Analysis of $D^0 - \bar{D}^0$ Mixing Using the CDF II Detector

DPF Meeting, 2009

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July 28, 2009

Charm Mixing Overview

- Mixing (Oscillations between matter and anti-matter)occurs when the mass eigenstates are not the same as flavor eigenstates.
- In $D^0 - \bar{D}^0$ system, assuming no CP violation, flavor eigenstates can be written in terms of mass eigenstates as:

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

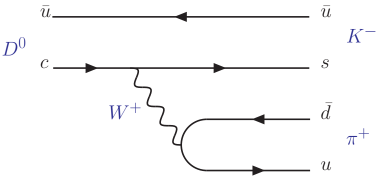
- Mixing is characterized by difference in masses and decay widths of $|D_1\rangle$ and $|D_2\rangle$ states.

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

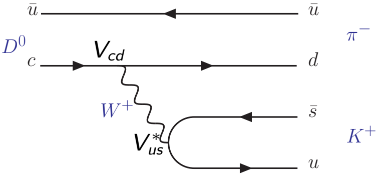
Charm Mixing Overview ...

- Cabibbo favored (CF) $D^0 \to K^-\pi^+$ decay and Doubly Cabibbo-suppressed (DCS) $D^0 \to K^+\pi^-$ decay.

CF Decay (RS)



DCS Decay (WS)



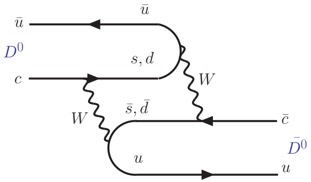
Suppressed at "*cdW*" and "*usW*" vertices by CKM factors.

- $\Gamma(K^+\pi^-)/\Gamma(K^-\pi^+) = 3.80 \pm 0.18 \times 10^{-3}$

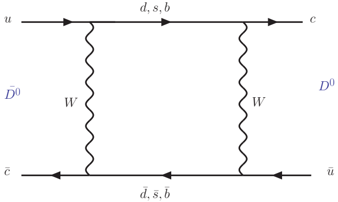
Charm Mixing Overview ...

- Mixing through long-range processes with intermediate $KK/\pi\pi$ states, followed by Cabibbo favored decay $\bar{D}^0 \to K^+\pi^-$ or through short-range processes.

Long-range



Short-range



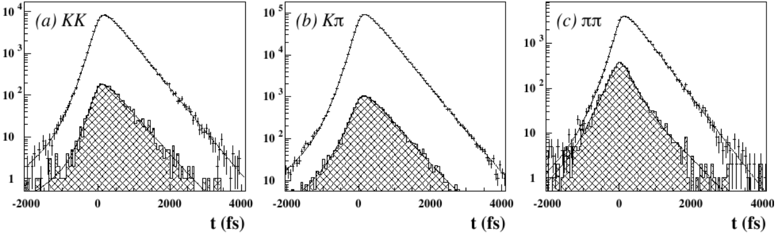
- Short range mixing is negligible in SM ($x_{box} = \mathcal{O}(10^{-5})$ and $y_{box} = \mathcal{O}(10^{-7})$)
- However exotic particles could enhance mixing.
- Long range calculations in SM yields $x, y < \mathcal{O}(10^{-3})$
- CP violations is extremely small in SM ($\approx \mathcal{O}(0)$); Evidence for CP violation will be an unambiguous signal to new physics.

Experimental Status

- First evidence for charm mixing came from Belle and BABAR in March 2007 at Moriond.

Belle

Decay time distribution of $D^0 \to KK/\pi\pi/K\pi$



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

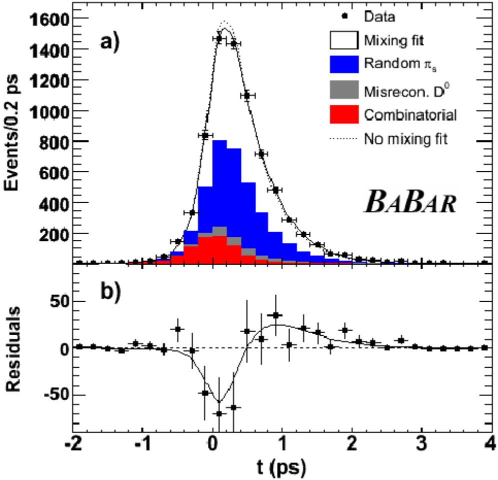
(here, t0 is free for each final state)

Confirmed by BABAR in December 2007

Experimental Status ...

BABAR

Difference in decay time distribution of $D^0 \to K^+\pi^-$ and $D^0 \to K^-\pi^+$



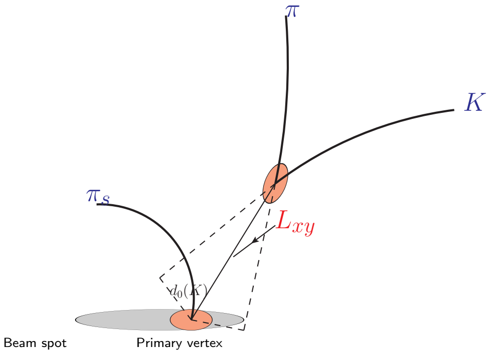
WS *mixing* fit projection in signal region

Confirmed by CDF in August 2007 at Lepton-Photon conference, with 3.8σ significance

Experimental Status ...

- Other charm mixing measurements (semi-leptonic decays, multi-pion hadronic decays, Dalitz plots) are 1-3 σ in significance.
- Heavy Flavor Averaging Group provides world average significance of 6.7σ
- However, no single analysis has observed mixing with significance $> 5\sigma$.
- No evidence of CP violation found.
- Plots presented today will show possibility of observation of mixing in $D^0 \rightarrow K\pi$ channel.

Event Reconstruction



$D^* \longrightarrow D^0\pi \longrightarrow K\pi$ decay in $x - y$ plane

- At CDF we analyze $D^* \rightarrow D^0\pi, D^0 \rightarrow K\pi$ decay chain.
- Pion from D^* has softer momentum
- D^0 decays to $K^+\pi^-$ or $K^-\pi^+$
- Reconstruct D^0 from K and π tracks
- This decay chain allows us to measure decay length from primary vertex.
- It also helps to improve signal significance.

Time-dependent decay rate

- Wrong sign signal:

$$D^{*+} \to D^0\pi^+,$$
$$D^0 \to K^+\pi^- \text{ (DCS/Mixing)}$$

  Right sign signal:

$$D^{*+} \to D^0\pi^+,$$
$$D^0 \to K^-\pi^+ \text{ (CF)}$$

  Similar for charge conjugates.

- Goal is to measure WS/RS ratio as a function of decay time t, given by (assuming no CP violation)

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

where,

$$R_D \equiv |\frac{A(DCS)}{A(CF)}|^2$$

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

$$x' = x\cos\delta + y\sin\delta$$

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

$\delta \equiv$ Strong Phase Difference between DCS and CF amplitudes

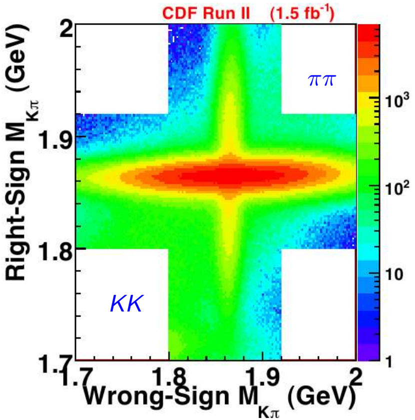
$\tau \equiv$ mean D^0 lifetime, $t \equiv$ Proper time

CDF Data

- Data collected from February 2002 to January 2009
- $\int Ldt \approx 4.0 \text{ fb}^{-1}$ with $\sqrt{s} = 1.96$ TeV
- Analysis technique is illustrated using $\int Ldt = 1.5 \text{ fb}^{-1}$
- Data passes Two-Track Trigger requirements.
  - Trigger is optimized for B-decays, but has good charm acceptance.
  - Tracks with displaced vertex
  - Good acceptance for proper decay times > 0.5 D^0 lifetimes.
- Trigger tracks are used to reconstruct D^0 candidate.

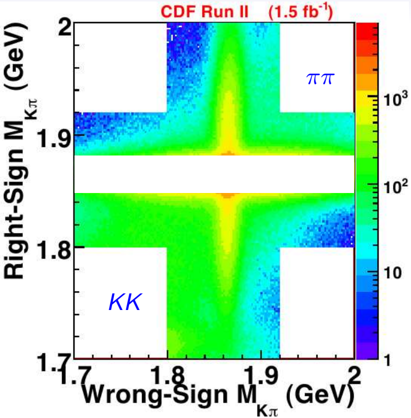
CDF Data ...

- D^0 candidates are reconstructed with both $K\pi$ and πK interpretations $\longrightarrow$ WS and RS.
- Huge RS events dominate WS signal



WS Signal Selection

- When looking for WS signal, exclude candidates with RS mass $|m_{K\pi}(RS) - m_{D^0}| < 20$ MeV
- We call this "Opposite Assignment Mass" cut
- To further clean up WS signal, we apply particle identification (PID) cut (dE/dx).
  - Compare two-track PID probability for $K\pi$ and πK assignments
  - Use higher value.

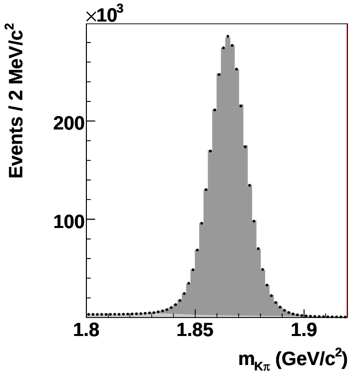


Opposite Mass Assignment + PID cuts exclude > 96.4% RS decays from WS signal. Keeps 78% of signal.

Analysis Method

- We measure the ratio of WS and RS D^*s a function of decay time and determine x'^2 and y'
- For the analysis assuming no CP violation, we combine D^{*+} and D^{*-}.
- To measure CP violation, the same technique is used separately for D^{*+} and D^{*-}.

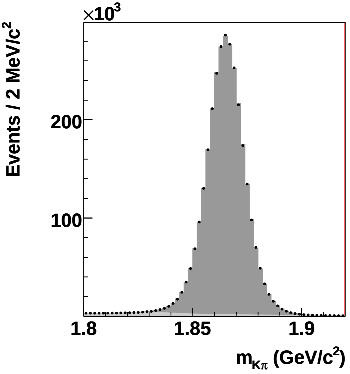
Clean RS signal



Right-sign $K\pi$ mass plot ($\int Ldt = 1.5$ fb^{-1}) to illustrate clean D^0 signal.
Dark grey: Signal fit
Light grey: Background fit

- We have a large and pure sample of RS D^0.

Clean RS signal



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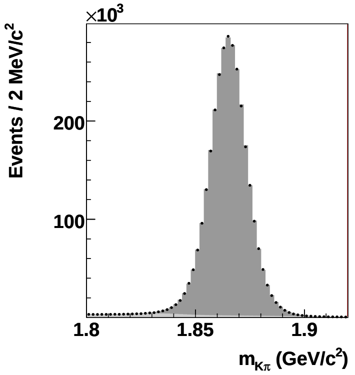
- Since RS and WS decays have the same kinematics, they have the same distributions.

Clean RS signal



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- We have a large and pure sample of RS D^0.
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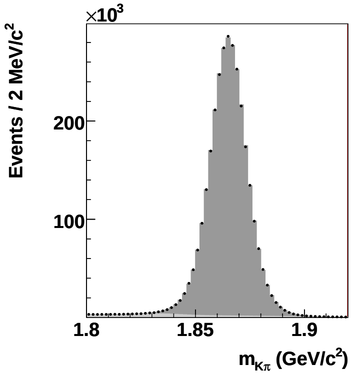
- We obtain signal shapes from RS distribution and use the same shapes for WS distributions.

Clean RS signal



Right-sign $K\pi$ mass plot ($\int Ldt = 1.5$ fb^{-1}) to illustrate clean D^0 signal.
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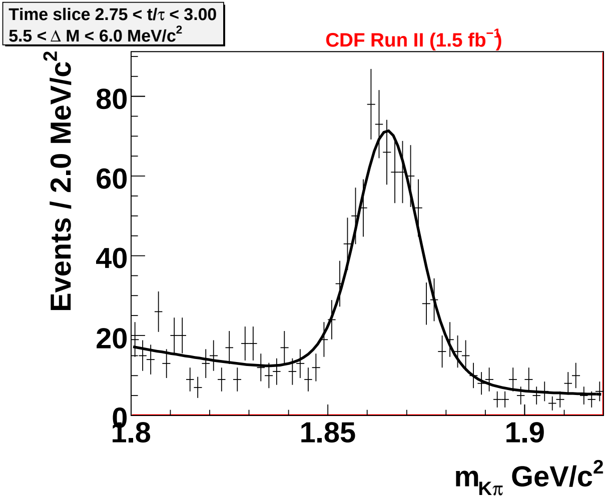
- We have a large and pure sample of RS D^0.
- Since RS and WS decays have the same kinematics, they have the same distributions.
- We obtain signal shapes from RS distribution and use the same shapes for WS distributions.
- No Monte Carlo is needed for this technique and avoids systematic uncertainties arising from fixing the signal and background shapes from Monte Carlo.

First Step: $K\pi$ Mass Fit

- Divide RS and WS data in 20 time bins and divide each time bin 60 mass difference bins. $\Delta M = \mathrm{m(D^*) - m(D^0) - m(\pi_s)}$

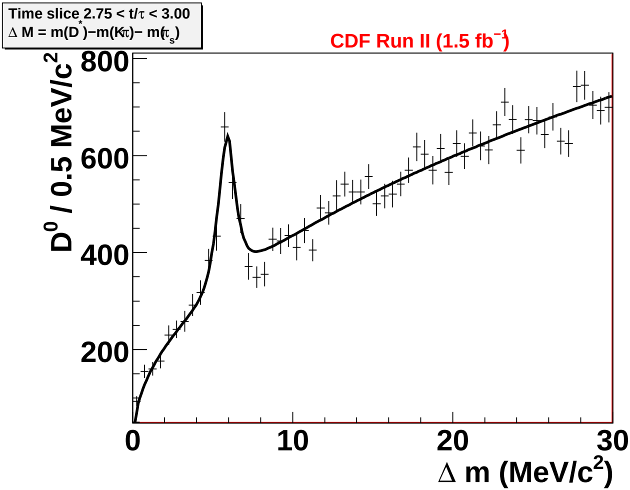
- Fitting $K\pi$ mass distribution for a given time bin and given mass difference bin gives D^0 yield corresponding to the ΔM bin.



- WS $K\pi$ Fit for $2.75 < t/\tau < 3.00$ and $5.5 < \Delta M < 6.0$ MeV/c^2
- Signal: Correctly reconstructed D^0 + random pion
- Background: Mis-identification + Combinatorial

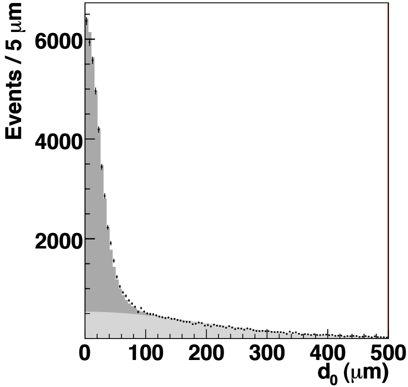
Step 2: Mass Difference Fit

- Fitting $K\pi$ mass distributions in all 60 mass difference bins gives # D^0 vs. ΔM distribution.
- ΔM fit give D^* yield for the given time bin.



- WS ΔM distribution for $2.75 < t/\tau < 3.00$ time bin
- Signal Peak: Correctly reconstructed D^*s
- Background: D^0+ random pion.

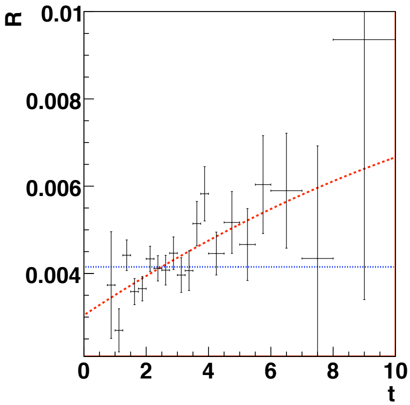
Impact Parameter of D^0



RS distribution for $5 < t/\tau < 6$ (1.5 fb^{-1}). Light grey: B-background

- D^* from B decays will have wrong decay time.
- Prompt D^* originating at the primary vertex form narrow peak in IP distribution.
- Wide distribution is from D^*s from secondary decays.

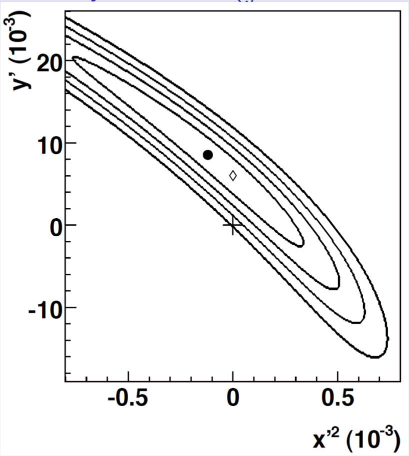
WS/RS Ratio ($\int L dt = 1.5 \text{ fb}^{-1}$)



- Best Fit $\chi^2 = 19.2$
- No Mixing Fit ($x'^2 = y' = 0$) $\chi^2 = 36.8$

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

Probability Contours ($\int Ldt = 1.5\ \text{fb}^{-1}$)



Bayesian probability contours equivalent to 1-4 σ

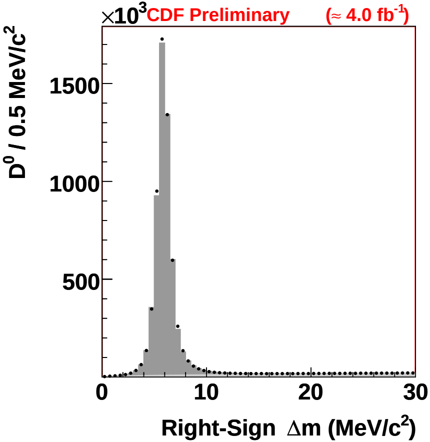
- $R_D = (3.04 \pm 0.55) \times 10^{-3}$
- $y' = (8.54 \pm 7.55) \times 10^{-3}$
- $x'^2 = (-0.12 \pm 0.35) \times 10^{-3}$

- No-mixing excluded at 3.8 Gaussian standard deviation level
- $+ \equiv$ No-mixing point ($x'^2 = y' = 0$)
- $\bullet \equiv$ Best fit point
- $\diamondsuit \equiv$ Highest probability physically allowed point ($x'^2 > 0$)

Current Developments

- We now have $\approx 4.0\ \text{fb}^{-1}$ luminosity available.
- We explored new cuts but did not find significant improvements.
- We also tried applying Artificial Neural Network technique. The result produced were comparable to the standard analysis confirming optimal cuts.

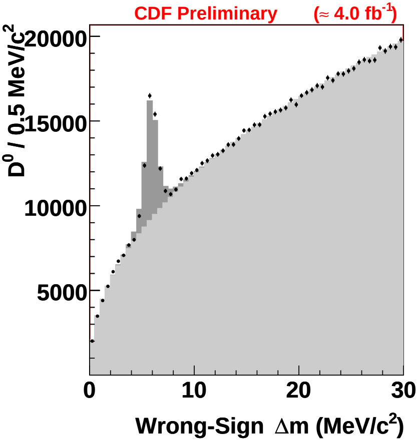
Time Integrated RS D^* distribution with $\approx 4.0\ \text{fb}^{-1}$



- RS D^* Yield: $\approx 5.7 \times 10^6$.
- With $\int L dt = 1.5\ \text{fb}^{-1}$, this number was 3.0 million.

Current Developments...

Time Integrated WS D^* with $\approx 4.0\ \text{fb}^{-1}$



- $\#$WS $D^* \approx 24000$
- For $1.5\ \text{fb}^{-1}$, $\#$ WS $D^* = 13000$

- Assuming that significance is proportional to square root of number of events (significance $\propto \sqrt{N}$) and that the central values remain the same, we may expect significance of $\approx 5\sigma$

Current Developments

- The work to incorporate new data is in progress
- Mixing can be measured separately for D^{*+} and D^{*-} for CP violation, using the same technique.
- Since Kaon and pion have different absorption cross-section in the detector material, we need to determine corrections on the mixing parameters.
- The CP violation study work is in progress.

Conclusion

- We presented $D^0 - \bar{D}^0$ mixing analysis technique using 1.5 fb^{-1} integrated luminosity.
- The published result excluded no-mixing with 3.8 Gaussian standard deviation.
- With $\approx 4.0\ \mathrm{fb}^{-1}$ integrated luminosity currently available, we are approaching observation in $D^0 \to K\pi$ channel.