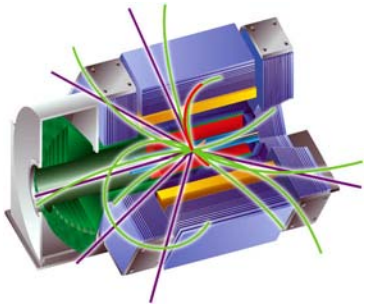
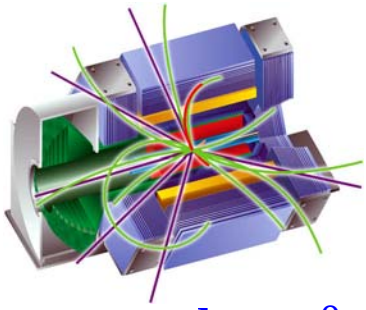


# Charm Mixing at BaBar

Ray F. Cowan
M.I.T.
for the BaBar Collaboration

1. Charm mixing phenomenology
2. Hadronic $D^0 \to K\pi$ decay analysis
3. Semileptonic $D^0 \to K^{(*)} e\, \nu$ decay analysis
4. Lifetime ratio analysis of $D^0 \to K^+K^-$, $\pi^+\pi^-$ decays
5. Summary & outlook



# Charm Mixing Phenomenology

- The $D^0$ can decay to a final state $f$ via direct decay or via mixing
- Time evolution is given by an effective Hamiltonian

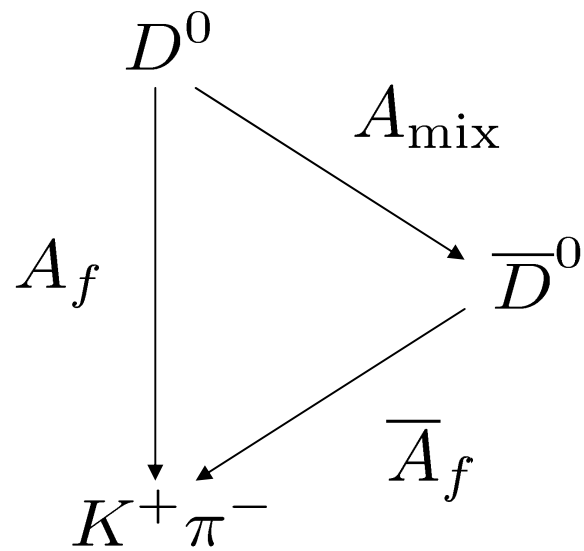
$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

- The mass eigenstates $D_1$, $D_2$ are

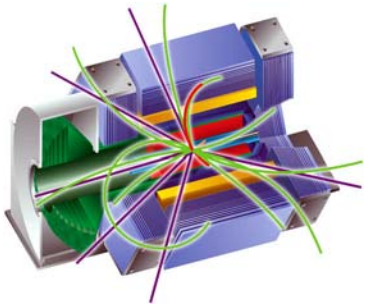
$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned}$$

where

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




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



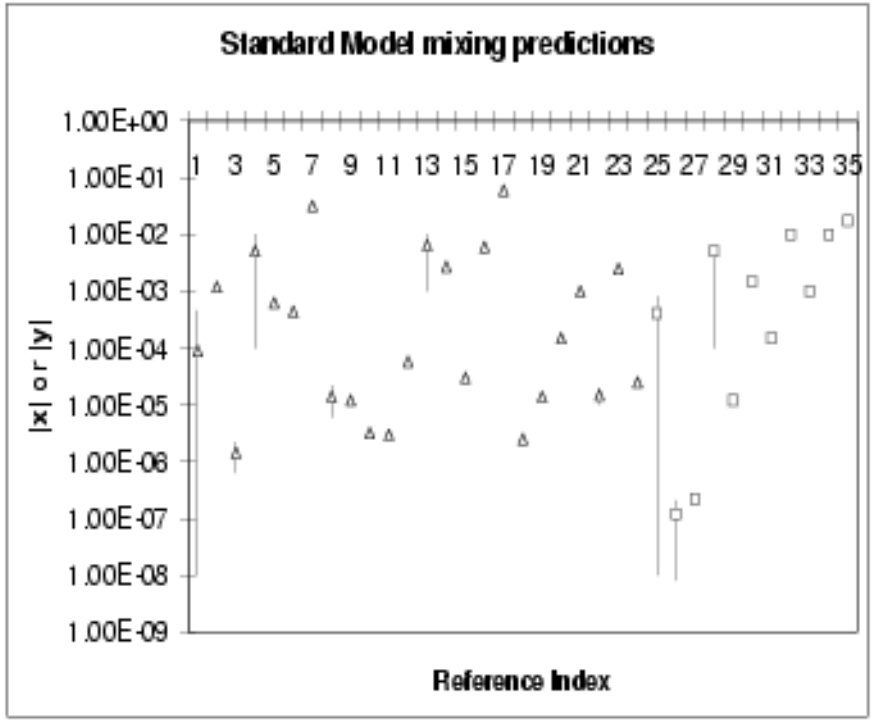
# Charm Mixing Phenomenology

- Mixing can be characterized in terms of the masses $m_1$, $m_2$ and widths $\Gamma_1$, $\Gamma_2$ of the mass eigenstates

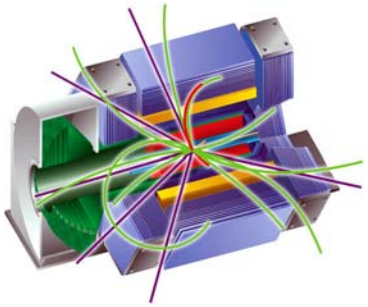
$$x = \frac{\Delta m}{\Gamma}, \qquad y = \frac{\Delta \Gamma}{2\Gamma}$$

- Mixing occurs if $x$ or $y$ is non-zero
- New physics models and the S.M. predict $|x|$, $|y| < 10^{-2}$
- Define the mixing rate $R_M \equiv (x^2+y^2)/2 < 10^{-4}$

Survey of mixing predictions




(From A. Petrov, hep-ph/0311371. Open triangles: $|x|$; open squares: $|y|$ )

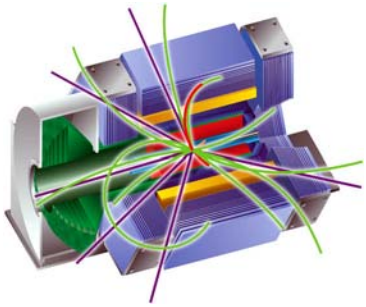


# CP Violation and $D^0$ Mixing

- *CP* violation can be characterized as one of three types
  - In mixing: $|q/p| \neq 1$
  - In decay: $|\overline{A}_f/A_f| \neq 1$
  - In interference between decays with and without mixing:

$$\lambda_f \equiv \frac{q}{p}\frac{\bar{A}_f}{A_f} \qquad |\lambda_f| = 1, \quad \Im(\lambda_f) \neq 0$$

- Observation of any sizeable *CP* violation would indicate new physics beyond the Standard Model
  - Dominant tree-level $D^0$decays described by real 2×2 Cabibbo matrix
  - Higher-order penguin, other processes suppressed by small $V_{cb}V^*_{ub}$(no higher mass, down-type quark available)



# *CP* Violation and $D^0$ Lifetimes

- Mixing affects $D^0$ lifetimes for *CP*-even (odd) final states
- If *CP* is conserved, then for *CP*-even final states

$$y \approx \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 = \frac{\tau(K^-\pi^+)}{\tau(\pi^-\pi^+)} - 1$$

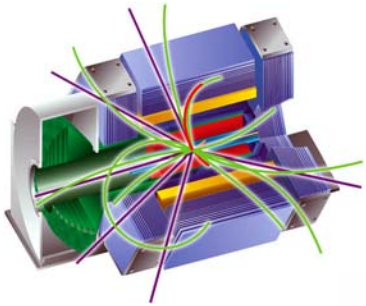
- Define effective lifetimes

$$\tau^0 \equiv D^0 \to K^-\pi^+ \text{ lifetime } (CP\text{-mixed state})$$

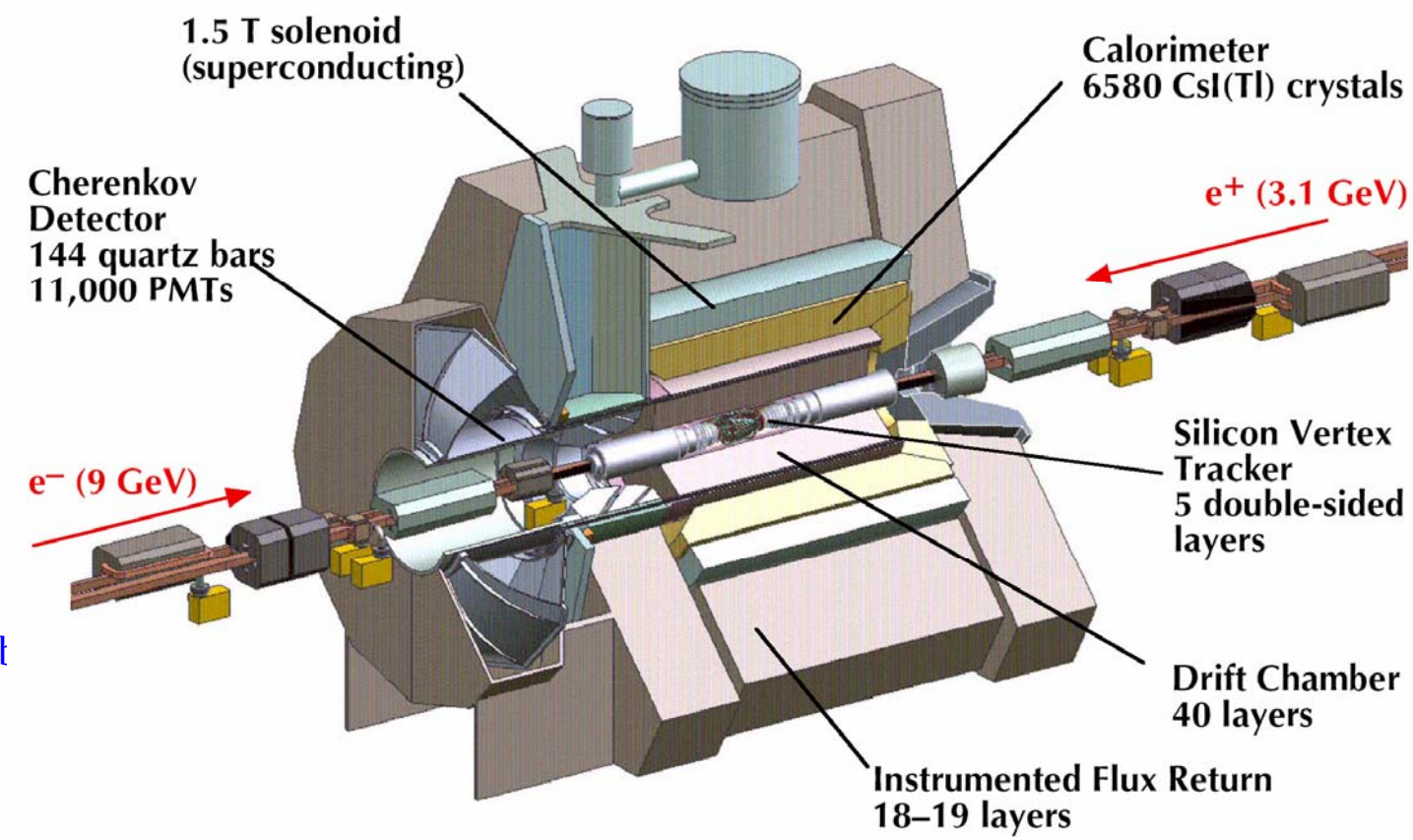
$$\tau^+ \ (\tau^-) \equiv D^0 \ (\overline{D}^0) \text{ lifetime of decay to } CP\text{-even final states } (K^-K^+,\ \pi^-\pi^+)$$

$$\langle\tau\rangle \equiv (\tau^+ + \tau^-)/2, \qquad A_\tau \equiv (\tau^+ - \tau^-)/(\tau^+ + \tau^-)$$

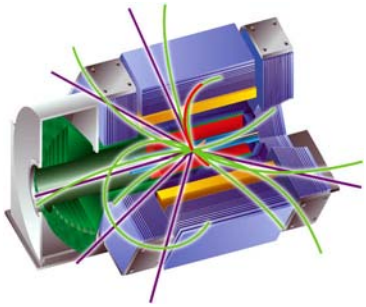
If no mixing: $\langle\tau\rangle = \tau^0$ If no CP violation: $A_\tau = 0$



# The BaBar Experiment

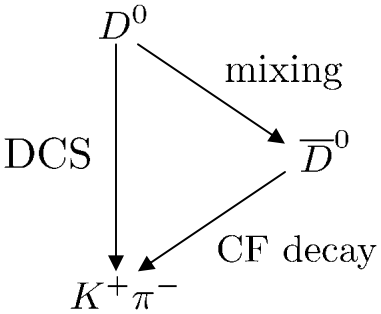



- PEP-II is a charm factory: charm cross-section ≈ 1.4 nb
- > 1M reconstructed $D^0 \to K\pi$ decays
- Used here: 60–90 $fb^{-1}$



# $K\pi$ Hadronic Mixing Analysis: Decay Modes

- Uses $D^0(\overline{D}^0) \to K\pi$ hadronic decays, 57 fb$^{-1}$
  - "Right-sign" (RS) $D^0 \to K^-\pi^+$ Cabibbo-favored (CF)
  - "Wrong-sign" (WS) $D^0 \to K^+\pi^-$
    - Doubly Cabibbo-suppressed (DCS)
    - Mixing would also create WS decays

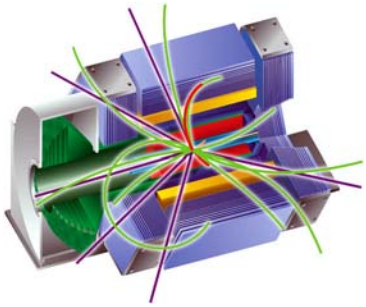



- Assuming *CP* conservation and that $|x|, |y| \ll 1$, the WS decay rate is approximately

$$T_{\rm WS}(t) = e^{-\Gamma t}\left(R_{\rm D} + \sqrt{R_{\rm D}}y'\,\Gamma t + \frac{x'^2 + y'^2}{4}(\Gamma t)^2\right)$$

  - $R_{\rm D}$ is the WS decay rate relative to the RS decays, and we have taken into account any CF to DCS relative strong phase $\delta_{K\pi}$ by defining

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

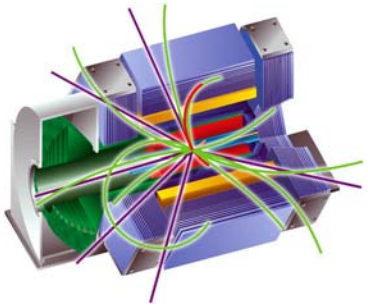


# $K\pi$ Hadronic Mixing Analysis: *CP* Violation

- Accommodate any *CP*-violating new physics by fitting the $D^0$, $\overline{D}^0$ events separately for $T_{\mathrm{WS}}(t)$
- Fit for $\{R^{\pm}_{\mathrm{WS}}, x'^{\pm 2}, y'^{\pm}\}$ where + (-) indicates $D^0(\overline{D}^0)$
- Combine results to form *CP* violation parameters

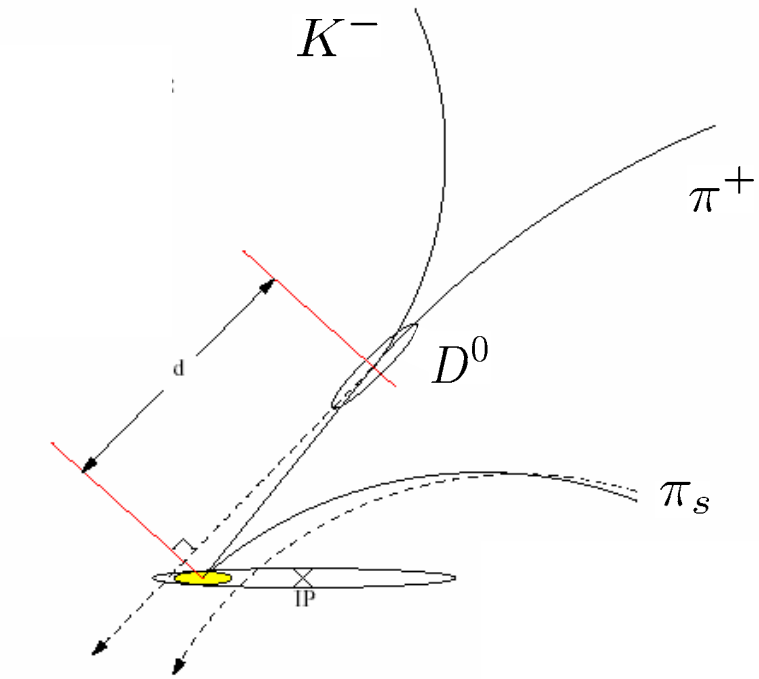
$$A_{\mathrm{D}} = \frac{R^+_{\mathrm{D}} - R^-_{\mathrm{D}}}{R^+_{\mathrm{D}} + R^-_{\mathrm{D}}}, \qquad A_{\mathrm{M}} = \frac{R^+_{\mathrm{M}} - R^-_{\mathrm{M}}}{R^+_{\mathrm{M}} + R^-_{\mathrm{M}}}$$

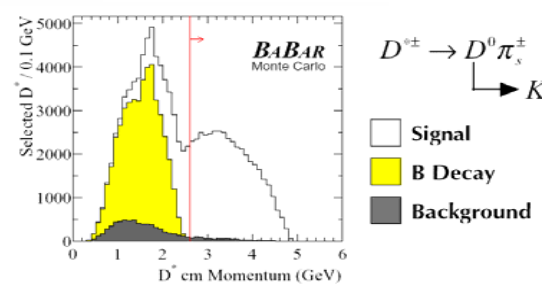
- $A_{\mathrm{D}}$ ($A_{\mathrm{M}}$) $\neq 0$ implies CP violation in DCS decay (mixing)



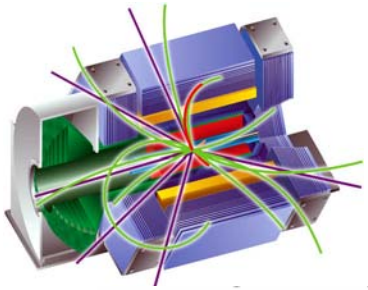
# Event Selection

- Select charged tracks of good quality
- Pair oppositely-charged tracks
  - Form $D^0$ candidates
- Determine production vertex
  - Intersect $D^0$ direction with beam spot
- Use $D^0$ reconstructed from decays $D^{*+} \to D^0 \pi_s^+$
- Require CMS $p(D^*) > 2.6$ Gev/$c$ to reject $B$ events
- Obtain $D^0$ proper decay time t and error $\sigma_t$ from production, decay vertices (typical $\sigma_t \approx$ 180 fsec)

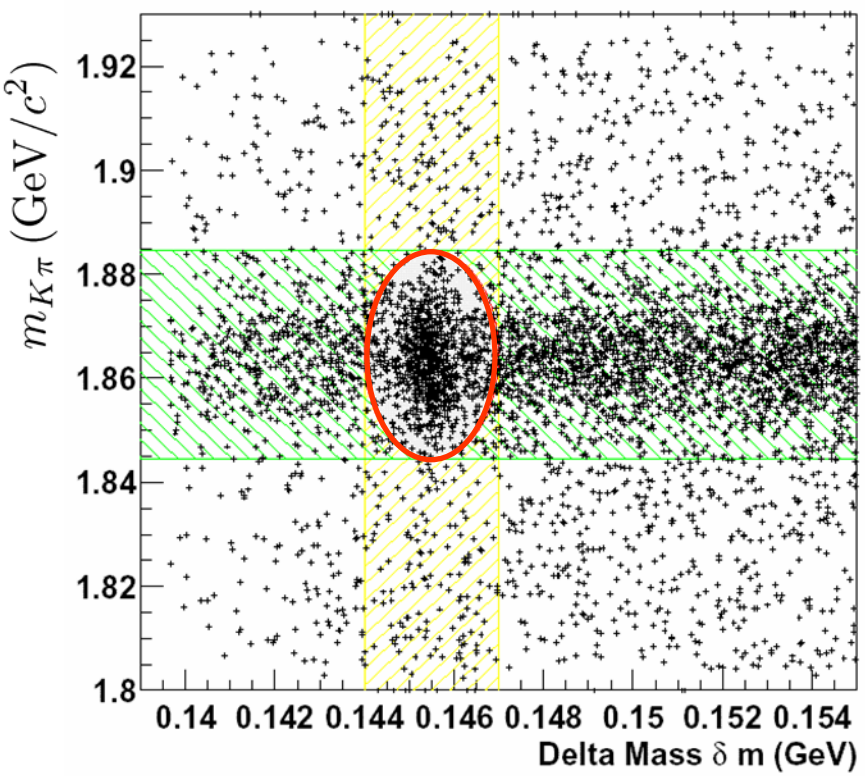


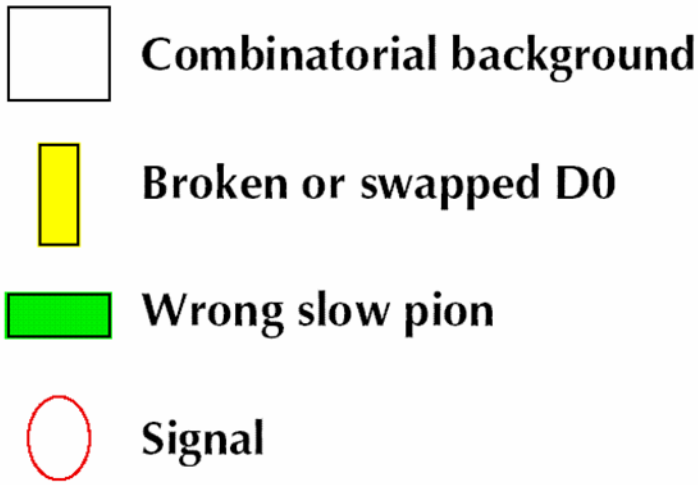

$D^*$ CM momentum (GeV/$c$)



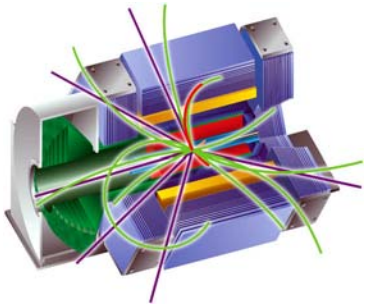
# $m_{K\pi}$ and $\delta m$ Distributions




$$\delta m = m_{D^*} - m_{K\pi}\,(\mathrm{GeV}/c^2)$$




| category | $\delta m$ | $m_{K\pi}$ | time |
|---|---|---|---|
| signal | peaking | peaking | long-lived |
| combinatoric | non-peaking | non-peaking | prompt & long-lived |
| wrong slow $\pi$ | non-peaking | peaking | long-lived |
| broken or swapped $D^0$ | peaking | non-peaking | long-lived |



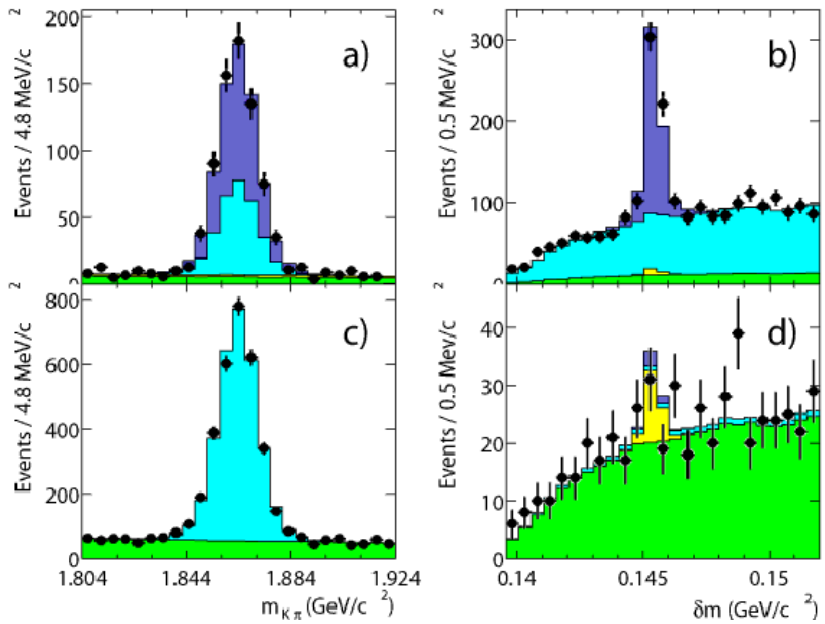
# Hadronic Mixing Analysis: Signals and Backgrounds

- Use $m_{K\pi}$, $\delta m$ distributions to distinguish signal, backgrounds
- Characterize & fit for three types of backgrounds in WS events
  - True $D^0$ decays matched with unassociated pions
  - Combinatorics
  - Double-misid ($K$ and $\pi$ id swapped)
    - Converts RS event $\leftrightarrow$ WS event
    - Level from fit consistent with PID performance

Wrong-sign events

Signal

Sideband

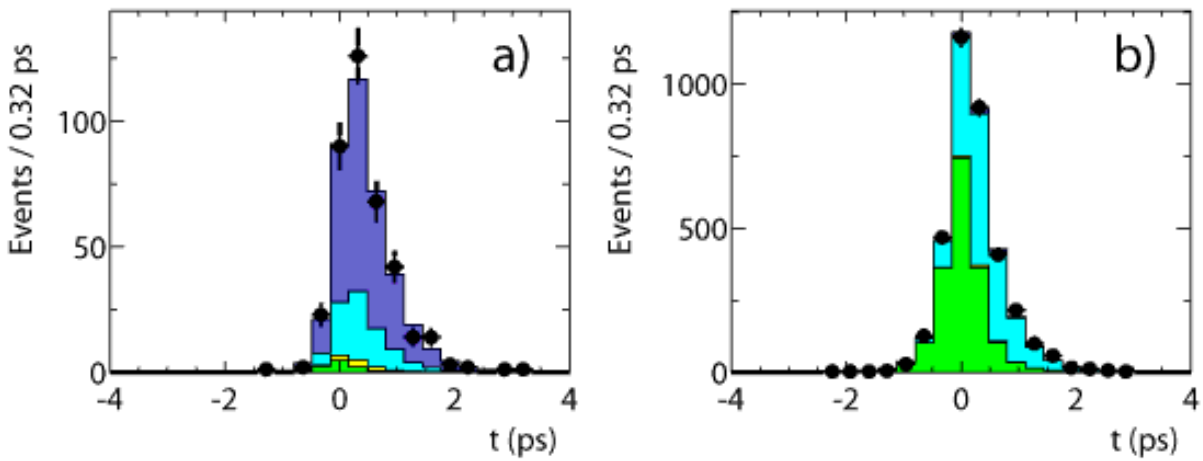



$m_{K\pi}$ $\delta m$

| | |
|---|---|
| | Signal |
| | Fake slow $\pi_s$ bkg |
| | Double mis-id bkg |
| | Combinatoric bkg |

# Hadronic Mixing Analysis Results

Wrong-sign Events Decay Time Distributions

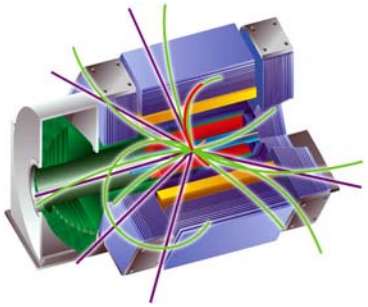



Signal region

Sideband region

Points: data.
Histogram: fit.

| | |
|---|---|
| | Signal |
| | Fake slow $\pi_s$ bkg |
| | Double mis-id bkg |
| | Combinatoric bkg |



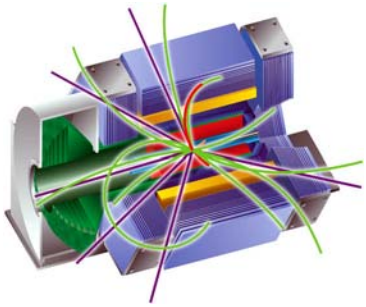
# Hadronic Mixing Analysis: Final Results

Fits performed for four scenarios

| Fit case | Parameter | Central value ($x'^2$=0) ($/10^{-3}$) | 95% CL interval ($/10^{-3}$) |
|---|---|---|---|
| *CP* violation allowed | $R_D$ | 3.1 | $2.3 < R_D < 5.2$ |
| | $A_D$ | 1.2 | $-2.8 < A_D < 4.9$ |
| | $x'^2$ | 0 | $x'^2 < 2.2$ |
| | $y'$ | 8.0 | $-56 < y' < 39$ |
| | $R_M$ | | $R_M < 1.6$ |
| No *CP* violation | $R_D$ | 3.1 | $2.4 < R_D < 4.9$ |
| | $x'^2$ | 0 | $x'^2 < 2.0$ |
| | $y'$ | 8.0 | $-27 < y' < 22$ |
| | $R_M$ | | $R_M < 1.3$ |
| No mixing | $R_D = (0.357 \pm 0.022\ (\text{stat.}) \pm 0.027\ (\text{syst.}))\%$ | | |
| | $A_D = 0.095 \pm 0.061\ (\text{stat.}) \pm 0.083\ (\text{syst.})$ | | |
| No *CP* viol. or mixing | $R_D = (0.359 \pm 0.020\ (\text{stat.}) \pm 0.027\ (\text{syst.}))\%$ | | |

| | |
|---|---|
| Mixing, with *CP* Violation | Mixing, without *CP* Violation |
| No Mixing, with *CP* Violation | No Mixing, no *CP* Violation |

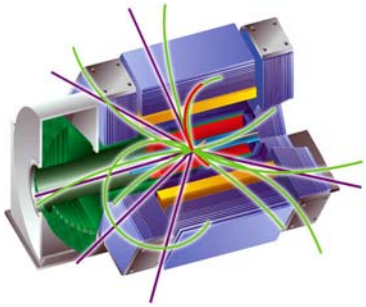
Phys. Rev. Lett. 91, 171801 (2003)



# Semileptonic Mixing Analysis

- Use decay chain $D^{*+} \to \pi^+ D^0, D^0 \to K^{(*)} e\nu$
- Uses 87 fb$^{-1}$
- Only electronic mode (for highest purity sample)
- Pion, electron charges tag production, decay flavors
  - Right-sign (unmixed) signal has same-sign *K*, *e* charges
  - Wrong-sign (mixed) signal has opposite *K*, *e* charges
- No doubly Cabibbo-suppressed mode to distinguish
  - Time dependence of mixing signal (in small *x*, *y* limit)

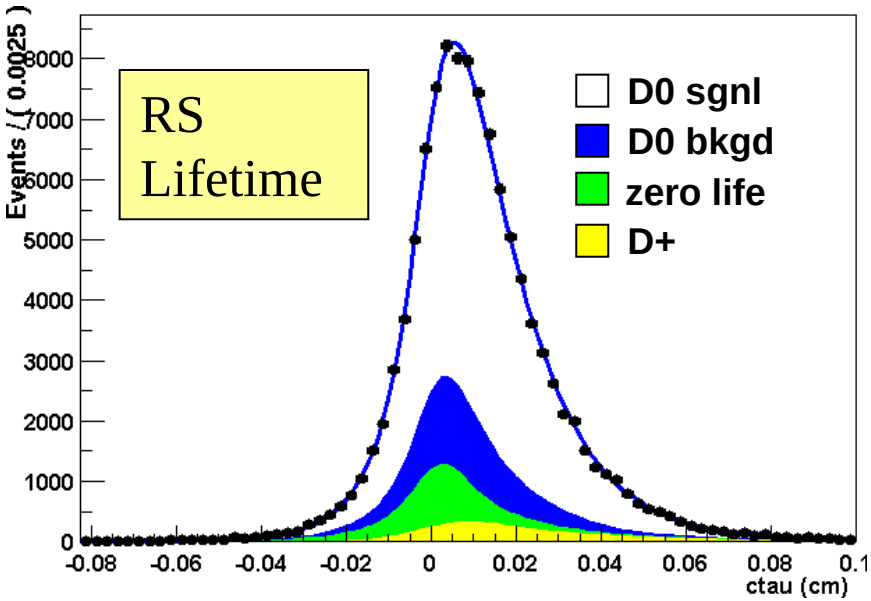
$$T_{\mathrm{WS}}(t) = T_{\mathrm{RS}}(t)\left(R_{\mathrm{D}} + \sqrt{R_{\mathrm{D}}}\,y'\,t + \frac{x'^2 + y'^2}{4}t^2\right)$$

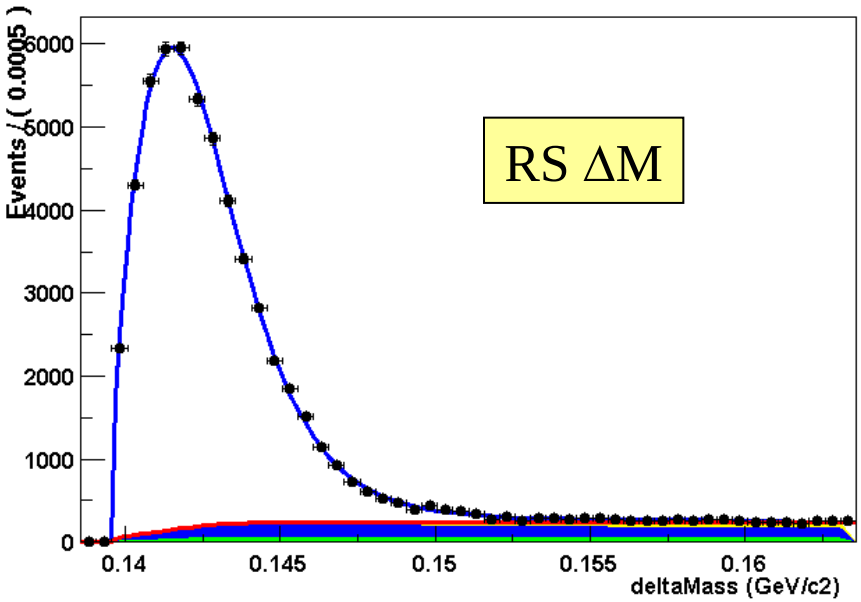


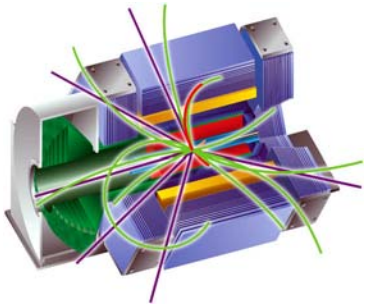
# Semileptonic Mixing Analysis: Right-sign Signal

- $R_{mix} = N_{WS}/N_{RS}$ signal events
- Unbinned, maximum-likelihood fits to signal plus backgrounds

Neural net for $D^0$ reconstruction
Improves $\Delta M$ resolution
($\sigma \sim 2.2$ MeV/$c^2$)





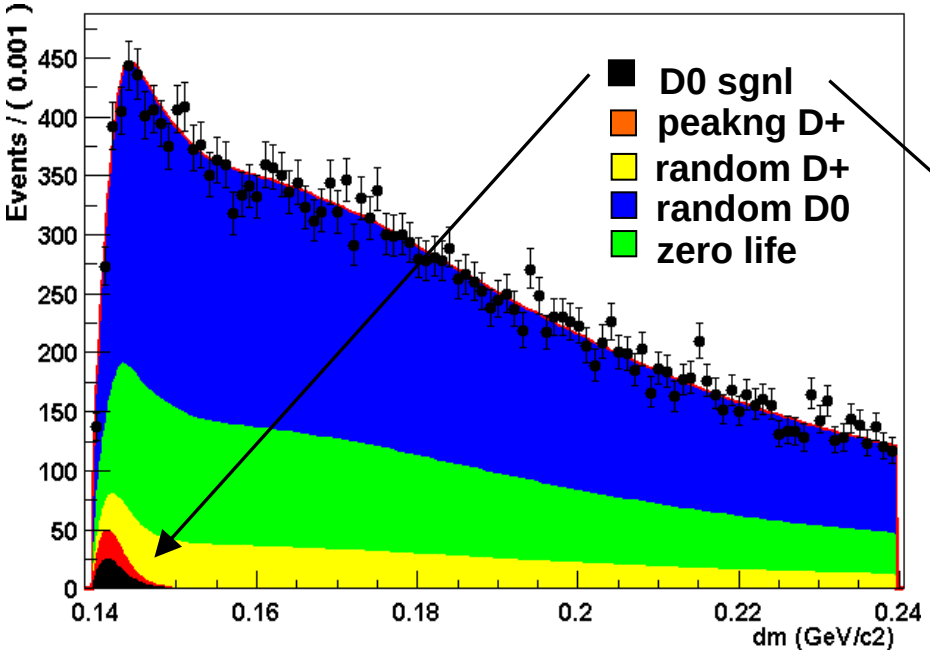
# Semileptonic Mixing Analysis: Wrong-sign Signal

Fit Result: 114±61 WS events

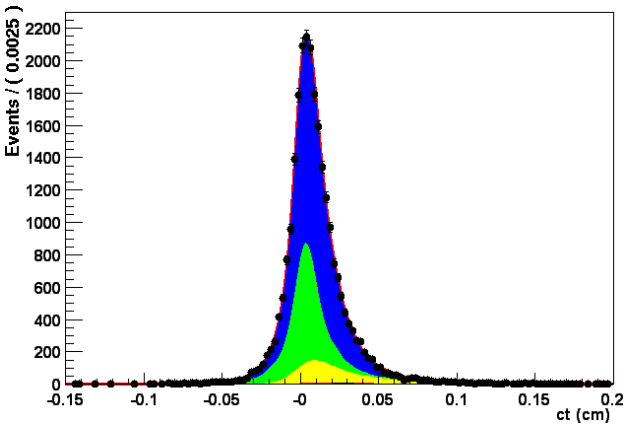
Normalize to #RS events, obtain

$R_{mix}$=0.0023±0.0012(stat.)±0.0004(syst.)

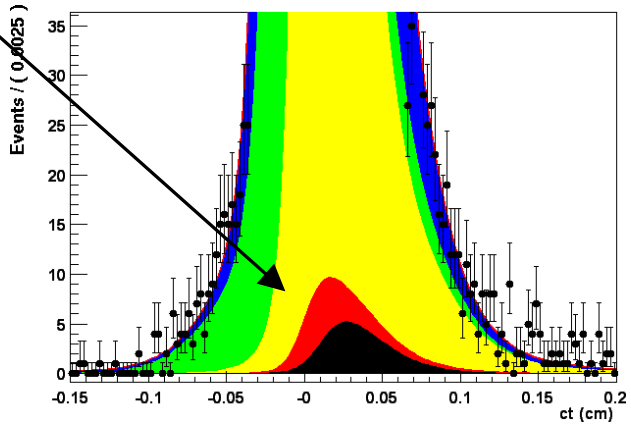
$R_{mix}$<0.0042 (90% C.L.)

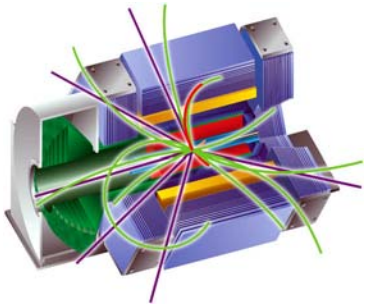



Full lifetime projection




Lifetime projection





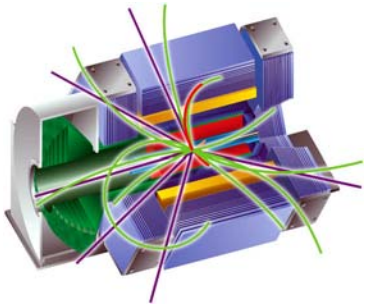
# Lifetime Ratio Analysis

- Use 91 fb$^{-1}$ dataset
- Look for specific final states:

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

- Require $D^0$ to be *tagged* via its production mode $D^{*+} \to D^0\pi_s^+$
- Also use untagged $K^-K^+$ sample

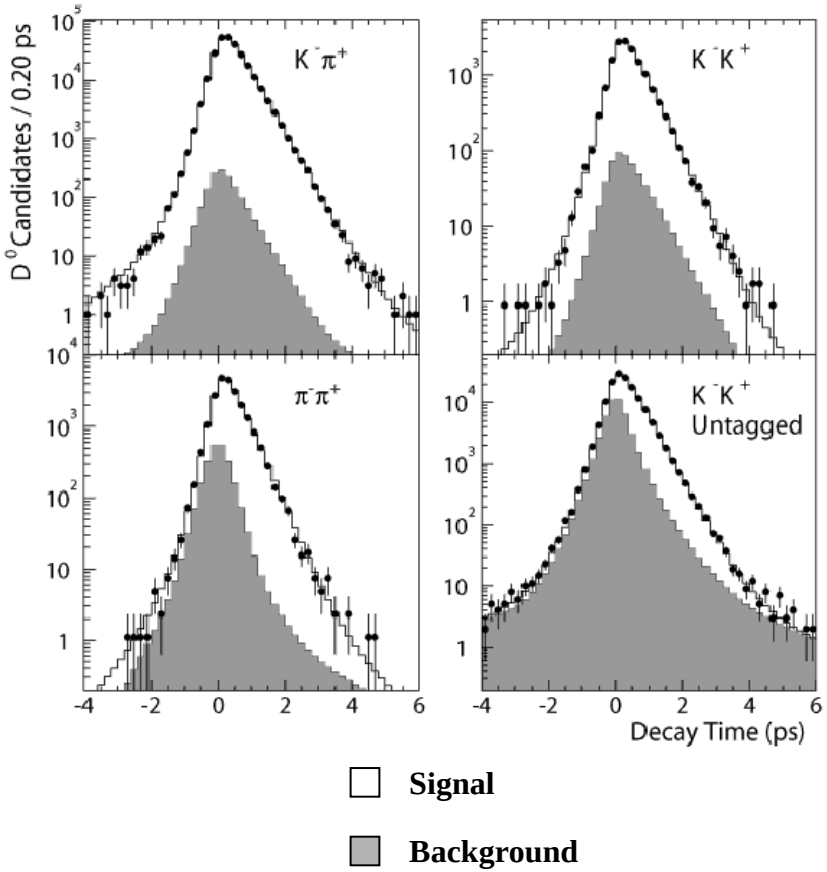
| Sample | Determines |
|---|---|
| $K^-\pi^+$ | $\tau^0$ |
| $K^-K^+$ | $\}\ \langle\tau\rangle,\ A_\tau$ |
| $\pi^-\pi^+$ | |
| Untagged $K^-K^+$ | $\langle\tau\rangle$ |

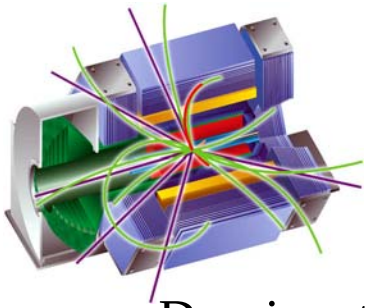


# Lifetime Ratio Analysis: Decay Time Fit

- Perform fit to $D^0$ decay time distributions for each sample
  - Unbinned, maximum-likelihood
  - Independent variables $m_{K\pi}$, $t$, $\sigma_t$ from each event
  - Use reconstructed $D^0$ mass value to assign probability event is signal (determined in the mass fit)
  - Histogram: fit
  - Points: data

Decay Time Fits





# Lifetime Ratio Analysis: Results

- Dominant systematics
  - Background models, for both $Y$ and $\Delta Y$
- For the three samples separately

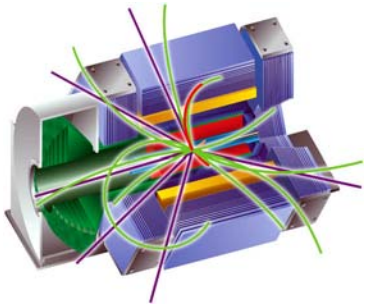
$$Y = \frac{\tau^0}{\langle\tau\rangle} - 1, \qquad \Delta Y = \frac{\tau^0}{\langle\tau\rangle} A_\tau$$

| Sample | $Y$ (%) | | $\Delta Y$ (%) | |
|---|---|---|---|---|
| $K^-K^+$ | $1.5 \pm 0.8$ | $\pm 0.5$ | $-1.3 \pm 0.8$ | $\pm 0.2$ |
| $\pi^-\pi^+$ | $1.7 \pm 1.2$ | $^{+1.2}_{-0.6}$ | $0.3 \pm 1.1$ | $\pm 0.2$ |
| Untagged $K^-K^+$ | $0.2 \pm 0.5$ | $^{+0.5}_{-0.4}$ | — | |
| Combined | $0.8 \pm 0.4$ | $^{+0.5}_{-0.4}$ | $-0.8 \pm 0.6$ | $\pm 0.2$ |

- Combined results

Phys. Rev. Lett. 91, 121801 (2003)

$$Y = (0.8 \pm 0.4^{+0.5}_{-0.4})\%, \qquad \Delta Y = (-0.8 \pm 0.6 \pm 0.2)\%$$



# Summary

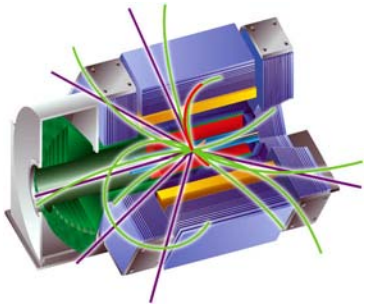
- Three separate charm mixing analyses
  - No mixing or *CP* violation observed so far
  - But not systematics-limited yet
  - May be able to see a signal with more data (500 $fb^{-1}$ by 2006)
- Observation of *CP* violation would imply new physics
- $K\pi$ decay analysis (Phys. Rev. Lett. **91**, 171801 (2003))

$$R_{\rm D} = (0.359 \pm 0.020\ (\text{stat.}) \pm 0.027\ (\text{syst.}))\%$$

- Semileptonic analysis: $R_{\rm mix}$<0.0042 (90% C.L.)

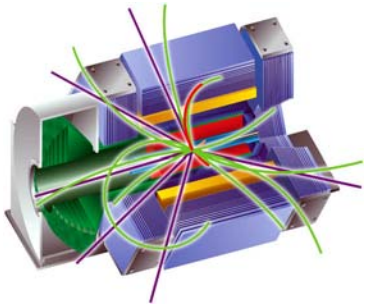
  (Phys. Rev. D**70**, 091102 (2004))
- Lifetime ratio analysis (Phys. Rev. Lett. **91**, 121801 (2003))

$$Y = (0.8 \pm 0.4^{+0.5}_{-0.4})\%, \qquad \Delta Y = (-0.8 \pm 0.6 \pm 0.2)\%$$

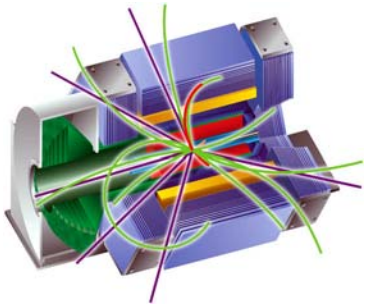


# Coming in 2006

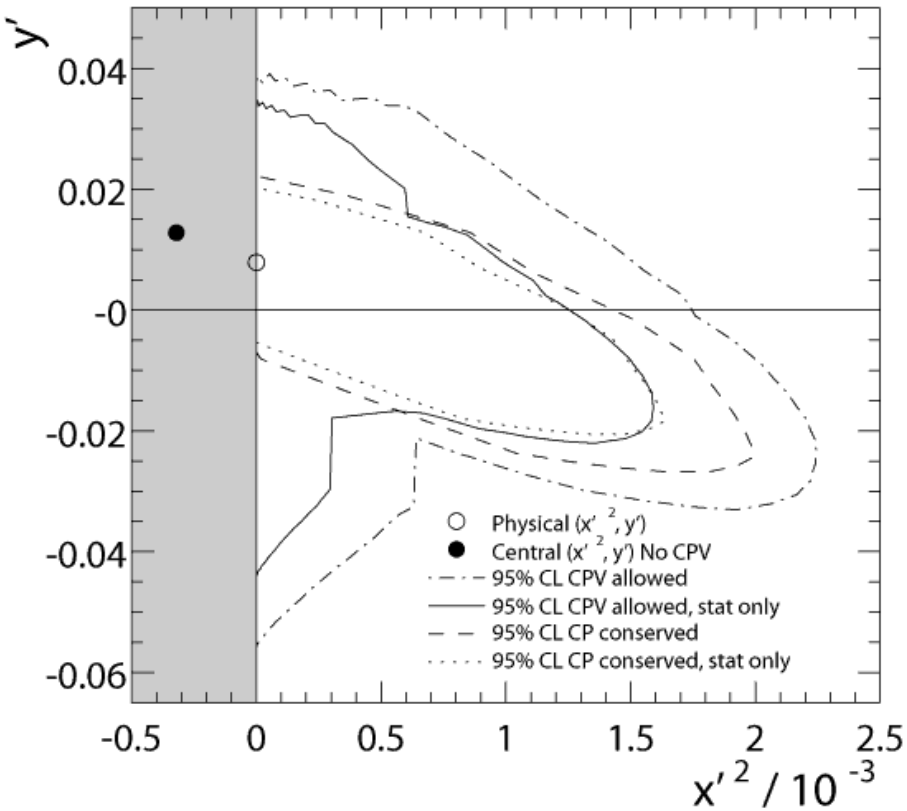
- Several charm mixing analyses are underway in BaBar
  - $K\pi$: updating to 250 $fb^{-1}$
  - $K\pi\pi^0$: new analysis
  - $K\pi\pi\pi$: new analysis
  - $K^{(*)}e\nu$ updating to 250 $fb^{-1}$
- Results will become available during the next year



# Backup Slides



# $K\pi$ Hadronic Mixing Analysis: 95% C.L. Contours

- Fit allows $x'^2$ to take values < 0
- Strong correlation of $x'^2$, $y'$
- Employ frequentist method (similar to Feldman-Cousins) to obtain 95% C.L contours
- Two of four scenarios illustrated here

Phys. Rev. Lett. **91**, 171801 (2003)