Challenging the SM through Charm at CDF

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Wine and Cheese,
April 27, 2012

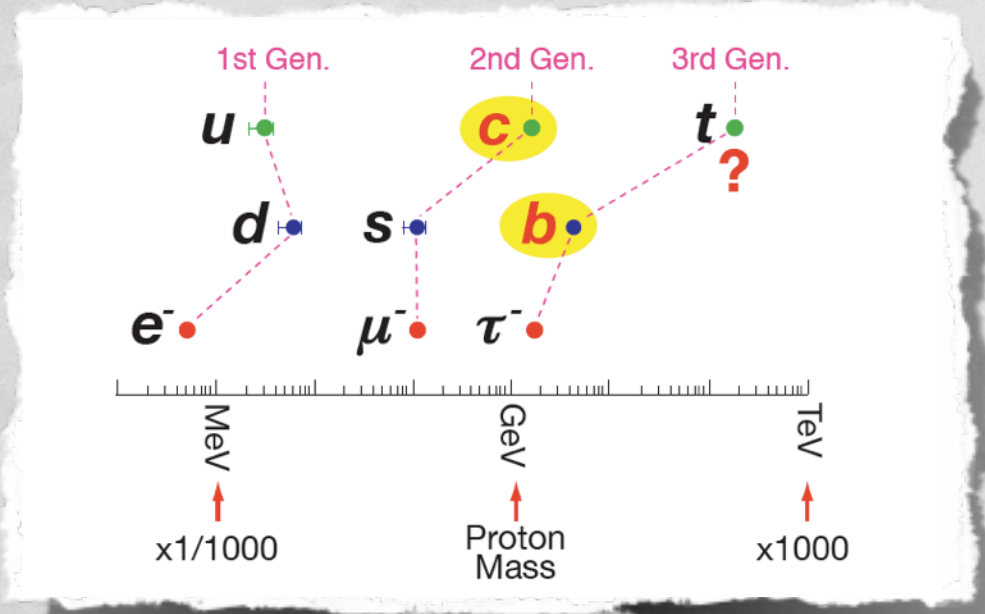
Challenging the SM

HE production of new particles. Probe directly structure of matter and its interactions

LE precision measurements access effects of exchange of virtual new particles. Quantum-probe of higher energies than directly accessible

Flavor matters

The physics of matter at its most fundamental level. Deals with masses and mixings of fermions



$$V \approx \begin{array}{c} \\ \\ \\ \end{array}\begin{array}{c} \begin{array}{ccc} d & s & b \end{array} \\ \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 & -\lambda^2 & 1 \end{pmatrix} \end{array}\begin{array}{c} \\ u \\ c \\ t \end{array}$$

$\lambda \approx 0.22$

Origin of mass? Why are masses so different across generations? Why are couplings different?...

CP violation

Physics laws are not invariant for mirror-reversal of the spatial arrangement and replacement of all particles with antiparticles

$$
\begin{array}{cc}
 & \begin{array}{ccc} d & s & b \end{array} \\
V \approx & \begin{pmatrix} 1 & \lambda & \lambda^3 e^{i\phi} \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 e^{-i\phi} & -\lambda^2 & 1 \end{pmatrix} \begin{array}{c} u \\ c \\ t \end{array}
\end{array}
$$

Who ordered this?

Not the SM - but has sufficient complexity to accommodate it. However, SM extensions generate additional sources of CP (or flavor) violation. Measuring them could guide us toward a more general theory.

State of the Art

The mantra: multiple, precise, and redundant experimental tests of flavor dynamics will reveal early signs of new particles/couplings.

Triggered dedicated experiments and theory advancements over the past 15+ years.

Formidable success.

SM explains satisfactorily CPV data in leading B/K transitions (barring 10-15% corrections)

- New particles are much heavier than O(1) TeV
- New particles at O(1) TeV, but have fine-tuned dynamics
- New particles couple very weakly with ordinary ones

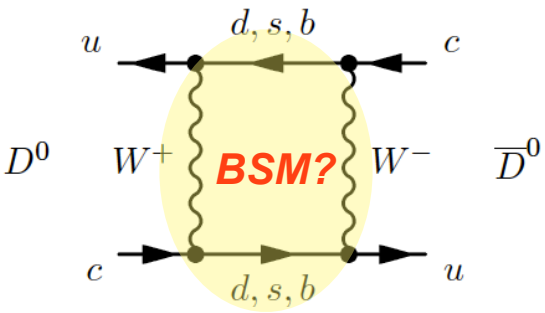
The end of the story?

Perhaps not. Charm potential to be fully explored yet

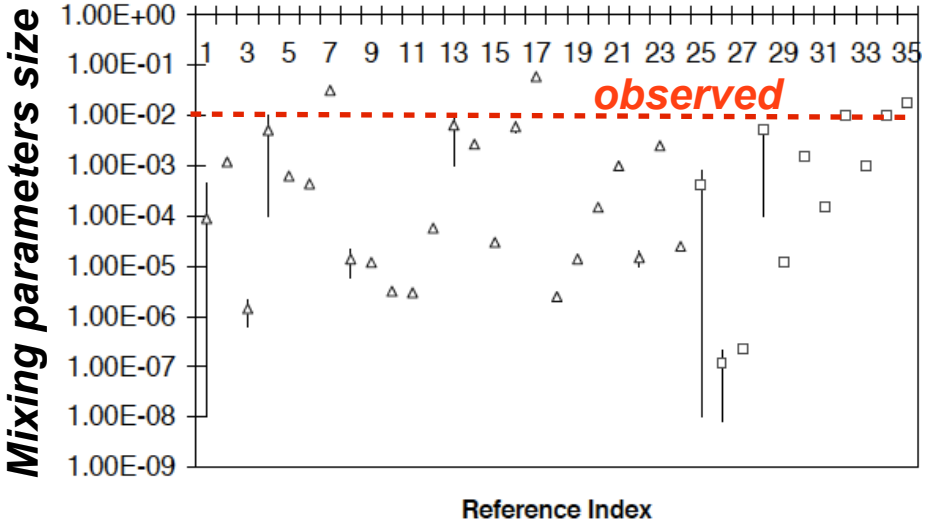
Complementary to K and B. Uniquely probes BSM that couples to up-type quarks

Only recently data reached the precision to probe interesting regions of SM and BSM scenarios

Interest fueled by oscillation strength greater than most predictions. Any BSM in loop? Enhanced CP violation may show up as well.



Standard Model mixing predictions



Downsides

- Effects are small.
Charm involves 1st and 2nd families where CPV is strongly suppressed .Calls for very large samples and control on systematics.

- Predictions are hard, if any.
M(charm) >> zero but M(charm) >≈ M(s, u, d) . Typical accuracy not better than order-of-magnitude

$$\begin{array}{cc} & \begin{array}{ccc} d & s & b \end{array} \\ V \approx & \begin{pmatrix} 1 & \lambda & \lambda^3 e^{i\phi} \\ -\lambda & 1 & \lambda^2 \\ -\lambda^3 e^{-i\phi} & -\lambda^2 & 1 \end{pmatrix} \begin{array}{c} u \\ c \\ t \end{array} \end{array}$$

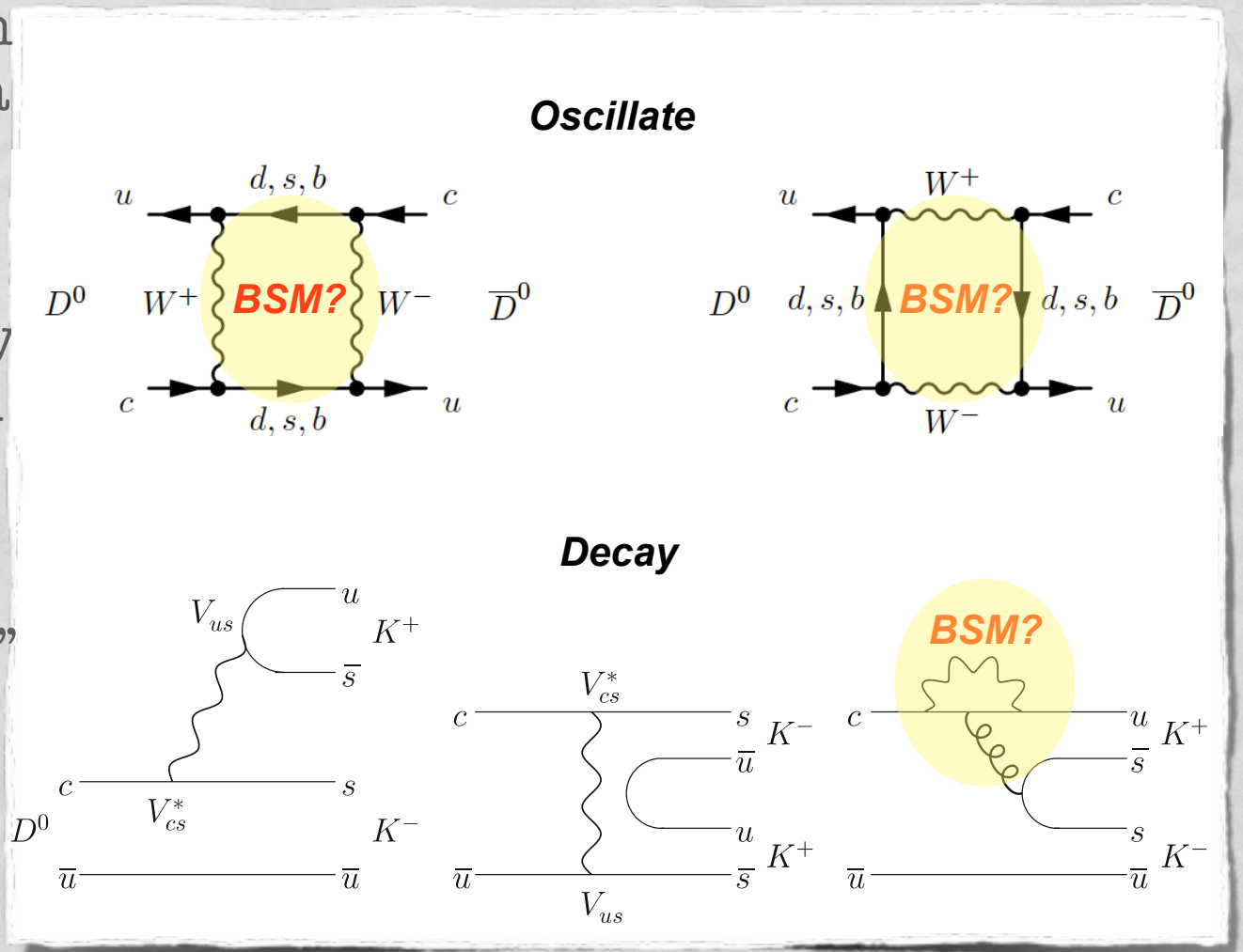
Difference of CP-violating asymmetries in $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays

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

Neutral flavored: can oscillate, providing a "box" for BSM to show up.

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

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



CPV predictions

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

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

Reality check

CDF early 2011: world's most precise measurements of CP-violating asymmetries in 2-body D decays 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)

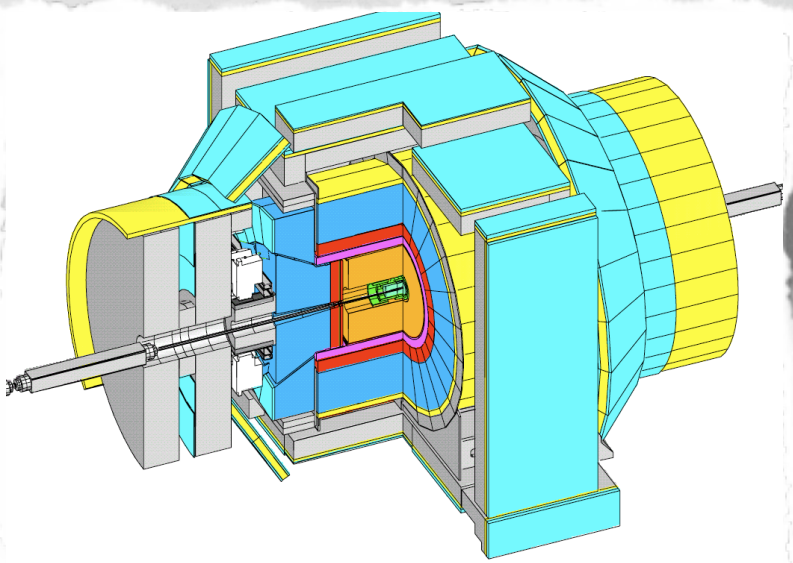
LHCb, late 2011: a more precise measurement of the difference, showing first evidence for CPV in charm with 1% size

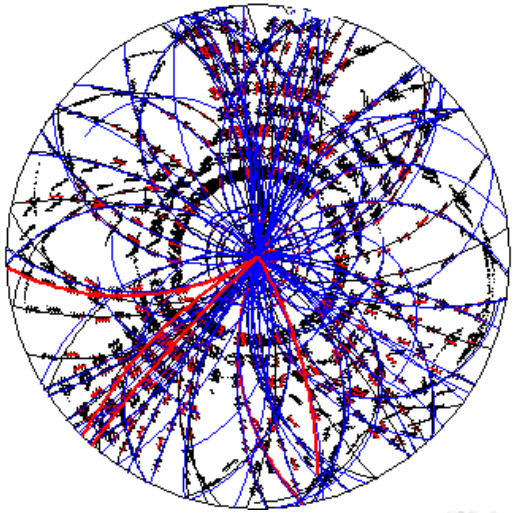
$\Delta A_{CP} = (-0.82 \pm 0.21 \pm 0.11)\%$ PRL 108, 111602 (2012)

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

Charm physics at CDF

- 10 years of 2 TeV $\bar{p}p$ collisions (10^{14} collisions)
- 1% of collisions yield D
- Trigger + offline efficiency 0.1-10%.
- Reconstruct only charged decay products.
- Precise momentum and decay-position
- Some PID (not in this analysis)





Silicon Vertex Trigger

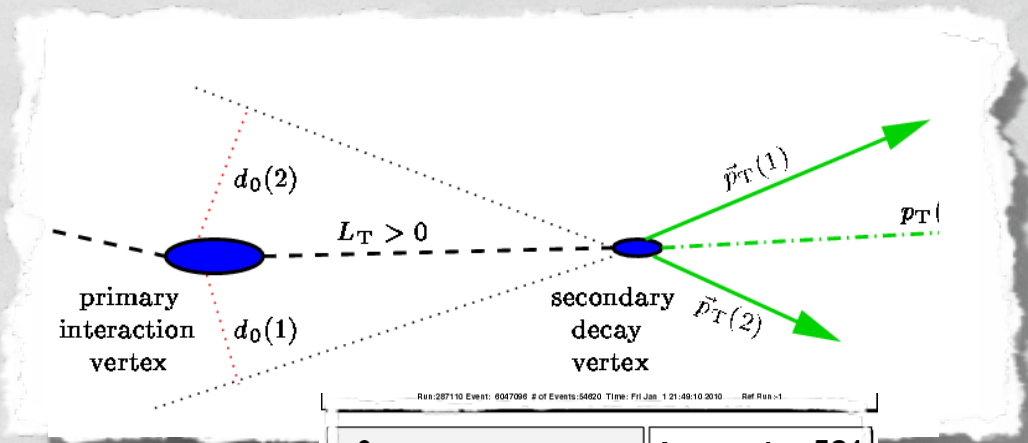
Dedicated hardware

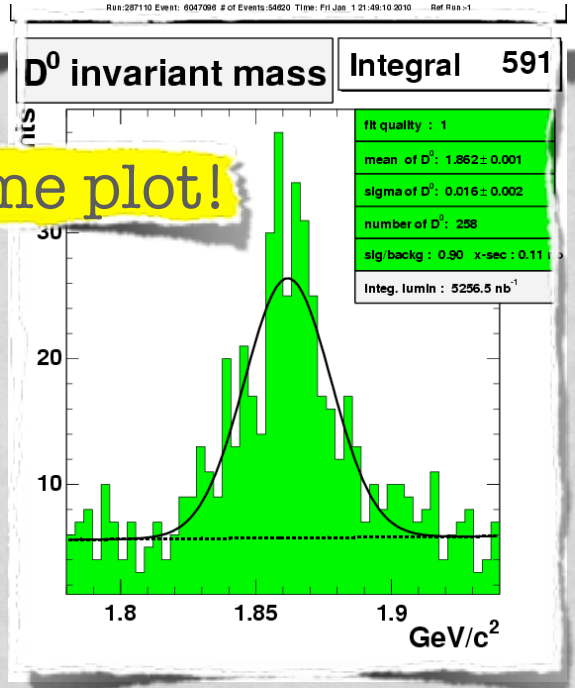
Combines information from drift chamber and silicon

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

Does so in less than 20 μs

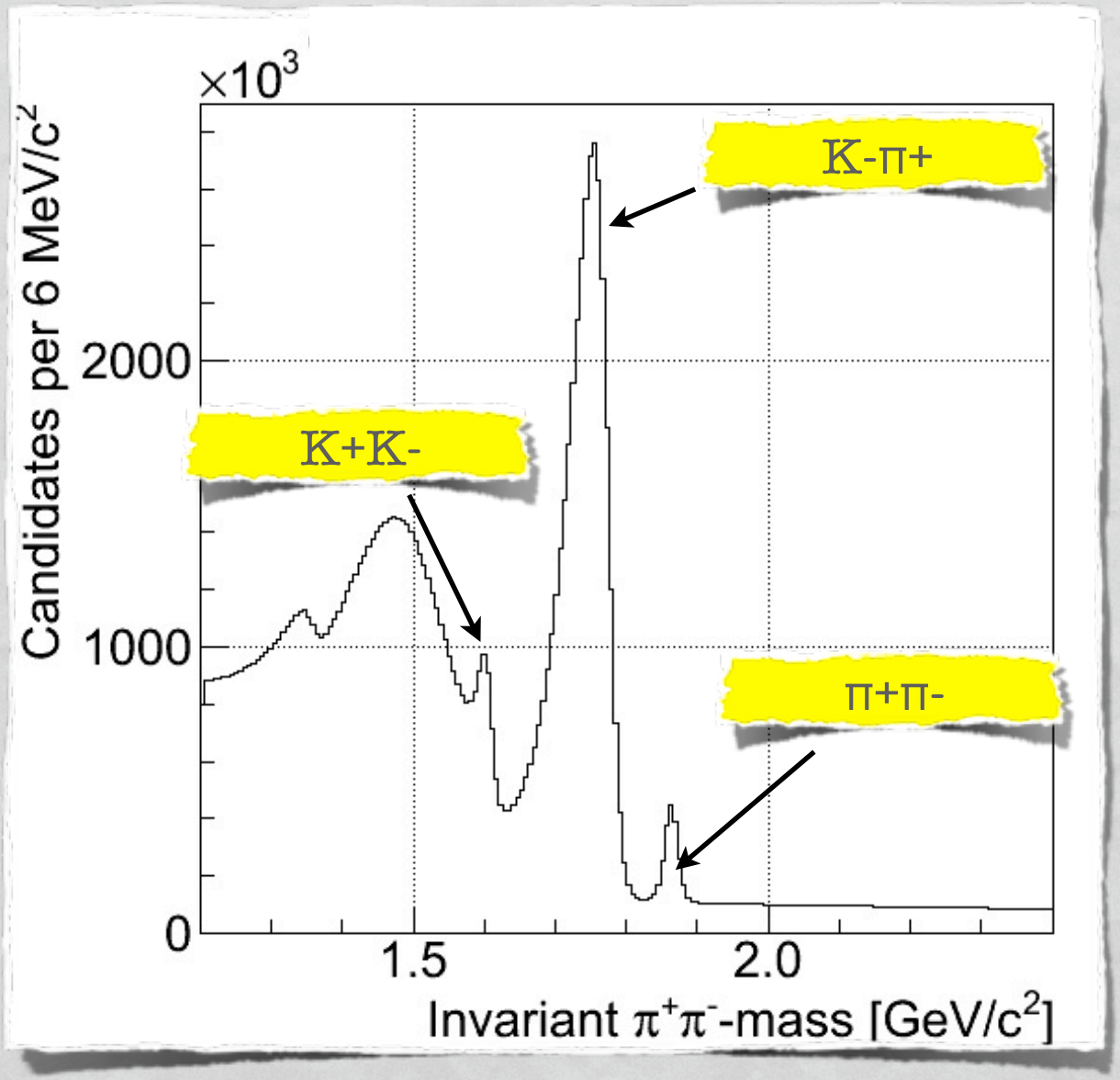
Crucial role in this analysis: boosts yields by factor 30k





Real-time plot!

The intensity frontier



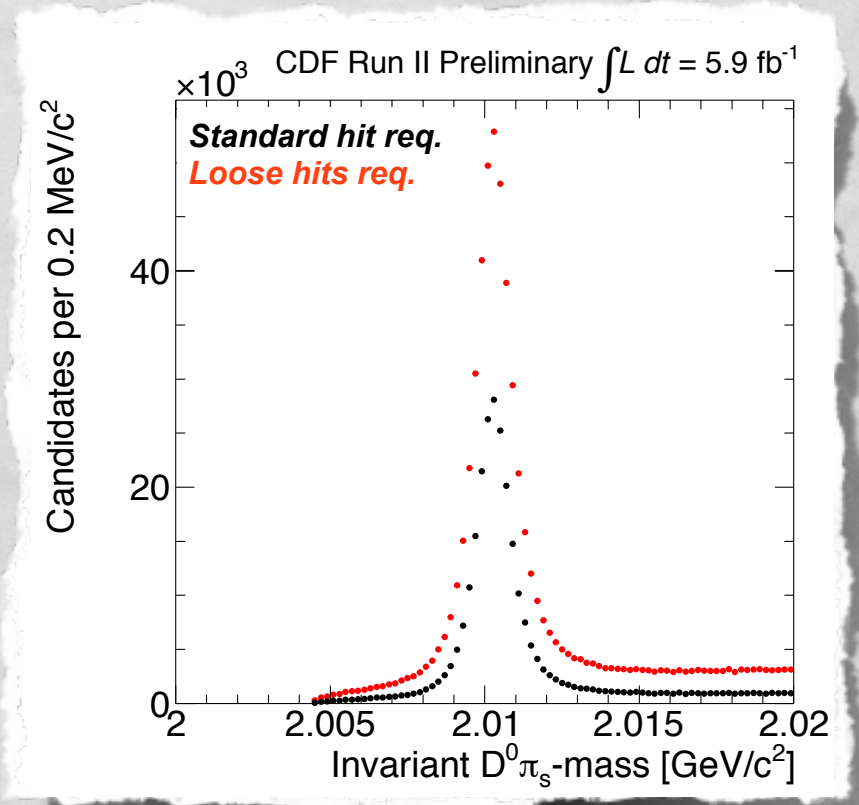
PS: Kπ- is skewed and wider because reconstructed as π-π-.

Squeezing the most out of data

Redesign selection toward measurement of asymmetry difference.

No large gain from 5.9 =>10 fb^{-1} .Displaced-track triggers heavily suppressed in late data

- ☐ Use all available displaced-track triggers
- ☐ Loosen track hits requirements
- ☐ use D from B decays. +12% signal with no bias on final results.



Doubled signal yields. Costs some more background.
Expect resolution on final result competitive with LHCb

Asymmetry

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

Exploiting symmetric production, determine how many decays come from D^0 and how many from anti-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 charged D* decay.

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

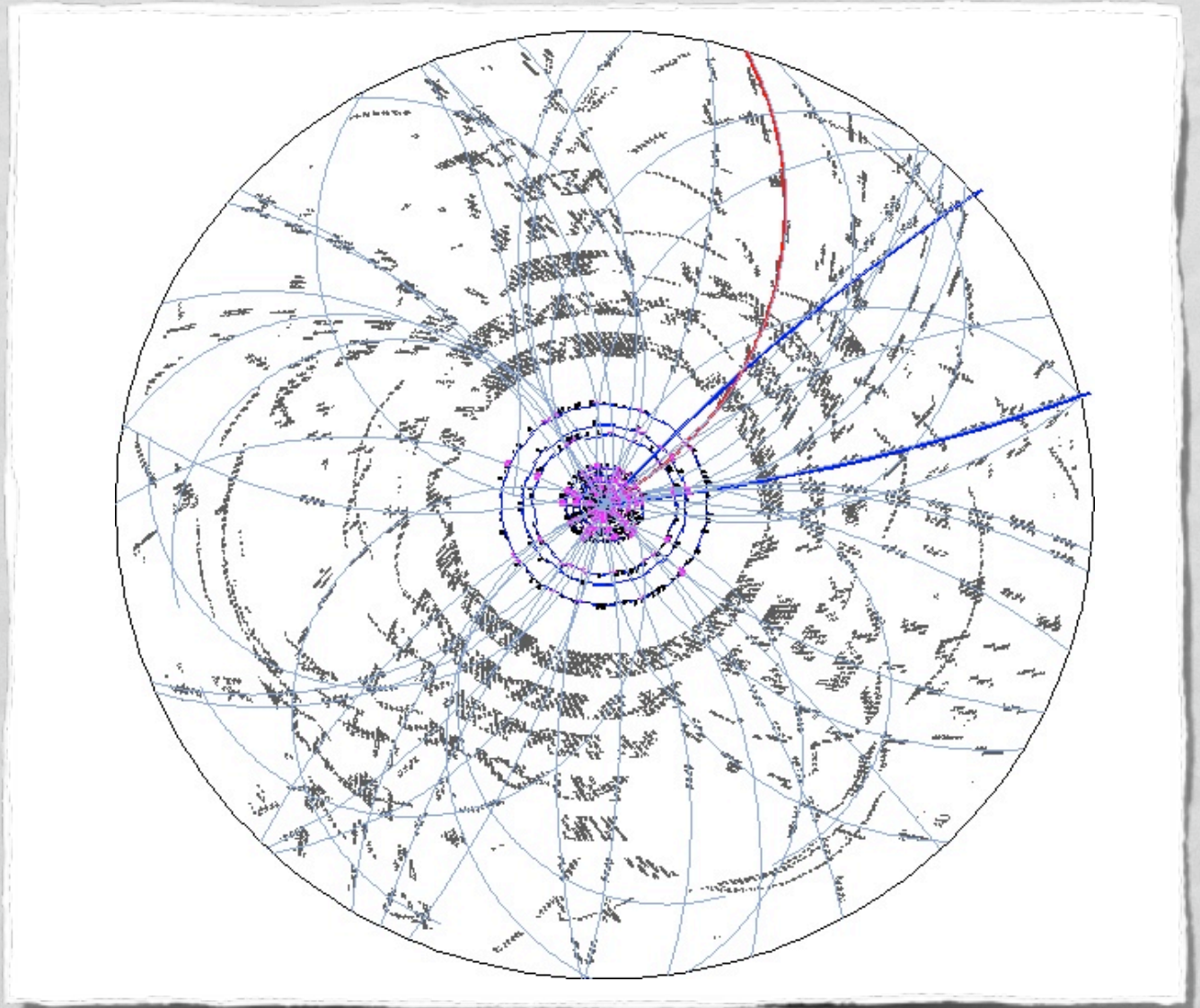
$D^{*-} \to \overline{D}^0\pi^- \to [h^+h^-]\,\pi_-$

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

Comes with a price.

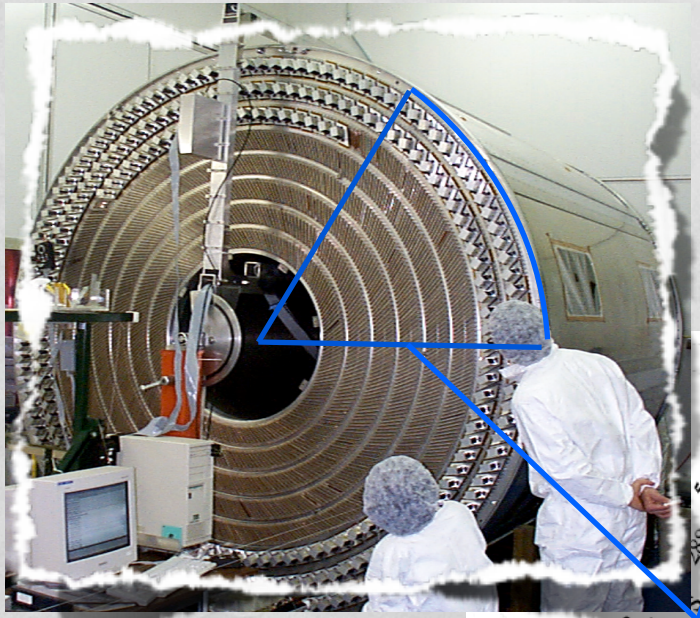
- Loose 85% of signal (but rejects lots of background)
- Injects a large (%) instrumental asymmetry.

Hello, charming..



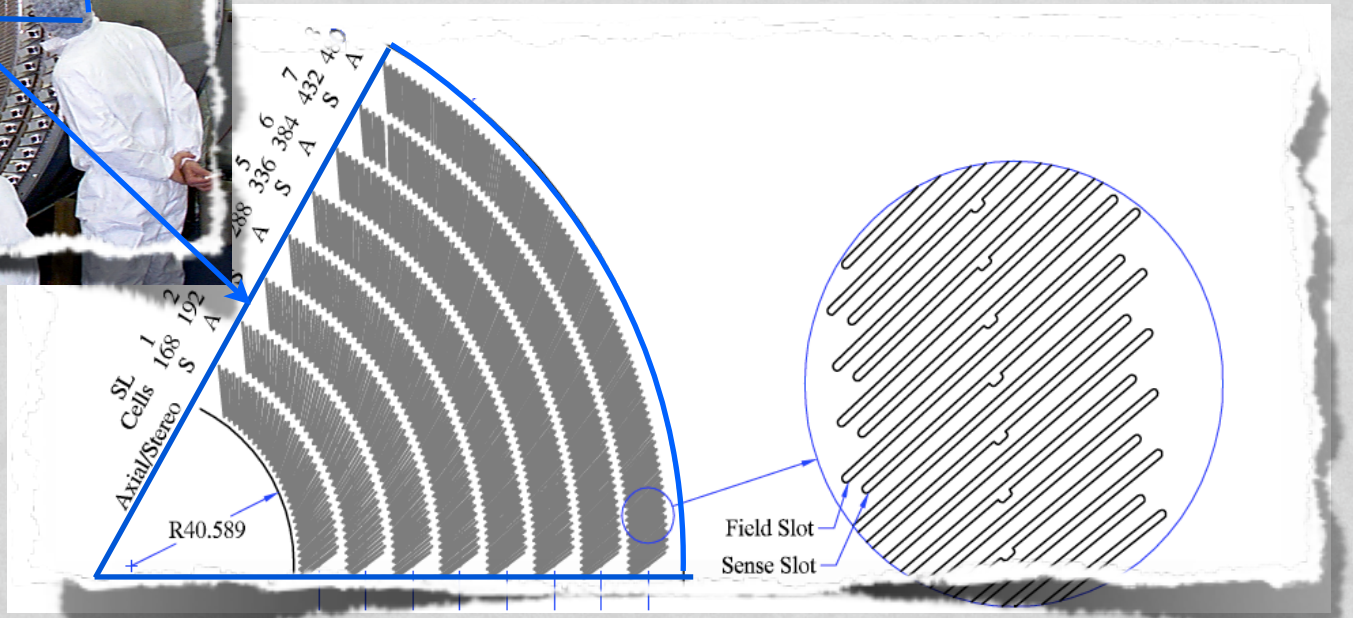
CDF not charge-symmetric

Requirement of D*-tag makes the final state charged



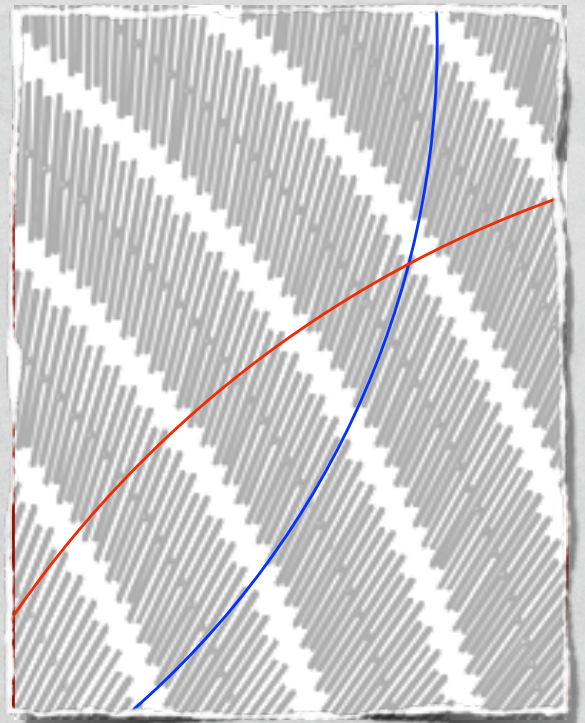
Large radius drift chamber.

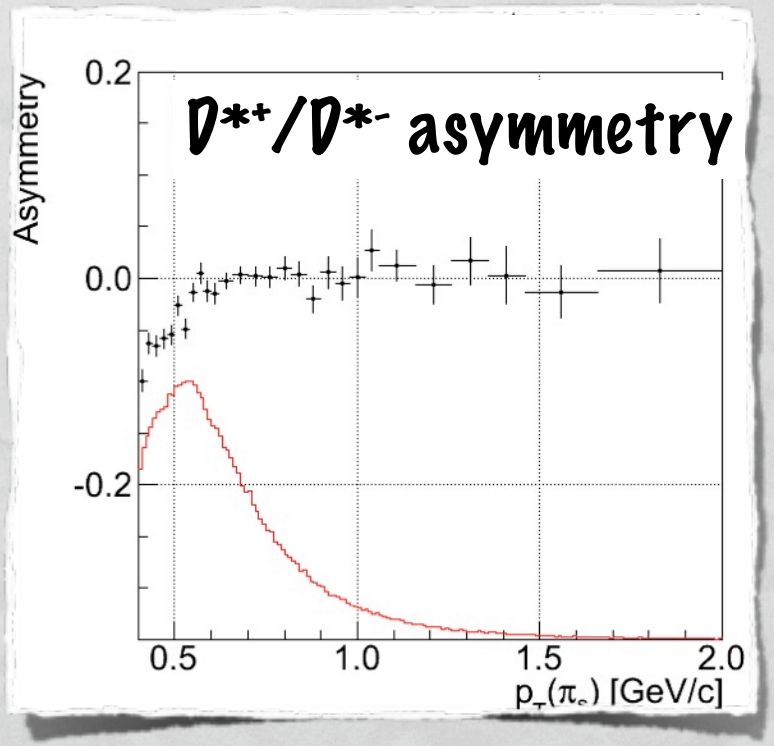
Cells tilt of 35° wrt radial direction



Instrumental asymmetry

+ and - particles hit cells at different angles. Impacts track efficiency, which becomes charge/momentum dependent.





Additional charged pion induces instrumental asymmetries that spoil physics asymmetry -- cancel them in the difference

The difference

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

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

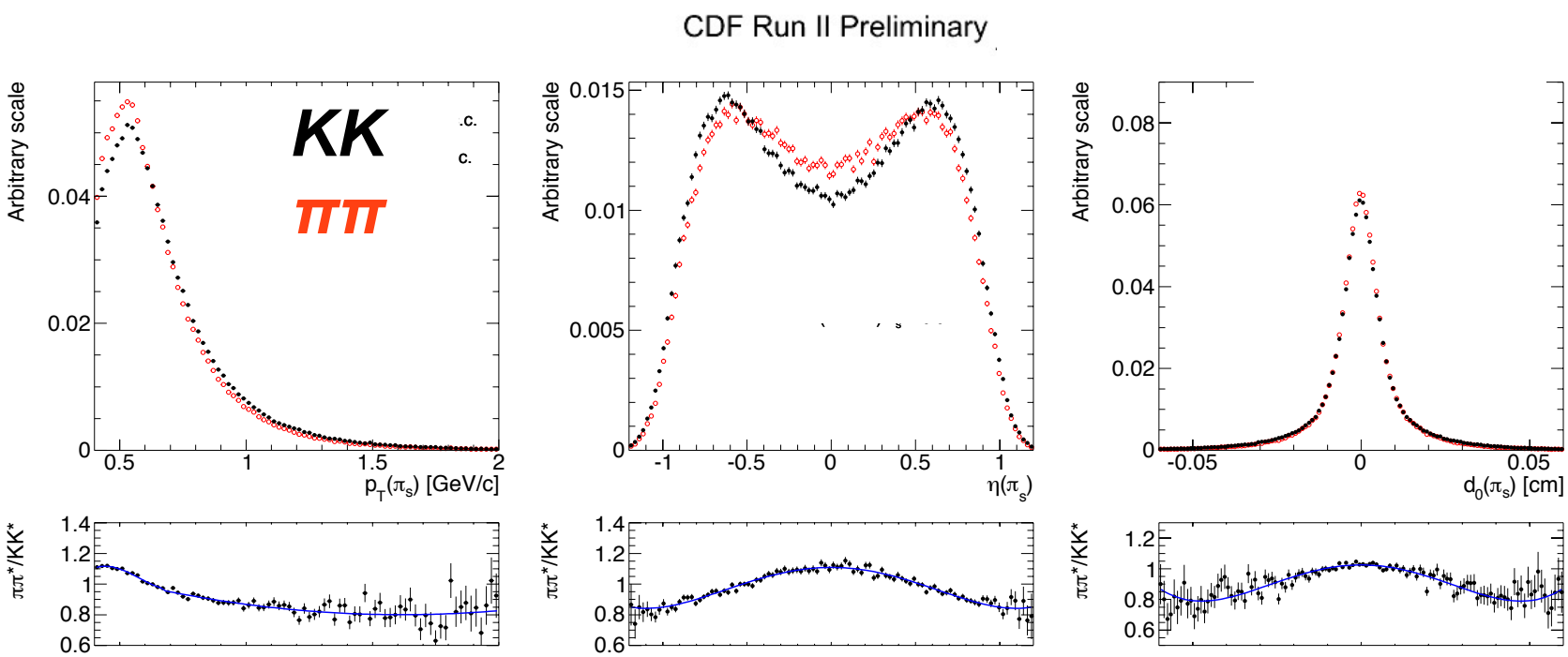
$A_{obs}(KK) = A_{CP}(KK) + \delta(\pi)$ $\qquad$ $A_{obs}(\pi\pi) = A_{CP}(\pi\pi) + \delta(\pi)$

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

Additional bonus: since most SM and BSM models predict asymmetries of opposite sign in KK and ππ, the difference is likely to be more sensitive to CPV than the individual asymmetries.

Kinematics differences

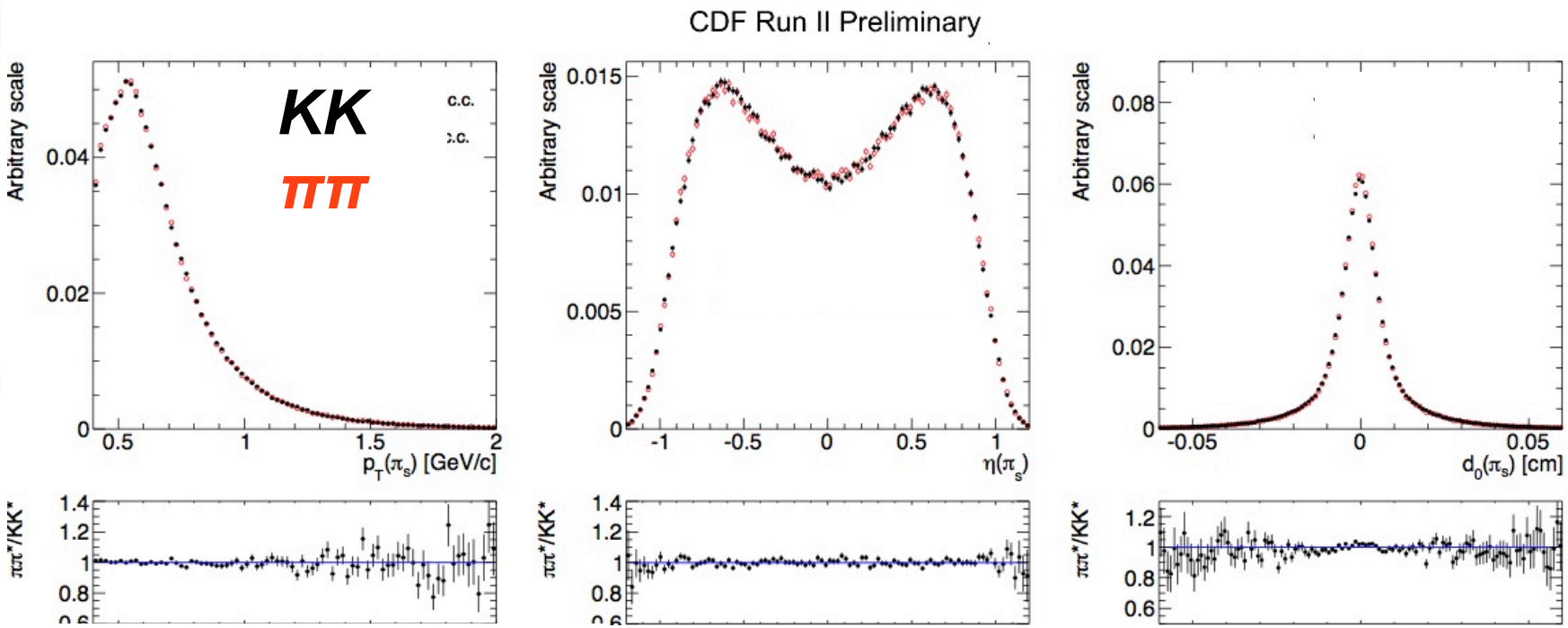
Instrumental effects depend on kinematics. Need to reweight KK and ππ kinematics for realizing cancellation



pion transverse momentum *pion pseudorapidity* *pion impact parameter*

Reweighting

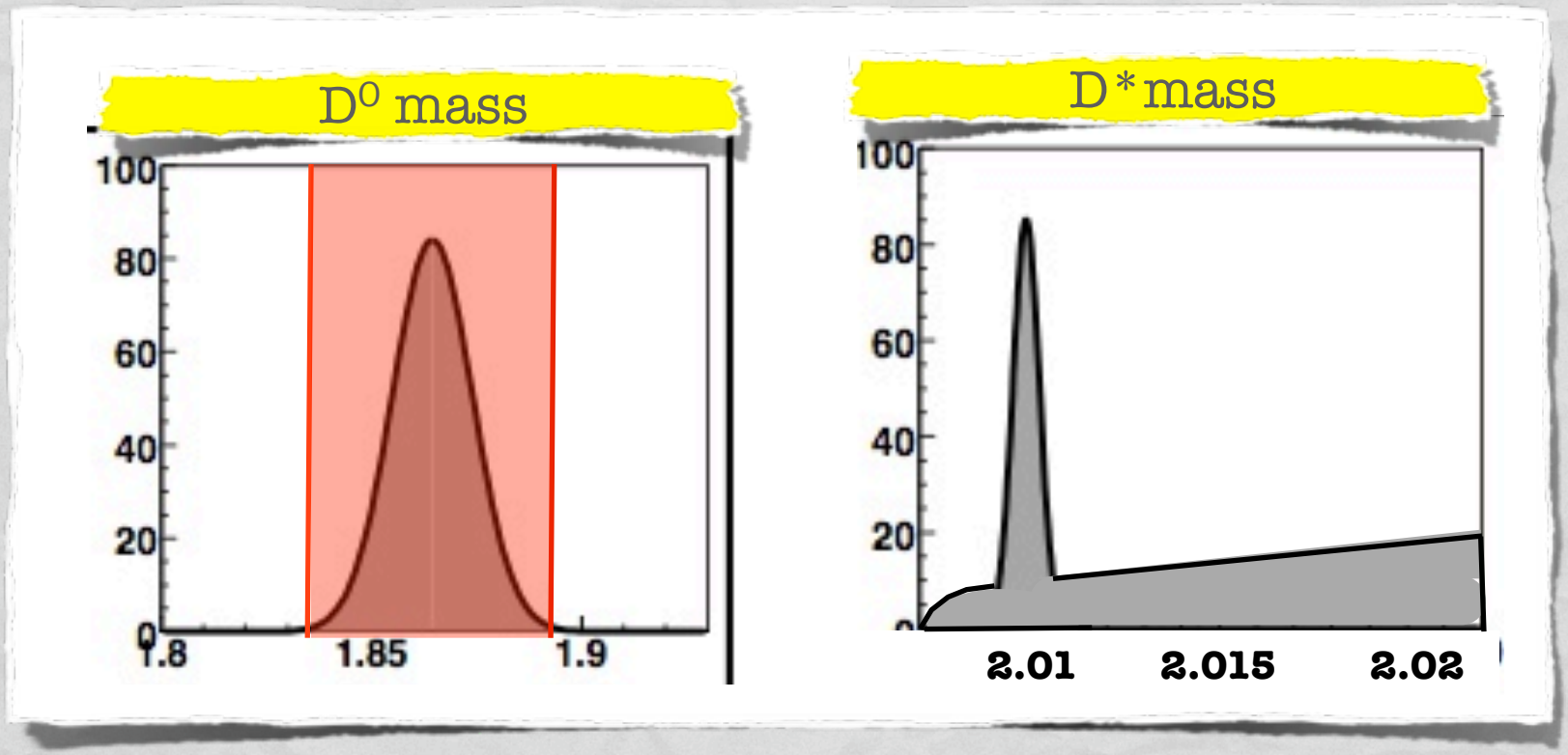
Reweight events so that kinematic distributions become equal



pion transverse momentum *pion pseudorapidity* *pion impact parameter*

Determining asymmetries

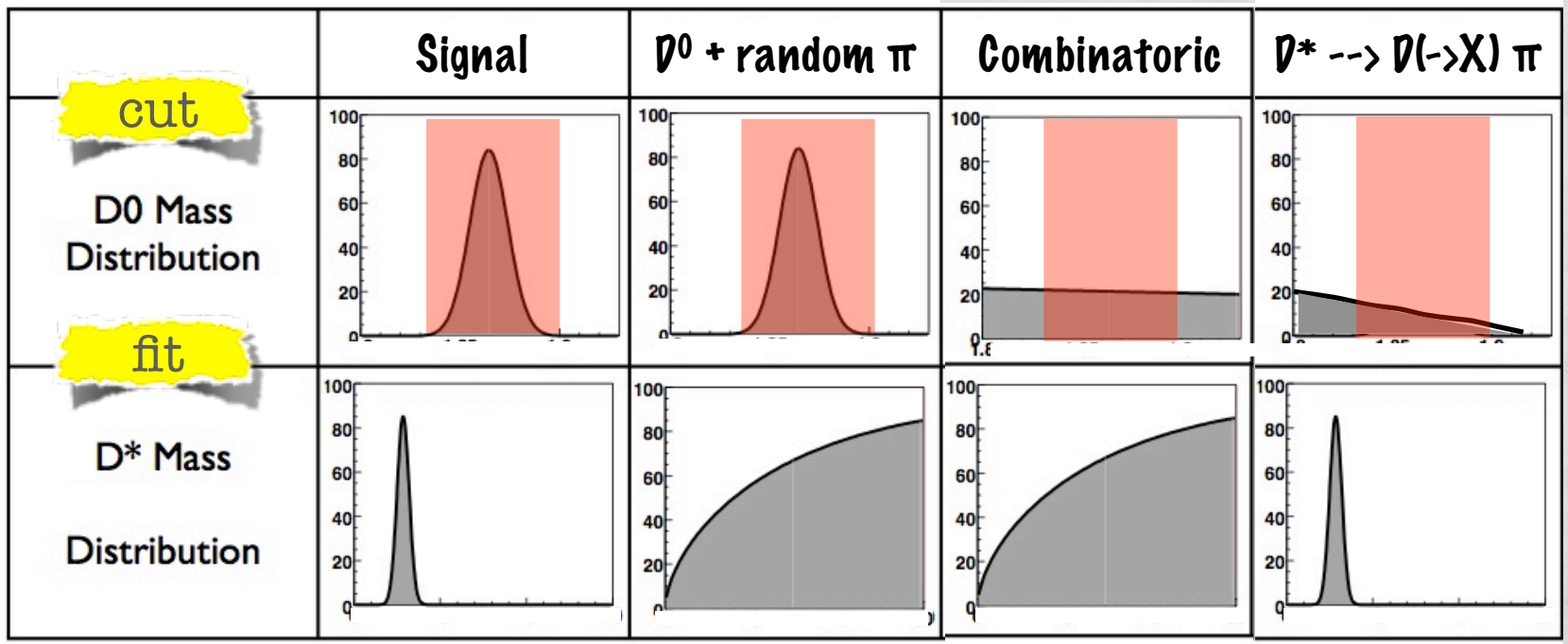
Two knobs to isolate signal and count events



Cut on this distribution

Fit this distribution for D*+ and D*- simultaneously

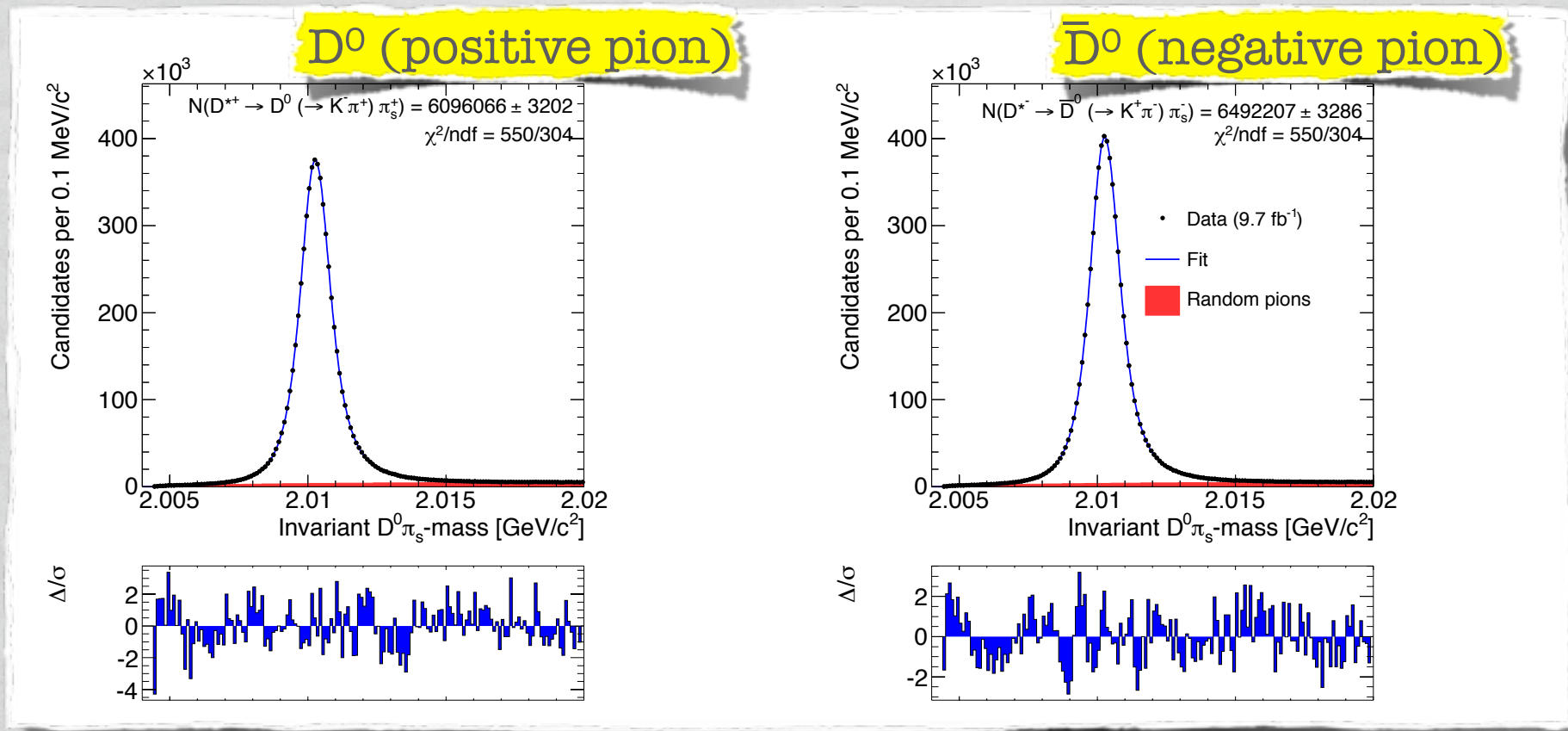
Sample composition



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

Remaining offender is D*->(D->X) π, which peaks in D* (eg D^0 --> K ππ). Most dangerous for KK. Get the shape from inclusive charm simulation and fit size in data.

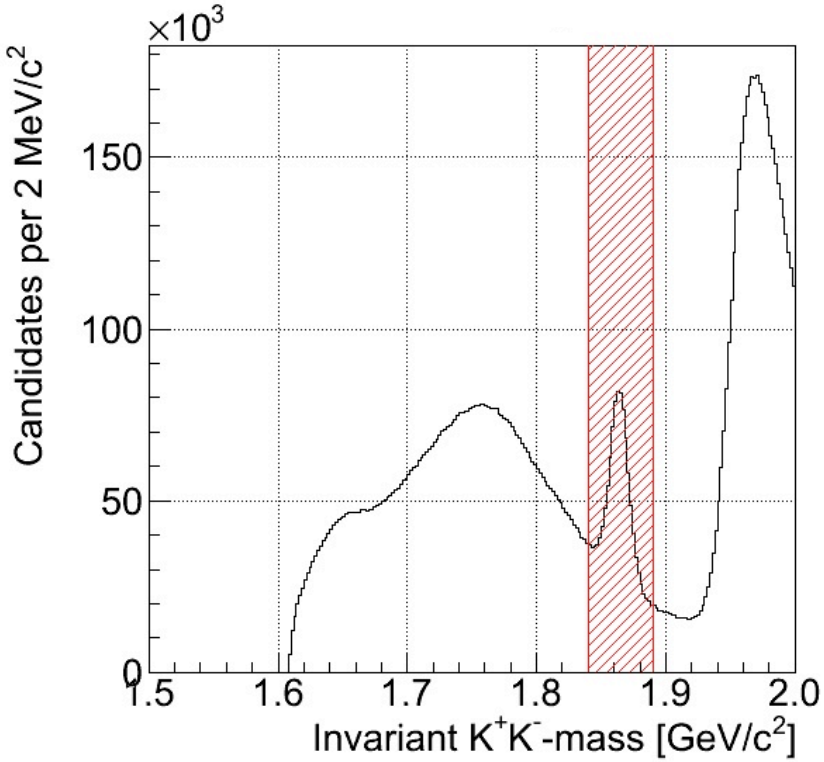
Getting the D* mass shapes

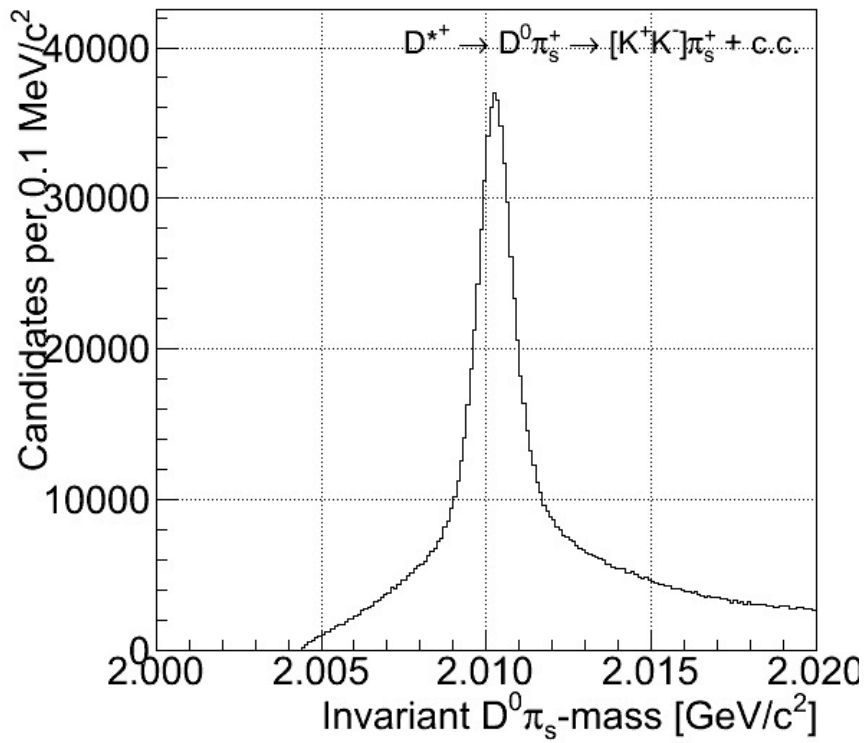


Signal: functional form from simulation. Tune parameters in 12.5M D^0->Kπ decays (10x more abundant wrt KK and ππ)

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

Cut on KK mass and fit D*mass





1.Cut on D^0 mass

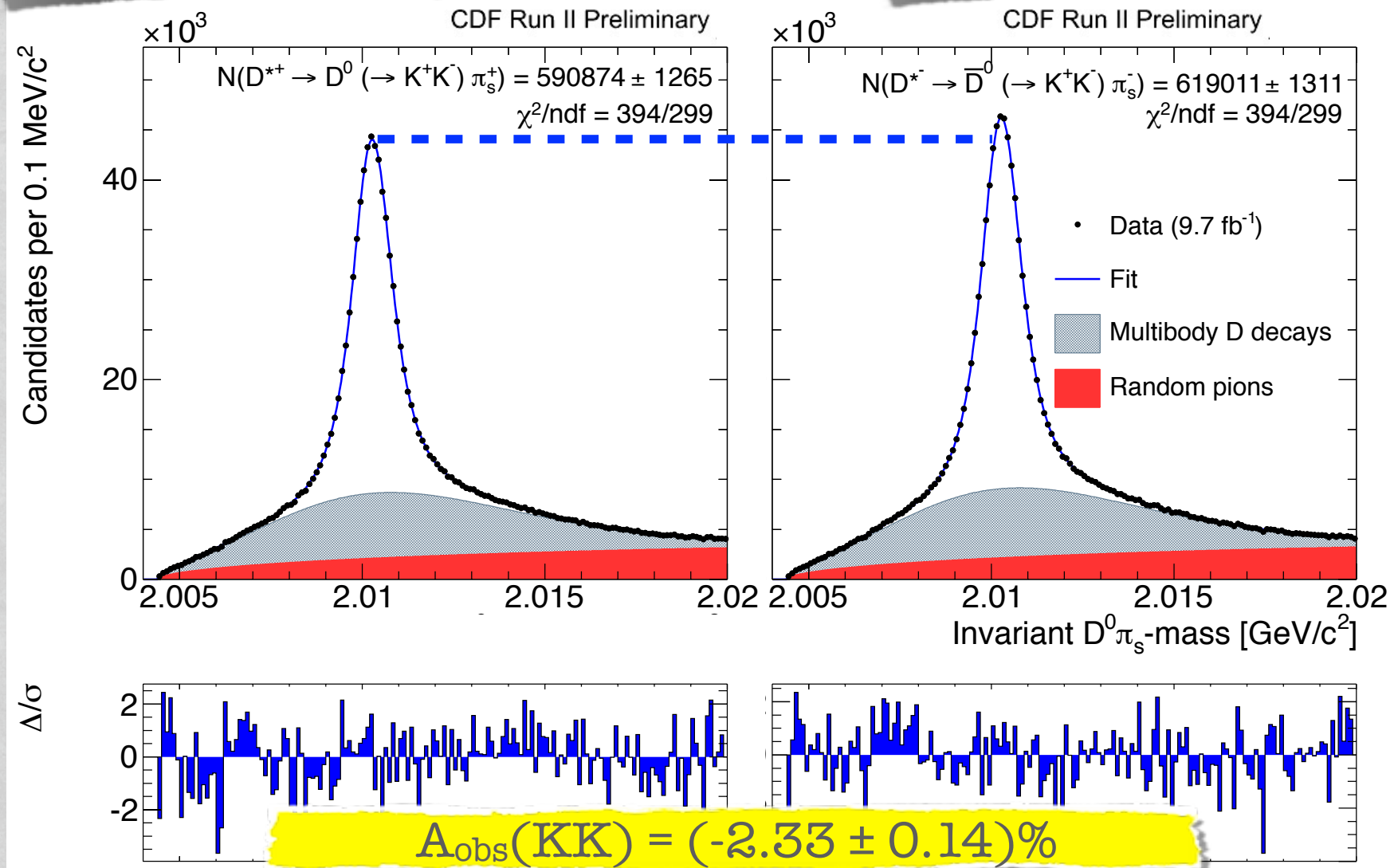
3. Fit in D*mass

2. Attach soft pion

D^0-->KK asymmetry

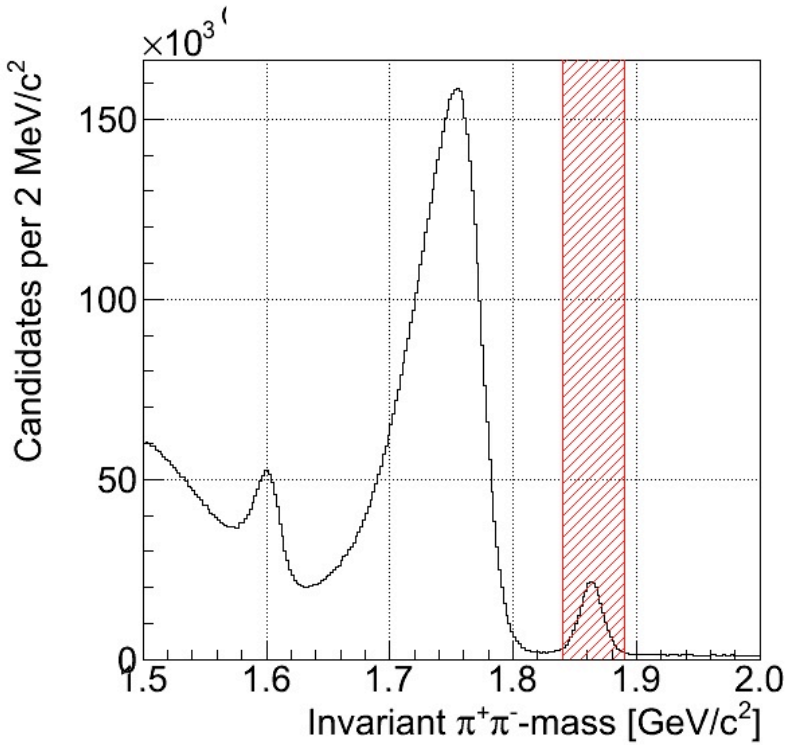
D^0 (positive pion)

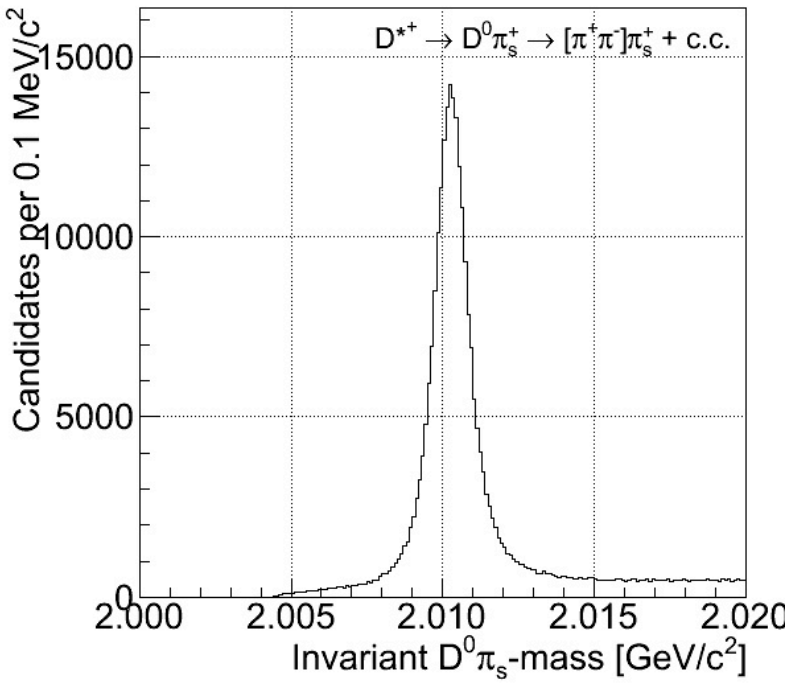
$\bar{D}^0$ (negative pion)



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

Cut on ππ mass and fit D* mass





1.Cut on D^0 mass

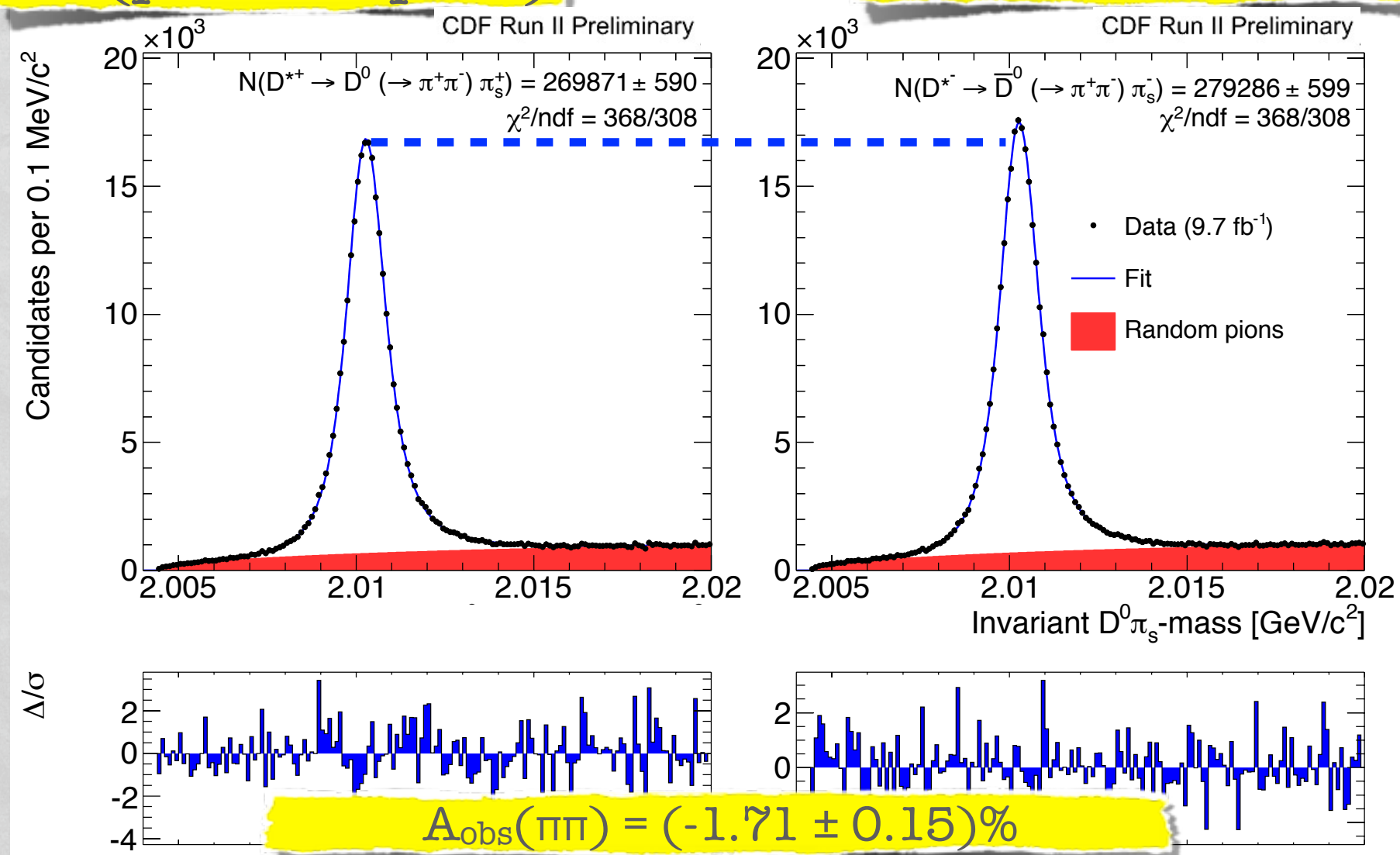
3. Fit in D* mass

2. Attach soft pion

$D^0 \to \pi\pi$ asymmetry

D^0 (positive pion)

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



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

Difference

Remember: 2% individual asymmetries include contributions from any physics asymmetry and the (dominant) instrumental asymmetry due to the soft pion.

Cancel the instrumental asymmetry:

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

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

Strong indication for a non-zero effect. Same direction and size as observed by LHCb. Same precision.

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

$\chi^2/ndf = 4.4/3$

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

$\chi^2/ndf = 0.38/1$

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

$\chi^2/ndf = 0.46/1$

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

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

CDF Public note 10784

This is 2.7σ different from zero, strongly indicating presence of CP violation in CDF charm data.

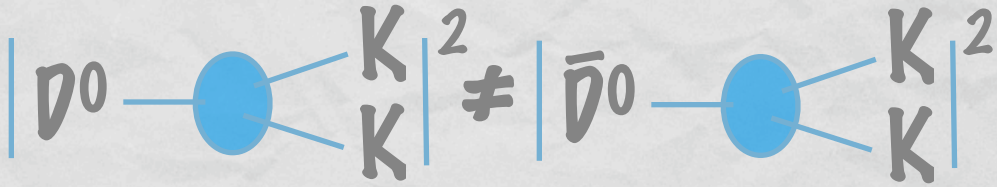
The uncertainty is 2 permil, dominated by the sample size.

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

Interpretation

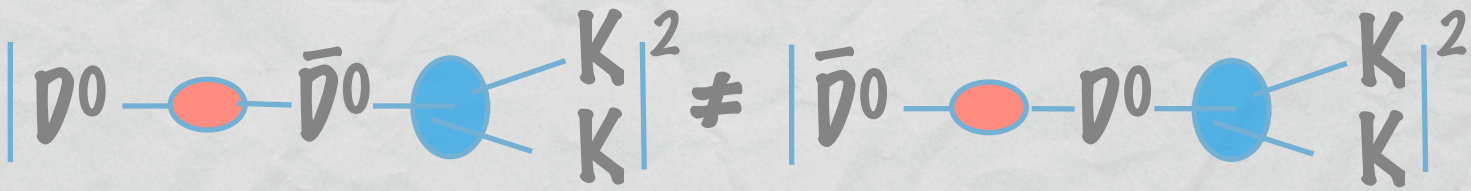
Direct

Decay-specific



Indirect

universal



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

<t> is the mean of the observed proper decay-time of D in each sample. About 2.5τ. Difference of asymmetries dominated by direct component

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

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

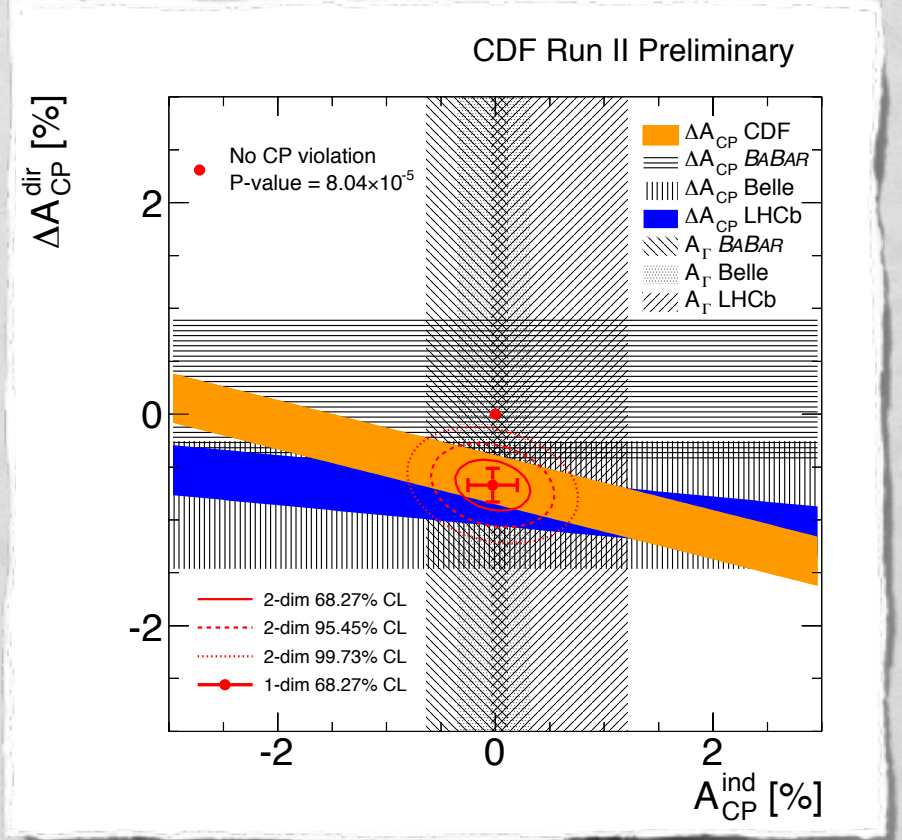
CP violation in charm

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

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

Slope is the difference in average decay-time between observed KK and ππ (experiment-dependent)

Combination assuming Gaussian uncertainties and no correlations excludes CP conservation in charm at 3.8σ



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

HFAG has very similar numbers

Hic sunt leones (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)

Resort to good ole data

Individual KK and ππ asymmetries probe whether the observed effect is likely due to hadronic corrections or BSM.

If rescattering is limited, then expect asymmetries of opposite sign and similar size.

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 (by CDF or anybody else)

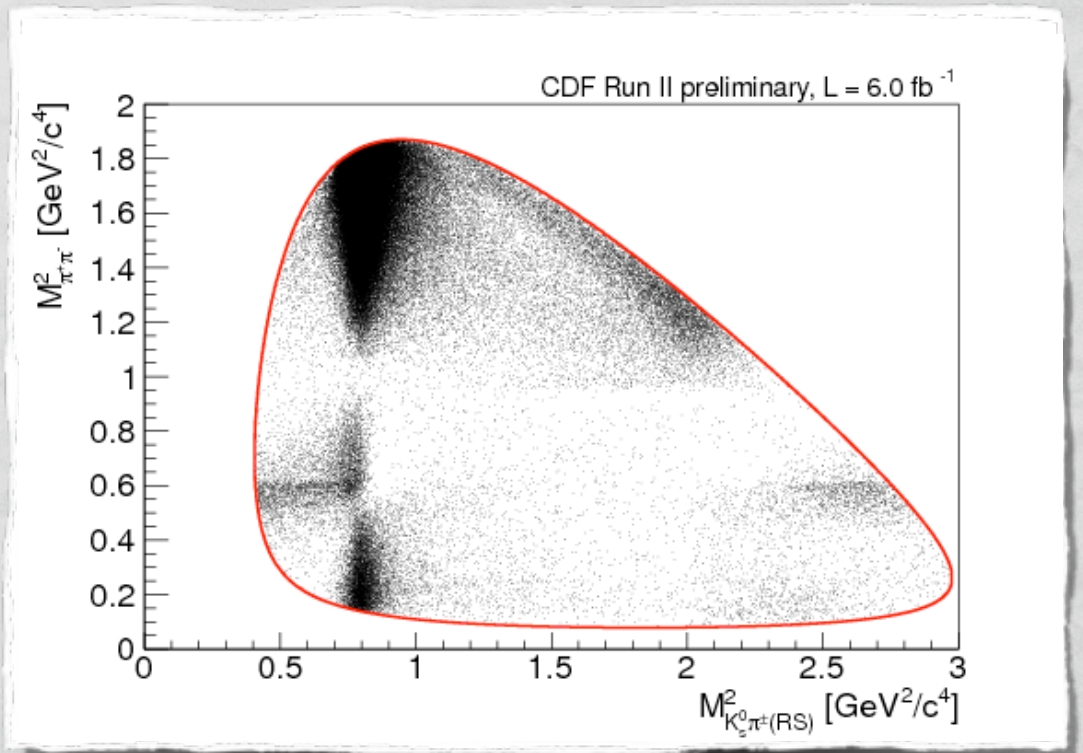
Expanding the portfolio

CPV in the resonant structures of D*-tagged $D^0 \to K_s\pi\pi$ decays.

First full Dalitz amplitude analysis in hadron collider.

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

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



A_{CP}= (-0.05 ± 0.57 ± 0.54)%

Just an example. Whole program available at CDF: $D^0 \to 4K$, $D^0 \to KK\pi\pi$, or $D^+ \to K^+\bar{K}^0$ and other SCS c->u penguin decays, as suggested in PRD 85, 054014 (2012)

Summary

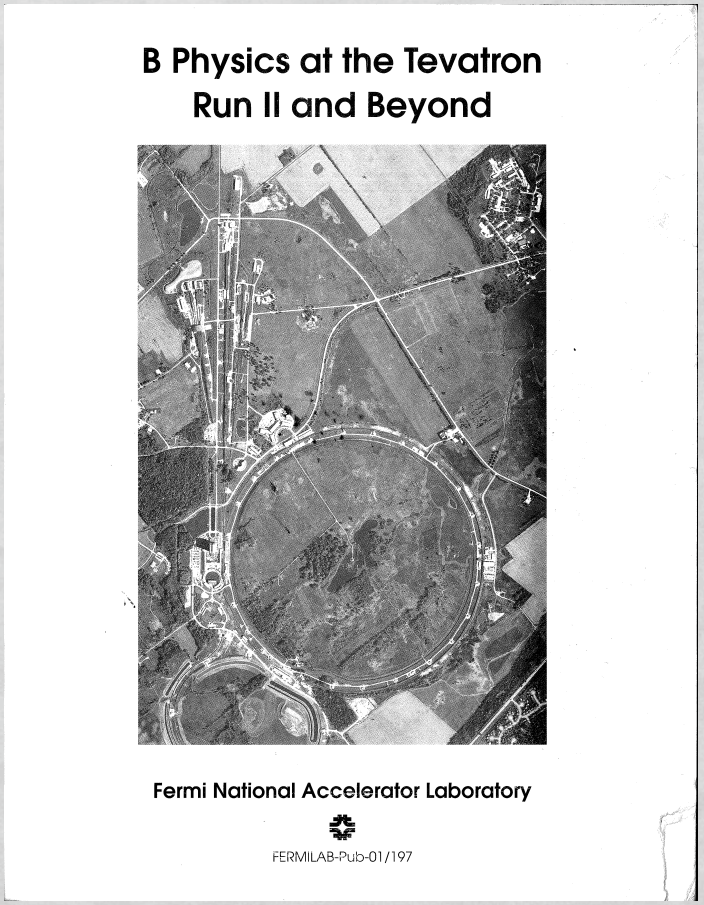
- Many open questions on current understanding of matter and interactions closely related to flavor.
- SM success doesn't preclude chance of detectable effects from BSM phenomena
- Charm physics promising (sensitive to up-type NP) and yet to be fully explored.
- CDF at the forefront of this effort: CP-invariant initial state, symmetric coverage, 10^7 reconstructed decays, accurate tracking.
- Updated measurement of CPV in D->hh decays using whole dataset finds strong indication of CPV in charm with a size suggestive of BSM physics. Supports similar results from LHCb and motivates further exploration

Charm Decay Factory

At the dawn of Run II: 550 pages of HF plans

..and not a single word on charm, which had become a small but high-impact portion of the CDF program:

- Ds+-D+ mass difference PRD68, 072004 (2003) 15 cit.
- Charm x-section PRL 91 241804 (2003) 139 cit.
- D->μμ PRD 68 091101 (2003) 31 cit. and PRD 82 091105 (2010) 5 cit.
- D->hh Br and CPV PRL 94, 122001 (2005) 55 cit. PRD 85, 012009 (2012) 20 cit.
- Excited D masses PRD 73 051104 (2006) 15 cit.
- D->Kπ WS analysis, PRD 74, 031109 (2005) 25 cit
- D mixing, PRL 100 121802 (2008) 111 cit.
- Charm baryons, PRD 84, 012003 (2011), 6 cit.


B Physics at the Tevatron
Run II and Beyond

Fermi National Accelerator Laboratory

FERMILAB-Pub-01/197

the end

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 $A_1, A_2 \approx O(\%)$

Individual asymmetries

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

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

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

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

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

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

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

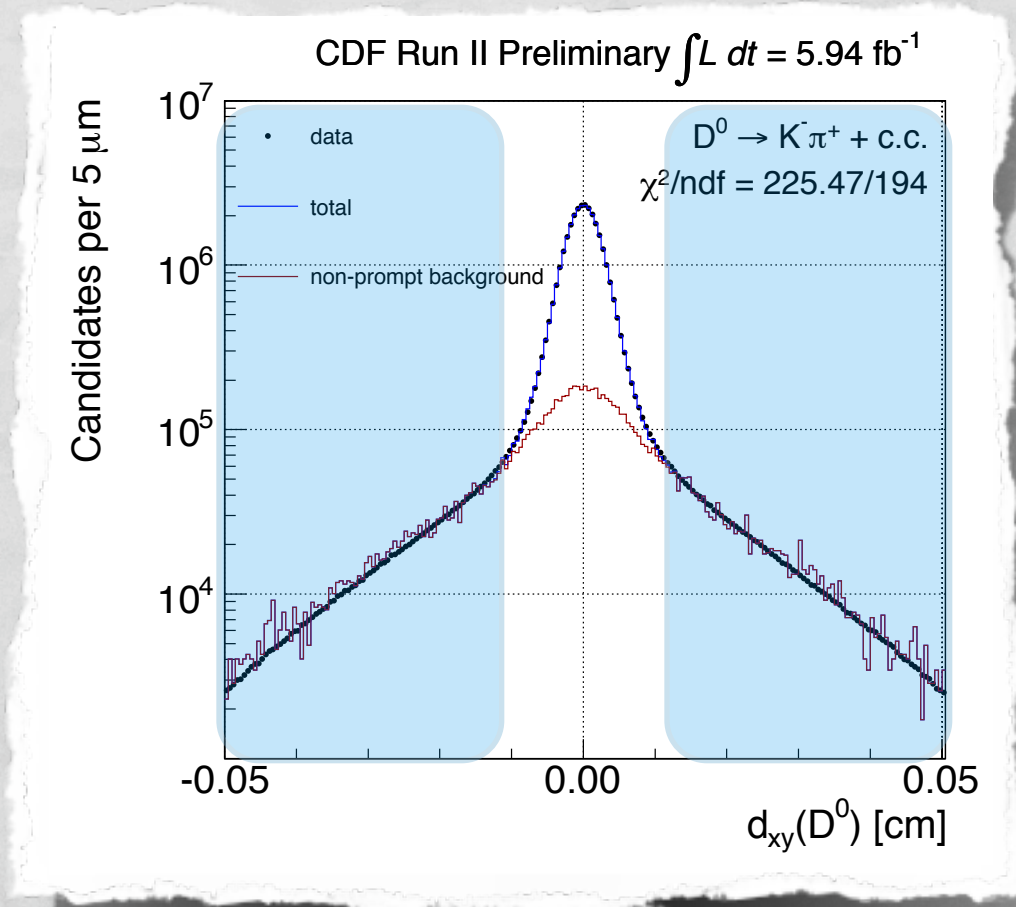
Secondary charm

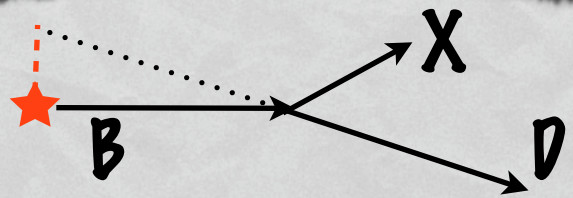
$c\tau(B) \approx 450$ microns

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



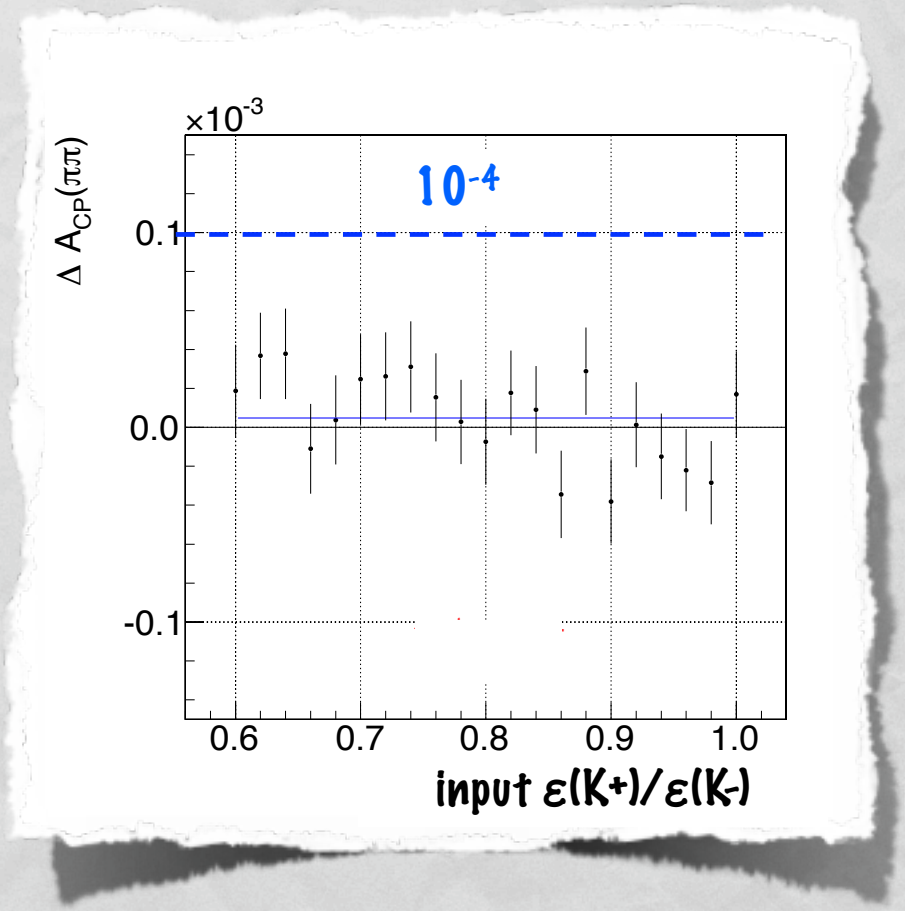


Higher order effetcs

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