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

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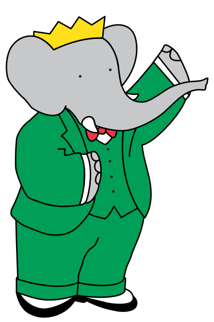
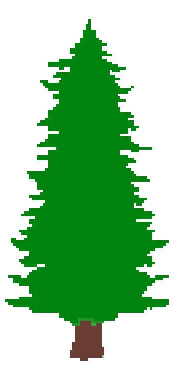




Outline

- Neutral Meson Mixing
- BaBar Experiment
- Charm mixing in $D^0 \rightarrow K\pi$ decays from BaBar
- Comparisons with other charm mixing results
- Summary

Neutral Meson Mixing

- Mixing can occur in four neutral meson systems:

$|K^0\rangle = |d\bar{s}\rangle, \quad |\overline{K}^0\rangle = |\bar{d}s\rangle$ 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

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

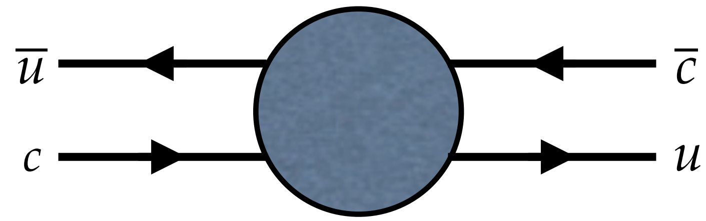
Will present mixing measurement for the D^0 system

Note: D^0 meson first discovered at SLAC

Mark-I, PRL 37, 255 (1976)

Neutral Meson Mixing

- neutral mesons distinguished by an internal quantum number (e.g., charm) can mix through the weak interaction:

$|D^0\rangle$  $|\overline{D}^0\rangle$

- time evolution by Schrödinger eqn:

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

2x2 hermitian matrices

- Mass eigenstates:

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

- propagate with masses $m_{1,2}$ and widths $\Gamma_{1,2}$:

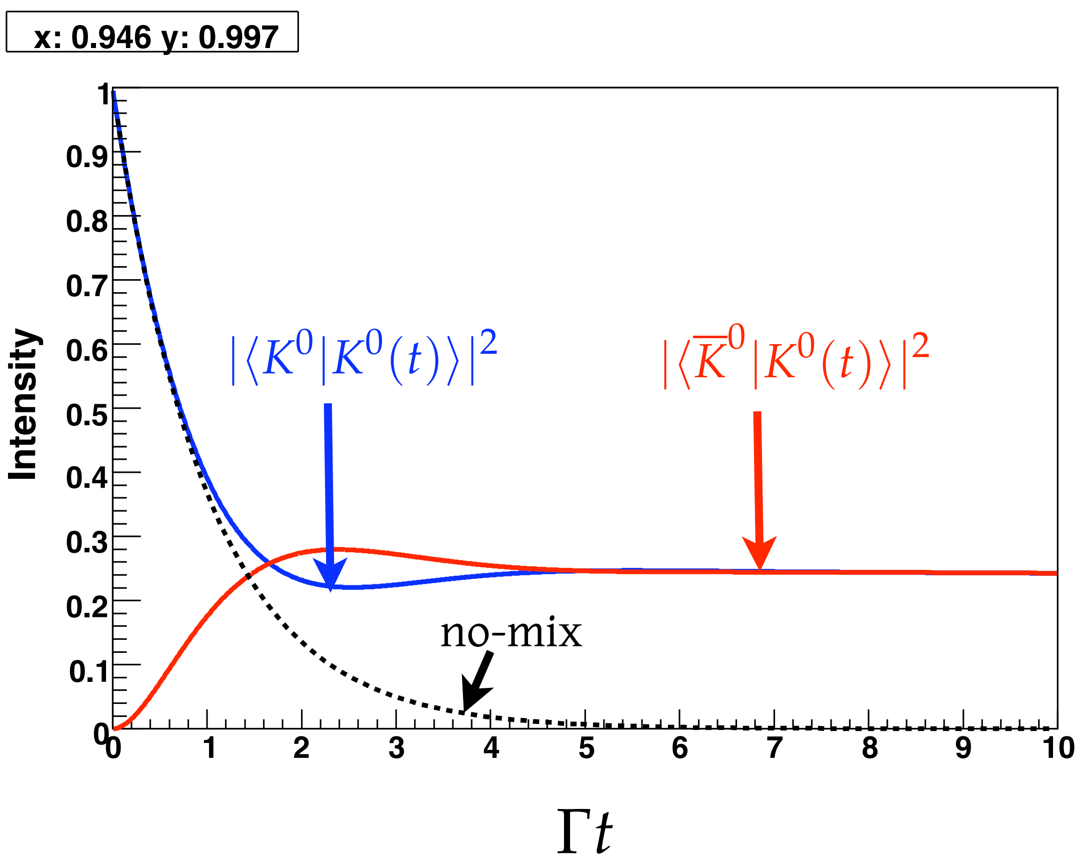
$$|D_{1,2}(t)\rangle = e^{-i(m_{1,2}-i\Gamma_{1,2}/2)t}\,|D_{1,2}(t=0)\rangle$$

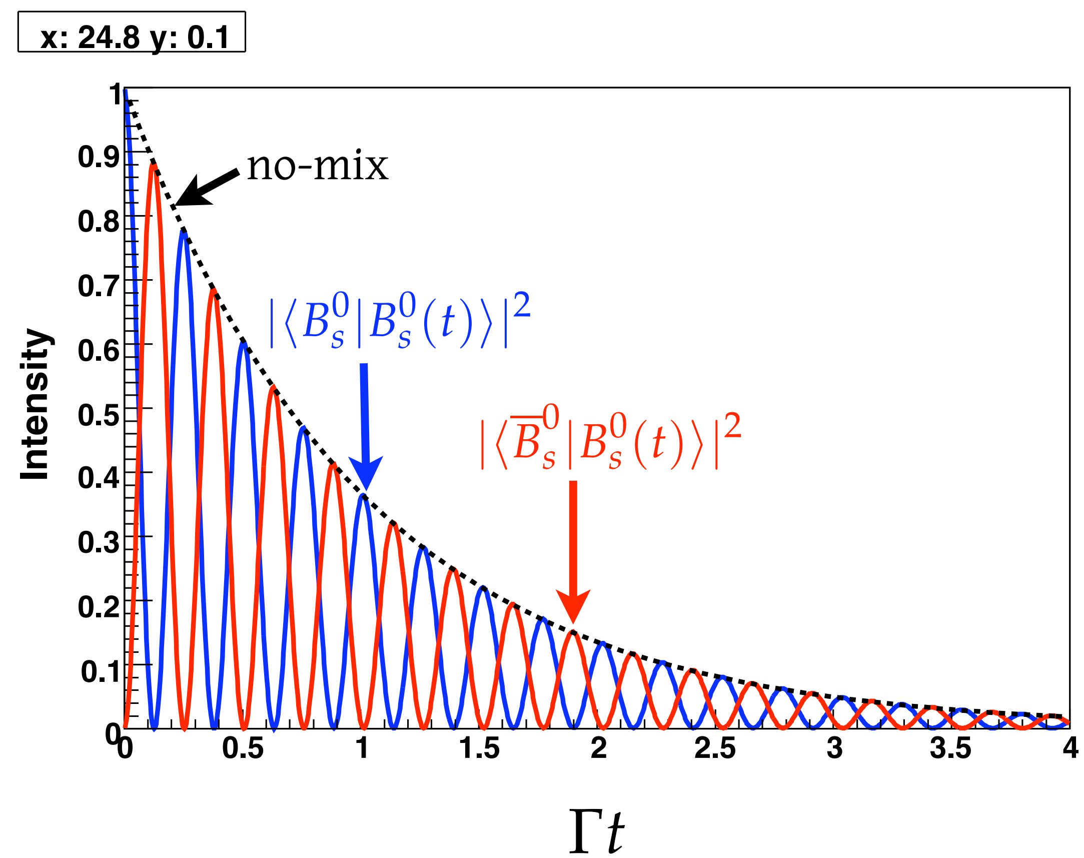
Neutral Meson Mixing

$$I(D^0 \to D^0; t): \quad |\langle D^0 | D^0(t) \rangle|^2 = \frac{e^{-\Gamma t}}{2} [\cosh(y\Gamma t) + \cos(x\Gamma t)]$$

$$I(D^0 \to \overline{D}^0; t): \quad |\langle \overline{D}^0 | D^0(t) \rangle|^2 = \frac{e^{-\Gamma t}}{2} [\cosh(y\Gamma t) - \cos(x\Gamma t)] \left|\frac{q}{p}\right|^2$$

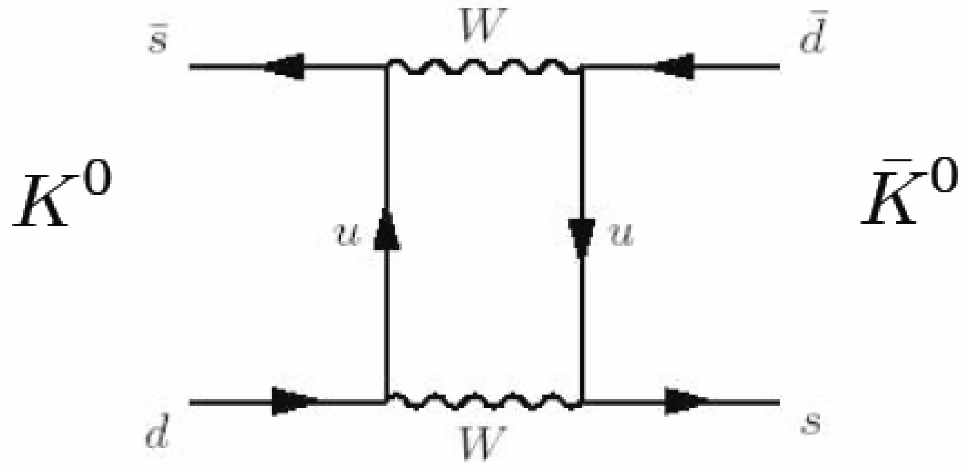
Mixing will occur if either $\boxed{x \equiv 2\frac{m_1 - m_2}{\Gamma_1 + \Gamma_2}}$ or $\boxed{y \equiv \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}}$ is non-zero





K^0 Mixing and 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

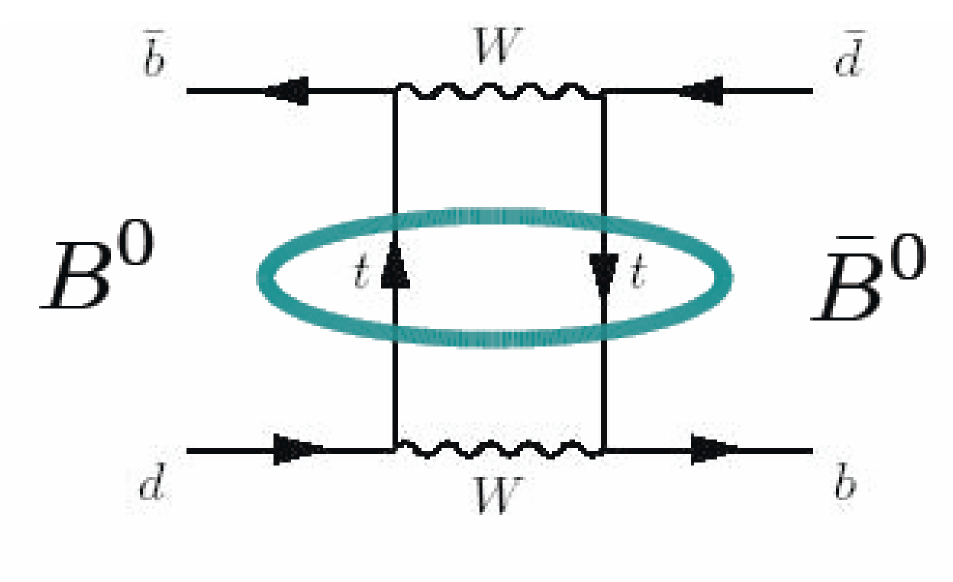
Introduce additional loop with new c quark

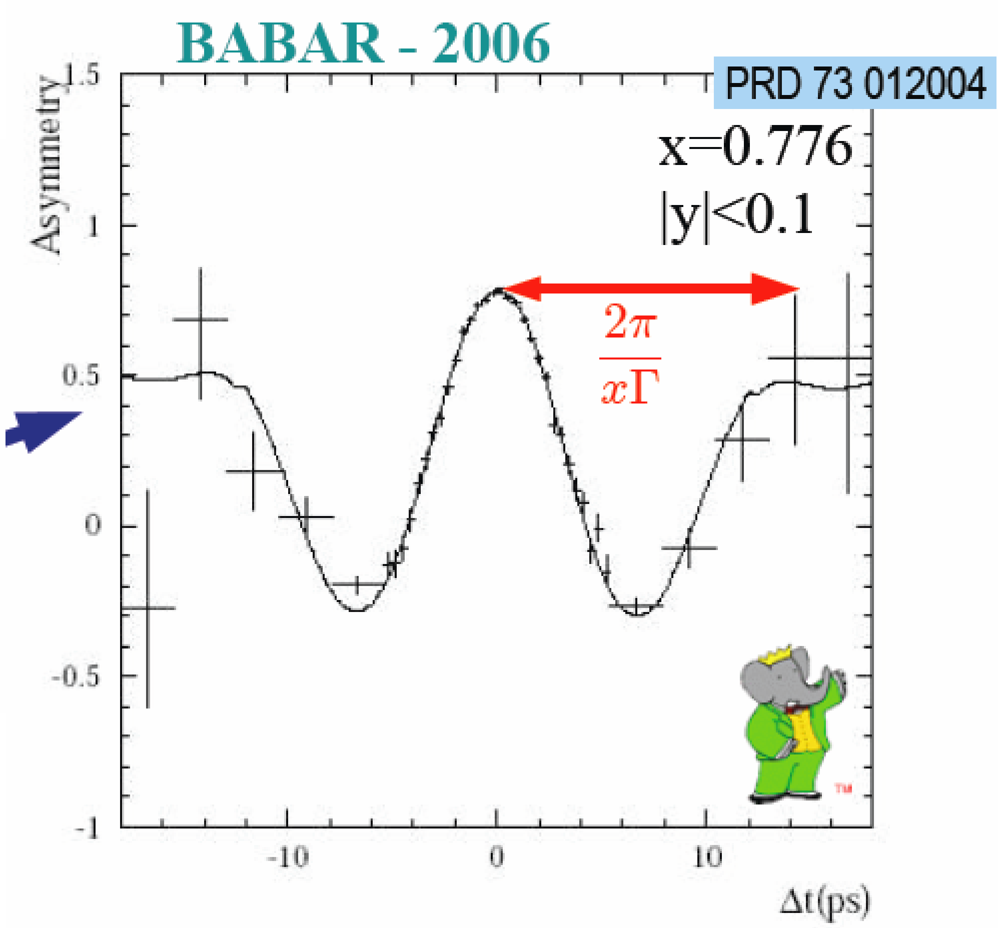
GIM predicted charm quark 4 years before observation

B^0 Mixing and discovery of top

B^0 mixing first observed by ARGUS experiment in 1987

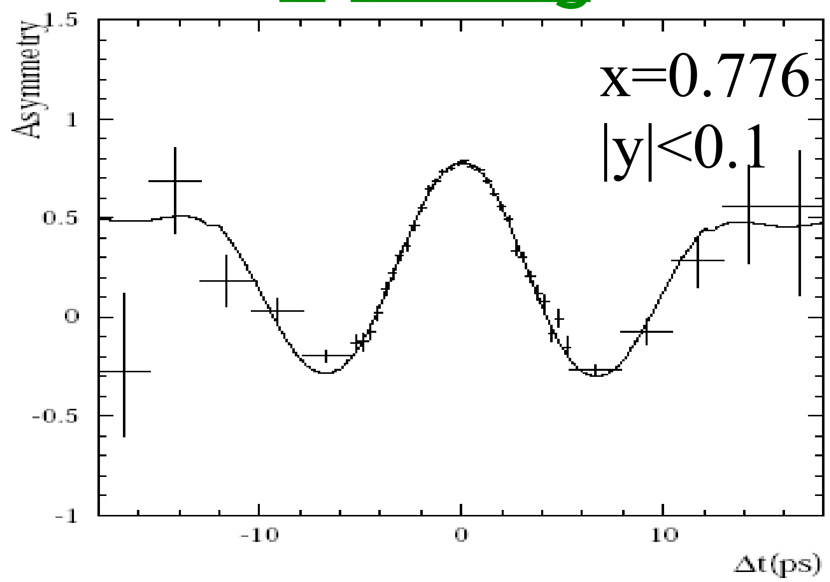
- large mixing frequency implied heavy top quark (m_t>50 GeV/c^2)
  - top discovered in 1995



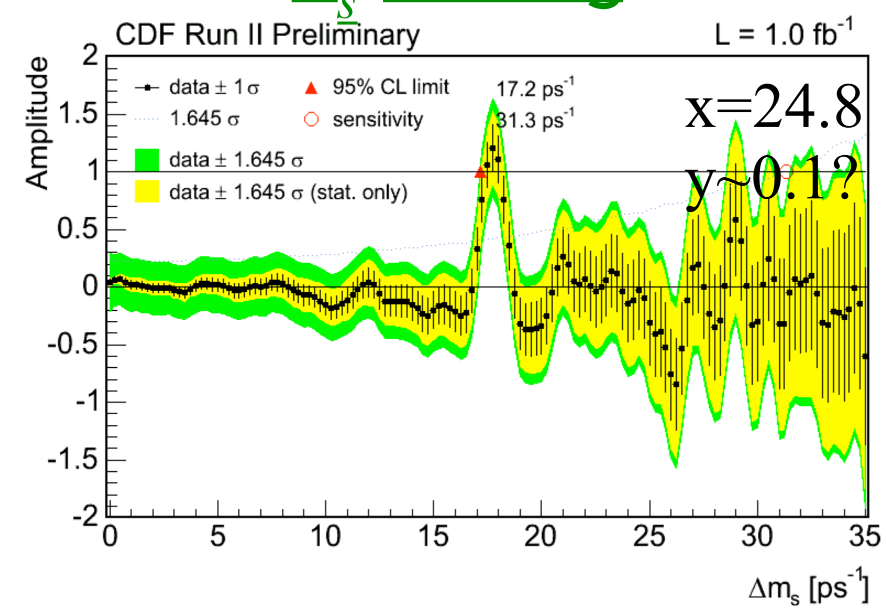


Status of mixing, Feb. 2007

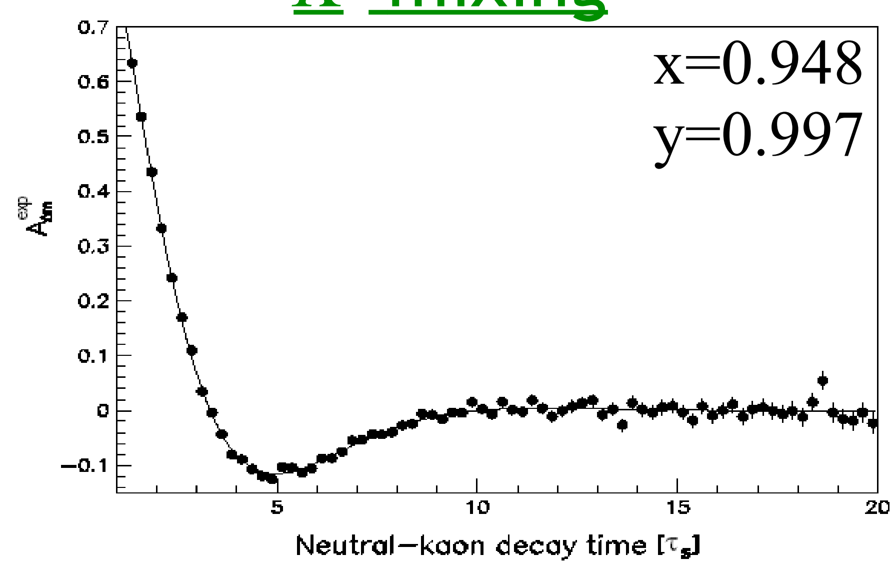
B^0 mixing



B_s^0 mixing



K^0 mixing



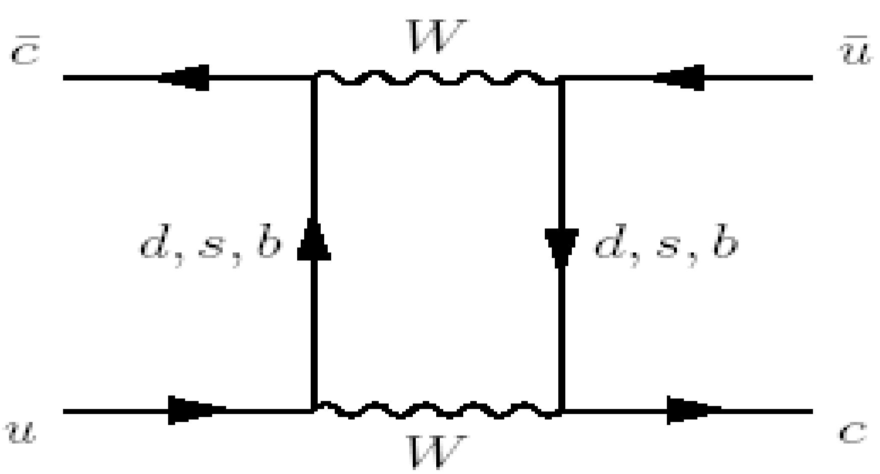
D^0 mixing

?

Charm Meson Mixing (SM)

- Short distance:

short distance ~ x ~ Δm



$O(10^{-5})$

Mixing loops with down-type quarks suppressed:

- supression of b loop: $|V_{ub}V_{cb}^{*}|^2 / |V_{us}V_{cs}^{*}|^2 \sim 1\%$
- s,d contributions suppressed due to:

$$(m_s^2 - m_d^2)/m_W^2 \text{ (GIM)}$$

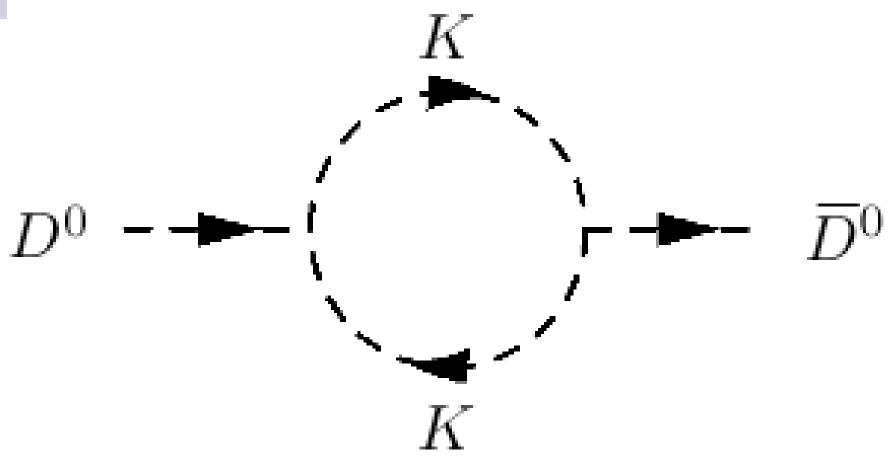
$$(m_s^2 - m_d^2)^2/m_c^2 \text{ (extern. } p\text{)}$$

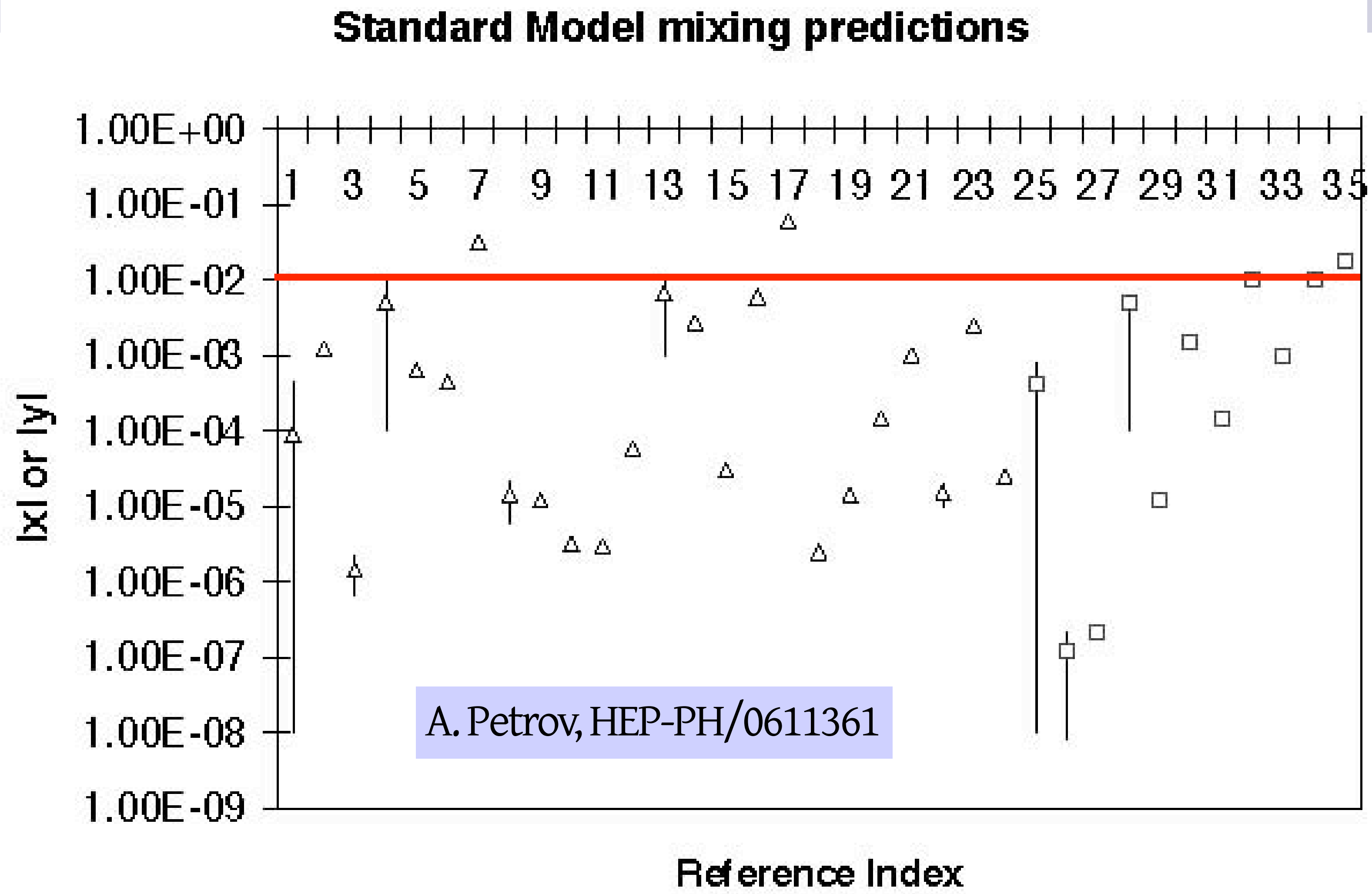
- SM short distance box diagram contributions negligible

$x_{box} \sim (O(10^{-6}) - O(10^{-5}))$

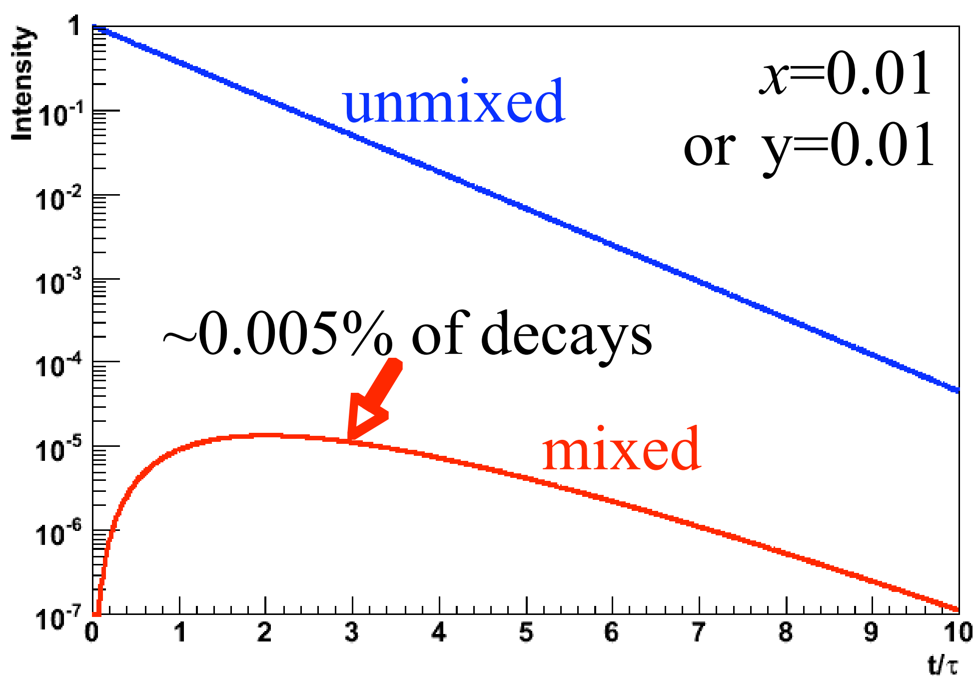
  - unlike the B system where the t-quark box diagram dominates

Long distance contributions





Most calculations give: x, y < 1%



low mixing rate: $R_{\mathrm{M}} = (x^2 + y^2)/2 \sim 0.005\%$

➡ difficult measurement!

Some recent calculations:

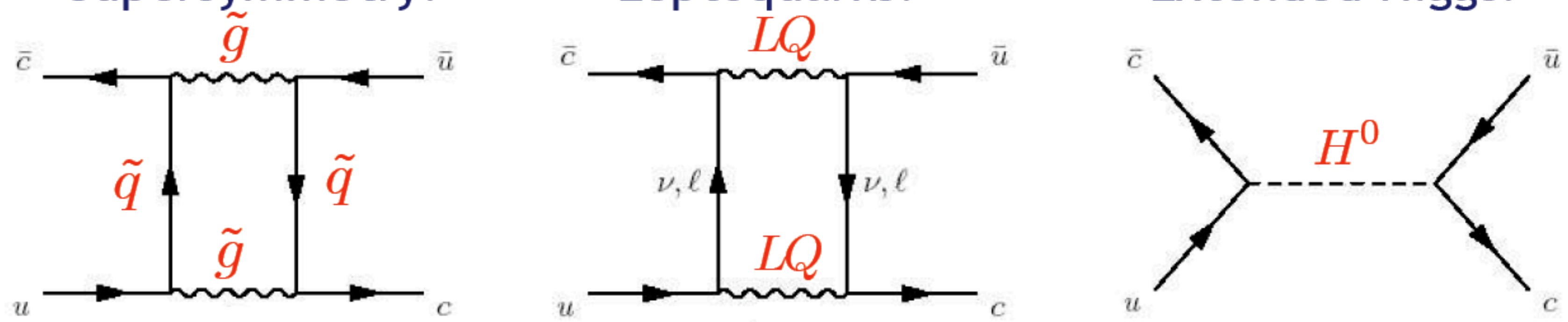
$|y| \leq 0.01$ — PRD 65 054034 (2002) Falk, Grossman, Ligeti and Petrov

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

Charm Mixing (NP)

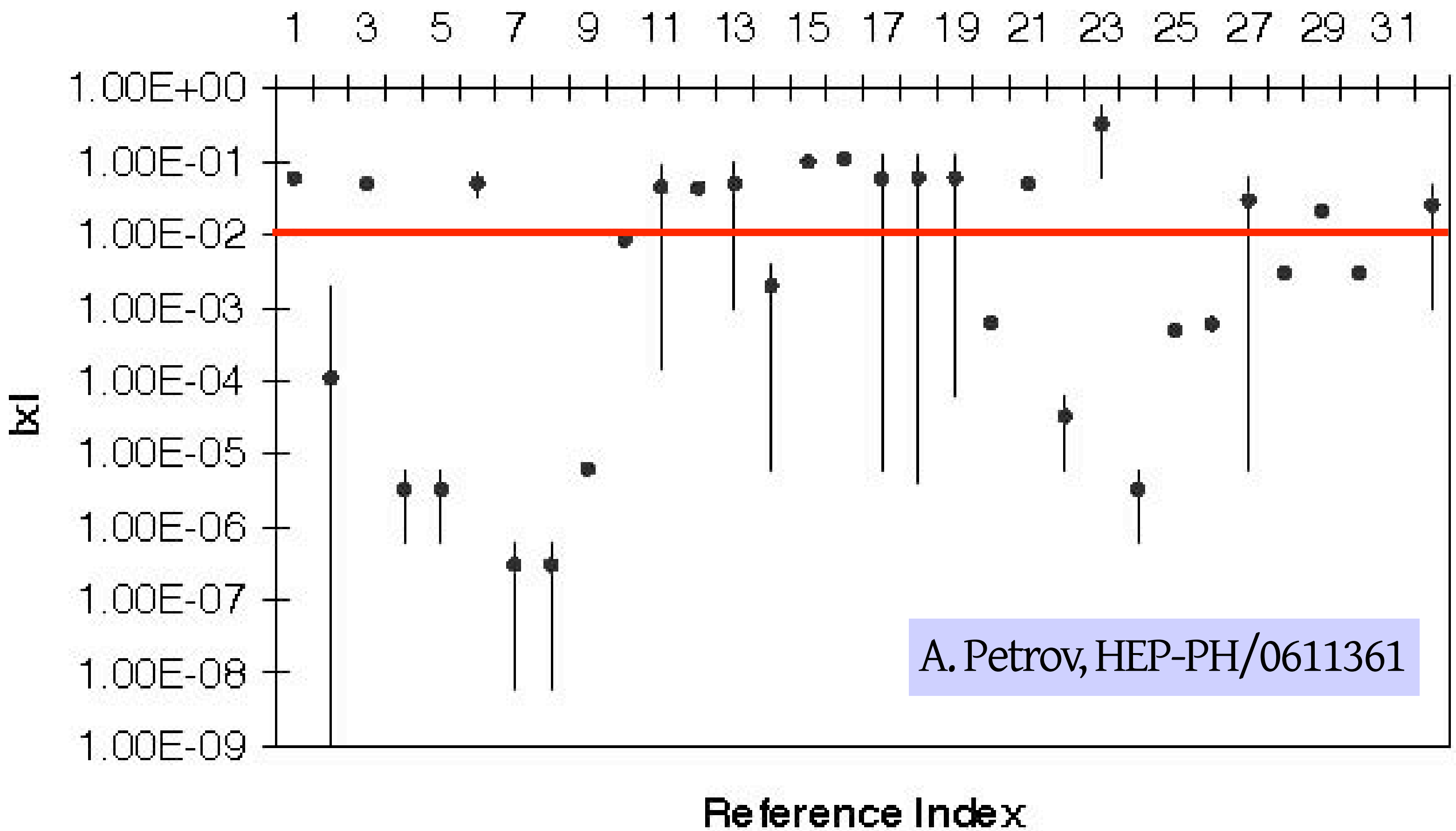
- Possible enhancements to mixing from NP

Supersymmetry: Leptoquarks: Extended Higgs:



Text

New Physics mixing predictions



NP signatures:

- *CP* violation in mixing
- $|x| >> |y|$

The BaBar Experiment

PEP-II: A Charm and B-Factory

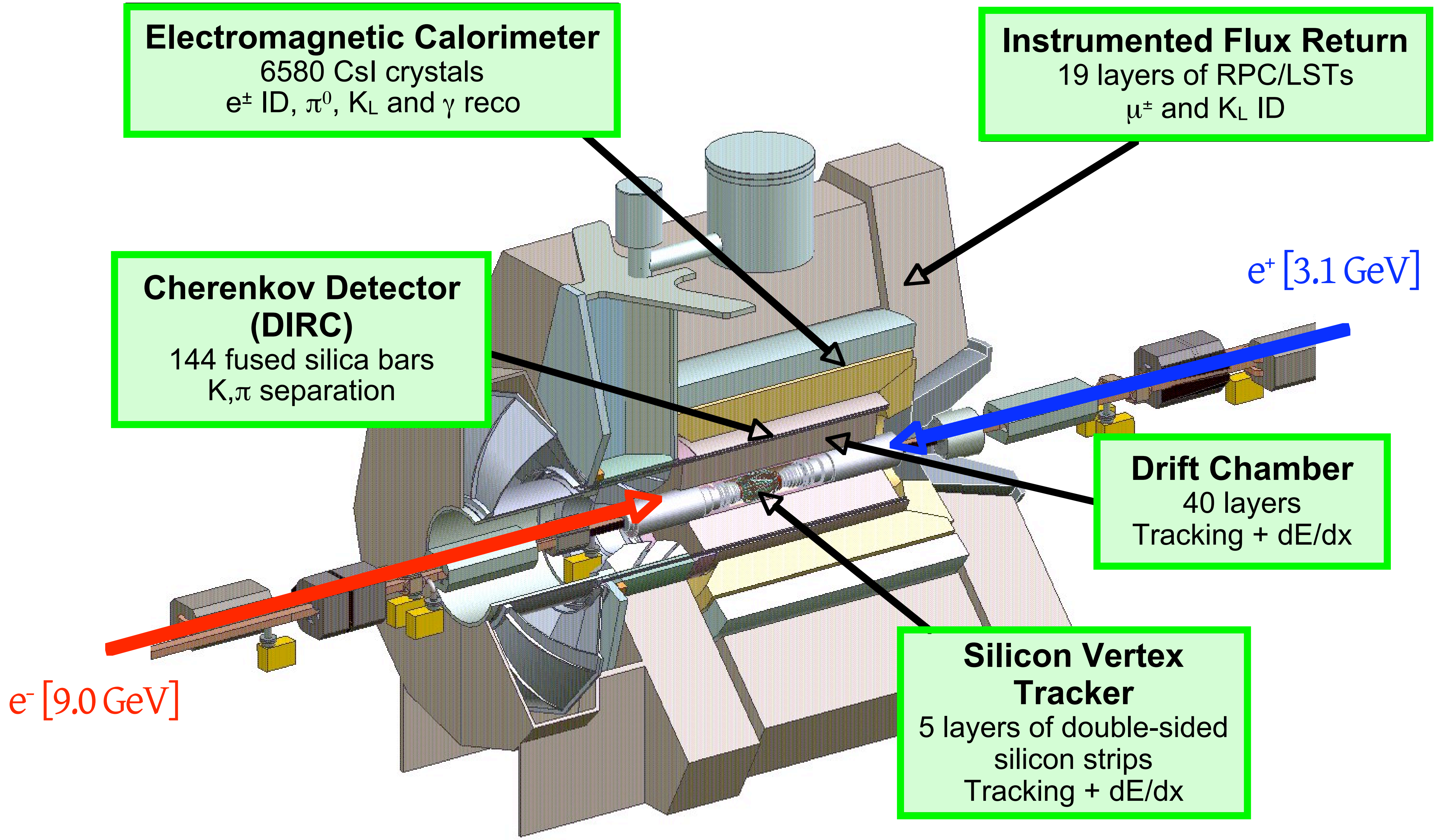
High-luminosity
asymmetric energy
e^+e^- collider
at Υ(4S) resonance

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

~10 Hz of BB

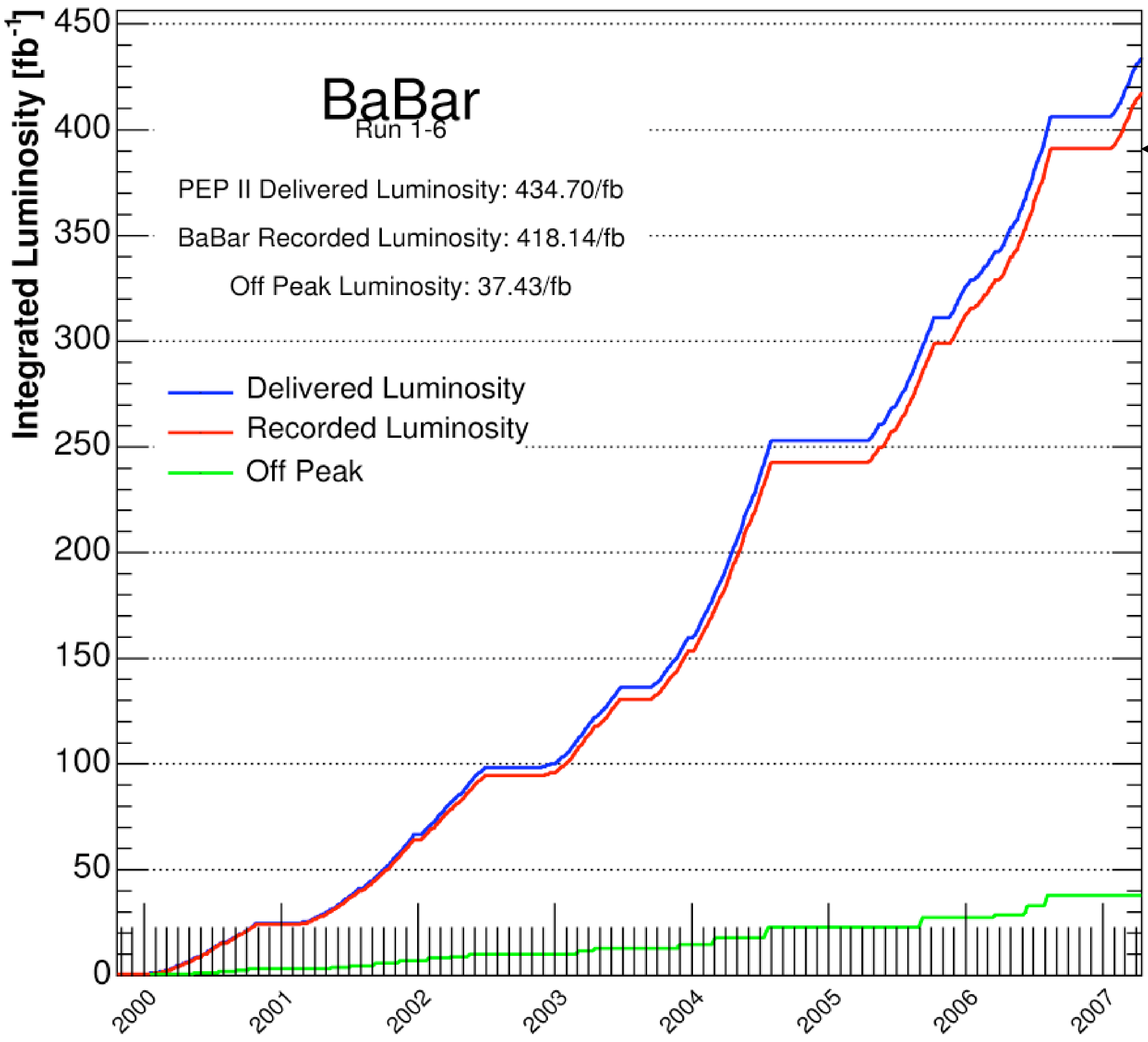
The BaBar Experiment

Large acceptance experiment, excellent particle reconstruction and identification capability



B-Factory: High Luminosity

High delivered luminosity recorded efficiently



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

in 384 fb^{-1}
>400M $B\overline{B}$ events
>500M $c\bar{c}$ events

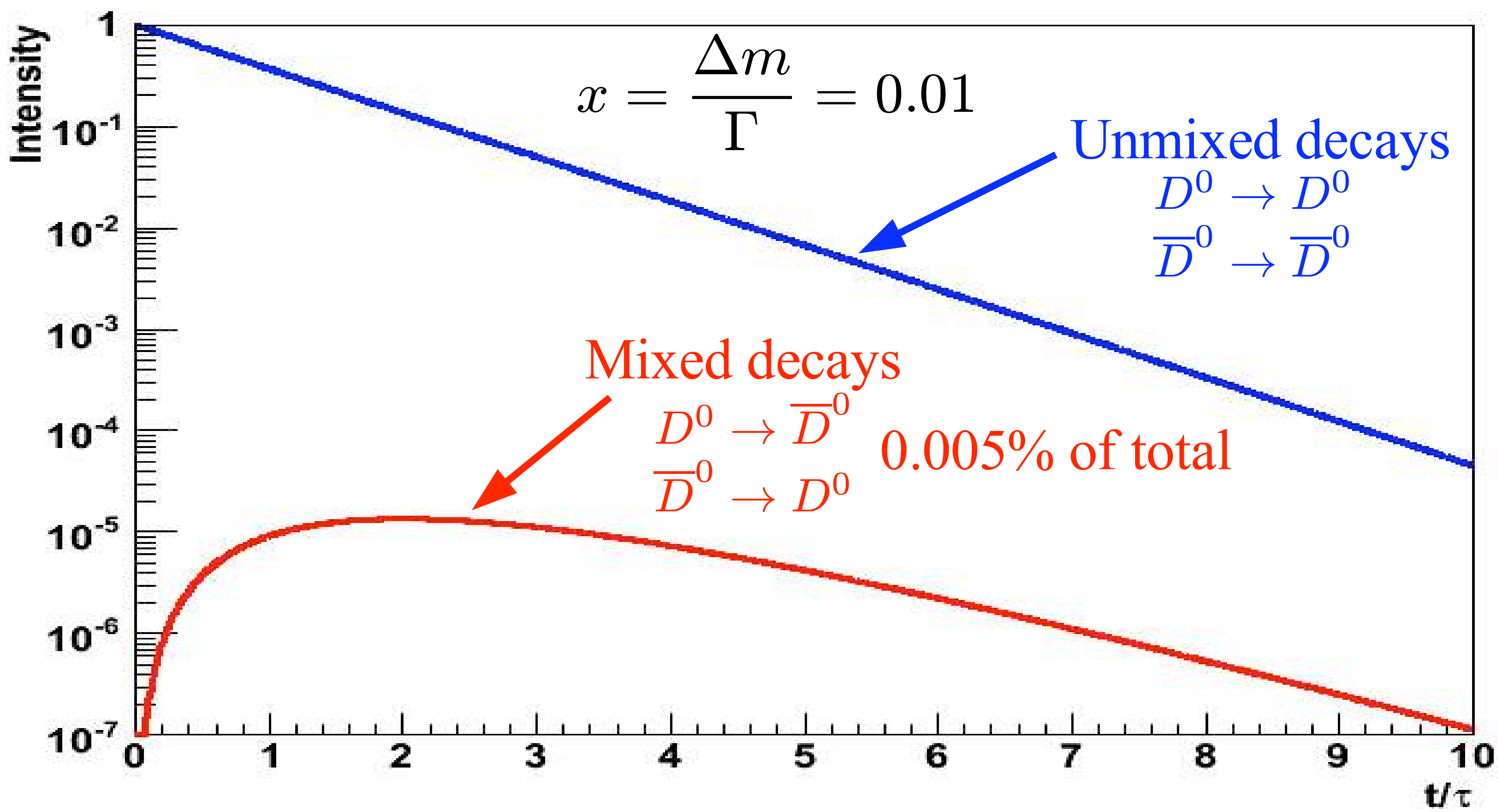
add 1M $c\bar{c}$ events/day

excellent sample to search for charm mixing

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

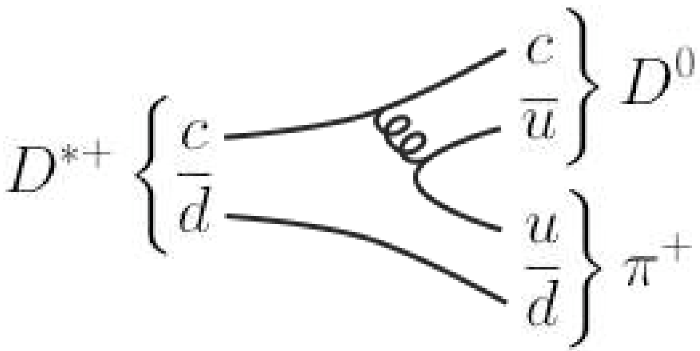
Principle of Mixing Measurement

- Produce clean samples of D^0 and $\overline{D}^0$
- Identify flavor (D^0 or $\overline{D}^0$) at production
- Measure rate of mixed decays as a function of proper time (distributions shown without proper time smearing)



Production Flavor

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



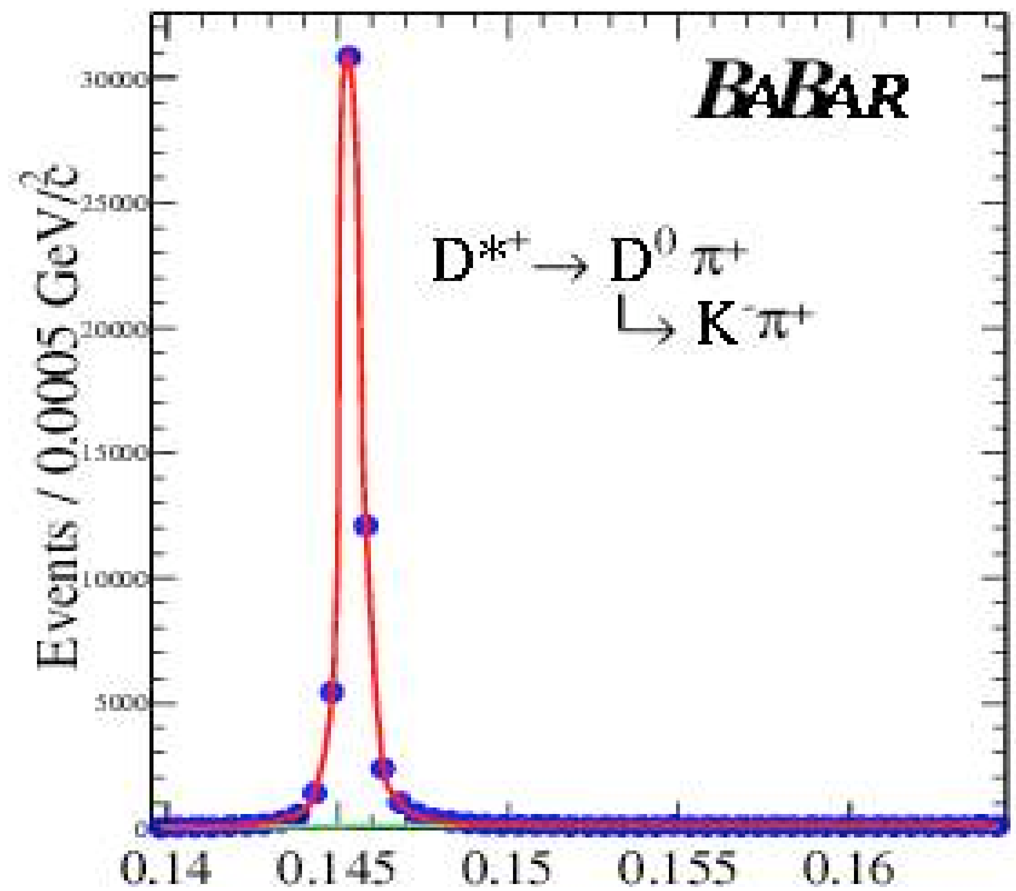
Charge of pion "tags" initial flavor as D^0 or $\bar{D}^0$

Additional benefit: low Q

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

yields narrow Q peak

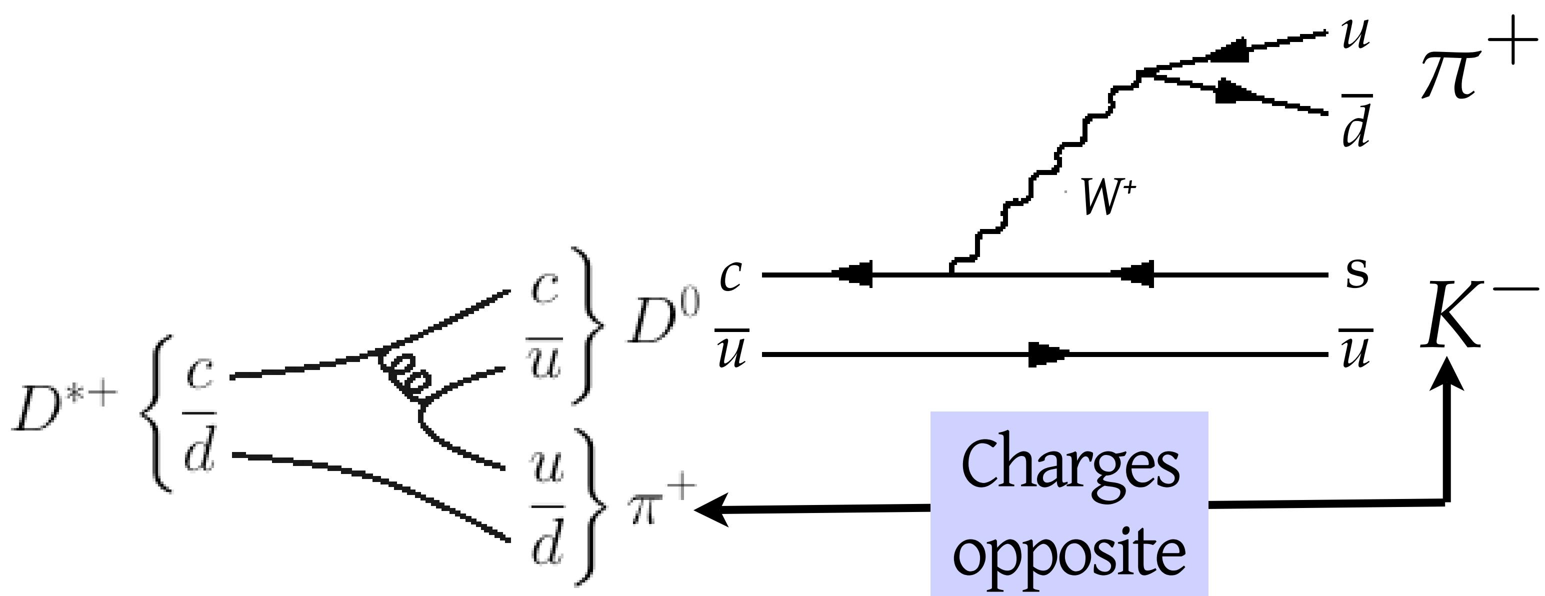
excellent background suppression



$\Delta m = \mathrm{m}(D^{*+}) - m(K\pi)$ (GeV/c^2)

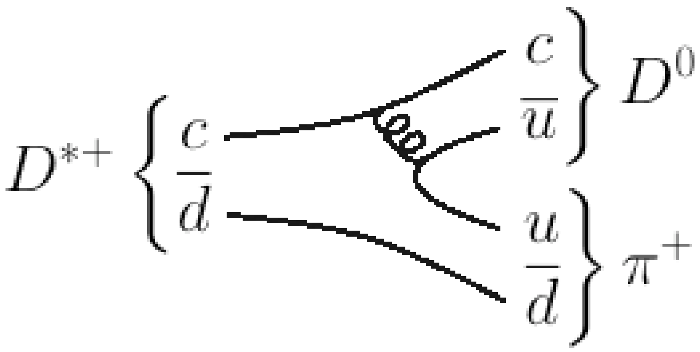
Right sign decays

$$D^{*+} \rightarrow \pi_s^+ D^0$$
$$\hookrightarrow K^- \pi^+$$

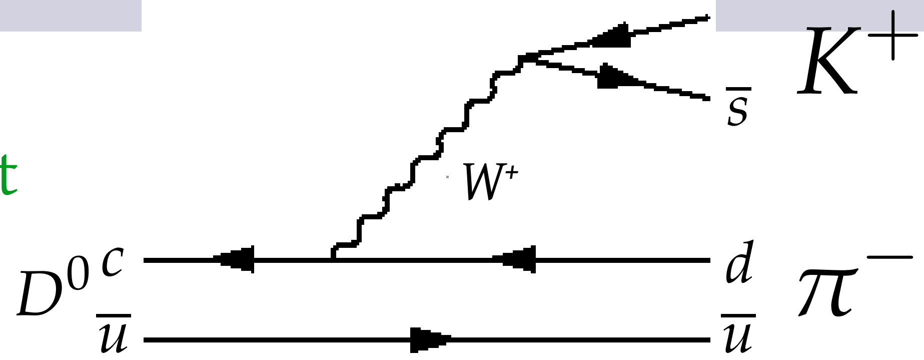


"Cabibbo favored" (CF)

Wrong sign decays



Direct

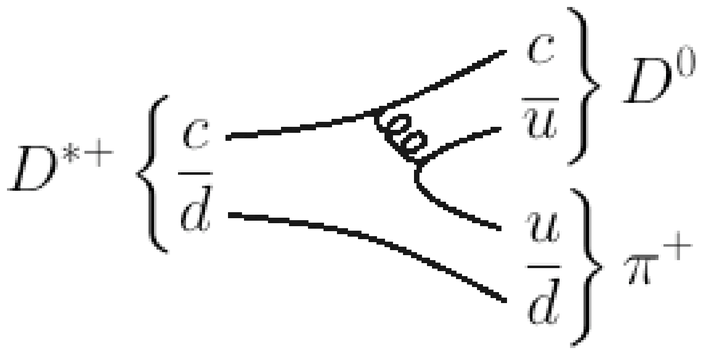


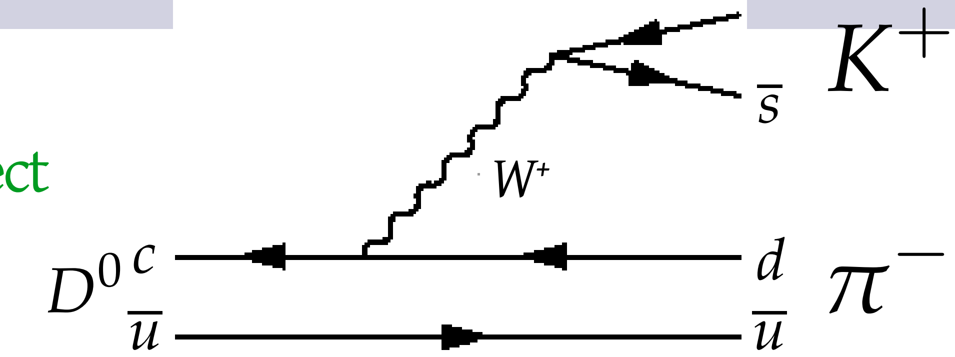
"Doubly Cabibbo suppressed" (DCS) decays

Relative rate: 0.3%

Wrong sign decays

Direct

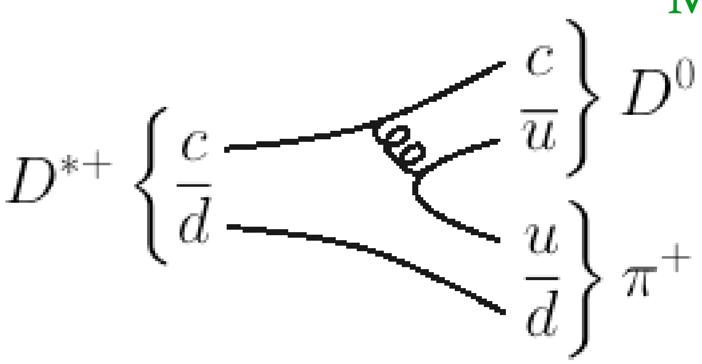


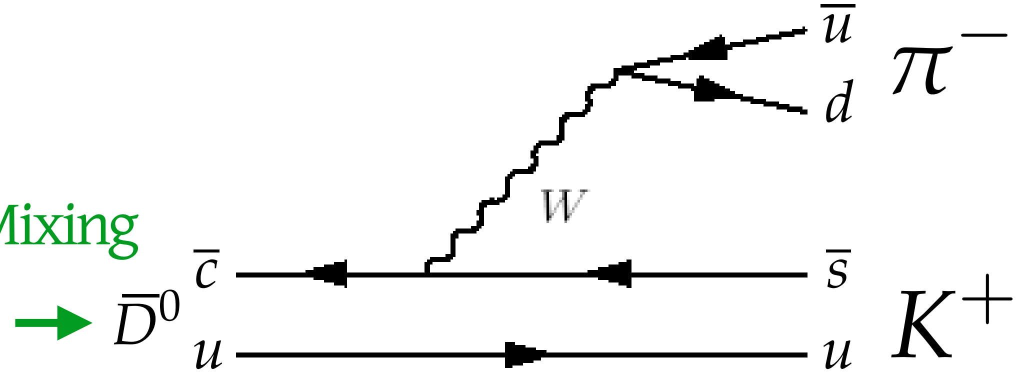


Relative rate: 0.3%

"Doubly Cabibbo suppressed" (DCS) decays

Mixing



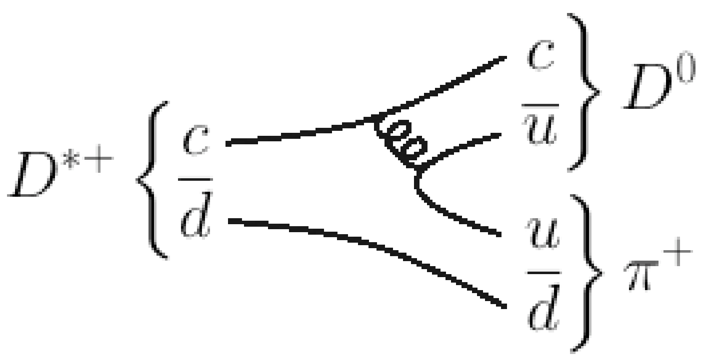


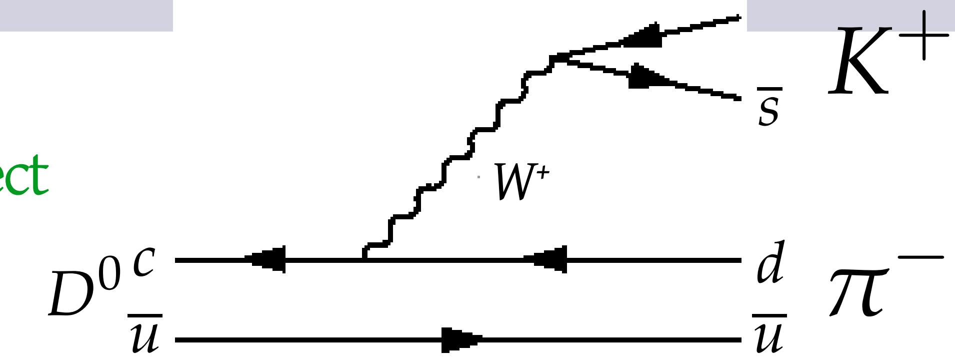
Relative rate: 0.005%
(for x or y=0.01)

Mixed decays

Wrong sign decays

Direct

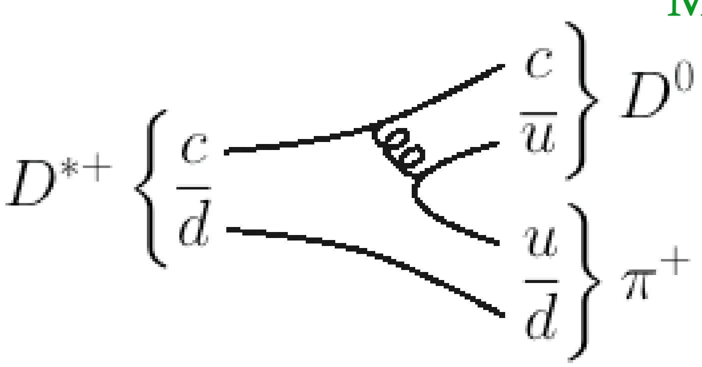


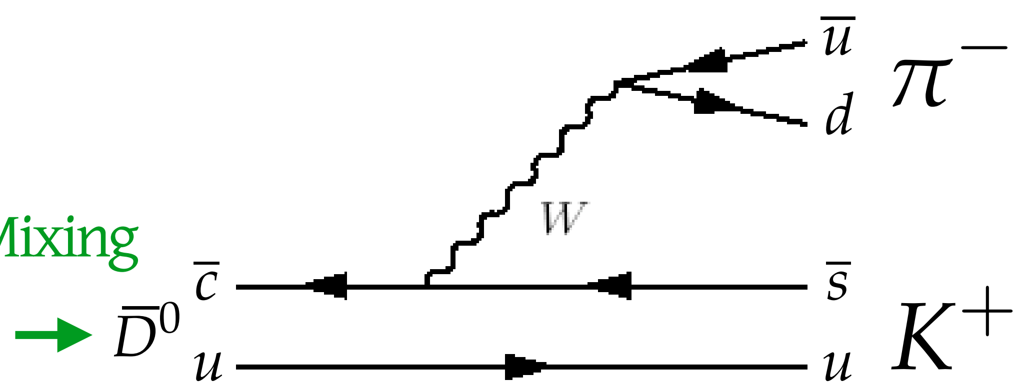


Relative rate: 0.3%

"Doubly Cabibbo suppressed" (DCS) decays

Mixing





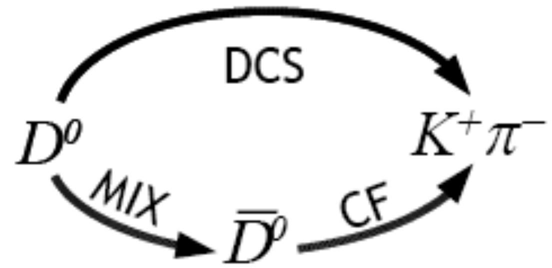
Relative rate: 0.005%
(for x or y=0.01)

Mixed decays

Same final state: ⇨ interference!

(increases sensitivity to mixing)

Time evolution of $D^0 \rightarrow K^+\pi^-$ decays



- Two ways to reach same final state:
  - ➔ interference
- Distinguish doubly Cabibbo-suppressed (DCS) from mixing using proper time evolution
  - DCS: exponential proper time distribution
  - Mixed decays only occur after some time
- Time evolution: $(|x| << 1,\ |y| << 1)$, CP-conserving

$$T_{\mathrm{WS}}(t) = e^{-\Gamma t}\left(\underbrace{R_{\mathrm{D}}}_{\text{DCS}} + \underbrace{\sqrt{R_{\mathrm{D}}}y'\ \Gamma t}_{\text{interference}} + \underbrace{\frac{x'^2 + y'^2}{4}(\Gamma t)^2}_{\text{mixing}}\right) \qquad (1)$$

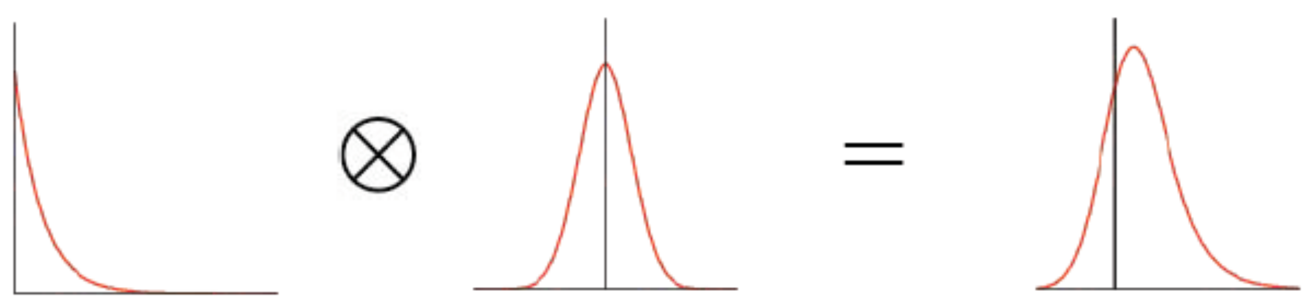
- strong phase: $x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}, \qquad y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi}$

  $\delta_{K\pi}$ is the strong phase between DCS and CF amplitides

Mixing analysis strategy

- Use $D^{*+} \rightarrow \pi^+ D^0$ decays to identify initial D^0 flavor
  - right sign (RS) $D^0 \rightarrow K^-\pi^+$ decays determine:
    - lifetime
    - signal PDF resolution parameters
  - In wrong-sign (WS) $D^0 \rightarrow K^+\pi^-$ sample:
    - Use proper time distribution to distinguish between DCS and mixing
  - use $(m_{K\pi}, \Delta m = m_{D*} - m_{K\pi})$ distribution to separate background from signal
- Unbinned likelihood fit to smeared RS, WS proper time (t) distributions

RS signal:



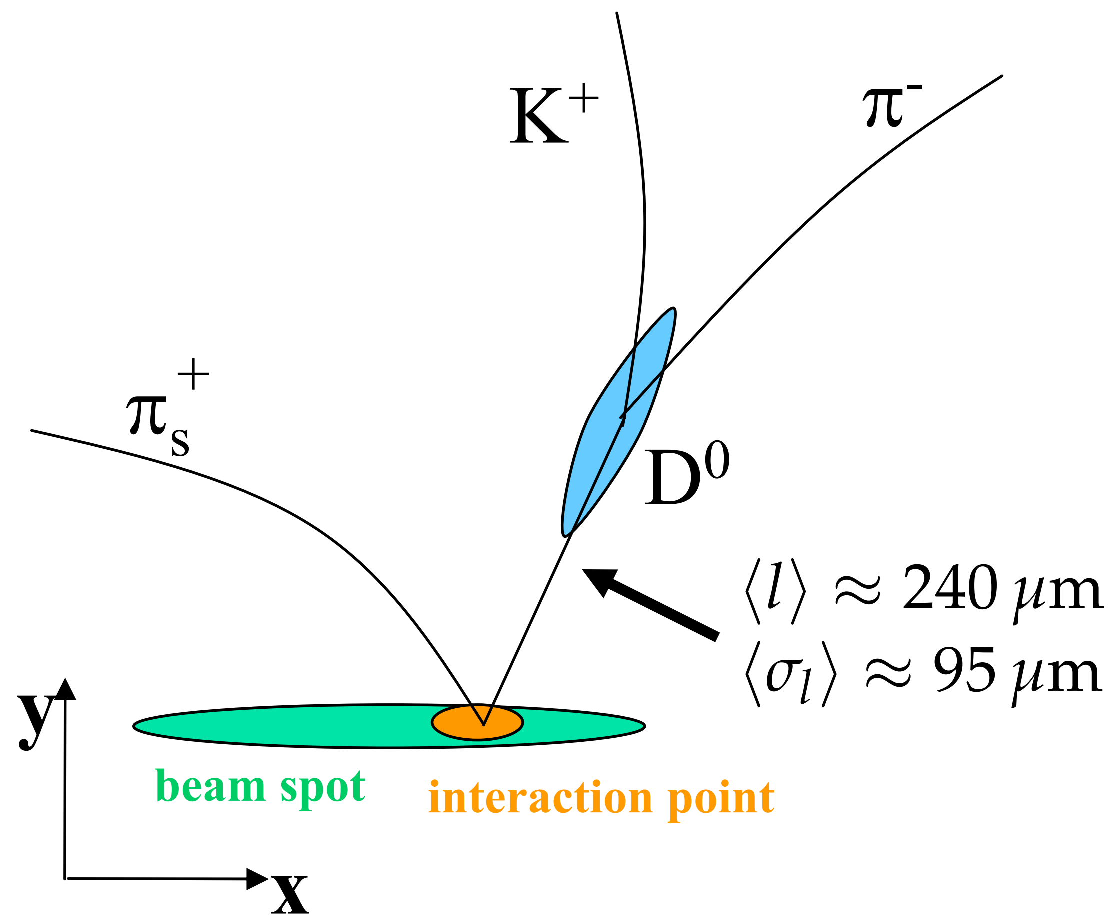
$$e^{-t/\tau} \otimes \frac{1}{\sqrt{2\pi}\sigma} e^{-t^2/2\sigma^2} = \frac{1}{\sqrt{2\pi}\sigma} \int_0^{\infty} e^{-t'/\tau} e^{-(t-t')^2/2\sigma^2}\, \mathrm{d}t'$$

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

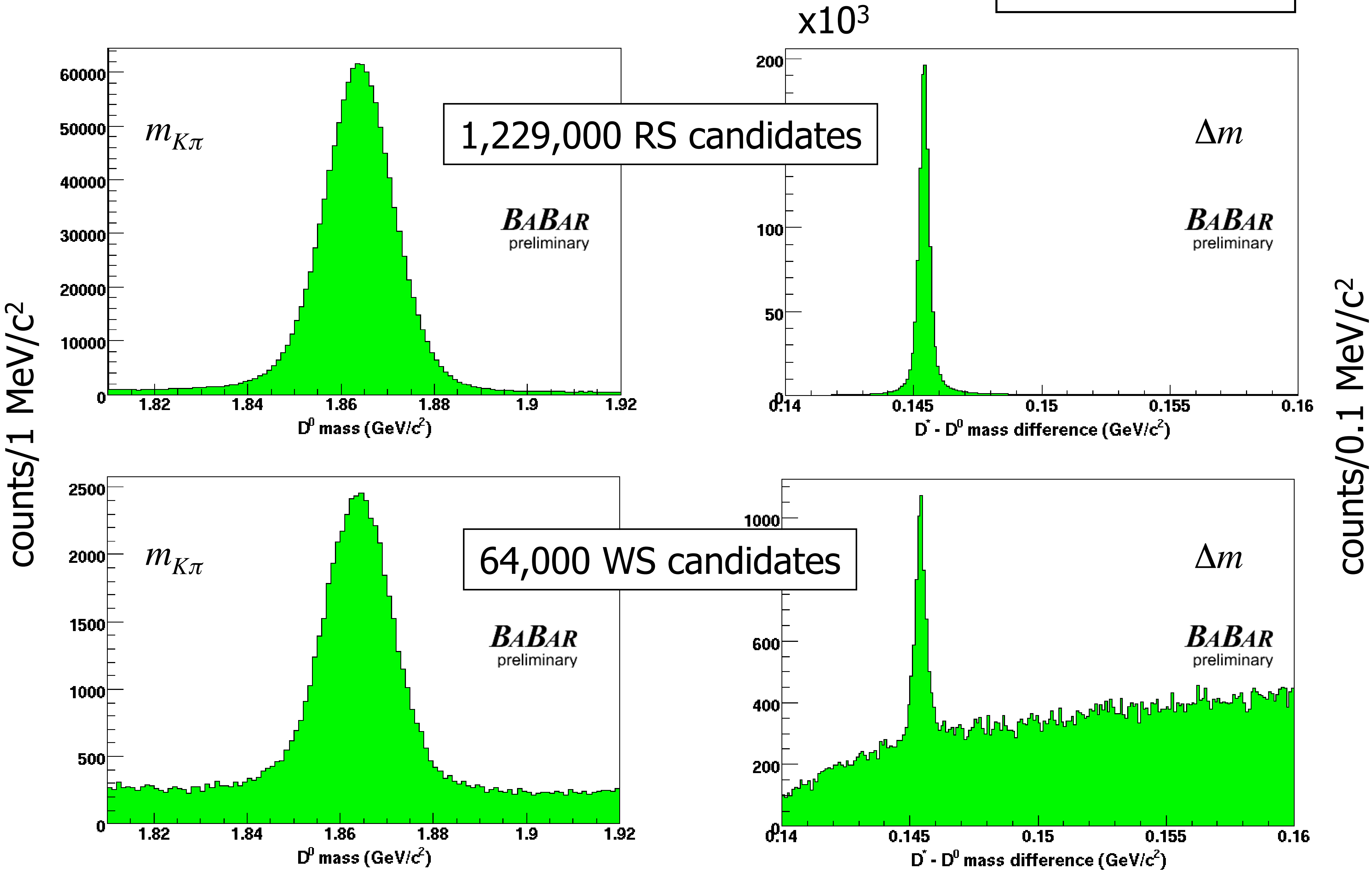
Δm=m($K\pi\pi_s$)-m($K\pi$)



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, δt<0.5 ps

Selected events

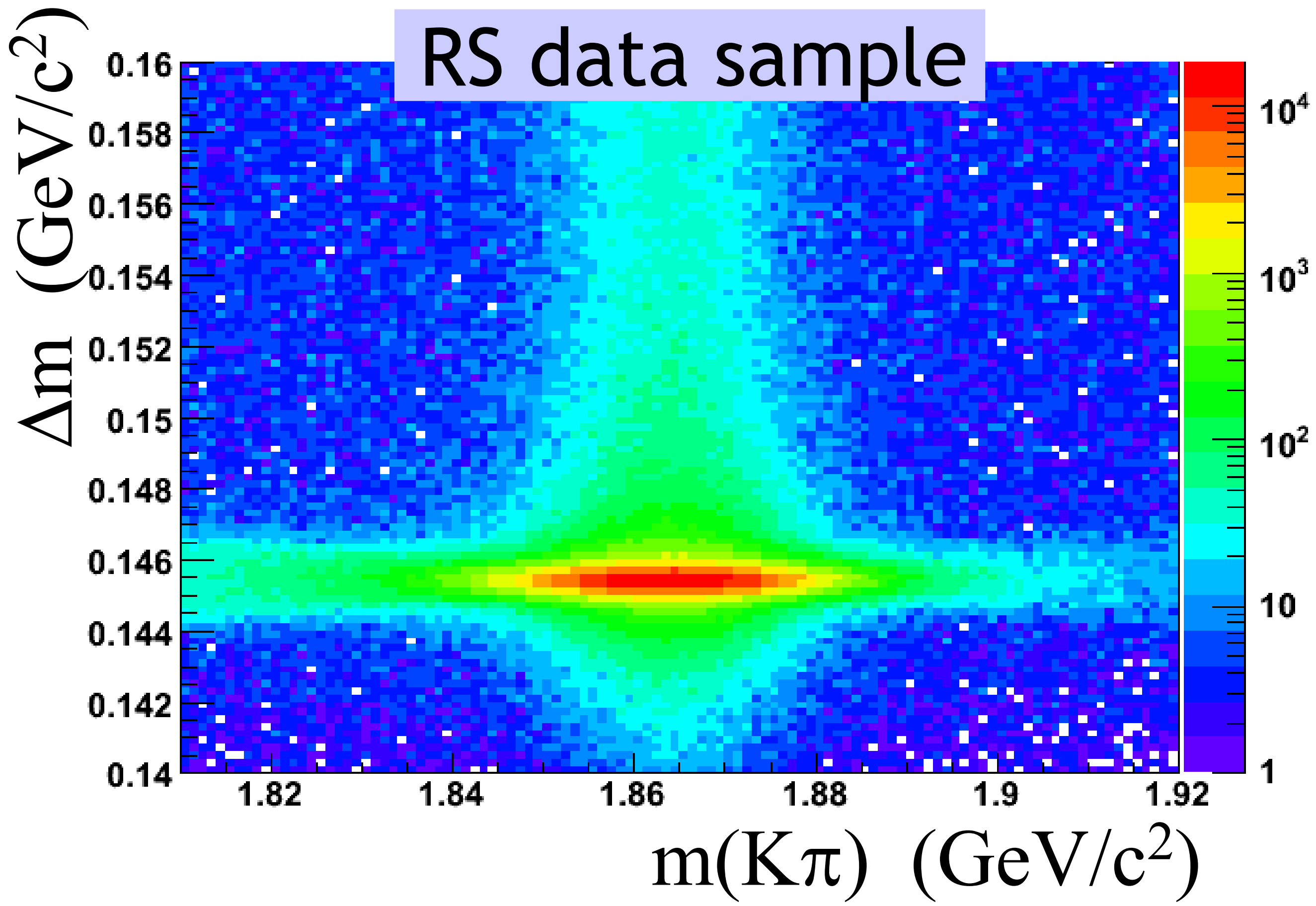
347 fb^{-1} on peak
37 fb^{-1} off peak
384 fb^{-1} total

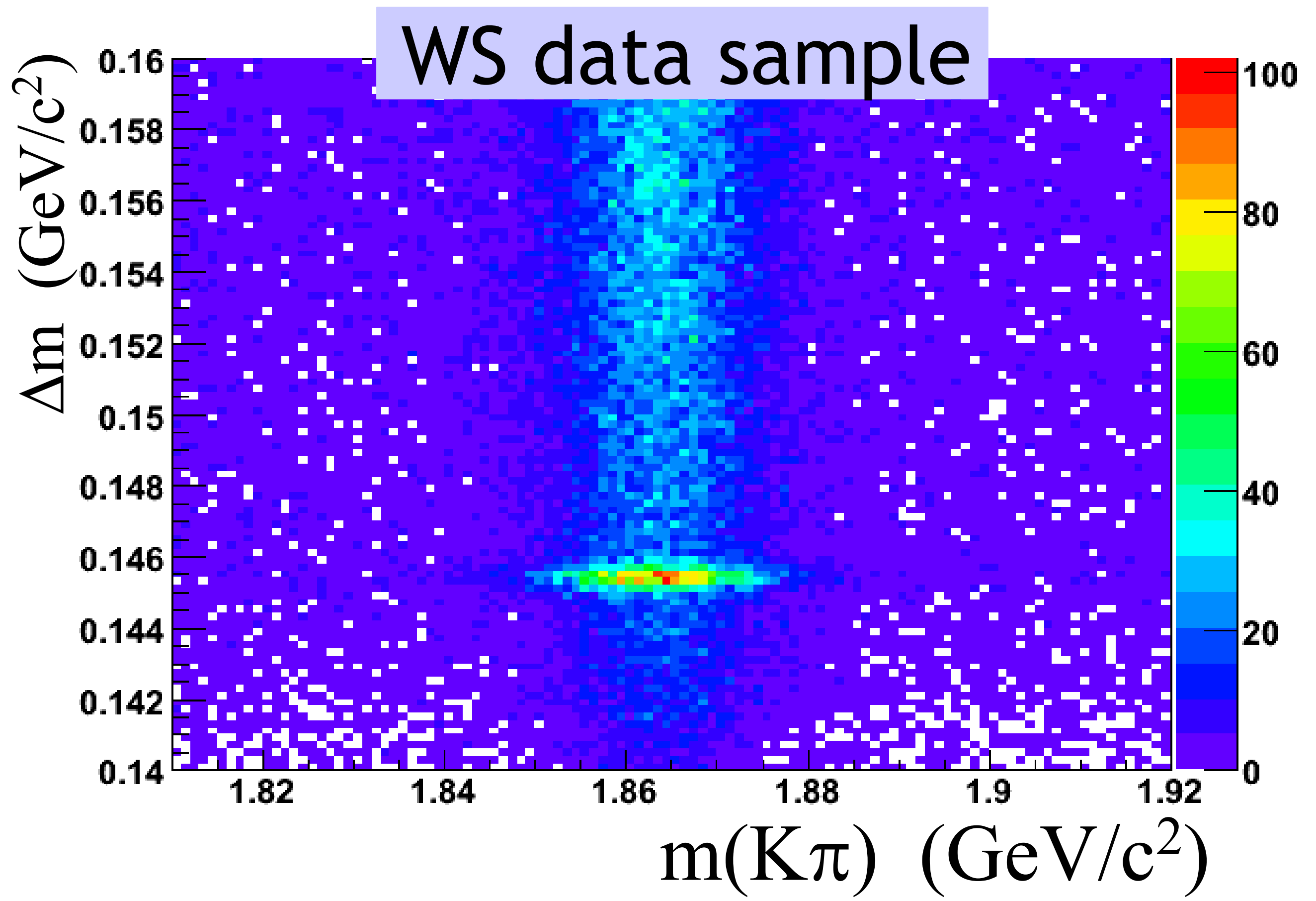


Δm vs. $m(K\pi)$

1,229,000 RS events

64,000 WS events





Separate signal from background using $m(K\pi)$ and Δm

Fit procedure

Unbinned extended maximum likelihood fit in several steps to reduce computational load

Fit to *m(Kπ)* and *Δm* distribution:

- separate signal from background in subsequent time fits
- RS and WS Samples fit simultaneously
- all parameters determined in fit to data, not MC

Fit RS proper time distribution:

- Determine D^0 lifetime and proper time signal resolution function $R(t)$
- include scaled proper time error in resolution function

Fit WS proper time distribution:

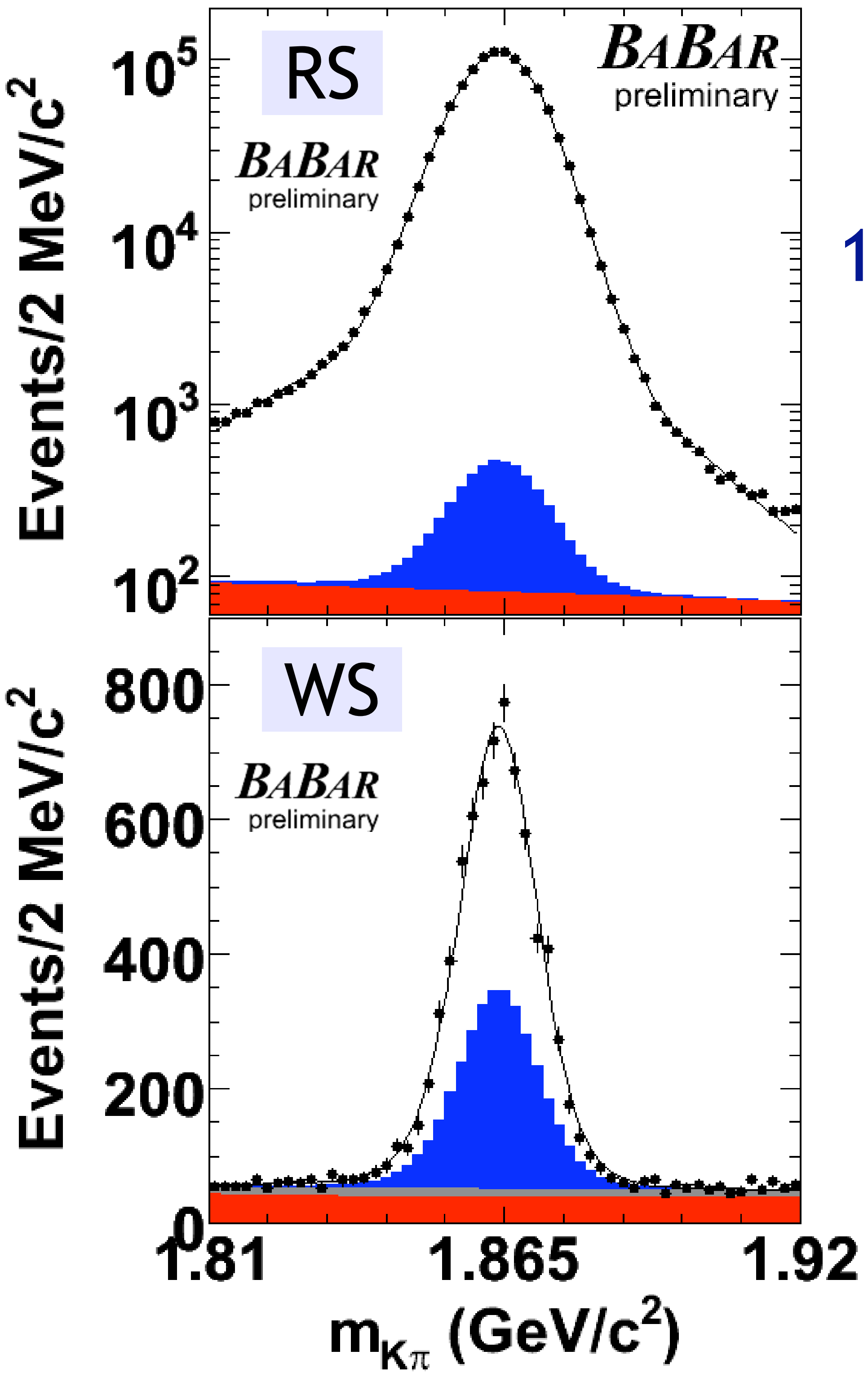
- fit signal with $T_{ws} \propto e^{-\Gamma t}\left[R_{\mathrm{D}} + \sqrt{R_{\mathrm{D}}}y'(\Gamma t) + (1/2)(x'^2 + y'^2)(\Gamma t)^2\right] \otimes R(t)$
- Resolution function $R(t)$ from RS fit
- RS model to fit D^0 background distributions
- Separate model for combinatorial background

Signal and Background components

- RS/WS samples each fitted with signal and 3 background PDFs based on distinct ($m_{K\pi}$, Δm) peaking structure

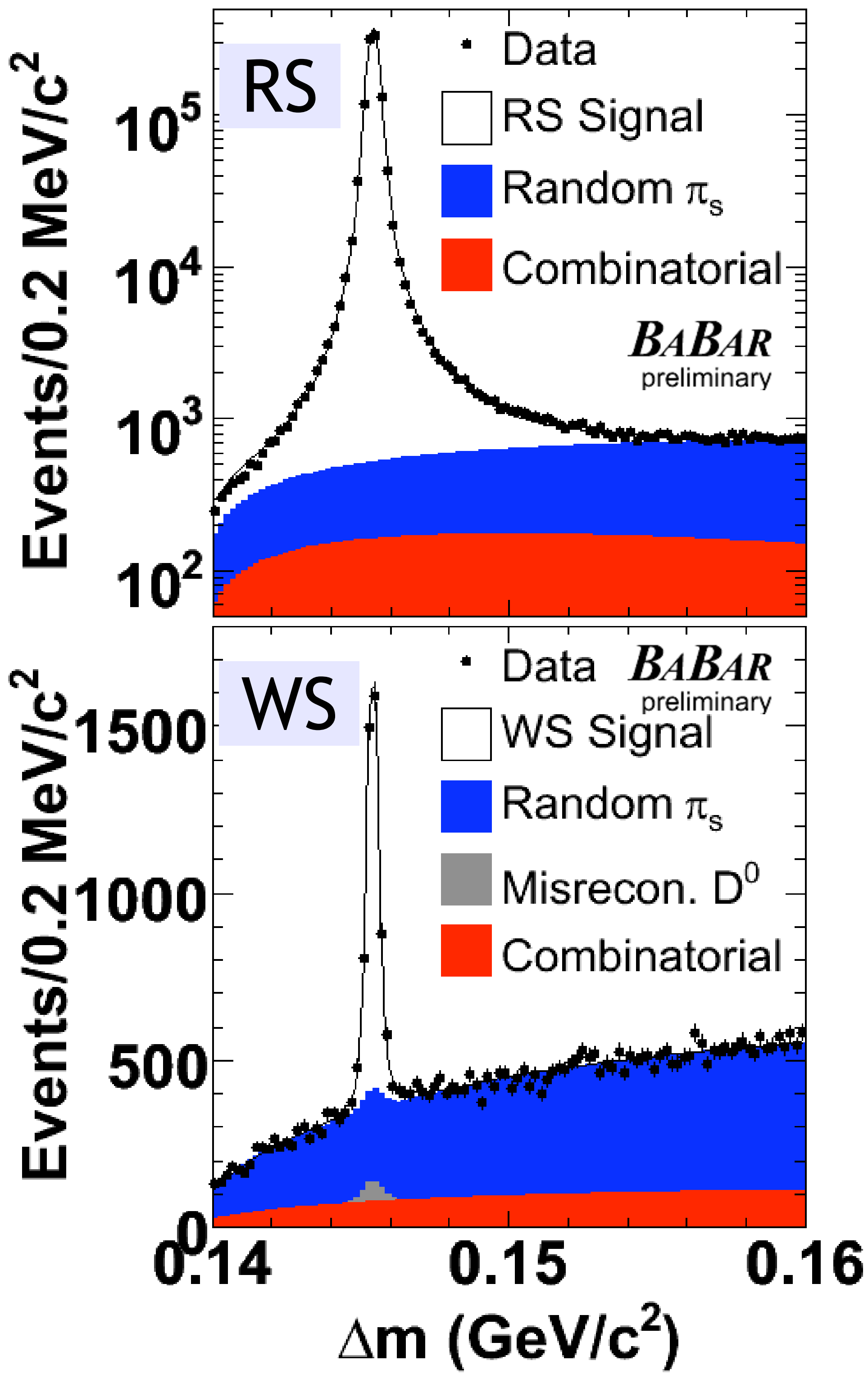
Category	Description	Peaking behavior
RS category 1	$D^0 \rightarrow K^- \pi^+$	m and Δm
RS category 2	Correctly reconstructed D^0 combined with an incorrect slow pion	m
RS category 3	Mis-reconstructed D^0, from $D^0 \rightarrow K^- l^+ \nu$, $D^0 \rightarrow \pi^- l^+ \nu$, $D^0 \rightarrow \pi^- \pi^+$, $K^- K^+$	Δm
RS category 4	Combinatoric	non-peaking
WS category 1	$D^0 \rightarrow K^+ \pi^-$	m and Δm
WS category 2	Correctly reconstructed D^0 combined with an incorrect slow pion	m
WS category 3	Doubly mis-ID'ed $D^0 \rightarrow K^- \pi^+$ decays and $D^0 \rightarrow \pi^- \pi^+$, $D^0 \rightarrow K^- K^+$	Δm
WS category 4	Combinatoric	non-peaking

Δm - $m(K\pi)$ fit results



RS signal:
1,141,500±1200
combinations

WS signal:
4,030±90
combinations



Proper time models

Model of signal and backgrounds containing a D^0

- Resolution function: sum of three Gaussians
- Gaussian width = proper time error × scale parameter
- mean of narrowest core Gaussian allowed to float

Model of combinatorial background

- Two Gaussians, one containing a power-law "tail" to model small non-prompt background

Separate proper time error distributions used in signal and combinatorial background models

RS proper time fit

D^0 lifetime and resolution function fitted in RS sample

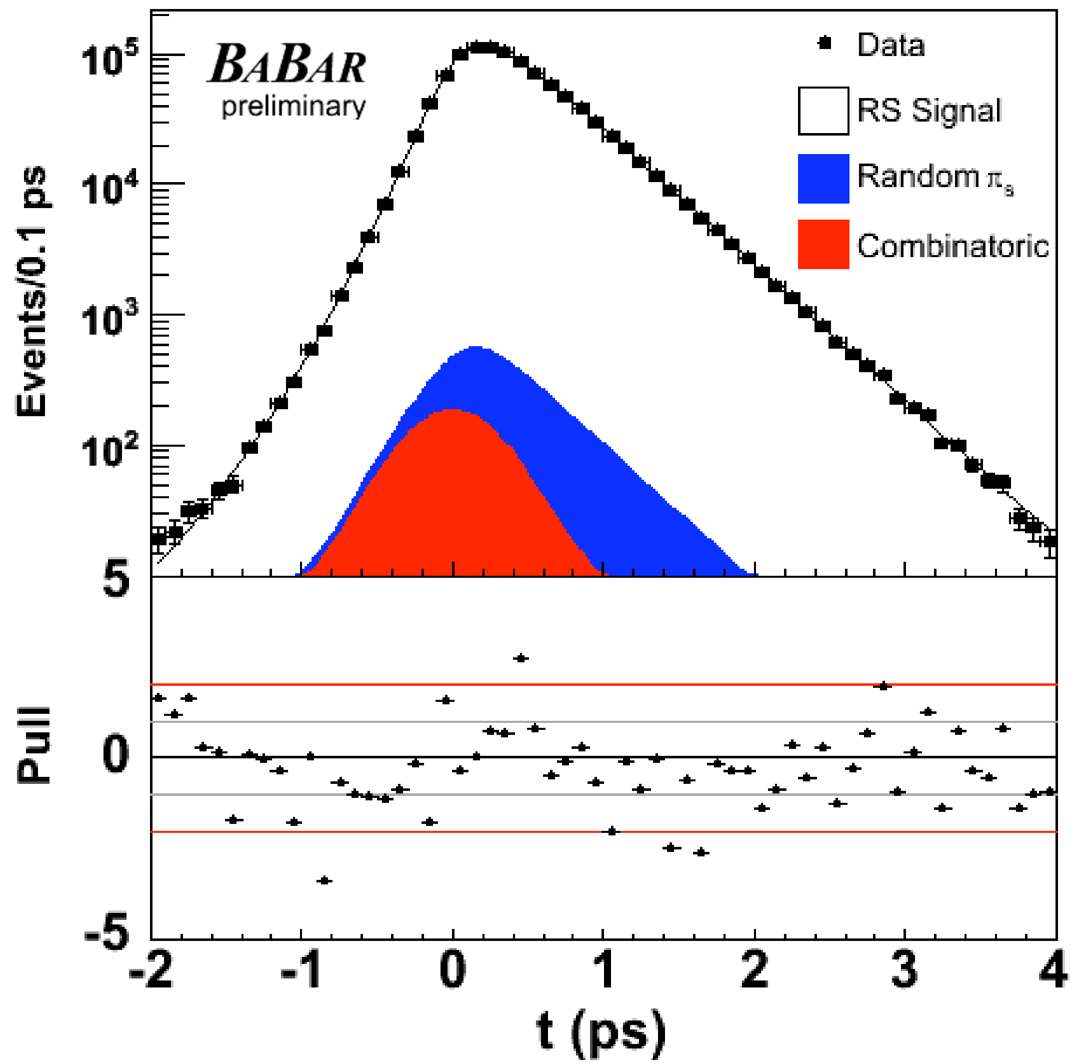
$$\tau = [410.3 \pm 0.6\,(stat)]\ \text{fs}$$

Consistent with PDG

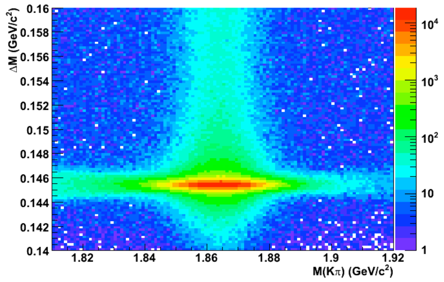
$$(410.1 \pm 1.5)\ \text{fs}$$

Systematics dominated by signal resolution function

RS decay time, signal region



plot selection:
$1.843 < m < 1.883$ GeV/c²
$0.1445 < \Delta m < 0.1465$ GeV/c²



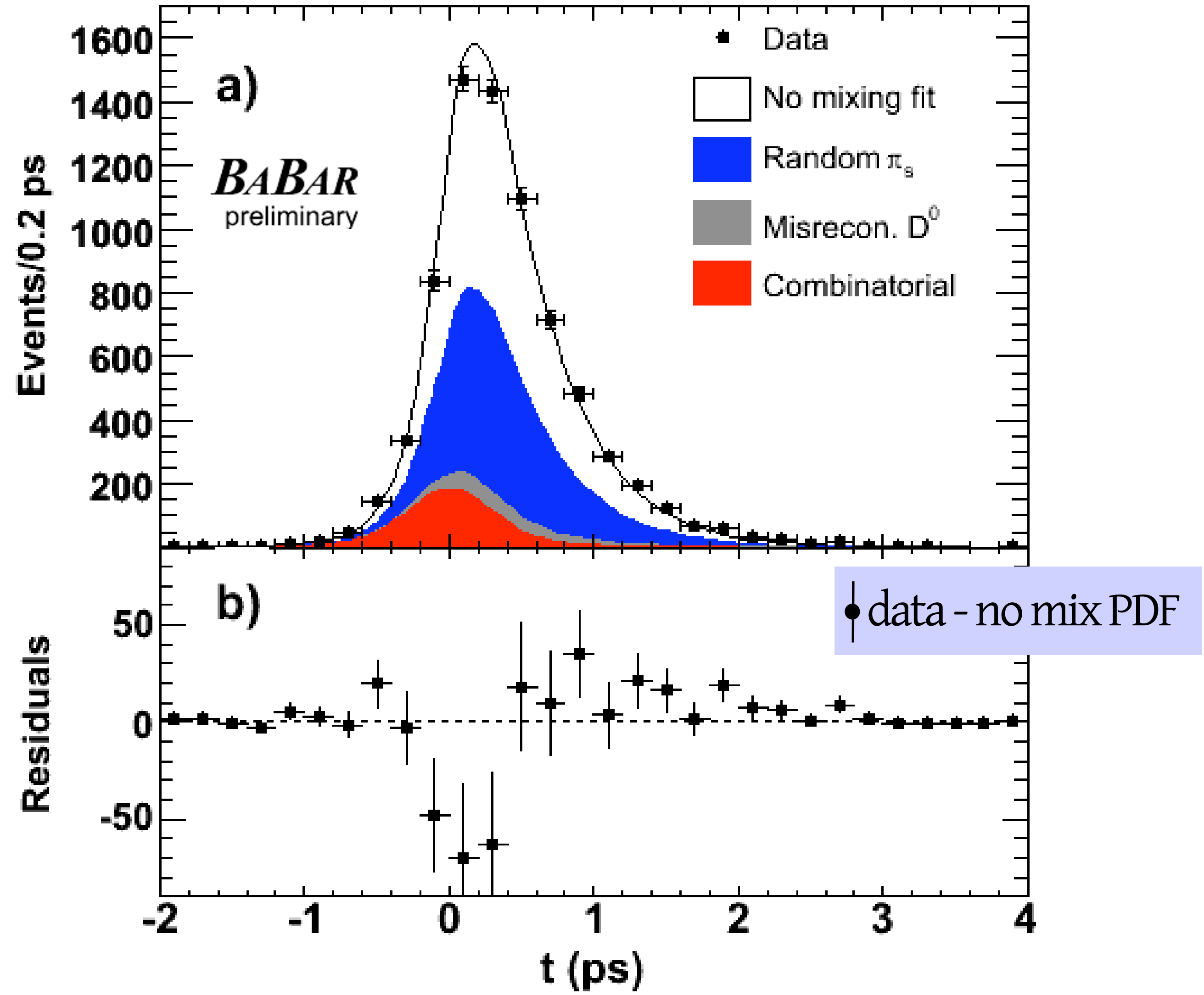
WS fit with no mixing

- Fit results assuming no mixing:

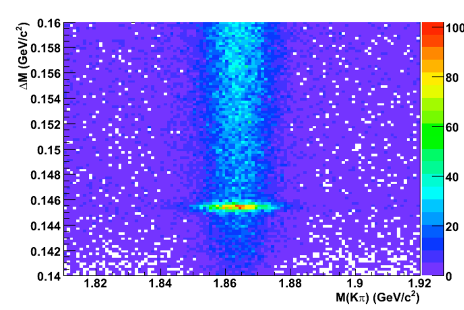
R_D: $(3.53\pm0.08\pm0.04)\times10^{-3}$

Residuals in signal region are unsatisfactory: $\chi^2/\text{bin} = 49.7/28$

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



WS fit with mixing

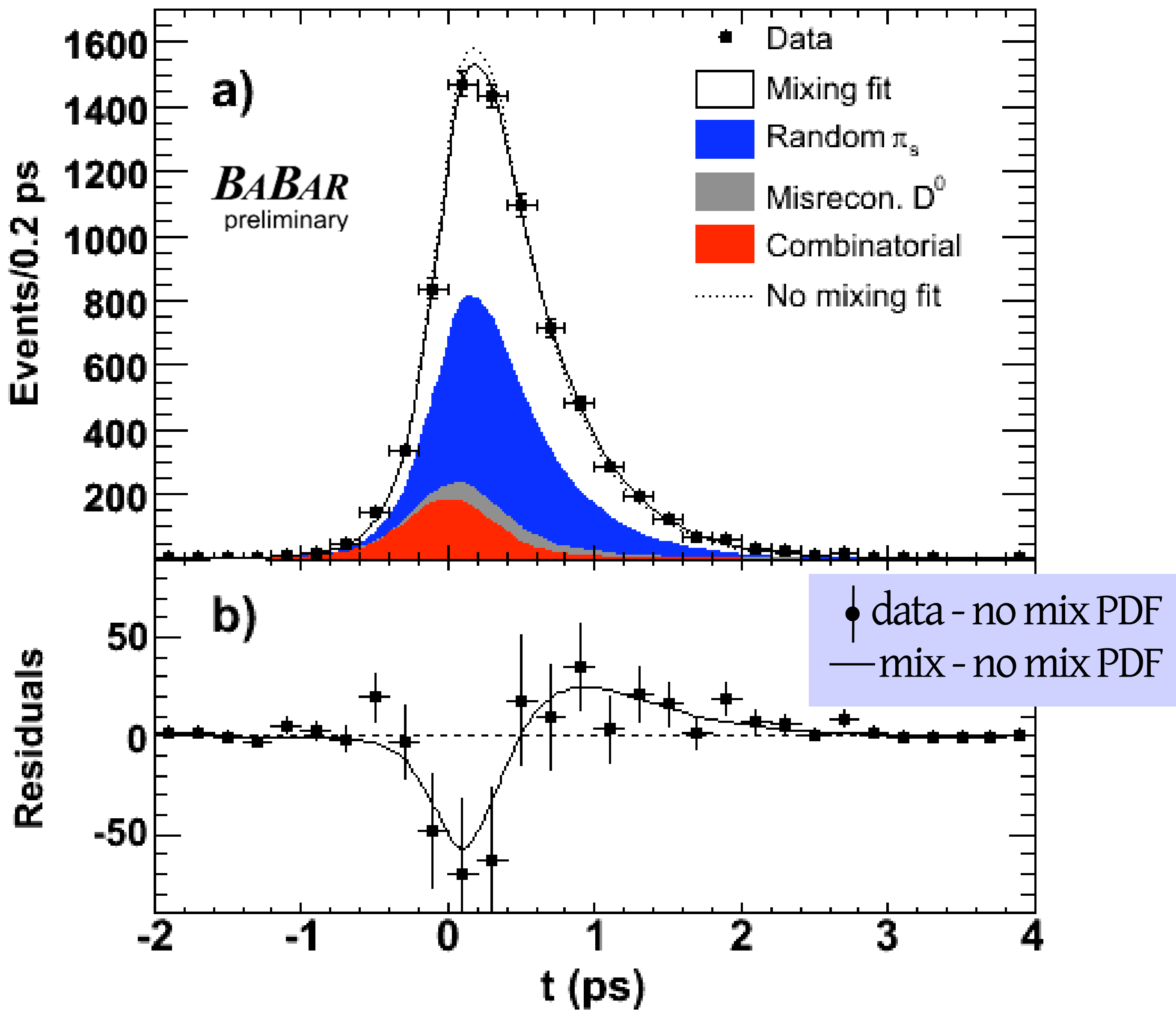
- Fit results allowing mixing:

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 mixing describes the data better: χ^2/bin = 31/28

How significant?



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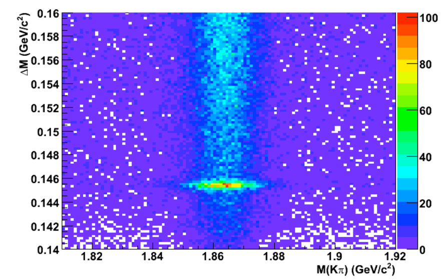
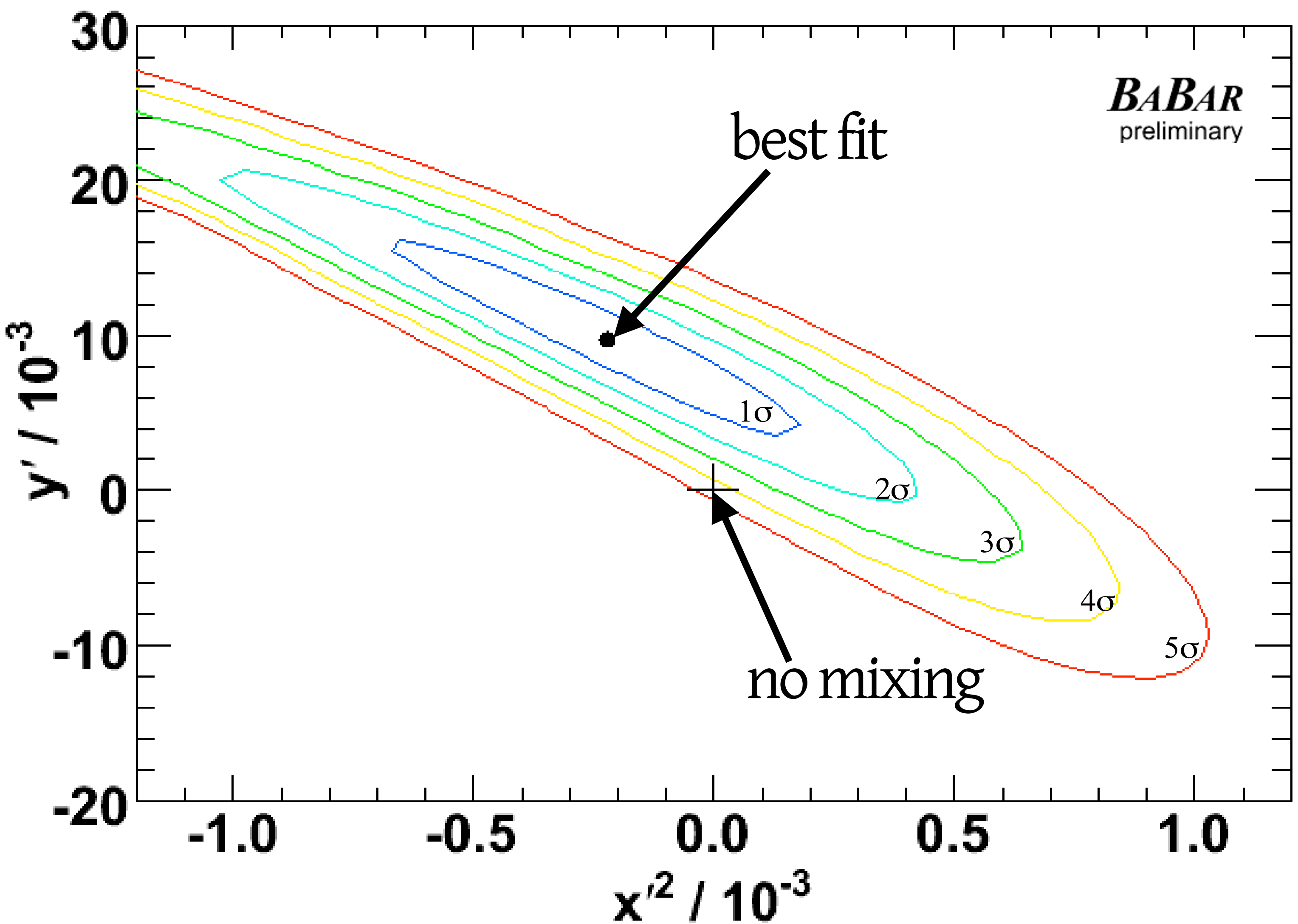


Signal Significance

Significance computed from change in log likelihood:

1 – CL =
3.17×10^{-1} (1σ)
4.55×10^{-2} (2σ)
2.70×10^{-3} (3σ)
6.33×10^{-5} (4σ)
5.73×10^{-7} (5σ)



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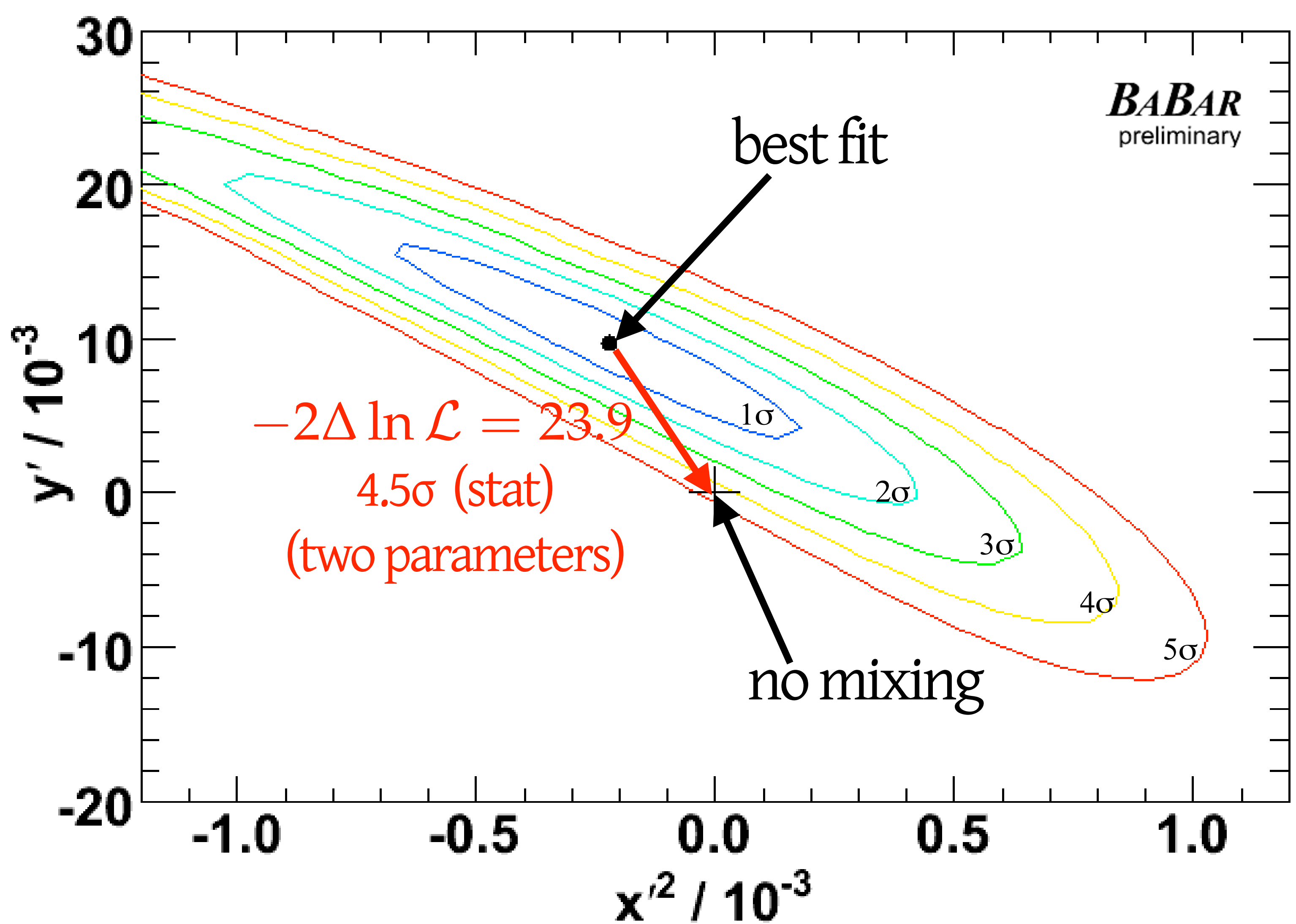
5.73 x 10^{-7} (5σ)



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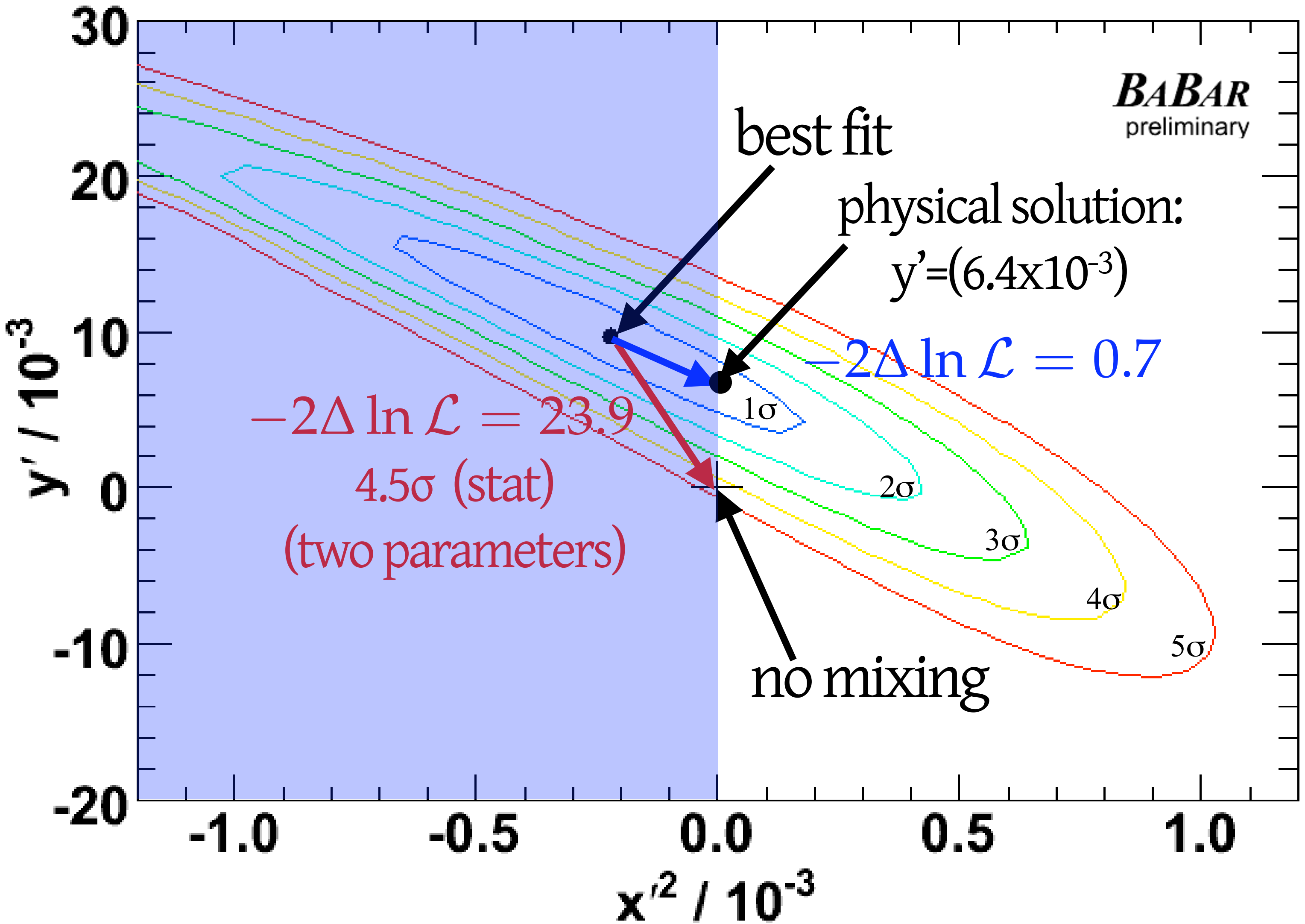
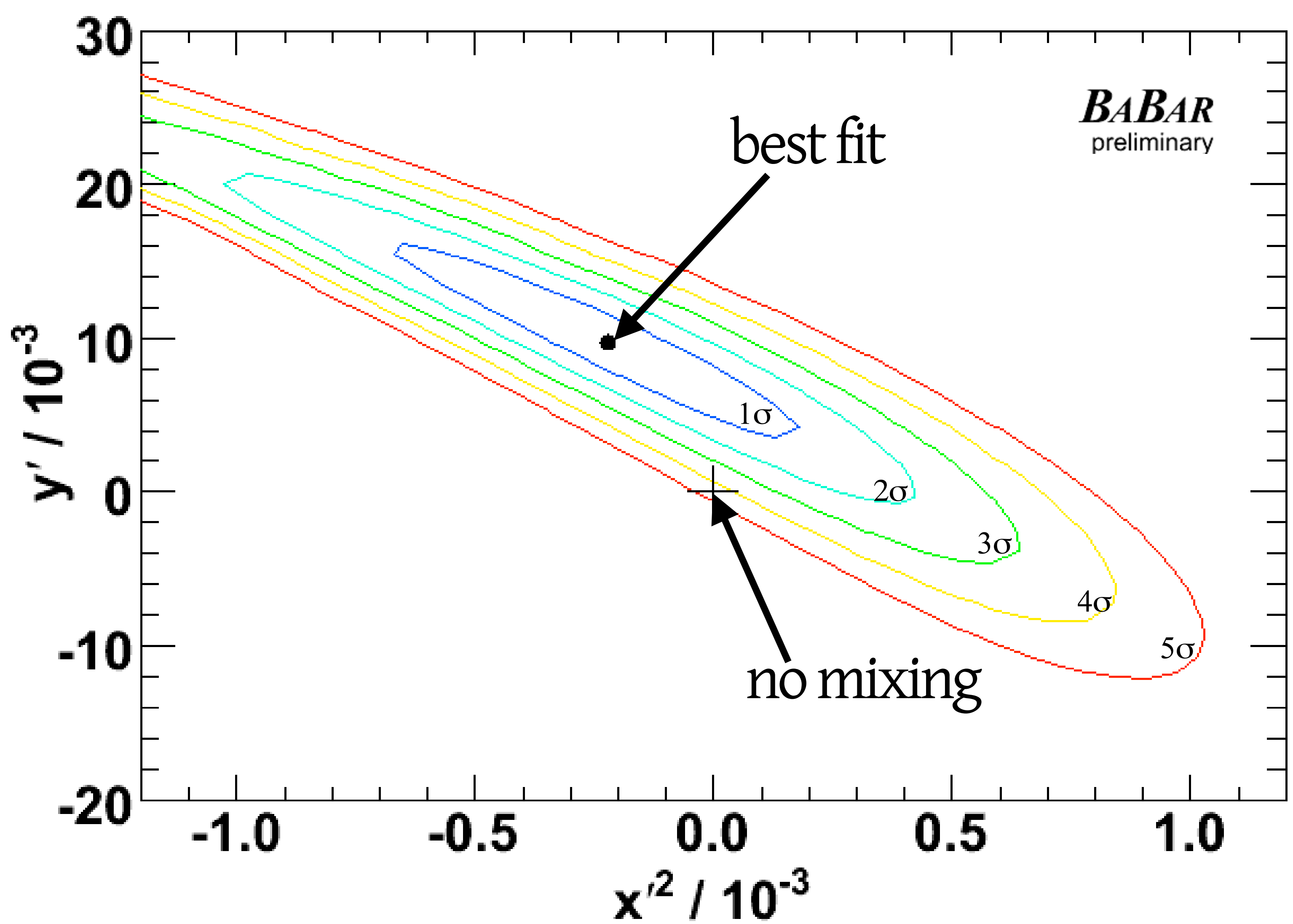


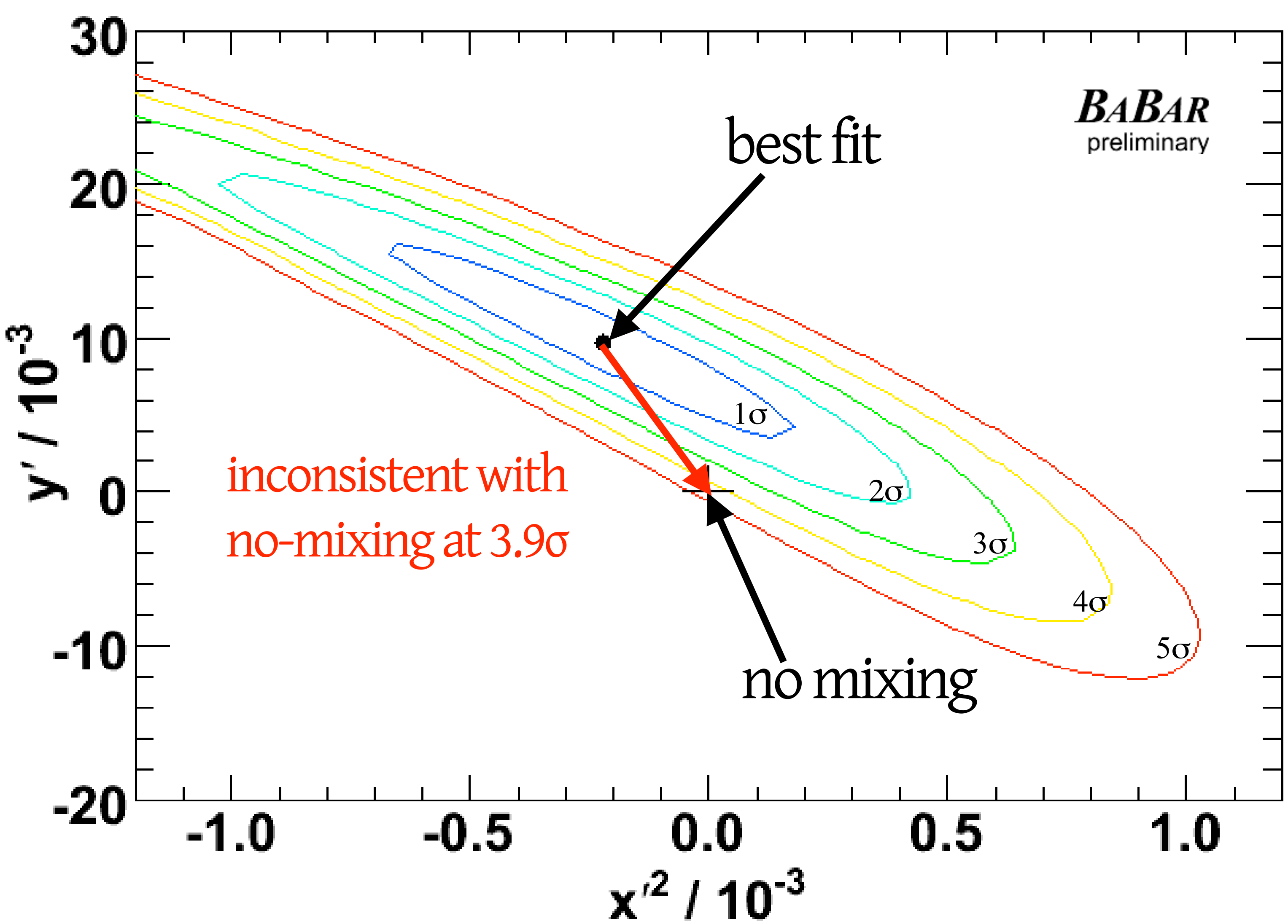
Signal significance with systematics

Including significance decreases mixing significance



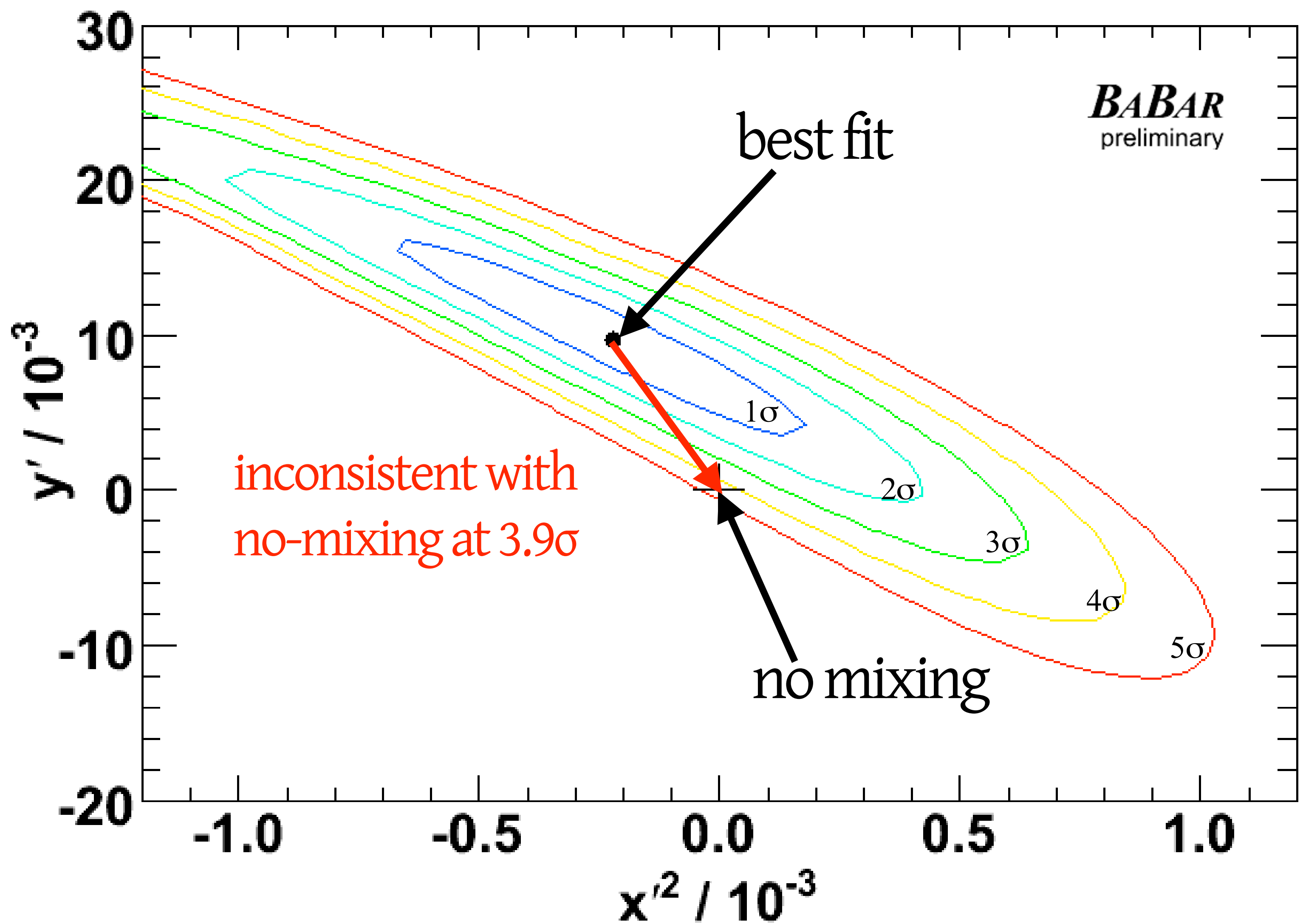
Signal significance with systematics

Including significance decreases mixing significance



Signal significance with systematics

Including significance decreases mixing significance



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

Validation studies

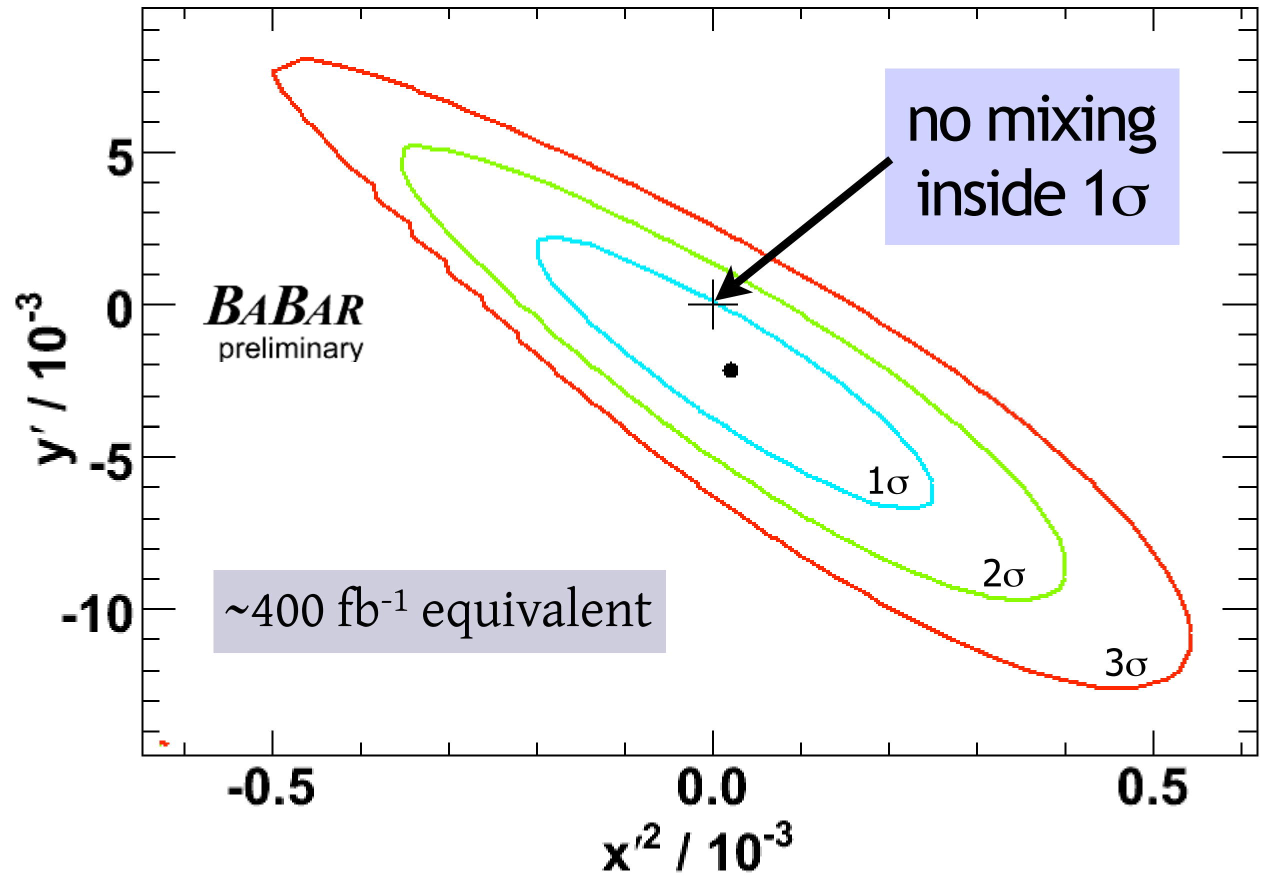
Performed extensive checks of mixing signal:

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

No significant mixing signal in MC:

x'^2: $(-0.02\pm0.18)\times10^{-3}$
y': $(-2.2\pm3.0)\times10^{-3}$

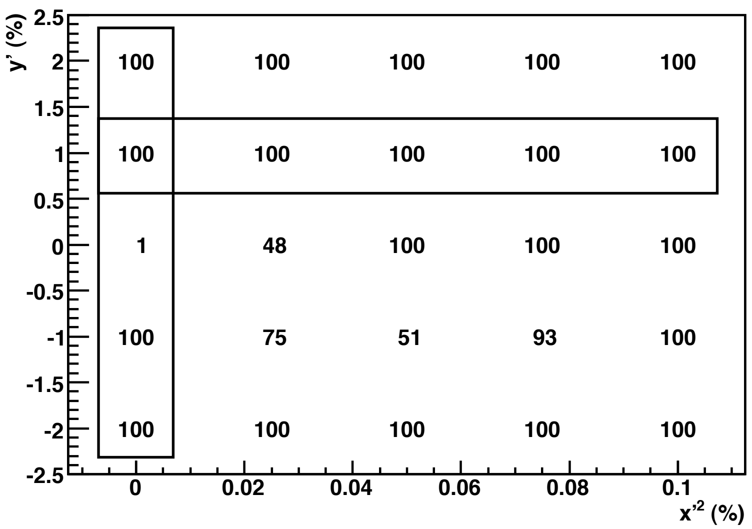
Fit to generic MC with no mixing



Bias studies

generated 100 toy MC samples
at each of 25 (x'^2,y') points:

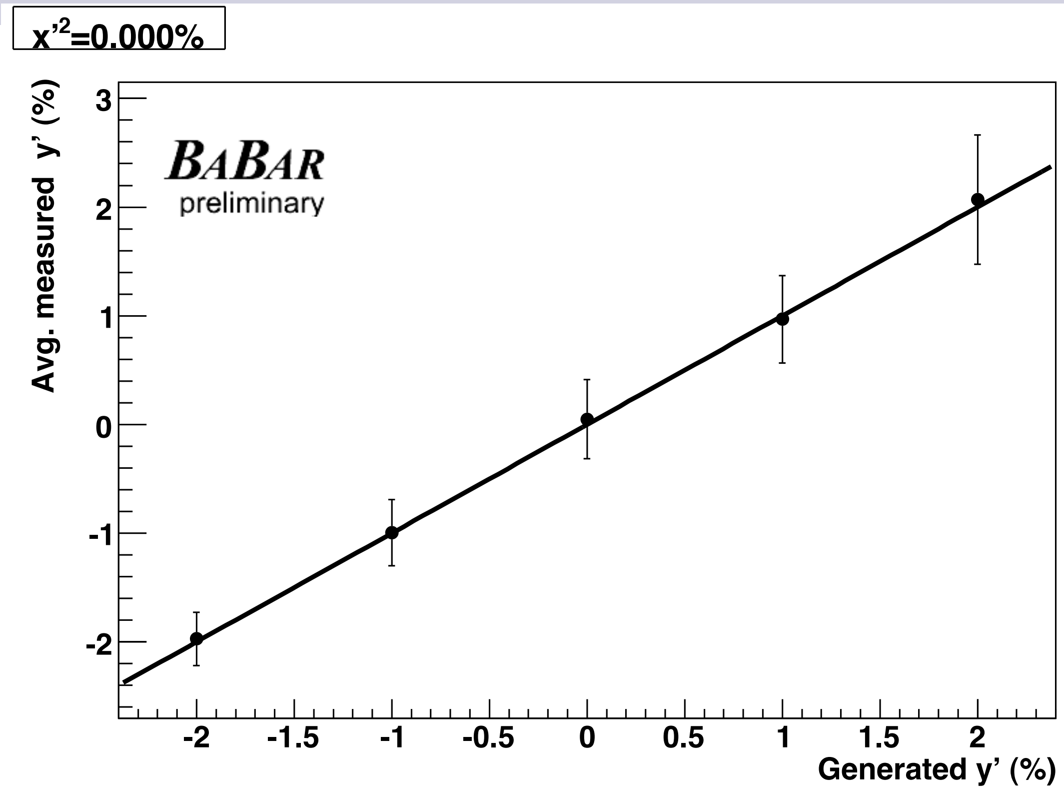
•sample sizes same as WS data

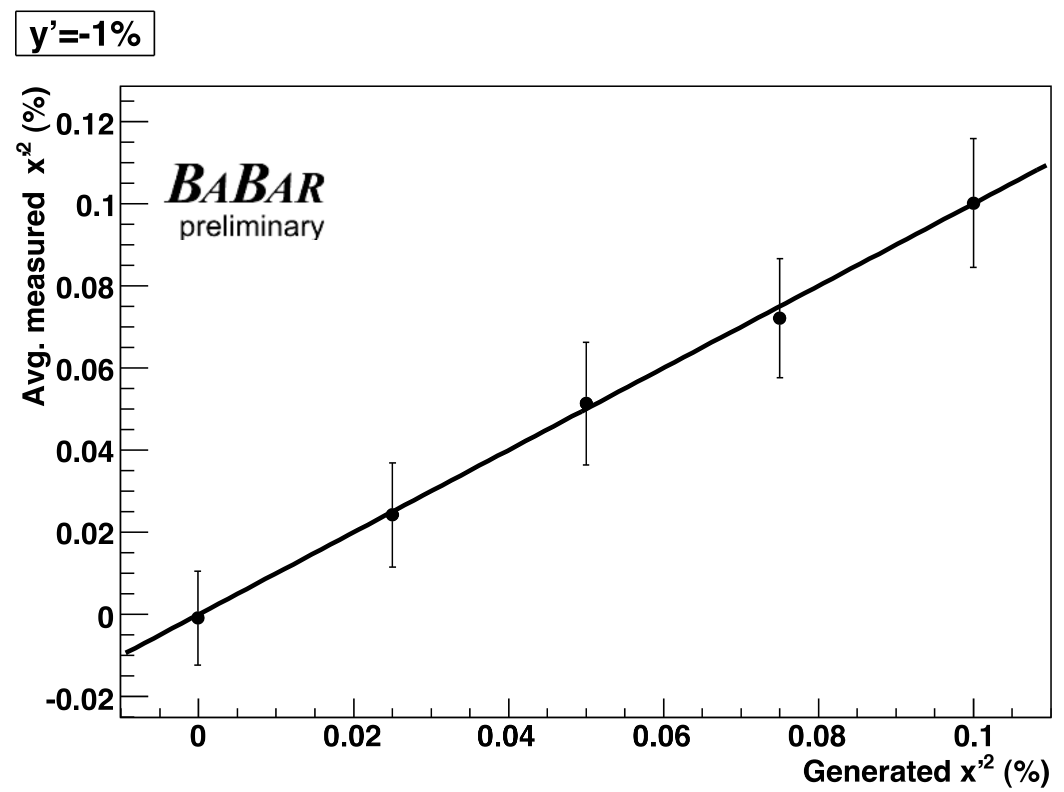


fits (out of 100) where the no-mixing hypothesis is excluded at more than 3σ

No biases seen at any of the 25 points

full MC samples generated with mixing also show no bias when fit for mixing





average and RMS of fitted vs generated mixing parameters

Validation: Fit RS Data for Mixing

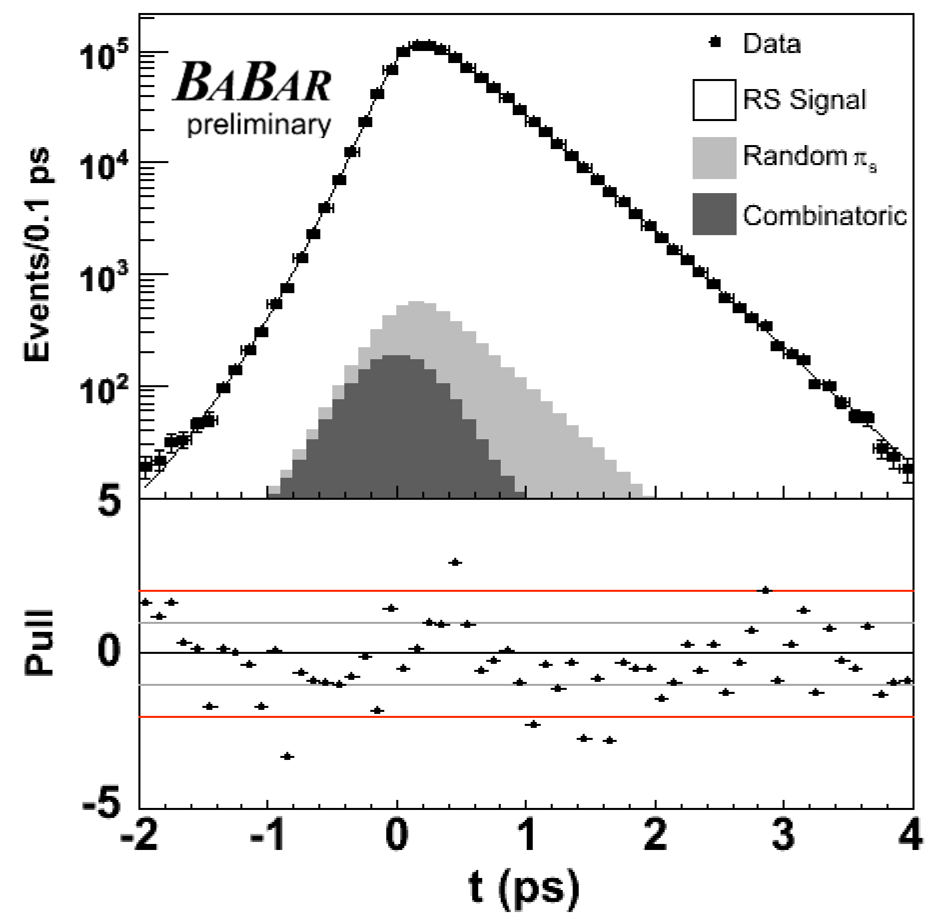
Fit RS data with PDF allowing mixing

x'^2: $(-0.01\pm0.01)\times10^{-3}$
y': $(0.26\pm0.24)\times10^{-3}$

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

- Mixing not signficant in large sample fit
- Proper time distribution is described properly

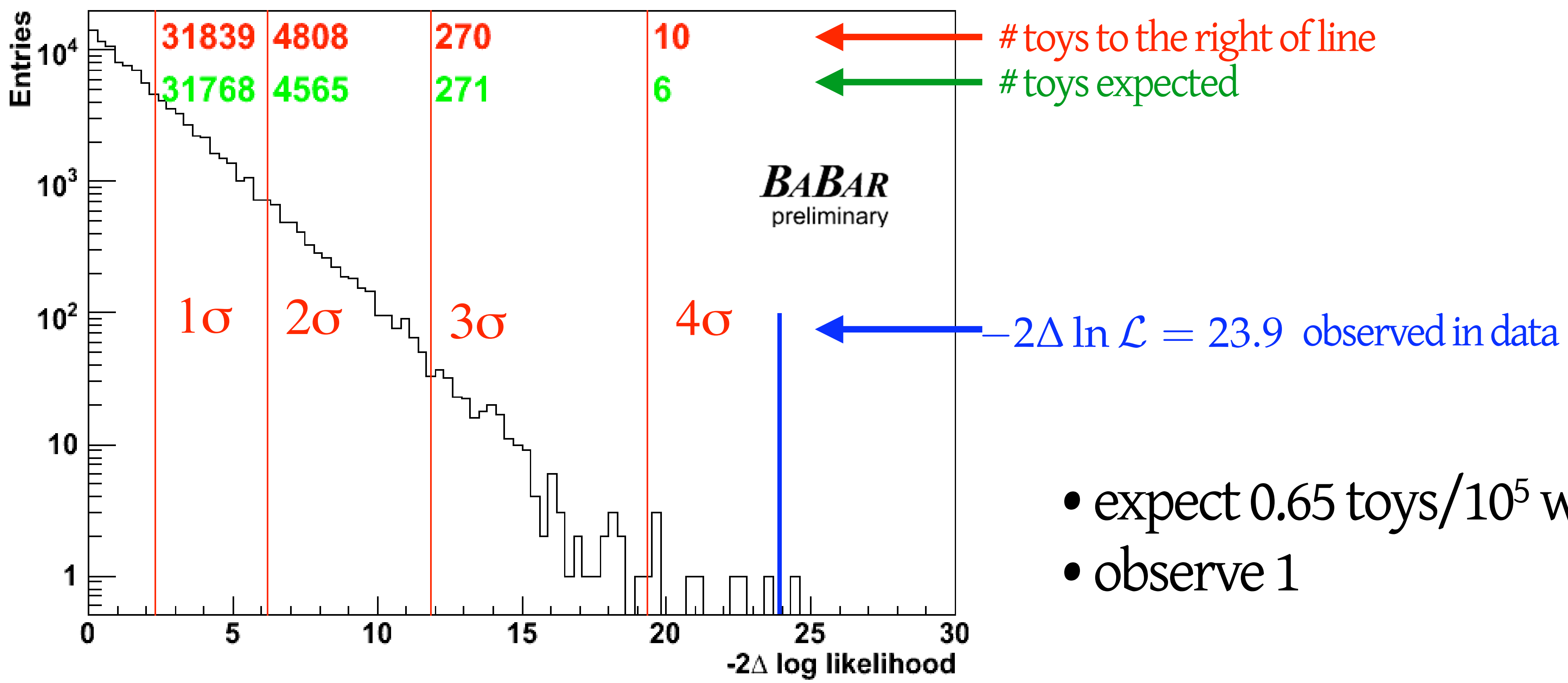
RS proper time, signal region



Validation: coverage of $-2\Delta \ln \mathcal{L}$

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



- expect 0.65 toys/10^5 with $-2\Delta \ln \mathcal{L} > 23.9$
- observe 1

$-2\Delta \ln \mathcal{L}$ accurately estimates significance

Validation: Alternate fit strategy

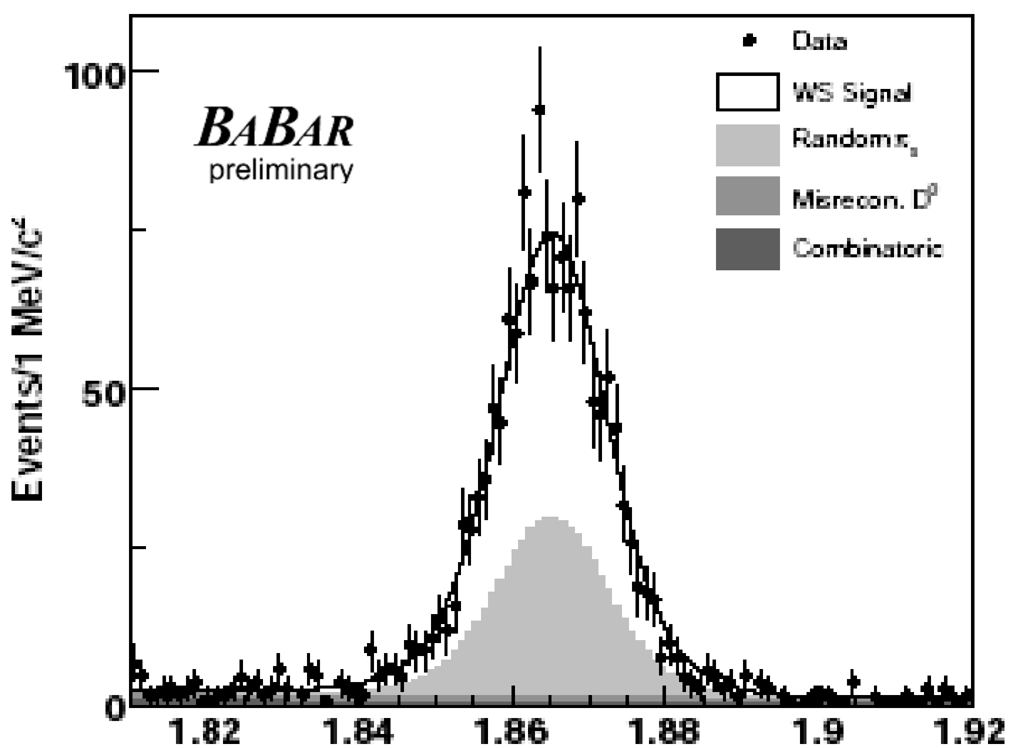
Fit $m(K\pi)$ and Δm in bins of proper time:

- 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

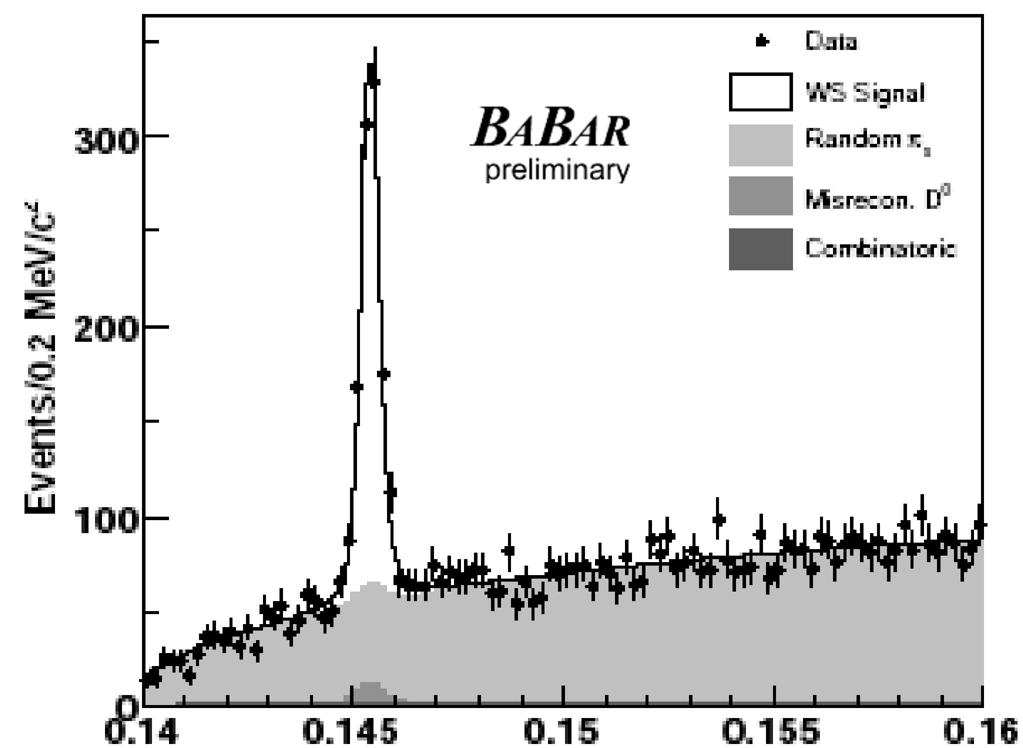
proper time bins:

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

example fit (0.75 < t < 2.5 psec):



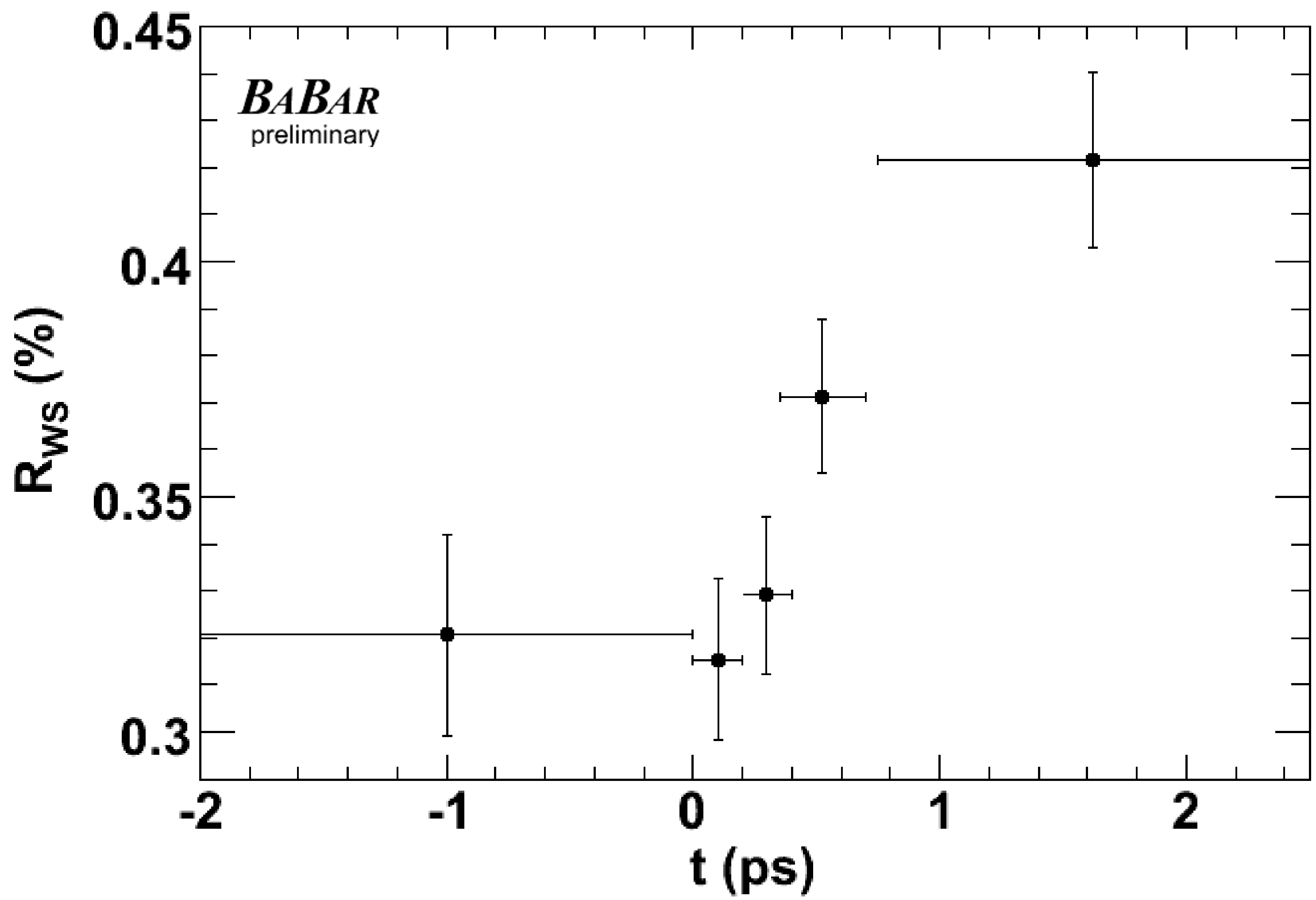
$m(K\pi)$ (GeV/c^2)



Δm (GeV/c^2)

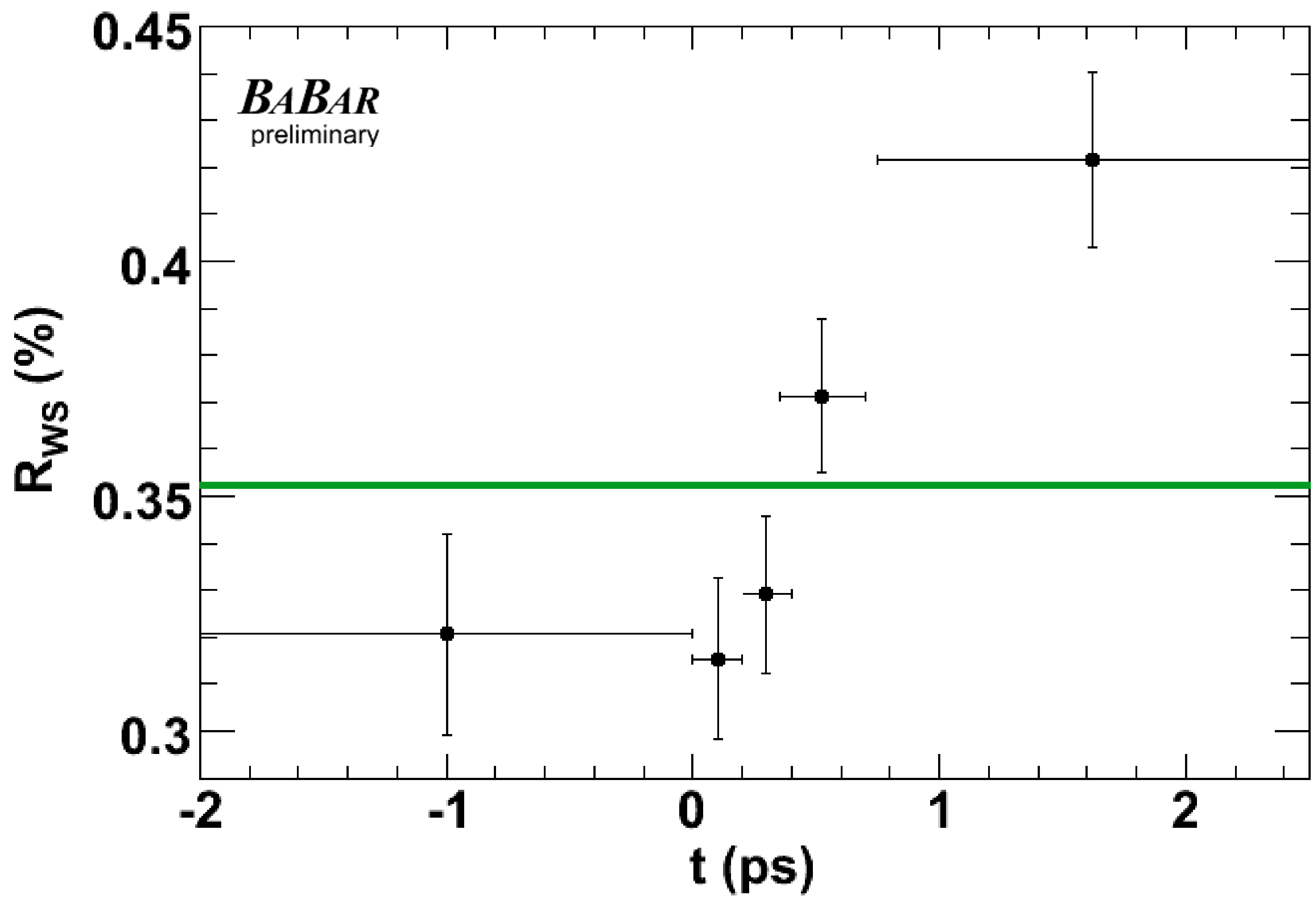
Validation: Alternate fit strategy

Rate of WS events clearly increase with proper time:



Validation: Alternate fit strategy

Rate of WS events clearly increase with proper time:

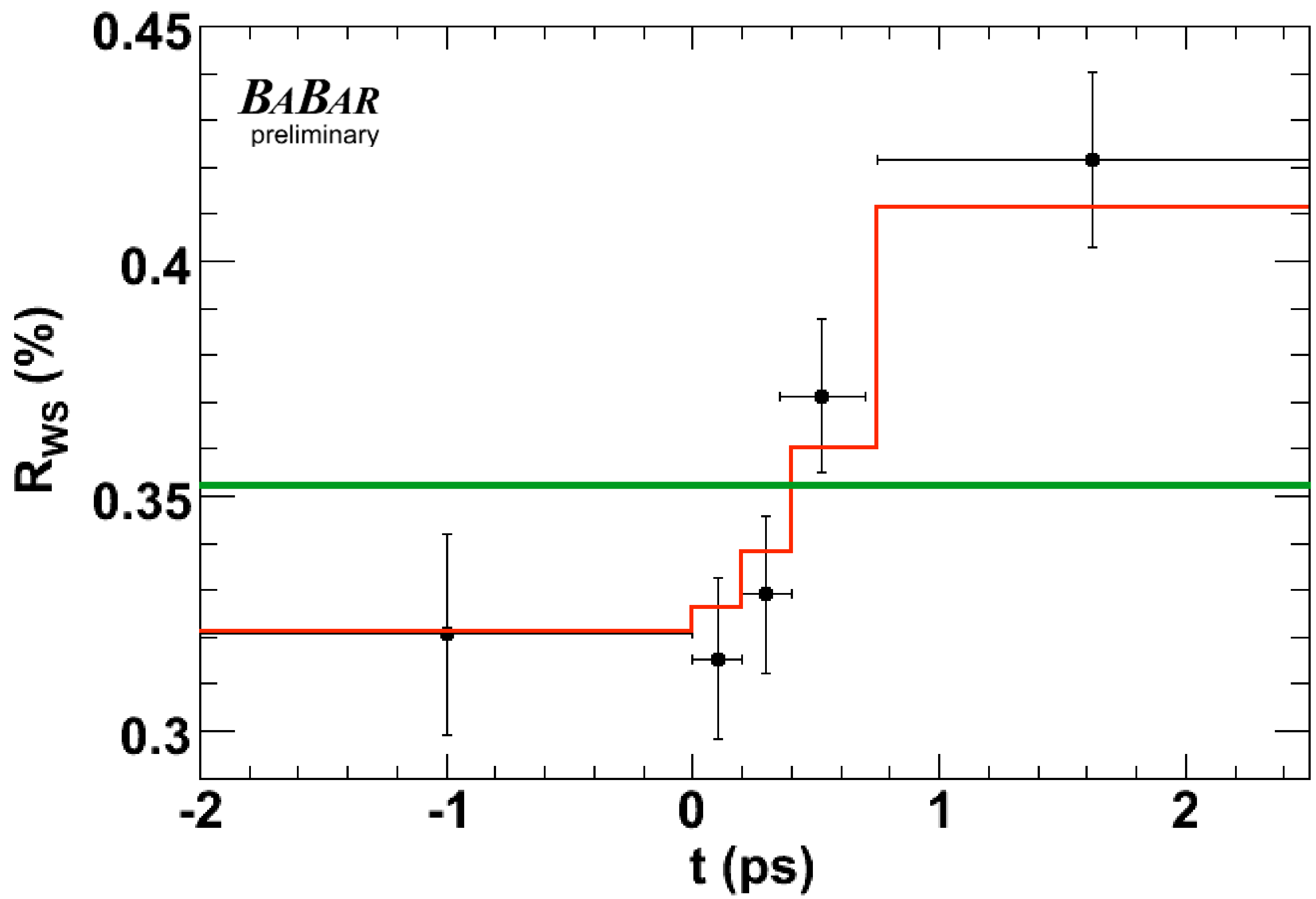


Inconsistent with no mixing hypothesis

χ^2=24

Validation: Alternate fit strategy

Rate of WS events clearly increase with proper time:



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

Inconsistent with no mixing hypothesis
χ^2=24

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:

- proper time range
- proper time error range
- keep/remove all overlapping candidates

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

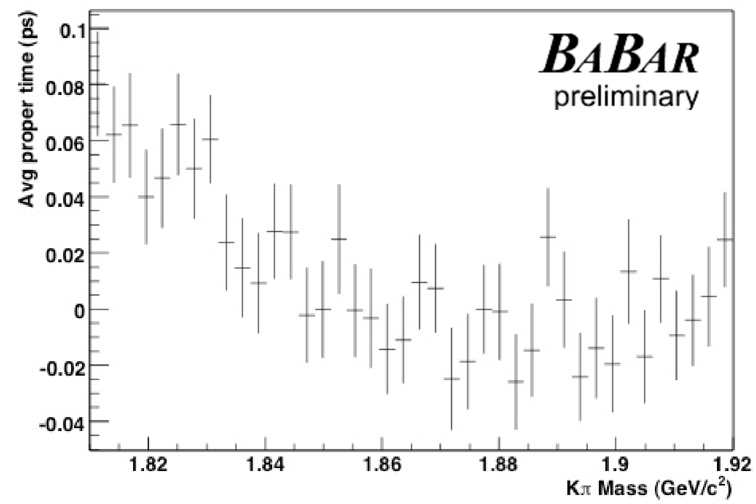
- systematic errors in units of statistical uncertainty in each variable
- computed using full difference with original value
- To estimate the significance of the results in (x'2,y'), we reduce

$-2\Delta \ln \mathcal{L}$ by a factor $1 + \Sigma s_i^2 = 1.3$ to account for systematic errors

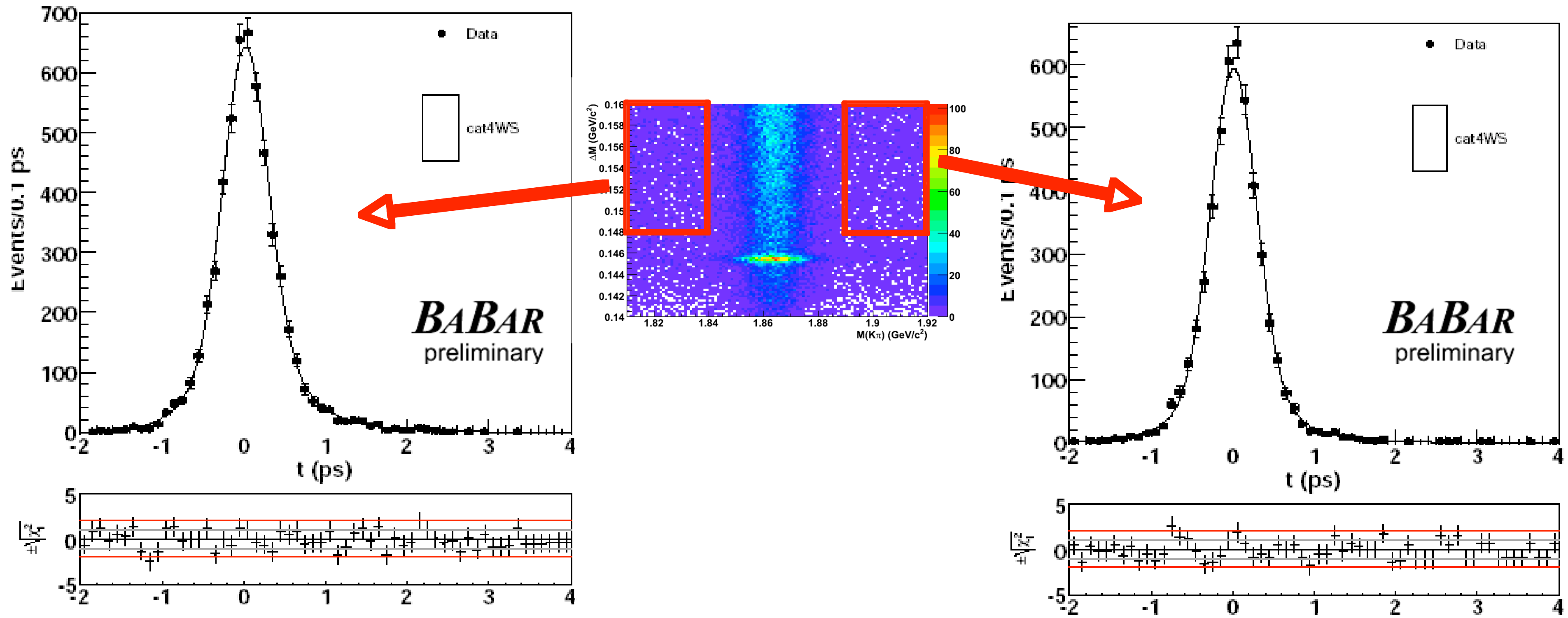
where $s_i^2 = 2\left[\ln \mathcal{L}(x'^2, y') - \ln \mathcal{L}(x'^2_i, y'_i)\right]/2.3$

Combinatorial Proper time systematic

<t> vs m(Kπ) for combinatorial MC events: not independent of m(Kπ)



Fix combinatorial PDF parameters to those obtained from fitting different background sidebands, refit for mixing



significance factor from this variation: $s_i^2 = 0.06$

Systematic: proper time resolution

proper time resolution function
in data has non-zero mean

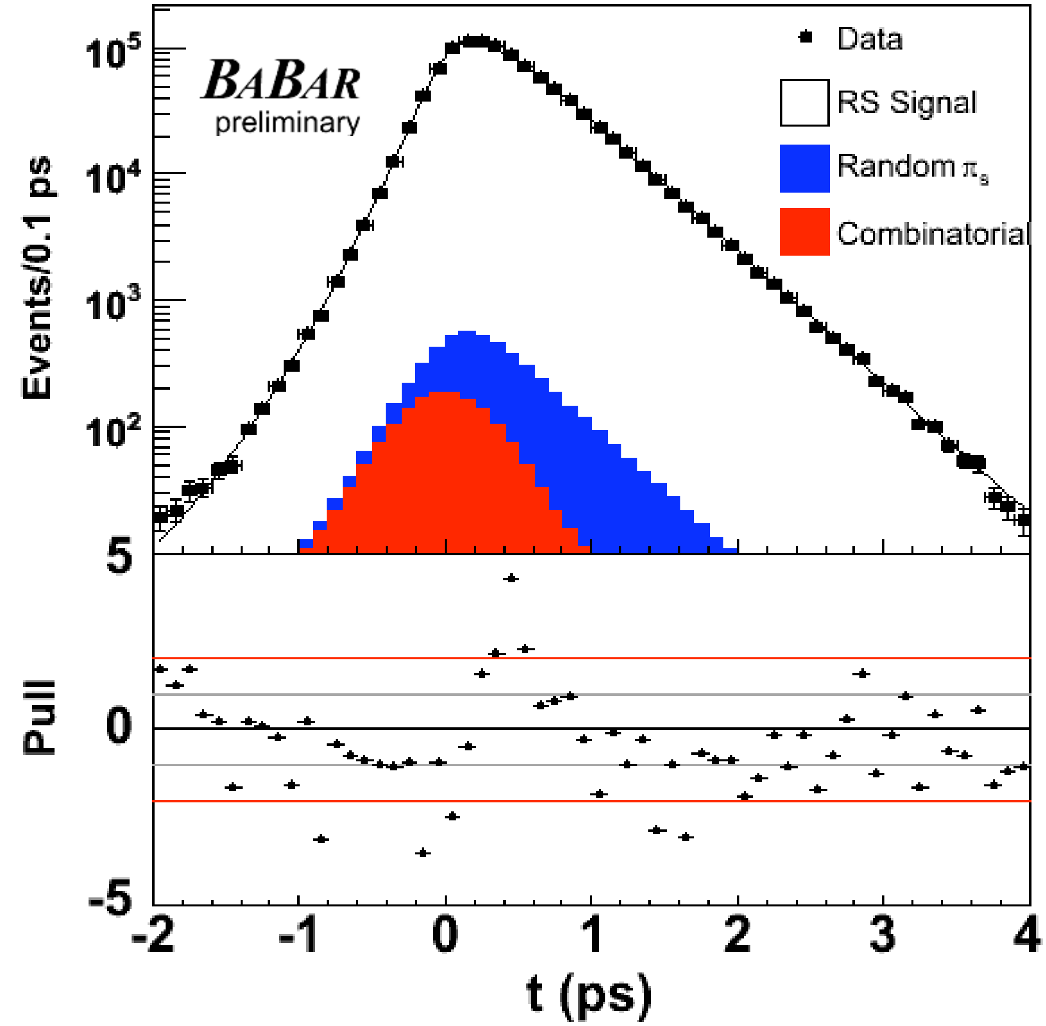
Core Gaussian shifted 3.6±0.6 fs

effect not seen in MC
probably due to detector misalignment

To estimate systematic, set mean to 0
Redo RS and WS proper time fits

significance factor from this variation: $s_i^2 = 0.045$

narrowest core gaussian mean fixed to 0



residuals somewhat worse
than in default fit

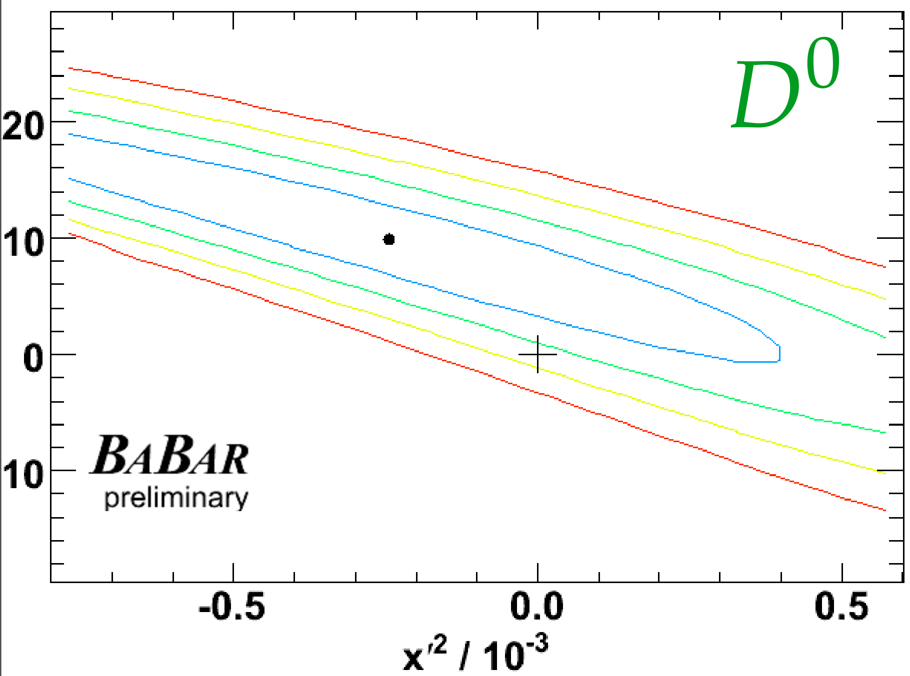
Allowing for *CP* violation

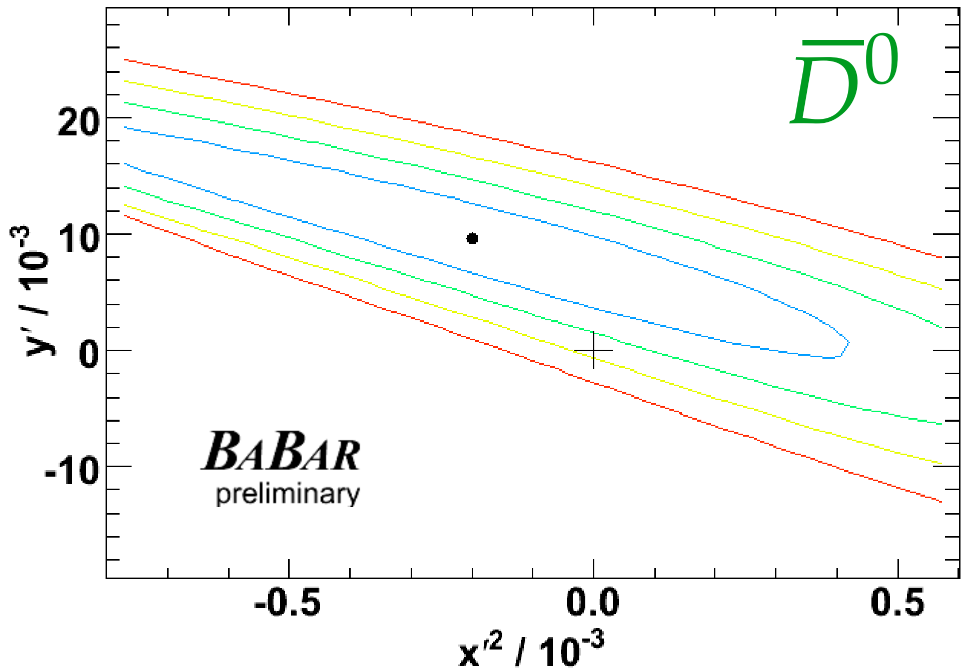
Perform proper time analysis on D^0 (+) and $\overline{D}^0$ (-) samples separately

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

CP violation if any (+) parameter differs from corresponding (-)

x'^{+2}: $(-0.24\pm0.43\pm0.30)\times10^{-3}$ y'^{+}: $(9.8\pm6.4\pm4.5)\times10^{-3}$	$R_D=(0.303\pm0.016\pm0.010)\%$ $A_D=(-2.1\pm5.2\pm1.5)\%$	x'^{-2}: $(-0.20\pm0.41\pm0.29)\times10^{-3}$ y'^{-}: $(9.6\pm6.1\pm4.3)\times10^{-3}$





No evidence for CP violation

Summary of mixing and CPV results

Fit results for:

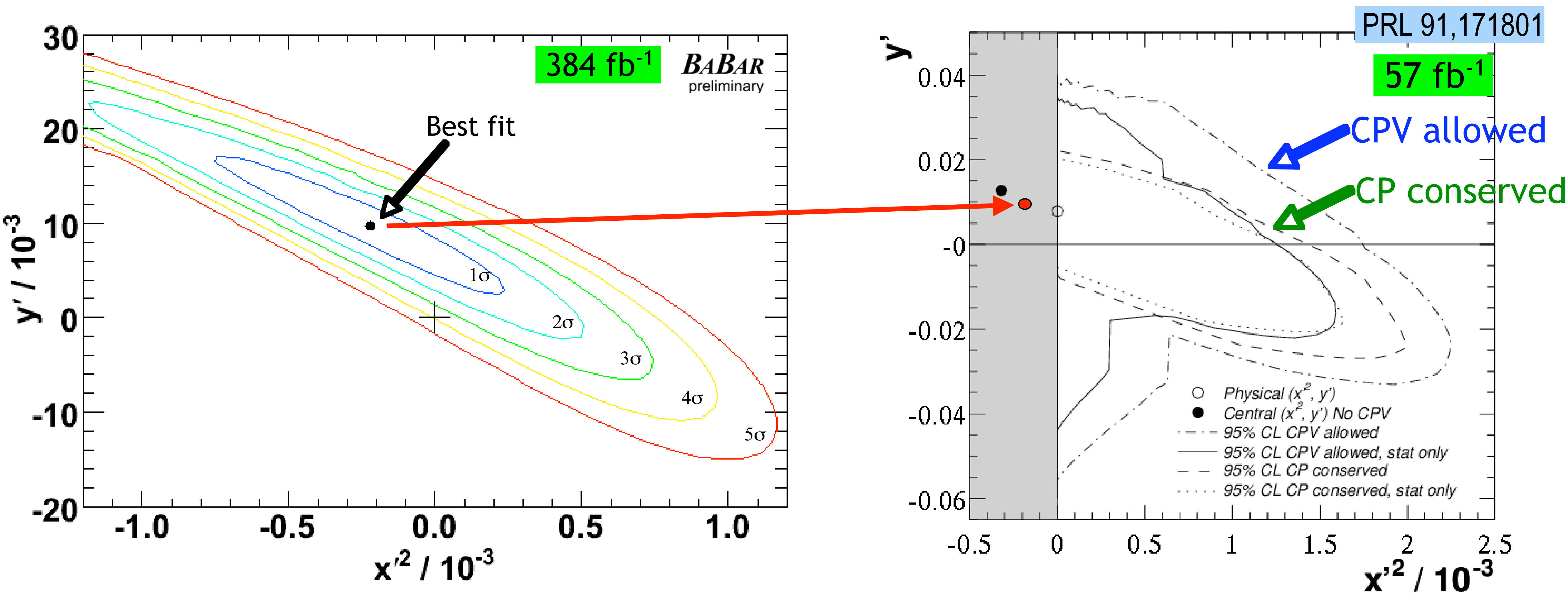
(1) no mixing or CPV; (2) mixing but no CPV; (3) mixing and CPV

Fit type	Parameter	Fit Results ($/10^{-3}$)
No CP viol. or mixing	R_D	$3.53 \pm 0.08 \pm 0.04$
No CP violation	R_D	$3.03 \pm 0.16 \pm 0.10$
	x'^2	$-0.22 \pm 0.30 \pm 0.21$
	y'	$9.7 \pm 4.4 \pm 3.1$
CP violation allowed	R_D	$3.03 \pm 0.16 \pm 0.10$
	A_D	$-21 \pm 52 \pm 15$
	x'^{2+}	$-0.24 \pm 0.43 \pm 0.30$
	y'^{+}	$9.8 \pm 6.4 \pm 4.5$
	x'^{2-}	$-0.20 \pm 0.41 \pm 0.29$
	y'^{-}	$9.6 \pm 6.1 \pm 4.3$

Note: R_D changes between no-mixing and mixing fits

Comparisons with other Charm Mixing Results

BaBar 2003 $D^0 \rightarrow K\pi$ result (57 fb^{-1})

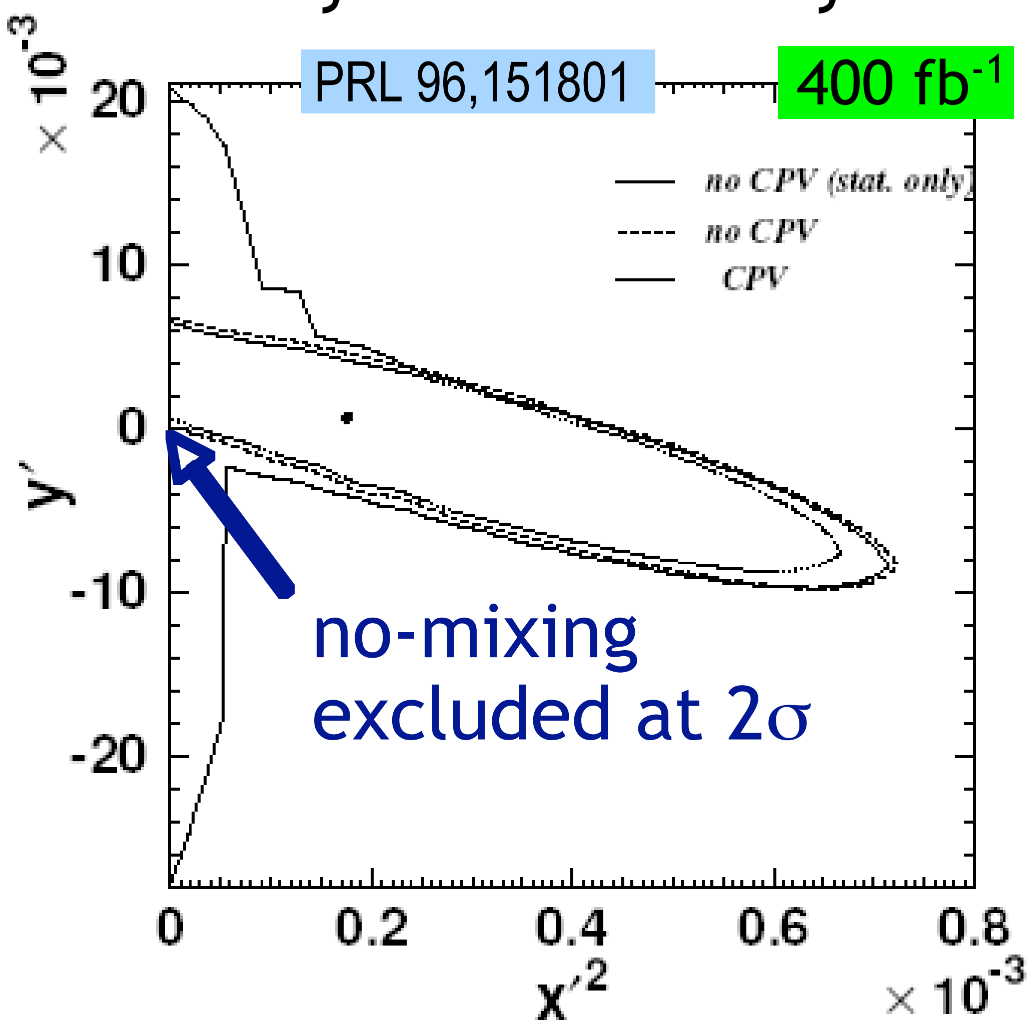


Current result fully consistent with previous BaBar result

BELLE 2006 $D^0 \rightarrow K\pi$ result

BELLE 2006 $D^0 \to K\pi$ result

Last year Belle published analysis of $K\pi$ decays:



BELLE 2006 $D^0 \rightarrow K\pi$ result

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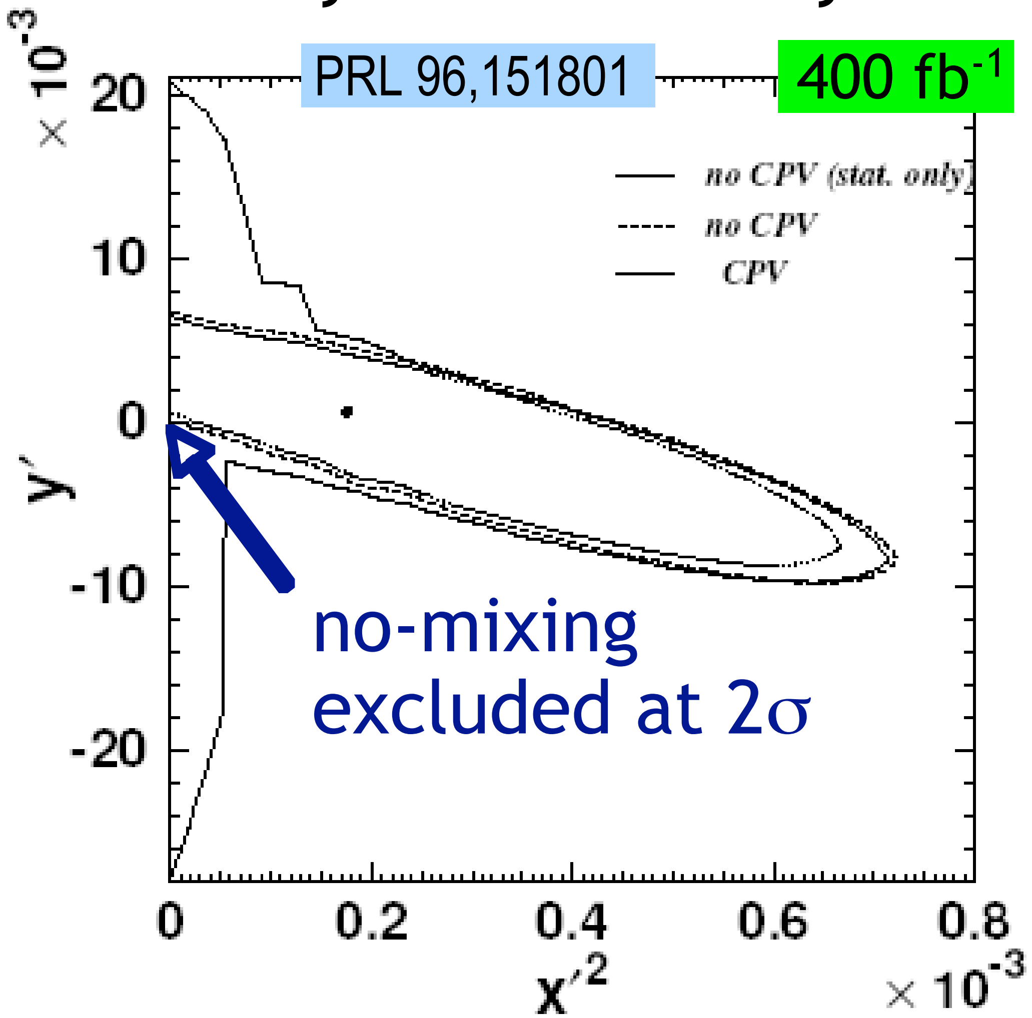
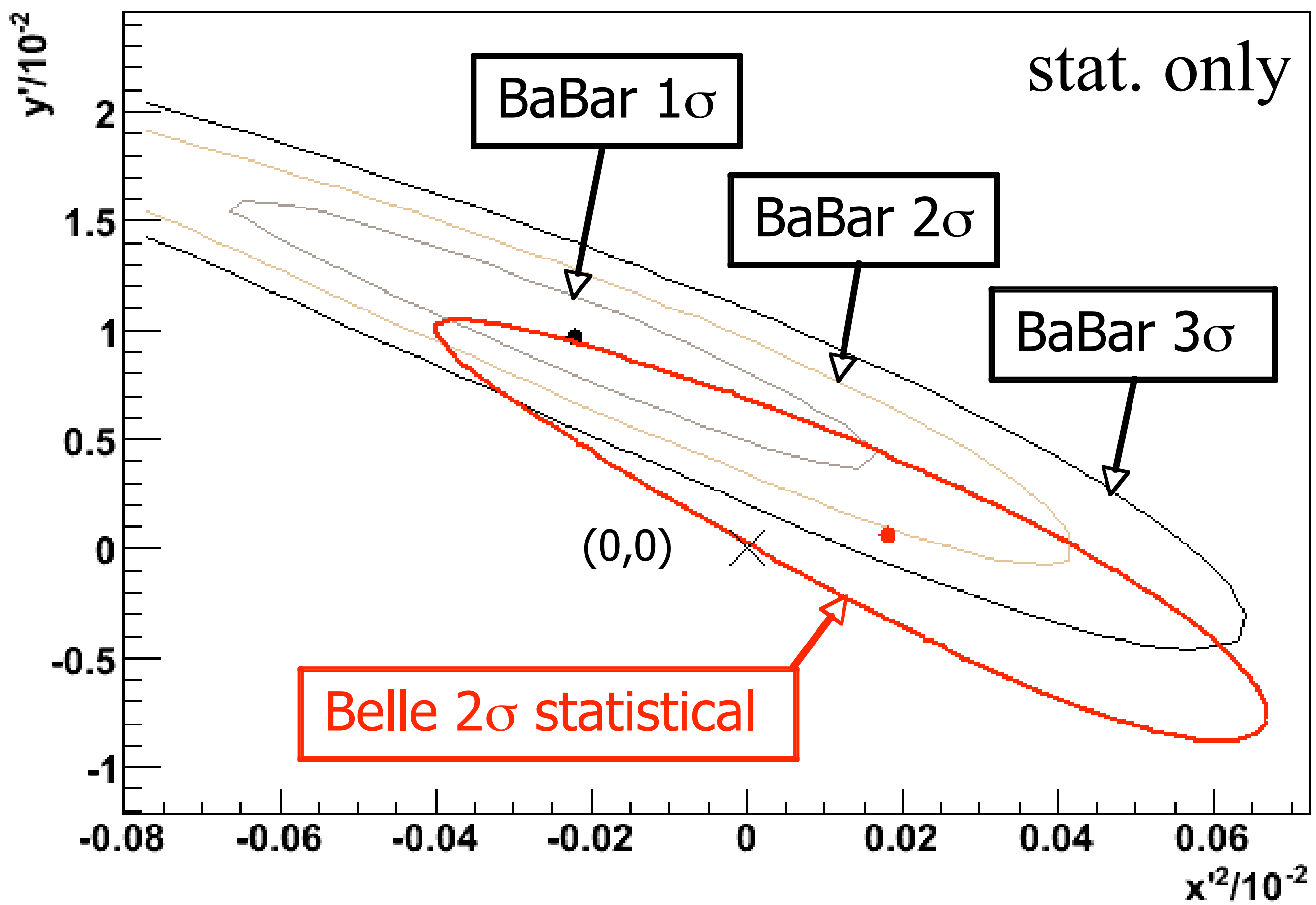


Results consistent within 2σ:



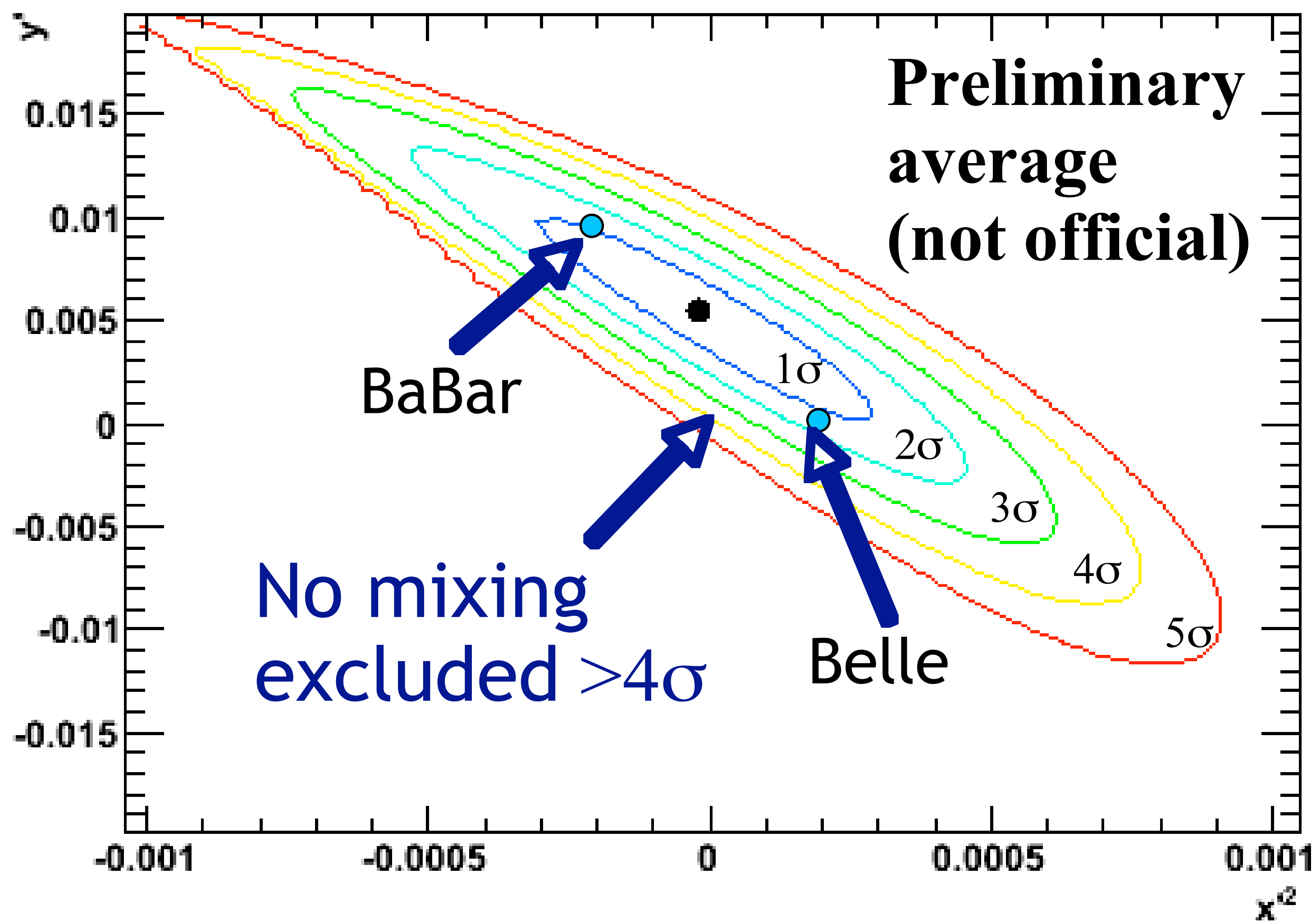
Averaged $D^0 \rightarrow K\pi$ mixing results

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: $(3.31 \pm 0.13) \times 10^{-3}$
x'^2: $(-0.01 \pm 0.20) \times 10^{-3}$
y': $(5.1 \pm 3.2) \times 10^{-3}$



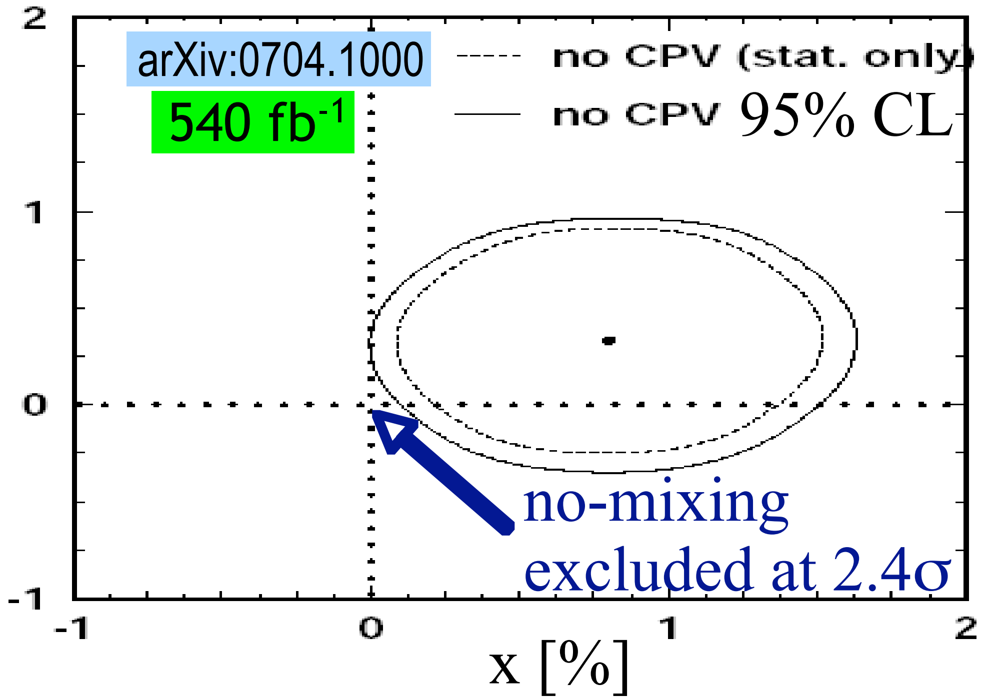
Belle Dalitz Analysis of $D^0 \rightarrow K_s\pi\pi$

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

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

(First done by CLEO, PRD 72, 012001)

Belle result:



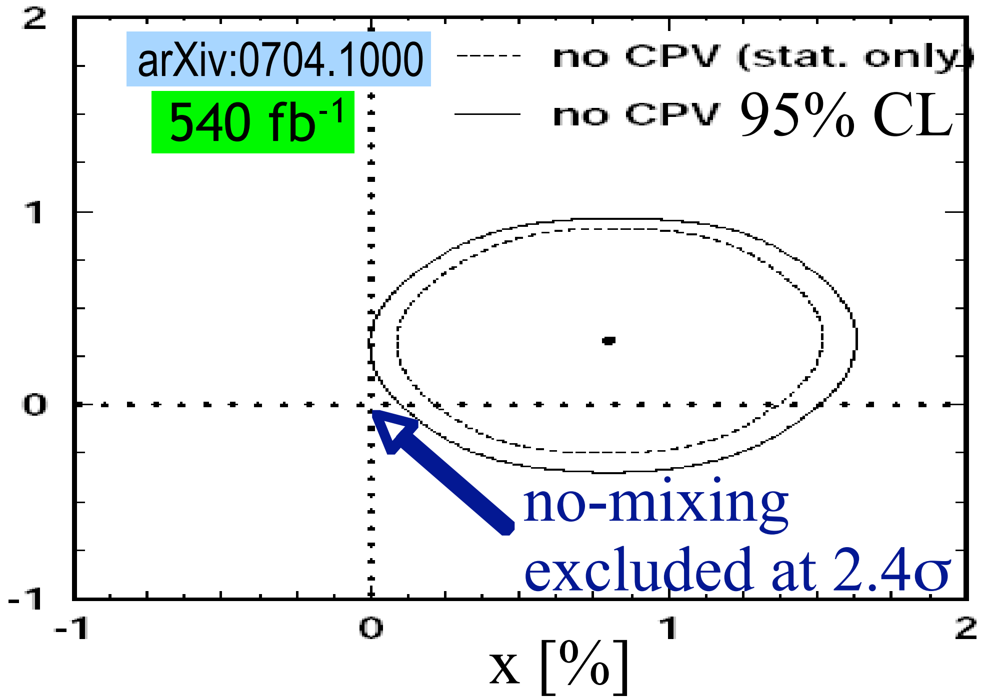
x: $(8.0\pm2.9\pm1.7)\text{x}10^{-3}$
y: $(3.3\pm2.4\pm1.5)\text{x}10^{-3}$

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

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

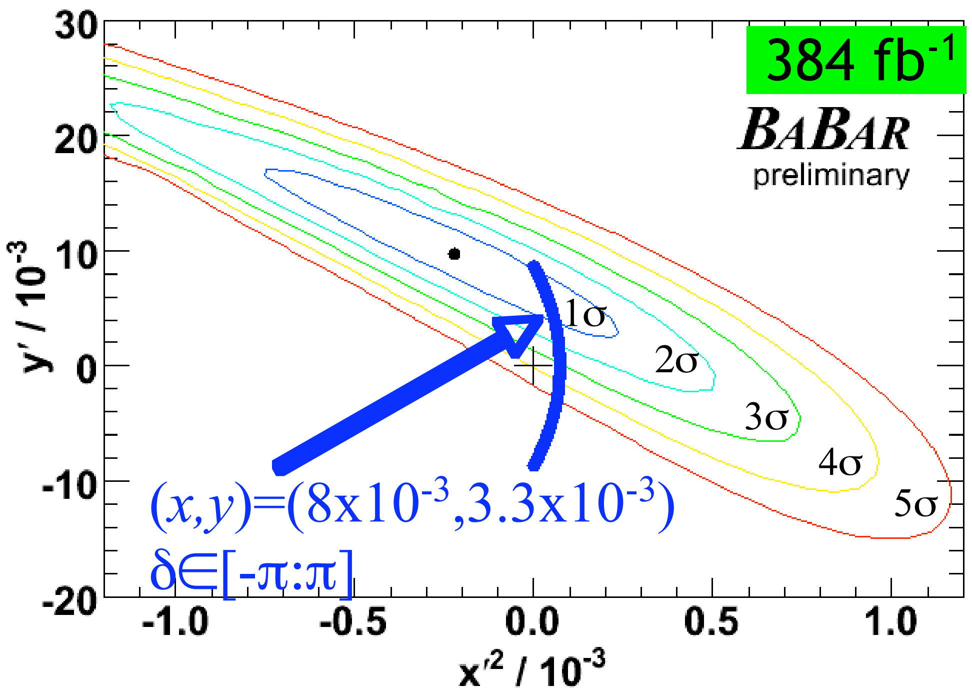
(First done by CLEO, PRD 72, 012001)

Belle result:



x: $(8.0\pm2.9\pm1.7)\times10^{-3}$
y: $(3.3\pm2.4\pm1.5)\times10^{-3}$

BaBar-Belle comparison:



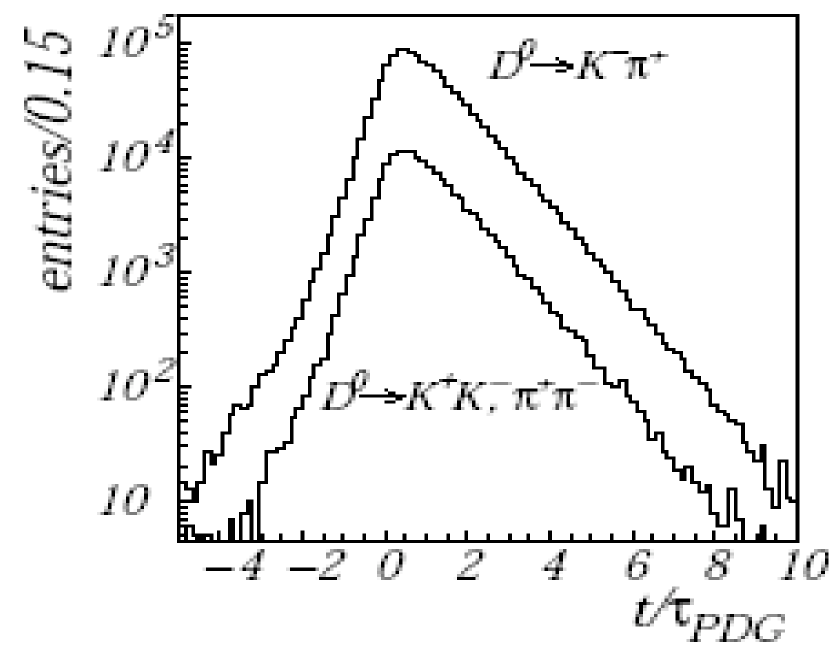
Within 1σ for certain values of the phase δ

BELLE lifetime ratio measurement

BELLE measures lifetime difference directly using CP+ *KK* and ππ together with mixed CP *K*π final states.
Assuming CP conservation:

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

proper time distributions



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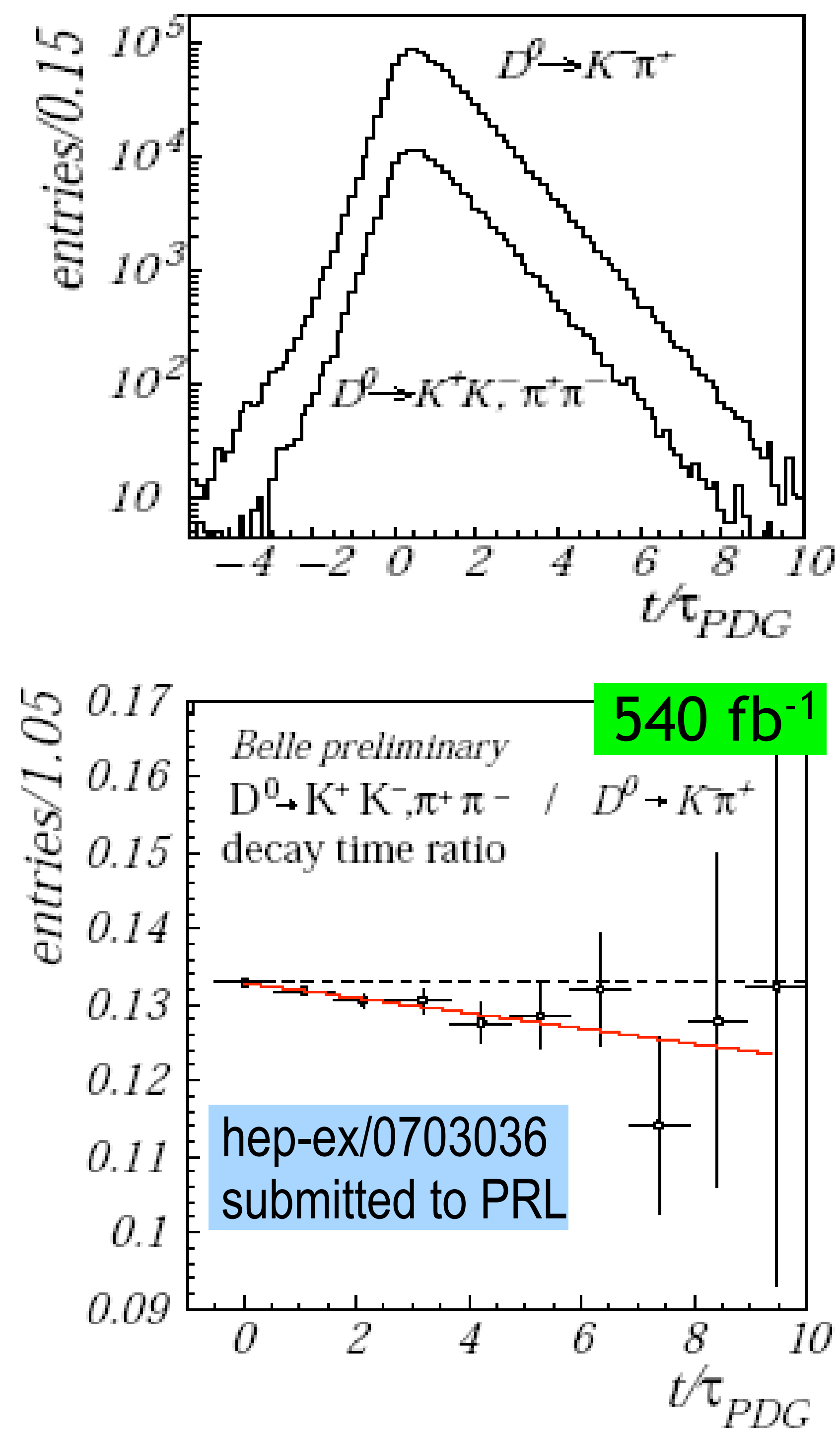
proper time distributions



BELLE result:

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

>3σ from no-mixing

4.1σ stat. only

Also evidence for D^0 mixing

Additional BaBar-BELLE comparisons

Lifetime ratio measurements consistent:

Belle: 540 fb^{-1}

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

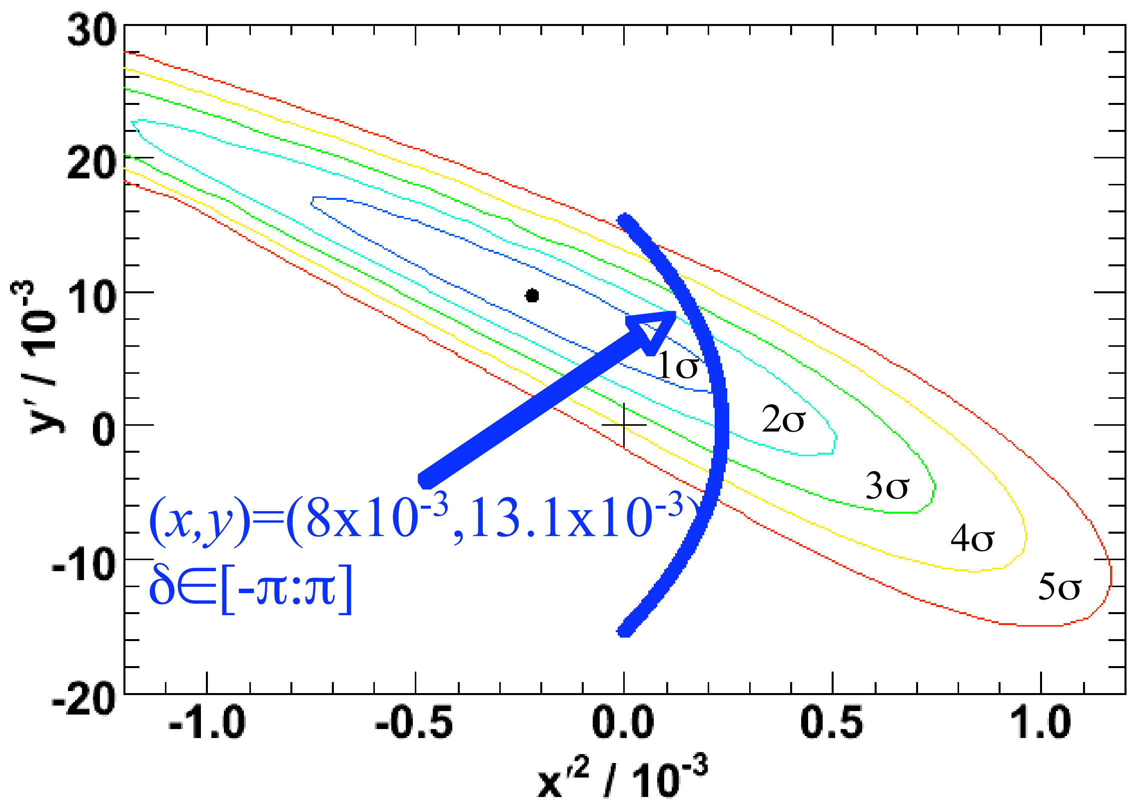
hep-ex/0703036 submitted to PRL

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 $K_s\pi\pi$ analysis

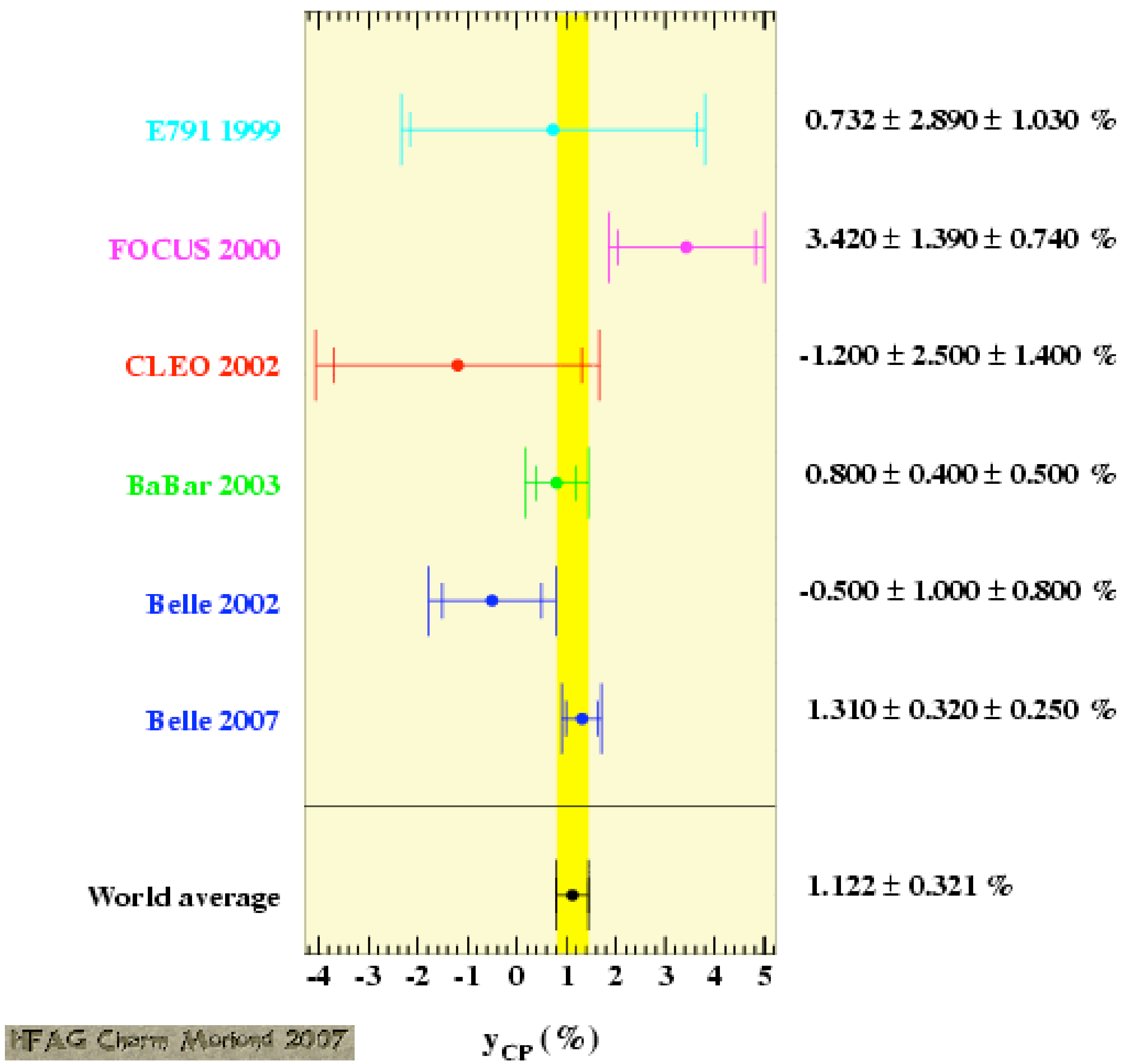
Results consistent within 1σ for a certain values of strong phase δ

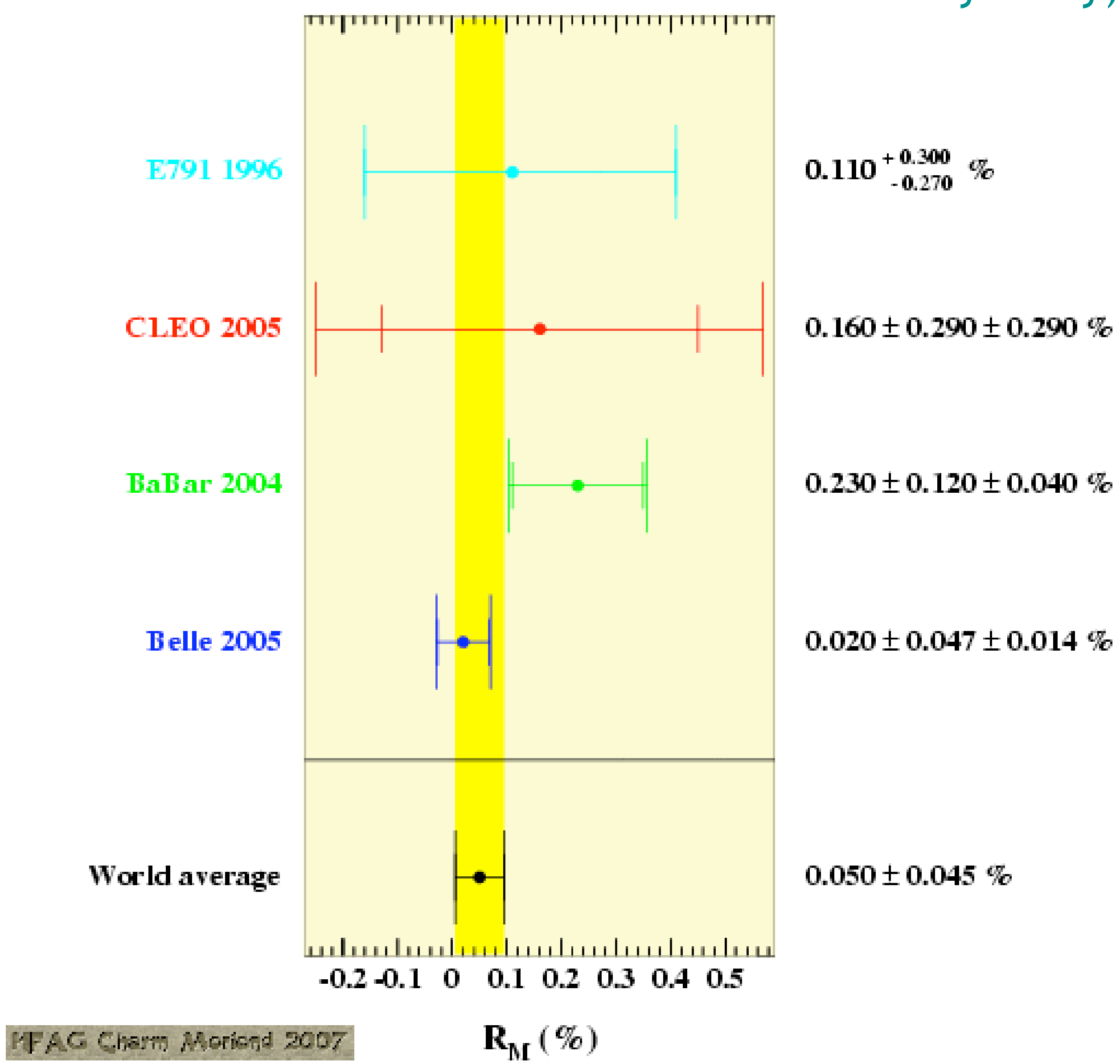
Combining mixing results

Preliminary averages for some measurements (HFAG):

y_{CP}

$R_M = (x^2 + y^2)/2$ (Semileptonic decays only)





$$\langle y_{CP} \rangle = (11.2 \pm 3.2) \times 10^{-3}$$

$$\langle R_M \rangle = (0.50 \pm 0.45) \times 10^{-3}$$

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

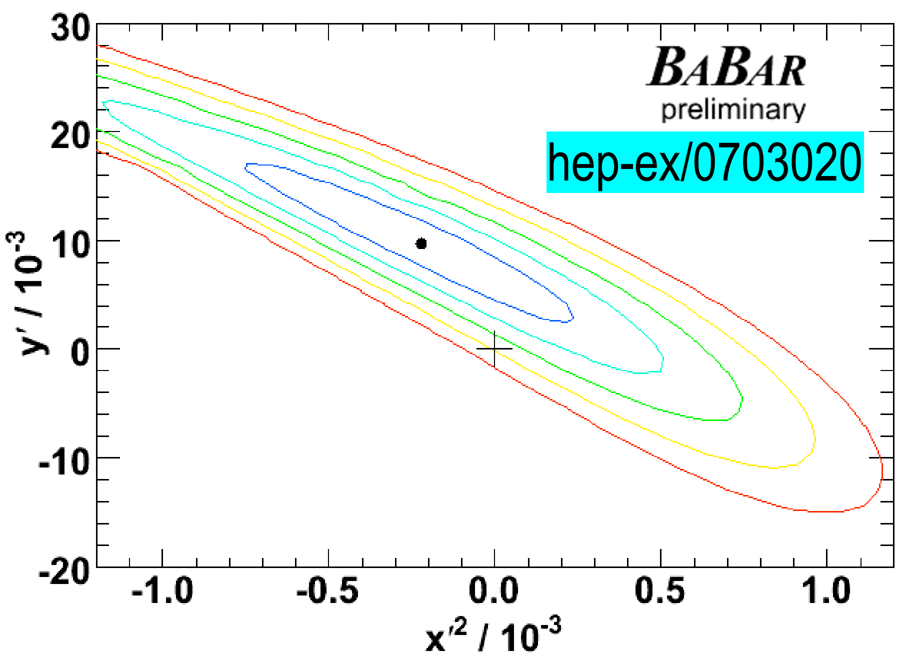
Light non-degenerate squarks unlikely to be observed at LHC

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

Summary

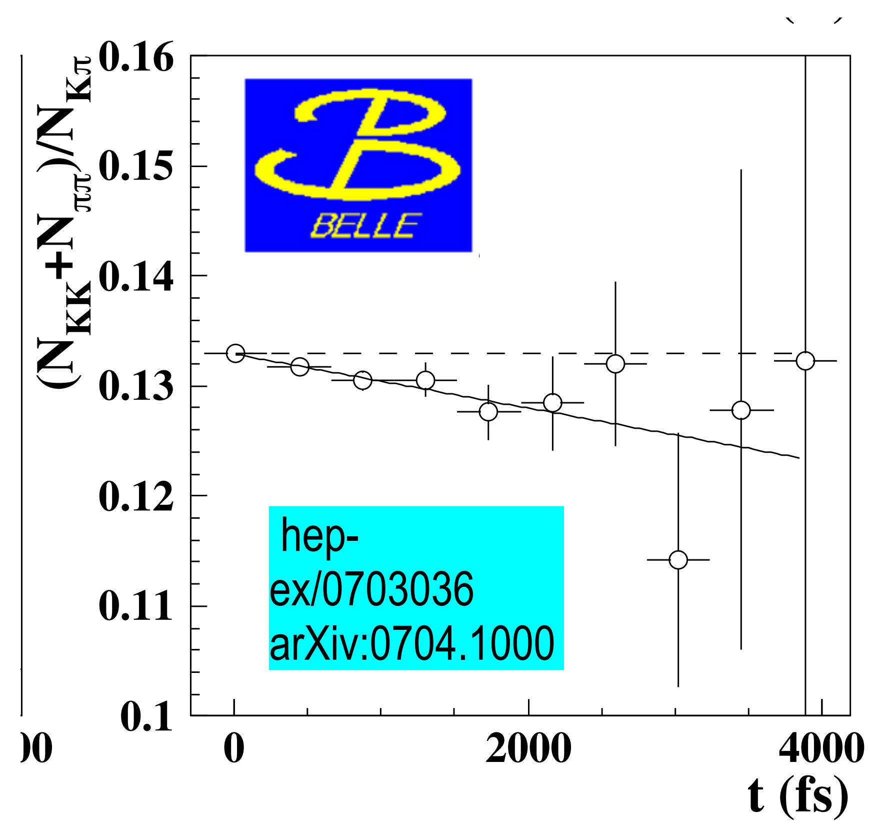
In 384 fb^{-1} of tagged D0$\rightarrow$Kπ data from BaBar:

- Evidence for mixing (3.9σ) (stat. + syst.)
  - $y' = [9.7 \pm 4.4\,(\text{stat.}) \pm 3.1\,(\text{syst.})] \times 10^{-3}$
  - $x'^2 = [-0.22 \pm 0.30\,(\text{stat.}) \pm 0.219\,(\text{syst.})] \times 10^{-3}$
  - $R_D = [0.303 \pm 0.016\,(\text{stat.}) \pm 0.010\,(\text{syst.})]\%$
- No evidence for CP violation
- Results consistent with other mixing measurements and Standard Model
- will appear in May 25, 2007 PRL



New results from BELLE:

- Evidence for mixing (3.2σ) in y_{CP} analysis
  - $y_{cp}=(13.1+3.2+2.5)\text{x}10^{-3}$
- most stringent limits on x to date from $K_S\pi\pi$
  - $x = (0.80 \pm 0.29 \pm 0.17)\%,\ y = (0.33 \pm 0.24 \pm 0.15)\%$
- No evidence for CP violation



Backup slides

BaBar analysis

vertexing

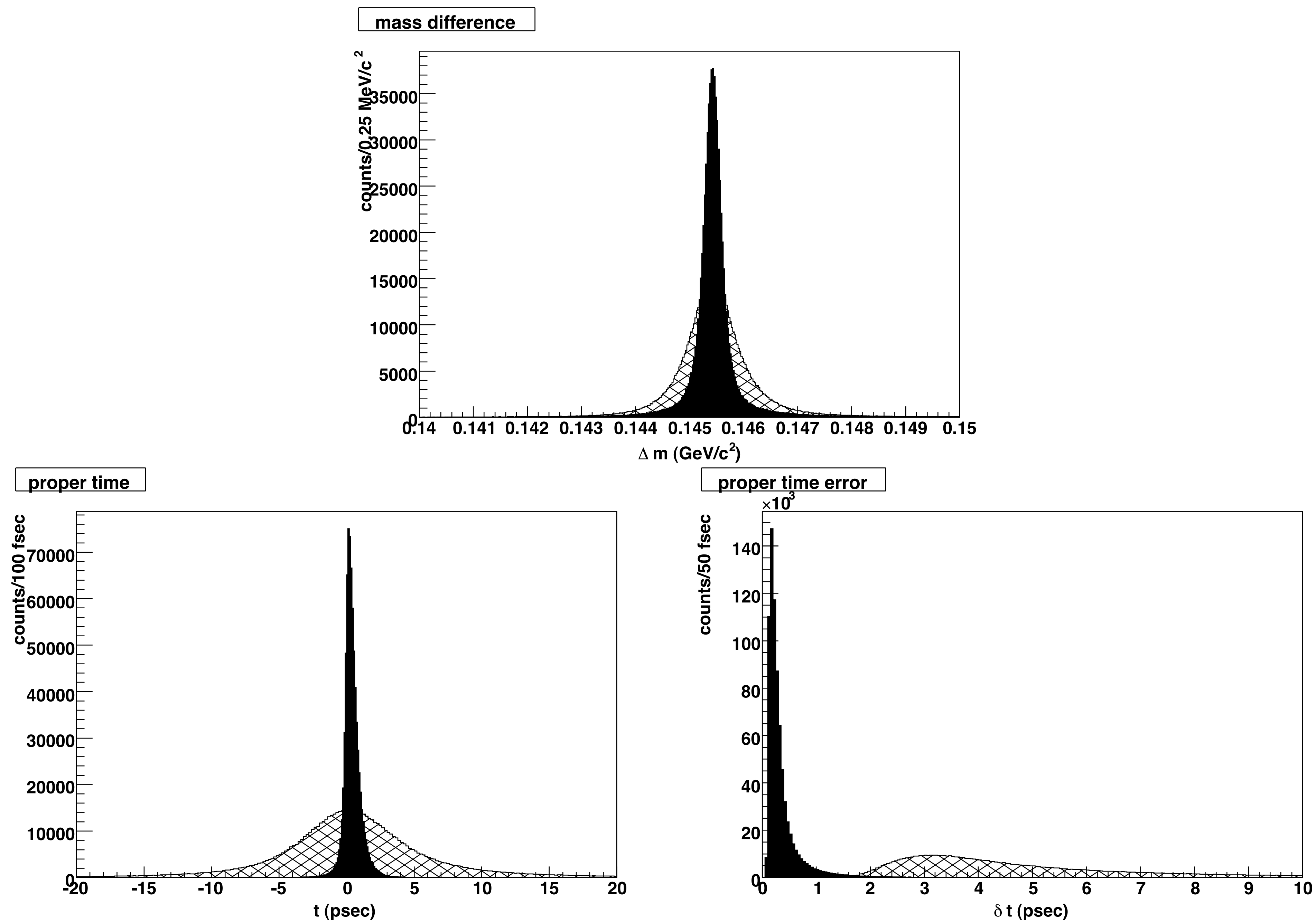


Figure 3: top: Δm distributions, bottom left: $t$distributions and bottom right: σ_t distributions. Beam constraint (solid); no beam constraint (hatched).

Theory

Belle results

Belle evidence on y_{CP}

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

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

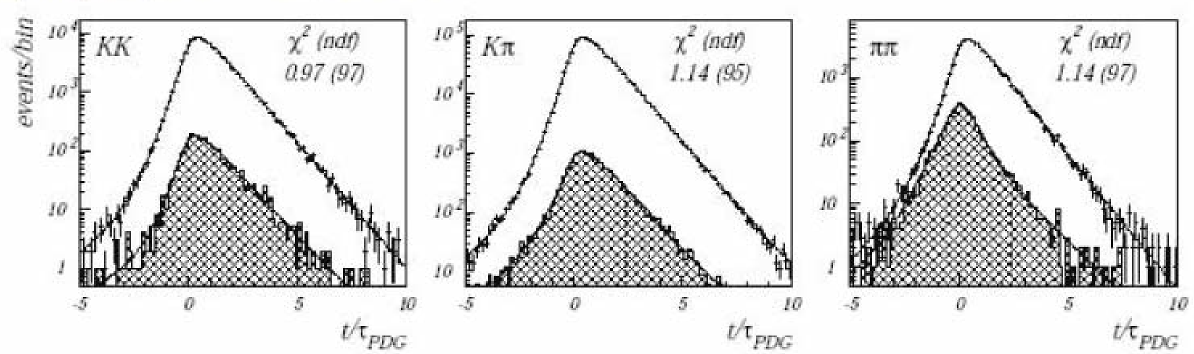
$$A_m = 1 - |q/p|$$

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

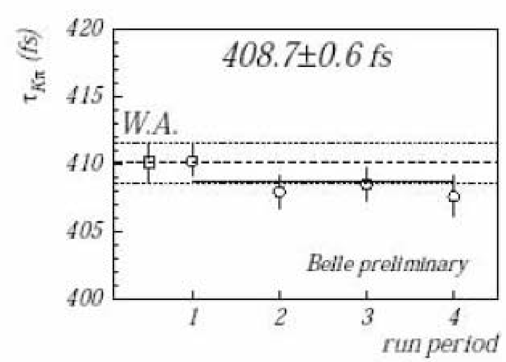
ϕ_D = mixing phase

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

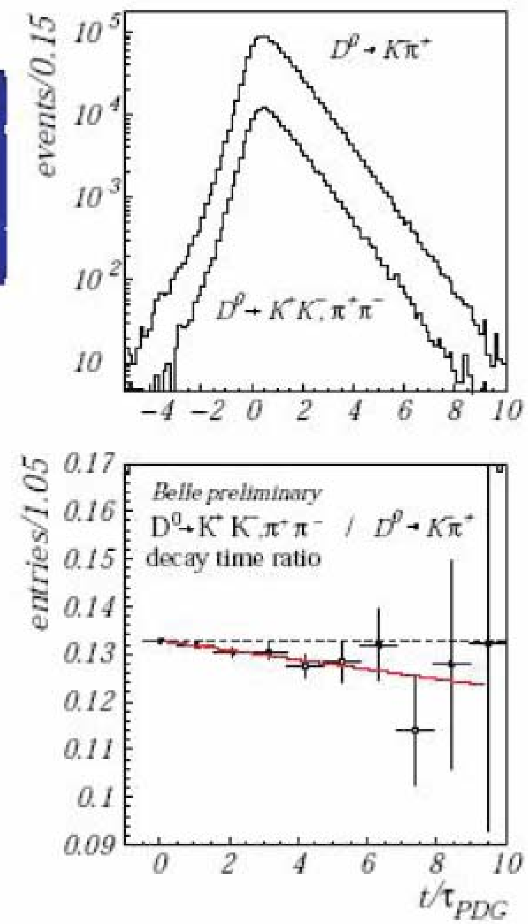
Belle hep-ex/0703036
Belle preliminary (540 fb^{-1})

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

$> 3\sigma$ 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



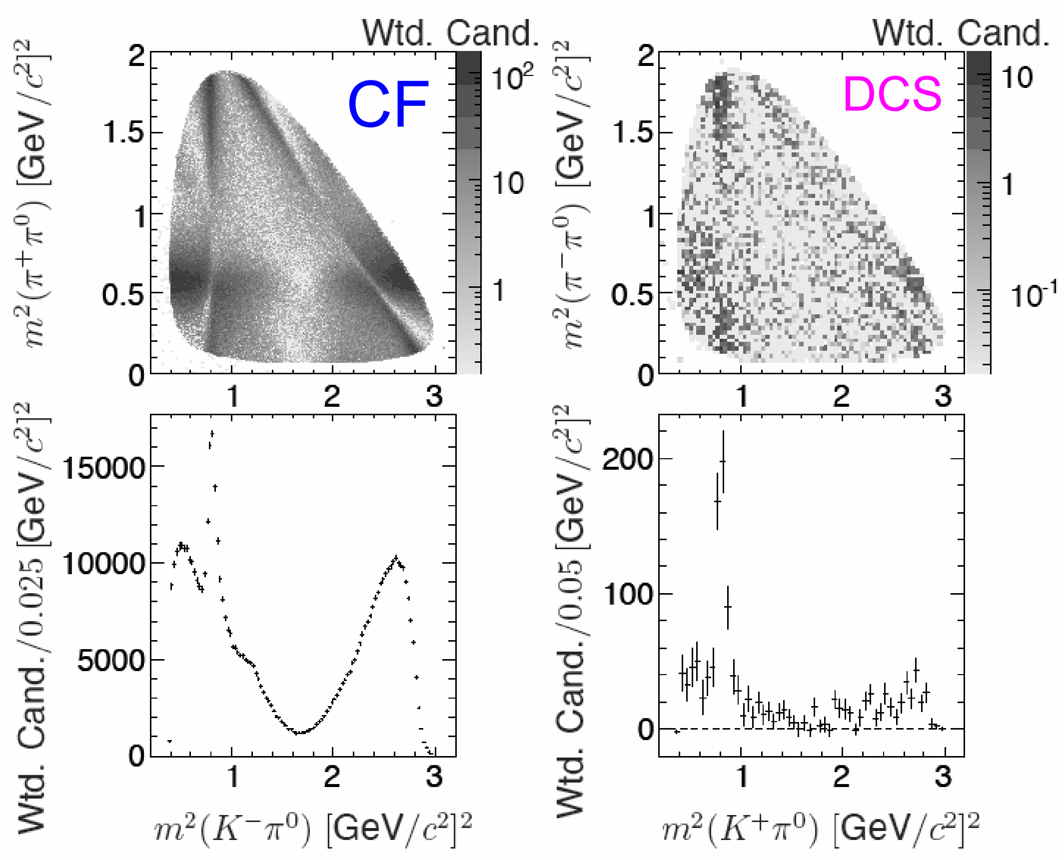
Separating x and y

 $K\pi$ 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

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

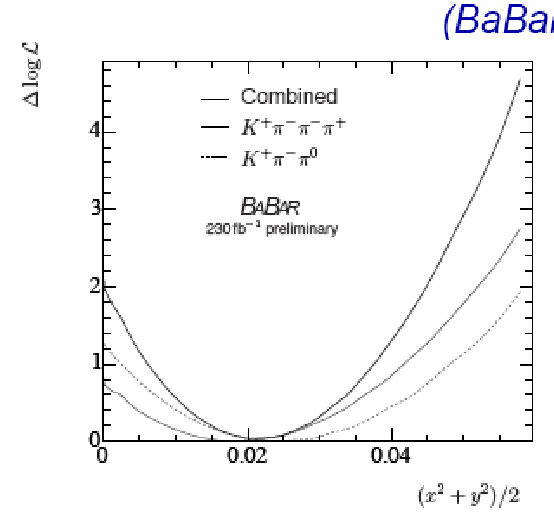
$$\widetilde{x}' = x\cos\widetilde{\delta} + y\sin\widetilde{\delta}$$
$$\widetilde{y}' = y\cos\widetilde{\delta} - x\sin\widetilde{\delta}$$

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.)

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

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

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

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

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

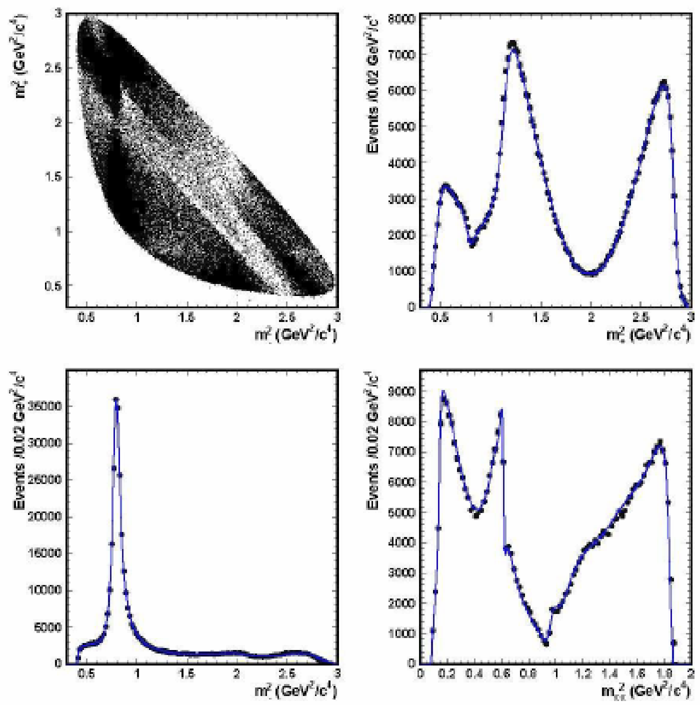
Both flavor ($K^{*-}\pi^+/K^{*+}\pi^-$) final states in the same Dalitz plot!

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

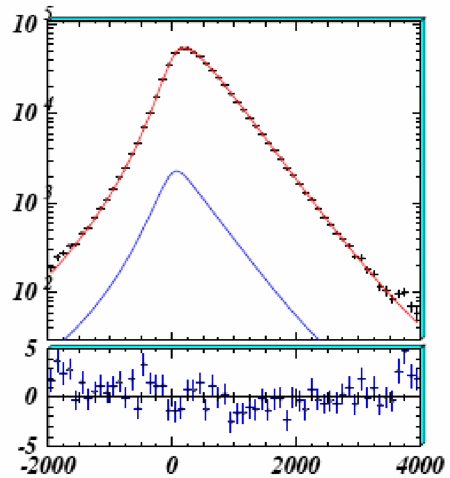


Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.629 ± 0.005	134.3 ± 0.3	0.6227
$K_0^*(1430)^-$	2.12 ± 0.02	-0.9 ± 0.5	0.0724
$K_2^*(1430)^-$	0.87 ± 0.01	-47.3 ± 0.7	0.0133
$K^*(1410)^-$	0.65 ± 0.02	111 ± 2	0.0048
$K^*(1680)^-$	0.60 ± 0.05	147 ± 5	0.0002
$K^*(892)^+$	0.152 ± 0.003	-37.5 ±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



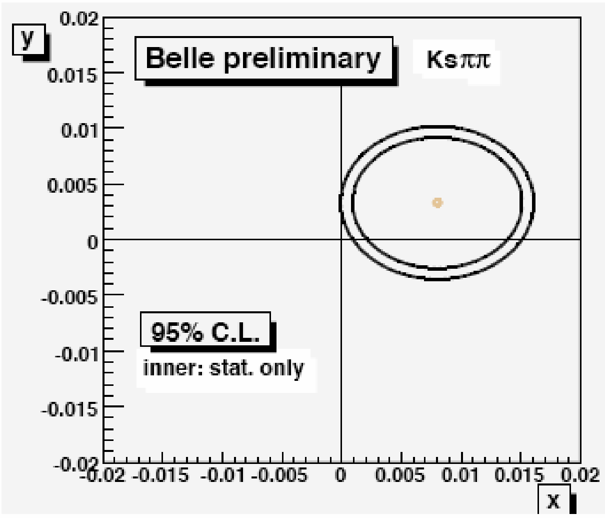
Systematics

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



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most stringent limits on x up to now

Cleo, PRD 72, 012001 (2005):

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

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

University of South Carolina High Energy Physics Group

Belle $D^0 \rightarrow K_s \pi\pi$ 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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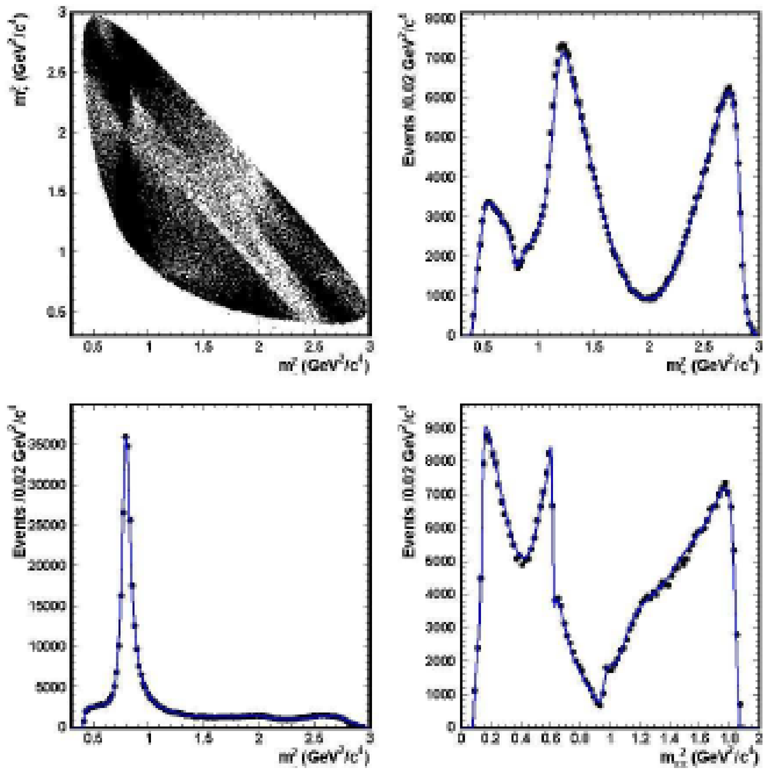

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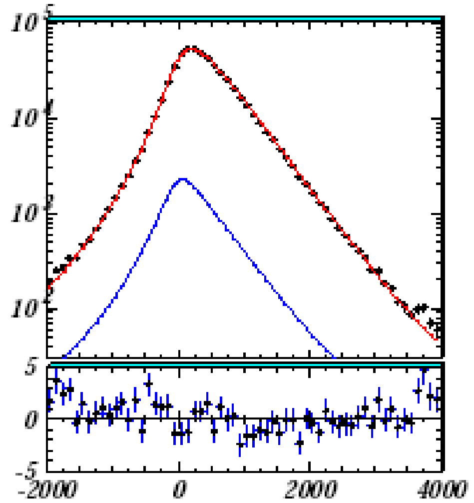

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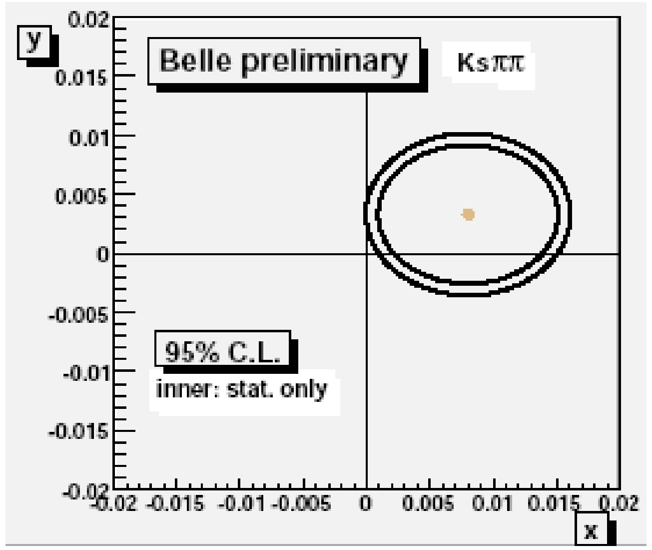

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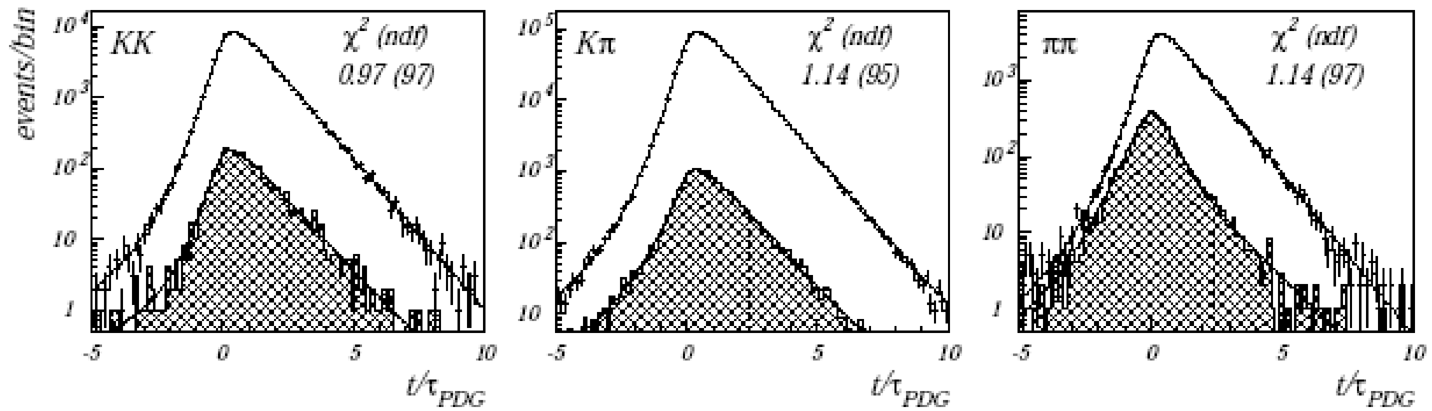

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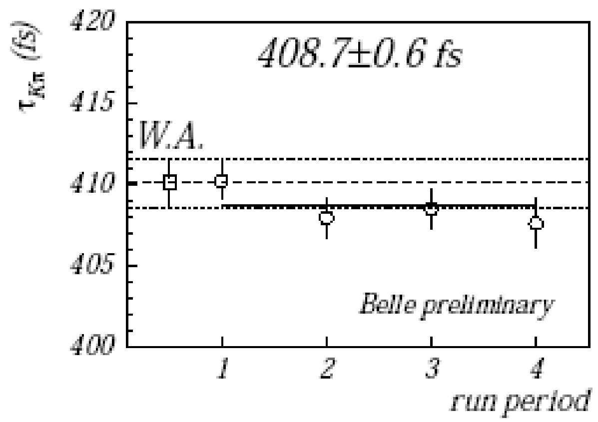

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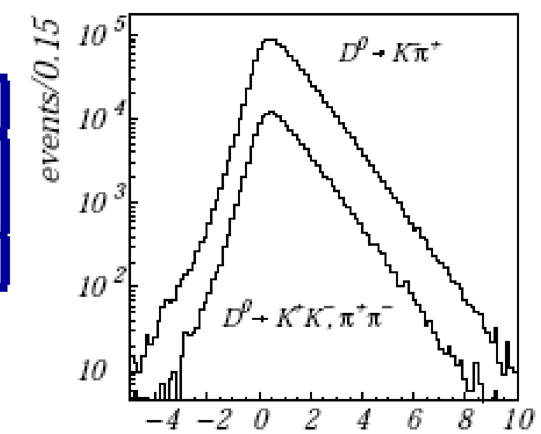

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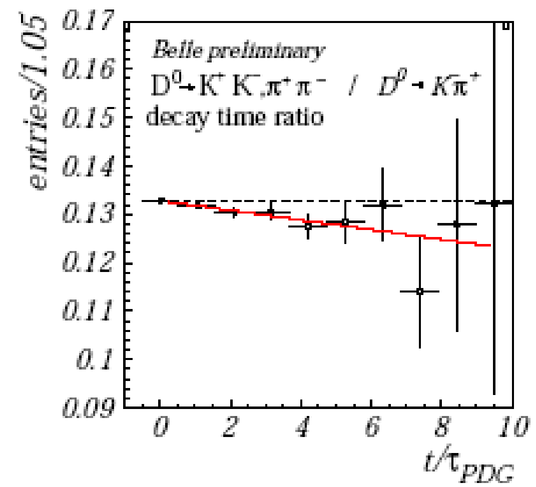

$$A_\Gamma = 0.01 \pm 0.30 \pm 0.15\ \%$$

no evidence for CP violation