation: Fit RS Data for Mixing

Fit RS data with PDF allowing mixing

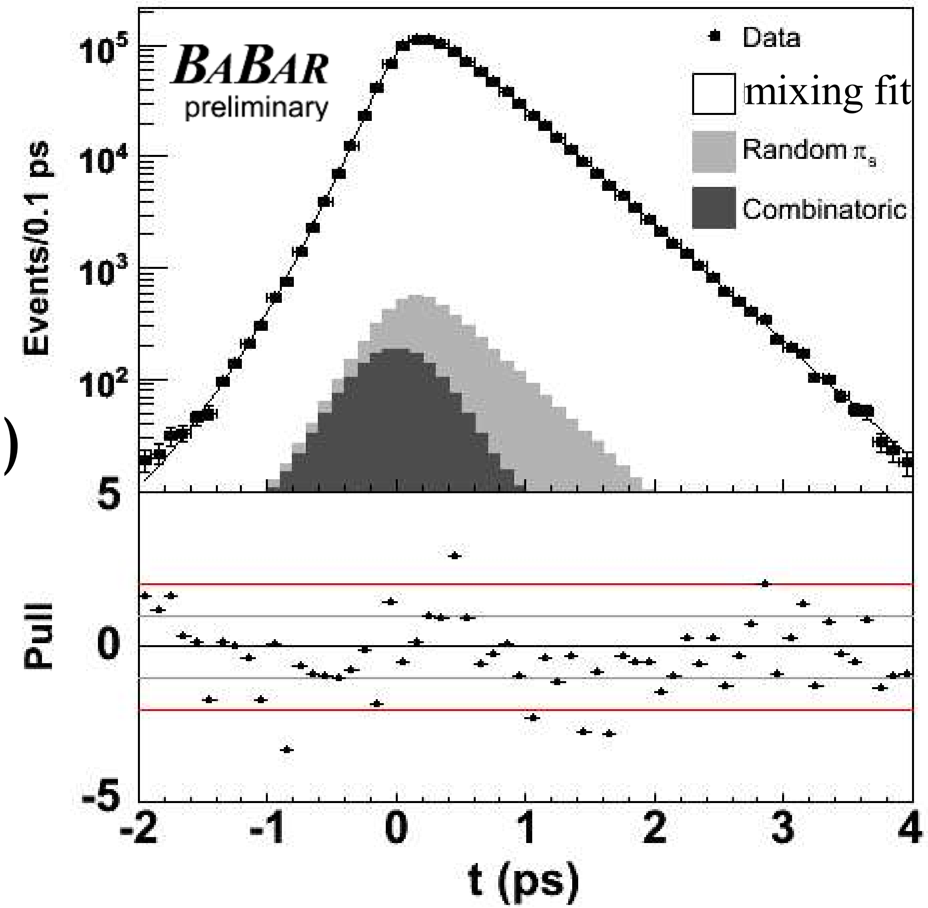
x'^2: $(-0.01 \pm 0.01) \times 10^{-3}$

y': $(0.26 \pm 0.24) \times 10^{-3}$

$-2\Delta \ln \mathcal{L} = 1.4$ (w.r.t. no mixing)

D^0 decay time distribution is described properly

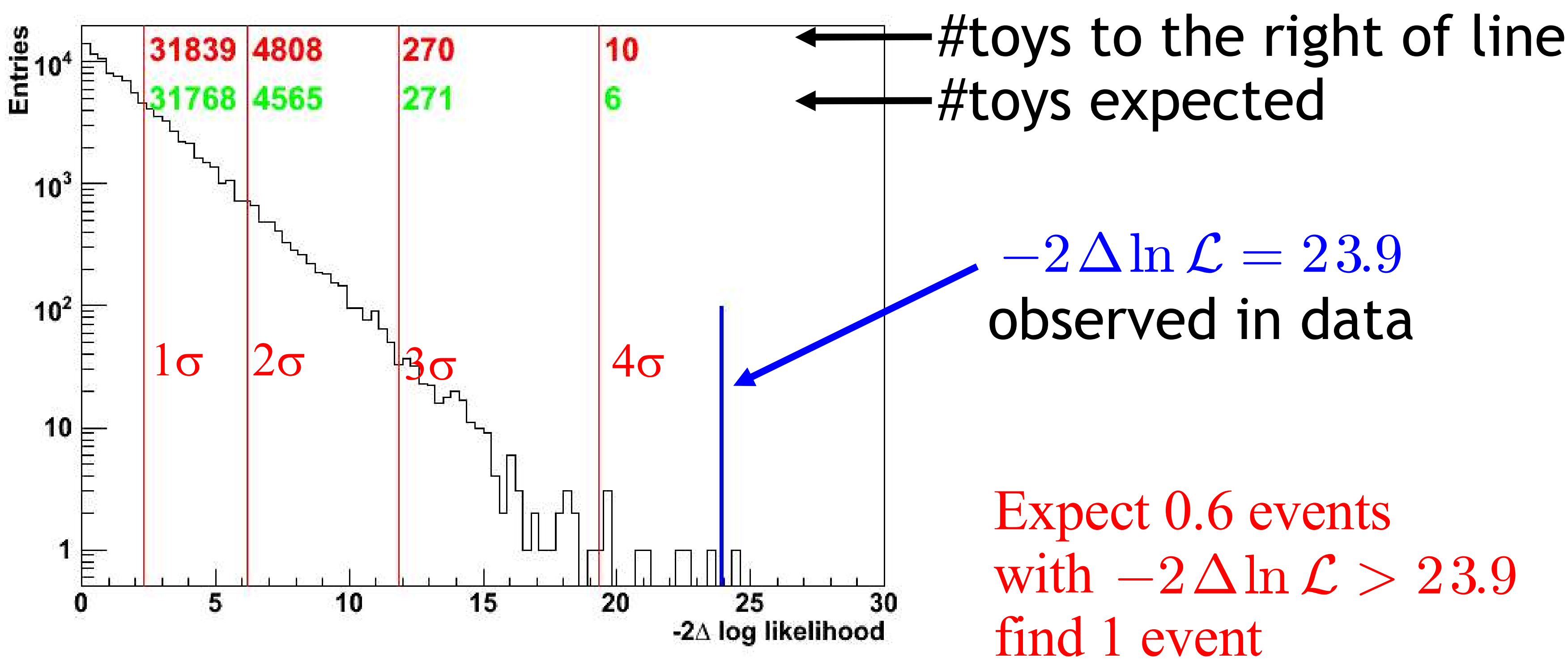
RS decay time, signal region



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

Significance of signal is calculated as change in log likelihood with respect to no-mixing hypothesis

Generated >100000 toys without mixing to test $-2\Delta \ln \mathcal{L}$ gives correct frequentist coverage



Systematic Uncertainties

Two types of systematic uncertainties considered:

Fit model variations:

- Change signal and background models used in fit, to test assumptions made

Selection criteria:

- Mainly decay time (error) ranges used in fit

Systematic:	R_D	x'^2	y'
Fit Model	0.59σ	0.40σ	0.45σ
Selection Criteria	0.24σ	0.57σ	0.55σ
Total	0.63σ	0.70σ	0.71σ

Fraction of statistical uncertainty

x'^2-y' correlation also present in systematics
Effectively the (x'^2, y') contours increase by ~15%

Allowing for CP Violation

CP violation could introduce different time dependence for D^0 (+) and $\bar{D}^0$ (-):

$$\frac{T^{\pm}_{\mathrm{WS}}(t)}{e^{-\Gamma t}} = \sqrt{\frac{1 \pm A_{\mathrm{D}}}{1 \mp A_{\mathrm{D}}}} R_{\mathrm{D}} + \sqrt{R_{\mathrm{D}}} \sqrt[4]{\frac{(1 \pm A_{\mathrm{D}})(1 \pm A_{\mathrm{M}})}{(1 \mp A_{\mathrm{D}})(1 \mp A_{\mathrm{M}})}} (y' \cos\varphi \mp x' \sin\varphi) \Gamma t + \sqrt{\frac{1 \pm A_{\mathrm{M}}}{1 \mp A_{\mathrm{M}}}} \frac{x'^2 + y'^2}{4} (\Gamma t)^2$$

Three possible types of CP violation:

- Direct CP violation in DCS decay $A_D \neq 0$
- CP violation in mixing $A_M \neq 0$
- CP violation in interference between mixing and decay $\cos\varphi \neq 1$

Simpler to fit D^0 (+) and $\bar{D}^0$ (-) separately:

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

CP violation if one or more "±" parameters are different

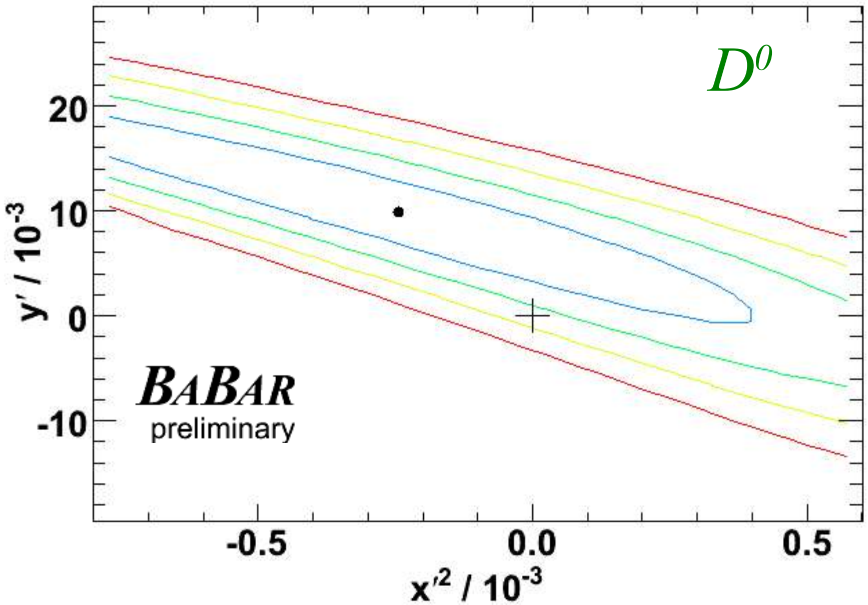
CPV Allowed Contours

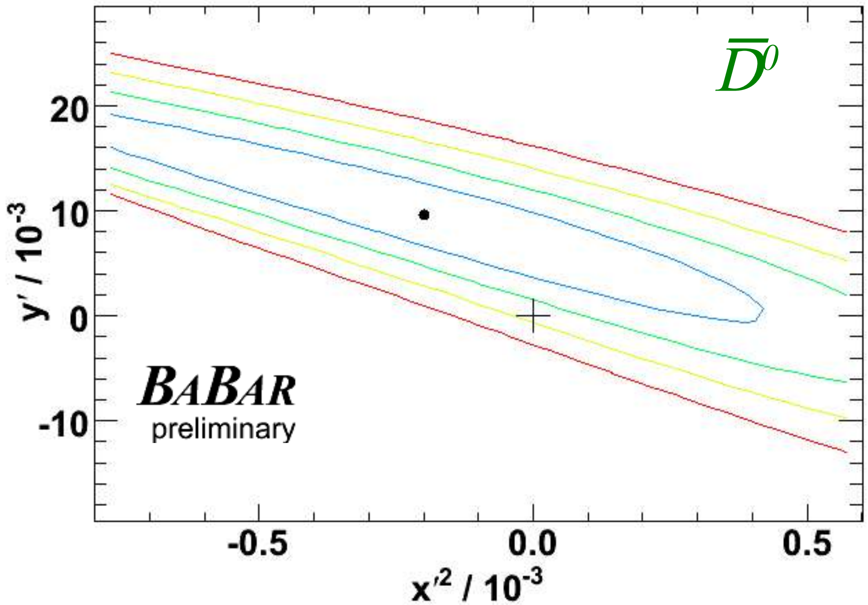
<u>Results of fitting D^0 and $\bar{D}^0$ separately:</u>

x'^{+2}: $(-0.24\pm0.43\pm0.30)\times10^{-3}$ x'^{-2}: $(-0.20\pm0.41\pm0.29)\times10^{-3}$

y'^{+}: $(9.8\pm6.4\pm4.5)\times10^{-3}$ y'^{-}: $(9.6\pm6.1\pm4.3)\times10^{-3}$

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



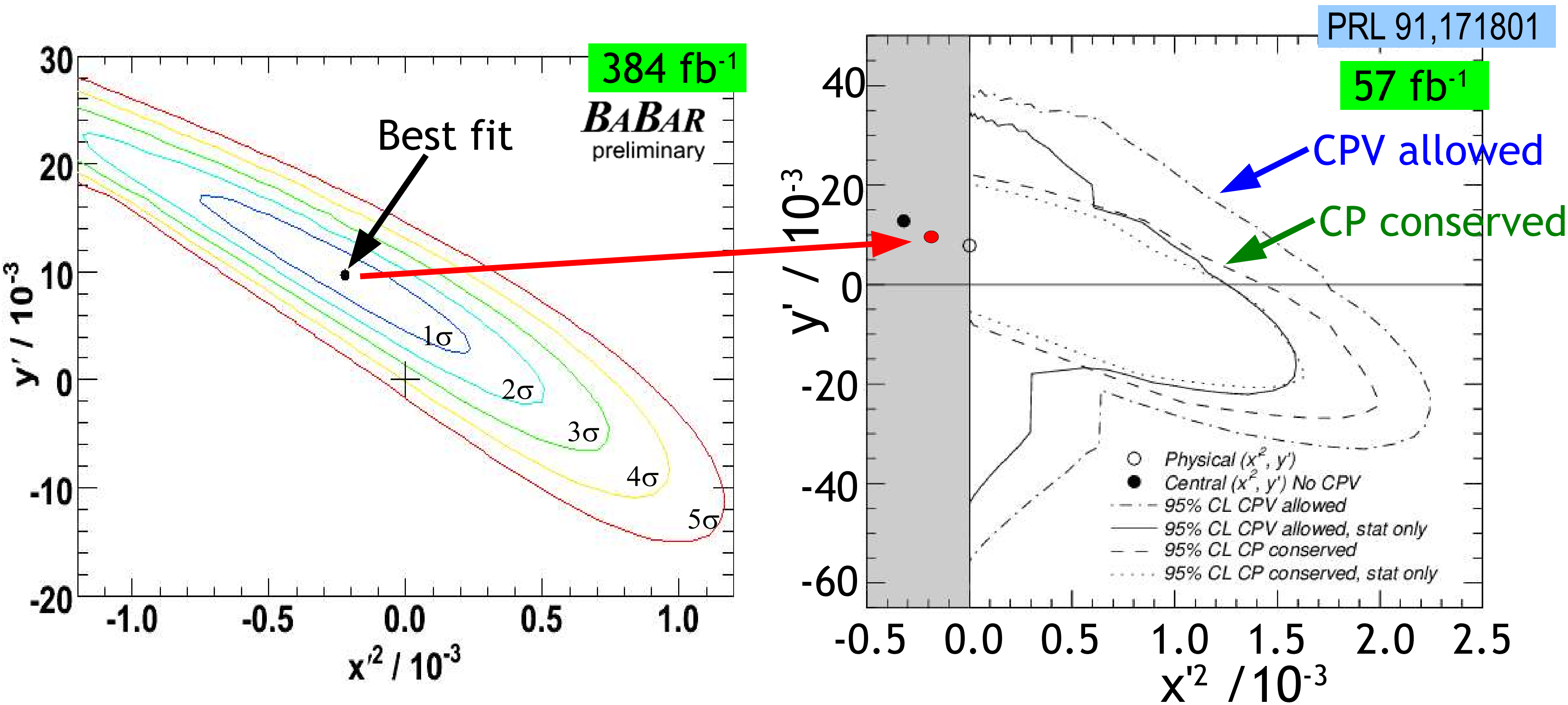


No evidence for CP violation found

Comparisons with other Charm Mixing Results

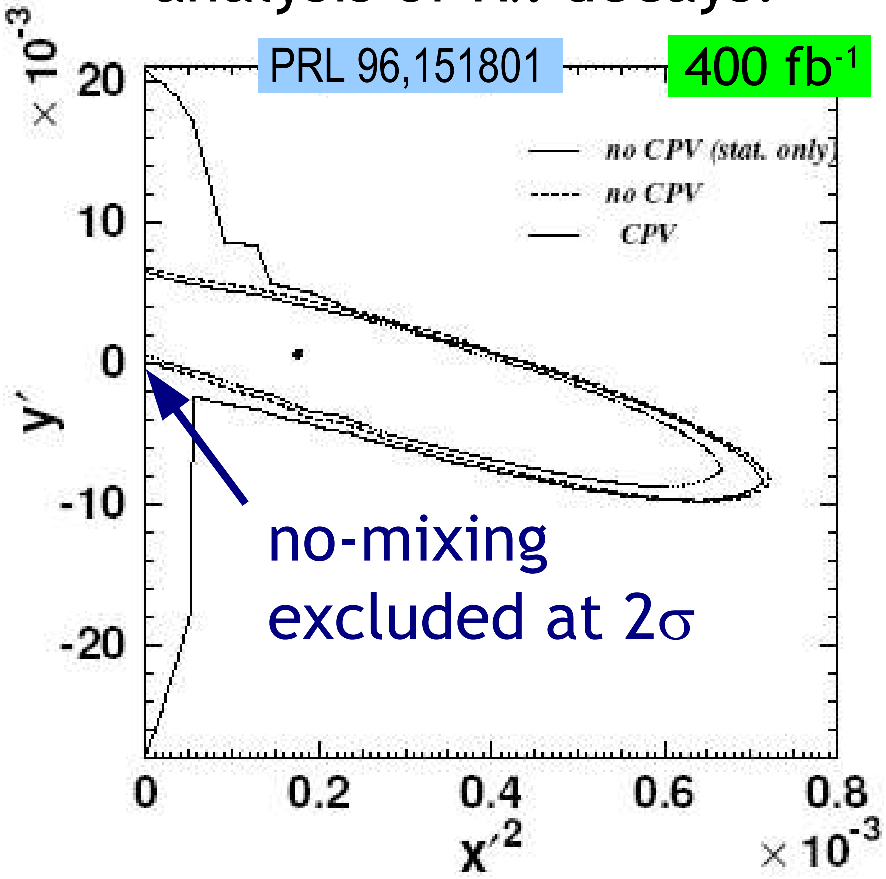
Previous BaBar Kπ Analysis

Fully consistent with previous BaBar analysis:



Kπ Analysis from Belle

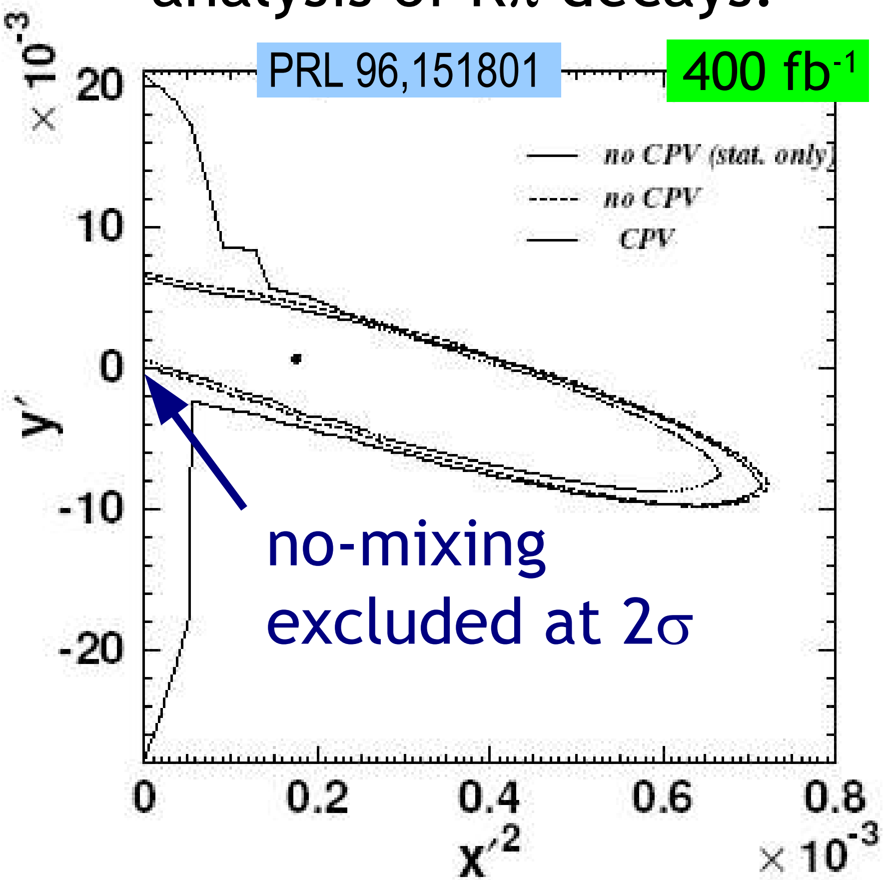
Last year Belle published analysis of Kπ decays:

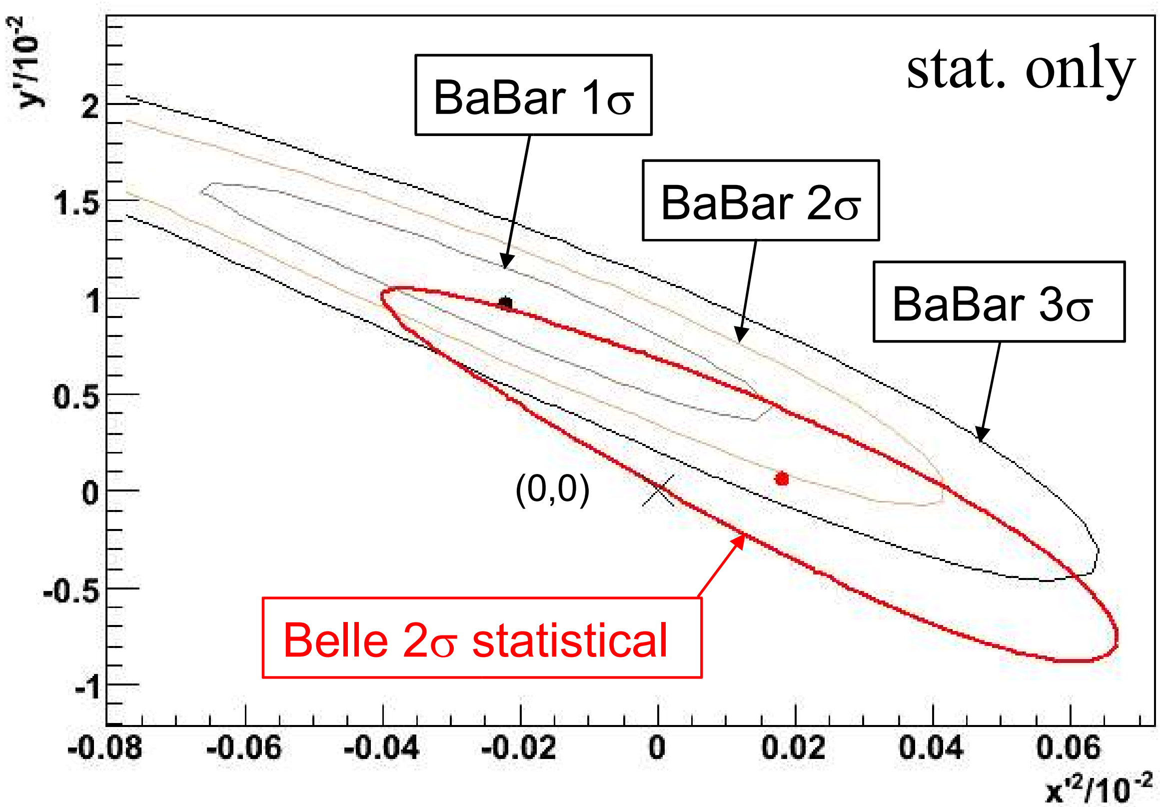


Kπ Analysis from Belle

Last year Belle published analysis of Kπ decays:

Results consistent within 2σ:





Average Kπ Mixing Results

Heavy flavor averaging group (HFAG) working on providing official averages

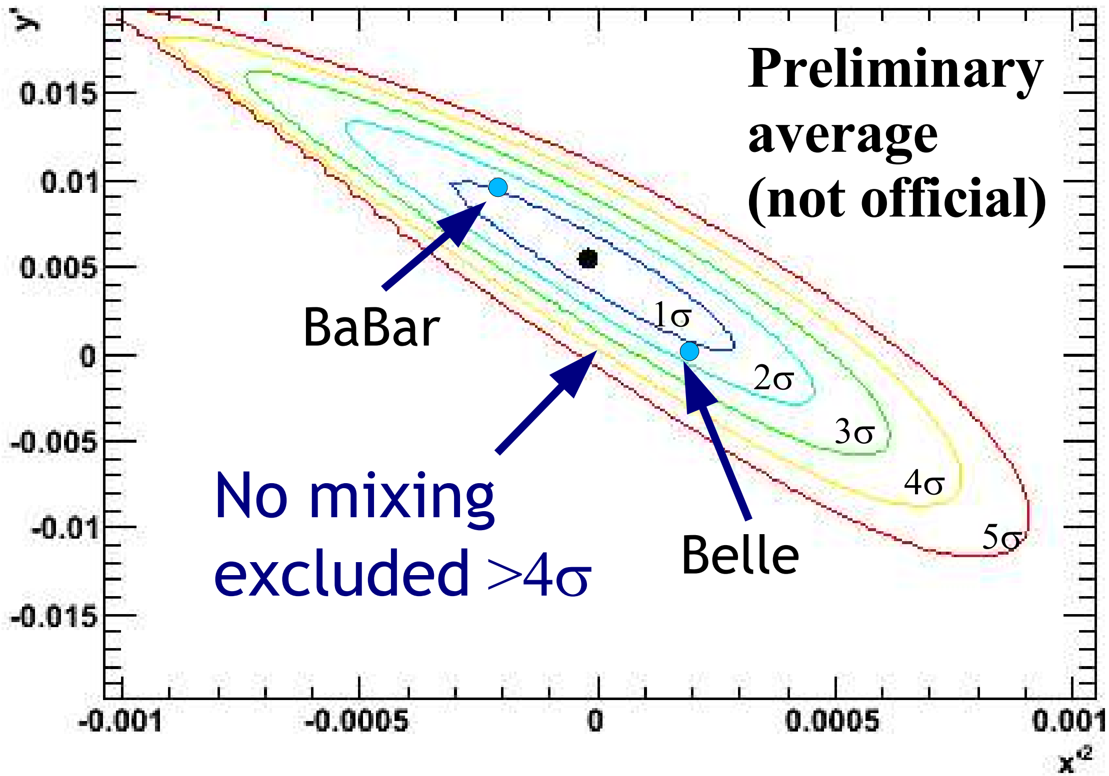
Combine BaBar and Belle likelihoods in 3 dimensions (R_D, x'^2, y')

<u>Preliminary average:</u>

R_D: $(3.31\pm0.13)\times10^{-3}$

x'^2: $(-0.01\pm0.20)\times10^{-3}$

y': $(5.1\pm3.2)\times10^{-3}$

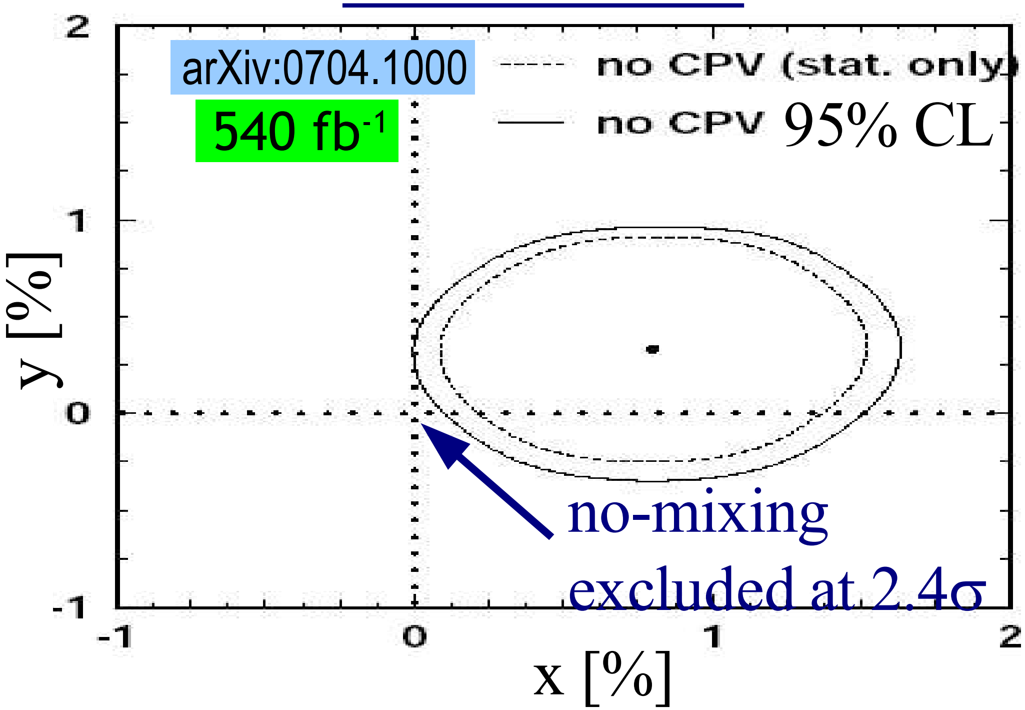


Belle Dalitz Analysis of $D^0 \to K_S \pi\pi$

Time-dependent Dalitz analysis of $D^0 \to K_S \pi\pi$ measures x and y without unknown phase

(First done by CLEO, PRD 72, 012001)

Belle result:



x: $(8.0 \pm 2.9 \pm 1.7) \times 10^{-3}$

y: $(3.3 \pm 2.4 \pm 1.5) \times 10^{-3}$

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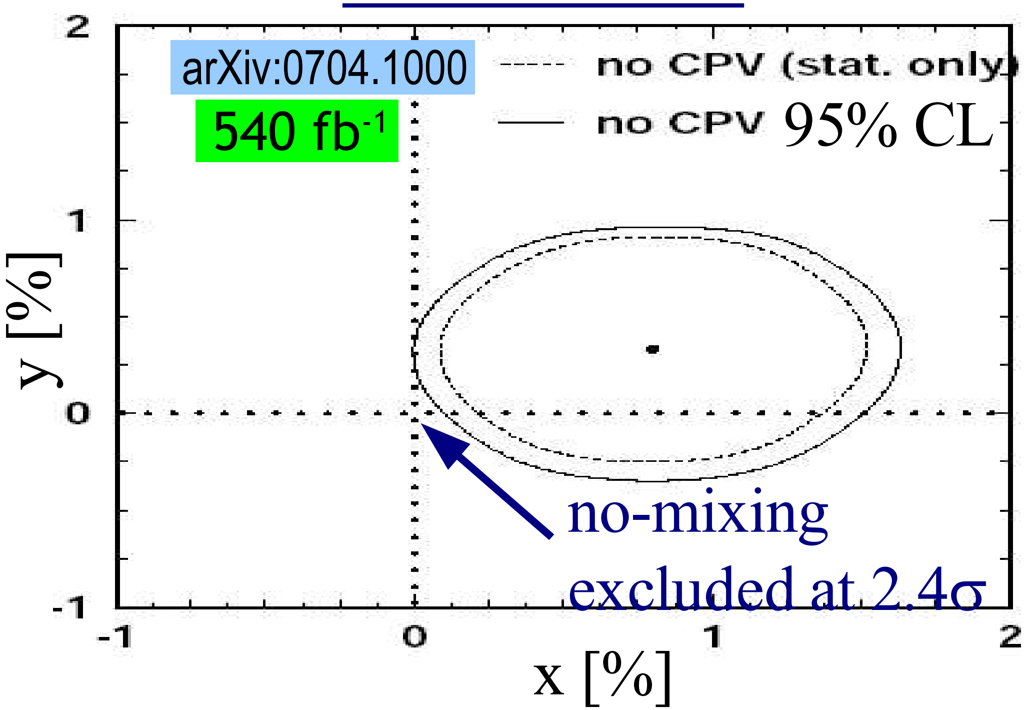
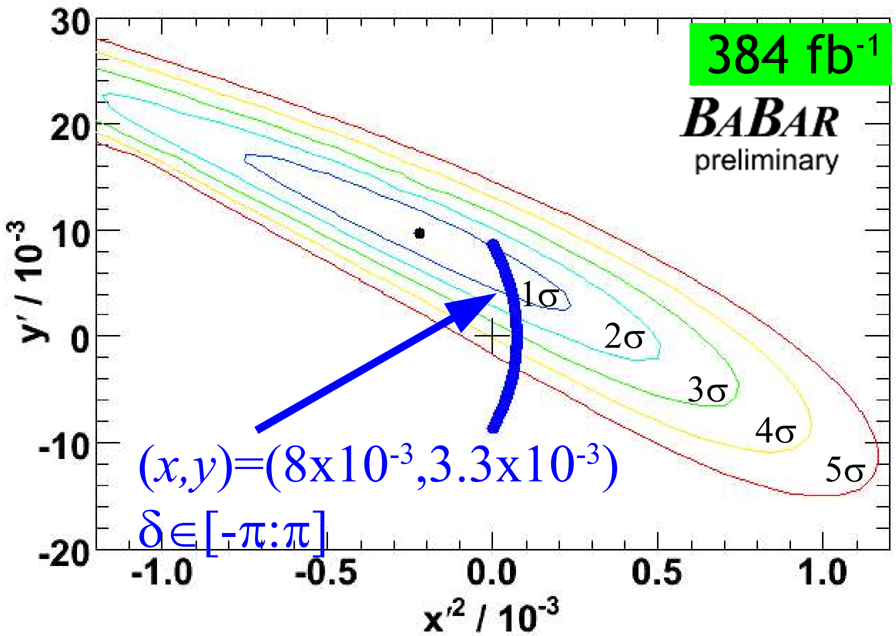


x: $(8.0 \pm 2.9 \pm 1.7) \times 10^{-3}$

y: $(3.3 \pm 2.4 \pm 1.5) \times 10^{-3}$

BaBar-Belle comparison:



Within 1σ for certain values of the phase δ

Belle Lifetime Ratio Measurement

Belle measure lifetime difference directly using CP eigenstates:

$$\tau(D^0 \to f_{CP+}) = \frac{\tau(D^0 \to K^-\pi^+)}{1 + y_{CP}}$$

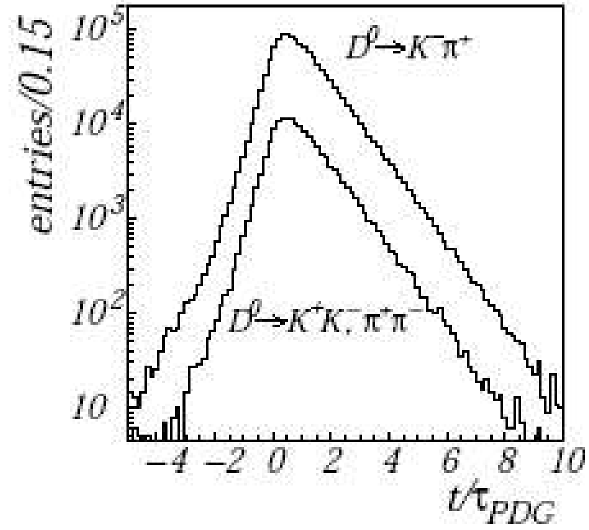
$y_{CP} = y \cos \phi$ ($=y$, if no CP violation)

(CP and mass eigenstates the same!)

Belle use two CP-even eigenstates:

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

Decay time distributions:



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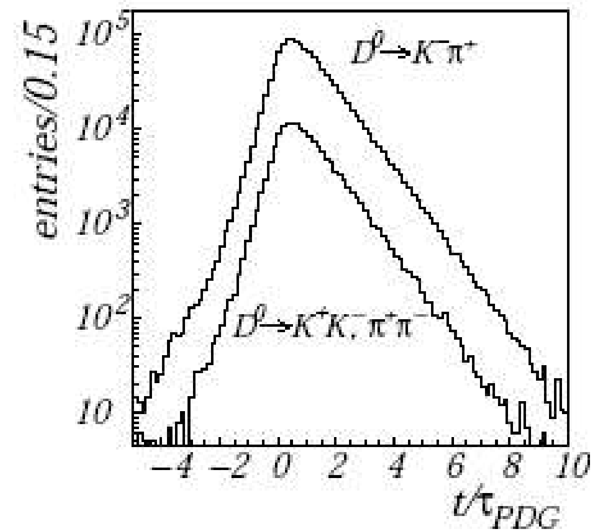
Belle result:

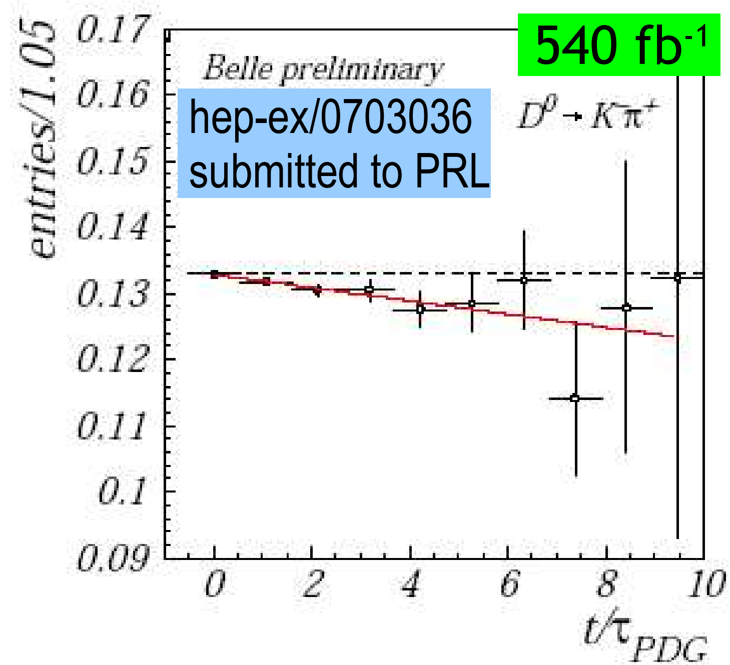
y_{CP}: $(13.1 \pm 3.2 \pm 2.5) \times 10^{-3}$

>3σ above zero (4.1σ stat. only)

Also evidence of D^0 mixing!

Decay time distributions:





More BaBar-Belle Comparisons

Belle measurement is consistent with old BaBar lifetime ratio measurement

Belle: 540 fb^{-1}

y_{CP}: $(13.1 \pm 3.2 \pm 2.5) \times 10^{-3}$

hep-ex/0703036 submitted to PRL

BaBar: 91 fb^{-1}

y_{CP}: $(8.0 \pm 4.0 \pm 5.0) \times 10^{-3}$

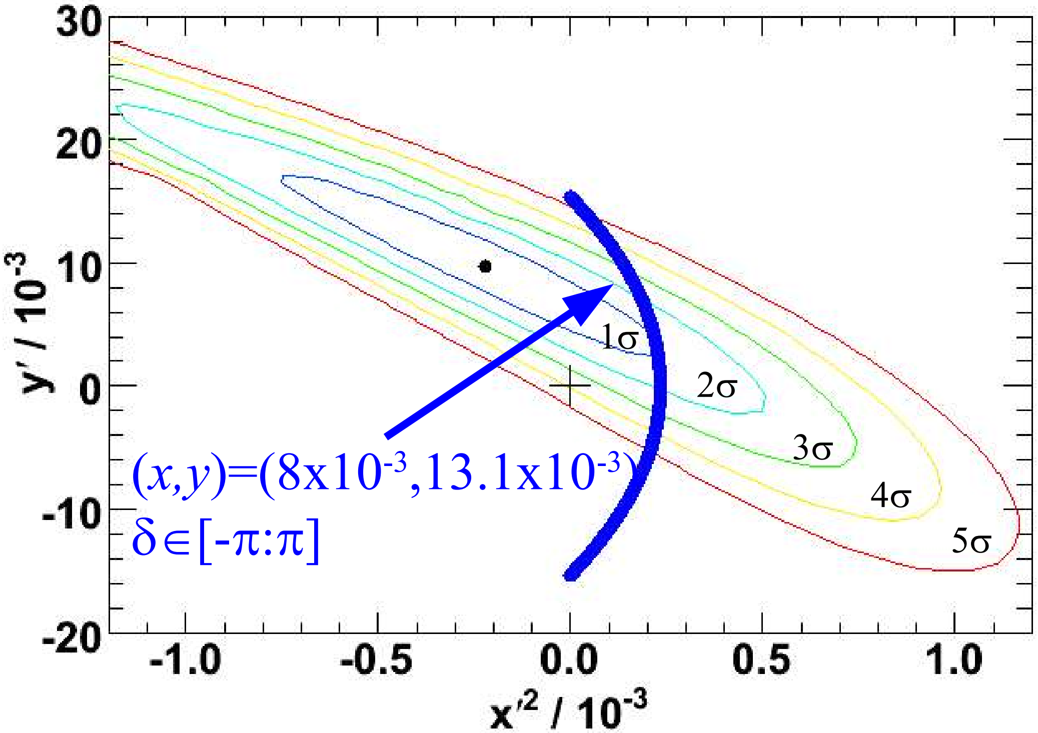
PRL 91, 121801

Comparison to BaBar $K\pi$ analysis:

Assume $y = y_{CP}$

Use $x = 8 \times 10^{-3}$ from Belle's $K_S\pi\pi$ analysis

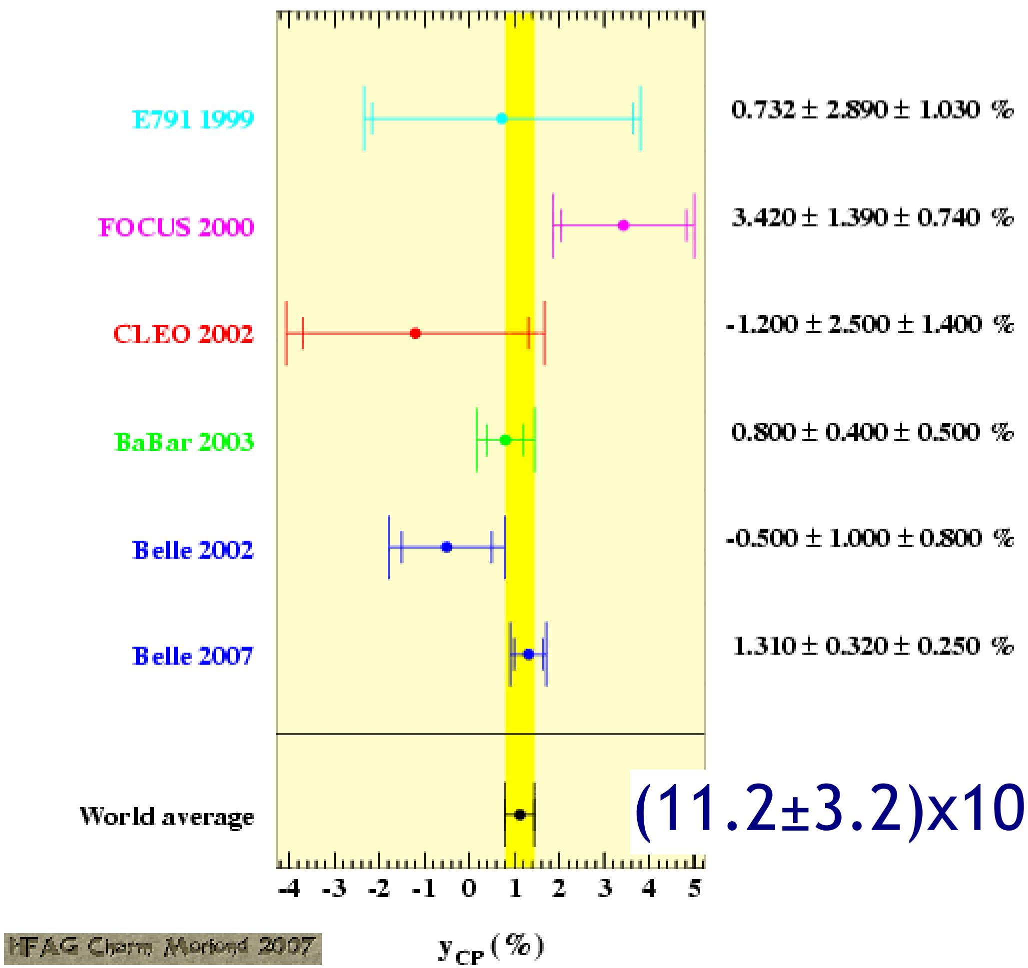
Results consistent within 1σ for certain values of phase δ



Combining Mixing Results

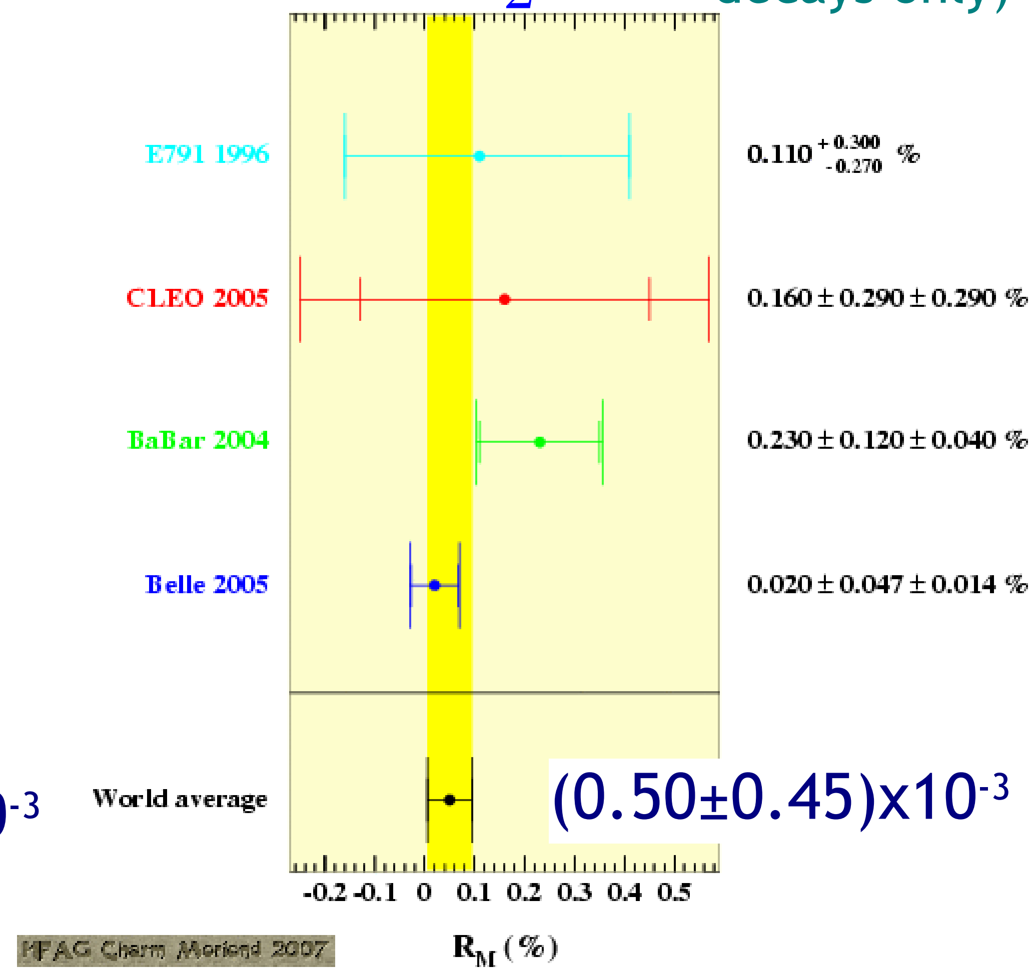
HFAG has first preliminary averages for some measurements:

$y_{CP} = y\cos\phi$



(11.2±3.2)x10^{-3}

$R_M = \frac{x^2 + y^2}{2}$ (Semileptonic decays only)



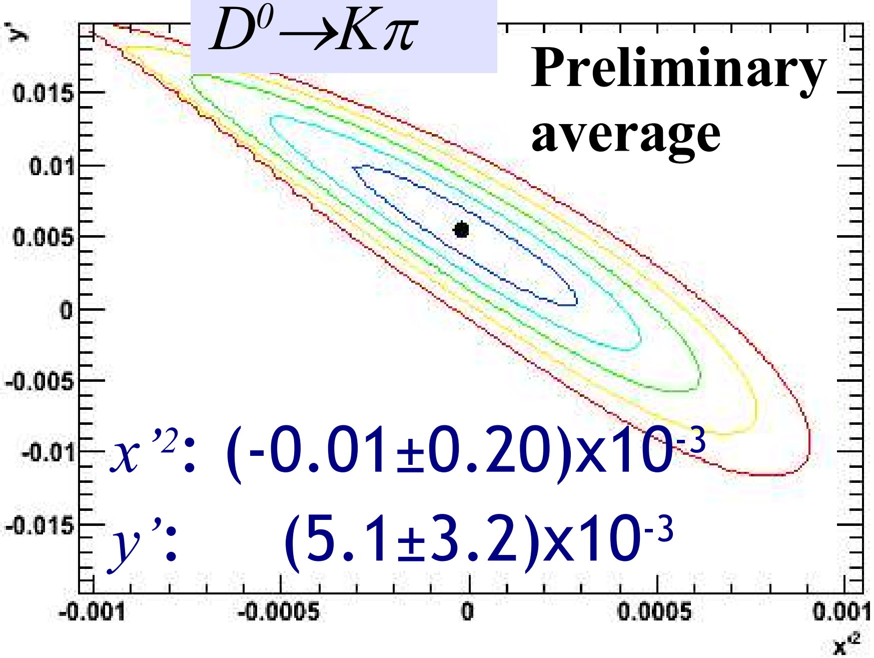
(0.50±0.45)x10^{-3}

Combining all D^0 Mixing Results

Next step for HFAG: combine all measurements:

$D^0 \to KK/\pi\pi$ y_{CP}=(11.2±3.2)x10^{-3} $D^0 \to K^{(*)} e\nu$ R_M=(0.50±0.45)x10^{-3}

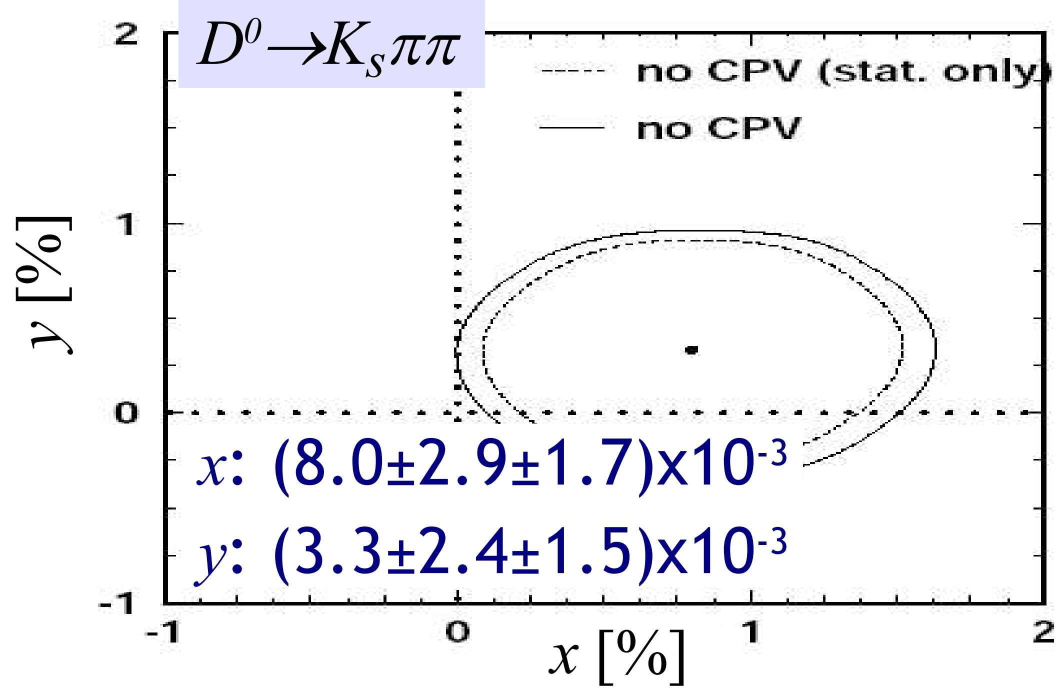
$D^0 \to K\pi$



x'^2: (-0.01±0.20)x10^{-3}

y': (5.1±3.2)x10^{-3}

$D^0 \to K_s \pi\pi$



x: (8.0±2.9±1.7)x10^{-3}

y: (3.3±2.4±1.5)x10^{-3}

HFAG will provide average for x, y and δ (available soon)

We plan to also provide averages allowing for CP violation

Implications of Charm Mixing

BaBar and Belle mixing results first presented at Moriond electroweak conference on March 17

8 new hep-ph preprints on charm mixing since then

Five use D^0 mixing results to evaluate limits on:

- Certain SUSY models (flavor suppresion by "alignment") hep-ph/0703204 hep-ph/0703235
- Several little Higgs models hep-ph/0703254, arXiv:0704.0601
- Non-universal Z' model hep-ph/0703270

Models are further constrained, but constraints are limited by lack of precise SM value → Light non-degenerate squarks unlikely to be observed at LHC

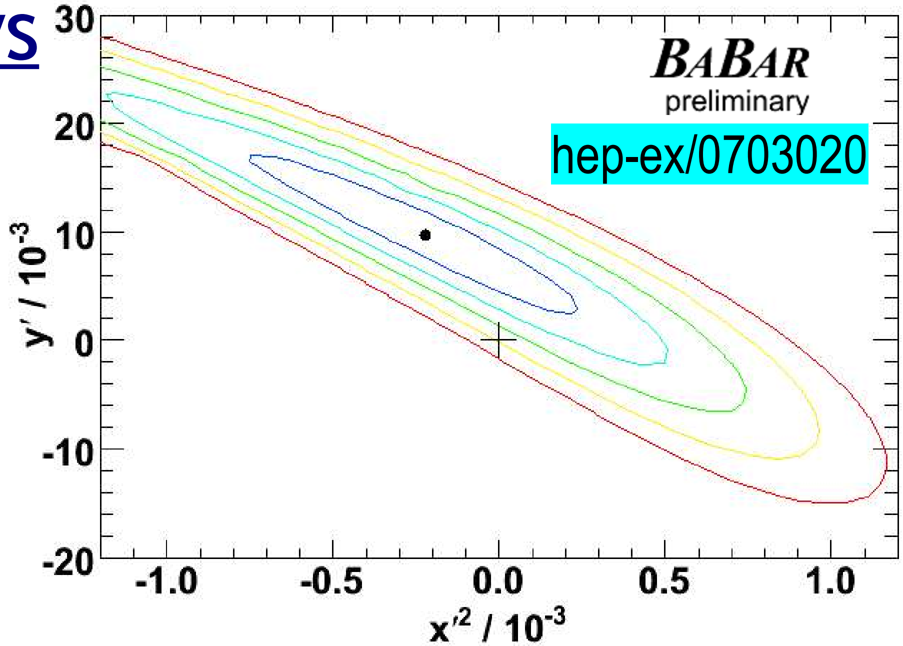
Currently only observation of CP violation would be a clear sign of New Physics

Summary

Summary and Outlook

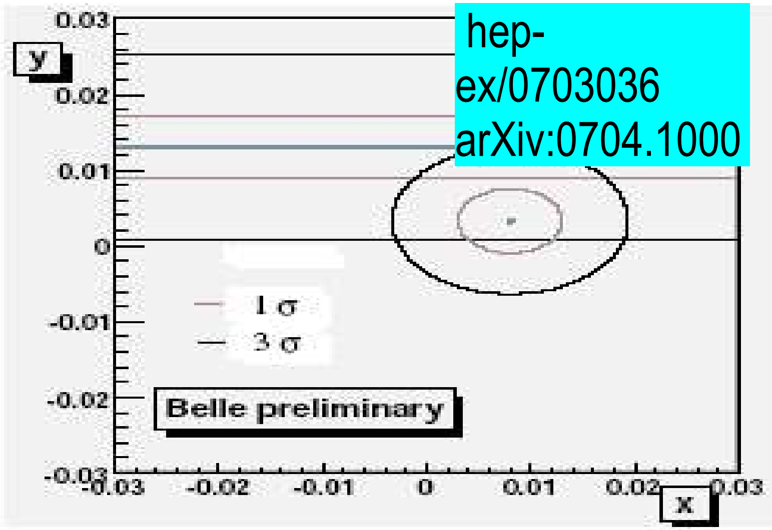
BaBar studied $D^0 \to K\pi$ decays

- Evidence for mixing (3.9σ)
- No sign of CP violation
- Consistent with other measurements and SM



New results from Belle

- Evidence for mixing (3.2σ)
- Measurement of x and y
- No sign of CP violation



Next steps

- Combine measurements (HFAG)
- Try to pin-down x, y and δ
- More searches for CP violation

Backup Slides

Belle $D^0 \to K_S\pi\pi$ Analysis

- 3-body decay modes:
  amplitudes $A(D^0 \to f)$ and $\bar{A}(\bar{D}^0 \to \bar{f})$ depend on Dalitz variables.
- Dalitz space dependent matrix element is for negligible CPV

$$M(m_-^2, m_+^2, t) = A(m_-^2, m_+^2)\frac{e_1(t)+e_2(t)}{2} + A(m_+^2, m_-^2)\frac{e_1(t)-e_2(t)}{2}$$

where $m_\pm$ is defined with the D^* tag

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

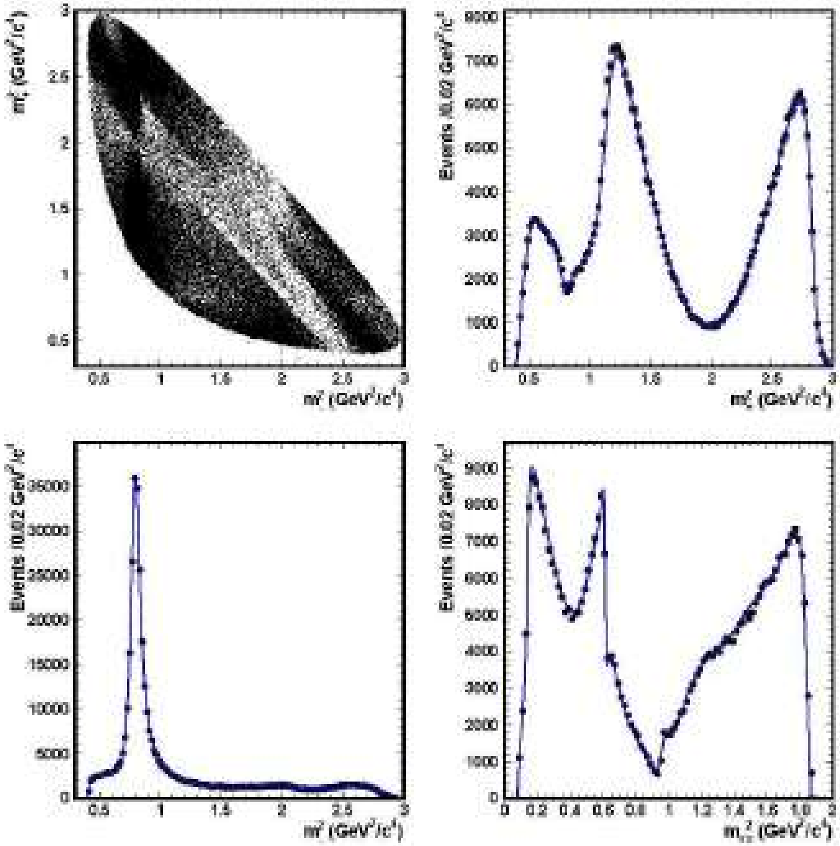
and time dependent functions with

$$e_{1,2}(t) = e^{-i(m_{1,2} - i\Gamma_{1,2}/2)t}$$

- $|M(m_-^2, m_+^2, t)|^2$ thus includes x and y
- The only measurement sensitive directly to x

Belle $D^0 \to K_S \pi\pi$ Analysis

Dalitz fit

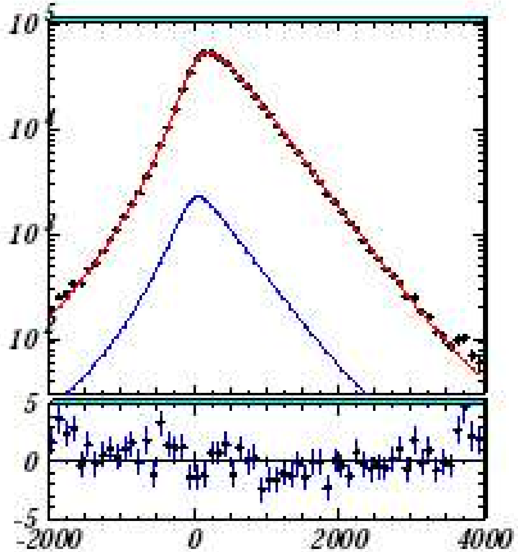


Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.629 ± 0.005	134.3 ± 0.3	0.6227
$K_0^*(1430)^-$	2.12 ± 0.02	-0.9 ± 0.5	0.0724
$K_2^*(1430)^-$	0.87 ± 0.01	-47.3 ± 0.7	0.0133
$K^*(1410)^-$	0.65 ± 0.02	111 ± 2	0.0048
$K^*(1680)^-$	0.60 ± 0.05	147 ± 5	0.0002
$K^*(892)^+$	0.152 ± 0.003	-37.5 ± 1.1	0.0054
$K_0^*(1430)^+$	0.541 ± 0.013	91.8 ± 1.5	0.0047
$K_2^*(1430)^+$	0.276 ± 0.010	-106 ± 3	0.0013
$K^*(1410)^+$	0.333 ± 0.016	-102 ± 2	0.0013
$K^*(1680)^+$	0.73 ± 0.10	103 ± 6	0.0004
$\rho(770)$	1 (fixed)	0 (fixed)	0.2111
$\omega(782)$	0.0380 ± 0.0006	115.1 ± 0.9	0.0063
$f_0(980)$	0.380 ± 0.002	-147.1 ± 0.9	0.0452
$f_0(1370)$	1.46 ± 0.04	98.6 ± 1.4	0.0162
$f_2(1270)$	1.43 ± 0.02	-13.6 ± 1.1	0.0180
$\rho(1450)$	0.72 ± 0.02	40.9 ± 1.9	0.0024
σ_1	1.387 ± 0.018	-147 ± 1	0.0914
σ_2	0.267 ± 0.009	-157 ± 3	0.0088
NR	2.36 ± 0.05	155 ± 2	0.0615

- Dalitz model: 13 different (BW) resonances and a non-resonant contribution
- Results with this refined model consistent with the analysis performed for the Belle ϕ_3 measurement, PRD73, 112009 (2006)
- To test the scalar $\pi\pi$ contributions, K-matrix formalism is also used

Belle $D^0 \to K_S\pi\pi$ Analysis

Time fit (in projection)



Systematics

Largest contributions ($\times 10^{-4}$)

x	y	
$^{+14.6}_{-13.6}$	$^{+7.8}_{-8.8}$	Model dependence
$^{+8.5}_{-6.8}$	$^{+6.6}_{-11.6}$	Time fit

Total ($\times 10^{-4}$)

x	y
$^{+16.9}_{-15.2}$	$^{+10.2}_{-14.6}$

Results (preliminary)

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

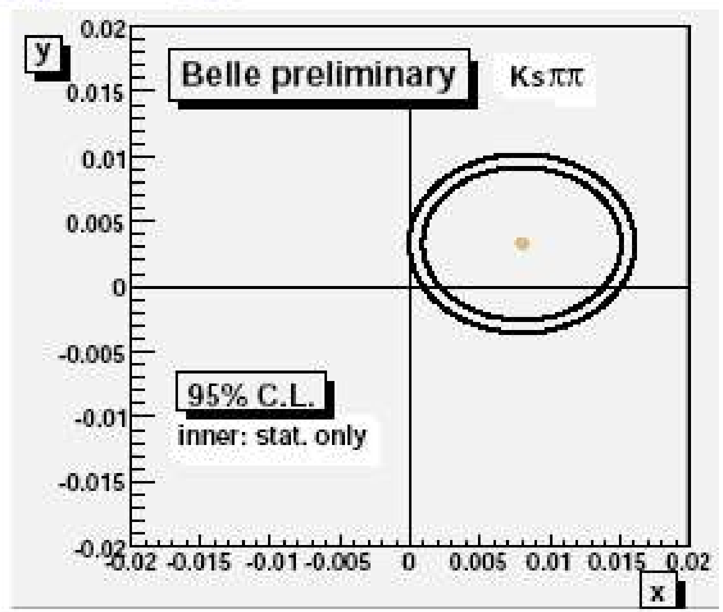
$$y = 0.33 \pm 0.24 \pm 0.15\ \%$$

most stringent limits on x up to now

Cleo, PRD 72, 012001 (2005):

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

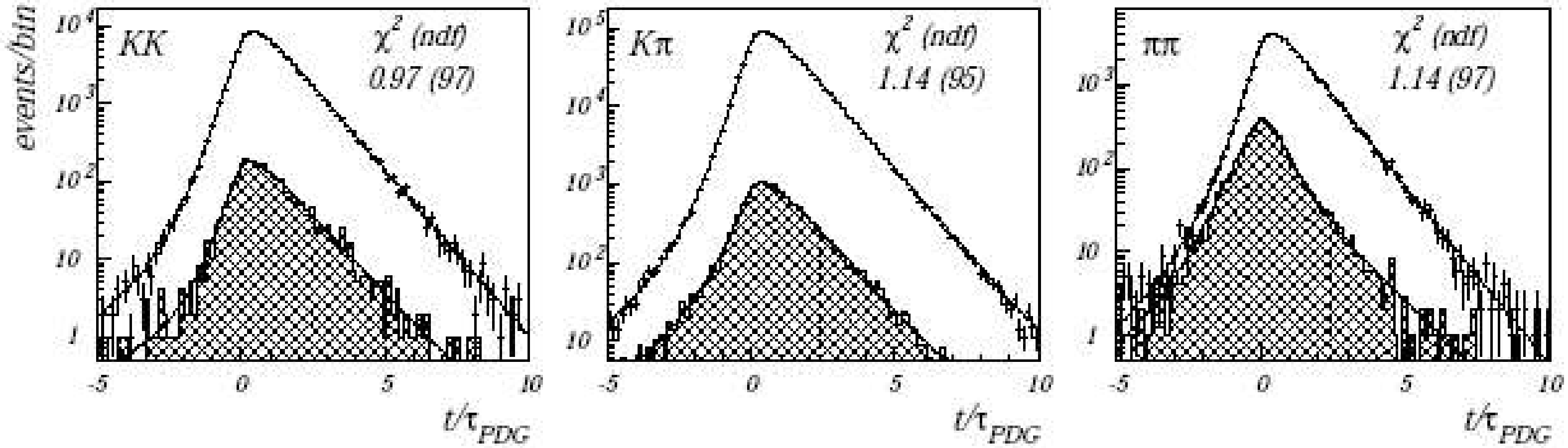
$$y = -1.4 \pm 2.5 \pm 0.9\%$$



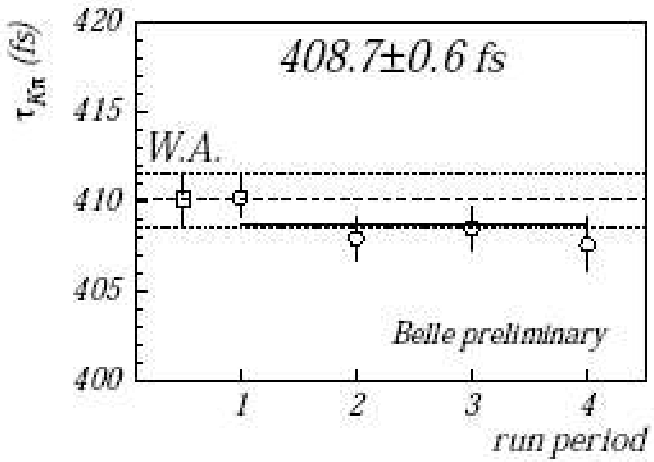
Belle $D^0 \to KK/\pi\pi$ Analysis

Simultaneous $KK/\pi\pi/K\pi$ binned likelihood fit

quality of fit: $\tilde{\chi}^2 = 1.084\ (289)$



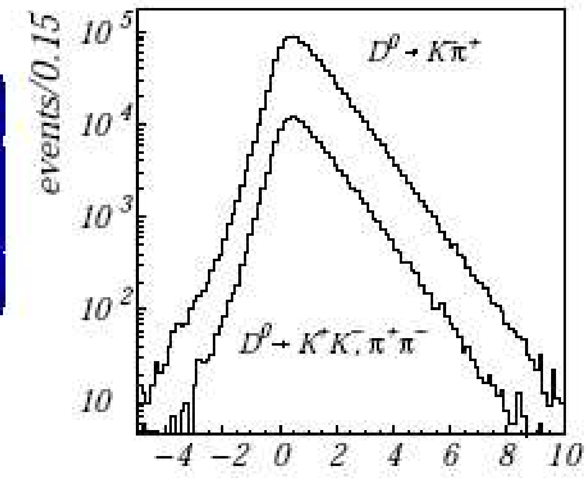
$D^0 \to K\pi$ lifetime very stable in slightly different running periods



Belle $D^0 \to KK/\pi\pi$ Analysis

Results (preliminary)

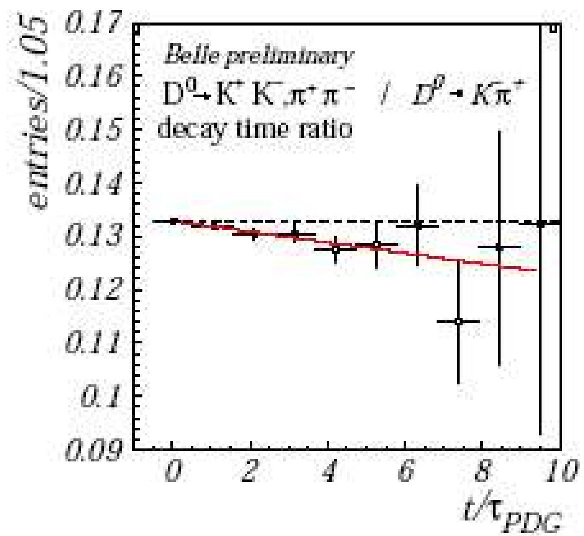
	y_{CP} (%)	A_Γ (%)
KK	1.25±0.39±0.28	0.15±0.34±0.16
$\pi\pi$	1.44±0.57±0.42	-0.28±0.52±0.30
$KK+\pi\pi$	1.31±0.32±0.25	0.01±0.30±0.15



Belle preliminary (540 fb^{-1})

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

$>3\sigma$ above zero
(4.1σ stat. only)
first evidence for $D^0 - \bar{D}^0$ mixing

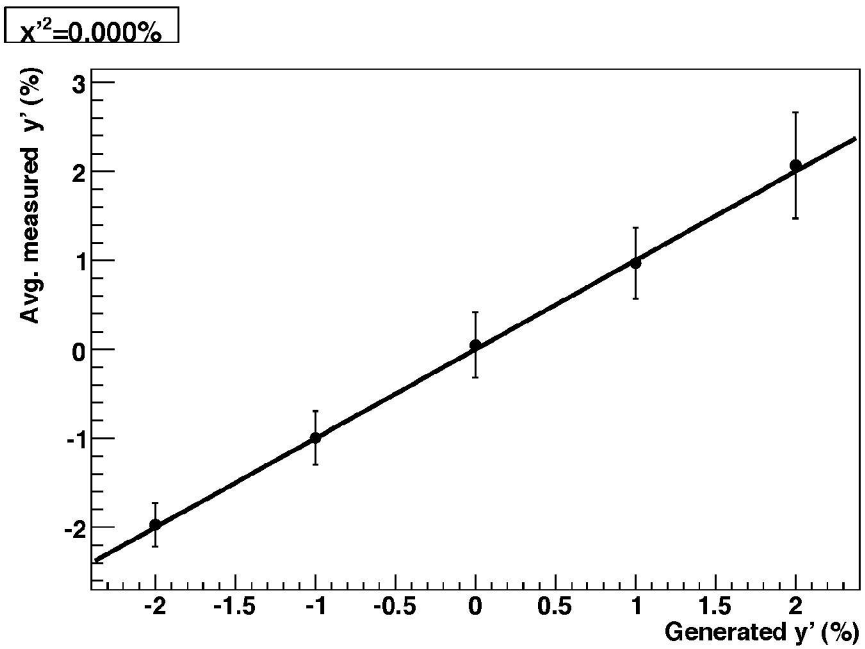


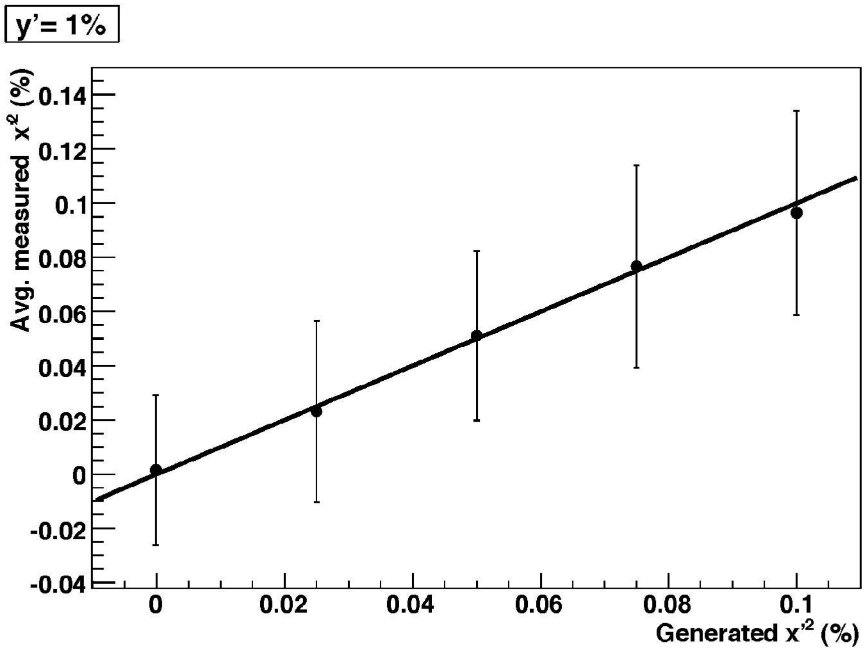
$$A_\Gamma = 0.01 \pm 0.30 \pm 0.15\ \%$$

no evidence for CP violation

Toy MC Tests

Test for unbiasedness:

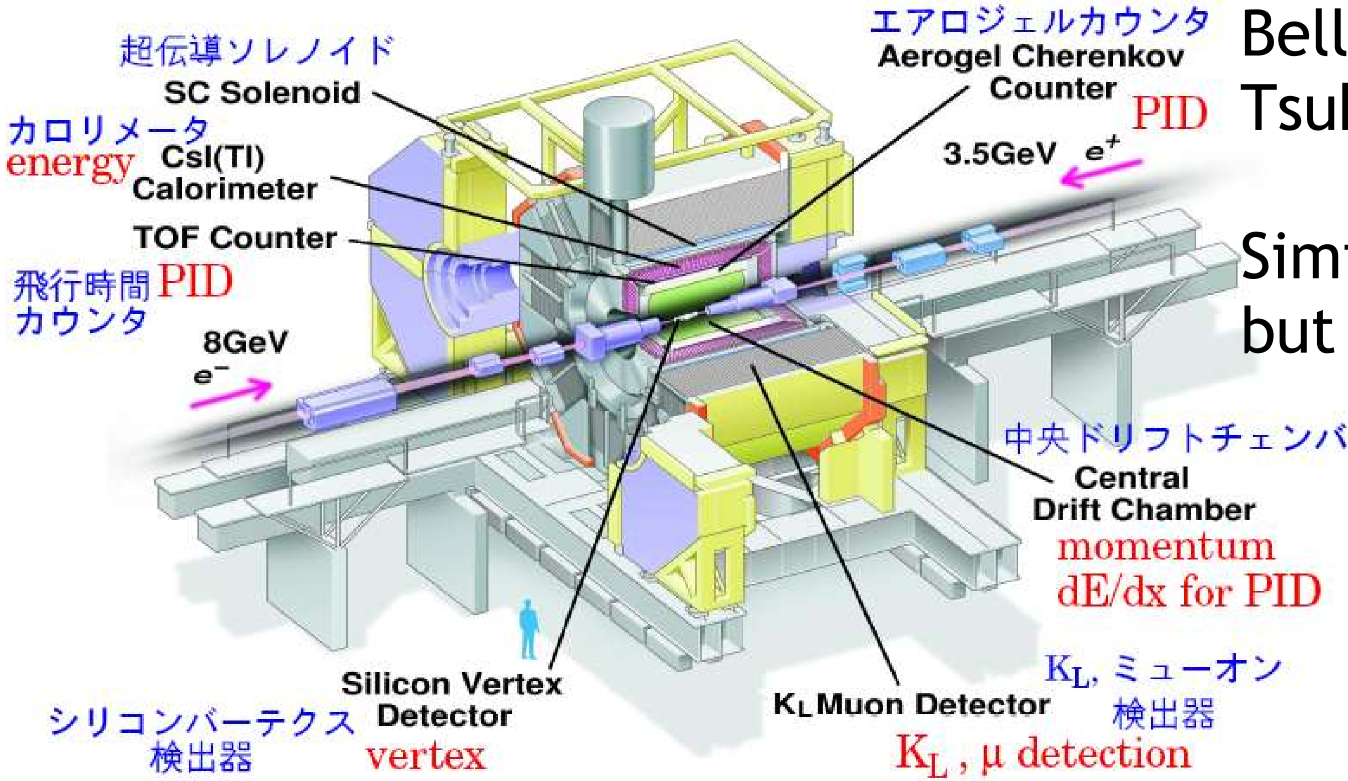




average fitted value of mixing parameter versus generated value.
Error bars: RMS of fitted values: expected parameter errors
Straight line has unit slope, 0 intercept.

Results indicate no bias in estimating mixing parameters

Other Charm Experiments



Belle is B-factory at Tsukuba, Japan

Similar to BaBar,
but has a larger dataset

Older charm experiments:

CLEO (${e^+e^-}$ collisions at Cornell)

FOCUS, E791 (fixed target at Fermilab)

K^0 Mixing

Neutral meson mixing first observed in K^0–$\overline{K}^0$ system

Short-lived "K_s" seen in 1947: τ=89 ps

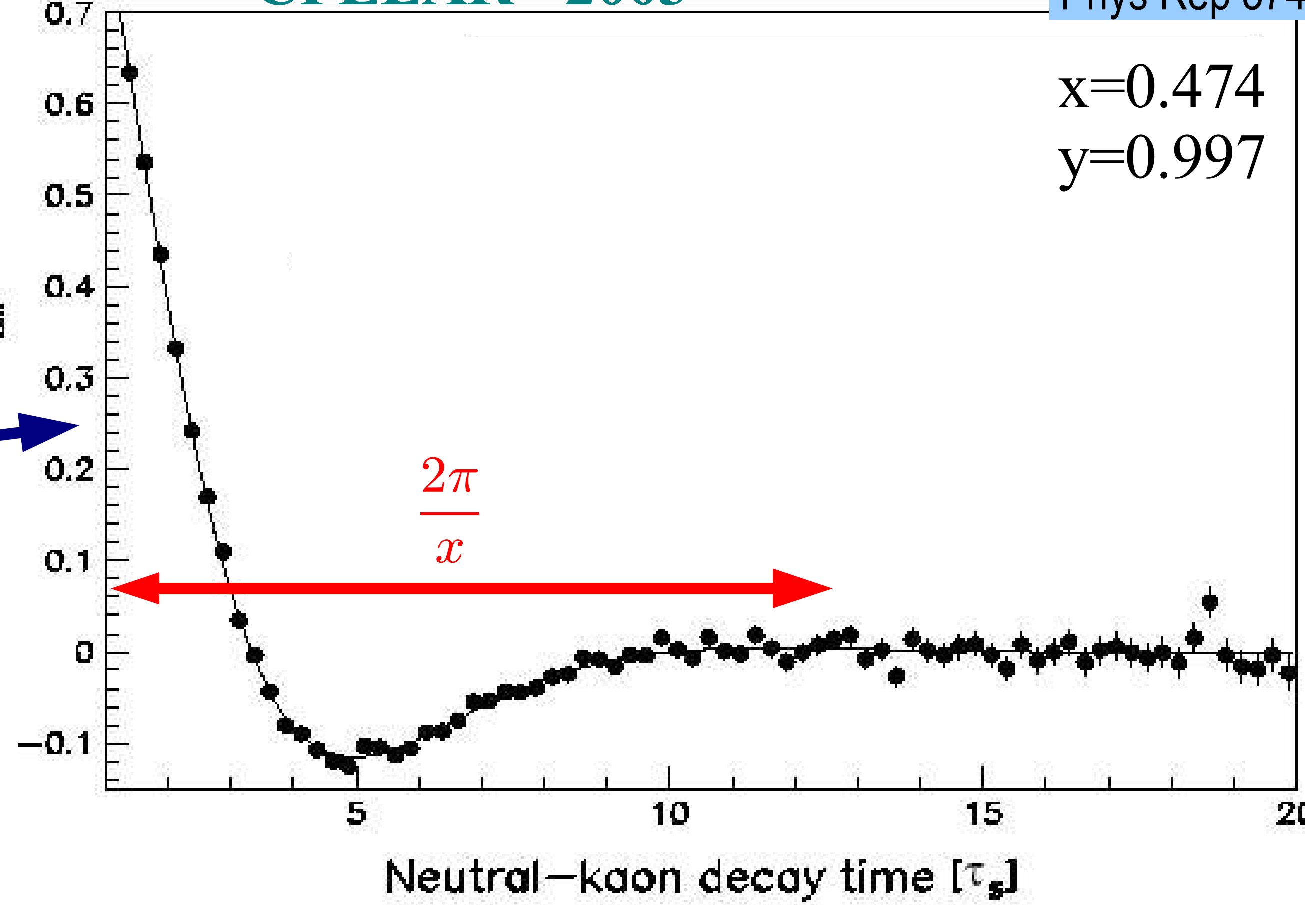
Long-lived "K_L" seen in 1956: τ=51 ns

Mixing frequency x first measured in 1958

Now measured precisely in many experiments

CPLEAR - 2003

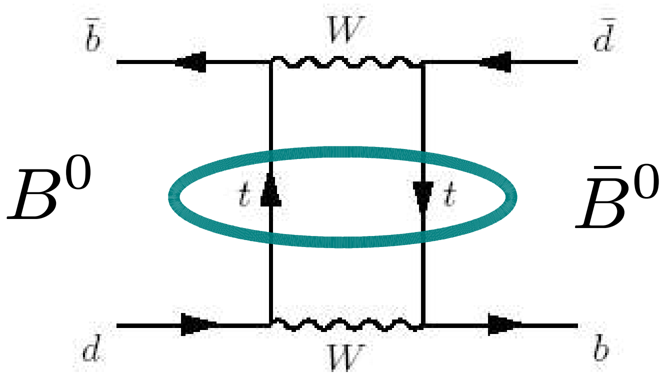
Phys Rep 374 165



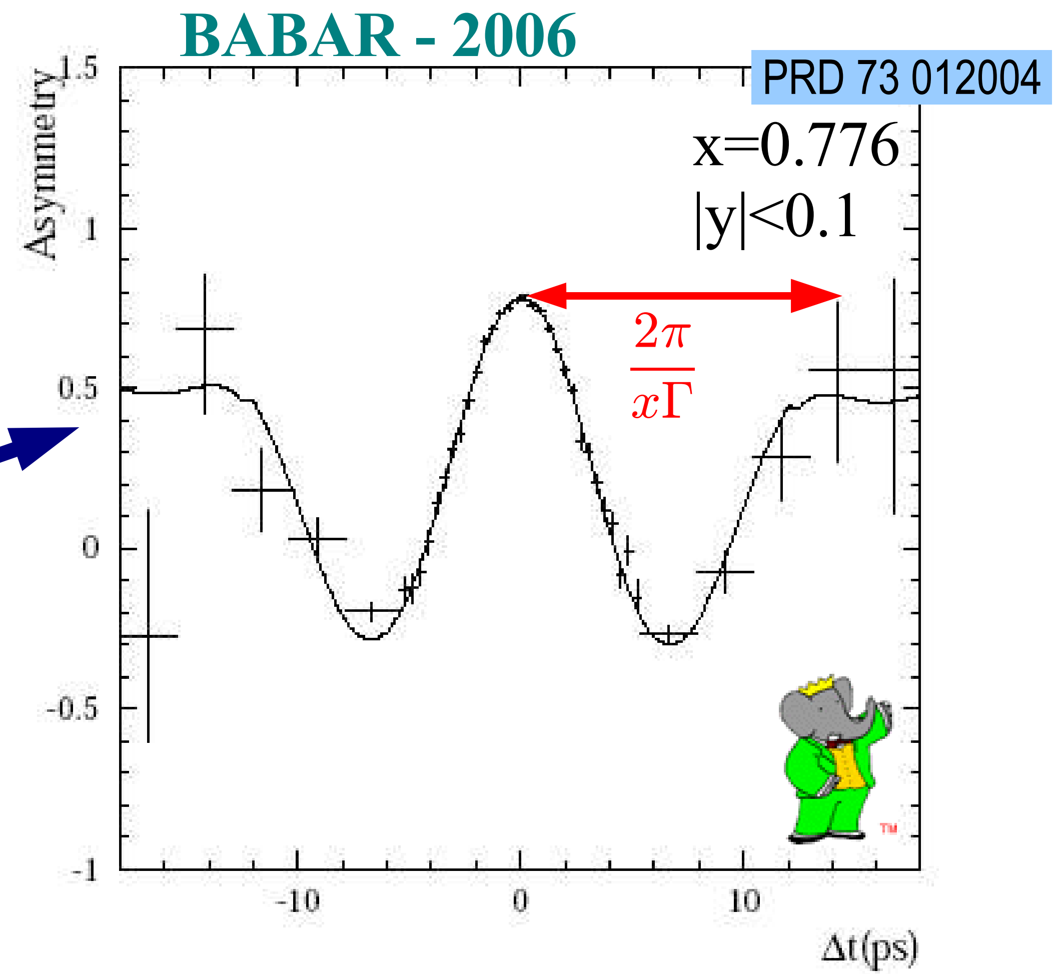
B^0 Mixing

B^0 mixing first observed by ARGUS experiment in 1987

Large mixing frequency implied t quark was heavy (m_t >50 GeV/c^2)



Mixing is now precisely measured at B-factories



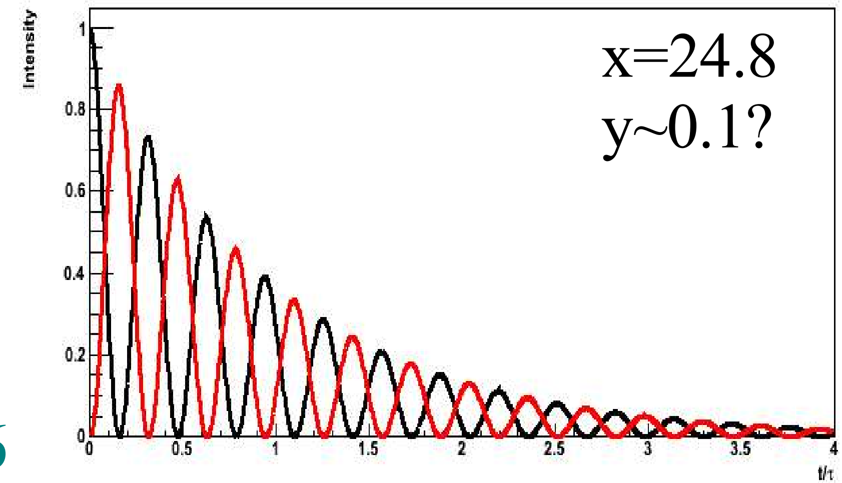
Lifetime difference has not been measured

Expected to be small

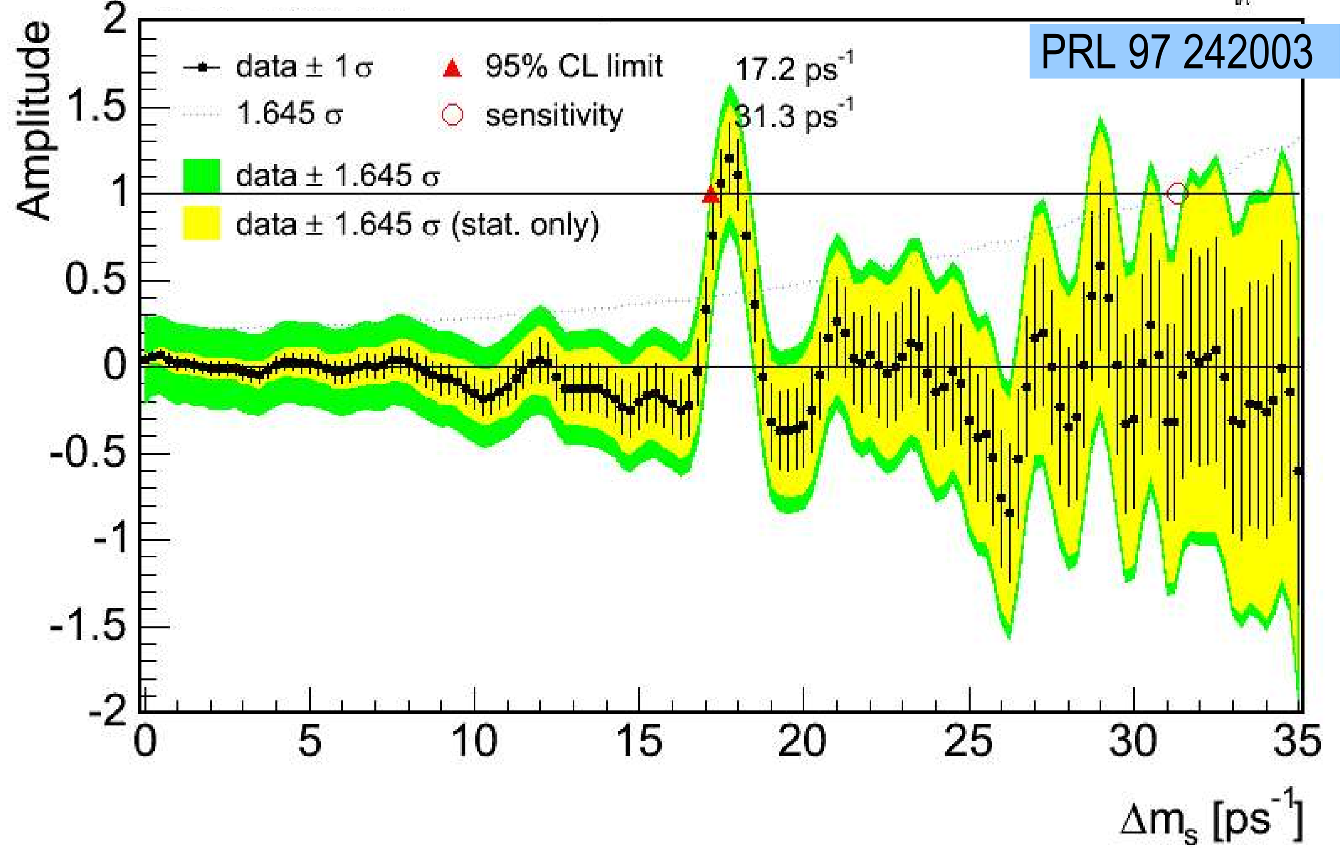
B_s^0 Mixing

B_s^0 oscillate very rapidly

Rate first measured in 2006 by CDF and D0



CDF-2006



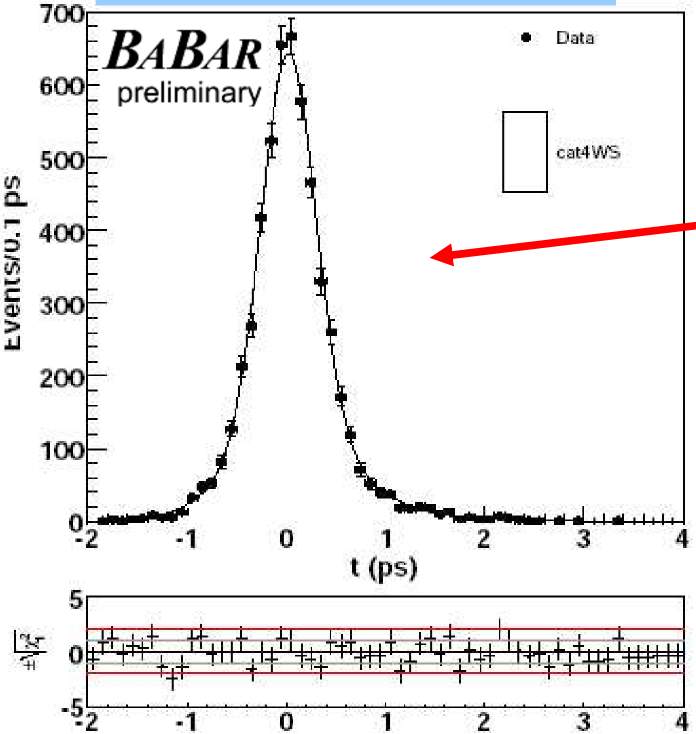
One of the main HEP discoveries in 2006

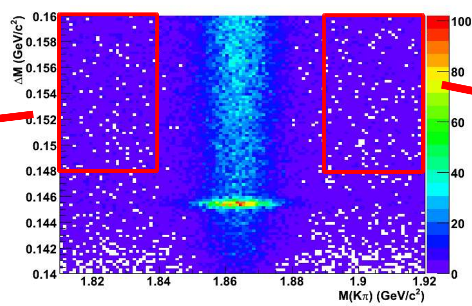
Brian Petersen

Systematic: Combinatorial Decay Time

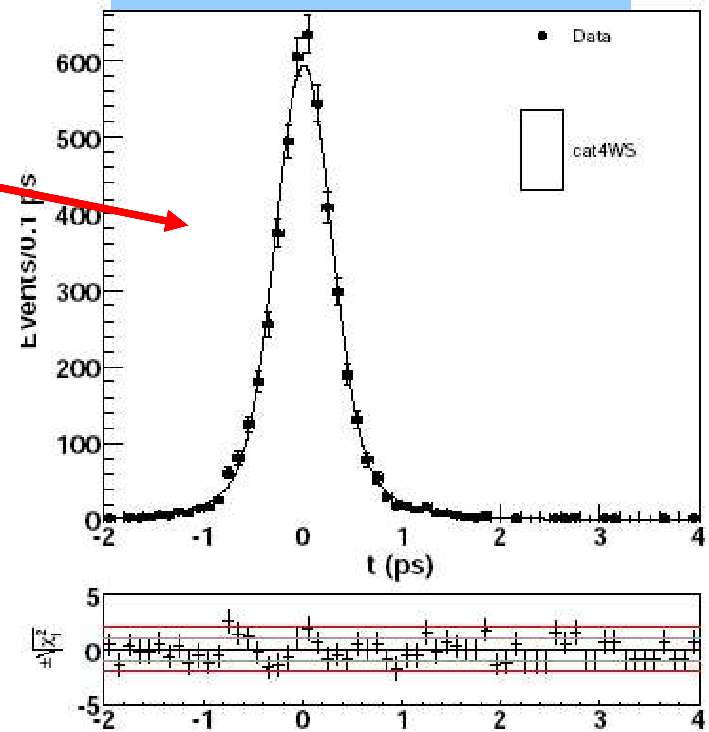
Decay time in combinatorial bkgd not independent of m(Kπ)
Fix PDF parameters to fits in different background sidebands:

$1.81 < m < 1.84$ GeV/c^2
$0.148 < \Delta m < 0.16$ GeV/c^2





$1.883 < m < 1.92$ GeV/c^2
$0.148 < \Delta m < 0.16$ GeV/c^2



Systematic variation:

y' -0.3σ
x'^2 $+0.2\sigma$

Systematic: Decay Time Resolution

Decay time resolution function in data has non-zero mean

Core Gaussian shifted 3.6±0.6fs

Effect is not seen in MC
- probably due to misalignment

For systematics set mean to 0:

Variation: y' 0.3σ
x'^2 -0.3σ

No reason why resolution should be different for RS and WS decays

RS decay time, resolution mean fixed to zero