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

(hep-ex/0703020, submitted to PRL)

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for the *BABAR* collaboration

Brookhaven National Lab
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University of South Carolina High Energy Physics Group

Outline

- Neutral meson oscillations
- D^0 oscillations
- The *BABAR* experiment
- Mixing in $D^0 \rightarrow K\pi$ decays
- Comparison with other results

Neutral Meson Oscillations

Neutral Meson Mixing

Mixing can occur in four neutral mesons:

K^0	Mass: ~0.5 GeV/c^2
D^0	Mass: ~1.9 GeV/c^2
B^0	Mass: ~5.3 GeV/c^2
B^0_s	Mass: ~5.4 GeV/c^2

Will present mixing measurement for D^0 meson

Note: D^0 meson first discovered at SLAC

Mark-I, PRL 37, 255 (1976)

Neutral Meson systems

– Two-level system $(M^0, \overline{M}^0)$
  - Weak interactions remove degeneracy, make them unstable

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

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 $\Gamma_{1,2}$:

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

Neutral mesons oscillations

Time evolution for meson of ***known flavor at t=0***

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

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

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

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

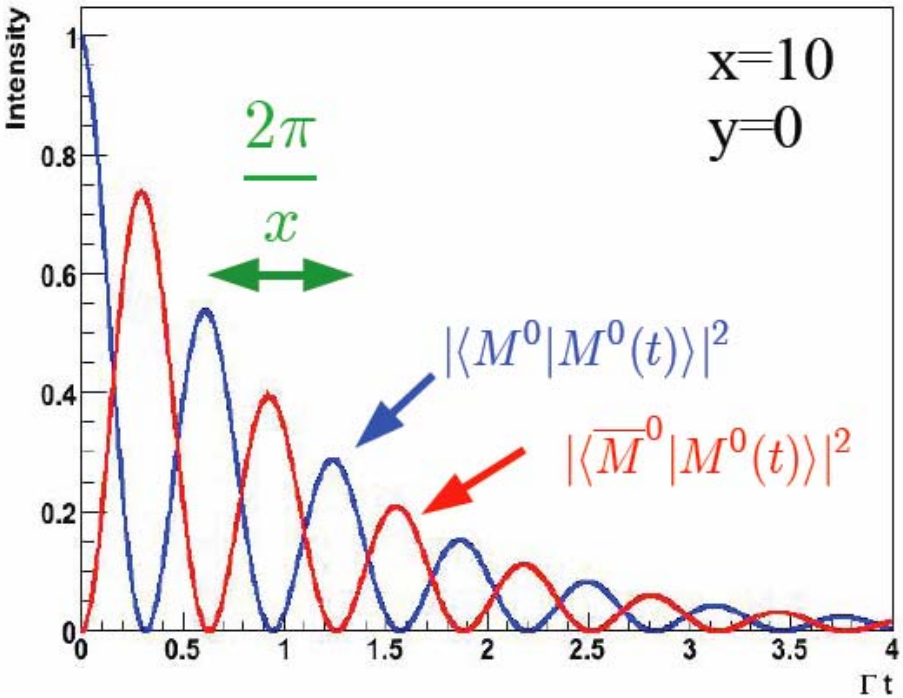
M^0 "oscillates" into $\overline{M}^0$!

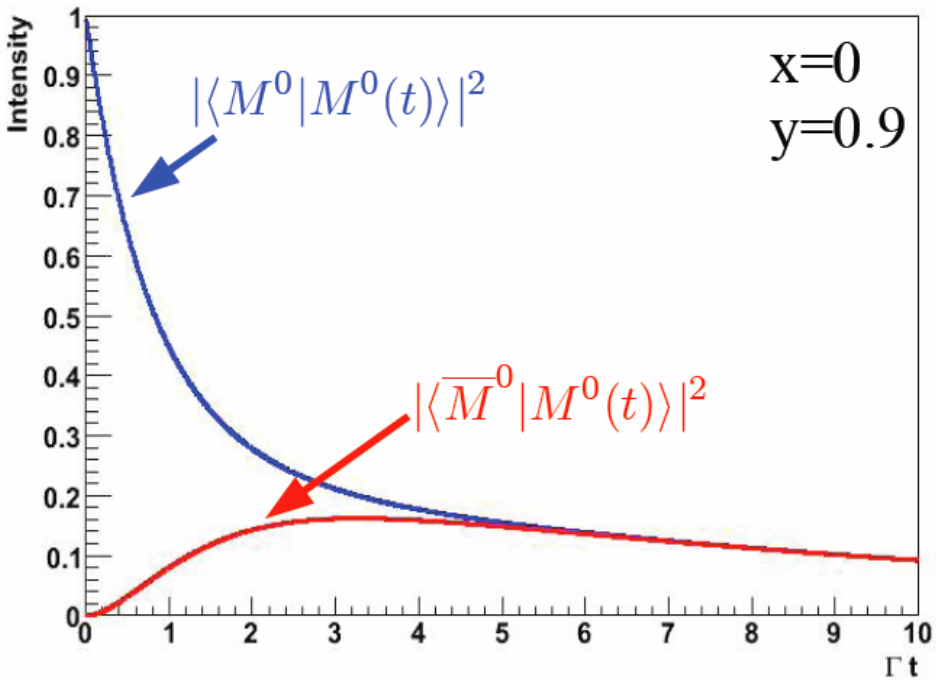
(also dubbed "mixing")

An opposite flavor component appears after a while!

Some visual examples

Probability to find a $M^0(\bar{M}^0)$ after a given time

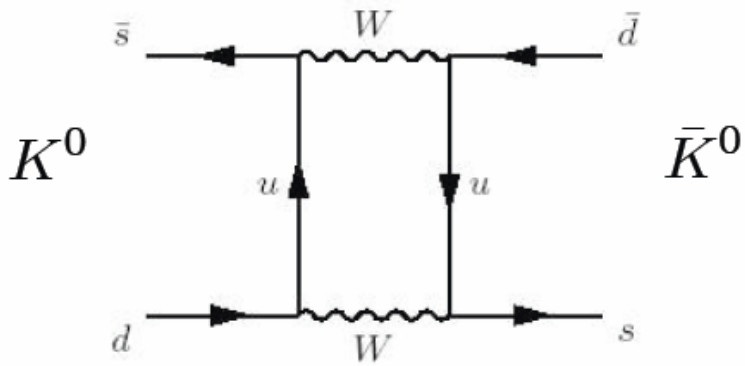




Lifetime units

The prediction of charm

Mixing through box diagram:



No tree level Flavor Changing Neutral Currents (FCNC) in SM

Glashow, Iliopoulus and Maiani (1970):

FCNC calculated from single quark loop still too large

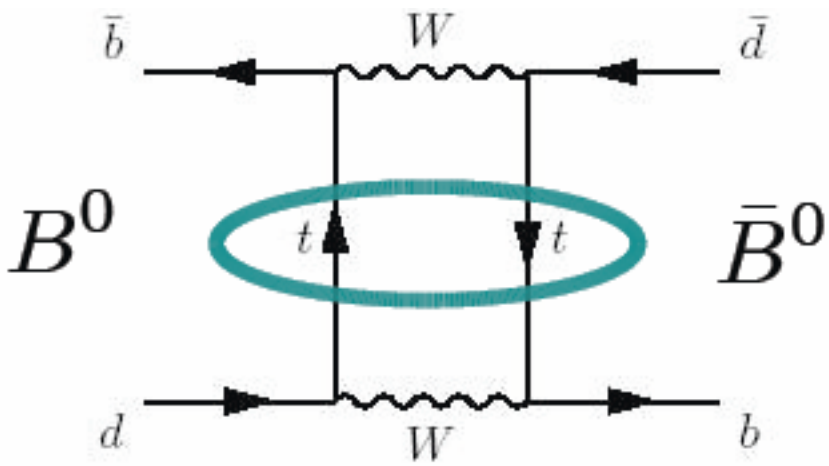
Introduce additional loop with new c quark

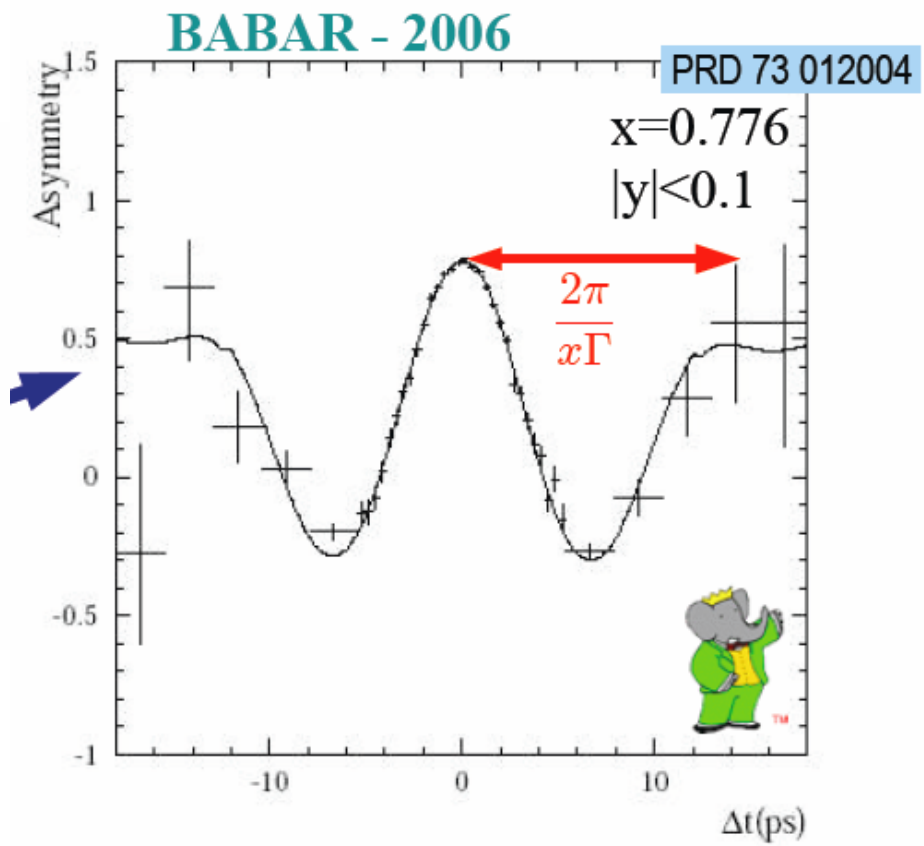
GIM predicted charm quark 4 years before observation

B^0 mixing and the discovery of the t

B^0 mixing was argued by UA1 and directly observed by ARGUS in 1987

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

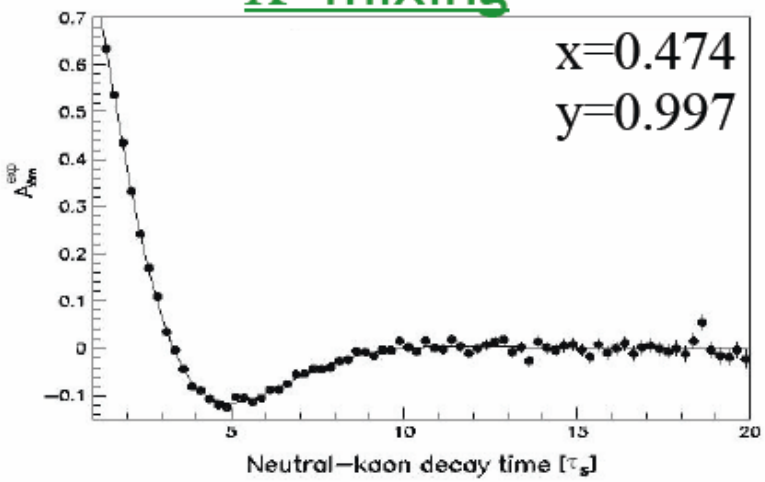




And the top was discovered 8 years after!

The missing tile

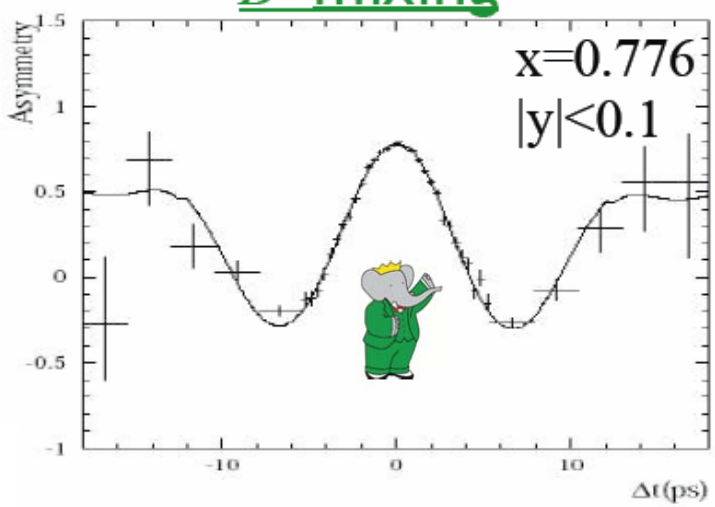
K^0 mixing



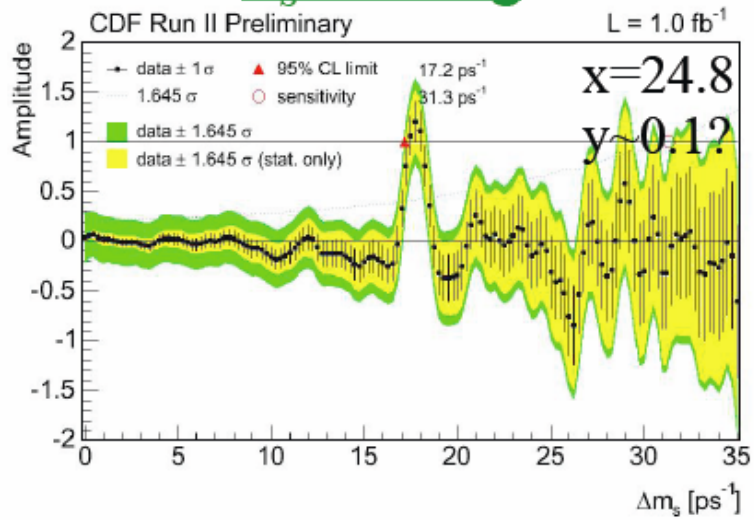
D^0 mixing

?

B^0 mixing



B_s^0 mixing



Charm Meson Mixing

Short and **Long** distance

- Prediction x and y

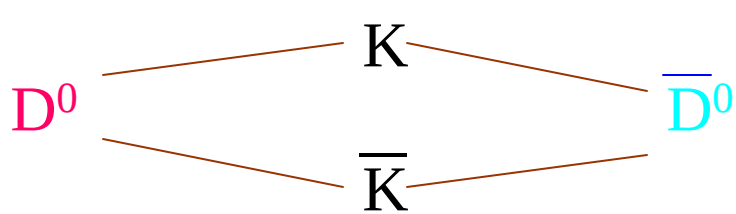
x *VIRTUAL* states

$$\left(\mathbf{M}-\frac{i}{2}\mathbf{\Gamma}\right)_{ij} = \frac{\langle D_i|H_{\rm eff}|D_j\rangle}{2m_D} = m_D^{(0)}\delta_{ij} + \frac{\langle D_i|H_w|D_j\rangle}{2m_D} + \frac{1}{2m_D}\sum_n \frac{\langle D_i|H_w|n\rangle\langle n|H_w|D_j\rangle}{m_D^{(0)}-E_n+i\epsilon}.$$

y

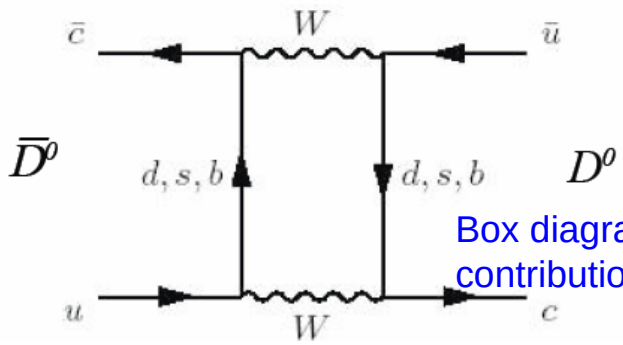
$$\Gamma_{ij} = \frac{1}{2m_D}\sum_n \langle D_i|H_w|n\rangle\langle n|H_w|D_j\rangle\ \delta(E_n-m_D).$$

Sum of intermediate **REAL states**



SM prediction for charm mixing

SM charm mixing box has down-type quarks in loop



Box diagram contribution

Effective GIM suppression:

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

bottom quark

ruled out by V_{CKM}

$$x \sim 10^{-5}$$ Tiny!

$$x,\ y \sim \sin\theta_c^2 \times [\mathrm{SU}(3)\ \text{breaking}].$$

Naively

$$x,\ y \sim \sin\theta_c^2 \times \left(\frac{m_s}{\Lambda_{\mathrm{hadr.}}}\right)^2 \lesssim O(10^{-3})$$

Always hard to evaluate SU(3) breaking !!!

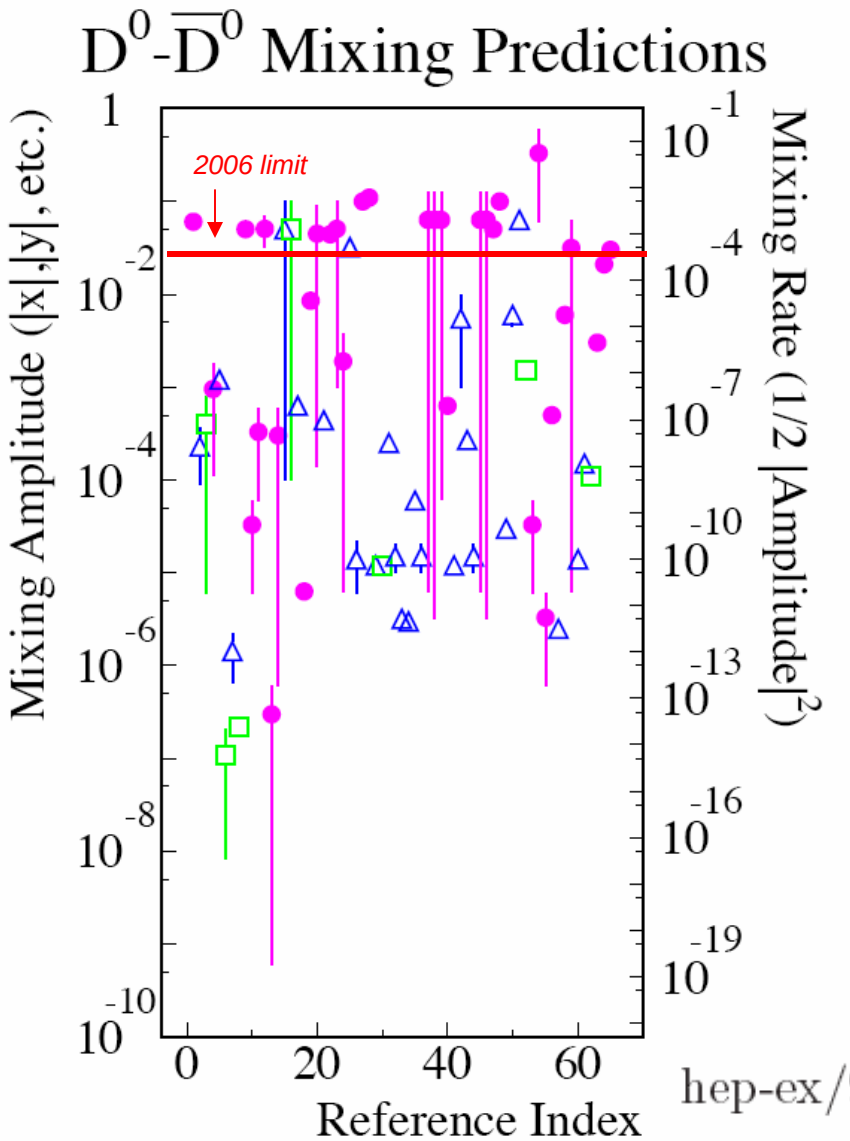
(HQET, propagation of common hadronic states,…)

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

SU(3) breaking effect more important for y

$$x \lesssim 10^{-3}, \qquad y \lesssim 10^{-2}.$$

New Physics in Charm ?



hep-ex/9908021

Δ: Standard model predictions for x

□: Standard model predictions for y

●: New physics predictions for x

Hard to see a clear prediction

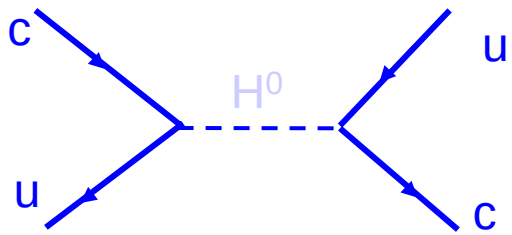
Pushing the limit down excludes models

Try to separate x and y!

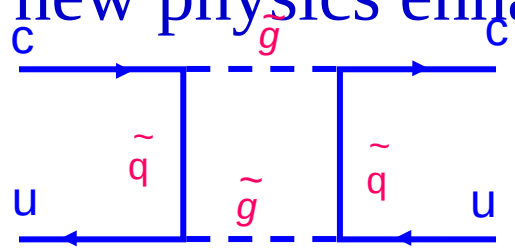
New Physics Contribution to Charm Mixing

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

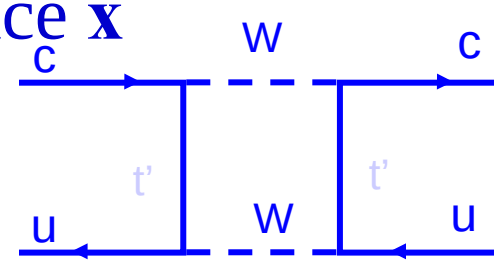
- Possible enhancements to mixing due to new physics
- Contributions from new physics enhance **x**



FCNC



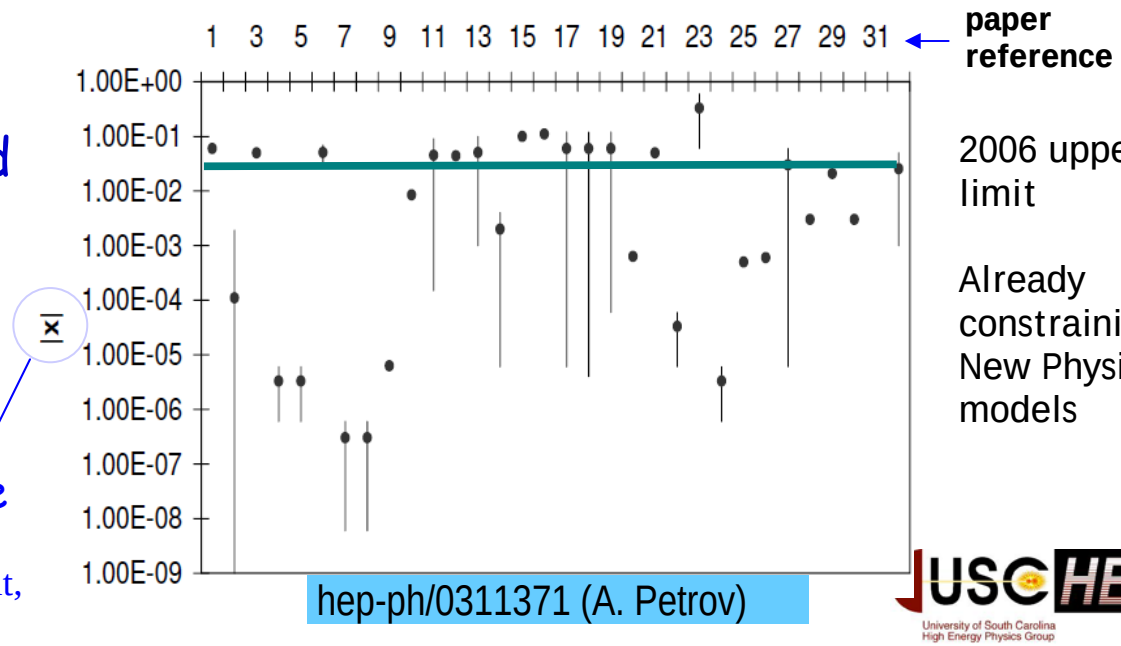
Supersymmetry



Fourth quark generation

- Indication of NP would be observation of CP-violation or Δ(mass)>>Δ(lifetime)

Mass difference

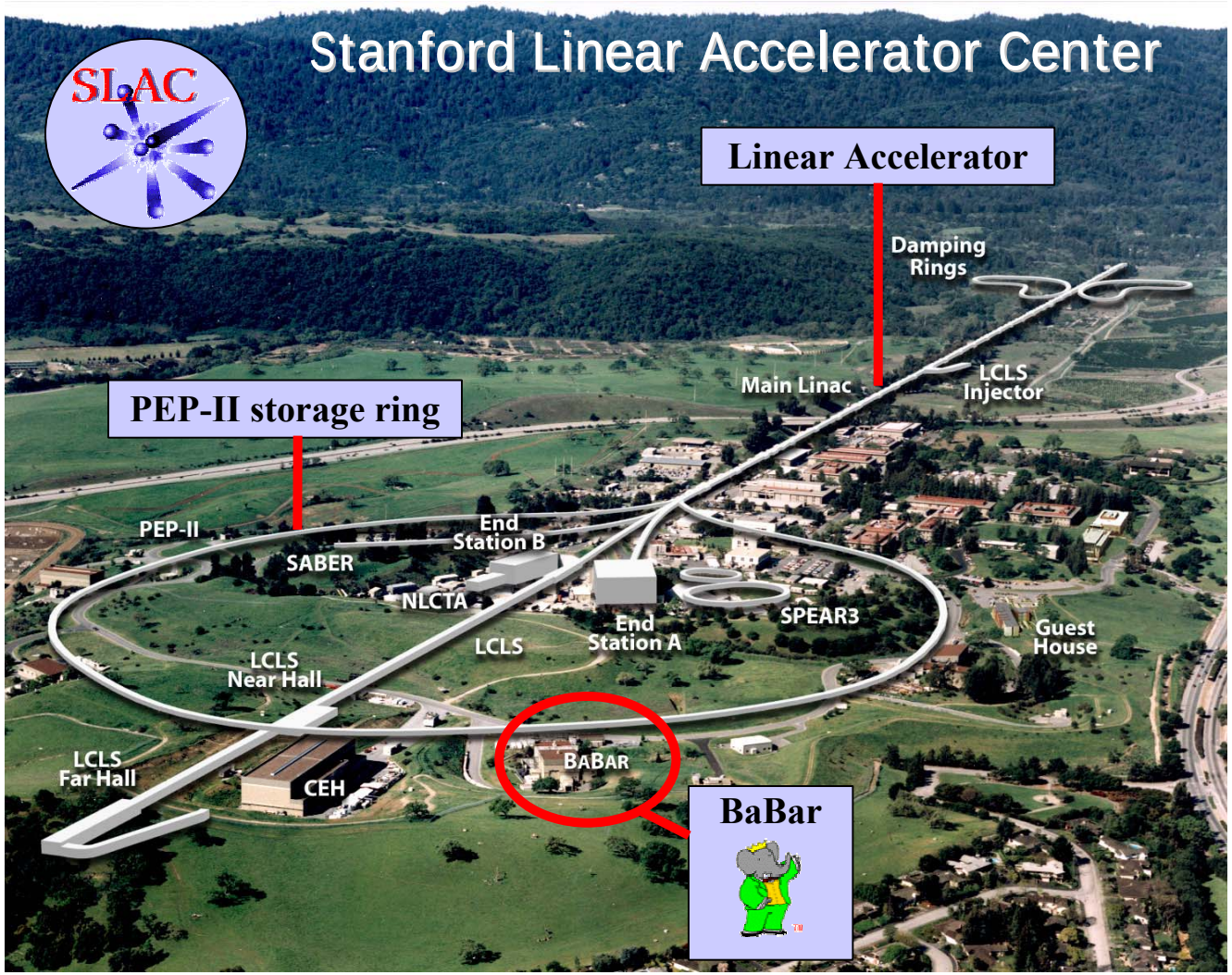


M. V. Purohit,

hep-ph/0311371 (A. Petrov)

The BaBar Experiment

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



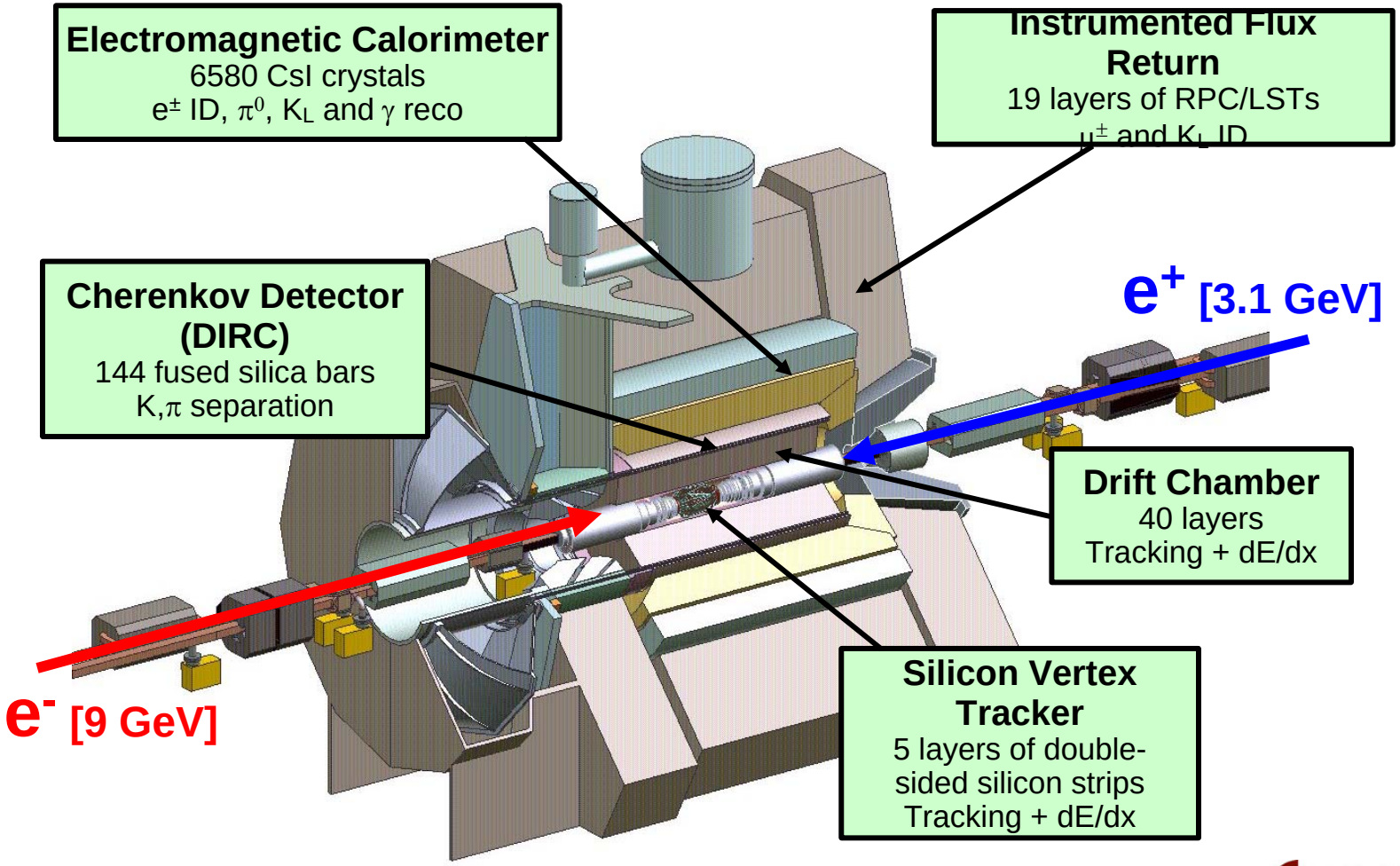
High-luminosity asymmetric energy e^+e^- collider at $\Upsilon(4S)$ resonance

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

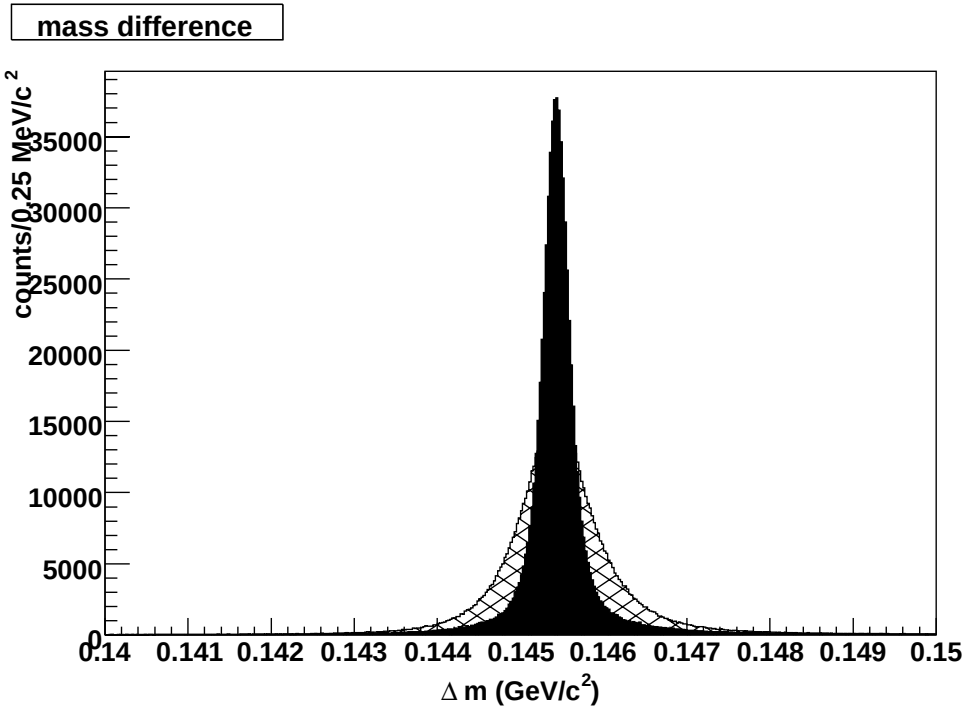
~10 Hz of $B\overline{B}$

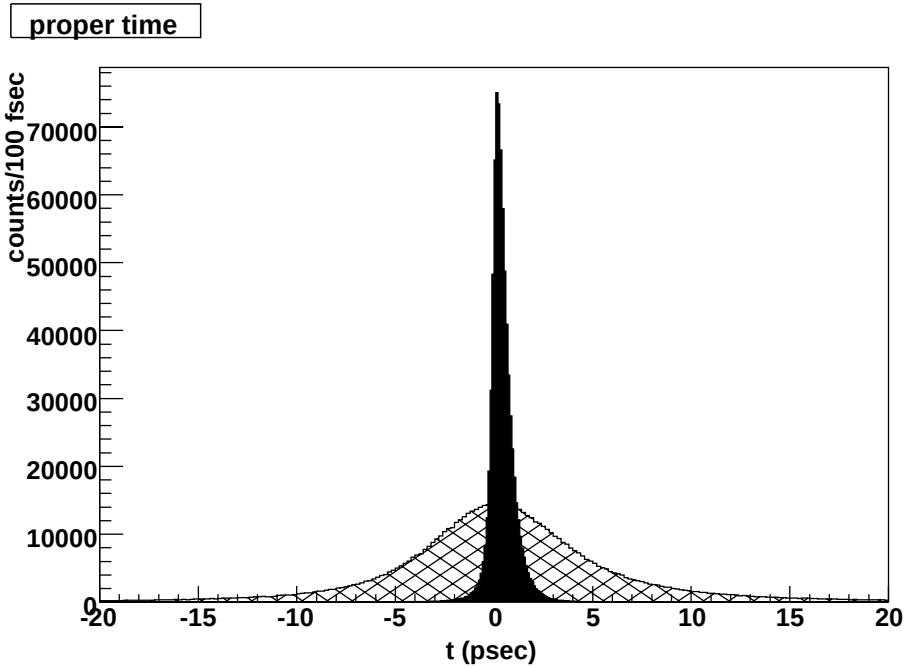
The BaBar Experiment

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



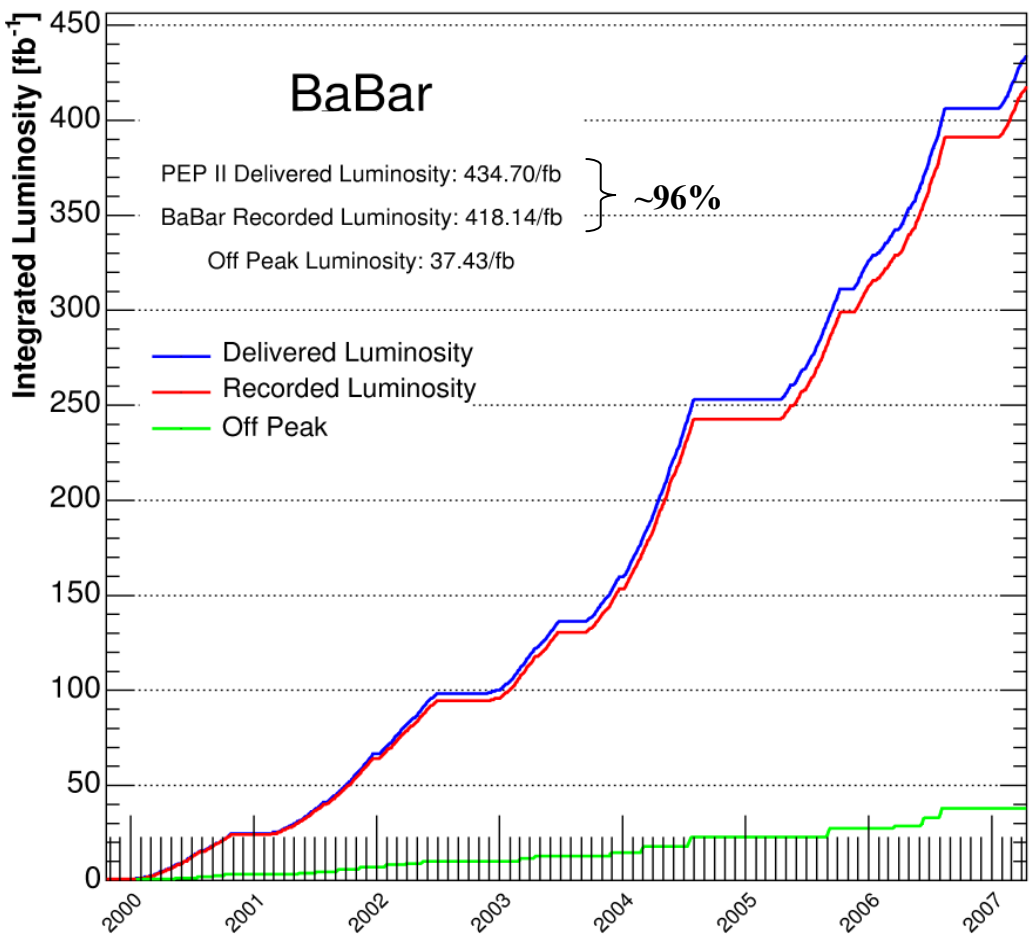
Effect of Beam Spot Constraint on ΔM and t





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

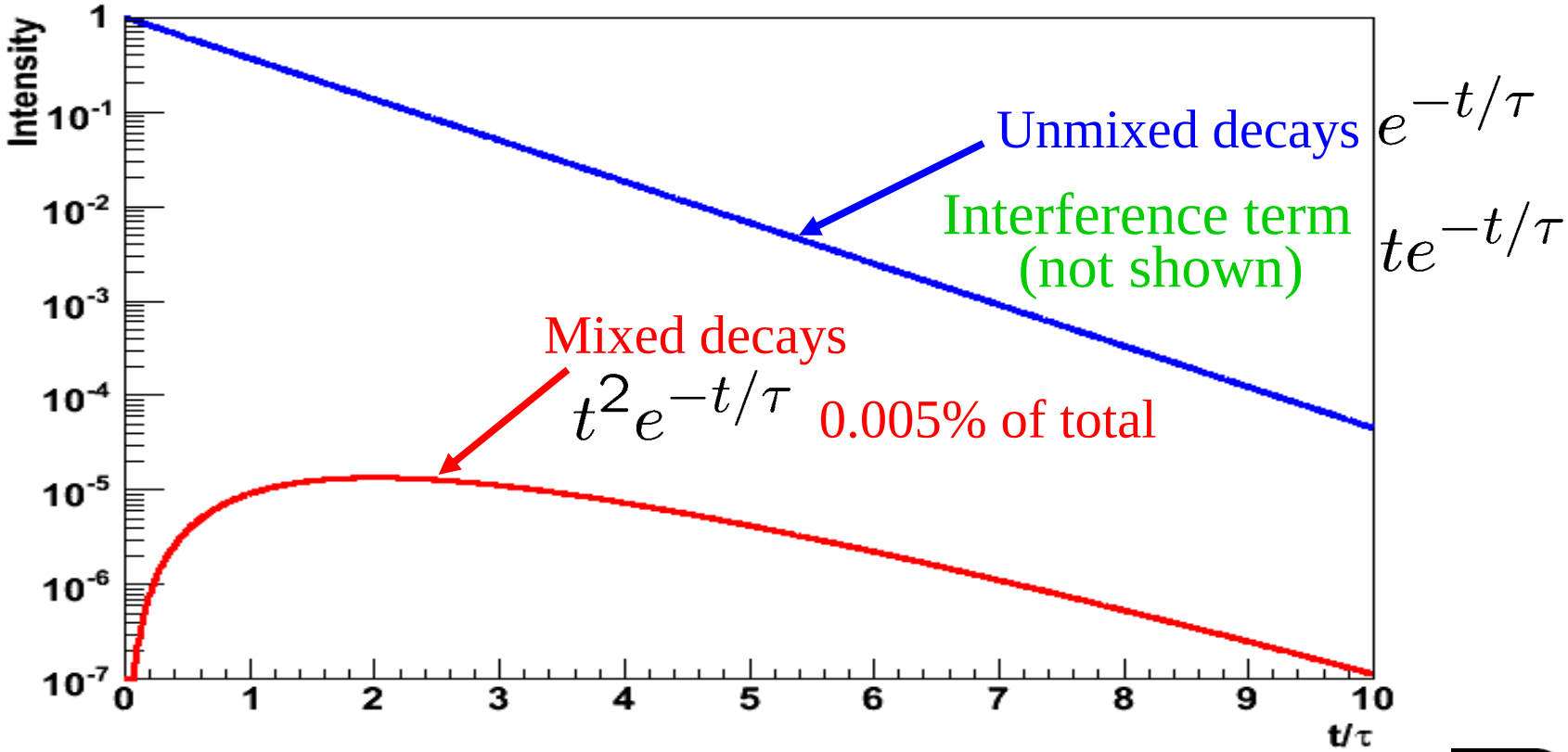
Add ~1M $c\bar{c}$ each day

Excellent sample to search for charm mixing

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

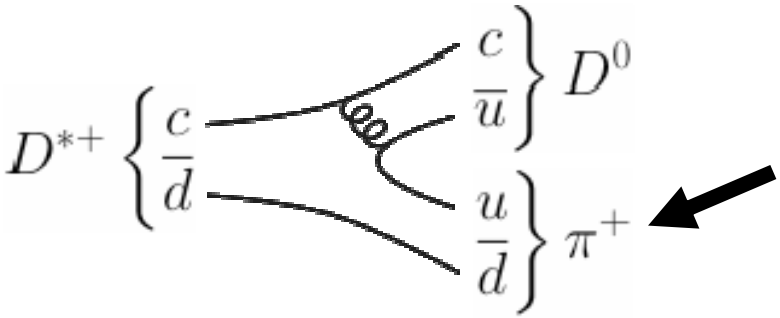
Principle of Mixing Measurement

- 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 (Distributions shown without time smearing)



Production Flavor

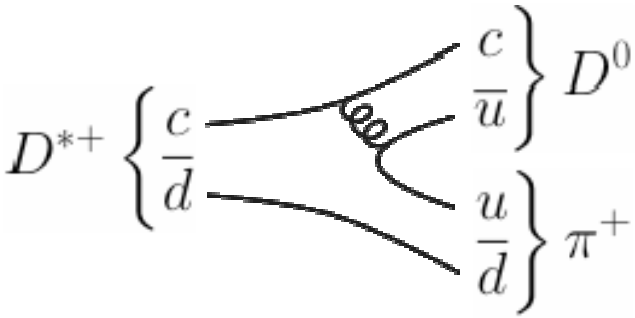
Use D^0 from $D^{*+} \to D^0 \pi^+$ decays:



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

Production Flavor

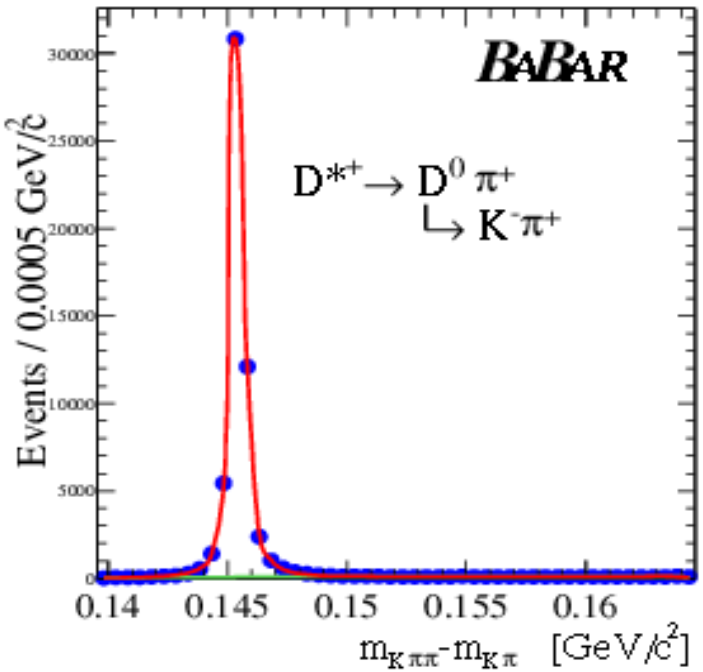
Use D^0 from $D^{*+} \rightarrow D^0 \pi^+$ decays:



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

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

Gives narrow mass peak

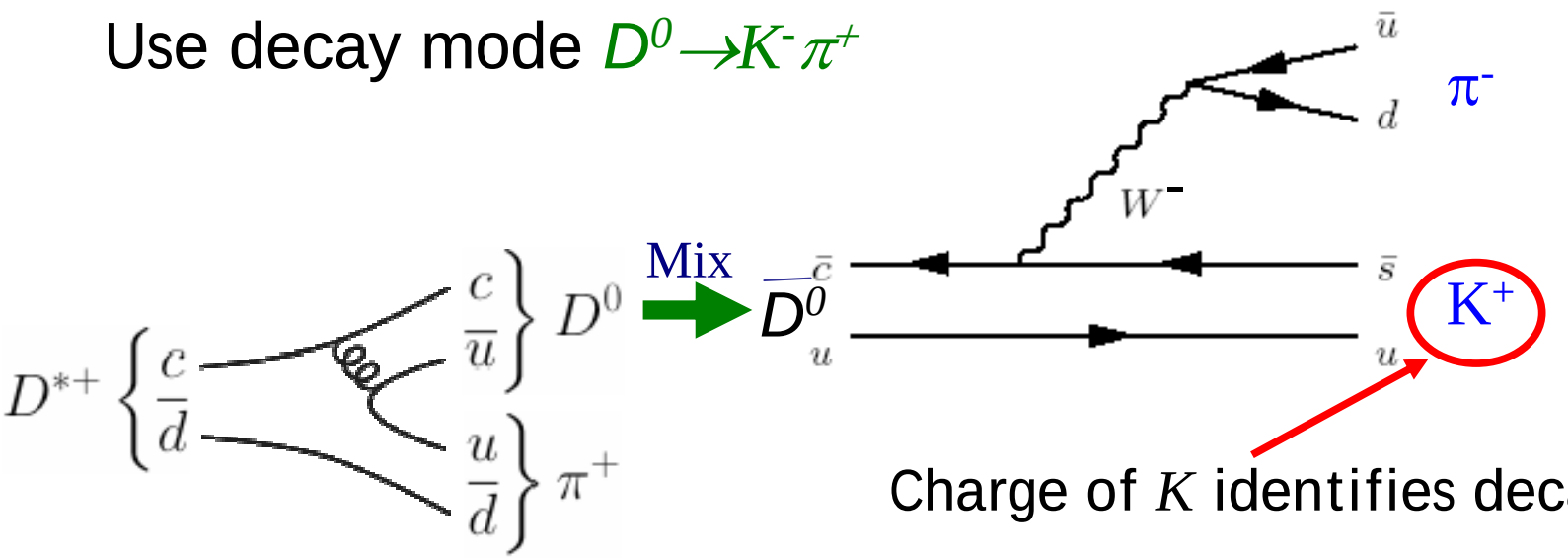


Excellent background suppression

$\Delta m = m(D^0 \pi^+) - m(D^0)$

Flavor at Decay

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



Charge of K identifies decay flavor

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

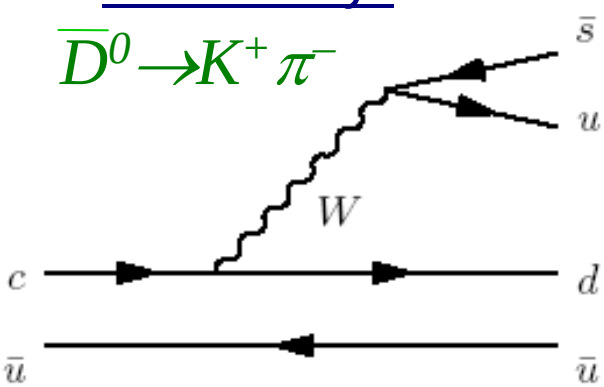
Doubly-Cabibbo Suppressed Decays

Hadronic decays do not uniquely identify decay flavor

Get unmixed wrong-sign decays from DCS decays

DCS decay:

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



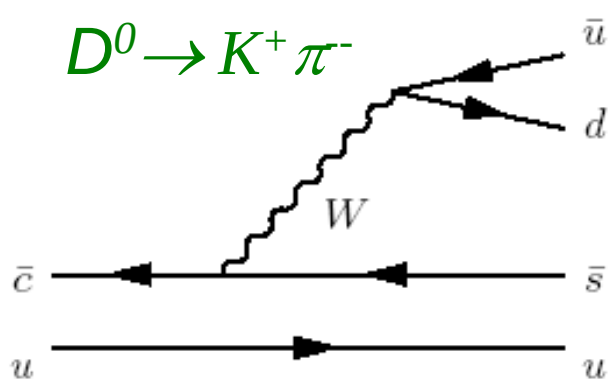
Relative rate ~0.3%

Mix

$D^0 \rightarrow \overline{D}^0$

Mixed decay:

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

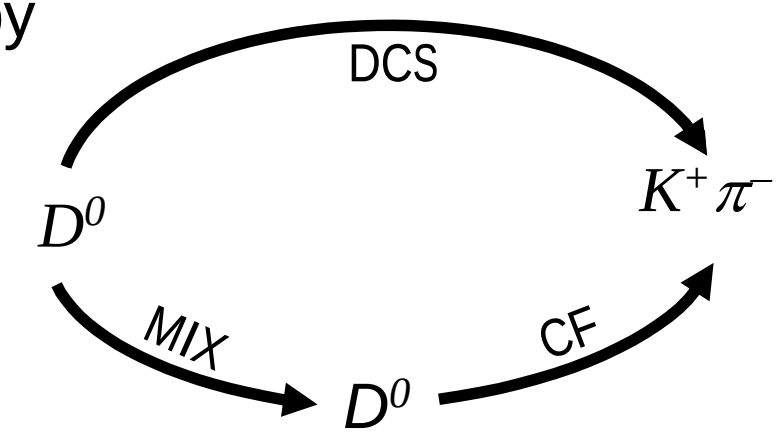


Relative rate: 0.005% (for x=0.01)

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

Discriminate DCS and mixing by their different time evolution

Also have interference effect:



Time evolution:

$$\frac{\Gamma_{WS}(t)}{e^{-t/\tau}} \propto R_D + \sqrt{R_D}y'\left(\frac{t}{\tau}\right) + \left(\frac{x'^2 + y'^2}{4}\right)\left(\frac{t}{\tau}\right)^2$$

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

and δ is the phase difference between DCS and CF decays.

Event Selection

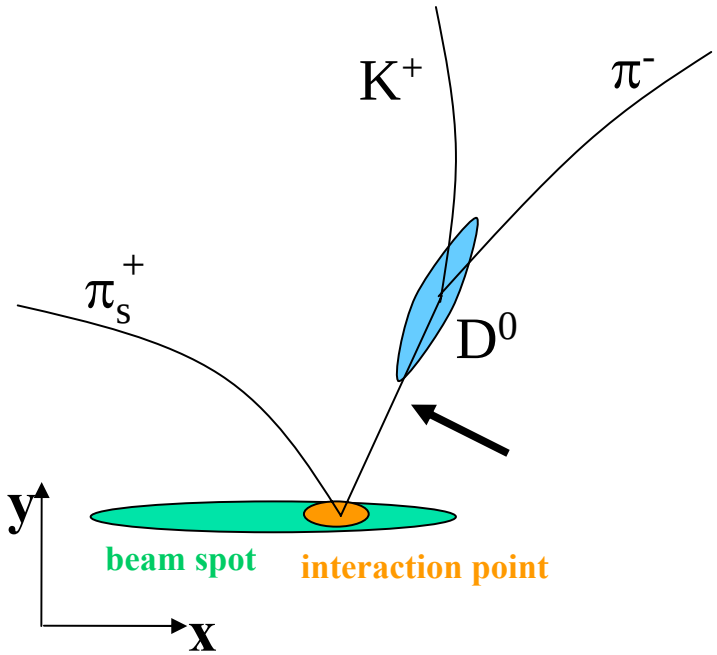
D^0 selection:

- 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
- $0.14 < \Delta m < 0.16$ GeV/c^2

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

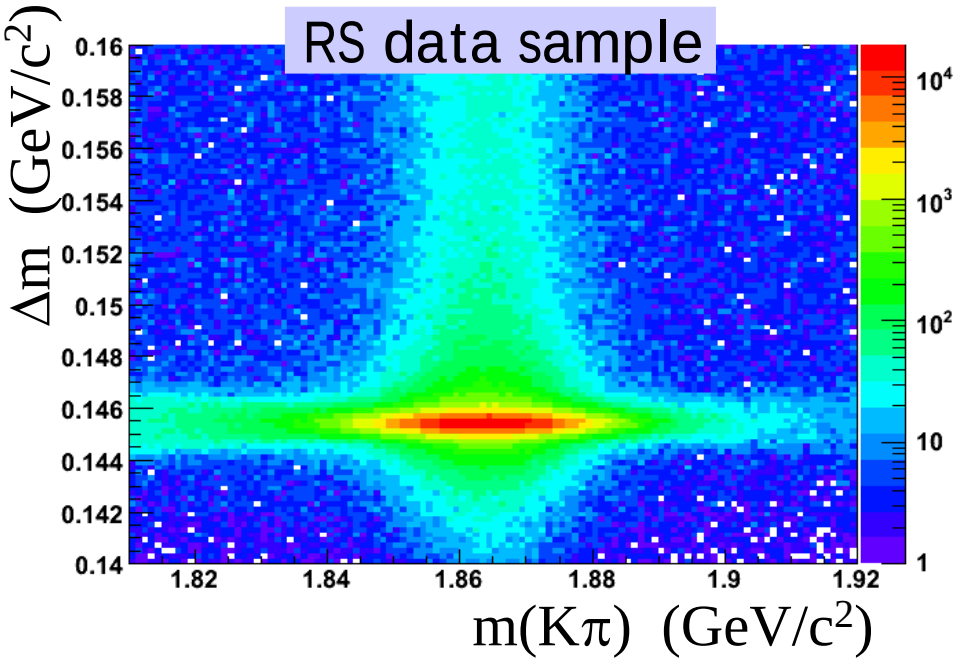


Vertexing: (Also greatly improves t resolution)

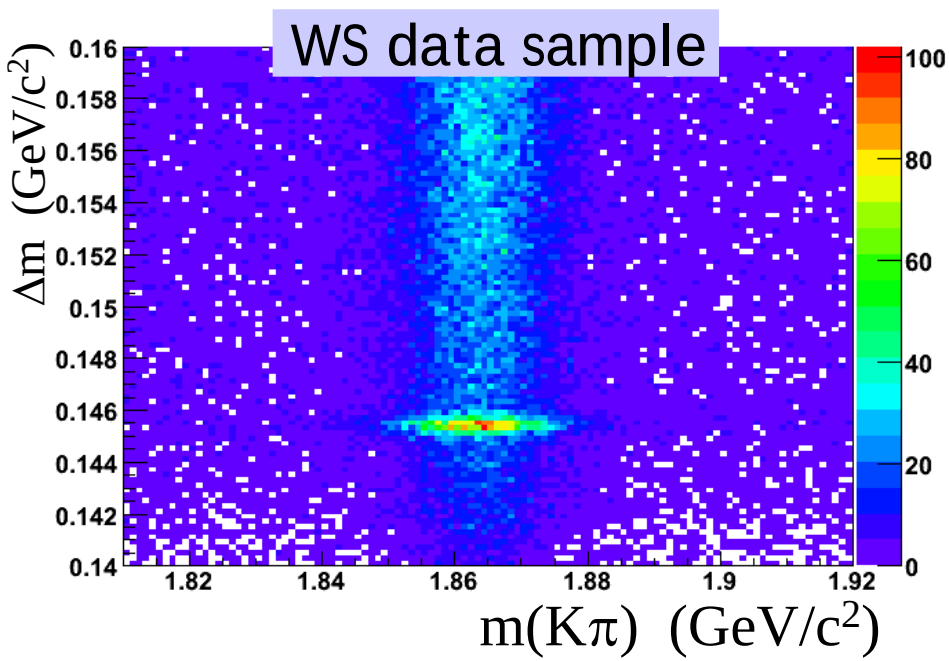
- D^0 and π_s constrained to luminous region
- Fit probability > 0.1%
- Reconstructed decay time, t: $-2 < t < 4$ ps
- Estimated decay time error, $\delta t < 0.5$ ps

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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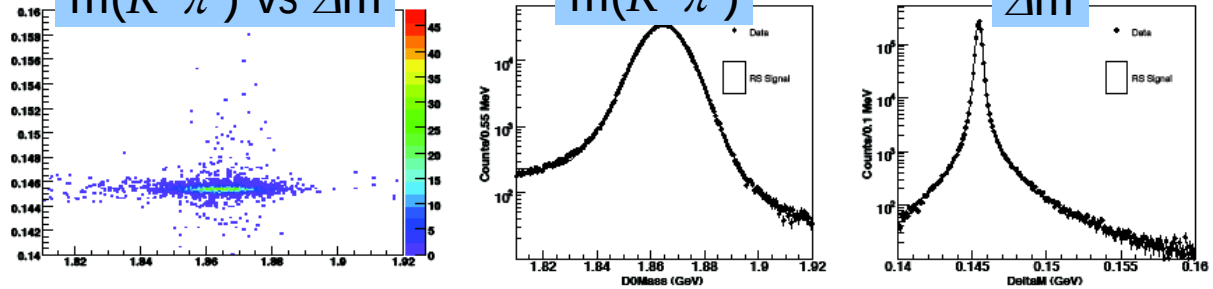
Signal and Background Components

m($K^+\pi^-$) vs Δm | m($K^+\pi^-$) | Δm

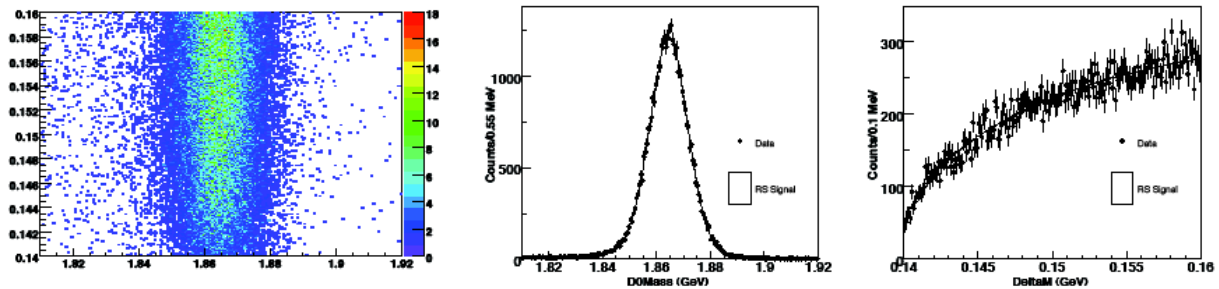
Signal: (MC)

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



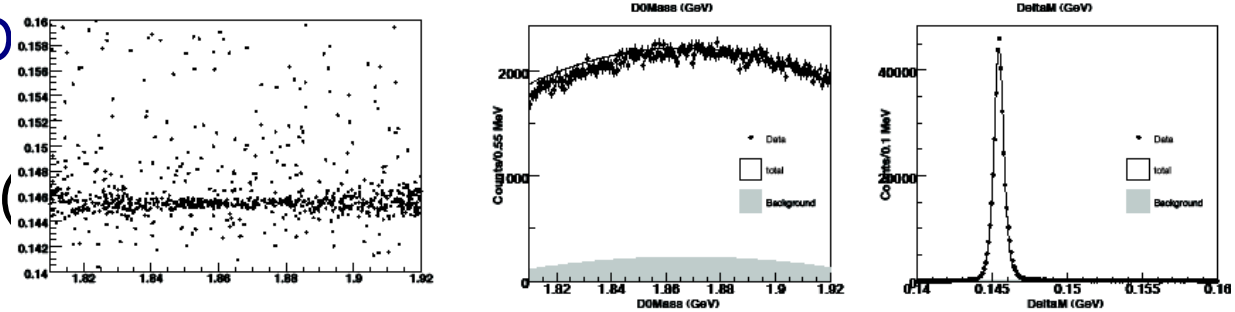
Random π_s: (MC)

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



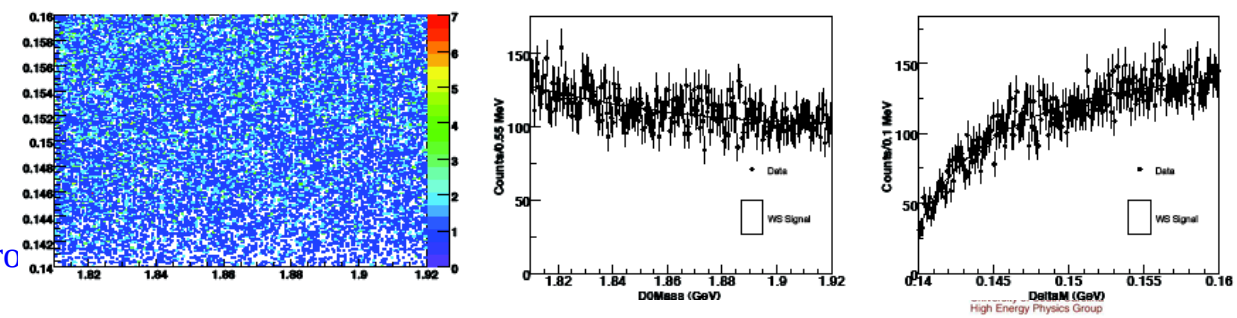
Misreconstructed D^0: (D

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

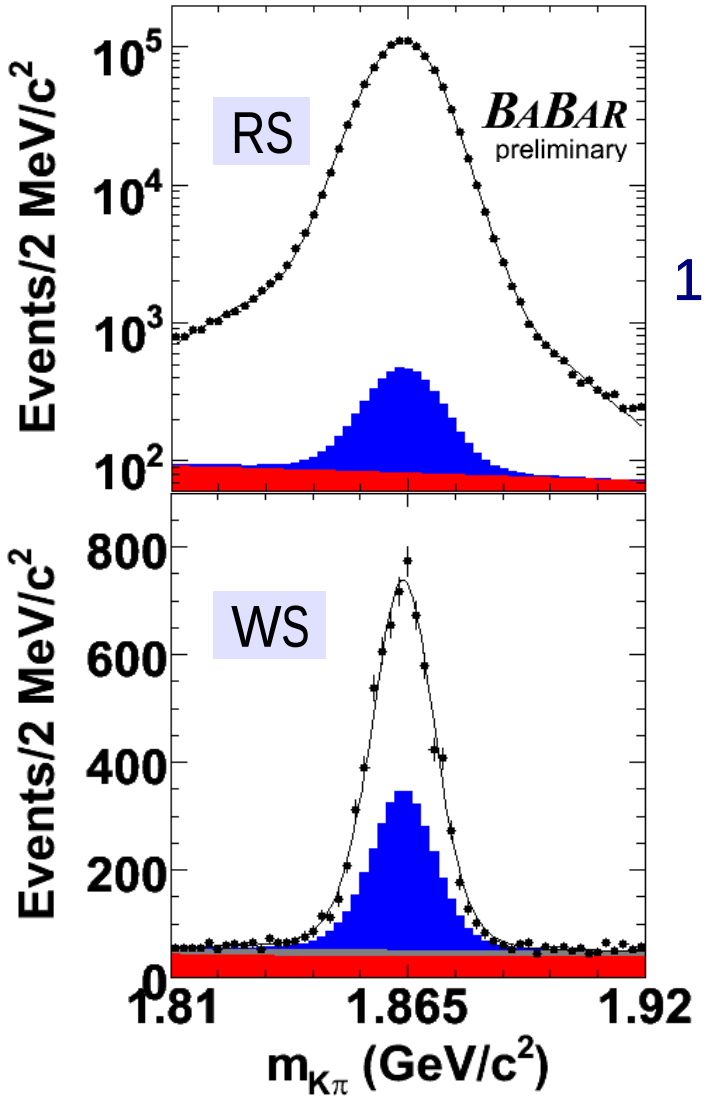


Combinatoric: (MC)

- Random tracks

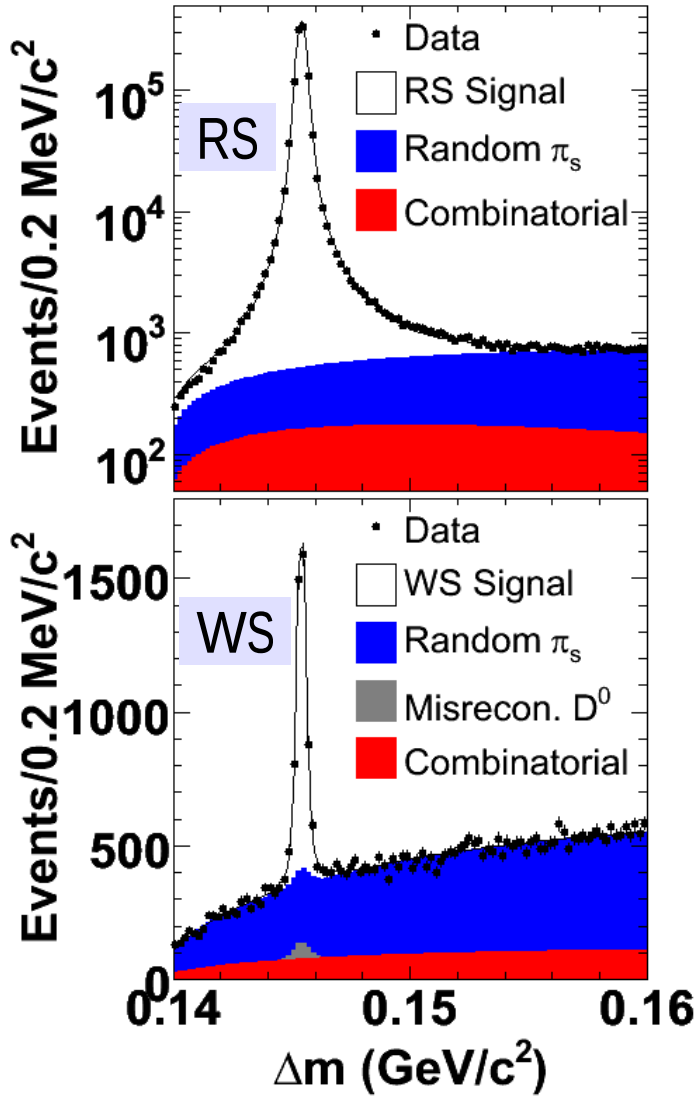


m(Kπ)-Δm Fit Results



RS signal:
1,141,500±1200
combinations

WS signal:
4,030±90
combinations



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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)

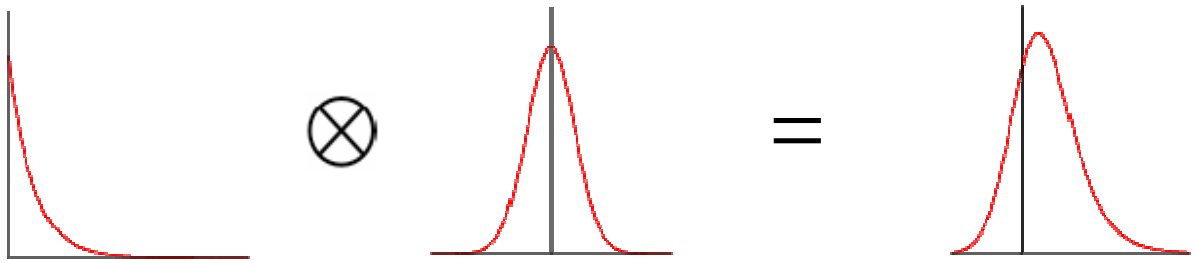
Fit WS decay time distribution:

- 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



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

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

RS Decay Time Fit

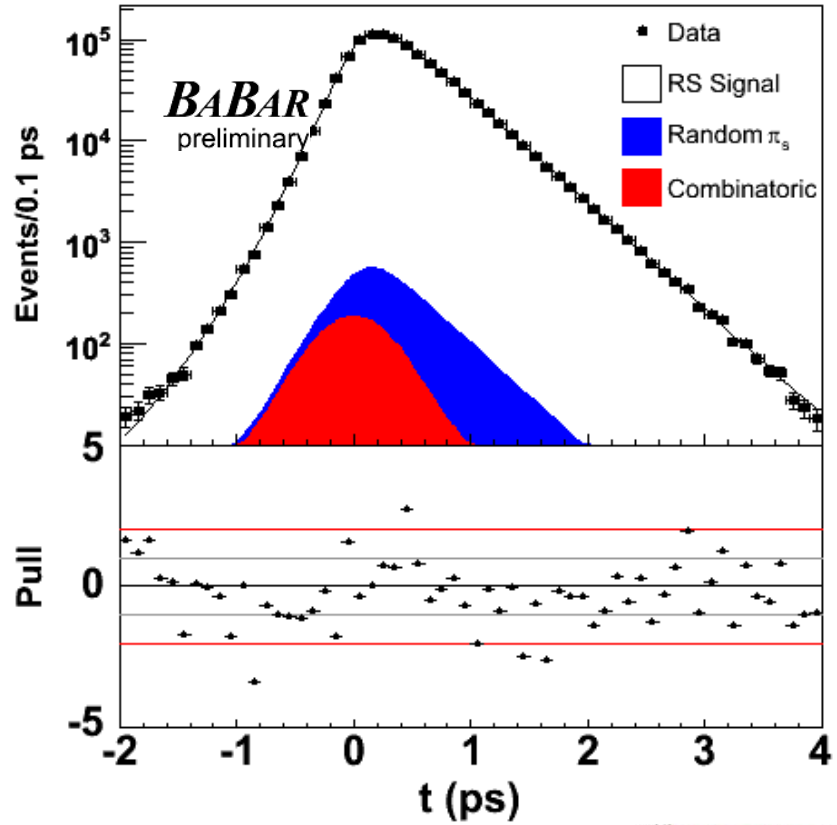
RS decay time, signal region

D^0 lifetime and resolution function fitted in RS sample

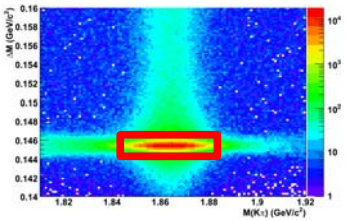
τ=(410.3±0.6(stat.)) fs

Consistent with PDG (410.1±1.5 fs)

Systematics dominated by resolution function



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



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)

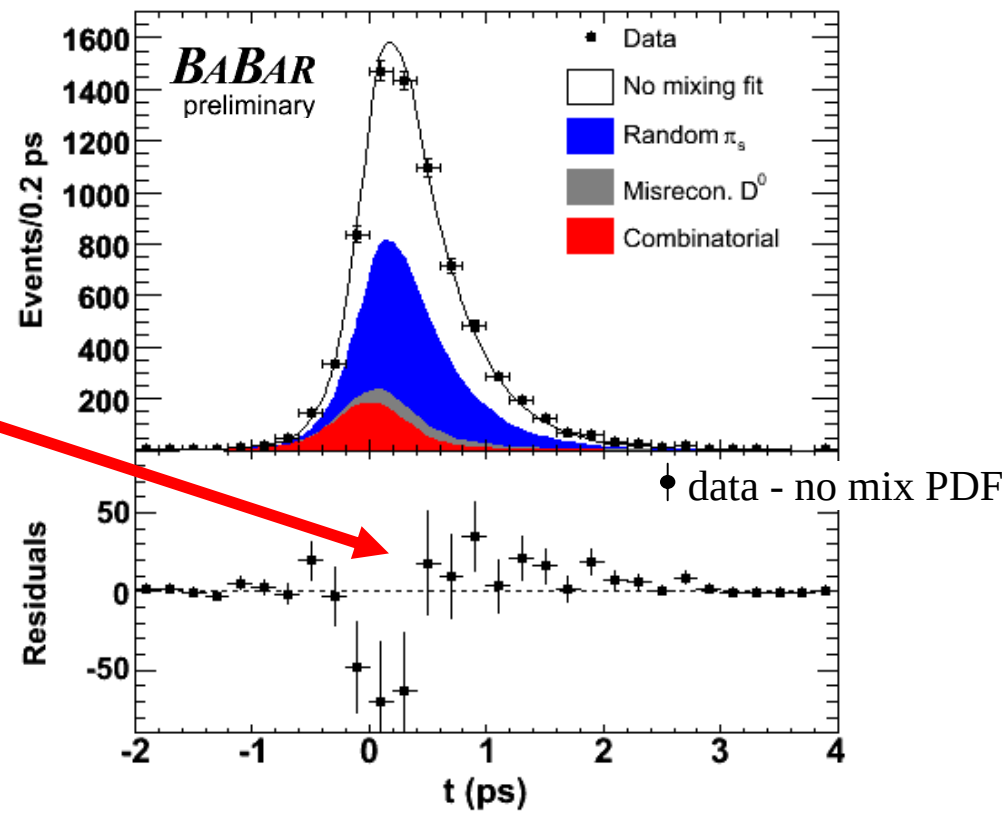
WS Fit with no Mixing

Fit results assuming no mixing:

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

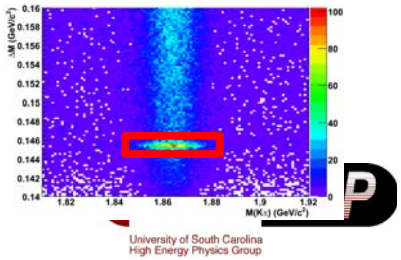
However, residuals in signal region are not good

WS decay time, signal region



Data and pdf projection are for signal region shown here:

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



WS Fit with Mixing

Fit results allowing mixing:

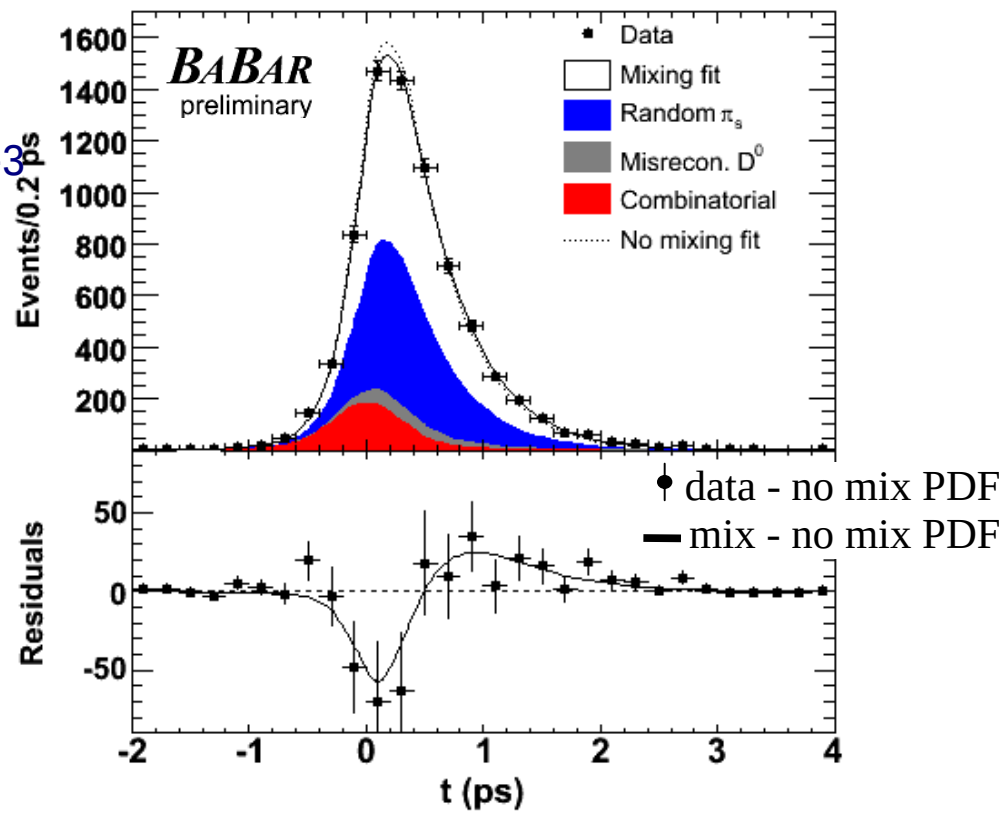
R_D: $(3.03 \pm 0.16 \pm 0.10) \times 10^{-3}$

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

WS decay time, signal region



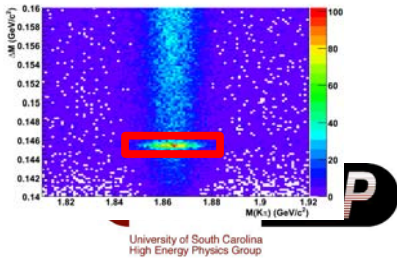
Fit with gives better description of data

How significant?

plot signal region:

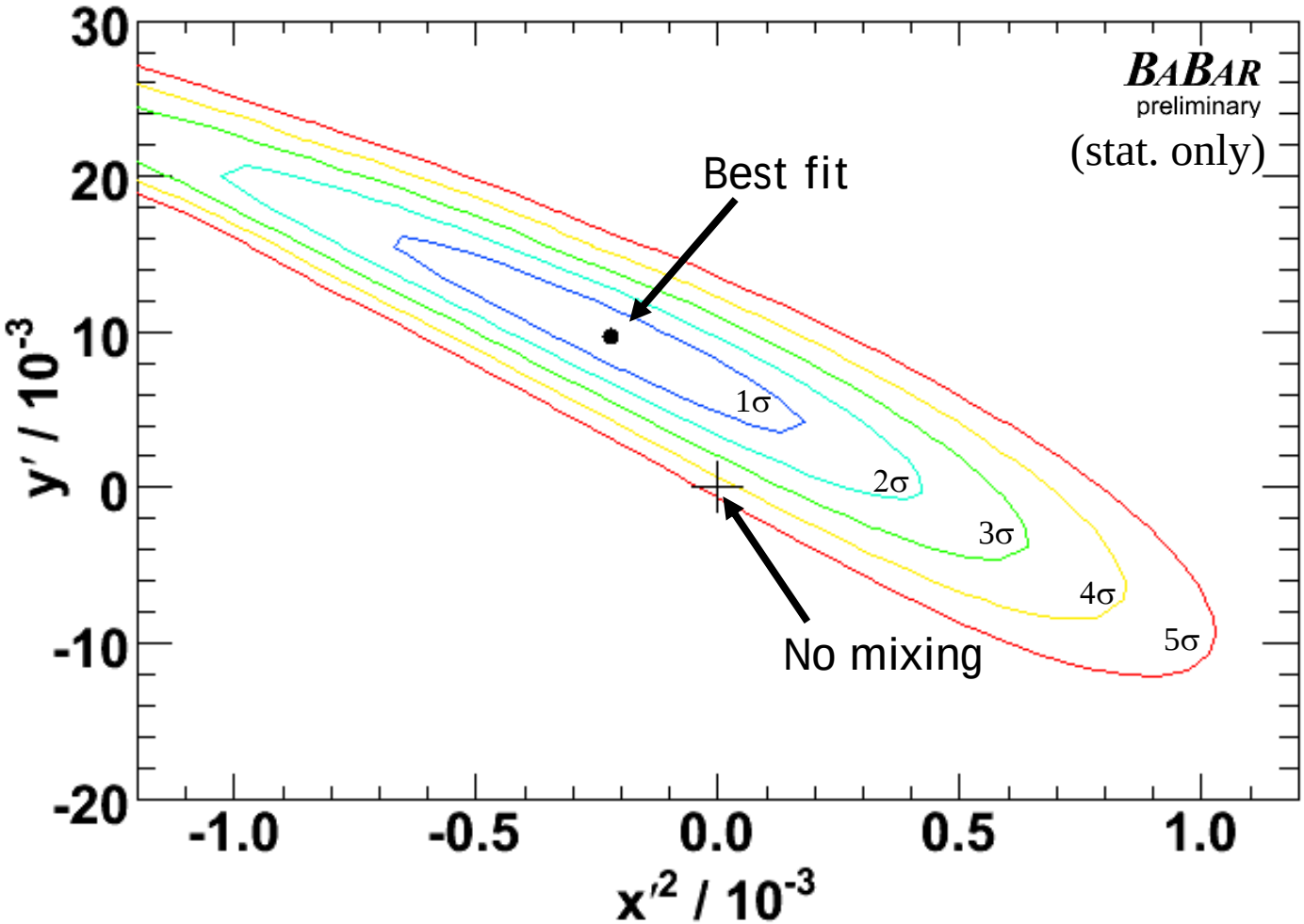
$1.843 < m < 1.883$ GeV/c^2

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



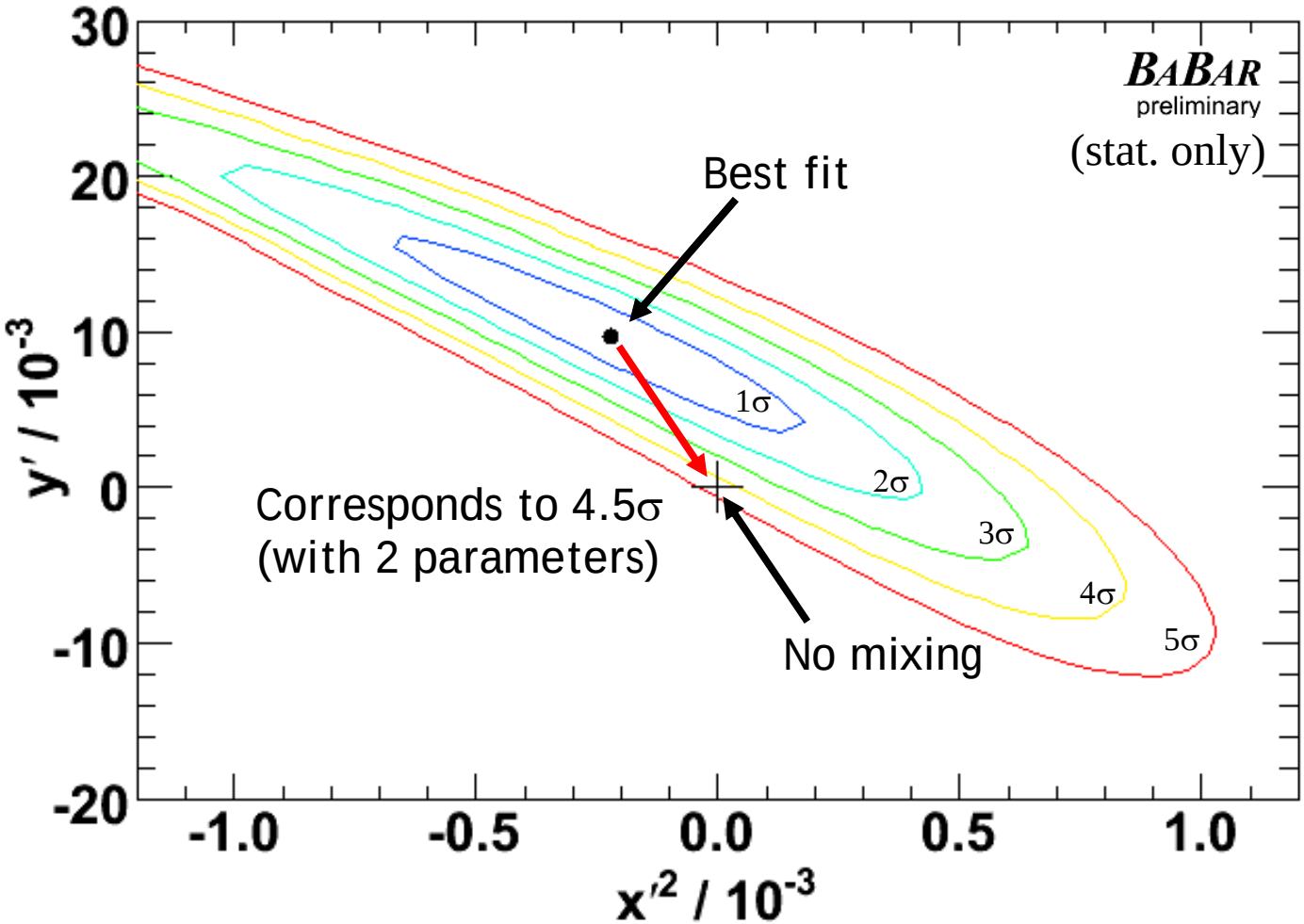
Signal Significance

Significance calculated from change in log likelihood:



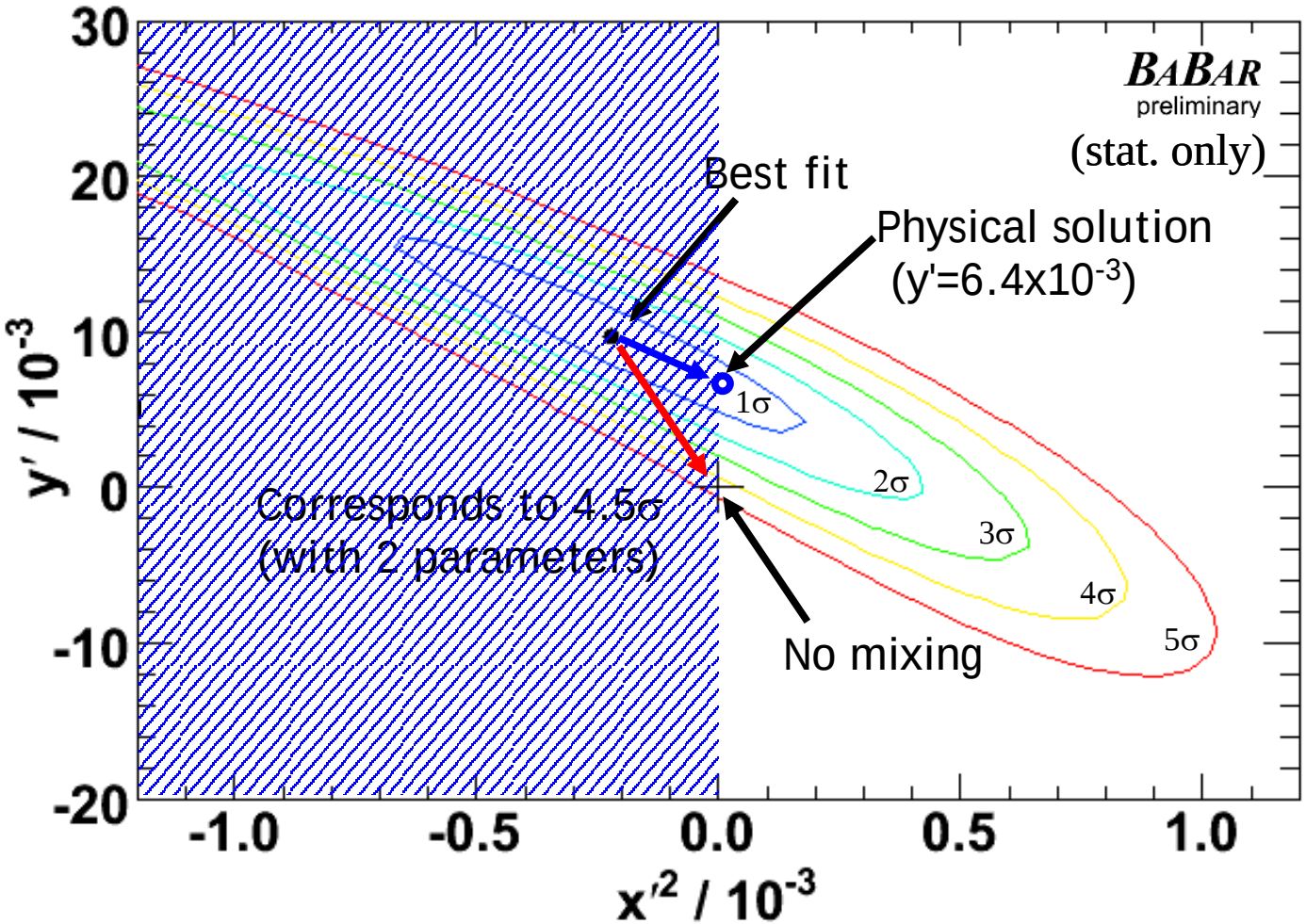
Signal Significance

Significance calculated from change in log likelihood:



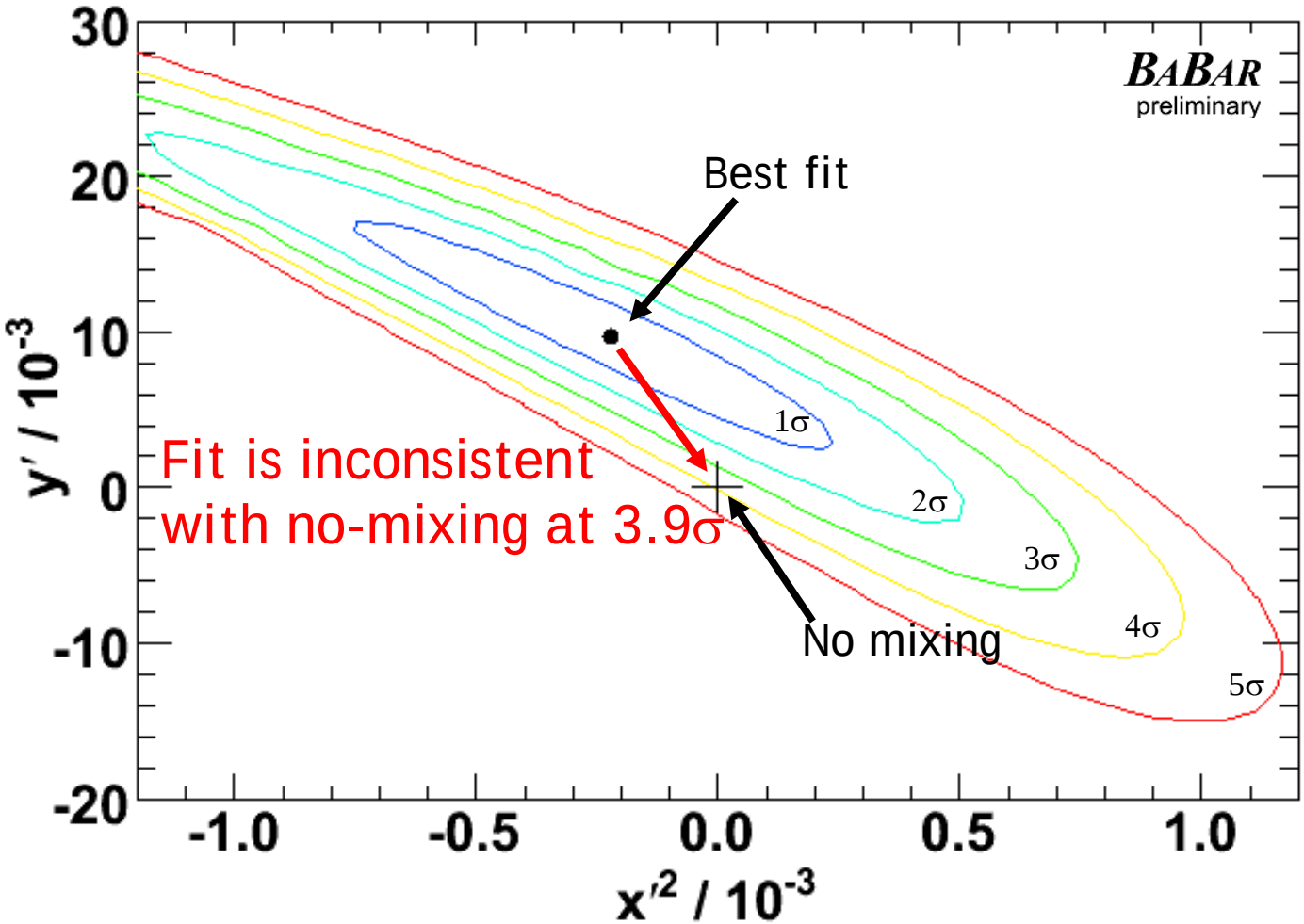
Signal Significance

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



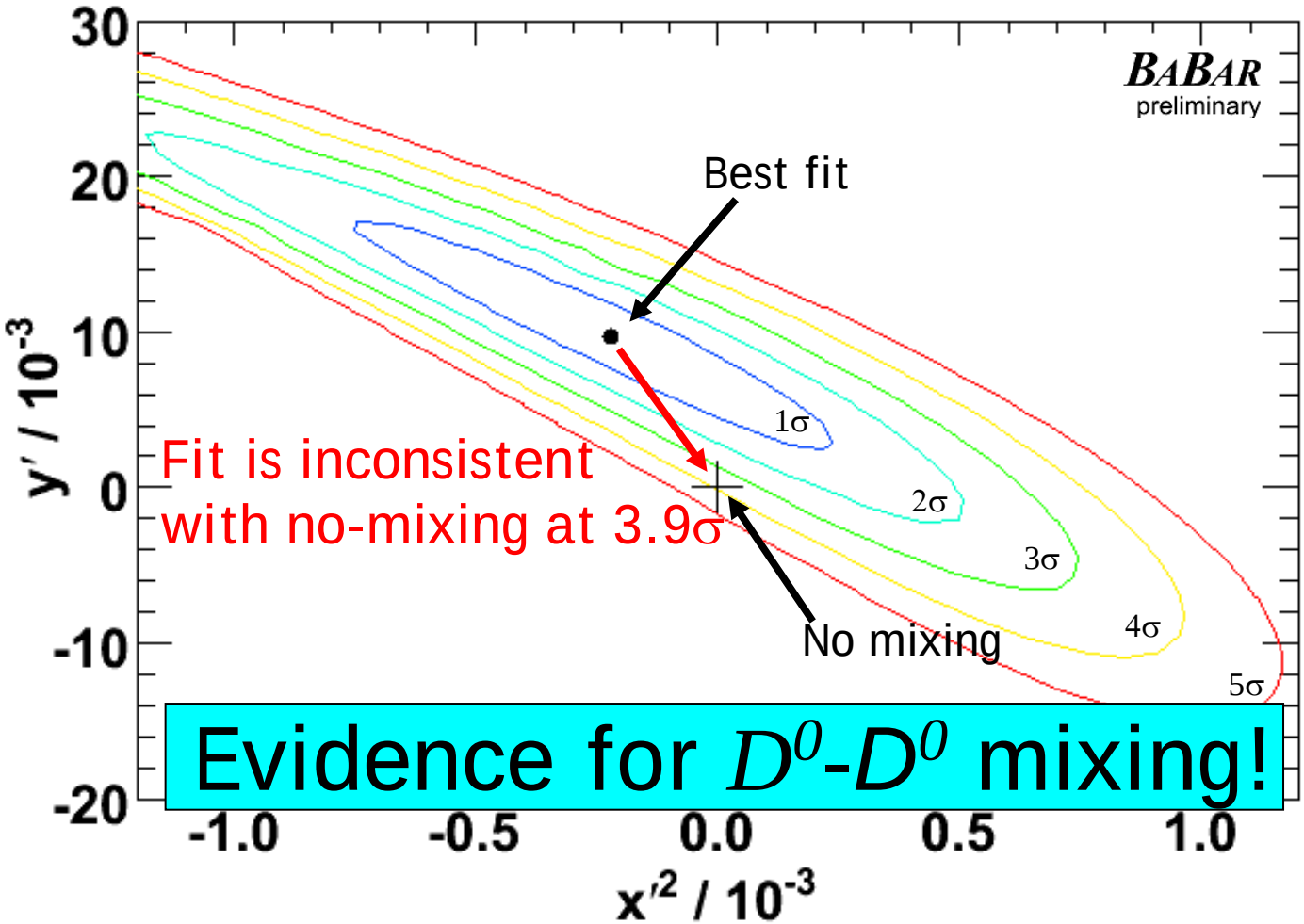
Signal Significance with Systematics

Including systematics decreases signal significance



Signal Significance with Systematics

Including systematics decreases signal significance



Evidence for D^0-D^0 mixing!

Validation Studies

Performed extensive checks of mixing signal:

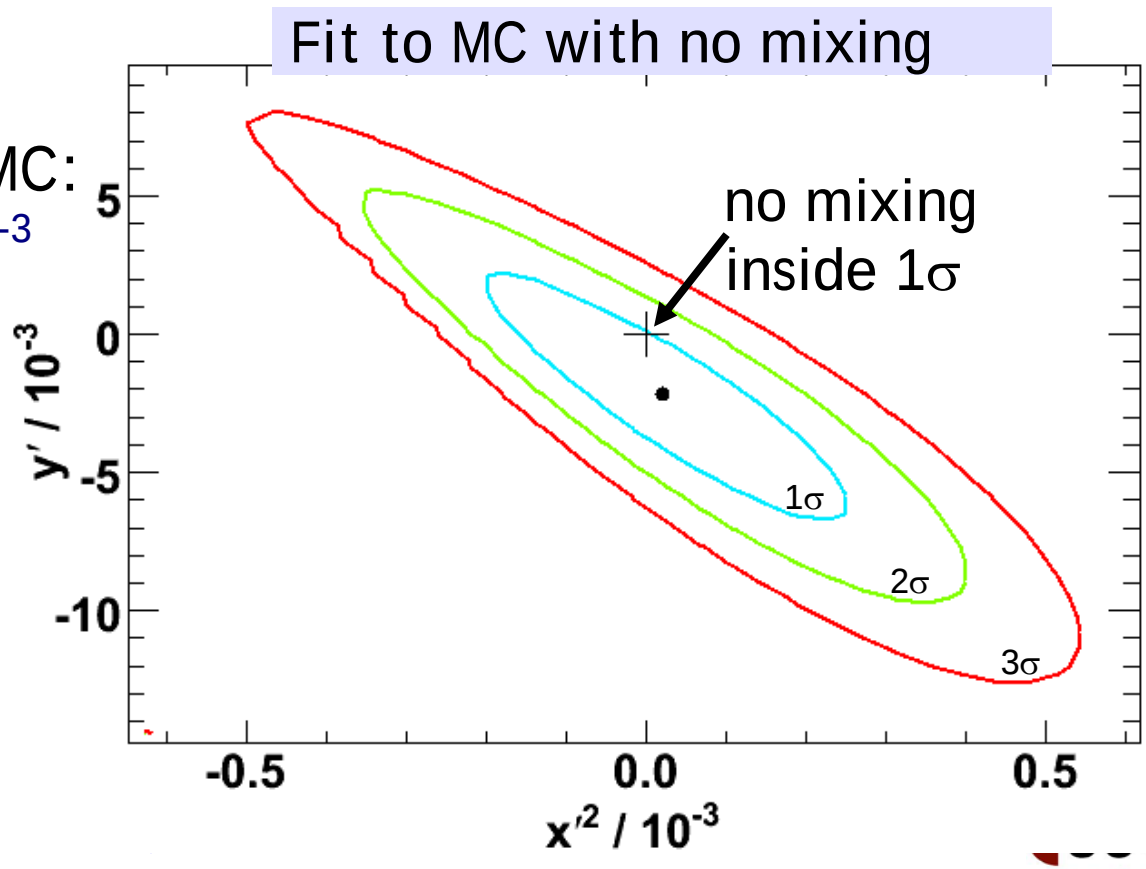
- ❖Could something fake signal?
- ❖Is significance estimated correctly?
- ❖Are mixing parameters unbiased?

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: Alternative Fit Strategy

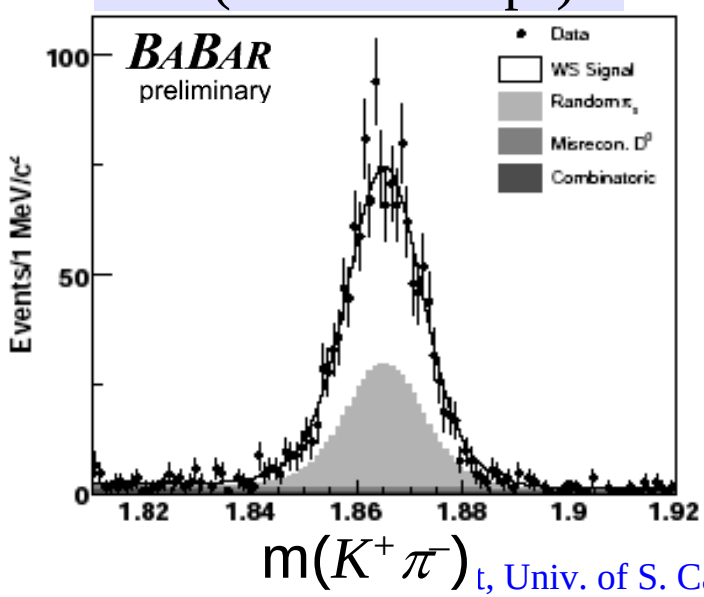
Fit m(Kπ) and Δm in bins of time:

- If no mixing, ratio of WS to RS signal should be constant
- No assumptions made on time-evolution of background
- Each time bin is fit independently

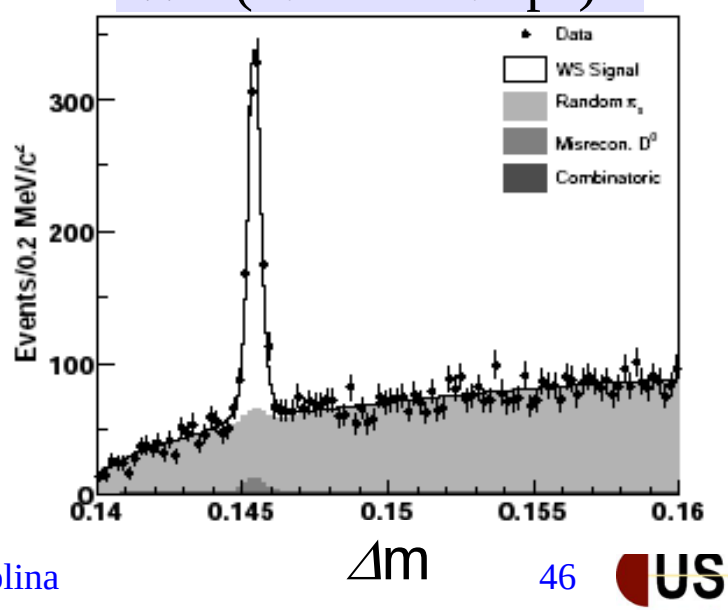
Time bins:

$-2 < t < 0$ psec
$0 < t < 0.2$ psec
$0.2 < t < 0.4$ psec
$0.4 < t < 0.75$ psec
$0.75 < t < 2.5$ psec

WS (0.75<t<2.5 ps)

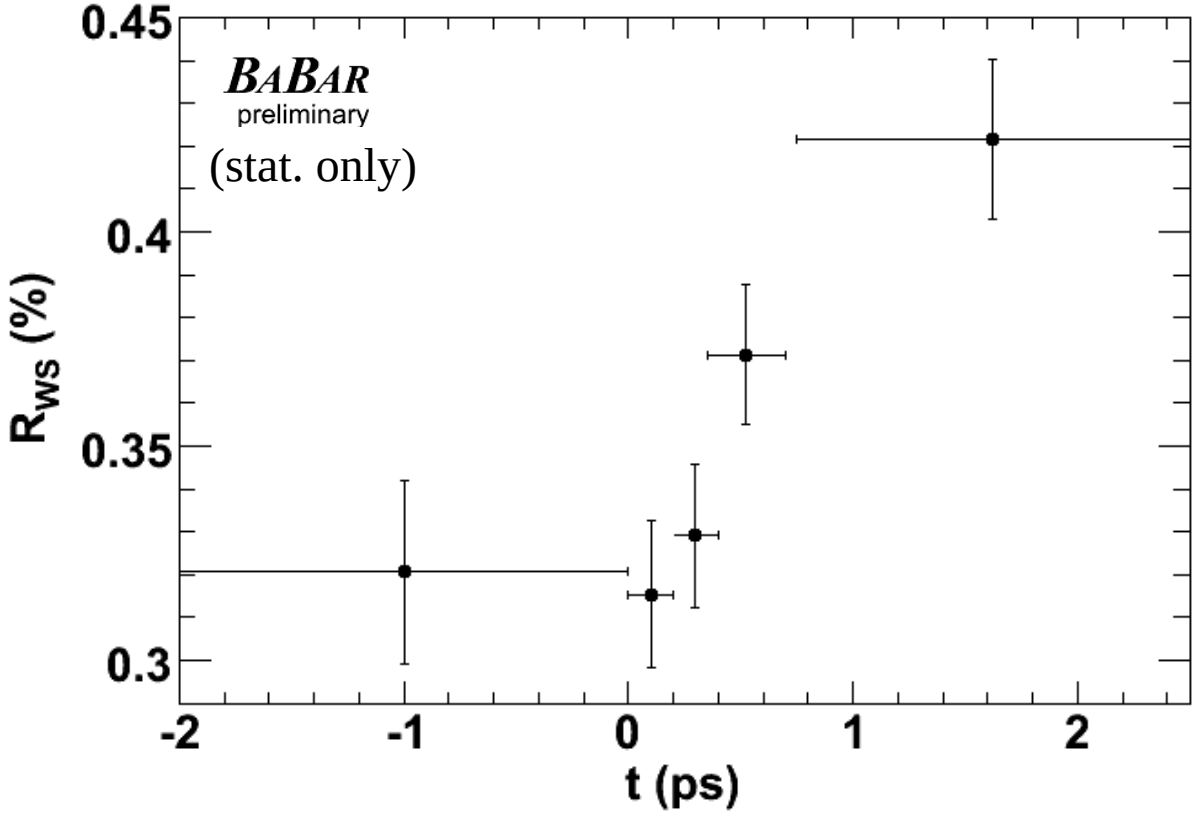


WS (0.75<t<2.5 ps)



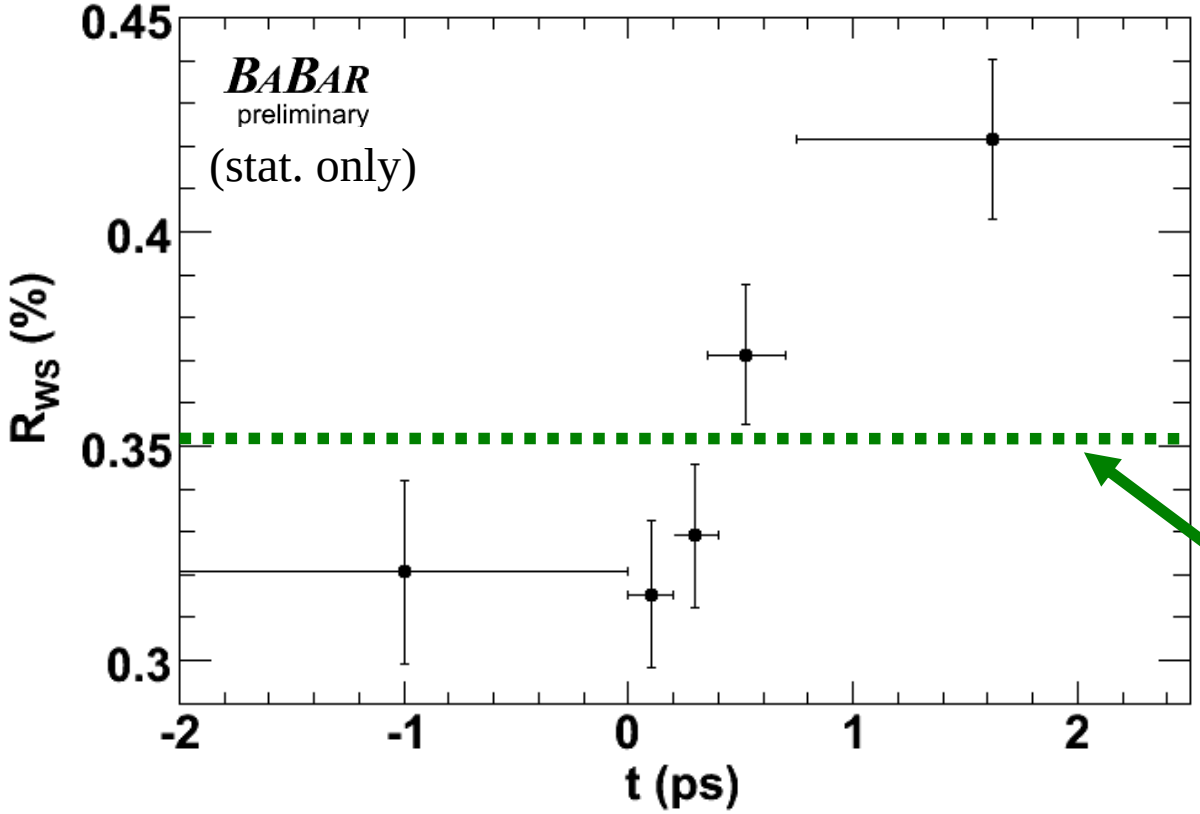
Validation: Alternative Fit Strategy

Rate of WS events clearly increase with time:



Validation: Alternative Fit Strategy

Rate of WS events clearly increase with time:

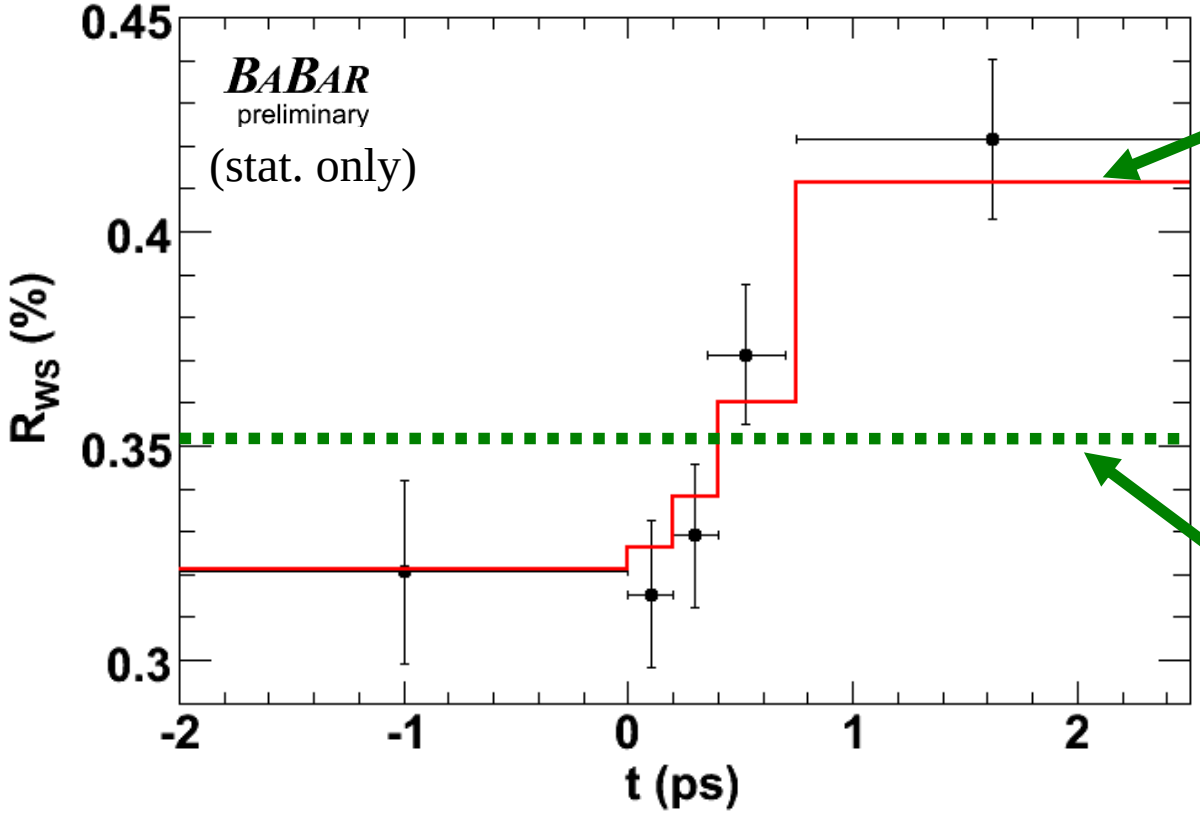


Inconsistent with no-mixing hypothesis

$\chi^2=24$

Validation: Alternative Fit Strategy

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

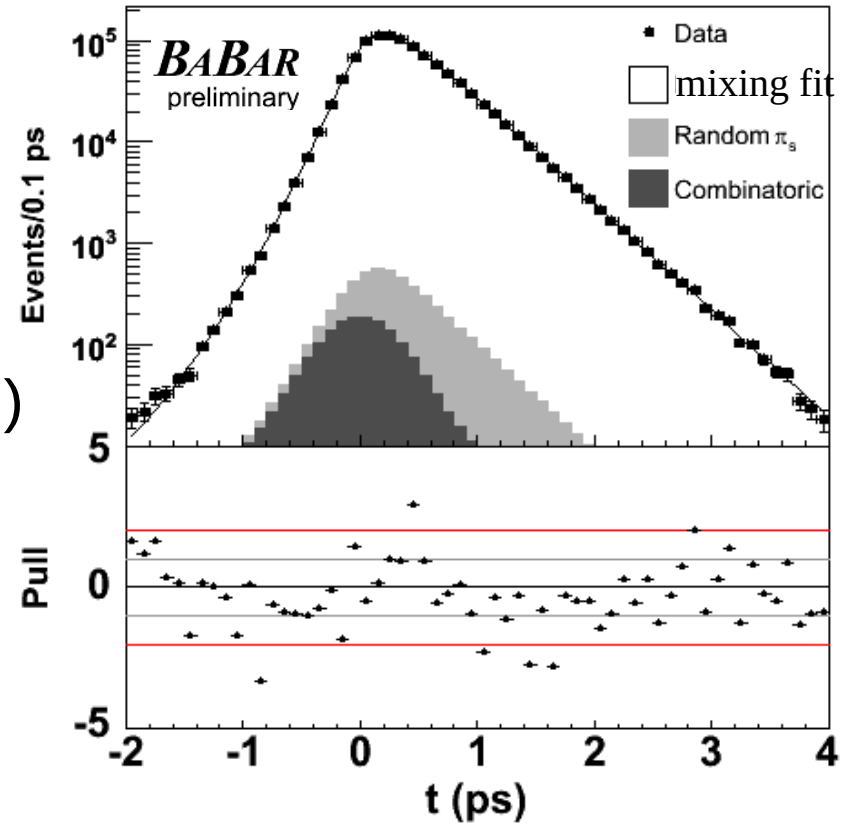
x'^2: $(-0.01 \pm 0.01) \times 10^{-3}$

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

(w.r.t. no mixing)

D^0 decay time distribution is described properly

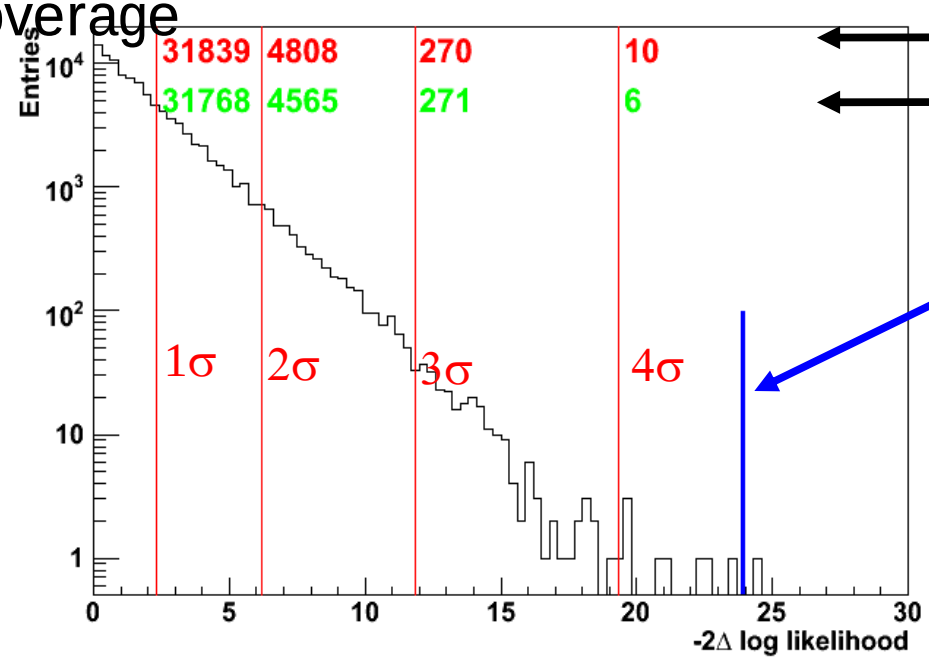
RS decay time, signal region



Validation: Coverage of -2ΔLog$\mathscr{L}$

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

Generated >100000 toys without mixing to test gives correct frequentist coverage



#toys to the right of line

#toys expected

observed in data

Expect 0.6 events with find 1 event

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

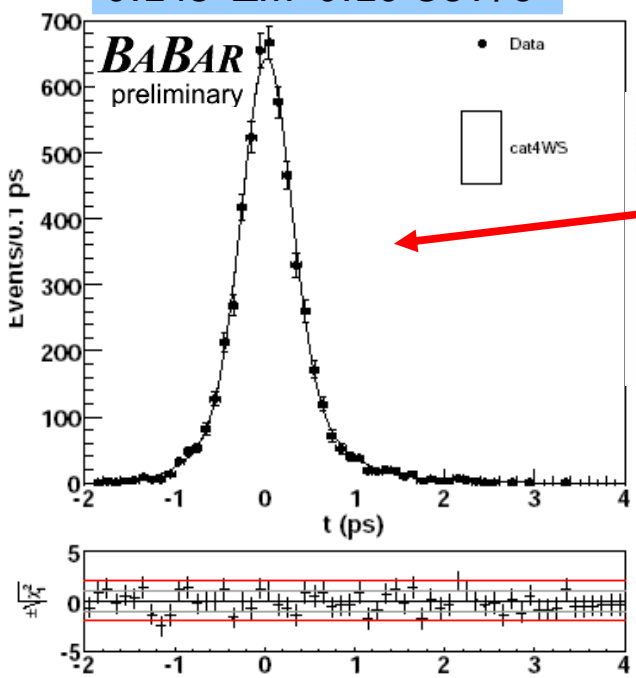
x'^2-y' correlation also present in systematics

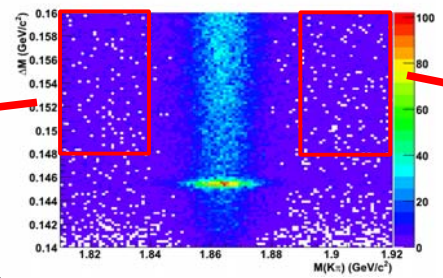
Effectively the (x'^2,y') contours increase by ~15%

Systematic: Combinatorial Decay Time

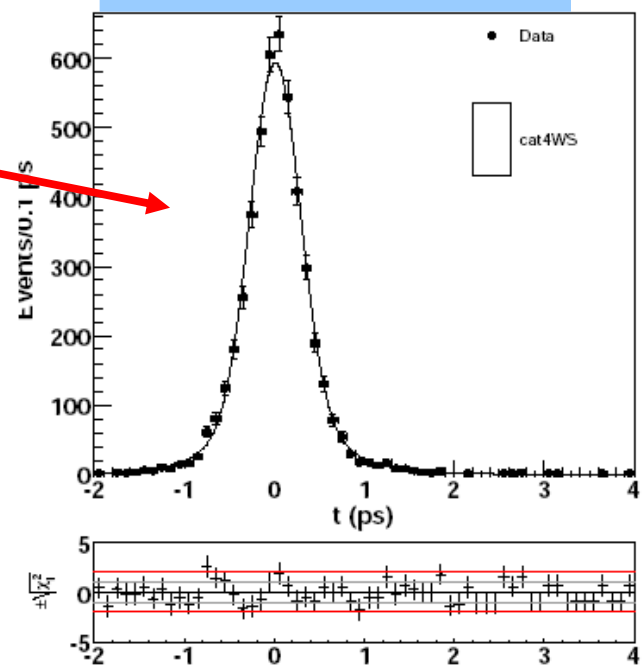
Decay time in combinatorial bkgd not independent of m(Kπ)
Fix PDF parameters to fits in different background sidebands:

1.81<m<1.84 GeV/c^2
0.148<Δm<0.16 GeV/c^2





1.883<m<1.92 GeV/c^2
0.148<Δm<0.16 GeV/c^2



Systematic variation:

y' -0.3σ
x'^{2} +0.2σ

Systematic: Decay Time Resolution

Decay time resolution function in data has non-zero mean

Core Gaussian shifted 3.6±0.6fs

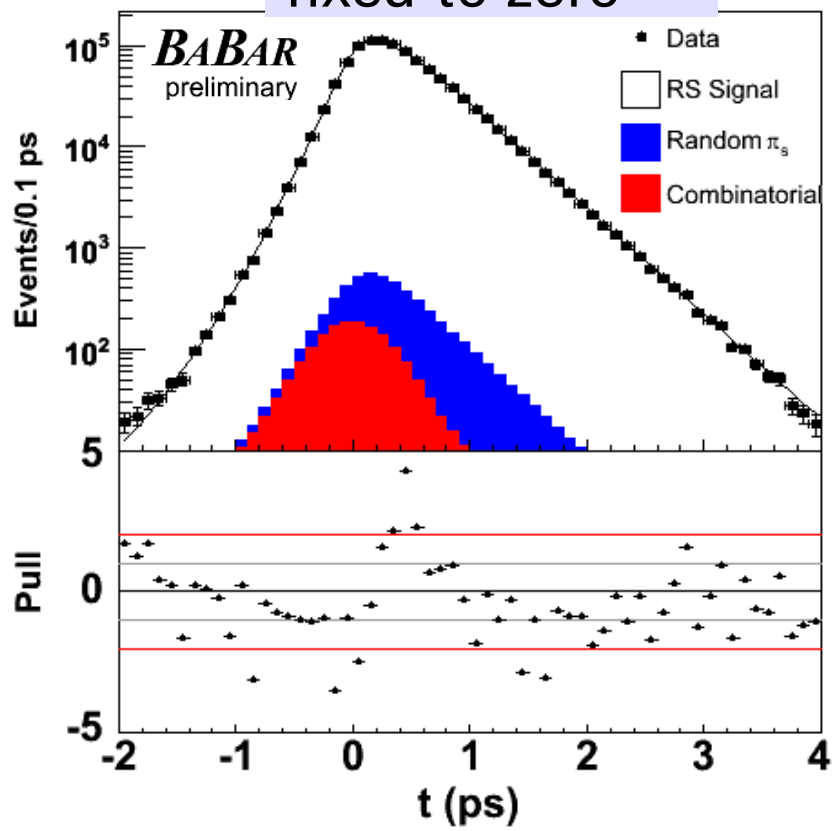
Effect is not seen in MC
- probably due to misalignment

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



Allowing for CP Violation

CP violation could introduce different time dependence for D^0 (+) and D^0 (-):

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

Three possible types of CP violation:

- Direct CP violation in DCS decay
- CP violation in mixing
- CP violation in interference between mixing and decay

Simpler to fit D^0 (+) and D^0 (-) separately:

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

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

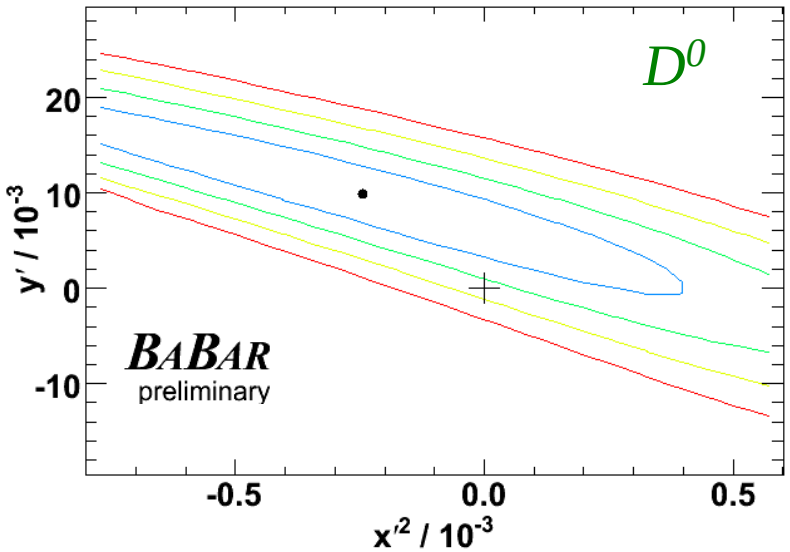
CPV Allowed Contours

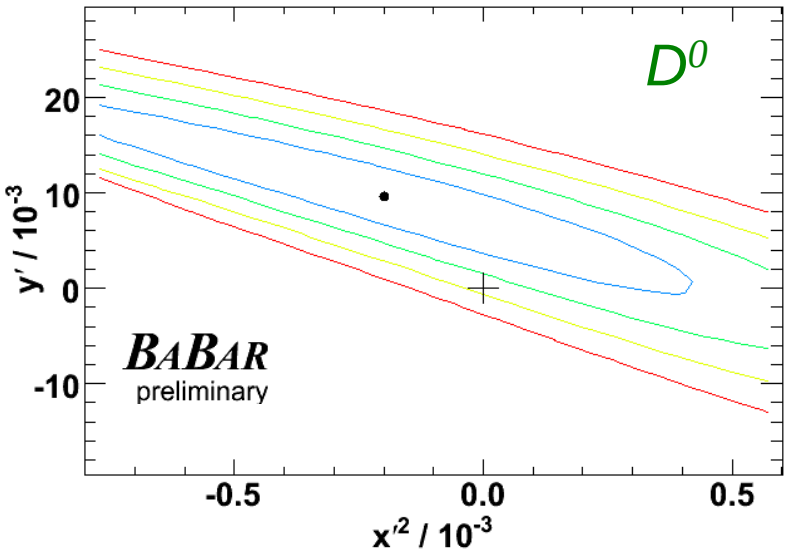
Results of fitting D^0 and D^0 separately:

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

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



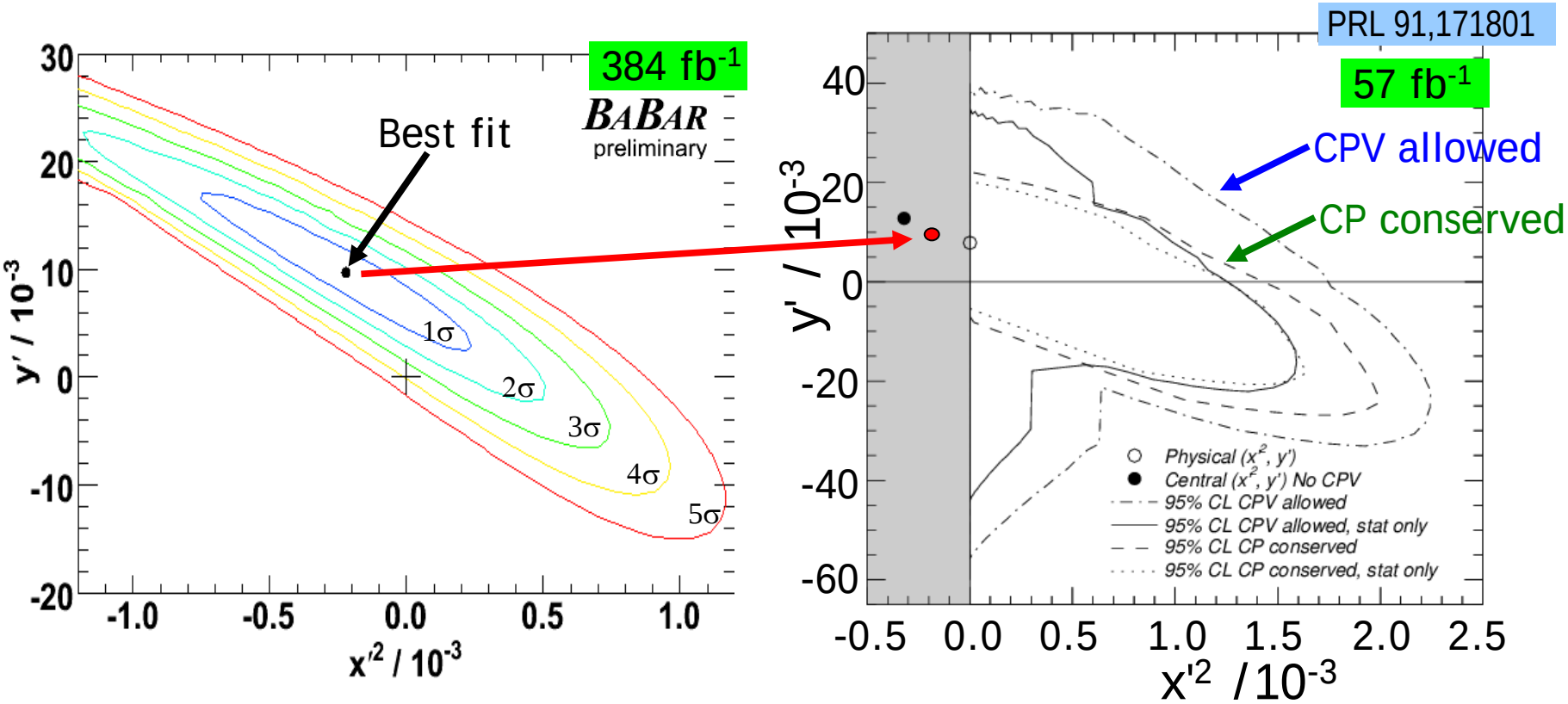


No evidence for CP violation found

Comparisons with other Charm Mixing Results

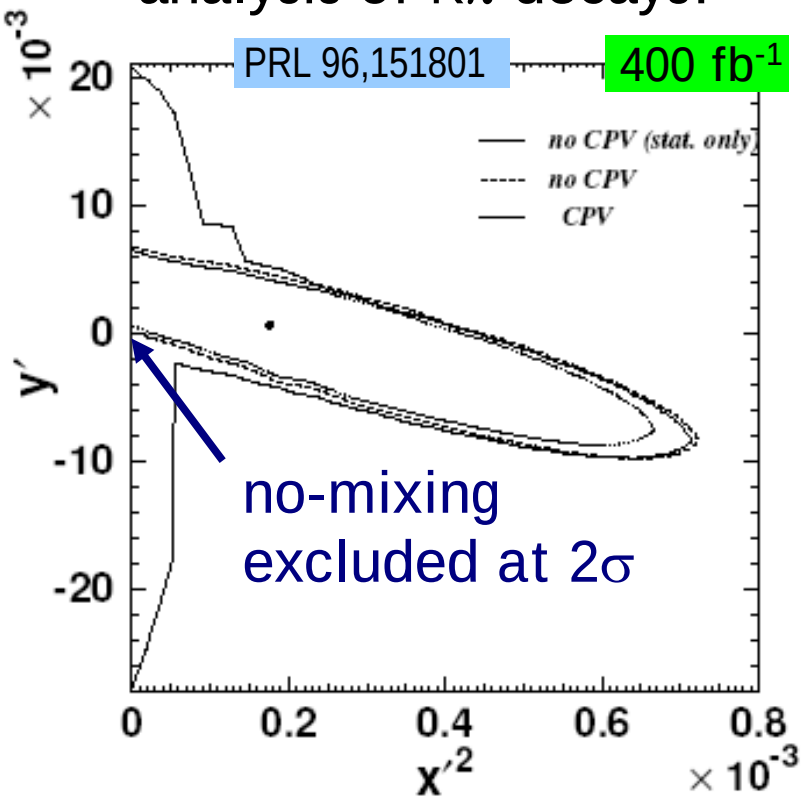
Previous BaBar Kπ Analysis

Fully consistent with previous BaBar analysis:



Kπ Analysis from Belle

Last year Belle published analysis of Kπ decays:



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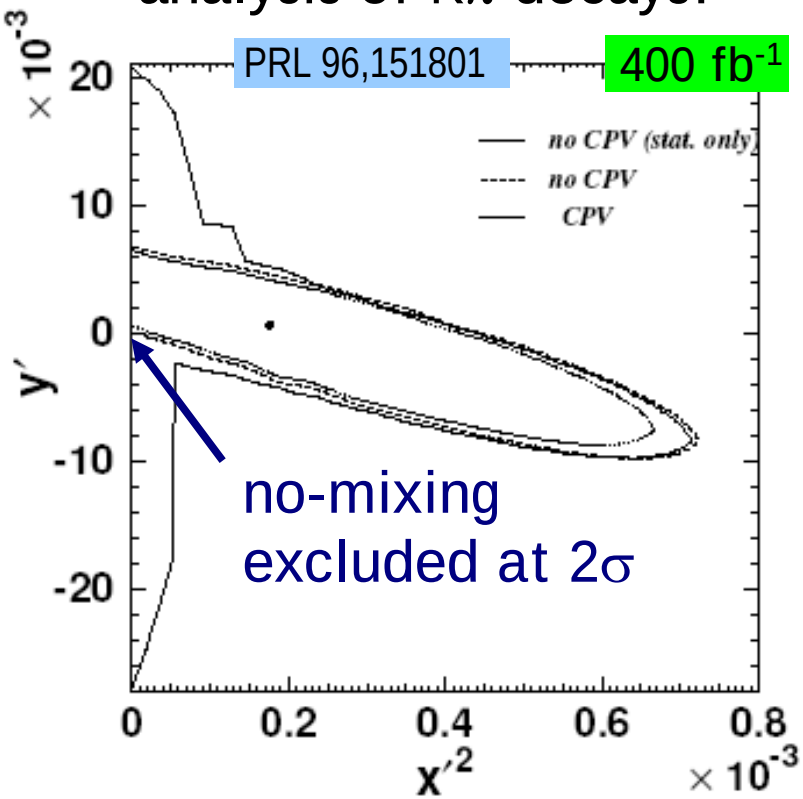
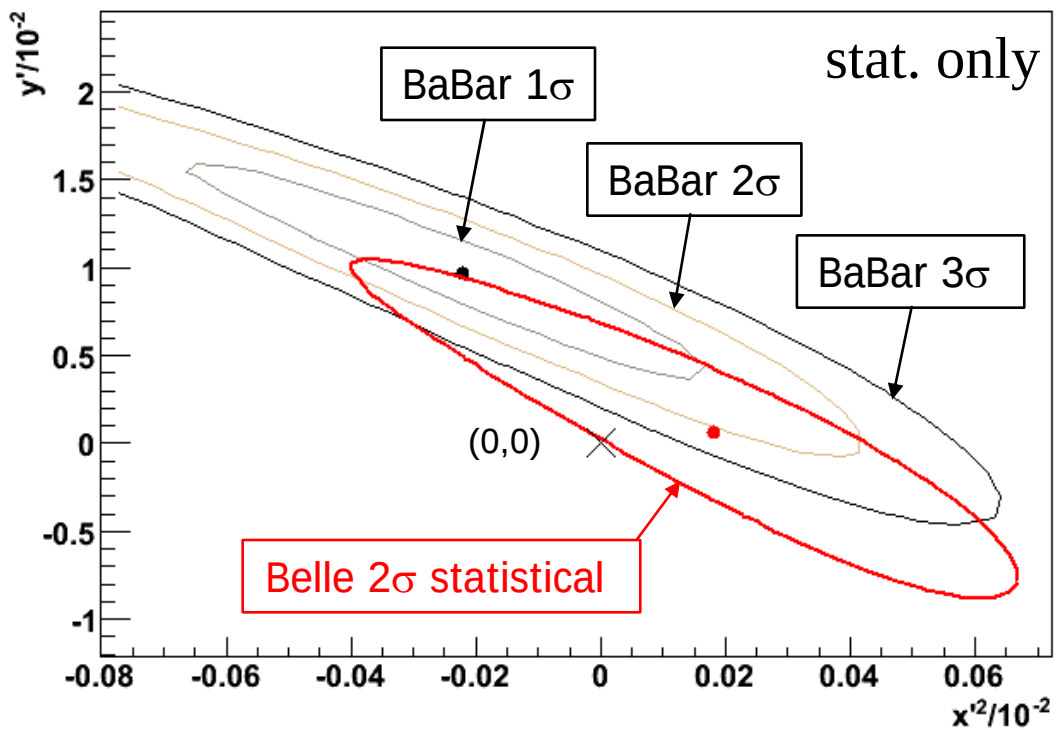


Results consistent within 2σ:



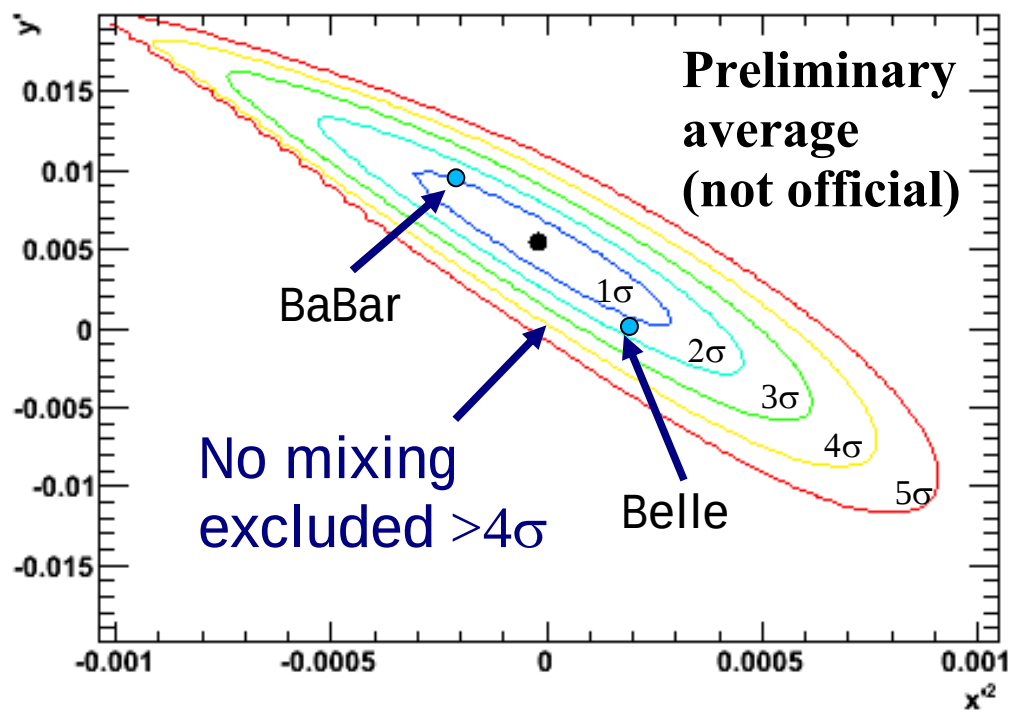
Average Kπ Mixing Results

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±0.13)x10^{-3}
x'^2: (-0.01±0.20)x10^{-3}
y': (5.1±3.2)x10^{-3}

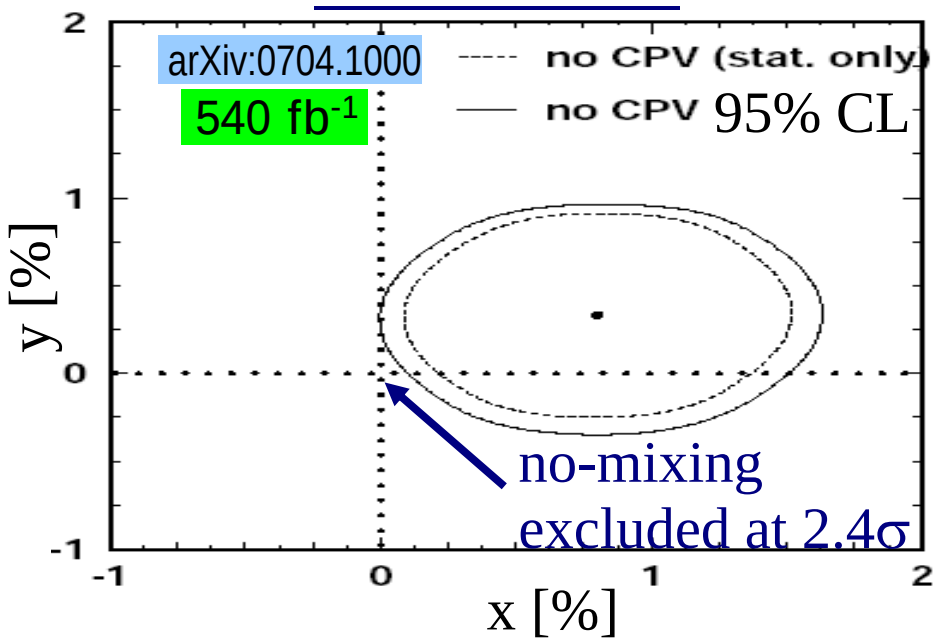


Belle Dalitz Analysis of $D^0 \to K_s \pi\pi$

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

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

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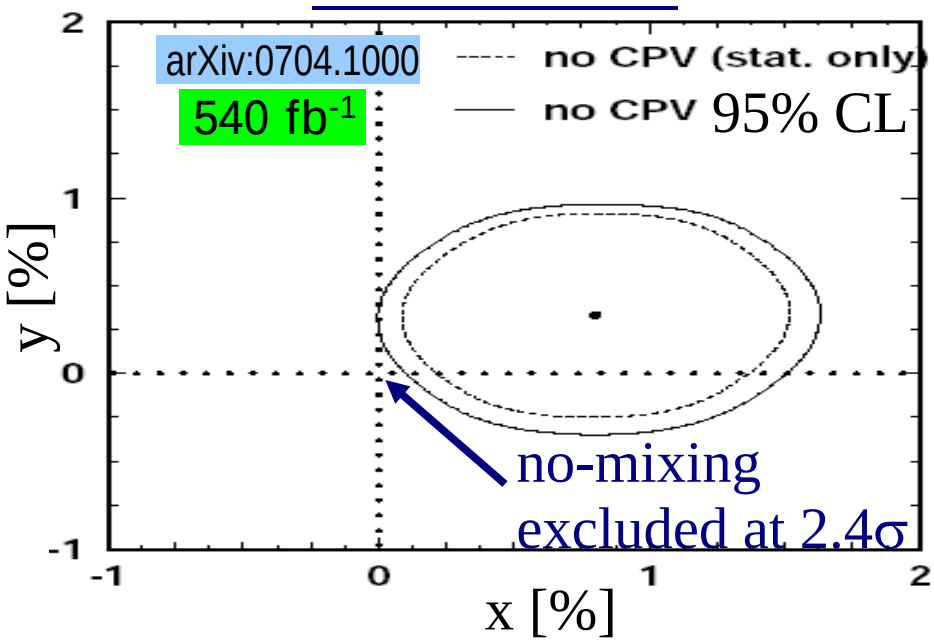
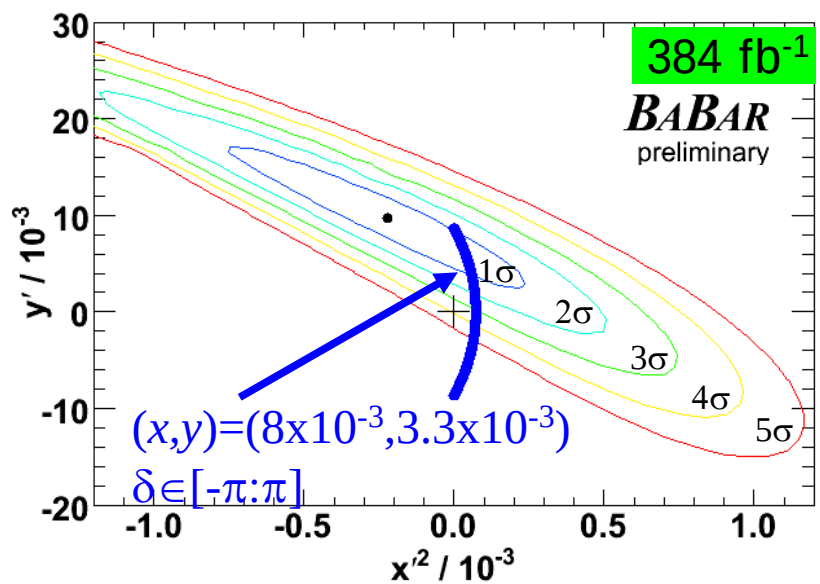
Belle result:



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

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

BaBar-Belle comparison:



Within 1σ for certain values of the phase δ

Belle Lifetime Ratio Measurement

Belle measure lifetime difference directly using CP eigenstates:

$$\tau_{K^-\pi^+}/\tau_{K^-K^+} - 1 = y_{CP}$$

(Belle actually use two CP-even eigenstates: $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$)

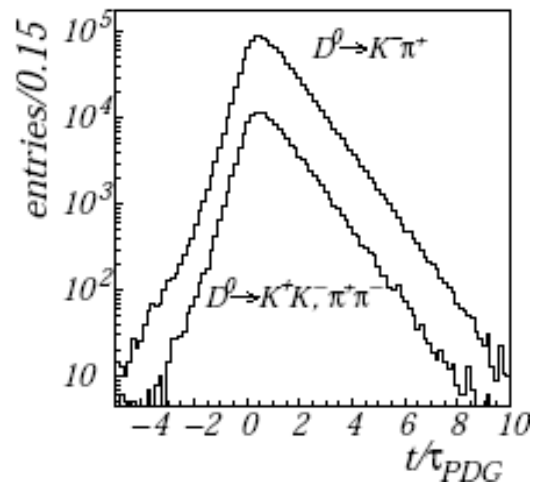
Belle result:

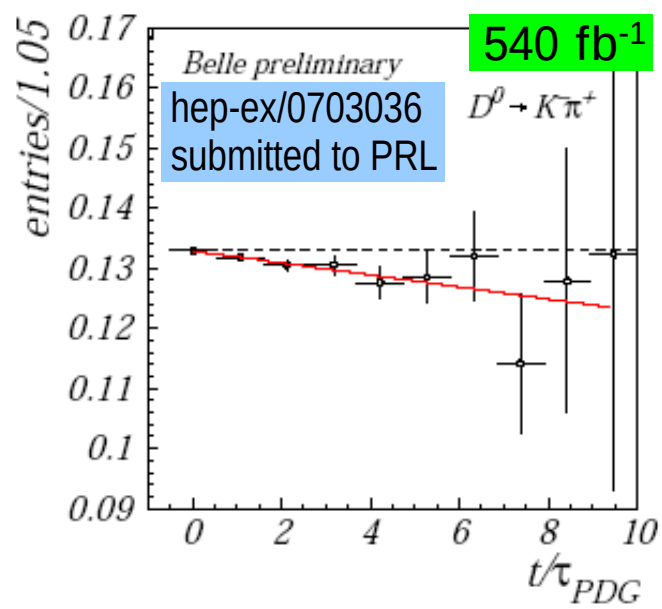
y_{CP}: (13.1±3.2±2.5)x10^{-3}

>3σ above zero
(4.1σ stat. only)

Also implies D^0 mixing!

Decay time distributions:

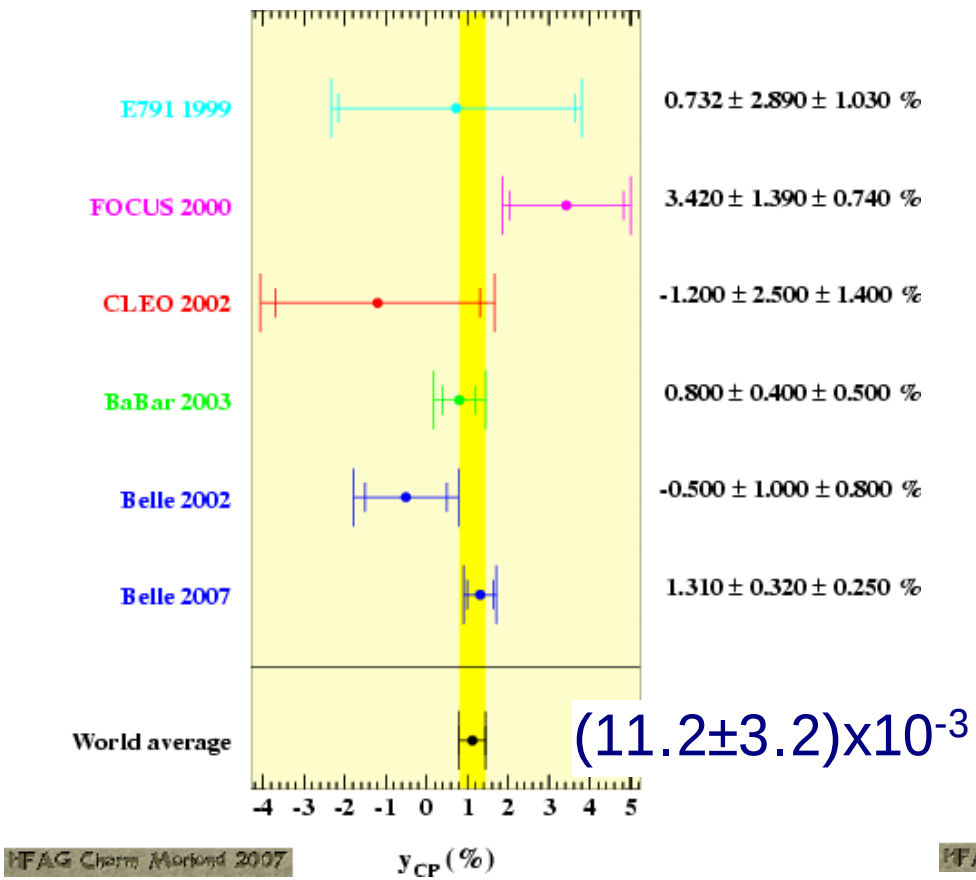




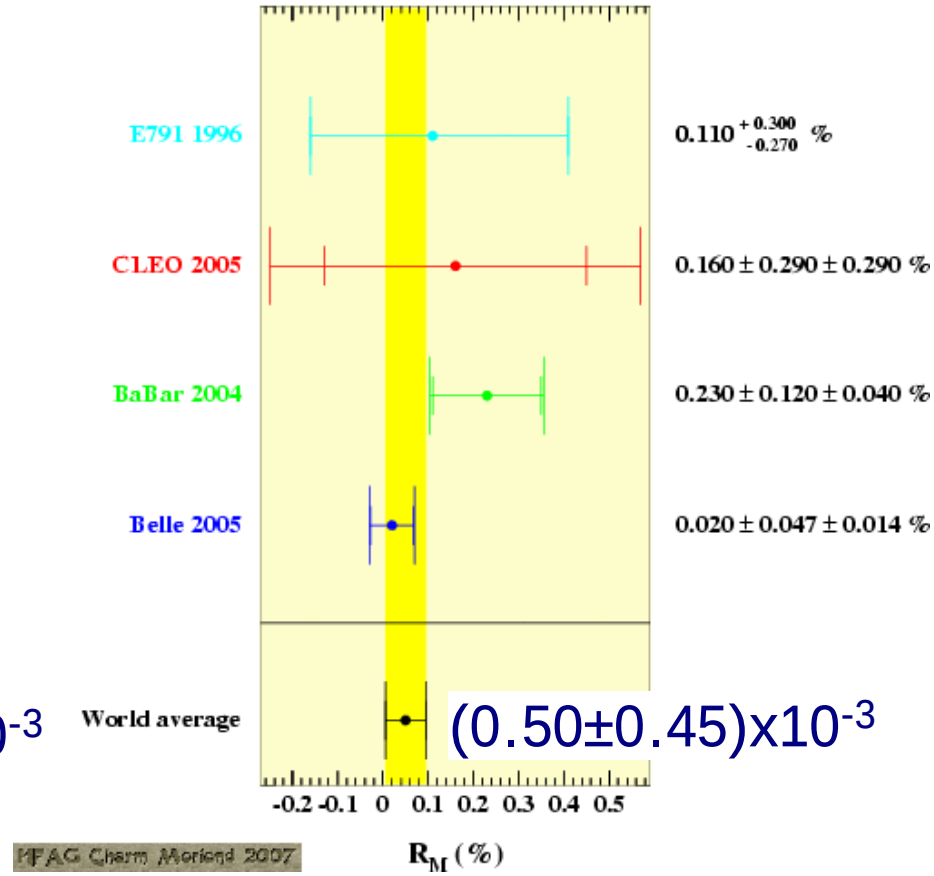
Additional Mixing Results

HFAG has first preliminary averages for some measurements:

(Semileptonic decays only)



$(11.2 \pm 3.2) \times 10^{-3}$



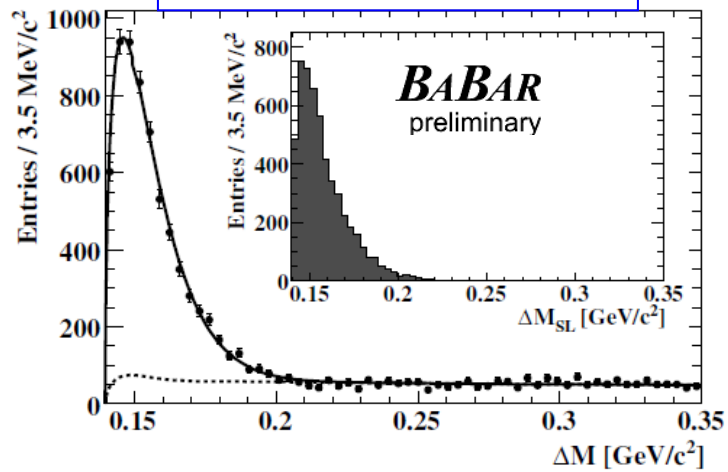
$(0.50 \pm 0.45) \times 10^{-3}$

$D^0 \rightarrow K e \nu$ Results from BaBar

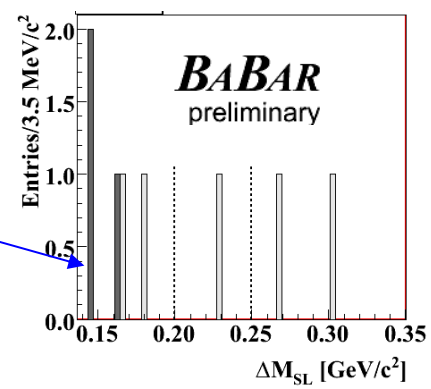
- Observable: $\Delta M = M(\pi K e) - M(K e)$, 344 fb^{-1}
- Double tag
  - $D^{*+} \rightarrow D^0 \pi_s^+$ in semileptonic
  - Five fully reconstructed hadronic tagging modes
- Unbinned maximum likelihood fit to RS ΔM
- Predict 2.85 background events, observe 3 (dark gray)

Presented at Moriond 2007

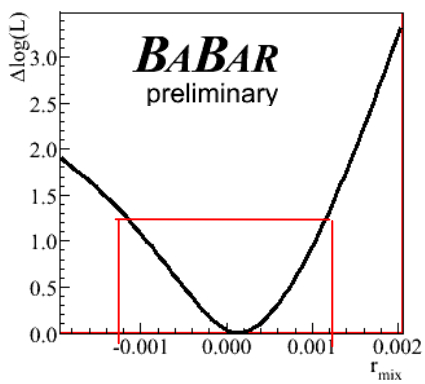
ΔM RS distribution



ΔM WS distribution



Likelihood profile



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

$D^0 \rightarrow K e \nu$ Results from Belle

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

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

$$D^{*+} \rightarrow D^0 \boxed{\pi^+}$$

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

WS: $D^0 \rightarrow K^+ \ell^- \bar{\nu}$

- In the limit of no CP violation measure time integrated mixing rate

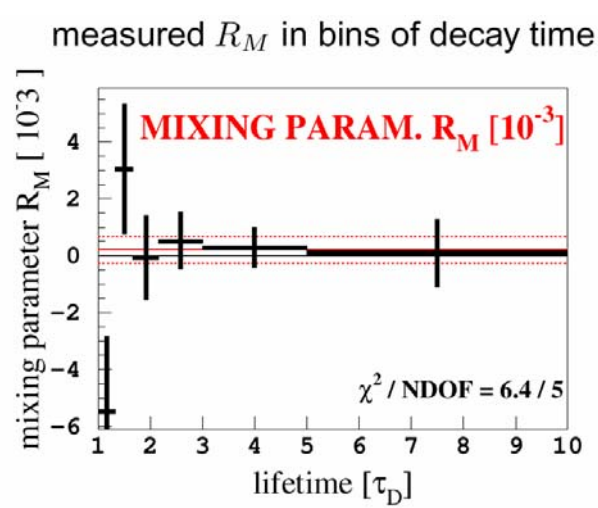
$$R_M = \frac{x^2+y^2}{2} = \frac{x'^2+y'^2}{2}$$

253 fb^{-1}

PRD (RC) 72, 071101 (2005)

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

$R_M < 1.2 \times 10^{-3}$ @95% CL

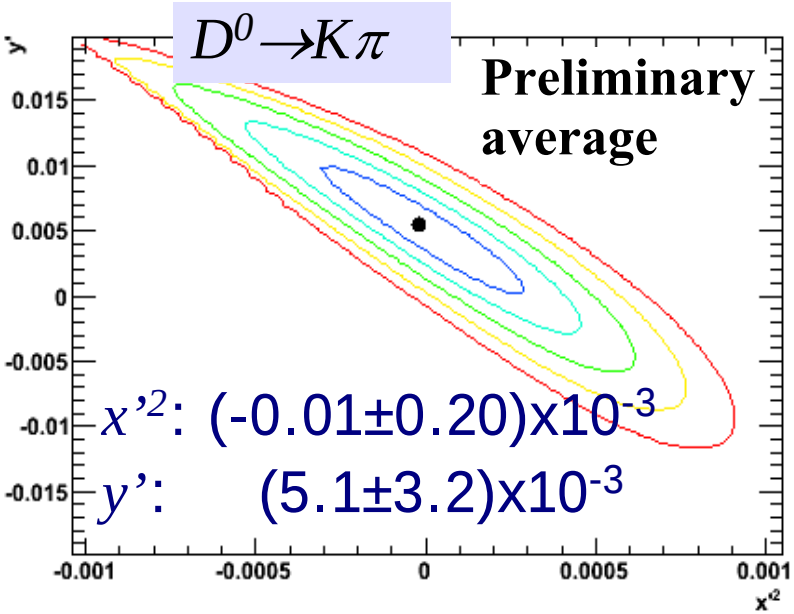


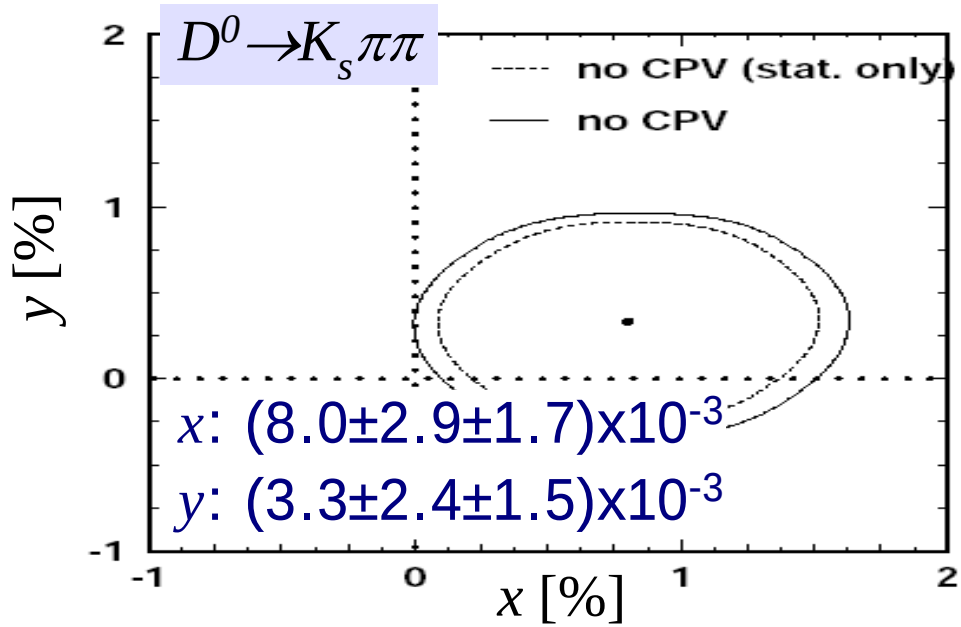
Combining all D^0 Mixing Results

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}





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

We plan to also provide averages allowing for CP violation

CLEO-c

Preliminary CLEO-c Results

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)
  - **$\cos\delta = 1.08 \pm 0.66 \pm ?$**
  - **$y = -0.057 \pm 0.066 \pm ?$**
- 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 δ
  - 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 $\sigma(\cos\delta_{K\pi}) \sim 0.1$-$0.2$

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

Uncertainties are statistical *only*

preliminary

Parameter	Value
$N_{D^0\overline{D}^0}$	$(1.09 \pm 0.04 \pm ?)\times10^6$
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	$(1.74 \pm 1.47 \pm ?)\times10^{-3}$

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

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

Interpreting the results

D^0 and $\bar{D}^0$

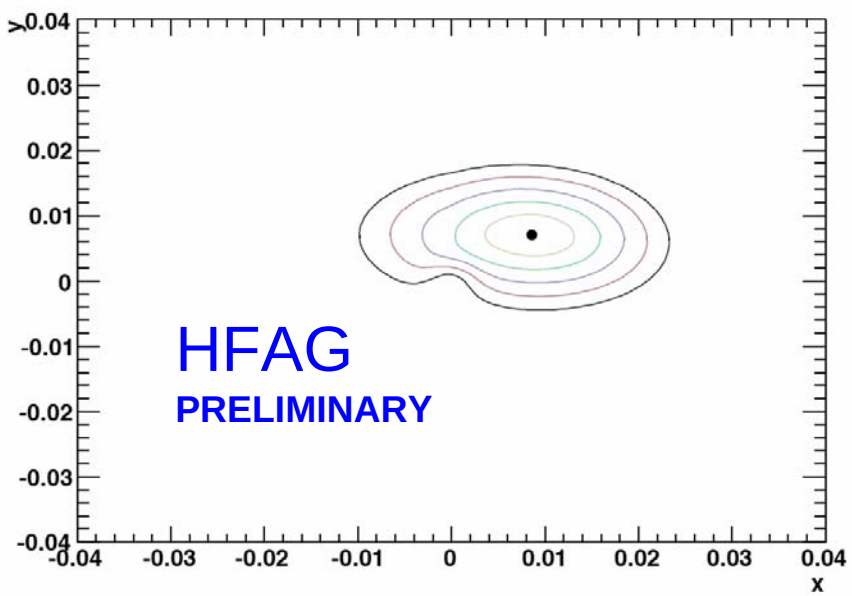
weak phase $2\phi_D$ of the mixing amplitude

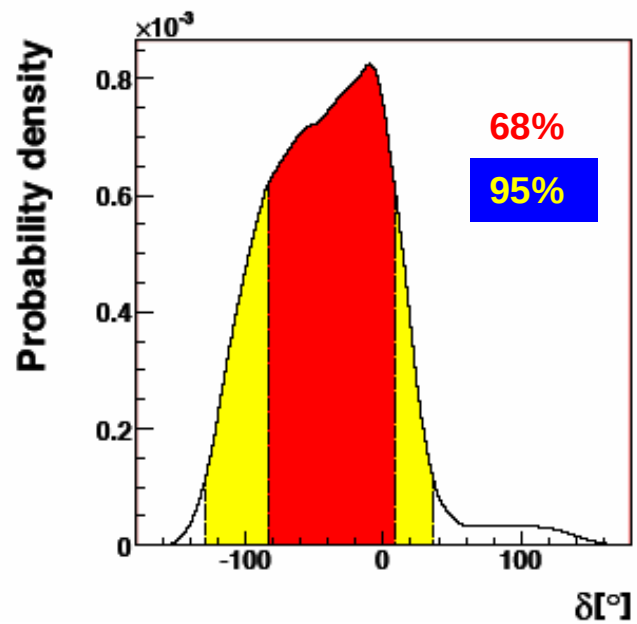
$$
\begin{aligned}
y'_{\pm} &= (1 \pm A_m)(y' \cos 2\phi_D \mp x' \sin 2\phi_D)\,, \\
x'^2_{\pm} &= (1 \pm 2A_m)(x' \cos 2\phi_D \pm y' \sin 2\phi_D)^2\,, \\
y_{\rm CP} &= y \cos 2\phi_D - A_m x \sin 2\phi_D\,, \\
A_\Gamma &= A_m y \cos 2\phi_D - x \sin 2\phi_D\,,
\end{aligned}
$$

Ciuchini et al.
hep-ph/0703294

CP Violating Parameter:

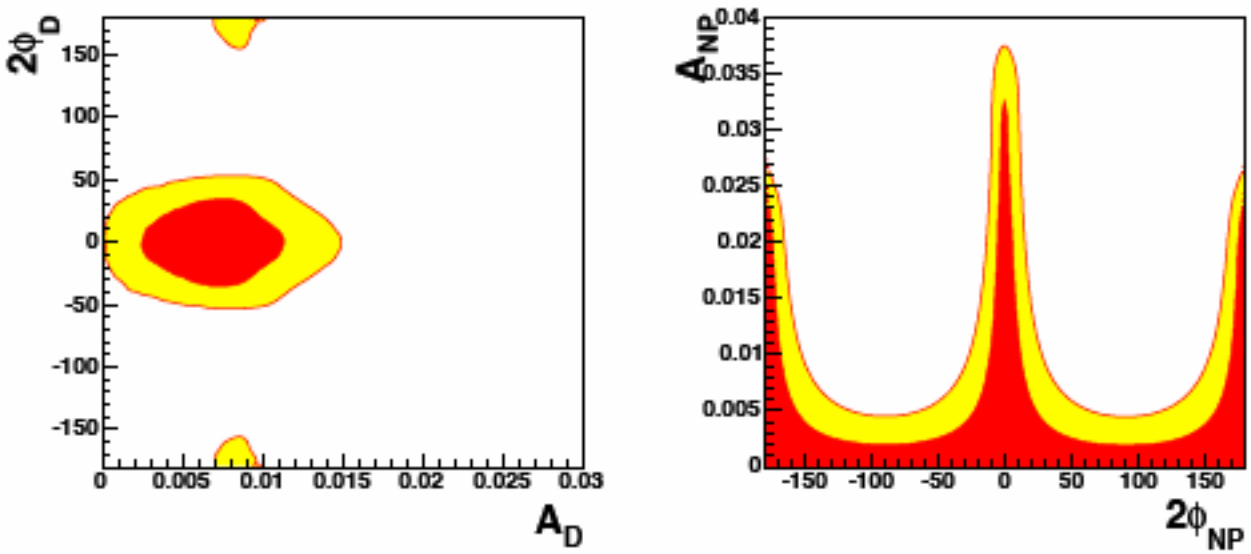
$$A_m = 1 - |q/p|$$





And CP violation?

In the standard model, $\phi \sim 2\,A^2\lambda^4\eta \lesssim 10^{-3}$



Ciuchini et al.
hep-ph/0703294

In general NP weakly constrained if SM not known

Nevertheless SUSY coupling can be constrained
hints on **squark and gluino masses**!

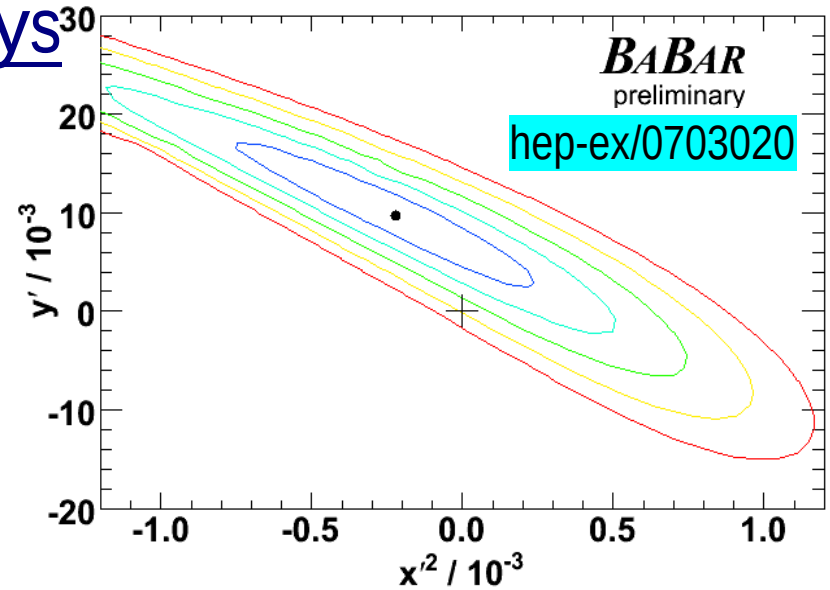
Neutral meson mixing always a window into unknown (virtual) states!

Summary

Summary and Outlook

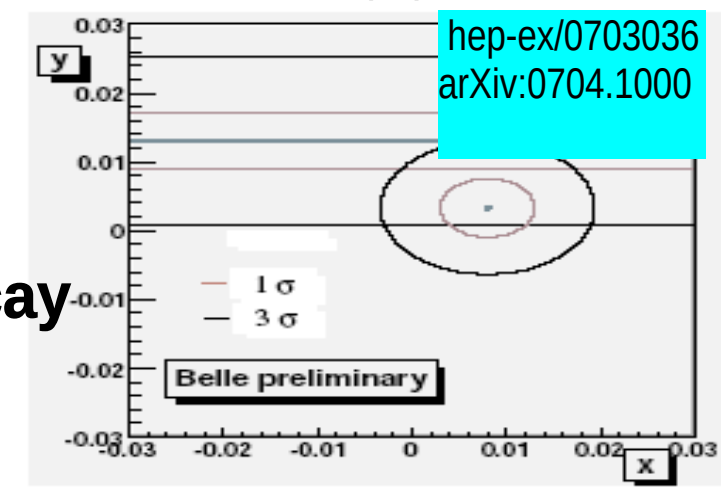
BaBar studied $D^0 \to K\pi$ decays

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



New results from Belle

- ❖y_{CP} (3.2σ) ⇒ mixing
- ❖Measurement of x and y
- ❖No sign of CP violation



Coming up

- ❖**BaBar is updating multibody decay analyses, y_{CP} measurements**

Backup Slides

D^0-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	$D^0 \rightarrow K\, l\, \nu$, etc.	Time integrated	$R_M = \frac{x^2+y^2}{2} = \frac{N_{WS}}{N_{RS}}$
WS hadronic decays	$D^0 \rightarrow K\, \pi$, etc.	Decay time analysis	x'^2, y' and r (Doubly Cabibbo Suppressed (DCS) Rate) $x' = x\cos(\delta) + y\sin(\delta)$ → Strong phase $y' = y\cos(\delta) - x\sin(\delta)$
CP eigenstate lifetime differences	$D^0 \rightarrow KK$, $(\pi\pi)$, etc.	Decay time analysis	$y_{CP} = \frac{\Gamma(CP+)-\Gamma(CP-)}{\Gamma(CP+)+\Gamma(CP-)}$ If no CPV: $y_{CP} = y$
Time dependent Dalitz plot analysis	$D^0 \rightarrow K_s\pi\pi$, etc.	Decay time analysis	x, y
Quantum Correlations $e^+e^- \rightarrow \psi(3770) \rightarrow DD$	-flavored ($K^-\pi^+$) -CP+ eigenstates (K^-K^+) -CP- eignestates ($K_s\pi^0$) -semileptonic ($X e \nu$)	Time integrated	x, y, δ, r

More BaBar-Belle Comparisons

Belle measurement is consistent with old BaBar lifetime ratio measurement

Belle: 540 fb^{-1}

y_{CP}: $(13.1\pm3.2\pm2.5)\times10^{-3}$

hep-ex/0703036 submitted to PRL

BaBar: 91 fb^{-1}

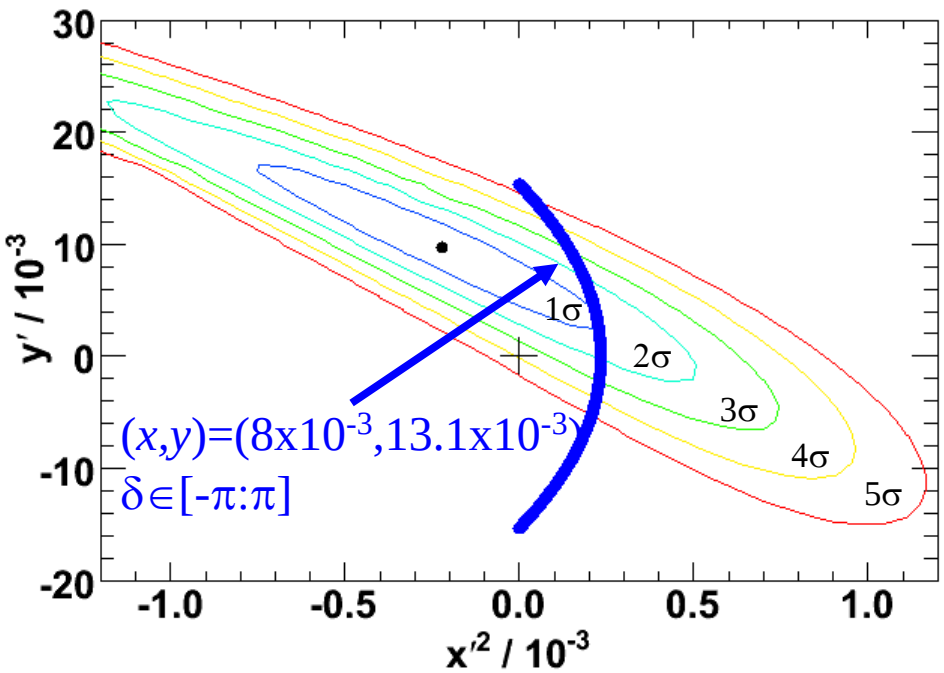
y_{CP}: $(8.0\pm4.0\pm5.0)\times10^{-3}$

PRL 91, 121801

Comparison to BaBar $K\pi$ analysis:

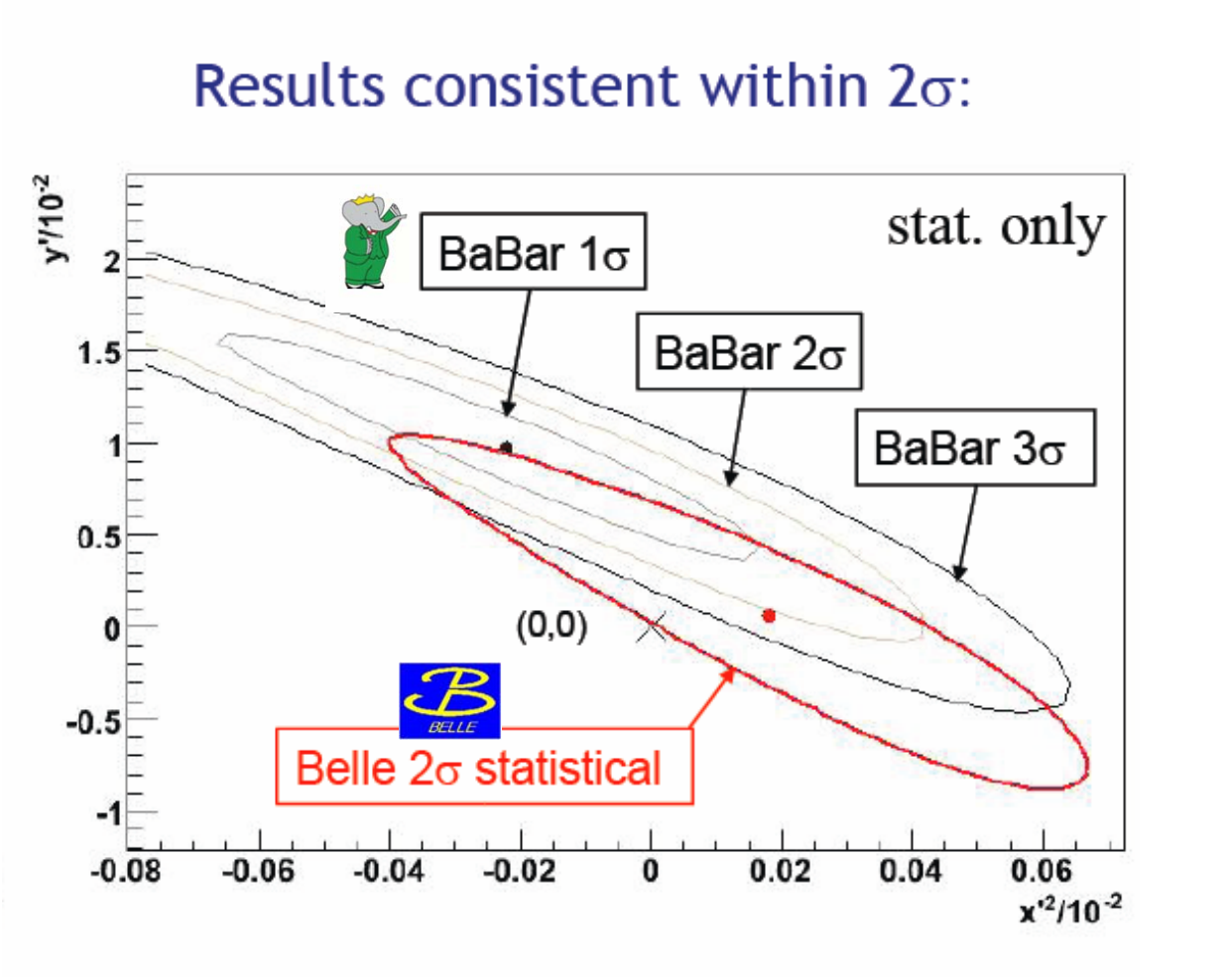
Assume $y=y_{CP}$
Use $x=8\times10^{-3}$ from Belle's $K_s\pi\pi$ analysis

Results consistent within 1σ for certain values of phase δ



Belle Results

Kπ analysis from Belle



Belle evidence on y_{CP}

"Apparent" lifetime difference between $D^0 \to K^-\pi^+$ and K^+K^-, $\pi^+\pi^-$

$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1 \longrightarrow y_{CP} = y\cos 2\phi_D - A_m x \sin 2\phi_D$$

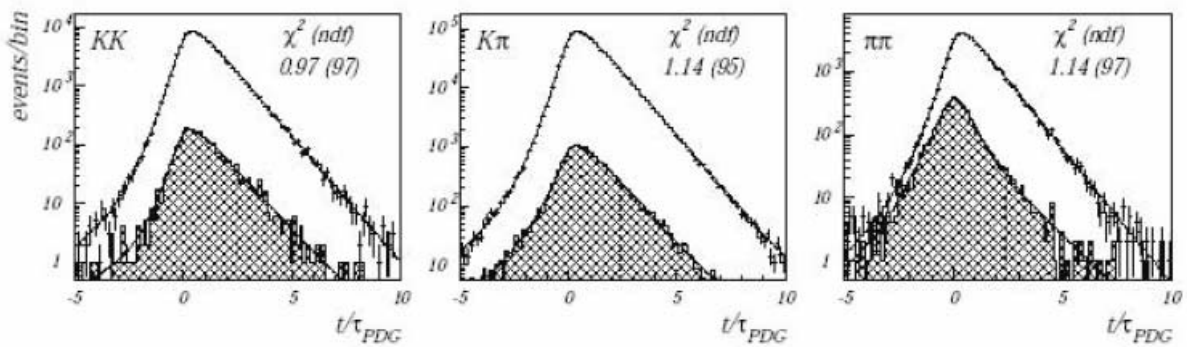
$$A_m = 1 - |q/p|$$

$$A_\Gamma = \frac{\tau(\overline{D}^0 \to K^-K^+) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^-K^+) + \tau(D^0 \to K^+K^-)} \longrightarrow A_\Gamma = A_m y \cos 2\phi_D - x \sin 2\phi_D$$

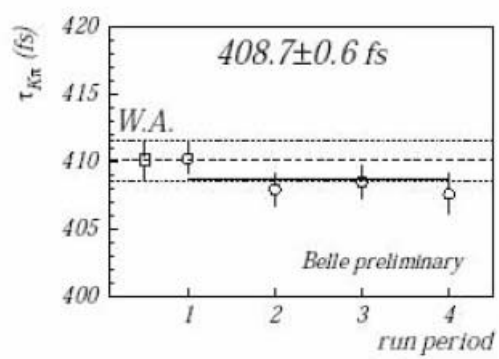
ϕ_D= mixing phase

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



Results on y_{CP}

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 hep-ex/0703036

Belle preliminary (540 fb^{-1})

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

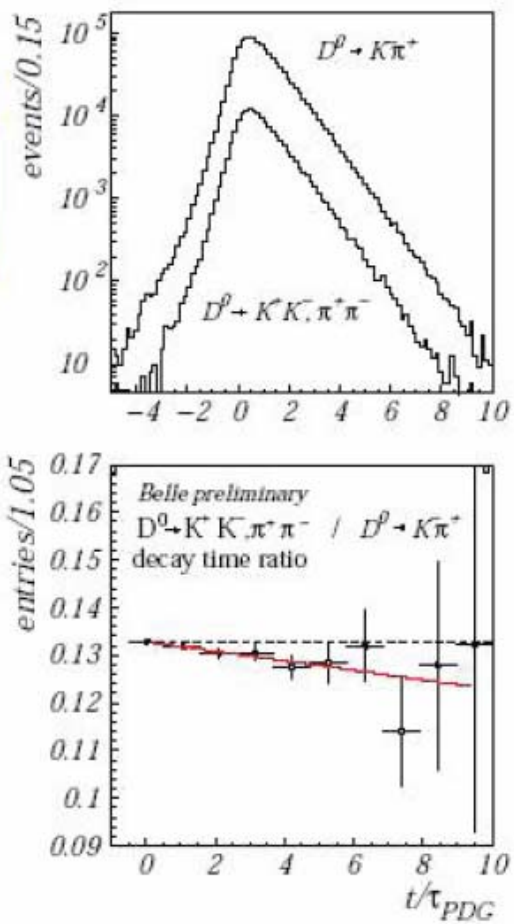
$> 3\sigma$ above zero

(4.1σ stat. only)

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

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

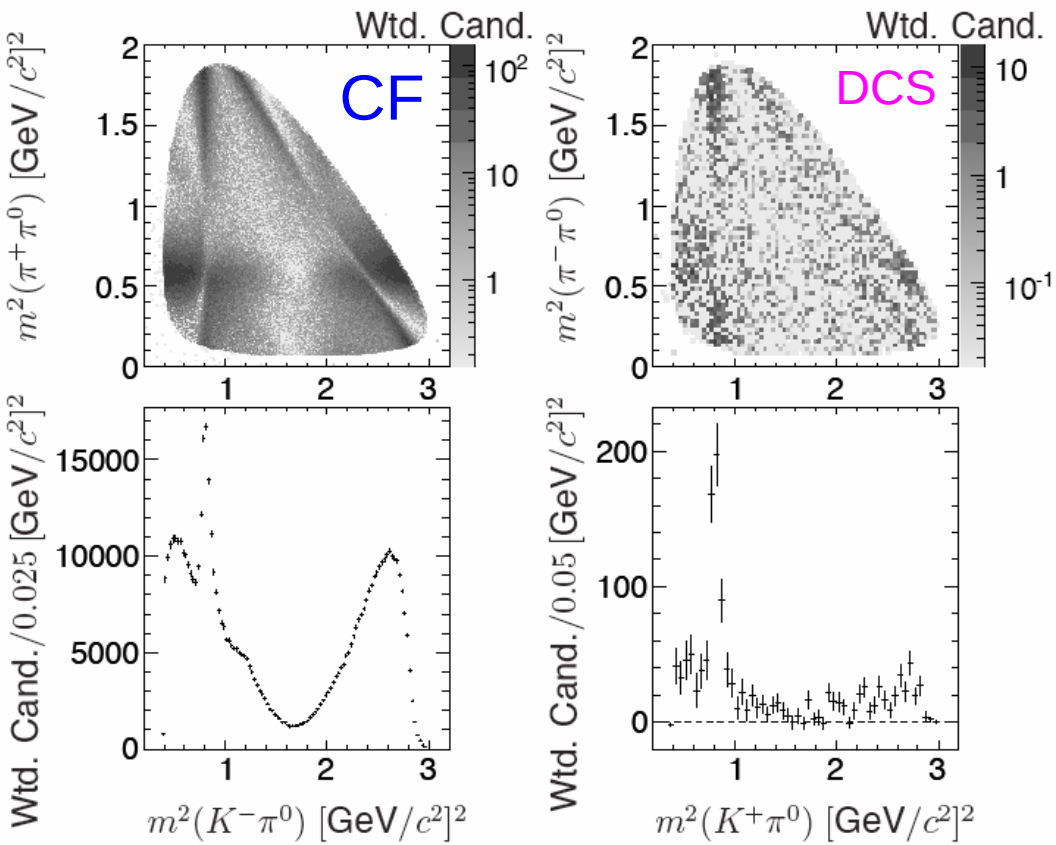
no evidence for CP violation



Separating x and y

- $K\pi$ only cannot separate x and y
- Need info on **strong phases**
  - Multibody decays:Dalitz models

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



DCS decays proceed primarily through $K^{*+}\pi^-$ while CF through $K^-\rho^+$

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

PRL 97, 221803 (2006)
hep-ex/0607090

Select special region of Dalitz plot

$$\frac{dN}{dt} \propto [\widetilde{R}_D + \alpha\widetilde{y}'\sqrt{\widetilde{R}_D}(\Gamma t) + \frac{\widetilde{x}'^2 + \widetilde{y}'^2}{4}(\Gamma t)^2]e^{-\Gamma t}\ , \qquad 0 \le \alpha \le 1$$

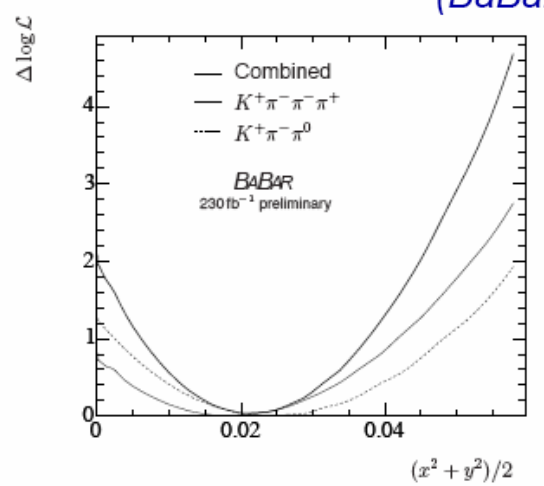
$$\widetilde{x}' = x\cos\widetilde{\delta} + y\sin\widetilde{\delta}$$
$$\widetilde{y}' = y\cos\widetilde{\delta} - x\sin\widetilde{\delta}$$

Effective phase

Mixing rate

$$R_M = \frac{\widetilde{x}'^2 + \widetilde{y}'^2}{2} = \frac{x^2 + y^2}{2}$$

(BaBar, 230 fb^{-1})



Results

- Assuming CP conservation
- Upper limits (95% C.L.)

$$K\pi\pi^0 \quad R_M < 0.054\%$$
$$K3\pi \quad R_M < 0.048\%$$

Combined result $\boxed{R_M < 0.42 \times 10^{-3} \quad @\ 95\%\ C.L.}$

USC HEP
University of South Carolina
High Energy Physics Group

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

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

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

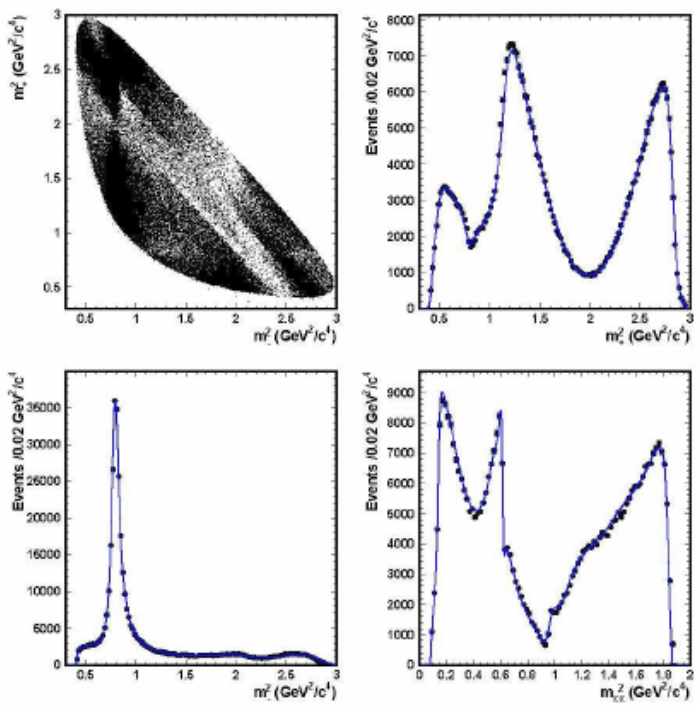
Both flavor ($K^{*-}\pi^+/K^{*+}\pi^-$) final states in the same Dalitz plot!

CP-eigenstate (ρK_S) and flavor states ($K^{*-}\pi^+$) in the same Dalitz plot!

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

Belle, 540 fb^{-1}

Dalitz fit

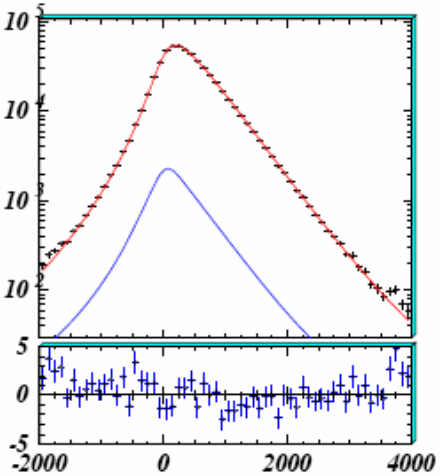


Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.629 ± 0.005	134.3 ± 0.3	0.6227
$K_0^*(1430)^-$	2.12 ± 0.02	-0.9 ± 0.5	0.0724
$K_2^*(1430)^-$	0.87 ± 0.01	-47.3 ± 0.7	0.0133
$K^*(1410)^-$	0.65 ± 0.02	111 ± 2	0.0048
$K^*(1680)^-$	0.60 ± 0.05	147 ± 5	0.0002
$K^*(892)^+$	0.152 ± 0.003	-37.5 ± 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 $D^0 \to K_S\pi^+\pi^-$ results

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)

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

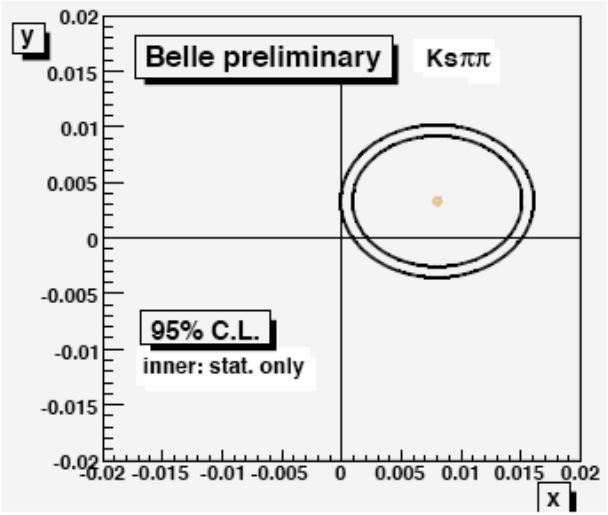
$$y = 0.33 \pm 0.24 \pm 0.15\ \%$$

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

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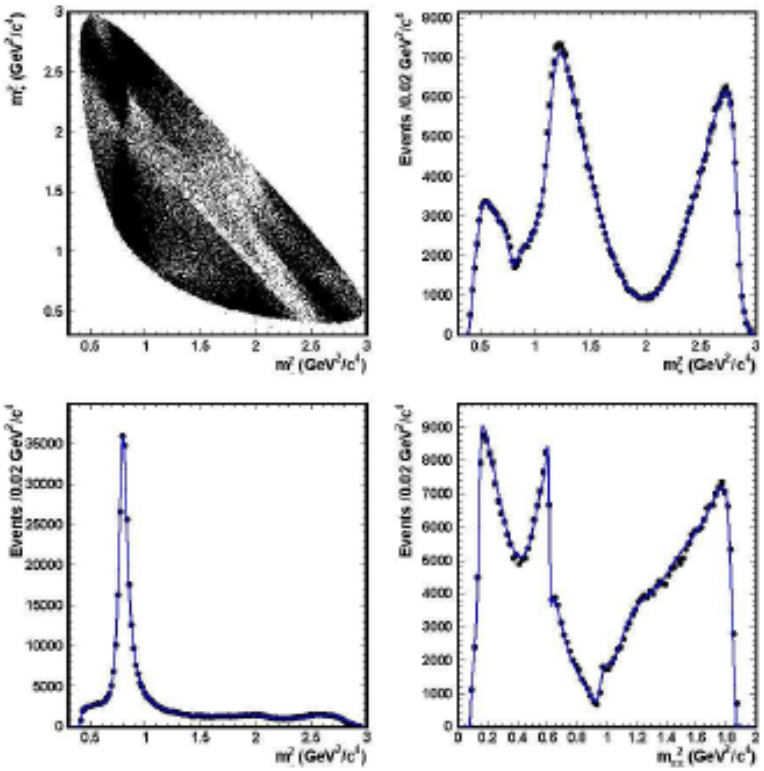
Belle $D^0 \to K_s \pi\pi$ Analysis

Dalitz fit



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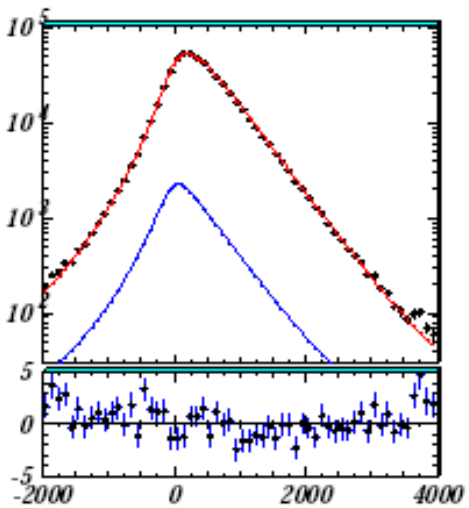
Belle $D^0 \to K_S \pi\pi$ Analysis

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)

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

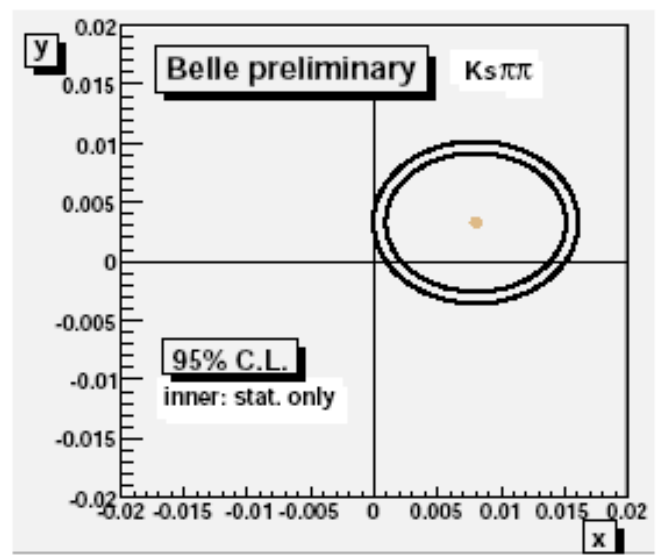
$$y = 0.33 \pm 0.24 \pm 0.15\ \%$$

most stringent limits on x up to now

Cleo, PRD 72, 012001 (2005):

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

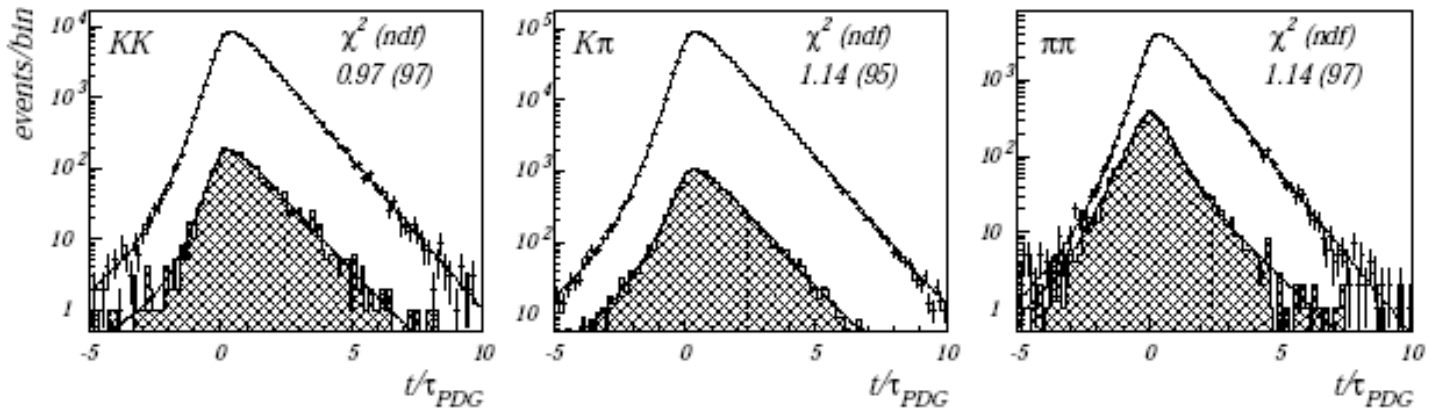
$y = -1.4 \pm 2.5 \pm 0.9\%$



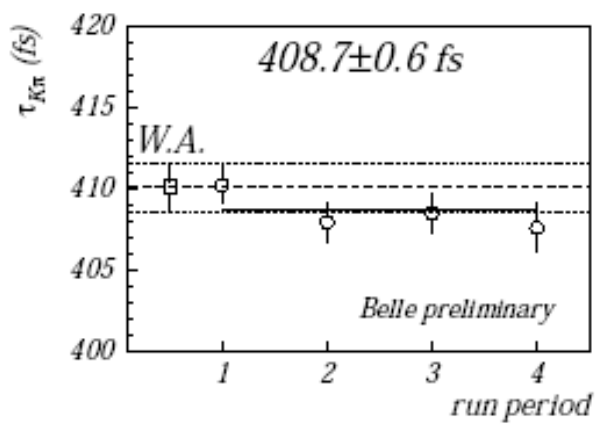
Belle $D^0 \to KK/\pi\pi$ Analysis

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

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



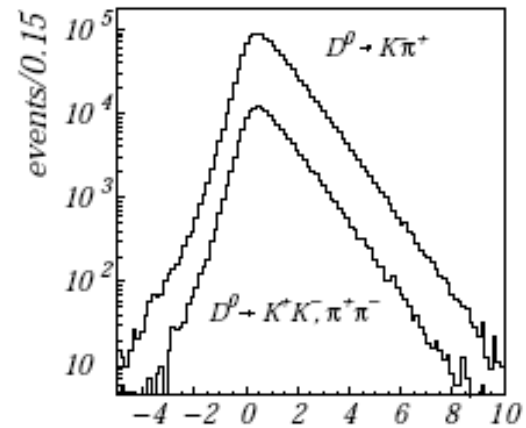
$D^0 \to K\pi$ lifetime very stable in slightly different running periods



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



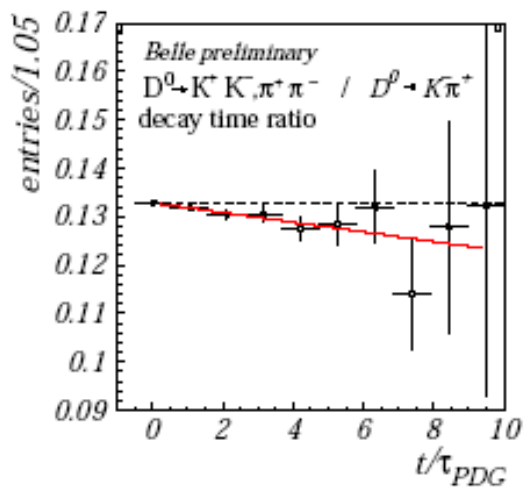
Belle preliminary (540 fb^{-1})

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

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

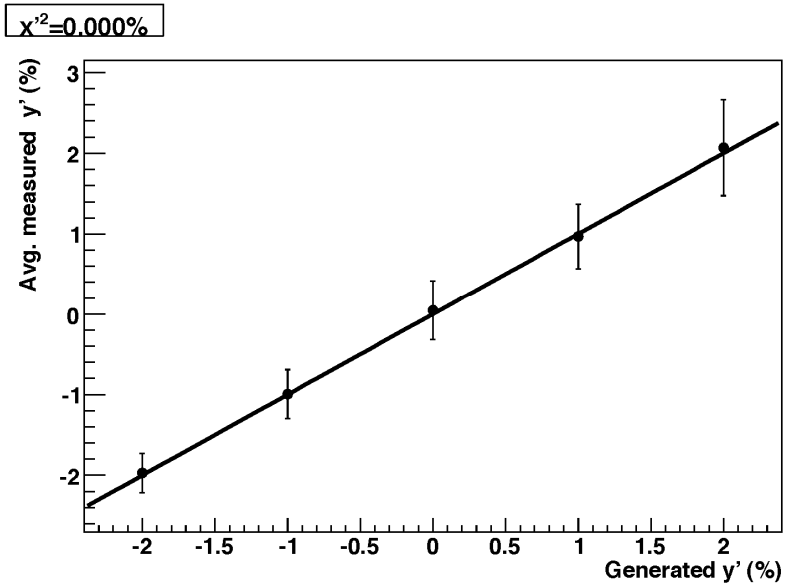
$$A_\Gamma = 0.01 \pm 0.30 \pm 0.15\ \%$$

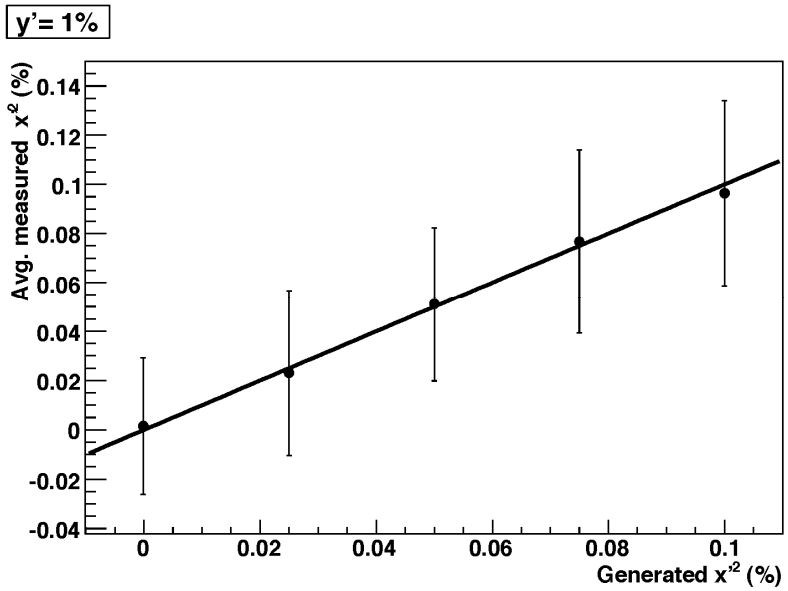
no evidence for CP violation



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

Double tag at ψ(3770) [CLEO-c]

$D_{CP\pm}$

neutral D CP eigenstate

ψ(3770) decay conserves CP

- Reconstruct Double Tags: CP vs Kπ
- Asymmetry in CP+ vs CP- related to cosδ

$$A \equiv \frac{B(D_{CP+} \to K^-\pi^+) - B(D_{CP-} \to K^-\pi^+)}{B(D_{CP+} \to K^-\pi^+) + B(D_{CP-} \to K^-\pi^+)}$$

- R_D is ratio of DCS to Cabibbo favored rates

$$\cos\delta = \frac{A}{2\sqrt{R_D}}$$

- Input R_D =(3.60±0.08)‰ from PDG2006+CDF ~±2%,

Need to run

On threshold

- Updated results with 281 pb^{-1} at Winter Conferences
  - Expect σ(y)~ ±1.5% and σ(cos $\delta_{K\pi}$) ~ ±0.3
  - Including systematic uncertainties
- Full CLEO-c dataset ~750 pb^{-1}
  - Expect σ(y)~ ±1.0% and σ(cos $\delta_{K\pi}$) ~ ±0.1-0.2

Final Systematics

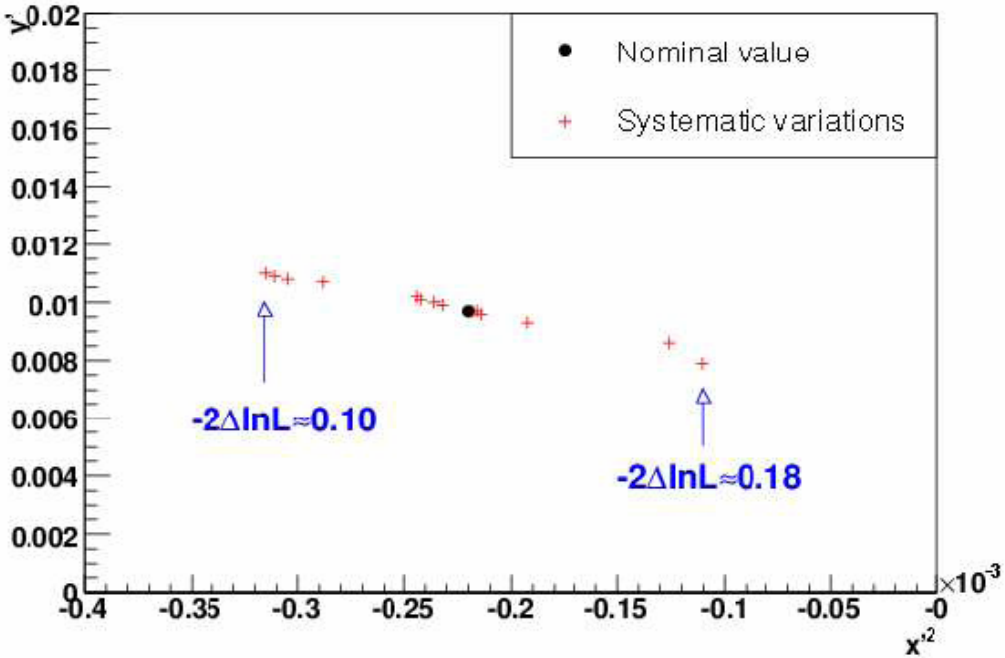
fit:	y' $(\times 10^{-2})$	$\delta_y/\sigma^{\rm sys}$	R_M $(\times 10^{-4})$	$\delta R_M^{\rm sys}/\sigma^{\rm sys}$	m^2
default fit:	0.97 ± 0.44	-	-0.63 ± 1.07	-	-
No offset in core resolution:	1.10 ± 0.44	$+0.30\sigma$	-0.97 ± 1.06	-0.33σ	0.045
offset in all resolution Gaussians:	0.97 ± 0.44	-0.01σ	-0.61 ± 1.07	$+0.02\sigma$	0.000
Proper time error distributions from sidebands, not sPlot:	1.01 ± 0.44	$+0.09\sigma$	-0.70 ± 1.07	-0.07σ	0.003
widest core Gaussian without per-event errors:	0.96 ± 0.44	-0.02σ	-0.61 ± 1.07	$+0.02\sigma$	0.001
Fix scale factor $s_1 = 1$:	0.93 ± 0.44	-0.09σ	-0.53 ± 1.08	$+0.10\sigma$	0.004
Fix D^0 lifetime to PDG value:	0.97 ± 0.44	-0.00σ	-0.62 ± 1.07	$+0.01\sigma$	0.001
Change Category 3 Model:	0.95 ± 0.44	-0.05σ	-0.61 ± 1.07	$+0.02\sigma$	0.003
Cat.4 tfrom low sideband:	0.85 ± 0.43	-0.28σ	-0.46 ± 1.06	$+0.16\sigma$	0.060
Cat.4 tfrom high sideband:	1.01 ± 0.44	$+0.08\sigma$	-0.63 ± 1.07	-0.02σ	0.011
Vary $\{m_{K\pi}, \Delta m\}$ fit model:	1.00 ± 0.44	$+0.06\sigma$	-0.68 ± 1.07	-0.05σ	0.002
Vary $\{m_{K\pi}, \Delta m\}$ parameters:	1.02 ± 0.44	$+0.10\sigma$	-0.70 ± 1.06	-0.07σ	0.007
$(-1 < t < 3.5)$ ps:	0.86 ± 0.44	-0.26σ	-0.26 ± 1.10	$+0.34\sigma$	0.061
$(-5 < t < 10)$ ps:	1.08 ± 0.44	$+0.24\sigma$	-0.94 ± 1.05	-0.30σ	0.039
$(\delta_t < 0.4)$ ps	1.07 ± 0.45	$+0.23\sigma$	-0.87 ± 1.07	-0.22σ	0.023
$(\delta_t < 0.6)$ ps	0.79 ± 0.43	-0.41σ	-0.27 ± 1.07	$+0.34\sigma$	0.077
Keep all overlapping candidates	0.99 ± 0.44	$+0.05\sigma$	-0.67 ± 1.06	-0.04σ	0.002
Remove all overlapping candidates	1.09 ± 0.45	$+0.27\sigma$	-0.96 ± 1.07	-0.31σ	0.042
Total variation:		0.71σ		0.70σ	0.306

Systematics summary:

systematic source:	R_D	y'	x'^2
PDF:	0.59σ	0.45σ	0.40σ
selection criteria:	0.24σ	0.55σ	0.57σ
Quadrature total:	0.63σ	0.71σ	0.70σ

Including Systematics in Contours

Systematic variations produce new mixing parameters sets
- tend to scatter along correlation axis:



CPV systematics use same scale factor plus tiny correction for charge asymmetry in efficiency

Included in contours as follows:

- for each variation calculate change in likelihood between new and old point in old likelihood

  $m_i^2=(-2\Delta\ln L)/2.3$ ← 1σ in 2D

- Scale likelihood with $\frac{1}{1+\sum m_i^2}$

- Should correspond to scaling the statistical uncertainty up