FERRARA 11 – 13 APRILE
IFAE
INCONTRI DI FISICA DELLE ALTE ENERGIE
2012

CP Violation in Charm at CDF

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SEZIONE DI PISA

CP Violation in neutral charmed decays

- Charm transitions involve first two generations of quarks, thus CPV in SM is expected to be very small... but how much?

$$
\begin{array}{c} \\ V_{\text{CKM}} = \end{array}
\begin{array}{c}
\begin{array}{ccc} d & s & b \end{array} \\
\begin{pmatrix}
1-\lambda^2/2 & \lambda & A\lambda^3(\rho - i\eta) \\
-\lambda & 1-\lambda^2/2 & A\lambda^2 \\
A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1
\end{pmatrix}
\end{array}
\begin{array}{c} \\ u \\ c \\ t \end{array}
$$

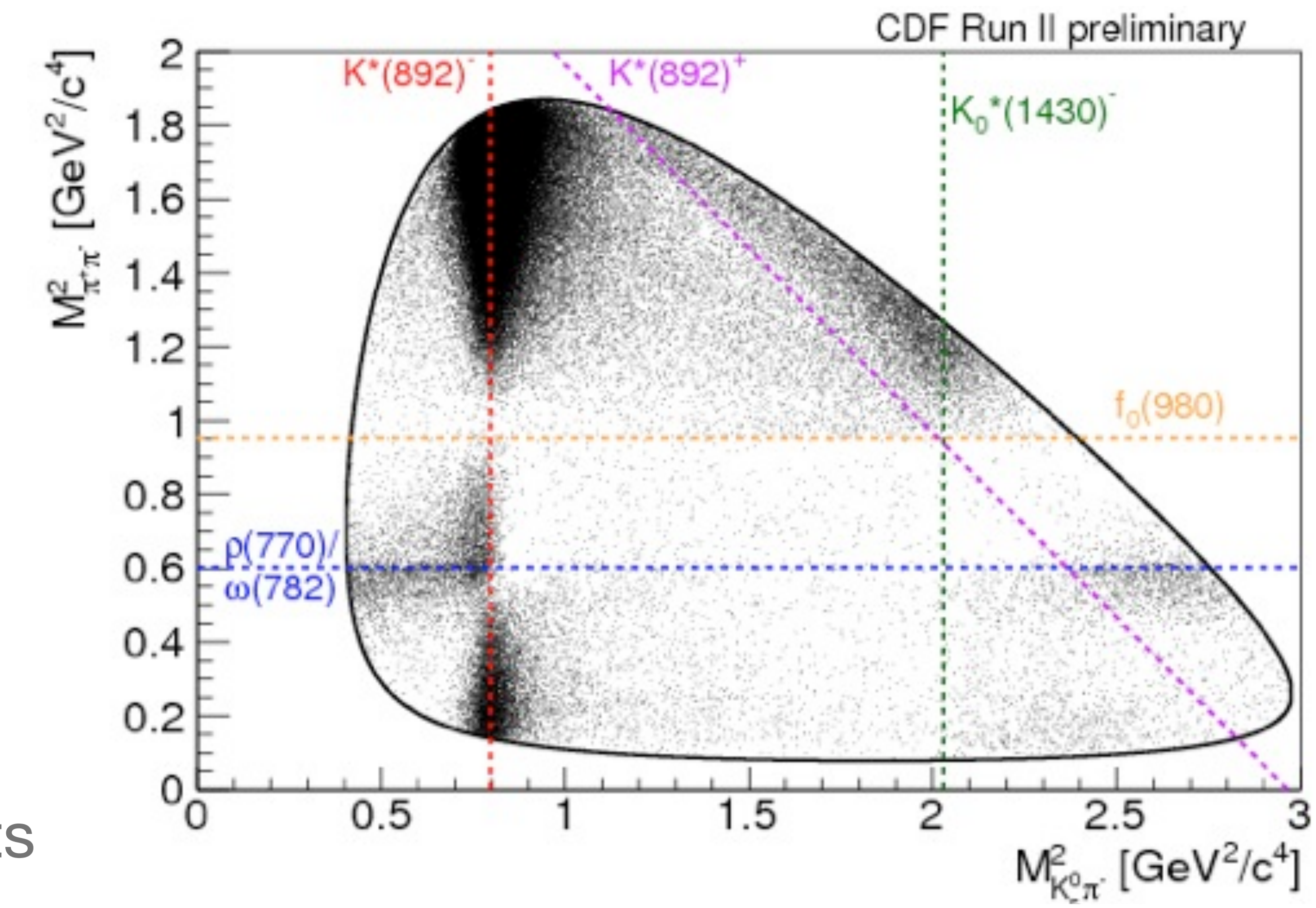
  - For long time there has been consensus that direct CPV in charm at 1% level would be a striking signal of New Physics...
  - ...now, after LHCb evidence for CPV in charm, there is no consensus anymore
- Thus, it is important to provide as much experimental information as possible

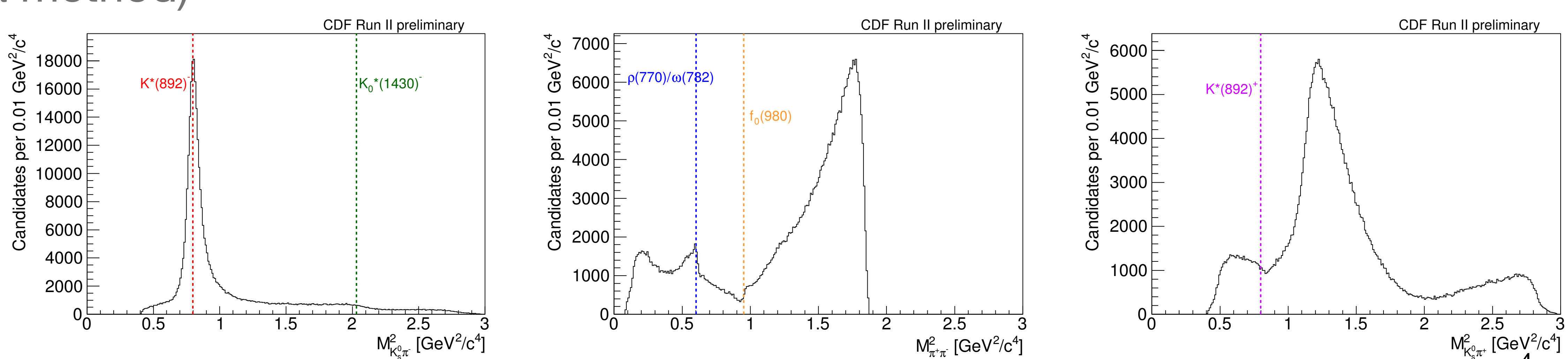
New results from CDF

- Time-integrated search for CP violation in $D^0 \rightarrow K_S \pi^+ \pi^-$
- $\Delta A_{CP}(D^0 \rightarrow h^+ h^-)$ with full Run II data sample

CP Violation in the $D^0 \to K_S\pi^+\pi^-$ Decay

- In 6/fb of two-track trigger data we search for time-integrated CPV in the resonant substructures of the 3-body $D^0 \to K_S\pi^+\pi^-$ decay
- First full Dalitz analysis at hadron collider, but also
- Model-independent bin-by-bin comparison of the D^0 and $\bar{D}^0$ Dalitz plots (Miranda method)





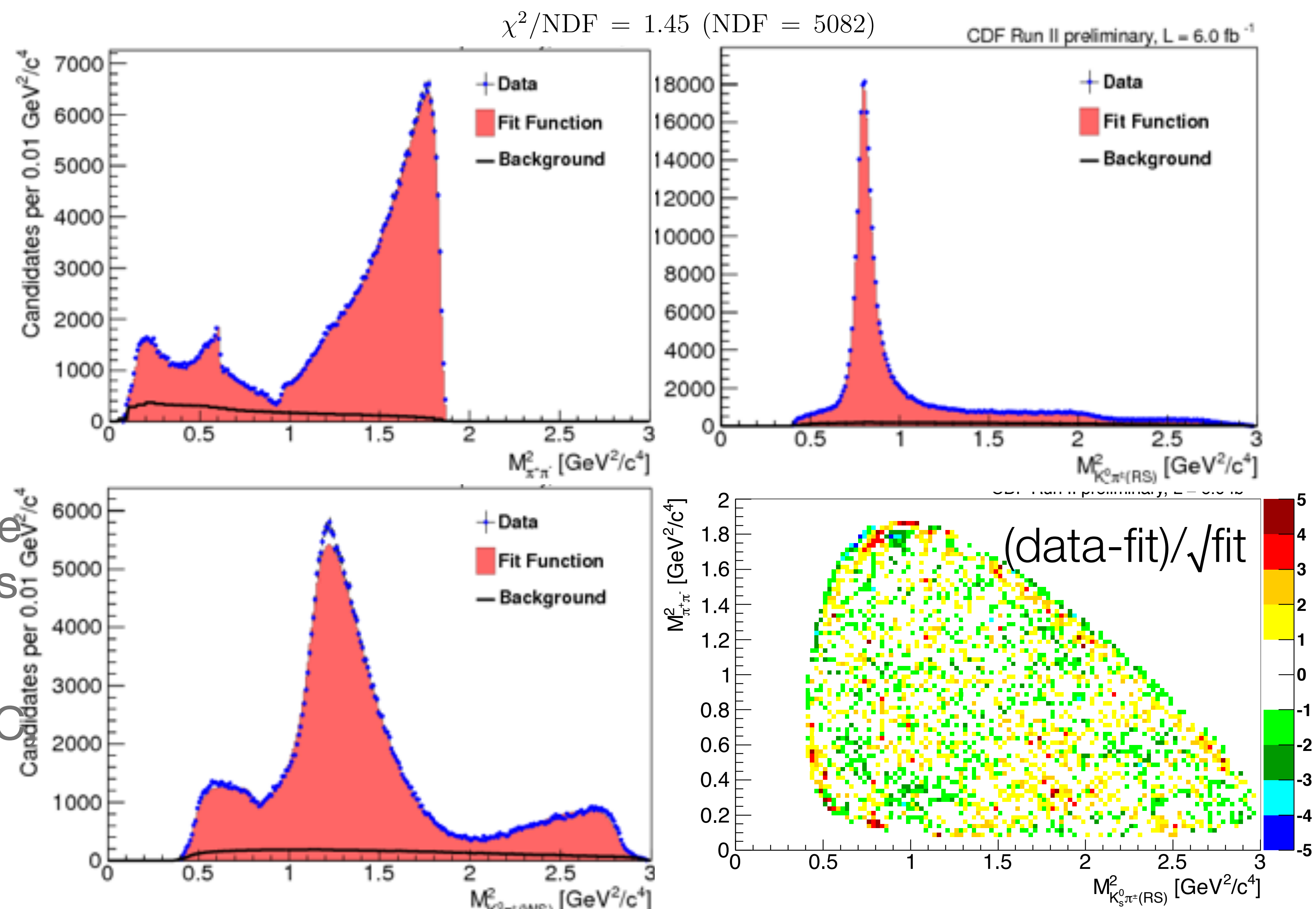
Dalitz fit description

- NN selection isolates ~350k $D^* \to D^0(\to K_S\pi^+\pi^-)\pi^+$ + c.c. decays

$$\mathcal{L} = \text{Efficiency} \cdot |\mathcal{M}|^2 + \text{Background}$$

$$\mathcal{M} = a_0 \cdot e^{i\delta_0} + \sum_j a_j \cdot e^{i\delta_j} \cdot \mathcal{A}_j$$

- Separate/combined binned fit to D^0 and D^0 Dalitz plots to search for CPV
  - Each asymmetry self normalized: no need to worry about overall spurious effects
  - Isobar model to describe the resonance structures
  - Efficiency taken from MC, background from mass sidebands



Results

- Table lists asymmetries between sub-resonances fit fractions
  - Big improvement wrt previous results from CLEO (PRD 70, 091101 (2004))...
  - ...but still no hints for any CP violating effect
- The measured value for the overall integrated CP asymmetry is

CDF Run II preliminary

Resonance	$\mathcal{A}_{\rm FF}$ (CDF) [%]	$\mathcal{A}_{\rm FF}$ (CLEO) [%]
$K^*(892)^-$	$0.36 \pm 0.33 \pm 0.40$	$2.5 \pm 1.9\,^{+1.5}_{-0.7}\,^{+2.9}_{-0.3}$
$K_0^*(1430)^-$	$4.0 \pm 2.4 \pm 3.8$	$-0.2 \pm 11.3\,^{+8.6}_{-4.9}\,^{+1.9}_{-1.0}$
$K_2^*(1430)^-$	$2.9 \pm 4.0 \pm 4.1$	$-7 \pm 25\,^{+8}_{-26}\,^{+10}_{-1}$
$K^*(1410)^-$	$-2.3 \pm 5.7 \pm 6.4$	$\cdots$
$\rho(770)$	$-0.05 \pm 0.50 \pm 0.08$	$3.1 \pm 3.8\,^{+2.7}_{-1.8}\,^{+0.4}_{-1.2}$
$\omega(782)$	$-12.6 \pm 6.0 \pm 2.6$	$-26 \pm 24\,^{+22}_{-2}\,^{+2}_{-4}$
$f_0(980)$	$-0.4 \pm 2.2 \pm 1.6$	$-4.7 \pm 11.0\,^{+24.9}_{-7.4}\,^{+0.3}_{-4.8}$
$f_2(1270)$	$-4.0 \pm 3.4 \pm 3.0$	$34 \pm 51\,^{+25}_{-71}\,^{+21}_{-34}$
$f_0(1370)$	$-0.5 \pm 4.6 \pm 7.7$	$18 \pm 10\,^{+2}_{-21}\,^{+13}_{-6}$
$\rho(1450)$	$-4.1 \pm 5.2 \pm 8.1$	$\cdots$
$f_0(600)$	$-2.7 \pm 2.7 \pm 3.6$	$\cdots$
σ_2	$-6.8 \pm 7.6 \pm 3.8$	$\cdots$
$K^*(892)^+$	$1.0 \pm 5.7 \pm 2.1$	$-21 \pm 42\,^{+17}_{-28}\,^{+22}_{-4}$
$K_0^*(1430)^+$	$12 \pm 11 \pm 10$	$\cdots$
$K_2^*(1430)^+$	$-10 \pm 14 \pm 29$	$\cdots$
$K^*(1680)^-$	$\cdots$	$-36 \pm 19\,^{+9}_{-35}\,^{+5}_{-1}$

$A_{CP}(D^0 \to K_S \pi^+\pi^-) = (-0.05 \pm 0.57\ (\text{stat.}) \pm 0.54\ (\text{syst.}))\%$

More information in CDF Public Note 10654

CP Violation in $D^0 \rightarrow h^+h^-$ Decays

- Last year, using 5.9/fb of two-track trigger data, CDF produced the world's most precise measurement of CP asymmetries in 2-body D^0 decays:

$$A_{CP}(D^0 \rightarrow K^+K^-) = (-0.24 \pm 0.22 \pm 0.09)\%$$

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

$$\Delta A_{CP} = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-0.46 \pm 0.31 \pm 0.12)\%$$

(PRD 85, 012009 (2012))

- In late November LHCb reported a more precise measurement of ΔA_{CP}, showing first evidence for CP violation in charm decays measuring:

$$\Delta A_{CP}(\text{LHCb}) = (-0.82 \pm 0.21 \pm 0.11)\%$$

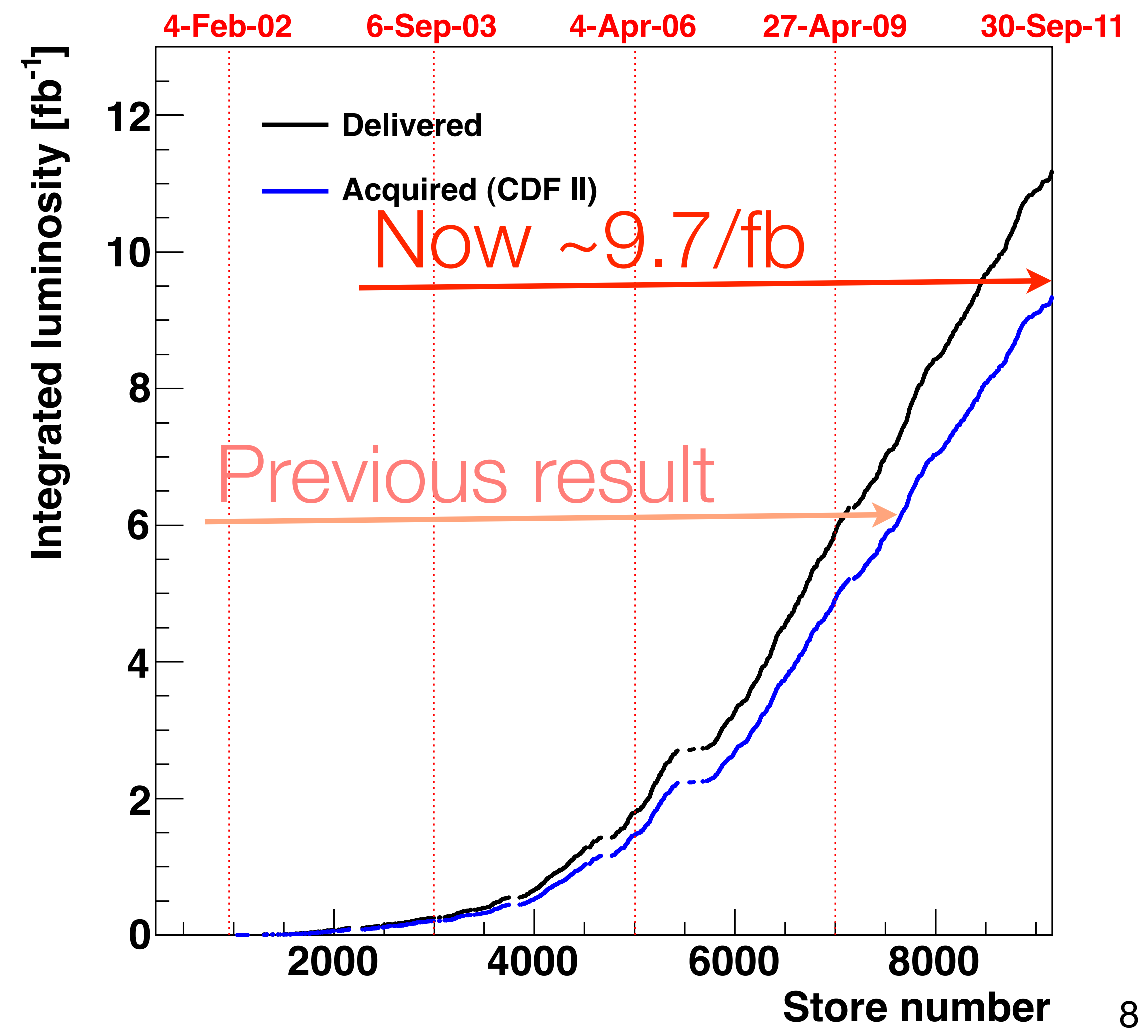
(PRL 108, 111602 (2012))

See next
talk by A. Carbone

- CDF difference compatible with LHCb but also with zero, insufficient resolution for a conclusive statement

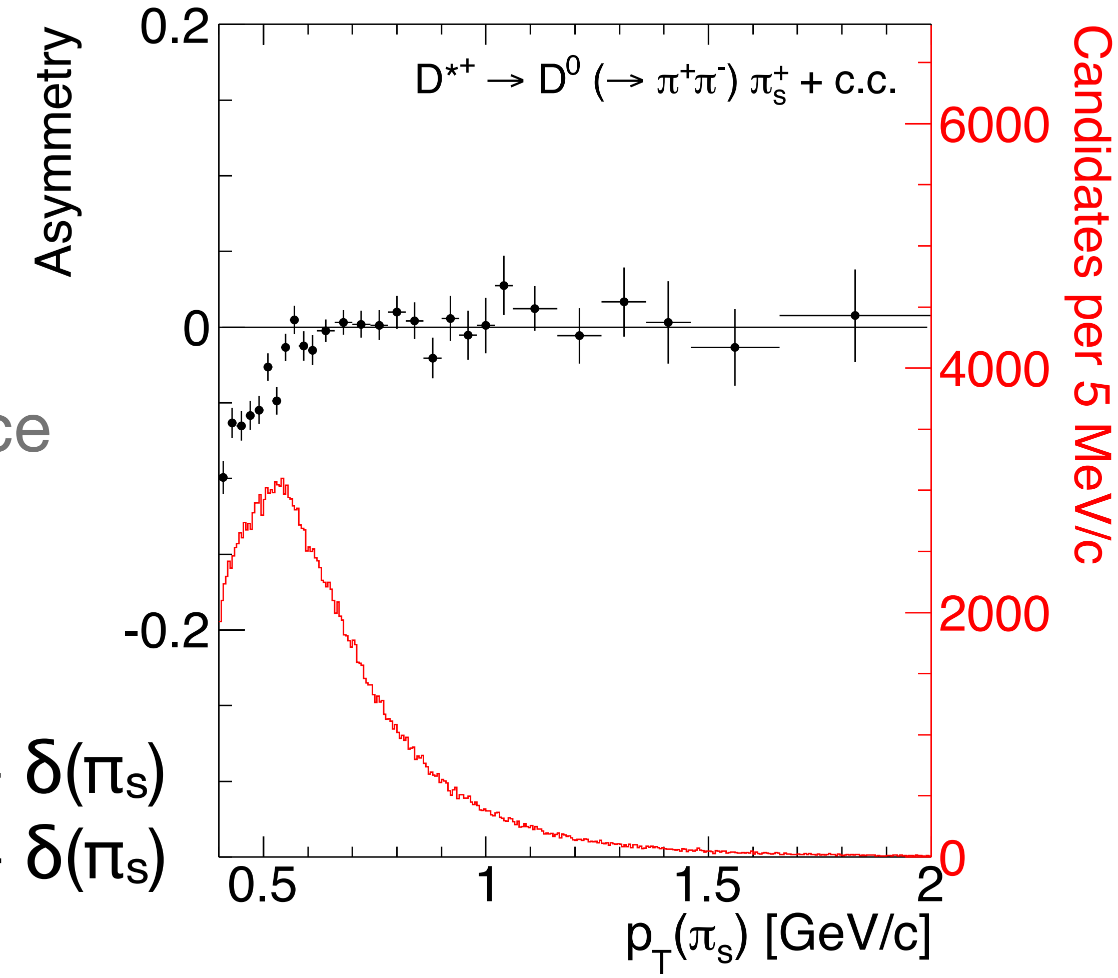
$\Delta A_{CP}(D^0 \rightarrow h^+h^-)$ with full Run II dataset

- Measurement updated with full Run II data sample
- Analysis strategy unchanged but new selection has been designed to specifically improve the resolution on ΔA_{CP}
    - About twice more signal events used in the new measurement
    - Expect resolution competitive with LHCb



Analysis overview

- D^0 flavor determined through the $D^* \rightarrow D^0 \pi_s$ decay, but soft pion induces O(1%) artificial asymmetries



- Cancel detector effects through the difference between raw asymmetries, A, of the two samples:

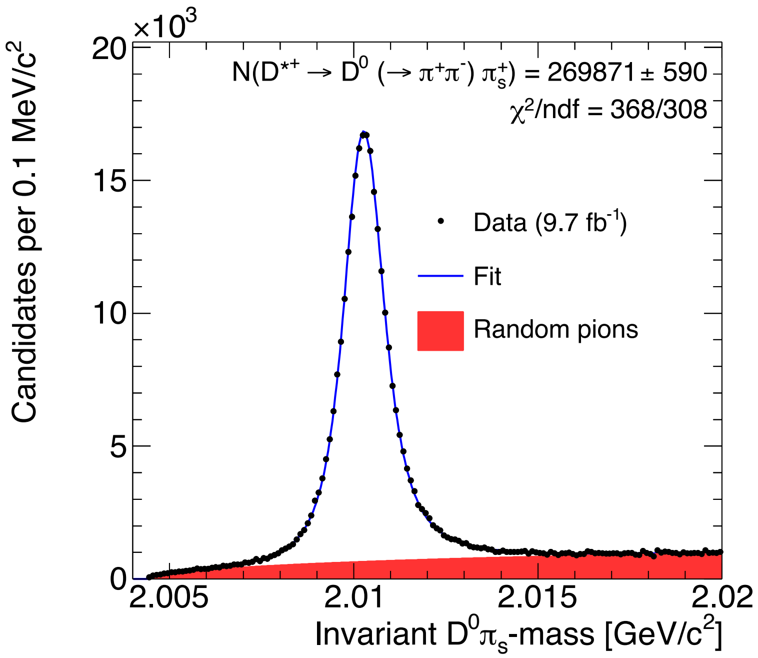
D^*-tagged $D^0 \rightarrow K^+K^-$ $\quad A(KK^*) = A_{CP}(K^+K^-) + \delta(\pi_s)$

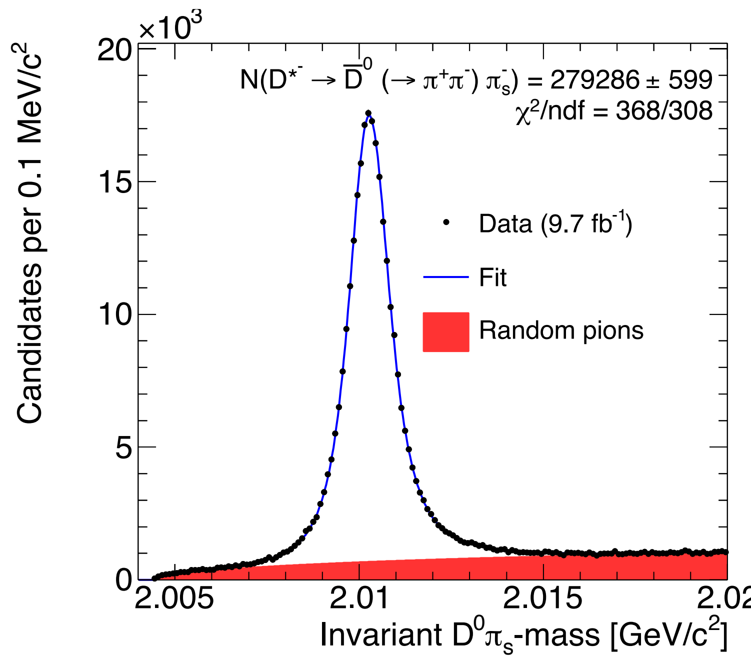
D^*-tagged $D^0 \rightarrow \pi^+\pi^-$ $\quad A(\pi\pi^*) = A_{CP}(\pi^+\pi^-) + \delta(\pi_s)$

$$\Delta A_{CP} = A(KK^*) - A(\pi\pi^*) = A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)$$

- Detector asymmetries are kinematic dependent, cancellation works if π_s distributions are the same between KK and ππ, make them equal by reweighting

Charm Decay Factory



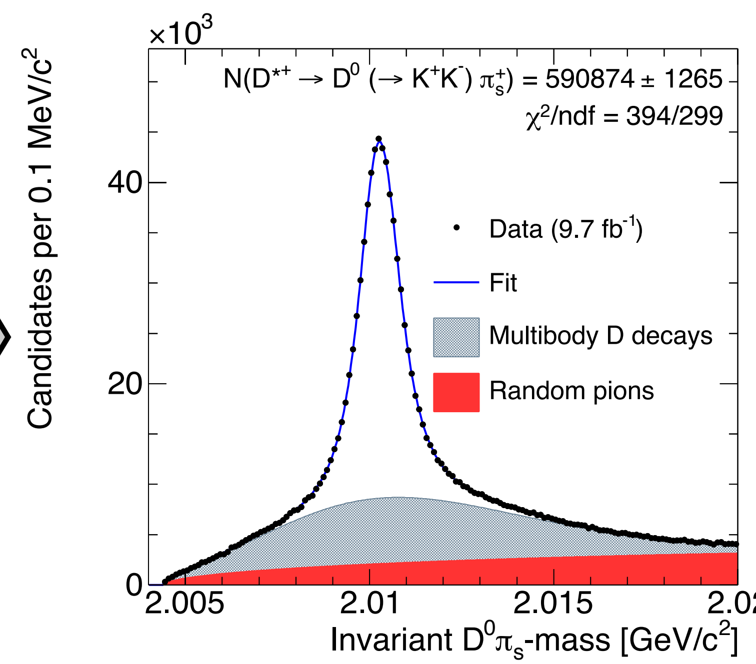


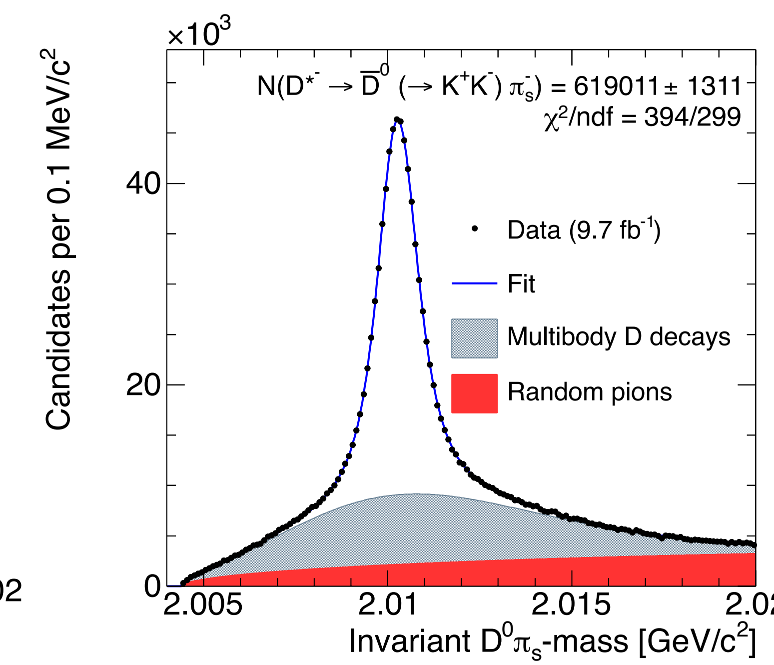
~550K D*-tagged $D^0 \rightarrow \pi^+\pi^-$

Raw $A(\pi^+\pi^-) = (-1.71 \pm 0.15)\%$

~1.21M D*-tagged $D^0 \rightarrow K^+K^-$

Raw $A(K^+K^-) = (-2.33 \pm 0.14)\%$





Final result

CDF Run II preliminary

$\Delta A_{CP} = [-0.62 \pm 0.21\ (\text{stat}) \pm 0.10\ (\text{syst})]\%$

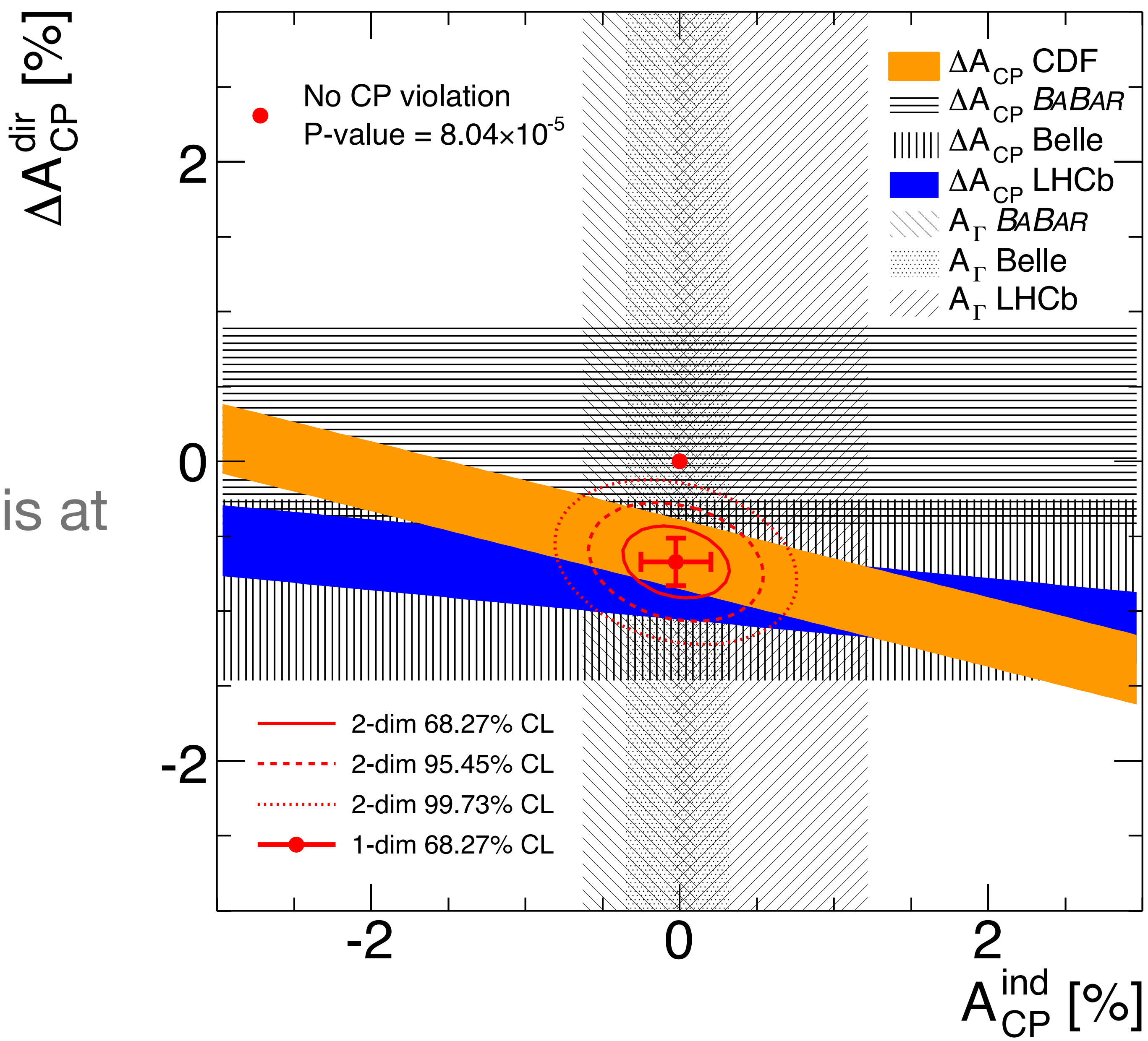
More information in [CDF Public Note 10784]

- New CDF result confirms LHCb result: same resolution, <1σ difference in central value

  $\Delta A_{CP}(\text{LHCb}) = [-0.82 \pm 0.21 \pm 0.11]\%$

- When combining à la HFAG with other available measurements, no CPV point is at ~3.8σ and

$$\Delta A_{CP}^{dir} = (-0.67 \pm 0.16)\%$$
$$A_{CP}^{ind} = (-0.02 \pm 0.22)\%$$



Conclusions

- CPV in charm became lately a very hot topic
- As shown today, CDF is positioned at the frontline of this effort
  - Best measurement of individual CPV asymmetries in $D^0 \rightarrow h^+h^-$ and $D^0 \rightarrow K_S\pi^+\pi^-$
  - Best measurement of ΔA_{CP}, which strongly supports evidence for CPV in charm previously seen by LHCb

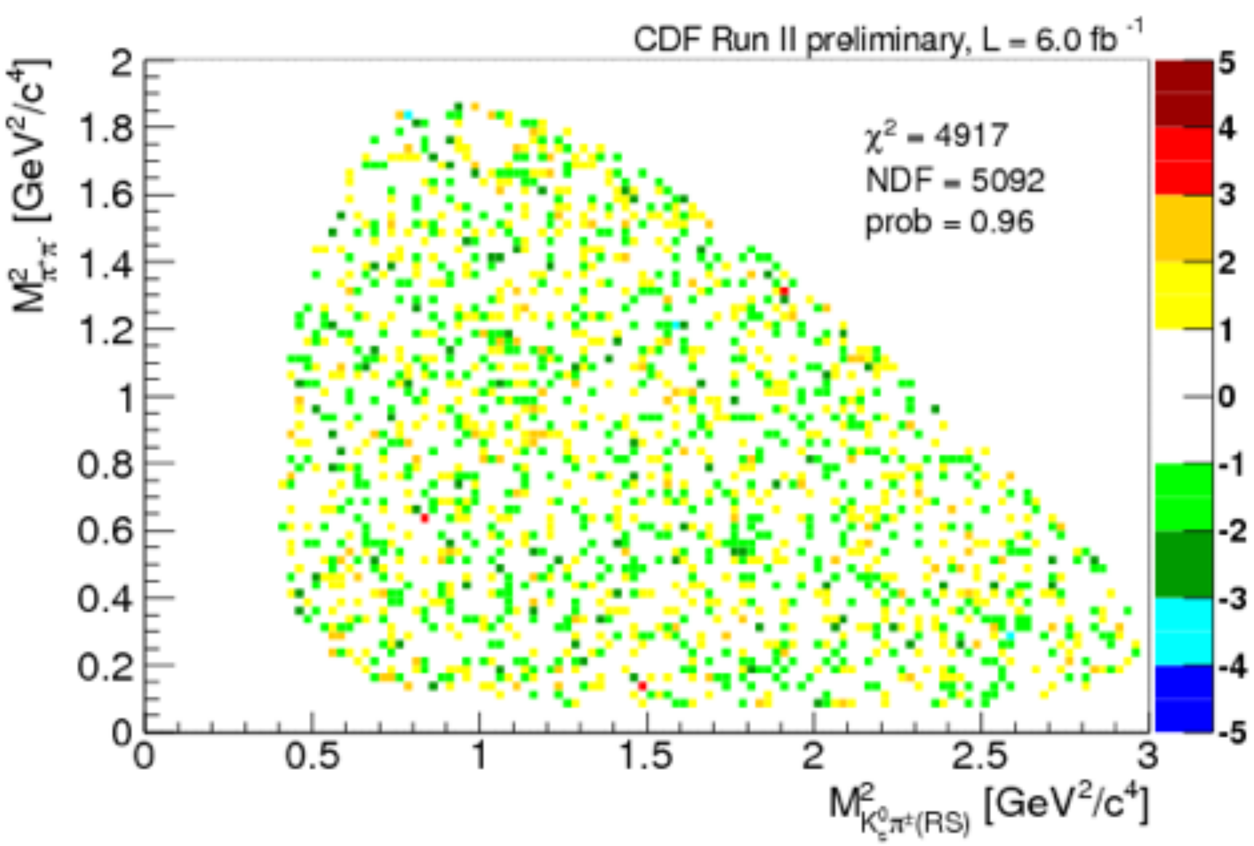
Backup Slides

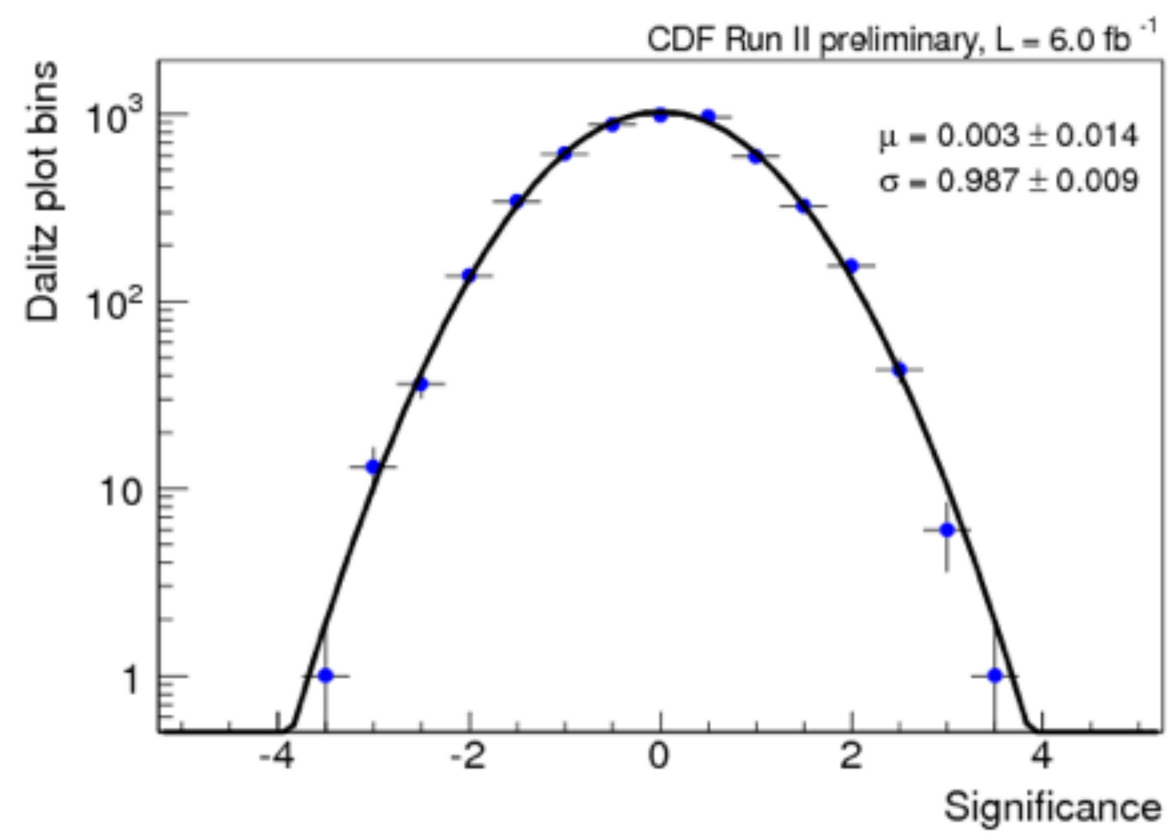
Miranda method

- Based on PRD 80, 096006 (2009)

- Consider the significance of per bin differences between D^0 and $\bar{D}^0$ Dalitz plots to look for large asymmetries:

$$\frac{N_{D^0} - N_{\bar{D}^0}}{\sqrt{N_{D^0} + N_{\bar{D}^0}}}$$





Single A_{CP} vs ΔA_{CP}

- To measure each single A_{CP} we need to compare raw asymmetries, A, of three event samples

D*-tagged $D^0 \to hh$	$A(hh^*) = A_{CP}(hh) + \delta(\pi_s)$
D*-tagged $D^0 \to K\pi$	$A(K\pi^*) = A_{CP}(K\pi) + \delta(\pi_s) + \delta(K\pi)$
Untagged $D^0 \to K\pi$	$A(K\pi) = A_{CP}(K\pi) + \delta(K\pi)$

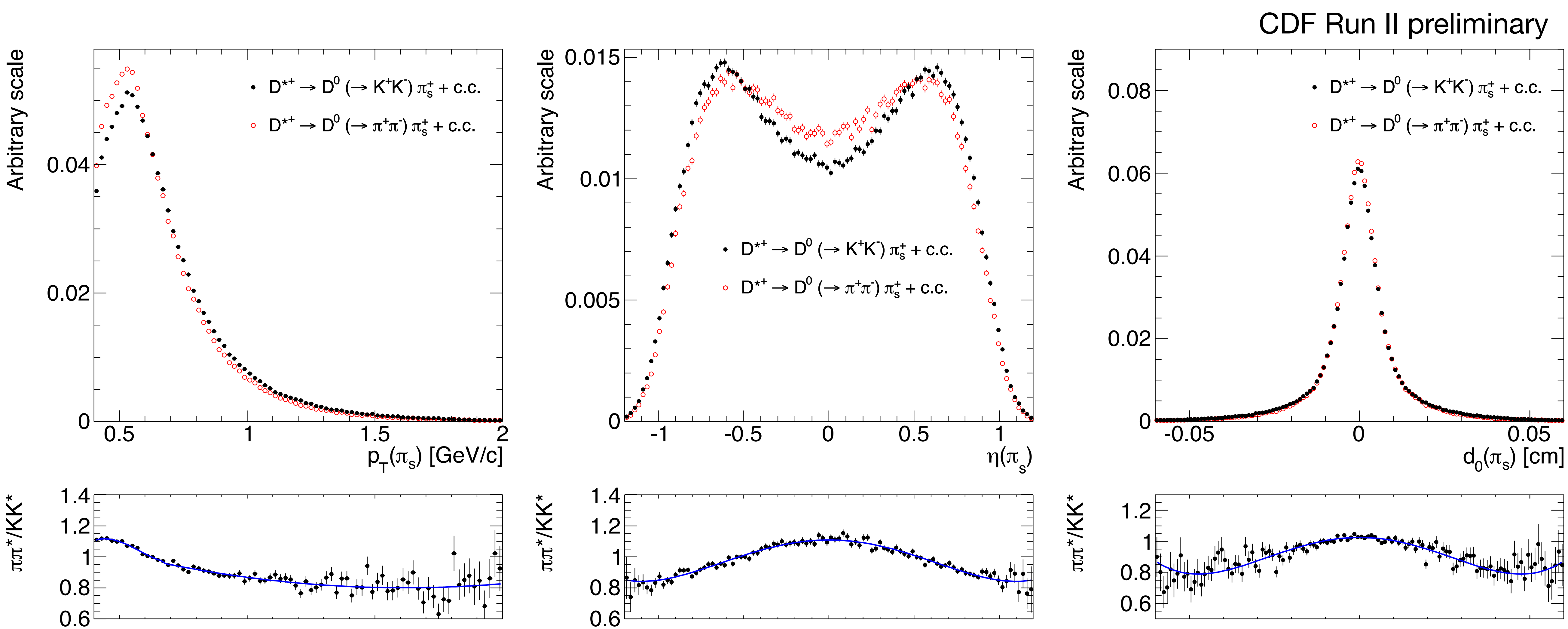
$$A_{CP}(hh) = A(hh^*) - A(K\pi^*) + A(K\pi)$$

- For ΔA_{CP} we need just two samples

$$\Delta A_{CP}(hh) = A(KK^*) - A(\pi\pi^*)$$

thus making the measurement easier and much more robust against second order effects which do not completely cancel in the linear combination of raw asymmetries

Soft pion’s kinematic reweight



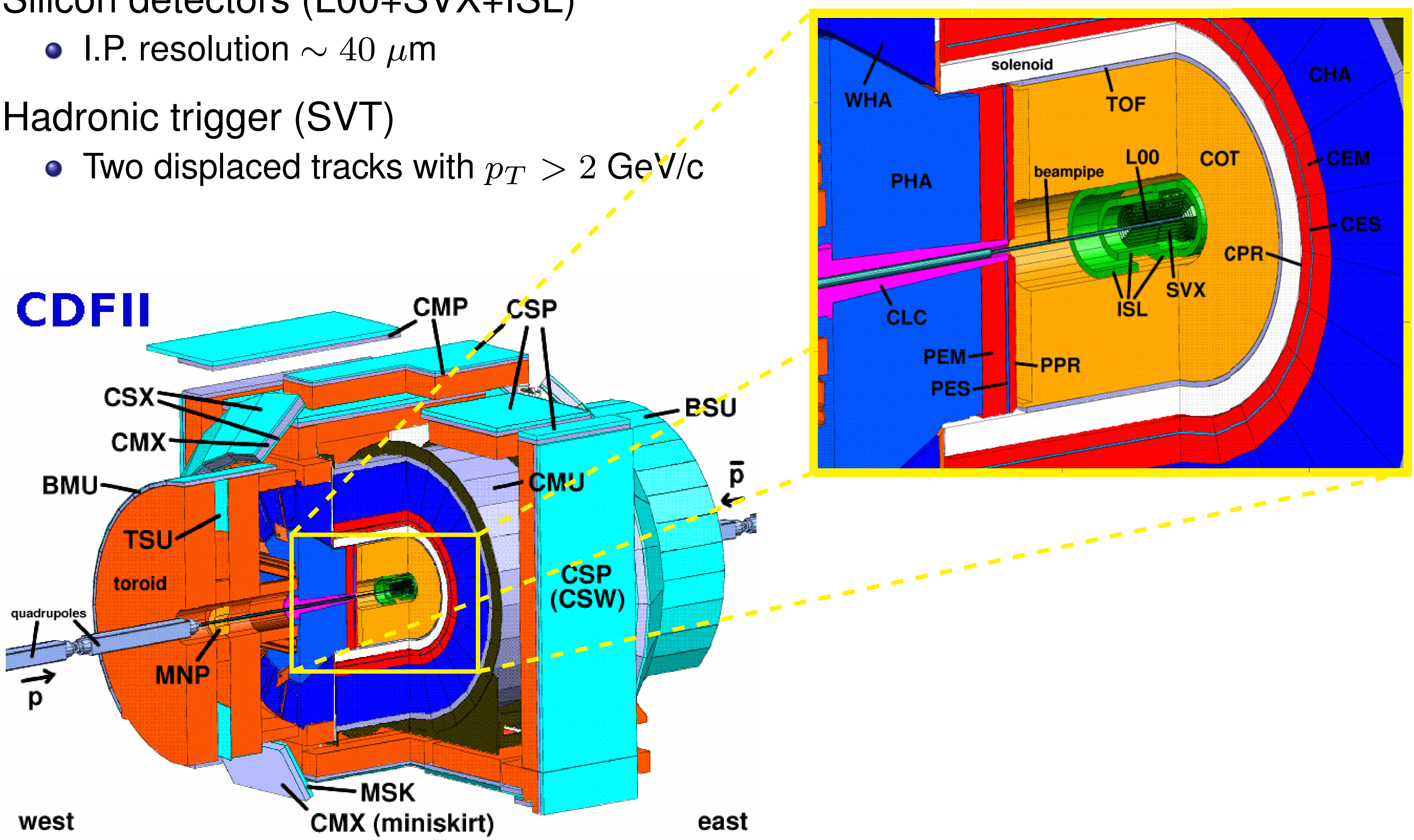
Systematics

Source	ΔA_{CP} [%]
Approximations in the suppression of detector-induced effects	0.009
Shapes assumed in fits	0.020
Charge-dependent mass distributions	0.100
Asymmetries from residual backgrounds	0.013
Total	0.103

- Intrinsically suppressed by data-driven method
- Major offenders: effects that impact differently $D^0/\bar{D}^0$ and $K^+K^-/\pi^+\pi^-$ final states, e.g. charge-dependent differences in signal/background D^* mass shapes

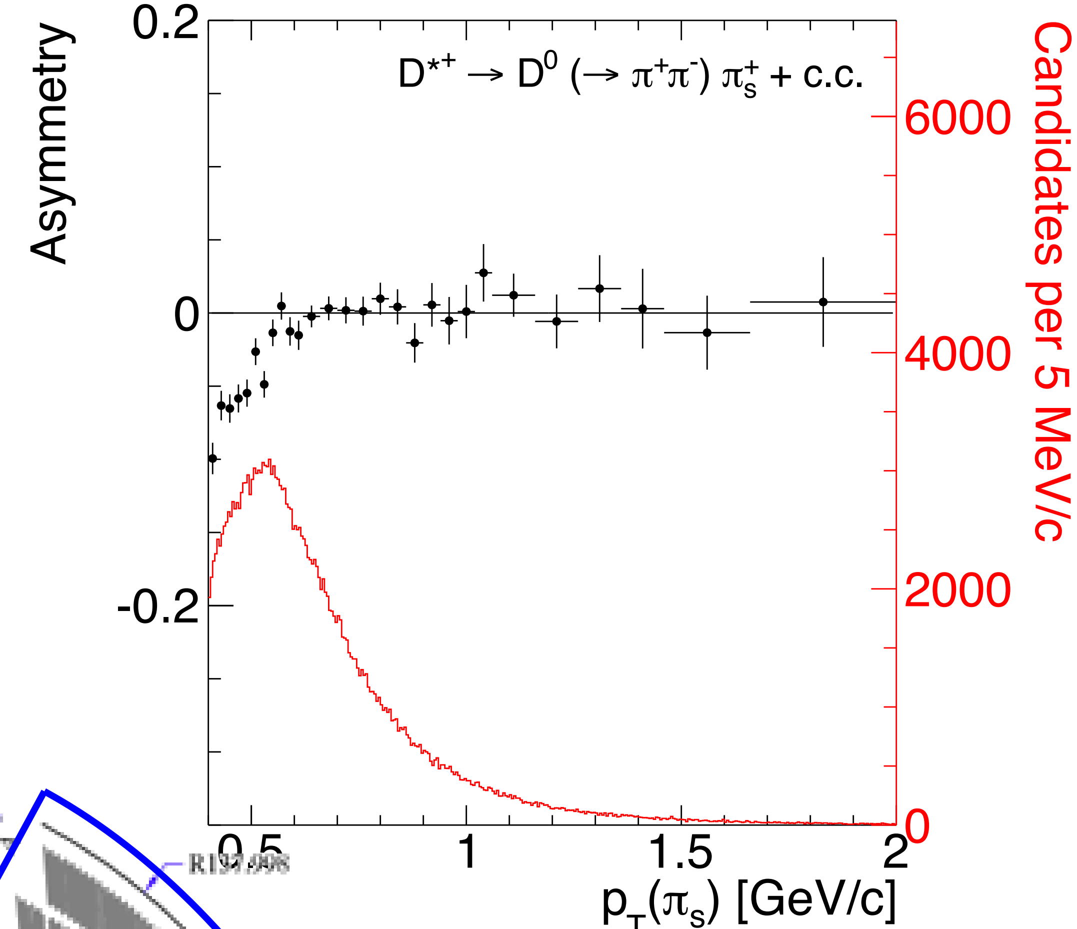
The CDF II detector

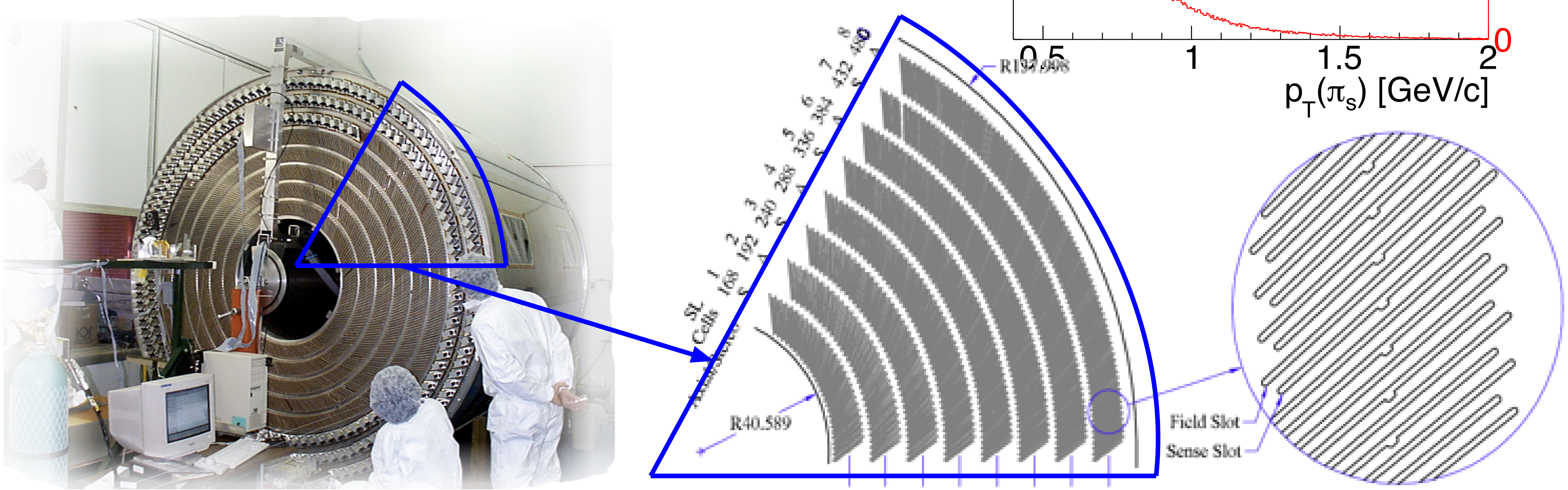
- Central drift chamber (COT) in magnetic field
  - $\sigma(p_T)/p_T^2 \sim 0.15\%$ (GeV/c)$^{-1}$ (excellent tracking/mass resolution)
- Silicon detectors (L00+SVX+ISL)
  - I.P. resolution $\sim 40\ \mu$m
- Hadronic trigger (SVT)
  - Two displaced tracks with $p_T > 2$ GeV/c



CDF is not charge-symmetric

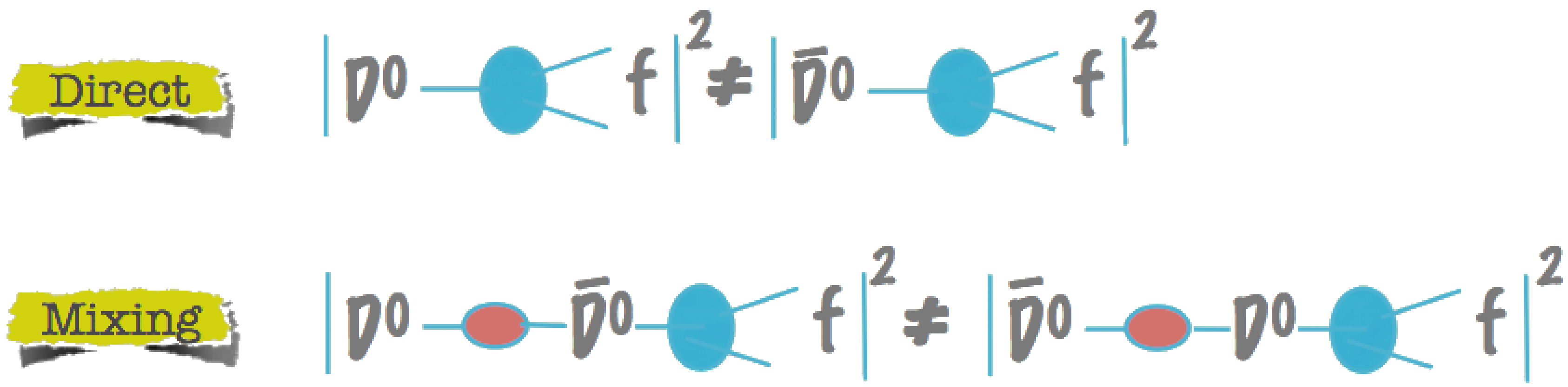
- ✓ Central drift chamber has cells tilt of 35° wrt radial direction
- ✓ Positive and negative particles hit cells at different angles
- ✓ Positive and negative pions have differences in absorption rates
- ✓ Asymmetry in reconstruction efficiency particularly large at low momentum





Direct and indirect CP violation

The time-integrated asymmetry receives contribution from both direct and indirect sources of CPV



Since flavour mixing parameters are small in the charm sector, at first order, the measured asymmetry is the linear combination of the two terms

$$A_{\text{CP}}(h^+h^-) \approx A_{\text{CP}}^{\text{dir}}(h^+h^-) + \frac{\langle t \rangle}{\tau} A_{\text{CP}}^{\text{ind}}$$

where $\langle t \rangle / \tau$ is the mean value of the D^0 meson proper decay-time in unit of lifetimes

Assuming no large weak phases in the decay, the indirect component is *universal*, then

$$\Delta A_{\text{CP}} = A_{\text{CP}}(K^+K^-) - A_{\text{CP}}(\pi^+\pi^-) = \Delta A_{\text{CP}}^{\text{dir}} + \frac{\Delta \langle t \rangle}{\tau} A_{\text{CP}}^{\text{ind}}.$$