OBSERVATION OF D^0 MIXING AT CDF

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Fermilab

Flavor mixing in the charm sector

- Neutral mesons can oscillate between matter and anti-matter
  - Mass eigenstates ≠ flavor eigenstates

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

  - Time evolution

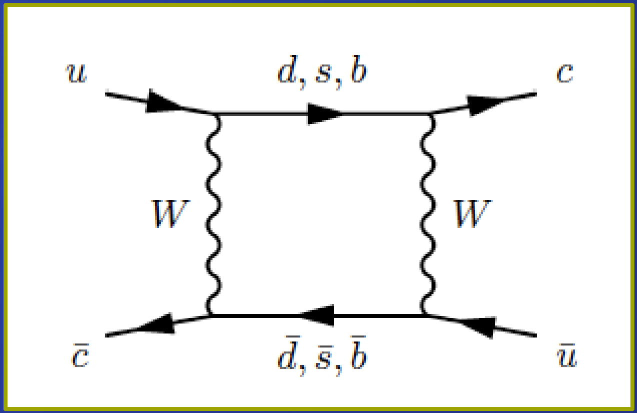
$$\left|D_{1,2}(t)\right\rangle = \left|D_{1,2}(0)\right\rangle e^{-t(\Gamma_{1,2}+iM_{1,2})}$$

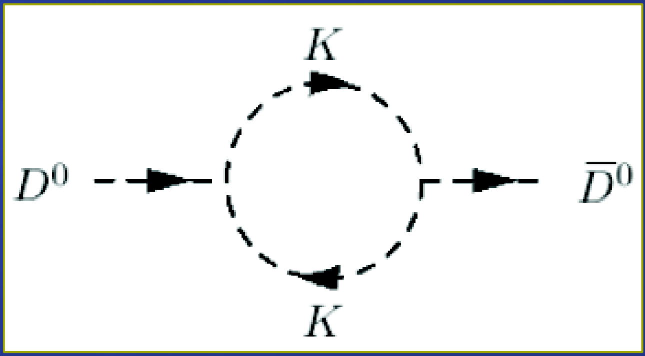
$$x = \frac{m_1 - m_2}{\Gamma_D} = 2\frac{m_1 - m_2}{\Gamma_1 + \Gamma_2} \qquad y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma_D} = \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

- Mixing well established in K^0 (1962), B^0 (1987), and B_s^0 (CDF 2006) decays
  - Evidence for D^0 from Belle (2006), Babar and CDF(2007)
  - Observation by LHCb (2012)

Mixing Characteristics

- Two sources
  - Short-range box diagram
    - Suppressed in SM
      - GIM suppression in absence of heavy top quark as in B and K
    - Possible enhancement by New Physics
  - Long-range intermediate states
    - Expected to dominate in SM
    - Large theoretical uncertainties

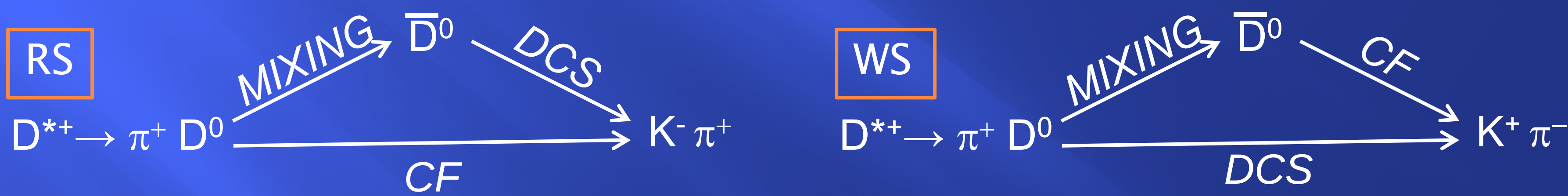




- Charm mixing slow
  - x,y $\ll$ 1

Mixing Signature

- Compare rate of wrong-sign $D^0 \to K^+\pi^-$ decays to right-sign $D^0 \to K^-\pi^+$ decays
  - Tag flavor at production with $D^{*+} \to D^0\pi^+$ decays
  - Wrong sign events can come from mixing or doubly Cabibbo-suppressed (DCS) decays
    - No oscillation in DCS decays



- Time evolution

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

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

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

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

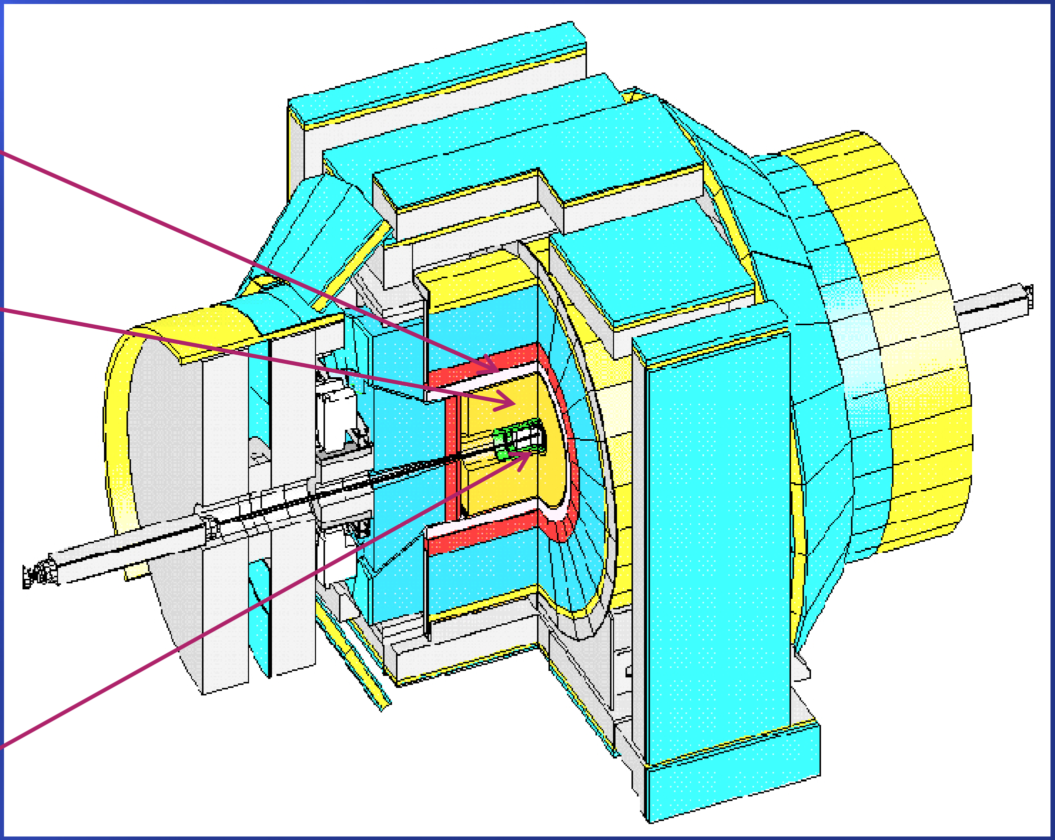
Data Sample

- Full CDF II data set
  - 9.6 fb^{-1} $p\bar{p}$ at $\sqrt{s}=1960$ GeV
- Heavy flavor hadronic decay trigger
  - Two opposite-charge tracks with $p_T>2$ GeV/c, $d_0>100\mu m$

1.4T Solenoid

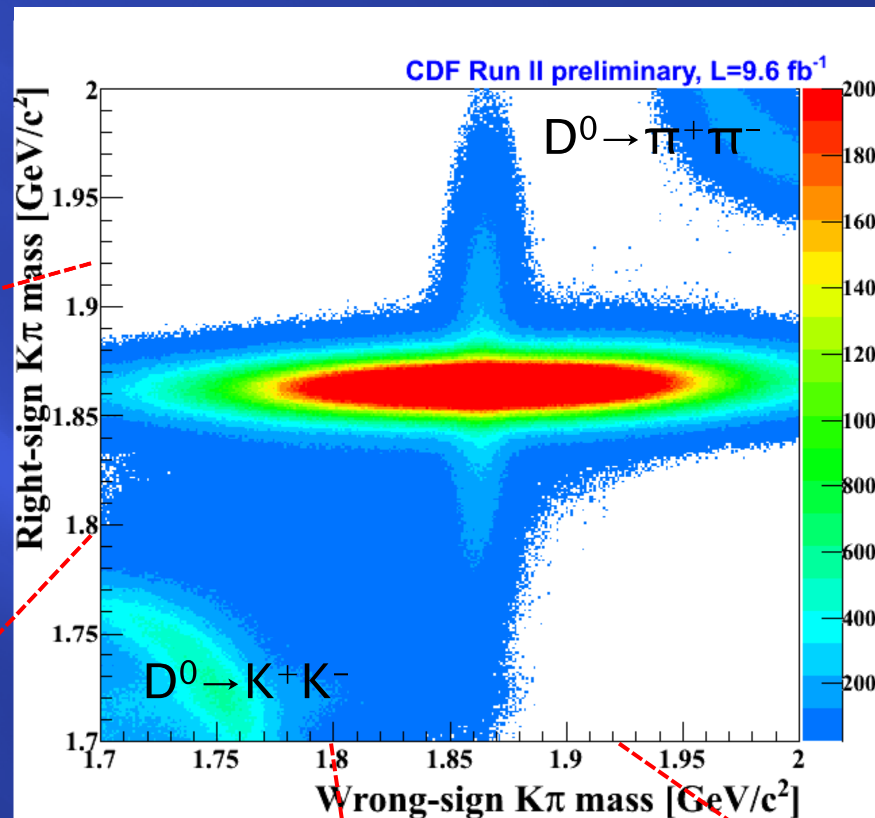
COT Drift Chamber
- $\delta p_T/p_T^2 \approx 0.07\%$
- PID from dE/dx with ~1.5σ K−π separation at pT=2 GeV

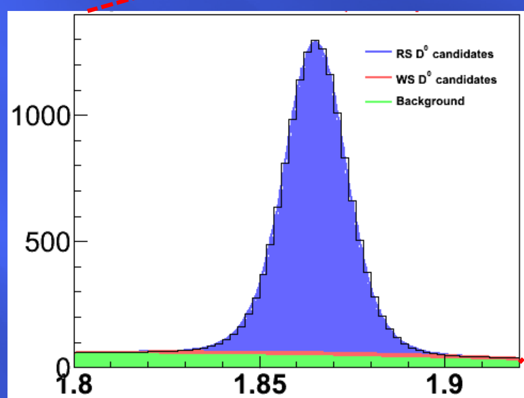
SVX Vertex Detector
- $\delta d_0 \approx 25\mu m$
- Beam spot rms 25μm



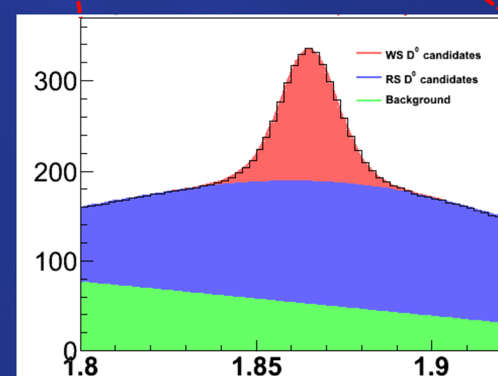
Reconstruction Method

- Reconstruct events with both RS and WS hypotheses



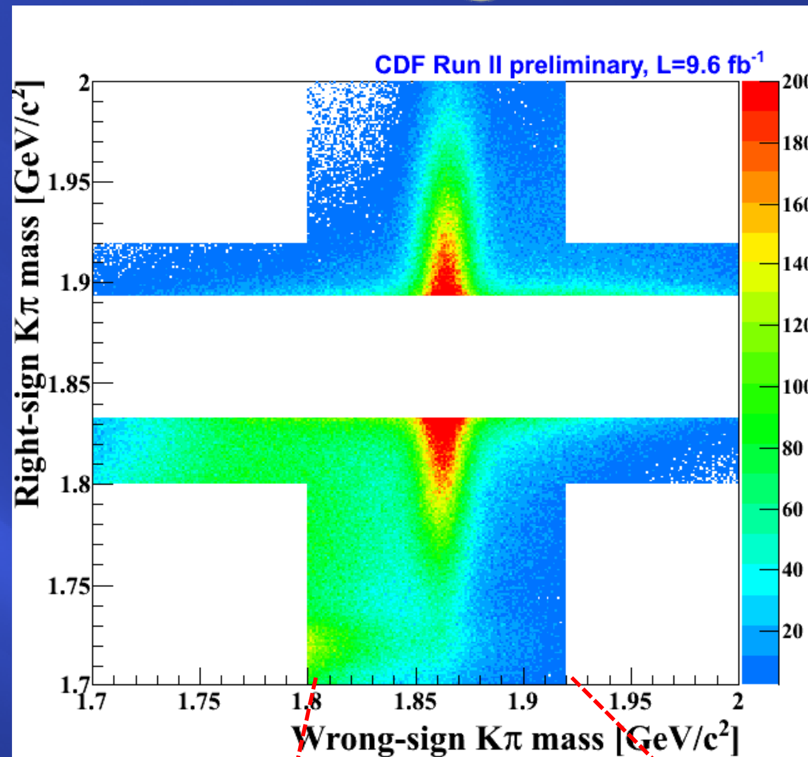


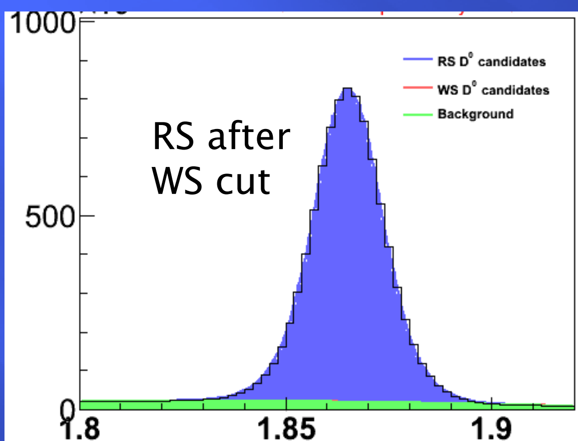
Large background to WS decays from incorrect charge assignment in RS decays

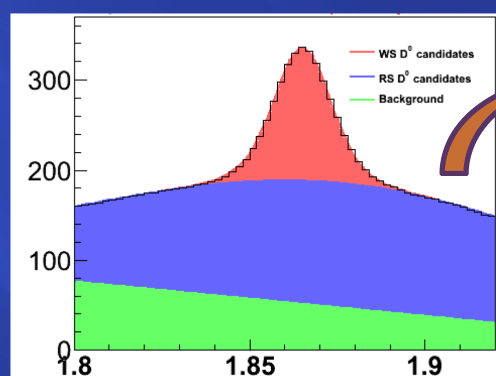


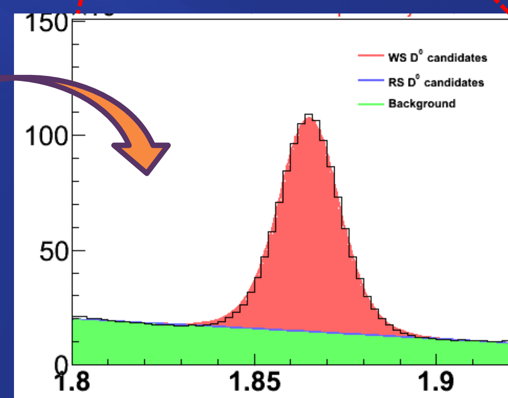
Reduce misassignment background

- Remove WS candidates consistent with RS hypothesis and vice versa
  - Removes 96% of background
  - 78% efficient for signal



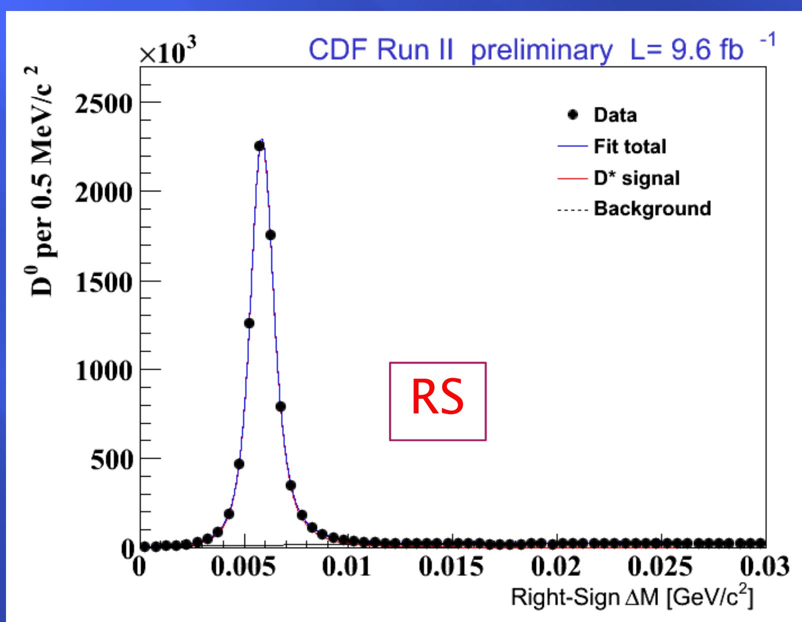


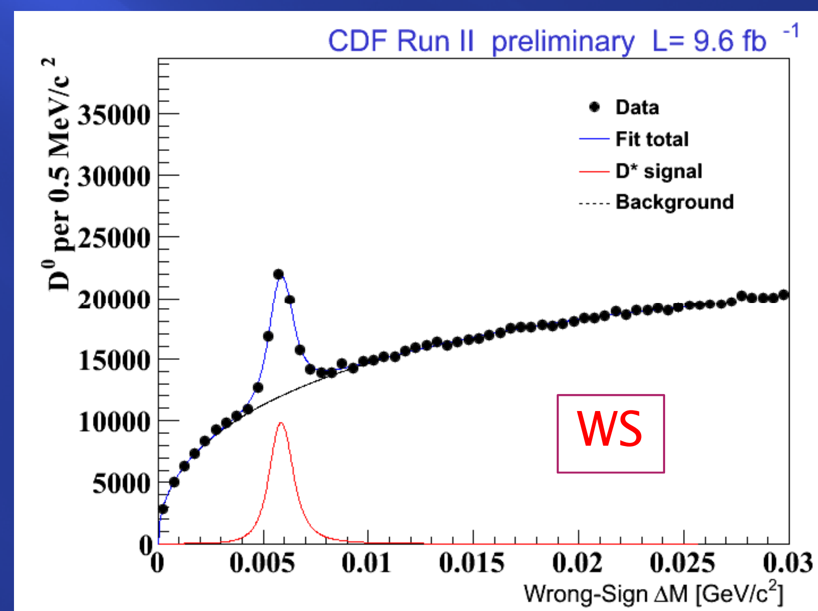




D* Reconstruction

- Standard method
  - Fit $\Delta m = m(K\pi\pi_{tag}) - m(K\pi) - m_{\pi}$
- Must account for D^0 and D* backgrounds
  - Cutting on D^0 peak would include fake D mesons in D* fit
  - In 10 bins of D^0 decay time, for RS and WS candidates, find the D^0 yield in 60 bins of Δm
    - Fit the resulting Δm distribution to get the D* yields

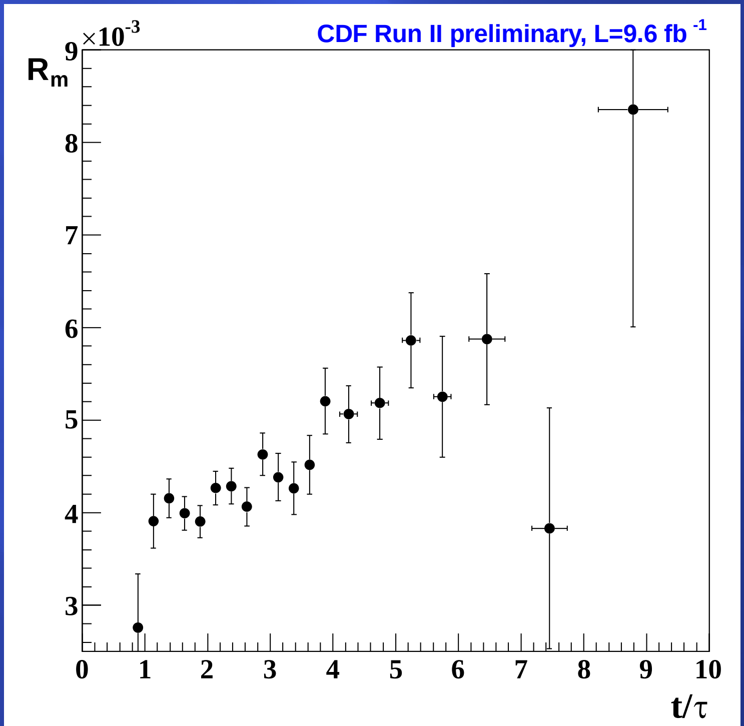




Wrong-Sign Ratio

- From D* yields, get measured ratio in each time bin

$$R_i = \frac{N_i(D^{*+} \to [K^+\pi^-]\pi^+) + N_i(D^{*-} \to [K^-\pi^+]\pi^-)}{N_i(D^{*+} \to [K^-\pi^+]\pi^+) + N_i(D^{*-} \to [K^+\pi^-]\pi^-)}$$

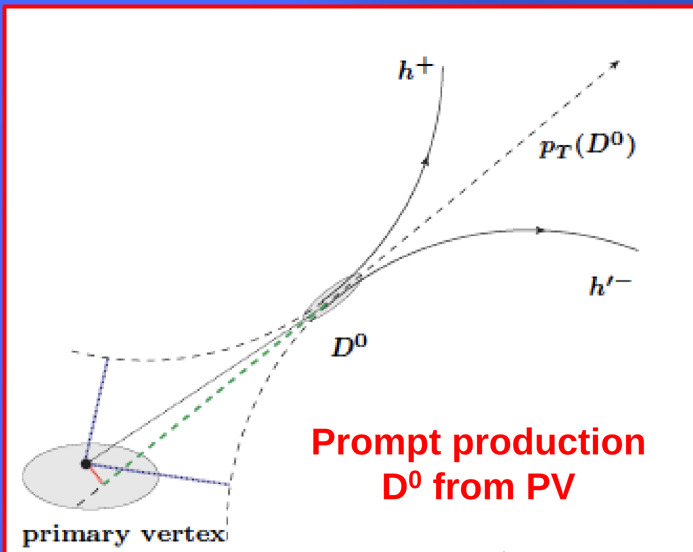


B Contamination

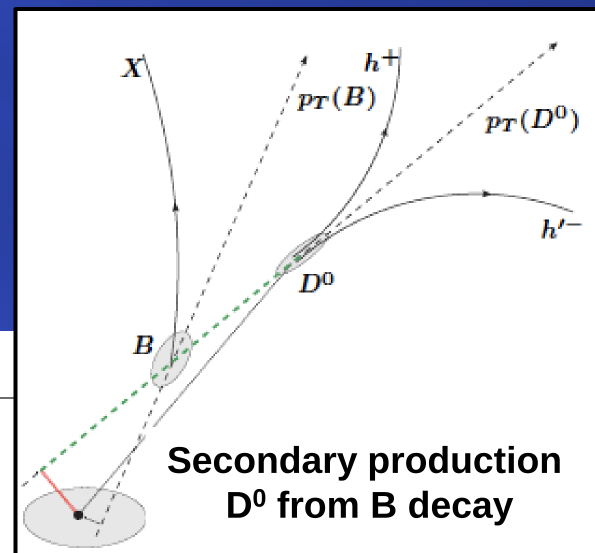
- Must account for B decay component
  - D^0 will have larger apparent lifetime
  - Mixing sample is required to be consistent with prompt production, but some B contamination remains

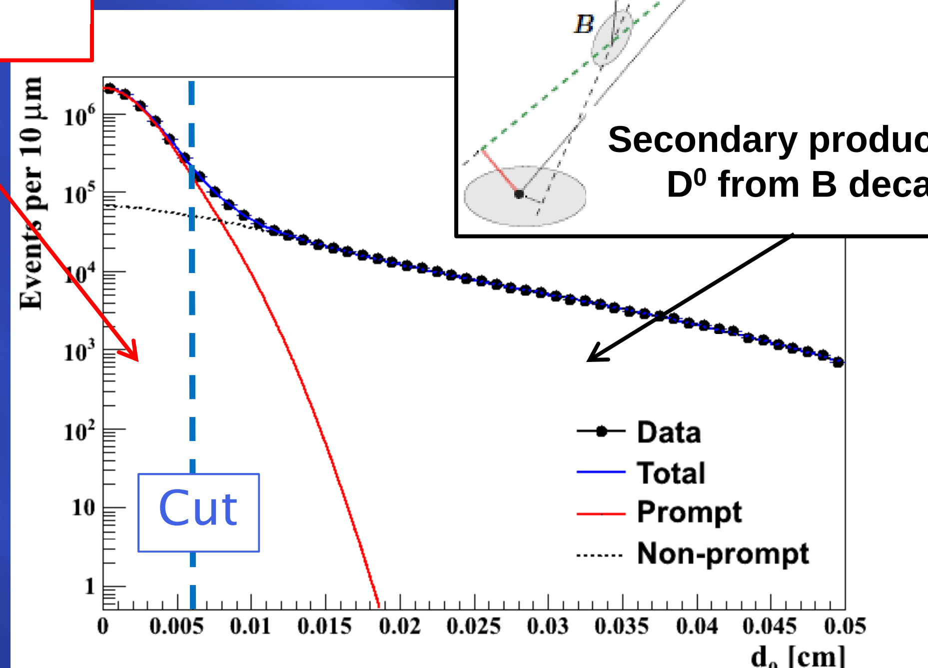
$$R_m(t) = \frac{N^{WS}(t) + N_B^{WS}(t)}{N^{RS}(t) + N_B^{RS}(t)}$$

B Fraction Measurement

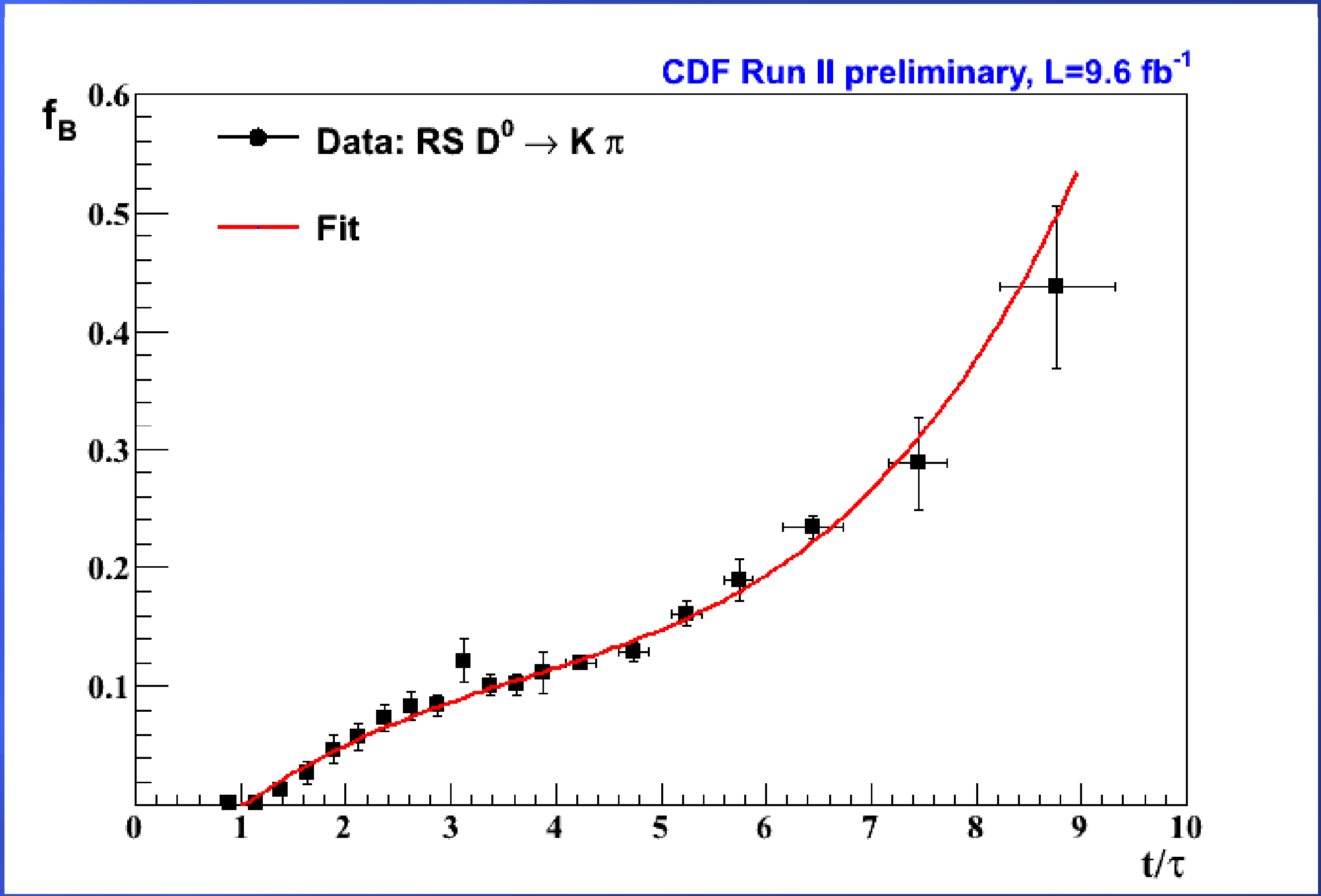


- Use impact parameter of reconstructed D^0 mesons





B Fraction



- Measured in RS data
- Fit to 4th order polynomial

Mixing Fit

- χ^2 fit vs. decay time
  - Correct for B component using MC for D decay time distribution as a function of apparent decay time

$$\chi^2 = \sum_{i=1}^{20} \left[\frac{r_i - R_m(t_i)}{\sigma_i} \right]^2 + C_{f_B}(\mathbf{p}) + C_{R_B}(\mathbf{h})$$

20 measured WS/RS points r_i with error σ_i

Gaussian constraint on f_B parameters (p)

Gaussian constraint on MC decay time distributions of D* from B

$$R_m(t) = \frac{N^{WS}(t) + N_B^{WS}(t)}{N^{RS}(t) + N_B^{RS}(t)} = R(t)\left[1 + f_B^{RS}(t)\left(\frac{R_B(t)}{R(t)} - 1\right)\right]$$

$$f_B^{RS}(t) = \frac{N_B^{RS}(t)}{N^{RS}(t) + N_B^{RS}(t)}$$

Fraction of RS D* from B decays

$$R_B(t) = \frac{N_B^{WS}(t)}{N_B^{RS}(t)}$$

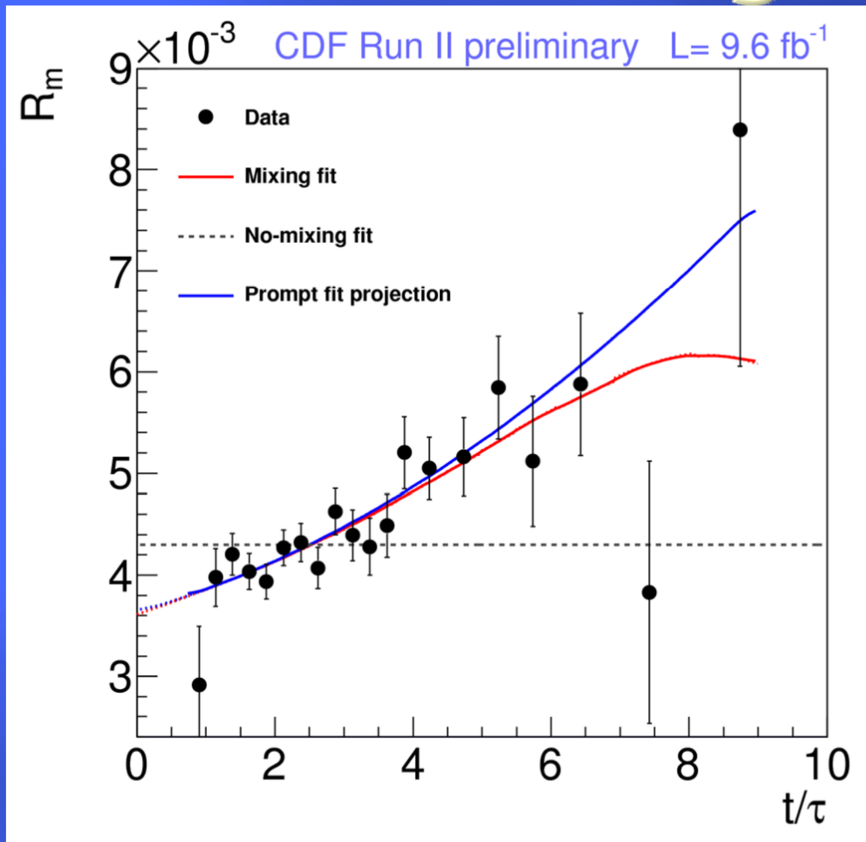
WS/RS ratio of non-prompt D^0

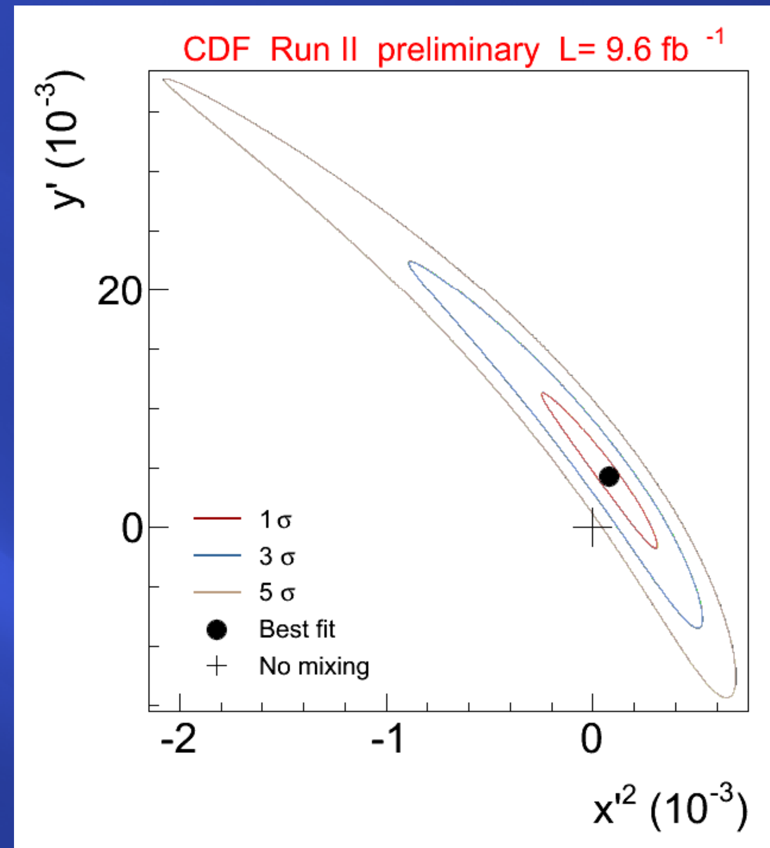
Calculated by weighting R(t) with the decay-time distribution of secondary D^0 from MC

Systematic Uncertainties

- The quoted uncertainties include the errors returned by the mass fits and uncertainties on the fractions f_B and the simulation time distributions.
- Investigated possible effects that could bias the result
  - Variation of D^0 signal shape
  - D^* signal shape
  - Partially reconstructed charm background in $K\pi$ fits
  - D^* background shape
  - Impact parameter non-prompt shape
  - Simulation time scale
  - Detector track reconstruction asymmetries
- Systematic uncertainties were found to be small relative to the statistical errors from data
  - For many, there is a common effect on the WS D^* and RS D^* fits, and the effect cancels in the WS/RS ratio

Mixing Fit Results

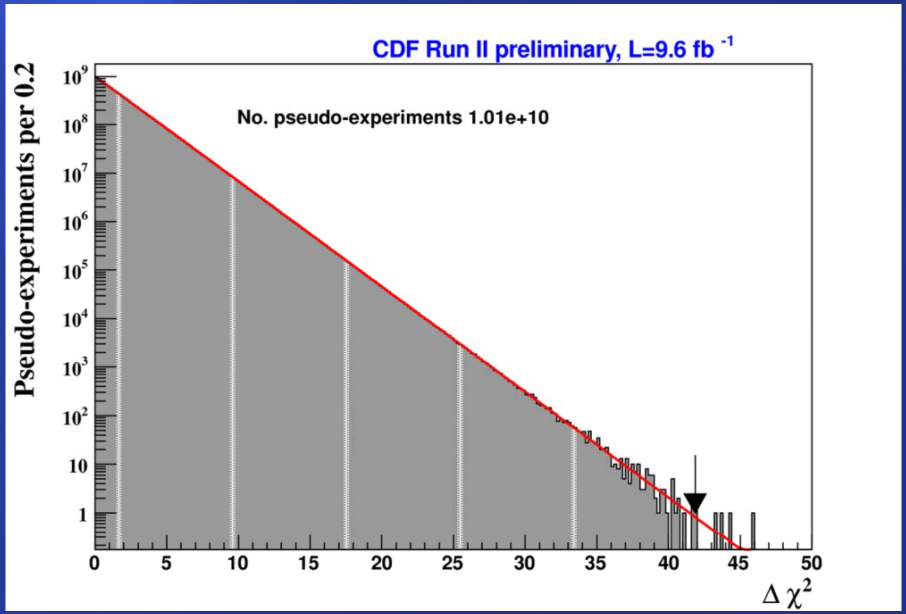




Fit type	χ^2/ndf	Parameter	Fitted values $\times 10^{-3}$	Correlation coefficient R_D	y'	x'^2
Mixing	16.91/17	R_D	3.51 ± 0.35	1	-0.967	0.900
		y'	4.3 ± 4.3		1	-0.975
		x'^2	0.08 ± 0.18			1
No-mixing	58.75/19	R_B	4.30 ± 0.06			

Signficance

- Beyesian probability contour
  - No mixing hypothesis excluded at 6.1σ
- Frequentist method using toy-MC in samples without mixing
  - χ^2 difference between mixing and no-mixing hypothesis exceeds observed in 6 of 10^{10} trials
  - No-mixing hypothesis excluded at 6.1σ



Summary

- CDF confirms observation of D^0 mixing at 6.1σ
  - Parameters similar to other experiments