CHARM AT CENTRAL COLLIDER DETECTOR(S)

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on behalf of CDF/DO/ATLAS/CMS coll.

Hadron Collider Physics Symposium, Kyoto 12 Nov 2012

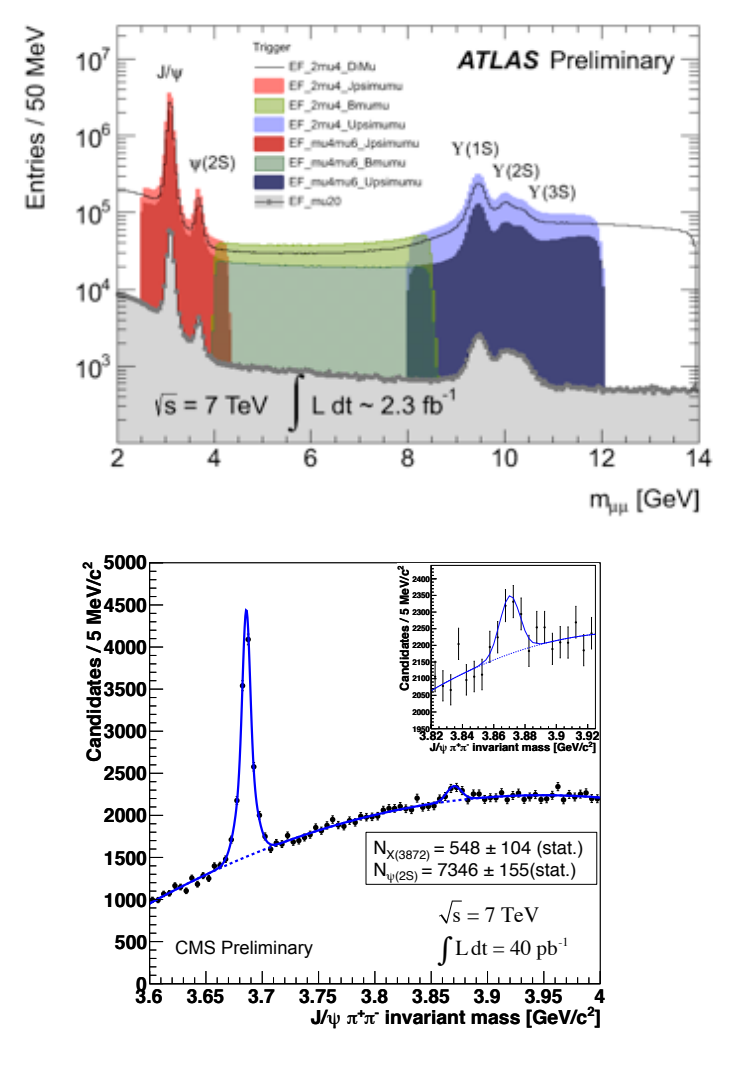
OUTLINE

- Open Charm production from Tevatron to LHC
- Two body $D^0 \rightarrow hh'$ decays at CDF
- Search for CP-violation in Dalitz $D^0 \rightarrow K_s \pi\pi$
- Conclusion

CHARM PRODUCTION

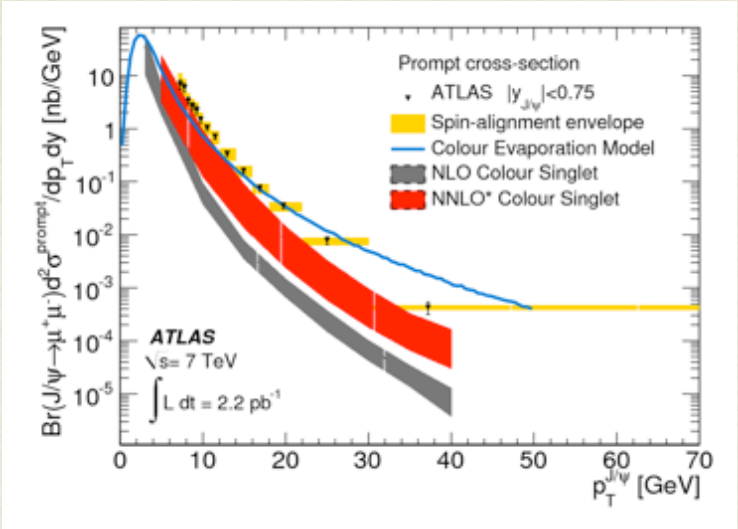
HIDDEN CHARM PRODUCTION/1

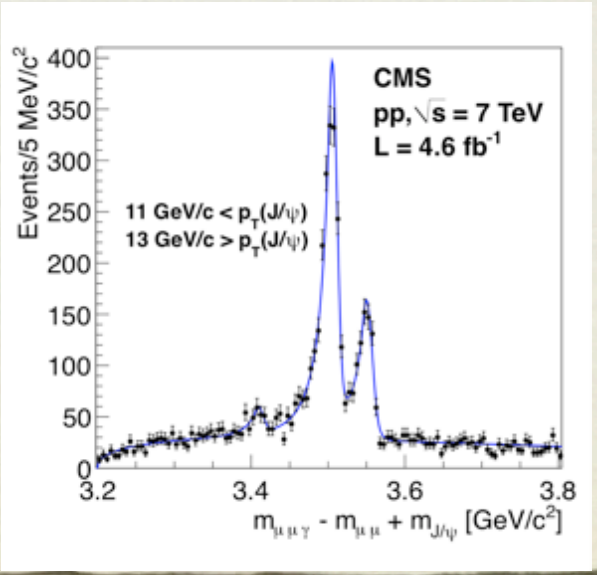
- High statistics samples collected with $\mu^+\mu^-$ decays
- Detailed investigations of charmonium cross section and polarizations from Tevatron and LHC experiments
- Also X(3872) production measurement [**CMS PAS BPH-10-0 18**]
- More results on charmonium/ bottomonium/spectroscopy in parallel session Wednesday



CHARMONIUM PRODUCTION/2

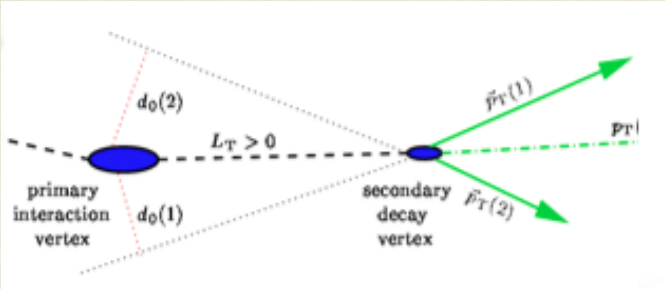
- J/psi and psi(2S) cross section at 7 TeV from prompt and non-prompt decays
- compared to:
  - NNLO color singlet model, reasonable but not perfect agreement ATLAS [Nucl.Phys. B 850(2011) 387]
  - NRQCD color singlet + color octet (fit to Tevatron data) model CMS data better [JHEP 02 (2012) 011]
- Other inputs needed, as an example:
- Relative χ_{c1}/χ_{c2} cross section ratio using converted photons from CMS [arXiv: 1210.0875]





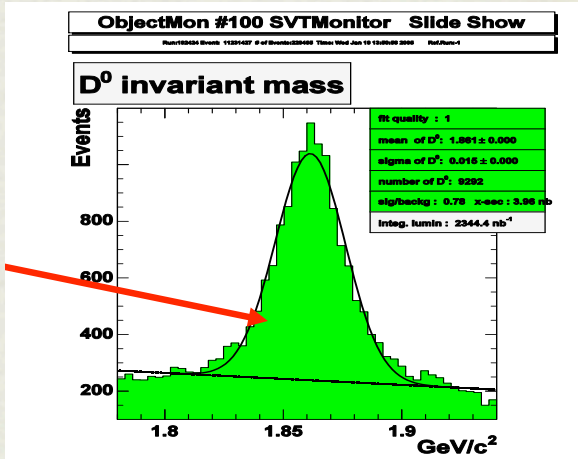
OPEN CHARM PRODUCTION

- Need dedicated trigger to collect a viable sample due to the overwhelming hadronic background at colliders



- Fully reconstructed hadronic decays from the displaced track trigger at CDF

- Online detection of the $D^0 \rightarrow K^- \pi^+$ peak: an unexpected success

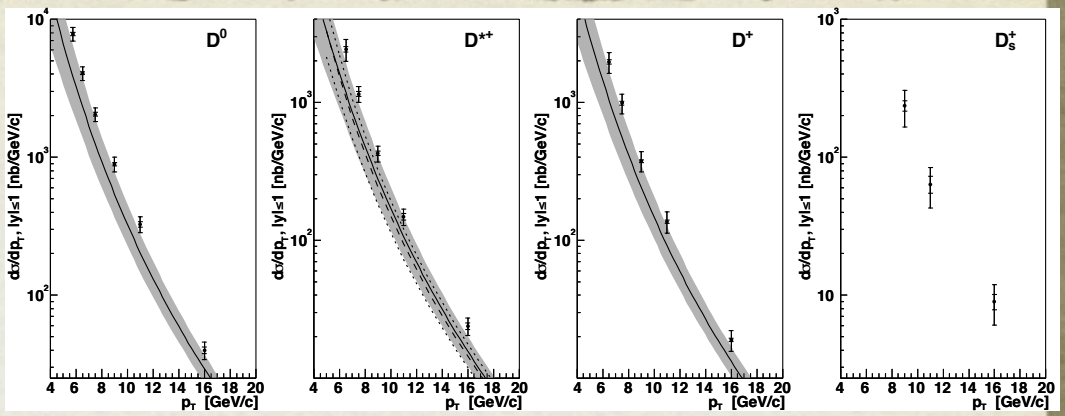


A window of opportunity for precison charm physics

at Tevatron Run II opened by a trademark CDF trigger

OPEN CHARM PRODUCTION/CDF

- Early measurement from CDF Run II (6 pb^{-1})
- D^0, $D^{\pm}$,$D^{*\pm}$, D_s samples collected with displaced track trigger
- Prompt charm fraction determined from reconstructed impact parameter of D mesons
- pQCD calculations at NLO, within a factor of 2 of measurements (large th. uncertainties)
  - A long list of CDF charm paper followed



Charm x-section PRL 91 241804 (2003) 139 cit.

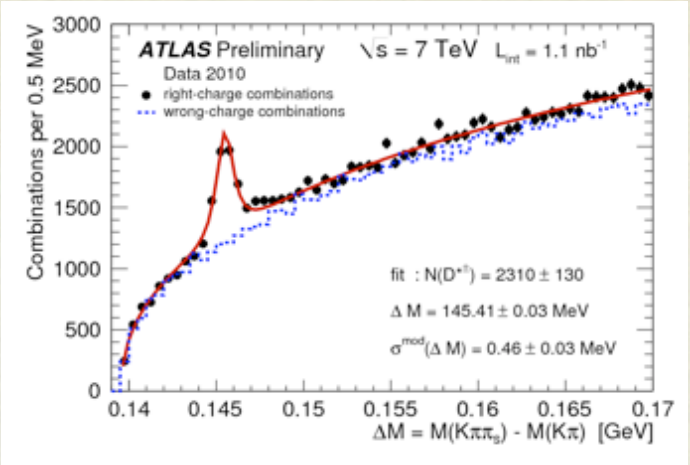
- Ds+-D+ mass difference PRD68, 072004 (2003) 15 cit.
- D->μμ PRD 68 091101 (2003) 31 cit. and PRD 82 091105 (2010) 5 cit.
- D->hh Br and CPV PRL 94, 122001 (2005) 55 cit. PRD 85, 012009 (2012) 20 cit.
- Excited D masses PRD 73 051104 (2006) 15 cit.
- D->Kπ WS analysis, PRD 74, 031109 (2005) 25 cit
-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

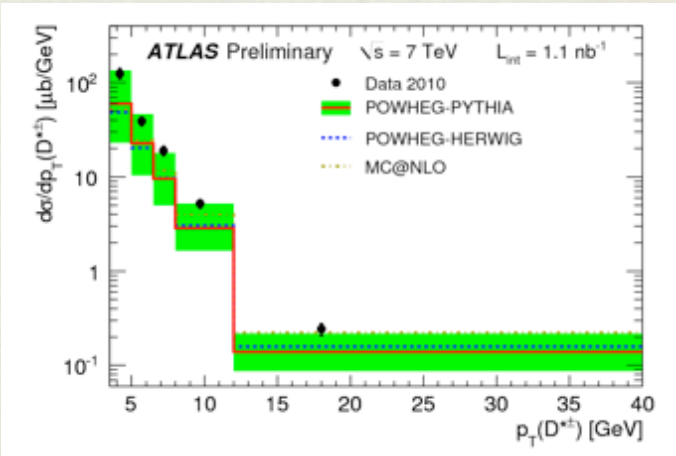
OPEN CHARM PRODUCTION/LHC

- Early production studies from Atlas and CMS limited to minimum bias samples
- Viable only at very low inst. luminosity
- Atlas measurement for $p_T(D^{(*)}) > 3.5$ GeV and $|\eta(D^{(*)})| < 2.1$ [ATLAS-CONF-2011-017]

$$\sigma^{vis}(D^{*\pm}) = 285 \pm 16(\text{stat.})^{+32}_{-27}(\text{syst.}) \pm 31(\text{lum.}) \pm 4(\text{br.})\,\mu\text{b},$$
$$\sigma^{vis}(D^{\pm}) = 238 \pm 13(\text{stat.})^{+35}_{-23}(\text{syst.}) \pm 26(\text{lum.}) \pm 10(\text{br.})\,\mu\text{b},$$
$$\sigma^{vis}(D^{\pm}_s) = 168 \pm 34(\text{stat.})^{+27}_{-25}(\text{syst.}) \pm 18(\text{lum.}) \pm 10(\text{br.})\,\mu\text{b},$$

- Powheg MC shows similar agreement as seen as Tevatron with NLO calculations





CHARM DECAYS

TWO BODY D^0 DECAYS @ CDF/TIMELINE

- Single Cabibbo suppressed decay BR and A_{CP}: 120 pb^{-1} [Phys. Rev. Lett. 94, 122001 (2005)]
- Doubly Cabibbo suppressed decays and evidence for mixing [PRD RC 74, 031109 2006, Phys. Rev. Lett. 100, 121802 (2008)]
- Precision measurement of CP asymmetries 6fb^{-1}/2011 [Phys. Rev. D 85, 012009 (2012)]
- Evidence for ΔA_{CP}, full Run II stat. earlier this year [Phys. Rev. Lett. 109, 111801 (2012)]

Measurement of Partial Widths and Search for Direct CP Violation in D^0 Meson Decays to K^-K^+ and $\pi^-\pi^+$

D. Acosta,[16] T. Affolder,[9] T. Akimoto,[54] M.G. Albrow,[15] D. Ambrose,[43] S. Amerio,[42] D. Amidei,[33] A. Anastassov,[56] K. Anikeev,[31] A. Annovi,[44] J. Antos,[1] M. Aoki,[54] G. Apollinari,[15] T. Arisawa,[56] J-F. Arguin,[32] A. Artikov,[13] W. Ashmanskas,[15] A. Attal,[7] F. Azfar,[41] P. Azzi-Bacchetta,[42] N. Bacchetta,[42] H. Bachacou,[28] W. Badgett,[15]

Evidence for $D^0 - \bar{D}^0$ Mixing Using the CDF II Detector

T. Aaltonen,[23] J. Adelman,[13] T. Akimoto,[54] M.G. Albrow,[17] B. Álvarez González,[11] S. Amerio,[42] D. Amidei,[34] A. Anastassov,[51] A. Annovi,[19] J. Antos,[14] M. Aoki,[24] G. Apollinari,[17] A. Apresyan,[47] T. Arisawa,[56] A. Artikov,[13] W. Ashmanskas,[17] A. Attal,[3] A. Aurisano,[52] F. Azfar,[41] P. Azzi-Bacchetta,[42] P. Azzurri,[45] N. Bacchetta,[42] W. Badgett,[17] A. Barbaro-Galtieri,[28] V.E. Barnes,[47] B.A. Barnett,[25] S. Baroiant,[7] V. Bartsch,[30] G. Bauer,[32]

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

T. Aaltonen,[21] B. Álvarez González[z],[9] S. Amerio,[40] D. Amidei,[32] A. Anastassov[x],[15] A. Annovi,[17] J. Antos,[12] G. Apollinari,[15] J.A. Appel,[15] T. Arisawa,[54] A. Artikov,[13] J. Asaadi,[49] W. Ashmanskas,[15] B. Auerbach,[57] A. Aurisano,[49] F. Azfar,[39] W. Badgett,[15] T. Bae,[25] A. Barbaro-Galtieri,[26] V.E. Barnes,[44] B.A. Barnett,[23]

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

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Ground breaking work @ hadronic collider

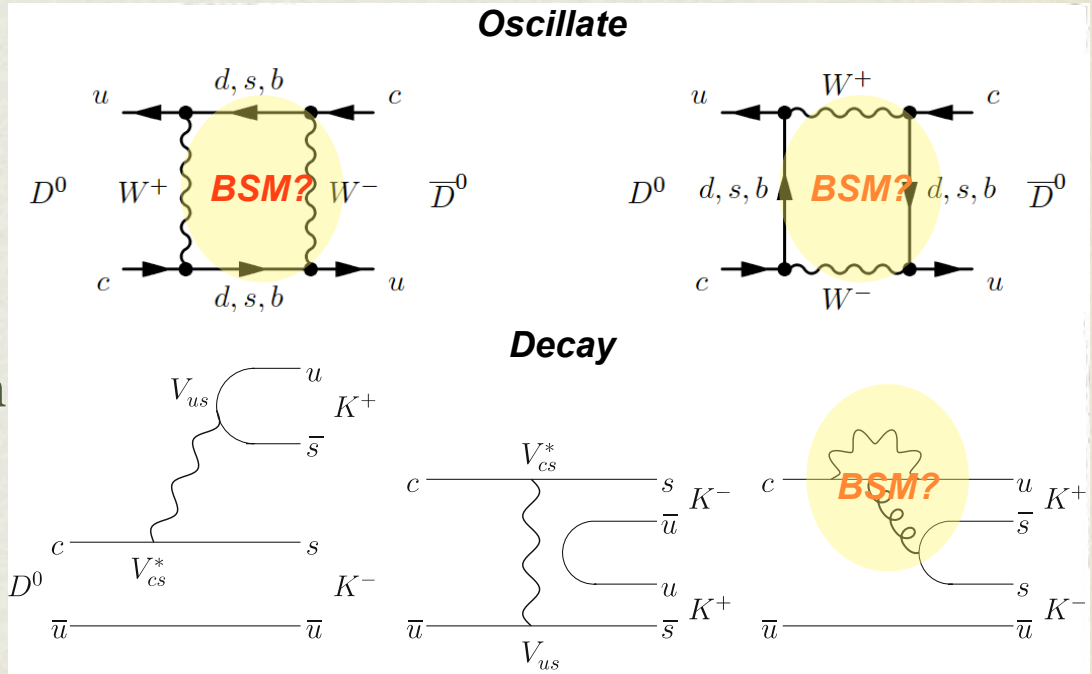
SINGLE CABIBBO SUPPRESSED DECAYS

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

$\bar{D}^0 \to \pi^+\pi^-,\ \bar{D}^0 \to K^+K^-$

→ indirect CP violation ?

- Tree and penguin diagram contribute
- Cabibbo suppressed tree diagram may allow competition of non SM processes
- A natural play ground for testing SM and looking for deviations



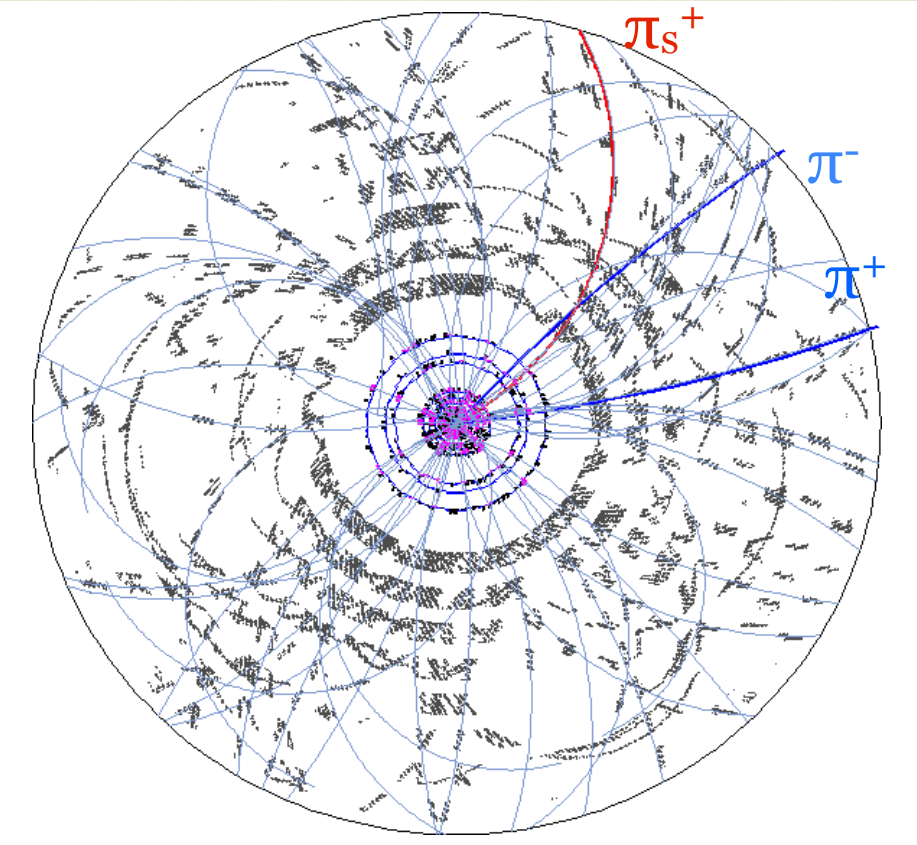
$$A_{\rm CP}(D^0 \to h^+h^-) = \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\overline{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\overline{D}^0 \to h^+h^-)}.$$

CLEAN D*+ SIGNALS

- Flavor at production given by D* tagging, exploting CP symmetric nature of strong interactions:

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

- Excellent momentum and vertexing resolution allow for extra clean signals

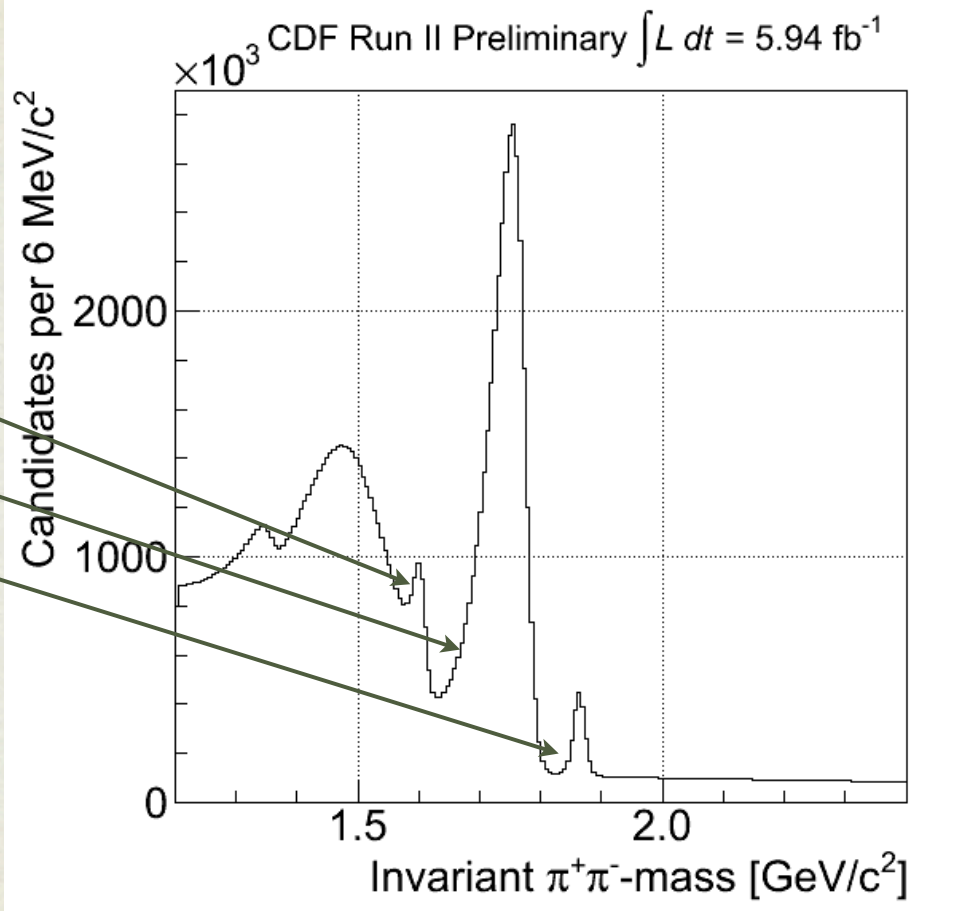


VERY LARGE SAMPLES IN TEVATRON RUN II

- ππ mass spectrum for D* tagged two body decays

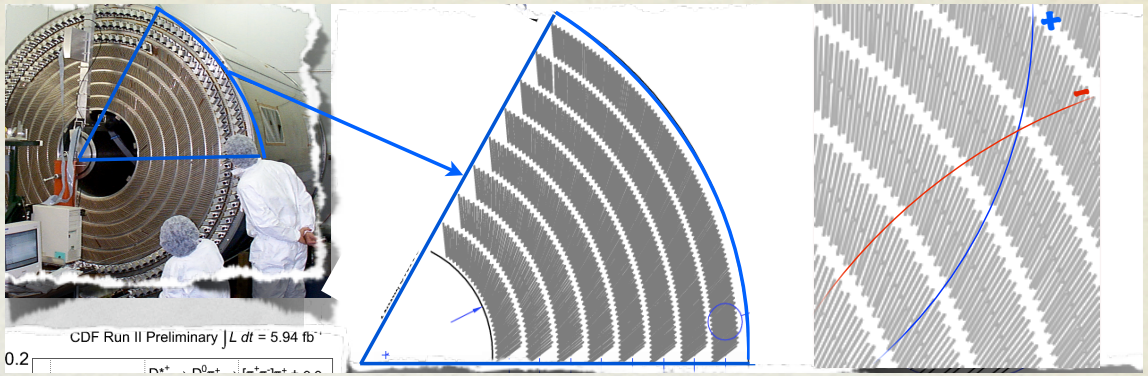
$$N(K^+K^-) = 476 \times 10^3$$
$$N(K\pi) = 5 \times 10^6$$
$$N(\pi^+\pi^-) = 215 \times 10^3$$

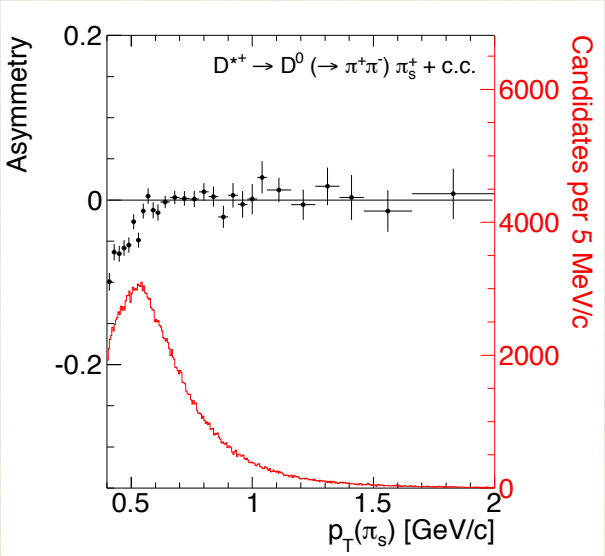
- 4 times larger than equivalent at B-factories (0.5 ab^{-1}) ... LHCb on another track



CONTROLLING DETECTOR CHARGE ASYMMETRIES

- Exploit charge symmetric initial state at Tevatron proton-antiproton collider to measure CP violation at the few per mil level
- Detector induced charge asymmetry at O(1%) level, need to control those with great precision
- Fully data driven method





METHOD

- Very similar decay kinematics for the decay modes:

$$D \to hh' \; (h = K, \pi)$$

- Exploit the more abundant $D \to K\pi$ tree level decay to subtract charge asymmetry in slow pion detection

- Further subtract measured asymmetry in Kπ to control $K^+\pi^-$ vs $K^-\pi^+$ effects

- Residual effects expected much smaller than experimental sensitivity (10^{-4})

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

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

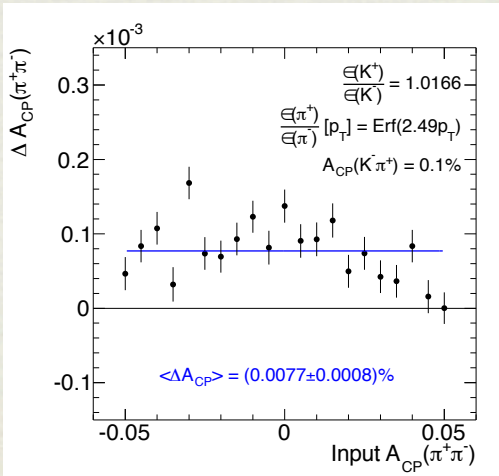
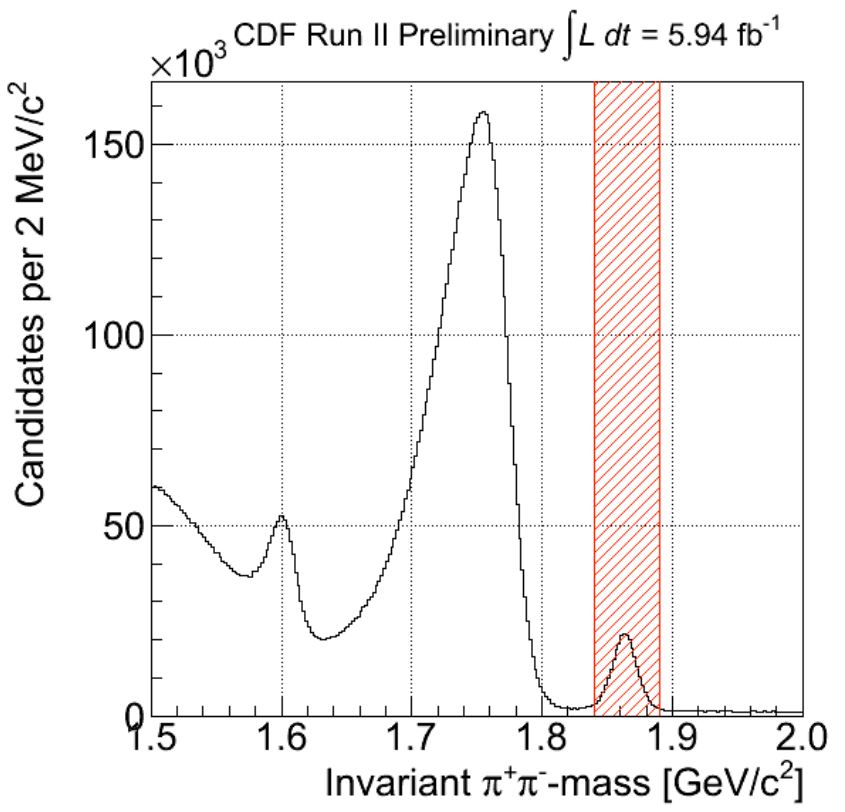
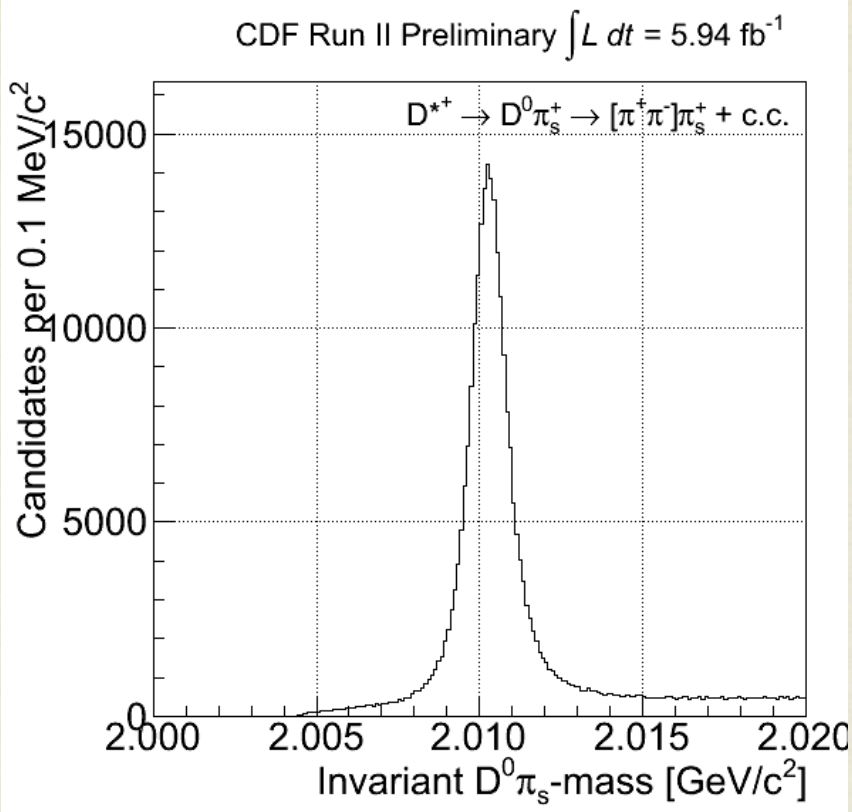


FIG. 20. Asymmetry residual as a function of the physical CP–violating asymmetry in $D^0 \to \pi^+\pi^-$ decays. Realistic effects other than shown in the scan are also simulated. The line represents the value averaged over the $-5\% < A_{CP}(\pi\pi) < 5\%$ range.

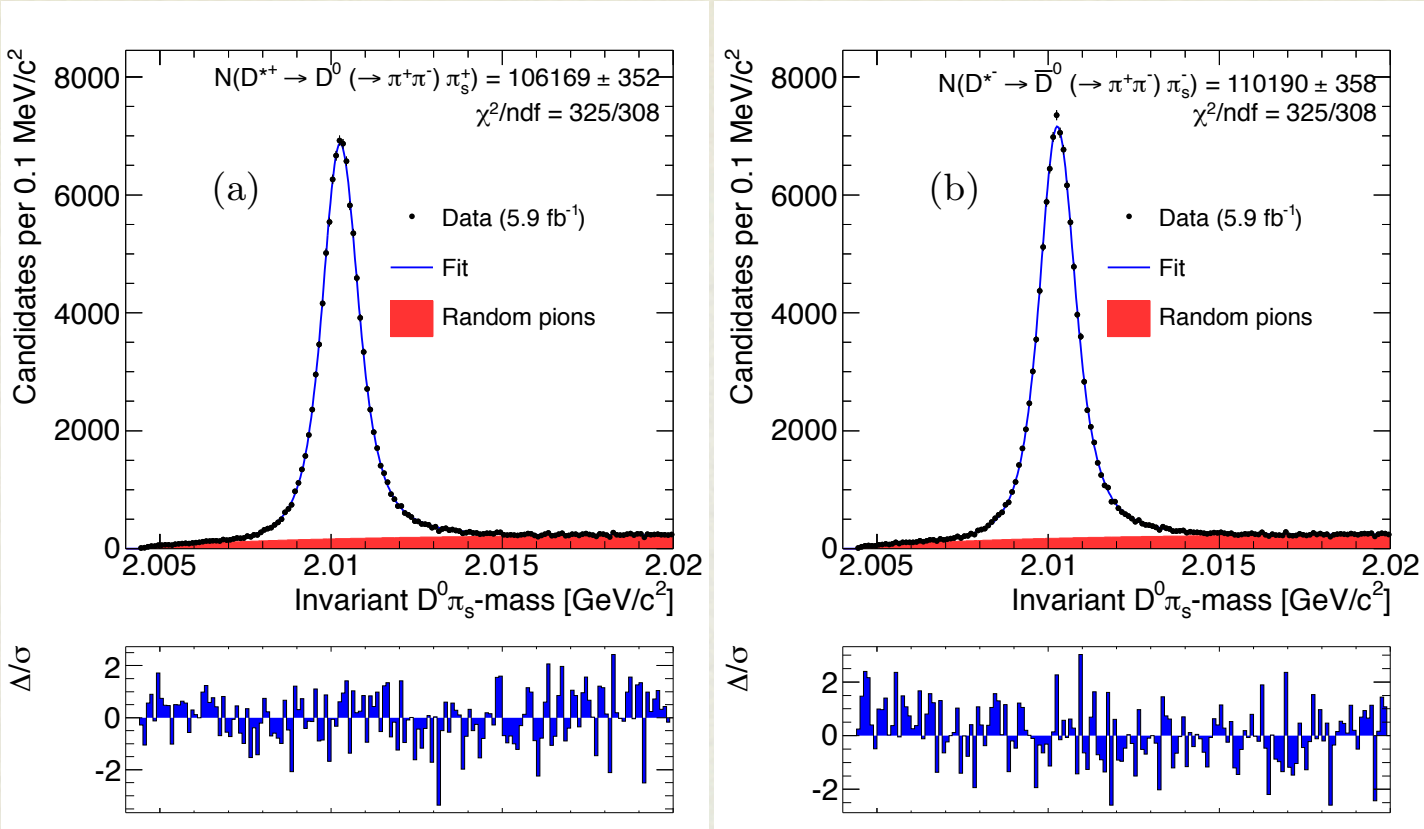
D* SIGNAL SHAPE





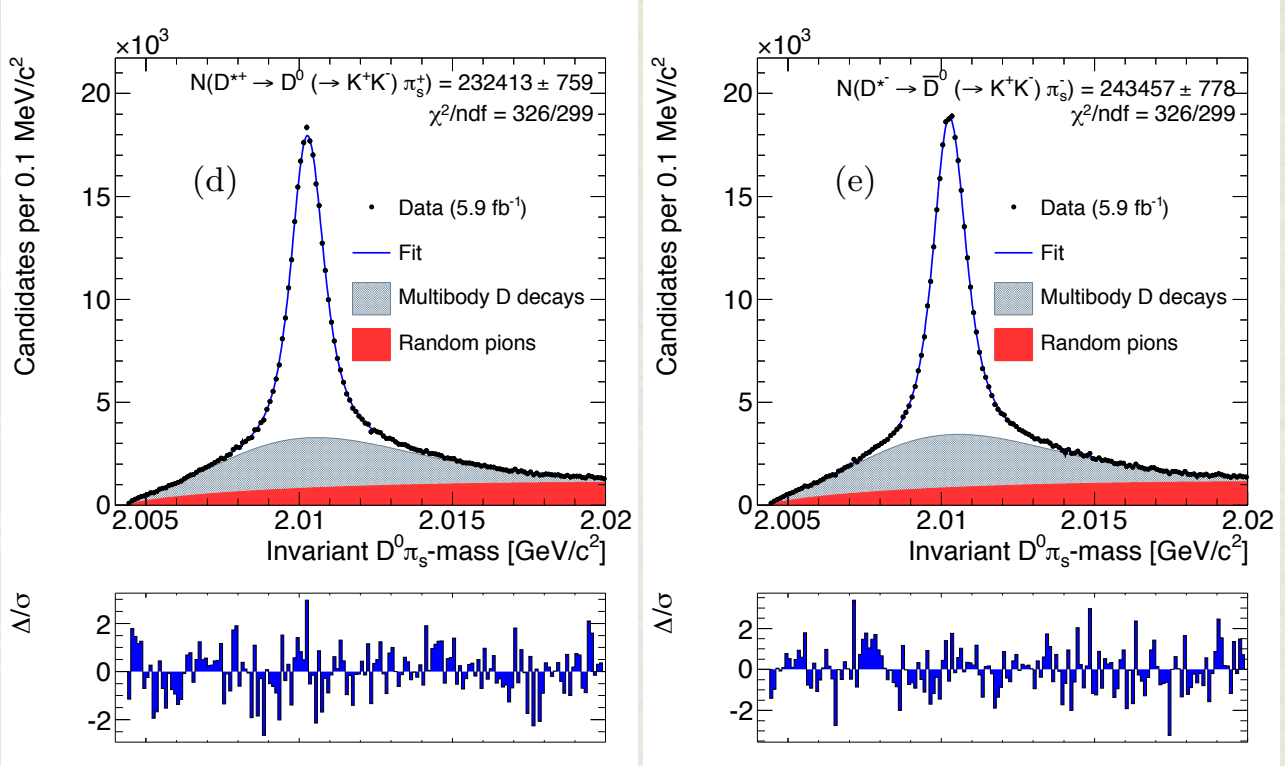
- Select D^0 within ± 24 MeV (3 sd of the mass measurement) → fit $D^{*\pm}$ mass

A(ππ*) FIT



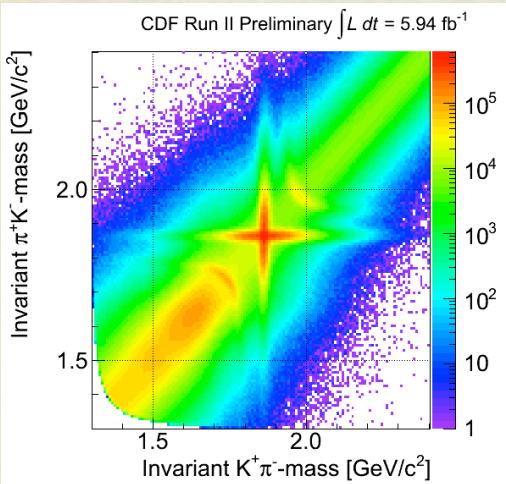
- Joint fit to the + and - sample allowing for different shape parameters and backgrounds
- Random association of unrelated pion to real D⁰'s from *random association* of a D⁰ candidate with soft pion tracks from different events

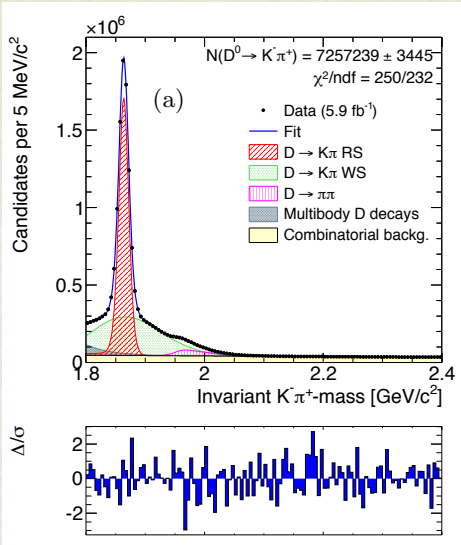
A(KK*) FIT

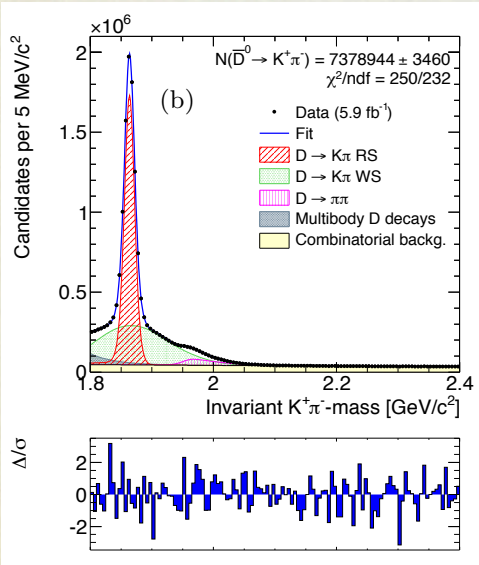


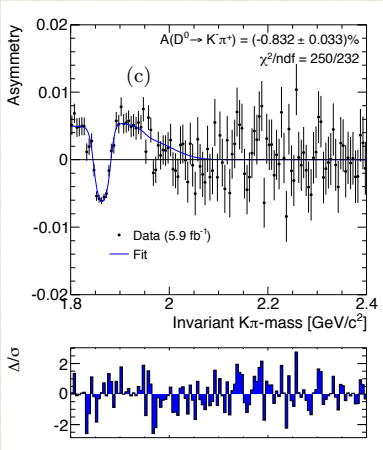
- Same as in the ππ case but consider also multibody (partially reconstructed) D decays: shape from inclusive charm decay simulation, normalization from data

DETERMINING $K^+\pi^-$ vs $K^-\pi^+$ ASYMMETRY









- Randomly divide untagged decays in two samples reconstructed as $K^+\pi^-$ or $K^-\pi^+$
- Fit the right sign, wrong sign and background to determine the asymmetry
- Assuming no CP violation determine

$$\begin{aligned} A_{K\pi} &= A_{CP}(K\pi) + \delta(K\pi) = \delta(K\pi) \\ &= (-0.834 \pm 0.033)\% \end{aligned}$$

TIME INTEGRATED CP ASYMMETRY

- Time dependent asymmetry due to D^0 mixing

$$A_{CP}(h^+h^-,t) = \frac{N(D^0 \to h^+h^-;t) - N(\overline{D}^0 \to h^+h^-;t)}{N(D^0 \to h^+h^-;t) + N(\overline{D}^0 \to h^+h^-;t)}$$

- However the mixing rate is low so to first order

$$A_{CP}(h^+h^-;t) \approx A_{CP}^{\rm dir}(h^+h^-) + \frac{t}{\tau}\ A_{CP}^{\rm ind}(h^+h^-)$$

$$A_{CP}^{\rm dir}(h^+h^-) \equiv A_{CP}(t=0) = \frac{\left|\mathcal{A}(D^0 \to h^+h^-)\right|^2 - \left|\mathcal{A}(\overline{D}^0 \to h^+h^-)\right|^2}{\left|\mathcal{A}(D^0 \to h^+h^-)\right|^2 + \left|\mathcal{A}(\overline{D}^0 \to h^+h^-)\right|^2},$$

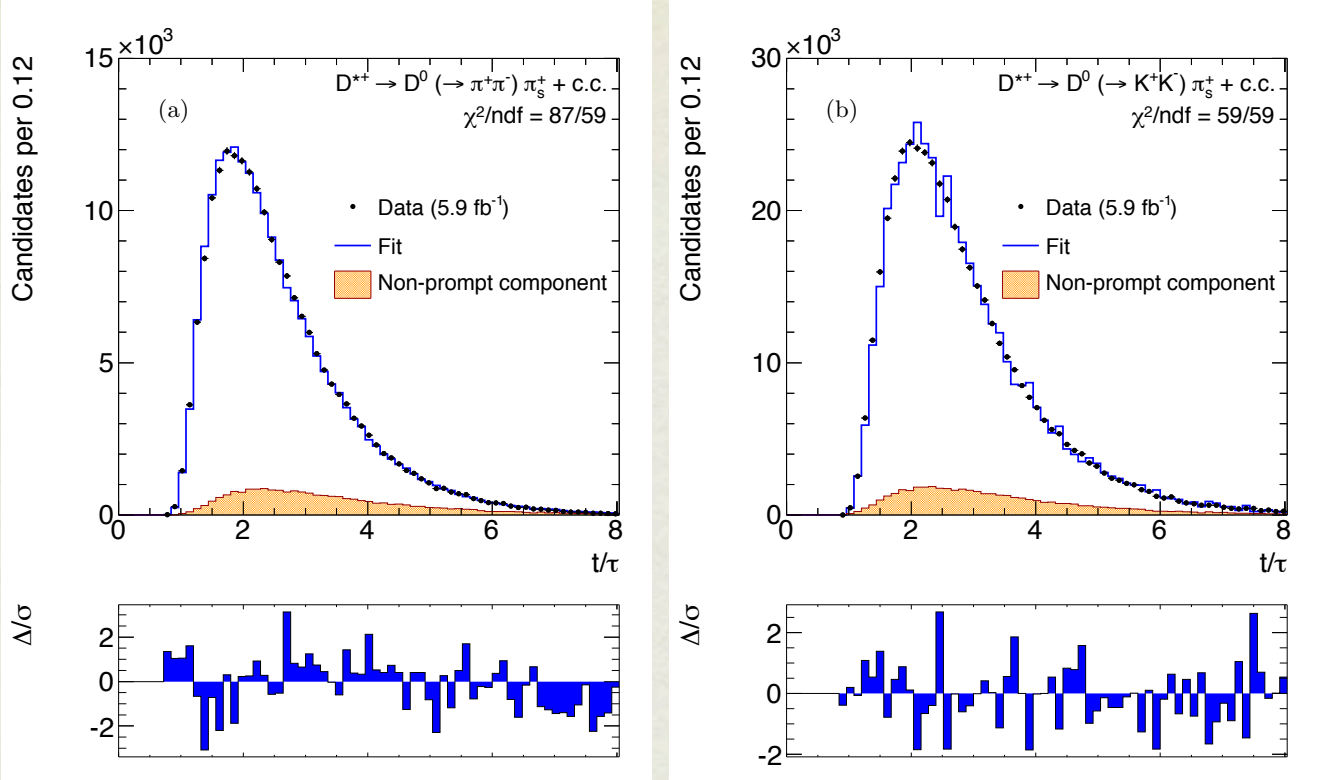
$$A_{CP}^{\rm ind}(h^+h^-) = \frac{\eta_{CP}}{2}\left[y\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\varphi - x\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\varphi\right],$$

- In a given experiment the time integrated CP asymmetry:

$$A_{CP}(h^+h^-) = A_{CP}^{\rm dir}(h^+h^-) + \frac{\langle t\rangle}{\tau}\ A_{CP}^{\rm ind}(h^+h^-).$$

with <t> average decay time of the sample

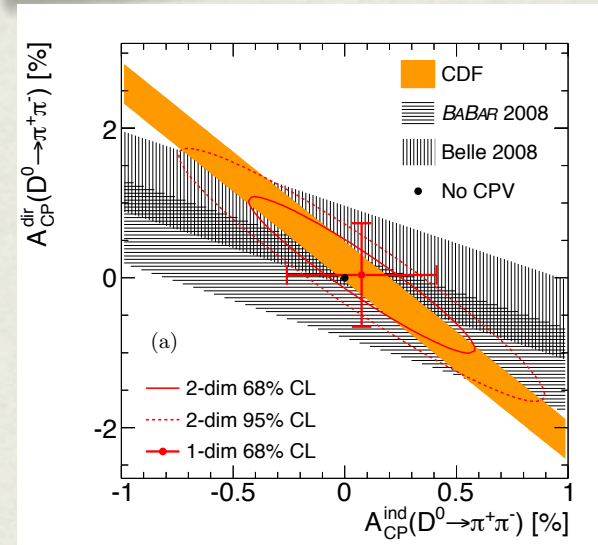
D⁰ DECAY TIME

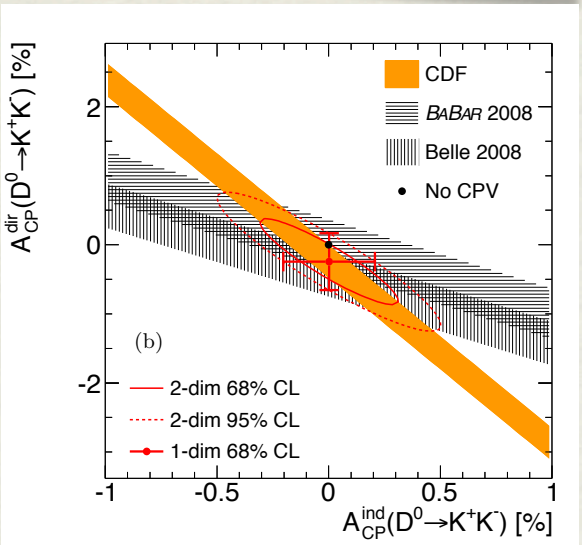


- Average decay time: $\langle t/\tau \rangle_{\pi\pi}=2.40\pm0.03$; $\langle t/\tau \rangle_{KK}=2.65\pm0.03$

RESULTS

$$A_{CP}(\pi^+\pi^-) = \big(+0.22 \pm 0.24\ (\text{stat}) \pm 0.11\ (\text{syst})\big)\%$$
$$A_{CP}(K^+K^-) = \big(-0.24 \pm 0.22\ (\text{stat}) \pm 0.09\ (\text{syst})\big)\%$$





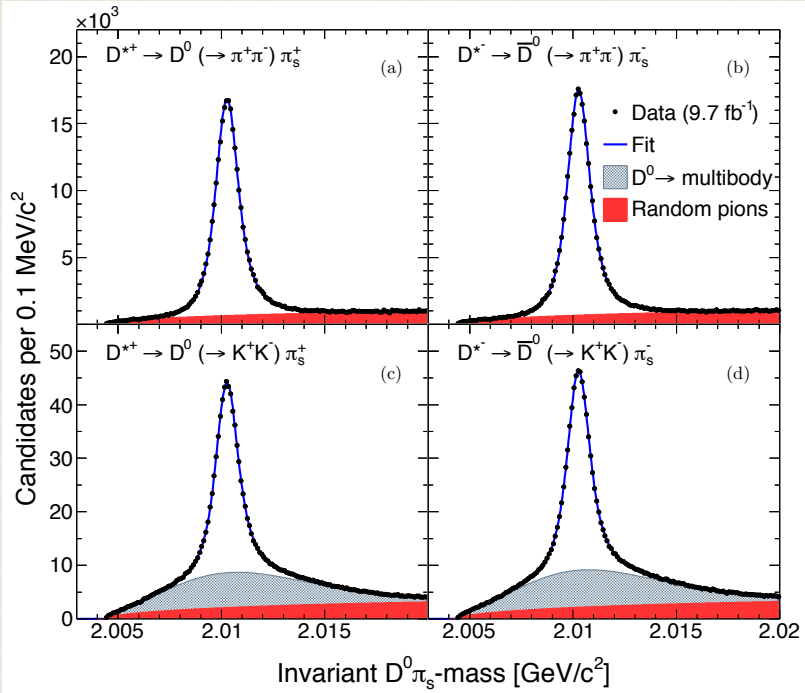
- Most precise published measurement to date
- Strong constraint on indirect CP due to the higher average <t>

$$A_{CP}^{\text{ind}}(D^0) = \big(-0.01 \pm 0.06\ (\text{stat}) \pm 0.04\ (\text{syst})\big)\%.$$

ΔA_{CP} MEASUREMENT

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

- Can be measured with better precision since most experimental uncertainties cancel
- Used the full CDF Run II sample
- Further increase statistics with a looser selection (no need to correct for K^+/K^- effects)



$$A(\pi^+\pi^-) = (-1.71 \pm 0.15\ (\text{stat}))\%,$$
$$A(K^+K^-) = (-2.33 \pm 0.14\ (\text{stat}))\%.$$

Raw asymmetries

CDF RESULT AND COMBINATION

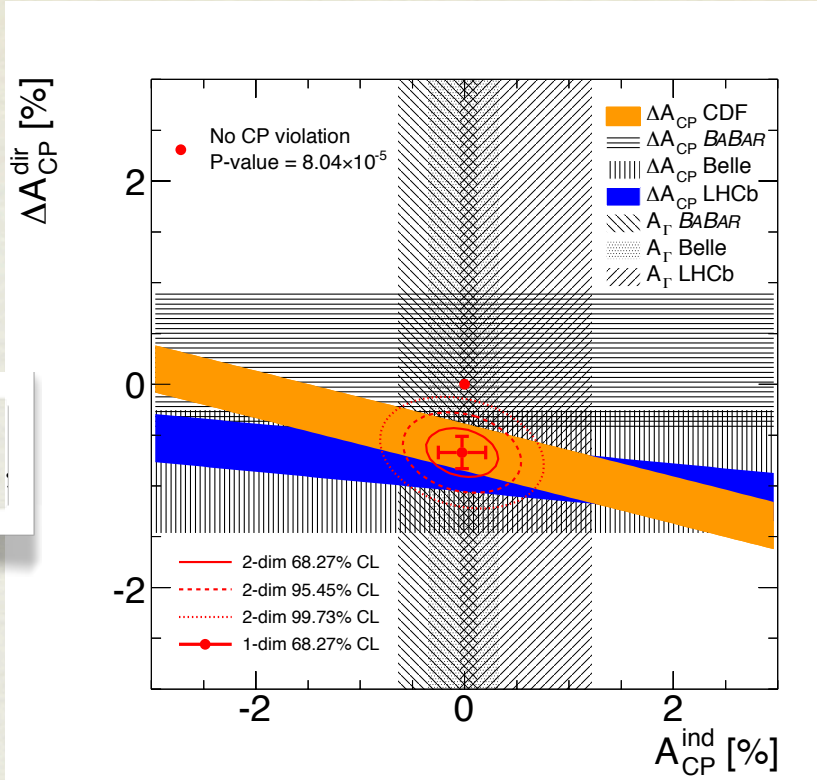
- Experimental asymmetry cancel in the difference:

$$\begin{aligned}\Delta A_{CP} =& A(K^+K^-) - A(\pi^+\pi^-)\\ =& A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-)\\ =& \Delta A_{CP}^{\rm dir} + A_{CP}^{\rm ind}\Delta\langle t\rangle/\tau.\end{aligned}$$

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

- 2.7 standard deviation from 0, confirms with same precision LHCb result

- Combining all (assuming Gaussian uncertainties and neglecting correlations) the no CP-violation hypothesis is excluded at 3.8 σ



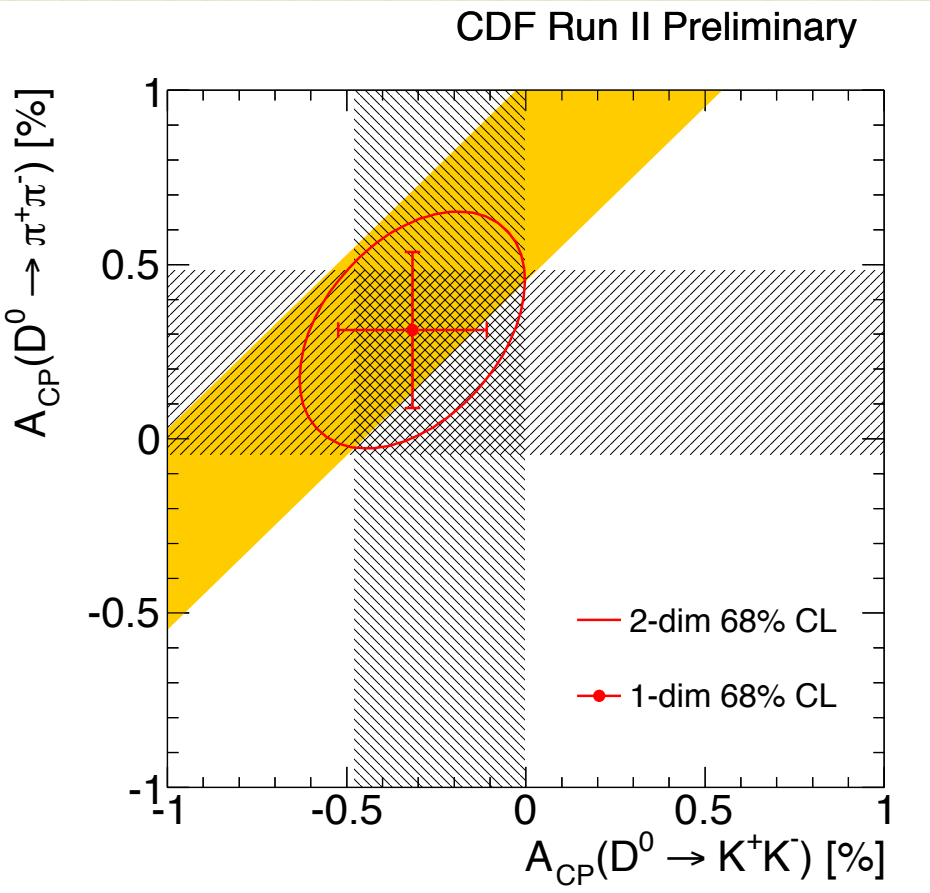
$$\Delta A_{CP}^{dir} = (-0.67 \pm 0.16)\%$$
$$A_{CP}^{ind} = (-0.02 \pm 0.22)\%$$

IMPROVING INDIVIDUAL ASYMMETRIES

- Most precise individual asymmetries by combining the published measurement with difference in the complementary sample :

  $\Delta A_{CP} = -0.74 \pm 0.2$

$A_{CP}(D^0 \to \pi^+\pi^-) = (+0.31 \pm 0.22)\%$,
$A_{CP}(D^0 \to K^+K^-) = (-0.32 \pm 0.21)\%$



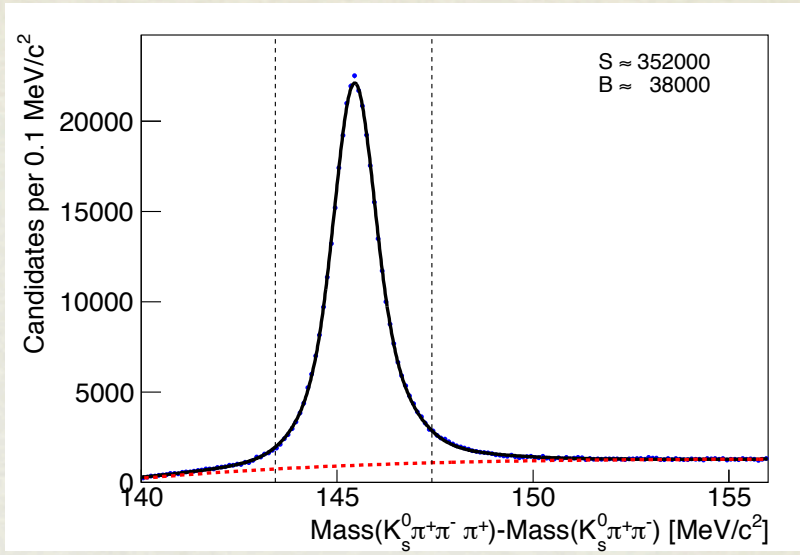
Still not significant, but indication that ππ and KK asymmetries might have opposite sign A_{CP} as predicted

MORE CHARM DECAYS

CP VIOLATION SEARCH IN $D^0 \to K_S \pi \pi$

Phys. Rev. D 86, 032007 (2012)

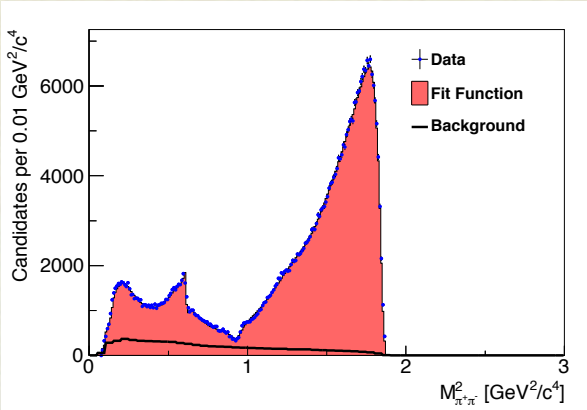
- Adding more data on charm CP-violation is crucial, use a large sample of D* tagged $D^0 \to K_S \pi^+ \pi^-$ decays
- Measure individual amplitudes and asymmetries with a Dalitz analysis
- Insensitive to instrumenatal effects once anti-D^0 kinematic distribution re-weighted to match D^0
- Background from D^0 mass sidebands
- Efficiency correction over Dalitz-plot from MC simulatiion

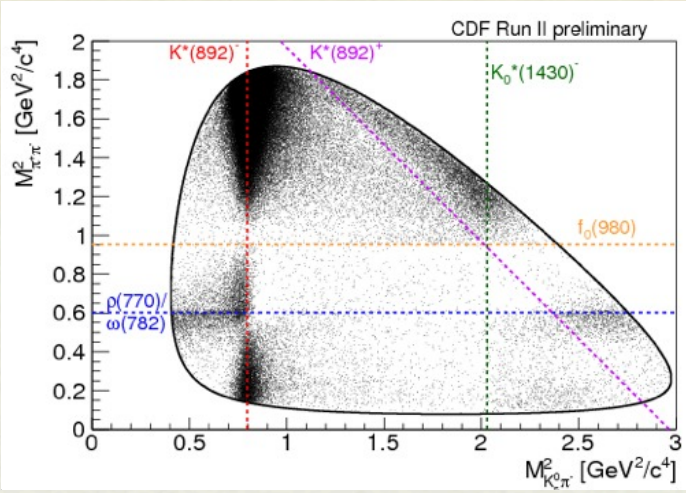


~350,000 D*-tagged candidates in $6 fb^{-1}$

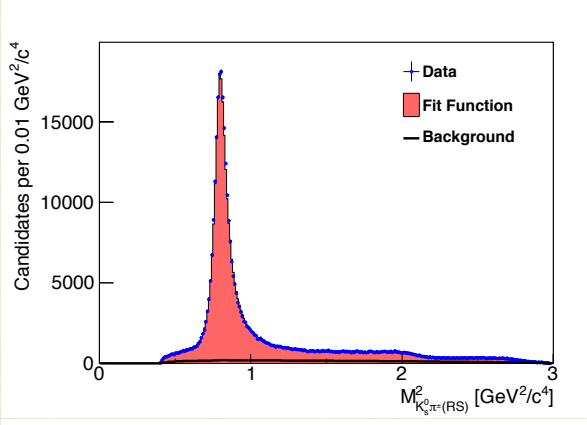
- First attempt ad hadron collider !

DALITZ FIT





Resonance	a	δ [°]	Fit fractions [%]
$K^*(892)^\pm$	1.911 ± 0.012	132.1 ± 0.7	61.80 ± 0.31
$K_0^*(1430)^\pm$	2.093 ± 0.065	54.2 ± 1.9	6.25 ± 0.25
$K_2^*(1430)^\pm$	0.986 ± 0.034	308.6 ± 2.1	1.28 ± 0.08
$K^*(1410)^\pm$	1.092 ± 0.069	155.9 ± 2.8	1.07 ± 0.10
$\rho(770)$	1	0	18.85 ± 0.18
$\omega(782)$	0.038 ± 0.002	107.9 ± 2.3	0.46 ± 0.05
$f_0(980)$	0.476 ± 0.016	182.8 ± 1.3	4.91 ± 0.19
$f_2(1270)$	1.713 ± 0.048	329.9 ± 1.6	1.95 ± 0.10
$f_0(1370)$	0.342 ± 0.021	109.3 ± 3.1	0.57 ± 0.05
$\rho(1450)$	0.709 ± 0.043	8.7 ± 2.7	0.41 ± 0.04
$f_0(600)$	1.134 ± 0.041	201.0 ± 2.9	7.02 ± 0.30
σ_2	0.282 ± 0.023	16.2 ± 9.0	0.33 ± 0.04
$K^*(892)^\pm$(DCS)	0.137 ± 0.007	317.6 ± 2.8	0.32 ± 0.03
$K_0^*(1430)^\pm$(DCS)	0.439 ± 0.035	156.1 ± 4.9	0.28 ± 0.04
$K_2^*(1430)^\pm$(DCS)	0.291 ± 0.034	213.5 ± 6.1	0.11 ± 0.03
Non-Resonant	1.797 ± 0.147	94.0 ± 5.3	1.64 ± 0.27
Sum			107.25 ± 0.65



- Isobar model for Dalitz analysis
- In agreement with earlier data

$$\mathcal{M} = a_0 e^{i\delta_0} + \sum_j a_j e^{i\delta_j} \mathcal{A}_j(M, \Gamma)$$

BOUNDS ON CP VIOLATION

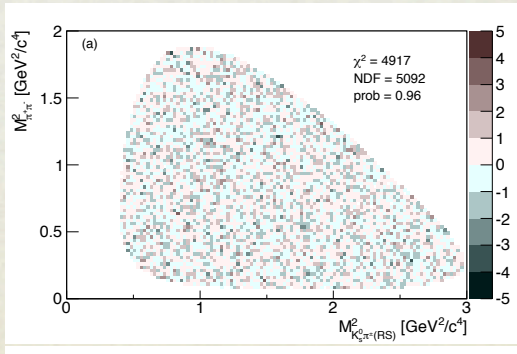
- No evidence for CP violation in any channel
- Greatly improve previous experiments [CLEO, PRD 70, 091101 2004]
- Overall CP asymmetry

$$A_{CP} = (-0.05 \pm 0.57(\text{stat}) \pm 0.54(\text{syst}))\% \,.$$

  - Cross check by directly comparing Dalitz plot for D⁰ and anti-D⁰
  - Plot asymmetry significance... flat !

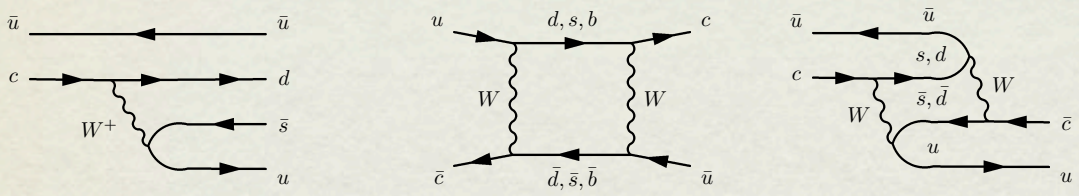
TABLE VIII: Fit-fraction asymmetries, $A_{\rm FF}$, for the included intermediate resonances. The first uncertainties are statistical and the second systematic.

Resonance	$A_{\rm FF}$ [%]
$K^*(892)^\pm$	$+0.36 \pm 0.33 \pm 0.40$
$K_0^*(1430)^\pm$	$+4.0 \pm 2.4 \pm 3.8$
$K_2^*(1430)^\pm$	$+2.9 \pm 4.0 \pm 4.1$
$K^*(1410)^\pm$	$-2.3 \pm 5.7 \pm 6.4$
$\rho(770)$	$-0.05 \pm 0.50 \pm 0.08$
$\omega(782)$	$-12.6 \pm 6.0 \pm 2.6$
$f_0(980)$	$-0.4 \pm 2.2 \pm 1.6$
$f_2(1270)$	$-4.0 \pm 3.4 \pm 3.0$
$f_0(1370)$	$-0.5 \pm 4.6 \pm 7.7$
$\rho(1450)$	$-4.1 \pm 5.2 \pm 8.1$
$f_0(600)$	$-2.7 \pm 2.7 \pm 3.6$
σ_2	$-6.8 \pm 7.6 \pm 3.8$
$K^*(892)^\pm$(DCS)	$+1.0 \pm 5.7 \pm 2.1$
$K_0^*(1430)^\pm$(DCS)	$+12 \pm 11 \pm 10$
$K_2^*(1430)^\pm$(DCS)	$-10 \pm 14 \pm 29$



MORE TO COME - D^0 MIXING

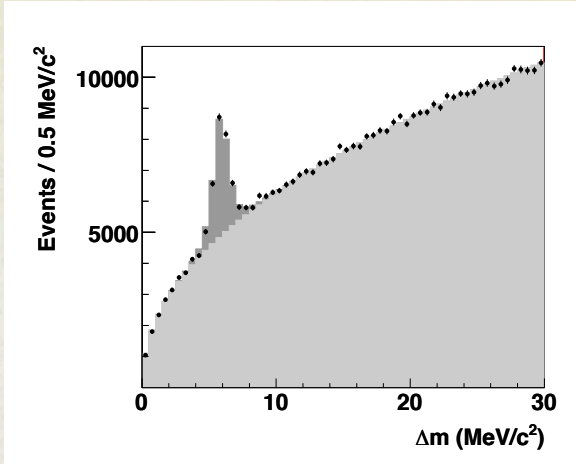
- Contributions to wrong sign decay rate R: double Cabibbo suppressed (DCS) decays and D^0 mixing



$$R(t/\tau) = R_D + \sqrt{R_D}y'\,(t/\tau) + \frac{x'^2 + y'^2}{4}\,(t/\tau)^2$$

- Evidence for mixing (3.8 σ) reported by CDF using 1.5 fb^{-1} (3 x 10^6 RS decays)

- Being updated with full dataset



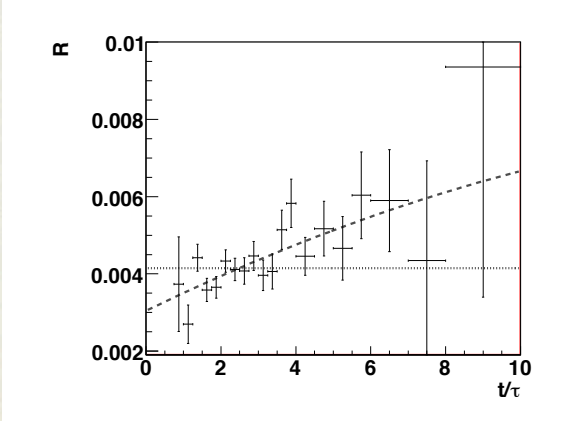


FIG. 3: Ratio of prompt D^* "wrong-sign" to "right sign" decays as a function of normalized proper decay time. The dashed curve is from a least-squares parabolic fit, which determines the parameters R_D, y', and x'^2. The dotted line is the fit assuming no mixing.

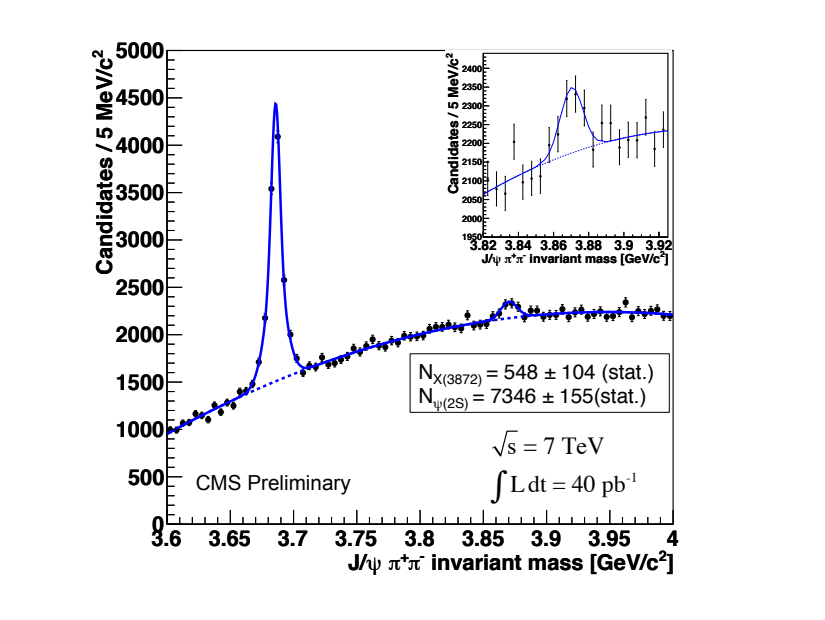
CONCLUSION

- Tevatron has been a main player in the charm renaissance of the last decade: large charm production rate, powerful vertexing detectors and charge symmetric initial state
- Need dedicated trigger and bandwidth
- Ground-breaking work from CDF on many fronts
- Some new result expected soon

SPARES

X3872 PRODUCTION

- Sizeable production at colliders



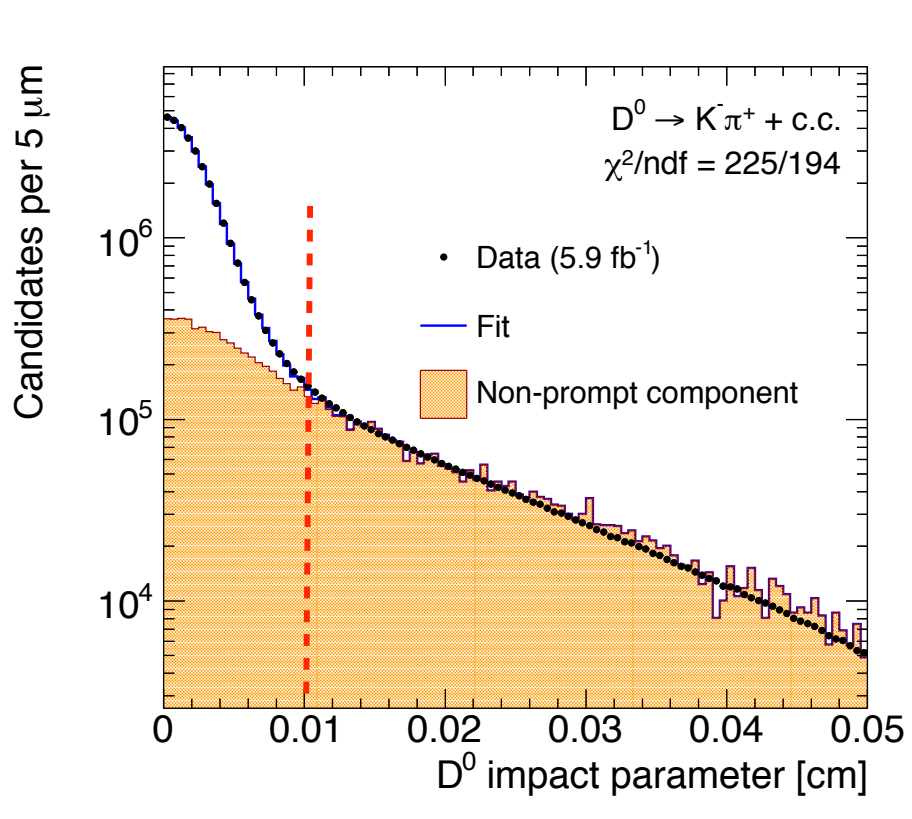
$$R = \frac{\sigma(pp \to X(3872) + \text{anything}) \times BR(X(3872) \to J/\psi\pi^+\pi^-)}{\sigma(pp \to \psi(2S) + \text{anything}) \times BR(\psi(2S) \to J/\psi\pi^+\pi^-)}$$

for pp collisions at 7 TeV, in the kinematic region $p_t > 8$ GeV and $|y| < 2.2$, is measured to be

$$R = 0.087 \pm 0.017(stat.) \pm 0.009(syst.),$$

$B \rightarrow D^0 X$ CONTRIBUTION

- Possible source of contamination from CP-violating B decays
- Expect to be negligible in an inclusive sample of $B \rightarrow D^0 X$ decays
- However contribution from B decays is minimized by requiring $|d_0|<100\ \mu m$ cut on D meson (residual B fraction 16.6%)
- Systematic uncertainties conservatively assigned based on the measured asymmetry in the $|d_0|>100\ \mu m$ sample



A_{CP} AND ΔA_{CP} SYSTEMATICS

TABLE III. Summary of most significant systematic uncertainties. The uncertainties reported for the last three sources result from the sum in quadrature of the contributions in the tagged and untagged fits.

Source	$A_{CP}(\pi^+\pi^-)$ [%]	$A_{CP}(K^+K^-)$ [%]
Approximations in the suppression of detector-induced effects	0.009	0.009
Production asymmetries	0.040	0.030
Contamination of secondary D mesons	0.034	0.034
Shapes assumed in fits	0.010	0.058
Charge-dependent mass distributions	0.098	0.052
Asymmetries from residual backgrounds	0.014	0.014
Limitations of sample reweighting	< 0.001	< 0.001
Total	0.113	0.092

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