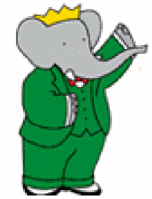
D^0-$\bar{D}^0$ Mixing at BABAR



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European Physical Society HEP

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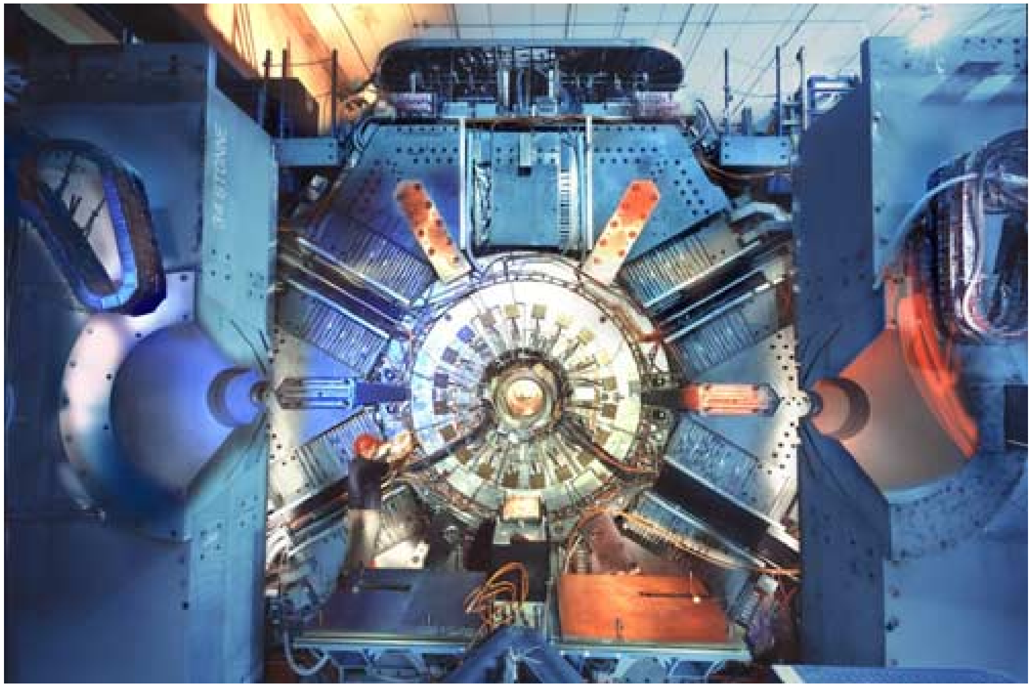


Outline

- B-Factories as Charm Factories
- Charm Mixing Formalism
- D^0-$\overline{D}^0$ Mixing Measurements
  - – $D^0 \to K^+\pi^-$ *decay time analysis*
  - – *Lifetime ratio from tagged* $D^0 \to K^+K^-, \pi^+\pi^-$
  - – *Lifetime ratio from untagged* $D^0 \to K^+K^-$ **new**
- Conclusions

Charm Physics at B-Factory ?

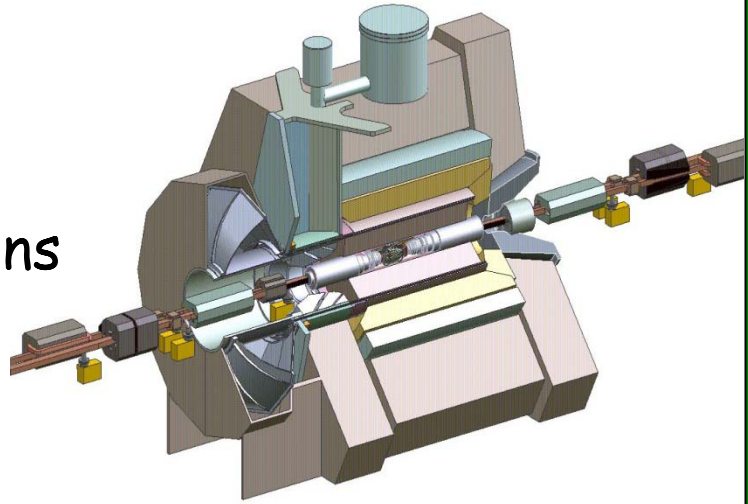
BaBar is a B-factory: $e^+e^- \rightarrow \Upsilon(4S) \rightarrow b\bar{b}$

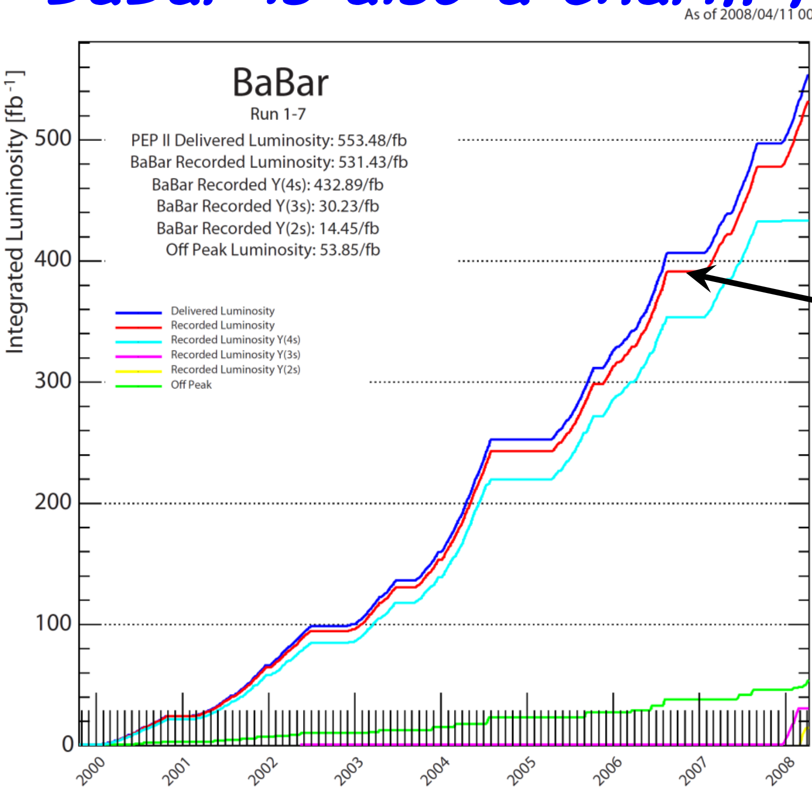
$\sigma(b\bar{b})$ = 1.1 nb, but

$\sigma(c\bar{c})$ = 1.3 nb

Millions of reconstructed charm hadrons

BaBar is also a charm factory





These Babar mixing measurements use a data sample of 384 fb^{-1}

Corresponds to >500M $c\bar{c}$ events

Excellent sample to search for charm mixing

D^0 Mixing Formalism

Neutral D mesons are produced as *flavor eigenstates* D^0 and $\overline{D}^0$ and decay via :

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

as *mass eigenstates* D_1, D_2

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned}$$

where $|q|^2 + |p|^2 = 1$ and

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}$$

D_1, D_2 have masses M_1, M_2 and widths Γ_1, Γ_2

Mixing occurs when there is a *non-zero* mass difference

$$\Delta M = M_1 - M_2$$

or lifetime difference

$$\Delta\Gamma = \Gamma_1 - \Gamma_2$$

For convenience define quantities ***x*** and ***y***

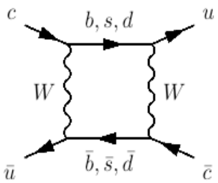
$$x = \frac{\Delta M}{\Gamma}, \quad y = \frac{\Delta\Gamma}{2\Gamma}$$

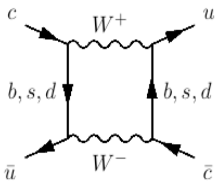
where $$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

Mixing in Neutral Meson System

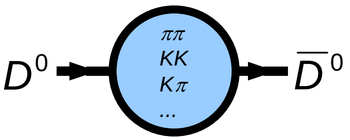
- Of all the neutral mesons, the *D* system exhibits the least mixing

- D^0-$\bar{D}^0$ mixing in the Standard Model is highly suppressed:
  - short distance (s,d) quark loop diagrams GIM suppressed
  - short distance b-quark loop diagrams CKM suppressed
  - mass difference amplitude $x \leq O(10^{-5})$, $y \sim 0$



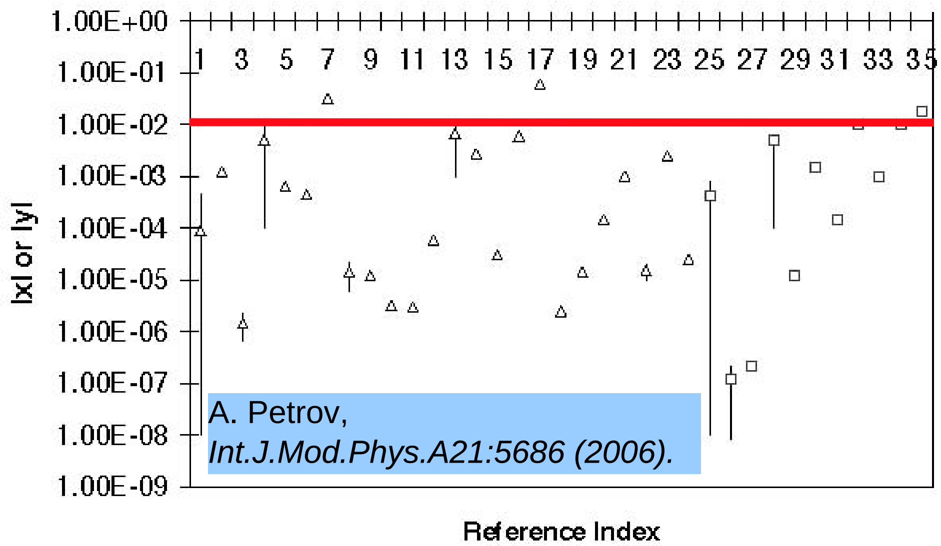


- long distance amplitudes predominate but hard to quantify:



- New Physics signature: *CPV*

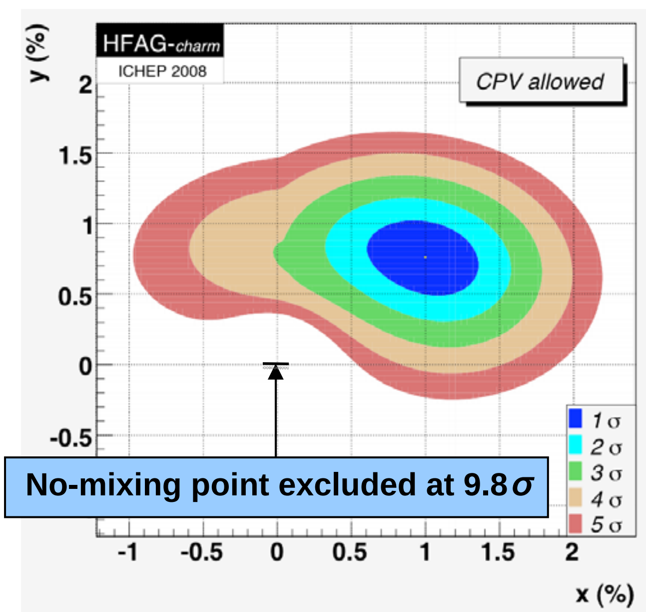
E. Golowich, J. Hewett, S. Pakvasa, A. Petrov, *Phys. Rev.* ***D76*** *095009 (2007)*



Combined Mixing Measurements

Best evidence for D^0-$\bar{D}^0$ mixing to date (mainly *BaBar*, *BELLE*, *CDF*, *CLEO-c*):

*BABAR: PRL **98** 211802 (2007)*	*$D^0 \to K^+\pi^-$ decay time analysis, BABAR*	3.9σ
*BELLE: PRL **98** 211803 (2007)*	*$D^0 \to K^+K^-$, $\pi^+\pi^-$ vs $K^+\pi^-$ lifetime difference analysis, BELLE*	3.2σ
*BELLE: PRL **99** 131803 (2007)*	*$D^0 \to K_s\pi^+\pi^-$ time dependent amplitude analysis, BELLE*	2.2σ
*CDF: PRL **100**, 121802 (2008)*	*$D^0 \to K^+\pi^-$ decay time analysis, CDF*	3.8σ
*BABAR: PRD **78**, 011105 R (2008)*	*$D^0 \to K^+K^-$, $\pi^+\pi^-$ vs $K^+\pi^-$ lifetime difference analysis, BABAR*	3σ
BABAR: arXiv:0807, 4544 (2008)	*$D^0 \to K^+\pi^-\pi^0$ time dependent amplitude analysis, BABAR*	3.1σ
CLEO-c PRD 78, 012001, (2008)	*$D^0 \to K^+\pi^-$ Relative Strong Phase Using Quantum-Correlated Measurements in $e^+e^- \to D^0 D^0$ at CLEO*	
Significance of all mixing results combined by Heavy Flavor Averaging Group ICHEP2008:		**~9.8σ**



$$x = 1.00^{+0.24}_{-0.26}\ \%$$

$$y = 0.76^{+0.17}_{-0.18}\ \%$$

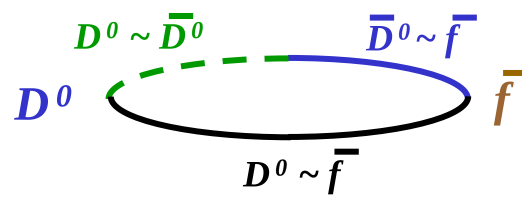
http://www.slac.stanford.edu/xorg/hfag/charm/ICHEP08/

$D^0 \to K^+\pi^-$ Decay Time Measurement

Mixing in "Wrong Sign" Decays ($D^0 \to K^+\pi^-$)

Two types of WS Decays:

- Doubly Cabibbo-supressed (DCS)
- Mixing followed by Cabibbo-Favored (CF) decay



Two ways to reach same final state $\Rightarrow$ interference!

Discriminate between DCS and Mixing decays by their proper time evolution

(assuming *CP*-conservation and $|x|\ll 1$, $|y|\ll 1$) :

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

DCS decay **Interference between DCS and mixing** **Mixing**

$\delta_{K\pi}$ strong phase difference between CF and DCS decay amplitudes

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

$\delta_{K\pi}$ measured by *CLEO-c PRD 78, 012001, (2008)*

"Wrong Sign" Fit with Mixing

Fit results allowing mixing:

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

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

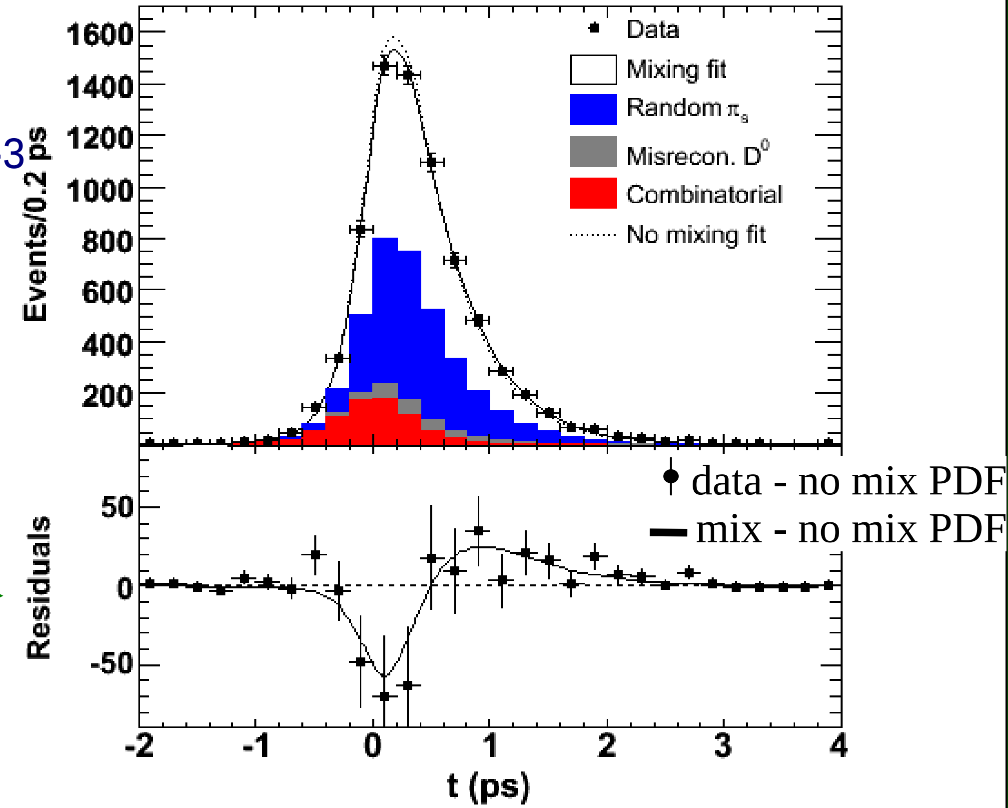
y': $(9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$

x'^2, y' correlation: -0.94

Fit with mixing terms gives better description of data

Fit is inconsistent with no-mixing at 3.9σ

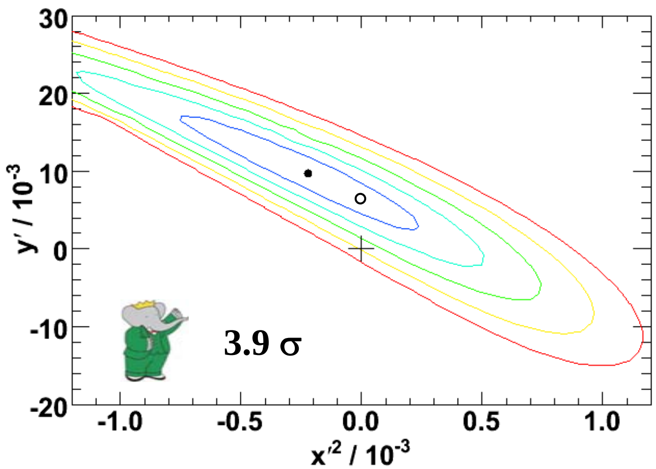
WS decay time, signal region



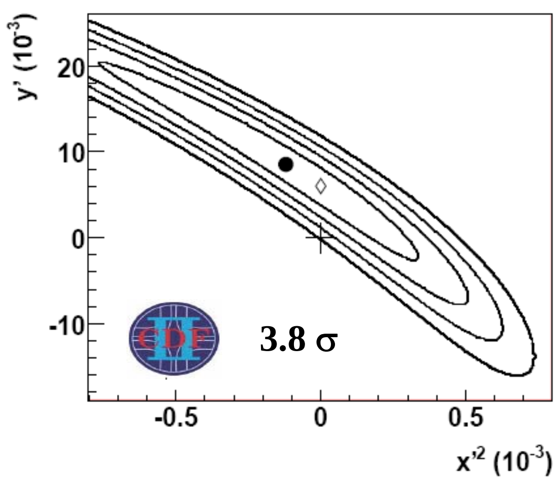
Observation of Mixing in $D^0 \rightarrow K^+\pi^-$

Evidence for mixing from *BaBar* (3.9σ) and confirmation by *CDF* (3.8σ)

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



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



Two completely different experiments (*BaBar* and *CDF*) yield nearly identical results:

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

Lifetime Ratio Measurements

Lifetime Ratio Observables

In the D^* tagged analysis, measure:

$\tau_{K\pi} \equiv \tau(D^0 \to K^-\pi^+ + c.c.)$ *CP*-mixed right-sign Cabibbo-favored (CF) decay lifetime

$\tau_{hh}^{D^0} \equiv \tau(D^0 \to h^- h^+)$ *CP*-even singly Cabibbo-suppressed (SCS) decay lifetime

with h=K or π

Construct mixing variable $\boxed{y_{CP} \equiv \frac{\tau_{K\pi}}{\tau_{hh}} - 1}$ where $\tau_{hh} = \frac{\tau_{hh}^{D^0} + \tau_{hh}^{\bar{D}^0}}{2}$

and CPV asymmetry: $\boxed{\Delta Y \equiv \frac{\tau_{K\pi}}{\tau_{hh}} A_\tau}$ where $A_\tau = \frac{\tau_{hh}^{D^0} - \tau_{hh}^{\bar{D}^0}}{\tau_{hh}^{D^0} + \tau_{hh}^{\bar{D}^0}} = -A_\Gamma$

In the untagged analysis, measure only:

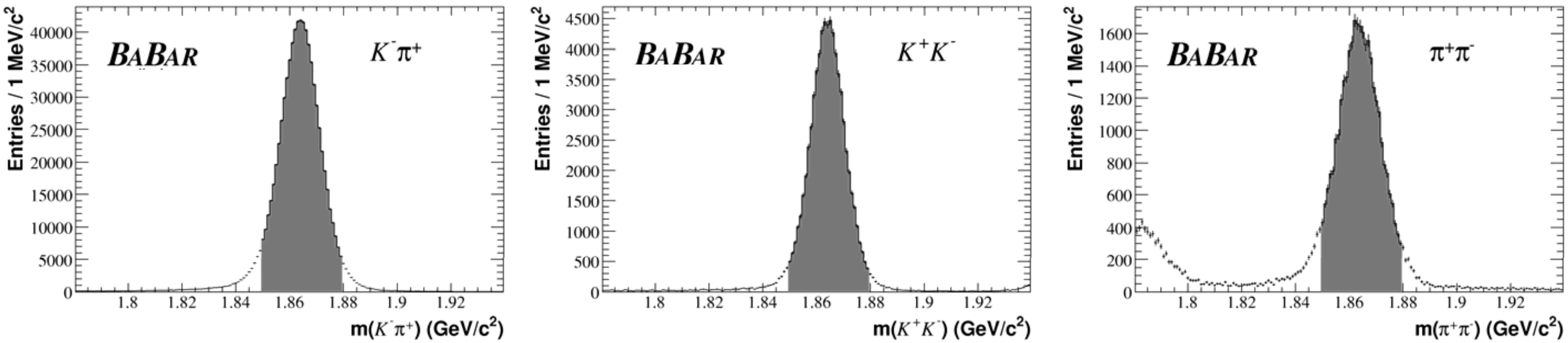
$$\boxed{y_{CP} \equiv \frac{\tau_{K\pi}^{RS+WS}}{\tau_{hh}} - 1}$$

where $\tau_{K\pi}^{RS+WS}$ is the lifetime of the right-sign decay, with a small admixture of wrong sign decays

In the limit of CP conservation, $y_{CP} = y$ and $\Delta Y = 0$

D^*-tagged D^0 mass projections

- Mass projections ($0.1447 < \Delta m < 0.1463$ GeV/c^2):

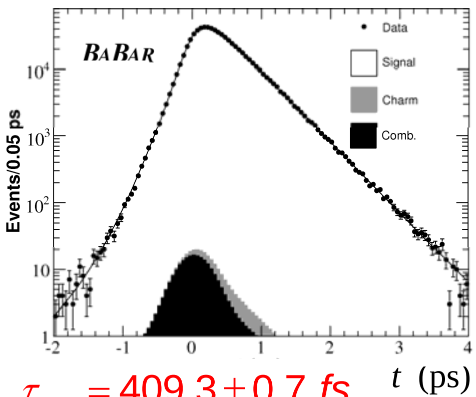


- Signal Purities ($1.8495 < m < 1.8795$ GeV/c^2):

Sample	Size	Purity (%)
$K^-\pi^+$	730,880	99.9
K^-K^+	69,696	99.6
$\pi^-\pi^+$	30,679	98.0

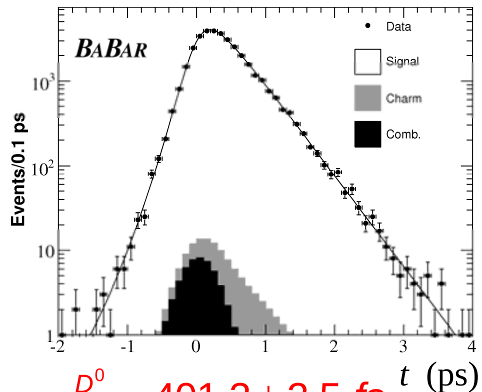
D*-tagged D^0 Lifetimes

$D^0 \to K^-\pi^+$ + c.c.



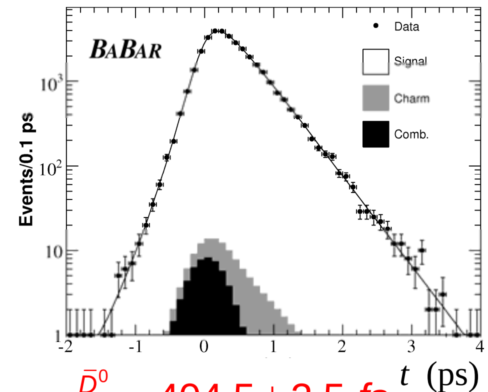
$\tau_{K\pi} = 409.3 \pm 0.7\ fs$

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

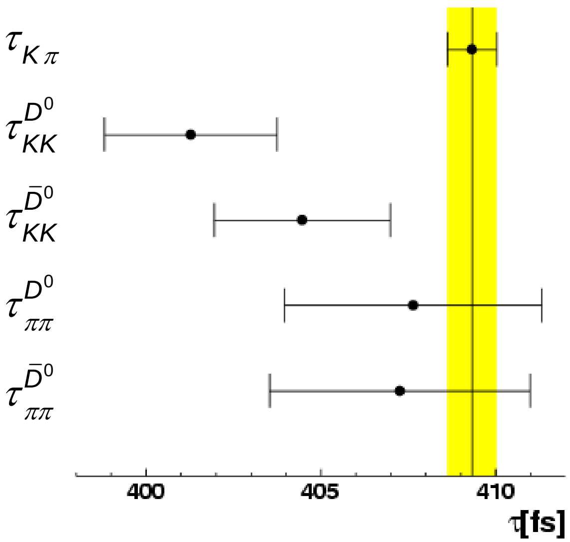


$\tau_{KK}^{D^0} = 401.3 \pm 2.5\ fs$

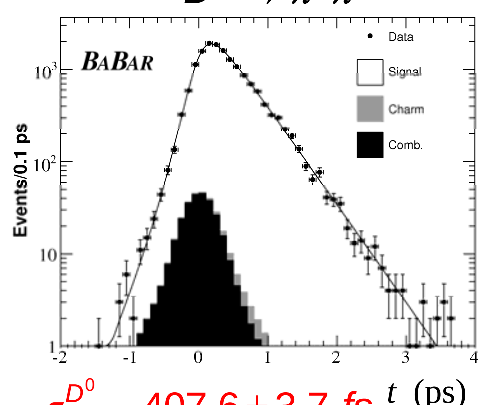
$\bar{D}^0 \to K^+K^-$



$\tau_{KK}^{\bar{D}^0} = 404.5 \pm 2.5\ fs$

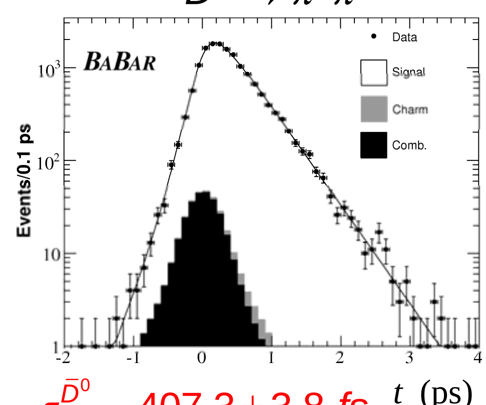


$D^0 \to \pi^+\pi^-$



$\tau_{\pi\pi}^{D^0} = 407.6 \pm 3.7\ fs$

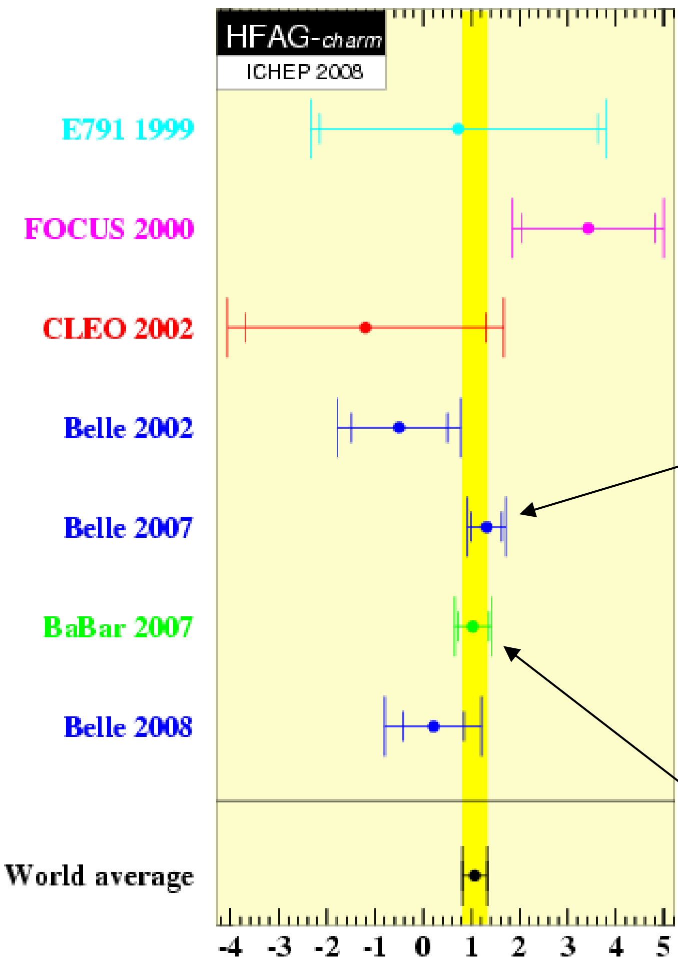
$\bar{D}^0 \to \pi^+\pi^-$



$\tau_{\pi\pi}^{\bar{D}^0} = 407.3 \pm 3.8\ fs$

$K\pi$ and KK lifetimes differ!

D*-tagged Lifetimes Ratio Results



Mode	y_{CP} (%)	$A_\Gamma = -A_\tau$ (%)
K^+K^-	$1.25 \pm 0.39 \pm 0.28$	$0.15 \pm 0.34 \pm 0.16$
$\pi^+\pi^-$	$1.44 \pm 0.57 \pm 0.42$	$-0.28 \pm 0.52 \pm 0.30$
Combined	$1.31 \pm 0.32 \pm 0.25$	$0.01 \pm 0.30 \pm 0.15$

3.2 σ evidence - no CPV (540 fb^{-1})

PRL 98 211803 (2007)

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

3.0 σ evidence - no CPV (384 fb^{-1})

PRD 78 011105(R) (2008)

Combining 384 fb-1 tagged and 91 fb-1 untagged (*BaBar*):
y_{CP} = [*1.03 ± 0.33(stat) ± 0.19(syst)*] %

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

?

y = [*0.76 ± 18*] % HFAG world average

Untagged Lifetimes Ratio Analysis

- **Samples:**
  - Untagged $D^0 \to K^- \pi^+$
  - Untagged $D^0 \to K^- K^+$

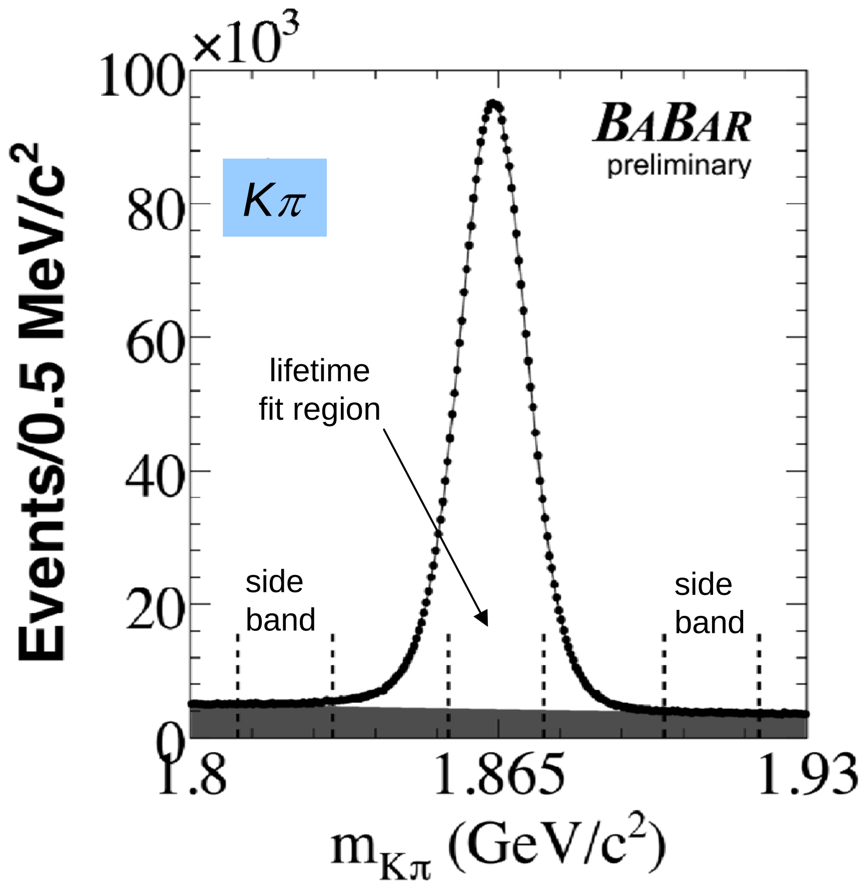
• Independent tagged and untagged samples
• Untagged sample size 4x tagged sample but higher backgrounds

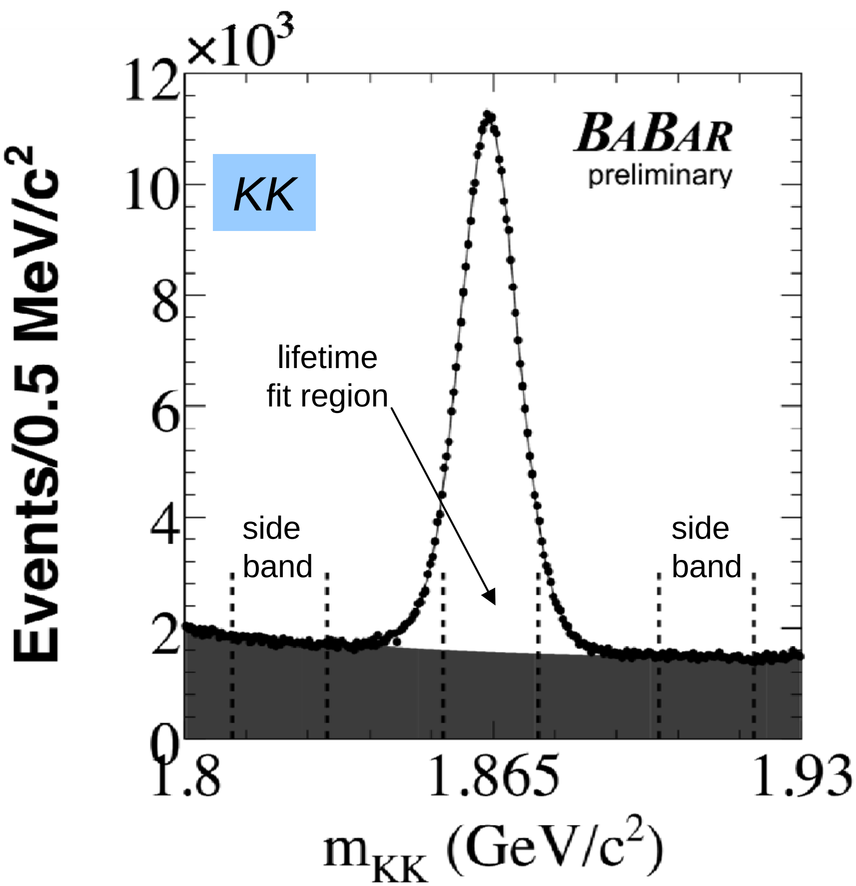
- **Systematics considerations:**
  - Signal systematics mostly cancel in y_{CP}
  - Background systematics don't cancel between modes
  - To minimize backgrounds, restrict sample to narrow D^0 mass region *symmetric* about nominal D^0 mass:
    - $1.8545 < m < 1.8745\ \mathrm{GeV}/c^2$
- **Backgrounds:**
  - Mainly combinatoric, small admixture of misreconstructed charm decays
  - Estimate combinatoric background decay time shape from sideband regions:
    - $1.81 < m < 1.83\ \mathrm{GeV}/c^2$ and $1.90 < m < 1.92\ \mathrm{GeV}/c^2$
  - Estimate charm backgrounds from MC events $(c\bar{c} + uds + b\bar{b} + \tau^+\tau^-)$

Untagged Sample Mass Fit to Data

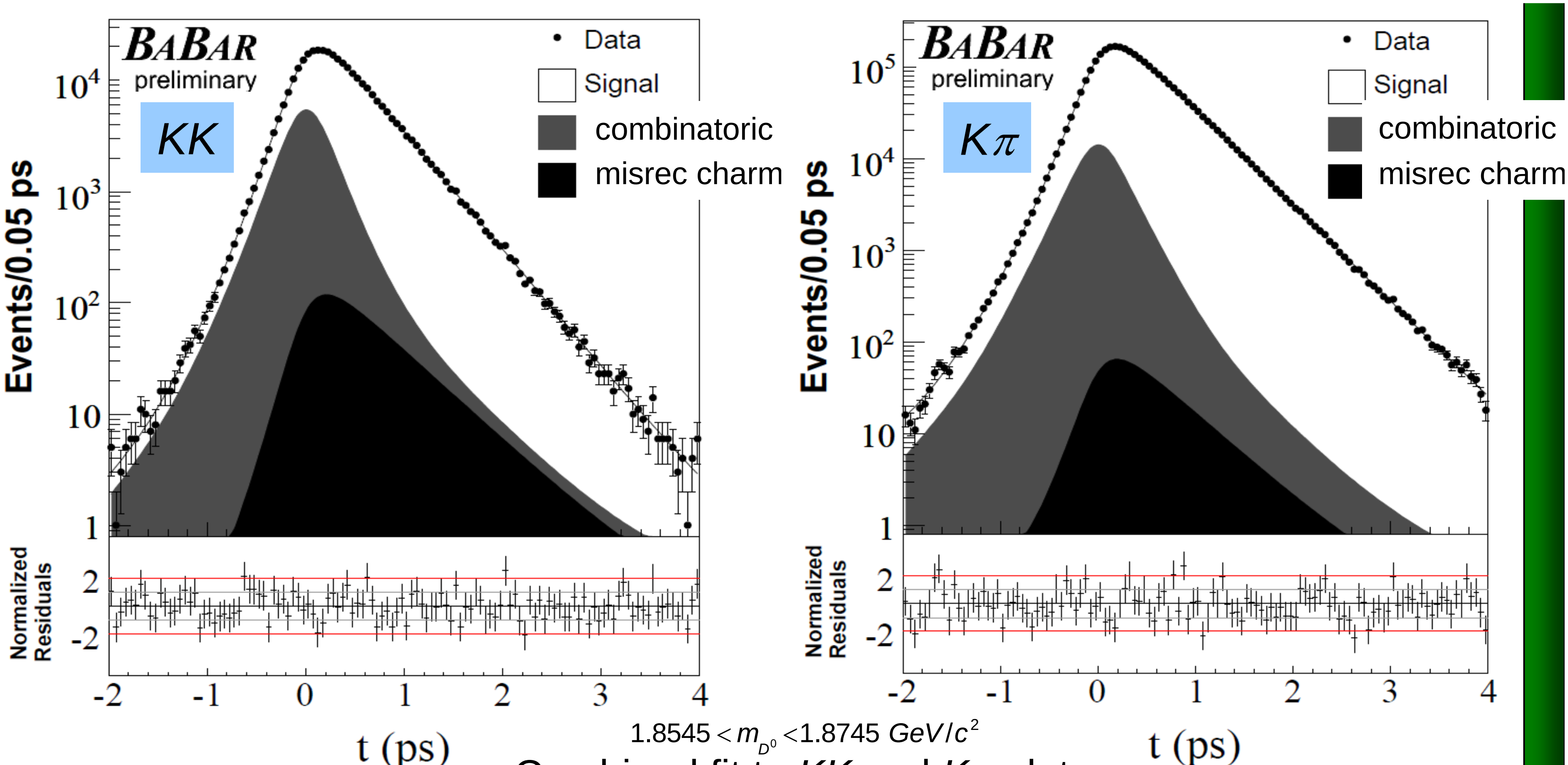
Data and purity yields in $1.8545 < m < 1.8745\ GeV/c^2$:

channel:	$K\pi$	KK
signal events in signal box:	2 710 235	263 639
purity in signal box:	94.2%	80.9%





Untagged D^0 Decay Time Fit to Data



Combined fit to *KK* and $K\pi$ data

τ_{KK} (fs) = 405.85 ± 1.00 (stat.)

$\tau_{K\pi}$ (fs) = 410.39 ± 0.38 (stat.)

$K\pi$ and *KK* lifetimes differ!

y_{CP} (%) = 1.12 ± 0.26 (stat.)

Systematic Uncertainties on Y_{CP}

Systematic variations:

- Signal:
  - Different resolution function models
  - Vary signal box size and position
- Combinatorial Background:
  - Vary parameters in a correlated manner using covariance matrices
- Charm Background:
  - Vary charm yields
  - Vary charm lifetimes
- Selection:
  - Vary decay time error selection
  - Vary multiple overlapping candidate selection
- Detector:
  - Apply different Silicon Vertex Tracker misalignments and beam spot positions in MC

Summary:

$$\Delta y_{CP} = y_{CP}(variation) - y_{CP}(standard)$$

Source of systematic error:	$\lvert \Delta y_{CP} \rvert$ (%)
Signal:	± 0.111
Combinatorial:	± 0.115
Charm:	± 0.086
Selection:	± 0.071
Detector:	± 0.093

y_{CP} systematic error: ± 0.22%

y_{CP} statistical error: ± 0.26%

Combined y_{CP} Results

- We obtain the untagged result (*384 fb*$^{-1}$ data set):

$$y_{CP}\ (untagged) = [\ 1.12 \pm 0.26\ (stat) \pm 0.22\ (syst)\ ]\%$$

Excludes the no-mixing hypothesis
with a significance of (incl. syst.) : ***3.3 σ***

- Our previously published D* tagged D^0 result from the *384 fb*$^{-1}$ data set is

$$y_{CP}\ (tagged) = [\ 1.24 \pm 0.39\ (stat) \pm 0.13\ (syst)\ ]\%$$

PRD 78 011105(R) (2008)

- The tagged and untagged datasets share no events in common and are thus statistically uncorrelated. Conservatively assuming a 100% correlation in the systematics between the two analyses, we obtain

$$y_{CP}\ (correlated) = [\ 1.16 \pm 0.22\ (stat) \pm 0.18\ (syst)\ ]\%$$

Excludes the no-mixing hypothesis
with a significance of (incl. syst.) : ***4.1 σ***

- Assuming the systematics to be uncorrelated, we find

$$y_{CP}\ (uncorrelated) = [\ 1.17 \pm 0.22\ (stat) \pm 0.14\ (syst)\ ]\%$$

Conclusions

- Wrong Sign decays, BABAR measures (384 fb^{-1}):
  - $x'^2 = (-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$ and $y' = (9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$ **PRL 98 211802 (2007)**
  - No-mixing hypothesis excluded at 3.9 σ

- From lifetime ratio, BABAR measures (384 fb^{-1}):

  Y_{CP} (untagged) = [1.12 ± 0.26 (stat.) ± 0.22 (syst.)]% **Preliminary**

  Y_{CP} (tagged) = [1.24 ± 0.39 (stat.) ± 0.13 (syst.)]% **PRD 78 011105(R) (2008)**

  - New Y_{CP} (untagged) in good agreement with world average (Y_{CP} =1.072%)
  - with a significance of 3.3 σ (including systematics)

- Combining tagged and untagged results, BABAR measures:

  Y_{CP} (combined) = [1.16 ± 0.22 (stat.) ± 0.18 (syst.)]%
  - with a significance of 4.1 σ (including 100% correlated systematics)
- Collective evidence for D^0-$\bar{D}^0$ mixing is compelling
  - The no-mixing point is excluded at >10σ, including systematic uncertainties
  - However, no single measurement exceeds 5σ
- BABAR will update all mixing measurements to full data set, stay tuned !

Backup Slides

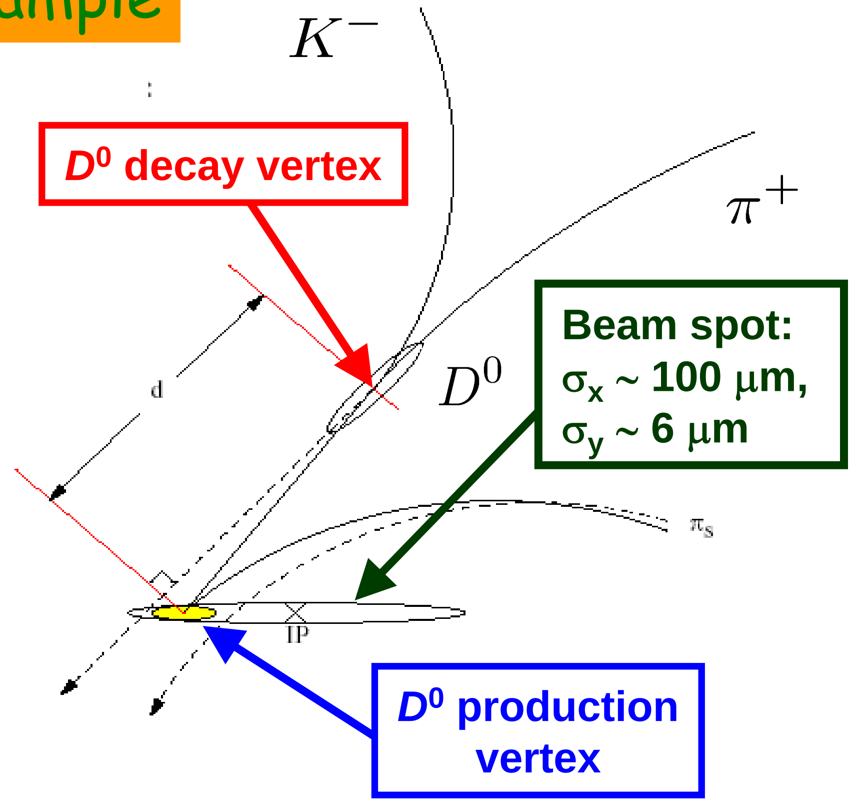
Generic BABAR Mixing Analysis

Tagged Sample

Identify the D^0 flavor at productio using the decays $D^{*\pm} \rightarrow \pi_s^{\pm} D^0$

- select events around the expect

  $\Delta m = m(D^{*+}_{\text{rec.}}) - m(D^0_{\text{rec.}})$
- The charge of the soft pion determines the flavor of the D^0

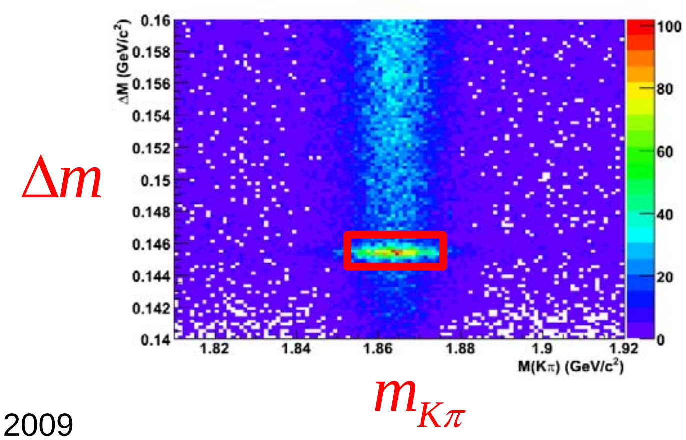


Identify the D^0 flavor at decay using the charge of the Kaon

$D^0 \rightarrow K^- \pi^+$ right-sign (RS)

$D^0 \rightarrow K^+ \pi^-$ wrong-sign (WS)

Vertexing with beam spot constraint determines $m_{K\pi}$, Δm, t decay time, and decay time error, σ_t



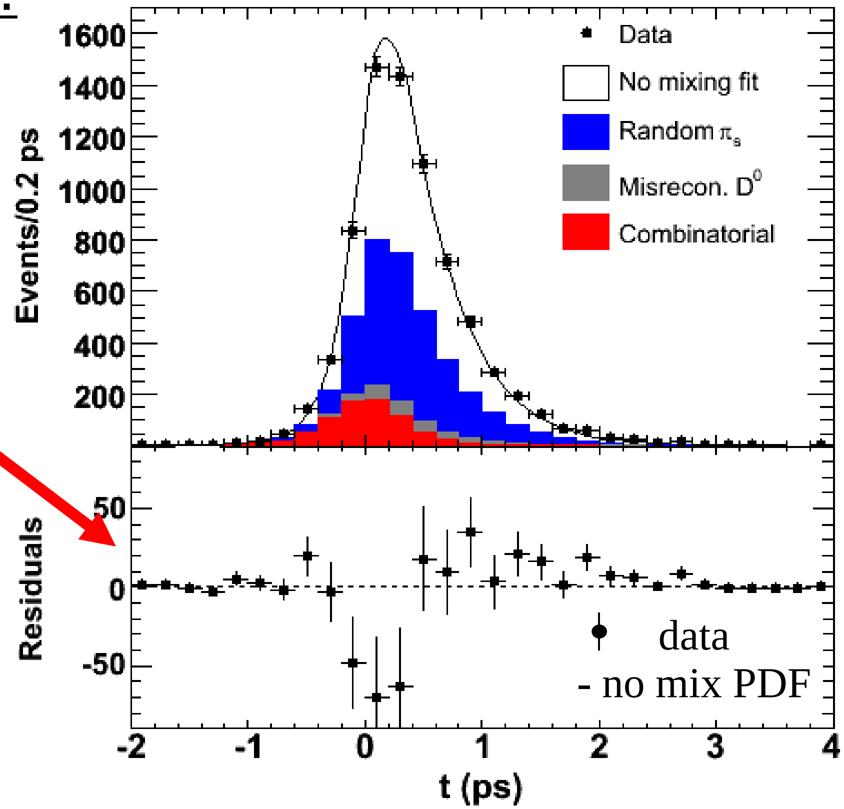
"Wrong Sign" Fit with no Mixing

Fit results assuming no mixing:

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

However, residuals in signal region are not good

WS decay time, signal region



Untagged Selection

- Selection requirements
  - ± tracks from a common point
  - KLHTight, piLHTight PID selectors
  - D^0 invariant mass m, reconstructed decay time t and its error σ_t from beam constrained TreeFitter vertex fit
    - $P(\chi^2) > 0.1\%$
    - $1.80 < m < 1.93\ GeV/c^2$
    - $-25 < t < 25$ psec
    - $\sigma_t < 0.5$ psec
  - Remove B decays using D^0 center of mass momentum cut
    - $P^* > 2.5$ GeV/c
  - D^0 daughter track number of DCH hits
    - $N_{DCH} \geqq 12$
  - Reduce uds backgrounds using helicity angle (angle between +track in D^0 rest frame and D^0 boost direction) cut:
    - $|\cos\theta_h| < 0.7$
  - Remove events containing a selected D^* tagged $D^0 \to \pi^+\pi^-$, $K^\mp\pi^\pm$, K^+K^- decay
  - For multiple D^0 candidates sharing tracks, keep the one with highest $P(\chi^2)$

Untagged Decay Time PDFs

- **Signal**: exponential folded with three Gaussian resolution functions:

$$\mathcal{D}(t,\sigma_t;s,t_0,\tau) = C_{\sigma_t}\int \exp(-t_{\rm true}/\tau)\exp\left(-\frac{(t-t_{\rm true}+t_0)^2}{2(s\cdot\sigma_t)^2}\right)dt_{\rm true}$$

$$\begin{aligned}\mathcal{R}_X(t,\sigma_t;\tau_X) &= f_{t3}\mathcal{D}(t,\sigma_t;S_Xs_3,t_0,\tau_X)\\ &+ (1-f_{t3})\Big[f_{t2}\mathcal{D}(t,\sigma_t;S_Xs_2,t_0,\tau_X)\\ &+ (1-f_{t2})\mathcal{D}(t,\sigma_t;S_Xs_1,t_0,\tau_X)\Big],\end{aligned}$$

where:
t_0 = common offset parameter
S_X = scale factor for each mode X, where $S_{K\pi}$ = 1, S_{KK} floating
σ_t = decay time error for each candidate
$C_{\sigma t}$= normalization constant

parameters shared between modes:
f_{ti}, s_i, t_0

- **Mis-reconstructed charm**: exponential folded with two Gaussian resolution functions: $\mathcal{P}^{\rm charm}_{hh}(t,\sigma_t) = f_{\rm charm}\mathcal{D}(t,\sigma_t;s_{1\rm charm},0,\tau_{\rm charm}) + (1-f_{\rm charm})\mathcal{D}(t,\sigma_t;s_{2\rm charm},0,\tau_{\rm charm})$.
- **Combinatoric:** sum of two Gaussians and a third Gaussian (CB) with a power-law tail, where the Gaussian widths do not depend on σ_t

$$\begin{aligned}\mathcal{P}^{\rm comb}_{hh}(t,\sigma_t) &= f_1G(t;\bar{t}_{\rm Gauss_1},\sigma_{\rm Gauss_1})\\ &+ (1-f_2)\Big[f_3G(t;\bar{t}_{\rm Gauss_2},\sigma_{\rm Gauss_2})\\ &+ (1-f_3)CB(t;\bar{t}_{\rm CB},\sigma_{CB},\alpha,n)\Big]\end{aligned}$$

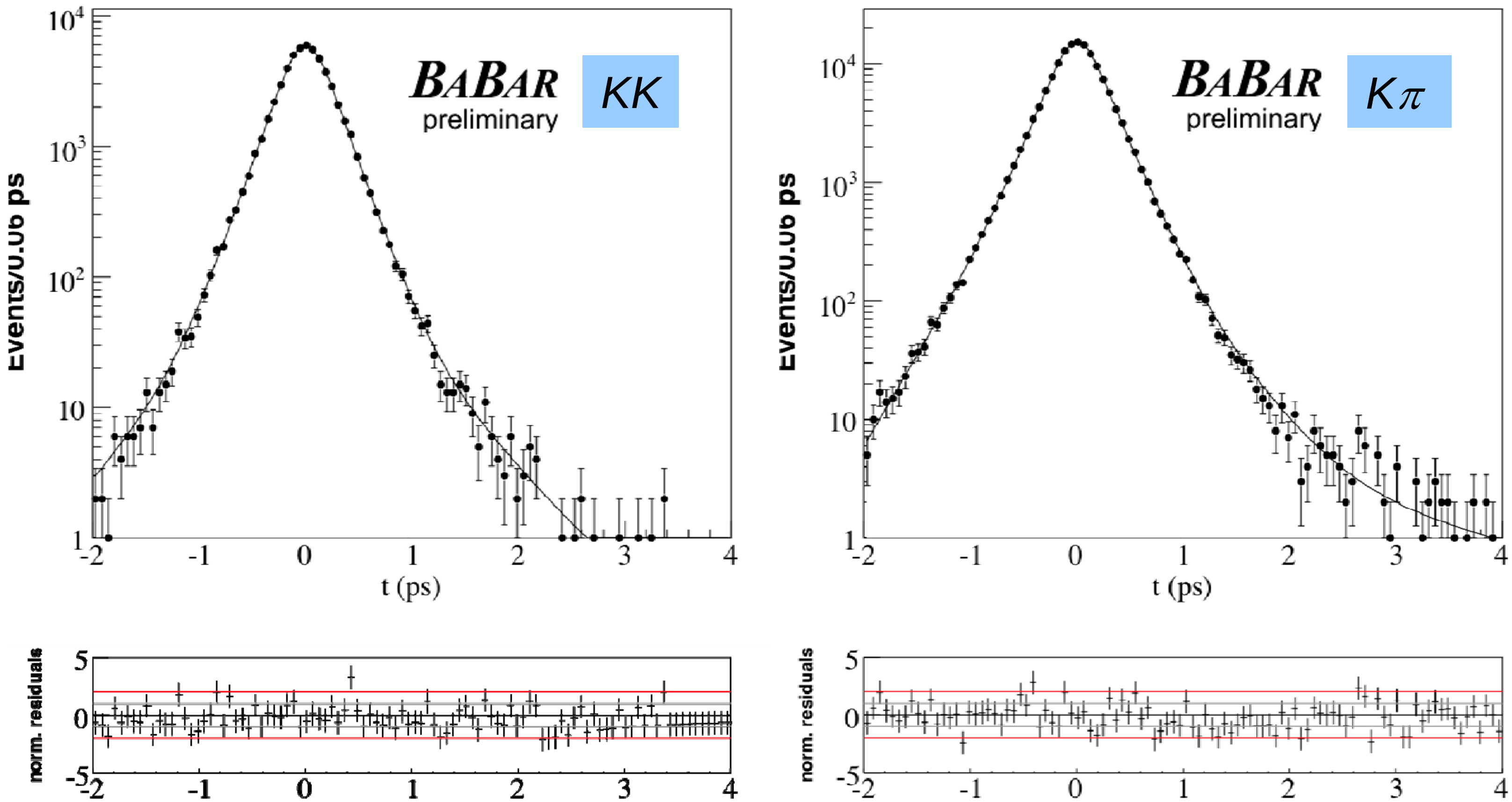
where $G(x;\bar{x},\sigma) \equiv C_{\rm G}\exp\left(-\frac{(x-\bar{x})^2}{2\sigma^2}\right)$ and

$$CB(x;\bar{x},\sigma,\alpha,n) = C_{\rm CB}\begin{cases}\exp\left(-\frac{(x-\bar{x})^2}{2\sigma^2}\right) & \text{if } \frac{x-\bar{x}}{\sigma} > -|\alpha|\\ \left(\frac{n}{|\alpha|}\right)^n \frac{\exp(-\frac{1}{2}\alpha^2)}{\left(\frac{n}{|\alpha|}-|\alpha|\pm\frac{x-\bar{x}}{\sigma}\right)^n} & \text{otherwise,}\end{cases}$$

Combinatorial Decay Time Distributions

From "cocktail" $(c\bar{c} + uds + b\bar{b} + \tau^+\tau^-)$ Monte Carlo in signal region:

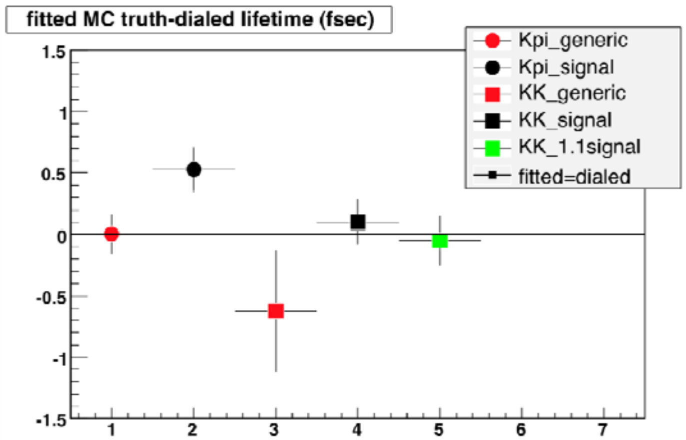
— Combinatorial probability density function from sideband fits
Truth matched combinatorial decay time distribution



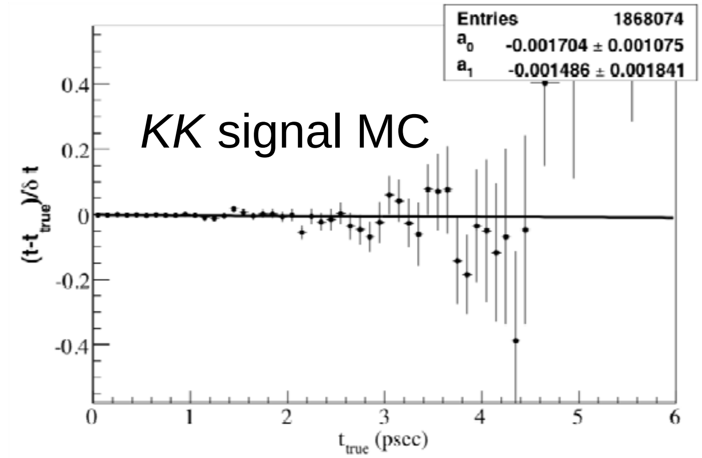
Cross Checks

Decay time fits to cocktail and signal MC datasets

find little bias in the difference between $\tau_{K\pi}$ and τ_{KK} lifetimes (<0.5 fsec)



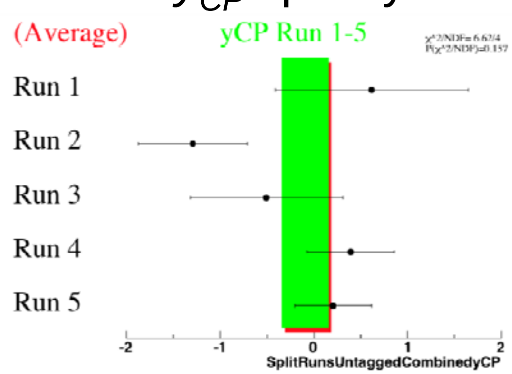
No significant variations in the efficiency to reconstruct signal decays versus true decay time



Unblinded $K\pi$ lifetime:

	lifetime (fs)
Tagged dataset:	409.33 ± 0.70(*stat*)
Untagged dataset:	410.39 ± 0.38(*stat*)
PDG 2008 average:	410.1 ± 1.5

blinded y_{CP} split by running period:



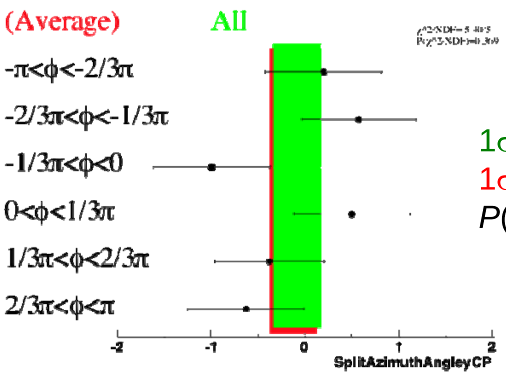
1σ nominal fit

1σ weighted average

P(χ^2)=*16%*

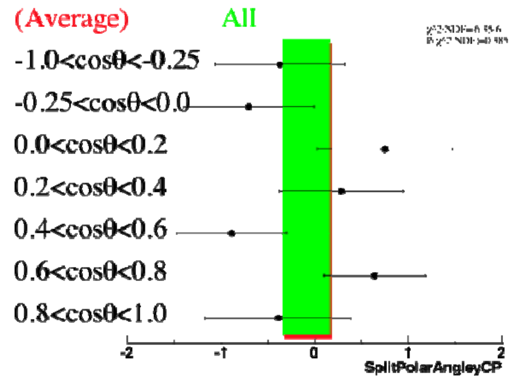
Cross Checks

blinded y_{CP} split by D^0 azimuth:



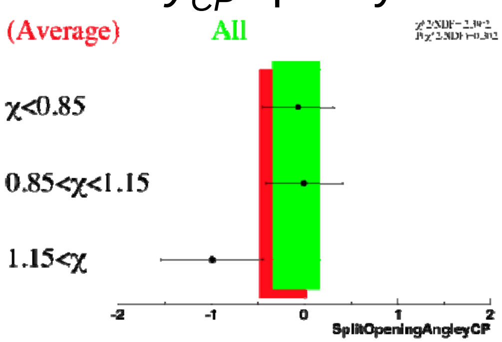
1σ nominal fit
1σ weighted average
$P(\chi^2)$=37%

blinded y_{CP} split by D^0 polar angle:



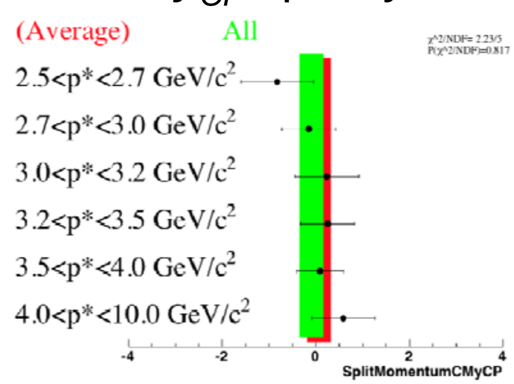
1σ nominal fit
1σ weighted average
$P(\chi^2)$=39%

blinded y_{CP} split by D^0 opening angle:



1σ nominal fit
1σ weighted average
$P(\chi^2)$=30%

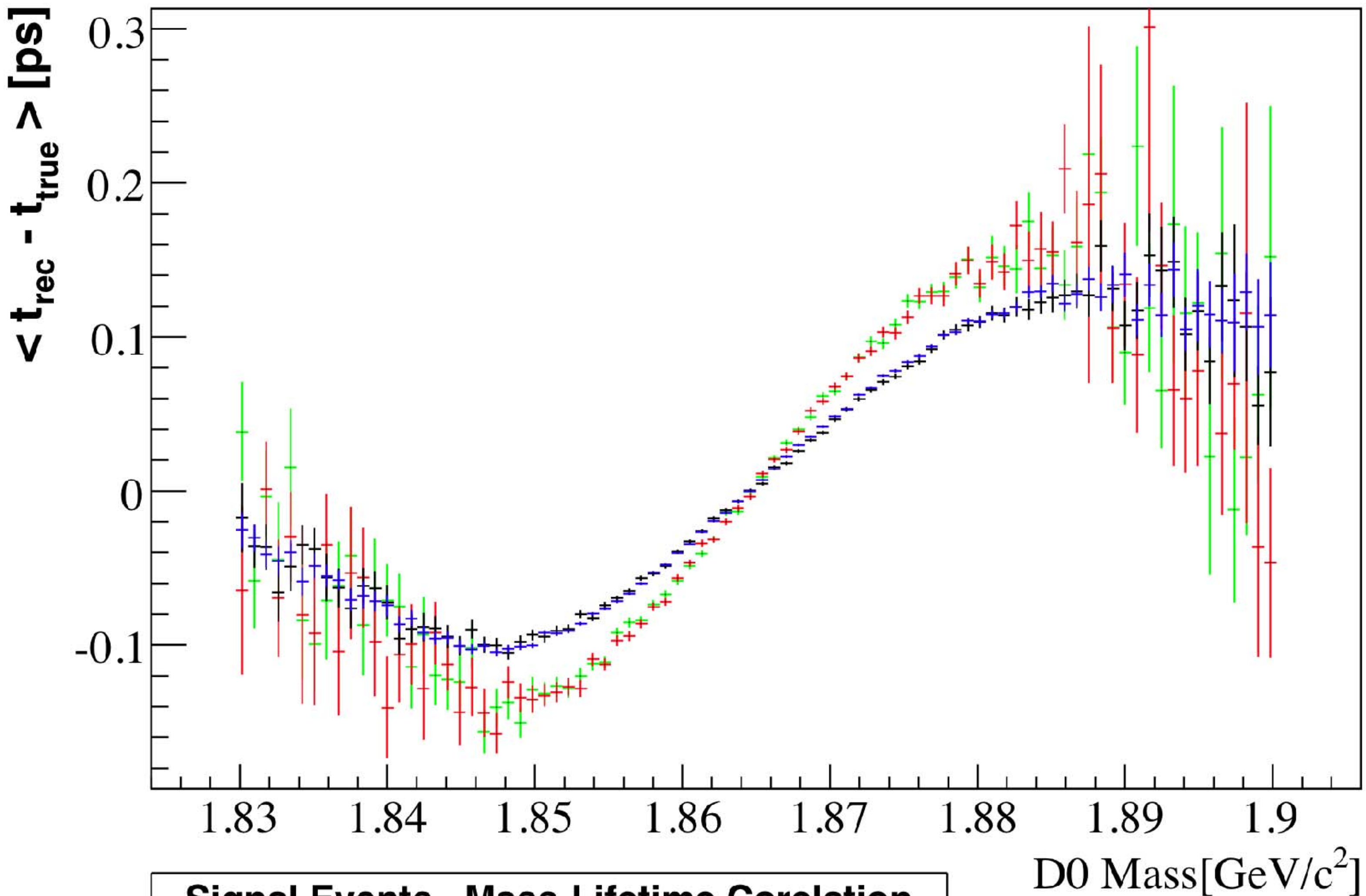
blinded y_{CP} split by D^0 *CM* momentum:



1σ nominal fit
1σ weighted average
$P(\chi^2)$=82%

➪ no significant variations seen in y_{CP}

Vertexing Bias



Signal Events, Mass-Lifetime Corelation