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

Mark Mattson
Wayne State University
January 11, 2008

Charm Mixing Overview

Neutral Meson Mixing

- Mixing: neutral mesons oscillating between matter and anti-matter
- Production eigenstates ≠ mass eigenstates

$$|D^0\rangle = \frac{1}{\sqrt{2}}\left(|D_1\rangle + |D_2\rangle\right) \qquad |\bar{D}^0\rangle = \frac{1}{\sqrt{2}}\left(|D_1\rangle - |D_2\rangle\right)$$

Assuming no CP violation

- Time evolution of mass eigenstates

$$i\frac{\partial}{\partial t}|D_{1,2}(t)\rangle = \left(M - \frac{i}{2}\Gamma\right)|D_{1,2}(t)\rangle$$

$$|D_{1,2}(t)\rangle = |D_{1,2}\rangle\, e^{-\left(\frac{\Gamma_{1,2}}{2}+iM_{1,2}\right)t}$$

Neutral Meson Mixing

- Mixing occurs when the mass eigenstates have different masses or decay widths

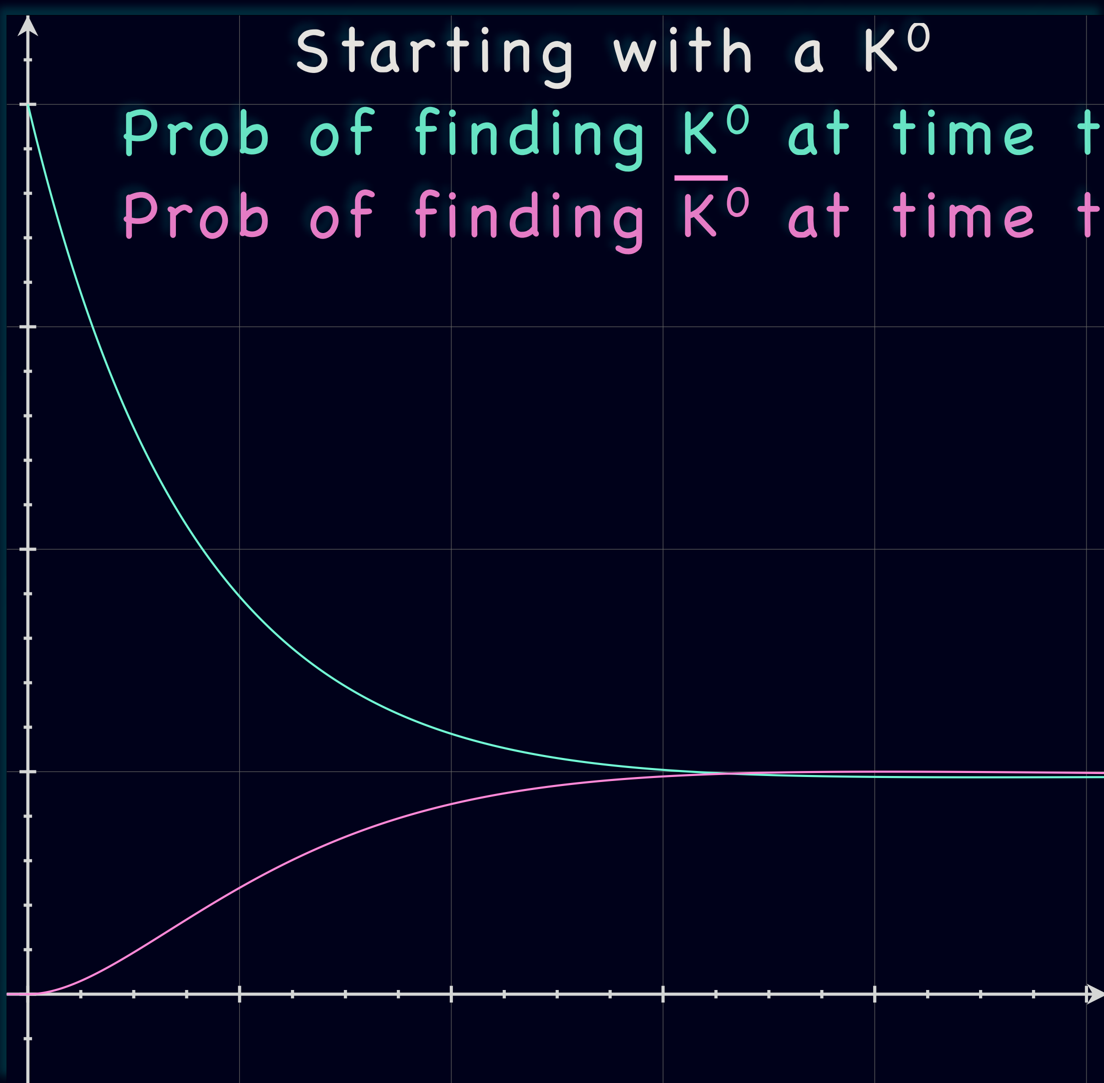
- Characterized by the mixing parameters

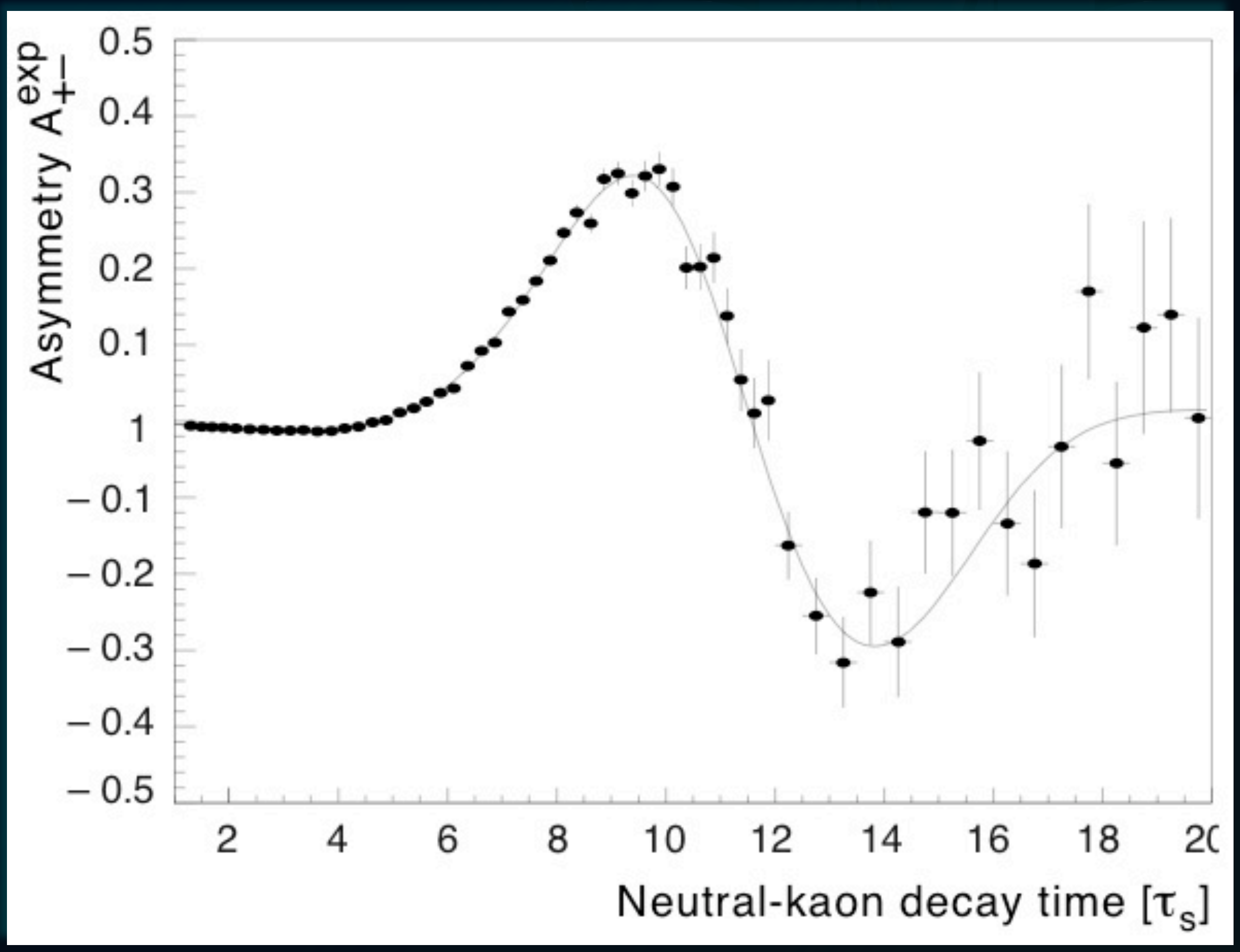
$$x \equiv \frac{M_2 - M_1}{\Gamma} \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

oscillation frequency

mean lifetime $\tau = \frac{1}{\Gamma} = \frac{2}{\Gamma_1 + \Gamma_2}$

Kaon Mixing

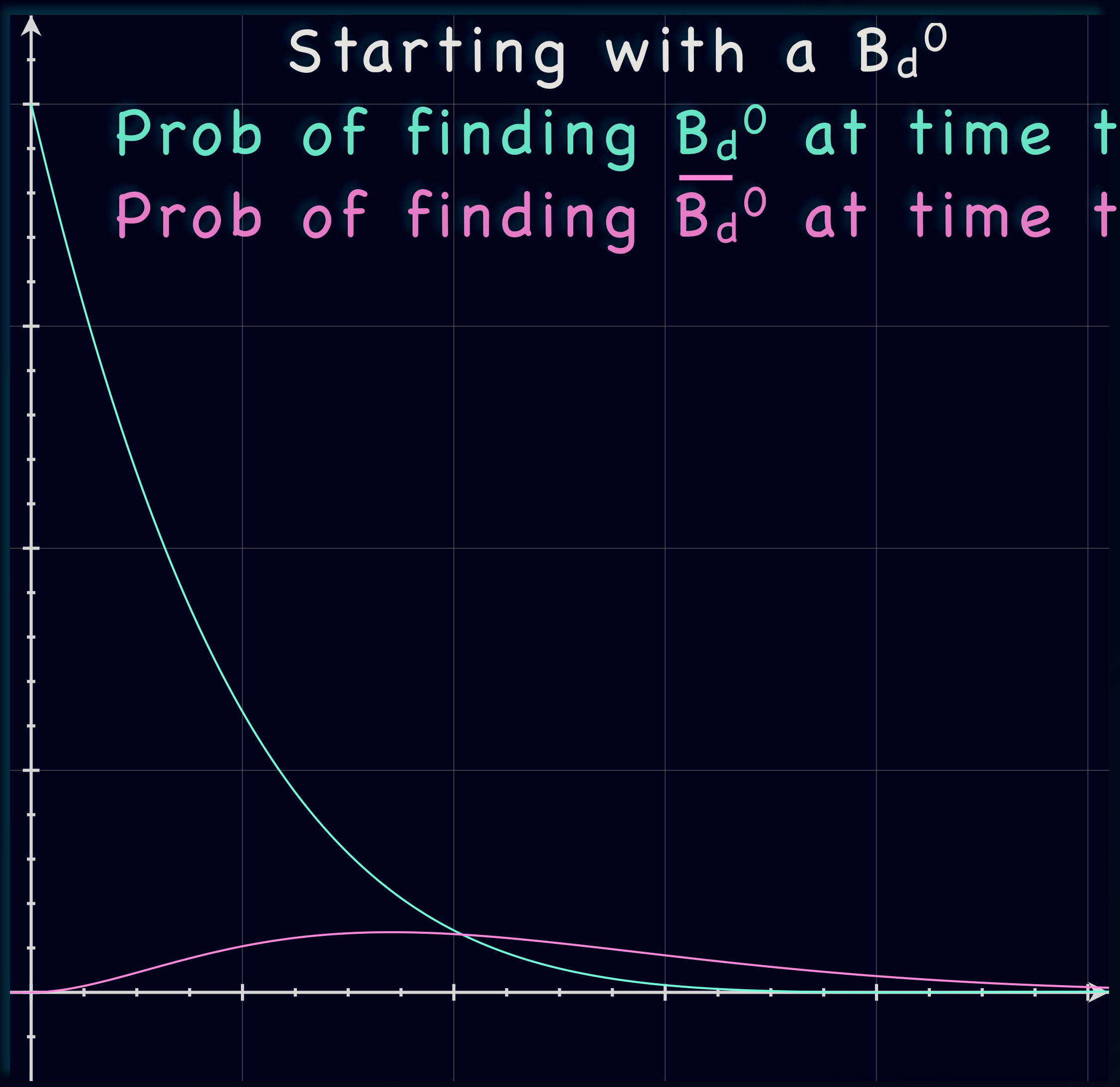


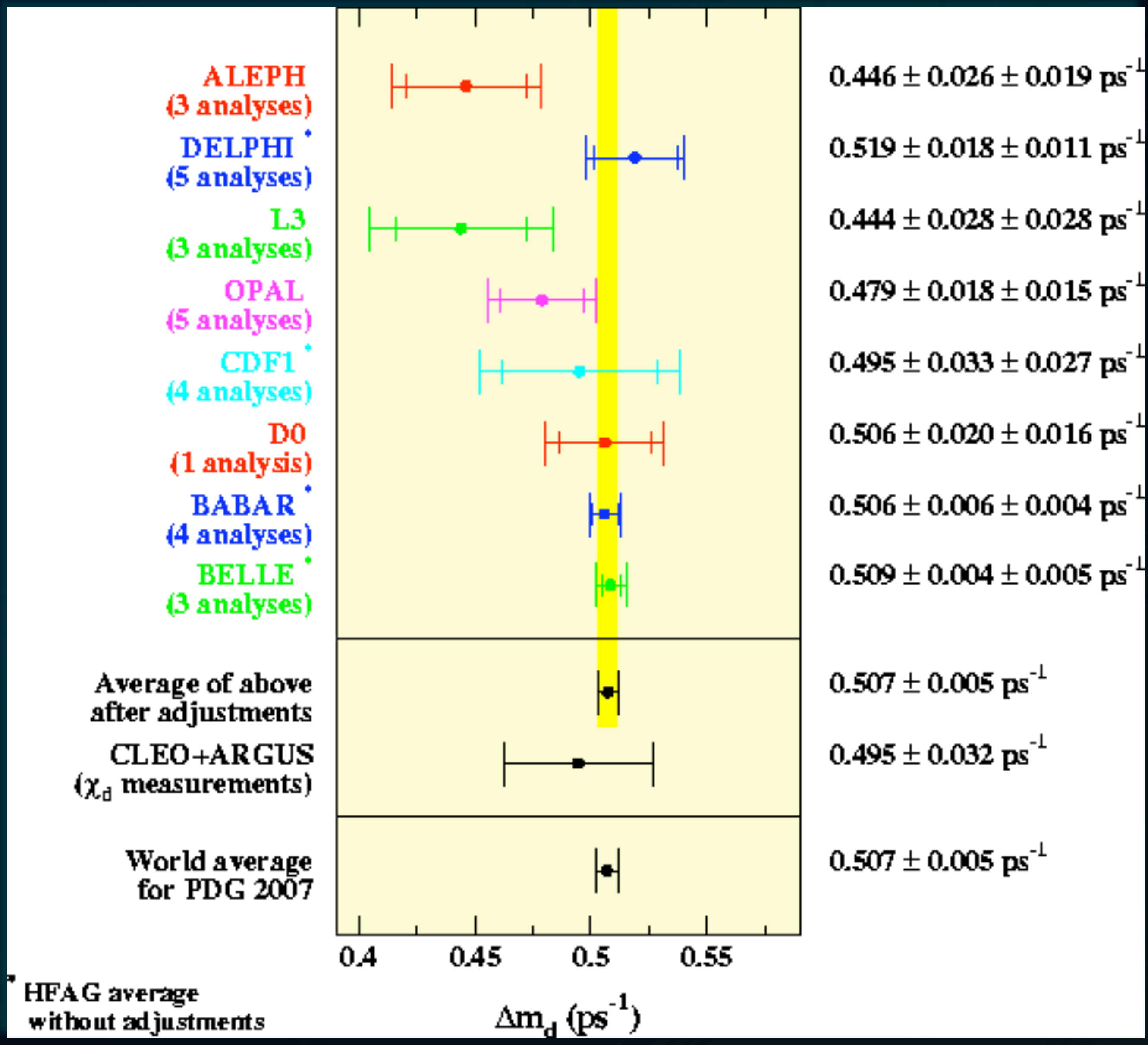


CP LEAR (2000)

- First signal of meson mixing
- y = 0.997 > x = 0.474
  - Relatively large lifetime difference (K_S, K_L)

B_d Mixing

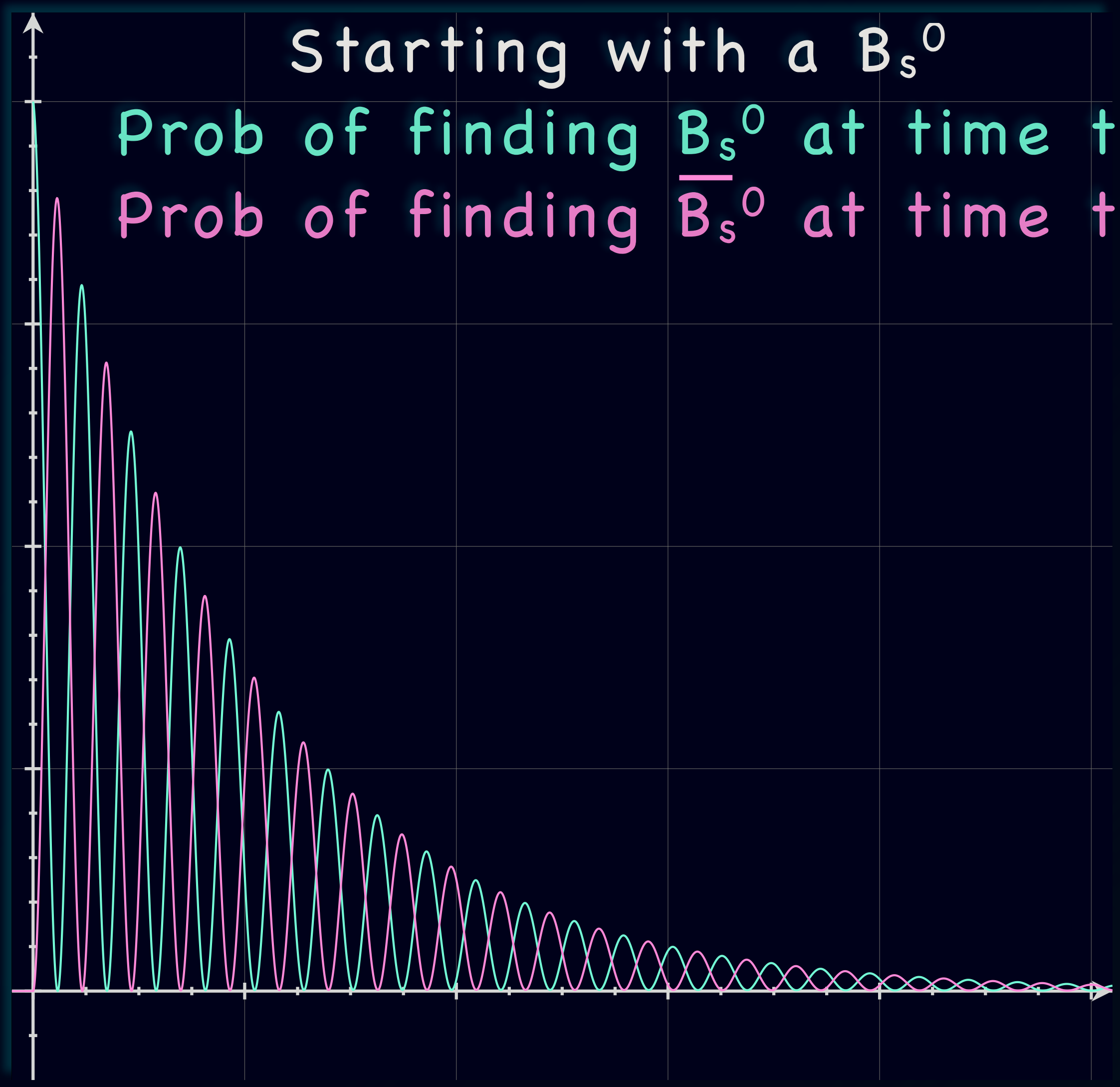


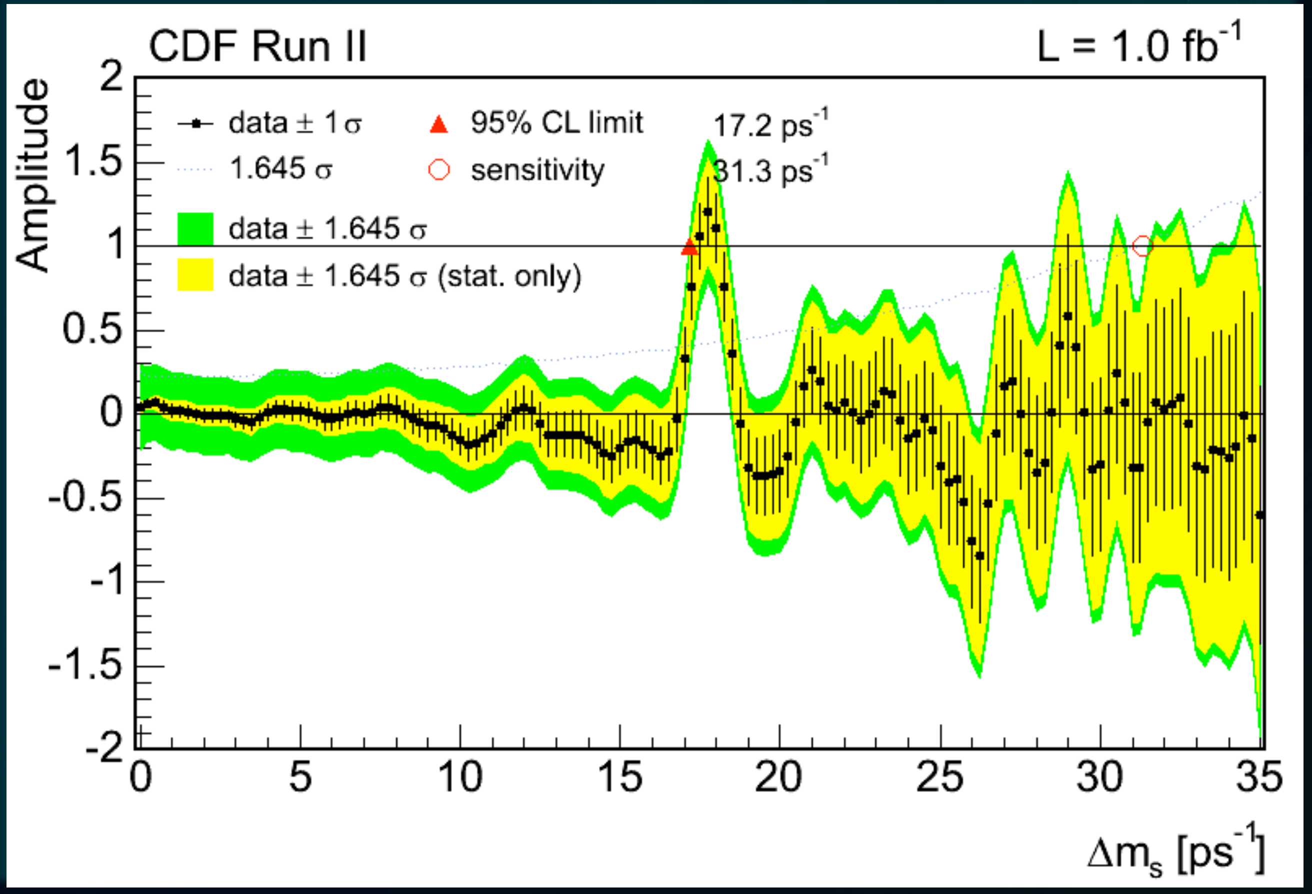


Published results up to March 2007

- $x = 0.77$, $y = 0.009$

B_s Mixing



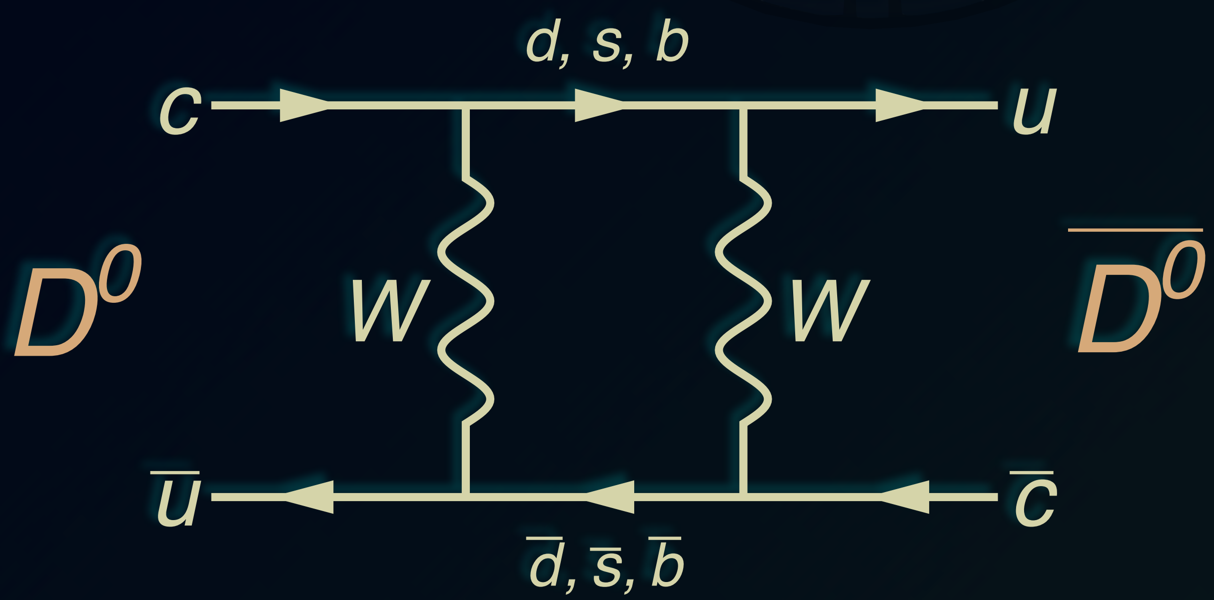


First Observation of B_s mixing

- $x \gg y$
  - $x = 25$, $y = 0.1$
    - (world average as of March 2007)

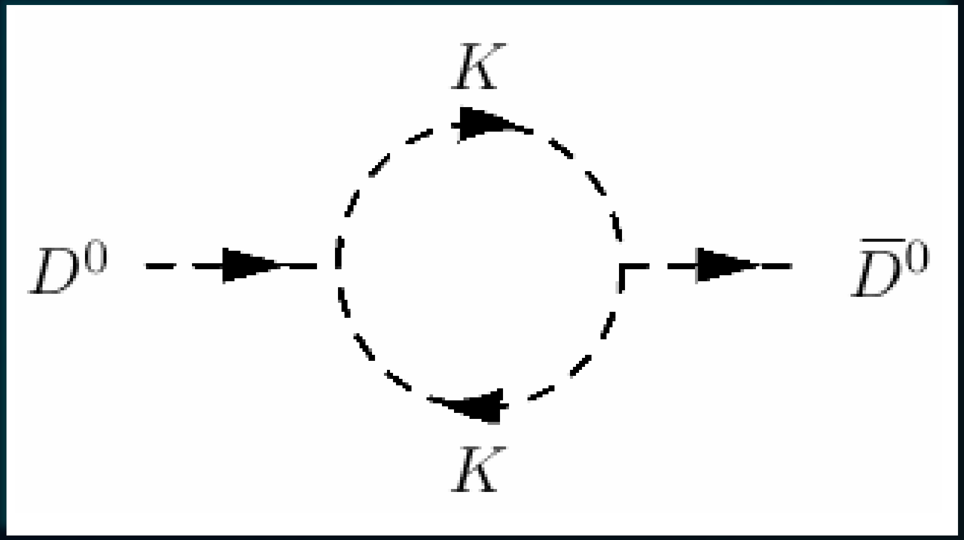
Calculating Mixing

- Kaon and Beauty mixing due to contributions from the box diagrams
  - superheavy quarks (i.e. top) destroying GIM cancellations
- For charm, the contributions are small
  - $O(10^{-5})$ or less
  - down-type quarks (no top)



Calculating Mixing

- Long-distance contributions are important for charm mixing
  - $O(10^{-2})$ or less
  - hadronic intermediate states like KK or $\pi\pi$
  - harder to get exact prediction
    - non-perturbative
    - model dependent



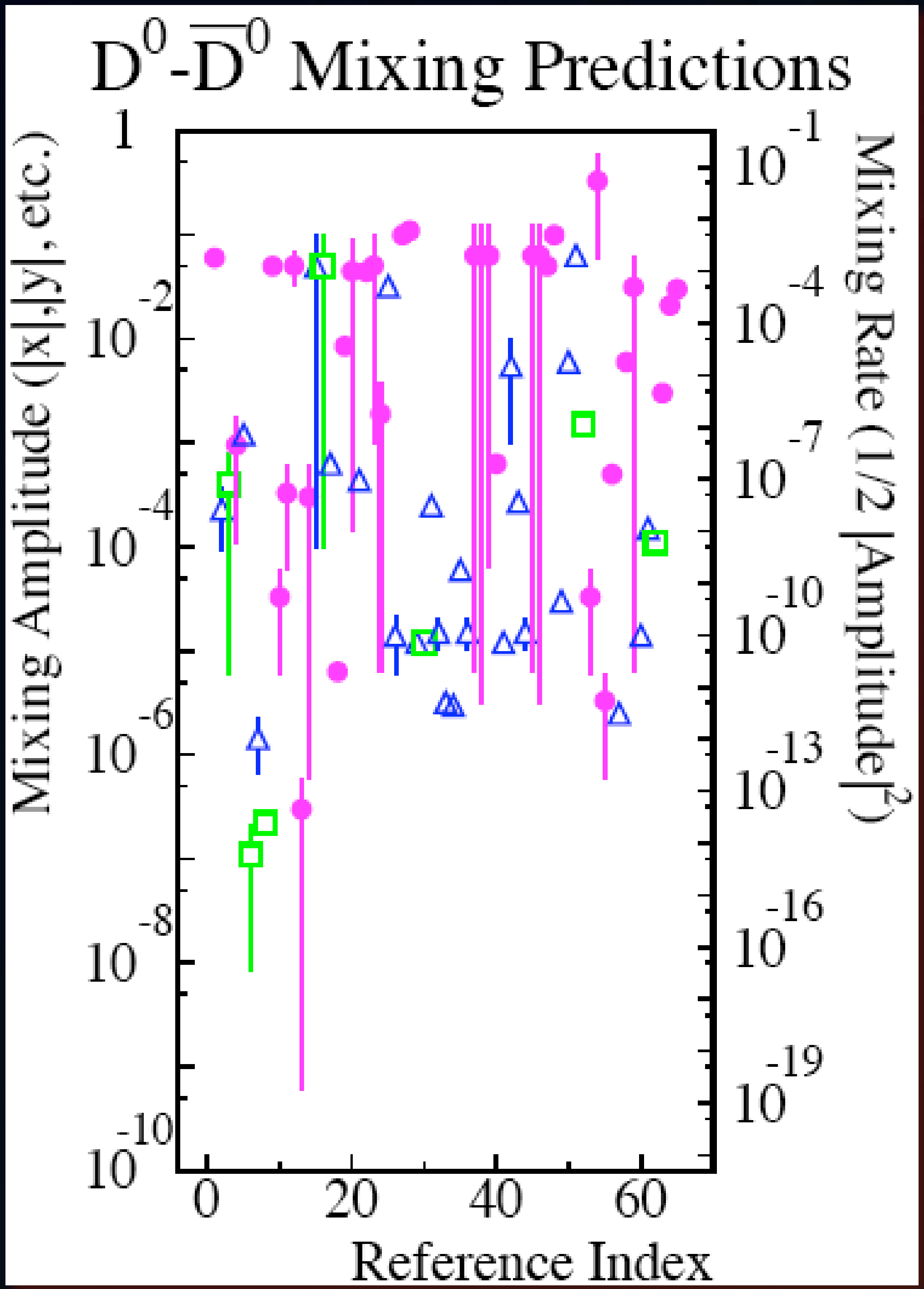
Predictions

△ : standard model prediction for x

□ : standard model prediction for y

• : new physics prediction for x

Horizontal axis uses references from: Nelson HN. in *Proc. 19th Int. Symp. Photon and Lepton Interactions at High Energy LP99*, ed. JA Jaros, ME Peskin, hep-ex/9908021

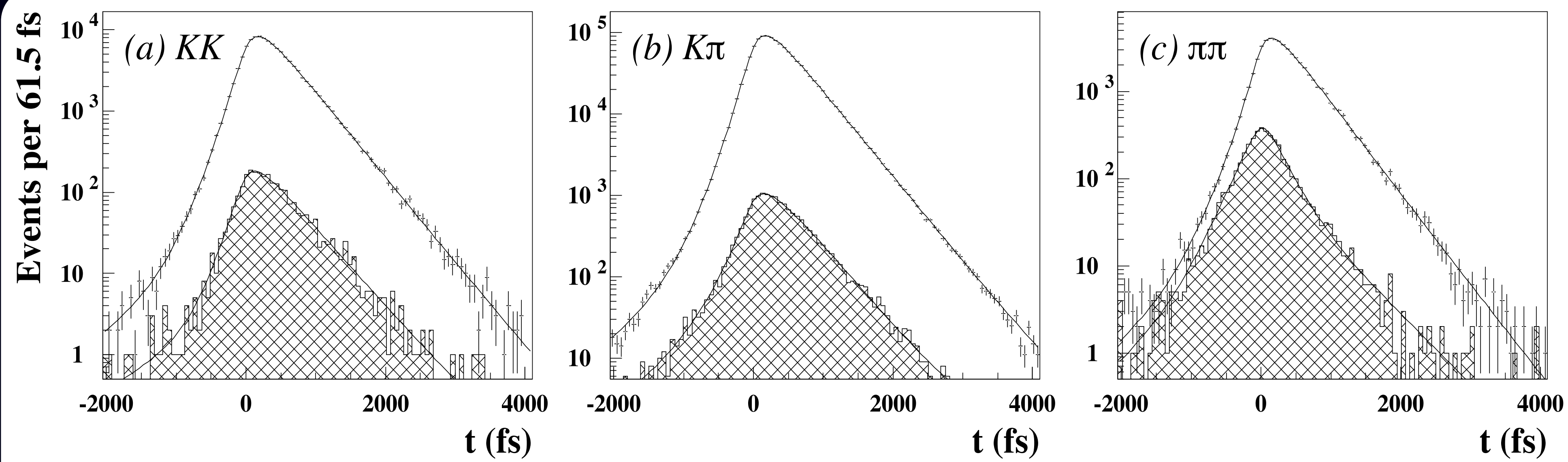


- The graph is dated (1999), but gives an idea of the range of possible predictions

Simplified History

- If charm mixing was observed with *x,y* much larger than SM predictions would be a sign of new physics
  - In recent years, the experimental upper limit for *x,y* was reduced to $O(10^{-2})$
- First evidence for charm mixing announced by BaBar and Belle at Moriond in March 2007
  - Surprising, since $|x|$, $|y| \approx 1\%$, upper edge of current SM predictions

Belle Evidence



τ = **404.0 ± 2.2 fs** (110k events)

τ = **408.7 ± 0.6 fs** (1200k events)

τ = **402.8 ± 3.3 fs** (50k events)

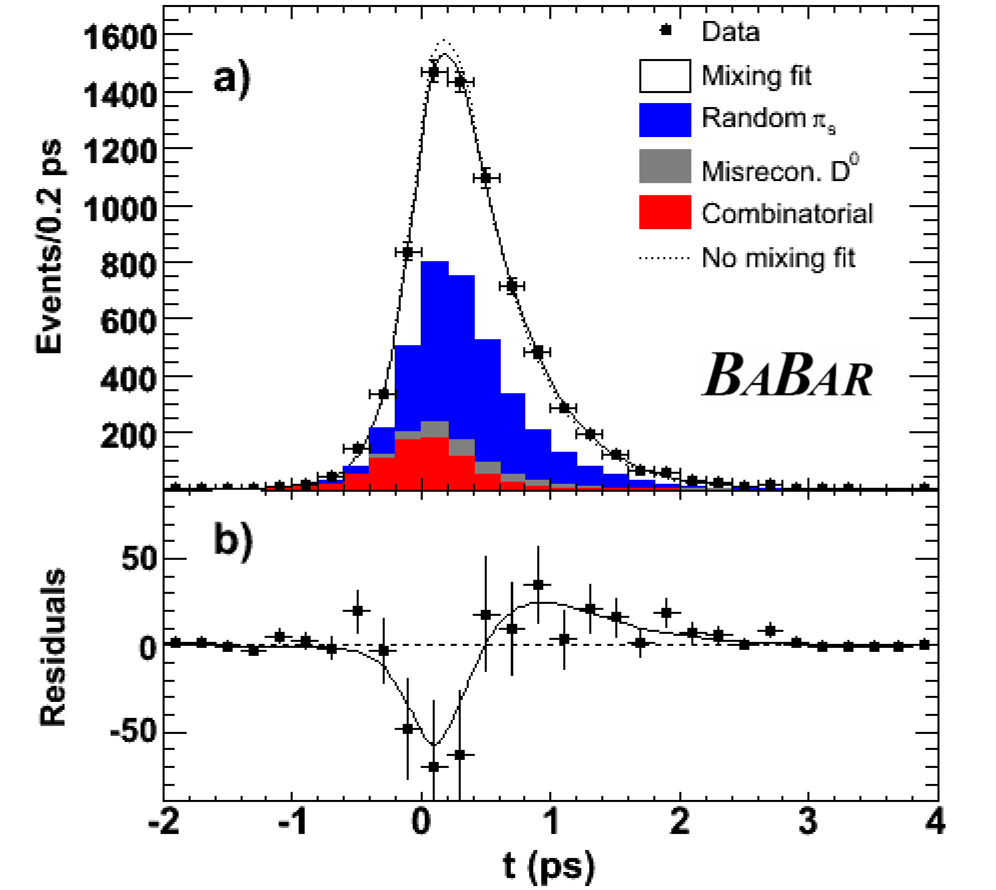
⇒ **there is a difference between *KK* and *K*π**

(here, t0 is free for each final state)

- Belle: Lifetime differences for $D^0 \rightarrow K\pi, KK, \pi\pi$
  - Phys. Rev. Lett. **98**, 211803 (2007)
  - Confirmation by BaBar in December
    - (preliminary) arXiv:0712.2249

BaBar Evidence

- BaBar: Different time-dependence for $D^0 \rightarrow K^+\pi^-, K^-\pi^+$
  - Phys. Rev. Lett. **98**, 211802 (2007)
- CDF result shown today uses a similar measurement
  - 1st confirmation of the BaBar result
  - Belle's analysis for this mode is (in)consistent with BaBar at 2σ level

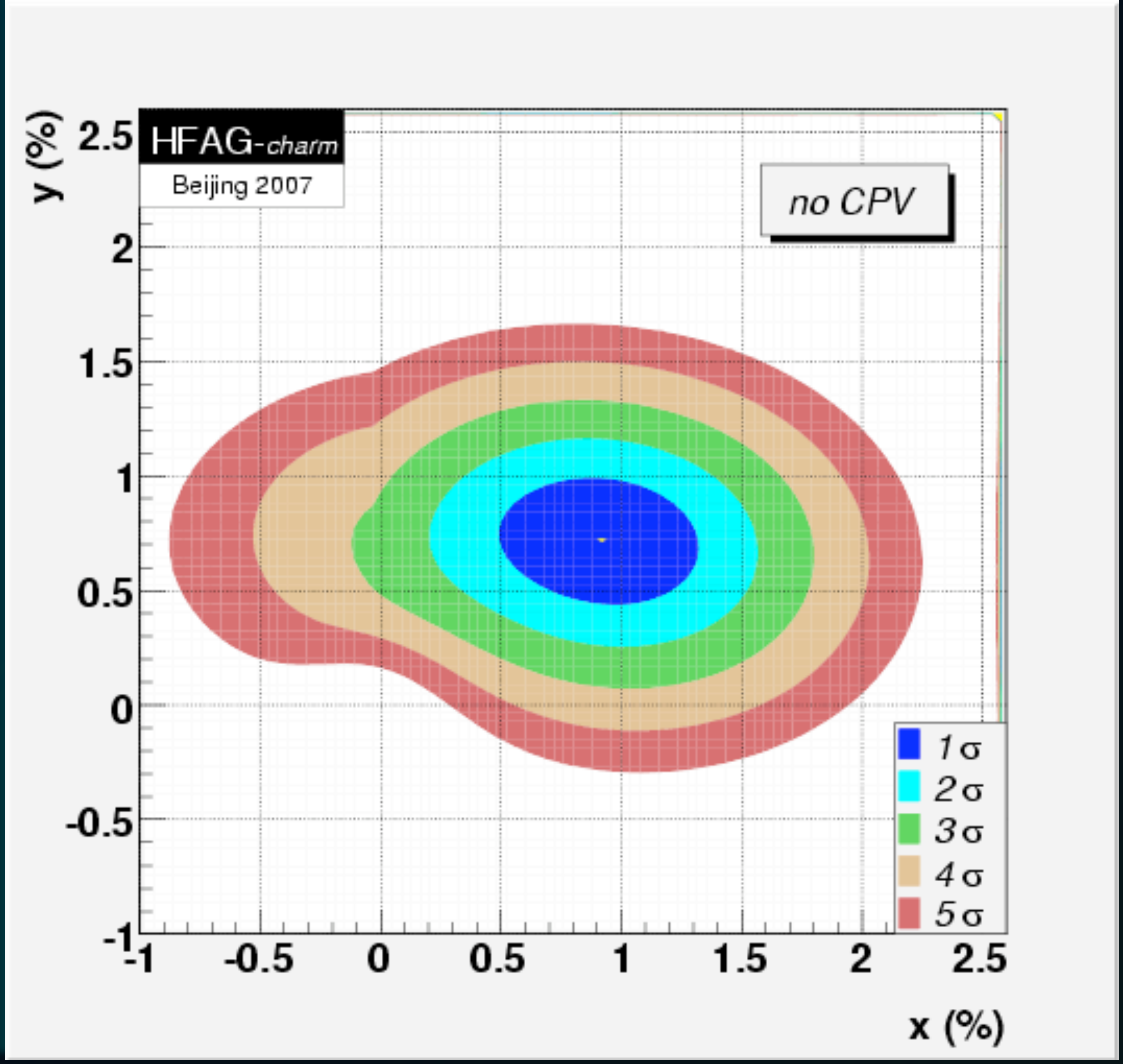


WS *mixing* fit projection in signal region

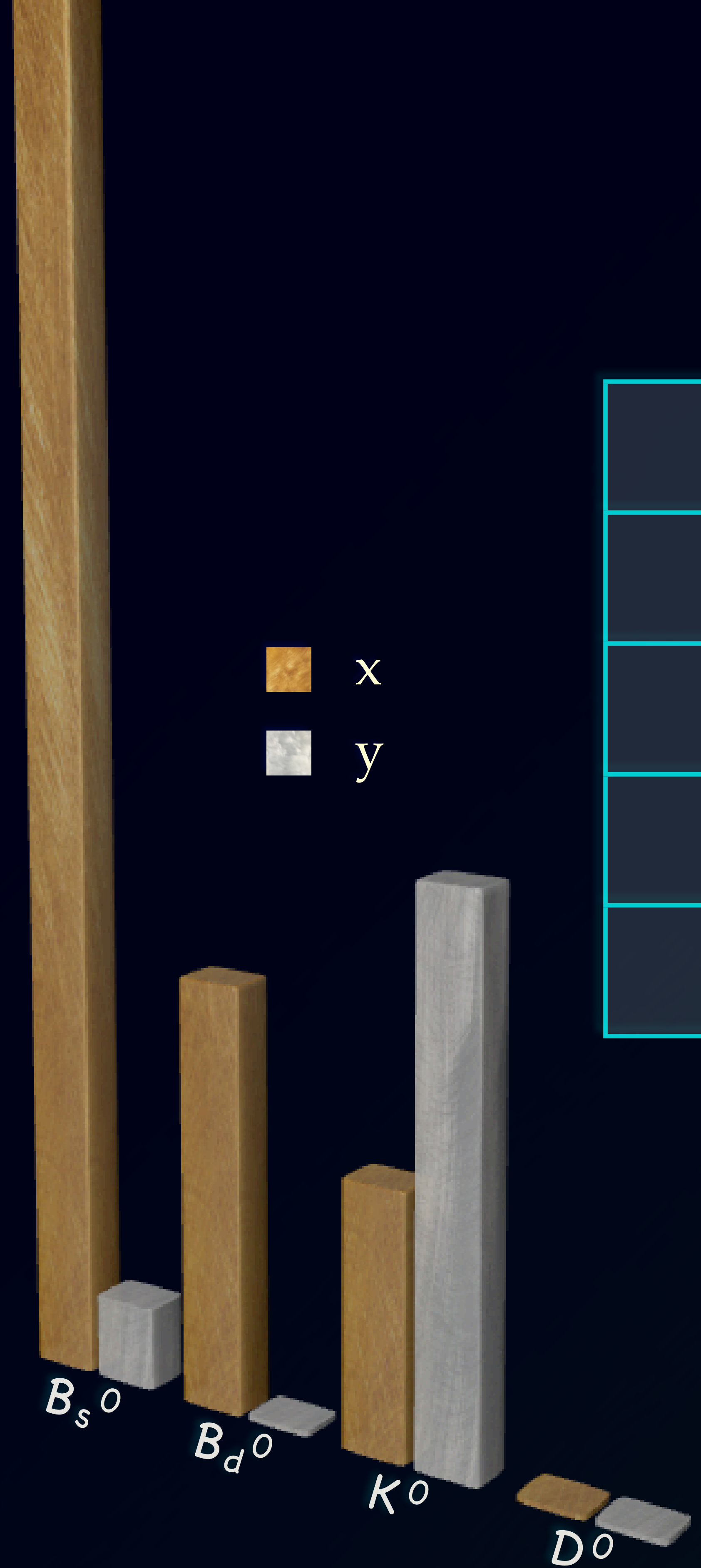
If there was no mixing, residual points would all be at zero

Charm Mix Measurements

- Other charm mixing measurements are 1-2 σ in significance
  - Semi-leptonic decays, multi-pion hadronic decays, Dalitz plots
  - Alan Schwartz's seminar from 4/27/07 is a good overview
  - Combining all measurements excludes no-mixing at > 5σ



Mixing



Mixing	x	y
$B_s{}^0$ - $\overline{B}_s{}^0$	25	0.10
B^0 - $\overline{B}^0$	0.77	0.01
K^0 - $\overline{K}^0$	0.474	0.997
D^0 - $\overline{D}^0$	0.010	0.008

charm x,y taken from the HFAG web page, using all charm mixing measurements

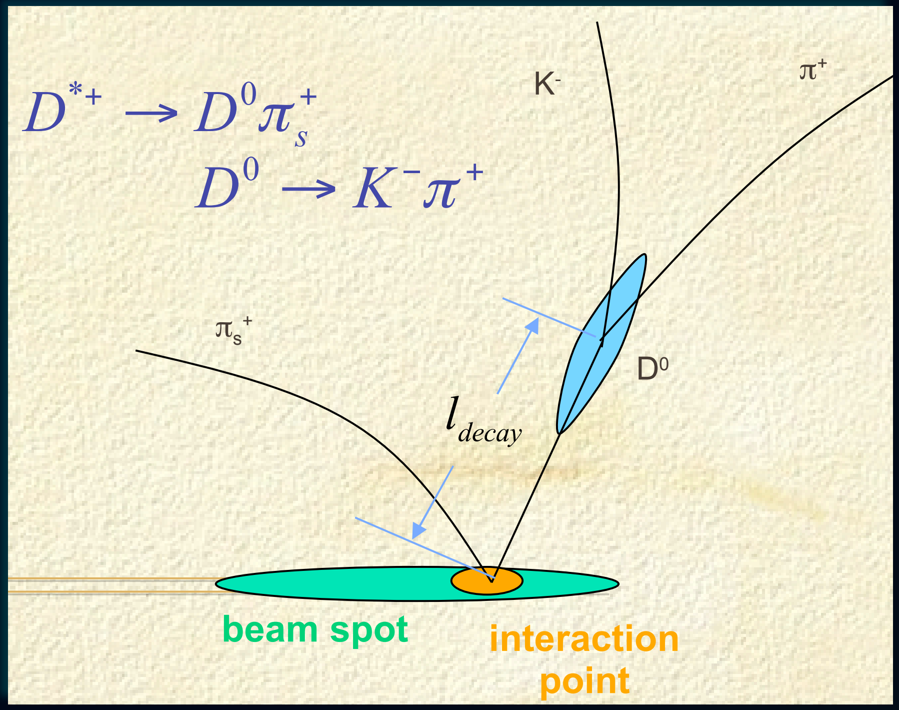
Theory & Exp.

- More theoretical papers inspired by recent results
  - I will use the conclusions from Golowich, Hewett, Pakvasa, and Petrov, *"Implications of D^0-$\overline{D}^0$ Mixing for New Physics"*, Phys. Rev. D76:095009, 2007
- Estimates of x_D and y_D have significant uncertainties (experimental and theoretical)
- Large CP violation ➜ New Physics
  - All results so far consistent with no CP violation
- Current results can still place restrictions on New Physics and SM (long-distance) models

Charm Mixing with $D^* \rightarrow \pi_s D^0$, $D^0 \rightarrow K\pi$

Advantages of D^*

- To measure charm mixing, we need:
  - Proper decay time for time evolution
  - Identify charm at production
  - Identify charm at decay

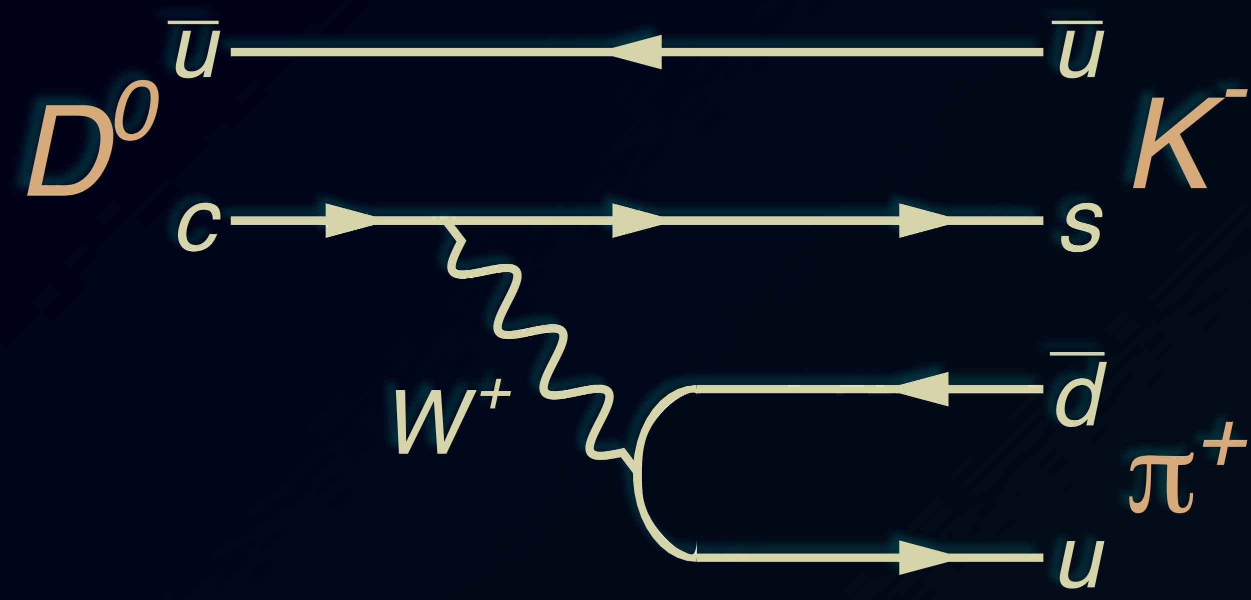


- $D^* \rightarrow \pi_s D^0$, with $D^0 \rightarrow K\pi$
  - Measure decay length from primary vertex
    - D^* decays strongly
  - $\pi_s^+ \longmapsto D^0$
    $\pi_s^- \longmapsto \overline{D}^0$
  - $K^+\pi^-$ or $K^-\pi^+$

"s" stands for softer momentum

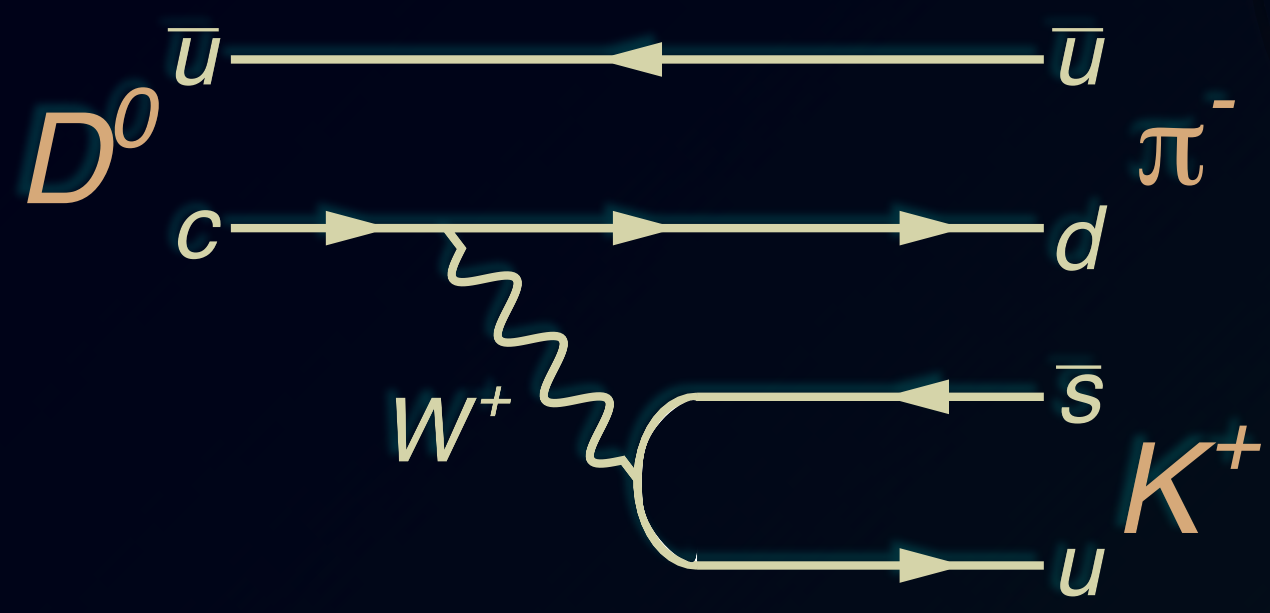
Requiring a D* also improves signal:background

Lingo: "Right-sign"

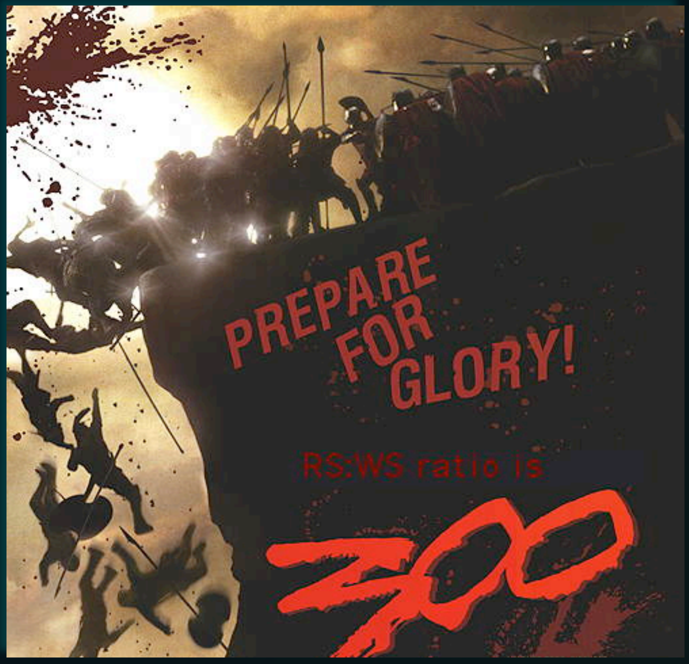


- "Right-Sign" events have pions with the same charge
  - $D^{*+} \rightarrow \pi_s^+ \quad \pi^+ K^-$
  - Cabibbo favored (CF) D0 decay

Lingo: "Wrong-sign"



- "Wrong-Sign" events have pions with opposite charge
  - $D^{*+} \rightarrow \pi_s^+ \pi^- K^+$
  - Doubly Cabibbo suppressed (DCS) decays
  - Mixing: $D0 \Leftrightarrow \overline{D}0$, followed by CF decay
- RS:WS roughly 300:1



Decay Rate Ratio

- With x, $y \ll 1$ and assuming no CP violation, the ratio of WS to RS events is

$$R(t/\tau) = R_D + \sqrt{R_D}\, y' \,(t/\tau) + \frac{x'^2 + y'^2}{4} (t/\tau)^2$$

DCS to CF ratio

Mixing

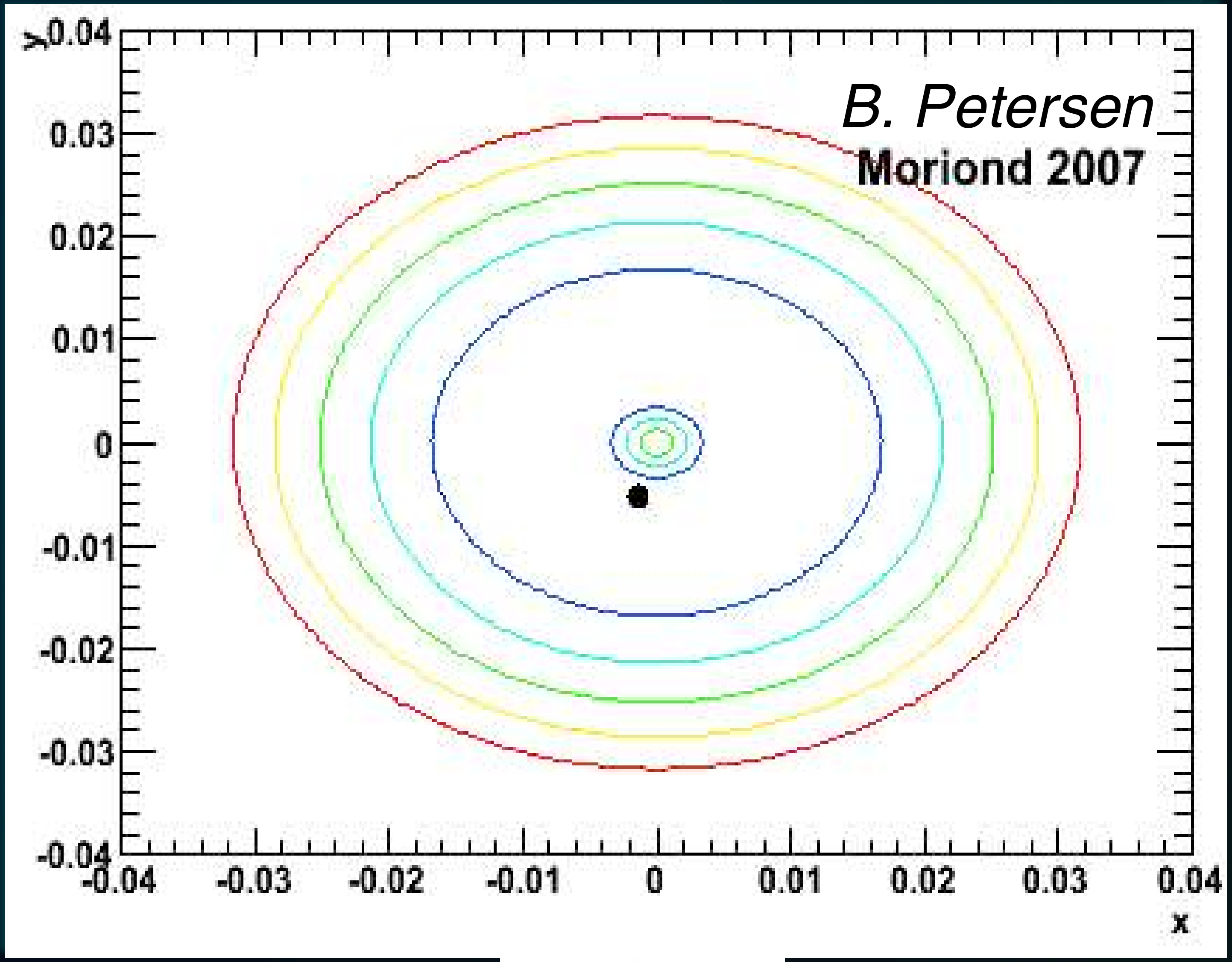
- Formula uses x′, y′ instead of x, y

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

  - Strong phase difference $\delta_{K\pi}$ between CF and DCS amplitudes

x,y and x', y'

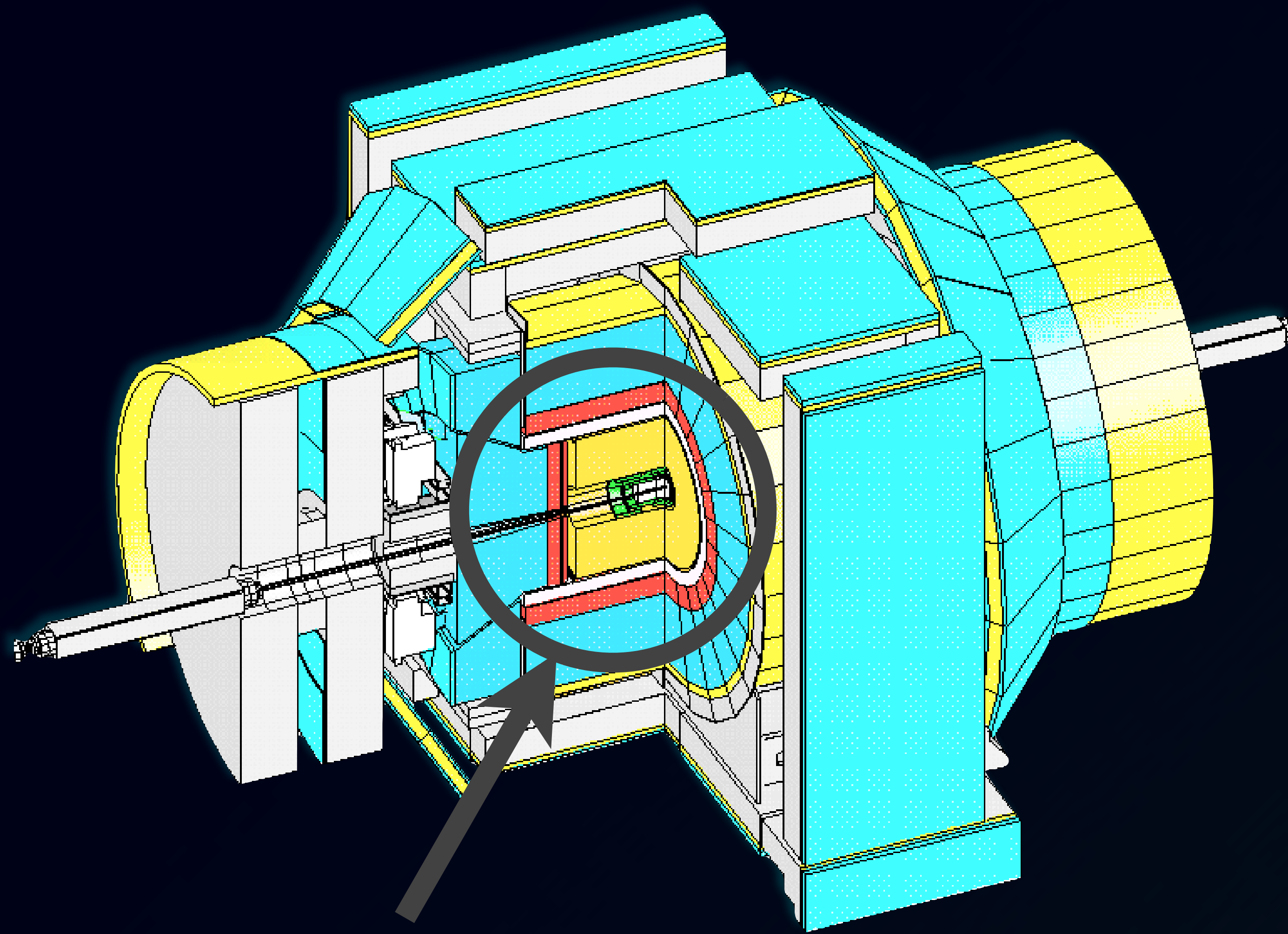
- Although the strong phase cannot be known from Kπ decays alone, the amplitude of the mixing parameters x,y can be constrained
  - $x^2 + y^2 = x'^2 + y'^2$

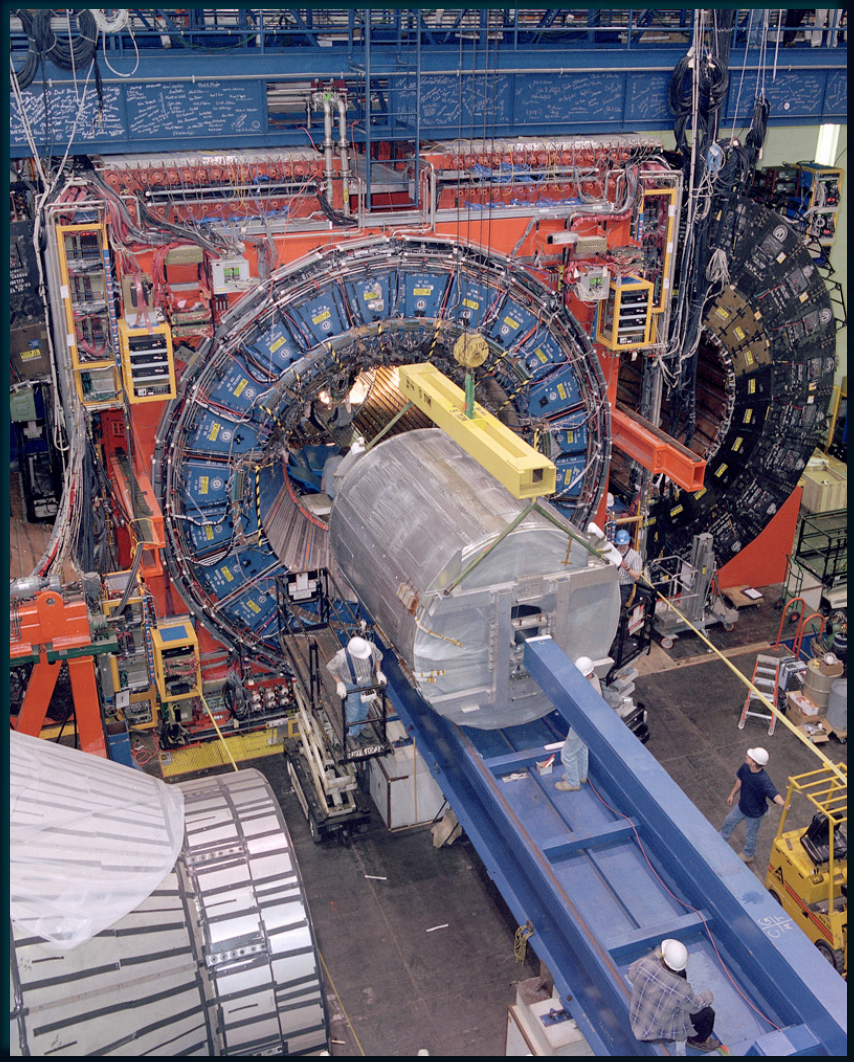


$-2 \ln \mathcal{L}$

CDF Event Selection

CDF II Detector





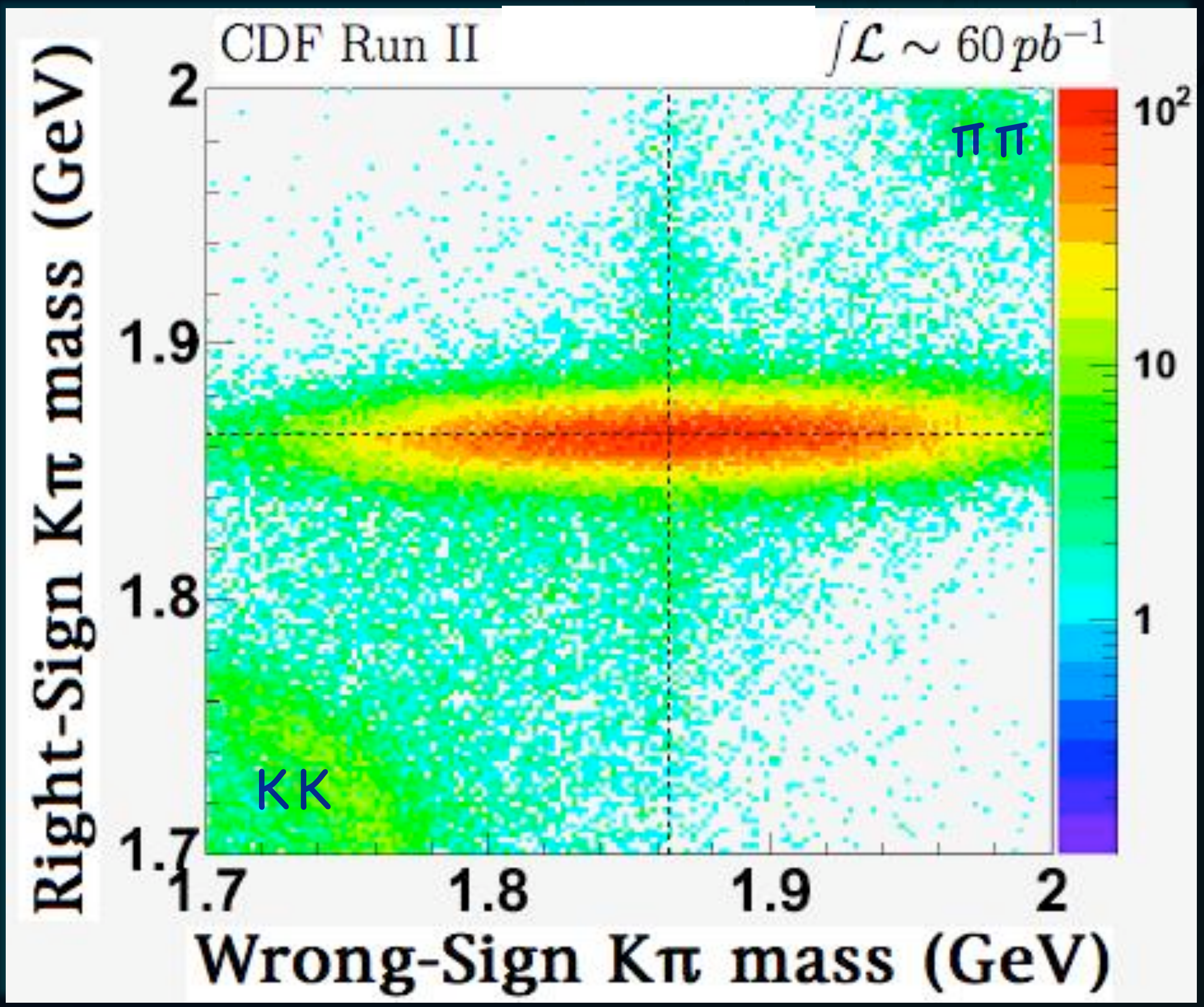
- This analysis uses charged particle track reconstruction
  - silicon detectors
  - central outer tracker (multi-wire drift chamber)
  - 1.4 T magnet

CDF Data

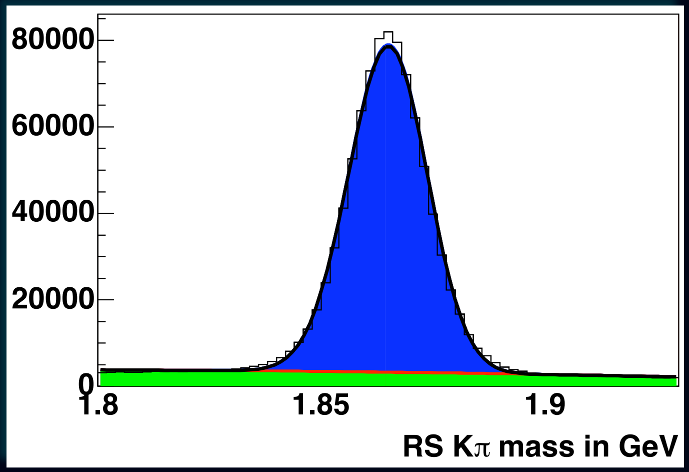
- Data collected from Feb 2002 -Jan 2007
- $\int L \approx 1.5\ fb^{-1}$ at $\sqrt{s} = 1.96$ TeV
- "Two-Track Trigger"
  - Optimized for *B* decays, but has good charm acceptance
  - tracks consistent with a displaced vertex
  - good acceptance for proper decay times > 0.5 D^0 lifetimes
- The trigger tracks are used to form $D^0 \rightarrow K\pi$ candidate
- Additional softer momentum track found off-line and added to form $D^{*+} \rightarrow \pi_s^+ D^0$ candidate

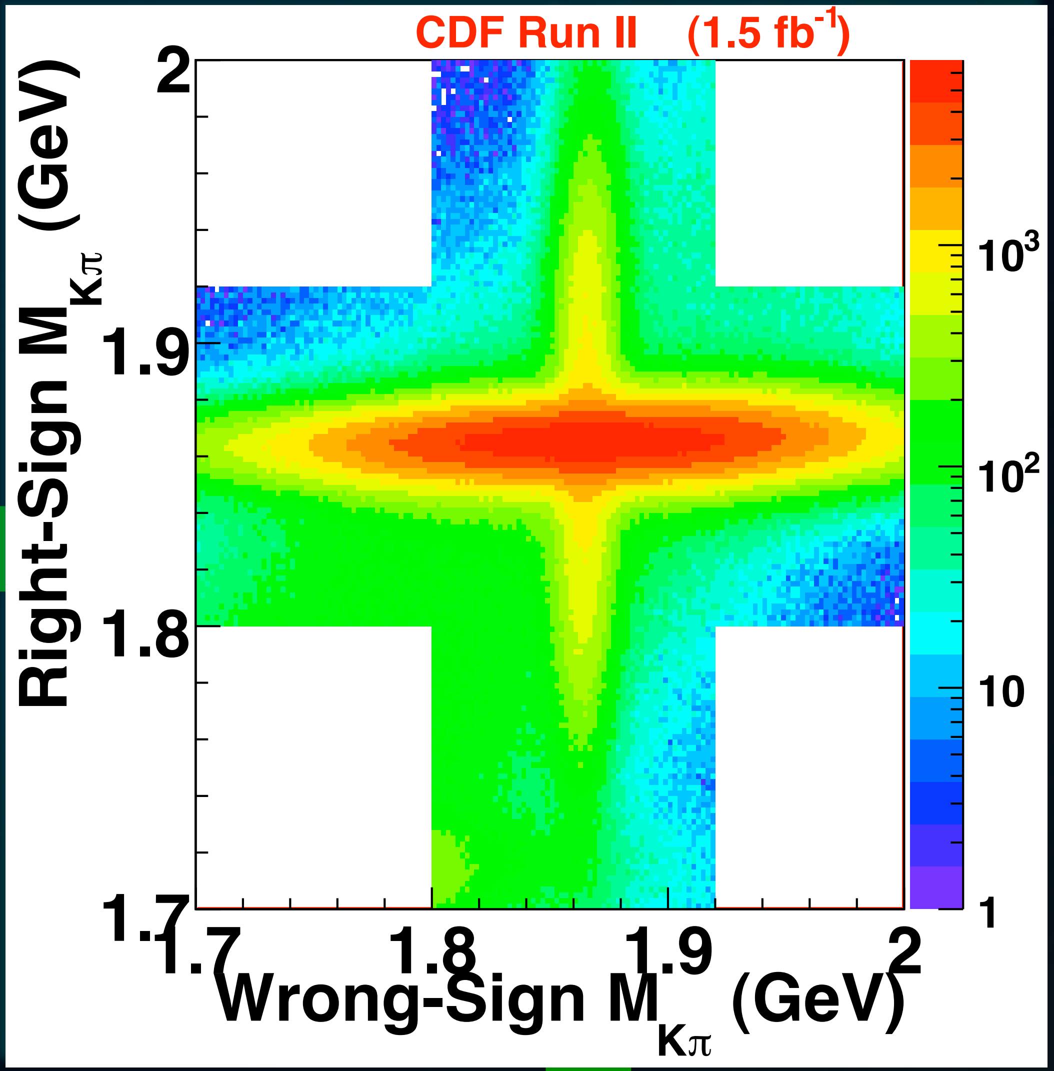
RS and WS Data

- D^0 candidate considered with both $K\pi$ and πK particle assignments
- limit mass range to $1.8 < m_{K\pi} < 1.92$ GeV / c^2
  - Excludes $D^0 \rightarrow KK, \pi\pi$



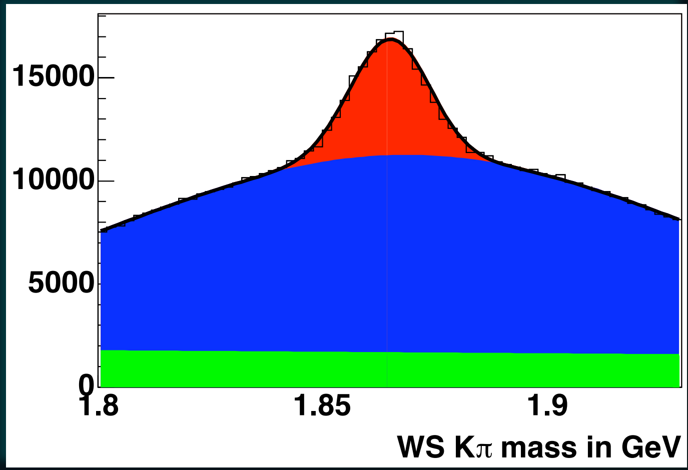
RS and WS Data





Blue events are CF (RS) D* decays

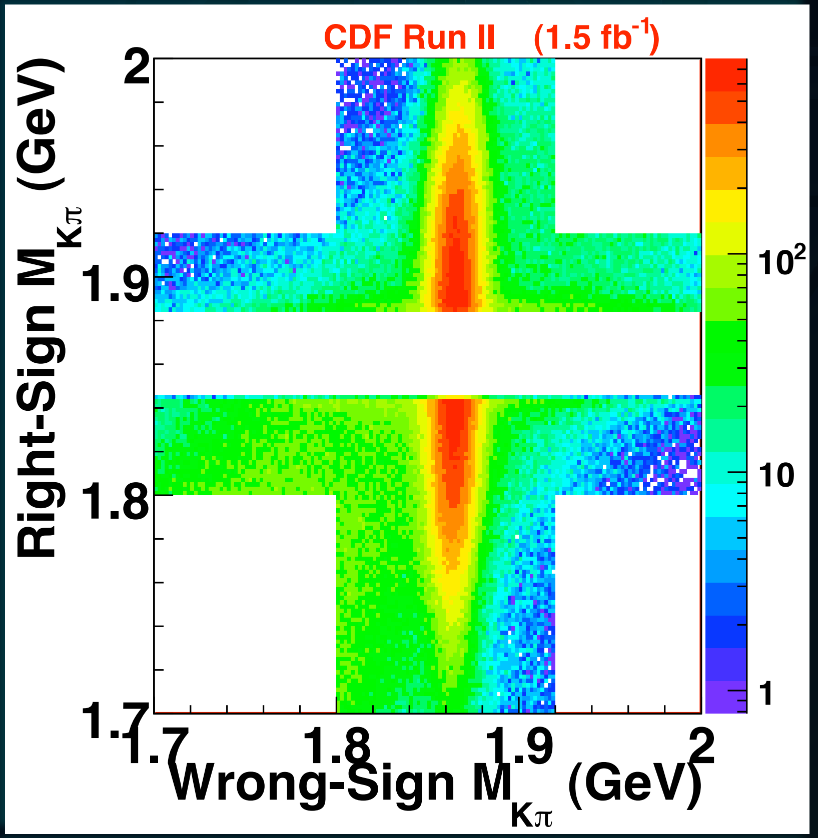
Red events are WS D*, and background from fake D* (D^0 + random track)

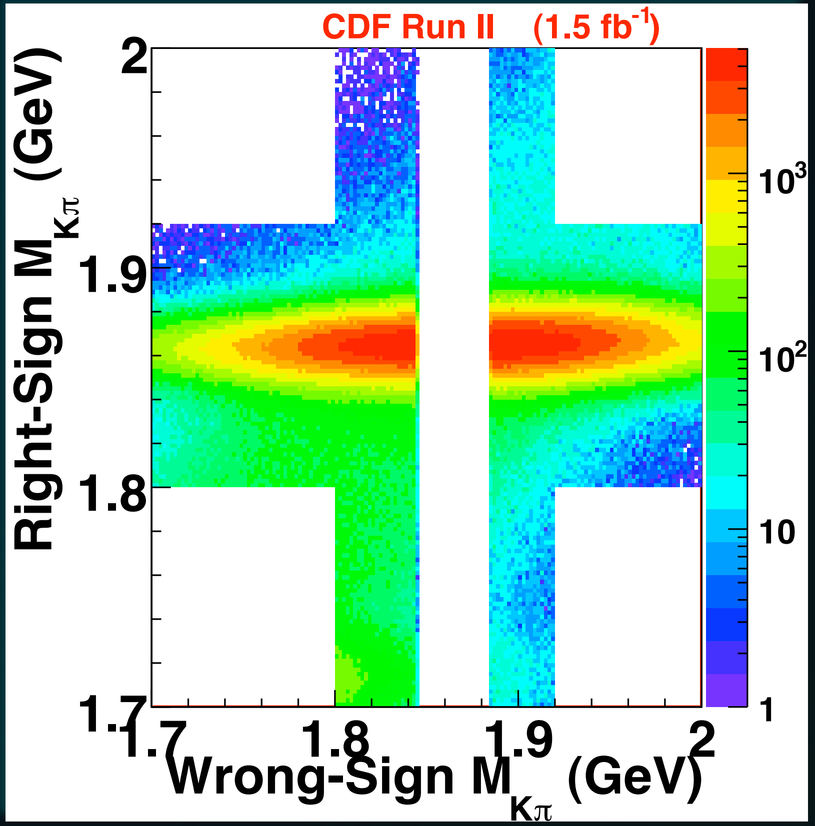


- Problem: Huge number of CF D^0 (RS) events can mask WS signal

WS, RS Selection

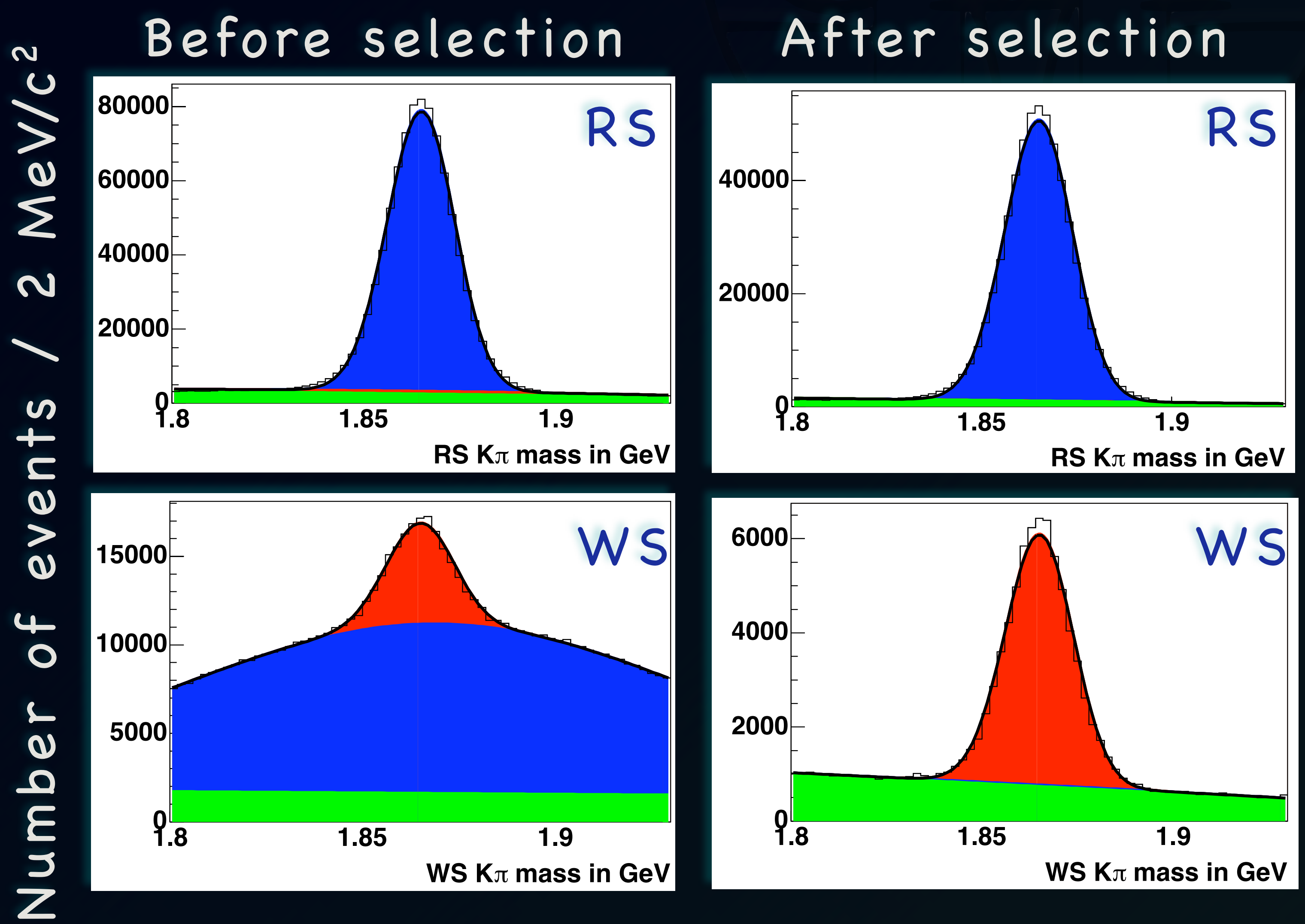
- When projecting the WS mass, exclude candidates with RS mass $|m_{K\pi} - m_{D0}| < 20$ MeV
  - Complementary selection for RS mass
  - Keeps 78% of signal, 3.6% mis-assigned
- Energy loss (dE/dx) measured in the COT allows particle identification
  - Compare two-track PID probability for $K\pi$ and πK assignments, use higher value





Mis-Assigned Clean-up

- Mass and PID cuts greatly clean up the CF D* background in the WS mass plots



Blue events are CF (RS) D* decays

Red events are WS D*, and background from fake D* (D⁰ + random track)

Analysis Method

Analysis Evolution

- Goal: Measure a small ratio, and then a small time-dependent variation of that ratio

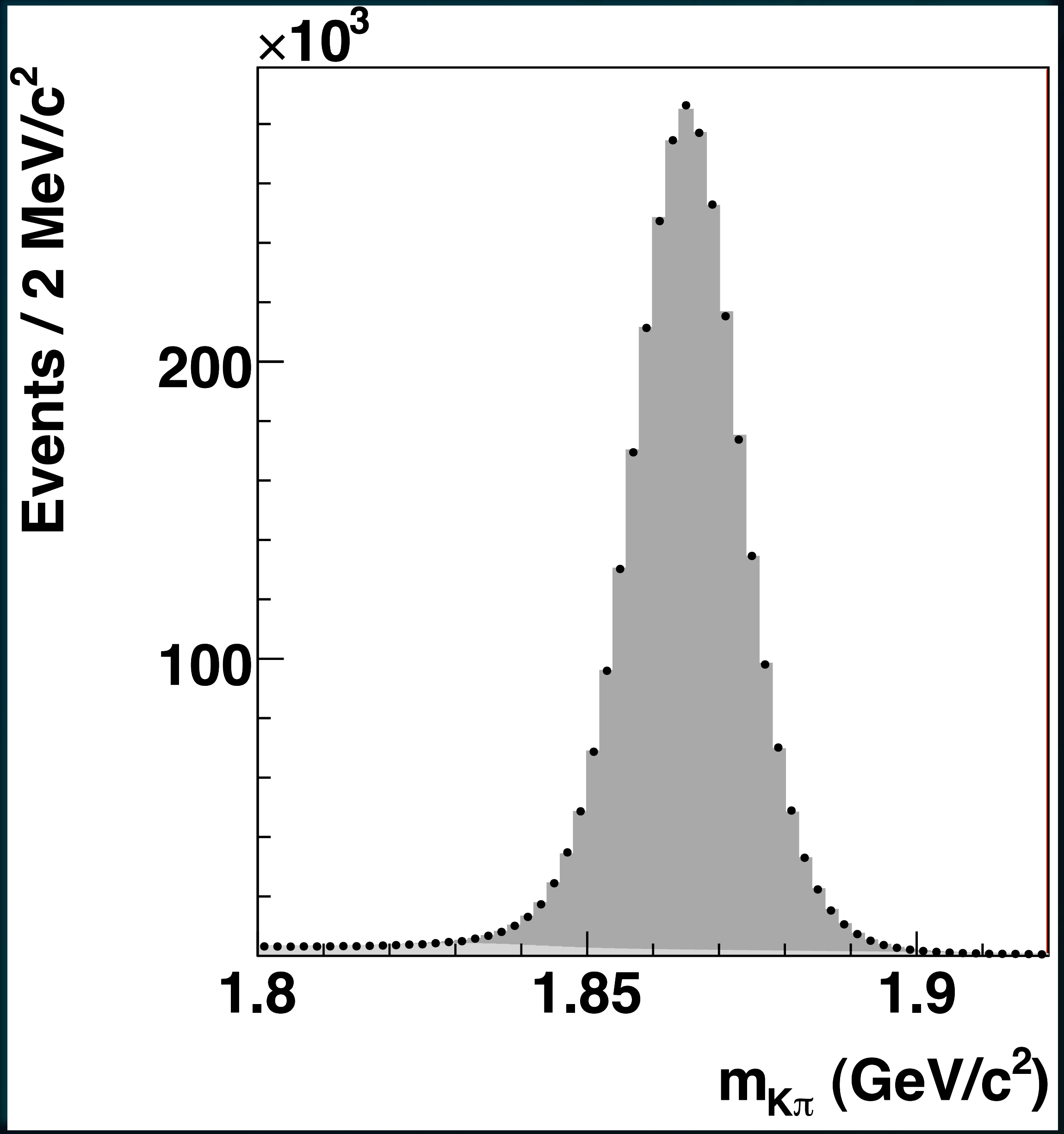
$$R(t/\tau) = R_D + \sqrt{R_D}\, y'\, (t/\tau) + \frac{x'^2 + y'^2}{4} (t/\tau)^2$$

- First step was to try the time-independent fit
  - assuming no mixing ($y'=x'=0$), $R = R_D$
  - Published in PRD RC 74, 031109 (2006)

Clean RS Signal

- WS signal blinded during development of analysis method and cut optimization
  - scaled RS signal acts as substitute
- Signal PDFs obtained from fits of the CF D* events
  - WS signal events have the same distribution shapes as RS except for decay time

CDF Run II (1.5/fb)



3.3×10^6 time integrated RS D^0

General Points

- Including charge conjugate decays (D^{*+} and D^{*-} combined)
  - simplifies some systematic errors in the ratio
- Events with decay times from 0.75-10 D^0 lifetimes
  - Trigger acceptance is low for shorter decay times
  - Few events at long decay times (exponential decay)
- Sequence of binned, least-chisquare fits
  - signal yields from one set of fits used as input for next fits
  - simplifies treatment of backgrounds

Stage 1: Division

- Divide the data into bins of...
  - decay time measured from primary vertex
  - RS or WS
  - d_0 - impact parameter
  - Δm - mass difference
  - $m_{K\pi}$

Start here

Finish here

20 decay time bins	Fit R(t) to determine mixing parameters
Divide events into RS and WS	Ratio R for each time bin
Two d_0 bins: $\leq 60\ \mu m$, $>60\ \mu m$	Prompt or from B-decay
60 bins Δm ($D^* - D^0 - \pi$)	D^* or not D^*
$K\pi$ mass distribution	D^0 or not D^0

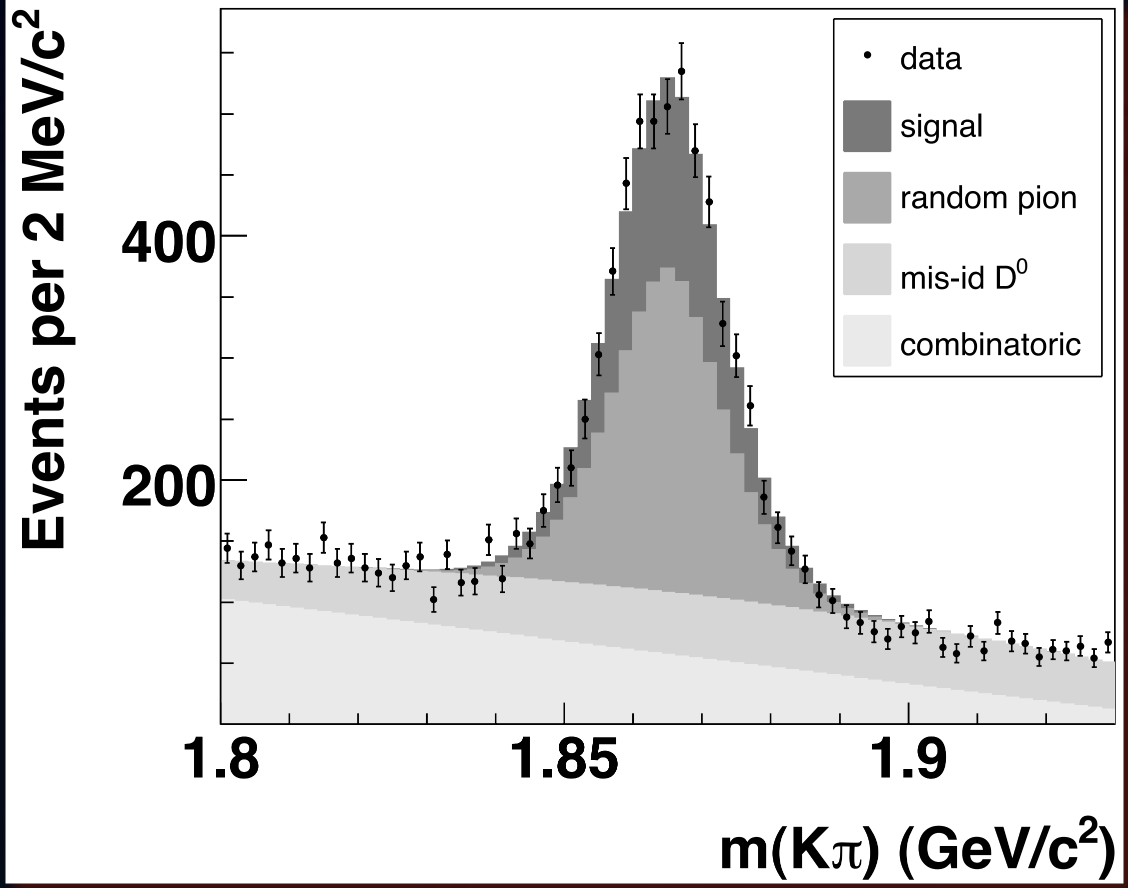
This variable is used...

... to distinguish this signal from this background

Stage 2: Kπ

Start | Finish

20 decay time bins	Fit R(t) to determine mixing parameters
Divide events into RS and WS	Ratio R for each time bin
Two d_0 bins: $\leq 60\ \mu m$, $>60\ \mu m$	Prompt or from B-decay
60 bins Δm ($D^* - D^0 - \pi$)	D^* or not D^*
Kπ mass distribution	D^0 or not D^0



Projection of WS D^0 fit results with 0.35 fb-1, to illustrate relative amounts of signal and background

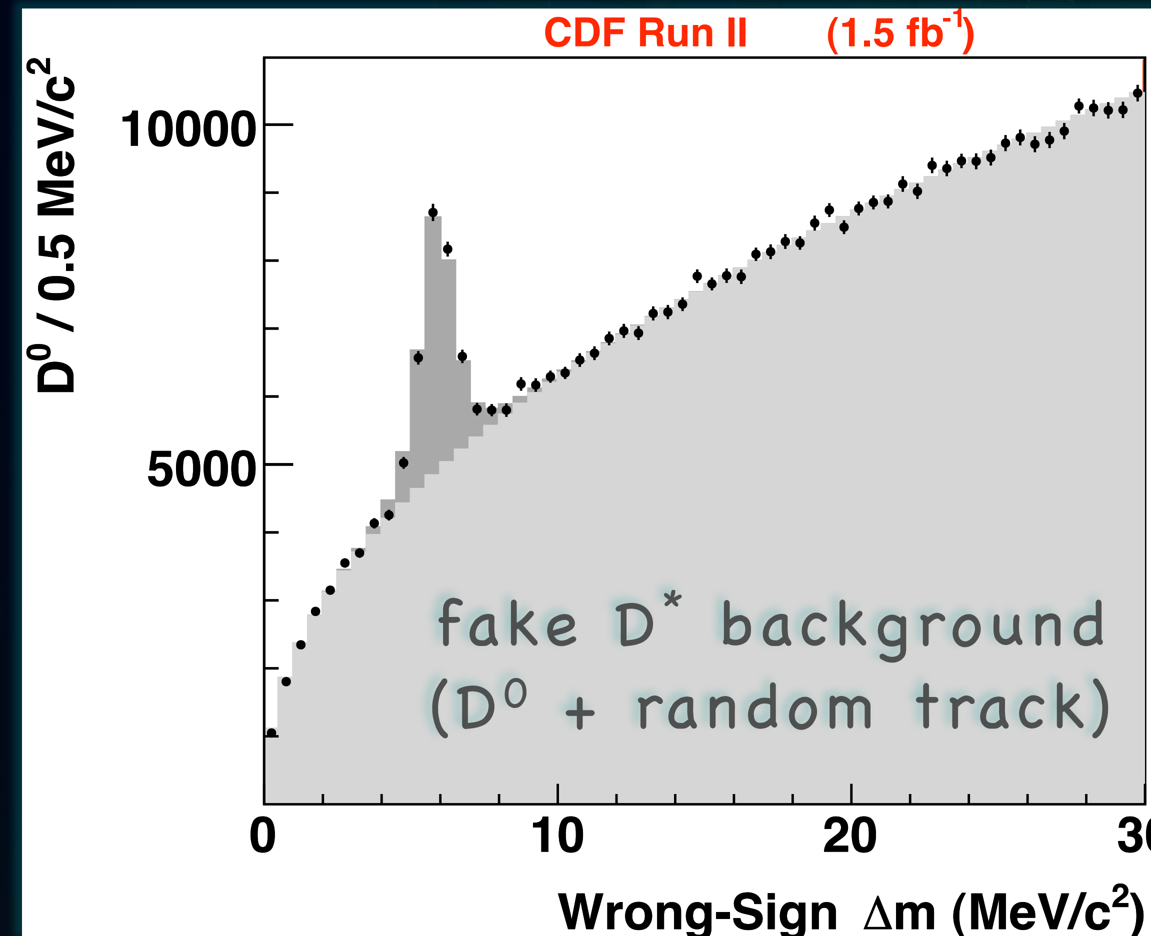
- Fit for D^0 yields
  - 4800 distributions of m(Kπ)
- Single signal shape used for all fits
- Parameters for background independent for all fits
- Typical χ^2/dof for these fits = 1.0

Stage 3: Mass Diff.

Start — Finish

20 decay time bins	Fit R(t) to determine mixing parameters
Divide events into RS and WS	Ratio R for each time bin
Two d_0 bins: $\leq 60\ \mu m$, $>60\ \mu m$	Prompt or from B-decay
60 bins Δm ($D^* - D^0 - \pi$)	**D* or not D***
$K\pi$ mass distribution	D^0 or not D^0

Time integrated WS D^0 per bin



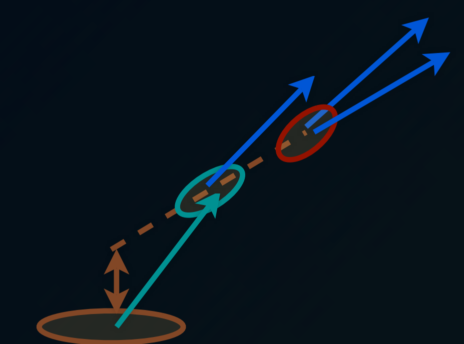
- Fit for D^* yield
  - 80 fits of # D^0 vs. $[m(\pi_s K\pi) - m(K\pi) - m(\pi_s)]$
- Same signal shape for all fits
- Background shape is time independent
- Independent parameters for signal and background amplitudes

B-Decay Background

- D^* produced from B-decays will have the wrong proper decay time
  - decay length is measured from the primary vertex

D^* at primary vertex

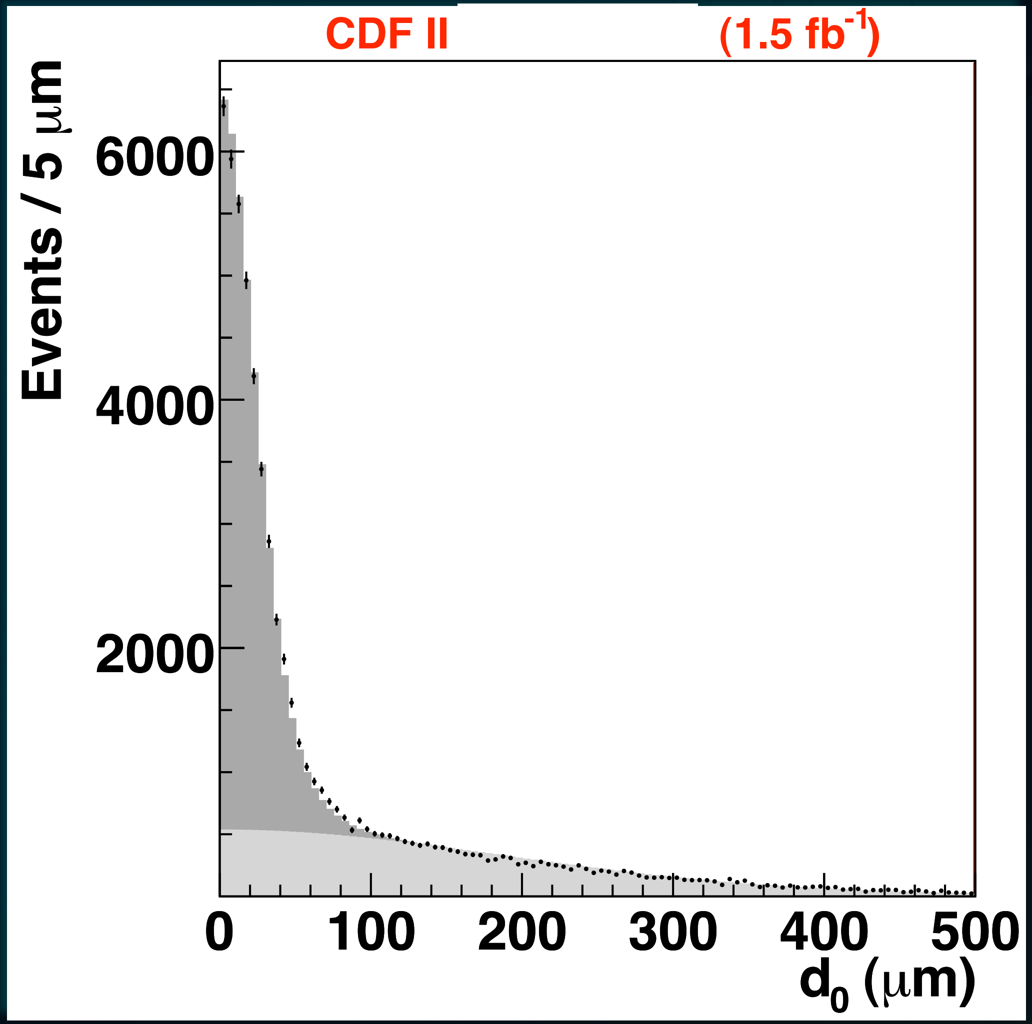
- Extrapolate the D^0 towards the primary vertex
  - d_0 : impact parameter
  - D^* produced at a secondary vertex will have a larger d_0 value



D^* from B decay
Decay length from primary vertex is longer than the D^0 decay length

Impact Parameter

- D* produced at the primary vertex have a narrow, time-independent impact parameter (d0) distribution
  - confirmed with data and MC
- D* from B decays have a wider distribution
  - width increases with decay time
  - fit distribution using RS signal
  - RS width same as WS



RS distribution for 5 < t < 6
light grey = B-background

Stage 4: d_0

- Limited by WS D* signal
- Get the fraction of the distribution with $d_0 < 60\ \mu m$ and $d_0 > 60\ \mu m$
  - Prompt D* : f_p and g_p
  - *B*-decay D*: f(t) and g(t)
- Get the number of D* with in the small and large d0 bins, for each time bin
  - $n_<(t)$ and $n_>(t)$
- Calculate the number of D* produced promptly $N_p(t)$
  - can also get the number from B-decays $n_B(t)$

Start / Finish

20 decay time bins	Fit R(t) to determine mixing parameters
Divide events into RS and WS	**Ratio R for each time bin**
Two d_0 bins: $\leq 60\ \mu m$, $>60\ \mu m$	**Prompt or from B-decay**
60 bins Δm ($D^* - D^0 - \pi$)	**D* or not D***
$K\pi$ mass distribution	**D^0 or not D^0**

$$\begin{pmatrix} n_<(t) \\ n_>(t) \end{pmatrix} = \begin{pmatrix} f_p & f(t) \\ g_p & g(t) \end{pmatrix} \begin{pmatrix} N_p(t) \\ n_B(t) \end{pmatrix}$$

Note on Uncertainties

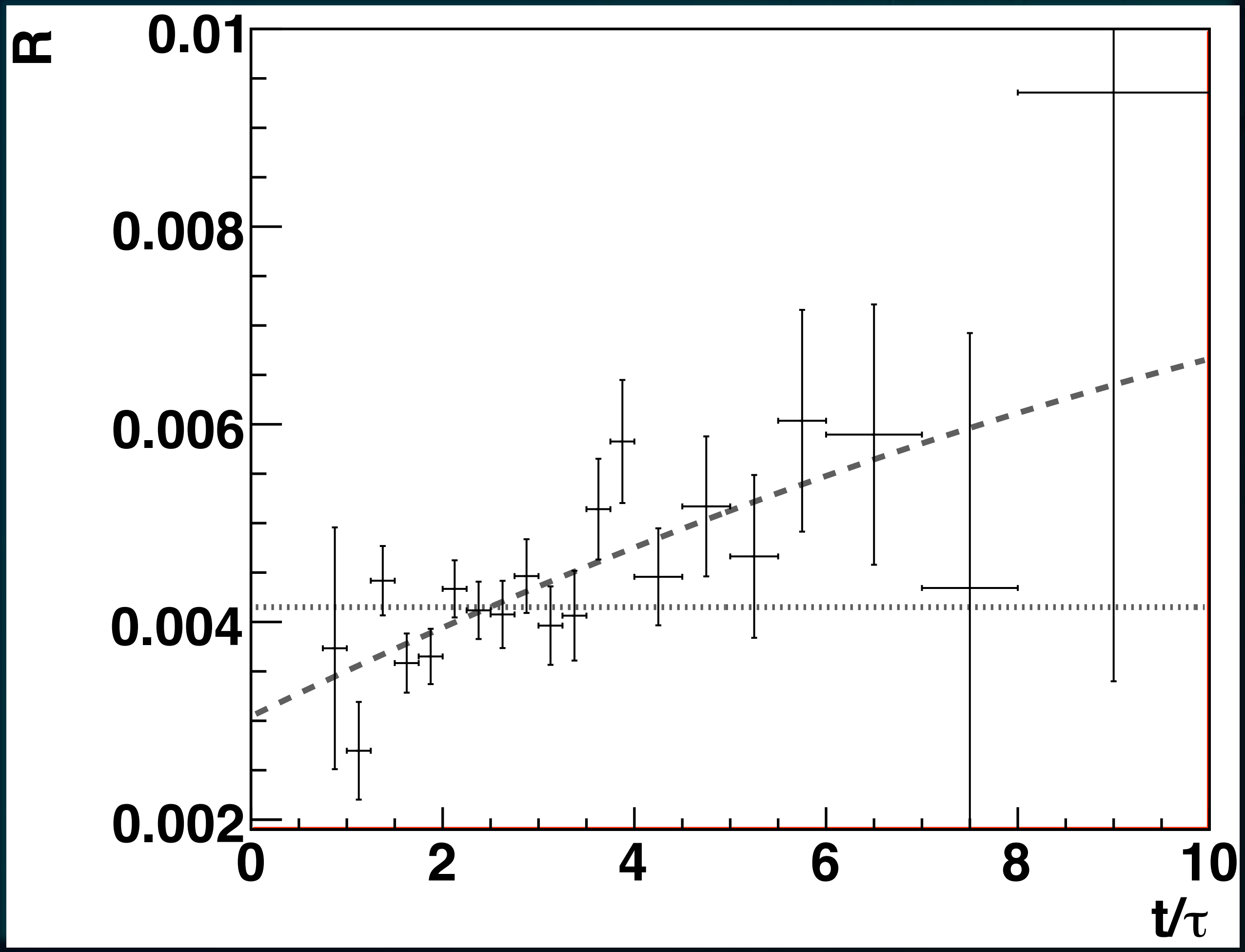
- The uncertainties are (statistical + systematic)
  - The parameters for the background shapes and amplitudes are part of the fits of the data
  - Syst. uncertainty from the background PDFs are included in the uncertainty on the signal yields
  - Added additional systematic effects that were not part of the fit procedure
    - Most effects, like time resolution and detector efficiencies, had a negligible effect on the WS/RS ratios, compared to the current uncertainties

Ratio Result

- Best Fit Parameters
  - $R_D = (3.04 \pm 0.55) \times 10^{-3}$
  - $y' = (8.54 \pm 7.55) \times 10^{-3}$
  - $x'^2 = (-0.12 \pm 0.35) \times 10^{-3}$
  - $\chi^2 = 19.2$ for 17 dof
- No mixing fit
  - $R_D = (4.15 \pm 0.10) \times 10^{-3}$
  - $x'^2 = y' = 0$
  - $\chi^2 = 36.8$ for 19 dof
- Note: Parameters are heavily correlated

Corr.	R_D	x'^2	y'
R_D	1.00	0.92	-0.97
x'^2	0.92	1.00	-0.98
y'	-0.97	-0.98	1.00

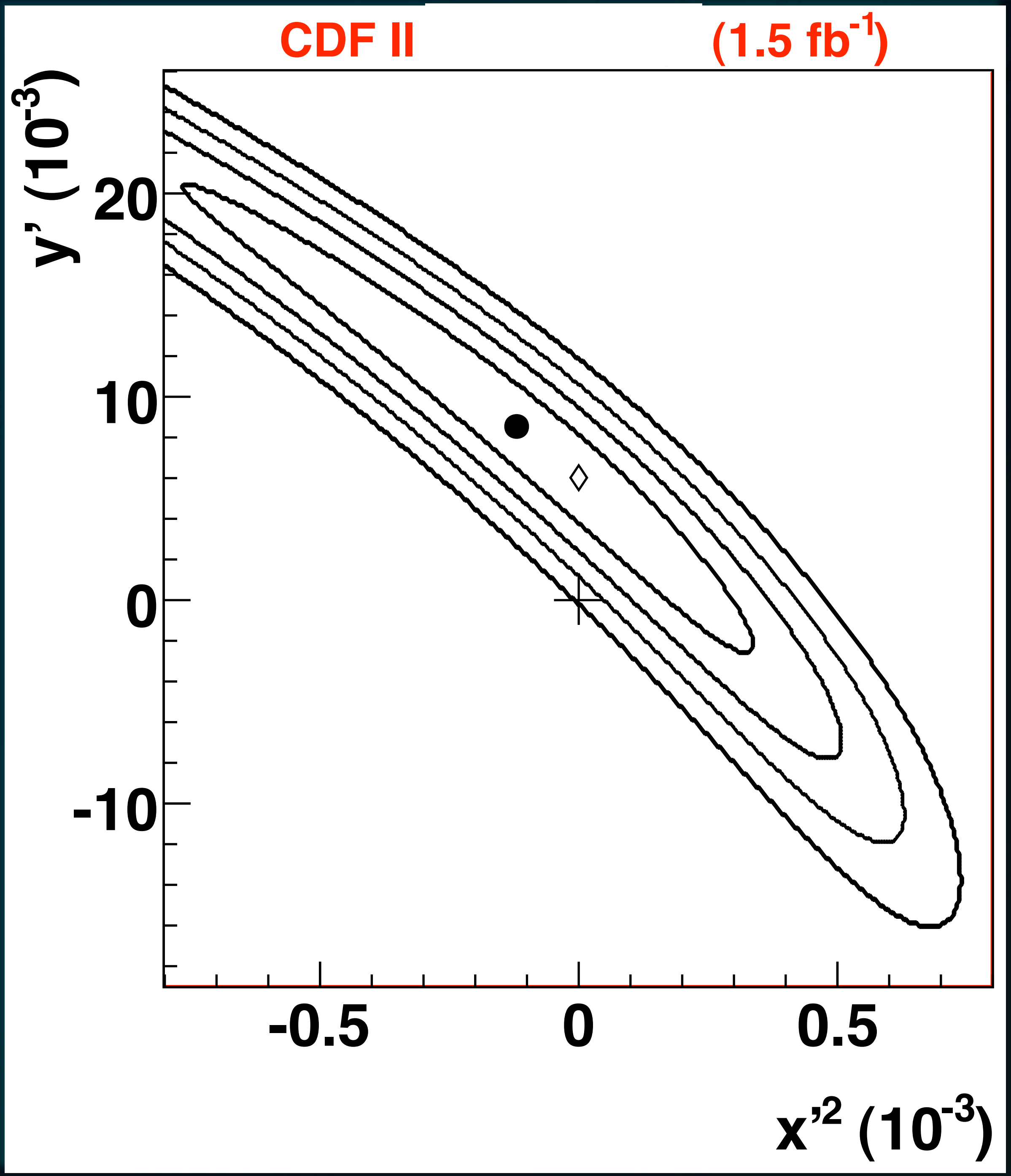
CDF Run II (1.5/fb)



$$R(t/\tau) = R_D + \sqrt{R_D}\, y'\,(t/\tau) + \frac{x'^2 + y'^2}{4}(t/\tau)^2$$

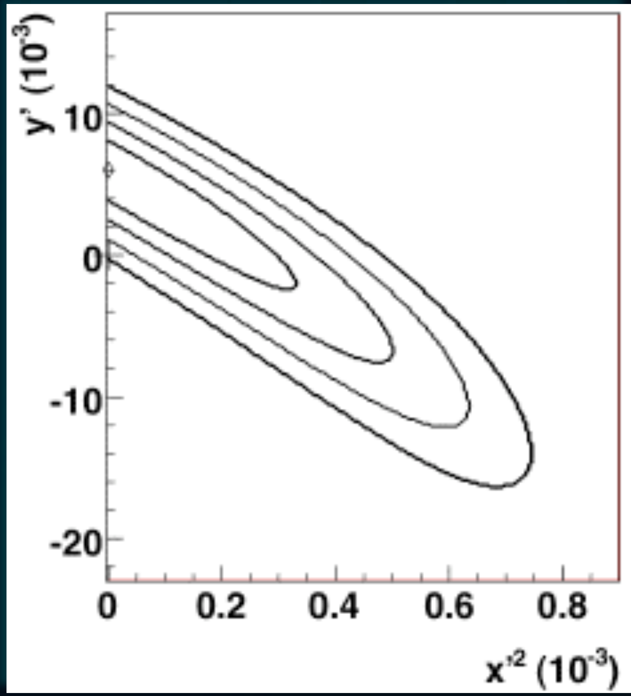
Probability Contours

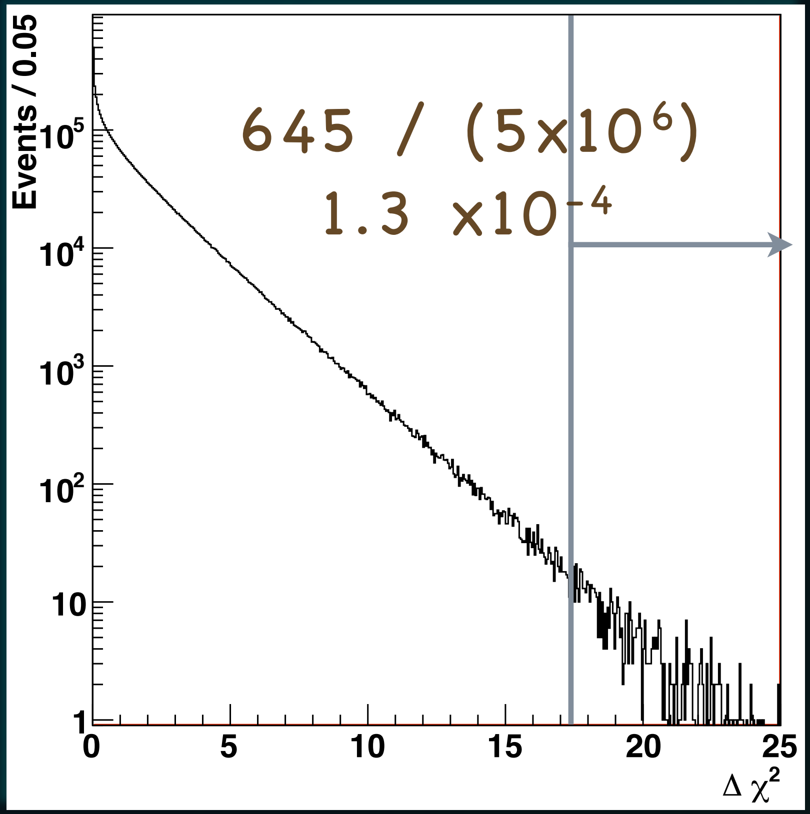
- Bayesian probability intervals equivalent to 1-4 σ
  - likelihood ~ $\exp(-\chi^2/2)$
  - solid point = best fit
  - cross = no-mixing ($y'=x'^2=0$)
  - open diamond = highest probability physically allowed point
    - x′ is a real number
    - fit chisquare is 0.1 units larger than unconstrained fit



No-mixing Significance

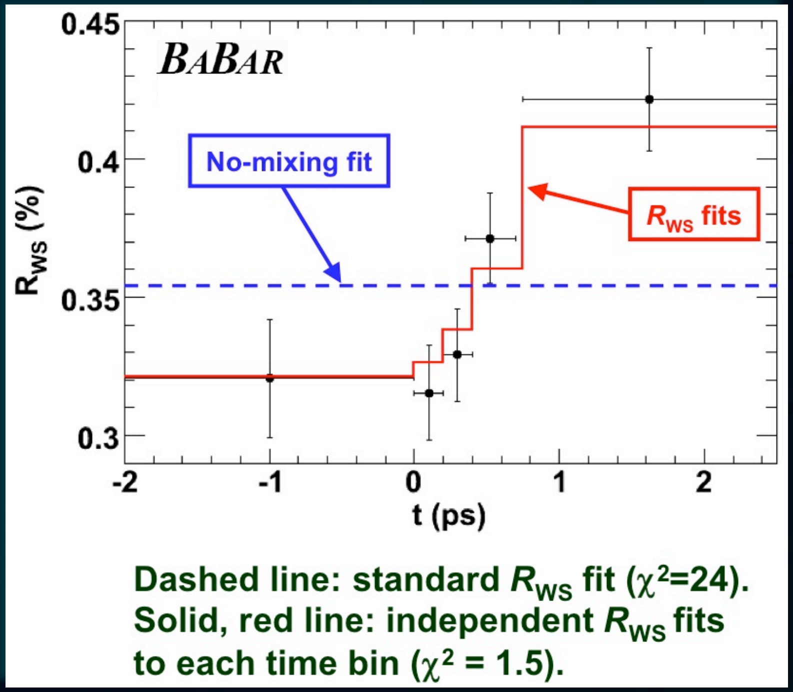
- Bayesian probability contour that excludes no-mixing point is equivalent to 3.8σ
- Alternate checks of the significance also resulted in 3.8σ
  - Bayesian probability restricted to $x'^2 \geq 0$
  - Probability for $-2\Delta\log(L) = 17.6$, between best fit and no-mixing point, assuming χ^2 distribution with 2 d.o.f.
  - p-value (frequentist): Number of toy MC simulations with $\Delta\chi^2 \geq 17.6$





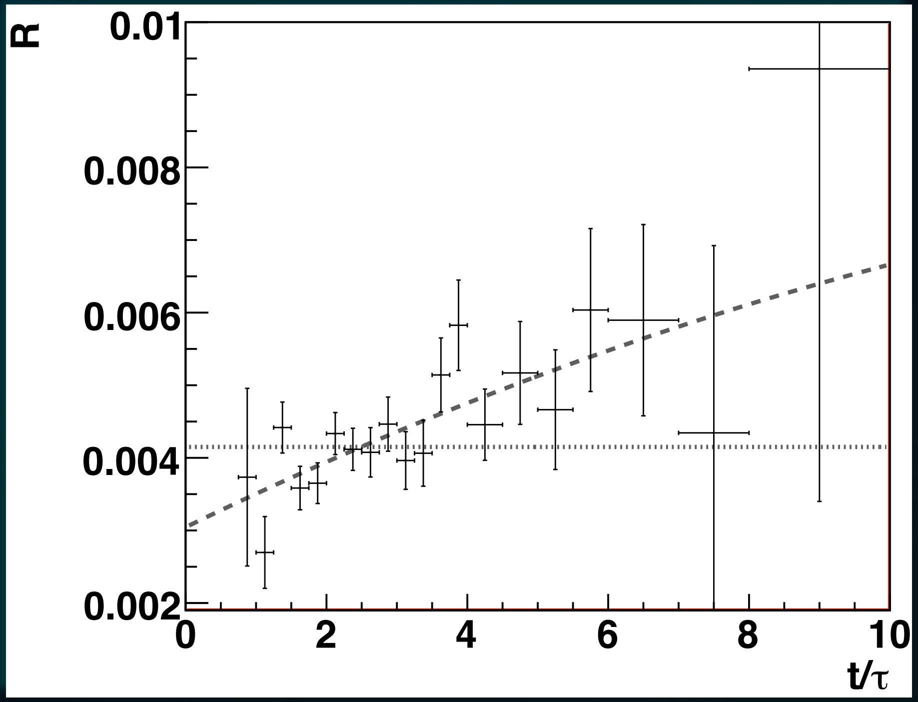
Exp. Comparisons

- Similar statistical precision with BaBar and Belle
  - 12.7 K ± 300 fully reconstructed WS D* produced at primary vertex
  - BaBar and Belle have approximately 4K ± 90 WS D*
- Poorer resolution on R_D, longer lever arm for mixing



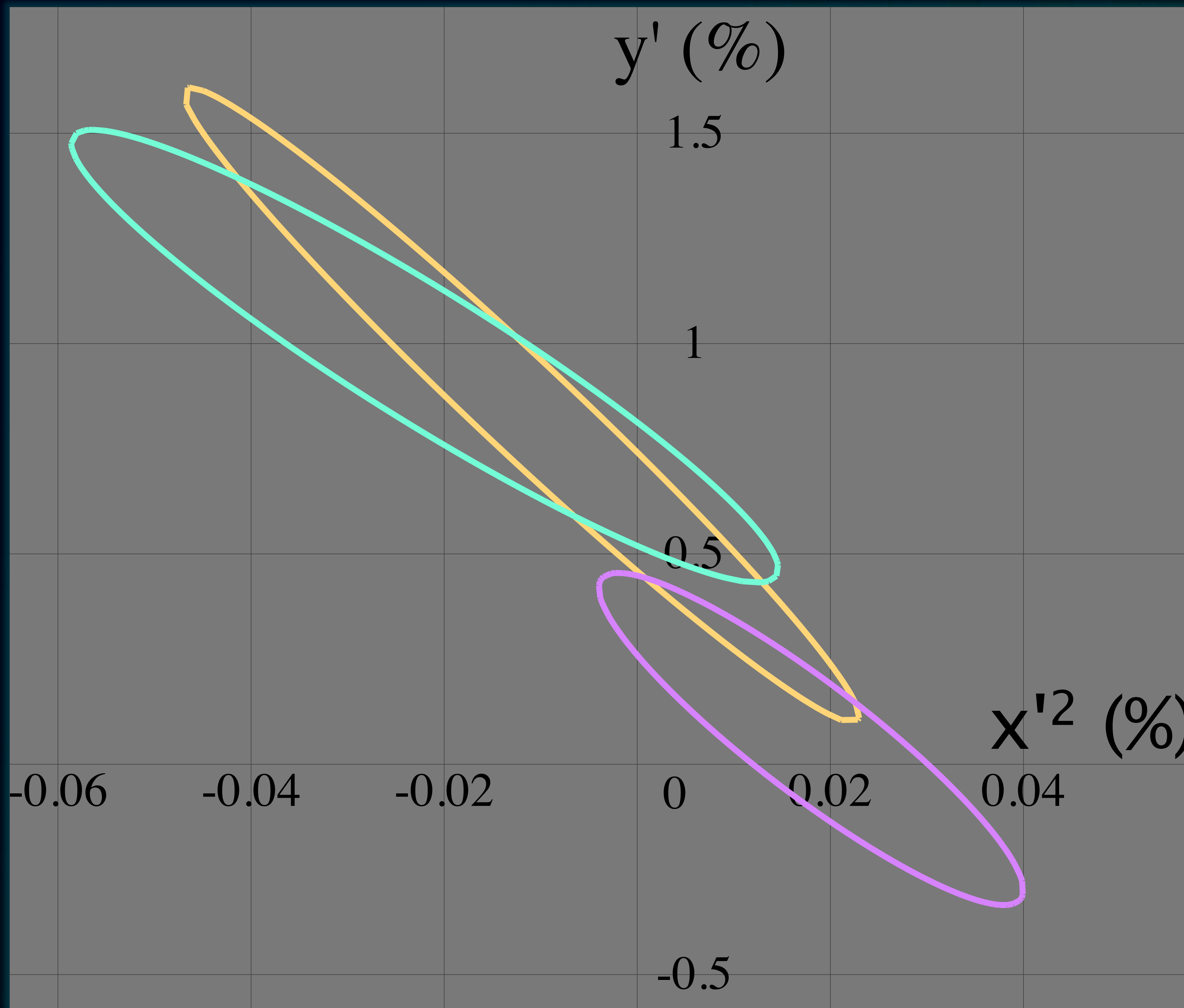
~2τ

CDF Run II (1.5/fb)



Mixing Comparisons

- 1σ contours based on the fit error matrices
- CDF
  - (y′=0.85, x′2=-0.012)%
- BaBar
  - (y′=0.97, x′2=-0.022)%
- Belle
  - (y′=0.06, x′2=0.018)%



Conclusion

- CDF confirms the evidence for charm mixing seen by BaBar with $D^0 \rightarrow K^+\pi^-$, $K^-\pi^+$
  - hep-ex/0712.1567 Submitted to PRL
- Possibilities for the future
  - Single experiment observation of charm mixing (3.8σ to 5σ)
    - Looking into improvements in the analysis
    - Might be possible with 3x current data sample
  - CP violation measurement
    - Need to be careful with systematic effects when separating D^{*+} and D^{*-}
  - Second confirmation of Belle's evidence?
    - Measured branching fractions for $D^0 \rightarrow KK/K\pi/\pi\pi$ (PRL 94, 122001, 2005), so the data is available to determine the lifetimes