D^0-$\bar{D}^0$ Mixing and CP Violation

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For the BaBar Collaboration

The oscillation in time of neutral D mesons into their antiparticles, and *vice versa*, commonly called D^0-$\bar{D}^0$ mixing, has been observed by several experiments in a variety of channels during the past two years. While K^0-$\bar{K}^0$ mixing and B^0-$\bar{B}^0$ mixing are (relatively) well understood in the Standard Model of particle physics, observations of D^0-$\bar{D}^0$ mixing indicate that the physical eigenstates have decay rate differences and/or mass differences greater than expected most naively. In this talk I will present $\Delta(\Gamma)$ results for two-body decays and the results of a time-dependent amplitude analysis of the decay $D^0 \rightarrow K^+\pi^-\pi^0$ from the BaBar experiment at SLAC. I will also present related CP violation results.

Mixing Phenomenology

Neutral *D* mesons are produced as *flavor eigenstates* D^0 and $\bar{D}^0$ 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, lifetime 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

$$\Delta M = M_1 - M_2$$

or lifetime difference

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

For convenience define, ***x*** and ***y***

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

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

and define the mixing rate

$$R_M = \frac{x^2 + y^2}{2}\ (< 5 \times 10^{-4})$$

How Mixing is Calculated

$$\left(M - \frac{i}{2}\Gamma\right)_{12} = \frac{1}{2m_D}\langle D^0|\mathcal{H}_w^{\Delta C=2}|\overline{D}^0\rangle + \frac{1}{2m_D}\sum_n \frac{\langle D^0|\mathcal{H}_w^{\Delta C=1}|n\rangle\,\langle n|\mathcal{H}_w^{\Delta C=1}|\overline{D}^0\rangle}{m_D - E_n + i\epsilon}$$

The first term is called the short distance contribution and the second the long distance contribution. Assuming the short distance contributions are small, and that CP is conserved, we can express y as the absorptive part of the second term

$$y = \frac{1}{\Gamma_{\rm D}}\sum_n \rho_n \langle\overline{D}^0|\mathcal{H}_w^{\Delta C=1}|n\rangle\langle n|\mathcal{H}_w^{\Delta C=1}|D^0\rangle,$$

where ρ_n is the phase space factor corresponding to the charmless intermediate state $|n\rangle$.

Points of theoretical consensus

- Short distance contributions to x and y are $\ll 10^{-2}$;
- CP is not significantly violated in the Standard Model;
- Large long-distance contributions to y may originate in the different phase spaces available for CP-even and CP-odd final states (but not in SM matrix elements); $y \sim \mathcal{O}(10^{-2})$ cannot be excluded in the Standard Model; $x \sim \mathcal{O}(10^{-2})$ is less likely, although it cannot be excluded absolutely.
- New Physics may contribute to mixing at the x, $y \sim \mathcal{O}(10^{-2})$ level.

Standard Model Mixing Predictions

Box diagram SM charm mixing rate naively expected to be very low ($R_M \sim 10^{-10}$) (Datta & Kumbhakar)

Z.Phys. C**27**, 515 (1985)

CKM suppression → $|V_{ub}V^*_{cb}|^2$

GIM suppression → $(m^2_s - m^2_d)/m^2_W$

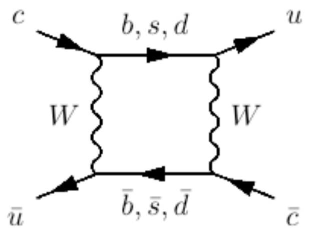
Di-penguin mixing, $R_M \sim 10^{-10}$

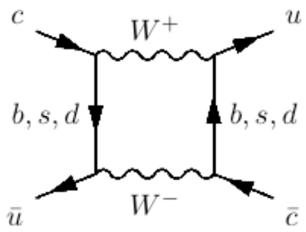
Phys. Rev. D **56**, 1685 (1997)

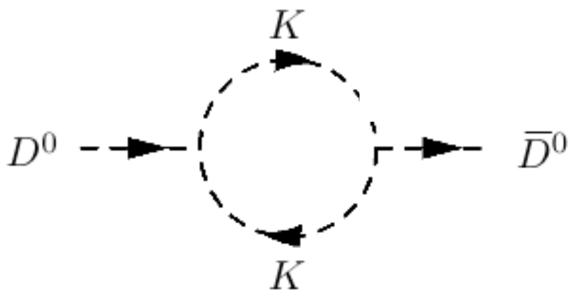
Enhanced rate SM calculations generally due to long-distance contributions:

first discussion, L. Wolfenstein

Phys. Lett. B **164**, 170 (1985)







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Partial History of Long-Distance Calculations

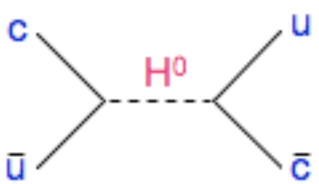
- Early SM calculations indicated long distance contributions produce $x \ll 10^{-2}$:
  - $x \sim 10^{-3}$ (dispersive sector)
    - PRD **33**, 179 (1986)
  - $x \sim 10^{-5}$ (HQET)
    - Phys. Lett. B **297**, 353 (1992)
    - Nucl. Phys. **B403**, 605 (1993)
- More recent SM predictions can accommodate x, y ~1% [of opposite sign] (Falk *et al.*)
  - $\boldsymbol{x,y} \approx \sin^2 q_C \times [SU(3)\ \text{breaking}]^2$
    - Phys.Rev. D **65**, 054034 (2002)
    - Phys.Rev. D **69**, 114021 (2004)
- For a discussion of local duality [Bigi & Uraltsev], see
  - Nucl. Phys. **B592**, 92-106 (2001)

New Physics Mixing Predictions

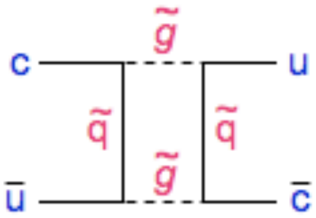
Possible enhancements to mixing due to new particles and interactions in new physics models

Most new physics predictions for x

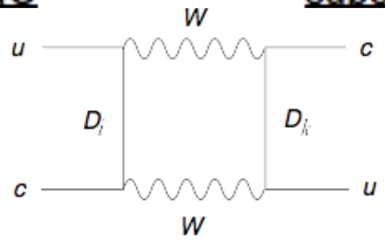
- Extended Higgs, tree-level FCNC
- Fourth generation down-type quarks
- Supersymmetry: gluinos, squarks
- Lepto-quarks



FCNC



supersymmetry



Heavy weak iso-singlet quarks

- Large possible SM contributions to mixing require observation of either a CP-violating signal or $|x| \gg |y|$ to establish presence of NP
- A recent survey (Phys. Rev. D76, 095009 (2007), arXiv:0705.3650) summarizes models and constraints:

Fourth generation	Vector leptoquarks
Q = -1/3 singlet quark	Flavor-conserving Two-Higgs
Q = +2/3 singlet quark	Flavor-changing neutral Higgs
Little Higgs	Scalar leptoquarks
Generic Z'	MSSM
Left-right symmetric	Supersymmetric alignment

and more

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

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

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

In the untagged analysis, measure only:

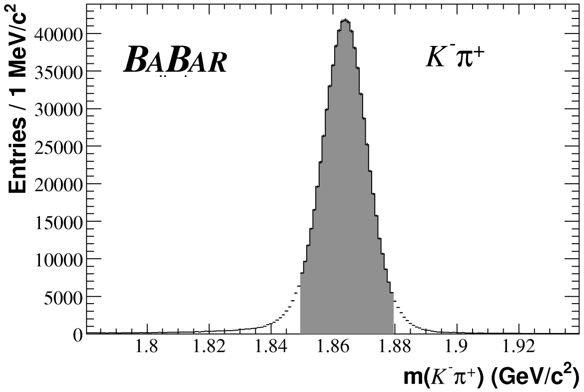
$$y_{CP} \equiv \frac{\tau_{K\pi}^{RS+WS}}{\tau_{hh}} - 1$$

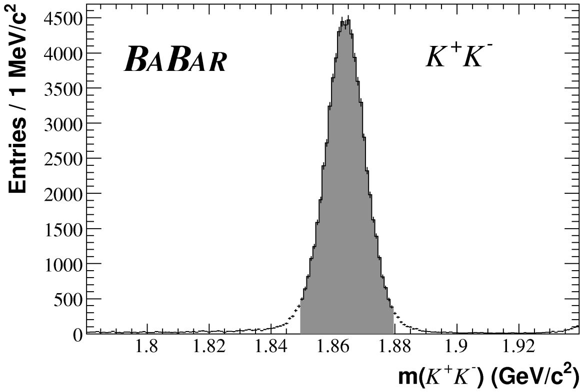
where $\tau_{K\pi}^{RS+WS}$ is the lifetime of the right-sign decay, with a small admixture of wrong sign decays

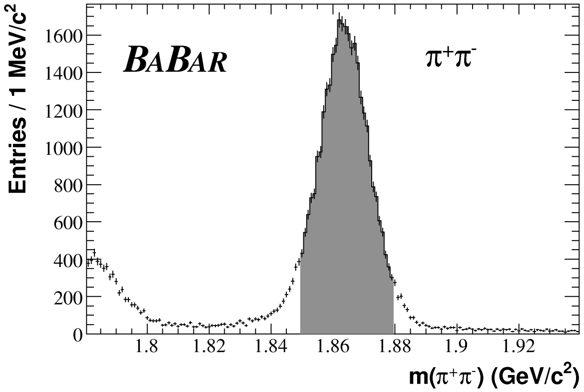
In the limit of CP conservation, $y_{CP} = y$ and $\Delta Y = 0$

D^*-tagged D^0 mass projections

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





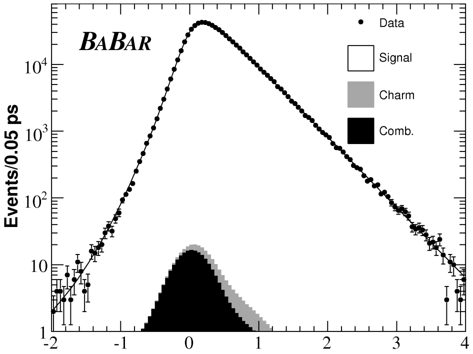


- Signal Purities ($1.8495 < m < 1.8795$ GeV/c^2):

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

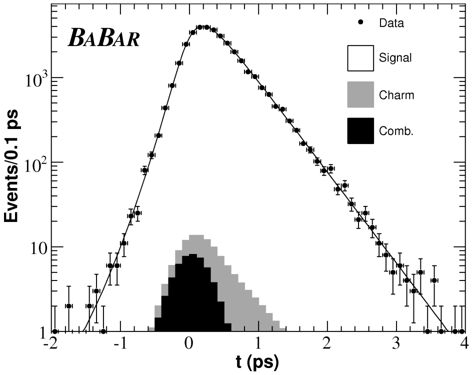
D^*-tagged D^0 Lifetimes

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



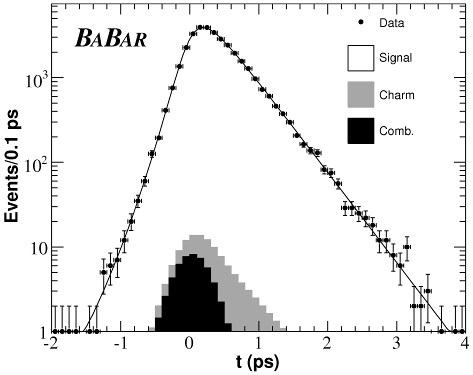
$\tau_{K\pi} = 409.3 \pm 0.7\ fs$

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

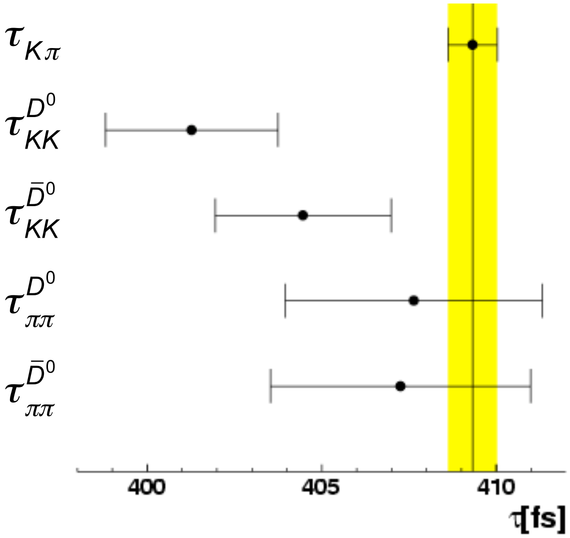


$\tau_{KK}^{D^0} = 401.3 \pm 2.5\ fs$

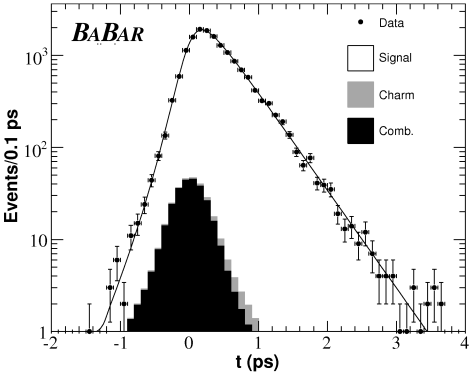
$\bar{D}^0 \rightarrow K^+K^-$



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

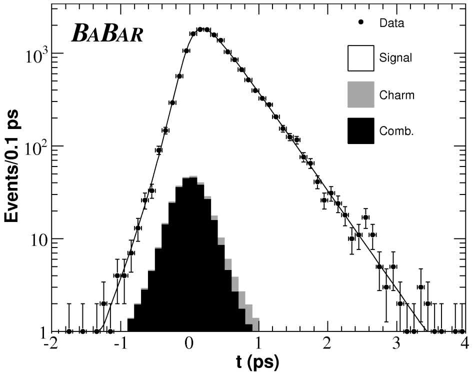


$D^0 \rightarrow \pi^+\pi^-$



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

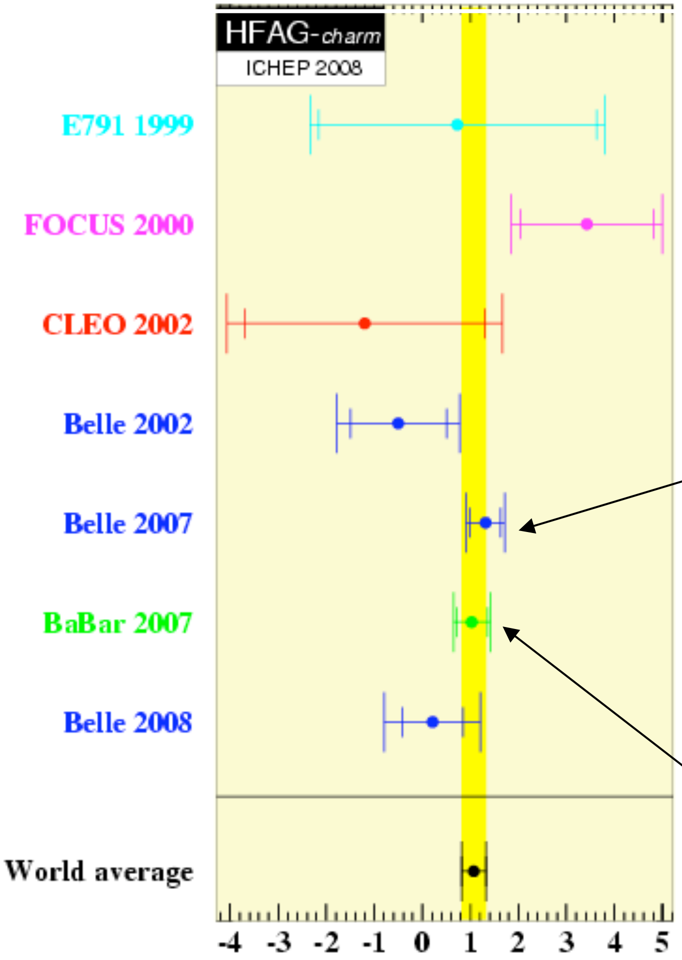
$\bar{D}^0 \rightarrow \pi^+\pi^-$

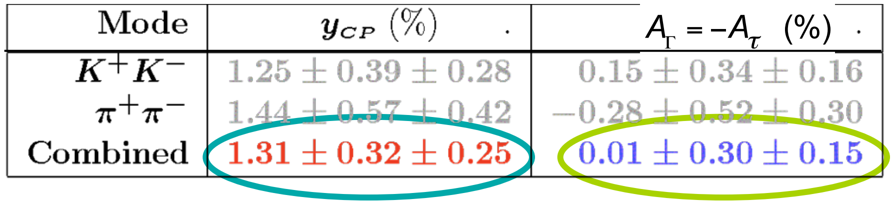


$\tau_{\pi\pi}^{\bar{D}^0} = 407.3 \pm 3.8\ fs$

$K\pi$ and KK lifetimes differ!

D*-tagged Lifetimes Ratio Results

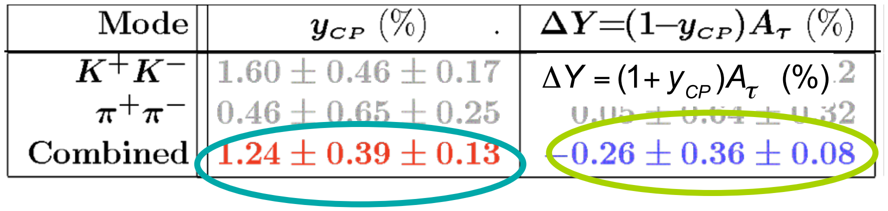




Mode	y_{CP} (%)	$A_\Gamma = -A_\tau$ (%)
K^+K^-	$1.25 \pm 0.39 \pm 0.28$	$0.15 \pm 0.34 \pm 0.16$
$\pi^+\pi^-$	$1.44 \pm 0.57 \pm 0.42$	$-0.28 \pm 0.52 \pm 0.30$
Combined	$1.31 \pm 0.32 \pm 0.25$	$0.01 \pm 0.30 \pm 0.15$

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^-	$1.60 \pm 0.46 \pm 0.17$	$\Delta Y = (1 + y_{CP})A_\tau$ (%) 2
$\pi^+\pi^-$	$0.46 \pm 0.65 \pm 0.25$	$0.05 \pm 0.64 \pm 0.32$
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)

Untagged Lifetimes Ratio Analysis

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

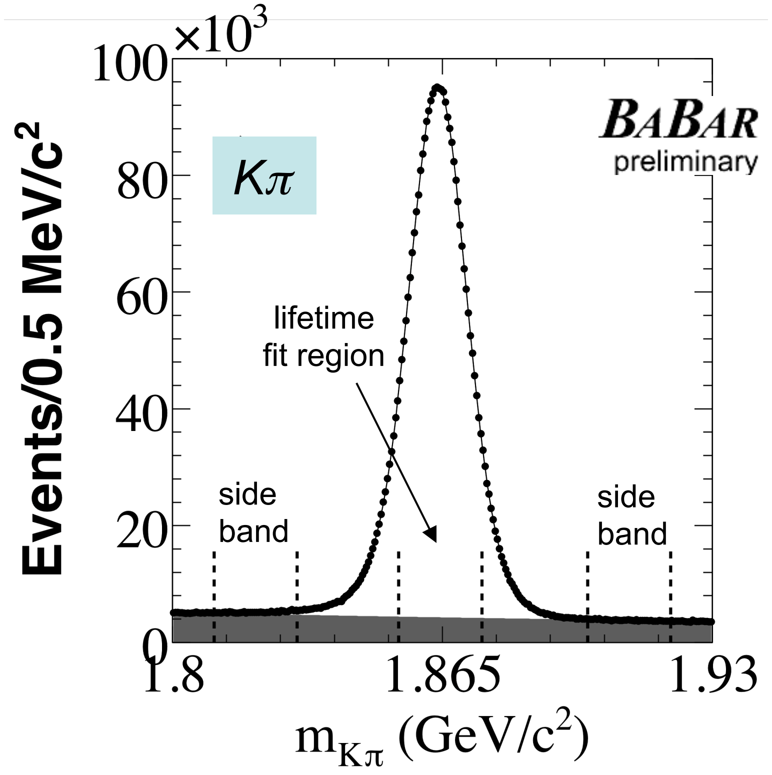
- Independent tagged and untagged samples
- Untagged sample size 4x tagged sample but higher backgrounds

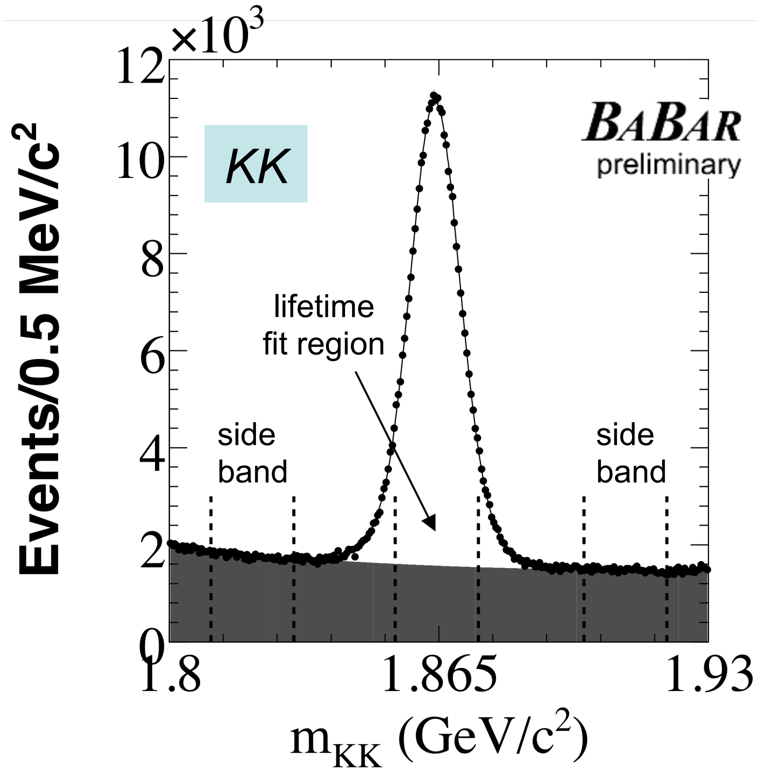
- Systematics considerations:
  - Signal systematics mostly cancel in y_{CP}
  - Background systematics don't cancel between modes
  - To minimize backgrounds, restrict sample to narrow D^0 mass region *symmetric* about nominal D^0 mass:
    - $1.8545 < m < 1.8745$ GeV/c^2
- Backgrounds:
  - Mainly combinatoric,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

Untagged Sample Mass Fit to Data

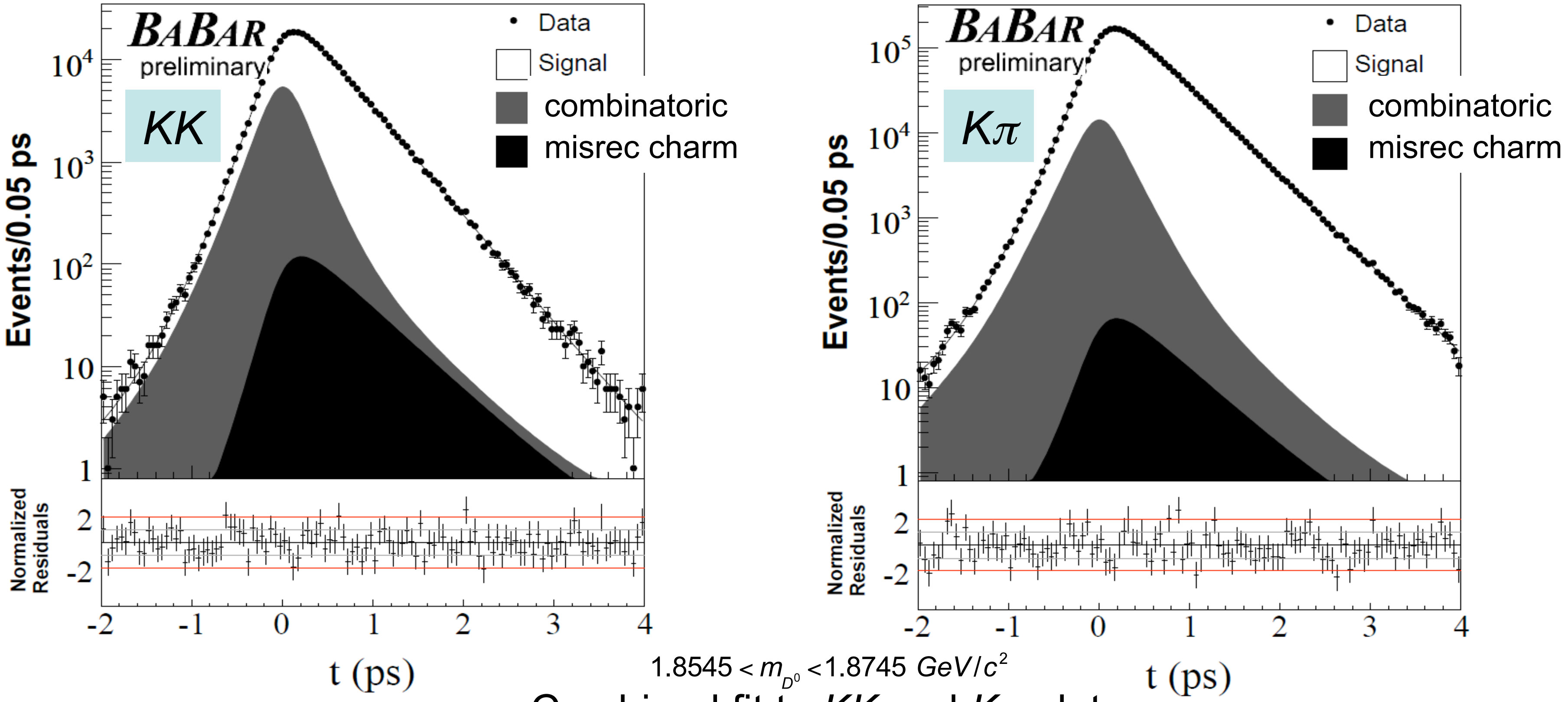
Data and purity yields in $1.8545 < m < 1.8745\ GeV/c^2$:

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



$1.8545 < m_{D^0} < 1.8745\ GeV/c^2$

Combined fit to *KK* and *Kπ* data

τ_{KK} (fs) = 405.85 ± 1.00 (stat.) $\tau_{K\pi}$ (fs) = 410.39 ± 0.38 (stat.)

Kπ 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:	$\|\Delta y_{CP}\|$ (%)
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):

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

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

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

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

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

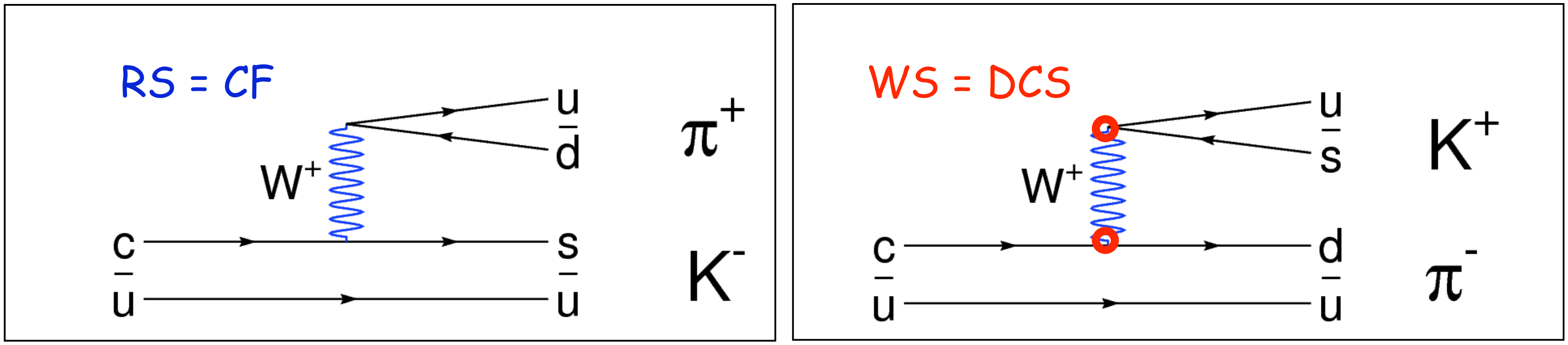
Excludes the no-mixing hypothesis

with a significance of (incl. syst.) : **4.1** σ

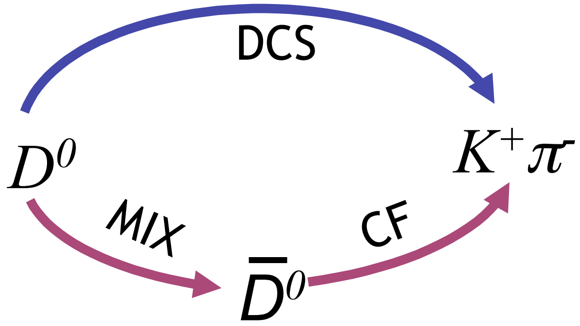
- Assuming the systematics to be uncorrelated, we find

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

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



DCS and mixing amplitudes interfere to give a "quadratic" WS decay rate (x, y << 1):



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

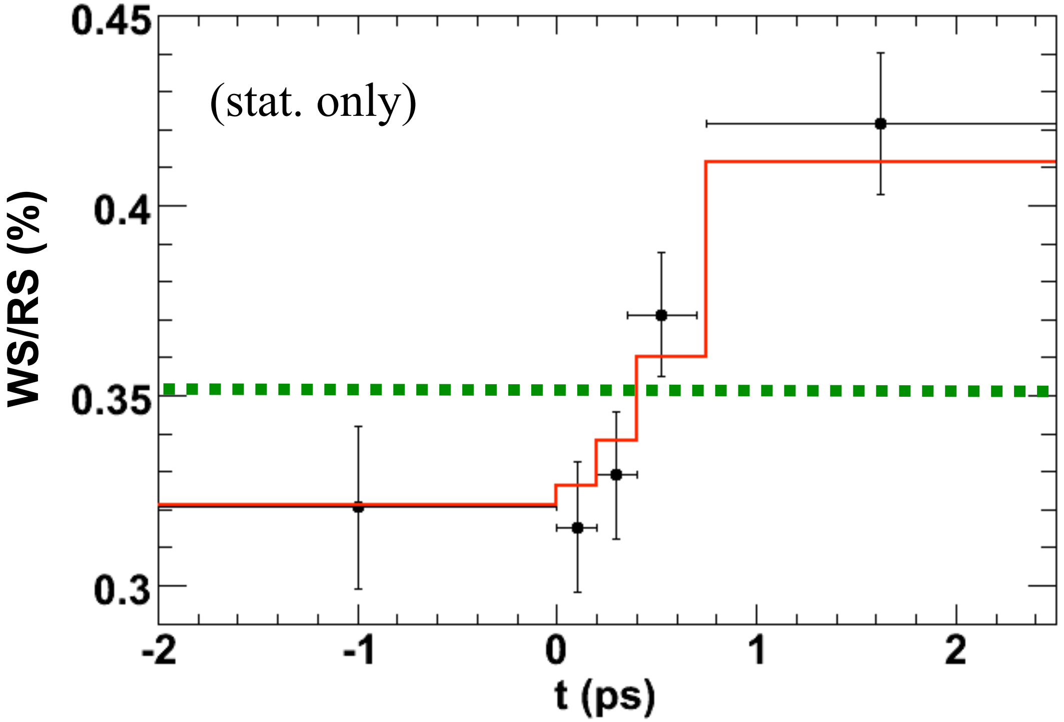
where $x' = x\cos\delta + y\sin\delta \qquad y' = y\cos\delta - x\sin\delta$

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

Simplified Fit Strategy & Validation

Rate of WS events clearly increases with time:

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



Consistent with prediction from full likelihood fit

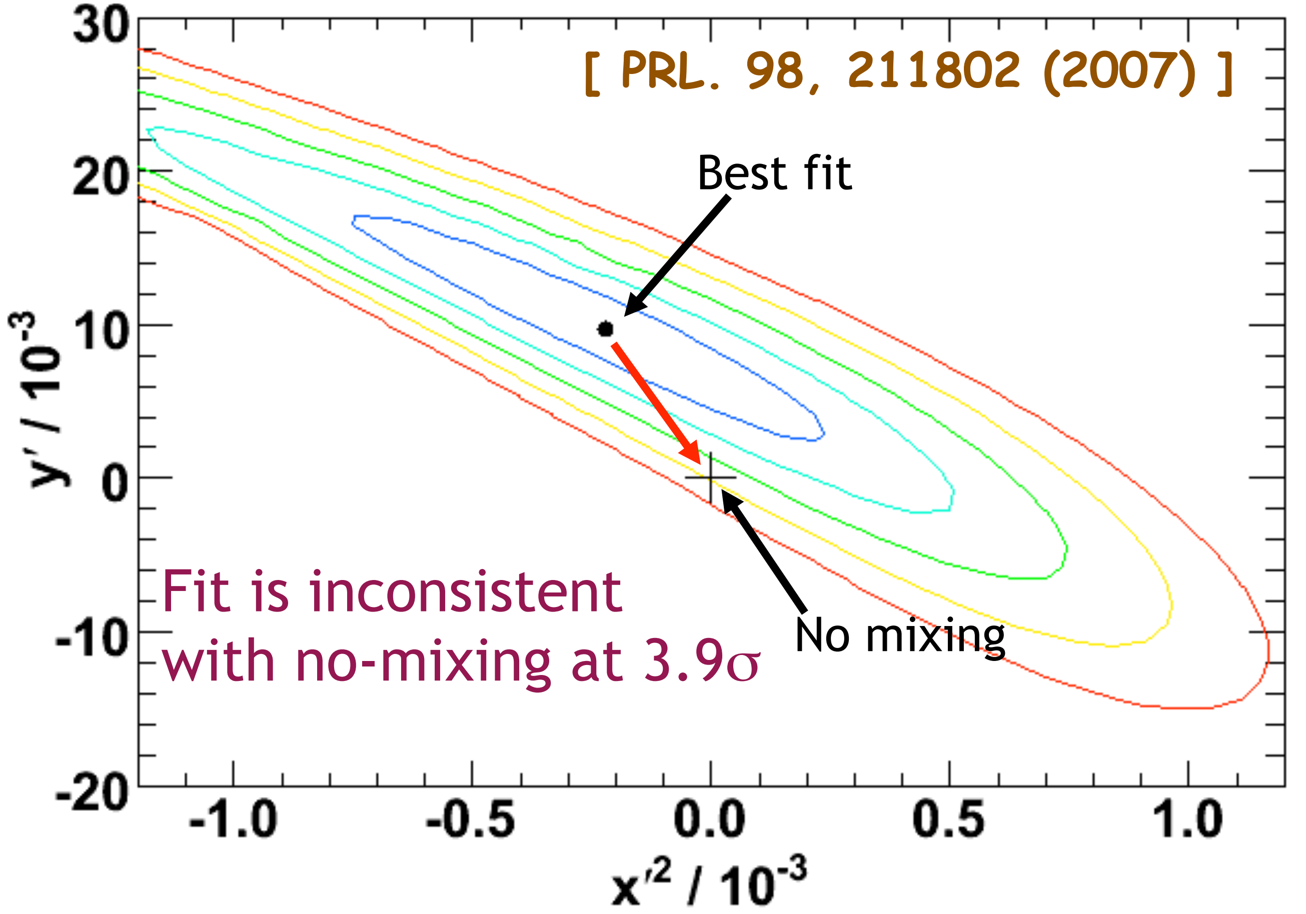
$\chi^2=1.5$

Inconsistent with no-mixing hypothesis:

$\chi^2=24$

Signal Significance with Systematics

Including systematics (~ 0.7 x stat)
decreases signal significance



Fit is inconsistent
with no-mixing at 3.9σ

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

"Wrong-sign" decay rate varies across the Dalitz plot:

DCS term

Resonance phase

$$\begin{aligned}\mathcal{A}(m_{K^-\pi^+}, m_{K^-\pi^0}, t) \;=\; & e^{-\Gamma t}[|\bar{A}_D|^2 + \\ & |\bar{A}_D||A_D|\,(y'' \cos\delta_D - x'' \sin\delta_D)\,\Gamma t \\ & |A_D|^2(x''^2 + y''^2)(\Gamma t)^2]\end{aligned}$$

Interference term

CF (mixed) term

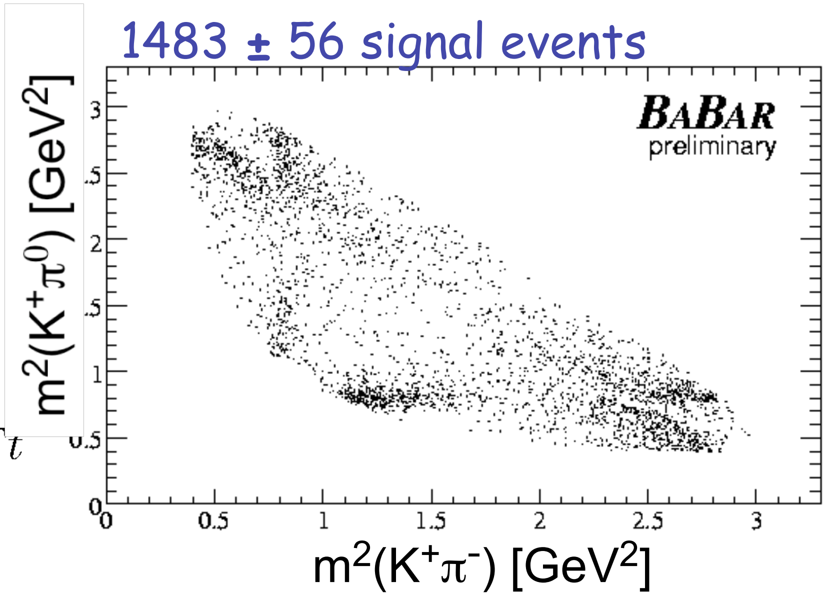
$$\begin{aligned} x'' &= x\cos\delta_{K\pi\pi^0} + y\sin\delta_{K\pi\pi^0} \\ y'' &= y\cos\delta_{K\pi\pi^0} - x\sin\delta_{K\pi\pi^0} \end{aligned}$$

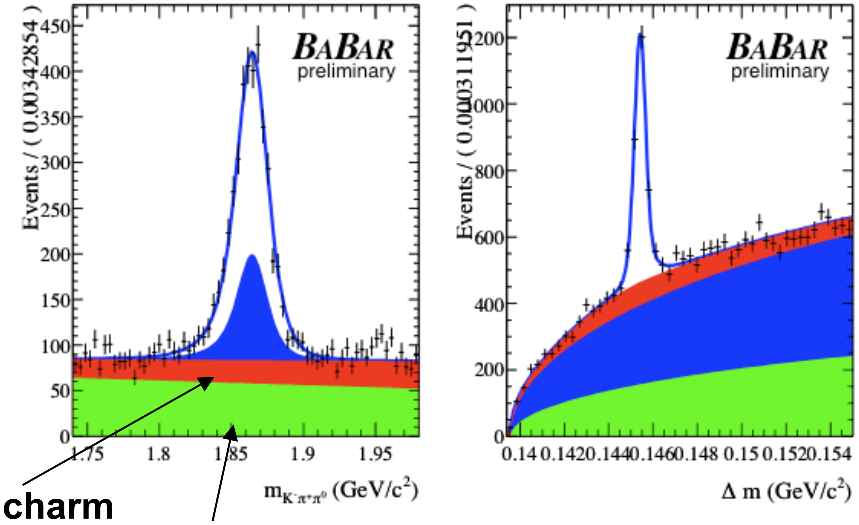
Phase between
RS and WS

Subscript D indicates dependence on position in the Dalitz plot.

Yields from 384 fb^{-1}

1483 ± 56 signal events





Bad charm

Combinatorics

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

x'': $(2.61 \, {}^{+0.57}_{-0.68} \pm 0.39)$ %

y'' : $(-0.05 \, {}^{+0.55}_{-0.64} \pm 0.34)$%

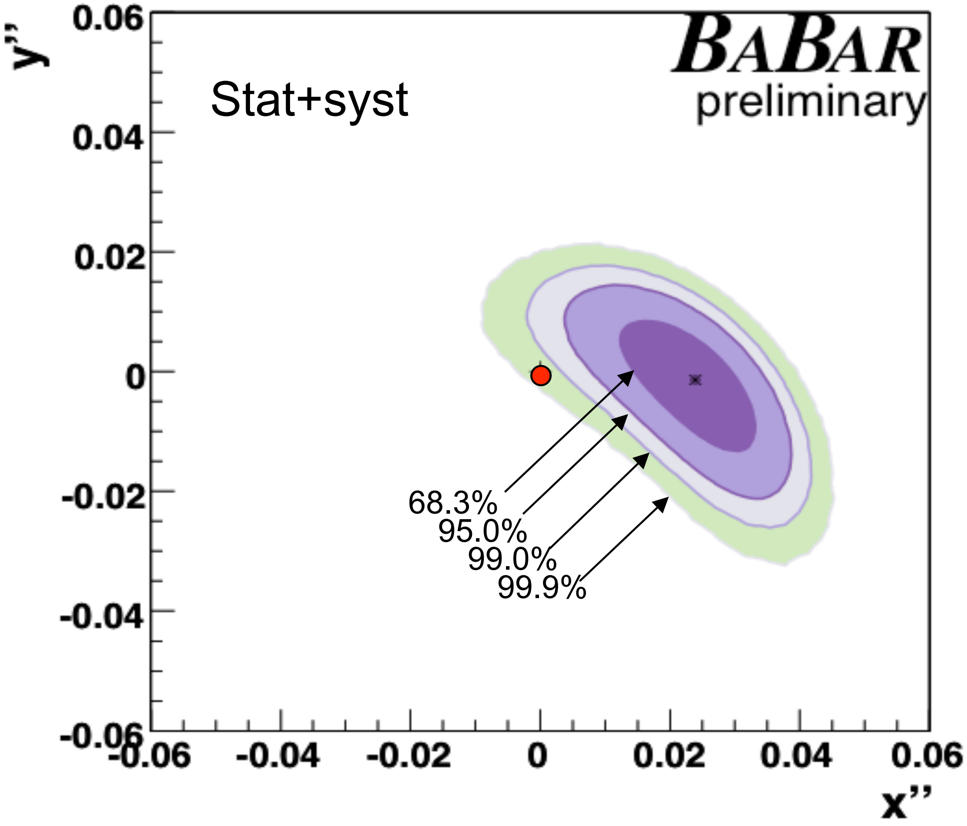
R_M: $(2.9 \pm 1.6) \times 10^{-4}$

x''^{+}: $(2.53 \, {}^{+0.54}_{-0.63} \pm 0.39)$ %

y''^{+}: $(-0.05 \, {}^{+0.63}_{-0.67} \pm 0.50)$%

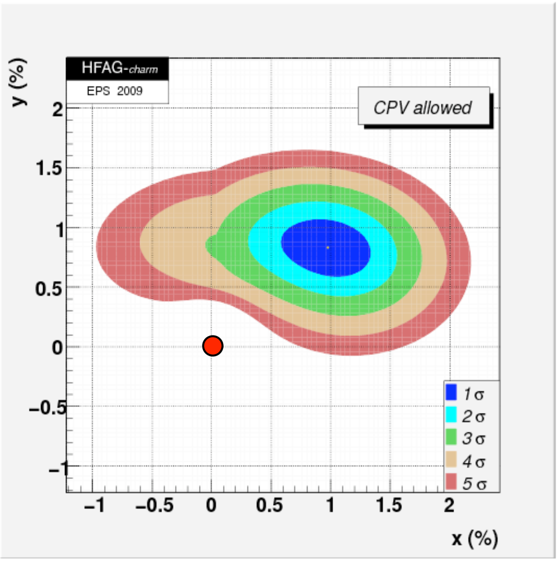
x''^{-}: $(3.55 \, {}^{+0.73}_{-0.83} \pm 0.65)$ %

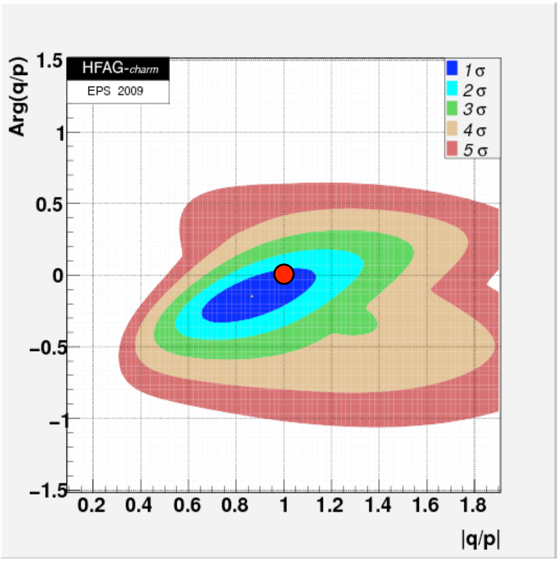
y''^{-}: $(-0.54 \, {}^{+0.40}_{-1.16} \pm 0.41)$%

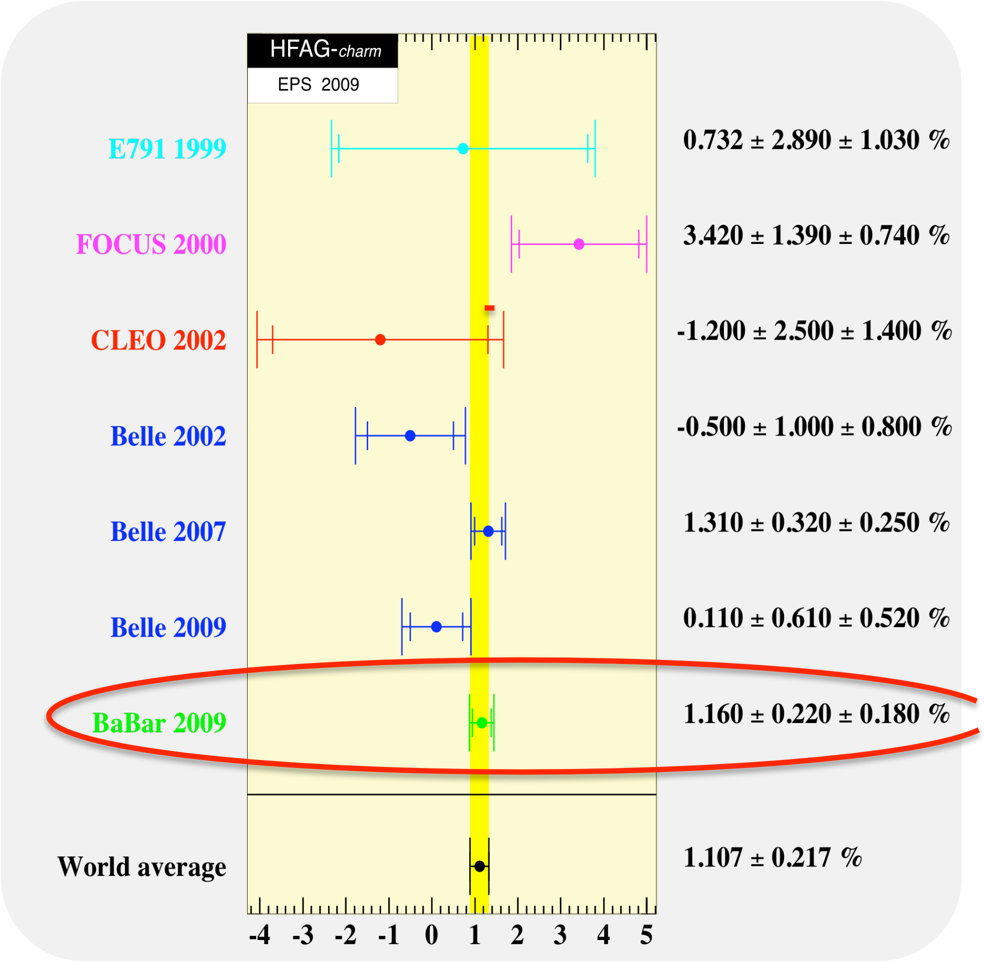


No mixing is excluded at the 99% confidence level.

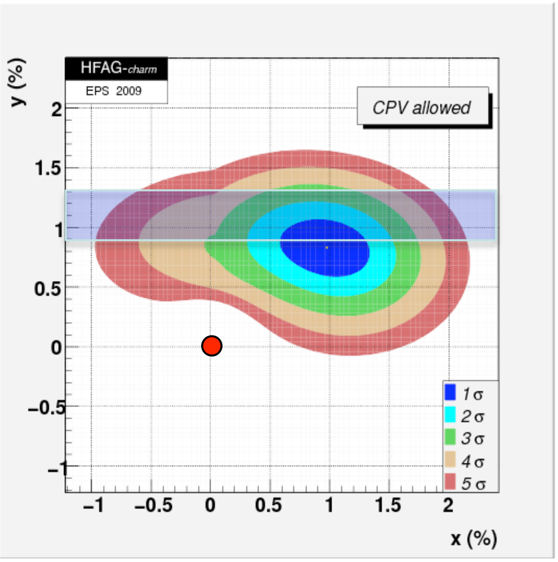
HFAG Preliminary Results

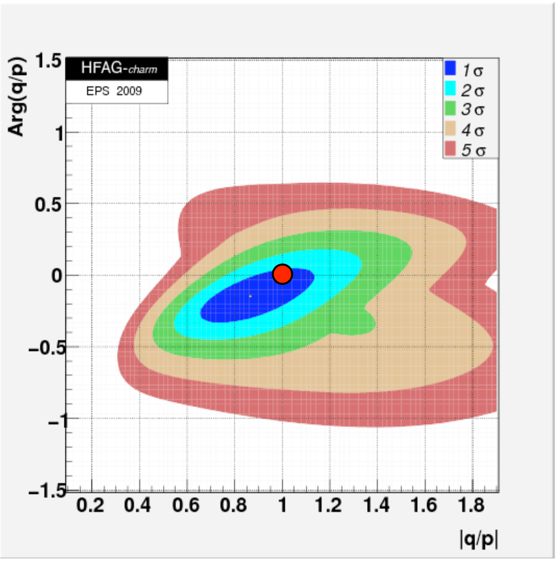


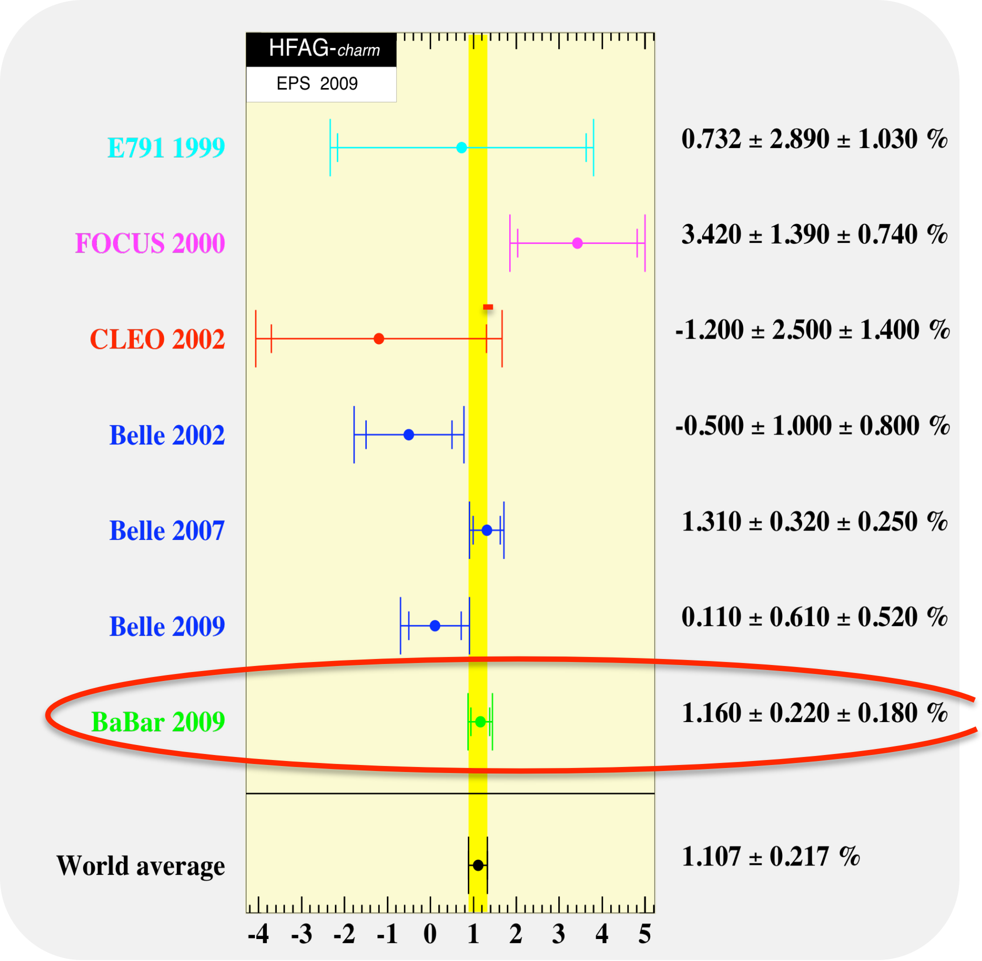




HFAG Preliminary Results







Conclusions

- 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)**

- 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)

- Time-dependent amplitude analysis of $D^0 \to K^+\pi^-\pi^0$ Dalitz plot yields

  $x'' = (2.39 \pm 0.61 \pm 0.32)$ %; $y'' = (-0.14 \pm 0.60 \pm 0.40)$

- Collective evidence for D^0-$\overline{D}^0$ mixing is compelling
  - The no-mixing point is excluded at >10σ, including systematic uncertainties. Results may be consistent with SM expectations.
  - No single measurement exceeds 5σ
- No evidence of CP violation

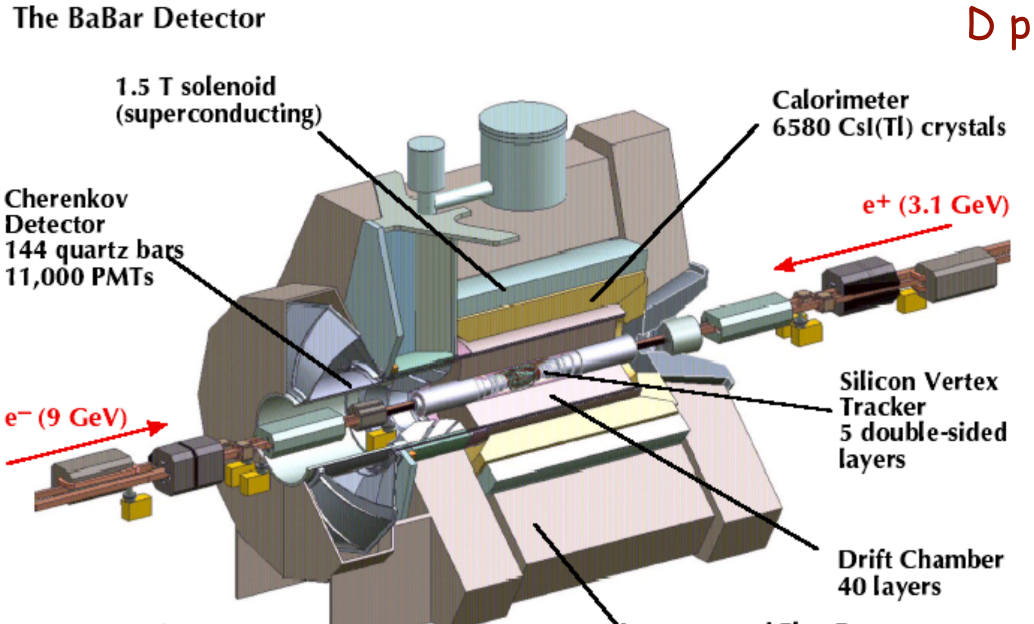
Backup Slides

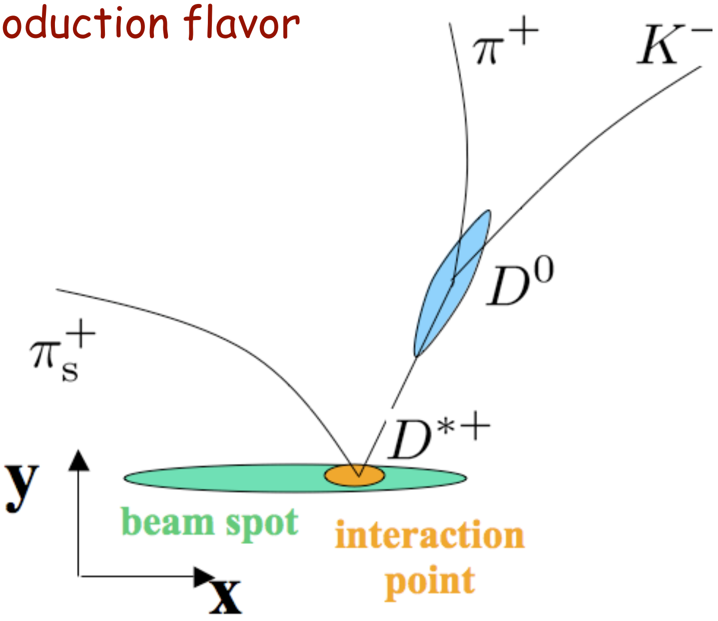
$D^0 \rightarrow K\pi$ Reconstruction

384 fb^{-1} $e^+e^- \rightarrow c,\bar{c}$

$$D^{*\pm} \longrightarrow \boxed{\pi_s^{\pm}} D^0, \; D^0 \longrightarrow K^{\mp}\pi^{\pm}$$

Slow pion charge tags neutral
D production flavor





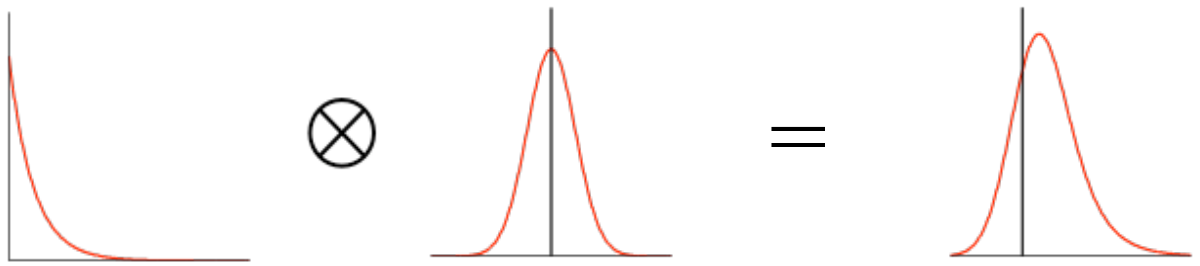
Typical D^0 flight length $d \sim 240\ \mu m$
Average resolution $\sigma_d \sim 95\ \mu m$

Beam spot:
$\sigma_x \approx$ 100 μm
$\sigma_y \approx$ 7 μm

Decay Time Resolution

Average D^0 flight length is 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
  - ➢ Observed core Gaussian shifted 3.6±0.6fs



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

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