# Precision measurements of CP violation and $D^0$-$D^0$bar mixing at CDF


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# Overview

- Why is charm mixing and CPV interesting?
- Quick overview of the CDF II detector
- Charm mixing with $D^0$ -> $K^+\pi^-$ or $\pi^+K^-$
  - Previous result, and prospects with current data
- CP violation measurements with $D^0$ -> $h^+h^-$
  - Previous result, and prospects with current data

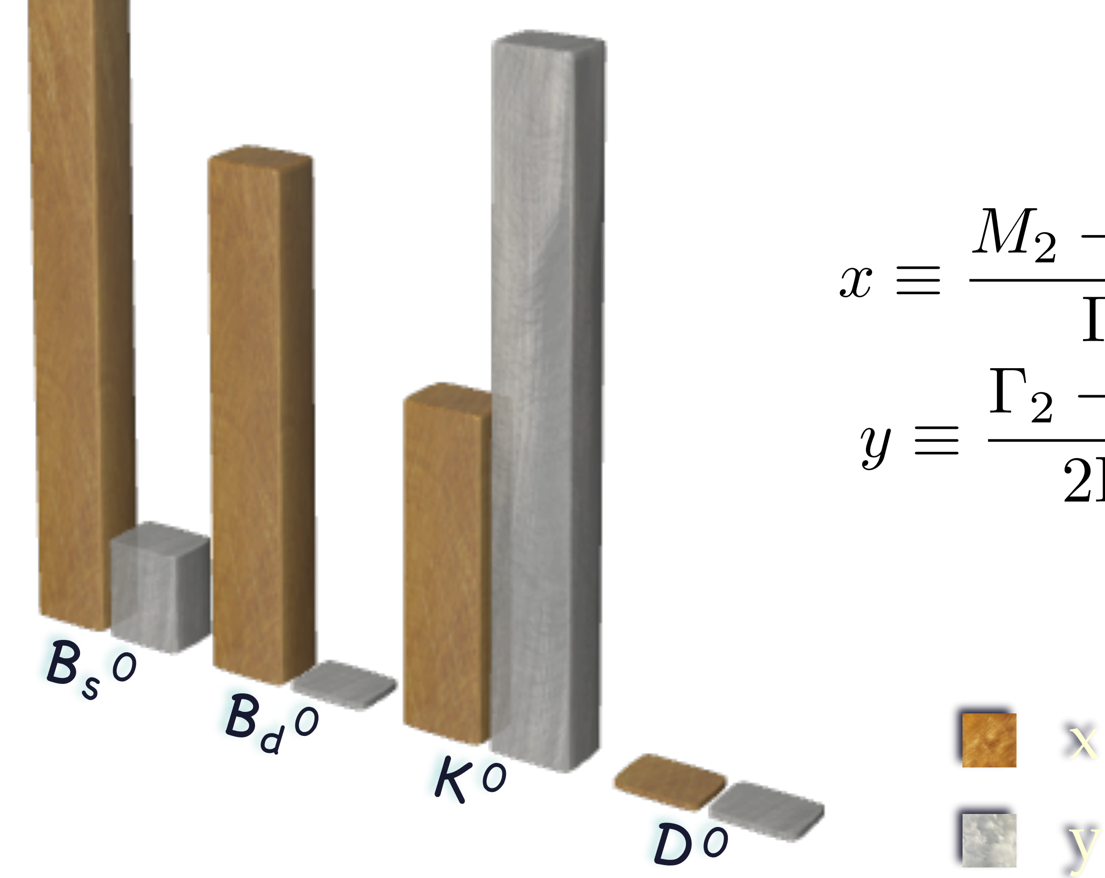
# Charm Mixing

$$|D_{1,2}\rangle = p\left|D^0\right\rangle \pm q\left|\bar{D}^0\right\rangle$$

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

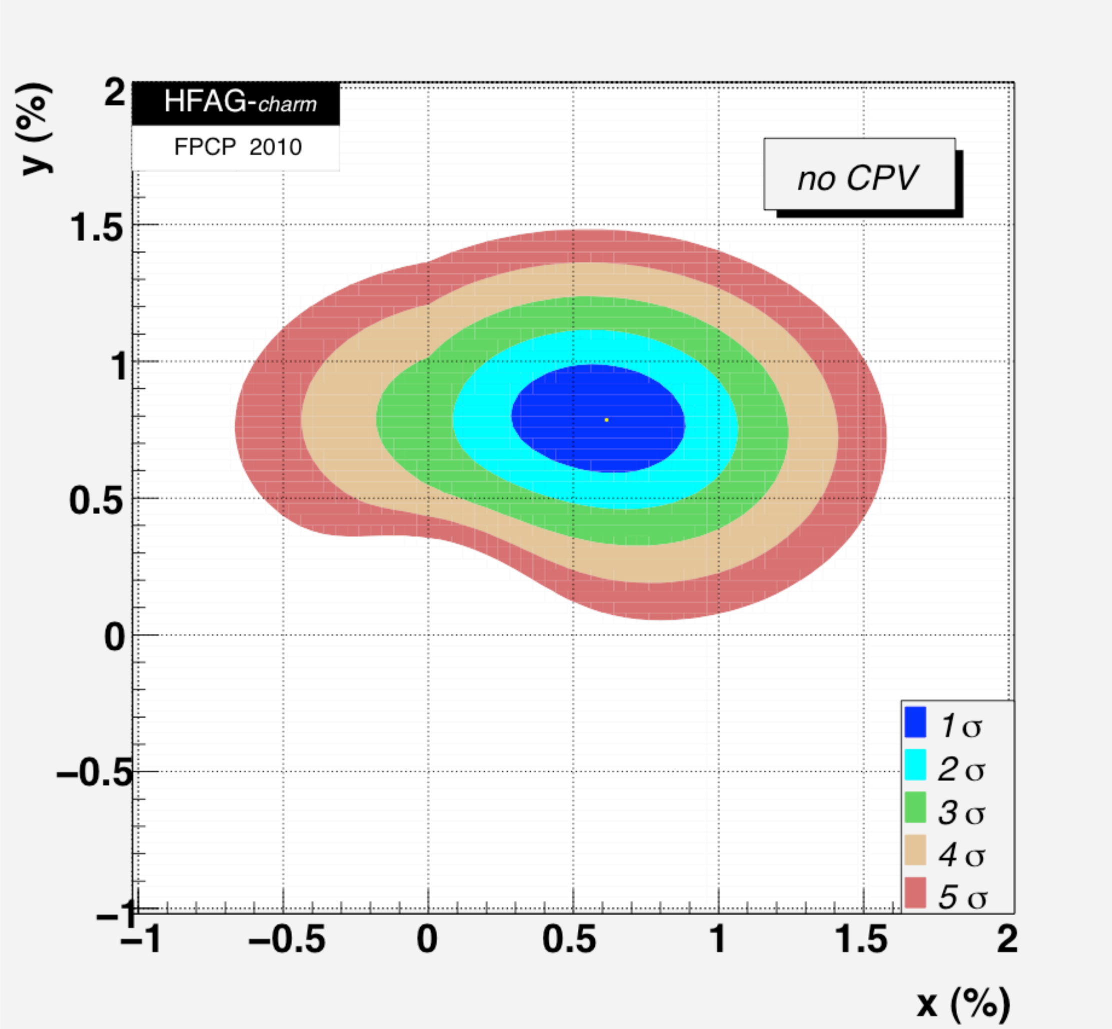
$$x \equiv \frac{M_2 - M_1}{\Gamma}$$

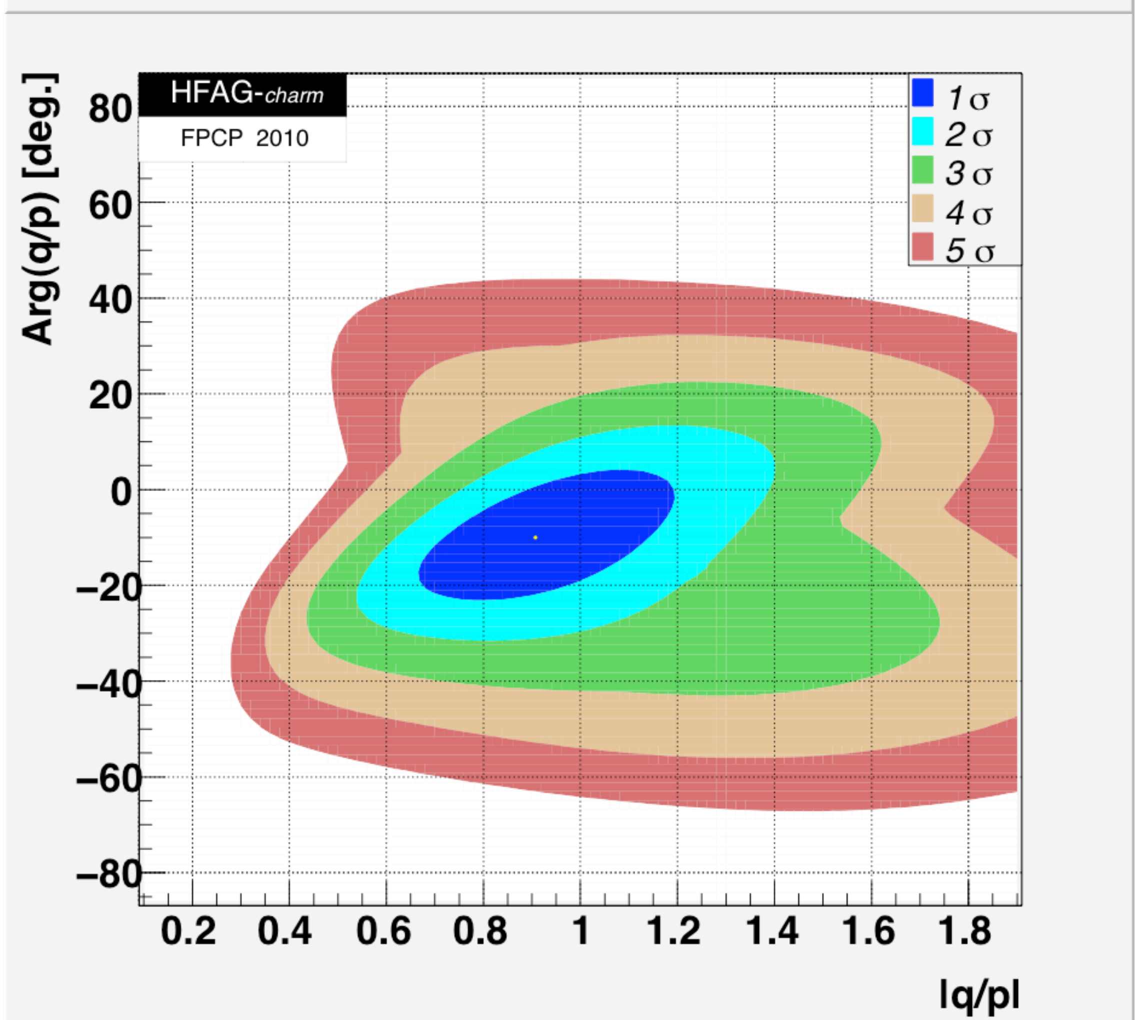
$$y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$




- Neutral *K*/*D*/*B* mesons can oscillate between matter to anti-matter
  - For no CPV, $|q/p| = 1$
- Charm mixing is small
  - x, y ~ O(1 %)
  - kaon mixing seen 1962
  - beauty mixing seen 1987
  - first evidence of charm mixing was in 2007

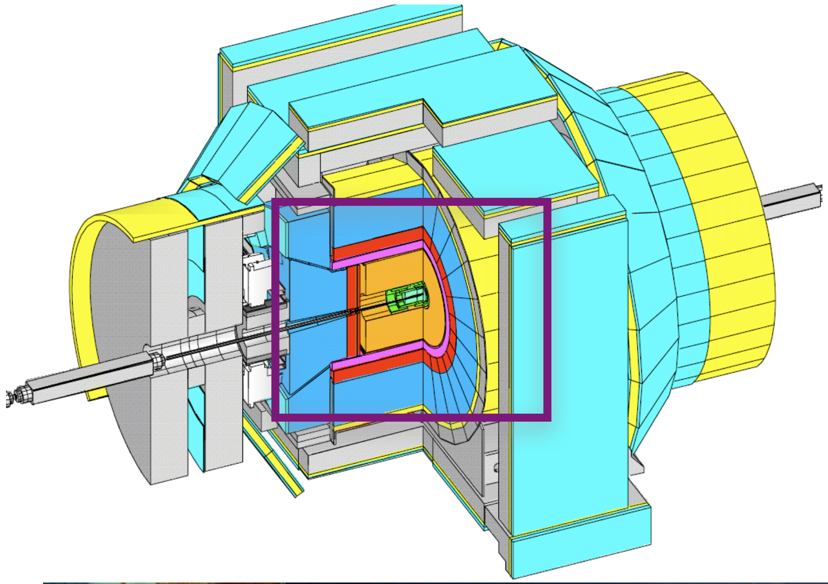
# World Average

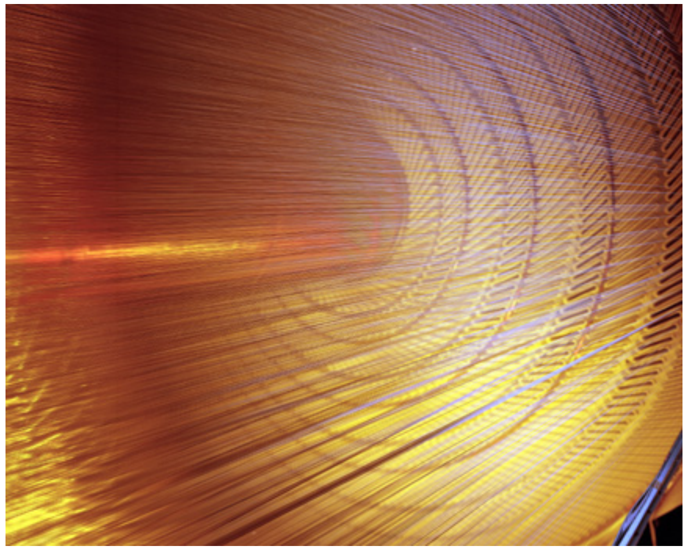


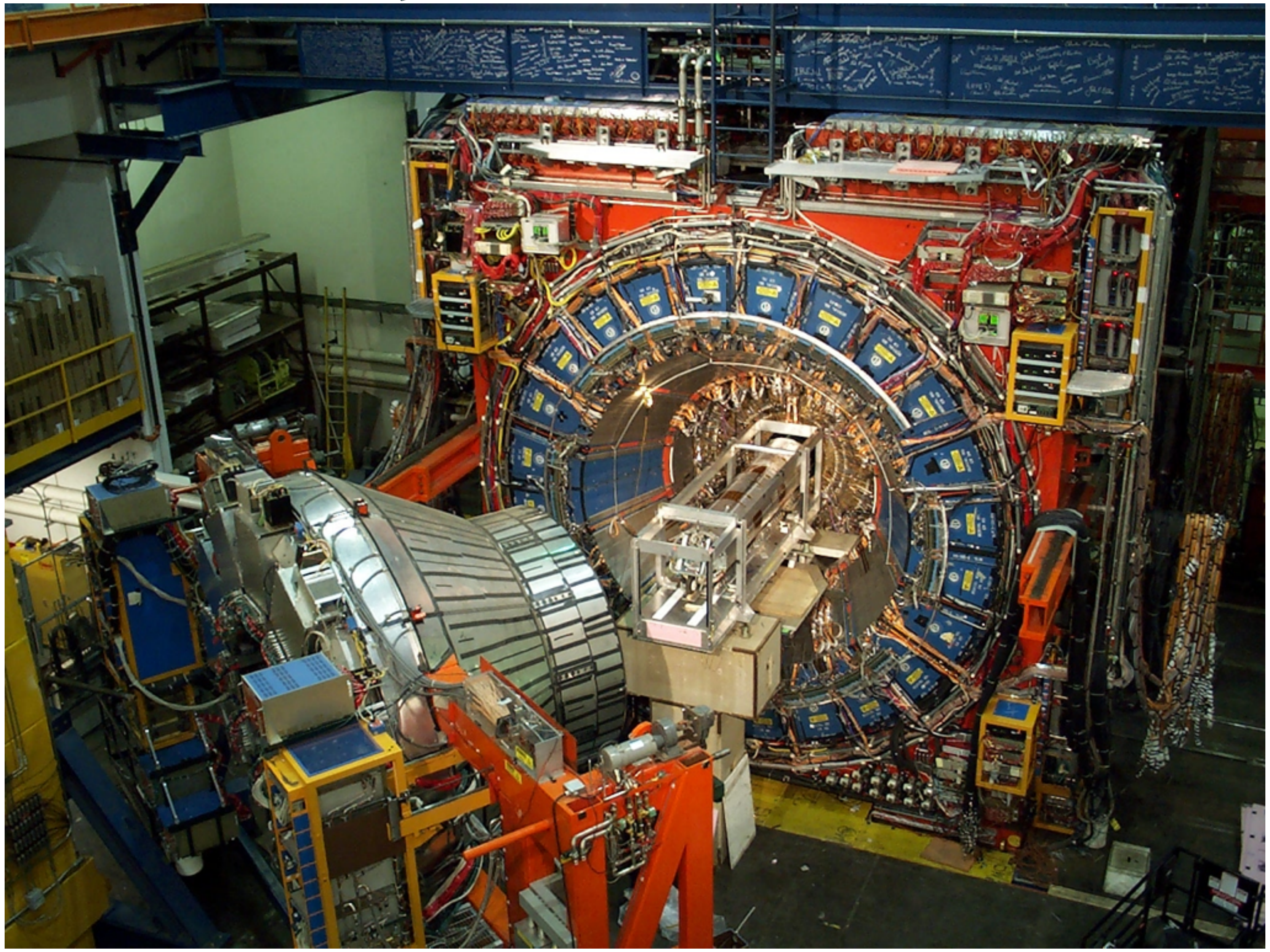




- No mixing point (0,0)
  - excluded at 10.2σ
  - Many results combined; no single measurement has reached 5σ significance
- No CPV (|q/p|, ϕ) = (1,0)
  - Experiments are currently consistent with CP conservation
- Experiment and theory need more precision to test for new physics

# CDF II Detector

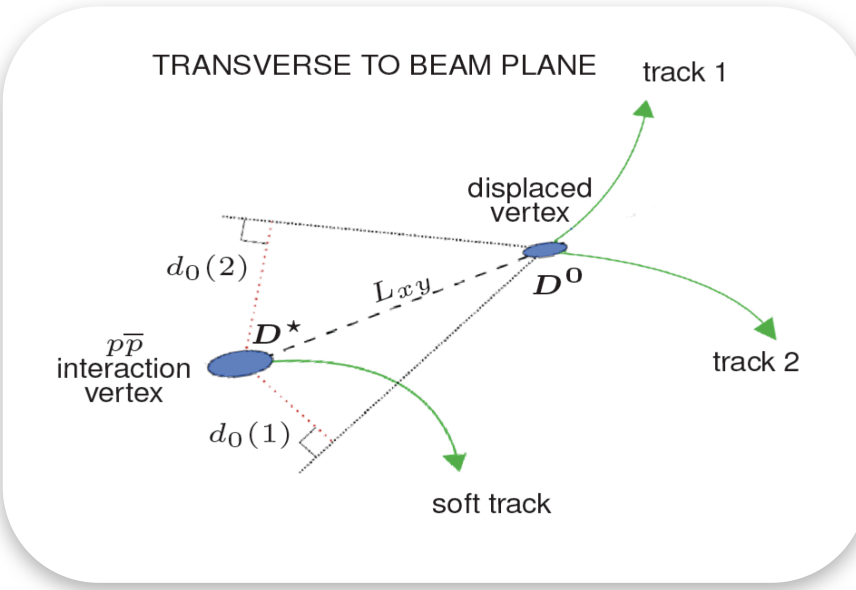


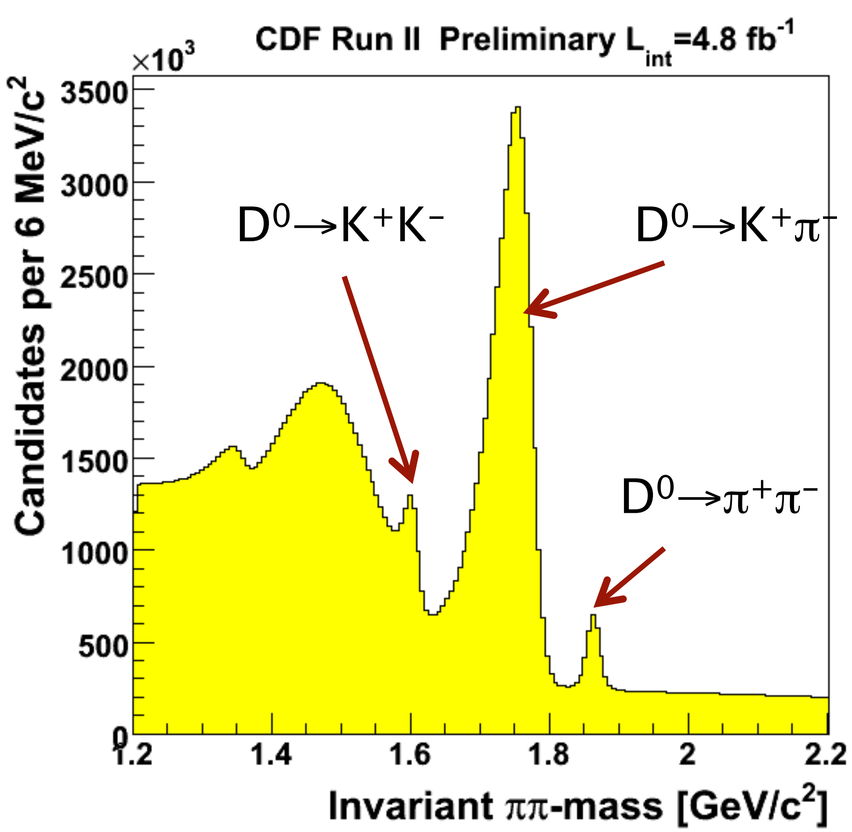




- Located at point B0 on the Fermilab Tevatron
- Looking at fully reconstructed D0 decaying to charged K and π
    - silicon vertex detector surrounded by wire drift chamber (COT) in 1.4T solenoid (central tracking)
    - These analyses do not use the (EM, hadronic, muon) calorimeters
- Particle identification using energy loss (dE/dX) in the COT

# Displaced Track Trigger




D* tagged

- Using events from trigger that selects two oppositely charged tracks that are consistent with a detached vertex
  - Track momentum transverse to the beam $p_T > 2.0$ GeV
  - Track impact parameter > 100 $\mu$m
- Initially optimized for B decays, but also good acceptance for charm

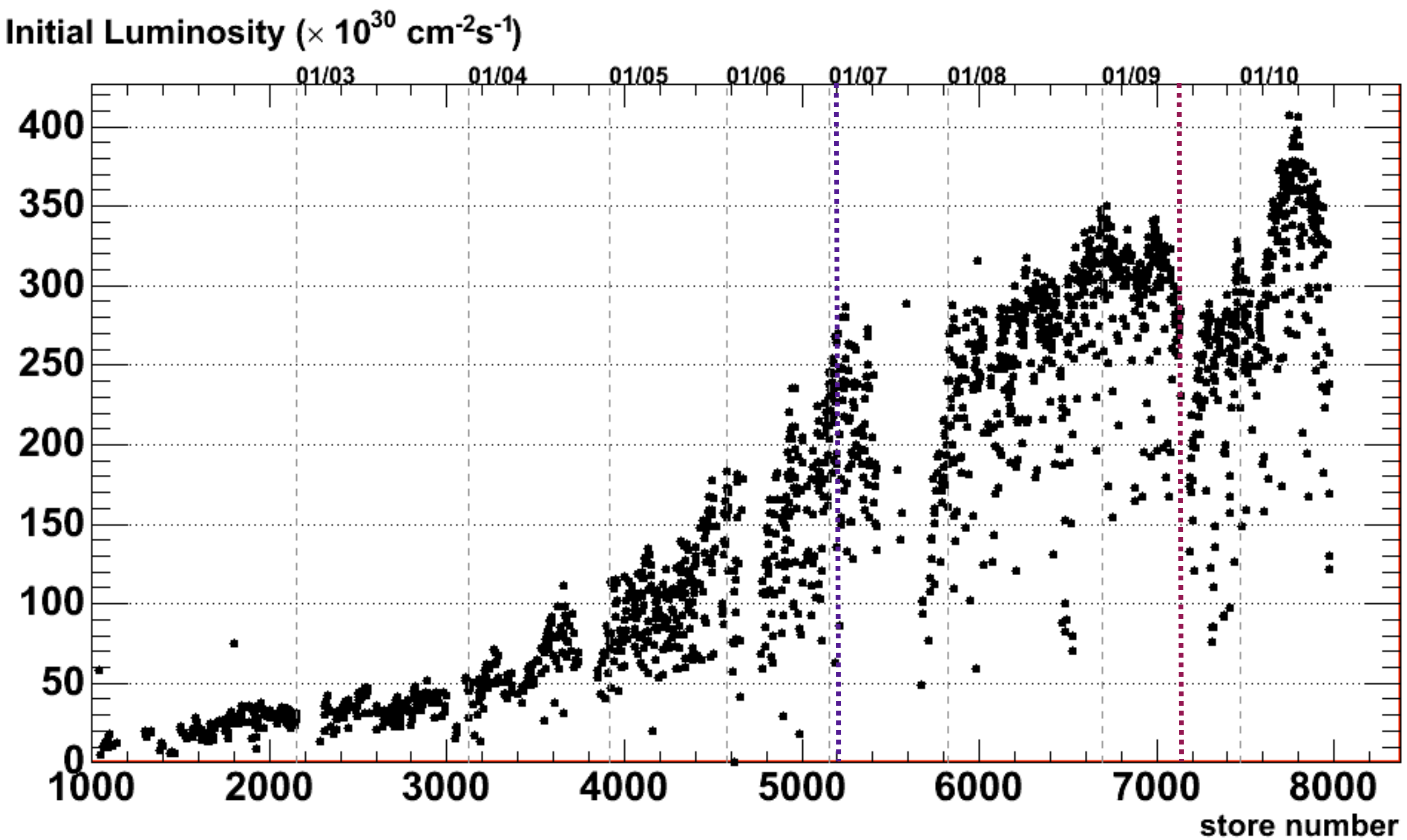
<u>Untagged D0</u>

$N(D^0 \to \pi^+\pi^-) \approx 1.7\times10^6$

$N(D^0 \to K^+K^-) \approx 4.7\times10^6$

$N(D^0 \to K^-\pi^+) \approx 47\times10^6$

# Note on Charm Yield & Luminosity




Jan 2007 1.5/fb good for hadronic charm analysis
Jun 2009 5 / fb good for hadronic charm analysis

- Number of D* does not scale linearly with integrated luminosity
  - Charm trigger is prescaled at higher beam luminosites
  - Earlier data had higher yield of charm per 1/fb

# Charm Mixing with Kπ

- Use D* to tag initial production of meson
- "right-sign" (RS) - Cabibbo favored decay

$$D^{*+} \to D^0\pi^+ \,,\, D^0 \to K^-\pi^+$$

- "wrong-sign" (WS) - doubly Cabibbo suppressed decay, or mixing followed by a CF decay

$$D^{*+} \to D^0\pi^+ \,,\, D^0 \to K^+\pi^- \qquad D^{*+} \to D^0\pi^+ \,,\, D^0 \leftrightarrow \bar{D}^0 \to K^+\pi^-$$

- In the limit of |x|, |y| << 1 and no CPV, ratio of WS to RS versus decay time is

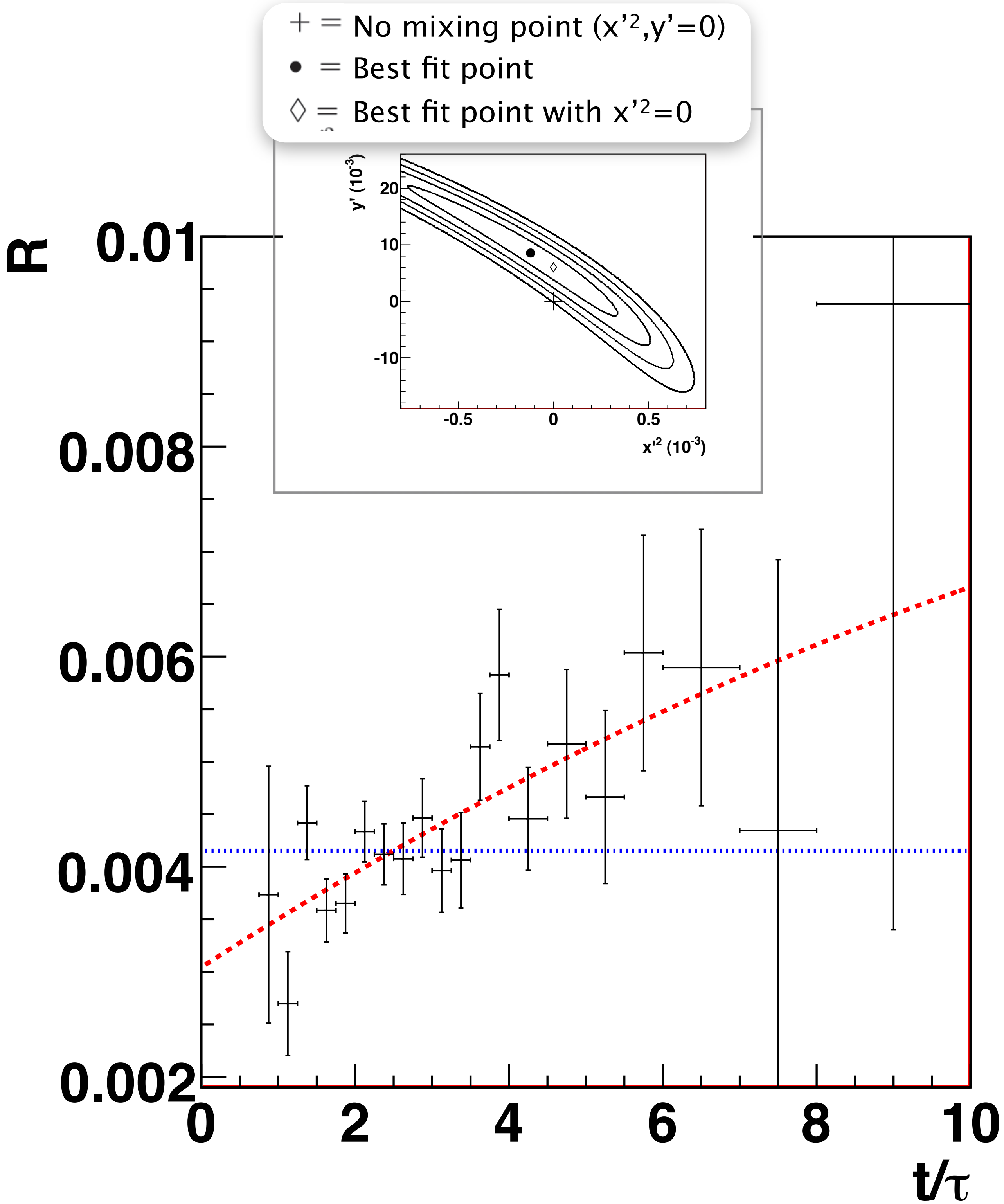
$$r(t) \propto e^{-\Gamma t}\left[R_D + \sqrt{R_D}\,y'(\Gamma t) + \frac{x'^2 + y'^2}{4}(\Gamma t)^2\right]$$

- Cannot measure mixing parameters directly, but still put limits on amplitude

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

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

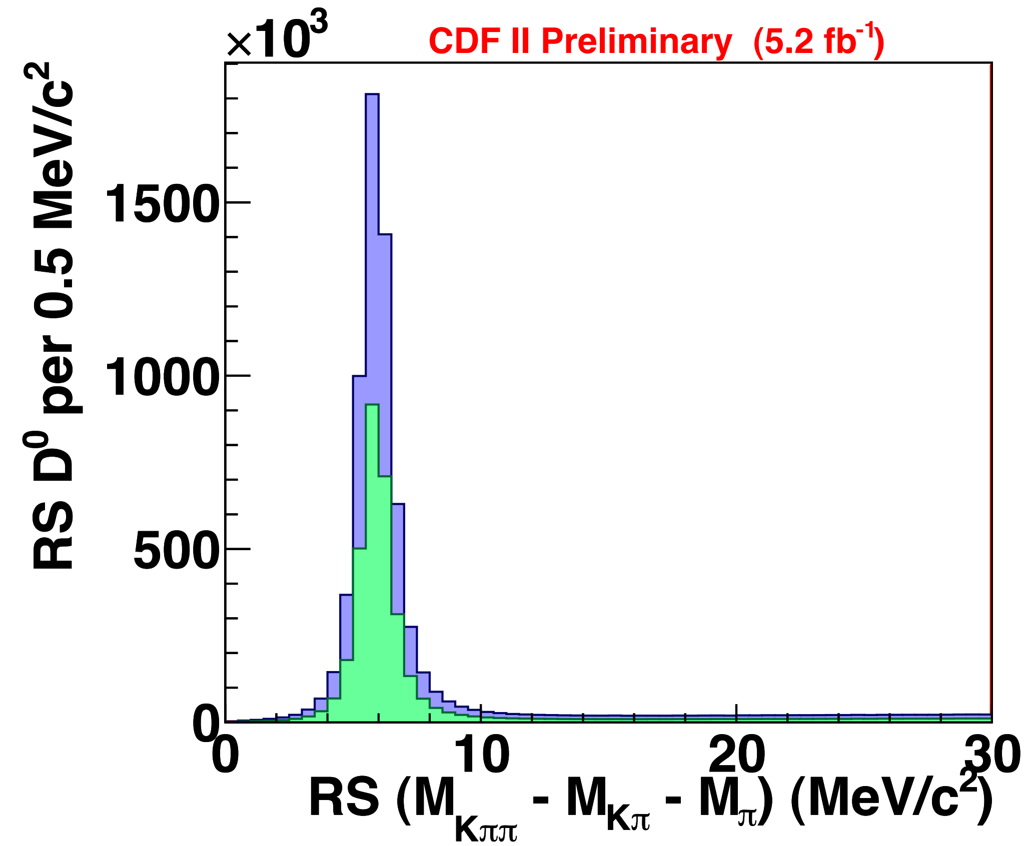
# Previous CDF Result




- PRL 100, 121802 (2008)
- "Evidence for D0-D0bar mixing using the CDF II Detector"
- Difference in chi2 between mixing fit (red dashed) and the no-mixing fit (blue bots) is 17.6
  - Equivalent to 3.8σ significance
- Results were competitive with the best experimental results at the time

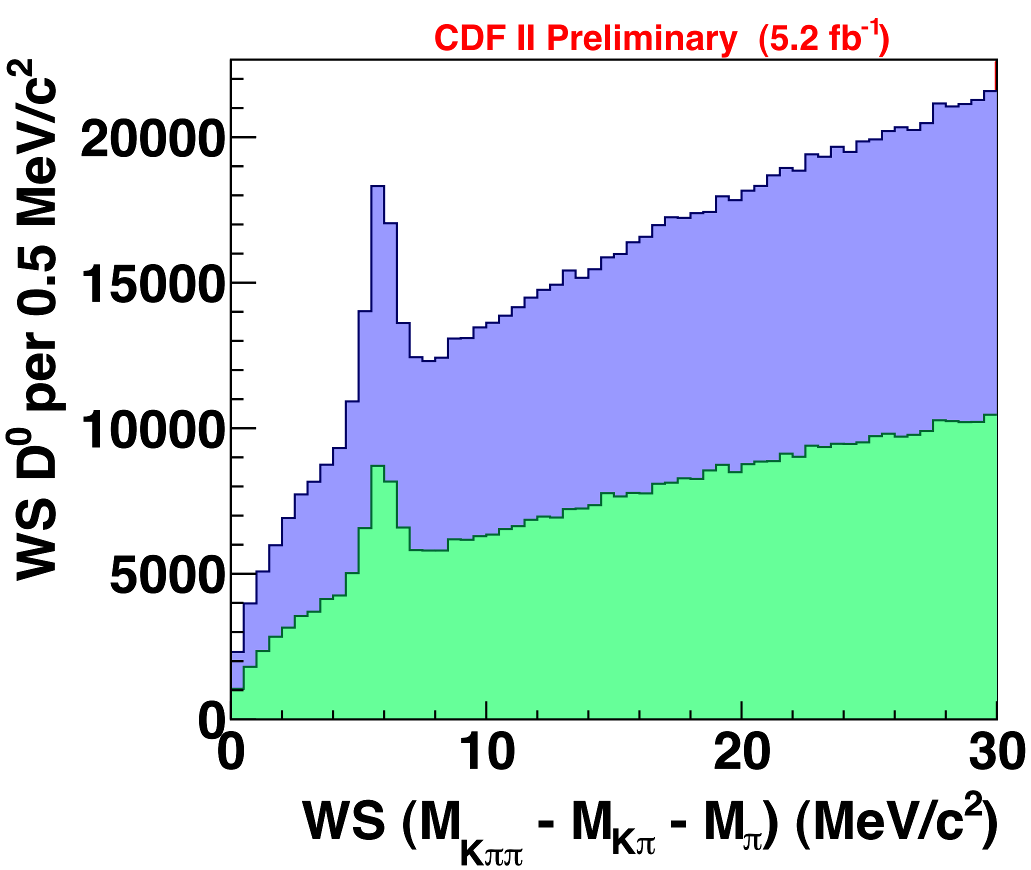
# Work in Progress

```
1.5/fb: 3.03 million RS D*
5.2/fb: ~6.3 million RS D*
```




- Time-integrated D*
  - Light green is the published result with 1.5/fb
  - Blue is current, with 5.2/fb

  - Peak at 5.9 MeV/c2 is D*
  - Rest of the distribution is D0 + random track from the primary vertex




- Working to improve systematic uncertainties on the analysis (ex. removing D* from B decays, dE/dX variation over time, etc.)

```
1.5/fb: 12.8 thousand WS D*
5.2/fb: ~26  thousand WS D*
```

# CP Violation with $D^0 \to h^+ h^-$

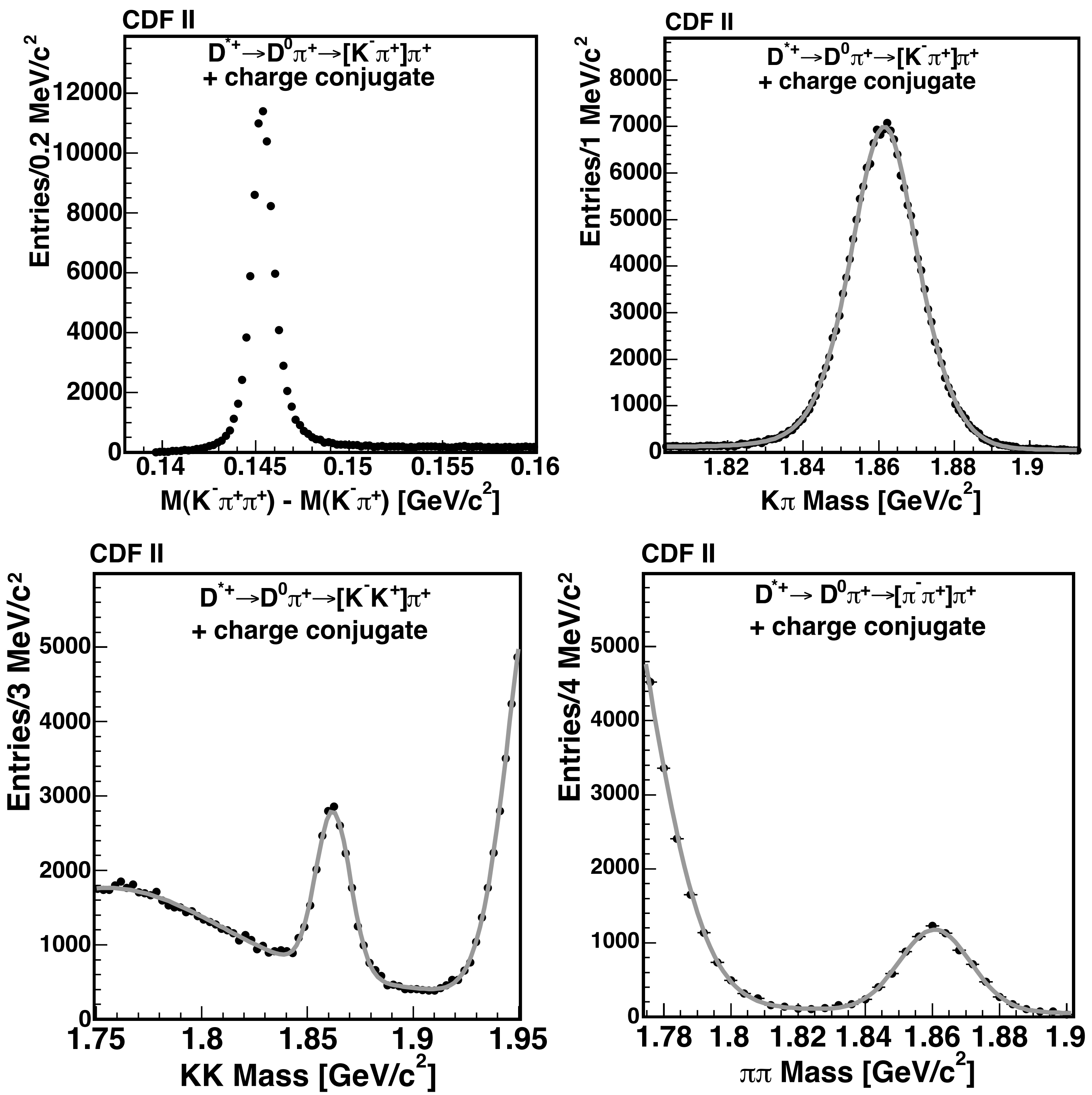
$$A_{CP}^{\pi\pi} = \frac{\Gamma(D^0 \to \pi^-\pi^+) - \Gamma(\overline{D}^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to \pi^-\pi^+) + \Gamma(\overline{D}^0 \to \pi^+\pi^-)}$$

$$\frac{\Gamma(D^{*-} \to \overline{D}^0\pi_s^- \to [h^+h^-]\pi_s^-)}{\Gamma(D^{*+} \to D^0\pi_s^+ \to [h^+h^-]\pi_s^+)} = \frac{N_{h^+h^-\pi_s^-}}{N_{h^+h^-\pi_s^+}} \cdot \frac{\varepsilon_{h^+h^-}}{\varepsilon_{h^+h^-}} \cdot \frac{\varepsilon_{\pi_s^+}}{\varepsilon_{\pi^-}}$$

$$\frac{\Gamma(\overline{D}^0 \to K^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+)} = \frac{N_{K^+\pi^-}}{N_{K^-\pi^+}} \cdot \frac{\varepsilon_{K^-\pi^+}}{\varepsilon_{K^+\pi^-}}$$

- In addition to direct CP violation, $D^0$ oscillations can generate time dependent CP asymmetries that survive integrating over time
- To make precision measurement, need to correct for detector systematics that can bias the asymmetry

# Previous CDF Result

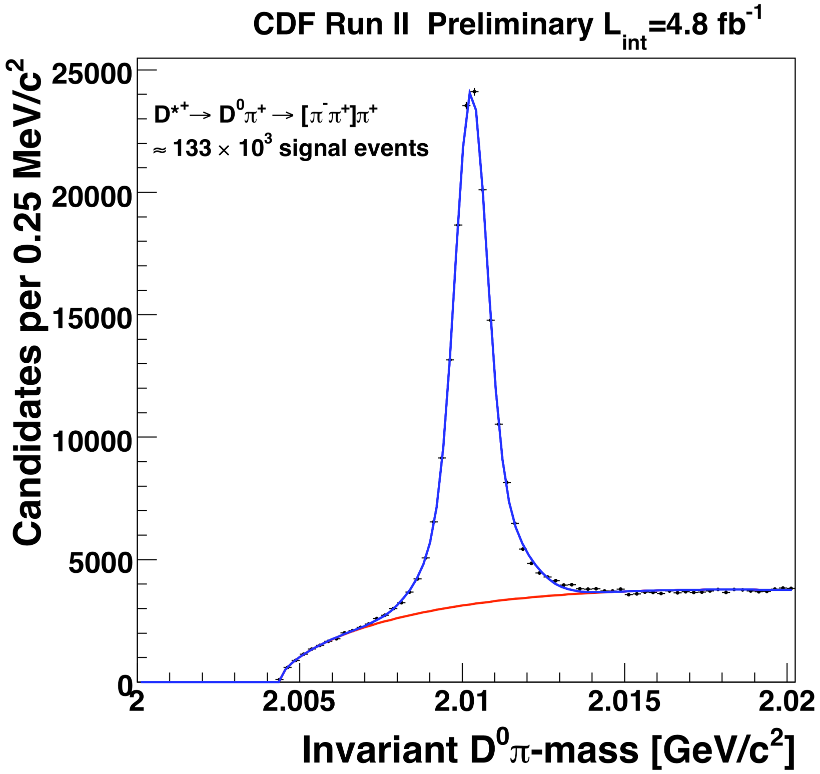



- PRL 94, 122001 (2005)
- "Relative Branching Fractions and Search for CP Asymmetry for D0 -> Kπ/KK/ππ
- L = 0.123 / fb
  - (first 15 months of data taking)
  - D0 -> KK 8.2 thousand
  - D0 -> ππ 3.7 thousand
  - D0 -> Kπ 88.3 thousand

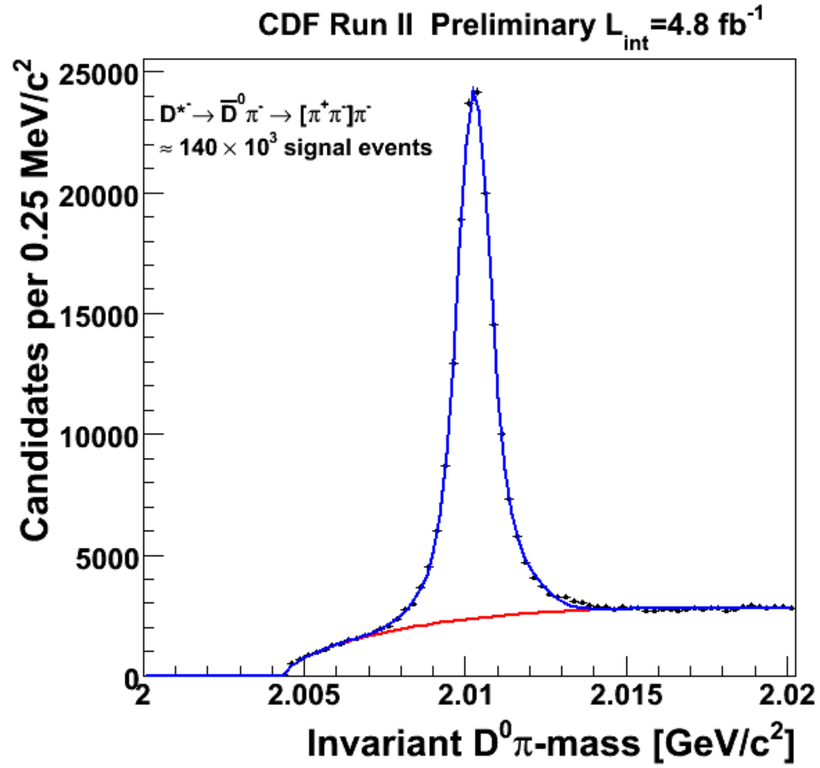
$$A(D^\circ \to K^+K^-) = 2.0 \pm 1.2(stat) \pm 0.6(syst)\ \%$$
$$A(D^\circ \to \pi^+\pi^-) = 1.0 \pm 1.3(stat) \pm 0.6(syst)\ \%$$

# $D^{*+} \to D^0\pi^+ \to [h^- h^+]\,\pi^+$ (now)

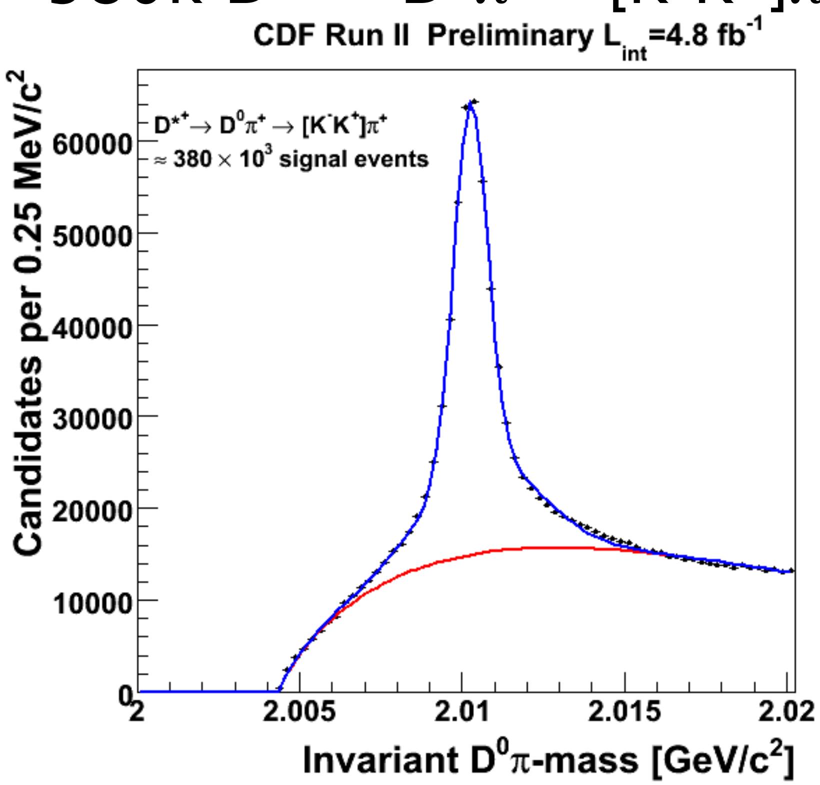
133k $D^{*+} \to D^0\pi^+ \to [\pi^-\pi^+]\pi^+$



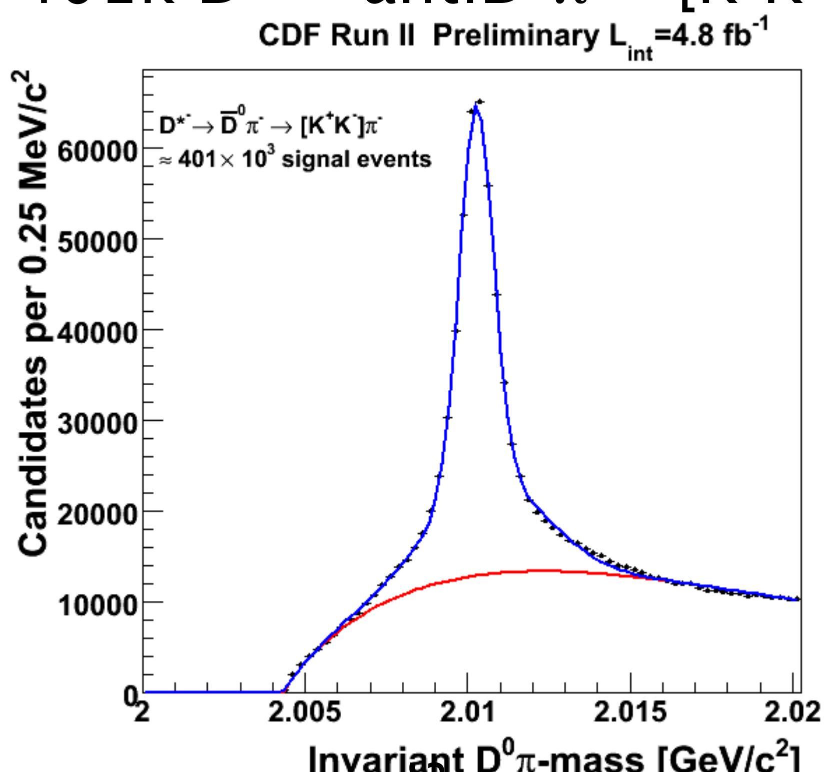

140k $D^{*-} \to \text{anti}D^0\pi^- \to [\pi^+\pi^-]\pi^-$




380k $D^{*+} \to D^0\pi^+ \to [K^-K^+]\pi^+$




401k $D^{*-} \to \text{anti}D^0\pi^- \to [K^+K^-]\pi^-$




- These plots are to get an estimate for current signal size
  - a lot more than previous published result)
- Different method
  - data-driven technique to measure detector efficiencies
  - previous used MC

# Work in Progress

Assuming: $\sigma_N \cong \sigma_{\bar{N}} \cong 1/\sqrt{N} \Rightarrow \sigma_{A_{CP}} = 1/\sqrt{N+\bar{N}}$

| **Experiment** | **N ($D^0 \to \pi^+\pi^-$)** | **$A_{CP}(D^0 \to \pi^+\pi^-)$ (%)** |
|---|---|---|
| CDF(0.123/fb) | 7.3K | 1.0 ± 1.3(stat) ± 0.6 (syst) |
| CDF(4.8/fb) | 273K | xxx ± 0.19(stat) ± xxx (syst) |
| Babar (386/fb) | 64K | –0.24 ± 0.52(stat) ± 0.22(syst) |
| Belle(540/fb) | 51K | +0.43 ± 0.52(stat) ± 0.12 (syst) |

| **Experiment** | **N ($D^0 \to K^+K^-$)** | **$A_{CP}(D^0 \to K^+K^-)$ (%)** |
|---|---|---|
| CDF(0.123/fb) | 7.3K | 1.0 ± 1.3(stat) ± 0.6 (syst) |
| CDF(4.8/fb) | 781K | xxx ± 0.11(stat) ± xxx (syst) |
| Babar (386/fb) | 129K | 0. ± 0.34(stat) ± 0.13(syst) |
| Belle(540/fb) | 120K | -0.43 ± 0.30(stat) ± 0.11 (syst) |

Systematic uncertainty is expected to be O(0.1%), comparable to statistical uncertainty.

# Conclusion

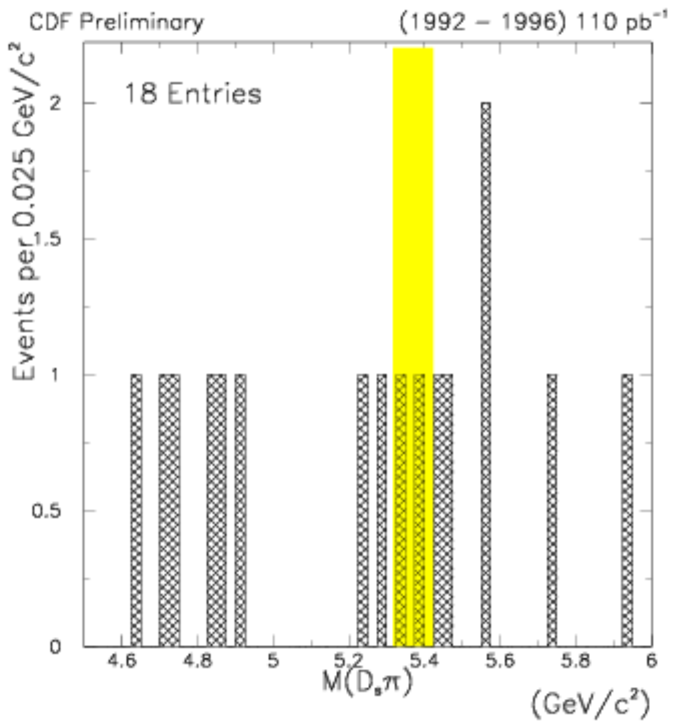
- Working to update two previous results (charm mixing, charm direct CPV) with more data
  - Substantial charm samples
- Mature detector, understood systematic effects
  - Working to improve precision of the syst. errors
- Stay tuned!

# Backup Slides

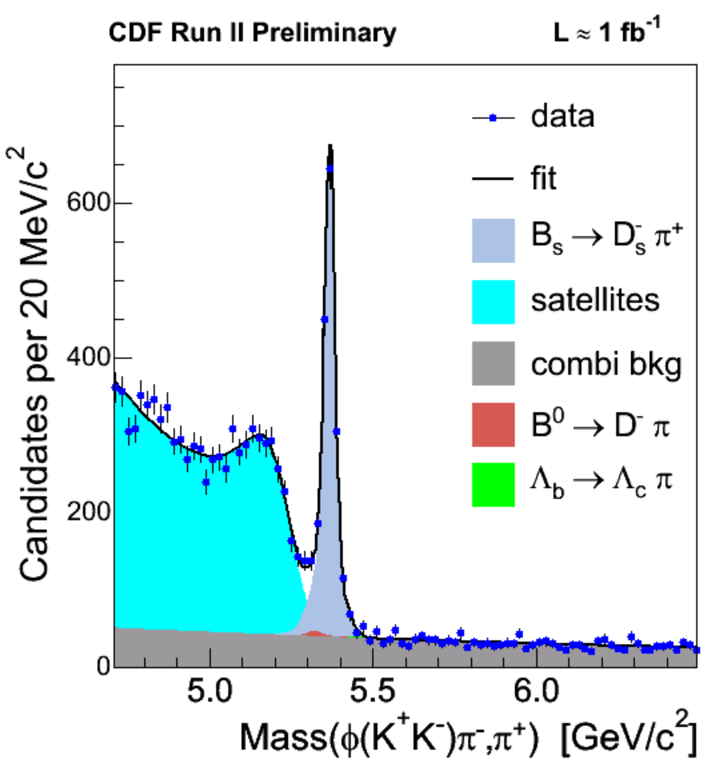
# Displaced Track Trigger

- Run I collected O(1) $B_s$--> $D_s\pi$ (all $D_s$ modes)
- Run II collected ~2000 $B_s$--> $D_s\pi$ ($D_s$--> $\phi$[-->$K^+K^-$] $\pi$)
- Compare with only 10x integrated luminosity!
- The trigger had a much bigger impact than Tevatron upgrade!!!

Without SVT

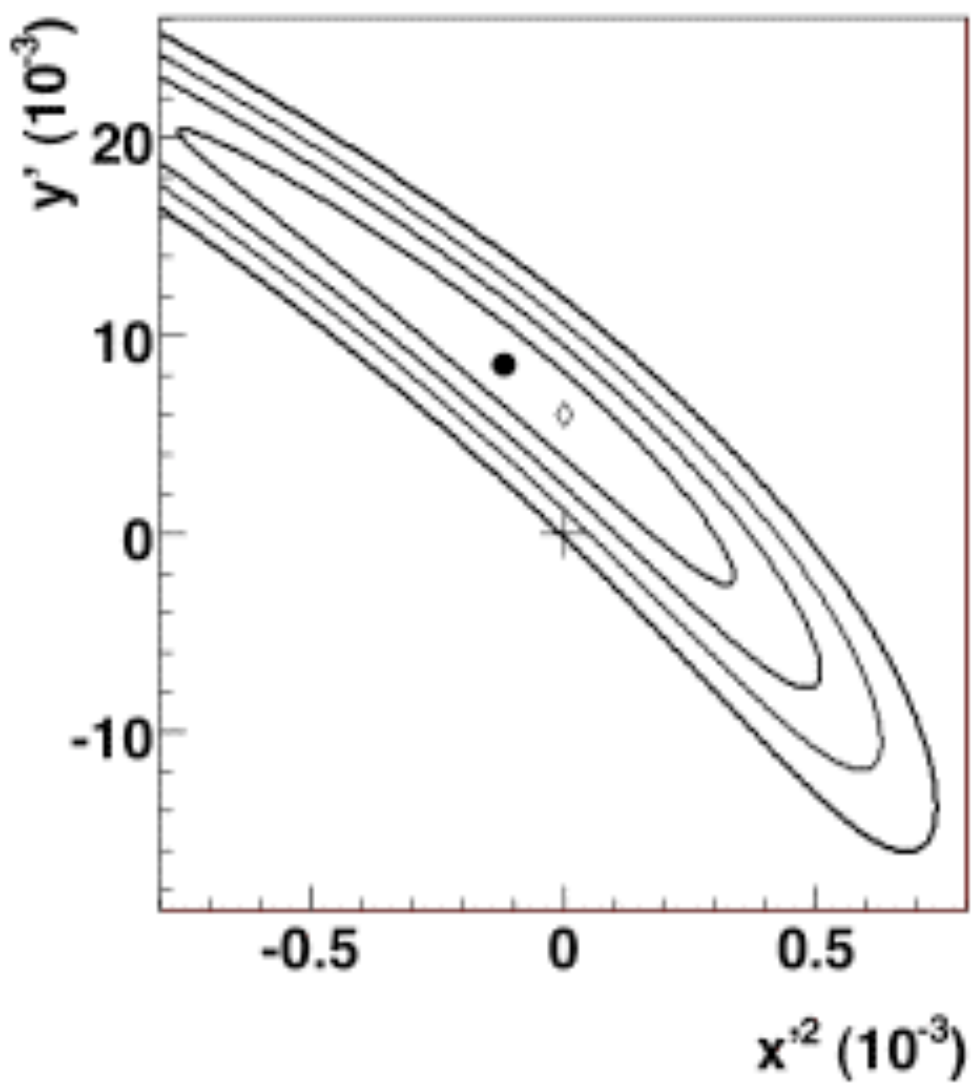



With SVT




M.J. Morello

# Charm Mix plots




| Experiment | $R_D(10^{-3})$ | $y'\,(10^{-3})$ | $x'^2\,(10^{-3})$ | Mixing Signif. |
|---|---|---|---|---|
| CDF | $3.04 \pm 0.55$ | $8.5 \pm 7.6$ | $-0.12 \pm 0.35$ | 3.8 |
| *BABAR* [8] | $3.03 \pm 0.19$ | $9.7 \pm 5.4$ | $-0.22 \pm 0.37$ | 3.9 |
| Belle [9] | $3.64 \pm 0.17$ | $0.6\ ^{+4.0}_{-3.9}$ | $0.18\ ^{+0.21}_{-0.23}$ | 2.0 |

+ = No mixing point (x'²,y'=0)
• = Best fit point
◊ = Best fit point with x'²=0