Precision measurements of CP violation in $D^0 \rightarrow \pi^+ \pi^-$ at CDF

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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 but 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).
- What about up-quarks? Why not look where we did not look before?
  - Charm is a unique window to NP 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 $A_{CP}(t)$ window between $[10^{-2} – 10^{-5}]$.

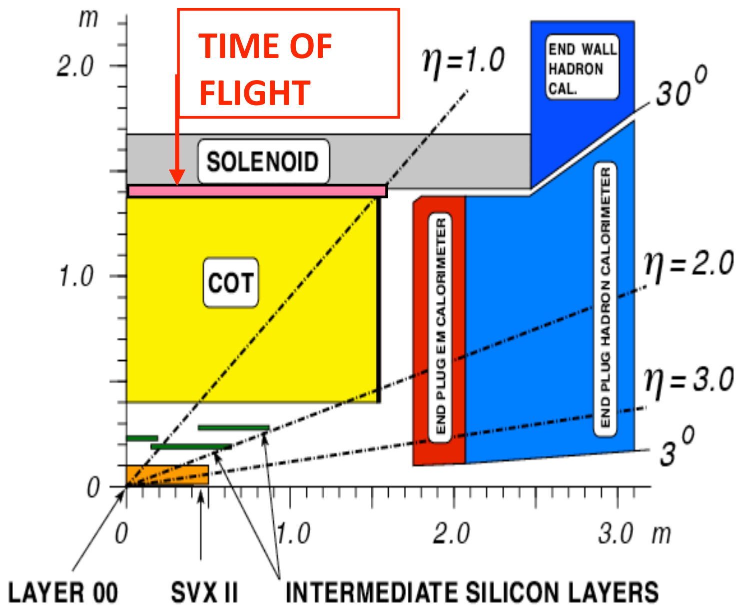
CDF detector at TeVatron

- **Drift Chamber (COT) in magnetic field**
  - Tracking resolution:

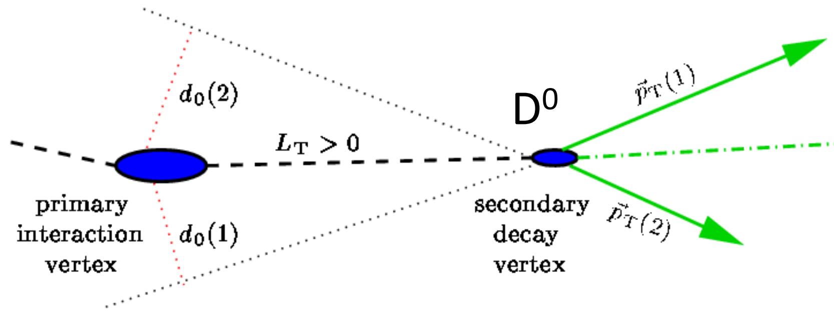
  $\delta p_T/p_T \sim 0.0015\ (\text{GeV}/c)^{-1} p_T$

- **Silicon Vertex Detector**
  - I.P. resolution ~ 35 μm, $p_T > 2$ GeV/c
  - Crucial for triggering on secondary vertices using a displaced track trigger (SVT)

Longitudinal view



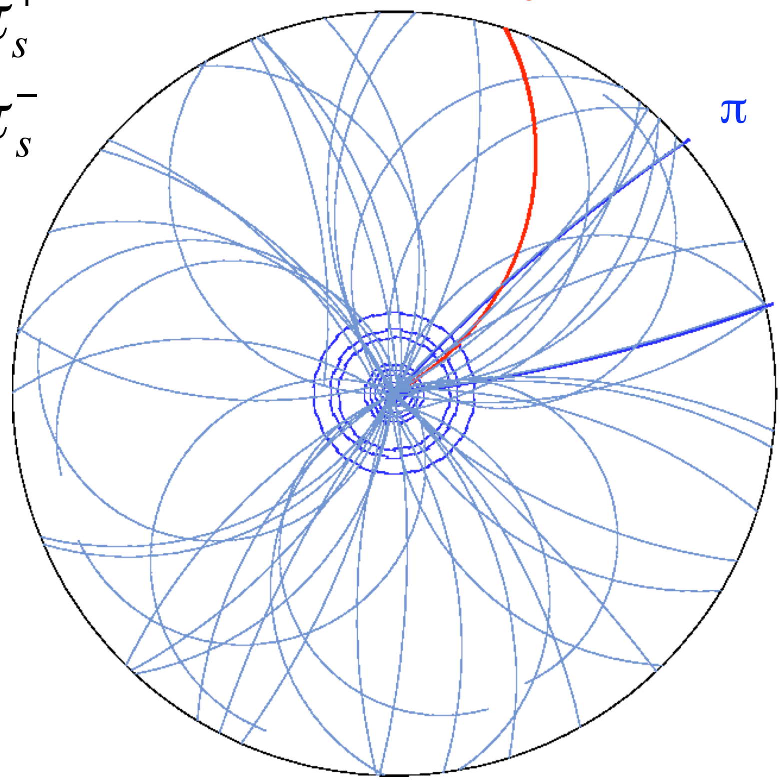
Transverse view



What do we measure?

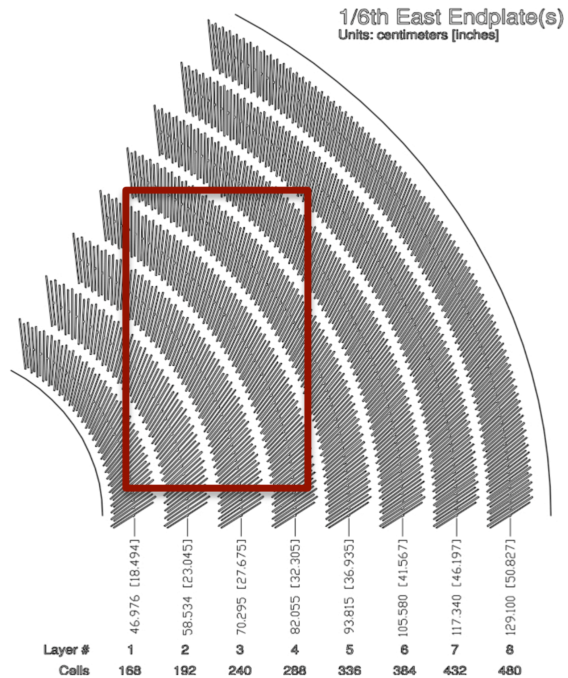
$$A_{CP}(D^0 \to \pi^+\pi^-) = \frac{\Gamma(D^0 \to \pi^+\pi^-) - \Gamma(\overline{D}^0 \to \pi^+\pi^-)}{\Gamma(D^0 \to \pi^+\pi^-) + \Gamma(\overline{D}^0 \to \pi^+\pi^-)}$$

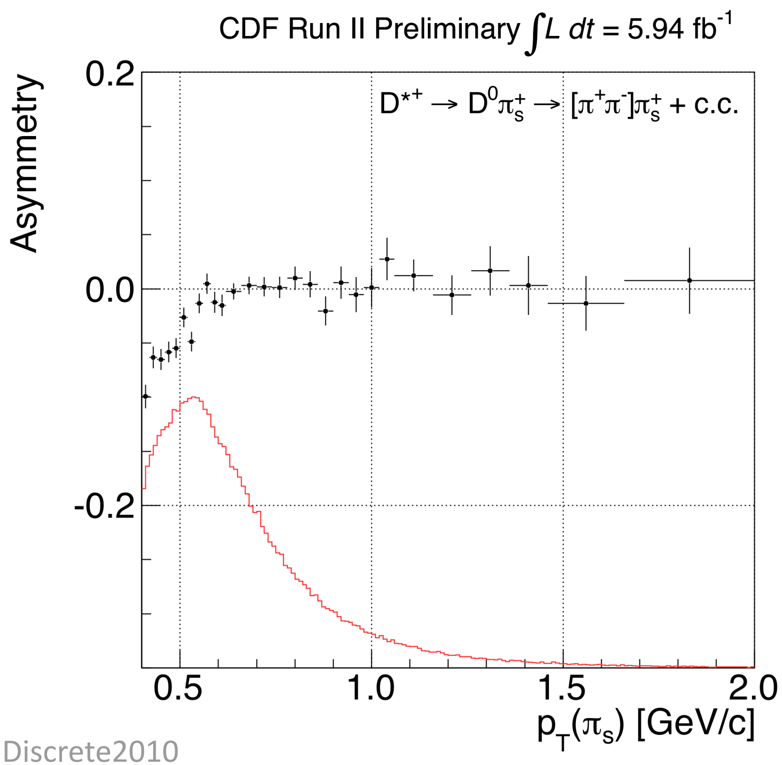
- Tagging the D^0 with D*: $\begin{cases} D^{*+} \to D^0\pi_s^+ \\ D^{*-} \to \overline{D}^0\pi_s^- \end{cases}$
- CP symmetric initial state (p-$\overline{\text{p}}$) ensures charge symmetric production
- World's largest sample. Using 5.94 fb^{-1}:
  ~215,000 $D^* \to D^0\pi$ with $D^0 \to \pi\pi$.
- Expected stat. resolution worse than
  $1/\sqrt{S} \sim 0.22\%$



Fighting detector asymmetries

Drift Chamber is intrinsically charge asymmetric, tracking efficiencies for positive and negative particles 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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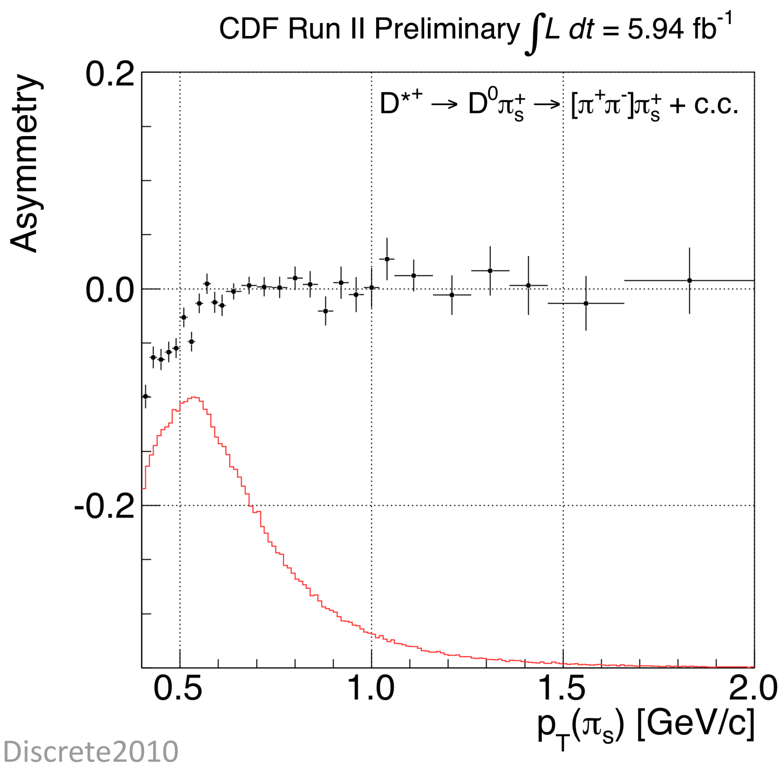

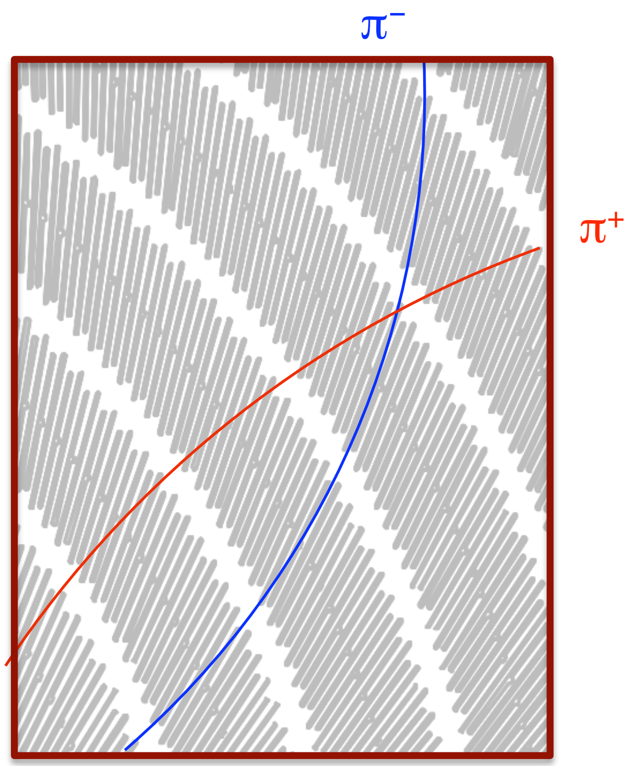

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How are we doing it?

Assuming at production N(D*⁺) = N(D*⁻) and N(D^0) = N($\bar{D}^0$)

Fully data-driven

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

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

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

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

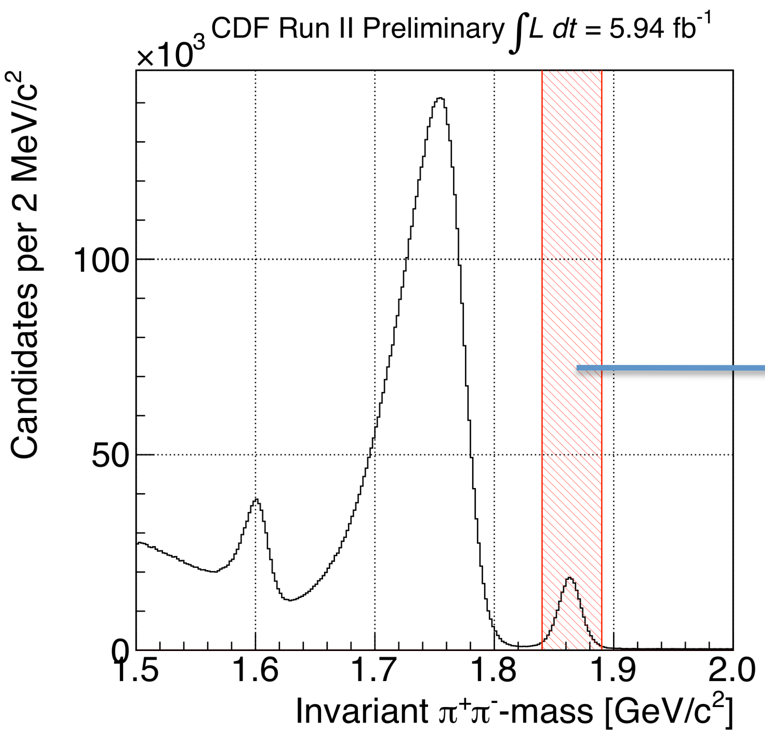
✓ $D^0 \to [K\pi]$ $A_{CP}^{raw}(K\pi) = A_{CP}(K\pi) + \delta(K\pi)$

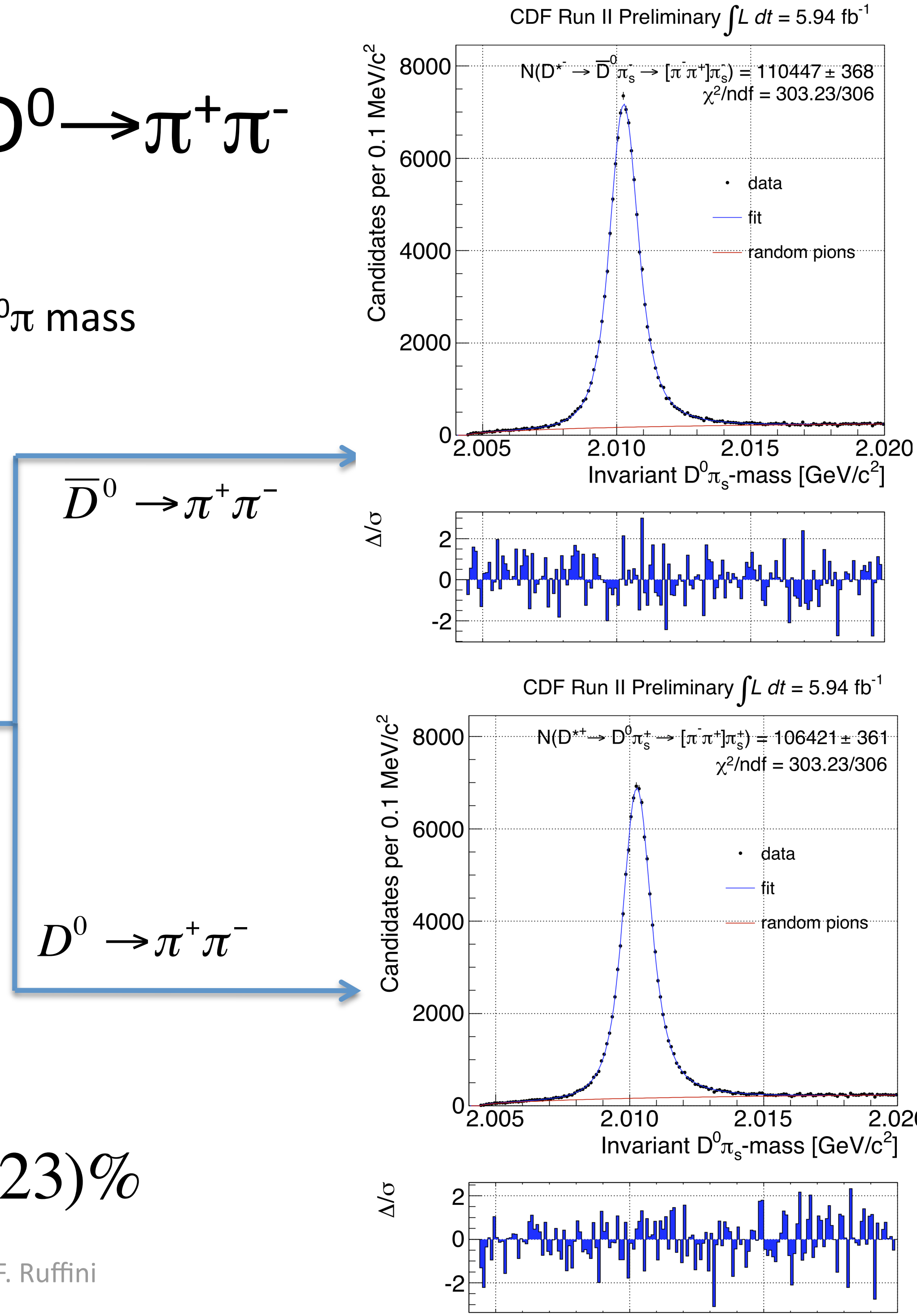
The physical A_{CP} extracted through the linear combination:

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

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

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

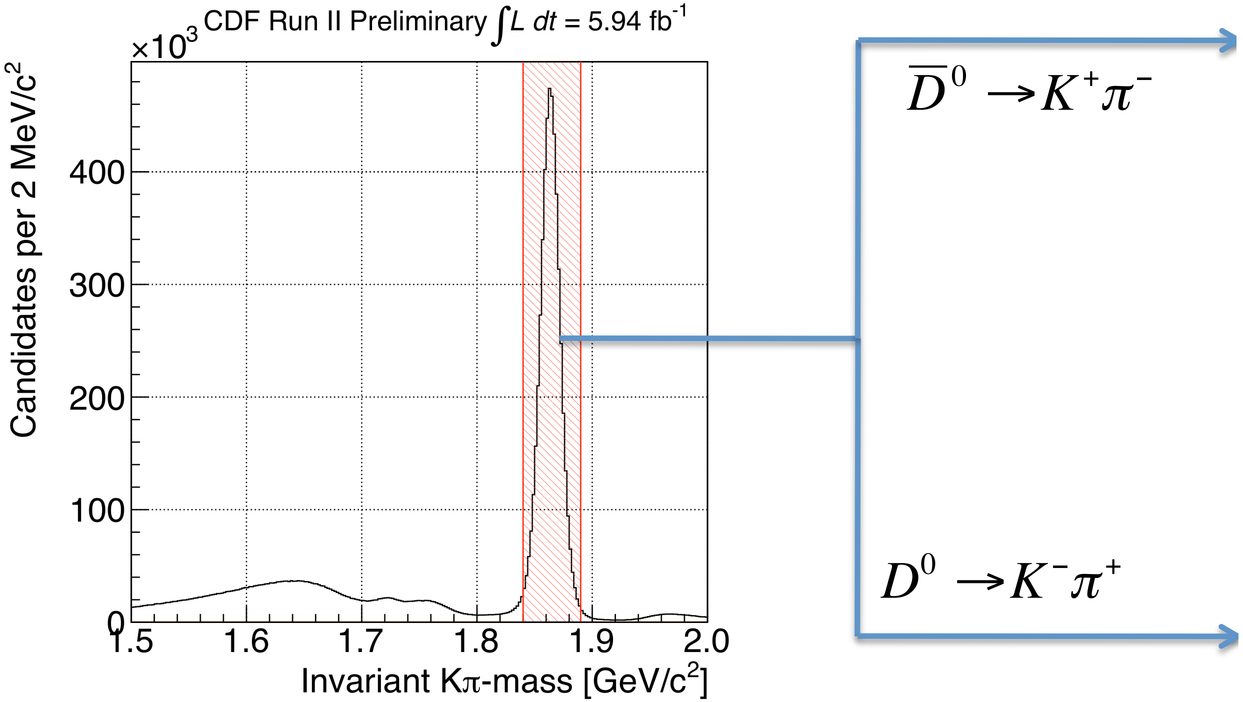


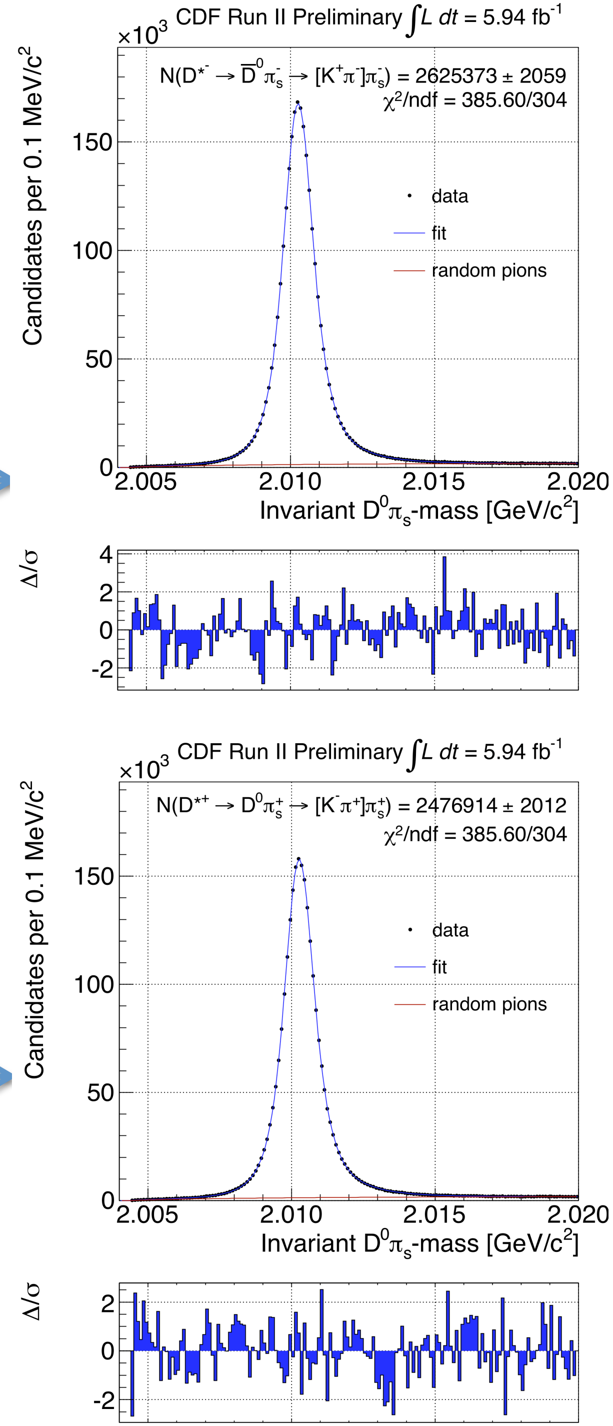


$$A_{CP}^{raw}(\pi\pi^*) = (-1.86 \pm 0.23)\%$$

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

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





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

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

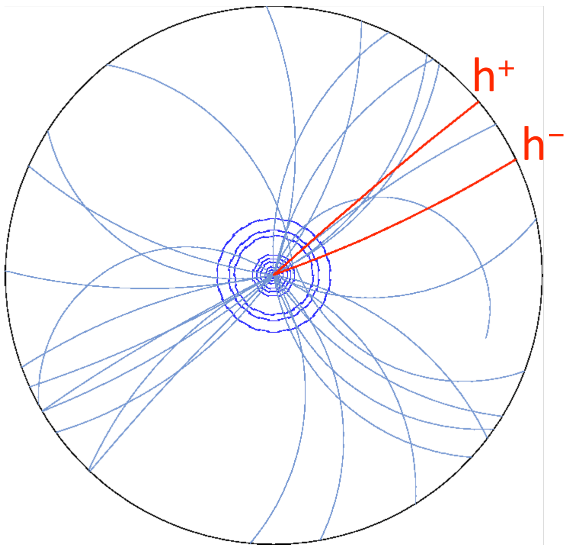
$\overline{D}^0 \rightarrow K^+\pi^-$ (and DCS D^0)

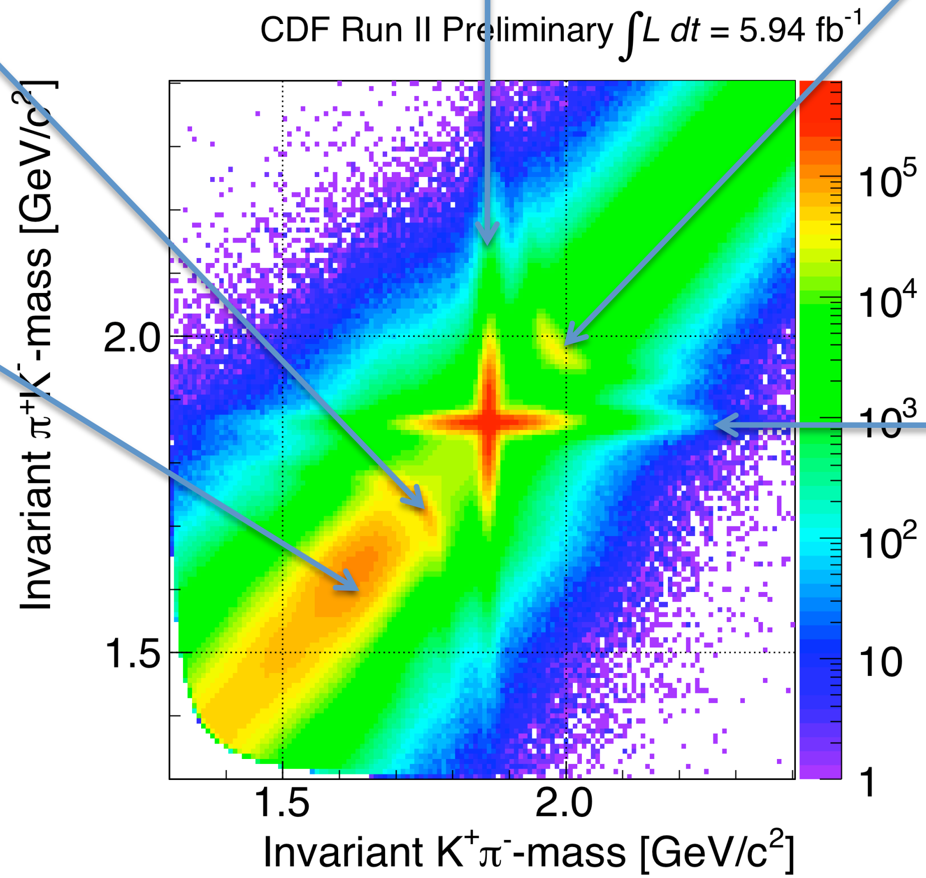
$D^0 \rightarrow K^+K^-$ (and cc)

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

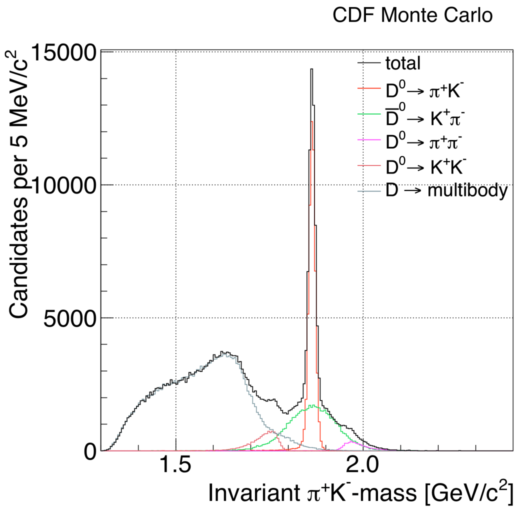
Partially reconstructed D^0, D^+, D^+_s multi-body decays

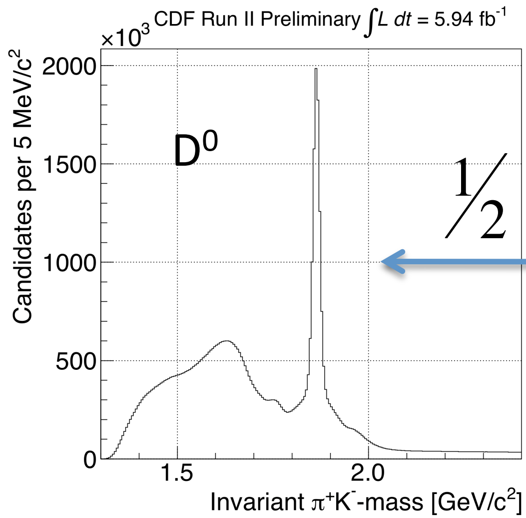
$D^0 \rightarrow K^-\pi^+$ (and DCS $\overline{D^0}$)

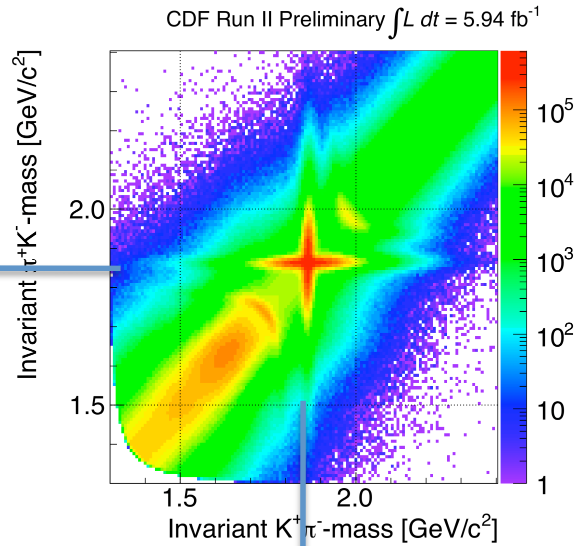


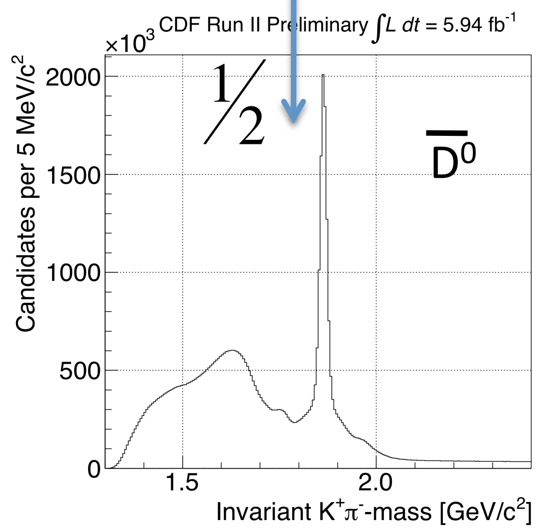


Counting untagged $D^0 \to K^- \pi^+$



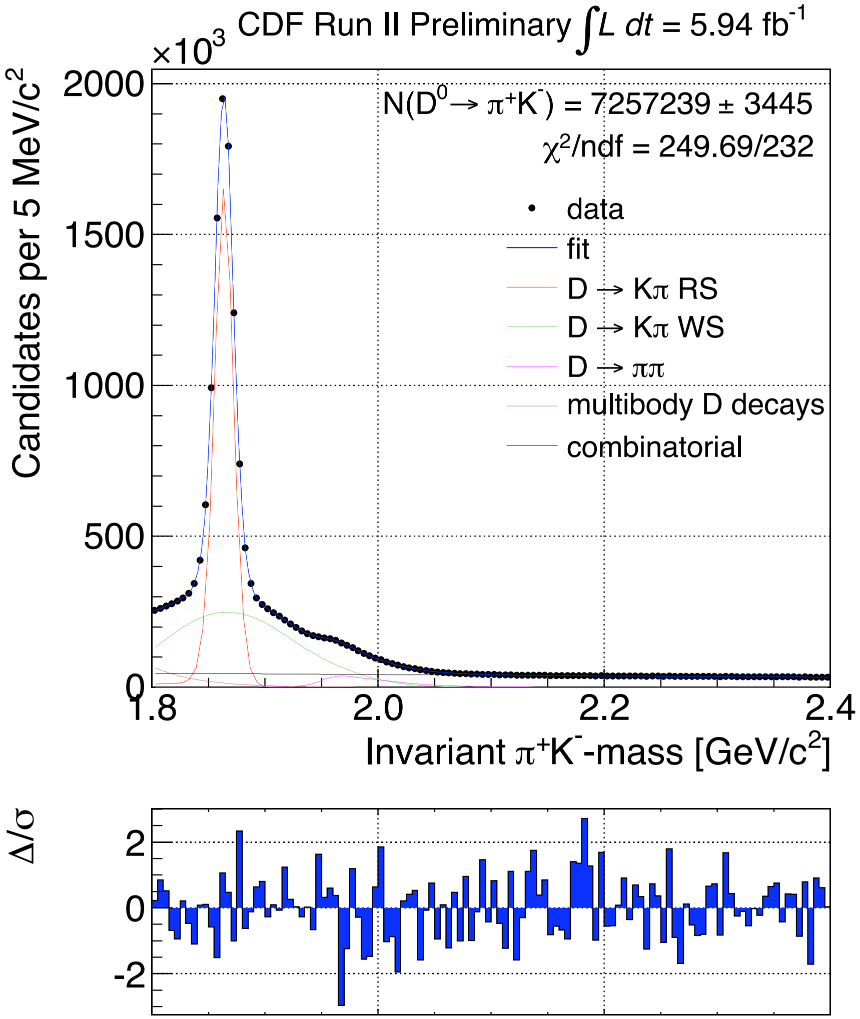


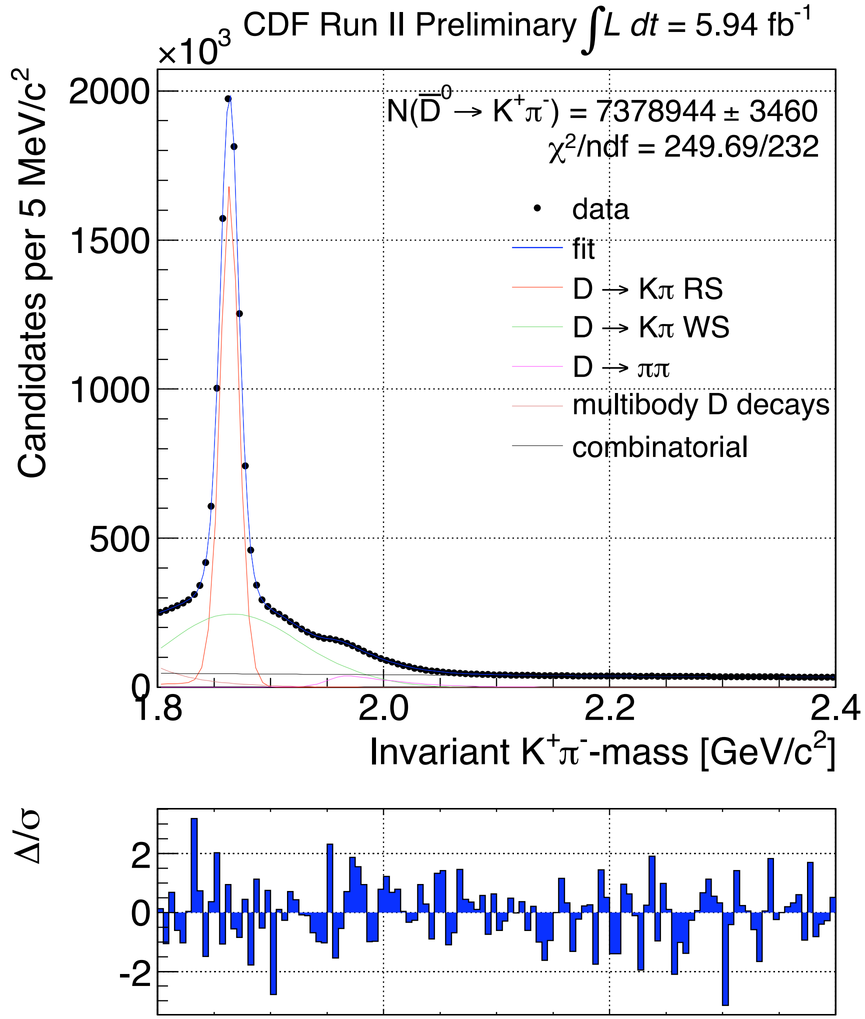




- two statistically independent samples (half each)
  - can easily afford to loose a factor of two in statistics
- simultaneous fit of two 1D mass projections
- signal is in narrow peak
  - ignore order of 10^{-4} DCS contribution

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





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

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^0 mesons	0.034%
Templates used in fits	0.010%
Templates charge differences	0.098%
Asymmetries from non-subtracted backgrounds	0.018%
Imperfect sample reweighting	0.0005%
Sum in quadrature	0.105%

0.034% is due to the contribution of D^0 mesons (coming from B decays) surviving the I.P. requirement.

0.098% is the error associated to the particular shapes of the mass distributions of the signal assumed in the fits. Largest effect is when the shapes used for positive and negative samples are varied independently.

Final result

- In 5.94 fb^{-1} using the formula $A_{\text{CP}}(\pi\pi) = A^{\text{raw}}_{\text{CP}}(\pi\pi^\star) - A^{\text{raw}}_{\text{CP}}(K\pi^\star) + A^{\text{raw}}_{\text{CP}}(K\pi)$

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

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

- Previous measurements:
  - BaBar on 386 fb^{-1} [−0.24 ± 0.52 ± 0.22]% PRL 100, 061803 (2008)
  - Belle on 540 fb^{-1} [−0.43 ± 0.52 ± 0.12]% PLB 670, 190 (2008)
  - CDF on 120 pb^{-1} [+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 $D^0 \rightarrow \pi^+\pi^-$

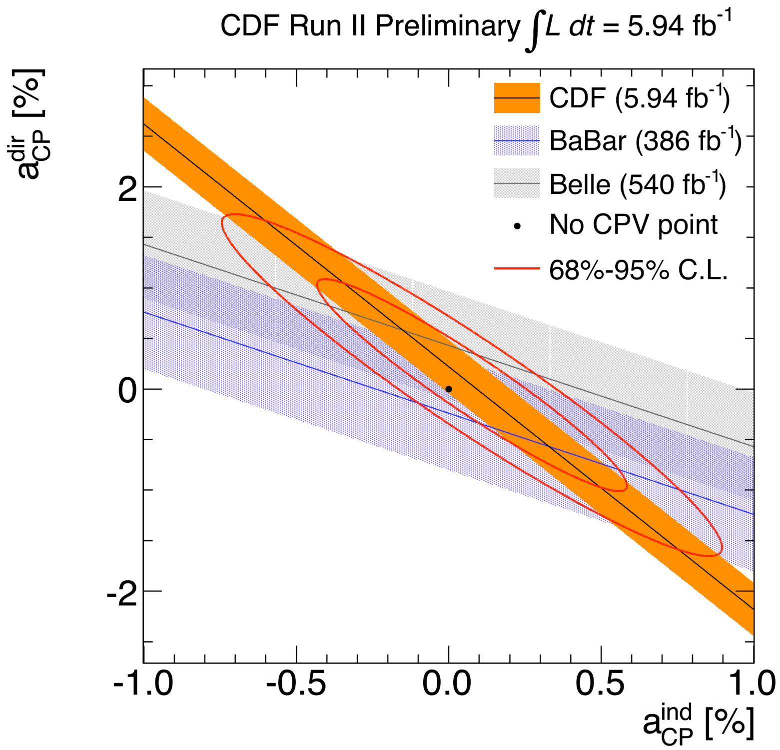
- "Time-integrated" A_{CP} receives contribution from direct CP violation and indirect CP violation (from mixing induced effects).
- The latter one produces a time-dependent asymmetry that persists when integrated over time.
- D^0 mixing parameters are small ($x\tau, y\tau \ll 1$), then the integrated asymmetry at the first order can be written as:

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

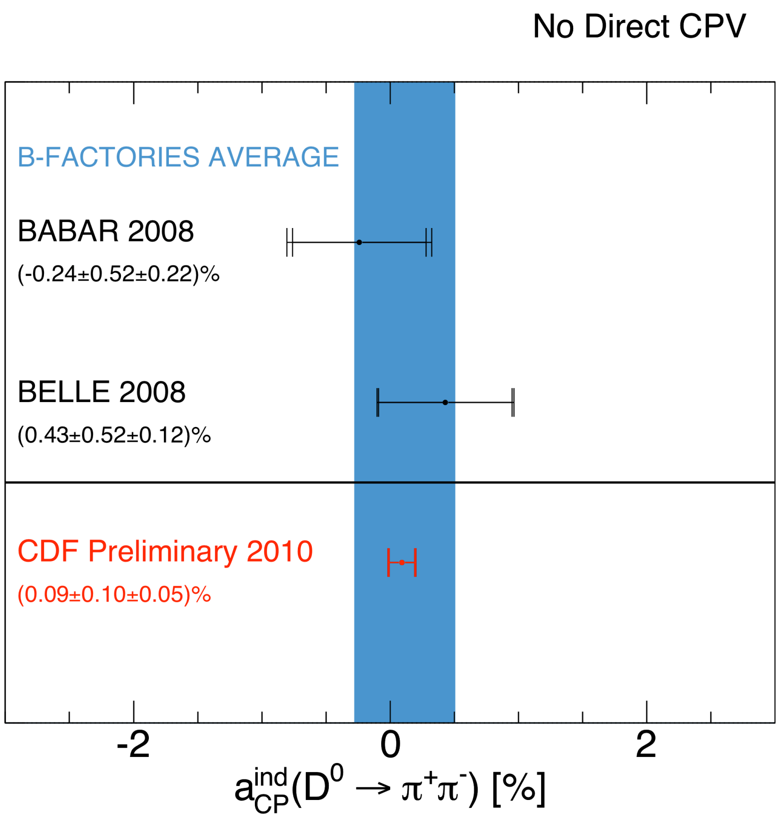
- A_{CP} describes a band in the plane (a_{CP}^{ind}, a_{CP}^{dir}) with a slope $<t>/\tau$, where t/τ is the proper decay time in unit of D^0 lifetime.

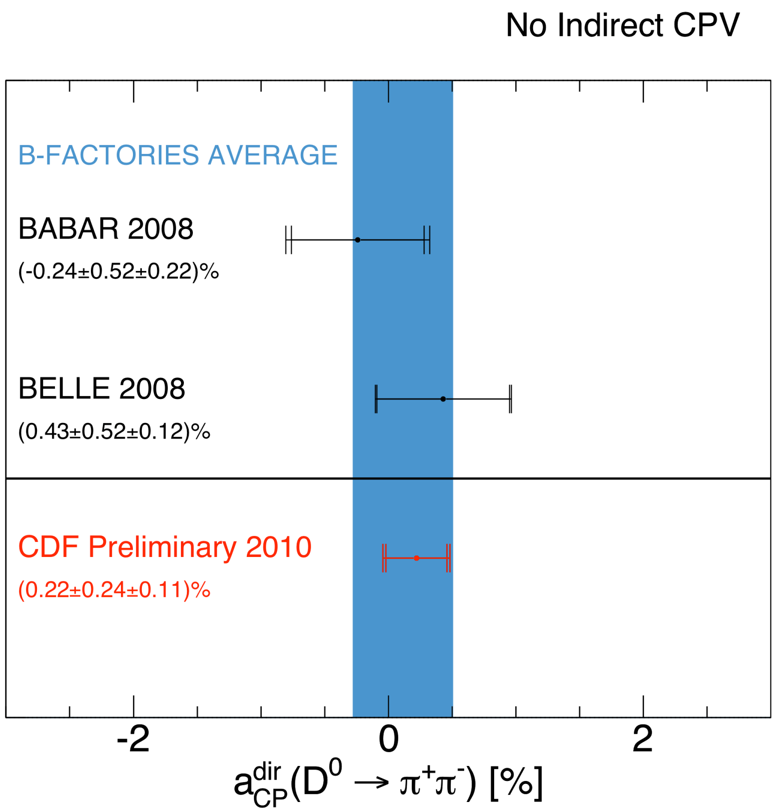
Proper decay time and (a_{CP}^{ind}, a_{CP}^{dir}) plane

- D^0 proper decay time is biased because of impact parameter trigger
  - At CDF : ⟨t⟩ ≈ [2.40 ± 0.03] τ
  - While at B-factories ⟨t⟩ = τ
- 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

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

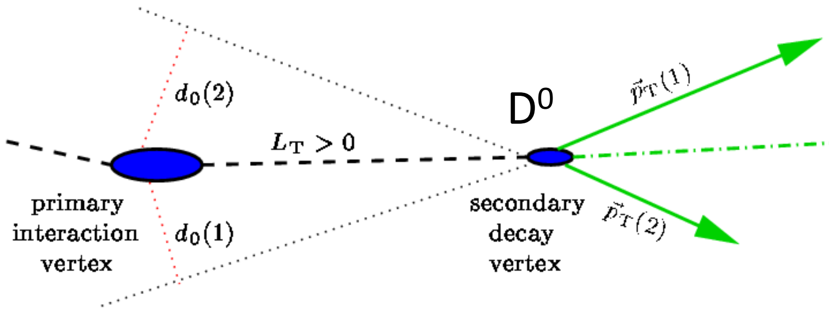
Conclusion & Prospects

- Result consistent with very small CP Violation as predicted in SM.
- This result is one of the most precise A_{CP} measurement in the Charm sector and shows that high precision measurements competitive or even superior to the B-factories are possible at the TeVatron.
- Enough precision to probe the Charm sector for NP in a significant way
- For the future:
  - Very soon: measurement of $A_{CP}(D^0 \to K^+K^-)$
  - With 10 fb^{-1} by the end of 2011 (maybe 15 fb^{-1} with 3 years extension):
    - More precise measurement of $A_{CP}(D^0 \to \pi^+\pi^-)$
    - Also time-dependent

Backup

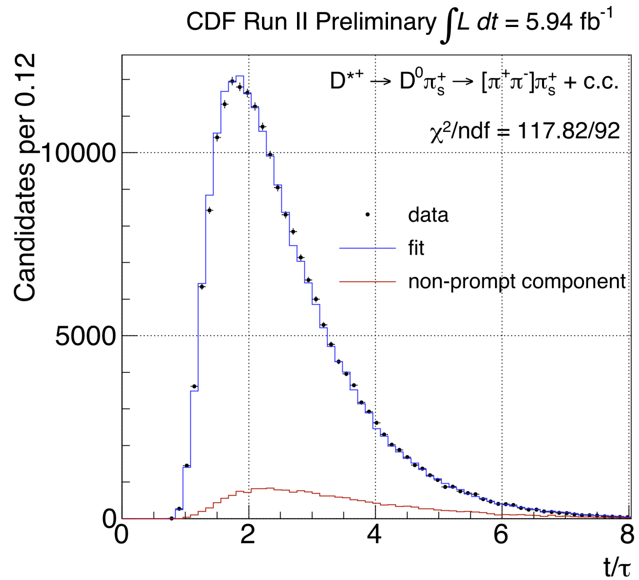
Silicon Vertex Trigger

- 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

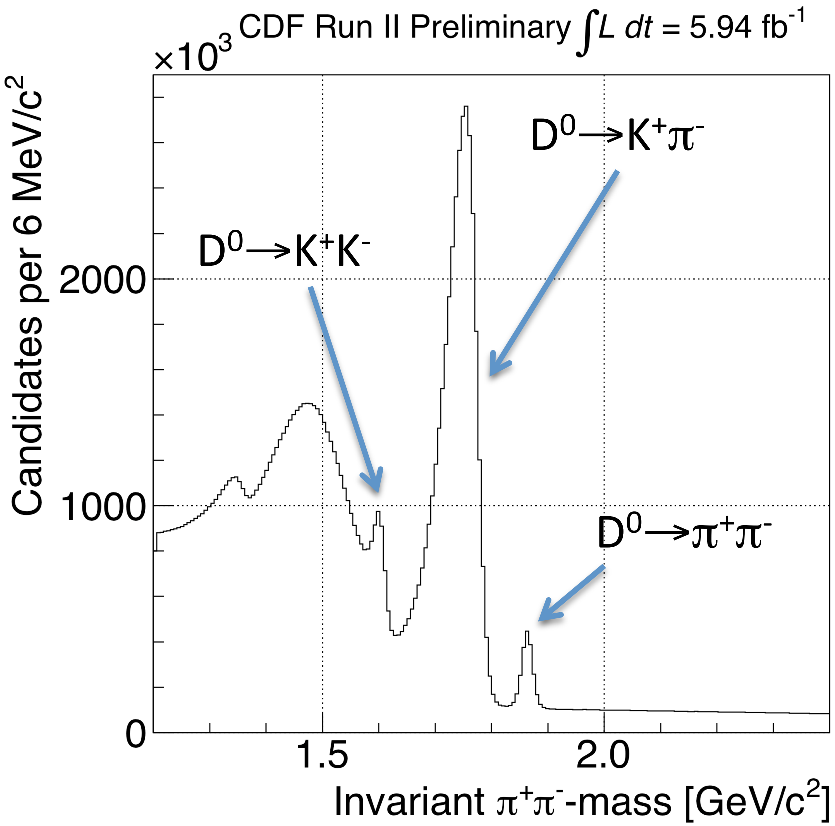


SVT plays a crucial role in charm physics:

- world's largest sample of $D^0 \to hh$
- boosted proper decay times enhance sensitivity to time dependent effects



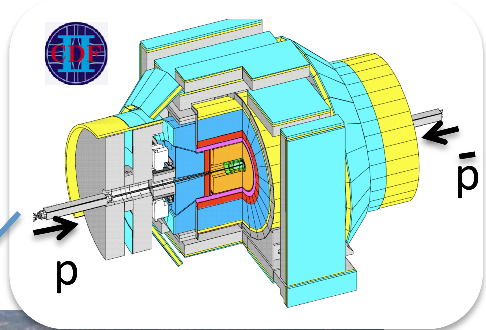
World's largest sample: $D^0 \rightarrow hh$



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

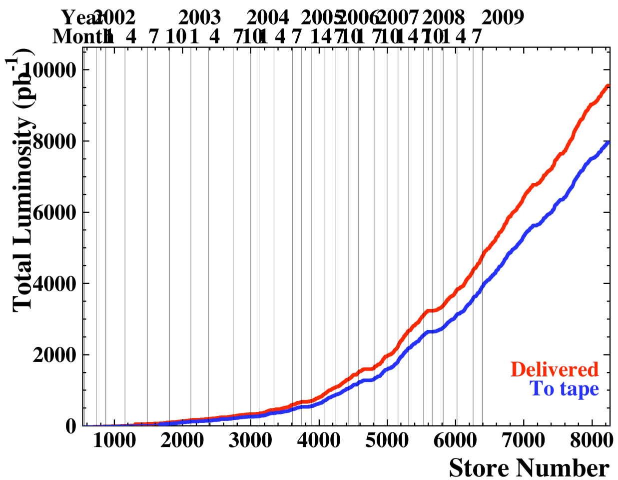
$N(D^0 \rightarrow \pi^+\pi^-) \approx 1.2\times10^6$
$N(D^0 \rightarrow K^+K^-) \approx 3\times10^6$
$N(D^0 \rightarrow K^-\pi^+) \approx 30\times10^6$

TeVatron



- $p\bar{p}$ collisions at $\sqrt{s}$=1.96 TeV.
- Peak luminosity ~ 3.5-3.8 × 10^{32} cm^{-2} s^{-1}.
- 50-60 pb^{-1} recorded a week .
- Collected about 8 fb^{-1} (on tape).

- >10 fb^{-1} by the end of 2011.
  - ~15 fb^{-1} with 3 years extension.



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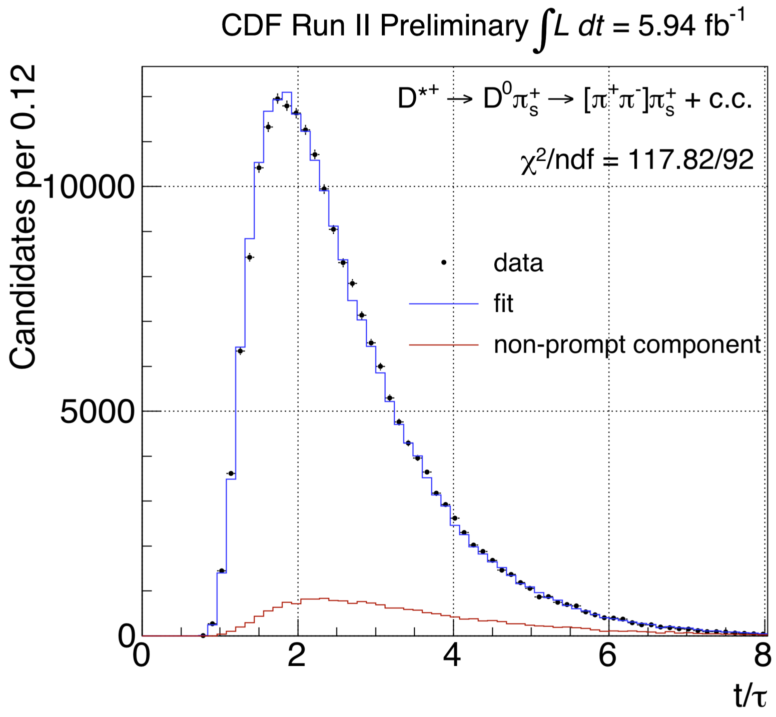
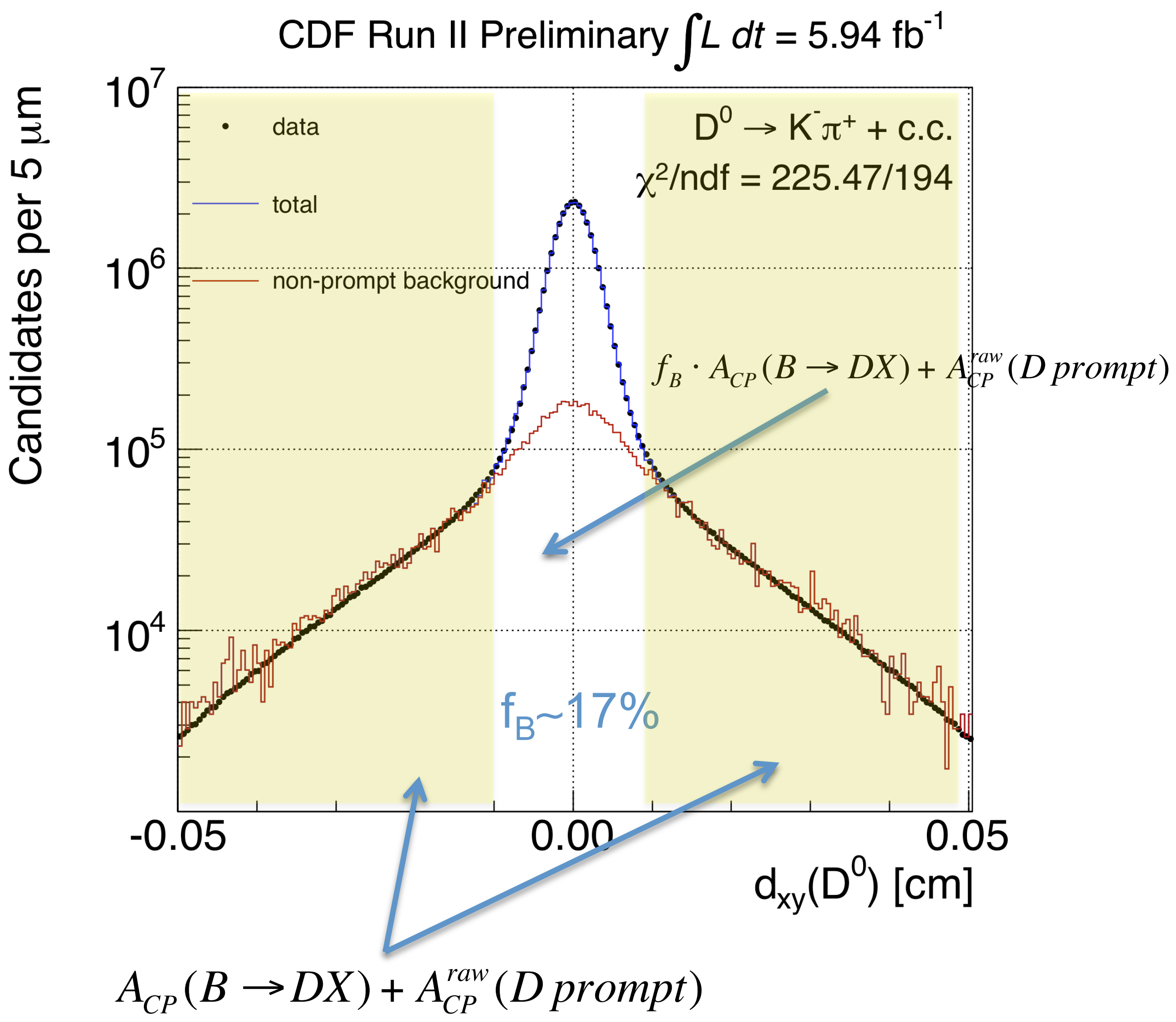


Uncertainty on the shapes

- 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%

Contamination from B → D^0 + X

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



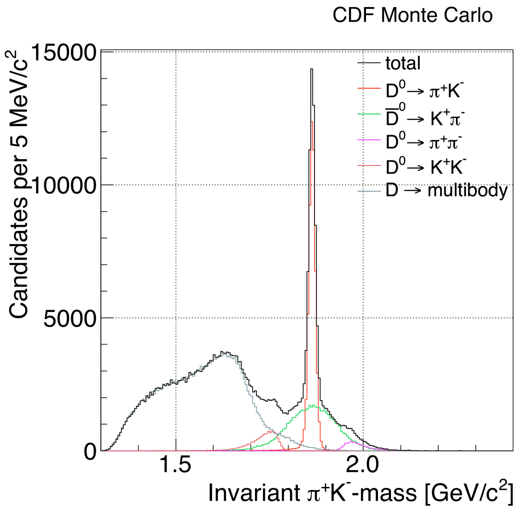
- About f_B = 17% of D^0 coming from B decays survives the I.P. cut.
- Comparing with the measured asymmetry with the one we obtained using only charm mesons with larger impact parameters we evaluate

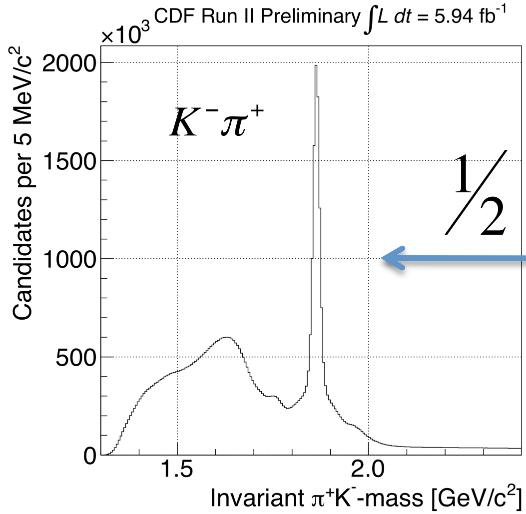
  $A_{CP}(B \to D^0X)$= (-0.21+- 0.20)%

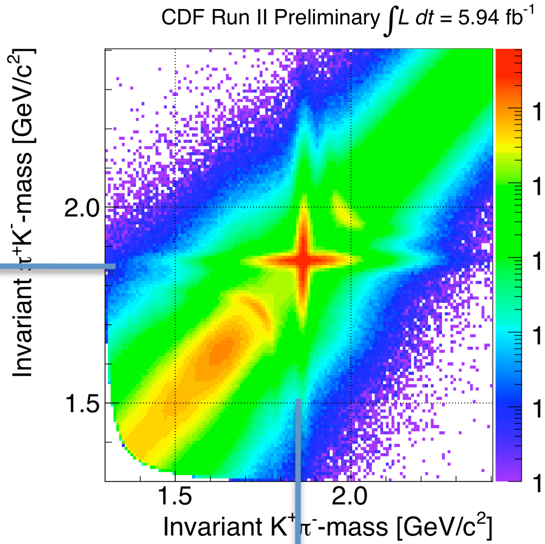
- Estimation of the systematic uncertainty for contamination:

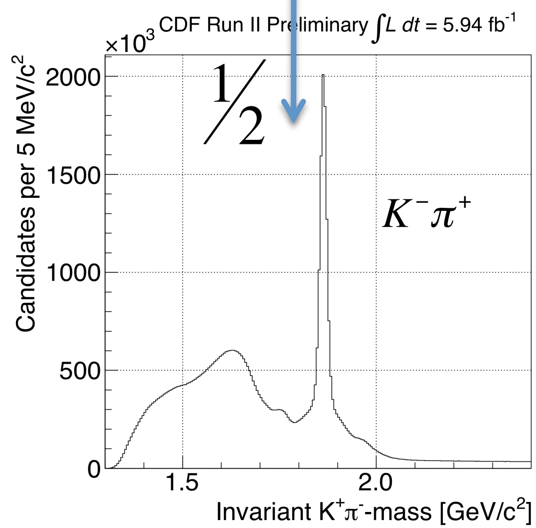
  0.20% * 17% = 0.034%

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









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Beam drag effects	0.004%	
Contamination of non-prompt D^0s	0.034%	1
Templates used in fits	0.010%	
Templates charge differences	0.098%	2
Asymmetries from non-subtracted backgrounds	0.018%	
Imperfect sample reweighing	0.0005%	
Sum in quadrature	0.105%	

1: Due to the contribution of D^0 mesons (coming from B decays) surviving the I.P. requirement.

2: Error associated to the particular shapes of the mass distributions of the signal assumed in the fits. Largest effect when the shapes used for positive and negative samples are varied independently.