D^0 mixing and CP violation from Tevatron

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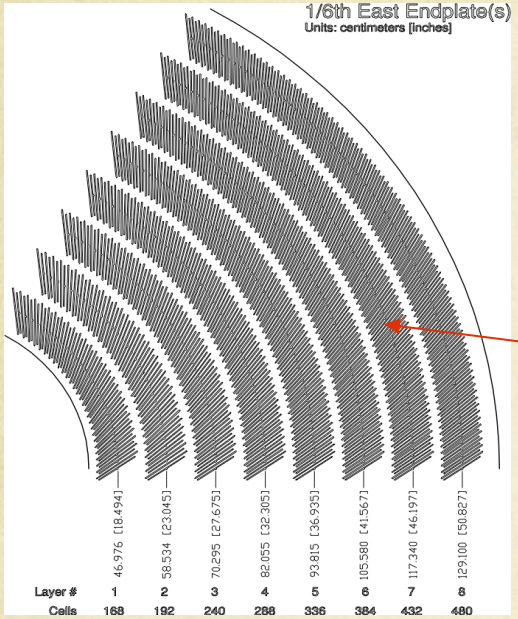
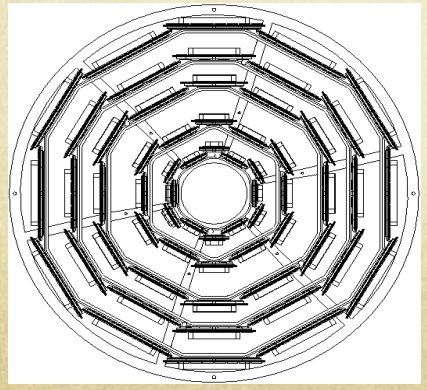
CP Violation in the charm sector

- Precision measurements of CP violation probe the possible existence of New Physics beyond what is currently accessible through direct searches.
- CP violation observed so far is explained within the Standard Model and is far from sufficient to explain the matter-antimatter asymmetry of the Universe, so there must be something else…
- Until recently most CP violation measurements have been done in the area of down-quarks (s, b), so what about up-quarks? Why not look where we did not look before?
- Charm is a unique window to New Physics because it probes up-quark sector (unaccessible through t or u quarks).
- Large D^0 mixing parameters recently observed open new possible scenarios to look inside. Really important to explore $A_{CP}(t)$ window between $[10^{-2} - 10^{-5}]$.

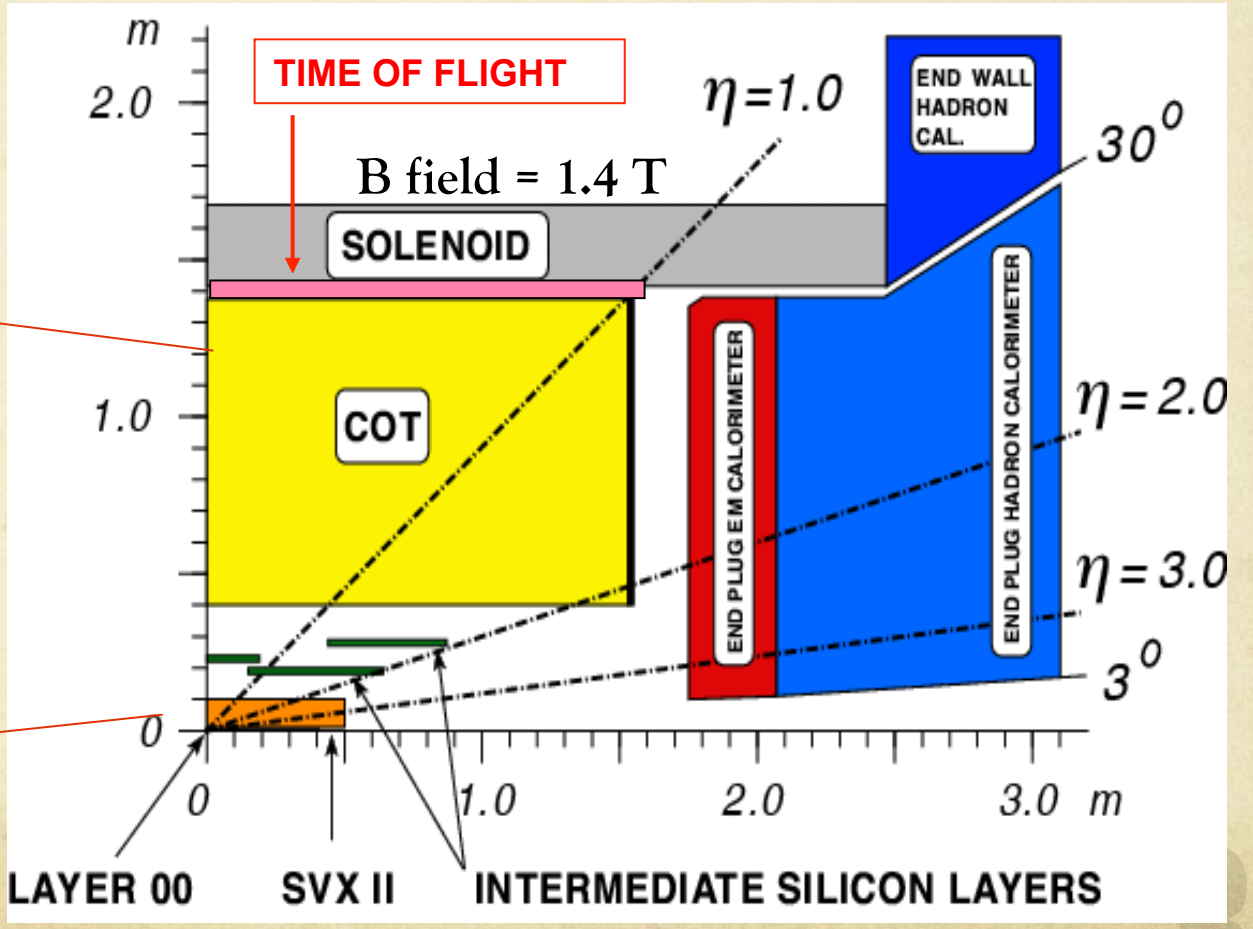
CDF Tracker

Transverse view



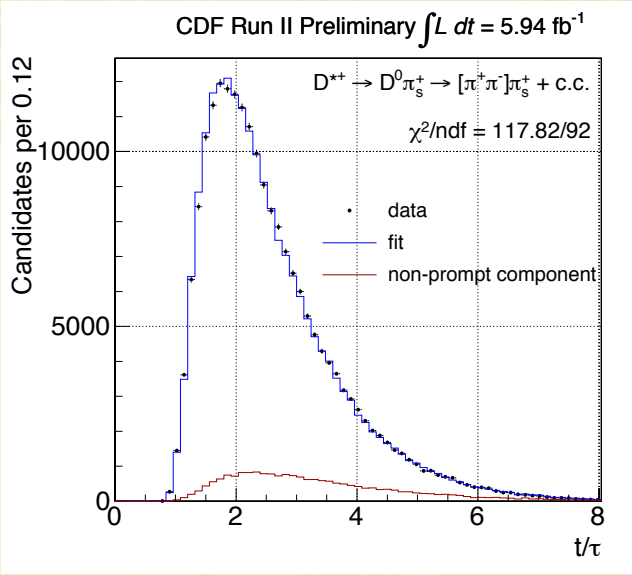


Longitudinal view



Silicon Vertex Trigger

- Part of CDF level 2 trigger
- Combines information from COT and SVX
- Finds all central tracks with $p_T > 2$ GeV/c
- Impact parameter resolution ~30 μm
- Total execution time ~ 20 μs/event



SVT plays a crucial role in charm physics

- World's largest sample of $D^0 \to hh$:

~ 29,000,000 $D^0 \to K^- \pi^+$

~ 5,000,000 $D^{*+} \to D^0 \pi^+ \to (K^- \pi^+) \pi^+$

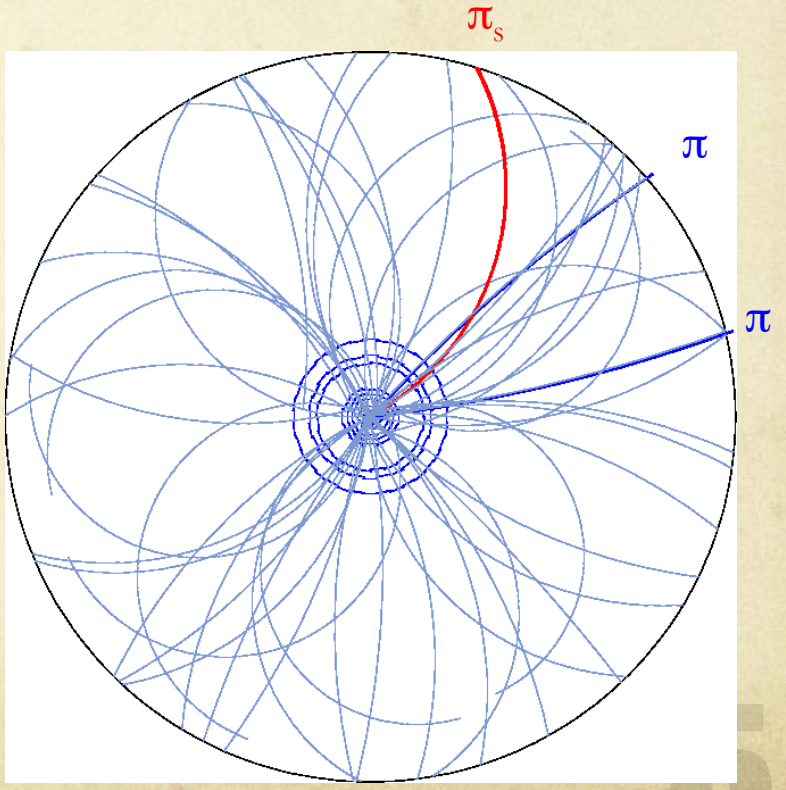
~ 215,000 $D^{*+} \to D^0 \pi^+ \to (\pi^+ \pi^-) \pi^+$

- Boosted proper decay times enhance sensitivity to time dependent effects

CP asymmetry in the $D^0 \to \pi^+\pi^-$

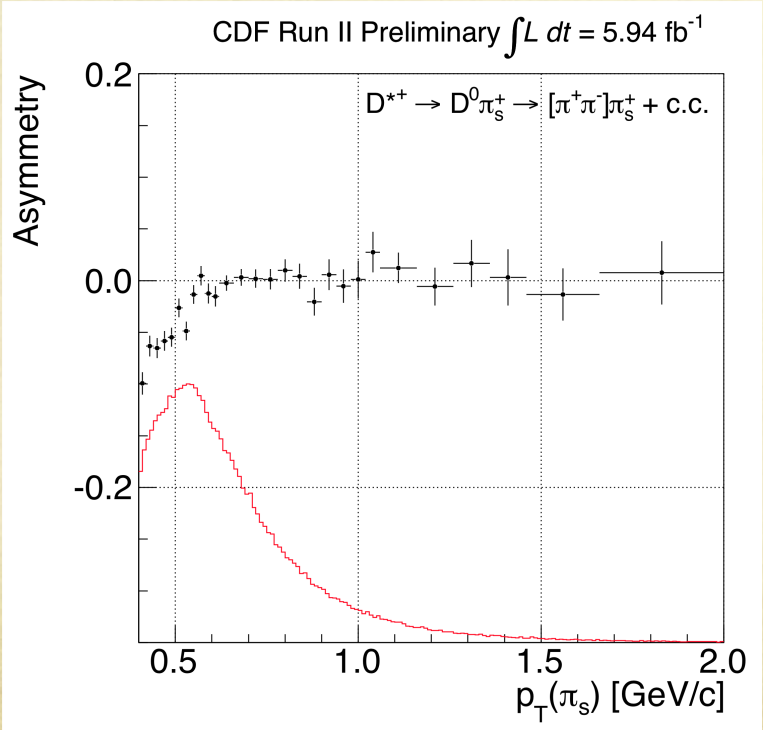
$$A_{CP}(D^0 \to \pi^+\pi^-) = \frac{\Gamma(D^0 \to \pi^+\pi^-) - \Gamma(\overline{D}^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to \pi^+\pi^-) + \Gamma(\overline{D}^0 \to \pi^+\pi^-)}$$

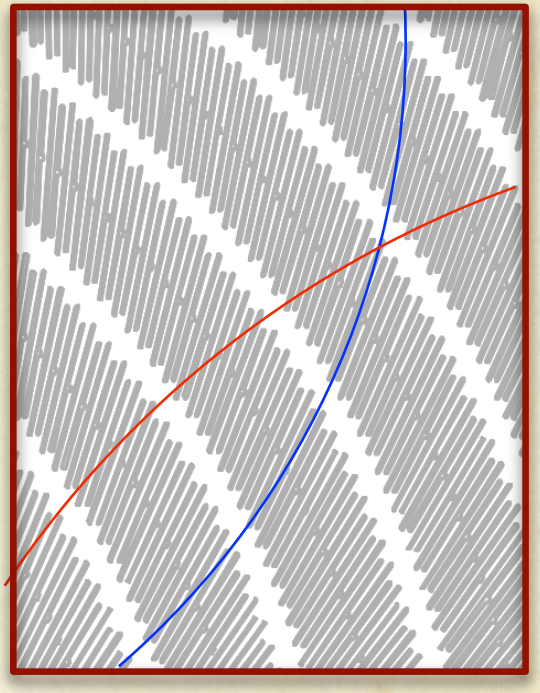
- $D^{*+} \to D^0\pi^+$ to tag the flavor at production
  - CP symmetric initial state (p-pbar) ensures charge symmetric production
- Small Q-value in D* decay causes π_s to be low momentum
  - typically in the range [0.4 – 1.0] GeV/c, where detector efficiency for tracks of opposite charge is asymmetric to the level of a few percents
- World's largest sample:
  - Expected stat. resolution ~ 0.2%



Fighting detector asymmetries

Different efficiencies for soft pions of opposite charge translate into different efficiencies for D* of opposite charge and may lead to a fake charge asymmetry in D^0 decay.





Need to suppress detector charge asymmetry by more than one order of magnitude to control systematics to better than 0.1%.

This can be done with a very high degree of confidence using only data - no need to rely on Monte Carlo.

How are we doing it?

Assuming in production (strong) the same number of D*+ and D*- , D0 and D0bar , combine the "raw" asymmetries of three different event samples:

Fully data-driven

✓ $D^\star \to D^0\pi_s \to [\pi\ \pi]\ \pi_s$ $\quad A_{CP}^{raw}(\pi\pi^\star) = A_{CP}(\pi\pi) + \delta(\pi_s)$

cancel asymmetry due to π_s^+/π_s^- different reconstruction efficiencies

✓ $D^\star \to D^0\pi_s \to [K\pi]\ \pi_s$ $\quad A_{CP}^{raw}(K\pi^\star) = A_{CP}(K\pi) + \delta(\pi_s) + \delta(K\pi)$

cancel asymmetry due to K^+/K^- different interaction with matter + possible CPV in $D^0 \to K\pi$

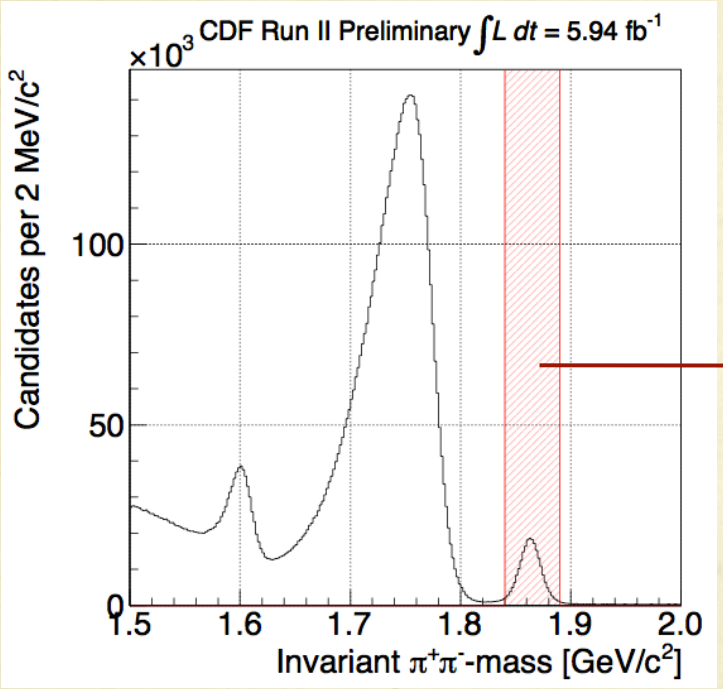
✓ $D^0 \to [K\pi]$ $\quad A_{CP}^{raw}(K\pi) = A_{CP}(K\pi) + \delta(K\pi)$

The physical A_{CP} extracted through the linear combination:

$$A_{CP}(\pi\pi) = A_{CP}^{raw}(\pi\pi^\star) - A_{CP}^{raw}(K\pi^\star) + A_{CP}^{raw}(K\pi)$$

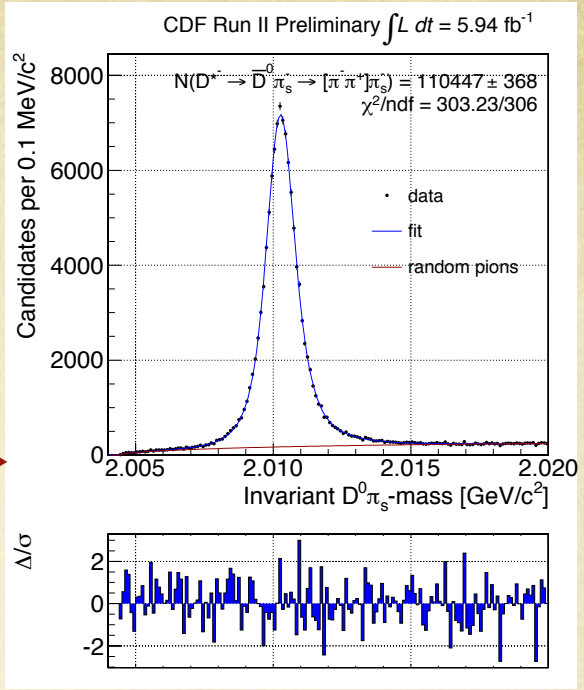
Counting D*-tagged $D^0 \to \pi^+\pi^-$

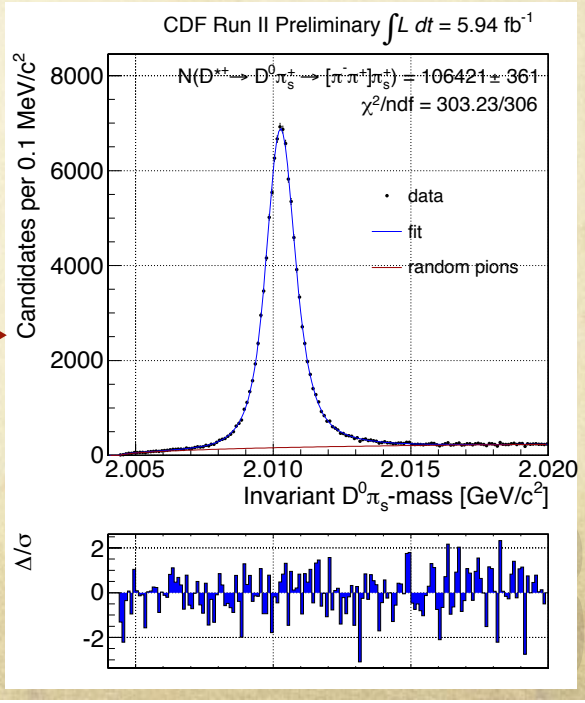
$|M_{\pi\pi} - M_{D0}| < 3\sigma$, then fit the invariant $D^0\pi$ mass



$\overline{D}^0 \to \pi^+\pi^-$

$D^0 \to \pi^+\pi^-$

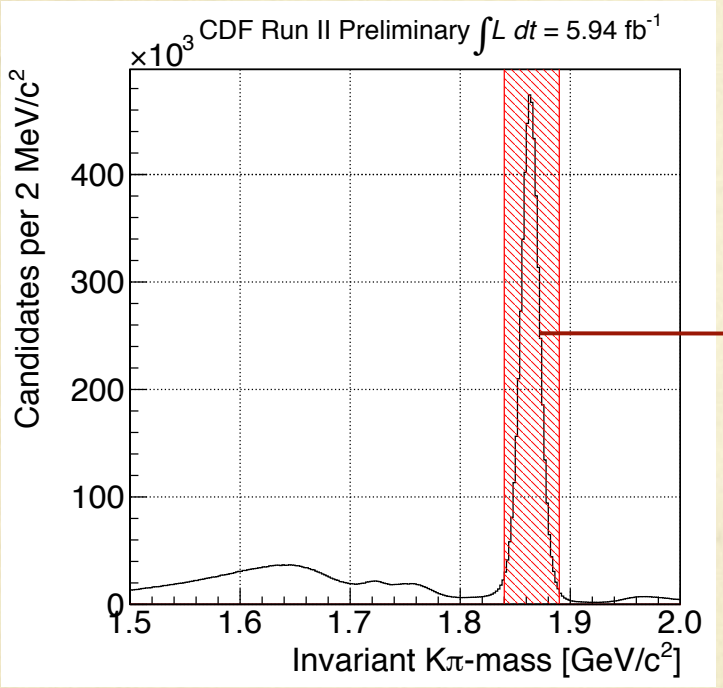




$$A_{CP}^{raw}(\pi\pi^*) = (-1.86 \pm 0.23)\%$$

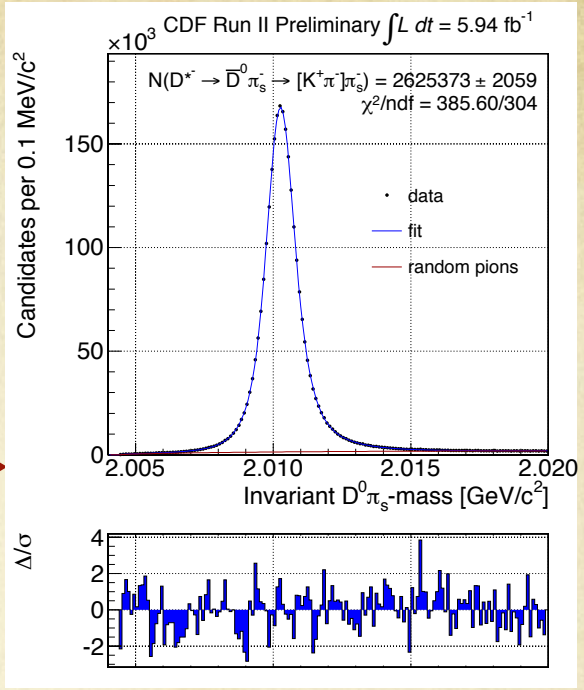
Counting D*-tagged $D^0 \to K^-\pi^+$

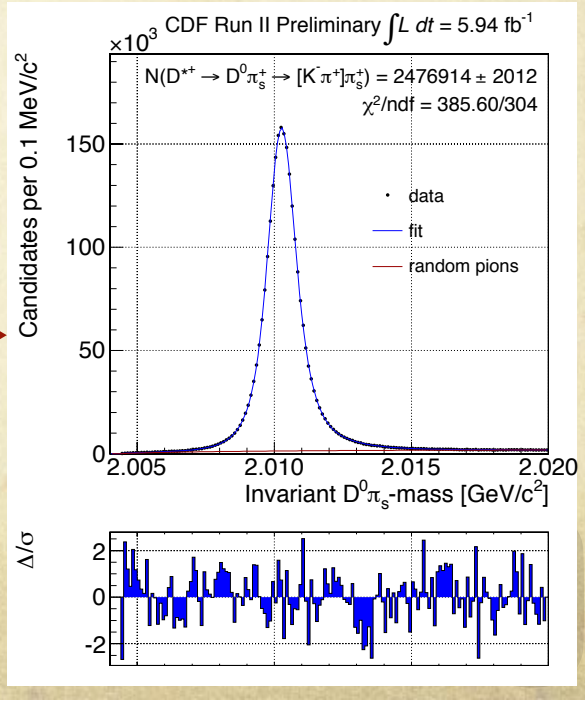
$|M_{K\pi} - M_{D0}| < 3\sigma$, then fit the invariant $D^0\pi$ mass



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

$D^0 \to K^-\pi^+$





$$A_{CP}^{raw}(K\pi^*) = (-2.91 \pm 0.05)\%$$

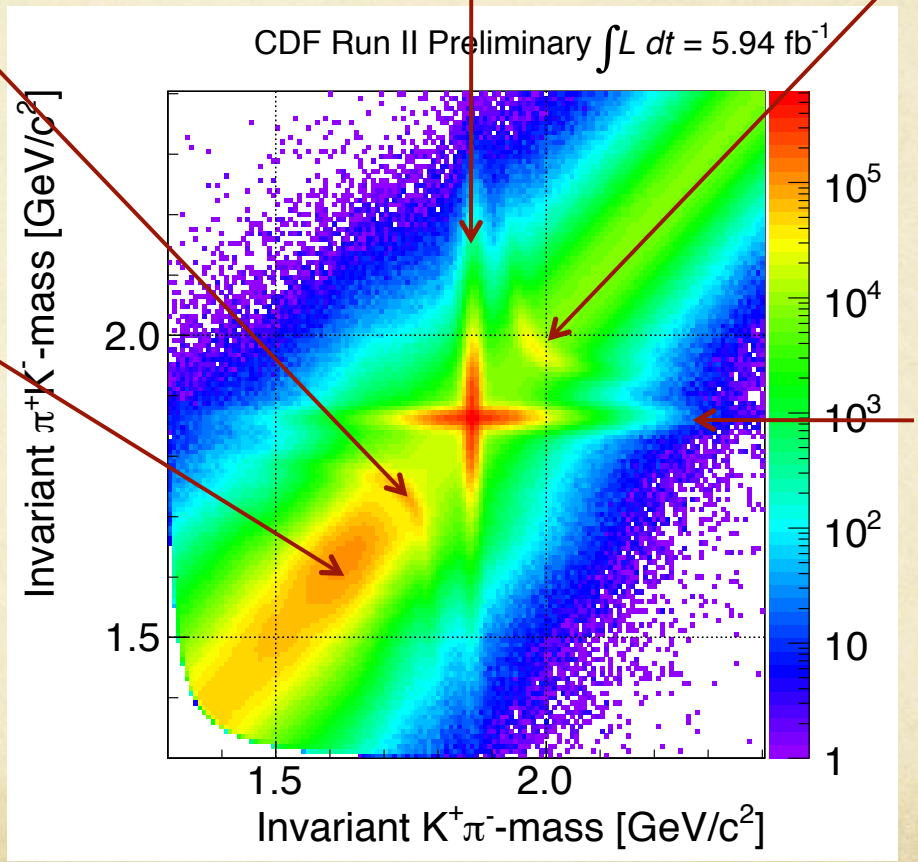
Counting untagged $D^0 \to K^-\pi^+$

$\overline{D}^0 \to K^+\pi^-$
(and DCS D^0)

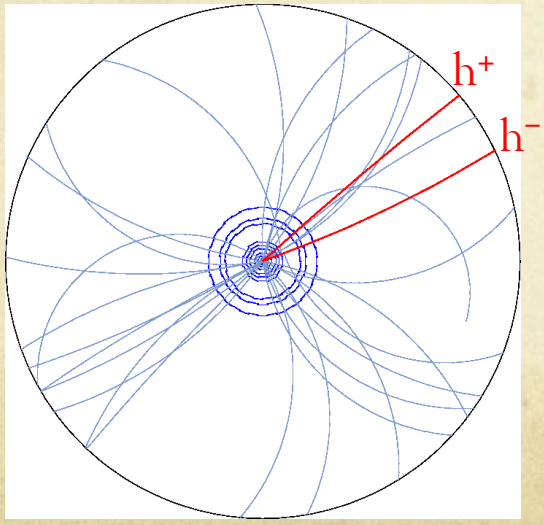
$D^0 \to K^+K^-$
(and cc)

$D^0 \to \pi^+\pi^-$
(and cc)

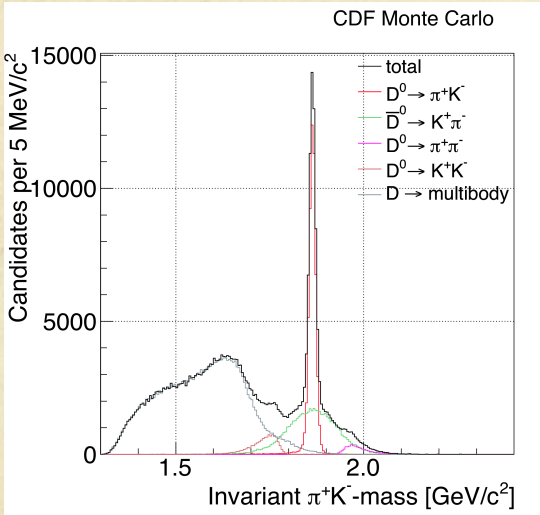
Partially reconstructed D^0,D^+,D^+_s multi-body decays

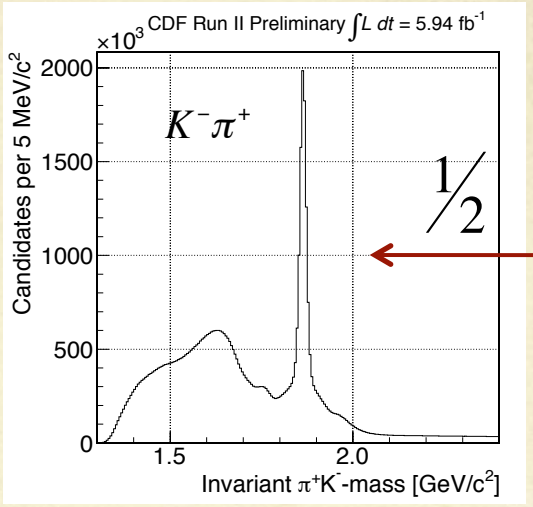


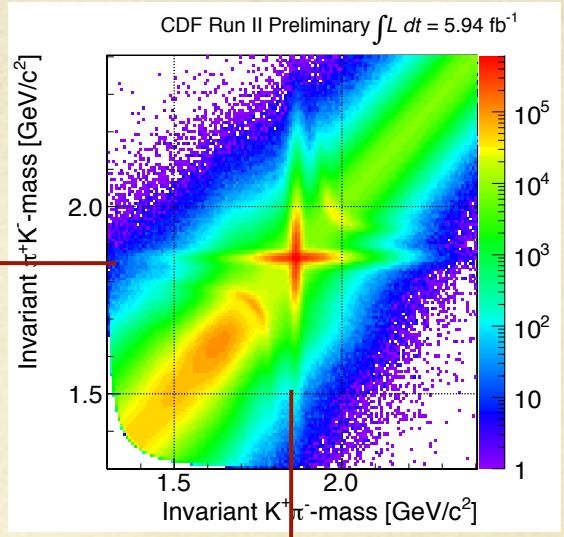
$D^0 \to K^-\pi^+$
(and DCS $\overline{D}^0$)

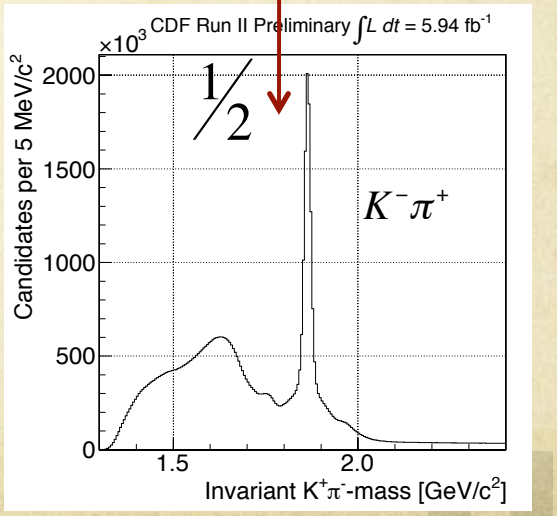


Counting untagged $D^0 \to K^-\pi^+$



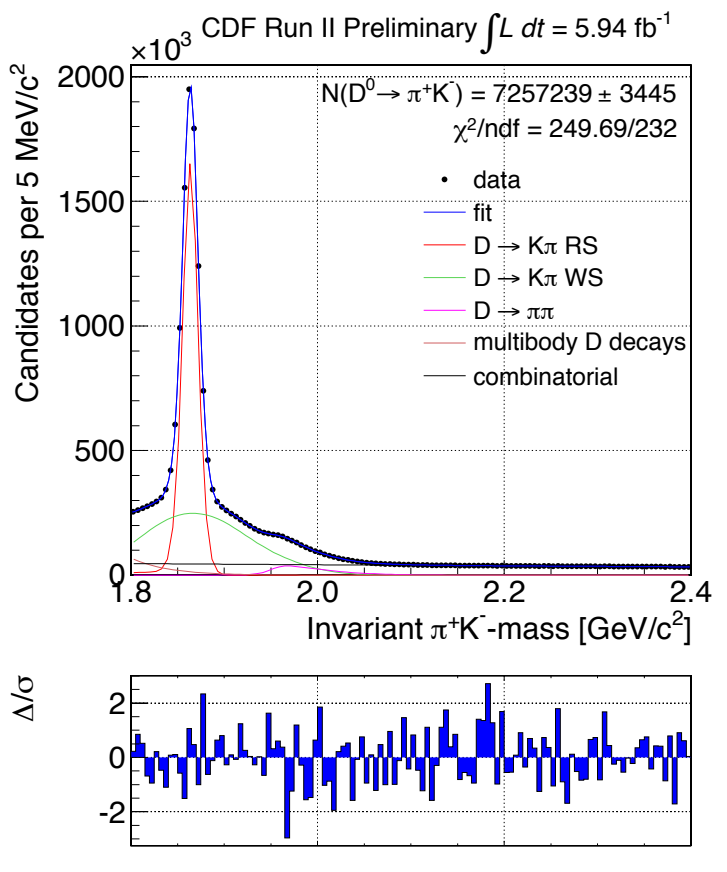


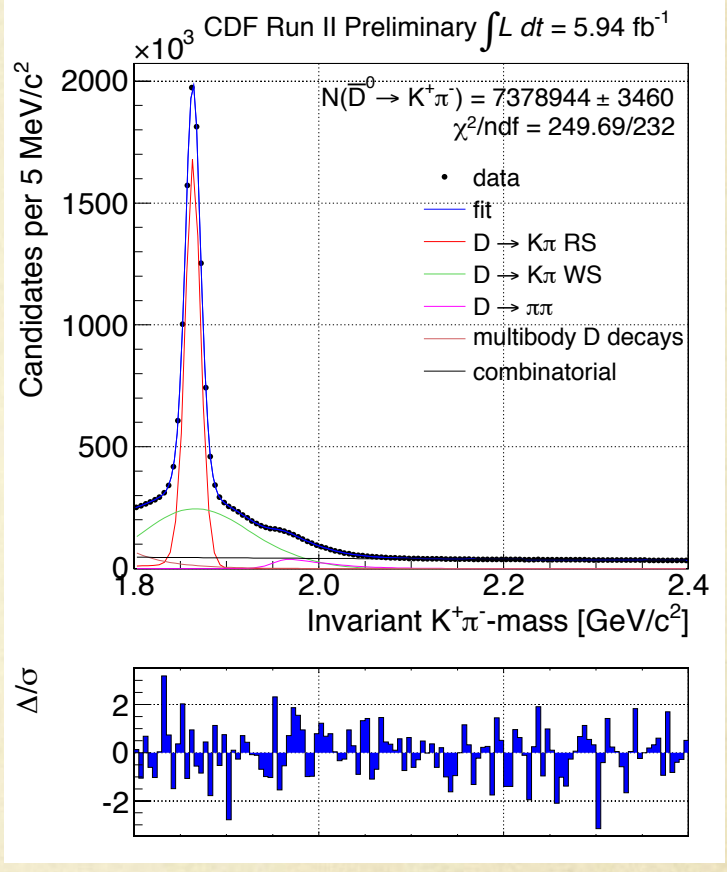




- Two statistically independent samples (half each)
  - can easily afford to loose a factor of two in statistics
- Simultaneous fit of two 1D mass projections
- Signal is in narrow peak
  - ignore order of 10^{-3} DCS contribution.

Counting untagged $D^0 \to K^-\pi^+$





~ (2 ×) 15·000·000 untagged $D^0 \to K^-\pi^+$ + cc

$$A_{CP}^{raw}(K\pi) = (-0.83 \pm 0.03)\%$$

Putting it all together

$$A_{\rm CP}(\pi\pi) = A_{\rm CP}^{\rm raw}(\pi\pi^\star) - A_{\rm CP}^{\rm raw}(K\pi^\star) + A_{\rm CP}^{\rm raw}(K\pi)$$

$$= (-1.86 \pm 0.23)\% - (-2.91 \pm 0.05)\% + (-0.83 \pm 0.03)\%$$

$$A_{CP}(D^0 \to \pi^+\pi^-) = (+0.22 \pm 0.24)\%$$

Statistical uncertainty only

Systematic uncertainties

Source of systematic uncertainty	Variation on $A_{CP}(\pi\pi)$
Approximations in the method	0.009%
Beam drag effects	0.004%
Contamination of non-prompt D^0s	0.034%
Templates used in fits	0.010%
Templates charge differences	0.098%
Asymmetries from non-subtracted backgrounds	0.018%
Imperfect sample reweighing	0.0005%
Sum in quadrature	0.105%

Final result

- In 5.94 fb^{-1} of CDF data we measure:

$$A_{CP}(D^0 \to \pi^+\pi^-) = (+0.22 \pm 0.24_{\text{stat}} \pm 0.11_{\text{syst}})\%$$

See CDF Public note 10296, http://www-cdf.fnal.gov/physics/new/bottom/100916.blessed-Dpipi6.0/

- Previous measurements:
  - BaBar on 386 fb^{-1} A_{CP} = [−0.24 ± 0.52 ± 0.22]% PRL 100, 061803 (2008)
  - Belle on 540 fb^{-1} A_{CP} = [−0.43 ± 0.52 ± 0.12]% PLB 670, 190 (2008)
  - CDF on 120 pb^{-1} A_{CP} = [+1.0 ± 1.3 ± 0.6]% PRL 94, 122001 (2005)

- However to properly compare with B-Factories need to better understand what we measured.

Direct and indirect CPV in the $D^0 \to \pi^+\pi^-$

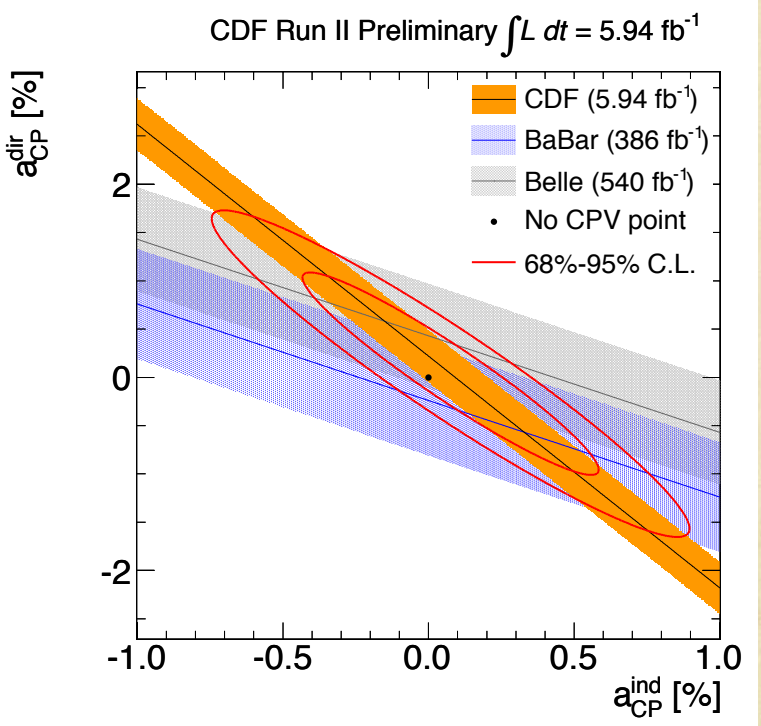
- "Time-integrated" A_{CP} receives contribution from direct CP violation and indirect CP violation (from mixing induced effects).
- D^0 mixing parameters are small (x,y<<1), then the integrated asymmetry, at the first order, can be written as:

$$A_{CP}(D^0 \to \pi^+\pi^-) \approx a_{CP}^{dir} + \frac{\langle t \rangle}{\tau} a_{CP}^{ind}$$

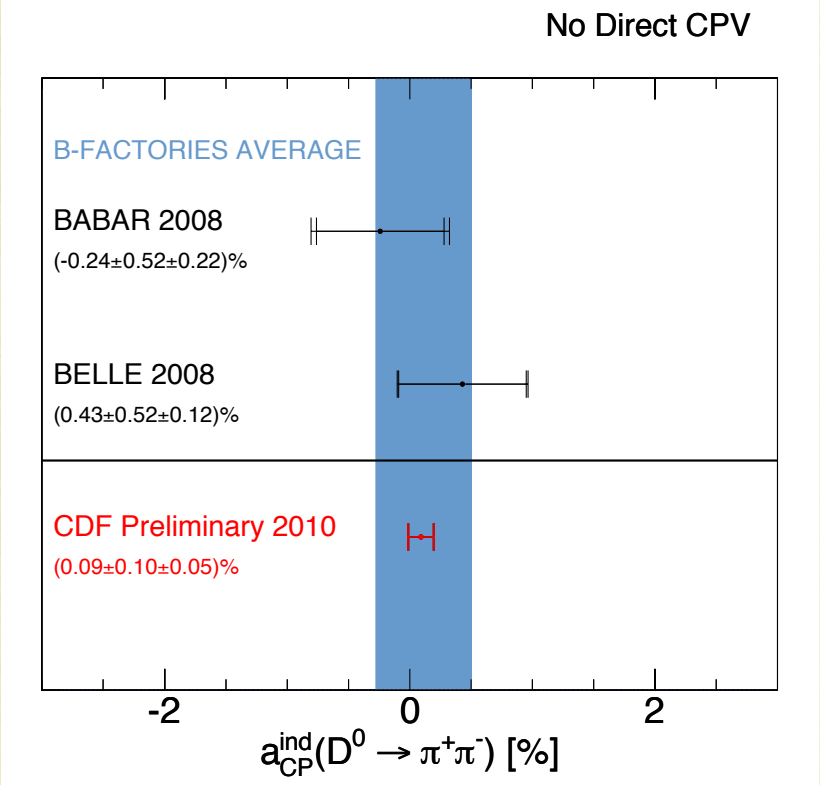
- A_{CP} describes a band in the plane (a_{CP}^{ind} , a_{CP}^{dir}) with a slope $\langle t \rangle/\tau$, where t/τ is the proper decay time in unit of D^0 lifetime.

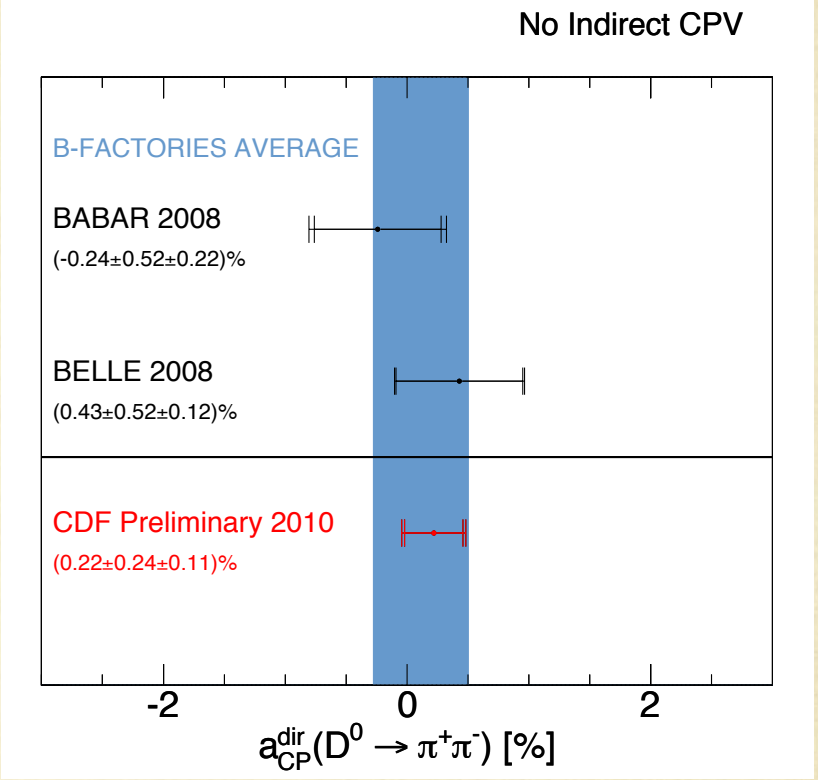
Proper decay time and (a_{CP}^{ind} , a_{CP}^{dir}) plane

- D^0 proper decay time is biased because of impact parameter trigger
  - At CDF : $\langle t \rangle \approx [2.40 \pm 0.03]\,\tau$
  - While at B-factories $\langle t \rangle = \tau$
- CDF and B-Factories are then complementary.
- Two bands with different slope can separate the direct and mixing-induced components.



A more appropriate comparison





CP violation is from mixing only

$$A_{CP}(D^0 \to \pi^+\pi^-) \approx \frac{\langle t \rangle}{\tau} a_{CP}^{ind}$$

no mixing

$$A_{CP}(D^0 \to \pi^+\pi^-) \approx a_{CP}^{dir}$$

Final remarks on $A_{CP}(D^0 \to \pi^+\pi^-)$

- This result shows that high precision measurements competitive or even superior to the B-factories are possible at the Tevatron.
- Most precise A_{CP} measurement ever in the Charm sector.
- For the first time enough precision to probe the Charm sector for new physics in a significant way.
- Still limited by statistics and will improve with integrated luminosity (5.9 fb^{-1} → 10 fb^{-1} → 20 fb^{-1}?)
  - $A_{CP}(D^0 \to K^+K^-)$ short term goal
- This is the consequence of the combination of a number of unique features of the Tevatron and the CDF detector:
  - large Charm production rate
  - CP symmetric initial state (...and η symmetric detector)
  - trigger on secondary vertices

Prospects and Conclusions

- More is coming:
  - (x',y') and CPV with WS/RS(t) in the $D^0 \to K^- \pi^+$ decays.
  - Possible (but very hard) y_{CP} from $\tau(D^0 \to h^+ h^-)/\tau(D^0 \to K^- \pi^+)$.
  - $D^0 \to \mu^+ \mu^-$
  - And many others...
- CDF is now the major player in the charm sector.
  - We have a plenty of charm decays and an enormous know-how.
- We do all the best to make life hard to our LHCb colleagues.

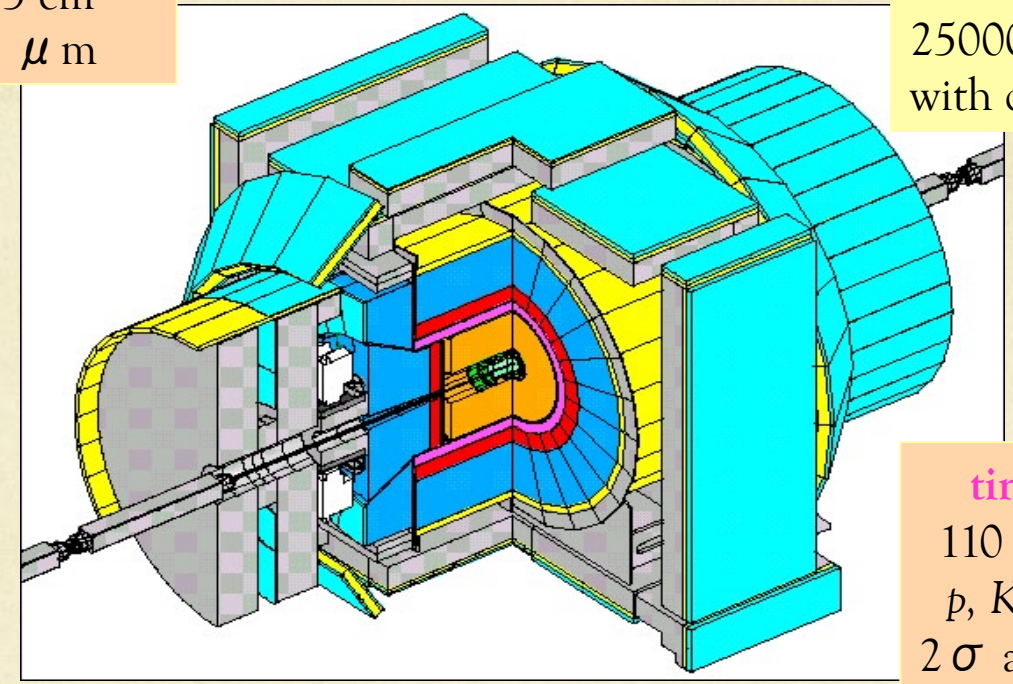
Backup

The CDF II detector

7 to 8 silicon layers
$1.6 < r < 28$ cm, $|z| < 45$ cm
$|\eta| \leq 2.0$ σ(hit) ~ 15 μm

1.4 T magnetic field
Lever arm 132 cm

132 ns front end
chamber tracks at L1
silicon tracks at L2
25000 / 300 / 100 Hz
with dead time < 5%



Some resolutions:
p_T ~ 0.15% p_T (c/GeV)
J/Ψ mass ~ 14 MeV
EM E ~ 16%/$\sqrt{E}$
Had E ~ 80%/$\sqrt{E}$
d_0 ~ 40 μm
(includes beam spot)

time-of-flight
110 ps at 150 cm
p, K, π identific.
2 σ at p_T<1.6 GeV

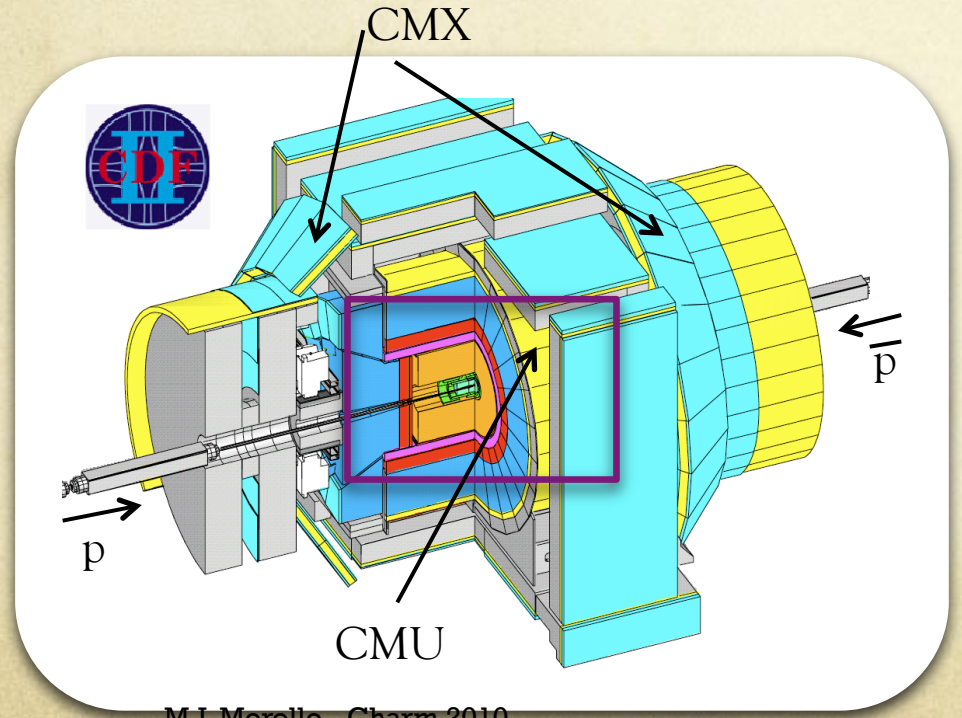
96 layer drift chamber
$|\eta| \leq 1.0$ $44 < r < 132$ cm, $|z| < 155$ cm
30k channels, σ(hit) ~ 140 μm
dE/dx for p, K, π identification

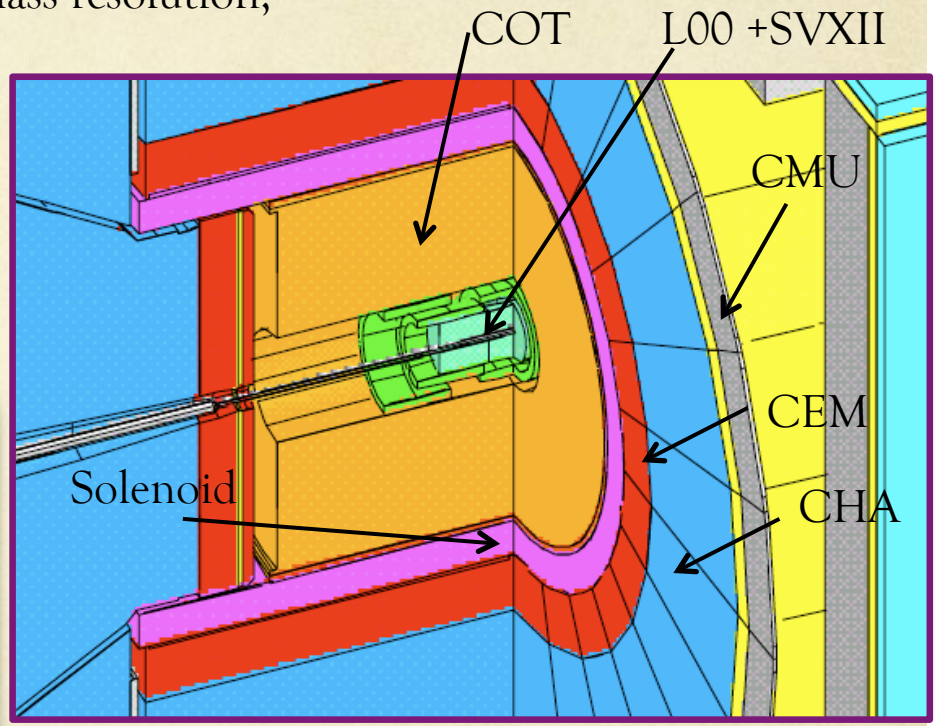
scintillator and tile/fiber sampling calorimetry
$|\eta| < 3.64$

μ coverage
$|\eta| \leq 1.5$
84% in Υ

CDFII detector

Central tracking includes silicon vertex detector surrounded by drift chamber;
p_T resolution $dp_T/p_T = 0.0015\ p_T$ → excellent mass resolution,
Particle identification: dE/dX and TOF;
Good electron and muon identification
by calorimeters and muon chambers.





CMU (|η|<0.6, pt>1.4GeV/c) 4 layers of planar drift chambers
CMX(0.6<|η|<1, pt>2GeV/c) conical sections of drift tubes

Uniqueness of Charm (I)

- Standard Model (SM)
  - FCNC greatly suppressed
  - even more so for up-type quarks
- New Physics (NP)
  - FCNC might be less suppressed for up-type quarks

SM `background' much smaller for FCNC of up-type quarks
→ cleaner (not larger) signal:

$$\left[\frac{\text{NP signal}}{\text{ther. SM noise}}\right]_{\text{up-type}} > \left[\frac{\text{NP signal}}{\text{ther. SM noise}}\right]_{\text{down-type}}$$

Uniqueness of Charm (II)

- Charm is the only up-type quark (u, c ,t) allowing full range of probes for NP.
  - top quarks do not hadronize → no T^0 - antiT^0 oscillations
    - hadronization while hard to force under theor. control enhances observability of CP violation
  - no π^0-π^0 oscillations possible
    - particle and anti-particle are identical

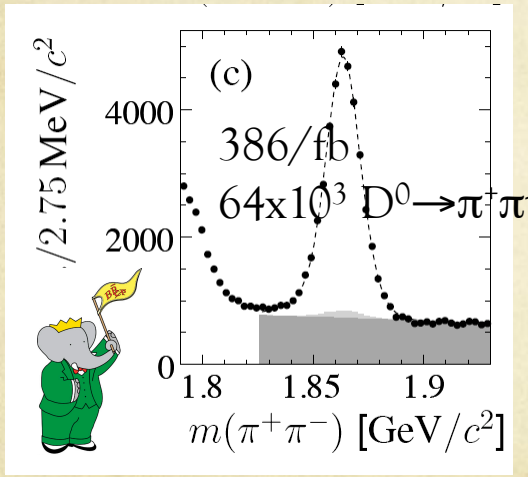
Charm transitions are a unique portal for obtaining a novel access to flavor dynamics with the experimental situation being a priori favorable.

$A_{CP}(D^0 \to h^+h^-)$: current status

D^0 oscillations can generate time dependent CP asymmetries that survive integrating over time. Crucial to investigate with extreme precision (per mil level and beyond):

tagged from $D^* \to$ $\quad A_{CP}^{\pi\pi} = \dfrac{\Gamma(D^0 \to \pi^-\pi^+) - \Gamma(\overline{D}^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to \pi^-\pi^+) + \Gamma(\overline{D}^0 \to \pi^+\pi^-)}$ (the same for K^+K^-)

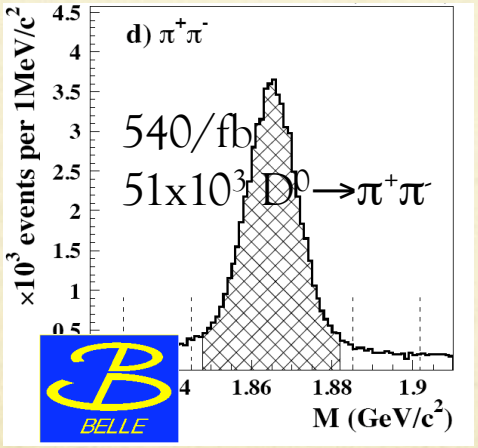
PRL100,061803(2008)



$A_{CP}^{KK} = [+0.00 \pm 0.34 \pm 0.13]\%$

$A_{CP}^{\pi\pi} = [-0.24 \pm 0.52 \pm 0.22]\%$

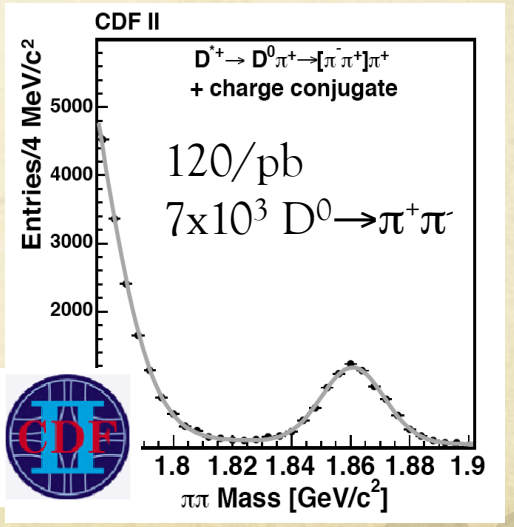
PLB670,190-195(2008)



$A_{CP}^{KK} = [+0.43 \pm 0.30 \pm 0.11]\%$

$A_{CP}^{\pi\pi} = [+0.43 \pm 0.52 \pm 0.12]\%$

PRL94,122001(2005)

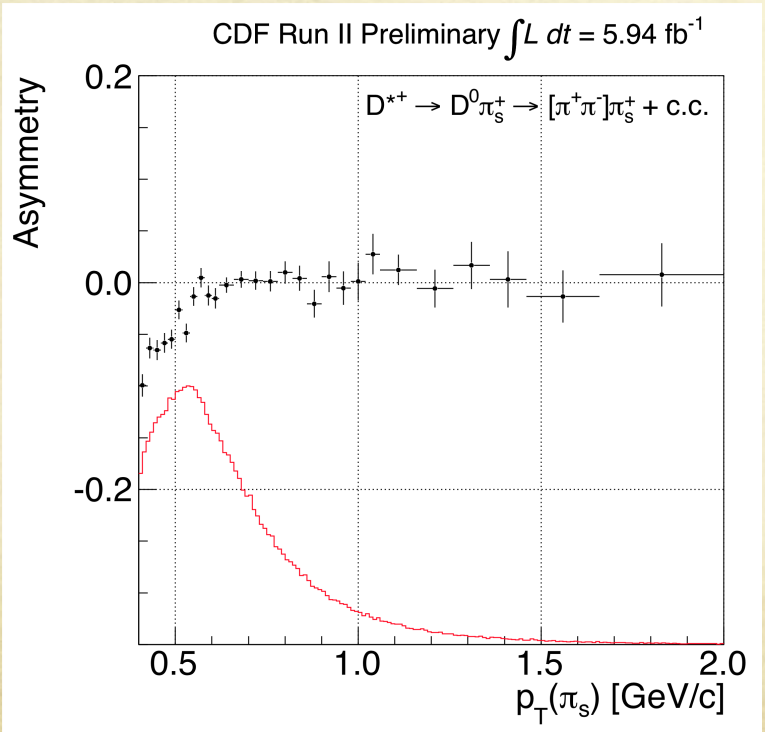


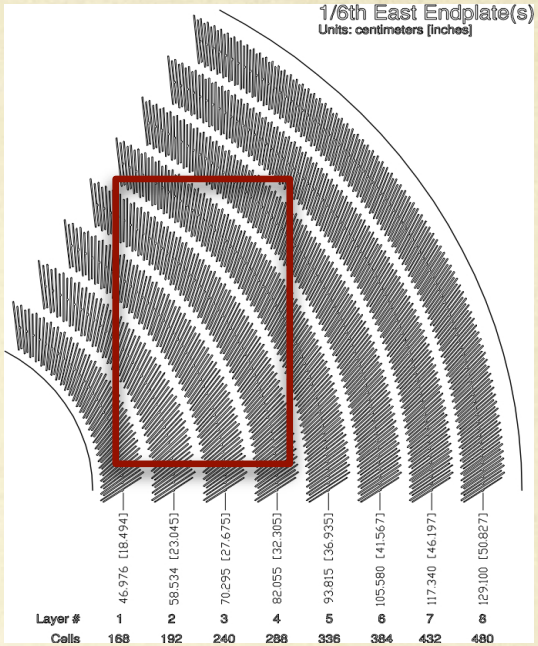
$A_{CP}^{KK} = [+2.0 \pm 1.2 \pm 0.6]\%$

$A_{CP}^{\pi\pi} = [+1.0 \pm 1.3 \pm 0.6]\%$

Fighting detector asymmetries

Different efficiencies for soft pions of opposite charge translate into different efficiencies for D* of opposite charge and may lead to a fake charge asymmetry in D^0 decay.





Need to suppress detector charge asymmetry by more than one order of magnitude to control systematics to better than 0.1%.

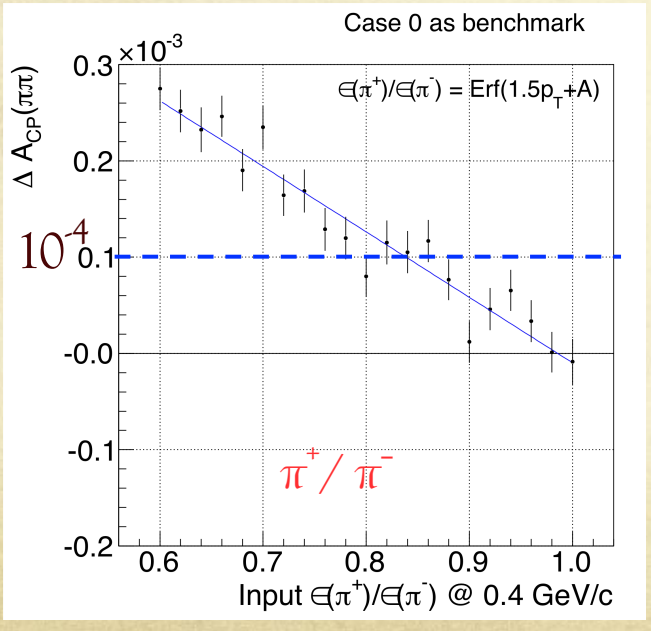
This can be done with a very high degree of confidence using only data - no need to rely on Monte Carlo.

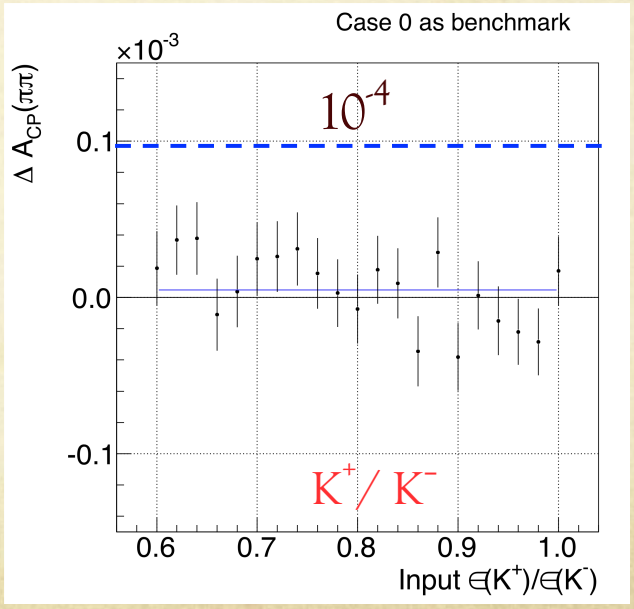
Uncertainty on the shapes

- in order to assess a systematic error associated with the particular shapes of the mass distributions of the signal assumed in the fits, we let them vary within reasonable limits and observe the corresponding change in the measured asymmetry
- when the same shape is used for the positive and negative samples, the small changes in estimated yields tend to compensate and cause a negligible effect on the measured asymmetry
- the largest effect is obtained when the shapes used for the positive and negative samples are varied independently
- we estimate a worst case effect of 0.098%

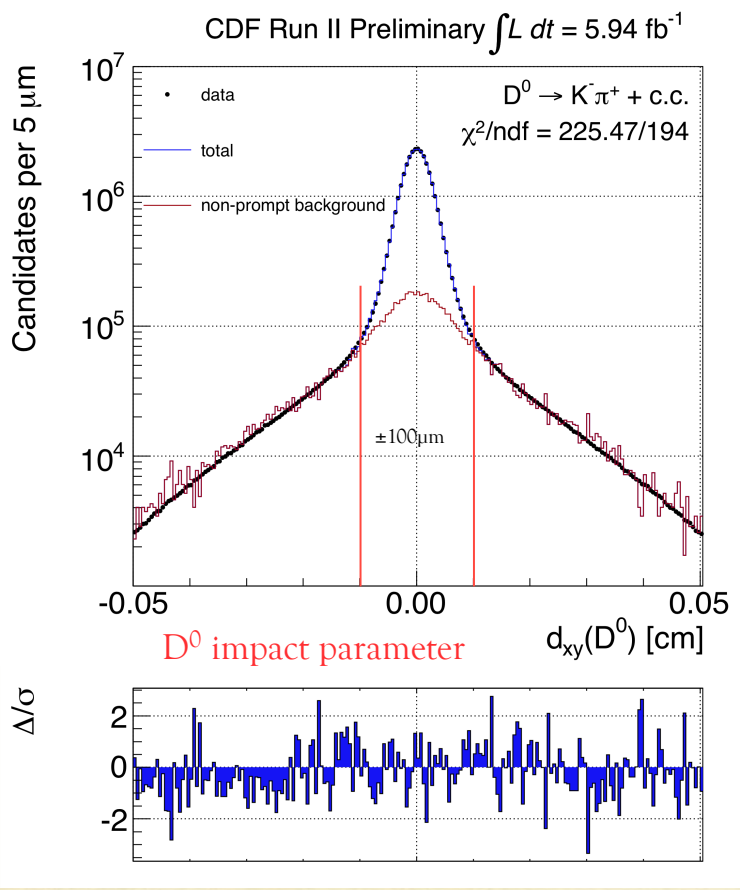
MC test of detector asymmetry cancellation

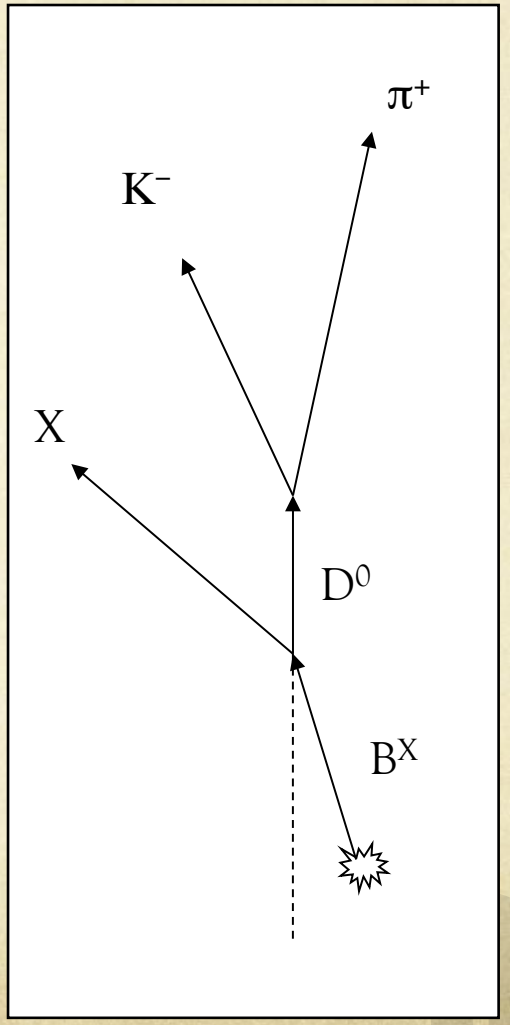
- use CDF MC with detailed detector simulation
- inject artificial detector asymmetries in simulation
- apply analysis method and measure bias on A_{CP} measurement





contamination from B → D^0 + X





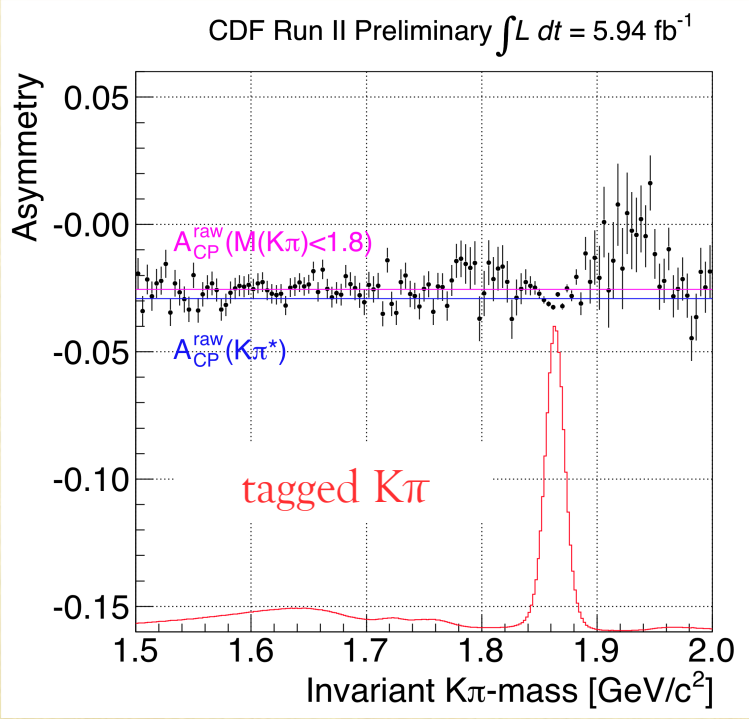
f_B ~ 17%

$A_{CP}(B \to D^0 X)$= (- 0.21± 0.20)%

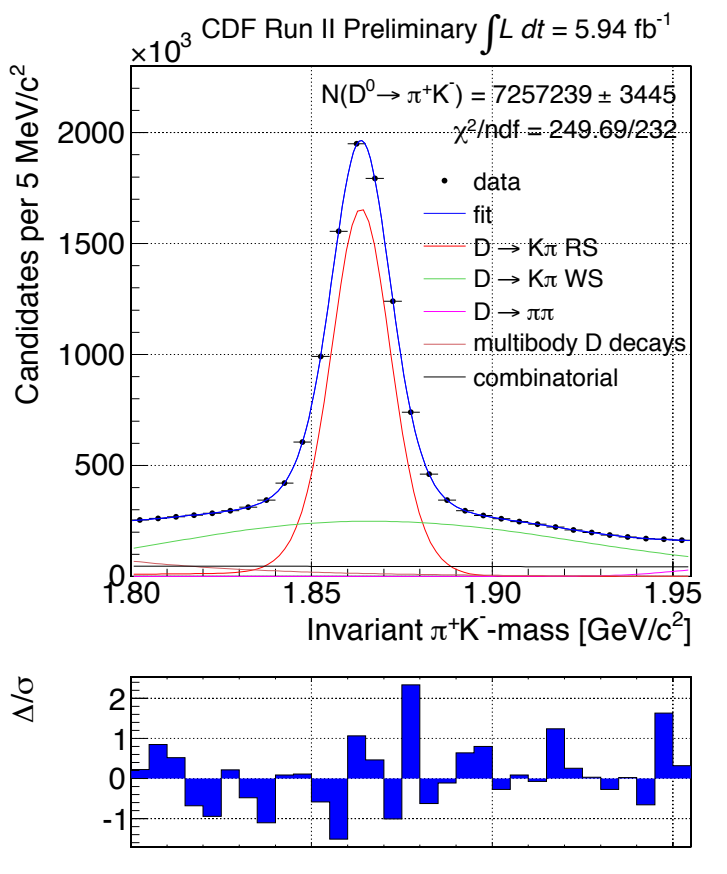
f_B xAcp ~ 0.034%

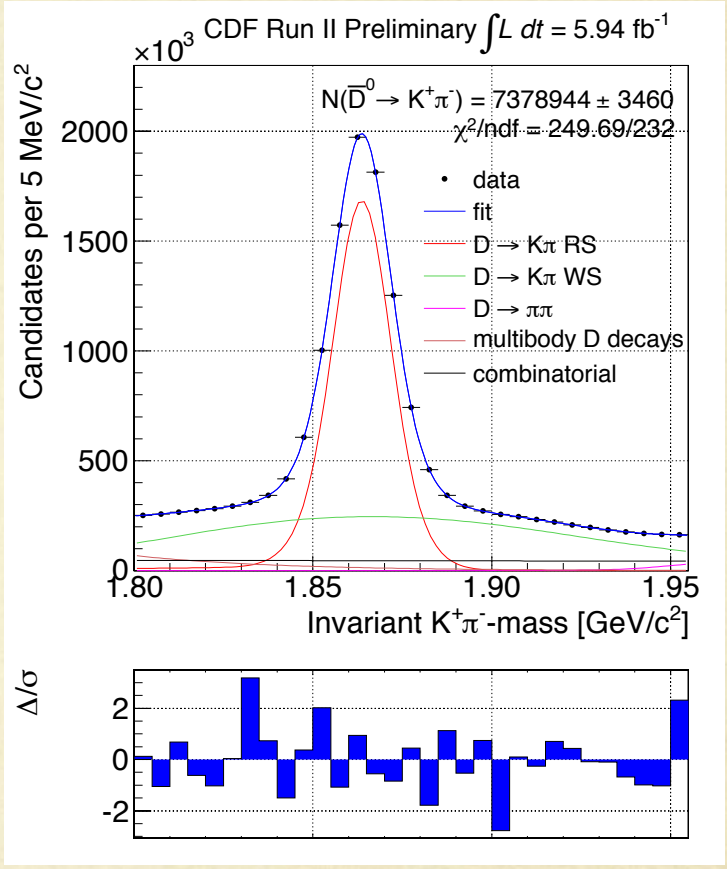
Contamination from other decays

The size of the effect is the fraction of the contaminant (~ 0.77%) times the <u>difference</u> in asymmetries (~ 0.36%) ⇒ < 10^{-4}



Counting untagged $D^0 \to K^-\pi^+$

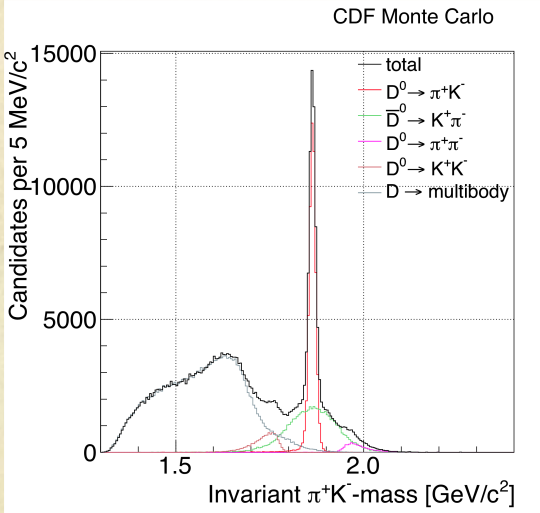


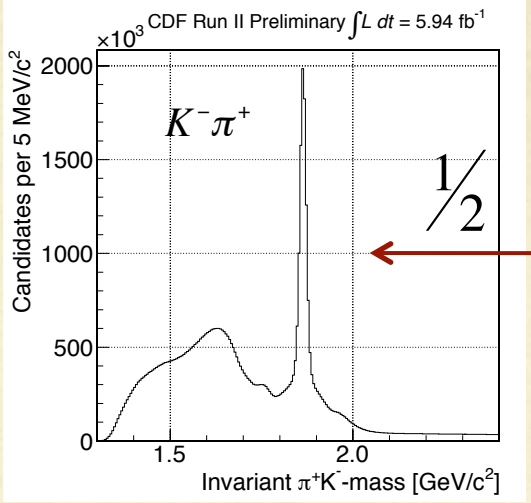


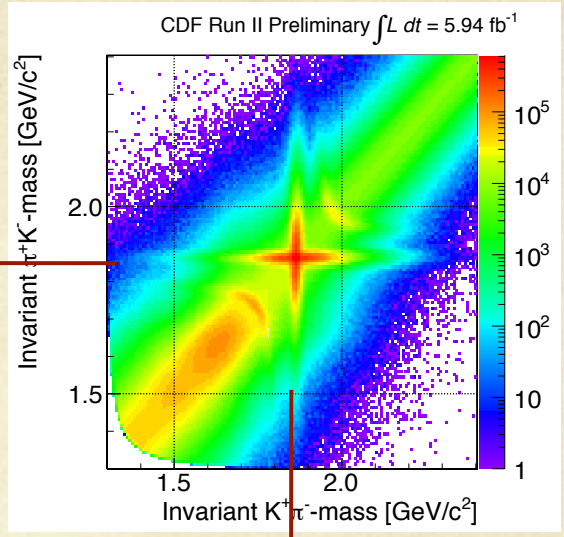
~ 2 × 15·000·000 untagged $D^0 \to K^-\pi^+$ + cc

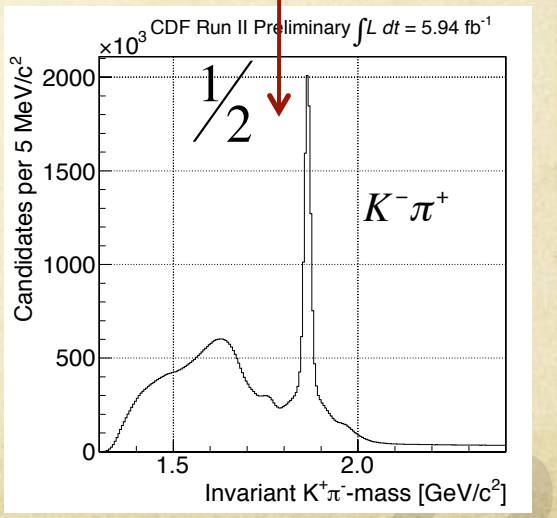
$$A_{CP}^{raw}(K\pi) = (-0.83 \pm 0.03)\%$$

Counting untagged $D^0 \to K^-\pi^+$









- two statistically independent samples with half the events each
  - can easily afford to loose a factor of two in statistics
- simultaneous fit of two 1D mass projections
- signal is in narrow peak
  - ignore order of 10^{-4} DCS contribution

A new scenario: Charm Mixing

"Evidence" of D^0 mixing open new scenarios:

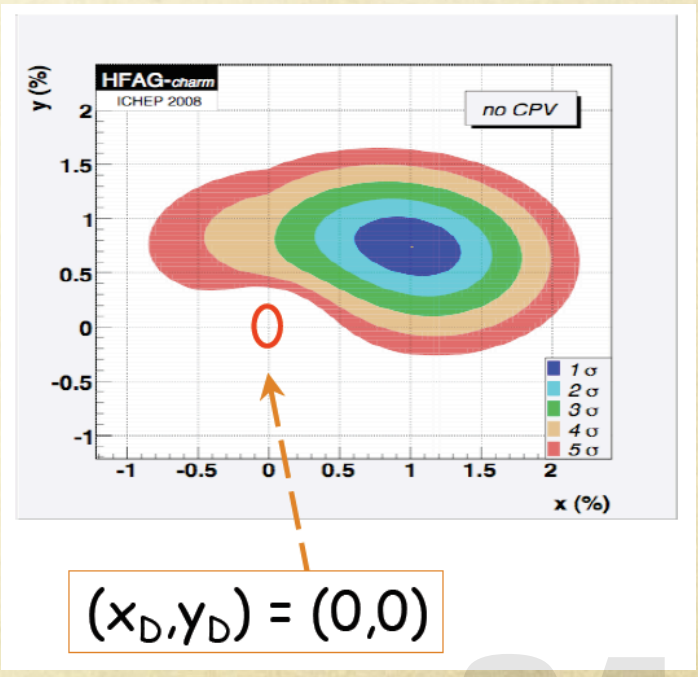
$$x_D = \frac{\Delta m_D}{\Gamma_D} \qquad y_D = \frac{\Delta \Gamma_D}{2\Gamma_D}$$

$x_D = (1.00 \pm 0.26)\ \%$
$y_D = (0.76 \pm 0.18)\ \%$

$$A_{CP}(t) = (x_D \sin\phi_{CP} - y_D \varepsilon_{CP} \cos\phi_{CP})(t/\tau) + \ldots$$

$x_D, y_D = 0.01$, $\sin\phi^{SM}_{CP}$, $\varepsilon^{SM}_{CP} < 0.001$

$\Rightarrow$ $A^{SM}_{CP}(t) < 10^{-5}$ vs. $A^{NP}_{CP}(t) < 10^{-2}$



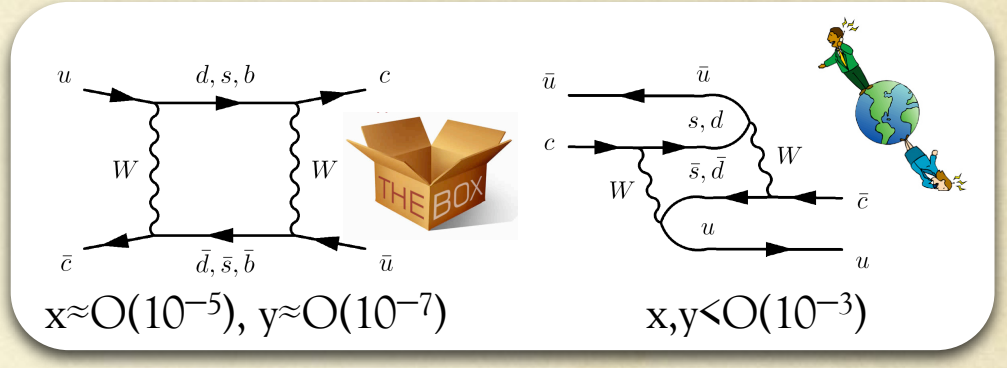
NP could be close! A nice window to look inside. Are D^0-mixing, $\sin(2\beta s)$, $A_{FB}(b\to s\mu\mu)$, $A_{CP}(B^0\to K\pi)$ indicating the presence of 4^{th} generation?

Charm totally complementary to direct searches in LHC age, not yet deeply explored.

Look for instance at the recent talk of Bigi "*On the Beauty of Charm*", Extreme Beam Lecture Series, 9/22/2009 – Fermilab.

D^0 mixing

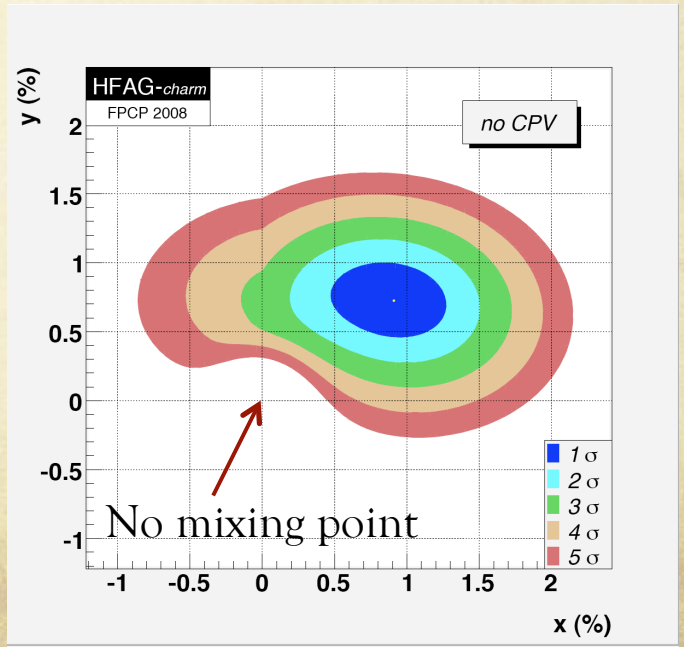
Charm mixing very small in the SM.
Top quark do not participate in the box diagram. "Long distance" contribution hard to calculate but lesser than $O(10^{-3})$.



Mixing parameters (x,y) larger than the expected or CP violation effects in the mixing would be "unequivocal" sign of NP.

First evidence of charm-mixing from
Babar PRL98,211802(2007) 3.9σ
and Belle PRL98,211803(2007) 3.2σ
confirmed by CDF 3.8σ. See next slides.

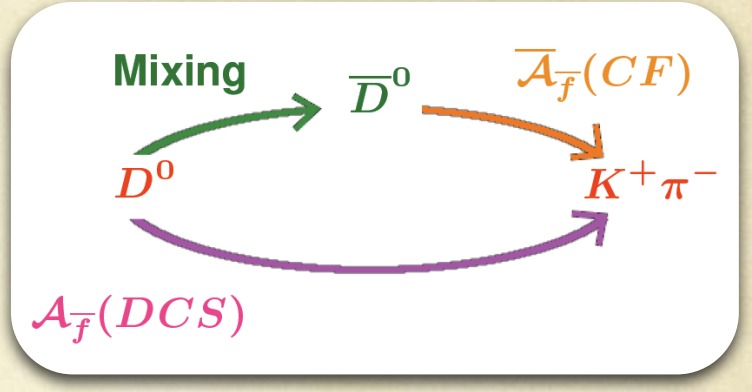
Average indicates no-mixing hypothesis ruled out with significance larger than 5σ, but "world" is still waiting for single experiment "observation".



D^0-mixing – $D^0 \to K^-\pi^+$

Use $D^0 \to K^-\pi^+$ decays tagged by charge of soft pion in the decay $D^{*+} \to D^0\pi^+$.

Measure time-dependent of R(t)=WS/RS where:
- wrong sign (WS) $D^{*+} \to D^0\pi^+ \to [K^+\pi^-]\pi^+$
- right sign (RS) $D^{*+} \to D^0\pi^+ \to [K^-\pi^+]\pi^+$.



WS from two processes: **Mixing** then **CF decays** or **DCS decays**.

(Assuming |x|,|y|<<1 and no CPV)

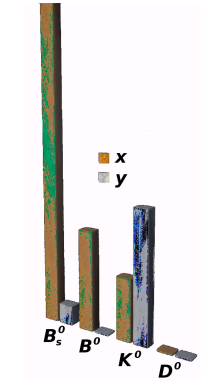
$$R(t) = R_D + \sqrt{R_D}\, y' \,(\Gamma_D t) + \frac{x'^2 + y'^2}{4}\,(\Gamma_D t)^2$$

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

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

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

$$y = \frac{\Delta\Gamma}{2\Gamma} = \frac{\Gamma_H - \Gamma_L}{(\Gamma_H + \Gamma_L)}$$



D^0-mixing – Analysis

1.5/fb of data collected with impact parameter trigger

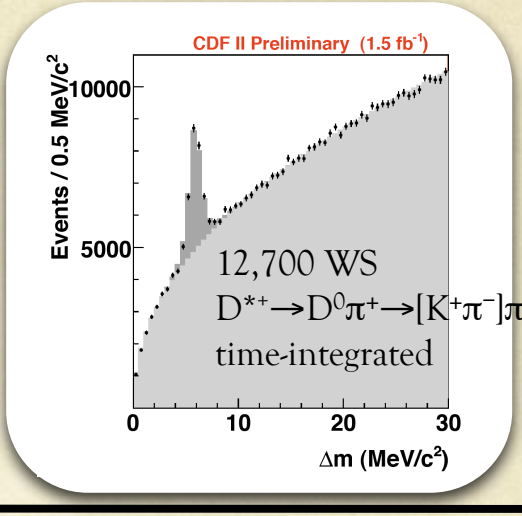
Clean up WS from RS → Apply opposite mass assignment + PID cuts exclude > 96.4% RS decays from WS signal. Keeps 78% of signal.

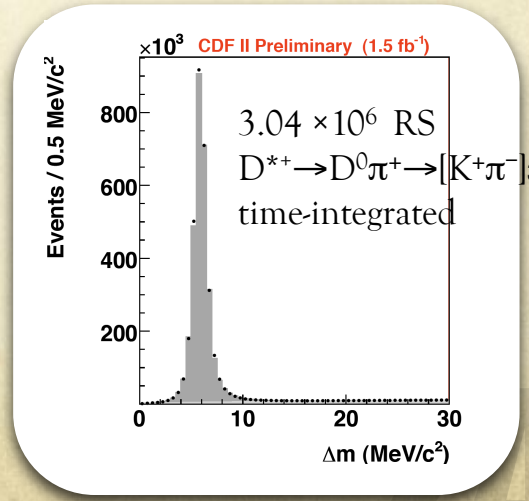
Shapes from RS events distributions. Data driven analysis.

Fit of WS and RS invariant Kπ-mass in 60 $\Delta m = m_{D^*} - m_{D0} - m_\pi$ bins, and in 20 $c\tau$ proper time bins.

Non-prompt B→D*X subtracted using impact parameter distribution of D*.

Most of systematic uncertainty enters at second order in the ratio WS/RS.



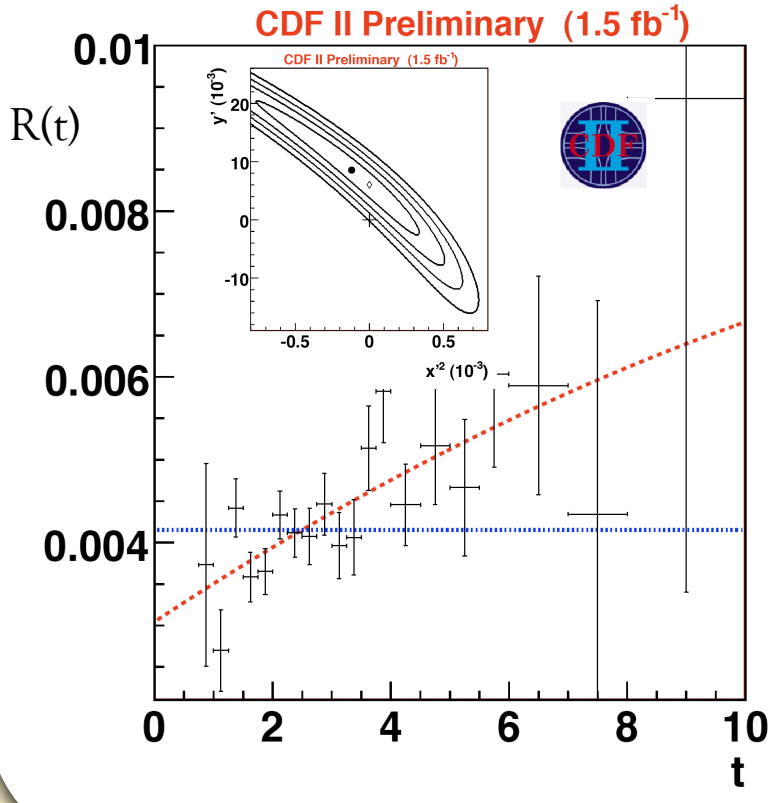


D^0-mixing at CDF

L_{int}= 1.5fb^{-1} PRL 100,121802(2008)

Fit type	$R_D(10^{-3})$	$y'\,(10^{-3})$	$x'^2\,(10^{-3})$	χ^2 / d.o.f.
Unconstrained	3.04 ± 0.55	8.5 ± 7.6	-0.12 ± 0.35	19.2 / 17
Physically allowed	3.22 ± 0.23	6.0 ± 1.4	0	19.3 / 18
No mixing	4.15 ± 0.10	0	0	36.8 / 19

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



Using just a "first part of data" available, CDF confirms evidence of mixing hypothesis at 3.8σ. Next step: observation and precise measurement with 6fb^{-1}.

D^0-mixing – Results

L_{int}= 1.5\fb PRL 100,121802(2008)

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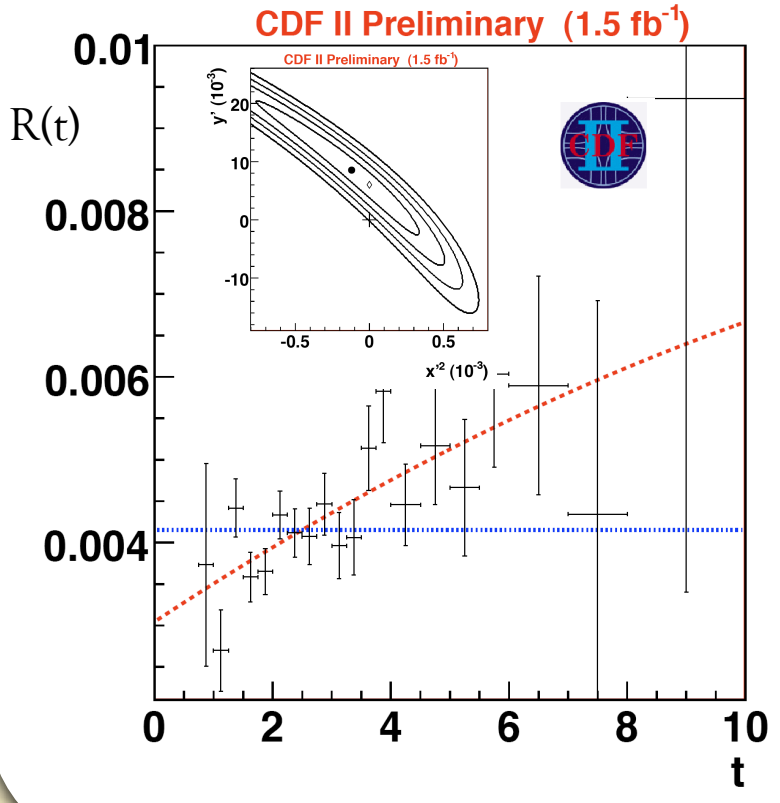

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Next step: observation and precise measurement.