A Future High Statistics Charm Mixing Experiment using the Tevatron

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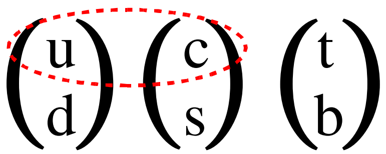
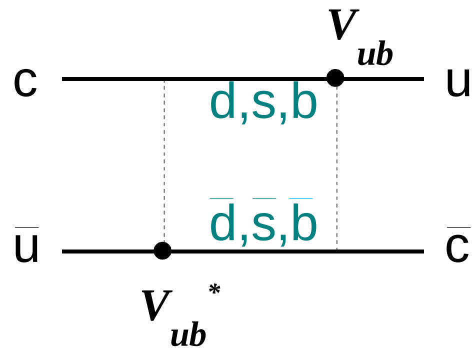
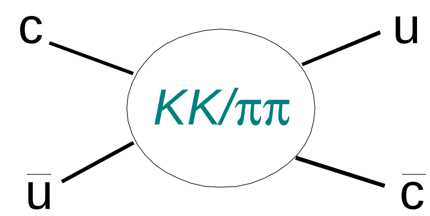
- *quick summary of D^0 meson mixing*
- *a Tevatron experiment: expected D^0 yields*
- *comparison with B factories/LHCb*
- *expected sensitivity to CPV*

D^0 meson mixing I:







off-shell ("virtual") states: Δm

on-shell states: $\Delta\Gamma$

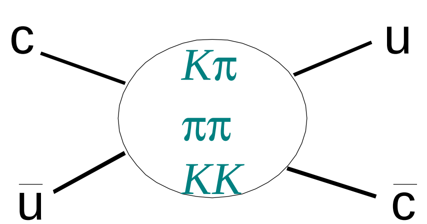
Meson	flavors	$\Delta m/\Gamma$	$\Delta\Gamma/2\Gamma$	mixing observed?
K^0	$\bar{s}d$	0.474	0.997	yes (1958)
B^0	$\bar{b}d$	0.77	$< 1\%$	yes (1987)
B_s^0	$\bar{b}s$	27	0.15 ± 0.07	yes (2006)
D^0	$c\bar{u}$	< 0.029	0.011 ± 0.005	yes (2007)

small because:
- doubly-Cabibbo-suppressed with respect to Γ_D
- GIM mechanism cancellation

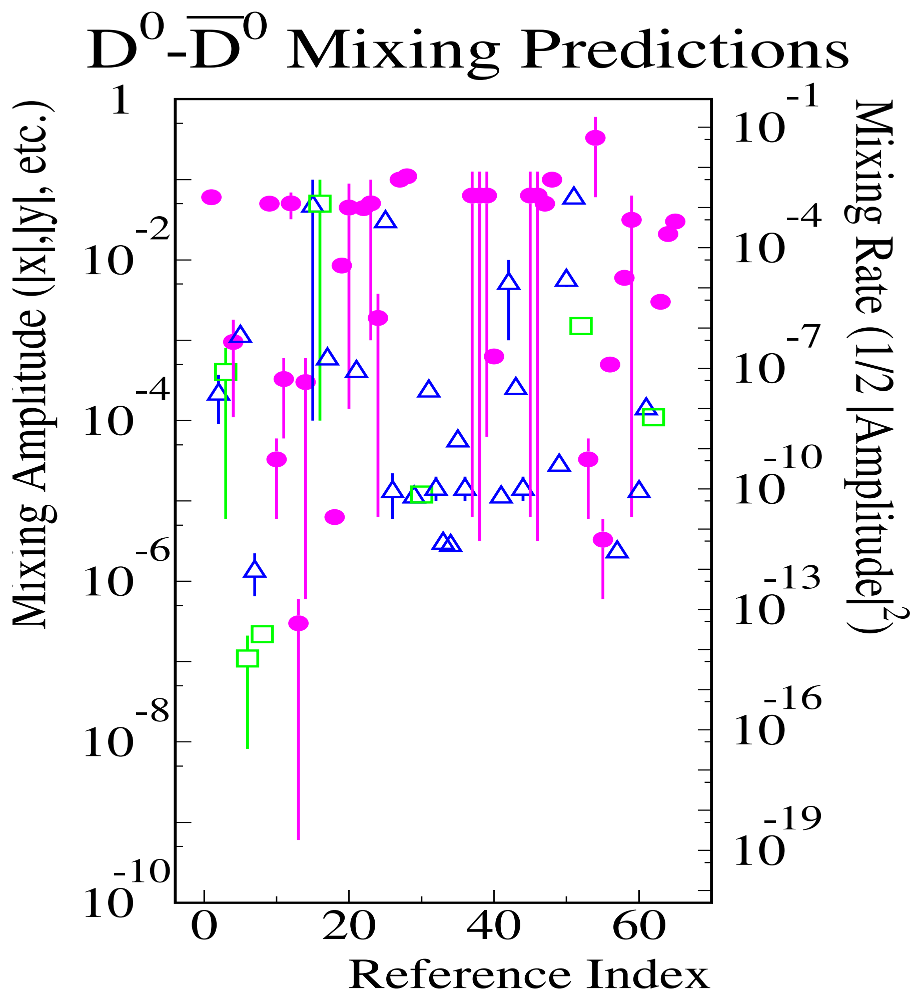
D^0 meson mixing II:

Nelson, hep-ex/9908021
Golowich, Petrov, PLB 625 (2005) 53
Bianco *et al.*, Riv.Nuov.Cim.26N7-8 (2003)

Expect in SM: ***mixing is dominated by "long-distance" (non-perturbative) contributions***



$$x \lesssim y \sim \begin{array}{ll} 10^{-6} - 10^{-3} & \text{(short distance)} \\ 10^{-3} - 10^{-2} & \text{(long distance)} \end{array}$$



D^0 *mixing measurements*

- **Wrong-sign semileptonic $D^0(t) \to K^+ l^- \nu$ decays**
  measures $x^2 + y^2$, no DCS contamination

- **Wrong-sign hadronic $D^0(t) \to K^+\pi^-$ decays**
  measures $x' = x\cos\delta + y\sin\delta$, $y' = y\cos\delta - x\sin\delta$,
  where δ is a strong phase difference

- **Decays to *CP* eigenstates: $D^0(t) \to K^+K^-$, $\pi^+\pi^-$**
  measures $y\cos\phi$, where ϕ is a weak phase difference

- **Wrong-sign hadronic $D^0 \to K^+\pi^-\pi^+\pi^-$, $K^+\pi^-\pi^0$ decays**
  measures $x^2 + y^2$, x'' and y'' with Dalitz plot analysis

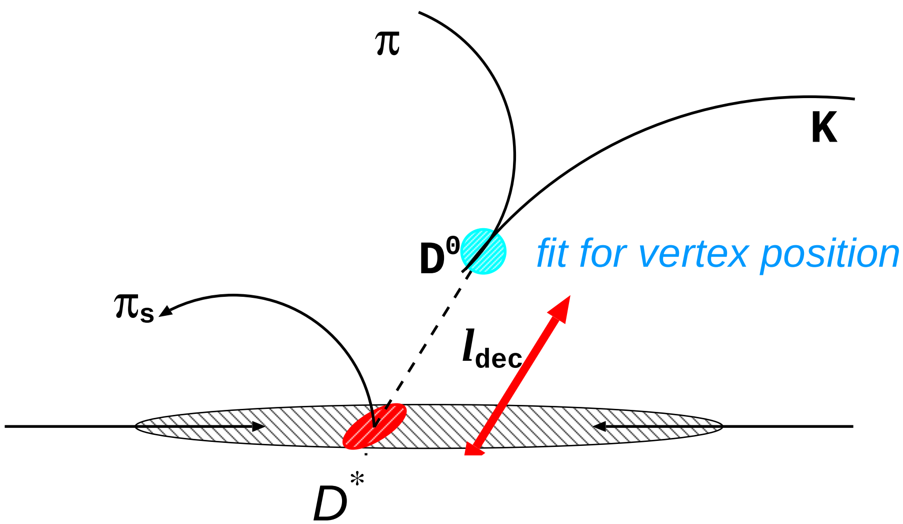
- **Dalitz plot analysis of $D^0(t) \to K^0\pi^+\pi^-$ decays**
  measures x, y

CLEOc
BESIII

- **Quantum correlations in $e^+e^- \to D^0\overline{D^0}(n\pi^0)$, $D^0\overline{D^0}\gamma(n\pi^0)$**
  measures y, $\cos\delta$

Experimental Method at FNAL: *back to fixed target*

- **Slow spill beam on target *a la E691, E769, E791, E687, E831, E789, E771***
  (proton beam, p ~800 GeV/c)
- **Initial flavor of $D^0(t)$ is determined from $D^{*+} \rightarrow D^0\pi^+$ or $D^{*-} \rightarrow D^0\pi^-$**
  This also greatly reduces background: $Q = m_{K\pi\pi} - m_{K\pi} - m_{\pi}$ only 6 MeV/c
  (*i.e.*, for D^* decays: very near threshold)
- **D^0 proper decay time $\Delta t = (d_{dec}/p) \times (m/c)$ measurement:**

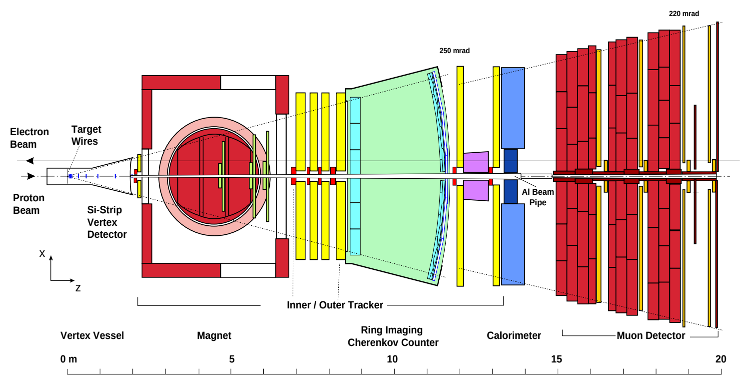


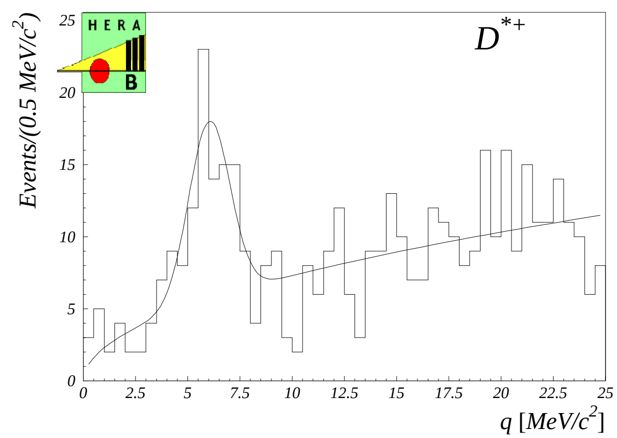
- **"modern" detector: pixels/striplets for vertexing, RICH detector for (very) high π/K discrimination, processor farm for triggering**

FNAL experiment: yield estimate #1

Scale from HERA-B: *61.3 ± 13 D*-tagged CF $D^0 \to K^-\pi^+$ in 182 x 10^6 hadronic interactions. Multiplying this rate by $\Gamma(D^0 \to K^+\pi^-)/\Gamma(D^0 \to K^-\pi^+)$=0.377% gives a fractional rate (including (loose) trigger + reconstruction efficiencies) of* ***1.3 x 10^{-9}***   *(Reference: I. Abt et al., Eur. Phys. Jour. C52, 531, 2007)*

proton beam, p = 920 GeV/c





One year of running, *assuming 7 MHz interaction rate and trigger efficiency of 50% relative to that of HERA-B:*

$$(7\ \text{MHz})(1.4 \times 10^7\ \text{s})(1.3 \times 10^{-9})(0.5) = 64000\ \text{D*-tagged}\ D^0 \to K^+\pi^-$$

⇒ ***192000 in 3 years of running***

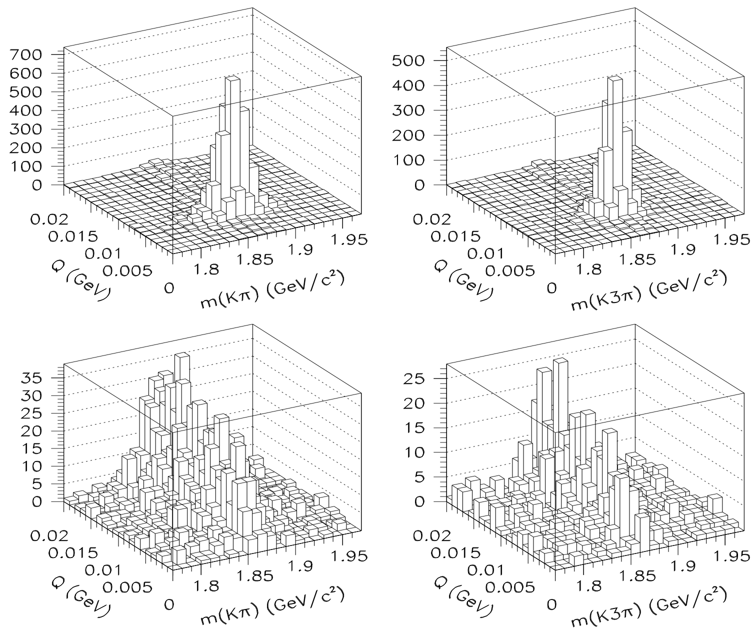
FNAL experiment: yield estimate #2

Scale from E791: *35 D*-tagged DCS* $D^0 \to K^+\pi^-$ *in 5 x* 10^{10} *hadronic interactions. This gives a fractional rate (including (loose) trigger + reconstruction efficiencies) of 7 x* 10^{-10} *(Reference: E. Aitala et al., PRD 57, 13, 1998)*

π^- beam,
p = 500 GeV/c

CF $D \to K^-\pi$ *CF* $D \to K^-\pi\pi$

DCS $D \to K^+\pi$ *DCS* $D \to K^+\pi\pi$



One year of running*, assuming 7 MHz interaction rate and the same trigger+reconstruction efficiency as E791:*

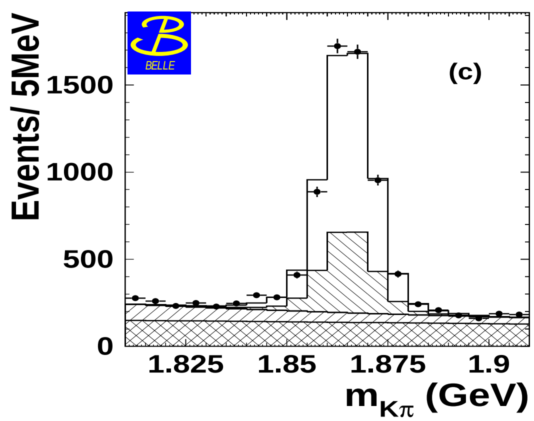
$$(7\ \text{MHz})(1.4 \times 10^7\ \text{s})(7 \times 10^{-10}) = 69000\ \text{D*-tagged}\ D^0 \to K^+\pi^-$$

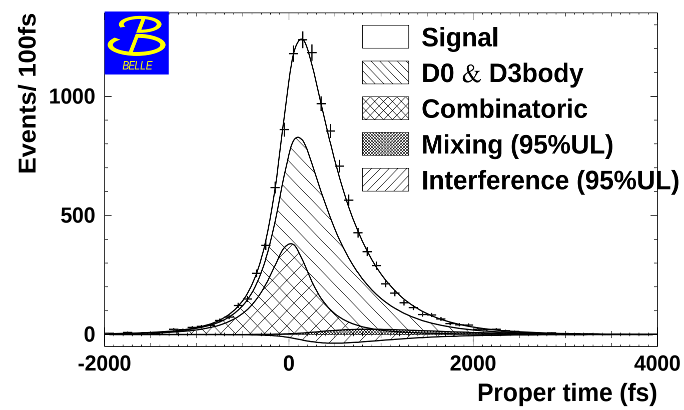
$\Rightarrow$ ***207000 in 3 years of running***

Comparison with Belle/Babar

Belle: 4024 D*-tagged DCS $D^0 \rightarrow K^+\pi^-$ in 400 fb^{-1} of data
(Reference: L. Zhang et al., PRL 96, 151801, 2006)

Babar: 4030 D*-tagged DCS $D^0 \rightarrow K^+\pi^-$ in 384 fb^{-1} of data
(Reference: B. Aubert et al., PRL 98, 211802 (2007)





Babar has stopped taking data; its final sample is 485 fb^{-1} (at 4S and continuum)
Belle is now at 839 fb^{-1}, will probably take another 100 fb^{-1} at 4S and continuum

$\Rightarrow$ **total sample is 1420 fb^{-1} or 14600 DCS $D^0 \rightarrow K^+\pi^-$ decays, 8% of the yield of a 3-year Fermilab experiment**

Comparison with LHCb

LHCb: ***have used Monte Carlo to study sensitivity to D*-tagged DCS $D^0 \to K^+\pi^-$ decays***

(Reference: P. Spradlin, G. Wilkinson, F. Xing, et al., LHCb public note LHCb-2007-049)

Assuming σ_{bb}= 500 μb and estimating several trigger and reconstruction efficiciencies, this study concludes that <u>58000</u> signal decays will be reconstructed per year (2 fb^{-1} of data)

This is similar to our yield estimate for a Tevatron experiment, BUT:

LHCb must use D*'s produced in B decays, rather than prompt D*'s, as the trigger is efficient only for the former. This introduces two issues:

(a) the decay time distribution will be a mixture of prompt D*'s and D*'s from B decays. These two components will need to be unfolded to measure mixing parameters. (FNAL experiment only has prompt D*'s)

(b) to recontruct the D* vertex position, one must reconstruct a B $\to$ D*X decay. The efficiency for this is estimated to be 51%, and it will add smearing to the D^0 decay time distribution. (FNAL experiment: D* vertex is at the target)

Estimate of sensitivity

Since sample size is very similar, we adopt the results of LHCb Monte Carlo study *(P. Spradlin et al., Note LHCb-2007-049)***:**

This study found that statistical errors for mixing parameters corresponding to 232500 D*-tagged $D^0 \to K^+\pi^-$ decays, S/B = 0.40, and σ_t =75 ps are:

$\delta x'^2$	6.4×10^{-5}
$\delta y'$	0.87×10^{-3}

best case after all B factory data analyzed: (1500 fb^{-1})

14×10^{-5}
2.2×10^{-3}

This yield corresponds to 3.6 years of running. One also expects a similar improvement in y_{CP} measured using $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays:

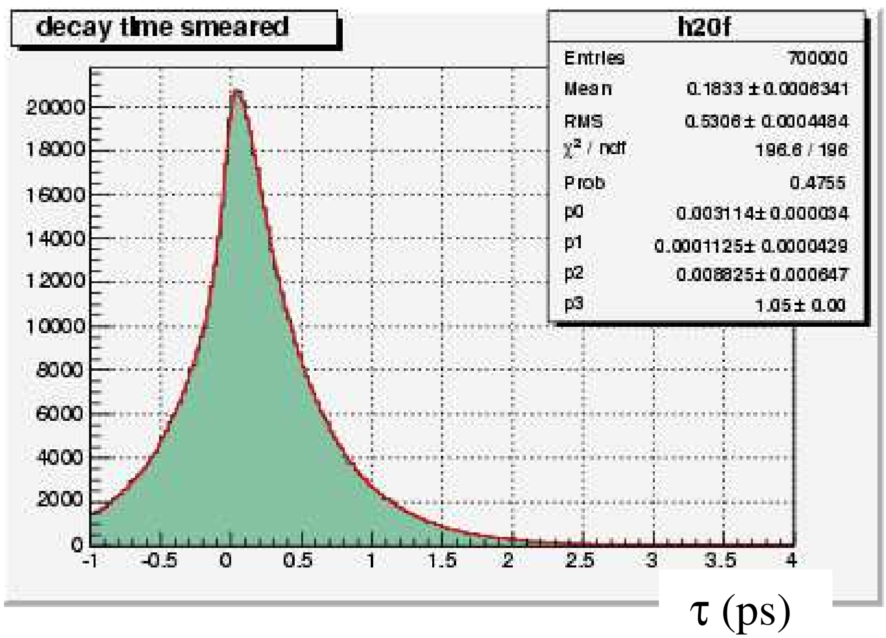
δy_{CP}	0.65×10^{-3}

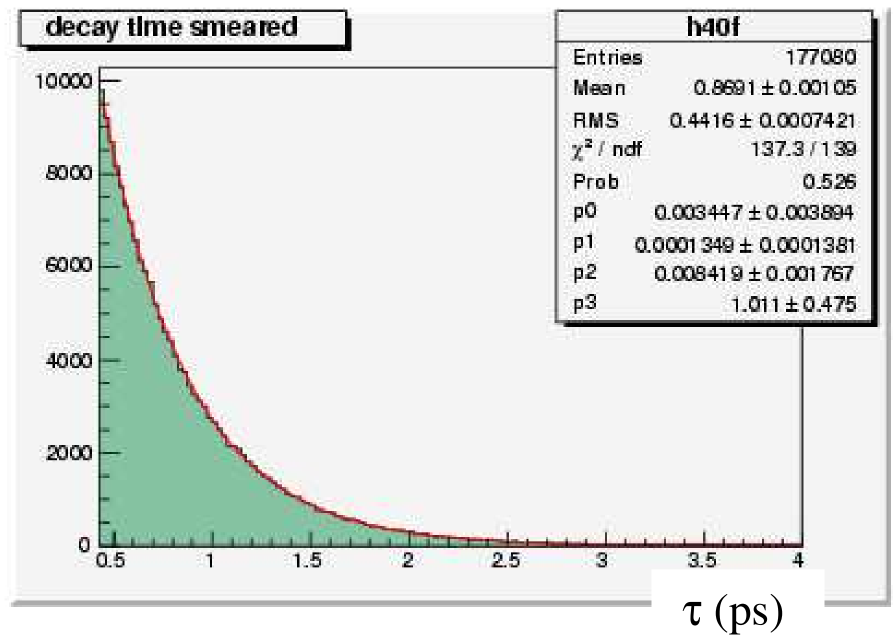
(we are now doing our own Monte Carlo studies of sensitivity to check these estimates)

Estimate of sensitivity, cont'd

Our own toy MC study

(<u>200000</u> D*-tagged $D^0 \to K^+\pi^-$ decays, <u>S/B = 0.40,</u> and <u>σ_t =75 ps</u>):





preliminary: $\delta x'^2 \sim 4.2 \times 10^{-5}$

$\delta y' \sim 0.64 \times 10^{-3}$

(consistent with LHCb study)

Estimate of sensitivity, cont'd

$$R_M = \frac{1}{2}(x^2 + y^2)$$

Global fit: *fit*
24 observables for
8 underlying parameters

$$\begin{aligned} 2y_{CP} &= \left(|q/p| + |p/q|\right) y\cos\phi \ - \ \left(|q/p| - |p/q|\right) x\sin\phi \\ 2A_\Gamma &= \left(|q/p| - |p/q|\right) y\cos\phi \ - \ \left(|q/p| + |p/q|\right) x\sin\phi \end{aligned}$$

$$\begin{aligned} x_{K^0\pi\pi} &= x \\ y_{K^0\pi\pi} &= y \\ |q/p|_{K^0\pi\pi} &= |q/p| \\ \mathrm{Arg}\,(q/p)_{K^0\pi\pi} &= \phi \end{aligned}$$

$$\begin{pmatrix} x'' \\ y'' \end{pmatrix}_{K^+\pi^-\pi^0} = \begin{pmatrix} \cos\delta_{K\pi\pi} & \sin\delta_{K\pi\pi} \\ -\sin\delta_{K\pi\pi} & \cos\delta_{K\pi\pi} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

$$\begin{aligned} x'^{\pm} &= \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (x'\cos\phi \pm y'\sin\phi) \\ y'^{\pm} &= \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4} (y'\cos\phi \mp x'\sin\phi) \end{aligned}$$

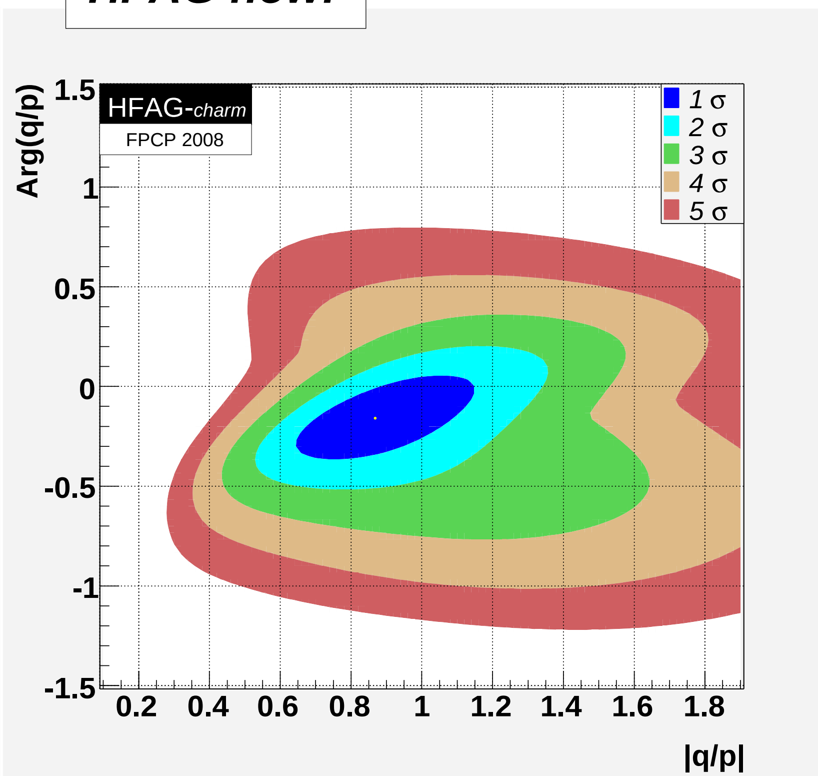
$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

$$A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}$$

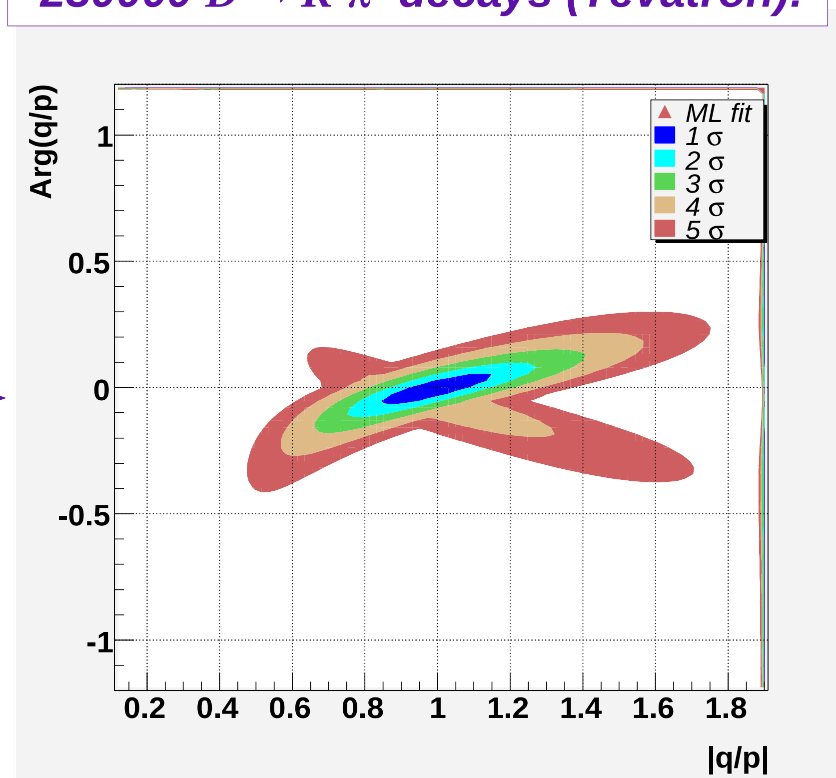
Sensitivity to CPV parameters |q/p|, ϕ

Global fit: *24 observables, 8 underlying parameters:*

HFAG now:



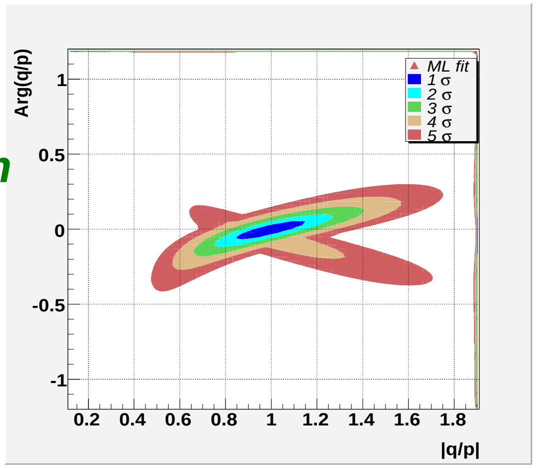
230000 $D^0 \to K^+\pi^-$ decays (Tevatron):



CPV is manifest as (|q/p|, ϕ) $\neq$ (1,0) – this would be new physics

Summary & comments

- Charm mixing now observed, interest switching to CP violation in charm decays.
- Advances since the old Fermilab fix-target experiments make a new experiment much more powerful/sensitive. Trigger concepts and prototypes exist (HERA-B, CDF, BTeV,LHCb); pixels and higher rate detectors now developed.
- Notably better sensitivity than all (10 x 2 = 20 years!) B factory data; notably simpler to analyze than LHCb data.
- Accelerator and beamline essentially available.
- Can significantly improve sensitivity to CPV in the charm system, help un-tangle whatever signals appear at the Tevatron or LHC.



Future Activity

Working group is now forming, a web page is setup:
http://www.nevis.columbia.edu/twiki/bin/view/FutureTev/WebHome

To subscribe to the listserv:
-- Send an e-mail message to listserv@fnal.gov
-- Leave the subject line blank
-- Type SUBSCRIBE Future_Charm_at_Fermilab FIRSTNAME LASTNAME
in the body of your message.

Working meeting:
"Possibilities of a Future Tevatron Program"

noon to noon, Sept 4-5 at Fermilab