Measurement of CP violation in the $D^0 \rightarrow \pi^+\pi^-$ at CDF

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CERN Joint EP/PP Seminar

CP Violation

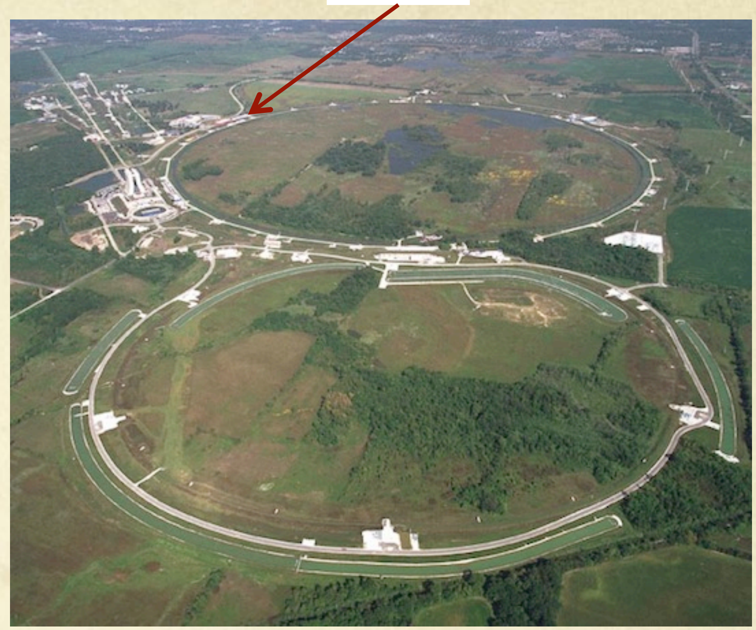
- The non-invariance of the weak interactions with respect to the combined charge-conjugation (C) and parity (P) dates back to year 1964. Measurement of $\varepsilon_K \approx 10^{-3}$ was the first manifestation of a **"CP violation"**.

- Ever since the understanding CPV is a crucial goal in HEP:
  - to study and test the SM.
  - to probe physics beyond the SM.
  - To shed light on cosmology issues.
    - CPV present in the SM seems to be small to generate the observed baryonic asymmetry $O(10^{-10})$.

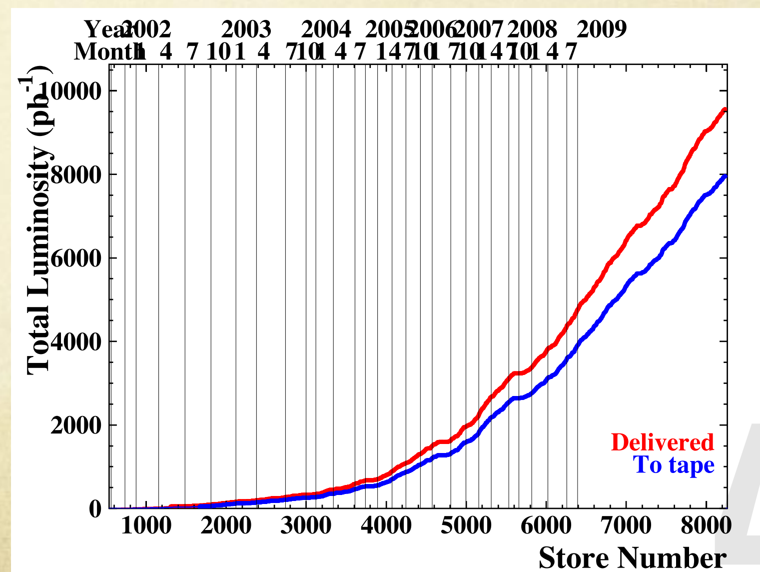
CP Violation in the charm sector

- Thus far 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 because it probes up-quark sector (unaccessible through t or u quarks).
- "Large" D^0 mixing parameters recently observed open new scenarios. Crucial to explore window $A_{CP}(t) \sim [10^{-2} - 10^{-5}]$.
- Any CP violation hint today may unambiguously indicate NP.

TeVatron

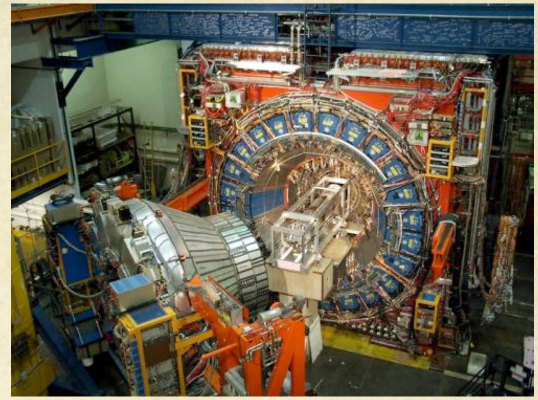


- $p\bar{p}$ collisions at $\sqrt{s}$=1.96TeV.
- Peak luminosity ~ 3.5–3.8 × 10^{32}.
- 50-60 pb^{-1} recorded a week .
- Collected about 8 fb^{-1} (on tape).
- >10 fb^{-1} by the end of 2011.
  - ~16 fb^{-1} with 3 years extension.

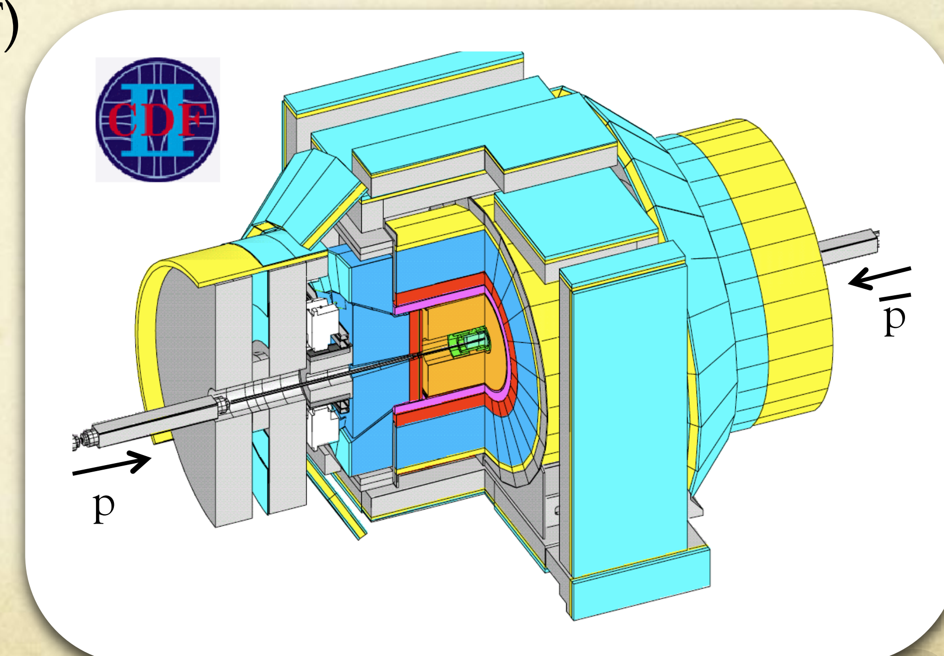


The CDFII detector

For this measurement only tracking information:

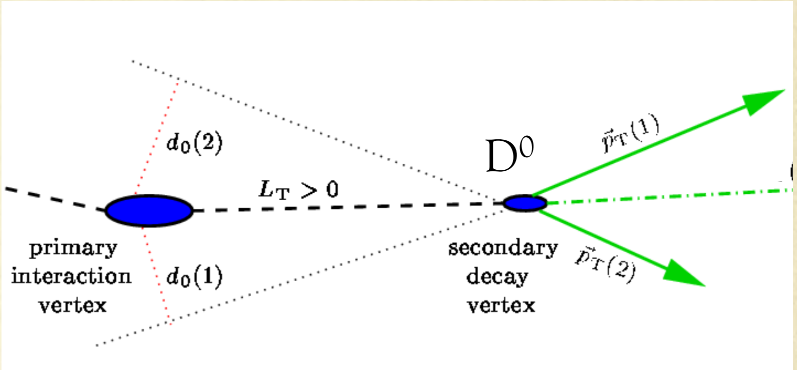


- Central Drift Chamber (COT)
  - $\delta p_T/p_T \sim 0.0015\ (\mathrm{GeV}/c)^{-1} p_T$
- Silicon Vertex Detector (SVX)
- Silicon Vertex Trigger (SVT)



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.
- Measures track impact parameter.
- Total execution time ~ 20 μs/event.



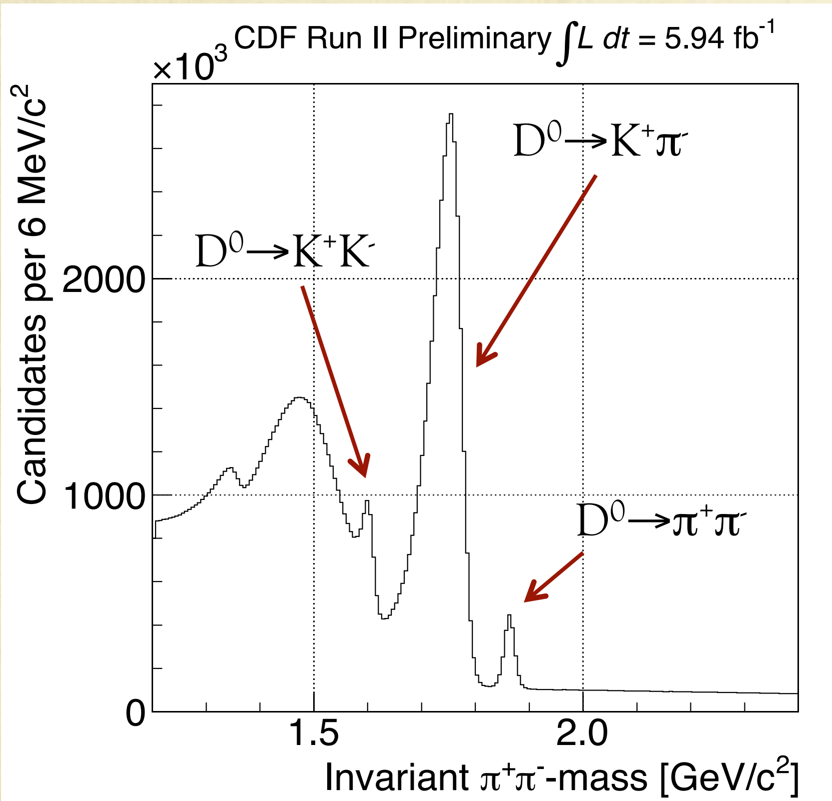
$$\sigma(d_0) \sim 30\mu m(SVT) \oplus 30\mu m(beam)$$

SVT plays a crucial role in charm physics

– World's largest sample of D^0, D^+, Ds^+, D^{*+}.

– Boosted proper decay times enhance sensitivity to time dependent effects.

World's largest sample: $D^0 \rightarrow hh$



No tag required from $D^{*+} \rightarrow D^0\pi^+$ decay

$N(D^0 \rightarrow \pi^+\pi^-) \approx 1.2 \times 10^6$

$N(D^0 \rightarrow K^+K^-) \approx 3 \times 10^6$

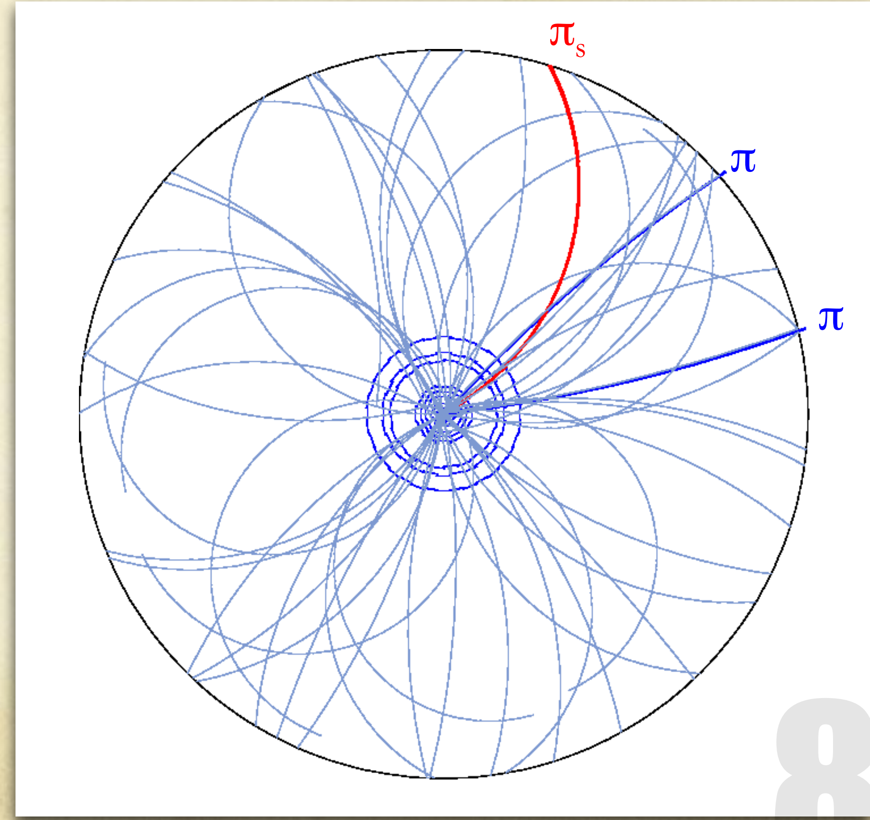
$N(D^0 \rightarrow K^-\pi^+) \approx 30 \times 10^6$

Without hadronic trigger in $6fb^{-1}$ just ~100 $D^0 \rightarrow K^-\pi^+$ (from Minimum Bias)

Measuring $A_{CP}(D^0 \to \pi^+\pi^-)$

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

Tagging the D^0 with D^*: $\begin{cases} D^{*+} \to D^0\pi_s^+ \\ D^{*-} \to \overline{D}^0\pi_s^- \end{cases}$



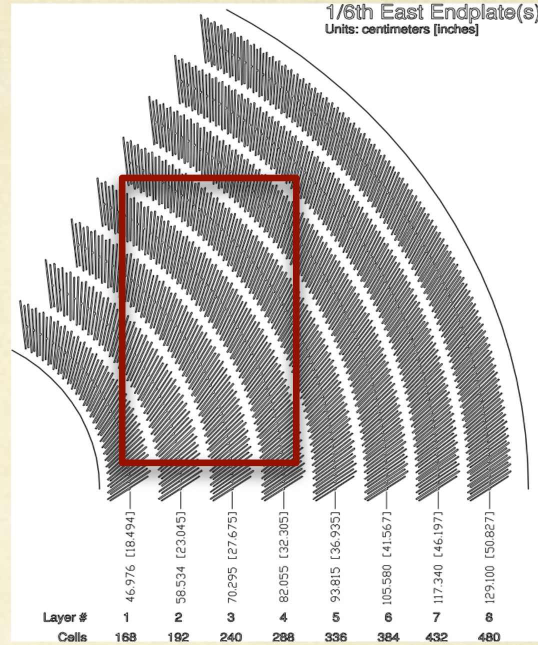
CP symmetric initial state ($p\overline{p}$)
ensures charge symmetric production.

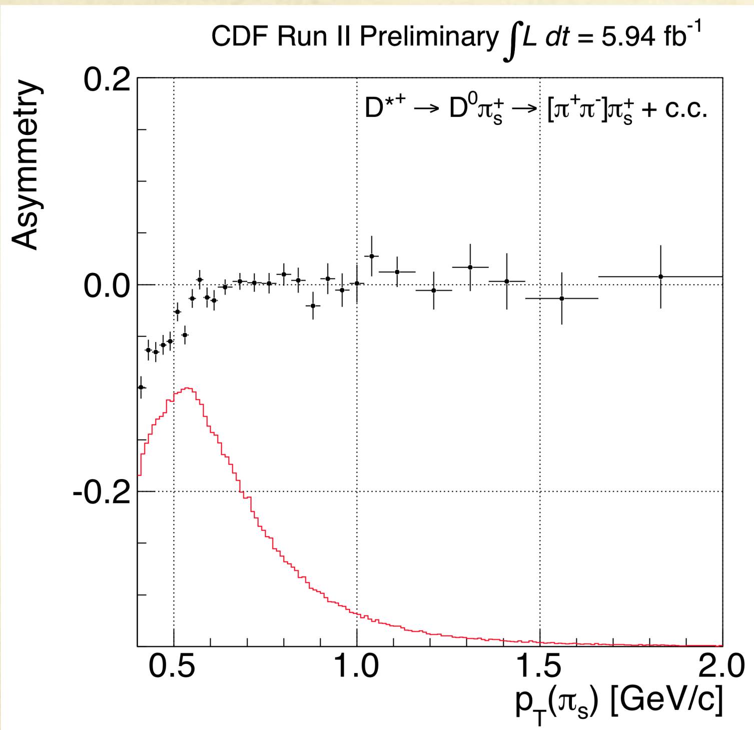
~ 215,000 $D^* \to D^0\pi$ with $D^0 \to \pi^+\pi^-$.

$1/\sqrt{S}$ ~ 0.22% statistical uncertainty

The challenge

Drift Chamber is intrinsically charge asymmetric, tracking efficiencies for positive and negative may differ by few %





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.

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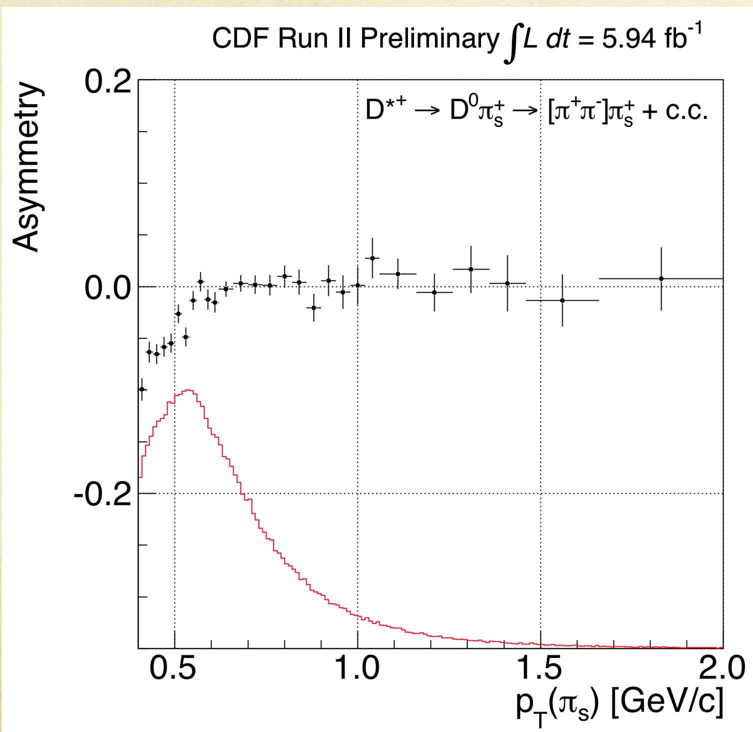

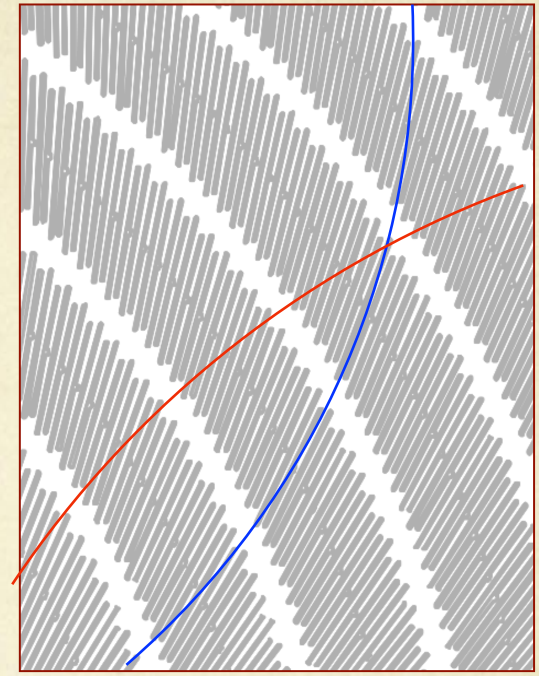

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This can be done with a very high degree of confidence using only data - no need to rely on Monte Carlo.

Suppress detector asymmetries

Fully data-driven

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

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

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

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

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

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

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

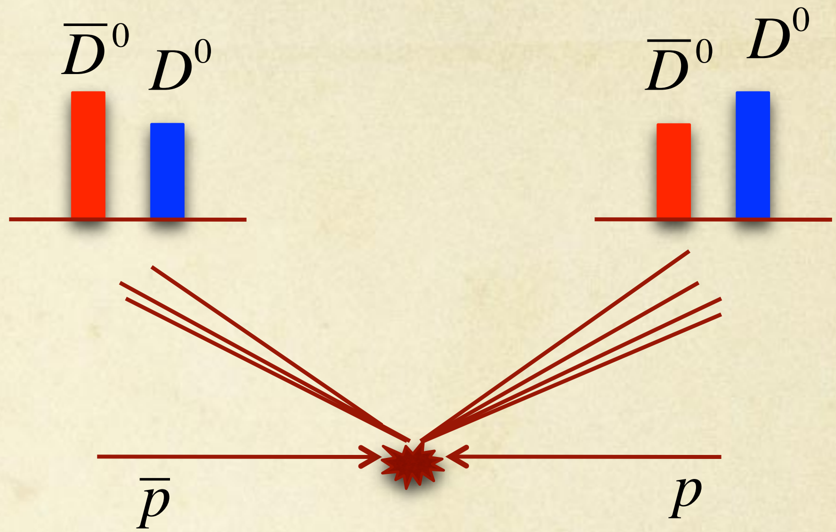
Basic assumptions

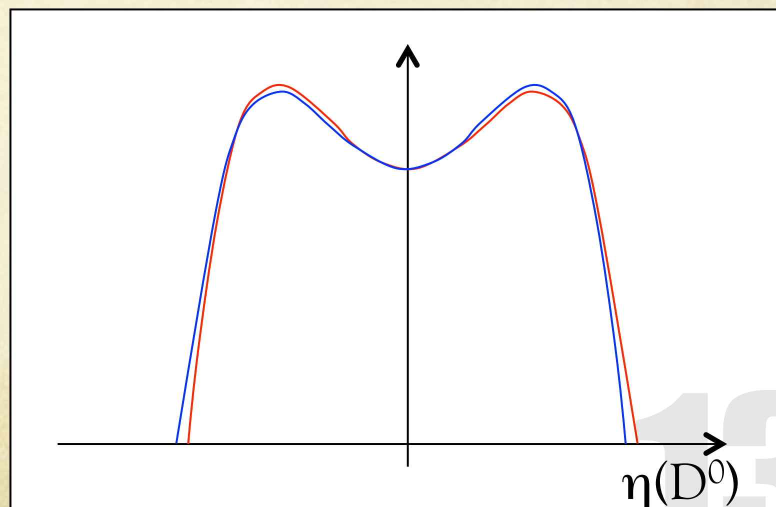
- At production $N(D^0)=N(\overline{D}^0)$ and $N(D^{*+})=N(D^{*-})$
  - $p\overline{p}$ initial state and CP conservation of strong interactions.
  - η - symmetric detector.
- Detection efficiency factorization
  - $\varepsilon(D^*) = \varepsilon(D^0) \times \varepsilon(\pi_s)$.
- Kinematic distributions should be equal across samples.
  - $\delta(\pi_s)^{\pi\pi*} = \delta(\pi_s)^{K\pi*}$ and $\delta(K\pi)^{K\pi} = \delta(K\pi)^{K\pi*}$

Systematic uncertainties have been assessed for all of them.

Why η-symmetric detector?

- D^0/D^*mesons may keep residual "memory" of the underlying beam (beam drag).
- Small forward-backward charge asymmetry may be present.
- A η-symmetric detector cancels out the effect
  - Need to integrate over η-symmetric region.





Reweighting the samples

Detector induced asymmetries are dependent on kinematics.

$D^* \rightarrow D^0 \pi_s \rightarrow (K\ \pi)\ \pi_s$

$D^* \rightarrow D^0 \pi_s \rightarrow (\pi\ \pi)\ \pi_s$

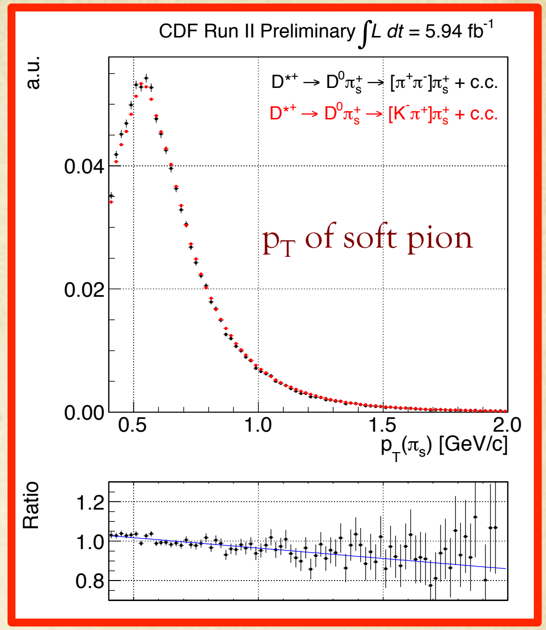
Distribution of π_s must be identical in the two samples for the cancellation to work.

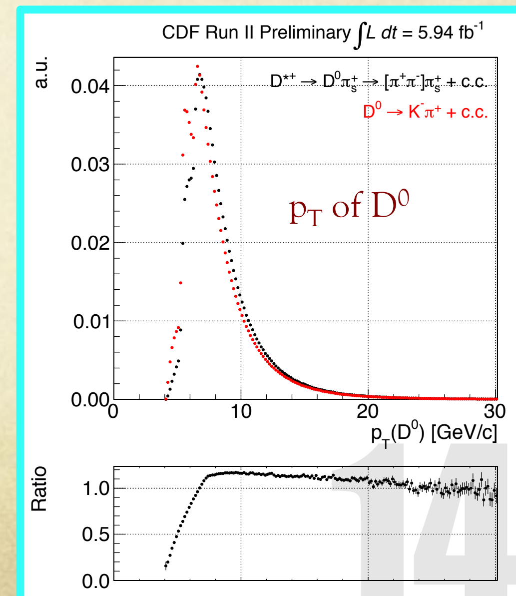
$D^0 \rightarrow (K\ \pi)$

$D^* \rightarrow D^0 \pi_s \rightarrow (K\ \pi)\ \pi_s$

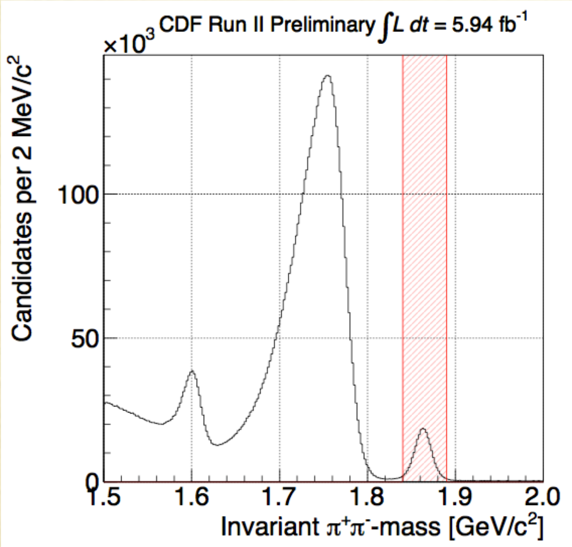
Same for $K\pi$.

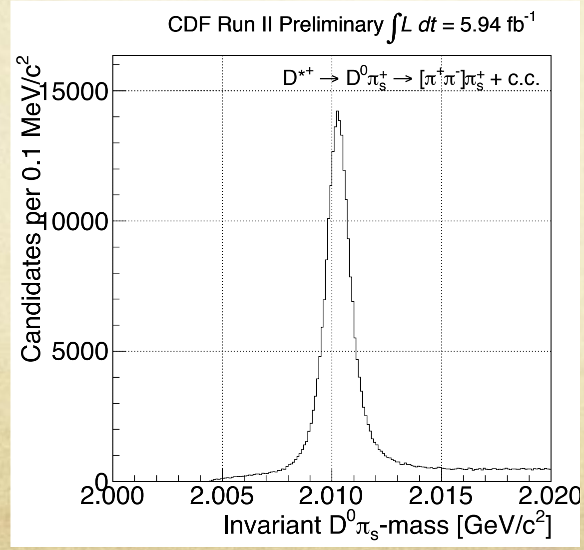
Distributions are made identical by sample reweighting





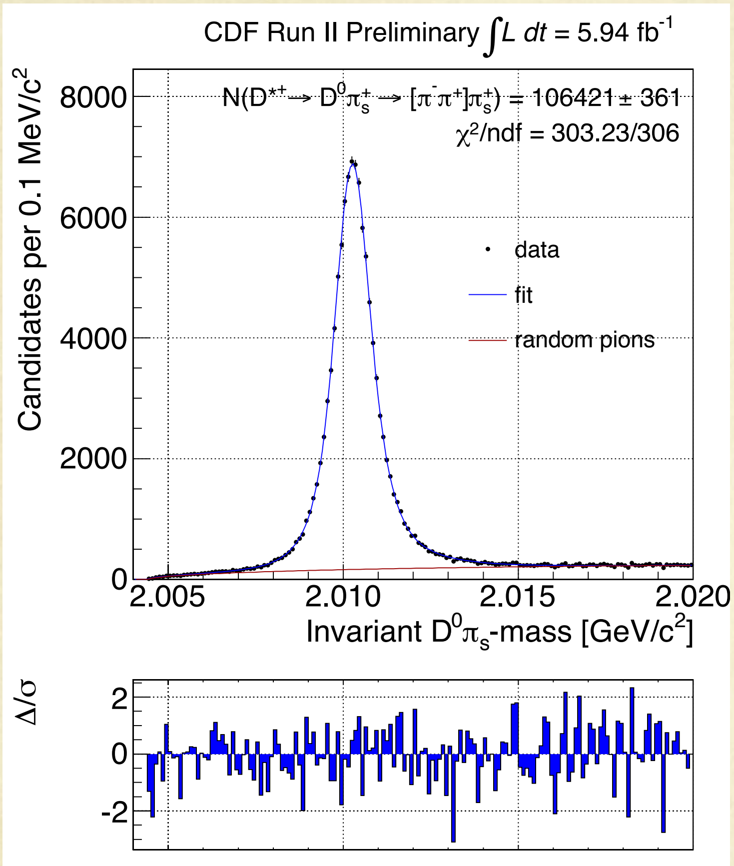
Counting tagged $\pi\pi$ events

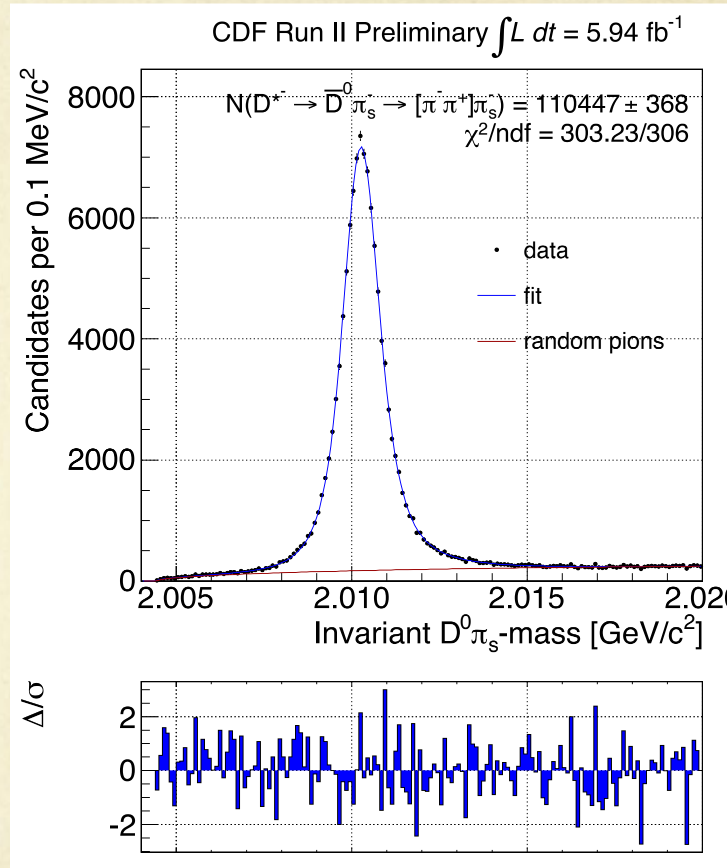




- cut on $\pi\pi$ invariant mass
- associate with soft pion
- fit D* invariant mass distribution

Tagged ππ combined fit



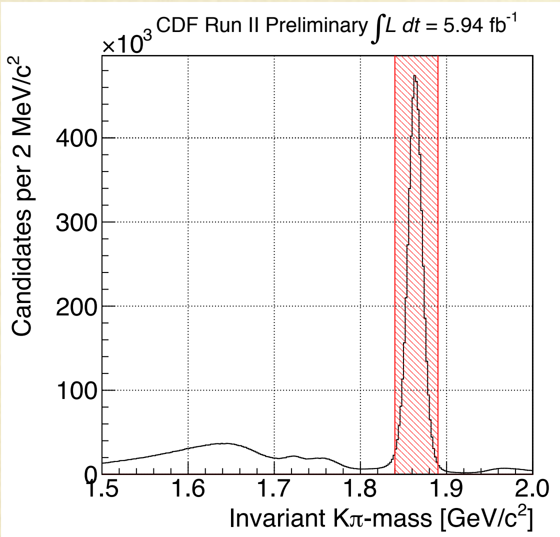


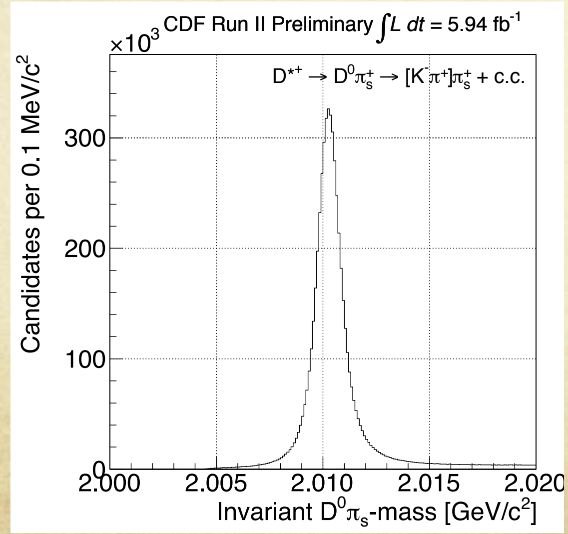
N^{+} = 106,421 ± 361

N^{-} = 110,447 ± 368

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

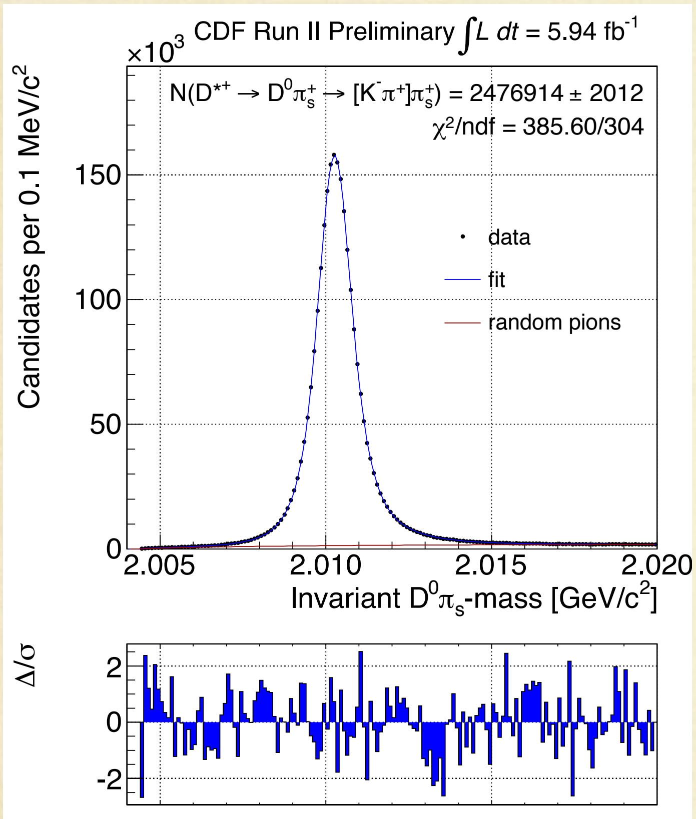
Counting tagged Kπ events

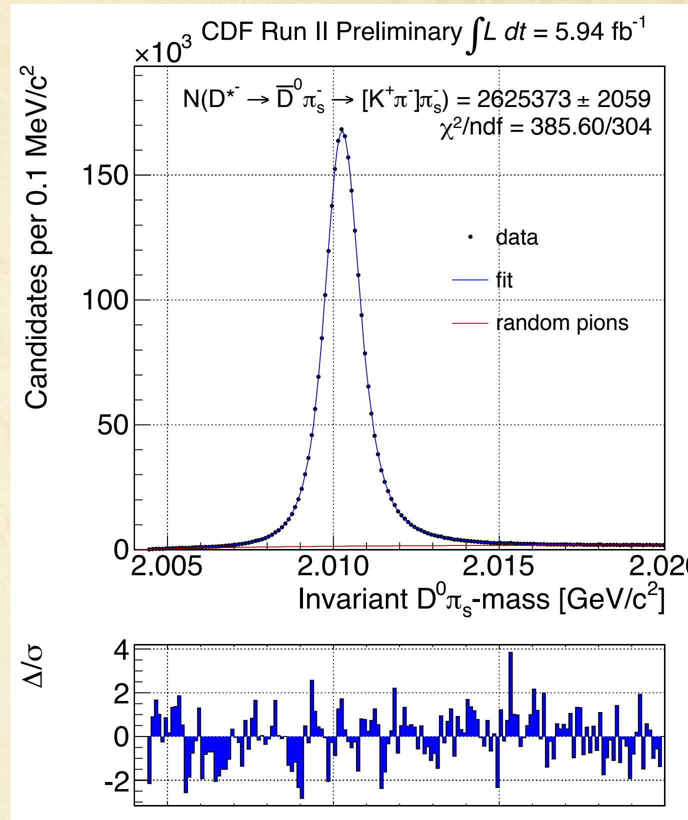




- cut on **Kπ** invariant mass
- associate with soft pion
- fit D* invariant mass distribution

Tagged Kπ combined fit





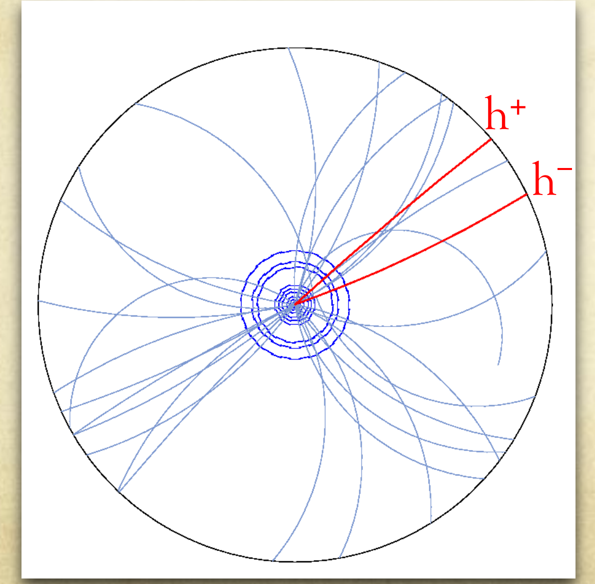
N^+ = 2,476,914 ± 2,012

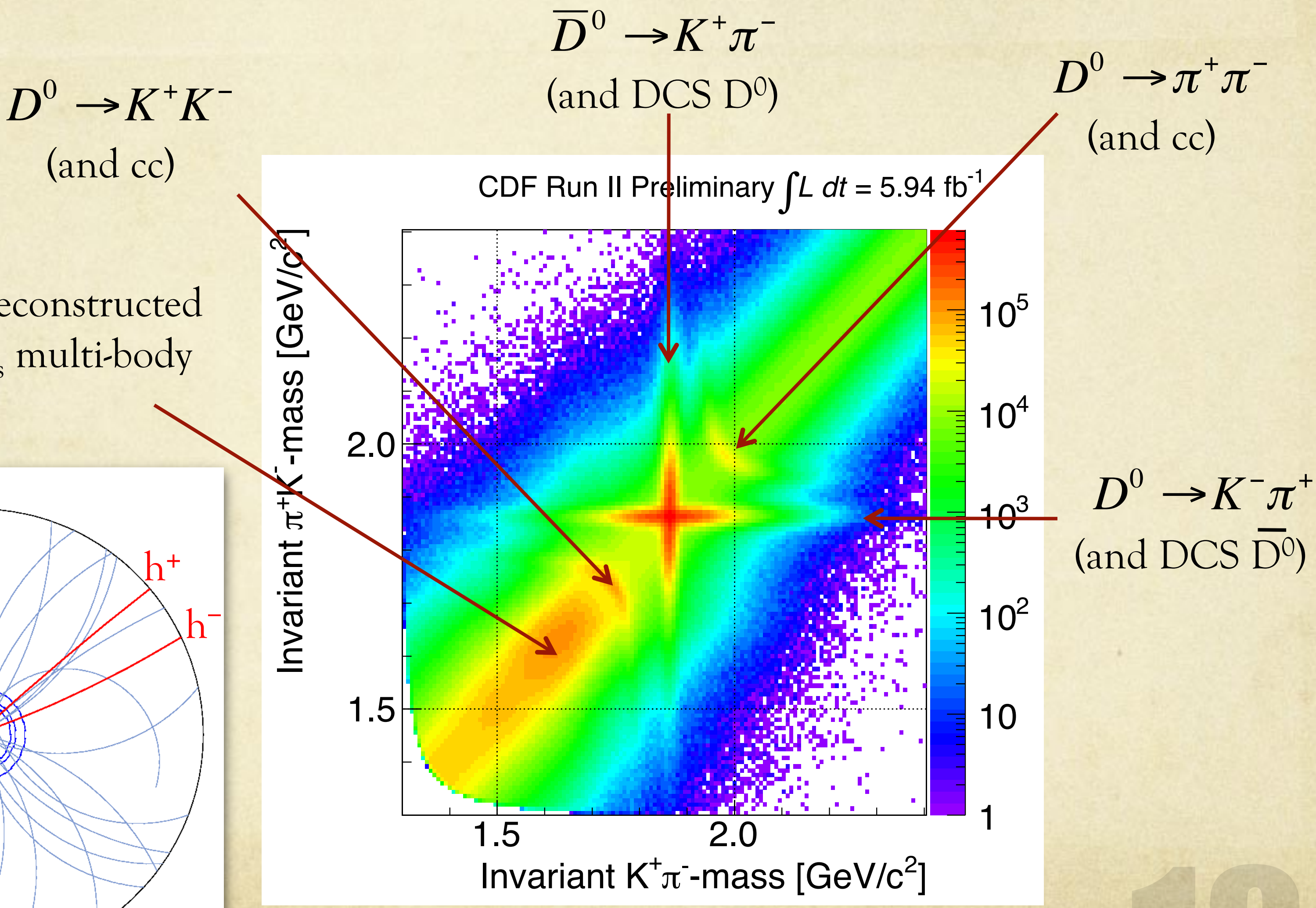
N^- = 2,625,373 ± 2,059

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

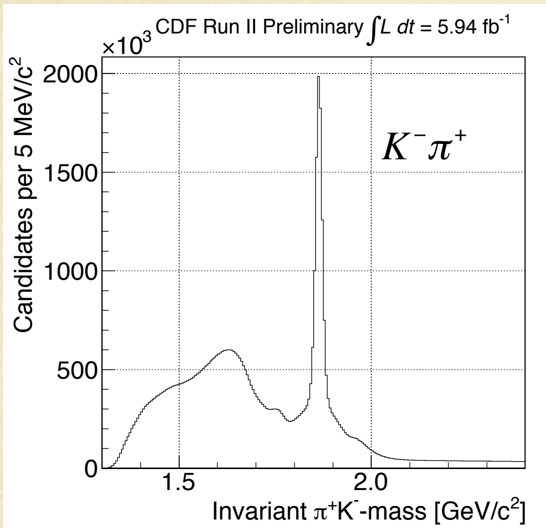
Counting untagged $D^0 \to K^- \pi^+$

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

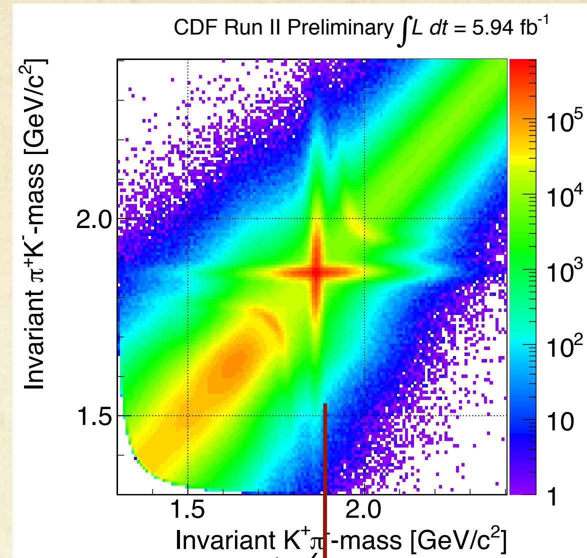




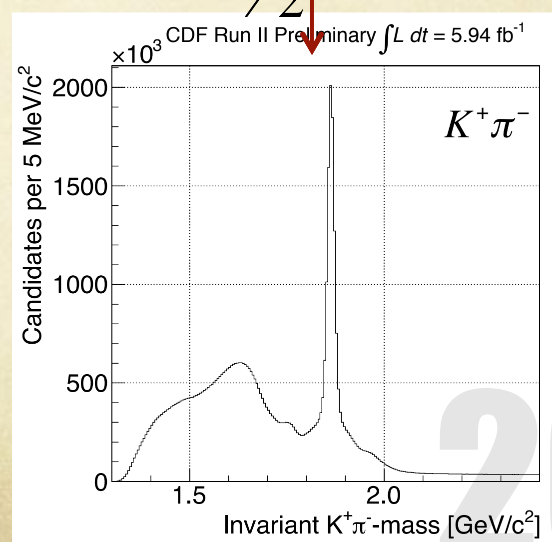
Counting untagged $D^0 \to K^- \pi^+$



½



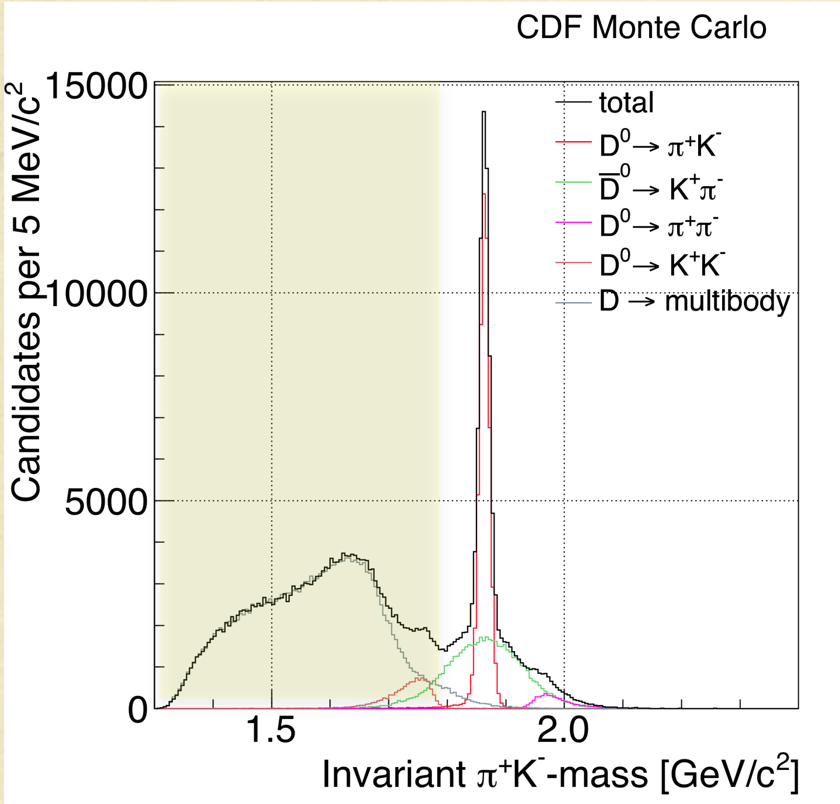
½



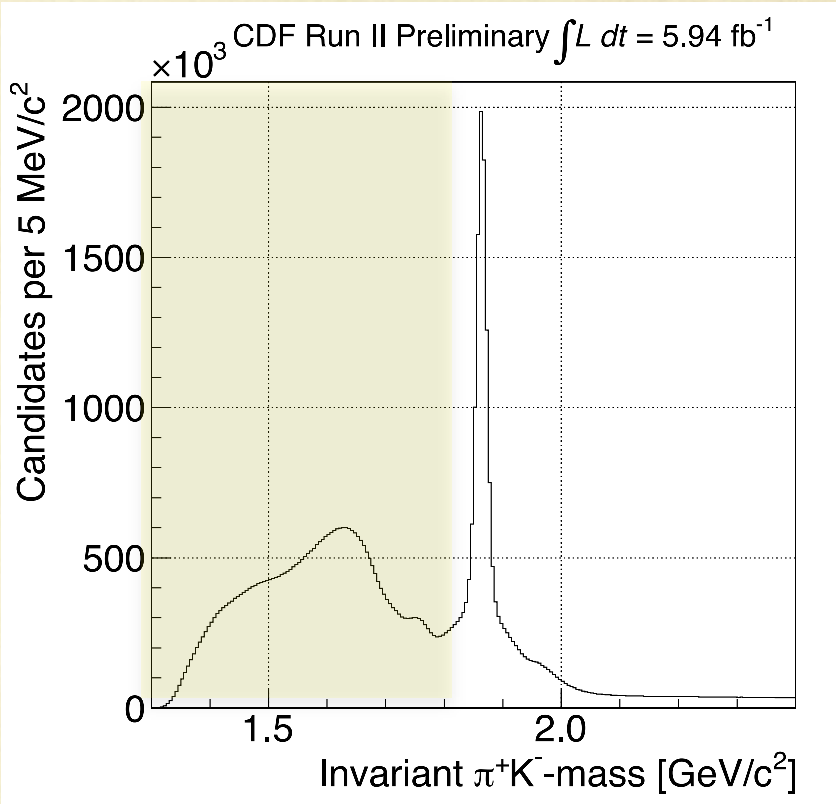
- Two statistically independent samples (half each)
- Can easily afford to lose a factor of two in statistics
- Signal is in narrow peak
  - ignore order of 10^{-3} DCS contribution.
- Mass fit for values > 1.8 GeV/c^2

MC vs. Data

MC

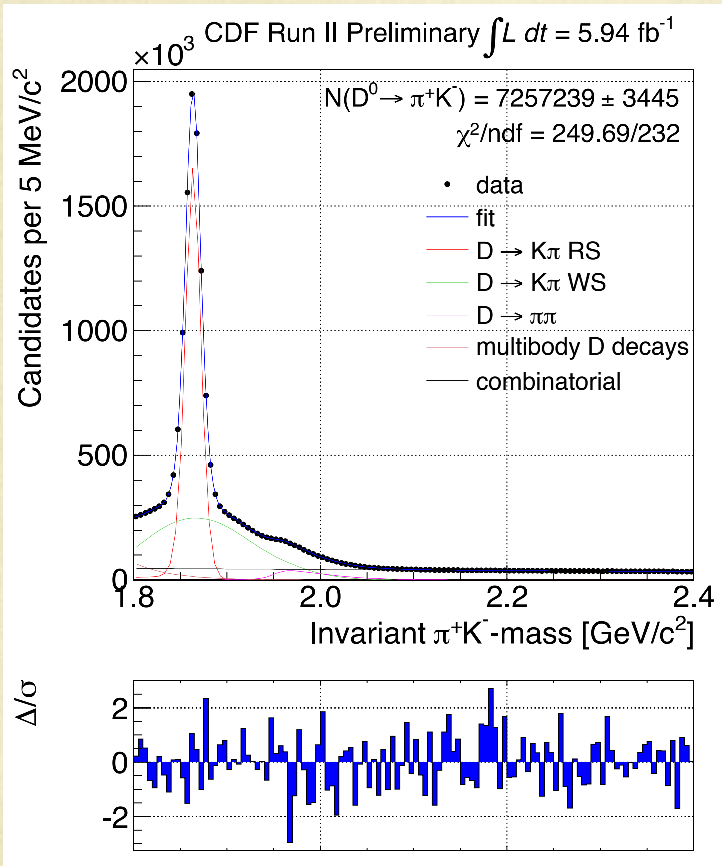


Data

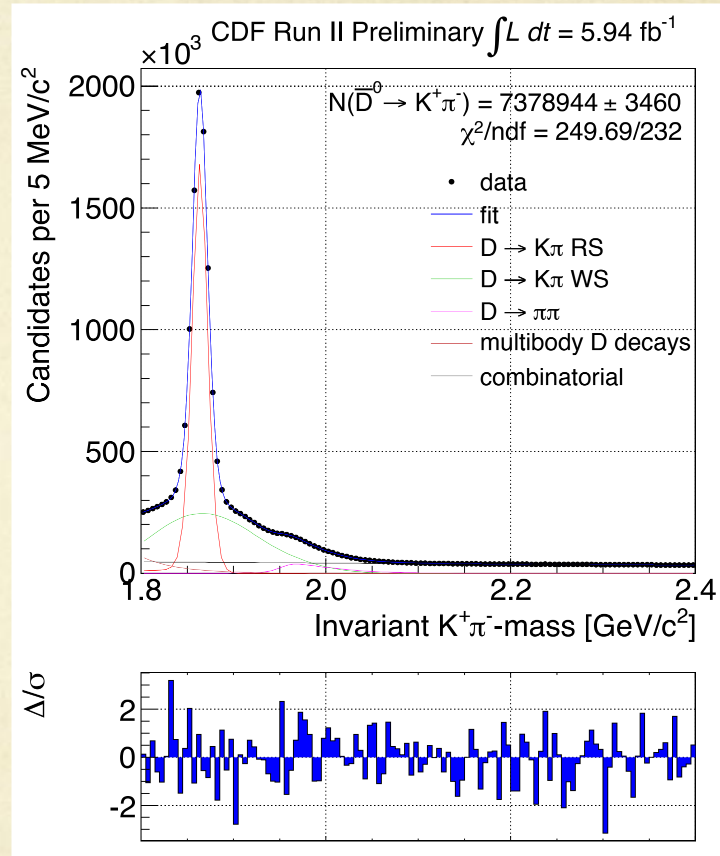


All features of the mass distribution are reproduced by MC

Untagged combined fit $D^0 \rightarrow K^- \pi^+$



$N^+ = 7,257,239 \pm 3,445$



$N^- = 7,378,944 \pm 3,460$

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

Putting it all together

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

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

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

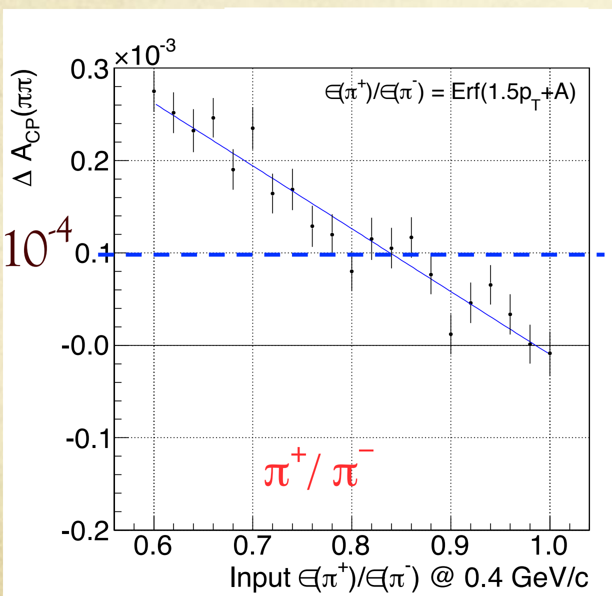
Statistical uncertainty only

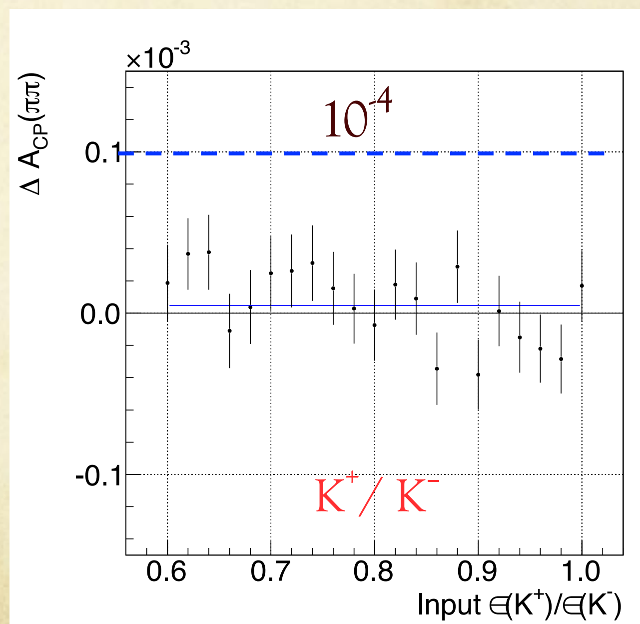
Systematic uncertainties

Source of systematic uncertainty	Variation on $A_{\mathrm{CP}}(\pi\pi)$
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%

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.





Beam Drag (I)

- Production forward-backward asymmetry due to the beam drag effect cancels out if:
  - η-symmetric detector
  - integration over η-symmetric region.
- However CDF is a “quasi” η-symmetric detector.
  - Beam drag production asymmetry may survive after integration.
- Turns out that the correction δA to the A_{CP} is of the order of the production charge asymmetry times the detector η-asymmetry, both averaged over total acceptance.

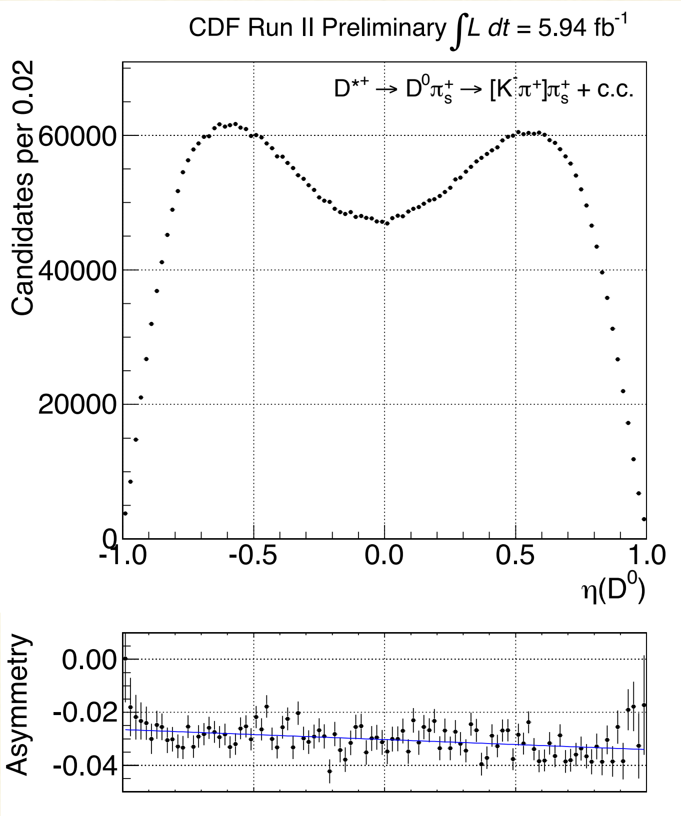
Beam Drag (II)

A good estimate of the detector η-asymmetry, averaged over total acceptance is:

$$A_{FB} = \frac{N(\eta > 0) - N(\eta < 0)}{N(\eta > 0) + N(\eta < 0)} = (1.15 \pm 0.05)\%$$

The slope of the charge asymmetry $(N^+ - N^-)/(N^+ + N^-)$ as a function of η provides a good estimate of the max production charge asymmetry due to the beam drag:

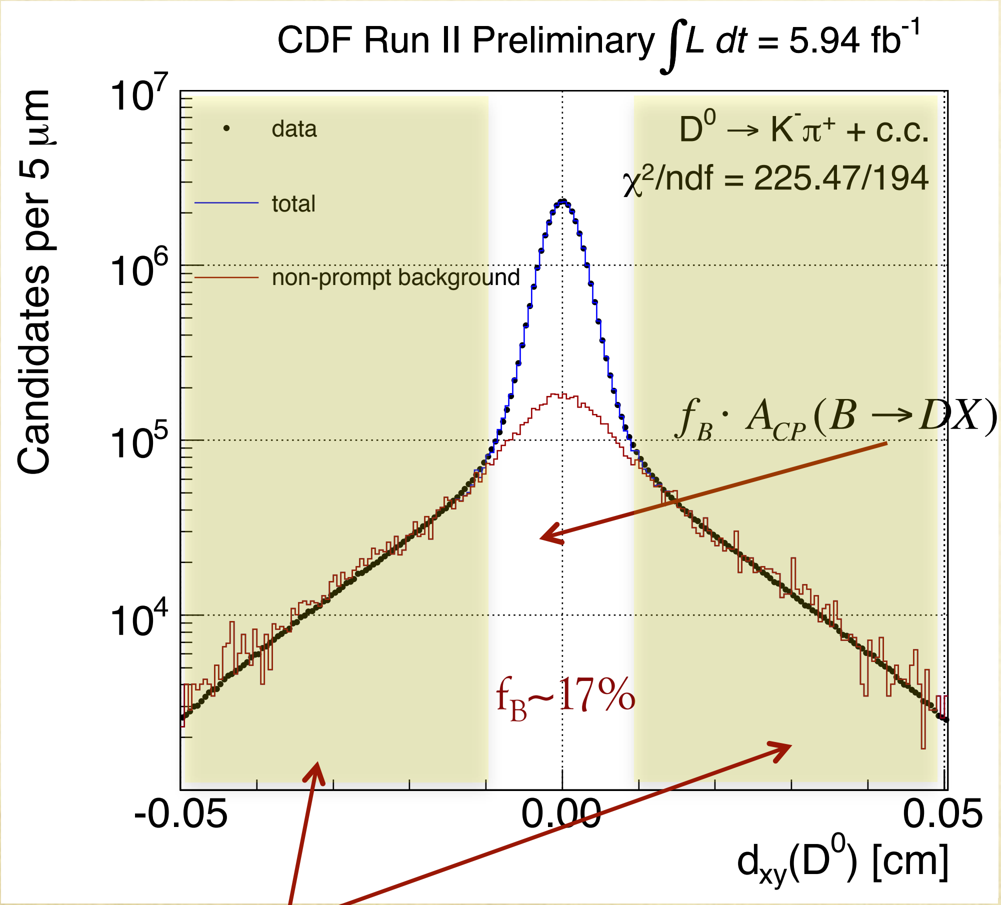
$$A_{BD}(\max) = (-0.38 \pm 0.09)\%$$



Syst ~ $\delta A < A_{FB} \times A_{BD} = 0.004\%$

Contamination from $B \to D^0 + X$

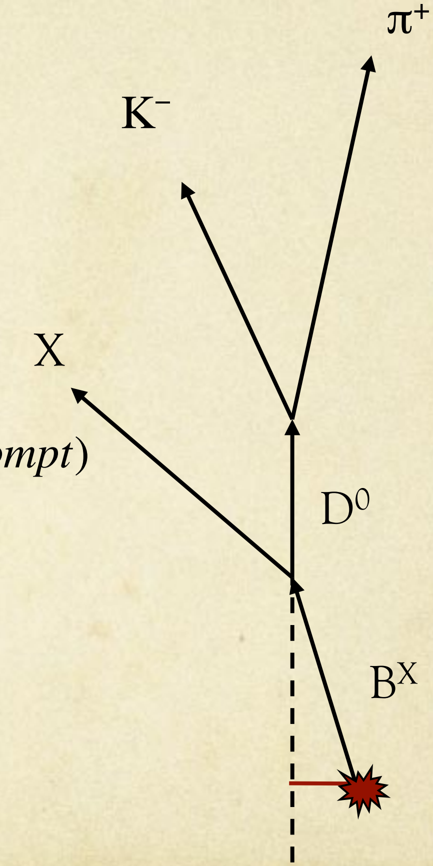
CP violation in the B meson → at production may be $N(D^0) \neq N(\overline{D}^0)$



$f_B \cdot A_{CP}(B \to DX) + A_{CP}^{raw}(D\,prompt)$

$f_B \sim 17\%$

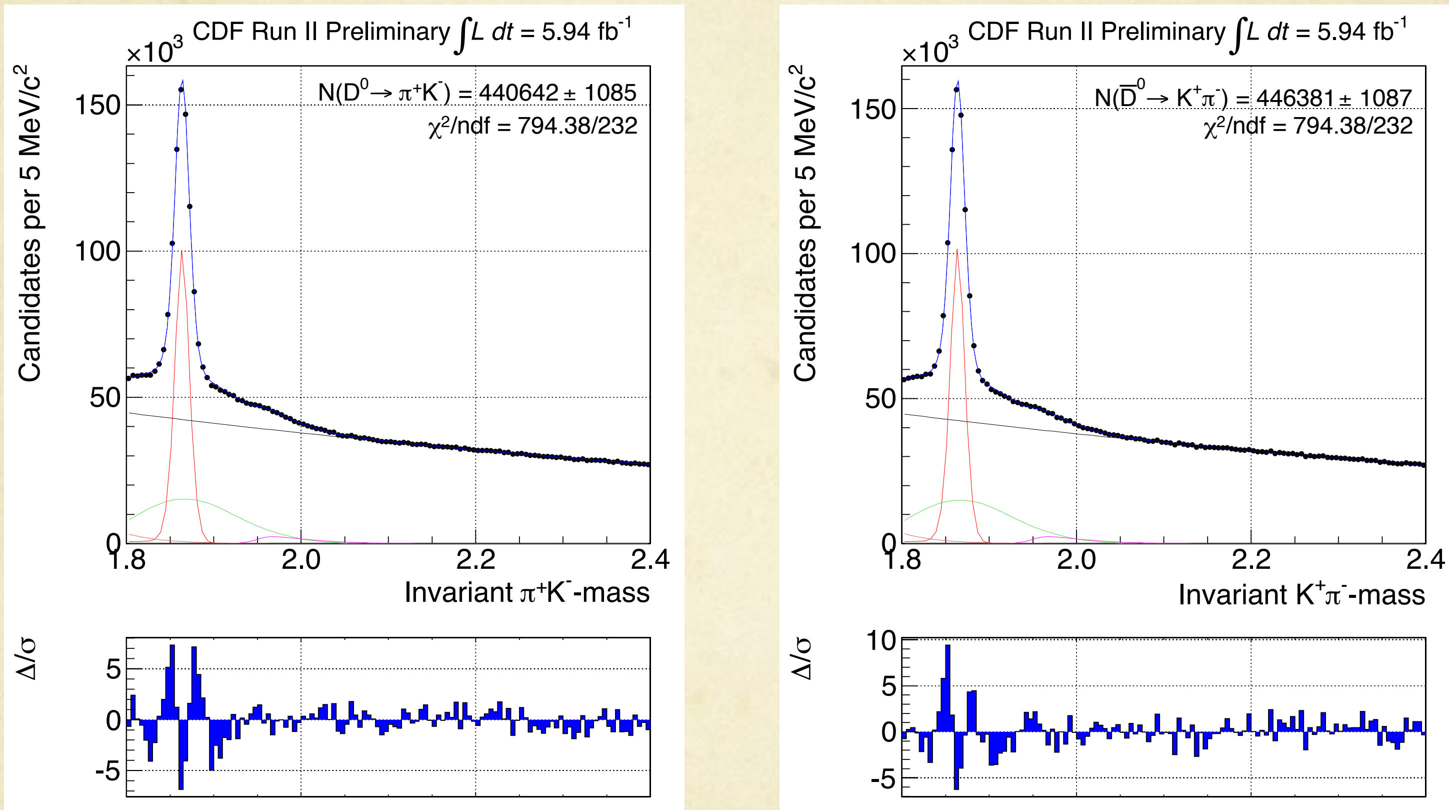
$A_{CP}(B \to DX) + A_{CP}^{raw}(D\,prompt)$



D^0 impact parameter

Contamination from $B \rightarrow D^0 + X$

Inverting the cut on the impact parameter of the D^0 meson



$f_B \sim 17\%$

$A_{CP}(B \rightarrow DX) = (-0.21 \pm 0.20)\%$

syst = $f_B \times A_{CP} \sim 0.034\%$

Uncertainty on the shapes (I)

- Simultaneous χ^2 binned mass fit of "positive" and "negative" samples to count D^0 and antiD^0.
- Mass templates:
  - Extracted from simulation and tuned on the average sample.
  - Untagged fit: fixed and identical for pos and neg sample.
  - D*-tagged fits : very small difference in charge has been observed.
- Fit just the composition of two samples to extract A_{CP}.

Uncertainty on the shapes (II)

- 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%.

Final result

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

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

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

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

Interpretation

What are we actually measuring?

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

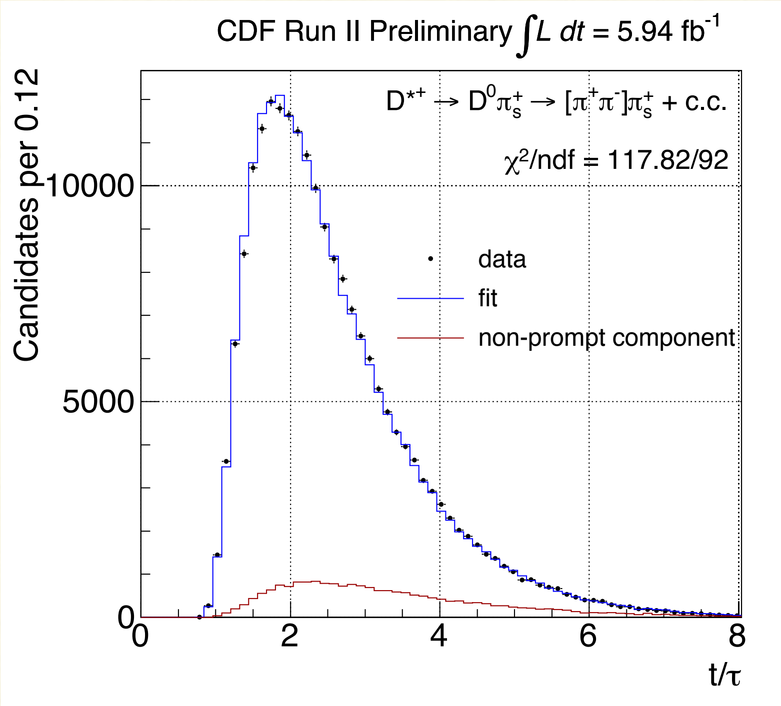
- "Time-integrated" A_{CP} receives contribution from direct CP violation and indirect CP violation (from mixing induced effects).
- D^0 mixing parameters are small ($x,y<<1$), then A_{CP} can be written at the first order as:

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

- A_{CP} describes a band in the plane (a_{CP}^{ind} , a_{CP}^{dir}) with a slope $<t>/\tau$, 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 separate direct and mixing-induced components.



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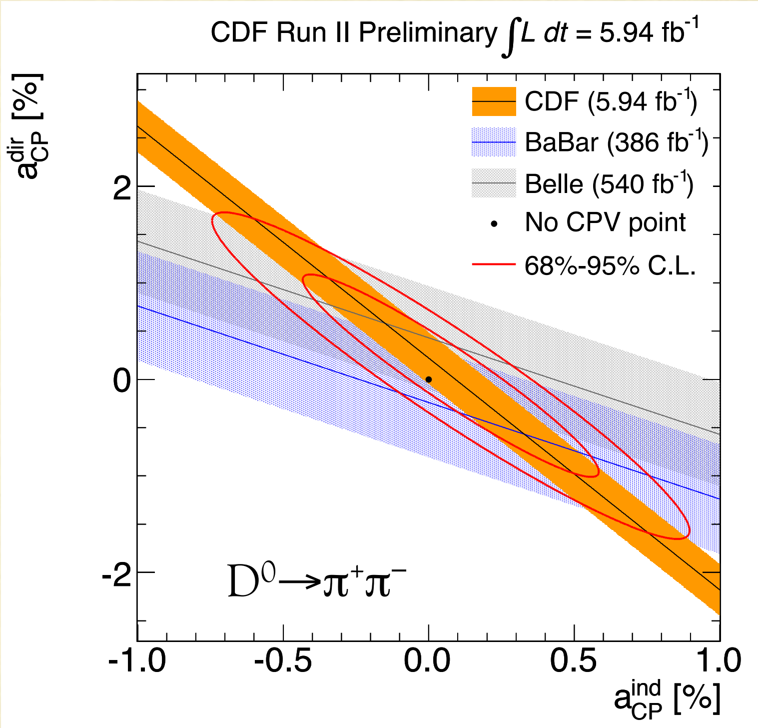
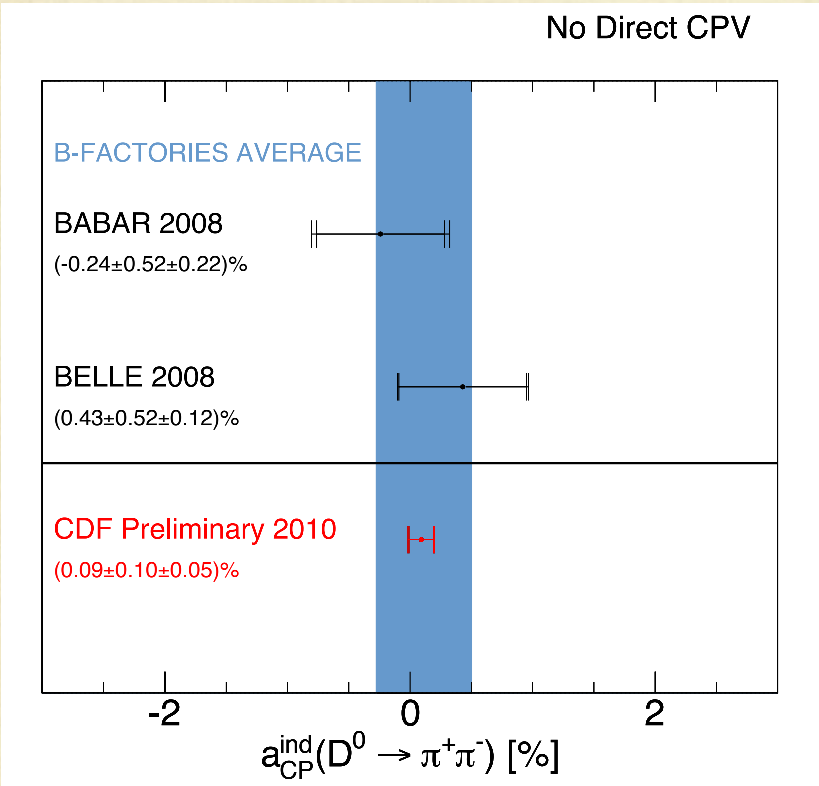
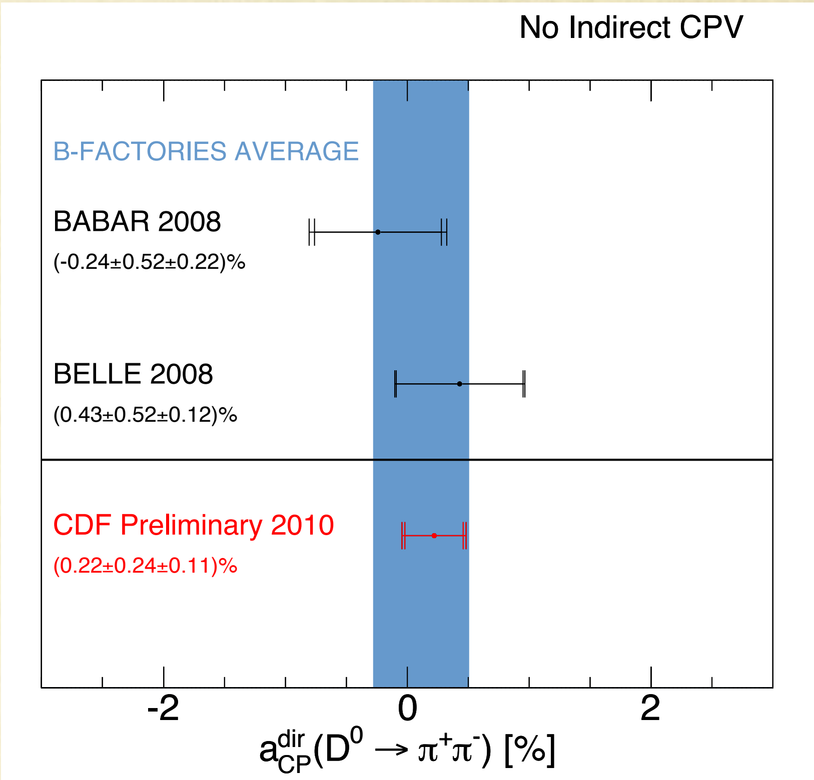
- CDF and B-Factories are then complementary.
- Two bands with different slope separate direct and mixing-induced components.



A comparison with some assumptions





CP violation is from mixing only

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

no mixing

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

Conclusions

- Consistent with very small CP Violation as predicted in the SM.
- This result shows that high precision measurements competitive or even superior to the B-factories are possible at the TeVatron.
- One of the most precise A_{CP} measurement in the Charm sector
  - enough precision to probe for NP in a significant way.
- Still limited by statistics and will improve with integrated luminosity ($5.9\ fb^{-1} \rightarrow 10\ fb^{-1} \rightarrow 16\ fb^{-1}$?).
- 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
  - trigger on secondary vertices.

} $p\bar{p}$ collisions

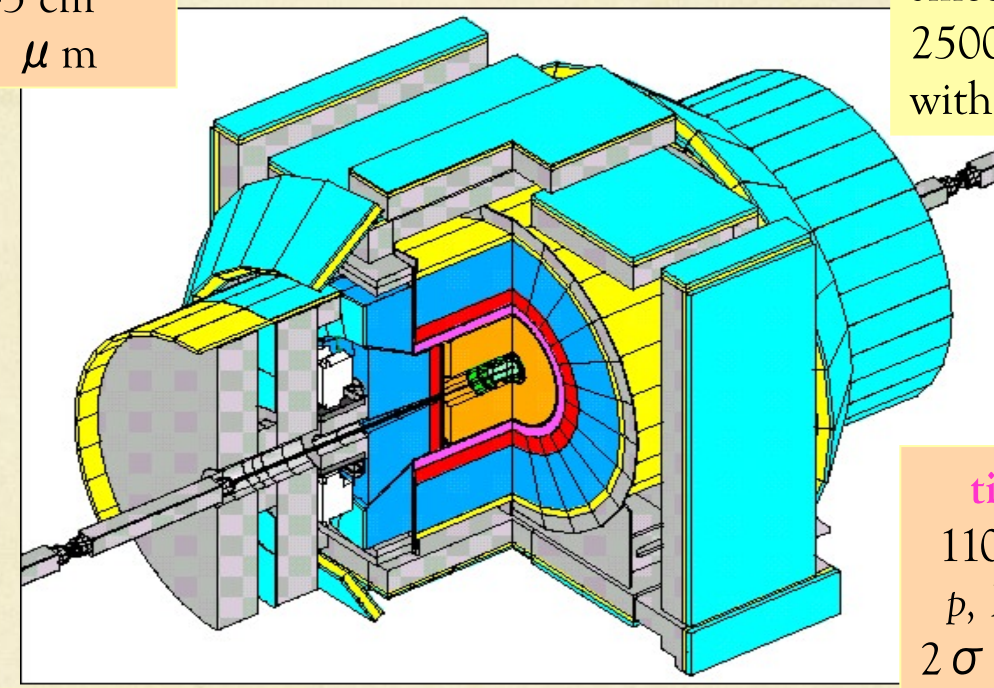
Backup

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%/√E
Had E ~ 80%/√E
d_0 ~ 40 μm
(includes beam spot)

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

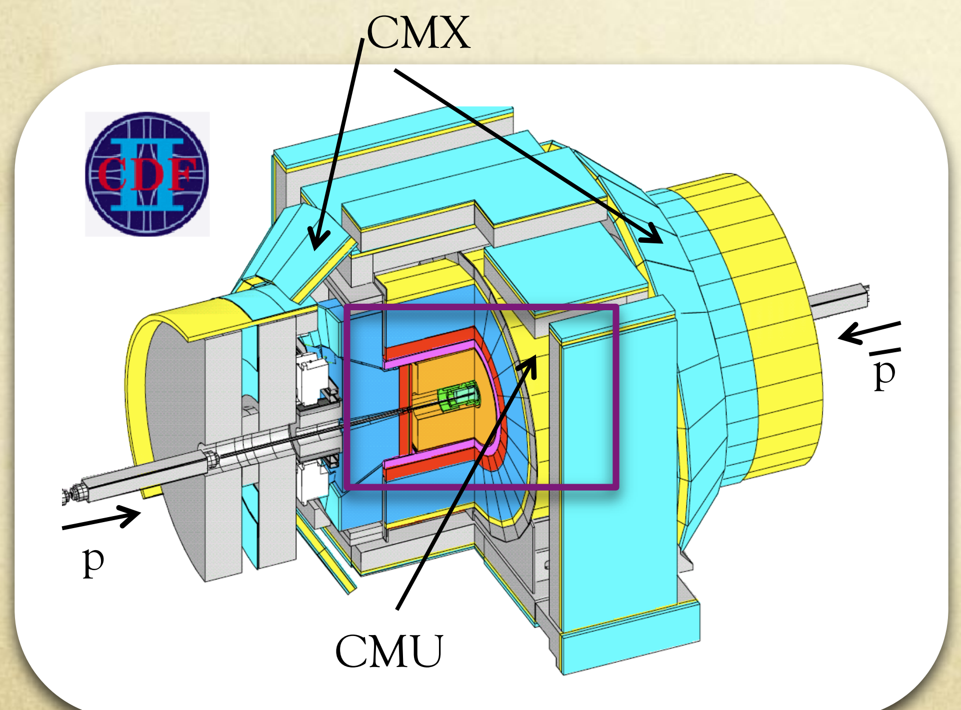
96 layer drift chamber
$|\eta| \leq 1.0$ $44 < r < 132$ cm, $|z|<155$ cm
30k channels, σ(hit) ~ 140 μm
dE/dx for p, K, π identification

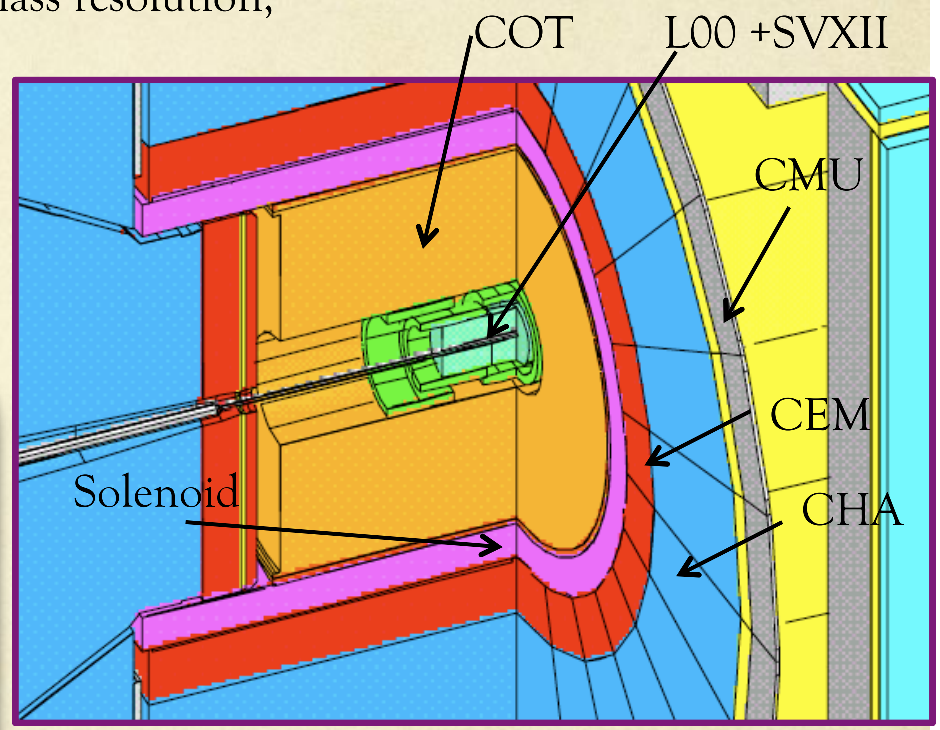
scintillator and tile/fiber sampling calorimetry
$|\eta| < 3.64$

μ coverage
$|\eta| \leq 1.5$
84% in

CDFII detector

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

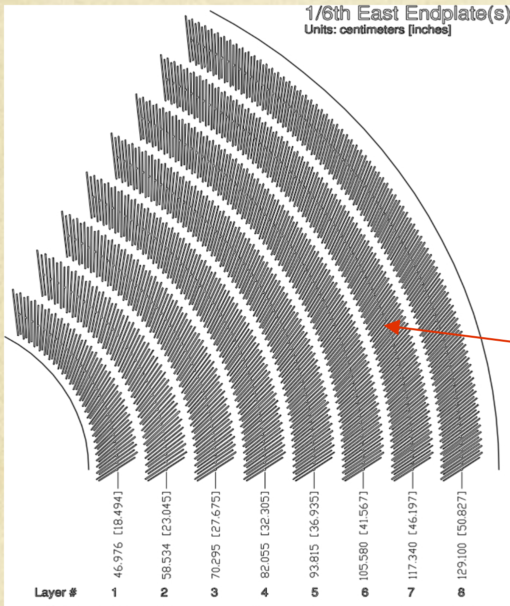


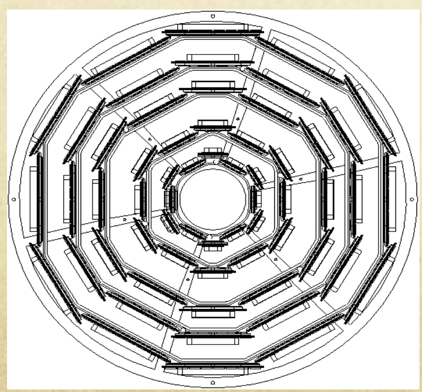


CMU ($|\eta|<0.6$, pt>1.4GeV/c) 4 layers of planar drift chambers
CMX($0.6<|\eta|<1$, pt>2GeV/c) conical sections of drift tubes

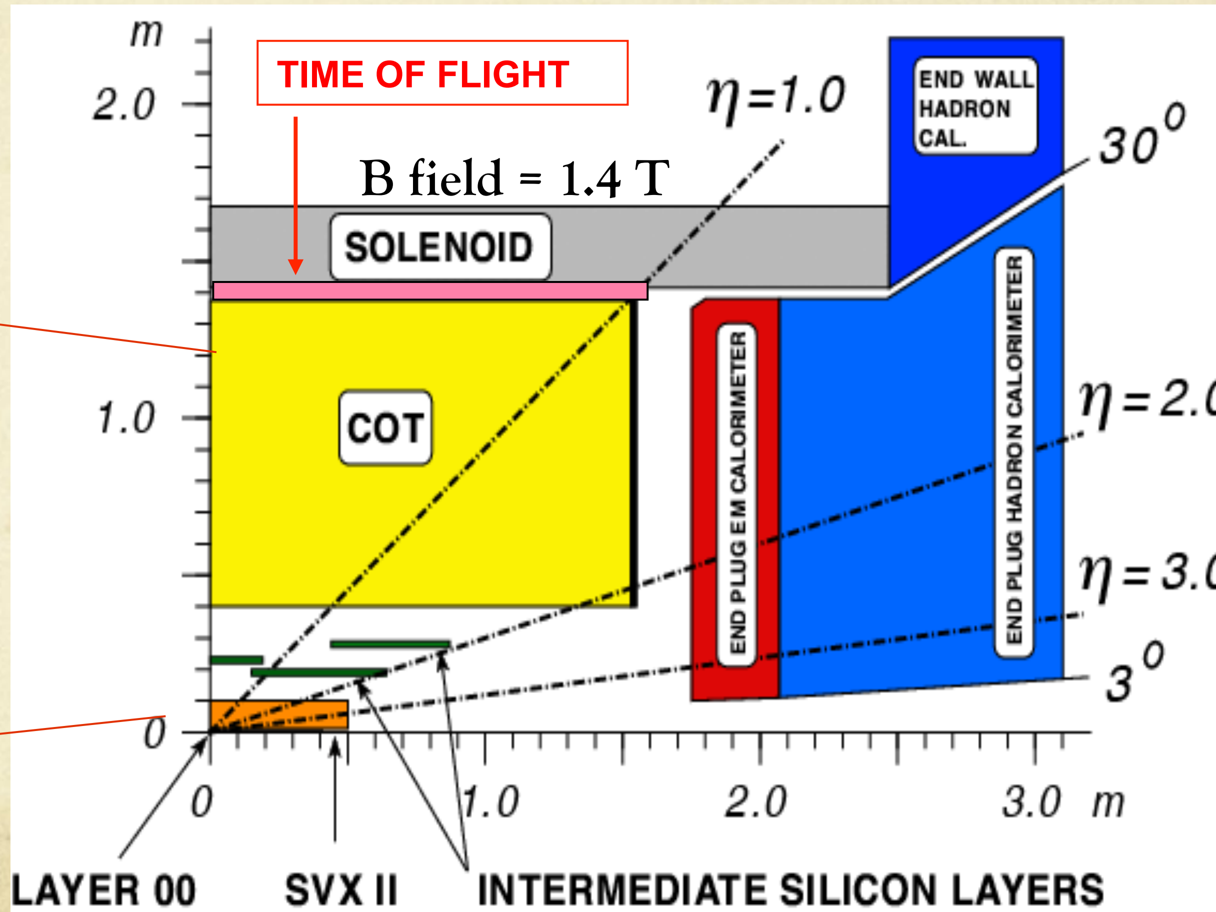
CDFII Tracker

Transverse view





Longitudinal view



Drift Chamber

- Wire planes are not aligned with r. A 35° azimuthal tilt is provided in order to offset the Lorentz angle of the drift paths which results from the combined effect of crossed electrical and magnetic field and the characteristics of the gas mixture.
- Moreover the tilted-cell geometry helps in the drift-velocity calibration as every high-pT (radial) track samples the full range of drift distances within each super- layer.
- Further benefit of the tilt is that the left-right ambiguity is cleared-up for track coming from the origin since the ghost track in each superlayer appears rotated of a large azimuthal angle becoming unfittable by pattern recognition.

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 new scenario: Charm Mixing

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

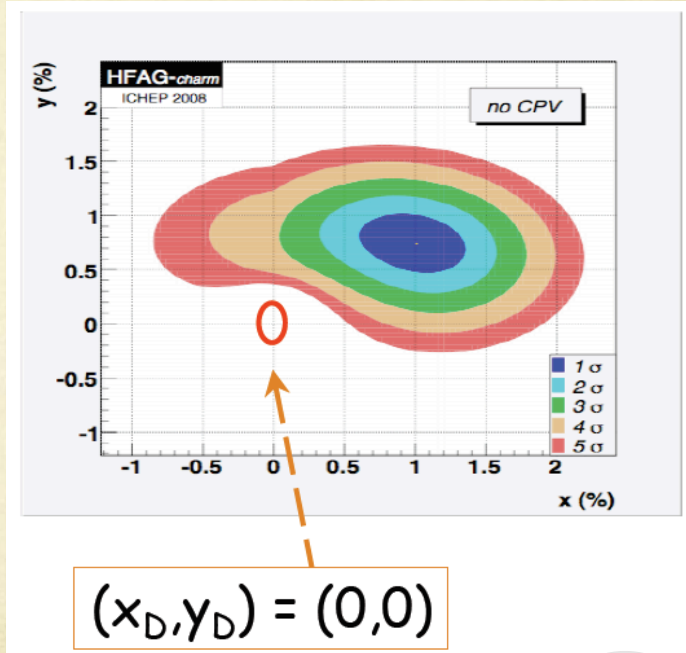
$$x_D = \frac{\Delta m_D}{\Gamma_D} \qquad y_D = \frac{\Delta\Gamma_D}{2\Gamma_D}$$

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

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

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

➡ $A^{SM}_{CP}(t) < 10^{-5}$ 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.

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

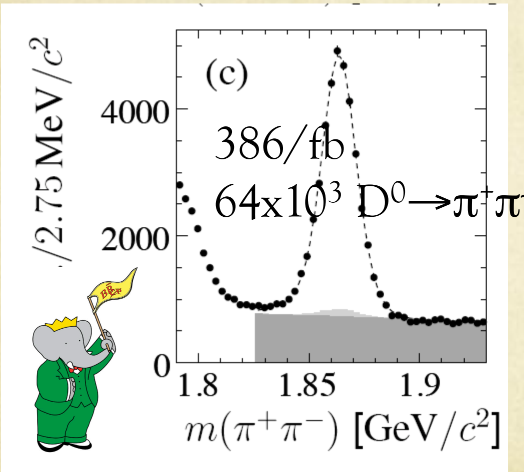
D^0 oscillations can generate time dependent CP asymmetries that survive integrating over time. Crucial to investigate with extreme precision (per mil level and beyond):

tagged from $D^* \to$

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

(the same for K^+K^-)

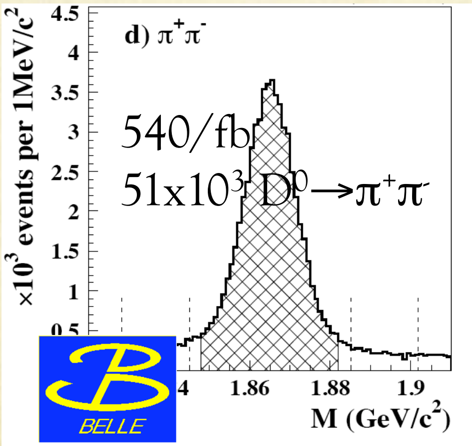
PRL100,061803(2008)



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

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

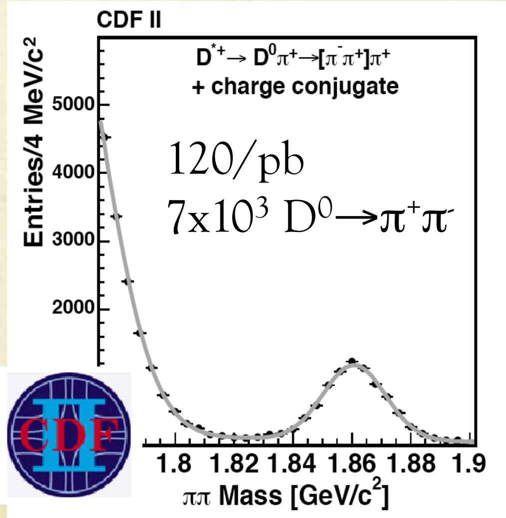
PLB670,190-195(2008)



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

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

PRL94,122001(2005)



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

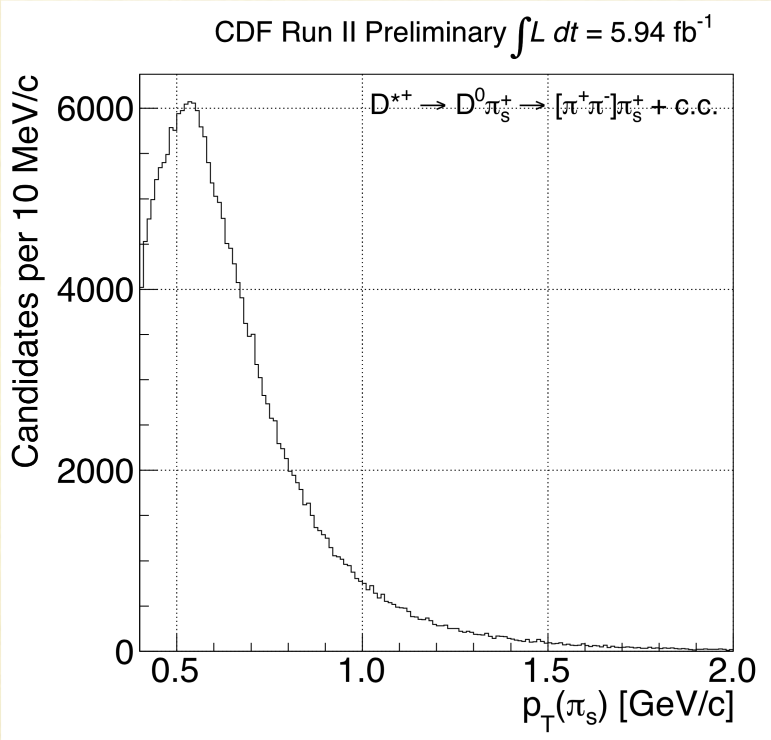
$A_{CP}^{\pi\pi} = [+1.0 \pm 1.3 \pm 0.6]\%$

“Soft” pion from D* decay

Small Q-value in D* decay causes p_T of pion to be ~ 1/13 of D^0.

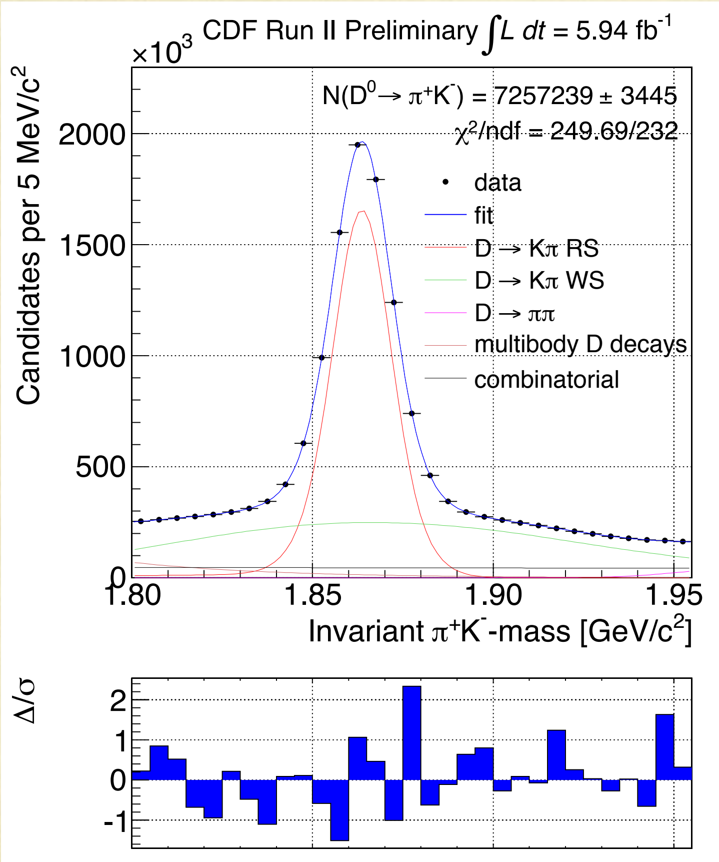
Given CDF acceptance for D^0 this is typically in the range [0.4 - 1.0] GeV/c where detector efficiency for tracks of opposite charge is asymmetric at the level of a few percent.

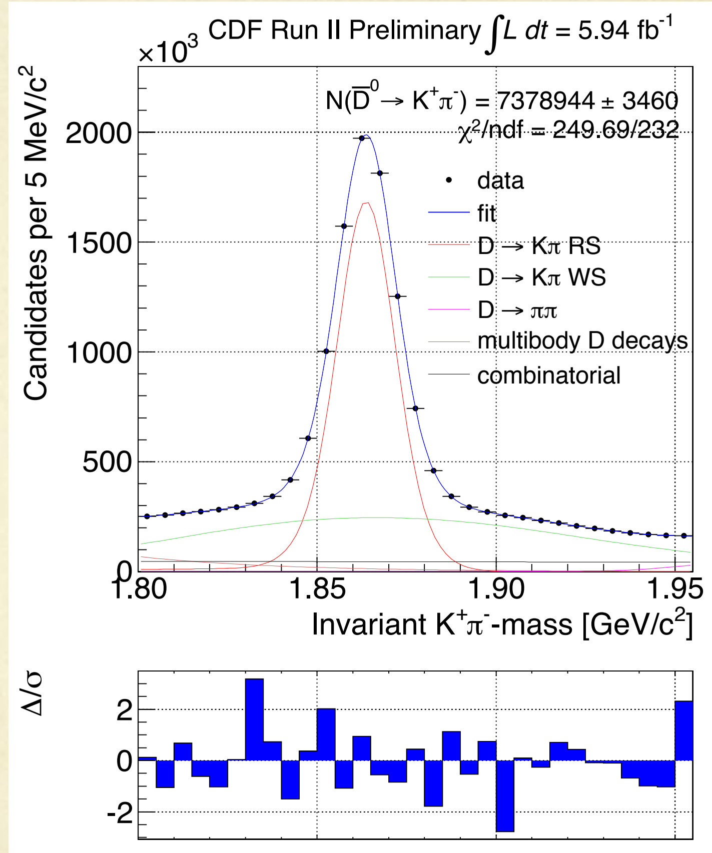
Different efficiencies for soft pions of opposite charge translate into different efficiencies for D* of opposite charge and may lead to a fake charge asymmetry in D^0 decay.



soft pion momentum spectrum

Untagged combined fit $D^0 \to K^- \pi^+$





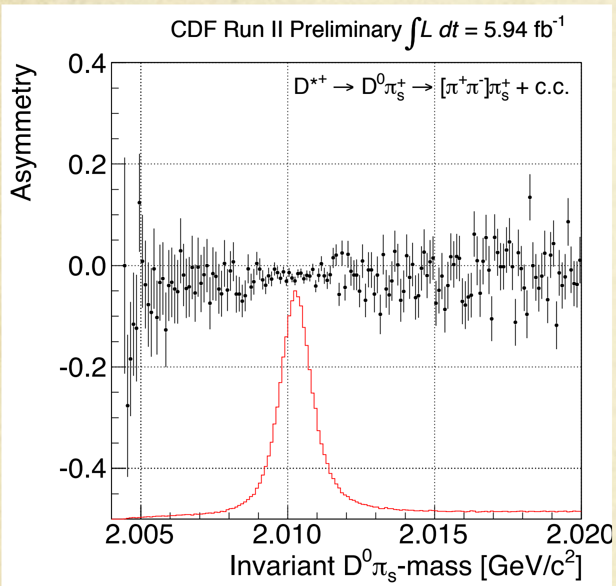
$N^+ = 7{,}257{,}239 \pm 3{,}445$

$N^- = 7{,}378{,}944 \pm 3{,}460$

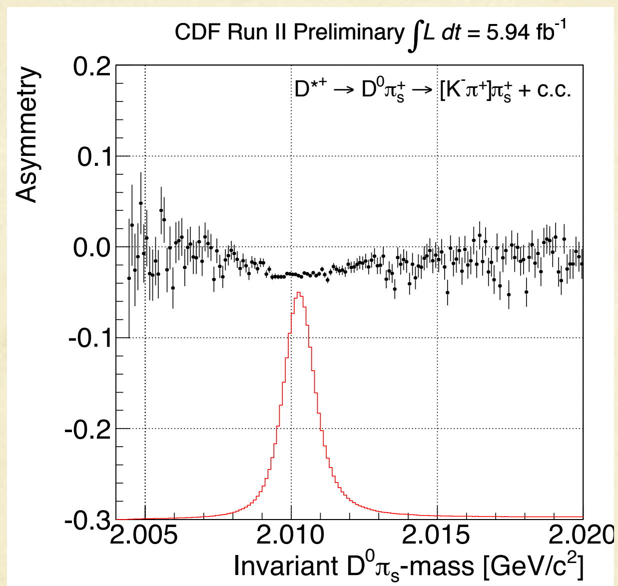
$$A_{CP}^{raw}(K\pi) = (-0.83 \pm 0.03)\%$$

Asymmetry as a function of mass

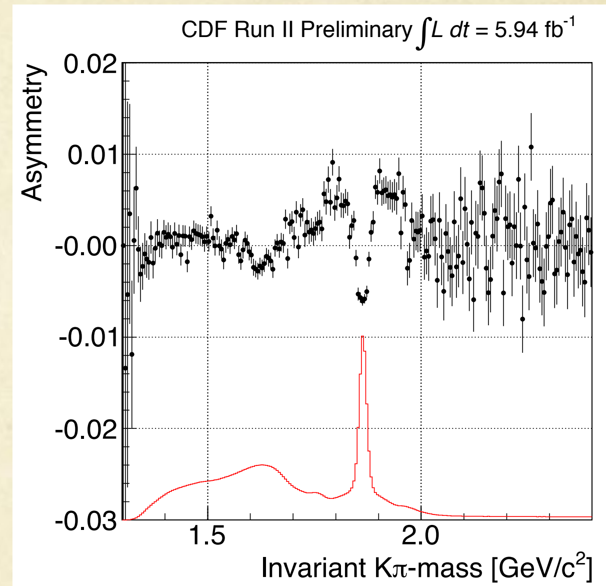
Tagged $D^0 \rightarrow \pi^+\pi^-$



Tagged $D^0 \rightarrow K^-\pi^+$

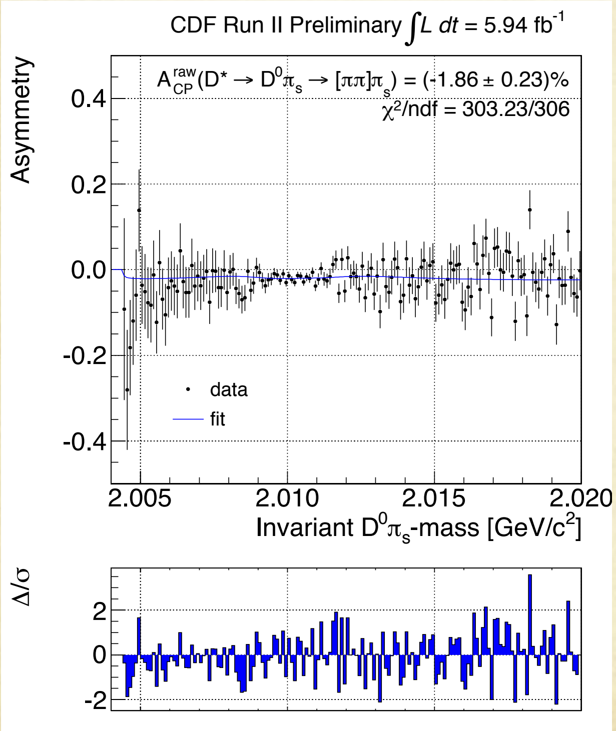


Untagged $D^0 \rightarrow K^-\pi^+$

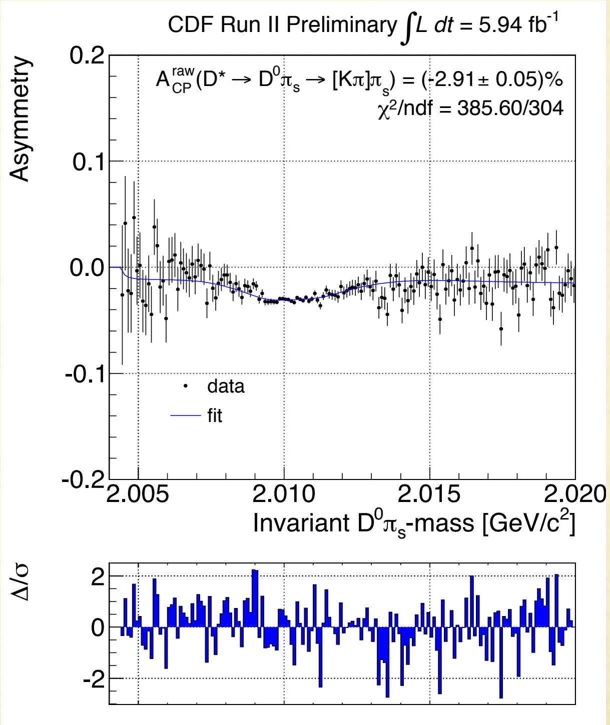


Asymmetry as a function of mass (fit projection)

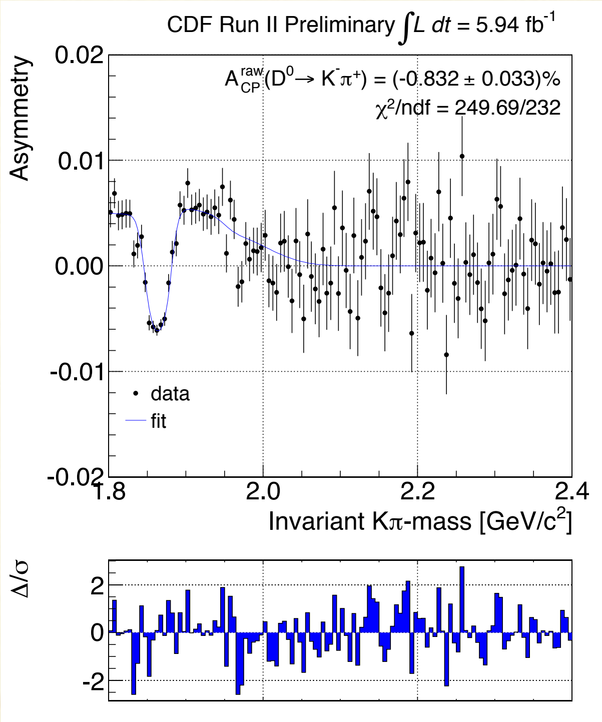
Tagged $D^0 \to \pi^+\pi^-$



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

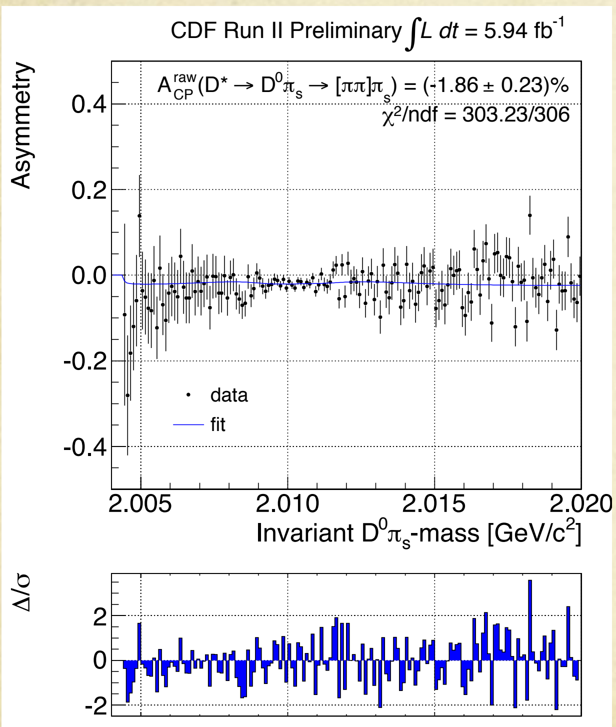


Untagged $D^0 \to K^-\pi^+$

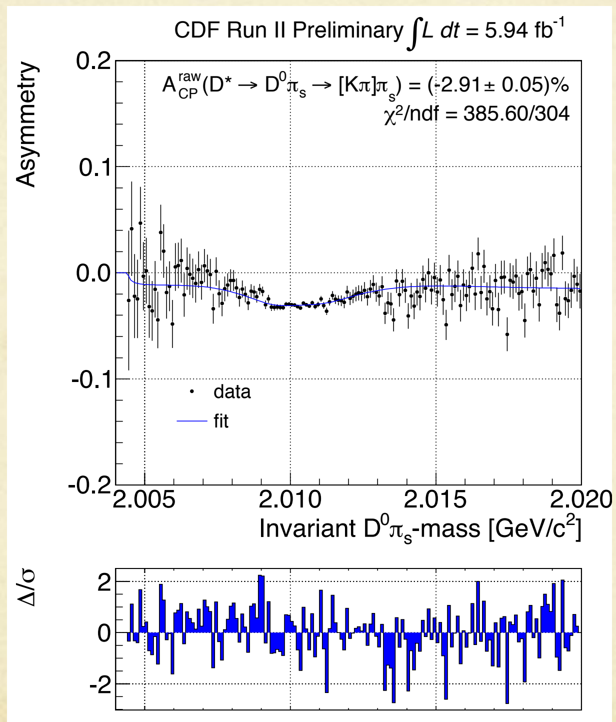


Asymmetry as a function of mass (fit projection)

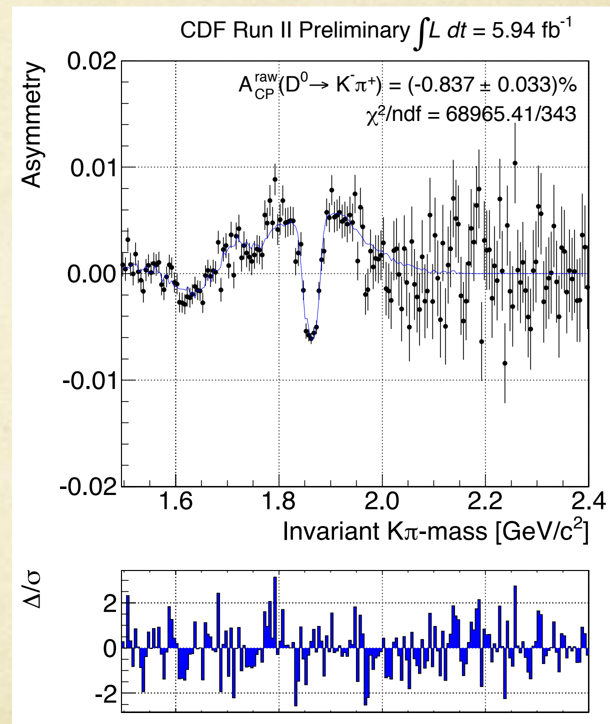
Tagged $D^0 \to \pi^+\pi^-$



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

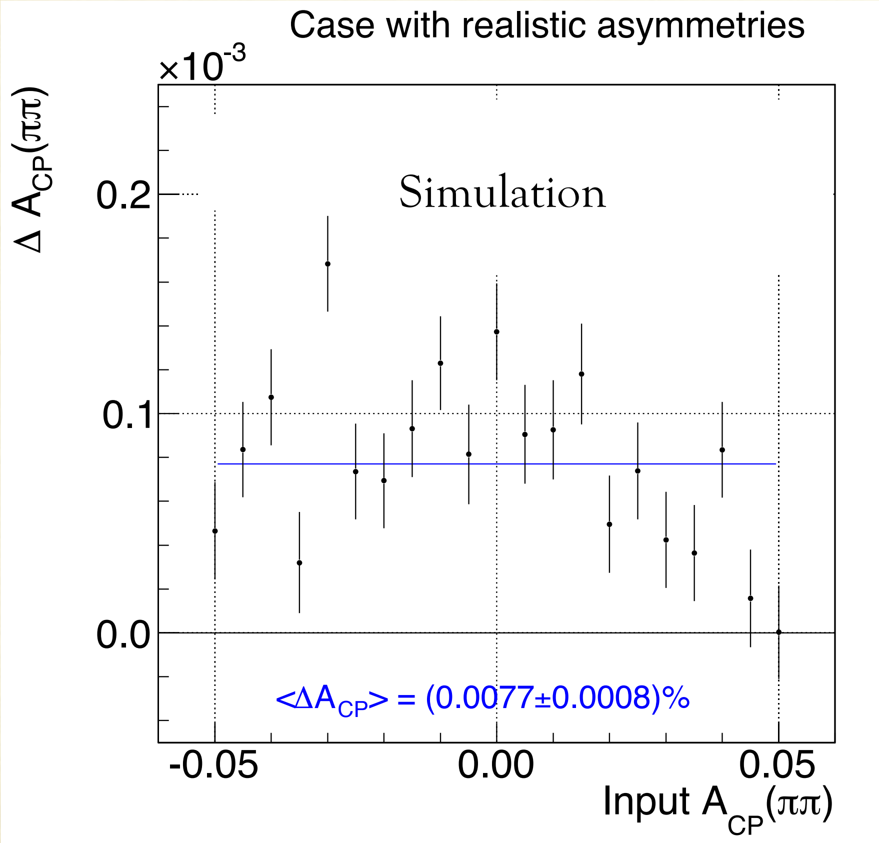


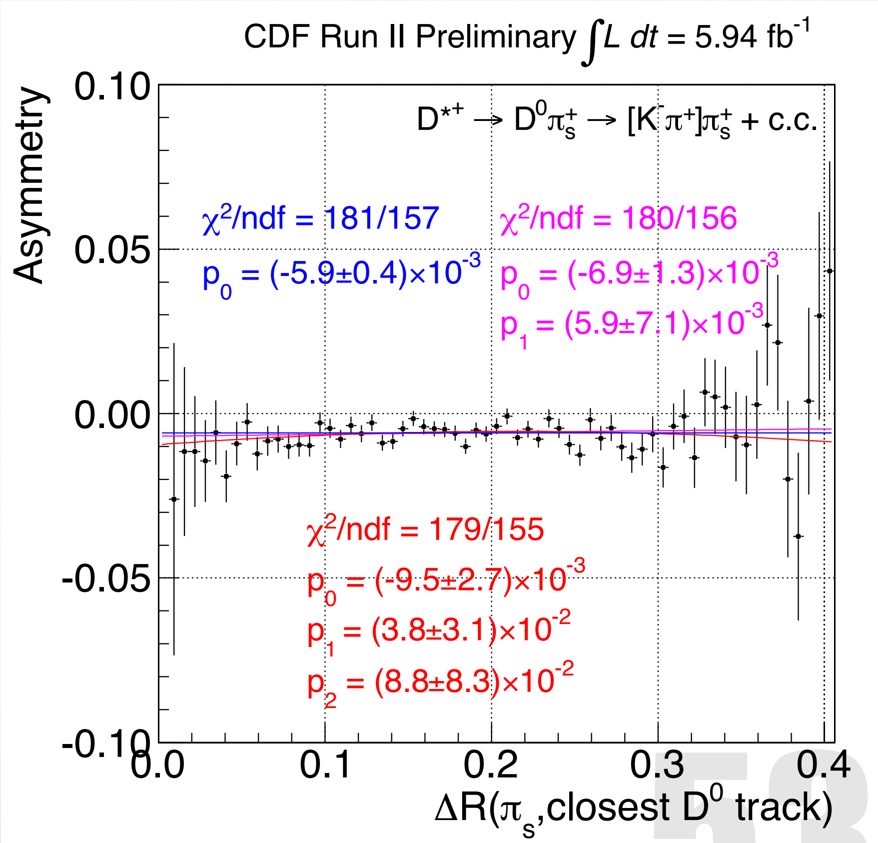
Untagged $D^0 \to K^-\pi^+$



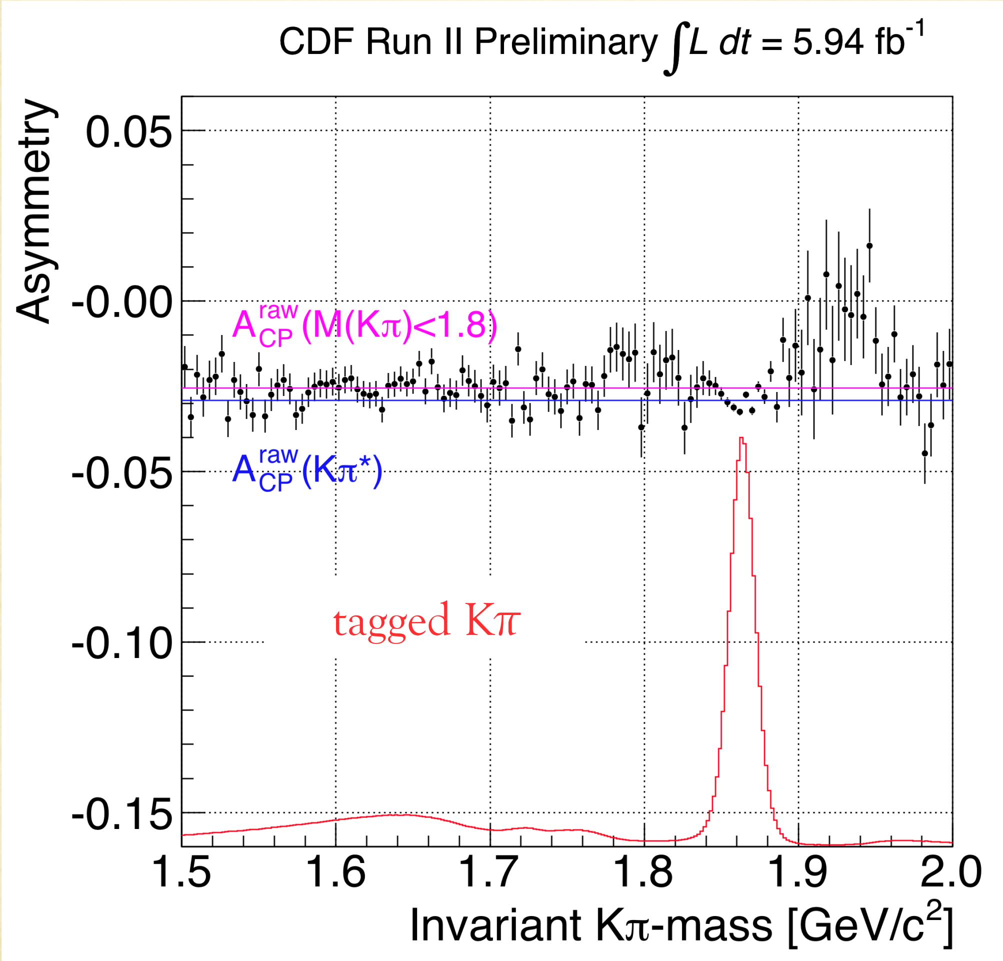
Efficiency factorization

Extensively tested using CDF Simulation and DATA.





Contamination from other decays



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

Effect of DCS

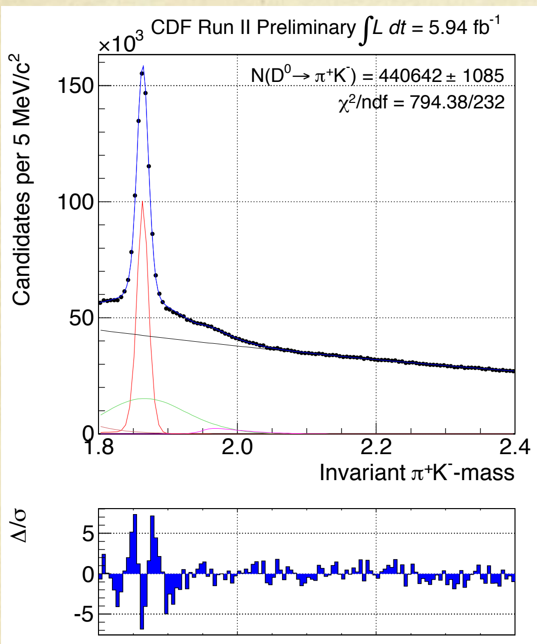
- We treat the Doubly Cabibbo Suppressed $K\pi$ decays as a contaminant to the CF decays.
- The size of the effect can be estimated as the relative fraction DCS/CF times the A_{CP} of the DCS
  - Syst ~ $0.0038 \times 0.054 = 2.10^{-4}$
- where for the A_{CP} of the DCS we take the PDG value + 1σ.

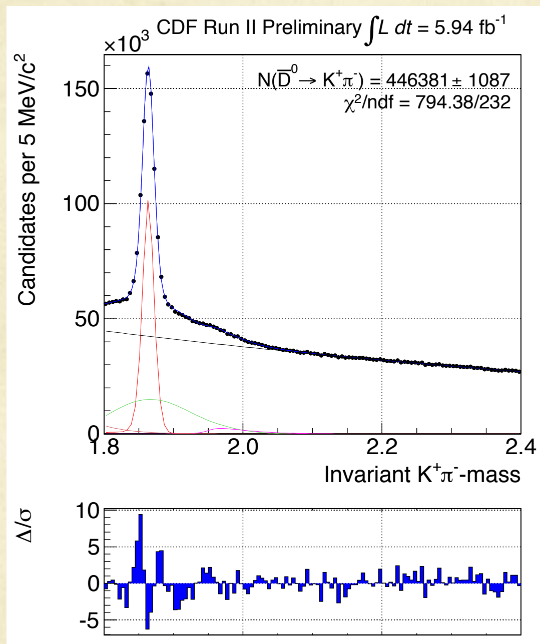
Why not particle ID?

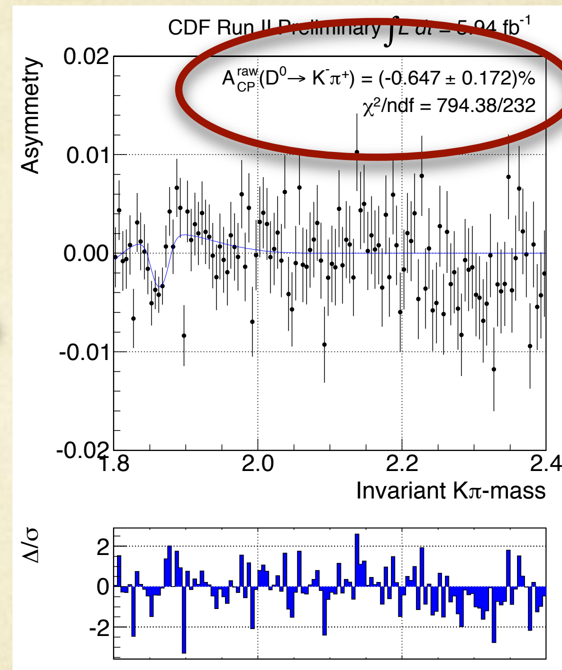
- CDF has some particle ID capability based on Time of Flight and dE/dx in the central drift chamber.
- This could be used to our advantage to separate pions from kaons and improve signal/background.
- We chose not to use it in this analysis in order to eliminate one potential source of spurious charge asymmetry.
- We might reconsider this choice in the future.

Systematics on $D^0 \rightarrow K^- \pi^+$ from B decays

Analysis entirely repeated reversing the cut on the impact parameter $\rightarrow |d_0| > 100\mu m$







The two A_{CP}s are compatible with an uncertainty of 0.17% (1σ), an upper bound to any possible CP violations in the B-meson system has been set to 16.6%×0.17%=0.028%.

Time-dependent A_{CP}

$$\tau \equiv \Gamma_D t, \qquad \Gamma_D \equiv \frac{\Gamma_{D_H} + \Gamma_{D_L}}{2},$$

$$A_f \equiv A(D^0 \to f), \qquad \overline{A}_f \equiv A(\overline{D}^0 \to f),$$

$$A_f \equiv A(D^0 \to \overline{f}), \qquad \overline{A}_{\overline{f}} \equiv A(\overline{D}^0 \to \overline{f}),$$

$$x \equiv \frac{\Delta m_D}{\Gamma_D} \equiv \frac{m_{D_H} - m_{D_L}}{\Gamma_D}, \qquad y \equiv \frac{\Delta \Gamma_D}{2\Gamma_D} \equiv \frac{\Gamma_{D_H} - \Gamma_{D_L}}{2\Gamma_D},$$

$$\lambda_f \equiv \frac{q}{p}\frac{\overline{A}_f}{A_f}, \qquad R_m \equiv \left|\frac{q}{p}\right|, \qquad R_f \equiv \left|\frac{\overline{A}_f}{A_f}\right|.$$

$$\Gamma(D^0(t) \to f) = e^{-\tau}|A_f|^2 \Big\{(1 + |\lambda_f|^2)\cosh(y\tau) + (1 - |\lambda_f|^2)\cos(x\tau) + 2\mathcal{R}e(\lambda_f)\sinh(y\tau) - 2\mathcal{I}m(\lambda_f)\sin(x\tau)\Big\},$$

$$\Gamma(\overline{D}^0(t) \to f) = e^{-\tau}|\overline{A}_f|^2 \Big\{(1 + |\lambda_f^{-1}|^2)\cosh(y\tau) + (1 - |\lambda_f^{-1}|^2)\cos(x\tau) + 2\mathcal{R}e(\lambda_f^{-1})\sinh(y\tau) - 2\mathcal{I}m(\lambda_f^{-1})\sin(x\tau)\Big\}.$$

Grossman et al. **arXiv:hep-ph/0609178v1**

direct vs. indirect A_{CP}

- D0 mixing is slow
- expand to first order in τ

$$\tau = \frac{\text{proper time}}{\text{lifetime}}$$

$$x\tau \ll 1 \quad y\tau \ll 1$$

$$A_{CP}(\tau) \simeq a_{CP}^{dir} + \tau\, a_{CP}^{ind}$$

$$a_{CP}^{dir} = A_{CP}(0) = \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2}$$

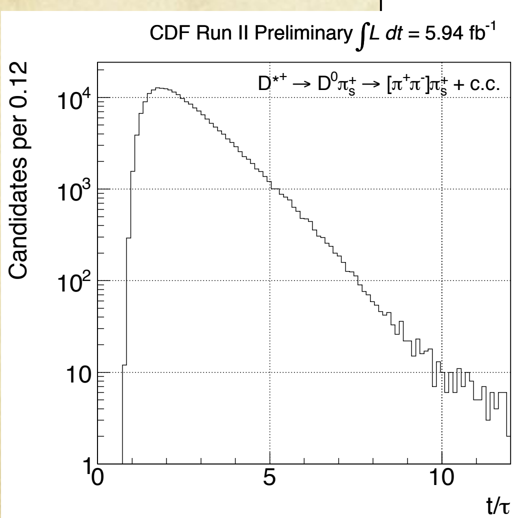
$$a_{CP}^{ind} = \frac{1}{2}\left\{\mathcal{R}e(\lambda_f - \lambda_f^{-1})y - \mathcal{I}m(\lambda_f - \lambda_f^{-1})x\right\}$$

what do we measure?

$$\langle A_{CP} \rangle = \int d\tau \; p(\tau) \left(a_{CP}^{dir} + \tau \; a_{CP}^{ind} \right) = a_{CP}^{dir} + \langle \tau \rangle \;\; a_{CP}^{ind}$$

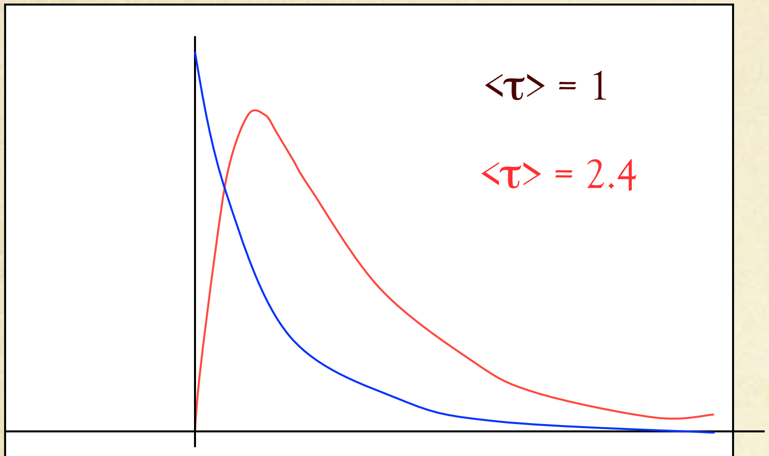
for B-factories: $\langle \tau \rangle = 1$ $\quad \langle A_{CP} \rangle = a_{CP}^{dir} + a_{CP}^{ind}$

for CDF: $\langle \tau \rangle = 2.4$ $\quad \langle A_{CP} \rangle = a_{CP}^{dir} + 2.4 \; a_{CP}^{ind}$



important difference between
CDF and B-factories

Different proper time distributions



proper time distributions

CDF collects D^0s triggering on secondary vertices and proper times are biased toward larger values

by comparing measurements of integrated A_{CP} for the same decay from CDF and B-factories one can separate the direct and mixing components