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

Milind V. Purohit
University of South Carolina

for the *BABAR* collaboration

13th Lomonosov Conference on Elementary Particle Physics

Saturday, August 25, 2007

Moscow State University

USC HEP
University of South Carolina High Energy Physics Group

Outline

- D^0-$\overline{D^0}$ oscillations
- Search for Mixing / CP violation using $D^0 \rightarrow K^- \pi^+$ decays
- Other searches for mixing / CPV:
  - Lifetime Ratios: $\tau(D^0 \rightarrow K^+K^-, \pi^+\pi^-)$ vs $\tau(D^0 \rightarrow K^-\pi^+)$
  - CPV in time-integrated $D^0 \rightarrow K^+K^-$ and $D^0 \rightarrow \pi^+\pi^-$ rates.
  - Mixing study using $D^0 \rightarrow K^+\pi^-\pi^0$ decays
- Comparison with other results, theory

D^0 -$\bar{D}^0$ Oscillations

Neutral Meson systems

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

Time evolution by Schrödinger eq.:

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

2x2 hermitian matrices

Mesons decay!

Mass eigenstates:

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

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

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

Neutral meson oscillations

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

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

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

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

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

An opposite flavor component appears after a while!

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

(also dubbed "mixing")

USC HEP University of South Carolina High Energy Physics Group

Short and **Long** distance

- Predictions for x and y:

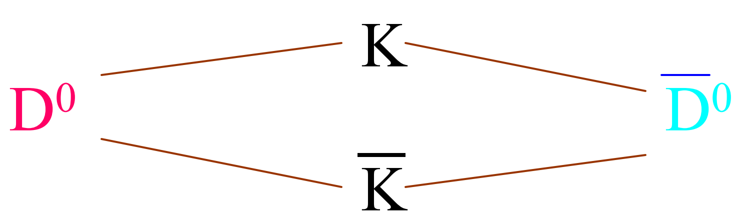
$$\left(\mathrm{M} - \frac{i}{2}\Gamma\right)_{ij} = \frac{\langle D_i | H_{\text{eff}} | D_j \rangle}{2m_D} = m_D^{(0)} \delta_{ij} + \frac{\langle D_i | H_w | D_j \rangle}{2m_D} + \frac{1}{2m_D} \sum_n \frac{\langle D_i | H_w | n \rangle \langle n | H_w | D_j \rangle}{m_D^{(0)} - E_n + i\epsilon}.$$

x *VIRTUAL* states

y

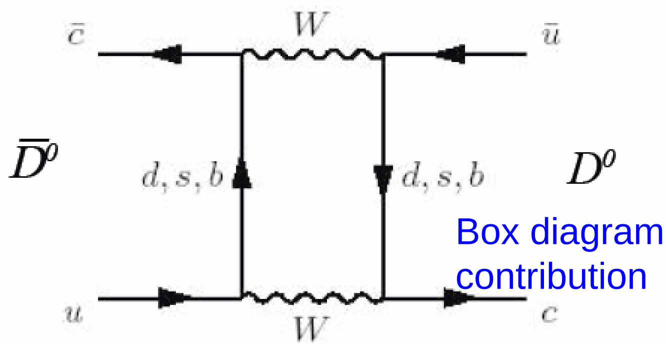
$$\Gamma_{ij} = \frac{1}{2m_D} \sum_n \langle D_i | H_w | n \rangle \langle n | H_w | D_j \rangle \, \delta(E_n - m_D).$$

Sum of intermediate
REAL states



SM prediction for charm mixing

SM charm mixing box has down-type quarks in loop



Effective GIM suppression:

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

(bottom quark ruled out by V_{CKM})

➡ $x \sim 10^{-5}$ Tiny!

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

Naively

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

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

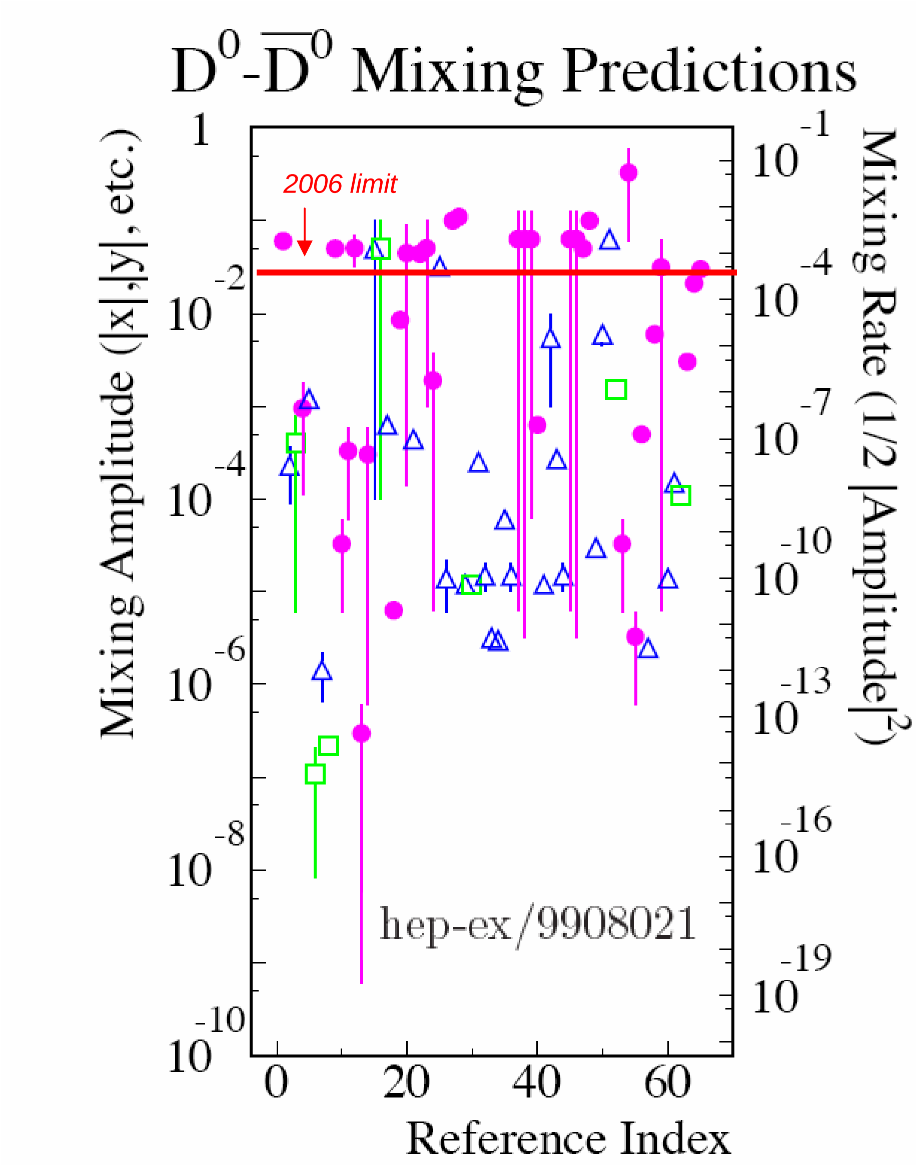
(HQET, propagation of common hadronic states,…)

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

SU(3) breaking effect more important for y

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

New Physics in Charm ?



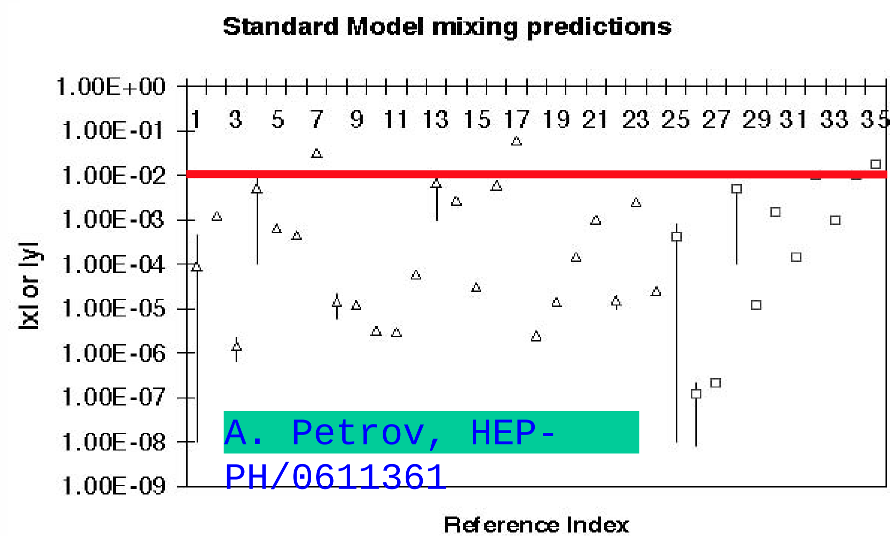
Δ: Standard model predictions for x

□: Standard model predictions for y

●: New physics predictions for x

- Hard to see a clear prediction
- *Pushing the limit down excludes models*

Try to separate x and y!



USC HEP University of South Carolina High Energy Physics Group

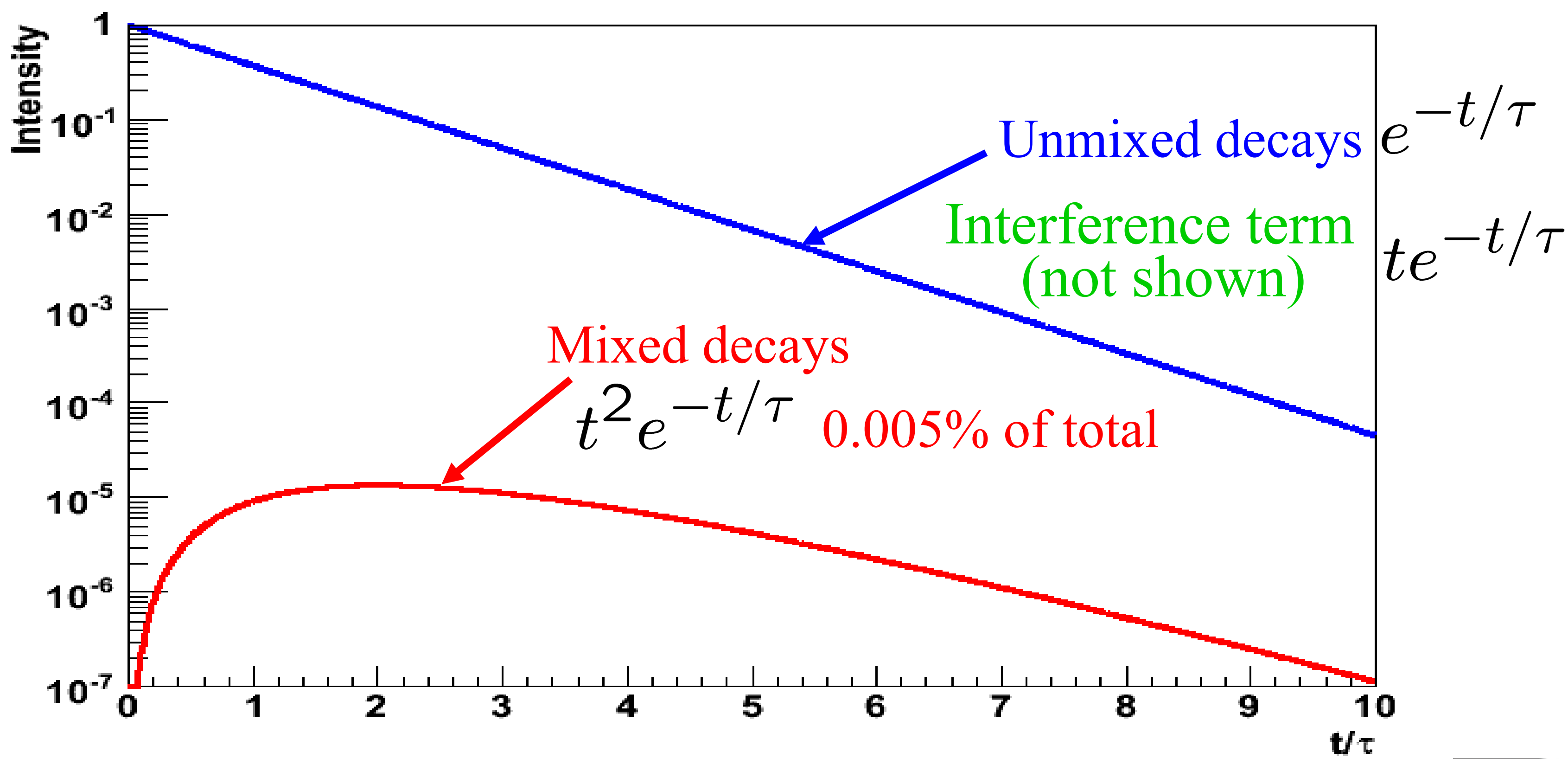
Charm Mixing in $D^0 \to K\pi$ Decay at BaBar

(Phys. Rev. Lett. 98:211802, 2007)

Principle of Mixing Measurement

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

(Distributions shown without time smearing)

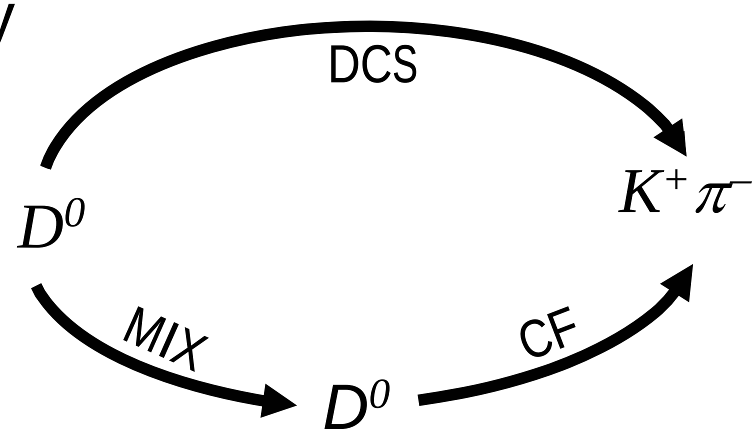


USC HEP University of South Carolina High Energy Physics Group

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

Discriminate DCS and mixing by their different time evolution

Also have interference effect:



Time evolution:

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

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

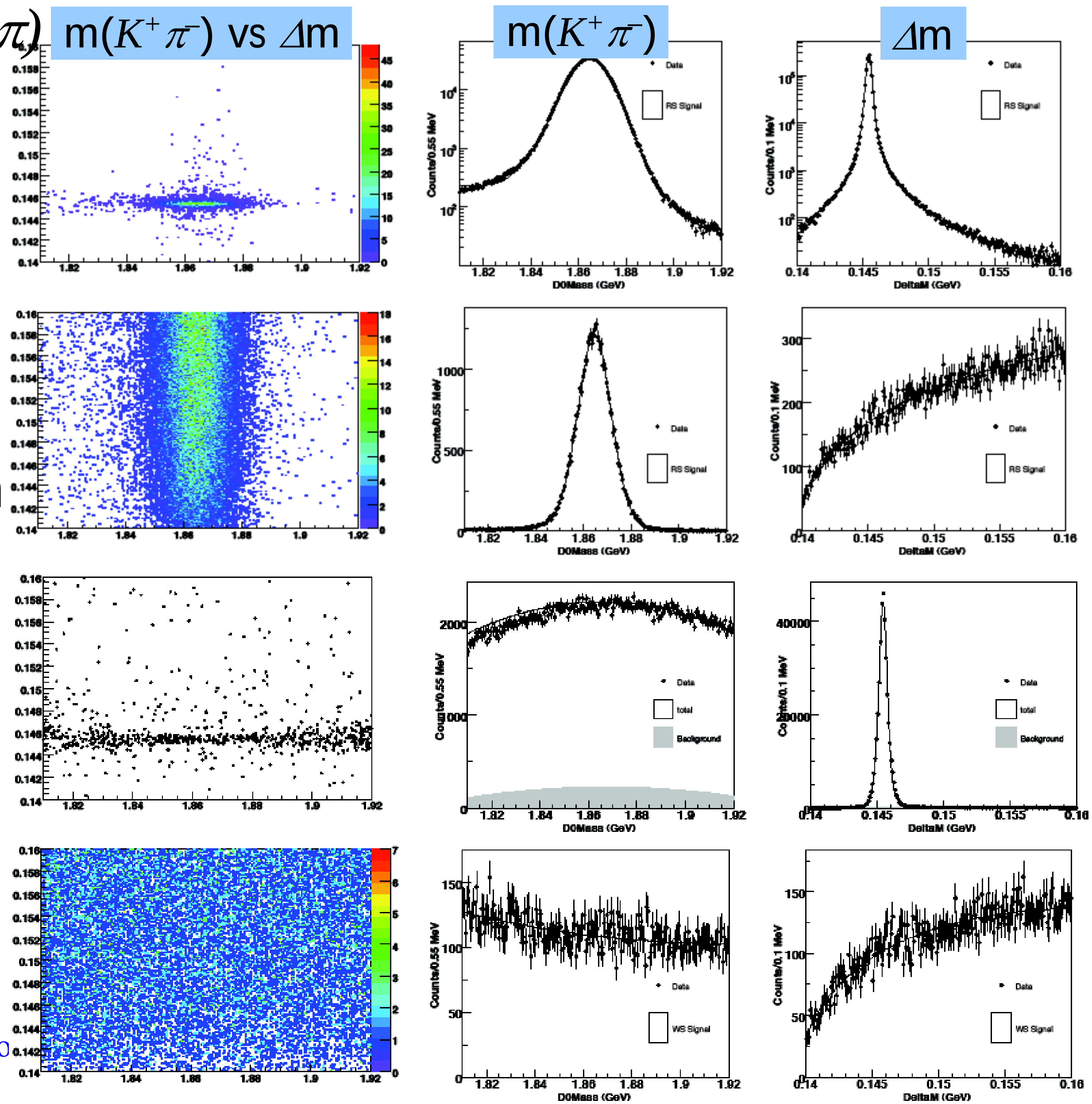
and δ is the phase difference between DCS and CF decays.

USC HEP University of South Carolina High Energy Physics Group

Signal and Background Components

$\Delta m \equiv m(K\pi\pi) - m(K\pi)$

$Q \equiv m(K\pi\pi) - m(K\pi) - m(\pi)$



Signal: (MC)

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

Random π_s: (MC)

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

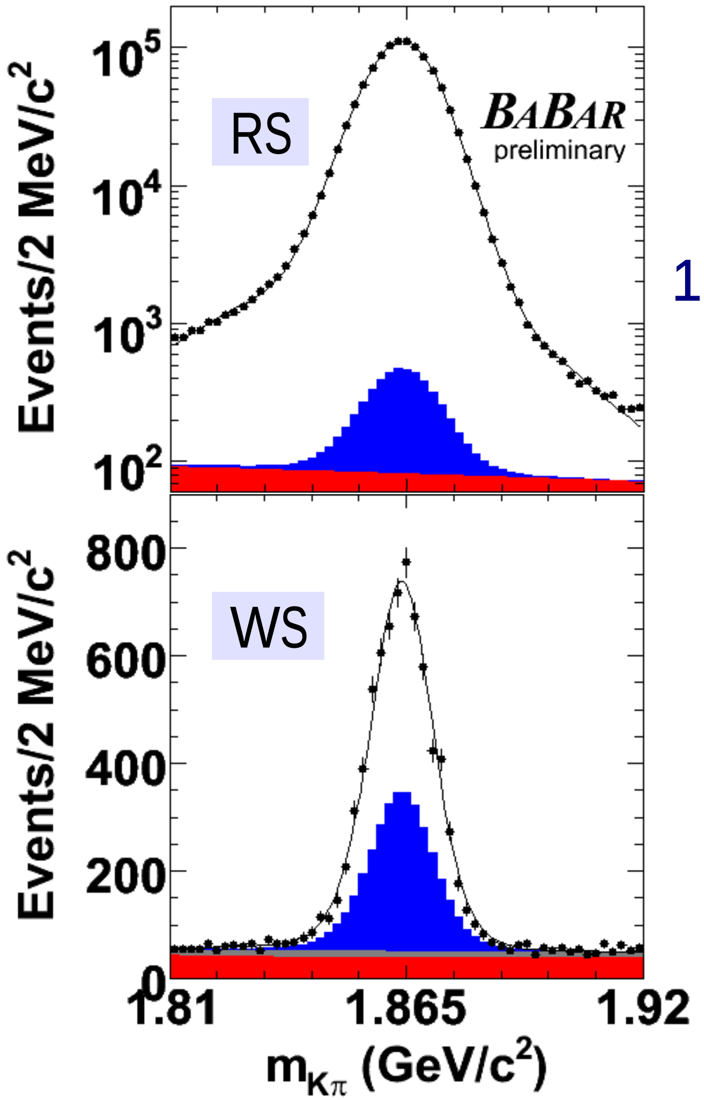
Mis-reco D^0: (Data)

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

Combinatoric: (MC)

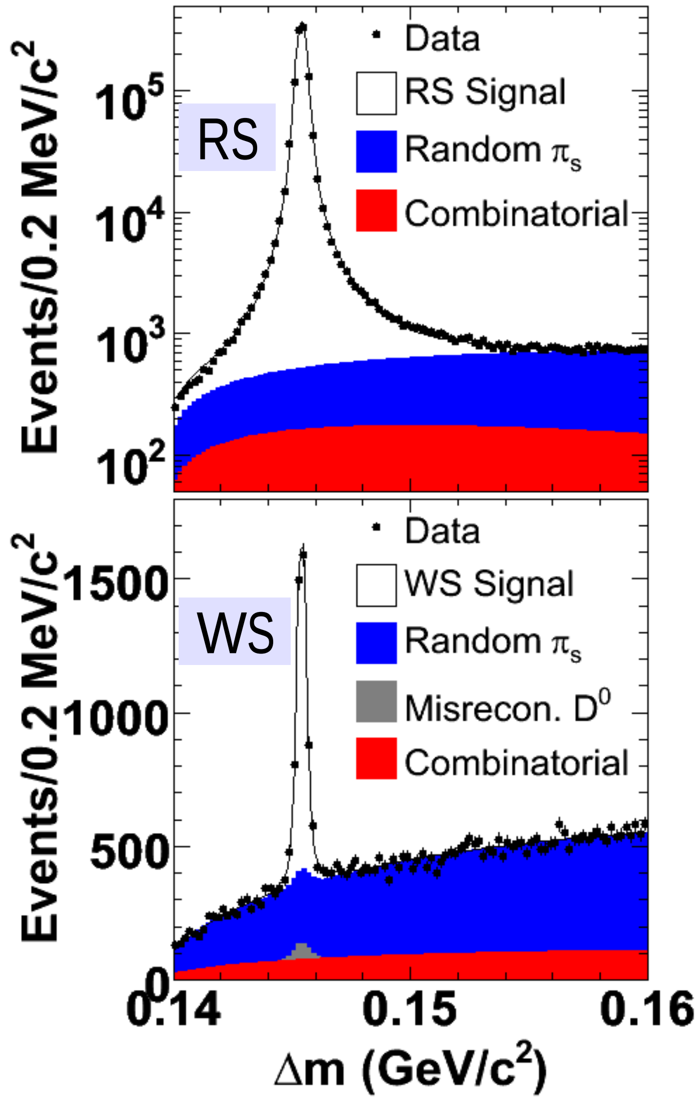
- Random tracks

m(Kπ)-Δm Fit Results



RS signal:
1,141,500±1200
combinations

WS signal:
4,030±90
combinations



RS Decay Time Fit

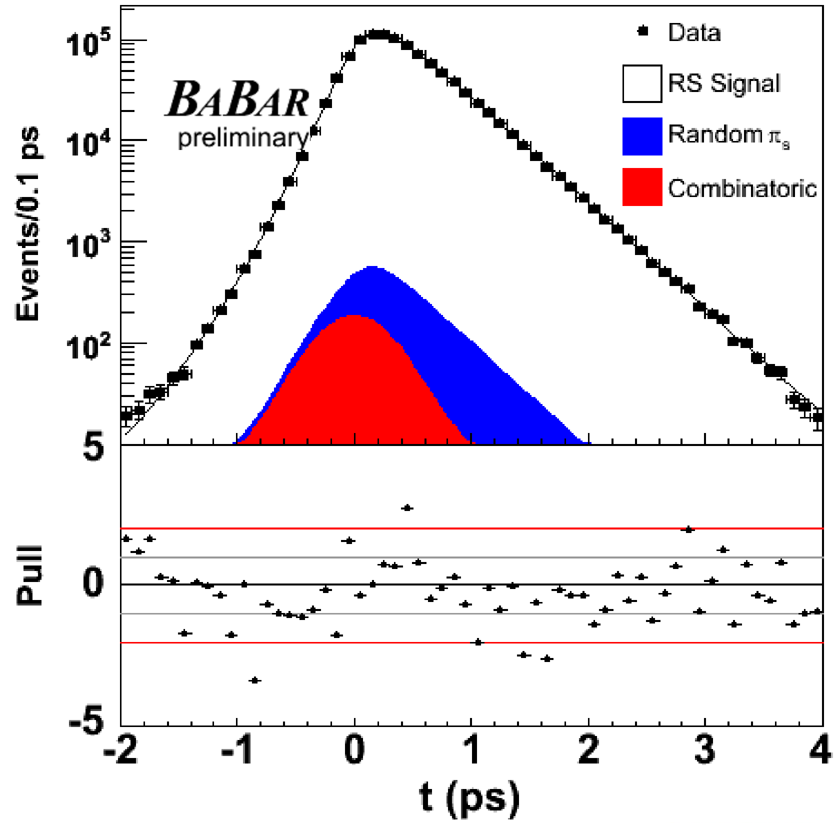
D^0 lifetime and resolution function fitted in RS sample

τ=(410.3±0.6(stat.)) fs

Consistent with PDG (410.1±1.5 fs)

Systematics dominated by resolution function

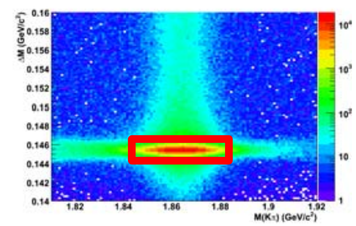
RS decay time, signal region



plot selection:

1.843<m<1.883 GeV/c^2

0.1445<Δm< 0.1465 GeV/c^2



USC HEP University of South Carolina High Energy Physics Group

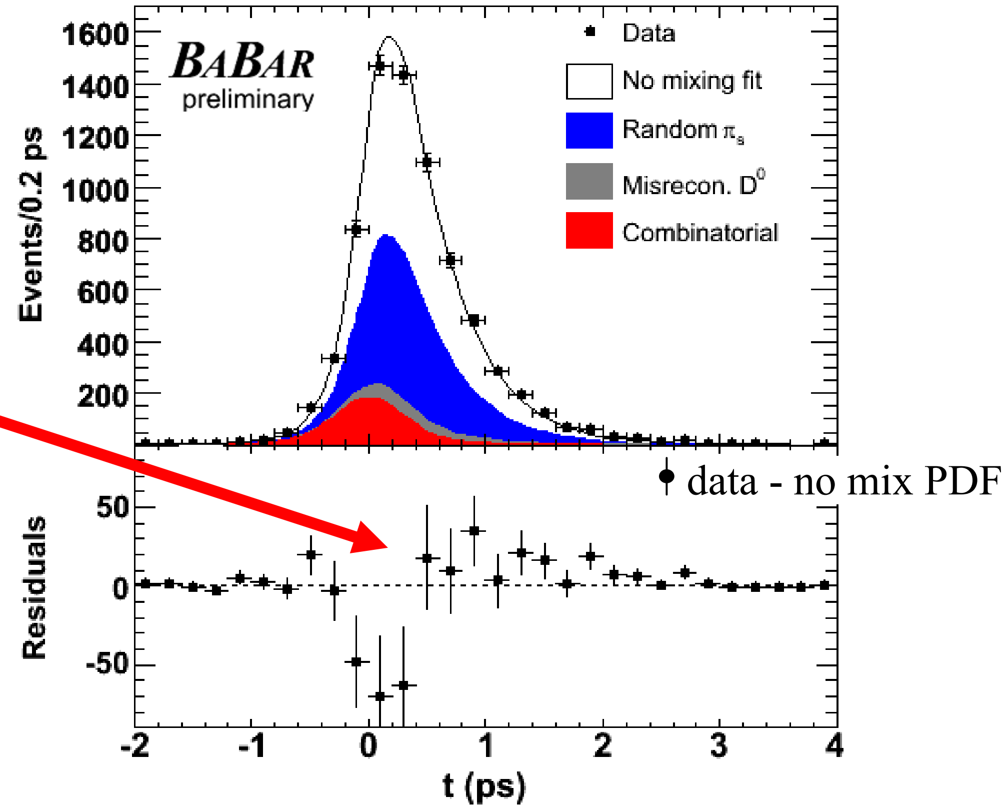
WS Fit with no Mixing

Fit results assuming no mixing:

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

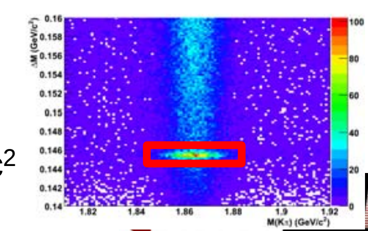
However, residuals in signal region are not good

WS decay time, signal region



Data and pdf projection are for signal region shown here:

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



WS Fit with Mixing

Fit results allowing mixing:

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

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

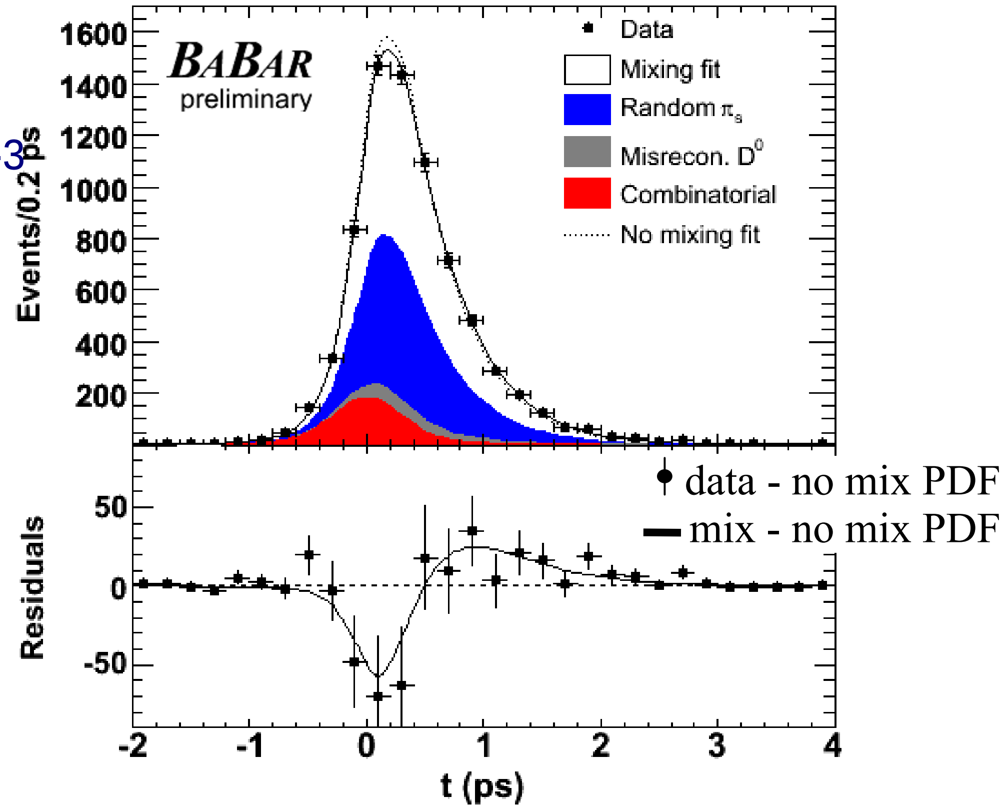
y': $(9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$

x'^2, y' correlation: -0.94

Fit with gives better description of data →

How significant?

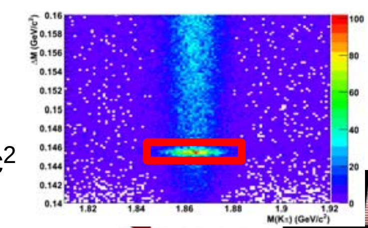
WS decay time, signal region



plot signal region:

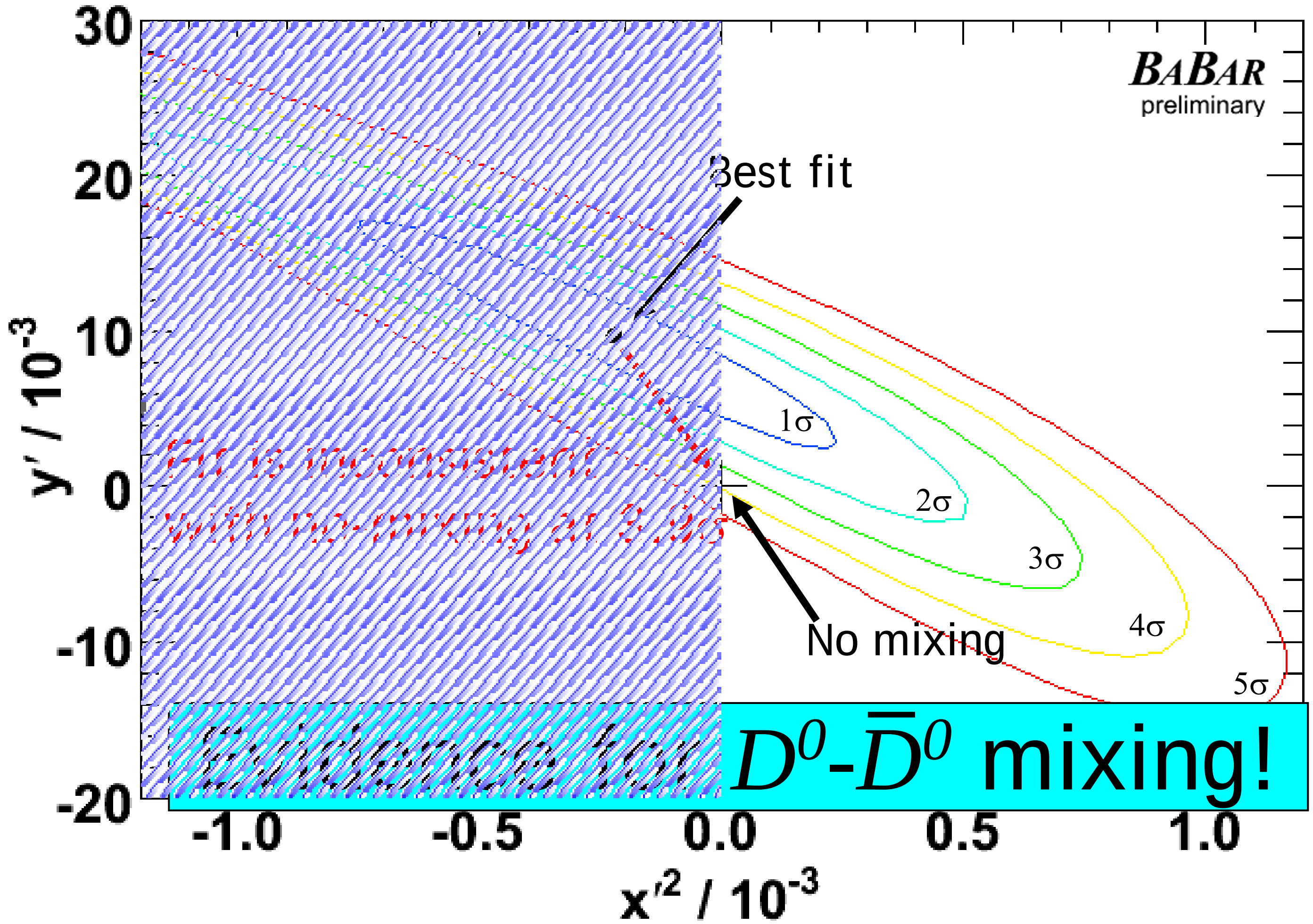
$1.843 < m < 1.883$ GeV/c^2

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



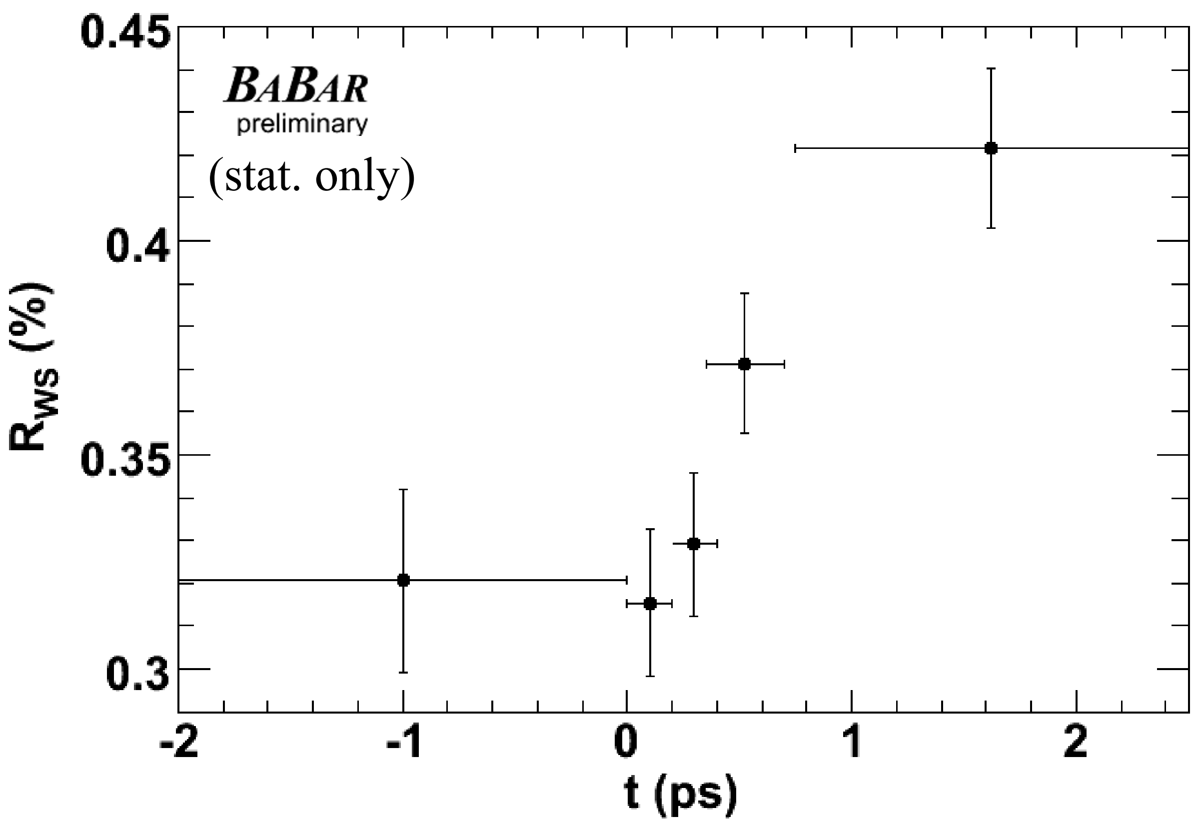
Signal Significance with Systematics

Including systematics decreases signal significance



Validation: Alternative Fit Strategy

Rate of WS events clearly increases with time:



University of South Carolina High Energy Physics Group

Allowing for CP Violation

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

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

Three possible types of CP violation:

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

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

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

CP violation if one or more “±” parameters are different

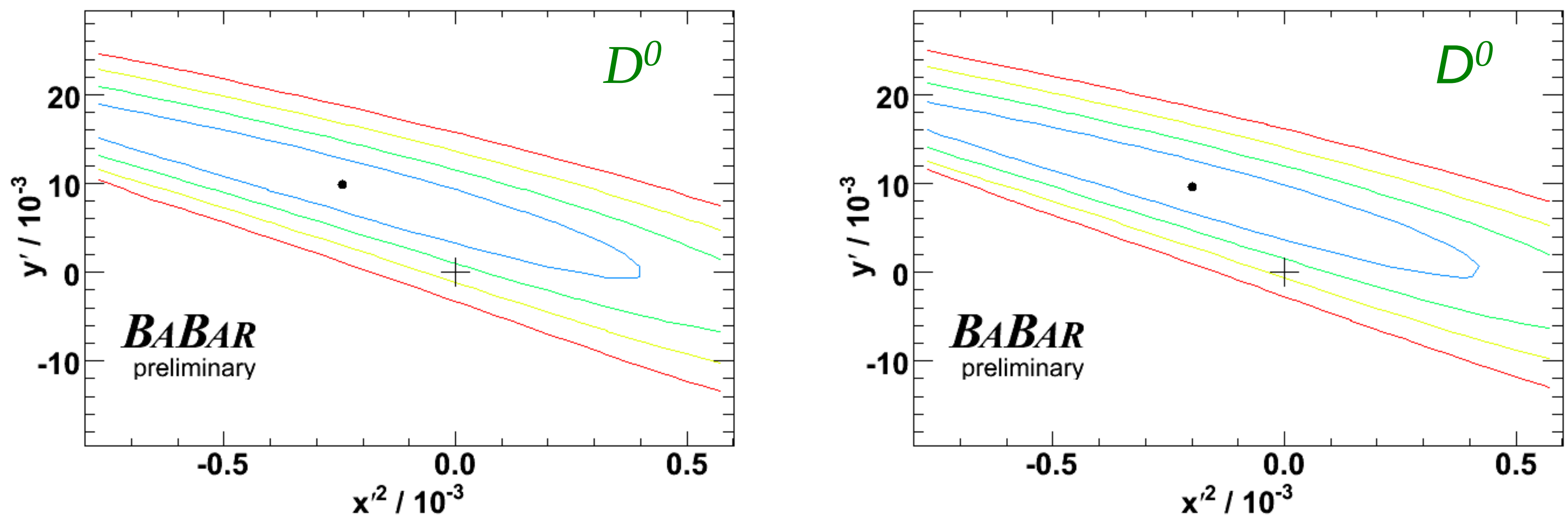
CPV Allowed Contours

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

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

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

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



No evidence for CP violation found

Other searches for D^0 mixing and for CP violation in D^0 decays

$\overline{D^0}$-D^0 Mixing in Lifetime Ratio of $D^0 \to K^+K^-$, $\pi^+\pi^-$ vs $D^0 \to K^-\pi^+$

$D^0 \to K^-\pi^+$: CP-mixed $D^0(t) \to K^+K^-$, $\pi^+\pi^-$: CP–even

Determine the quantities

$$h = K \text{ or } \pi$$

$$\begin{aligned} \langle \tau_{hh} \rangle &= (\tau^+_{hh} + \tau^-_{hh})/2 \\ A_\tau &= (\tau^+_{hh} - \tau^-_{hh})/(\tau^+_{hh} + \tau^-_{hh}) \end{aligned}$$

$$y_{CP} = \frac{\tau_{K\pi}}{\langle \tau_{hh} \rangle} - 1, \qquad \Delta Y = \frac{\tau_{K\pi}}{\langle \tau_{hh} \rangle} A_\tau$$

$$x \equiv 2\frac{m_1 - m_2}{\Gamma_1 + \Gamma_2} \qquad y \equiv \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

CPV in interference of mixing and decay:

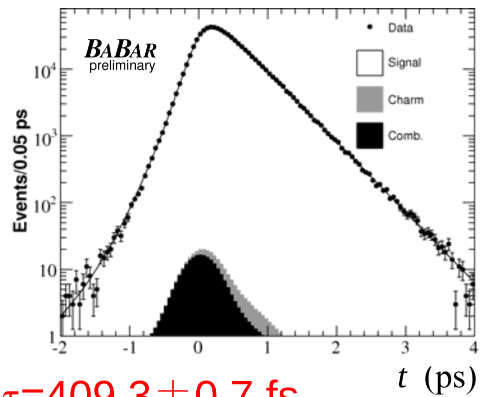
$$\varphi_f \equiv \arg\left(\frac{q}{p}\frac{\langle f|\mathcal{H}_D|\overline{D}^0\rangle}{\langle f|\mathcal{H}_D|D^0\rangle}\right) \neq 0$$

If CP is conserved $y_{CP} = y$, $\Delta Y = 0$

$$\begin{aligned} y_{CP} &= y \cos\varphi_f \\ \Delta Y &= x \sin\varphi_f \end{aligned}$$

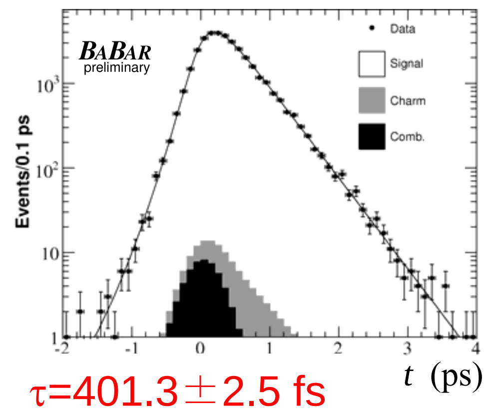
Decay time fits to determine (y_{CP}, ΔY)

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



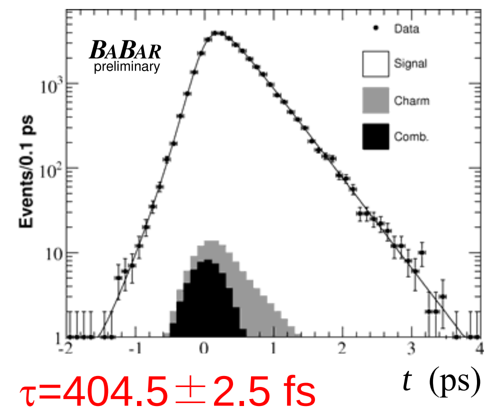
τ=409.3±0.7 fs

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

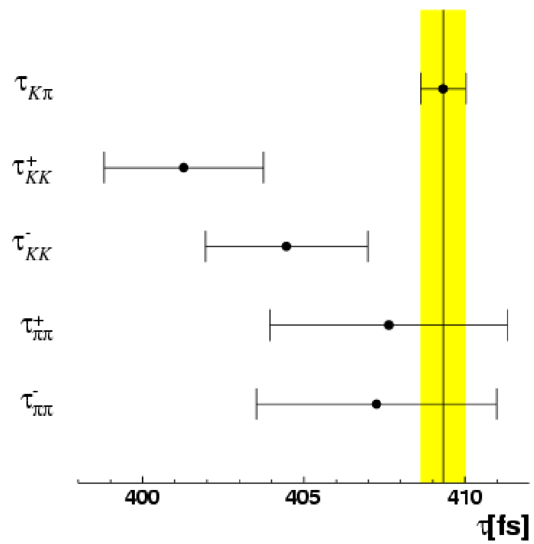


τ=401.3±2.5 fs

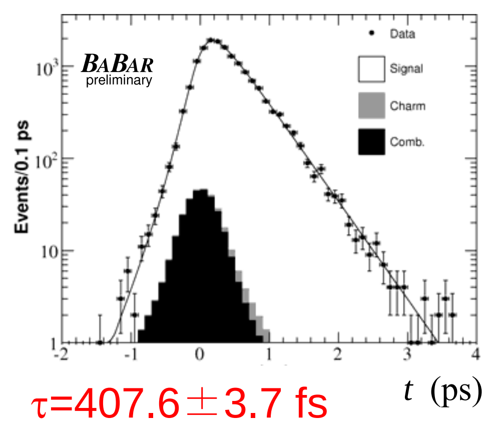
$\overline{D}^0 \to K^+K^-$



τ=404.5±2.5 fs

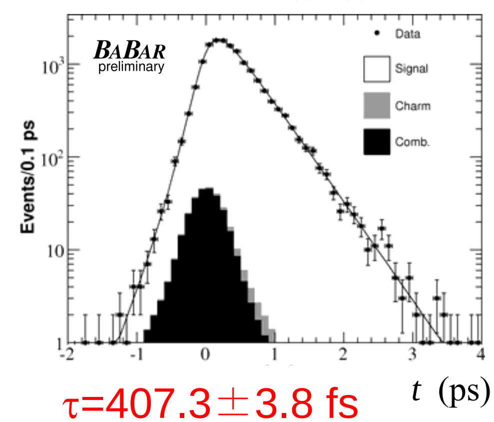


$D^0 \to \pi^+\pi^-$



τ=407.6±3.7 fs

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



τ=407.3±3.8 fs

***Kπ* and *KK* lifetimes differ!**

BaBar (y_{CP}, ΔY) results

Tagged results from 384 fb^{-1}:

	y_{CP}	ΔY
K^+K^-	$(1.60 \pm 0.46(\text{stat}) \pm 0.17(\text{syst}))\%$	$(-0.40 \pm 0.44(\text{stat}) \pm 0.12(\text{syst}))\%$
$\pi^+\pi^-$	$(0.46 \pm 0.65(\text{stat}) \pm 0.25(\text{syst}))\%$	$(0.05 \pm 0.64(\text{stat}) \pm 0.32(\text{syst}))\%$
Combined	$(1.24 \pm 0.39(\text{stat}) \pm 0.13(\text{syst}))\%$	$(-0.26 \pm 0.36(\text{stat}) \pm 0.08(\text{syst}))\%$

3.0σ

0

Good agreement with Belle 540 fb^{-1} measurement:

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

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

M. Staric et al. (Belle Collab.), Phys. Rev. Lett. 98, 211803 (2007).

University of South Carolina High Energy Physics Group

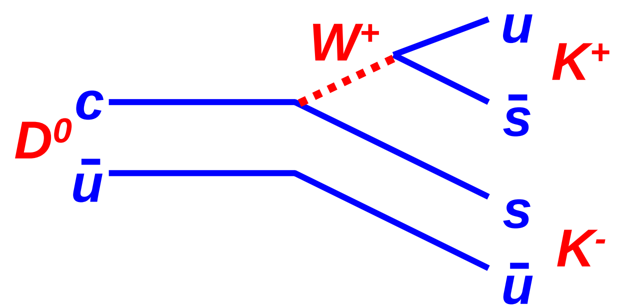
Search for direct CPV in time-integrated $D^0 \to K^+K^-, \pi^+\pi^-$ rates

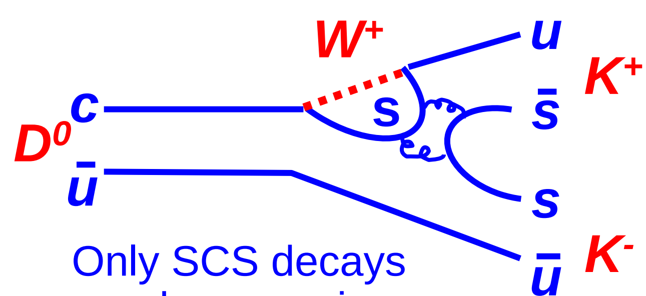
$$A_{CP} = \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})} = \frac{2\,\mathrm{Im}(A_1 A_2^*)\, sin(\delta_1 - \delta_2)}{|A_1|^2 + |A_2|^2 + 2\,\mathrm{Re}\,A_1 A_2^* cos(\delta_1 - \delta_2)}$$

2 weak amplitudes with phase difference

strong phase difference

e.g., $D^0 \to K^+K^-$:





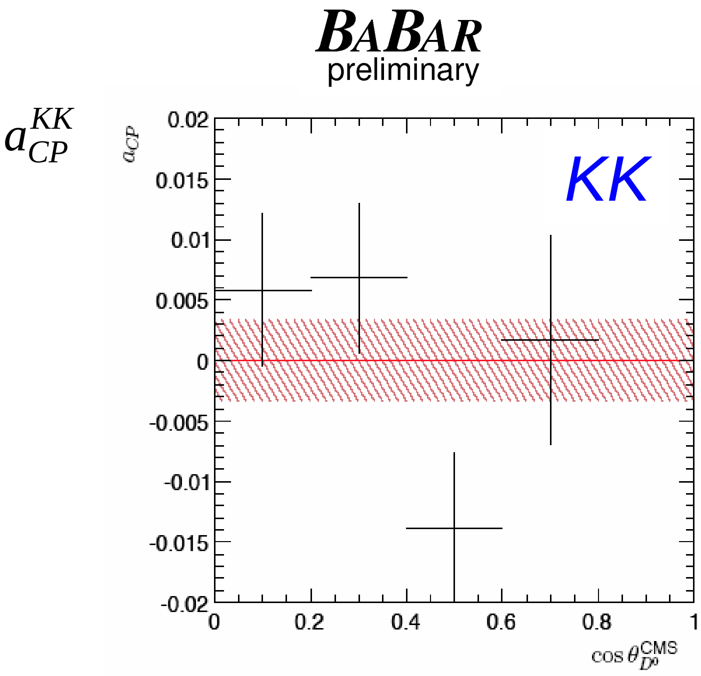
Only SCS decays probe penguins

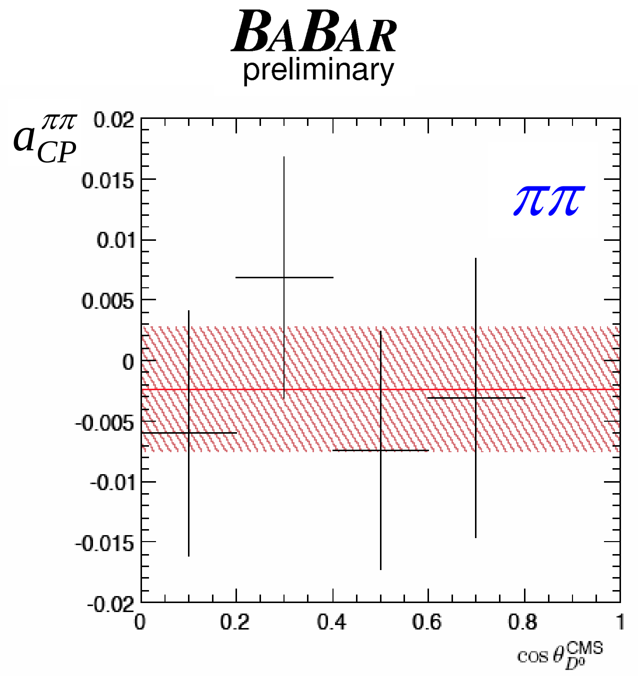
Two amplitudes with different strong & weak phases needed to observe CPV (in SM from tree and penguins)

Standard model predictions for direct CPV asymmetries in these modes: O(0.001% - 0.01%)

F. Bucella et al., Phys. Rev. **D51**, 3478 (1995).
S. Bianco et al., Riv. Nuovo Cim. 26N7, 1(2003).

Search for CPV in $D^0 \rightarrow K^+K^-$, $\pi^+\pi^-$





$$a_{CP}^{KK} = (0.00 \pm 0.34\ (\text{stat.}) \pm 0.13\ (\text{syst.}))\%$$
$$a_{CP}^{\pi\pi} = (-0.24 \pm 0.52\ (\text{stat.}) \pm 0.22\ (\text{syst.}))\%$$

No evidence for CPV in either mode

USC HEP
University of South Carolina
High Energy Physics Group

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

Two types of WS Decays:

- Doubly Cabbibo-supressed (DCS) $D^0 \to K^+\pi^-\pi^0$
- Mixing followed by Cabibbo-Favored (CF) decay $D^0 \underset{\text{mix}}{\to} \overline{D}^0 \to K^+\pi^-\pi^0$

Two ways to reach same final state ⇒ interference!

Time dependent WS rate :

$$\begin{aligned}\Gamma_{\bar f}(s_{12}, s_{13}, t) &= e^{-\Gamma t}\{|A_{\bar f}|^2 \quad \leftarrow \text{DCS} \\ \text{Interference} \rightarrow &+ |A_{\bar f}||\bar A_{\bar f}|\left[y'' \cos\delta_{\bar f} - x'' \sin\delta_{\bar f}\right](\Gamma t) \\ \text{Mixing} \rightarrow &+ \frac{x''^2 + y''^2}{4}|\bar A_{\bar f}|^2(\Gamma t)^2\}\end{aligned}$$

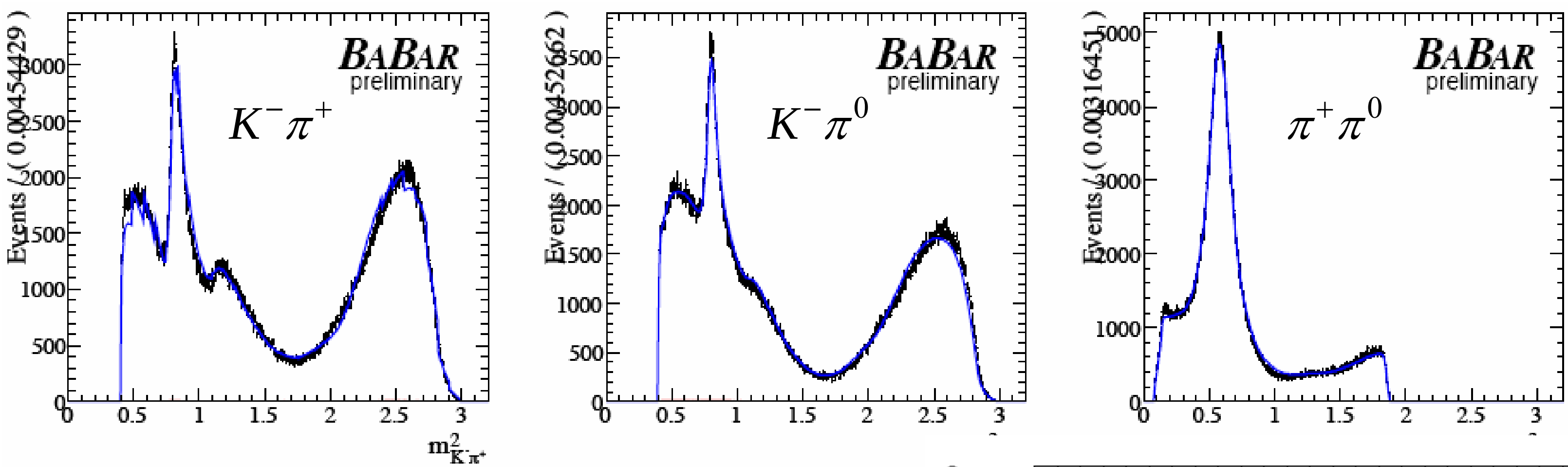
$\bar f = K^+\pi^-\pi^0$ $\quad A_{\bar f} = \langle \bar f|\mathcal{H}|D^0\rangle,\ \bar A_{\bar f} = \langle \bar f|\mathcal{H}|\overline{D}^0\rangle$

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

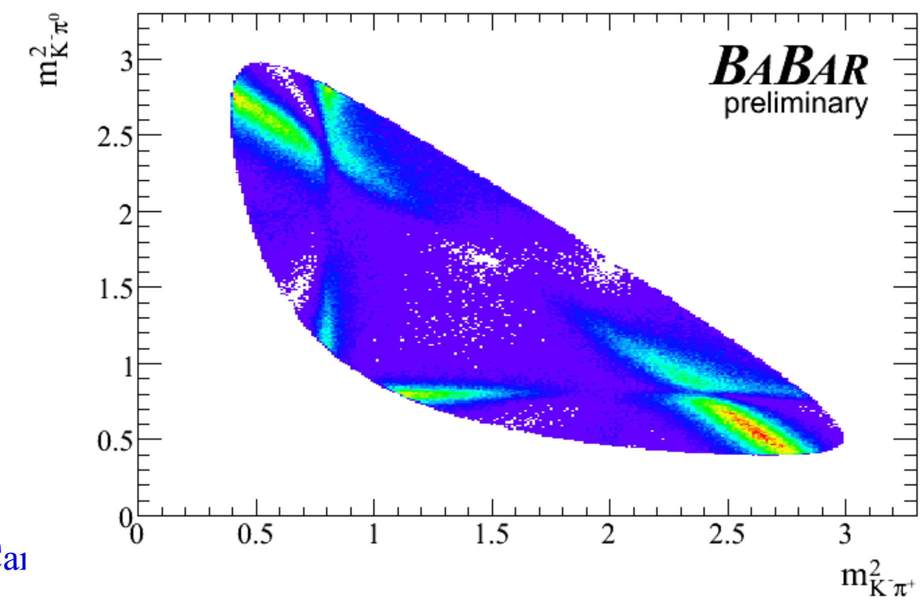
$\delta_{K\pi\pi^0}$: strong phase difference between CF and DCS decay amplitudes

$D^0 \to K^- \pi^+ \pi^0$ RS Dalitz fit

Time-integrated analysis to determine CF amplitudes, $\bar{A}_{\bar{f}}$

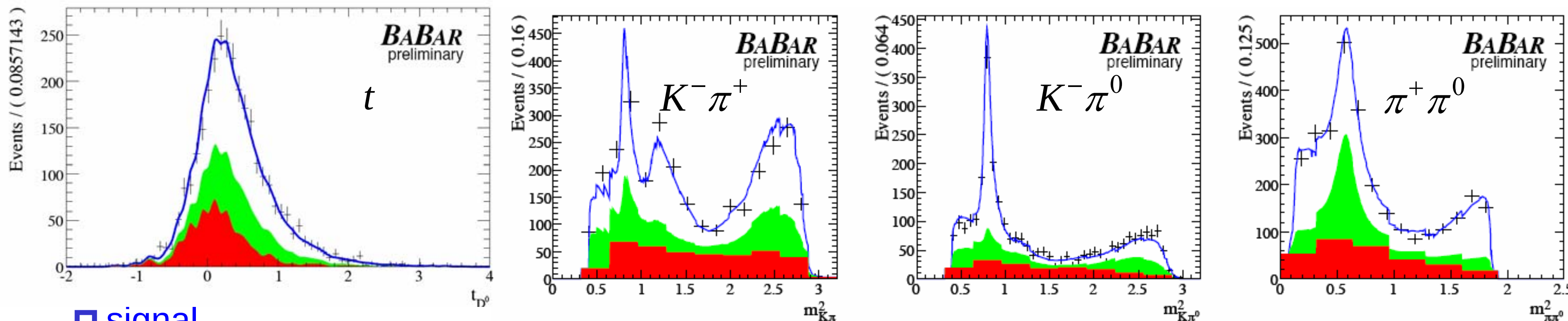


Resonance	Amplitude	Phase (degrees)	Fit Fraction (%)
$\rho(770)$	1 (fixed)	0 (fixed)	65.2 ± 4.5
$K^{*-}(1680)$	1.52 ± 0.06	144.3 ± 3.2	0.39 ± 0.04
$K_2^{*-}(1430)$	0.030 ± 0.001	-167.5 ± 2.5	0.31 ± 0.03
$K_2^{*0}(1430)$	0.0431 ± 0.0007	13.4 ± 0.9	0.73 ± 0.06
$K^{*-}(1410)$	0.24 ± 0.01	39.1 ± 4.1	0.17 ± 0.02
$K_0^{*-}(1430)$	2.95 ± 0.05	183.7 ± 0.9	3.6 ± 0.3
$K^{*-}(892)$	0.382 ± 0.001	163.3 ± 0.2	10.3 ± 0.7
$K^{*0}(1410)$	0.17 ± 0.01	-221.0 ± 3.5	0.009 ± 0.0001
$K_0^{*0}(1430)$	2.53 ± 0.01	91.6 ± 0.3	8.3 ± 0.6
$K^{*0}(1680)$	2.74 ± 0.07	-17.0 ± 1.5	1.4 ± 0.1
$K^{*0}(892)$	0.400 ± 0.001	3.4 ± 0.3	11.1 ± 0.7
$\rho(1700)$	6.06 ± 0.09	136.3 ± 0.7	4.1 ± 0.3
Total fit fraction = 106%			



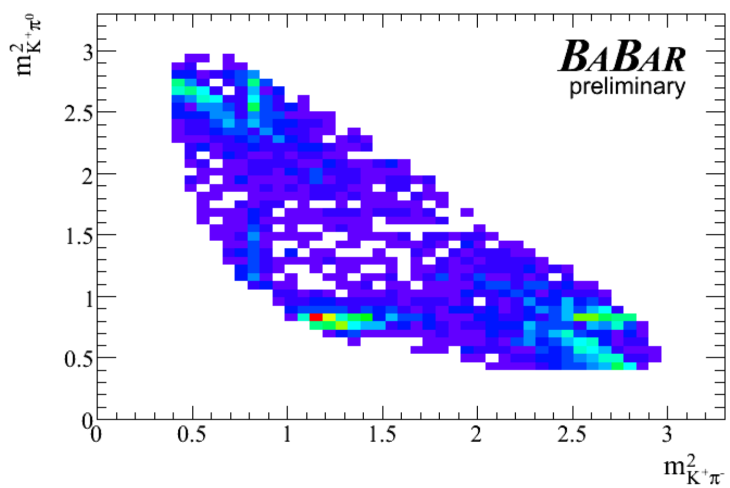
$D^0(t) \to K^+\pi^-\pi^0$ WS Dalitz fit results

Through t-dependence, distinguish DCS amplitudes from the CF amplitudes arising from mixing.

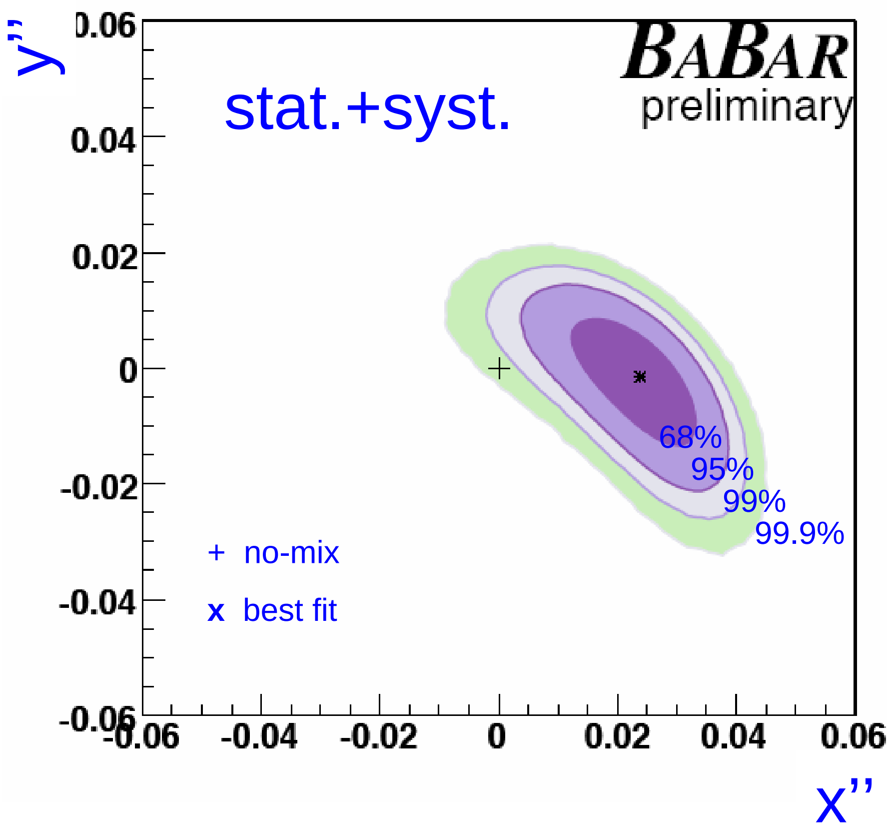


- signal
- mis-tagged D^0
- mis-reconstructed D^0 +combinatoric

Resonance	Amplitude	Phase (degrees)	Fit Fraction (%)
$\rho(770)$	1 (fixed)	0 (fixed)	39.8 ± 6.5
$K_2^{*0}(1430)$	0.088 ± 0.017	-17.2 ± 12.9	2.0 ± 0.7
$K_0^{*+}(1430)$	6.78 ± 1.00	69.1 ± 10.9	13.1 ± 3.3
$K^{*+}(892)$	0.899 ± 0.005	-171.0 ± 5.9	35.6 ± 5.5
$K_0^{*0}(1430)$	1.65 ± 0.59	-44.4 ± 18.5	2.8 ± 1.5
$K^{*0}(892)$	0.398 ± 0.038	24.1 ± 9.8	6.5 ± 1.4
$\rho(1700)$	5.4 ± 1.6	157.4 ± 20.3	2.0 ± 1.1
$\chi^2/ndof = 188/215 = 0.876$			
Total fit fraction = 102%			



Mixing parameter contours and results



$$x'' = (\quad 2.39 \pm 0.61\ (\text{stat.}) \ \pm 0.32\ (\text{syst.}))\%$$
$$y'' = (-0.14 \pm 0.60\ (\text{stat.}) \ \pm 0.40\ (\text{syst.}))\%$$

$$R_{\text{mix}} \equiv \frac{x''^2 + y''^2}{2} = (2.9 \pm 1.6) \times 10^{-4}$$
$$\text{world average} \quad = (2.1 \pm 1.1) \times 10^{-4}$$

Results are consistent with no mixing at 0.8%, including systematics

BaBar D^0-$\bar{D}^0$ Mixing Summary

From $K^{\pm}\pi^{\mp}$ decays:

x'^2: (-0.22±0.30±0.21) x 10^{-3}, y': (9.7±4.4±3.1) x 10^{-3}

Further evidence for D^0-$\bar{D}^0$ mixing from the *BaBar* experiment:

– $D^0 \to K^-\pi^+$ to $D^0 \to K^+K^-$, $\pi^+\pi^-$ lifetimes:

$$y_{CP} = (\ 1.24 \pm 0.39\ (\text{stat.})\ \pm 0.13\ (\text{syst.}))\%$$

– $D^0 \to K^+\pi^-\pi^0$ time-dependent Dalitz analysis:

$$x'' = (\ 2.39 \pm 0.61\ (\text{stat.})\ \pm 0.32\ (\text{syst.}))\%$$
$$y'' = (-0.14 \pm 0.60\ (\text{stat.})\ \pm 0.40\ (\text{syst.}))\%$$

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

– no evidence for direct CP violation

$$a_{CP}^{KK} = (\ 0.00 \pm 0.34\ (\text{stat.}) \pm 0.13\ (\text{syst.}))\%$$
$$a_{CP}^{\pi\pi} = (-0.24 \pm 0.52\ (\text{stat.}) \pm 0.22\ (\text{syst.}))\%$$

– no evidence for CP violation in mixing:

$$\Delta Y = (-0.26 \pm 0.36\ (\text{stat.})\ \pm 0.08\ (\text{syst.}))\%$$

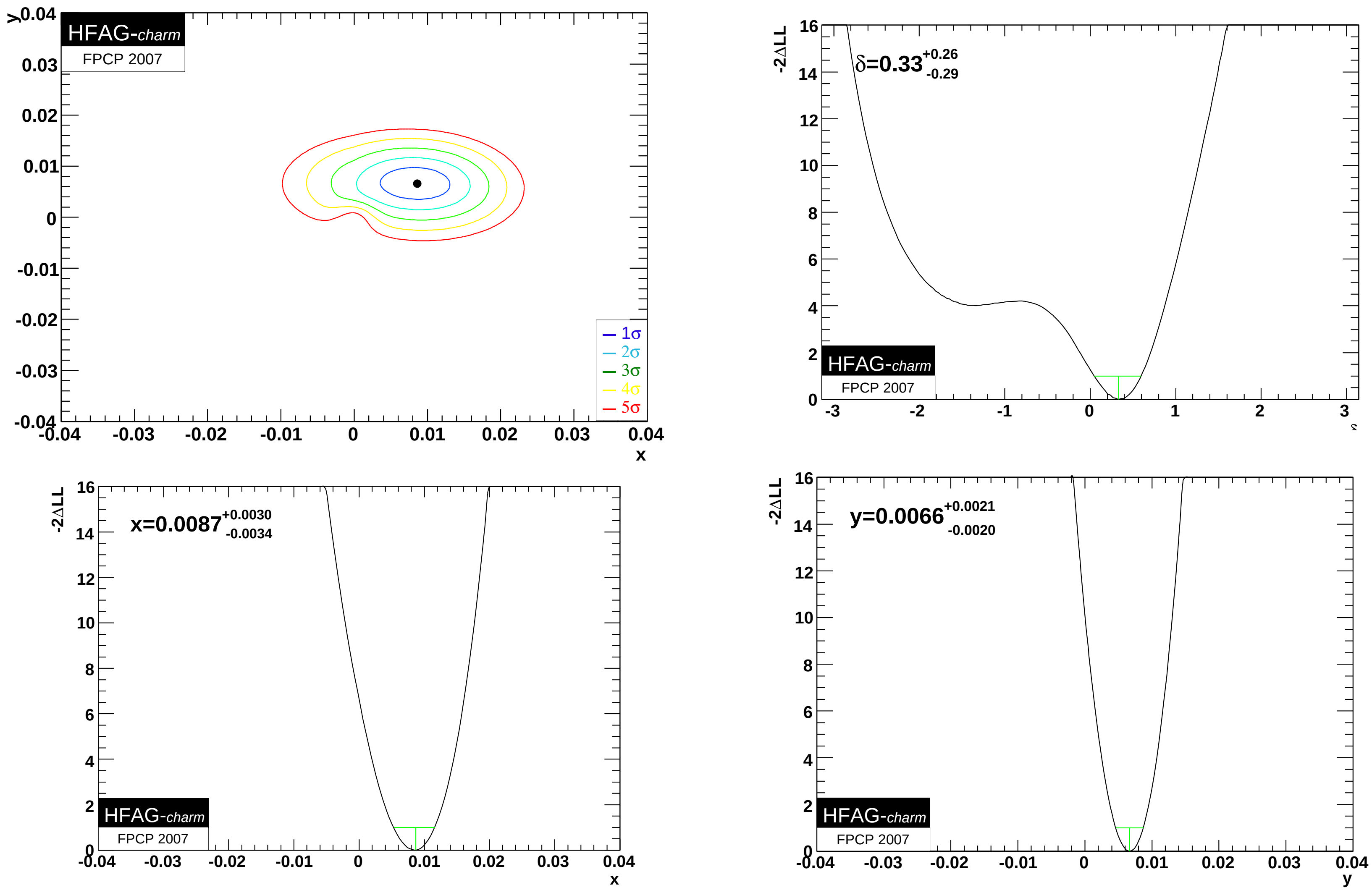
BABAR

Combining with other results, a comparison with Theory, and Conclusions

USC HEP
University of South Carolina High Energy Physics Group

HFAG Results assuming no CPV

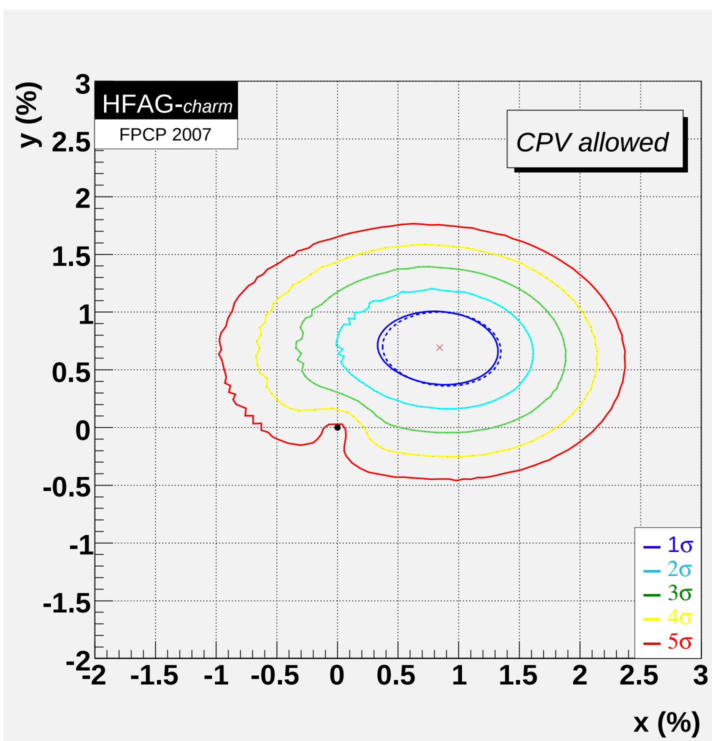
(Visit http://www.slac.stanford.edu/xorg/hfag/charm/index.html)

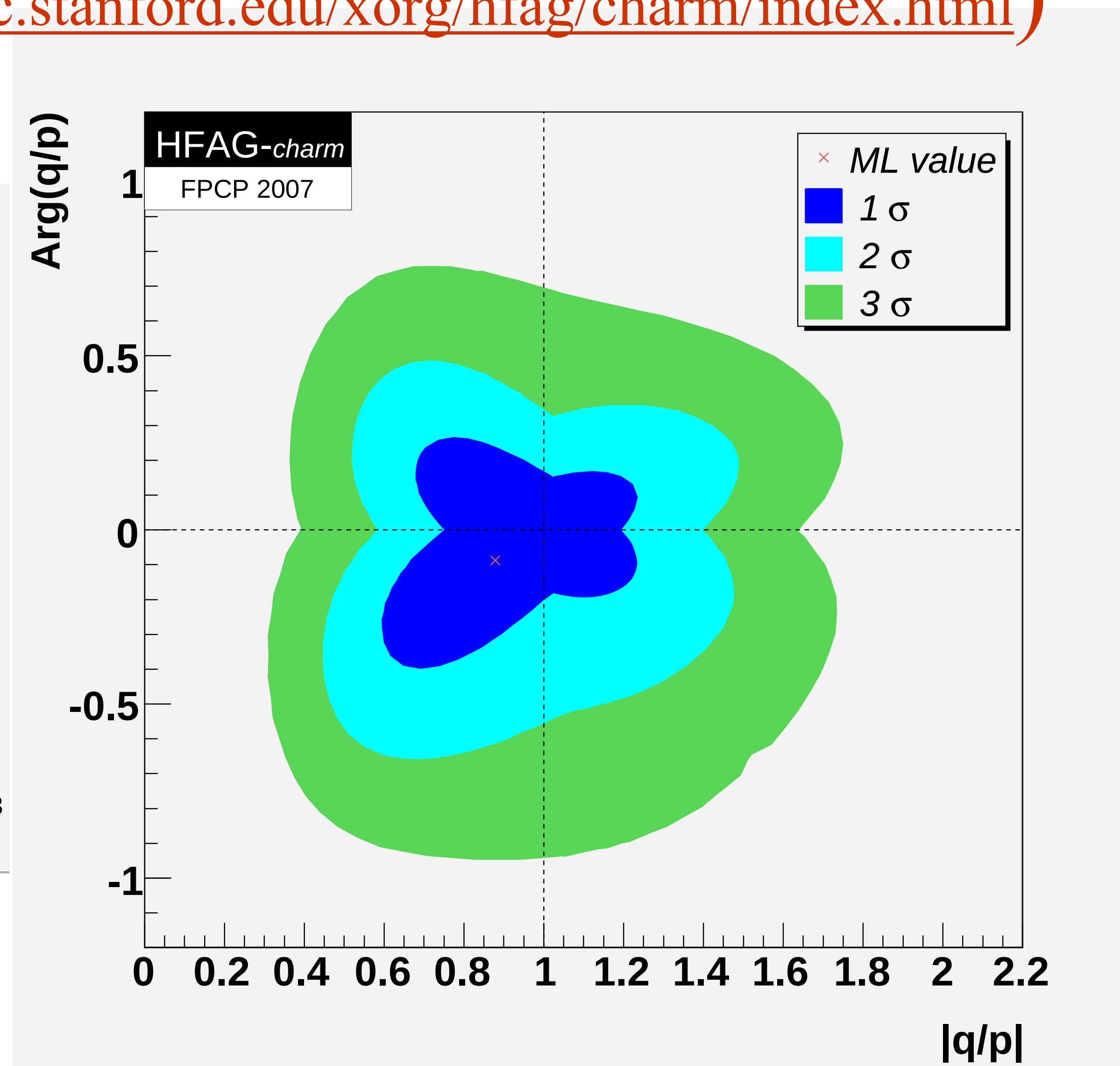


USC HEP
University of South Carolina High Energy Physics Group

HFAG results allowing for CPV

(Visit http://www.slac.stanford.edu/xorg/hfag/charm/index.html)





USC HEP
University of South Carolina High Energy Physics Group

Implications of Charm Mixing

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

Several new hep-ph preprints on charm mixing since then, e.g.,

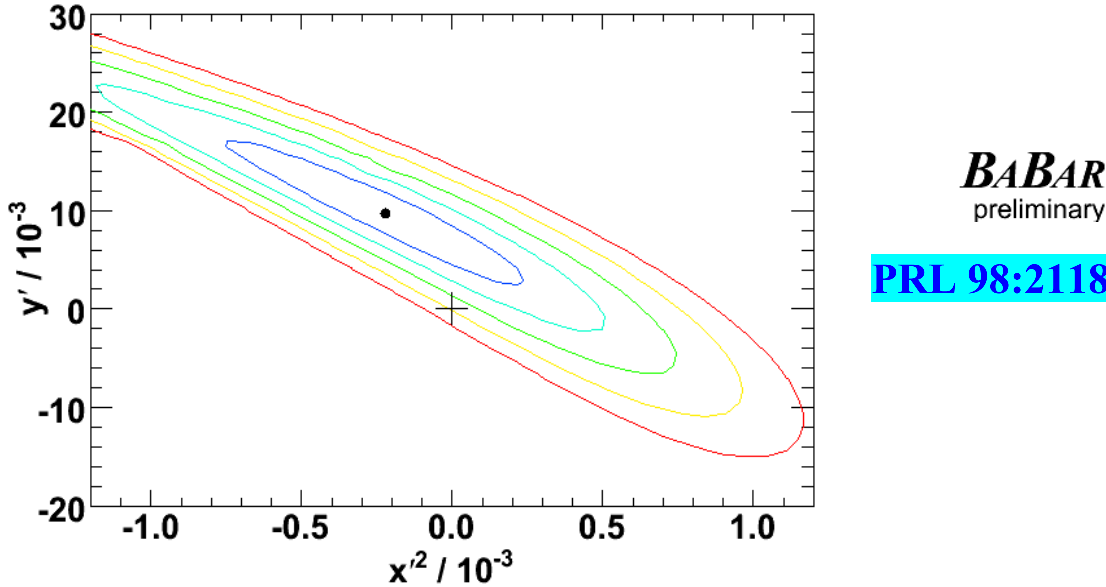
Five use D^0 mixing results to evaluate limits on:

- ❖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 an observation of CP violation in mixing would be a clear sign of New Physics

Summary and Outlook



PRL 98:211802, 2007

BaBar studied $D^0 \to K\pi$ and other D^0 decays for mixing, CPV

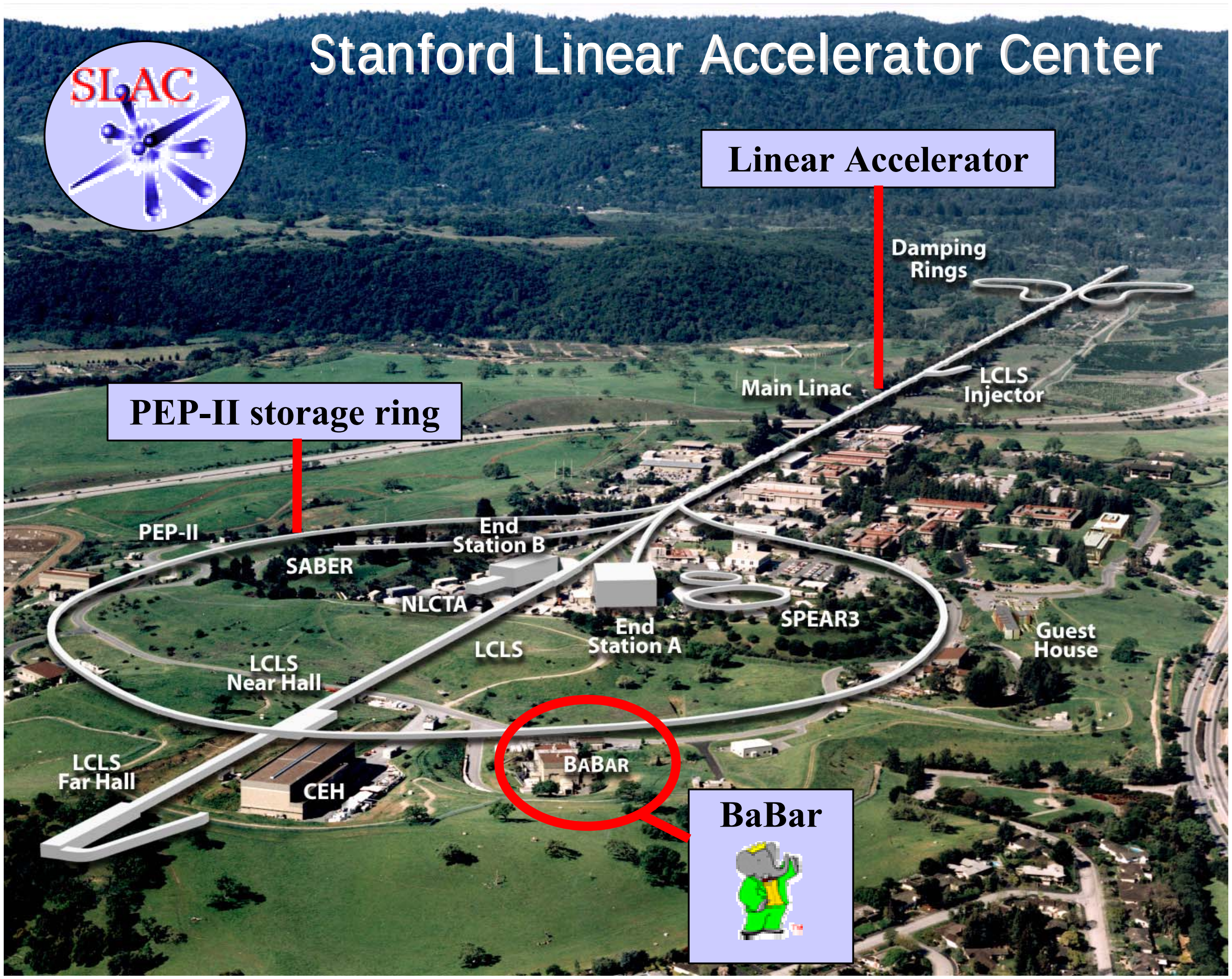
- Evidence for mixing in $K\pi$ decays (3.9σ)
- Evidence for mixing in lifetime differences (3.0σ)
- No sign of CP violation at the ~½% level
- Consistent with other measurements and SM
- More BaBar data and analyses coming up

USC HEP University of South Carolina High Energy Physics Group

BABAR™

Backup Slides

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



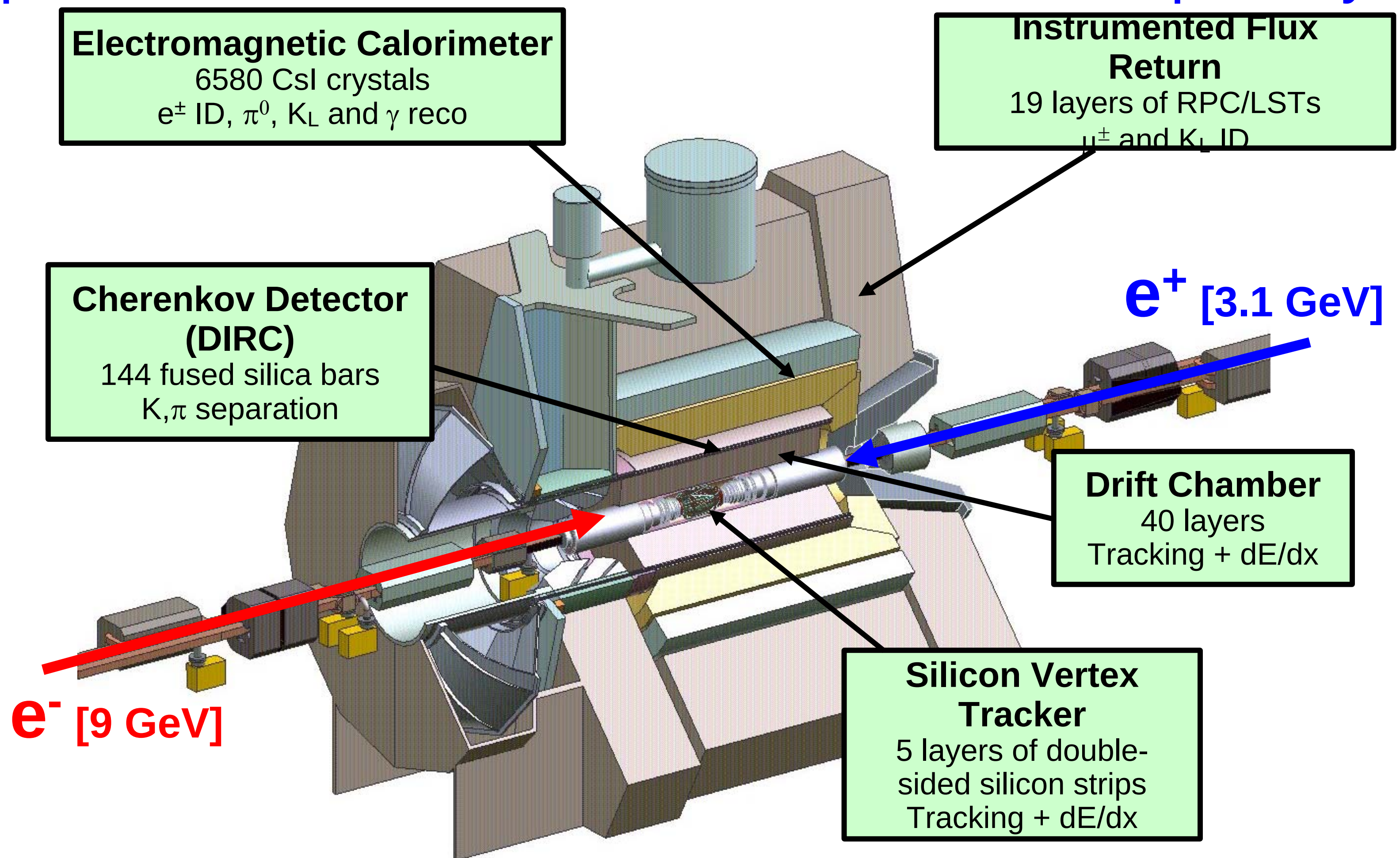
High-luminosity asymmetric energy e^+e^- collider at $\Upsilon(4S)$ resonance

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

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

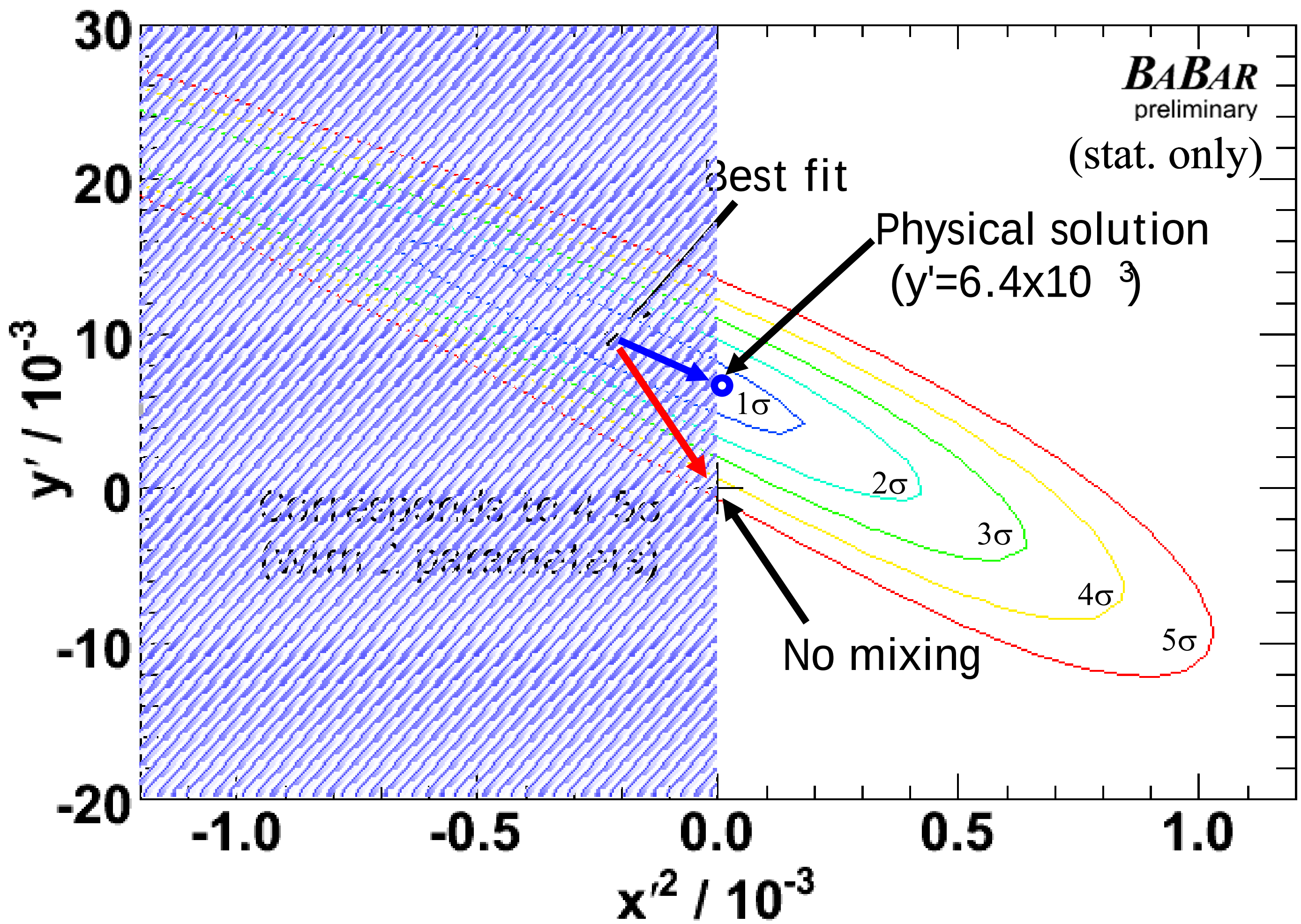
The BaBar Experiment

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



Signal Significance

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



Systematic Uncertainties

Two types of systematic uncertainties considered:

Fit model variations:

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

Selection criteria:

❖Mainly decay time (error) ranges used in fit

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

Fraction of statistical uncertainty

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

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

USC HEP University of South Carolina High Energy Physics Group

Interpreting the results

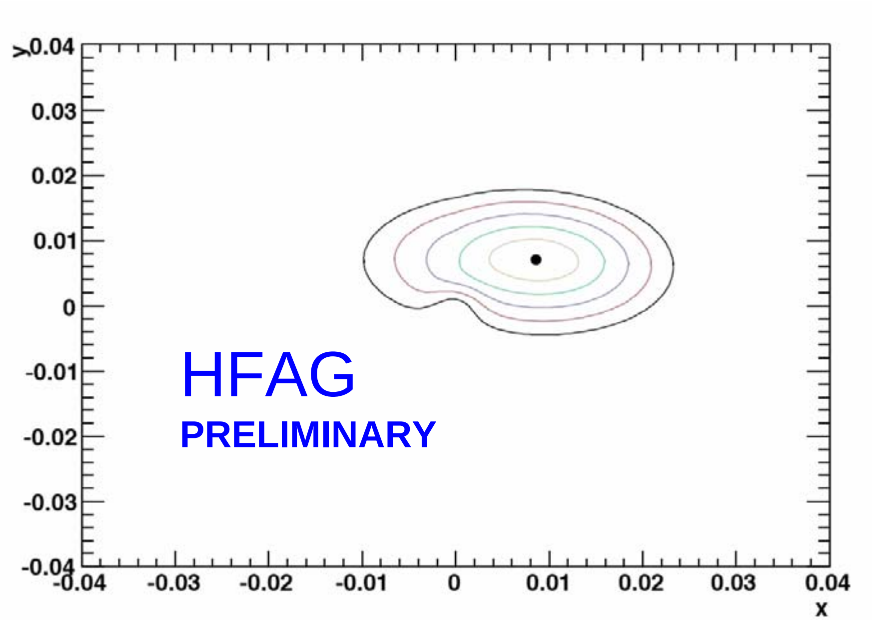
D^0 and $\bar{D}^0$

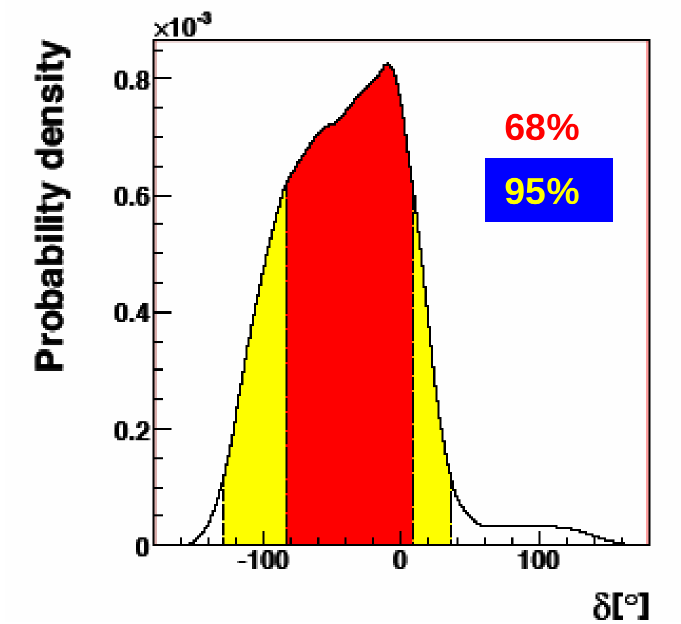
weak phase $2\phi_D$ of the mixing amplitude

Ciuchini et al.
hep-ph/0703294

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

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

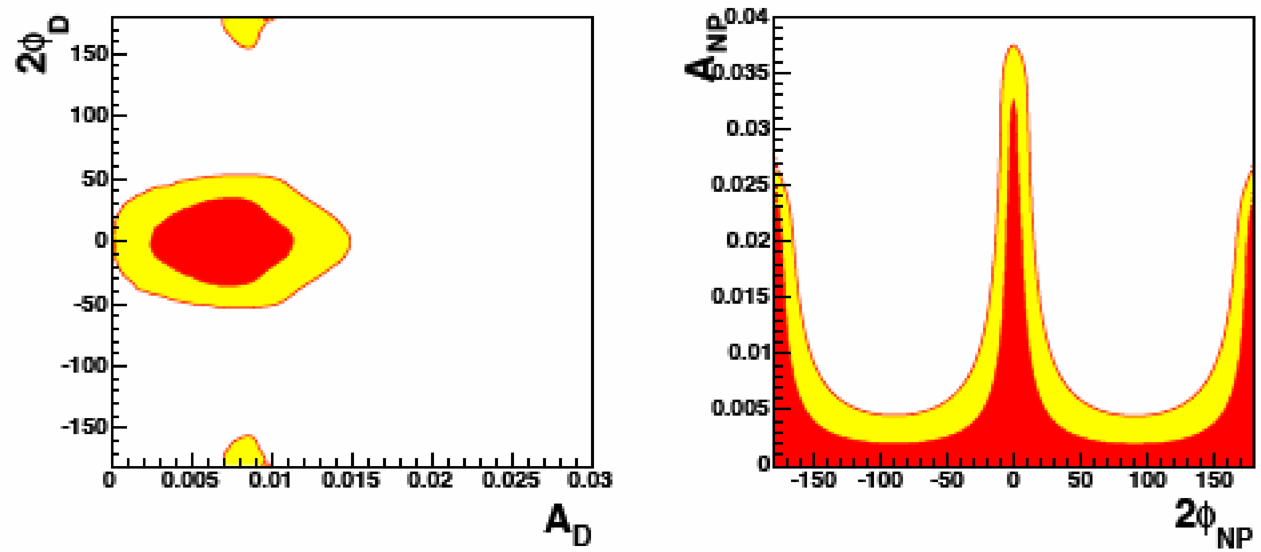




USC HEP
University of South Carolina High Energy Physics Group

And CP violation?

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



Ciuchini et al. hep-ph/0703294

In general NP weakly constrained if SM not known

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

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

Double tag at ψ(3770) [CLEO-c]

$D_{CP\pm}$

neutral D CP eigenstate

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

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

- R_D is ratio of DCS to Cabibbo favored rates

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

ψ(3770) decay conserves CP

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

Need to run

On threshold

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

BaBar (y_{CP}, ΔY) systematics

Systematic uncertainties (%):

Systematic	Δy_{CP}^{KK}	$\Delta y_{CP}^{\pi\pi}$	Δy_{CP}	$\Delta(\Delta Y^{KK})$	$\Delta(\Delta Y^{\pi\pi})$	$\Delta(\Delta Y)$
Signal Model	0.130	0.059	0.085	0.072	0.265	0.062
Charm Bkgd	0.062	0.037	0.043	0.001	0.002	0.001
Combinatorial Bkgd	0.019	0.142	0.045	0.001	0.005	0.002
Selection	0.068	0.178	0.046	0.083	0.172	0.011
Detector Model	0.064	0.080	0.064	0.054	0.040	0.054
Quadrature sum	0.172	0.251	0.132	0.122	0.318	0.083

Variations:

- Signal: PDF shape, polar angle dependent resolution offset, signal interval
- Charm backgrounds: yields and charm lifetime
- Combinatorial backgrounds: yields, shape and sideband region
- Selection: σ_t criterion, treatment of multiple candidates
- Detector: Alignment and energy loss

Search for CPV in $D^0 \to K^+K^-$, $\pi^+\pi^-$

Measure the time integrated CP asymmetries

$$a_{CP}^{KK} = \frac{\Gamma(D^0 \to K^-K^+) - \Gamma(\overline{D}^0 \to K^+K^-)}{\Gamma(D^0 \to K^-K^+) + \Gamma(\overline{D}^0 \to K^+K^-)}$$

$$a_{CP}^{\pi\pi} = \frac{\Gamma(D^0 \to \pi^-\pi^+) - \Gamma(\overline{D}^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to \pi^-\pi^+) + \Gamma(\overline{D}^0 \to \pi^+\pi^-)}.$$

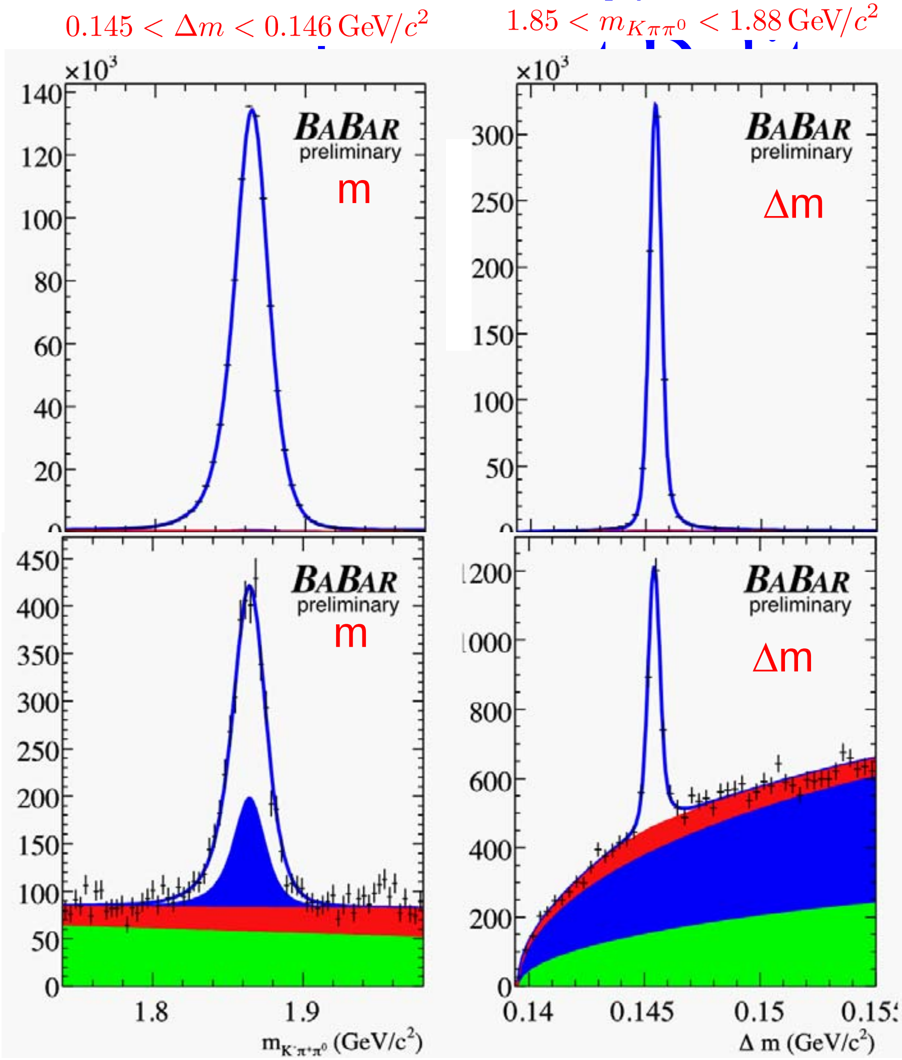
Experimental procedure:

- fit m,Δm distributions to determine raw signal weights
- Determine relative $D^0/\overline{D}^0$ soft pion tagging efficiency using $\overline{D}^0 \to K\pi$ data
  - ⇒greatly reduces systematic uncertainties

Category	Δa_{CP}^{KK}	$\Delta a_{CP}^{\pi\pi}$
2-Dim. PDF shapes	$\pm 0.04\%$	$\pm 0.05\%$
π_s correction	$\pm 0.08\%$	$\pm 0.08\%$
a_{CP} extraction	$\pm 0.09\%$	$\pm 0.20\%$
Quadrature sum	$\pm 0.13\%$	$\pm 0.22\%$

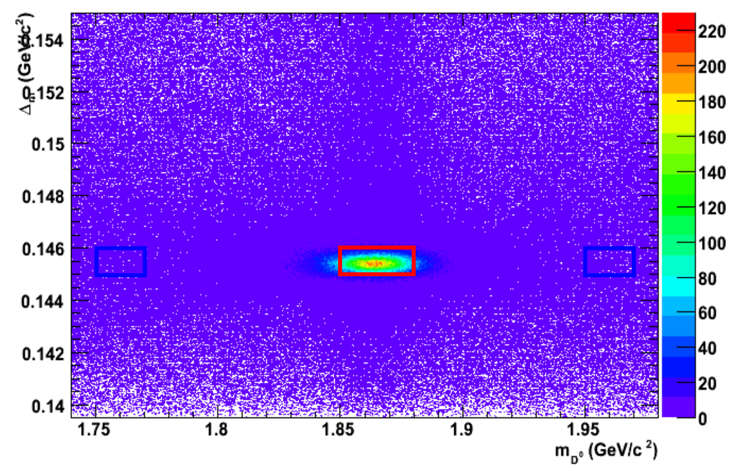
RS and WS ($m_{K\pi\pi}$, Δm) fits

Determine signal and background yields in … analyses.



- signal
- mis-tagged D^0
- mis-reconstructed D^0
- combinatoric

signal and sideband regions



signal box yields:

Category	N events (RS)	N events (WS)
Signal	639802 ± 1538	1483 ± 56
Combinatoric	1537 ± 57	499 ± 57
Mistag	2384 ± 57	765 ± 29
Misreconstructed D^0	3117 ± 93	227 ± 75

University of South Carolina High Energy Physics Group

Model	Approximate Constraint
Fourth Generation (Fig. 2)	$\lvert V_{ub'}V_{cb'}\rvert \cdot m_{b'} < 0.5$ (GeV)
$Q = -1/3$ Singlet Quark (Fig. 4)	$s_2 \cdot m_S < 0.27$ (GeV)
$Q = +2/3$ Singlet Quark (Fig. 6)	$\lvert\lambda_{uc}\rvert < 2.4 \cdot 10^{-4}$
Little Higgs	Tree: See entry for $Q = -1/3$ Singlet Quark
	Box: Region of parameter space can reach observed x_D
Generic Z' (Fig. 7)	$M_{Z'}/C > 2.2 \cdot 10^3$ TeV
Family Symmetries (Fig. 8)	$m_1/f > 1.2 \cdot 10^3$ TeV
	(with $m_1/m_2 = 0.5$)
Left-Right Symmetric (Fig. 9)	No constraint
Alternate Left-Right Symmetric (Fig. 10)	$M_R > 1.2$ TeV ($m_{D_1} = 0.5$ TeV)
	$(\Delta m/m_{D_1})/M_R > 0.4$ TeV^{-1}
Vector Leptoquark Bosons (Fig. 11)	$M_{VLQ} > 55(\lambda_{PP}/0.1)$ TeV
Flavor Conserving Two-Higgs-Doublet (Fig. 13)	No constraint
Flavor Changing Neutral Higgs (Fig. 15)	$m_H/C > 2.4 \cdot 10^3$ TeV
FC Neutral Higgs (Cheng-Sher ansatz) (Fig. 16)	$m_H/\lvert\Delta_{uc}\rvert > 600$ GeV
Scalar Leptoquark Bosons	See entry for RPV SUSY
Higgsless (Fig. 17)	$M > 100$ TeV
Universal Extra Dimensions	No constraint
Split Fermion (Fig. 19)	$M/\lvert\Delta y\rvert > (6 \cdot 10^2$ GeV)
Warped Geometries (Fig. 21)	$M_1 > 3.5$ TeV
Minimal Supersymmetric Standard (Fig. 23)	$\lvert(\delta^u_{12})_{\rm LR,RL}\rvert < 3.5 \cdot 10^{-2}$ for $\tilde{m} \sim 1$ TeV
	$\lvert(\delta^u_{12})_{\rm LL,RR}\rvert < .25$ for $\tilde{m} \sim 1$ TeV
Supersymmetric Alignment	$\tilde{m} > 2$ TeV
Supersymmetry with RPV (Fig. 27)	$\lambda'_{12k}\lambda'_{11k}/m_{\tilde{d}_{R,k}} < 1.8 \cdot 10^{-3}/100$ GeV
Split Supersymmetry	No constraint

75

Table from

Golowich, Hewett, Pakvasa and Petrov:

arXiv:0705.3650 [hep-ph]

"... for some models (Split Fermions, Flavor Changing Neutral Higgs) the constraints can be strong."

"Such a list is by nature approximate, and we refer the reader to the body of the paper for a more precise presentation of our results."