D-mixing at CDF

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On behalf of the CDF collaboration

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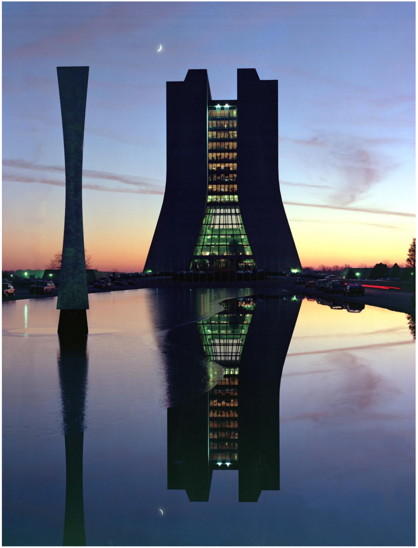
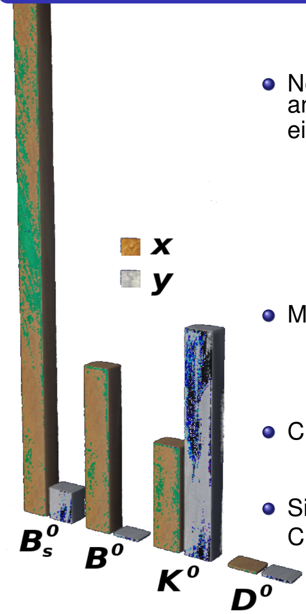
Outline

1. Introduction
   - Neutral Flavored Mesons Mixing
   - Charm Mixing in $D^0 \to K^+\pi^-$
   - Important CDFII features
2. D-Mixing Analysis - PRL 100 (2008) 121802
   - Data Sample
   - Extract RS and WS Signals
   - Strategy
   - Results on Mixing Hypothesis
3. Prospects
   - Charm Mixing
   - CP Violation
4. Conclusions





- Neutral mesons can oscillate between matter and anti-matter: mass eigenstates are different from flavor eigenstates

$$i\frac{d}{dt}\begin{pmatrix}|D^0\rangle\\ |\overline{D}^0\rangle\end{pmatrix}=\left[\begin{pmatrix}M_{11} & M_{12}\\ M_{12}^* & M_{22}\end{pmatrix}-\frac{i}{2}\begin{pmatrix}\Gamma_{11} & \Gamma_{12}\\ \Gamma_{12}^* & \Gamma_{22}\end{pmatrix}\right]\begin{pmatrix}|D^0\rangle\\ |\overline{D}^0\rangle\end{pmatrix}$$

$$|D_{L,H}\rangle = p\,|D^0\rangle \pm q\,|\overline{D}^0\rangle \qquad \text{where} \qquad \frac{q}{p}=\sqrt{\frac{M_{12}^*-\frac{i}{2}\Gamma_{12}^*}{M_{12}-\frac{i}{2}\Gamma_{12}}}$$

- Mixing usually described by two parameters

$$x=\frac{\Delta M}{\Gamma}=\frac{M_H-M_L}{(\Gamma_H+\Gamma_L)/2}, \qquad y=\frac{\Delta\Gamma}{2\Gamma}=\frac{\Gamma_H-\Gamma_L}{(\Gamma_H+\Gamma_L)}$$

- Charm mixing is much slower than kaon or beauty mixing

$$x, y \lesssim \mathcal{O}(10^{-3})$$

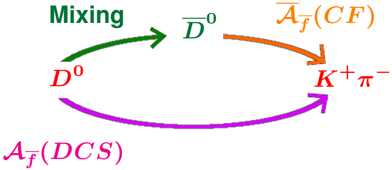
- Signals for New Physics would be $|x| \gg |y|$ or evidence for CP violation

Charm Mixing in $D^0 \to K^+\pi^-$

- Tag D^0 flavor at production time by $D^{\star +} \to D^0 \pi_s^+$ decay
- Measure time-dependence of Wrong-Sign $D^{\star +} \to [K^+\pi^-]\pi_s^+$ to Right-Sign $D^{\star +} \to [K^-\pi^+]\pi_s^+$ decay rates ratio

For WS two processes interfere:

- Mixing then Cabibbo-Favoured decay
- Doubly-Cabibbo-Supressed decay



assumes $|x|, |y| \ll 1$
and No-CPV

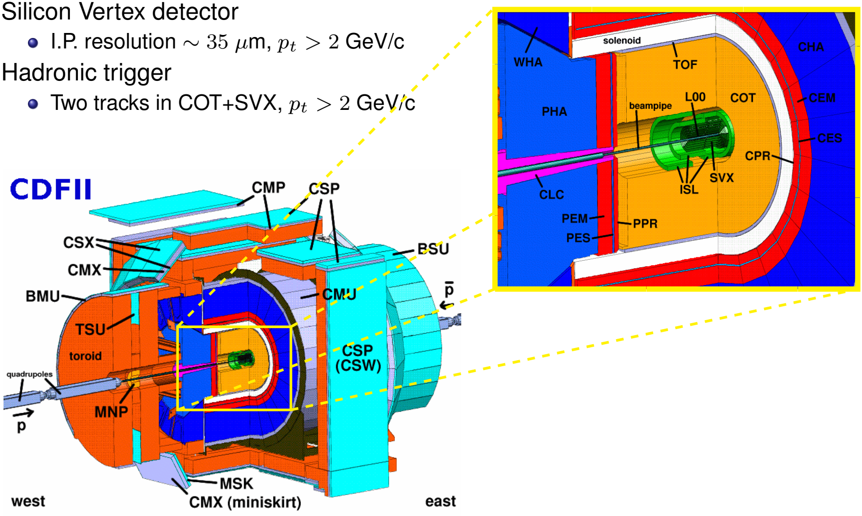
$$\boxed{R(t) = R_D + \sqrt{R_D}\, y' \,(\Gamma_D t) + \frac{x'^2 + y'^2}{4}\,(\Gamma_D t)^2}$$

$$\frac{\mathcal{A}_{\overline{f}}(DCS)}{\overline{\mathcal{A}}_{\overline{f}}(CF)} = \sqrt{R_D}\, e^{-i\delta_{K\pi}}$$

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

Important CDFII features

- Central drift chamber in magnetic field
  - $\sigma(p_t)/p_t^2 \sim 0.15\%$ (GeV/c)$^{-1}$ (excellent tracking/mass resolution)
  - dE/dx measurement
- Silicon Vertex detector
  - I.P. resolution $\sim 35\ \mu$m, $p_t > 2$ GeV/c
- Hadronic trigger
  - Two tracks in COT+SVX, $p_t > 2$ GeV/c



Data Sample

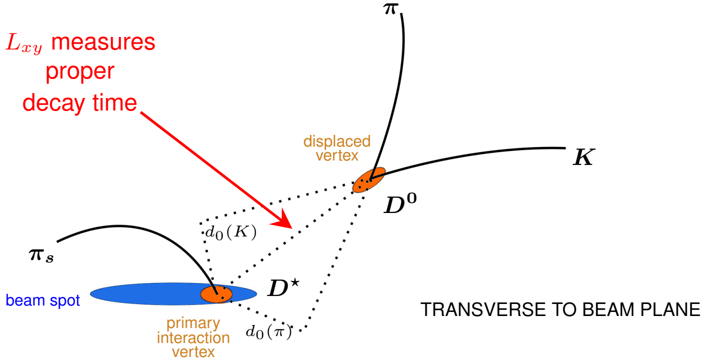
Data collected from Feb 2002 to Jan 2007: $\int \mathcal{L}dt \sim$1.5/fb @ $\sqrt{s}$ =1.96 TeV

Decay reconstruction:

- Two opposite charge tracks from a displaced vertex (hadronic trigger) form $D^0 \to K\pi$ candidate
  - $|d_0(K,\pi)| > 100$ μm
  - $L_{xy} > 200$ μm

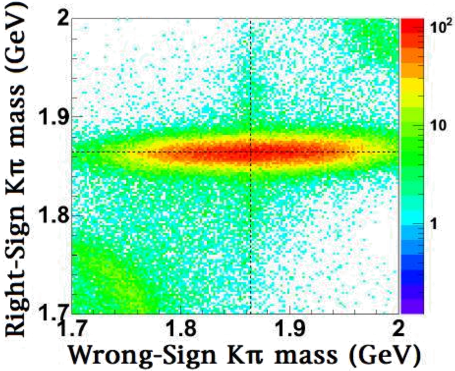
(good acceptance for proper decay time $\gtrsim 0.5$ D^0 lifetimes)

- Add a "soft" track to form $D^\star \to D^0\pi_s$ candidate



Extract RS and WS Signals

- D^0 candidate considered with both $K^-\pi^+$ and π^-K^+ particle assignments
  - Mis-assigned mass distribution has width $10\times$ the correct assignment width (~ 8 MeV/c^2)



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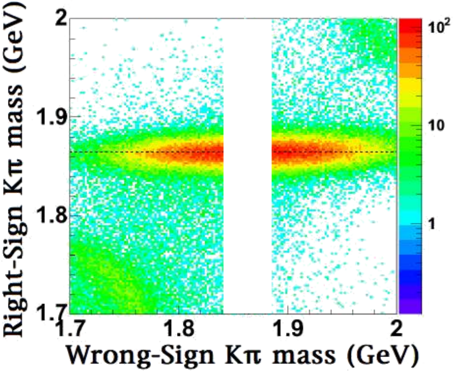
- For RS exclude candidates with WS mass $|m_{K\pi} - m_{D^0}| < 20$ MeV/c^2 and viceversa
  - Keeps 78% of signal, 3.6% mis-assigned



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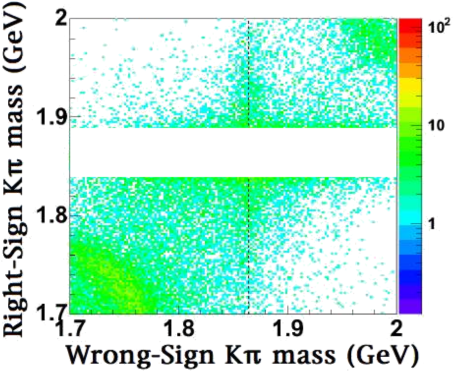

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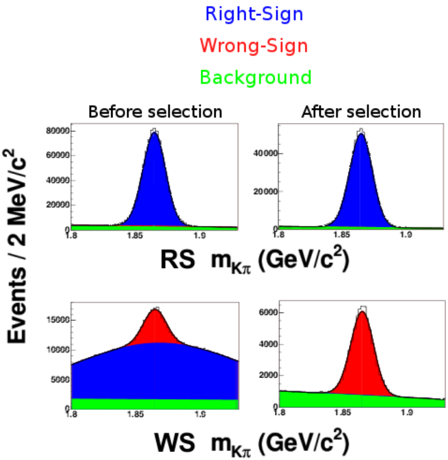
- For RS exclude candidates with WS mass $|m_{K\pi} - m_{D^0}| < 20$ MeV/c^2 and viceversa
  - Keeps 78% of signal, 3.6% mis-assigned
- Compare two-track PID probability (from measured dE/dx) for $K^-\pi^+$ and π^-K^+ assignments, use higher value
- Mass and PID cuts greatly clean up the mis-assigned background



Analysis Strategy

fit $R(t)$ to determine mixing parameters

proper decay time	ratio R for each decay time bin
$D^\star$ impact parameter	prompt or from B-decay
Δm	$D^\star$ or not $D^\star$
$m_{K\pi}$	D^0 or not D^0

When events are divided into RS and WS perform a series of binned fits to look for mixing:

- Signal yields from a set of fits is used in the next round of fits
- Deal with particular backgrounds one at a time
- Backgrounds from early fit stages are not present in later fits

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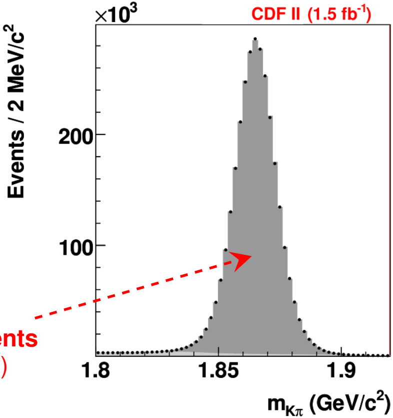

$3.04 \cdot 10^6$ **RS events**
(time integrated)

Clean RS signal:

- RS signal PDFs obtained from fits of the RS data
- WS signal events have the same distributions as RS except for decay time (same kinematics)
- Use data as much as possible, MC only for guidance

fit $R(t)$ to determine mixing parameters

proper decay time	ratio R for each decay time bin
$D^\star$ impact parameter	prompt or from B-decay
Δm	$D^\star$ or not $D^\star$
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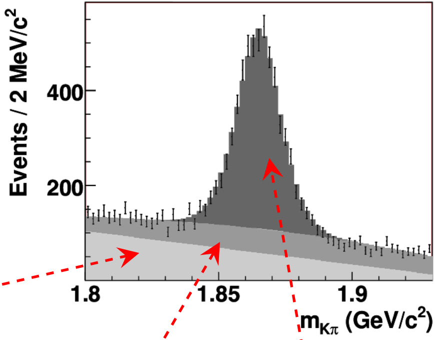


combinatorial bkg

mis-identified D^0

D^0 signal

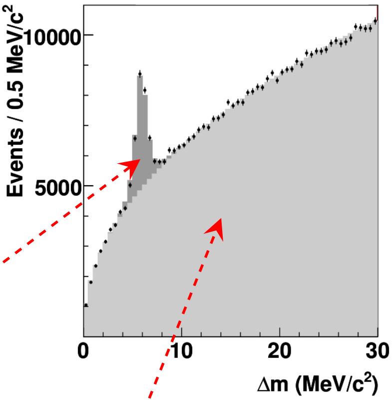
Fit for D^0 yield:

- Single signal shape used for all fits
- Parameters for background independent for all fits
- Typical χ^2/ndf ≈ 1

Analysis Strategy: step 2

fit $R(t)$ to determine mixing parameters

proper decay time	ratio R for each decay time bin
$D^\star$ impact parameter	prompt or from B-decay
$\boxed{\Delta m}$	$D^\star$ or not $D^\star$
$m_{K\pi}$	D^0 or not D^0



WS $D^\star$ signal
12700 events
(time integrated)

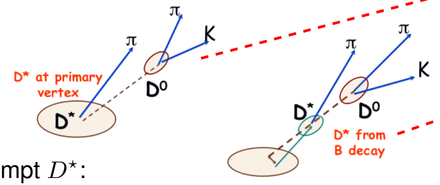
D^0 + random π_s

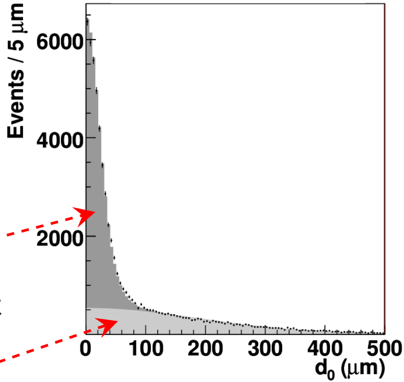
Fit for $D^\star$ yield:

- Same signal shape for all fits
- Background shape constant in time
- Time-independent parameters for signal and background yields

fit $R(t)$ to determine mixing parameters

proper decay time	ratio R for each decay time bin
$D^\star$ impact parameter	prompt or from B-decay
Δm	$D^\star$ or not $D^\star$
$m_{K\pi}$	D^0 or not D^0





Fit for prompt $D^\star$:

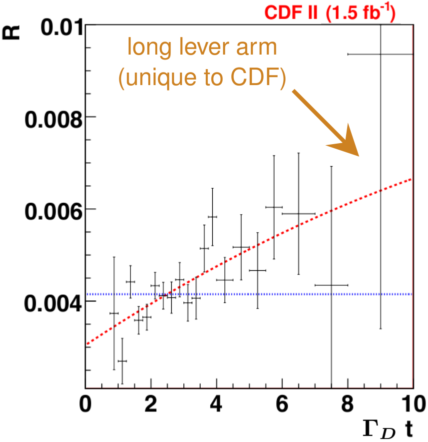
- $D^\star$ from B decays will have wrong decay time
- $D^\star$ from B decays have a broader impact parameter (d_0) distribution than promptly produced $D^\star$

Analysis Strategy: step 4

fit $R(t)$ to determine mixing parameters

proper decay time	ratio R for each decay time bin
$D^\star$ impact parameter	prompt or from B-decay
Δm	$D^\star$ or not $D^\star$
$m_{K\pi}$	D^0 or not D^0

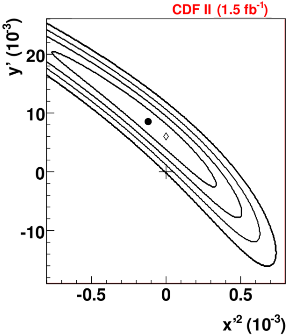
$$R(t) = R_D + \sqrt{R_D}\, y' \,(\Gamma_D t) + \frac{x'^2 + y'^2}{4} (\Gamma_D t)^2$$



Quoted uncertainties are statistical + systematic

	χ^2/ndf	$R_D(10^{-3})$	$y'(10^{-3})$	$x'^2(10^{-3})$
Best fit (red curve)	$19.2/17$	3.04 ± 0.55	8.54 ± 7.55	-0.12 ± 0.35
No mixing fit (blue line)	$36.8/19$	4.15 ± 0.10	0	0

Results on Mixing Hypothesis



No-mixing excluded at 3.8 Gaussian standard deviations level

- Probability intervals for the mixing parameters equivalent to 1-$4\ \sigma$
- $+$ $=$ no mixing point $(x'^2, y' = 0)$
- $\bullet$ $=$ best fit point
- $\Diamond$ $=$ highest probability physically allowed point $(x'^2 > 0)$

	data	N_{WS}	$x'^2(10^{-3})$	$y'(10^{-3})$	signif.
Belle *Phys. Rev. Lett.* **96** (2006) 151801	400/fb	4024	$0.18^{+0.21}_{-0.23}$	$0.6^{+4.0}_{-3.9}$	$2.0\ \sigma$
BaBar *Phys. Rev. Lett.* **98** (2007) 211802	384/fb	4030	-0.22 ± 0.37	9.7 ± 5.4	$3.9\ \sigma$
CDF *Phys. Rev. Lett.* **100** (2008) 121802	1.5/fb	12700	-0.12 ± 0.35	8.5 ± 7.6	$3.8\ \sigma$

Prospects

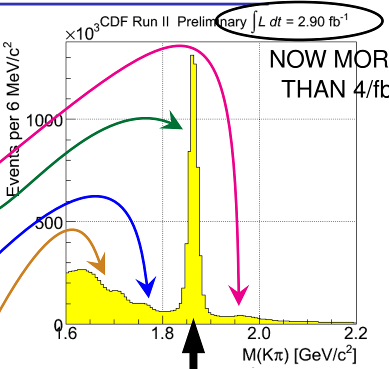
CDF has world's largest charm sample:

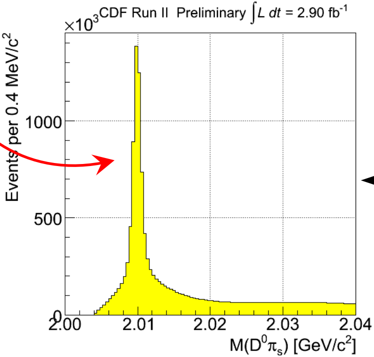
$D^{\star +} \to D^0 \pi_s^+ +$ C.C.

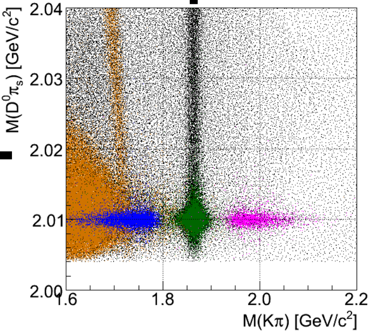
- $\pi^+\pi^- \approx 170 \cdot 10^3$ events
- $K^\mp\pi^\pm \approx 4 \cdot 10^6$ events
- $K^+K^- \approx 360 \cdot 10^3$ events

Physics backgrounds:

Partially reconstructed $D^{0/\pm} \to 3$Bodies







Prospects: Charm Mixing

- Improve the existing analysis
  - more data
  - more sophisticated techniques
  - allowing for CPV
- Perform also lifetime analysis in $D^0 \to h^+h^-$ ($h = K$ or π)

$$y_{\text{CP}} = \frac{\tau(K^-\pi^+)}{\tau(h^-h^+)} - 1$$

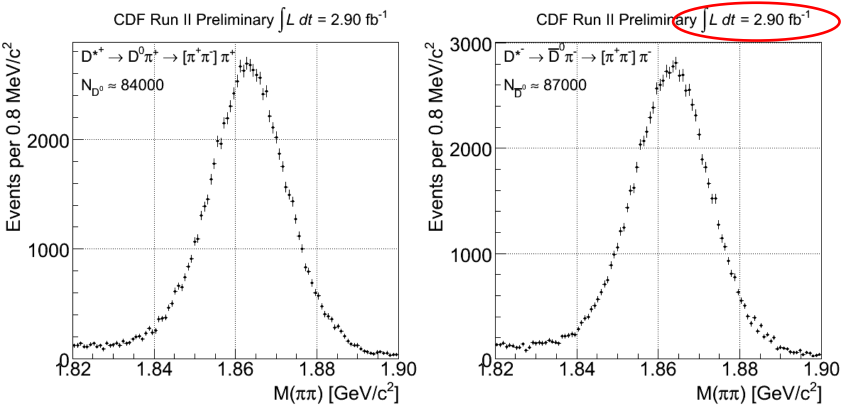
	data	$y_{CP}(\%)$	signif.
Belle	540/fb	$1.31 \pm 0.32\ (stat.) \pm 0.25\ (syst.)$	$3.2\ \sigma$
Phys. Rev. Lett. **98** (2007) 211803			
BaBar	384/fb	$1.03 \pm 0.33\ (stat.) \pm 0.19\ (syst.)$	$3.0\ \sigma$
Phys. Rev. **D 78** (2008) 011105			

Prospects: CP Violation

Update CDF published results on CPV asymmetries in Cabibbo-supressed D^0 decays: *Phys. Rev. Lett.* **94** (2005) 122001

Preliminary study on 2.9/fb to estimate statistical resolution

DATA BACKGROUND-SUBTRACTED



Prospects: CP Violation

Estimated statistical uncertainty on $D^0 \to \pi^+\pi^-$ CP asymmetry based on counting:

$$A_{\mathrm{CP}}(h^+h^-) = \frac{N(\overline{D}^0 \to h^+h^-) - N(D^0 \to h^-h^+)}{N(\overline{D}^0 \to h^+h^-) + N(D^0 \to h^-h^+)}$$

	data	$A_{\mathrm{CP}}(\pi^+\pi^-)$ (%)
Our estimate	2.9/fb	$\mathrm{xxx} \pm 0.24\ (stat.)$
CDF *Phys. Rev. Lett.* **94** (2005) 122001	0.123/fb	$+2.00 \pm 1.20\ (stat.) \pm 0.60\ (syst.)$
BaBar *Phys. Rev. Lett.* **100** (2008) 061803	386/fb	$-0.24 \pm 0.52\ (stat.) \pm 0.22\ (syst.)$
Belle *Phys. Lett.* **B 670** (2008) 190	540/fb	$-0.43 \pm 0.52\ (stat.) \pm 0.12\ (syst.)$

similar estimate for $D^0 \to K^+K^-$

Conclusions

- CDF has the world's largest charm sample: rich program that includes access to CPV asymmetries, branching fractions, mixing, mixing-induced CPV
- In 2007 CDF confirmed the *BaBar* evidence for charm mixing with time dependent $D^0 \to K^+\pi^-$ analysis: no mixing excluded @ $3.8\ \sigma$
- Now a lot of promising work in progress: e.g. expected statistical resolutions on CPV asymmetries in Cabibbo-suppressed D^0 decays 2$\times$ better than B-Factories

Backup Slides

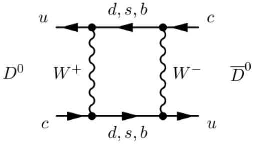
Charm Mixing Predictions

Standard Model

[arXiv:hep-ph/0310076]

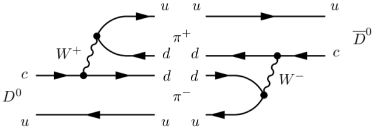
- Box diagram SM charm mixing rate naively expected to be very low:

$x, y \lesssim \mathcal{O}(10^{-5})$



  - b loop CKM suppressed $\longrightarrow$ $|V_{ub}V_{cb}^*|^2 \ll 1$
  - s, d loops GIM suppressed $\longrightarrow$ $(m_s^2 - m_d^2)/m_W^2$
- Enhanced rate SM calculations generally due to long-distance y contributions:

$$x, y \lesssim \mathcal{O}(10^{-3})$$

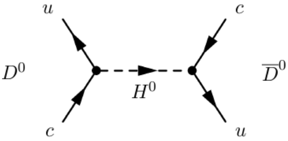


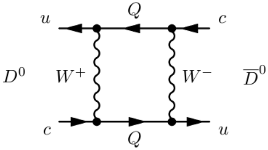
- **Generally: calculations are difficult and uncertainties are quite large**

New Physics

[arXiv:0705.3650]

- Possible enhancements to mixing due to new particles and interactions in new physics models
- Most new physics predictions for x:
  - Fourth generation down-type quarks
  - Extended Higgs, tree-level FCNC
  - Supersymmetry: gluinos, squarks





- **Signals for NP would be $|x| \gg |y|$ or evidence for CPV**

Methods Comparison

CDF:

- Binned fits
- 12700 WS $D^{\star}$ produced at primary vertex
- D^0 decay times from 0.75 to 10 lifetimes
- Only no CPV fit ($D^{\star +}$ and $D^{\star -}$ combined)

BaBar and *Belle*:

- Unbinned maximum likelihood fit
- 4000 WS but better signal/background
- D^0 decay times from 0 to ~ 4 lifetimes
- Additional fit allowing for CPV ($D^{\star +}$ and $D^{\star -}$ separated)

Uncertainties

Quoted uncertainties are statistical + systematic

- Most parameters for the background shapes and amplitudes are determined by the fits of the data, associated syst. uncertainties already included in the uncertainty on the RS and WS signal yields
- We added additional systematic effects that were not part of the fit procedure (bkg shape in the Δm distribution)
- Detector geometric acceptance, trigger efficiency, PID, time resolution have negligible effect on the WS/RS ratio (compared to current uncertainties)