CDF Measurement of CP Violation in

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

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for the CDF Collaboration

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see public CDF note:
http://www-cdf.fnal.gov/physics/new/bottom/100916.blessed-Dpipi6.0/

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

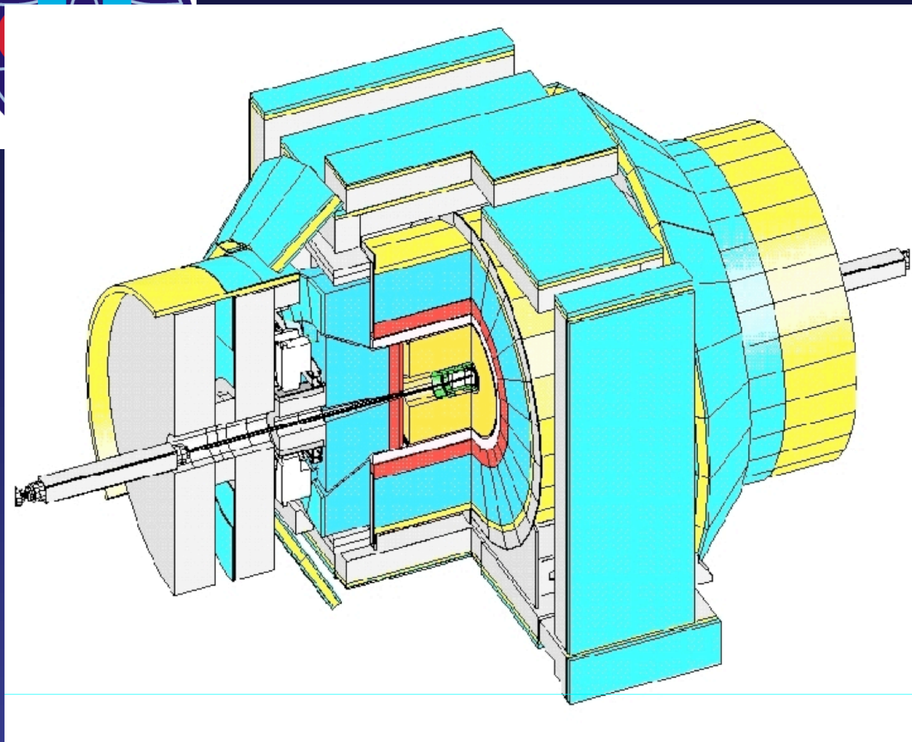
CP violation observed so far is explained within the Standard Model and is far from sufficient to explain the matter-antimatter asymmetry of the Universe, so there must be something else...

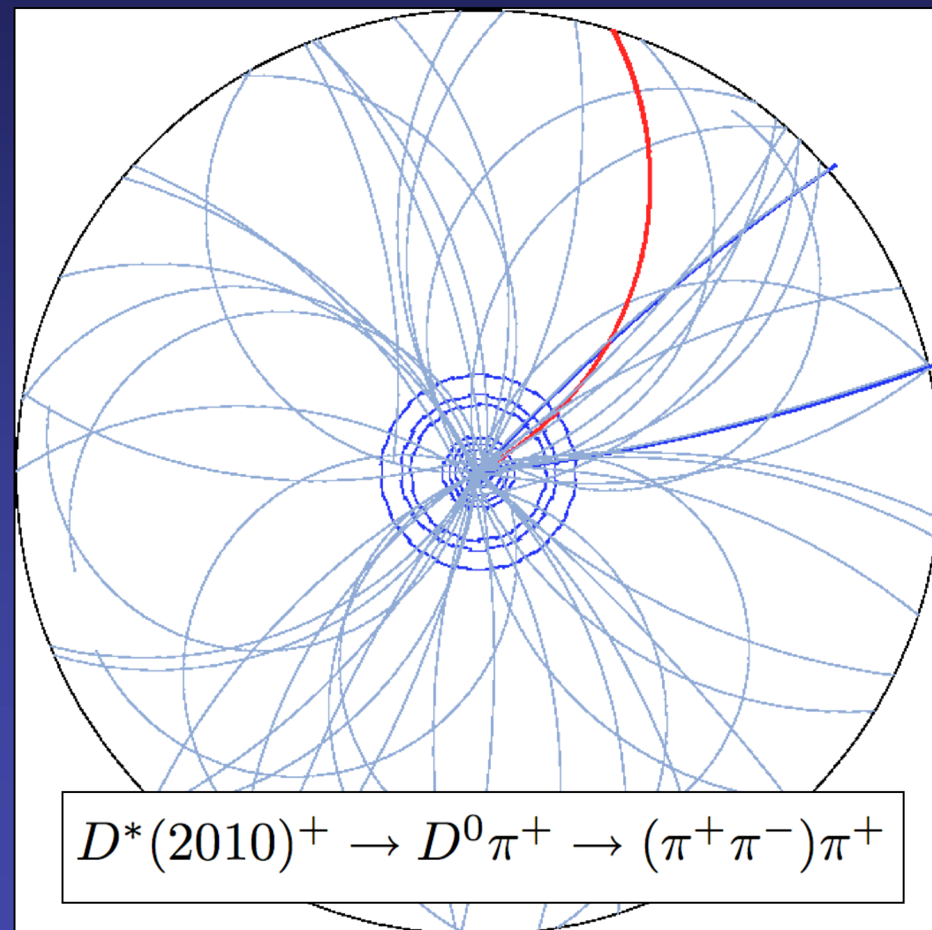
until recently most CP violation measurements have been done in the area of down-quarks (s, b), so what about up-quarks? why not look where we did not look before?

CPV in Charm is unique probe for NP because it probes up-quark sector (unaccessible through *t* or *u* quarks)

Observed D^0 mixing rate is large, consistent only with most stretched SM predictions. Could this be a first hint of new physics?

the CDF detector





- Central drift chamber
- Silicon Vertex Detector
- Silicon Vertex Trigger

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

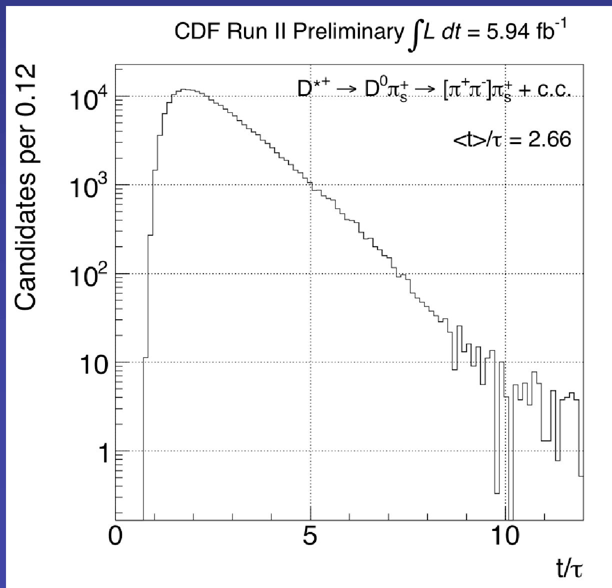
SVT plays a crucial role in this analysis

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

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

~ 220,000 $D^{*+} \to D^0 \pi^+ \to (\pi^+ \pi^-) \pi^+$

- boosted proper decay times enhance sensitivity to time dependent effects



measuring Acp

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

tagging the D^0 with D^*

$$D^{*+} \to D^0 \pi_s^+$$

$$D^{*-} \to \bar{D}^0 \pi_s^-$$

CP symmetric initial state (p-pbar) ensures charge symmetric production

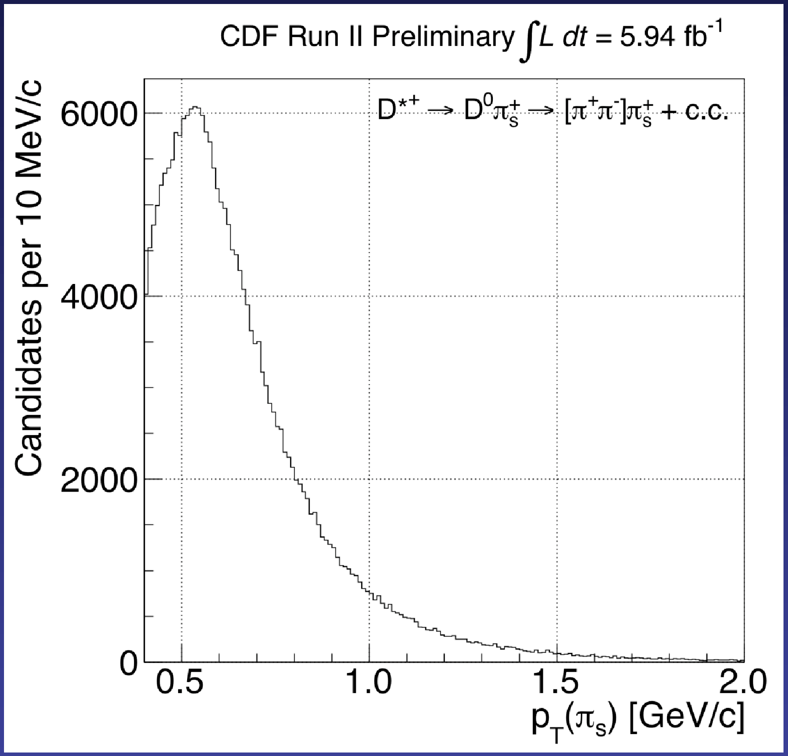
~220K very clean $D^* \to D^0\,\pi$ with $D^0 \to \pi\,\pi$

⇨ ~ 0.21 % statistical error

soft pions from D* decay

small Q in D* decay causes p_T of pion to be ~ 1/13 of D^0

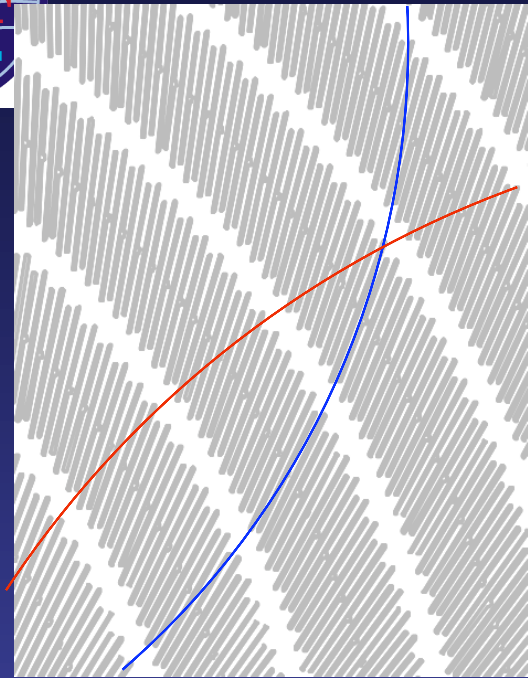
Given CDF acceptance for D^0 this is typically in the range [0.4 - 1.0] GeV/c where detector efficiency for tracks of opposite charge is asymmetric to the level of a few percent



soft pion spectrum

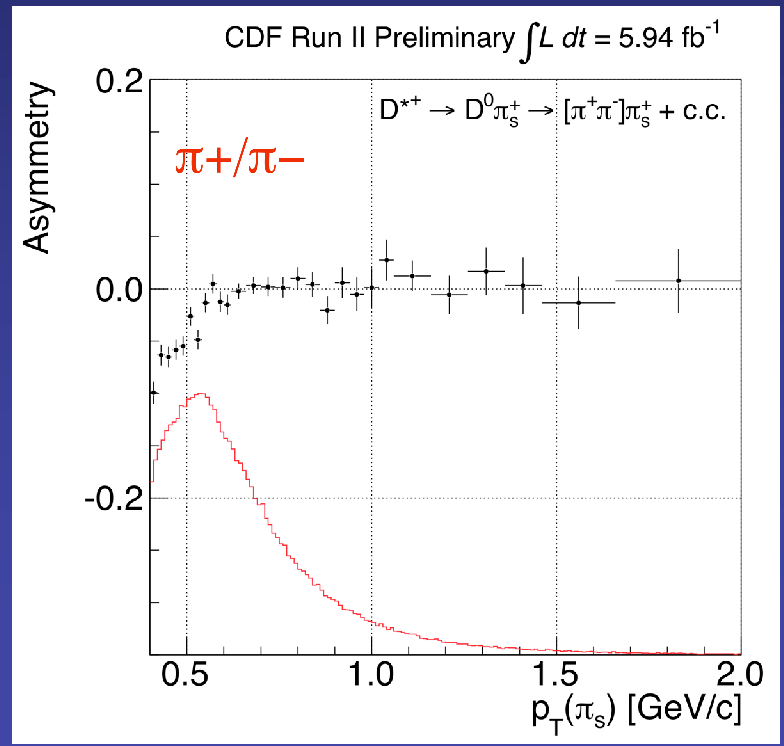
different efficiencies for soft pions of opposite charge translate into different efficiencies for D* of opposite charge and may lead to a fake charge asymmetry in D^0 decay

fighting detector asymmetries



COT is intrinsically charge asymmetric

tracking efficiencies for +/- 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 %
- turns out this can be done with a very high degree of confidence using only data - no need to rely on Montecarlo

suppress detector asymmetries by combining three event samples

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

cancel $K^+\ \pi^-$ vs $K^-\ \pi^+$ asymmetry

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

cancel π_s^+ vs π_s^- asymmetry

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

K+/K- different interaction with matter

summing three raw asymmetries

$$A_{CP}^{raw}(\pi\pi^\star) = A_{CP}(\pi\pi) + \delta(\pi_s)^{\pi\pi^\star}$$

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

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

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

$$A_{CP}^{raw}(K\pi) = A_{CP}(K\pi) + \delta(K\pi)^{K\pi},$$

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

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

one obtains a measurement of the intrinsic Acp of the process of interest with detector asymmetries suppressed by more than one order of magnitude, well below one permille in our case

reweighting the samples

detector induced asymmetries are dependent on kinematic

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

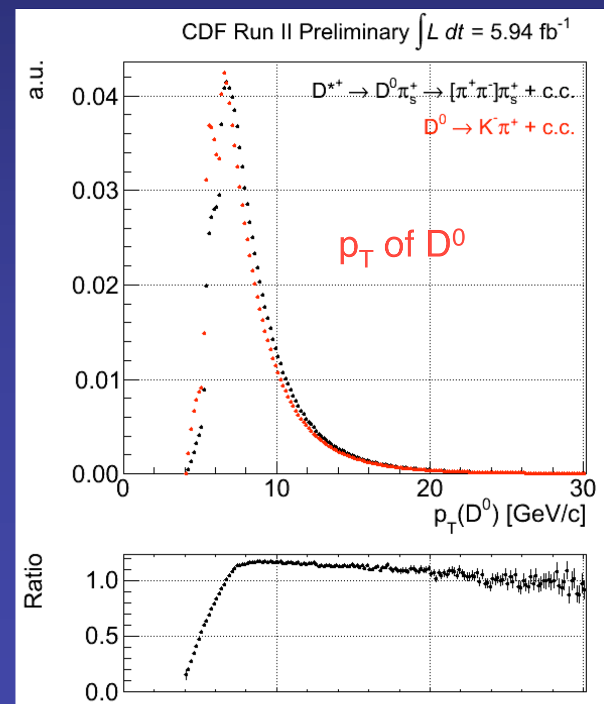
$D^* \rightarrow D^0 \pi_s \rightarrow (\pi \pi)\, \pi_s$

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

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

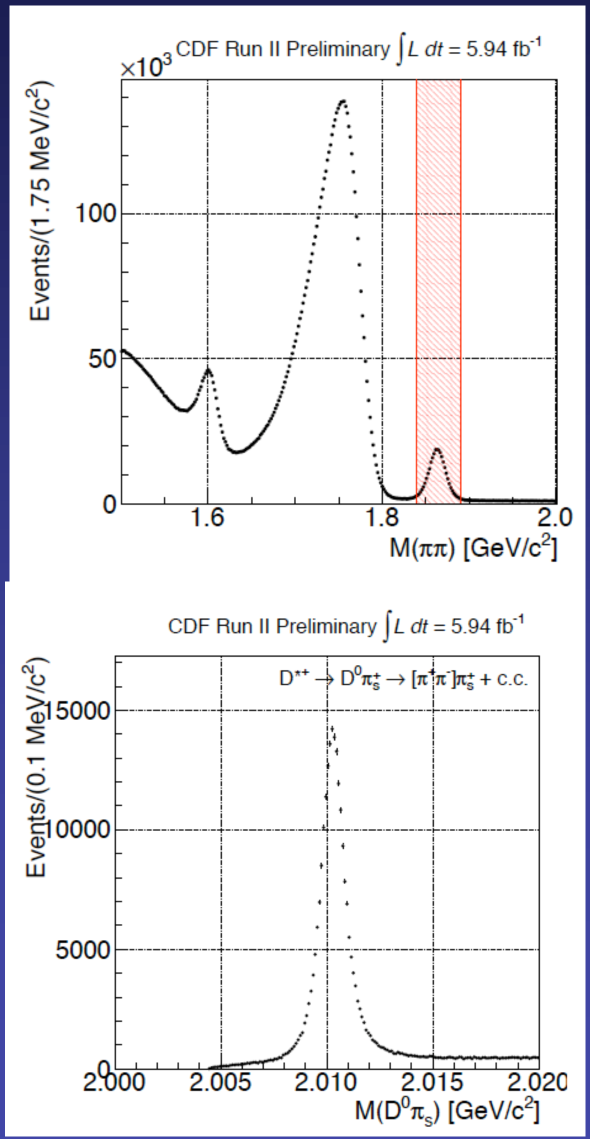
$D^* \rightarrow D^0 \pi_s \rightarrow (K \pi)\, \pi_s$

same for $K\pi$



distributions are made identical by sample reweighting

counting tagged π π events

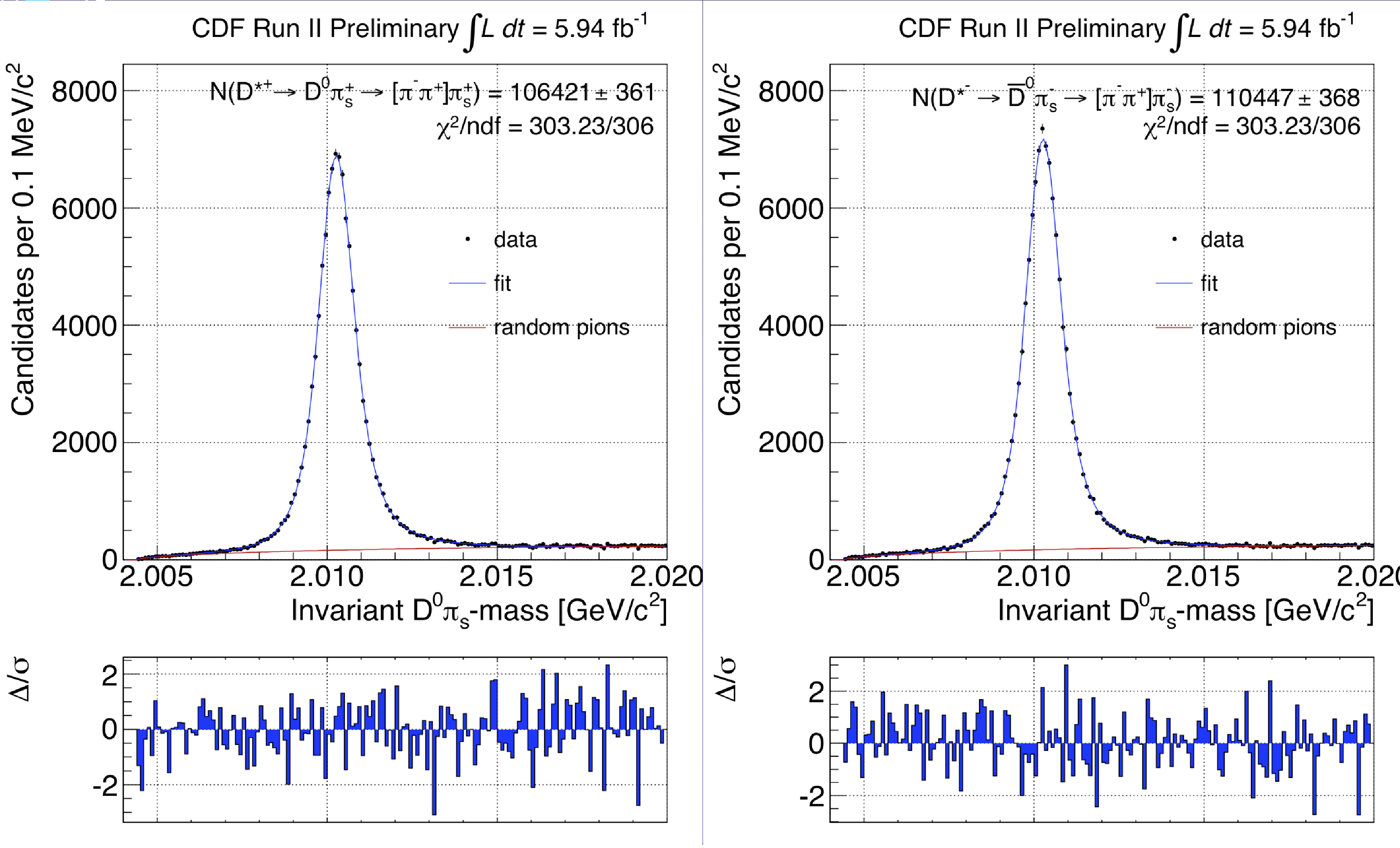


1. cut on π π invariant mass

2. associate with soft pion

3. fit D* invariant mass distribution

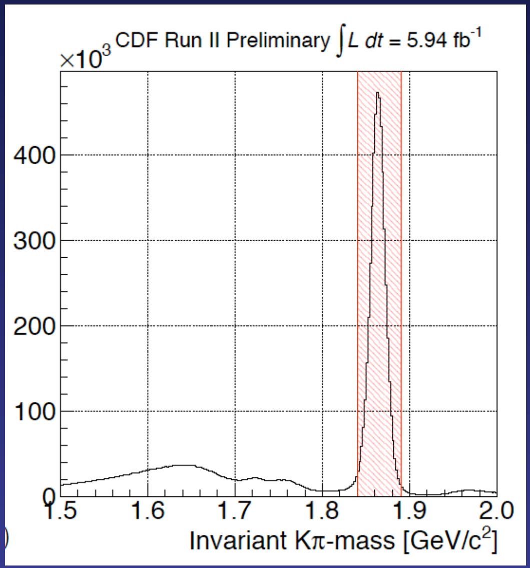
tagged π π combined fit

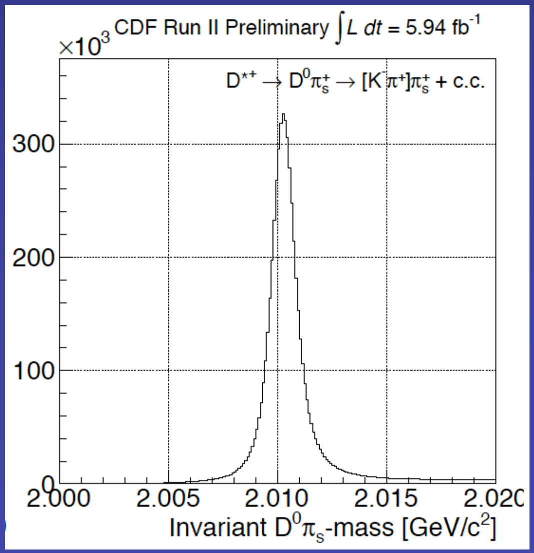


$N^+ = 106{,}421 \pm 361$ $N^- = 110{,}447 \pm 368$

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

counting tagged Kπ events





1. cut on Kπ invariant mass

2. associate with soft pion

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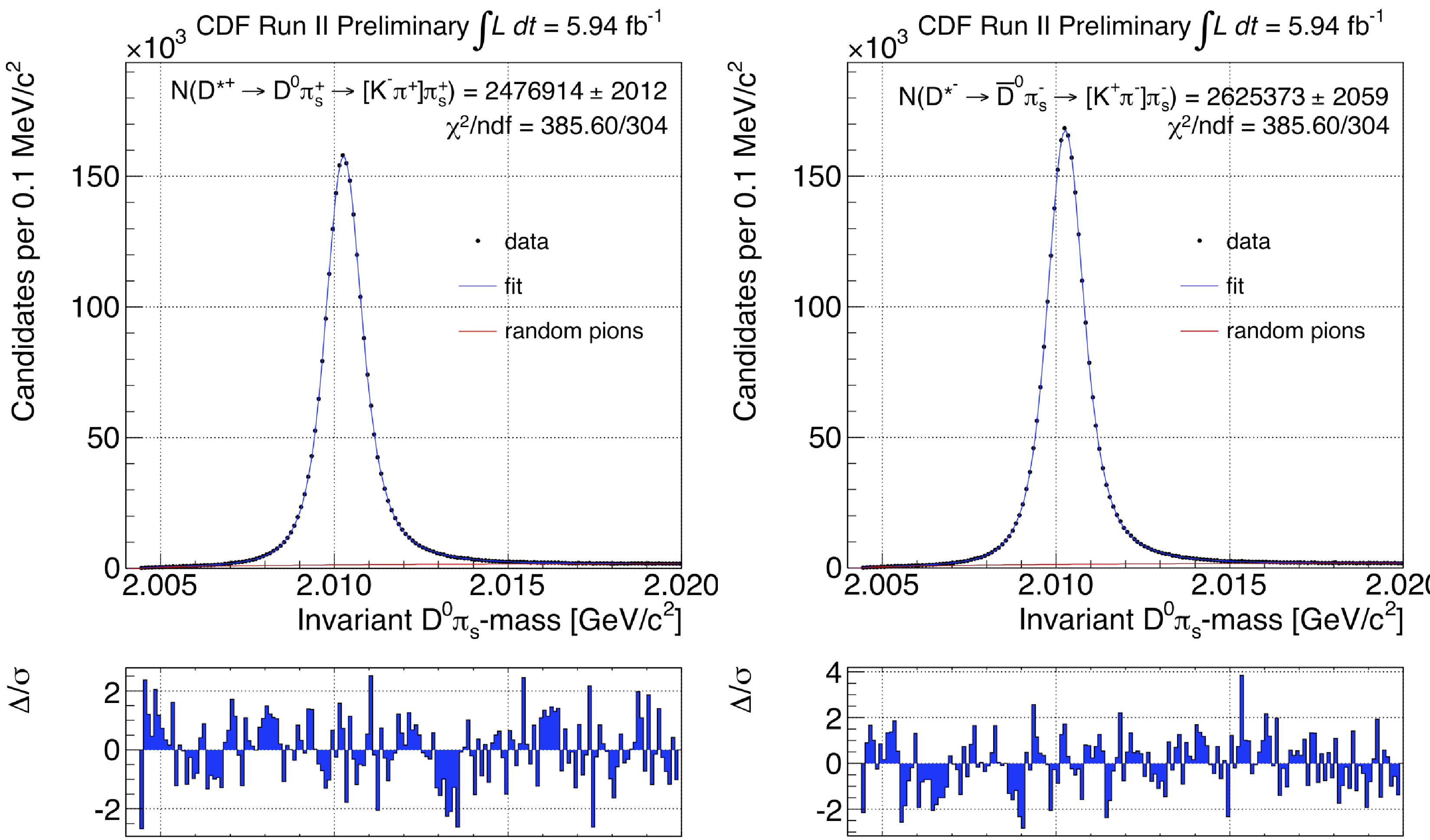
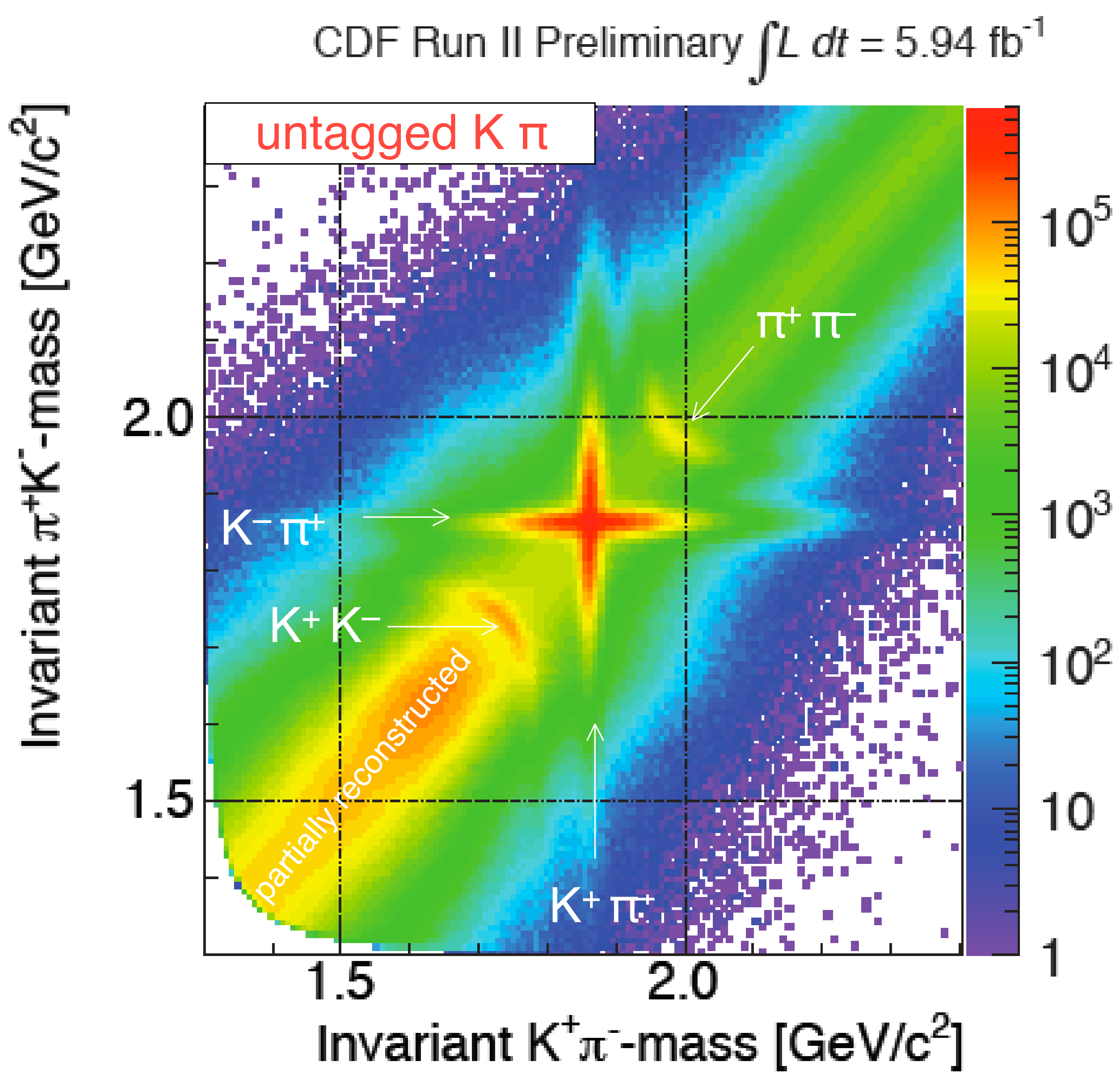
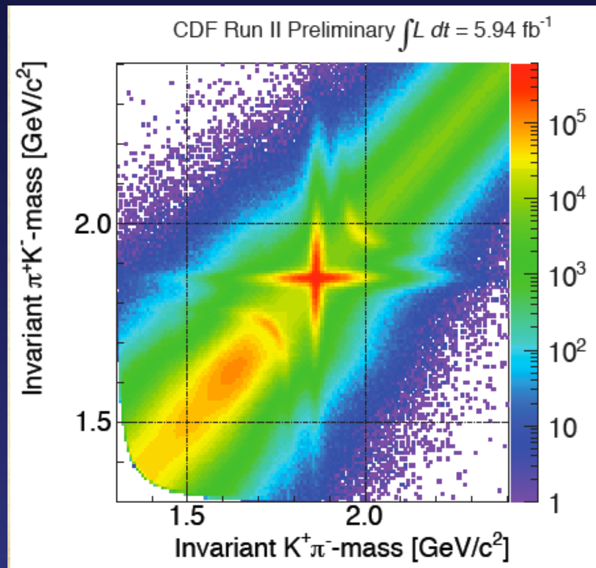
tagged K π combined fit

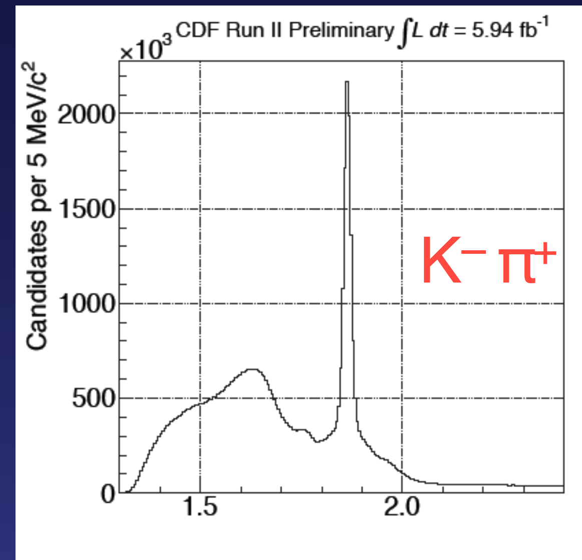


$N^+ = 2{,}476{,}914 \pm 2{,}012$ $\qquad$ $N^- = 2{,}625{,}373 \pm 2{,}059$

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

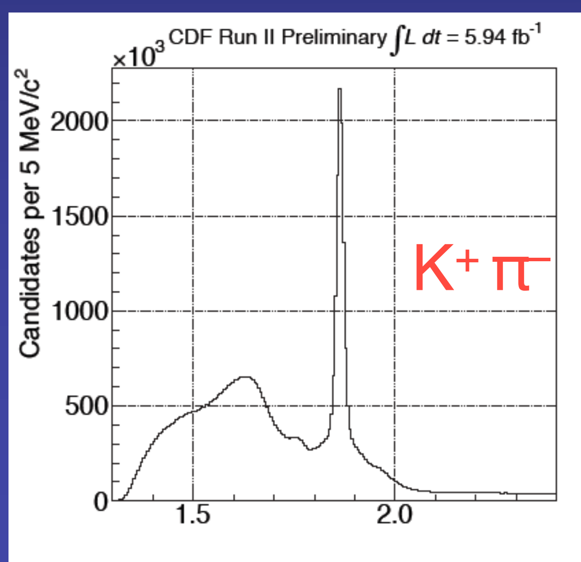

CDF Run II Preliminary $\int L\, dt = 5.94\ fb^{-1}$
untagged K π
π⁺ π⁻
K⁻ π⁺
K⁺ K⁻
partially reconstructed
K⁺ π⁻
Invariant π^+K^--mass [GeV/c²]
Invariant $K^+\pi^-$-mass [GeV/c²]
1.5
2.0
10^5
10^4
10^3
10^2
10
1





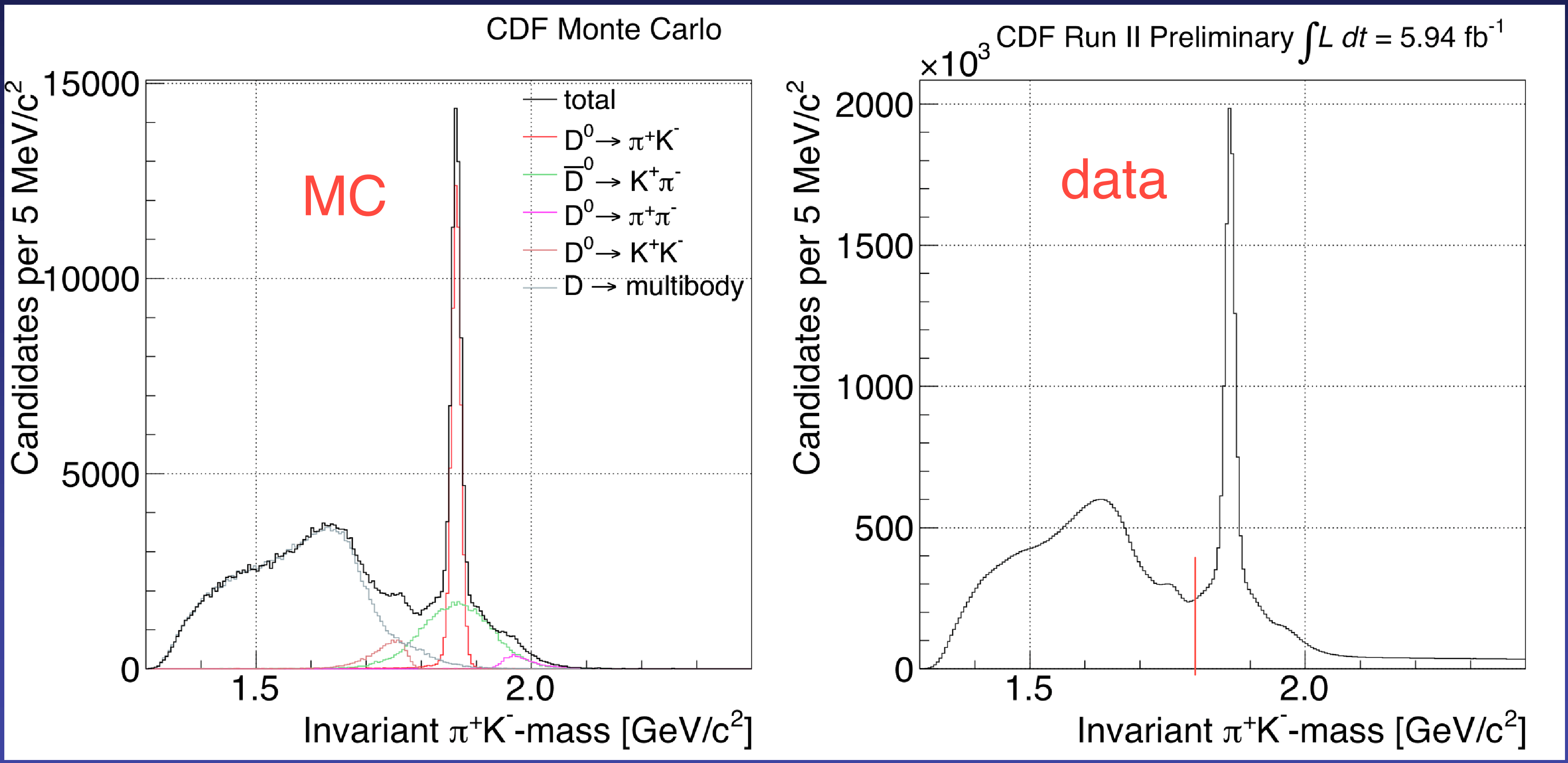
D^0

$\bar{D}^0$



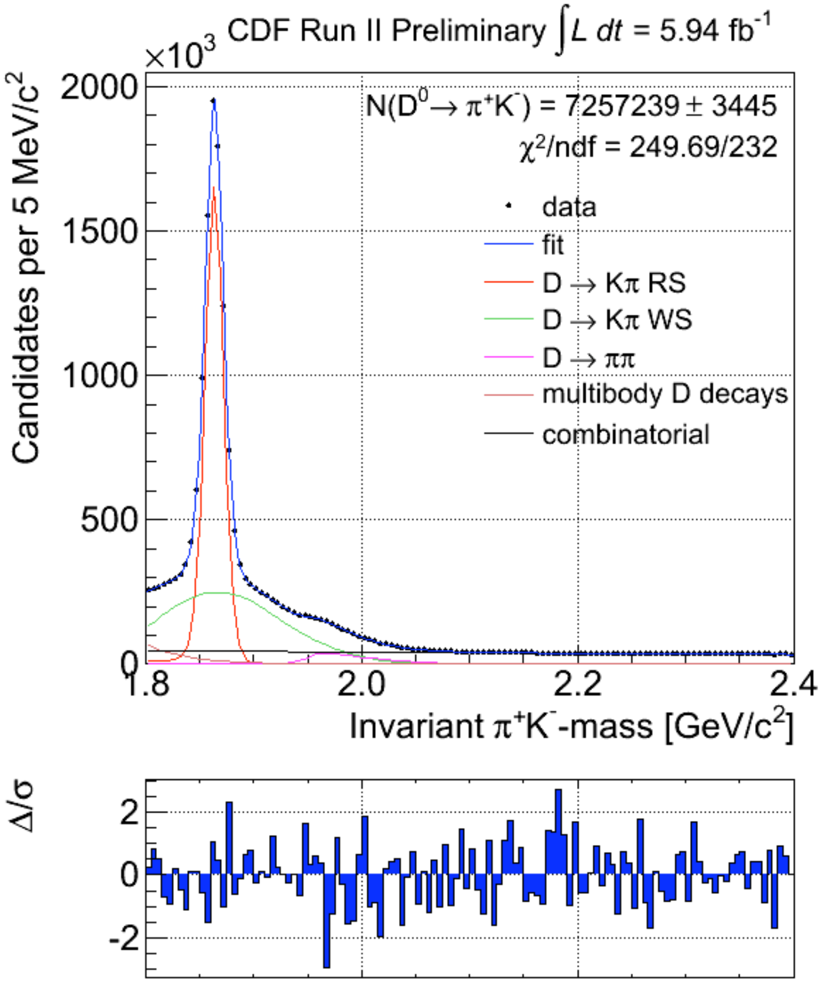
- simultaneous fit of two projections
- signal is in narrow peak
- two statistically independent samples with half the events each
- can easily afford to loose a factor of two in statistics here

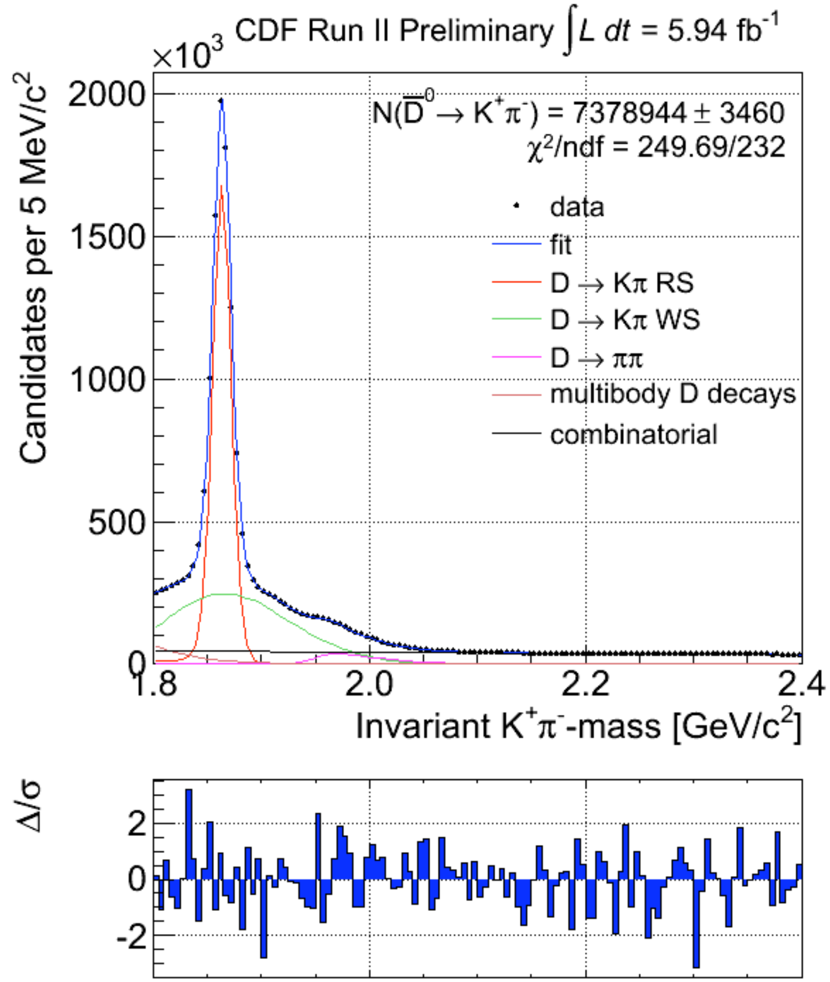
MC vs. data



all features of the mass distribution are reproduced by MC

untagged K π combined fit



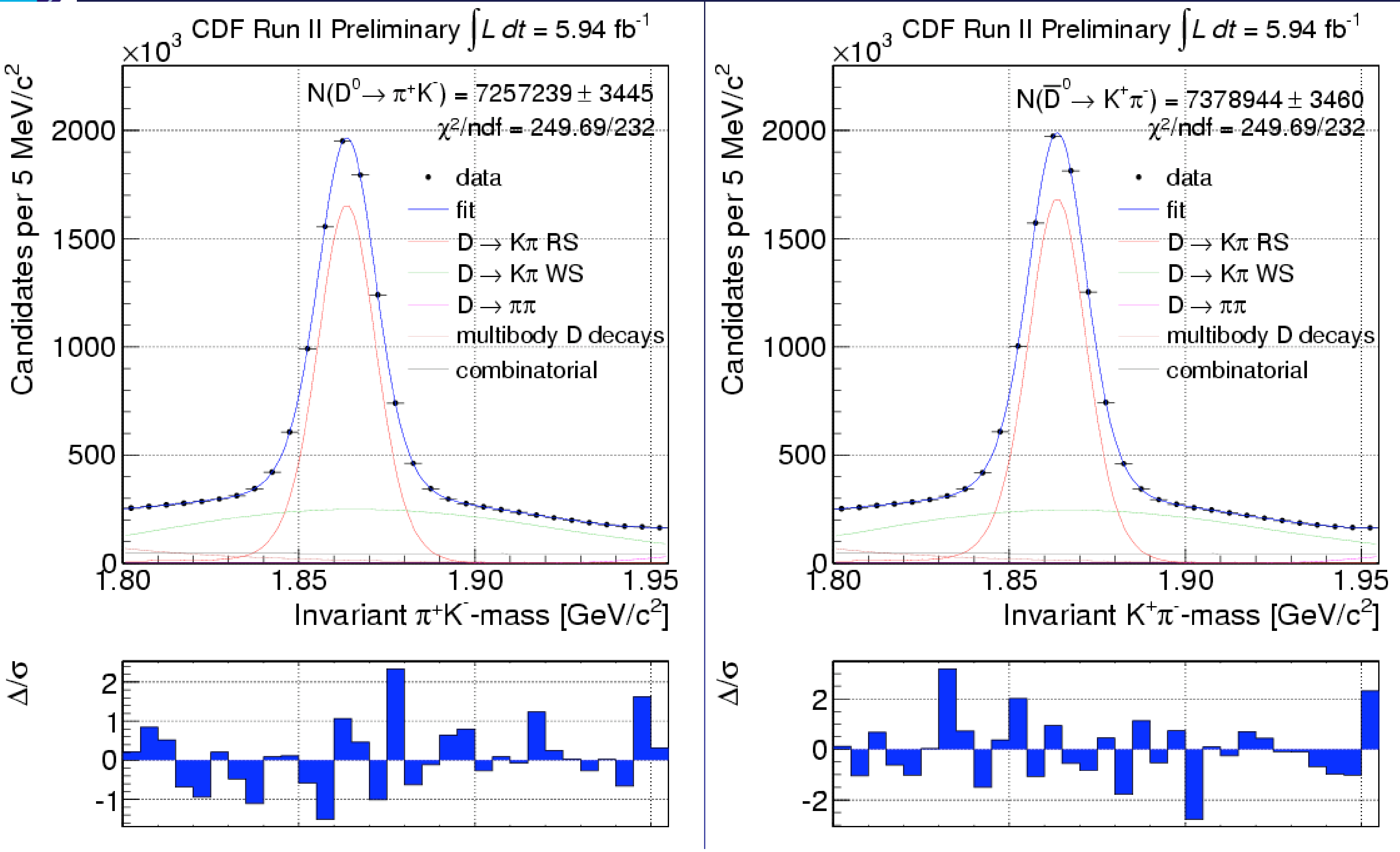


$N^{+} = 7{,}257{,}239 \pm 3{,}445$

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

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

untagged K π combined fit



$N^{+} = 7{,}257{,}239 \pm 3{,}445$ $N^{-} = 7{,}378{,}944 \pm 3{,}460$

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

putting it all together

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

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

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

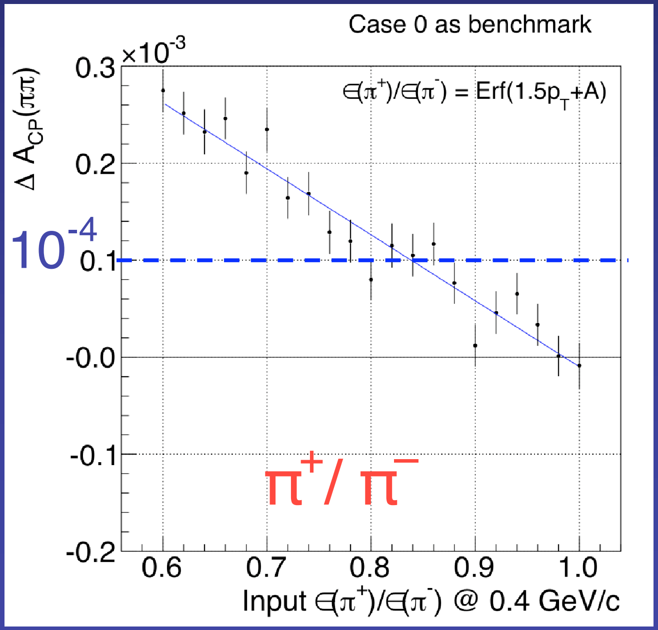
statistical error only

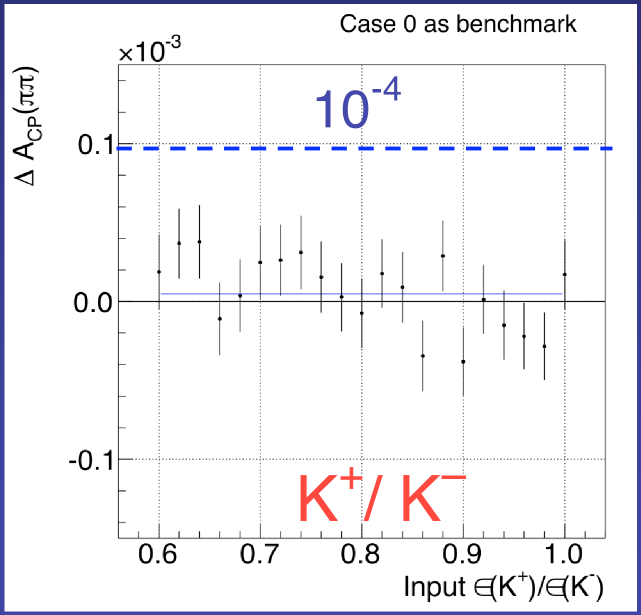
systematics

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%

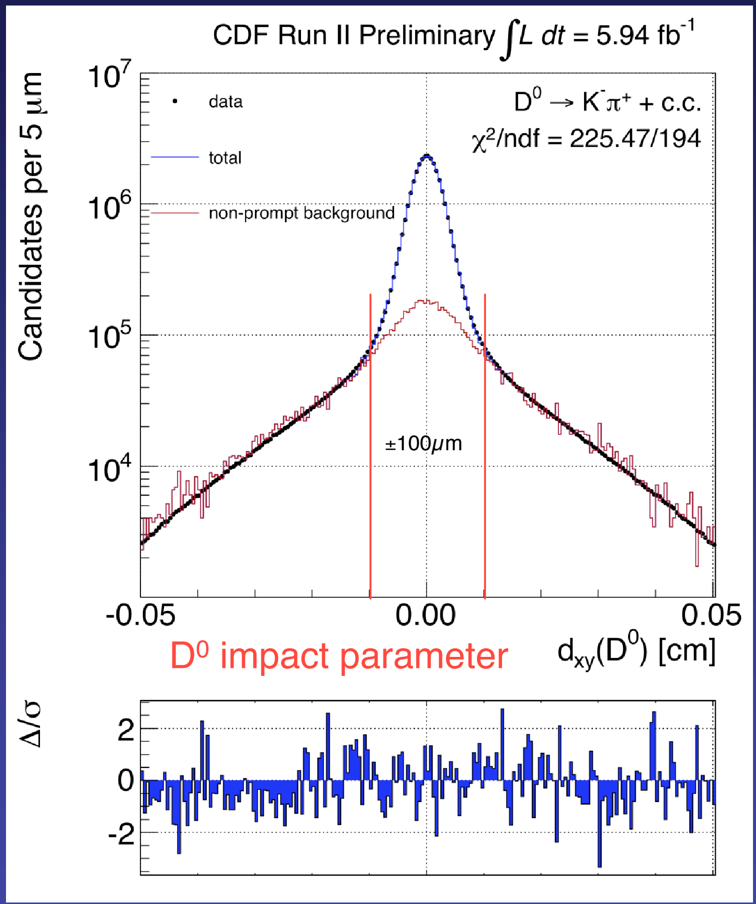
MC test of detector asymmetry cancellation

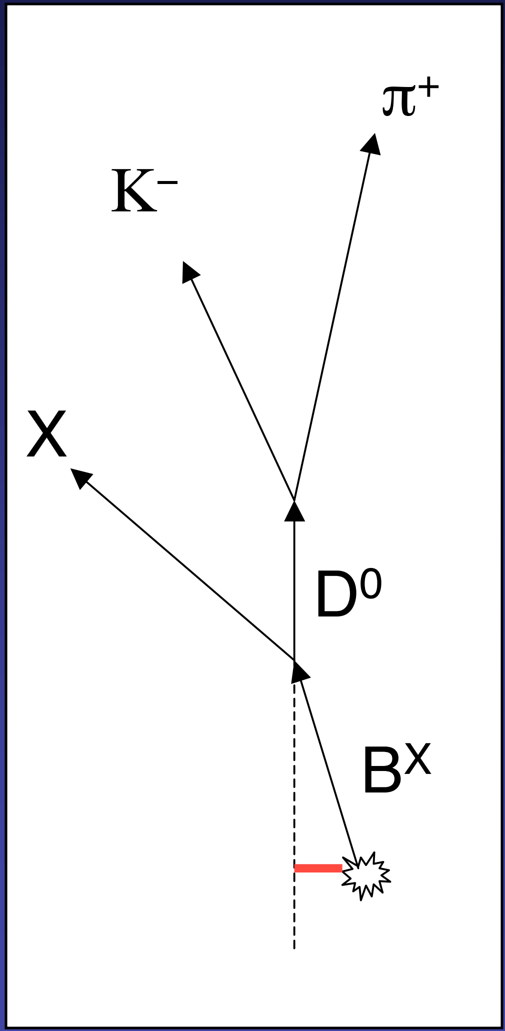
- use CDF MC with detailed detector simulation
- inject artificial detector asymmetries in simulation
- apply analysis procedure and measure bias on Acp measurement





contamination from B → D^0 + X

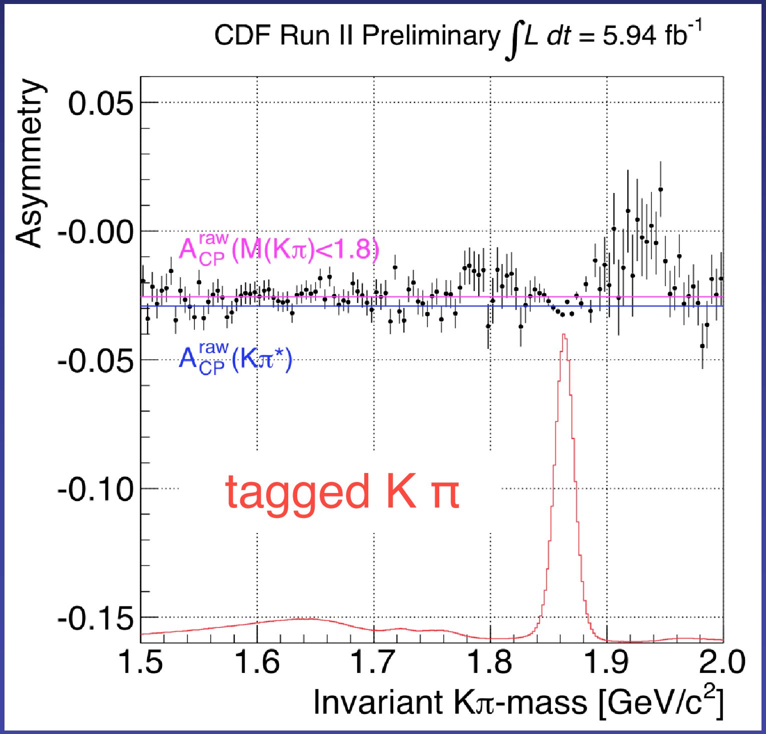




$f_B \sim 17\%$
$Acp(B \rightarrow D^0\ X) = (-0.21 \pm 0.20)\%$
$f_B\ xAcp \sim 0.034\%$

contamination from other decays

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



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

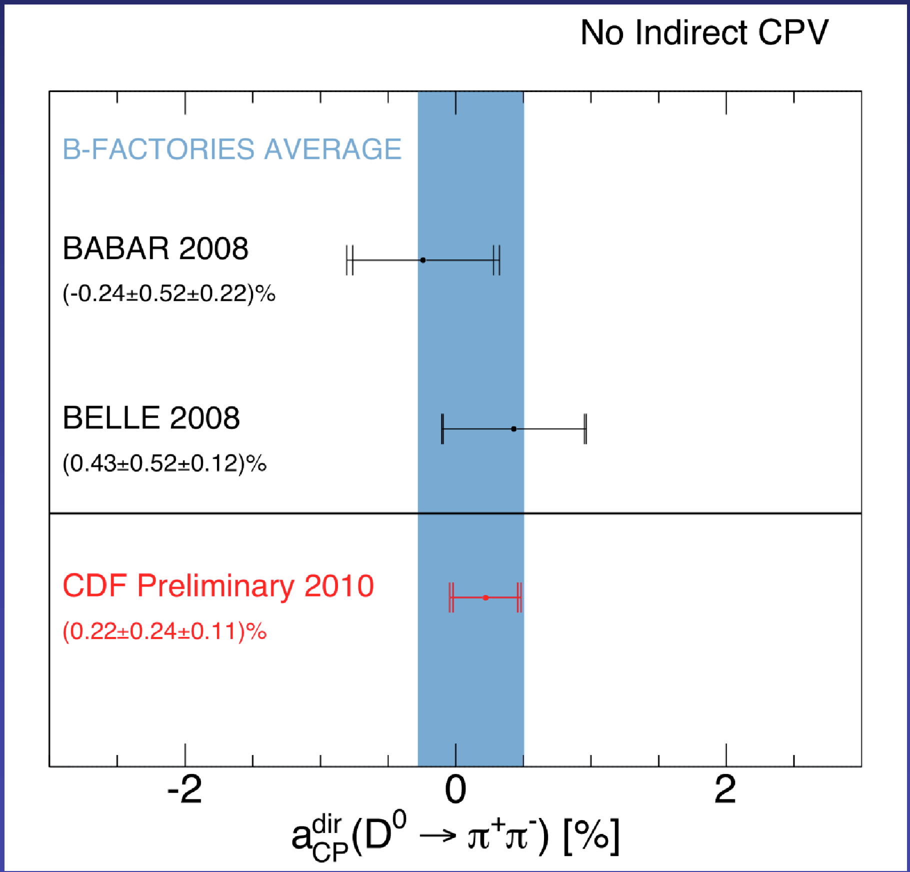
- the largest effect is obtained when the shapes used for the positive and negative samples are varied independently

- we estimate a worst case effect of 0.098%

finally

$$A_{CP}(D^0 \rightarrow \pi^+\pi^-) = (+0.22 \pm 0.24 \pm 0.11)\%$$

stat syst



interpretation

what are we actually measuring?

time-dependent Acp

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

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

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

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

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

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

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

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

direct vs. indirect A_{cp}

- D^0 mixing is slow
- expand to first order in τ

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

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

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

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

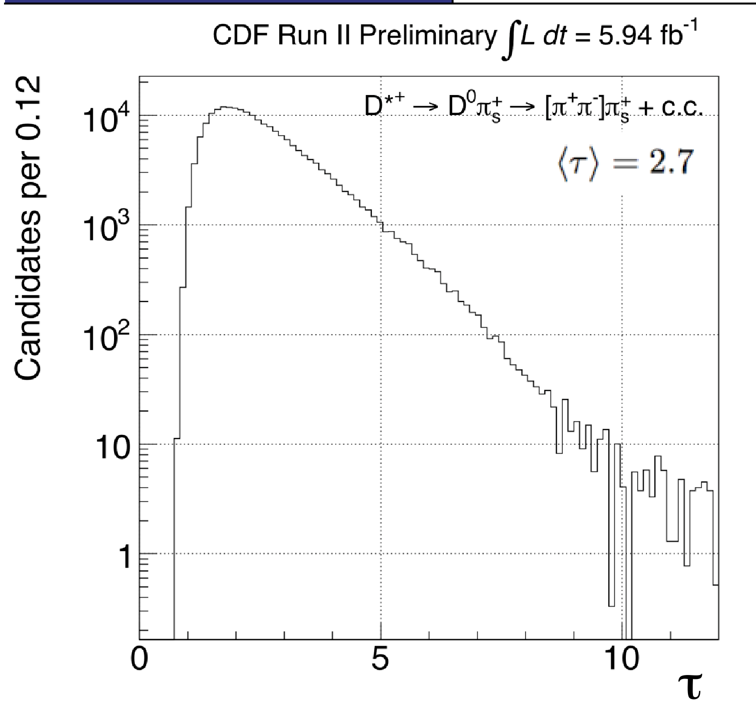
$$a_{CP}^{ind} = \frac{1}{2}\left\{\mathcal{R}e(\lambda_f - \lambda_f^{-1})y - \mathcal{I}m(\lambda_f - \lambda_f^{-1})x\right\}$$

what do we measure?

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

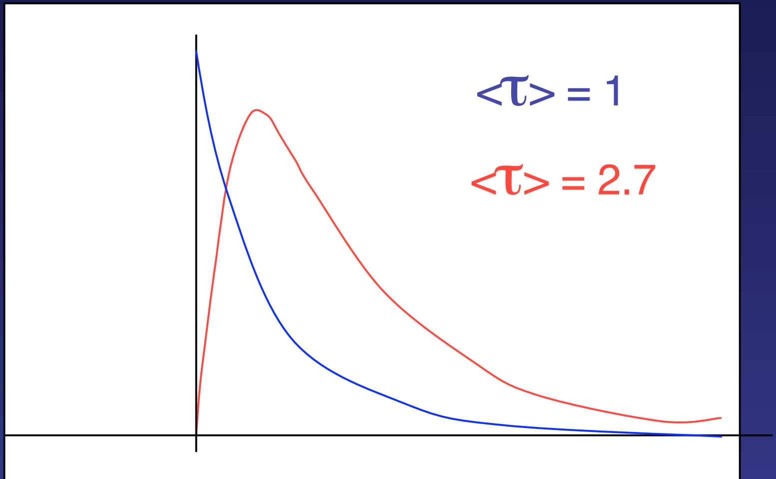
for B-factories: $\langle \tau \rangle = 1$ $\quad \langle A_{CP} \rangle = a_{CP}^{dir} + a_{CP}^{ind}$

for CDF: $\langle \tau \rangle = 2.7$ $\quad \langle A_{CP} \rangle = a_{CP}^{dir} + 2.7 \, a_{CP}^{ind}$



important difference between CDF and B-factories

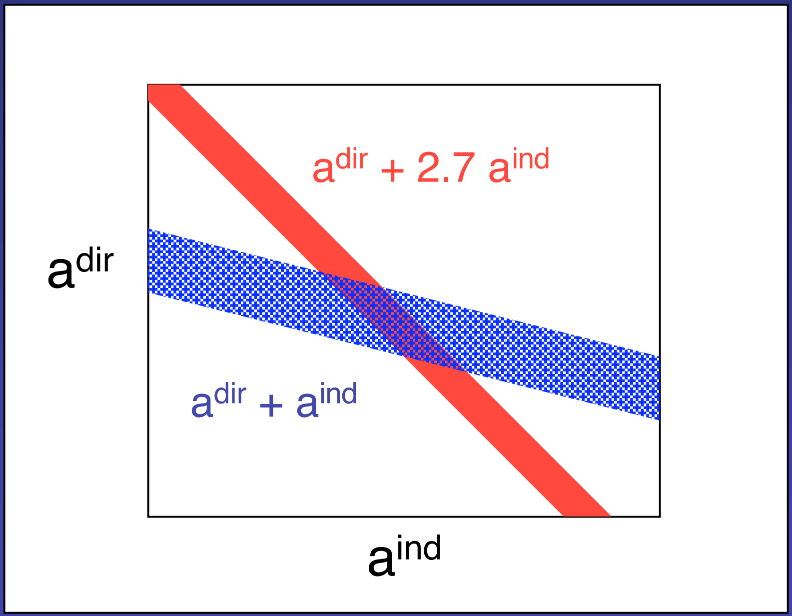
different proper time distributions



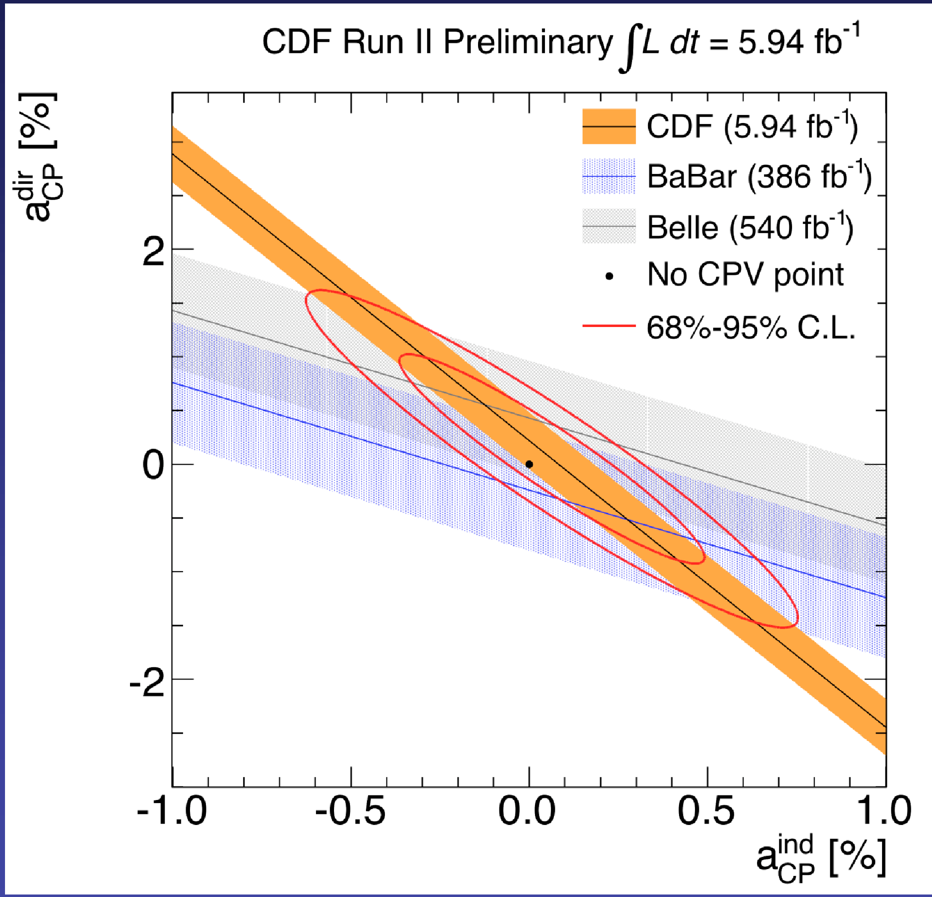
proper time distributions

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

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



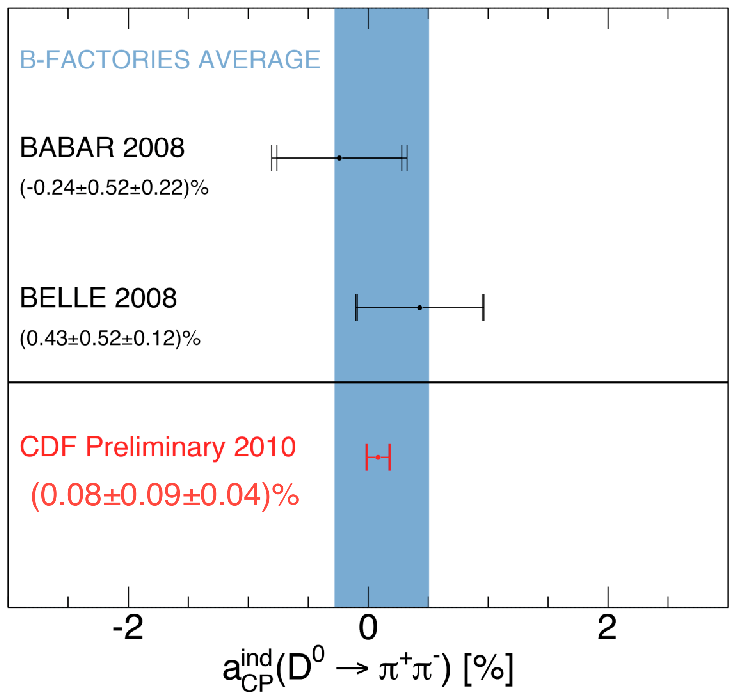
combining CDF and B-factories



contours drawn assuming gaussian errors

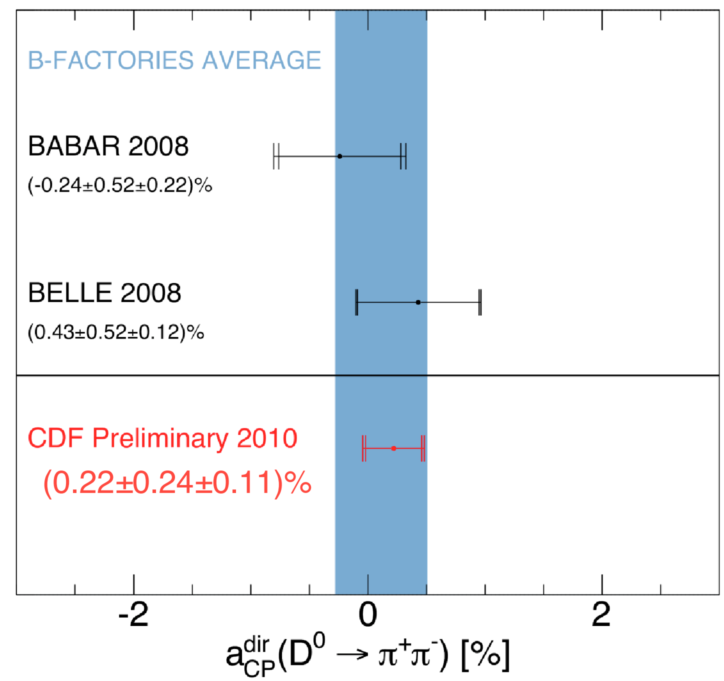
CDF vs. B-factories

no direct CPV



Acp is from mixing only

no indirect CPV



no mixing

final remarks

• most precise Acp measurement ever in the Charm sector

• we have now enough precision to probe the Charm sector for new physics in a significant way

• this result shows that high precision measurements competitive or even superior to the B-factories are possible at the Tevatron

• still limited by statistics and will improve with integrated luminosity ($5.9\ fb^{-1} \rightarrow 10\ fb^{-1} \rightarrow 20\ fb^{-1}$?)

• this is the consequence of the combination of a number of unique features of the Tevatron and the CDF detector:

1. large Charm production rate
2. CP symmetric initial state
3. trigger on secondary vertices

future prospects

- more integrated luminosity
- add $D^0 \rightarrow K^+ K^-$

public note:

http://www-cdf.fnal.gov/physics/new/bottom/100916.blessed-Dpipi6.0/

THE END