CP violation in charm at CDF

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for the CDF Collaboration
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CPV in charm?

Experimental tests + theory advancements established CKM ansatz success (within 10%) in CPV. End of story?

Perhaps not, charm potential yet to be fully explored.

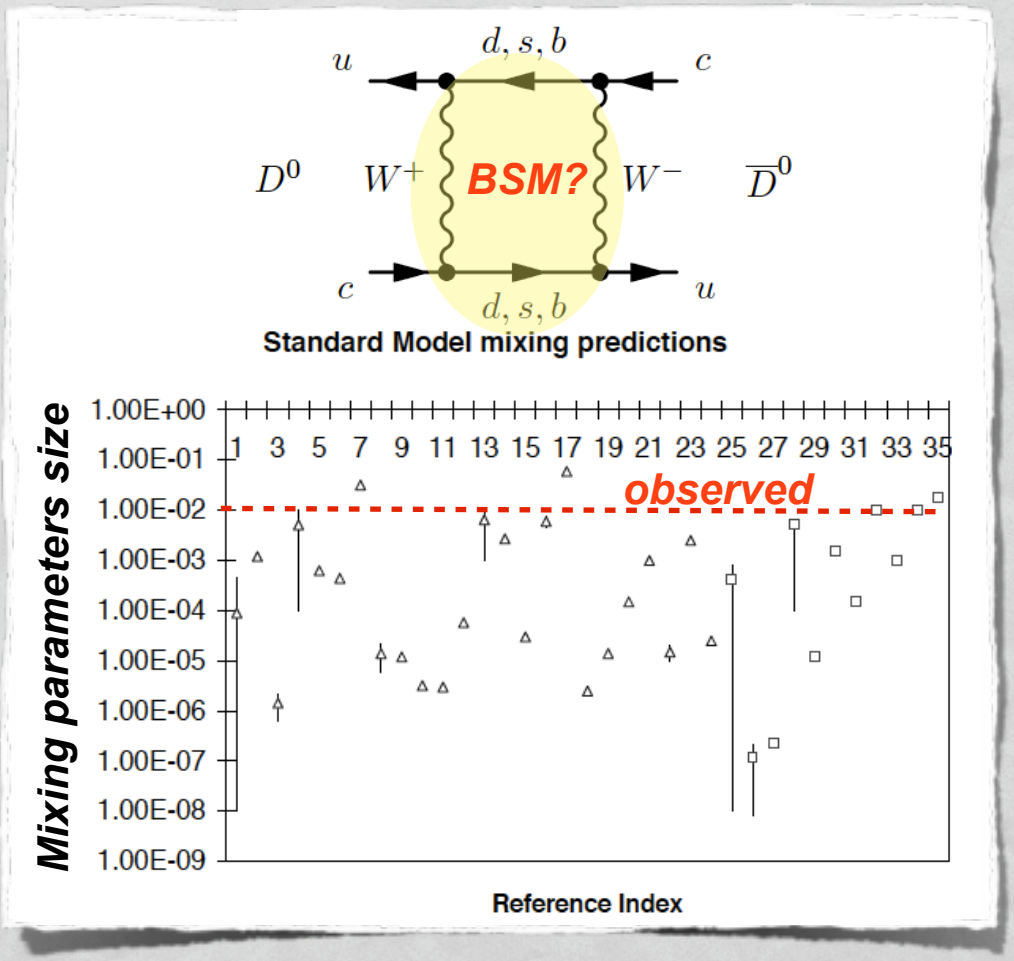
Complementary to K/B, probes BSM coupled to up quarks.
Only now reaching sensitivity to see SM/BSM effects

- Effects are small.

1st & 2nd families: CPV is suppressed. Large samples and control on systematics.

- Predictions are hard.

0 << M(charm) >≈ M(s, u, d).
Accuracy not better than order-of-magnitude



Difference of CP-violating asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$

CDF Public note 10784

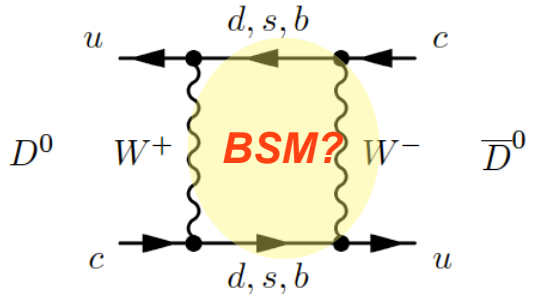
$D^0 \to \pi^+\pi^-$ and K^+K^-

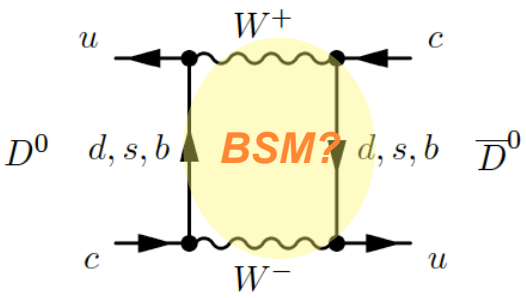
D^0-$\bar{D}^0$ oscillate, providing a "box" for BSM to show up.

Both D^0 and $\bar{D}^0$ decay to KK and ππ, with and without oscillation.

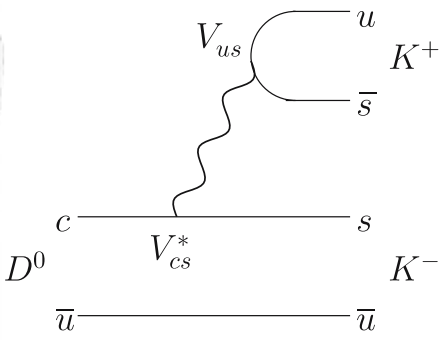
Tree + penguin make CPV observable and provide loop for BSM to show up

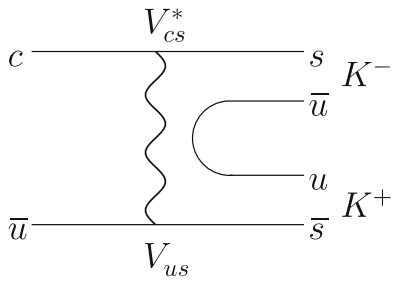
Oscillate

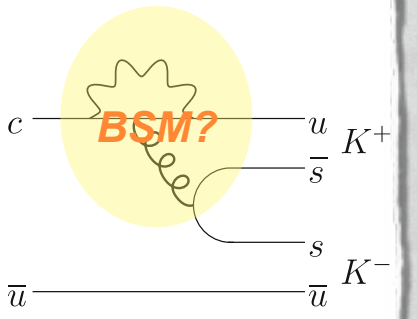




Decay







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

Predictions 1989-2011: nearly unanimous -- CPV close to 1% strongly signals BSM physics

Reality check

CDF early '11: world's most precise measurements using 5.9 fb^{-1}.

$A_{CP}(D\to KK) = (-0.24 \pm 0.22 \pm 0.09)\%$

$A_{CP}(D\to \pi\pi) = (+0.22 \pm 0.24 \pm 0.11)\%$

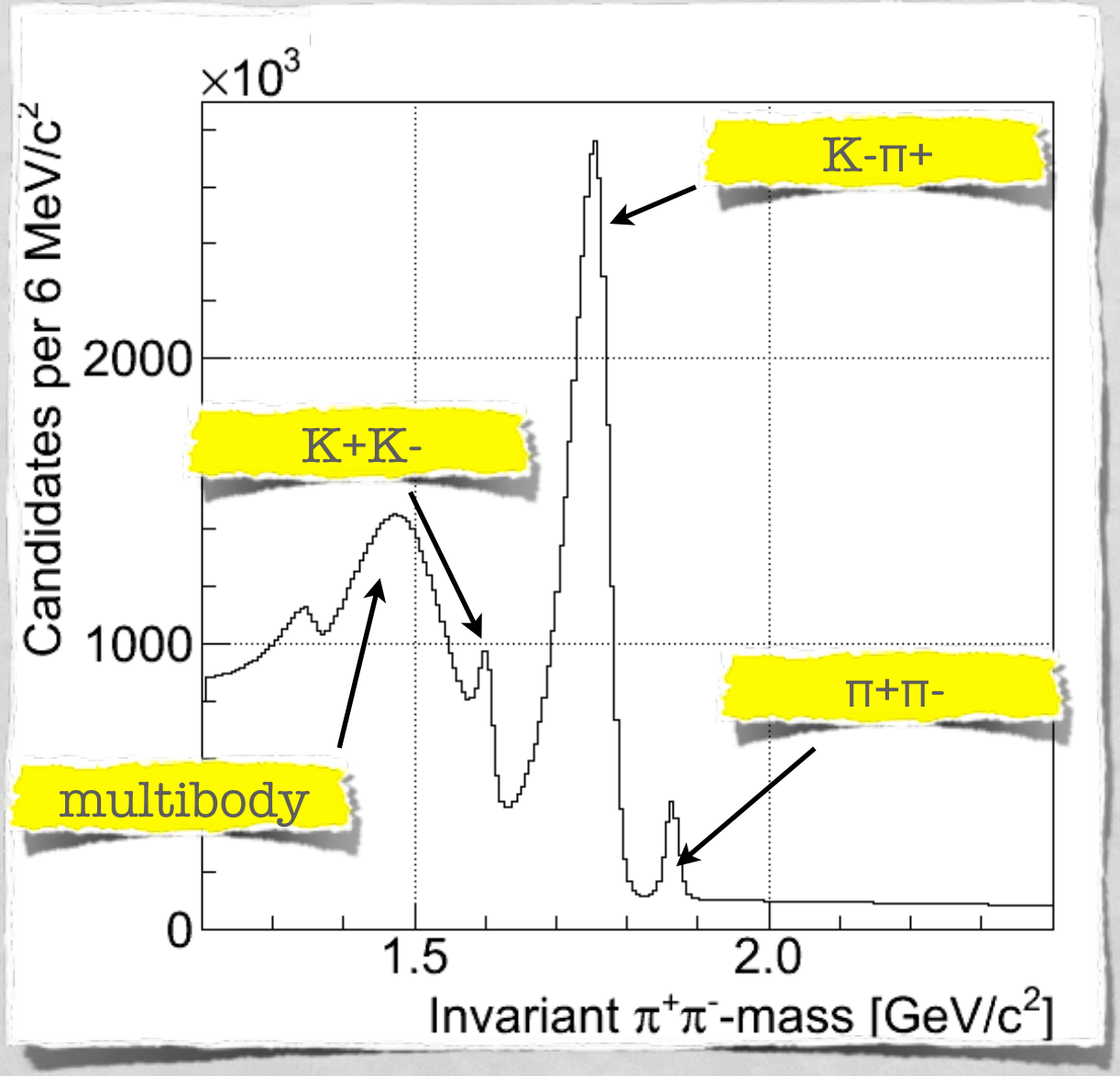
$\Delta A_{CP} = (-0.46 \pm 0.31 \pm 0.12)\%$ PRD 85, 012009 (2012)

LHCb, late '11: a more precise measurement of the difference, showing first evidence for CPV in charm with nearly 1% size

$\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$ PRL 108, 111602 (2012)

(LHCb only measures difference to cancel poorly-known production asymmetries)

Charm Decay Factory



Kπ- skewed and wider because reconstructed as π-π-.

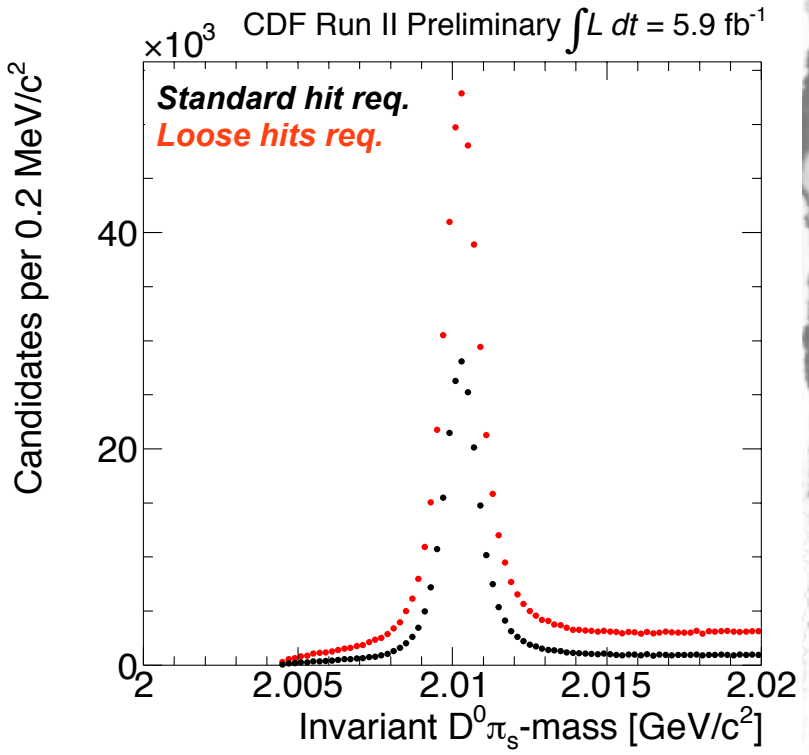
Squeezing the most out of data

Optimize '11 analysis toward asymmetry difference.

5.9 =>10 fb^{-1} yields only +20%. D triggers suppressed in late data

- +10% from using all displaced-track triggers.
- +80% from loosened track hits requirements.
- +12% from use of D from B decays.

Doubled signal yields. Costs some more background.



Expect resolution on final result competitive with LHCb

Measuring the asymmetry

Reconstruct KK/ππ decays in whole CDF data set (10 fb^{-1}).

Production is symmetric. Just need to count how many decays come from D^0 and how many from $\bar{D}^0$

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

Infer flavor by identifying D produced in D* decay.

$D^{*+} \to D^0\pi^+ \to [\,h^+h^-\,]\,\pi^+$

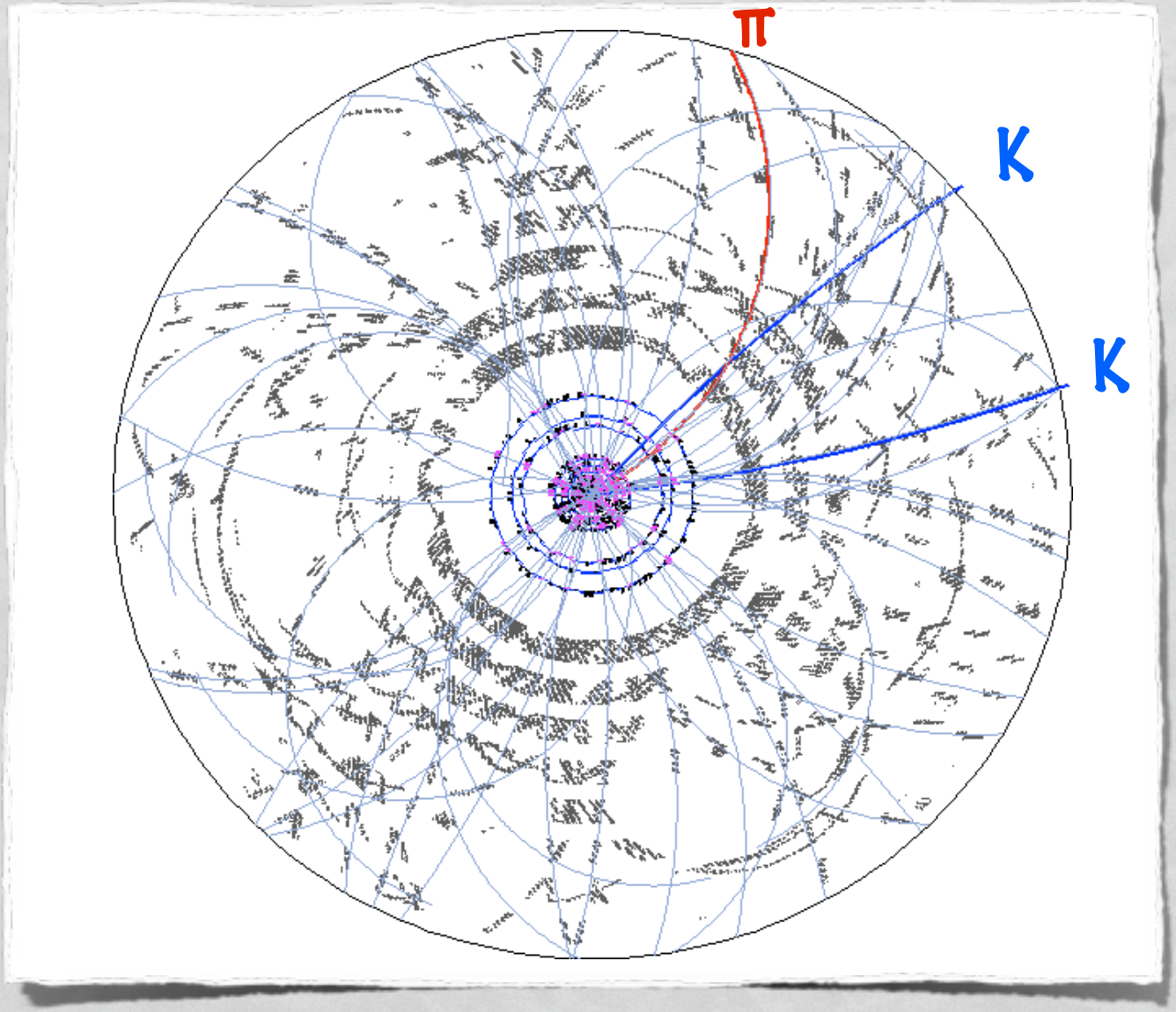
$D^{*-} \to \bar{D}^0\pi^- \to [\,h^+h^-\,]\,\pi^-$

Strong D* decay conserves charm flavor, correlated with the pion charge

Comes with a price.

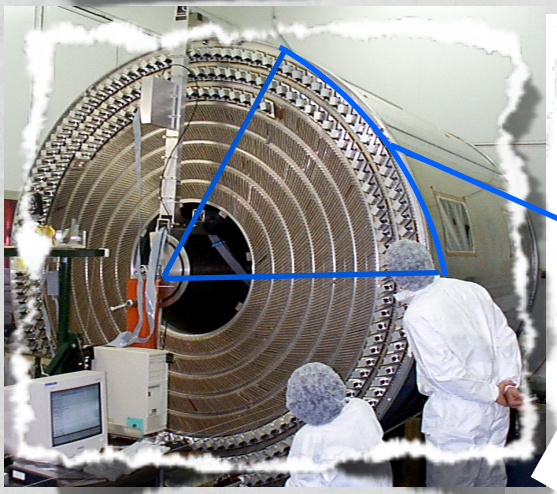
- ☐ Lose 85% of signal (but rejects lots of background)
- ☐ Injects a large (%) instrumental asymmetry.

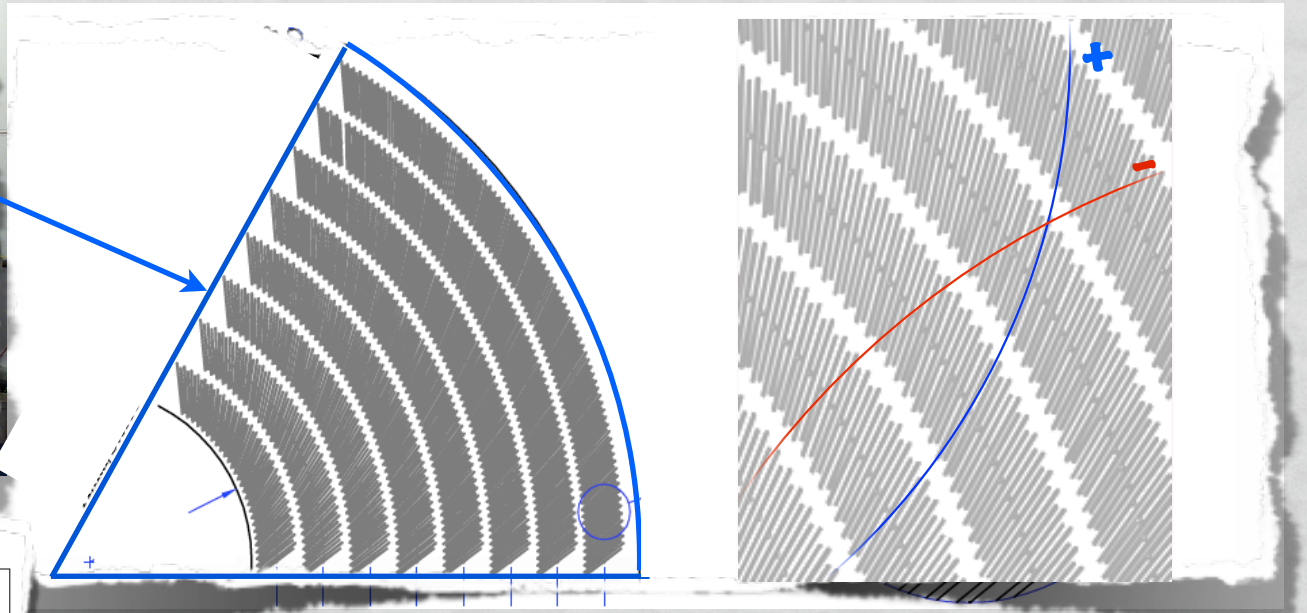
Hello, charming..

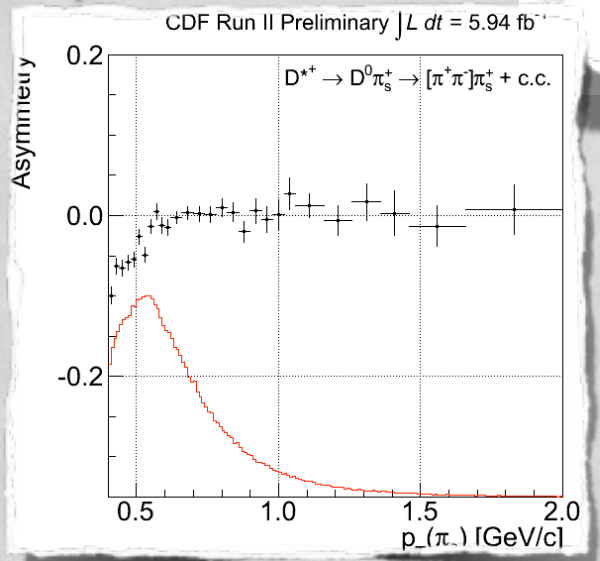


Instrumental charge-asymmetry

Requirement of D*-tag makes the final state charged







Drift chamber cells tilted by 35° wrt radius

Additional low-p charged pion induces instrumental asymmetries that spoil physics asymmetry -- use difference to cancel them

The difference

$D^{*+} \to D^0\pi^+ \to [K^+K^-]\pi_+$ $\quad$ $D^{*+} \to D^0\pi^+ \to [\pi^+\pi^-]\pi_+$

$D^{*-} \to \bar{D}^0\pi^- \to [K^+K^-]\pi_-$ $\quad$ $D^{*-} \to \bar{D}^0\pi^- \to [\pi^+\pi^-]\pi_-$

$A_{obs}(KK) = A_{CP}(KK) + \delta(\pi)$ $\quad$ $A_{obs}(\pi\pi) = A_{CP}(\pi\pi) + \delta(\pi)$

$$A_{obs}(KK) - A_{obs}(\pi\pi) = A_{CP}(KK) - A_{CP}(\pi\pi)$$

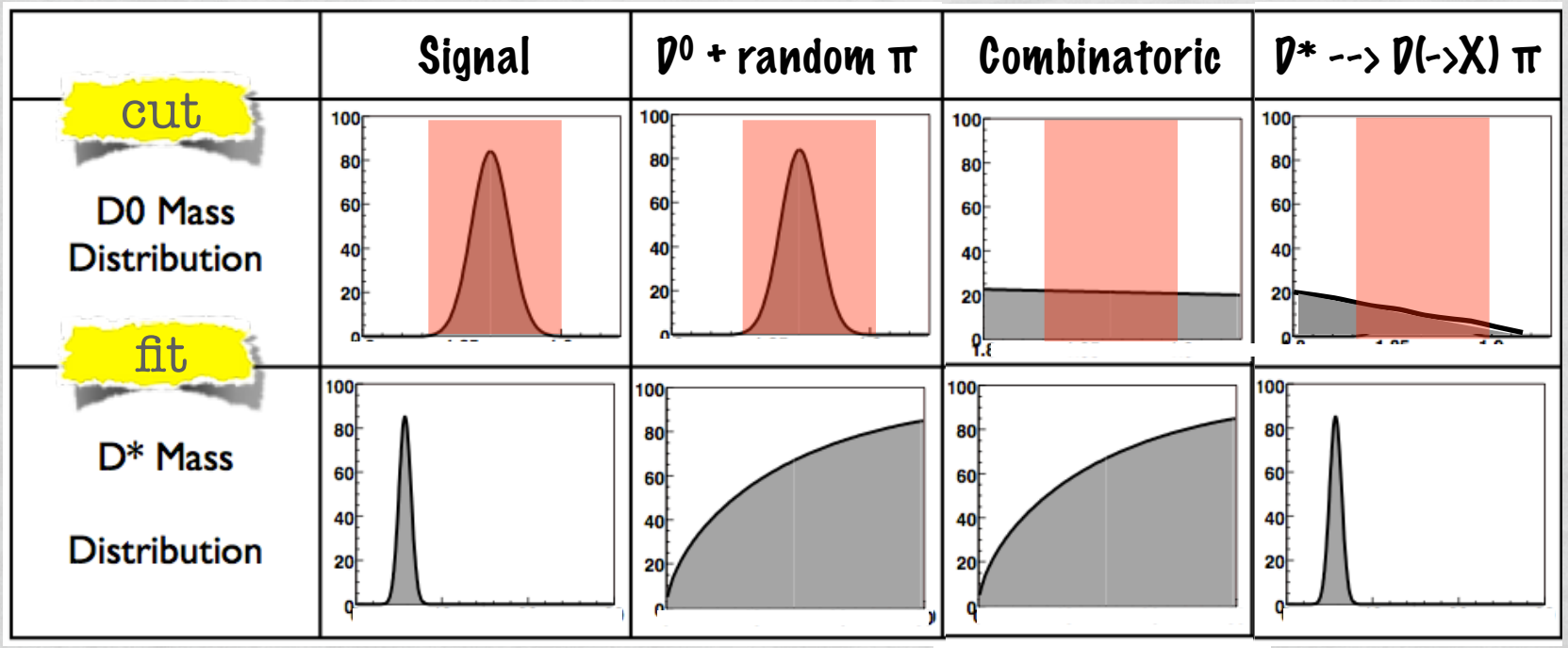
Reweighting kinematics of the two samples to make them equal.

Additional bonus: most SM and BSM models predict asymmetries of opposite sign in KK and ππ.

Difference likely to be more sensitive to CPV than the individual asymmetries.

Determining the asymmetries

Cut on D^0 mass, fit simultaneously D^{*+} and D^{*-} mass



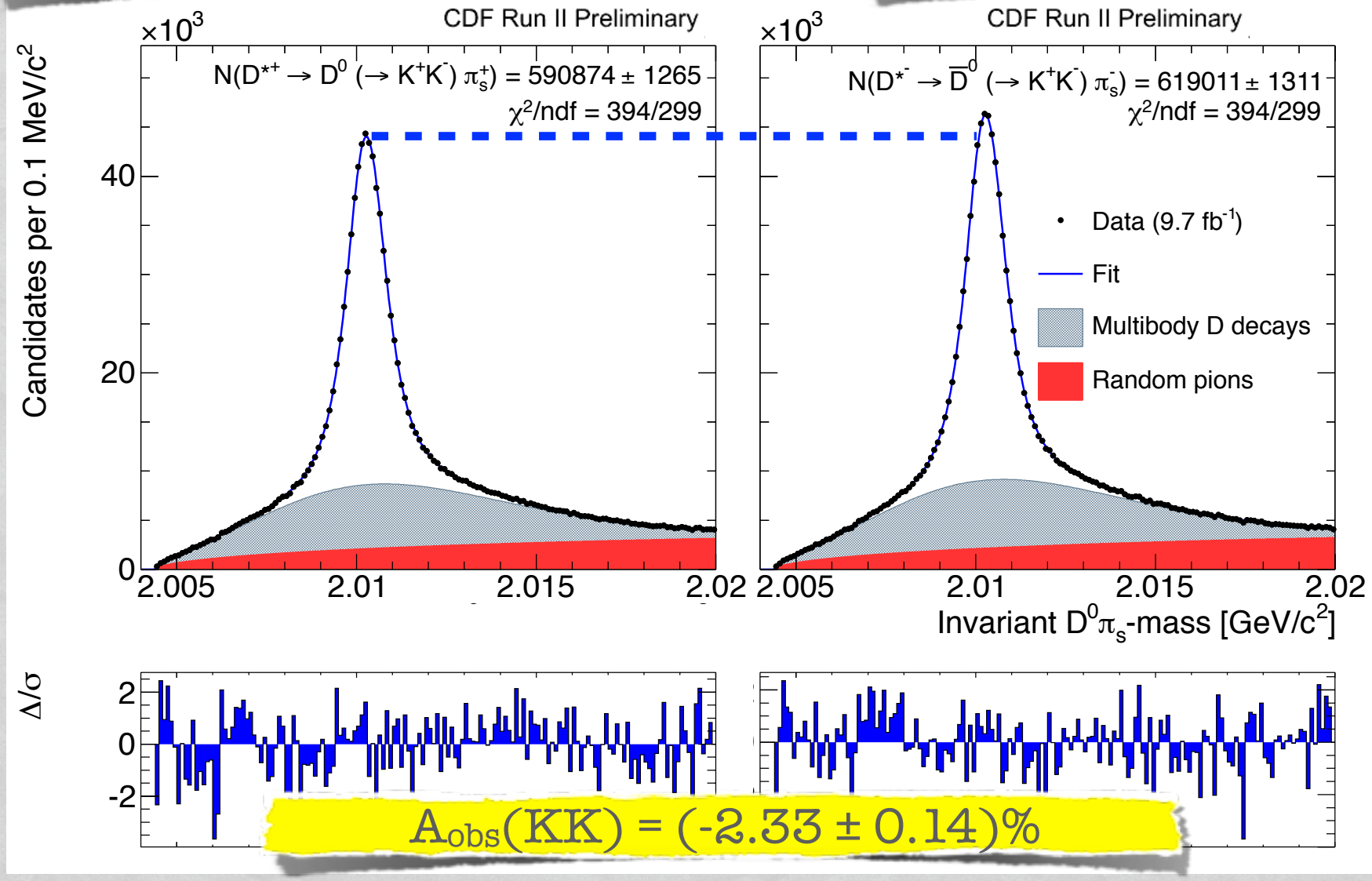
All backgrounds taken care by the fit of the D^* tail.

Remaining offender is D^*->(D->X) π, which peaks in D^*. Most dangerous for KK. Get the shape from inclusive charm simulation and fit size in data.

D^0-->KK asymmetry

D^0 (positive pion)

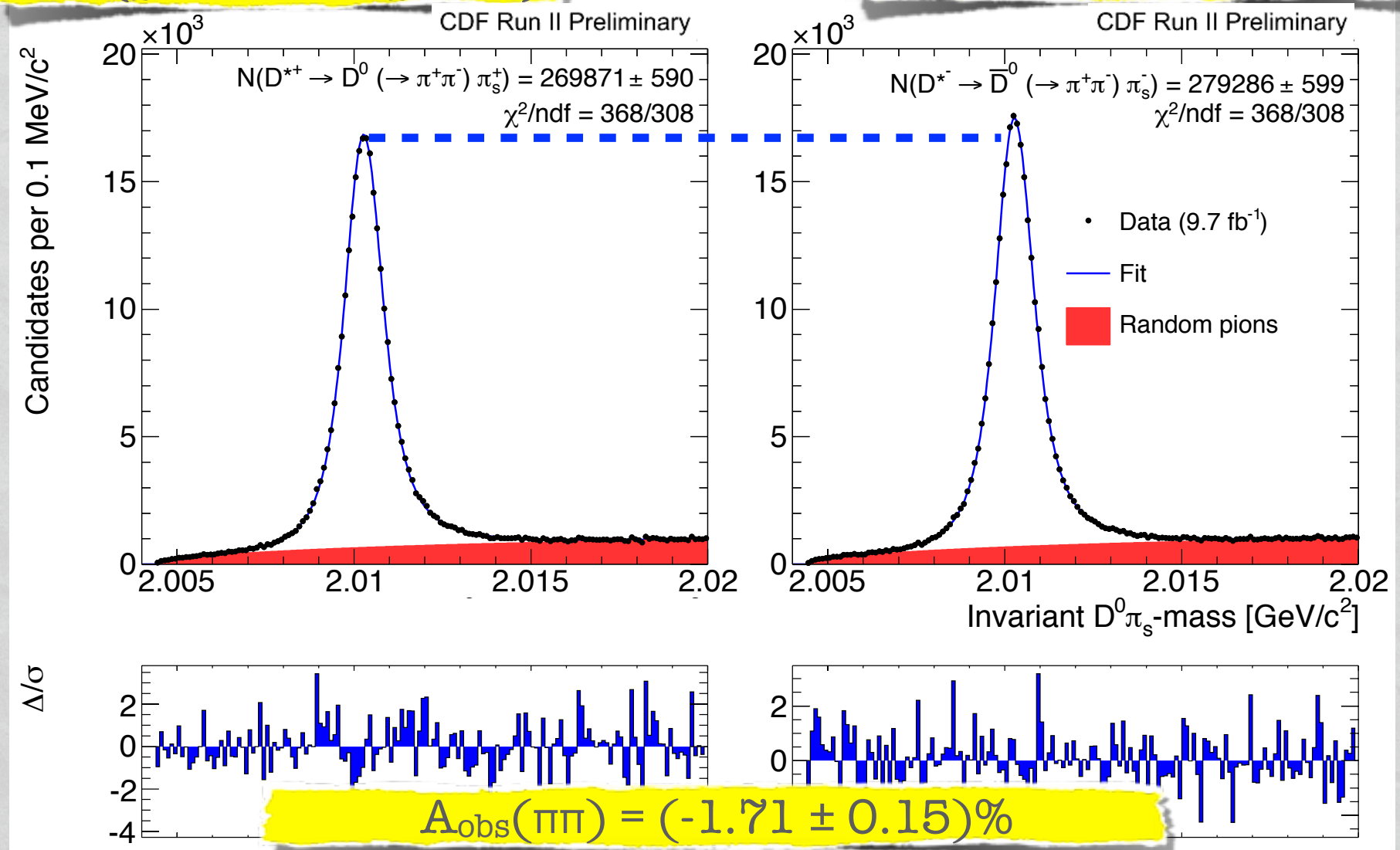
$\bar{D}^0$ (negative pion)



D^0--> ππ asymmetry

D^0 (positive pion)

$\bar{D}^0$ (negative pion)



$A_{obs}(\pi\pi) = (-1.71 \pm 0.15)\%$

Known unknowns

Simulation constrains residual, higher-order instrumental effects

Uncertainties on mass shapes. Possible residual mismodeling constrained with “anti-tuned” fits.

Shape differences btw positive and negative D*. Repeat fits with independent models for + and - signals and backgrounds.

Kπ tail leaks into ππ. Effect is the product of the measured Kπ asymmetry (3%) times the size (0.93%) of the contribution

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

The result

$A_{obs}(KK) - A_{obs}(\pi\pi) = (-2.33 \pm 0.14)\% - (-1.71 \pm 0.15)\% =$

$\Delta A_{CP} = (-0.62 \pm 0.21 \text{ (stat.)})\%$

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

CDF Public note 10784

This is 2.7σ different from zero, strongly indicating presence of CP violation in the decays of D^0 mesons

Uncertainty is 2 per mil, dominated by the sample size.

Confirms LHCb result (-0.82 ± 0.21 ± 0.11)%.
Same resolution, <1σ difference in central values

Combination assuming Gaussian, uncorrelated uncertainties excludes CP conservation at >3.5σ

Hic sunt leones (postdictions)

Supporters of BSM origin and of SM+hadronic corrections origin equally split. More data needed.

Individual CPV in KK and ππ may help. If rescattering is limited, $A_{CP}^{dir}(KK) = -A_{CP}^{dir}(\pi\pi)$ is expected.

CDF measurement by far the most precise, but still insufficient for conclusive understanding.

PHYSICAL REVIEW D **85,** 012009 (2012)

Measurement of *CP*-violating asymmetries in $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays at CDF

We report on a measurement of *CP*-violating asymmetries (A_{CP}) in the Cabibbo-suppressed $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays reconstructed in a data sample corresponding to 5.9 fb^{-1} of integrated luminosity collected by the upgraded Collider Detector at Fermilab. We use the strong decay $D^{*+} \to D^0\pi^+$ to identify the flavor of the charmed meson at production and exploit *CP*-conserving strong $c\bar{c}$ pair production in $p\bar{p}$ collisions. High-statistics samples of Cabibbo-favored $D^0 \to K^-\pi^+$ decays with and without a $D^{*\pm}$ tag are used to correct for instrumental effects and significantly reduce systematic uncertainties. We measure $A_{CP}(D^0 \to \pi^+\pi^-) = (+0.22 \pm 0.24(\text{stat}) \pm 0.11(\text{syst}))\%$ and $A_{CP}(D^0 \to K^+K^-) = (-0.24 \pm 0.22(\text{stat}) \pm 0.09(\text{syst}))\%$, in agreement with *CP* conservation. These are the most precise determinations from a single experiment to date. Under the assumption of negligible direct *CP* violation in $D^0 \to \pi^+\pi^-$ and $D^0 \to K^+K^-$ decays, the results provide an upper limit to the *CP*-violating asymmetry in D^0 mixing, $|A_{CP}^{\text{ind}}(D^0)| < 0.13\%$ at the 90% confidence level.

Not easy to improve

Measurements of CP violation in the resonant structure of $D^0 \to K_S \pi^+ \pi^-$ decays

arXiv:1207.0825

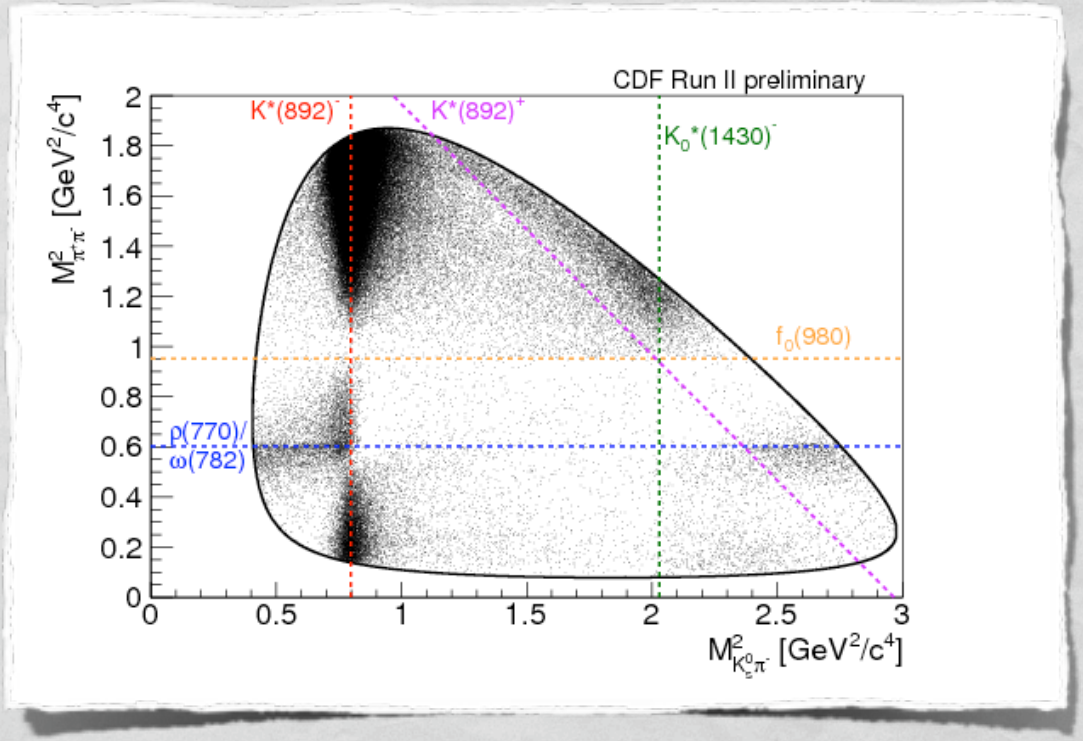
Expanding the portfolio

Search for CPV in resonant structures of D*-tagged 3-body $D^0 \to K_S\pi\pi$ decays.

350 000 decays in 6 fb^{-1}

Isobar Dalitz fit to measure fit-fraction asymmetries - insensitive to instrumental effects.

Efficiency from MC. Background from mass sidebands.



Consistency-check with model-independent test for the presence of CPV (Miranda): bin-by-bin evaluation of $(N_{D^0} - N_{\bar{D}^0})/\sqrt{N_{D^0} + N_{\bar{D}^0}}$

$D^0 \to K_S \pi\pi$ results

No evidence for any CP violating effects in 6 fb^{-1}

arXiv:1207.0825

Bounds greatly tightened with respect to CLEO PRD 70, 091101 (2004)

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

$A_{CP} = (-0.05 \pm 0.57 \pm 0.54)\%$

Summary

Charm's chance to show hints of BSM physics becoming real. Sensitive to up-type NP and far from being fully explored.

CDF at the forefront of this challenge owing to CP-invariant initial state, 10^7 decays, and accurate tracking.

- Updated CPV in D->hh using final data set. Strong indication of CPV in charm with BSM-like size. Supports LHCb result and calls for further exploration.

- Dalitz plot analysis $D^0 \to K_S\pi^+\pi^-$ decays shows no sign of CPV within 0.8% uncertainties.

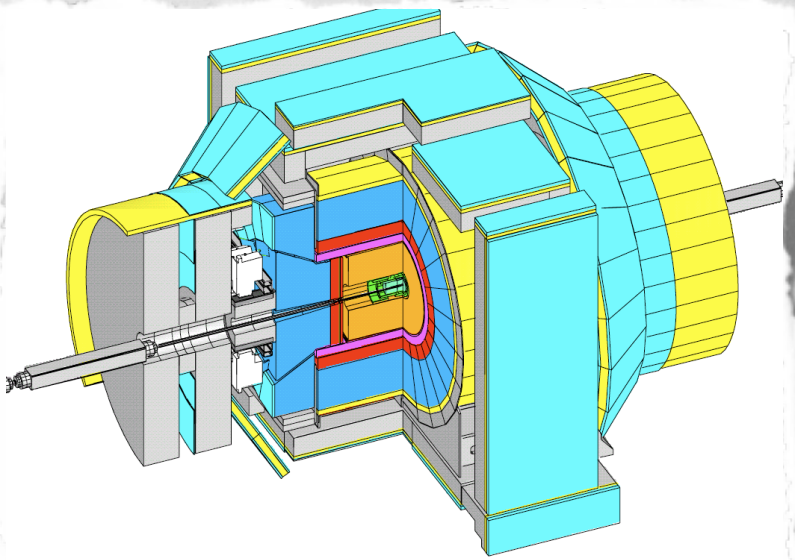
(Amazing for experiment designed 30 years ago to see W/Z)

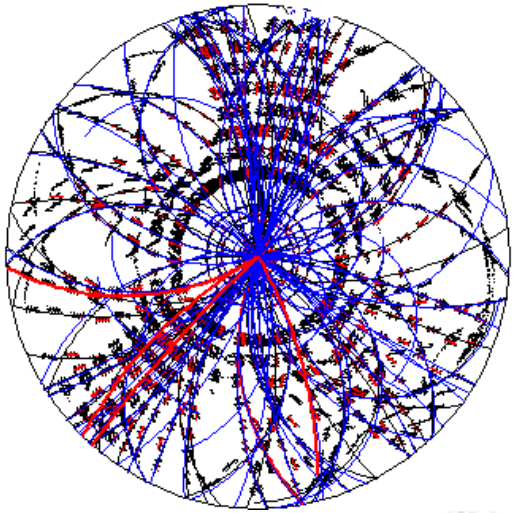
A few aces up our sleeve before passing the baton for good.

The end

Charm physics at CDF

- 10 years of 2 TeV $\bar{p}p$ collisions (10^{14} collisions)
- 1% of collisions yield D
- 0.1-10% retained by trigger + offline
- Trigger on displaced tracks
- Reconstruct only charged decay products.
- Precise momentum and decay position





Silicon Vertex Trigger

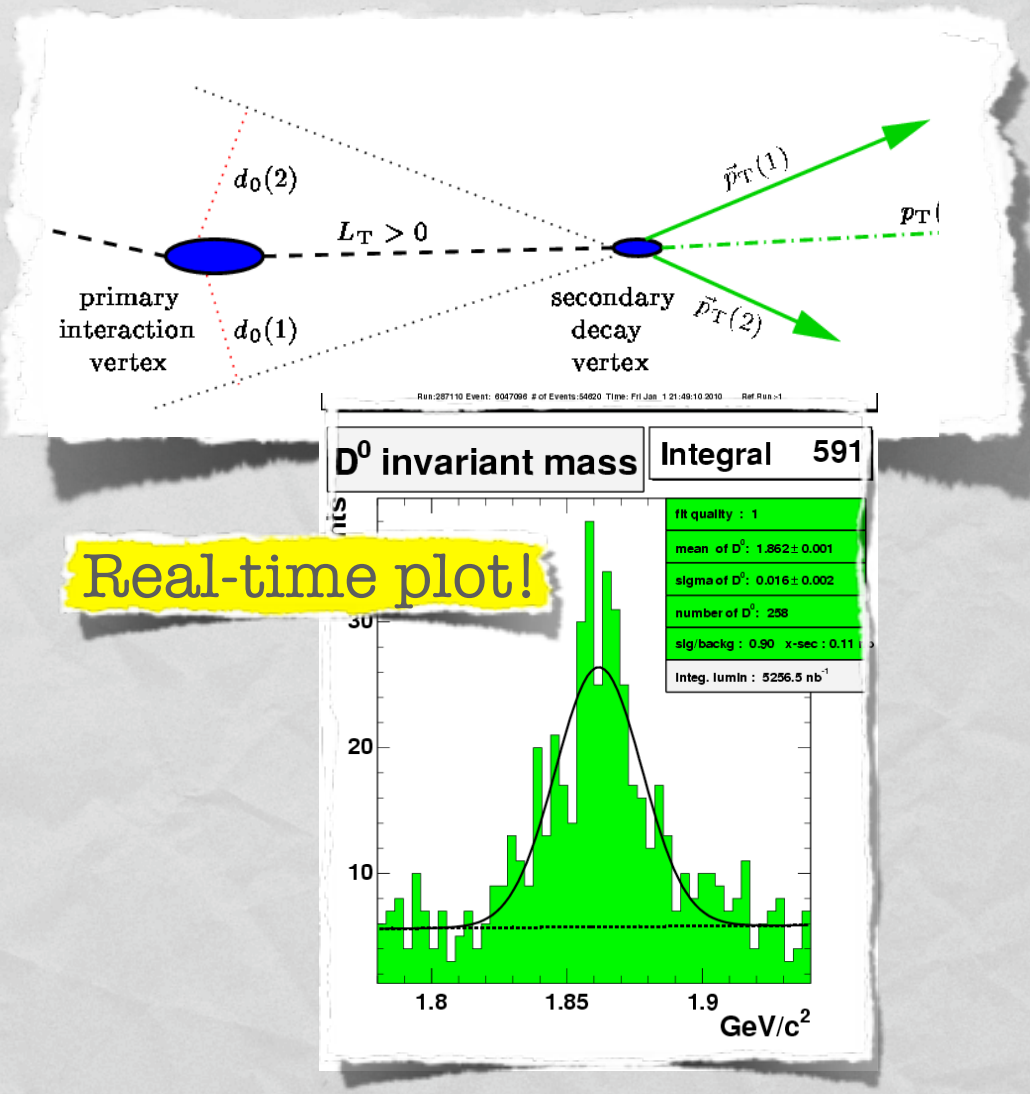
Dedicated hardware

Combines information from drift chamber and silicon

Finds all central tracks with $p_T > 2$ GeV/c and determines their impact parameters

Does so in less than 20 μs

Crucial role in this analysis: boosts yields by factor 30k



Combining asymmetries

Combination of small asymmetries is additive.

Two asymmetries A_1 and A_2 combine as

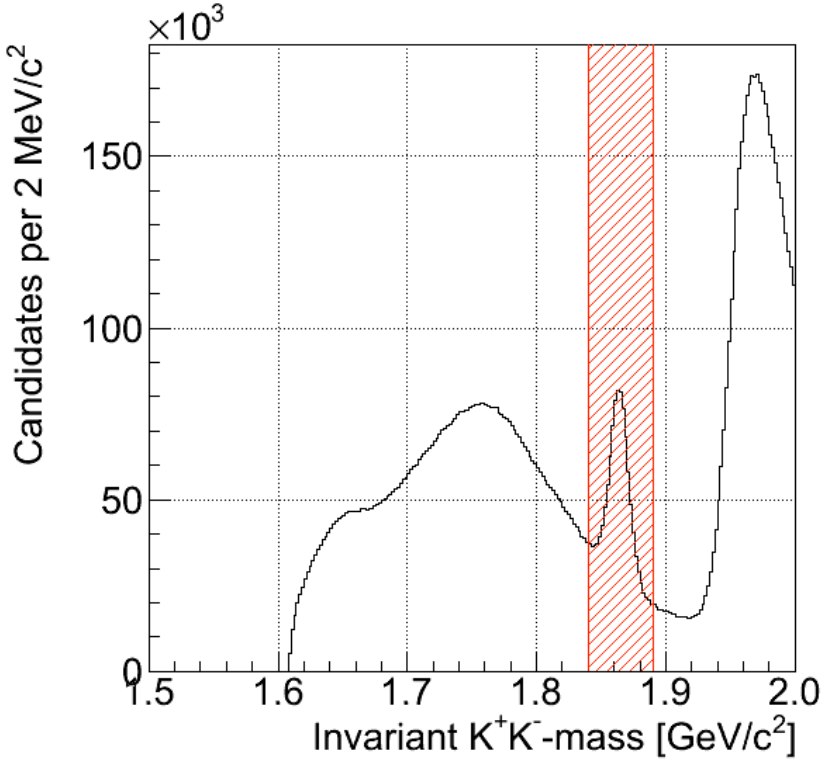
$$A = (A_1 + A_2)/(1+A_1A_2)$$

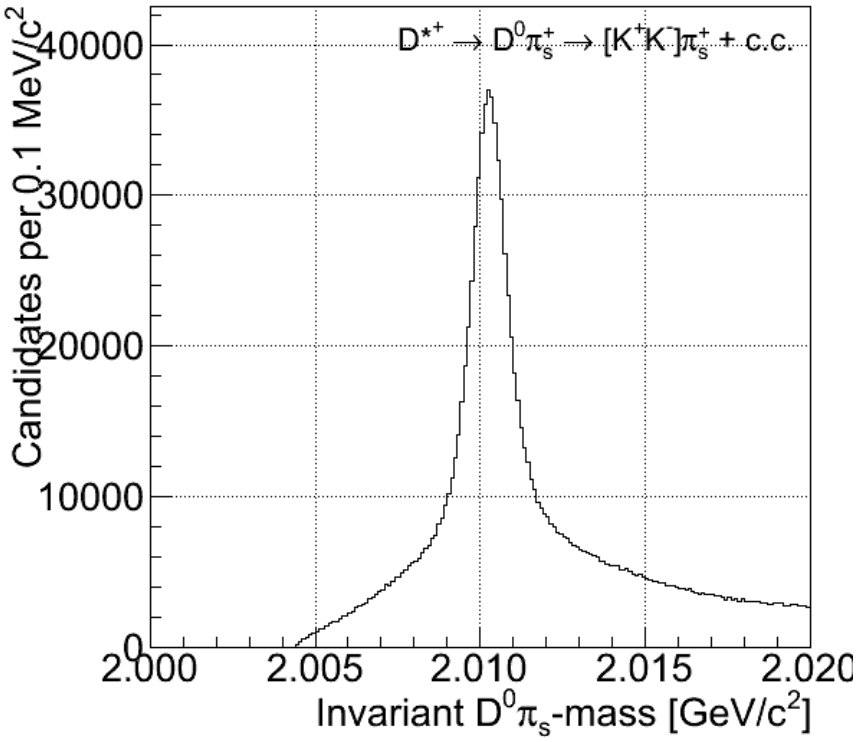
The exact expression expanded in power series gives

$$A = A_1 + A_2 - A_1A_1A_2 - A_1A_2A_2 + \ldots$$

where the first neglected terms are $O(10^{-6})$ for $A_1, A_2 \approx O(\%)$

Cut on KK mass and fit D*mass



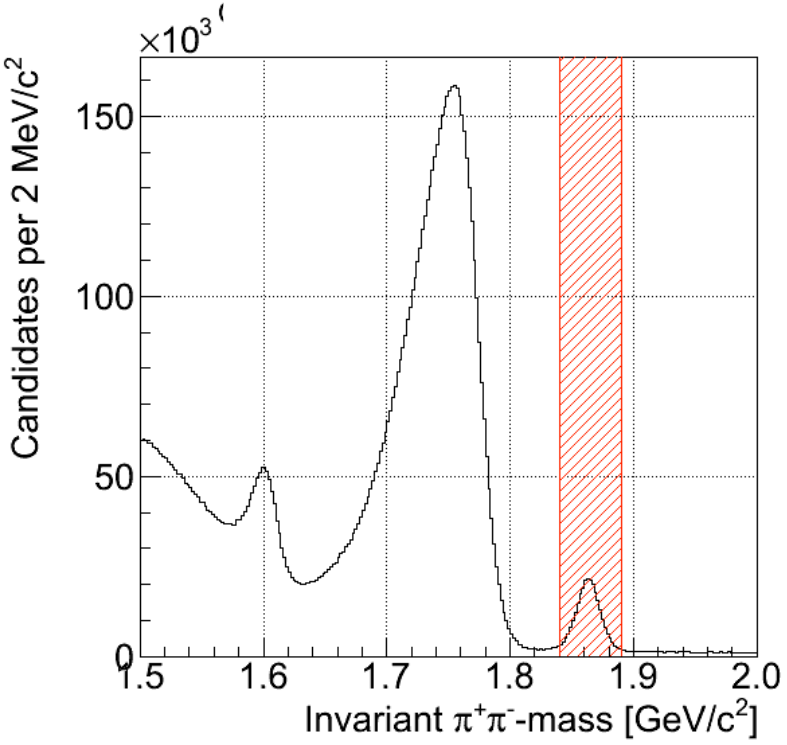


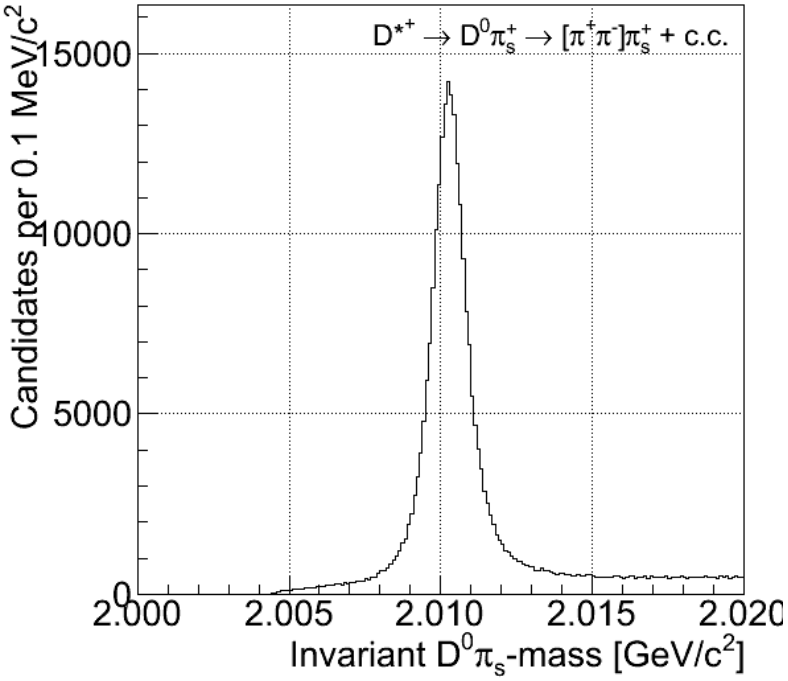
1.Cut on D^0 mass

2. Attach soft pion

3. Fit in D*mass

Cut on ππ mass and fit D* mass





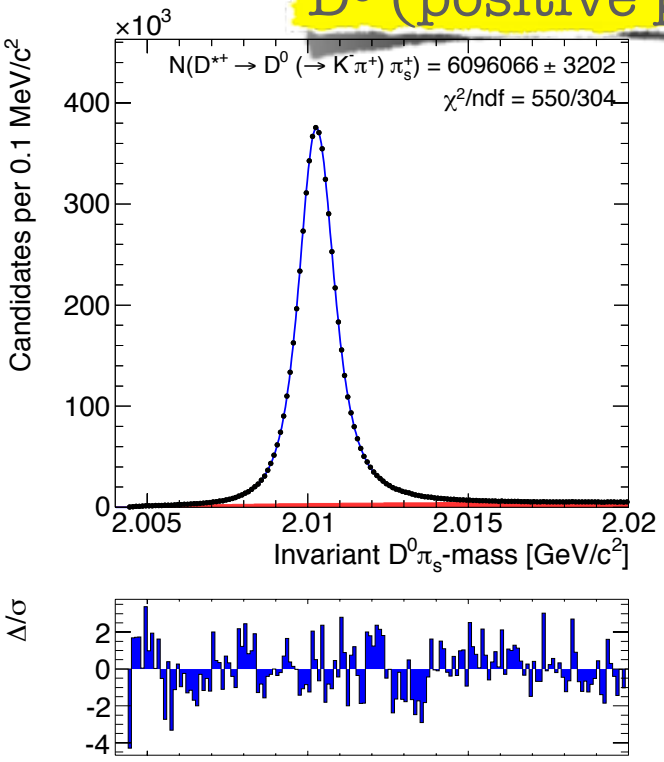
1.Cut on D^0 mass

2. Attach soft pion

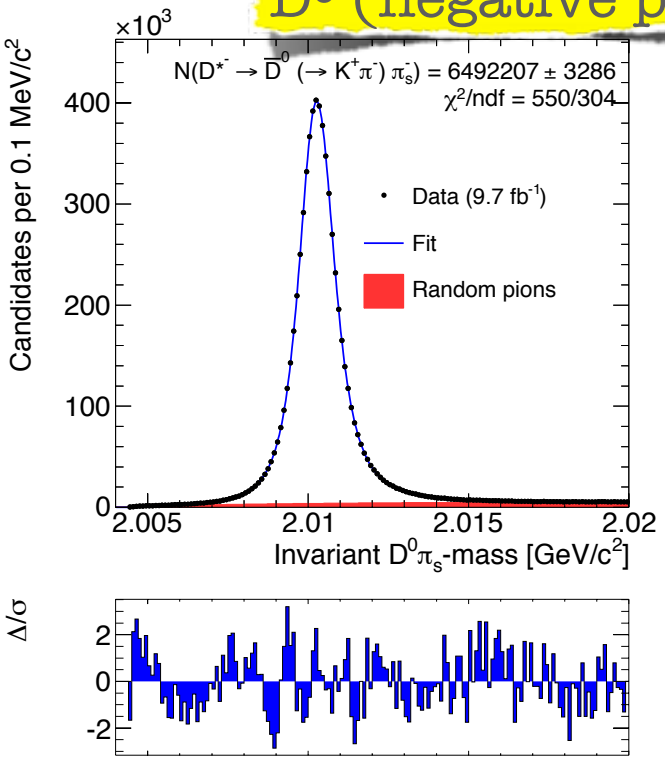
3. Fit in D* mass

Getting the D* mass shapes

D^0 (positive pion)



$\bar{D}^0$ (negative pion)



Signal: functional form from simulation. Tune parameters in 12.5M D^0->Kπ decays (10x more abundant wrt KK and ππ)

Random pion: combine real D^0 with all π from subsequent events in data.

Consistency checks

Soft pion's direction	ΔA_{CP} (%)
Upward-Forward	-0.37 ± 0.39
Upward-Backward	-1.15 ± 0.40
Downward-Forward	-0.08 ± 0.40
Downward-Backward	-0.89 ± 0.40

χ^2/ndf = 4.4/3

Data-taking periods	ΔA_{CP} (%)
Pre–July 2008	-0.75 ± 0.28
Post–July 2008	-0.50 ± 0.30

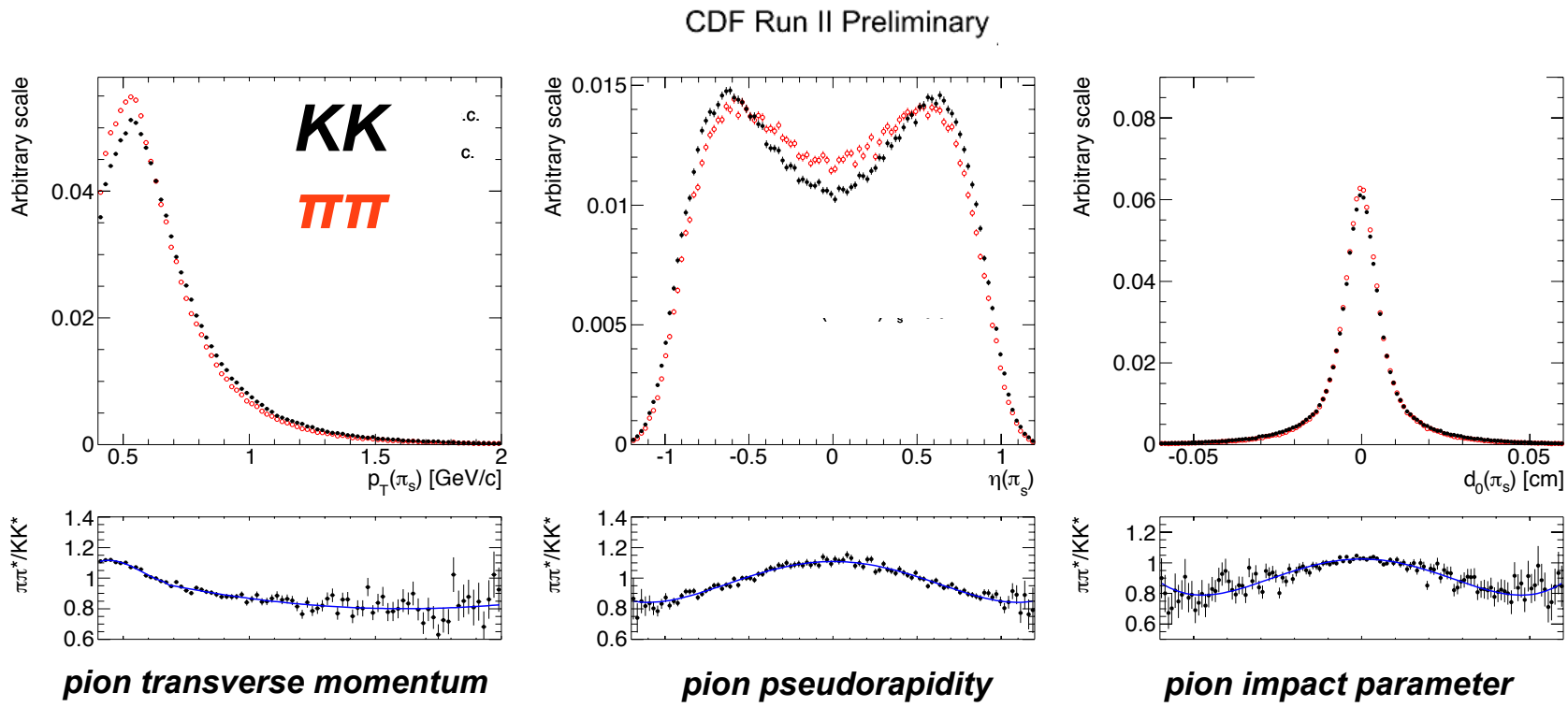
χ^2/ndf = 0.38/1

Sub-sample	ΔA_{CP} (%)
New candidates only	-0.74 ± 0.27
Old candidates only	-0.46 ± 0.31

χ^2/ndf = 0.46/1

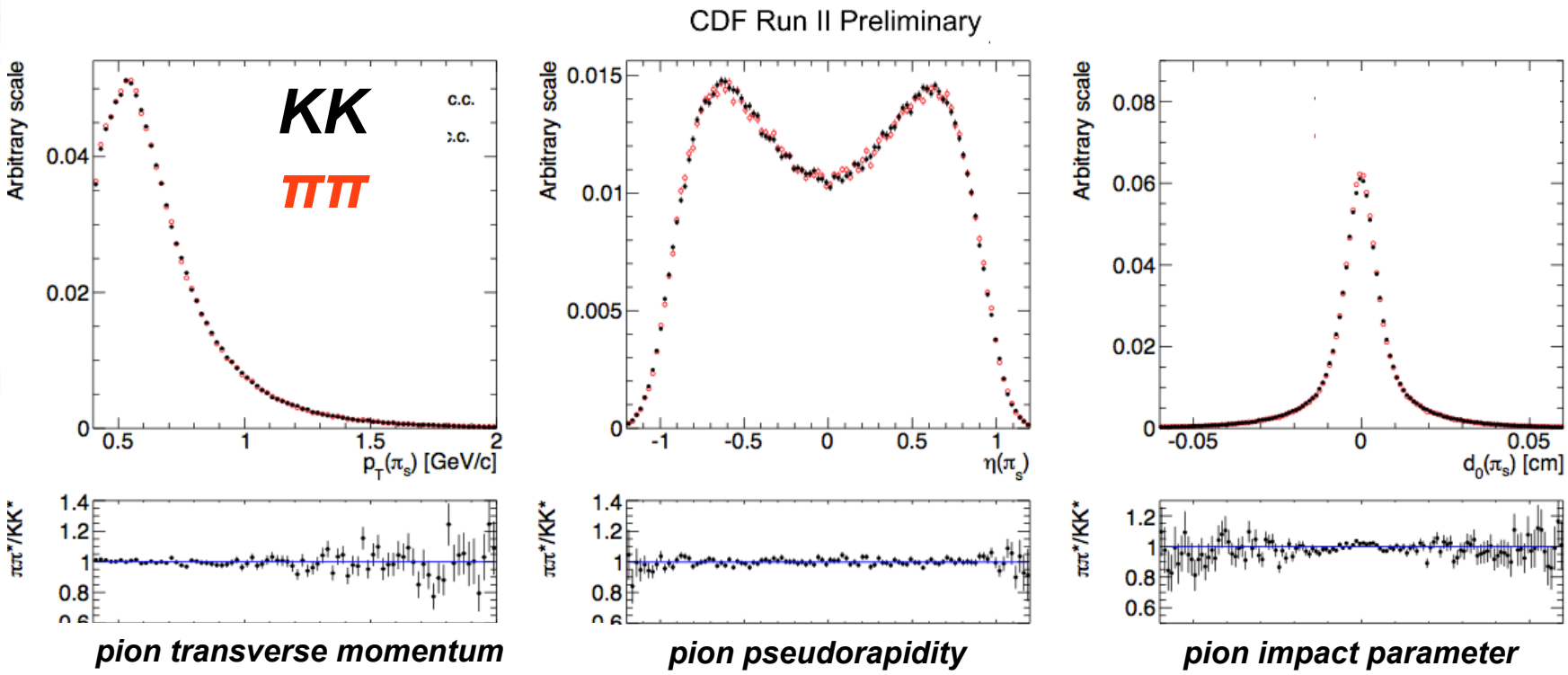
Kinematics differences

Instrumental effects depend on kinematics. Need to reweight KK and ππ kinematics for realizing cancellation



Reweighting

Reweight events so that kinematic distributions become equal



Interpretation

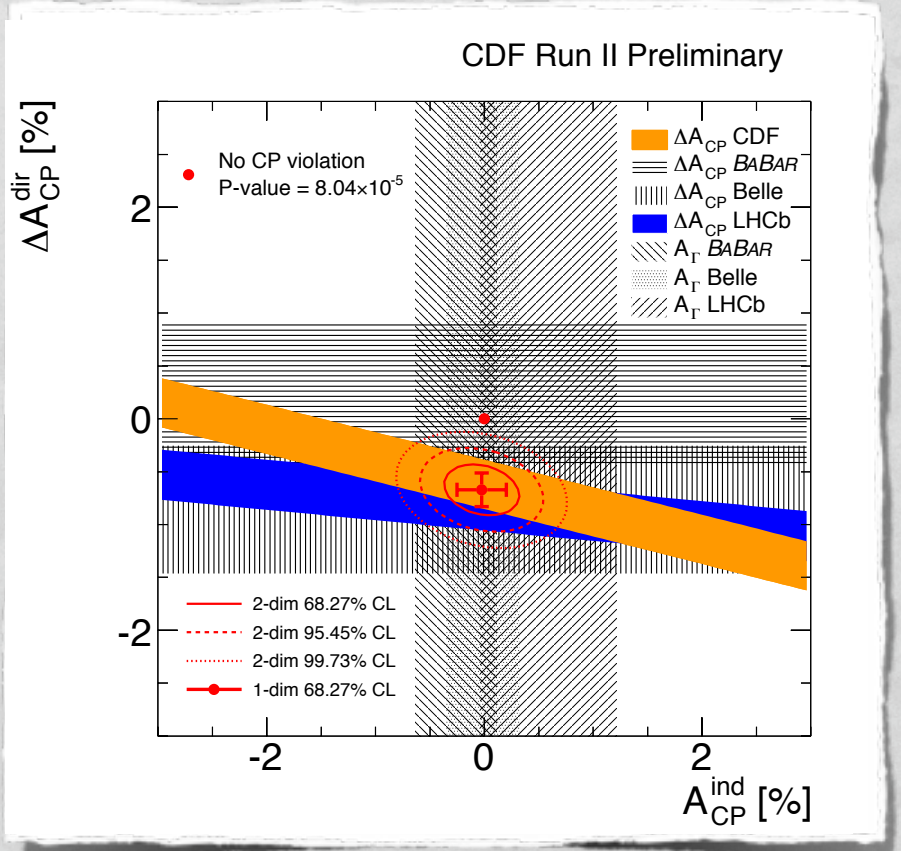
Each asymmetry is a combination of direct CPV (decay-specific) and indirect CPV (universal). Difference dominated by the direct component.

$$\Delta A_{CP} = \Delta A_{CP}^{dir} + (\Delta\langle t\rangle/\tau)\, A_{CP}^{ind}$$

Linear relation between the difference of direct CPV and indirect CPV.

Slope is the difference in average decay-time between observed KK and ππ (0.27 at CDF)

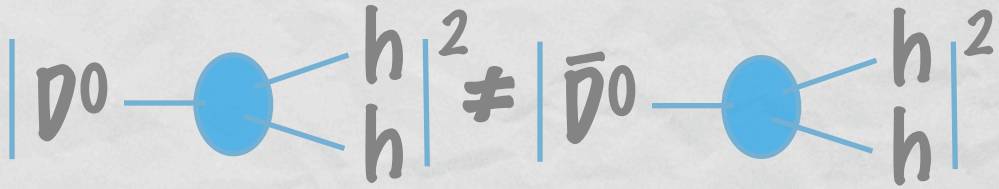
Combination assuming Gaussian, uncorrelated uncertainties excludes CP conservation at >3.5σ



Interpretation

Direct

Decay-specific



Indirect

universal

$$A_{CP} = A_{CP}^{dir} + (\langle t \rangle/\tau)\, A_{CP}^{ind}$$

<t> is mean observed decay-time of D in each sample (≈2.5τ).
Difference of asymmetries dominated by direct component

$$\Delta A_{CP} = A_{CP}^{dir}(KK) - A_{CP}^{dir}(\pi\pi) + (\Delta\langle t \rangle/\tau)\, A_{CP}^{ind}$$

$$\Delta A_{CP} = \Delta A_{CP}^{dir} + (\Delta\langle t \rangle/\tau)\, A_{CP}^{ind}$$

CPV predictions

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

mixing $M_1/M_2 \sim s_1 \times$ (penguin/tree matrix elements). One expects in general very small asymmetries $\lesssim O(10^{-5})$. This kind of asymmetries has been considered in the standard model in a relatively favorable case [7], $D_s^+ (D_s^-) \to K^0\pi^+ (\bar{K}^0\pi^-)$: the two interfering amplitudes are here the Cabibbo forbidden tree ($\sim V_{cd}^* V_{ud}$) and penguin ($\sim V_{cs}^* V_{us}$) diagrams. The asymmetry is estimated to be of $O(10^{-4})$. This asymmetry could be much larger, of O(20%), if a fourth generation exists [7].

Le Yaouanc, Oliver, Raynal (1992)

an excellent approximation by physics of the first two generations. Consequently, the Standard Model makes a clean prediction that any CP violating effects in these processes are negligibly small. We can thus safely set $\phi = 0$ and $R_m = 1$. The statements below

Bergmann, Grossman, Ligeti, Nir, Petrov (2000)

CP violation in D-meson decays provides a unique probe of new physics. First, the Standard Model predicts very small effects, smaller than $\mathcal{O}(10^{-3})$, so that a signal at the present level of experimental sensitivity [1, 2, 3, 4, 5, 6, 7], $\mathcal{O}(10^{-2})$, would clearly signal new physics. Second, the neutral D system is the only one where the external up-sector

Grossman, Kagan, Nir (2004)

are of the order $\mathcal{O}(\lambda)$ (where $\lambda \simeq 0.22$), while the last one is $\mathcal{O}(\lambda^5)$. Thus, the CP-violating asymmetry is expected to be at most $a_f \sim 10^{-3}$ in the SM. Model-dependent estimates of this asymmetry exist and are consitent with this estimate [4].

Petrov (2011)

It's unanimous: CPV close to 1% strongly signals BSM physics

CPV postdictions

phenomena. On this basis, we conclude that large direct CP asymmetries of order a few per mille are not surprising given the size of $\mathrm{Br}(D \to K^+K^-)/\mathrm{Br}(D \to \pi^+\pi^-)$.

Brod, Grossman, Kagan, Zupan (2012)

amplitude P_C. However, this piece of correction should not modify our predictions much. We conclude that the LHCb and CDF data will reveal a new-physics signal, if their central values persist.

Li, Lu, Yu (2012)

Considering the more conservative three-channel scenario, we conclude that, with present errors, the observed asymmetries are marginally compatible with the SM. This conclusion holds also for the most general scenario with even more coupled channels in the $I = 0$ rescattering, where no significant constraints arise from unitarity. Should the present central value be confirmed with smaller errors, it would require a factor of six (or larger) enhancement of the penguin amplitude with respect to all other topologies, well beyond our theoretical expectations. Thus, improving the experimental accuracy could lead to an indirect signal of new physics.

Franco, Mishima, Silvestrini, (2012)

non-leptonic D^0 decays with large strong phases. As a consequence, a SM interpretation of the present data on direct CP asymmetries in $D^0 \to P^+P^-$ is plausible. On the other

Feldmann, Nandi, Soni (2012)

If strong dynamics of D resembles K, then effect can be SM.
If D behaves more like B, then it's likely to be BSM (and BMFV)

Individual asymmetries

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

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

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

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

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

The physical A_{CP} could be extracted through the combination:

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

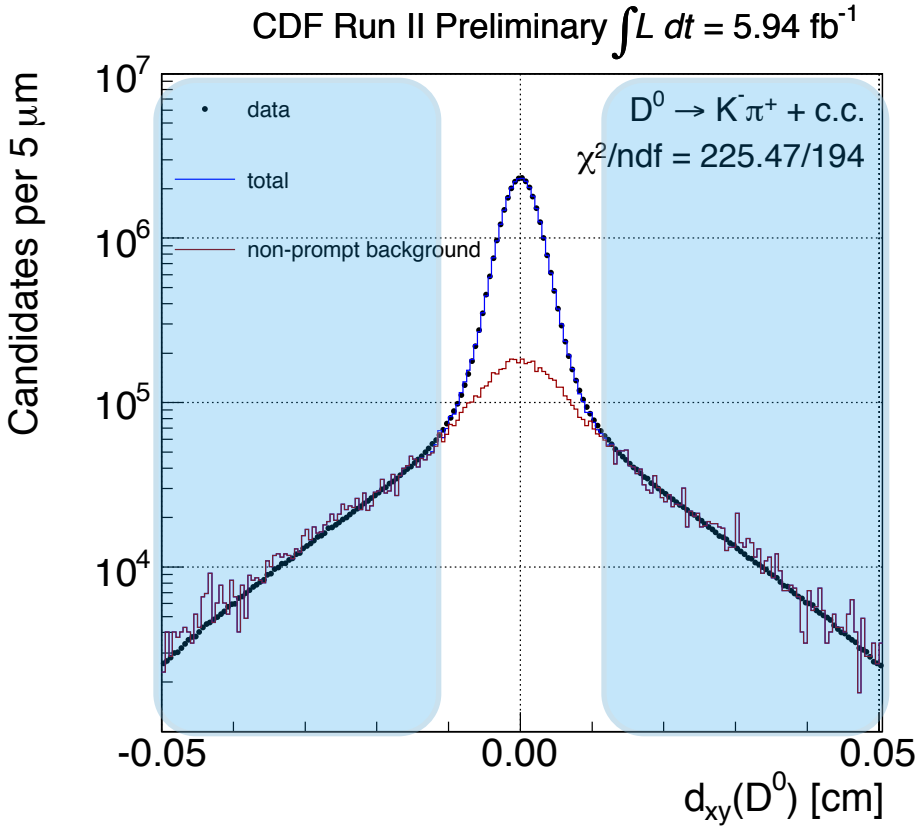
Secondary charm

$c\tau(B) \approx 450$ microns

D from B are 12% of the sample.

If there's CP violation in the relevant B decay, that would be propagate into the individual asymmetries results.

It cancels in the difference

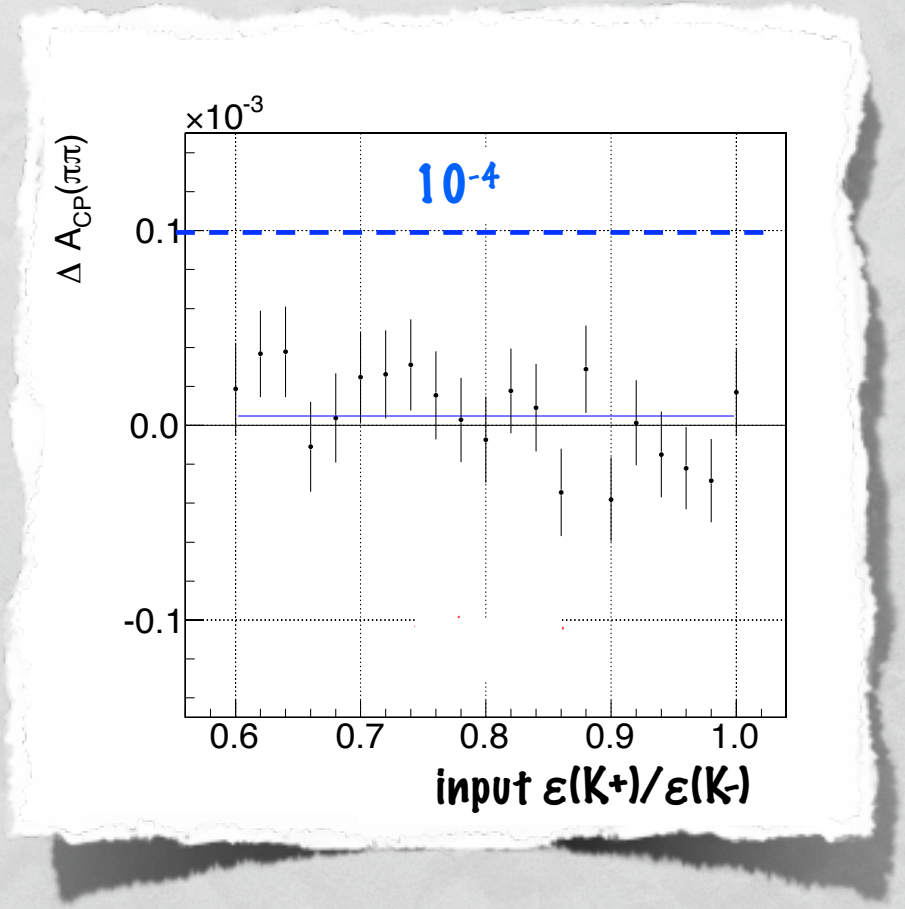


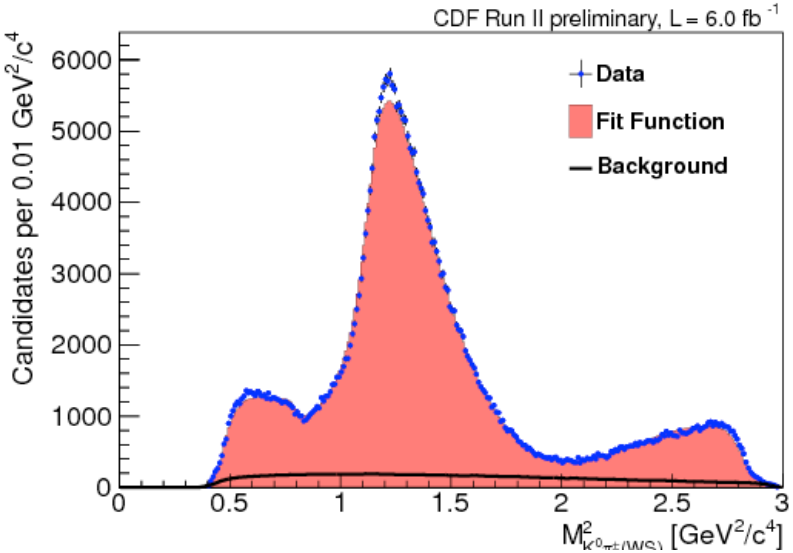
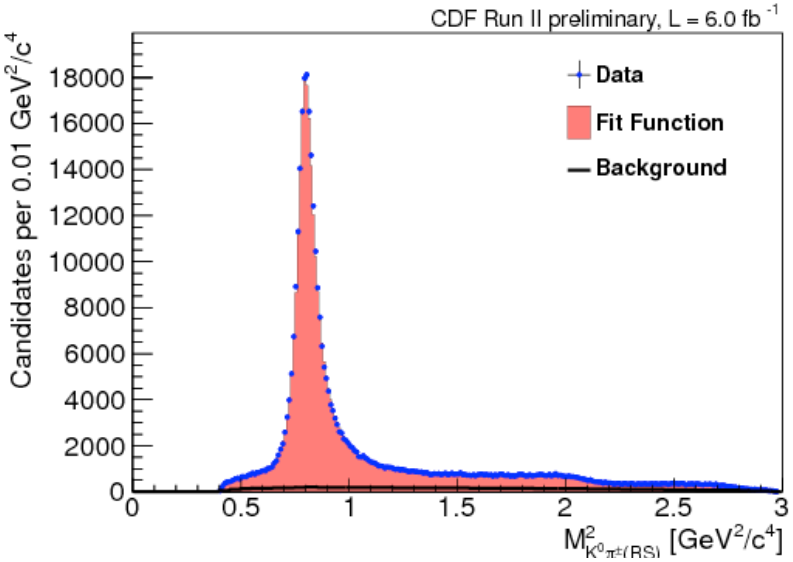
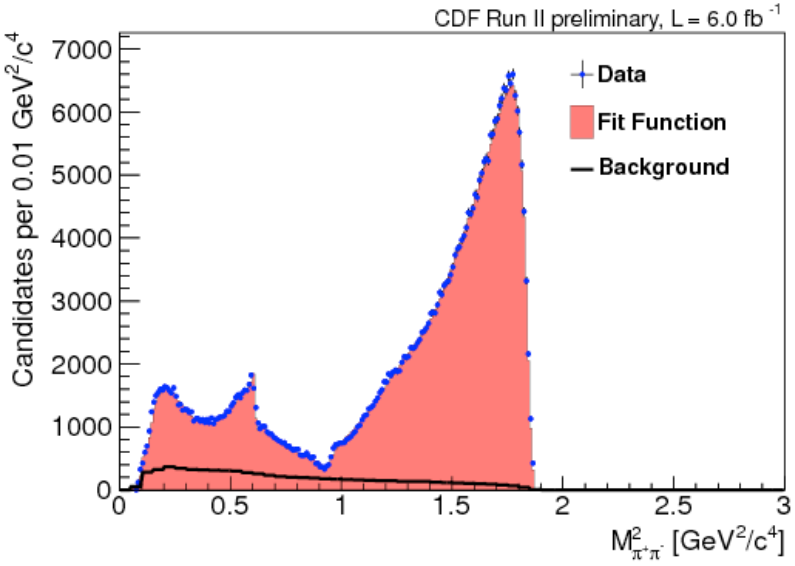
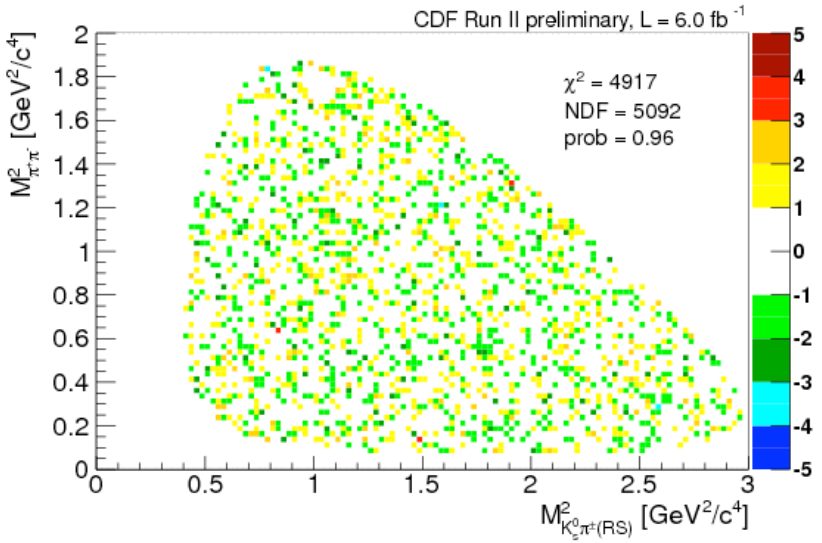
Higher order effetcs

Measurement repeated on many simulated samples.

Known and different instrumental asymmetries are injected as functions of kinematics.

Larger effect seen quoted as systematic uncertainty



Different relative efficiencies for detecting + vs - kaons

Dalitz analysis at CDF