Charm Production Studies at CDF

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for the CDF Collaboration

- Open Charm Production:
  Charm Meson Pair Cross Sections
- Hidden Charm Production:
  J/ψ and ψ' polarization

Motivation

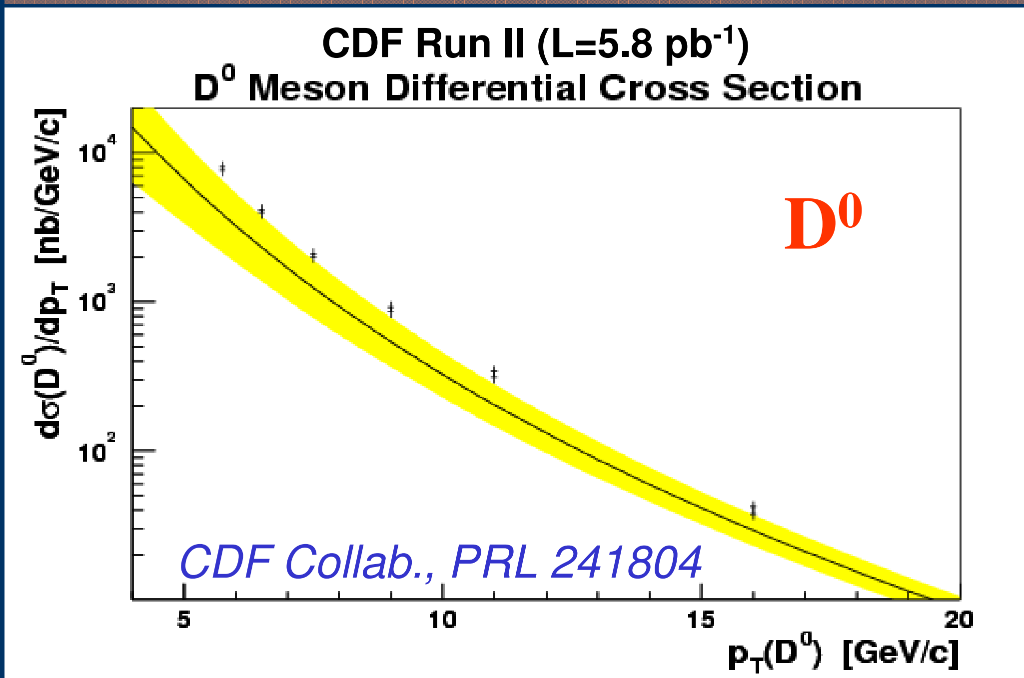
Heavy Quark Production:

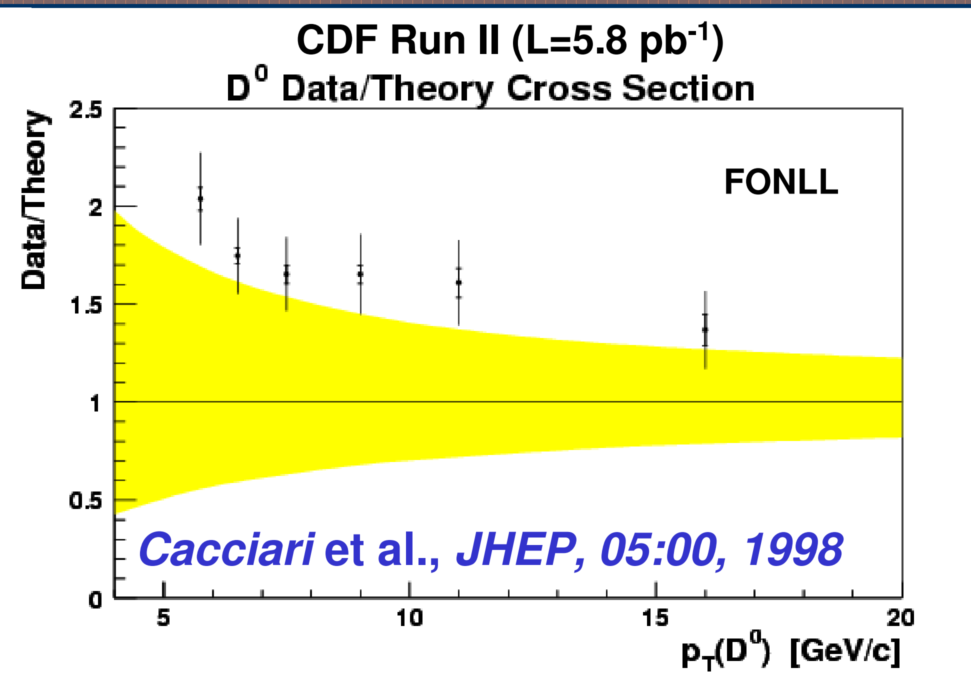
- Test of Quantum Chromodynamics at the transition from perturbative to non-perturbative regime - masses of *c*, *b* quarks provide hard scale for QCD calculations

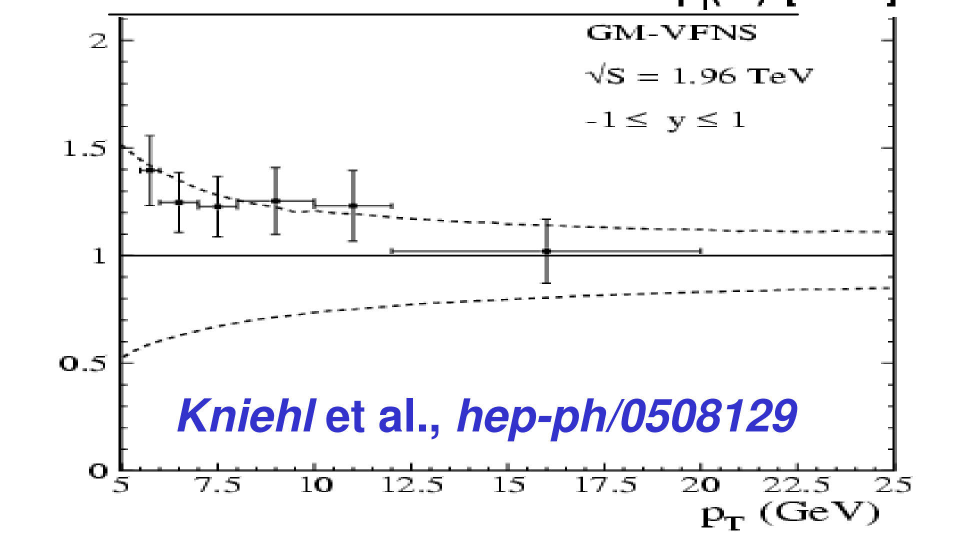
- Charm cross sections in proton anti-proton collisions are measured to be larger than expected (→next slide)

- Important engineering number for other CDF measurements and future experiments (Atlas, CMS. LHCb)
  e.g.: background to b-tagged events such as top measurements and Higgs/SUSY searches,
  tagger dilution for Bs mixing,
  production rates of beauty & charm hadrons, etc …

Inclusive Charm Meson Cross Sections



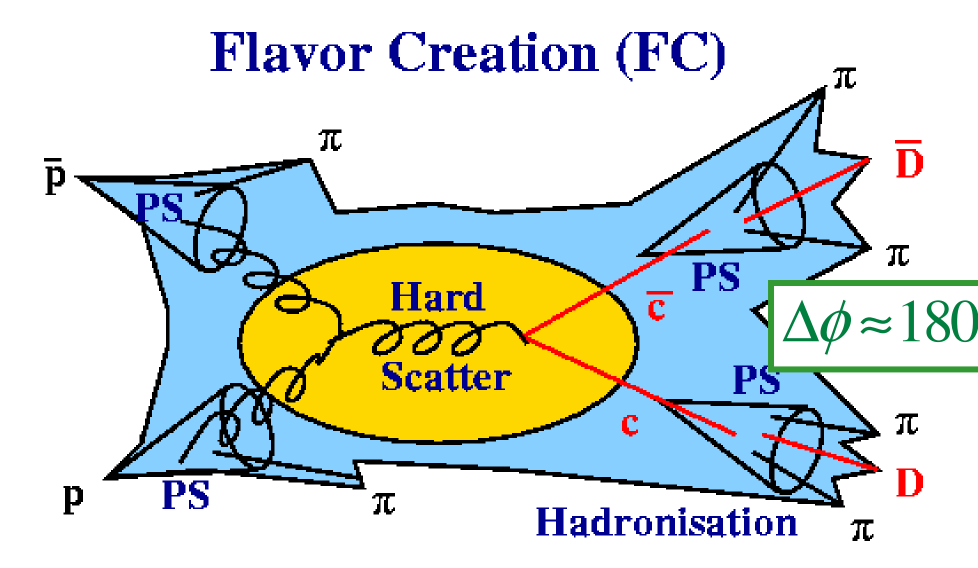


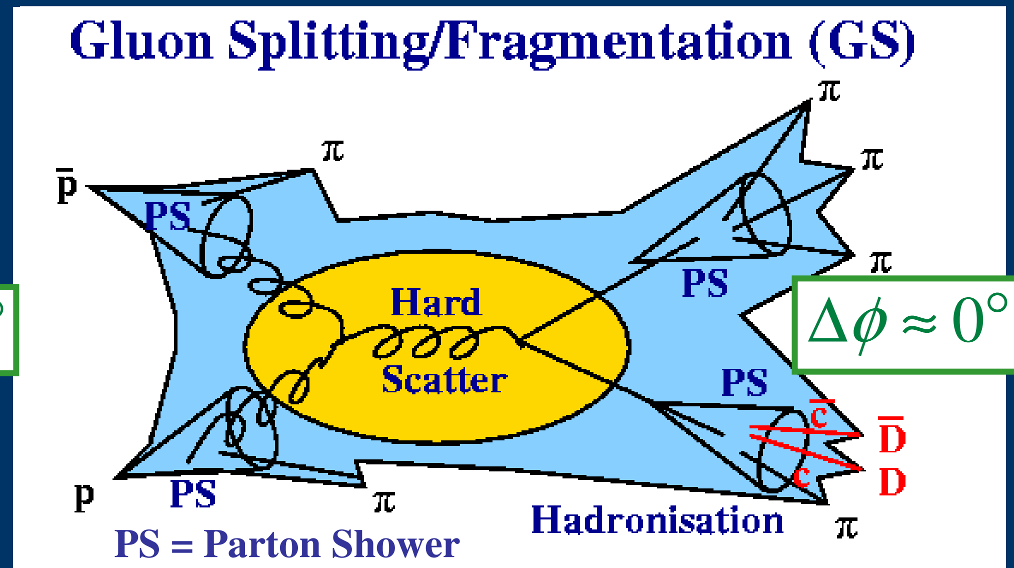


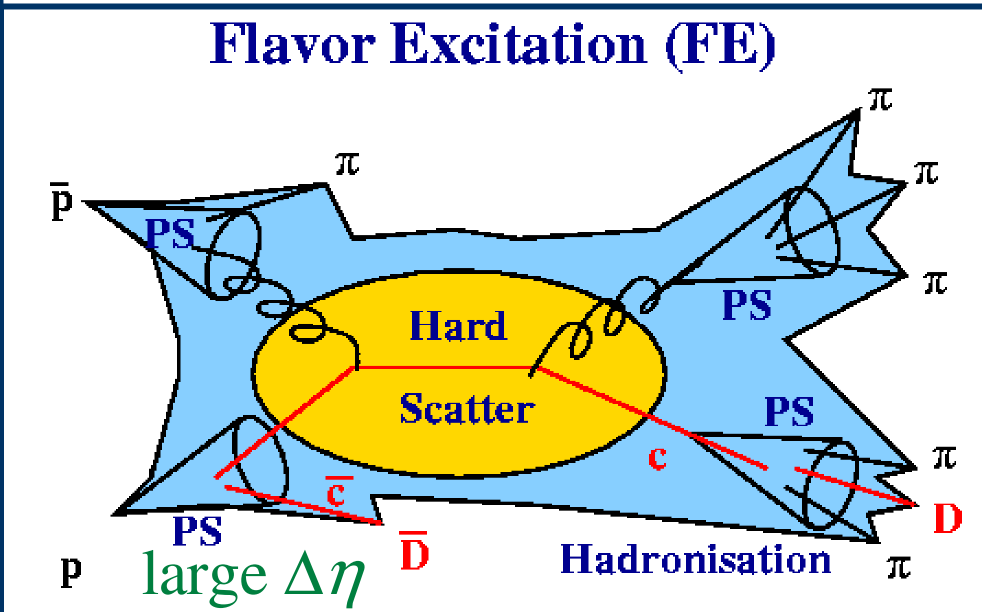
Inclusive charm (D^0, $D^{*\pm}$, D^+, D_s^+) cross sections was one of the first CDF Run II results

- factor ~2 higher than expected
- progress in theory reduced deviation
- measurement systematically limited

Heavy Quark Production: Leading Order Picture

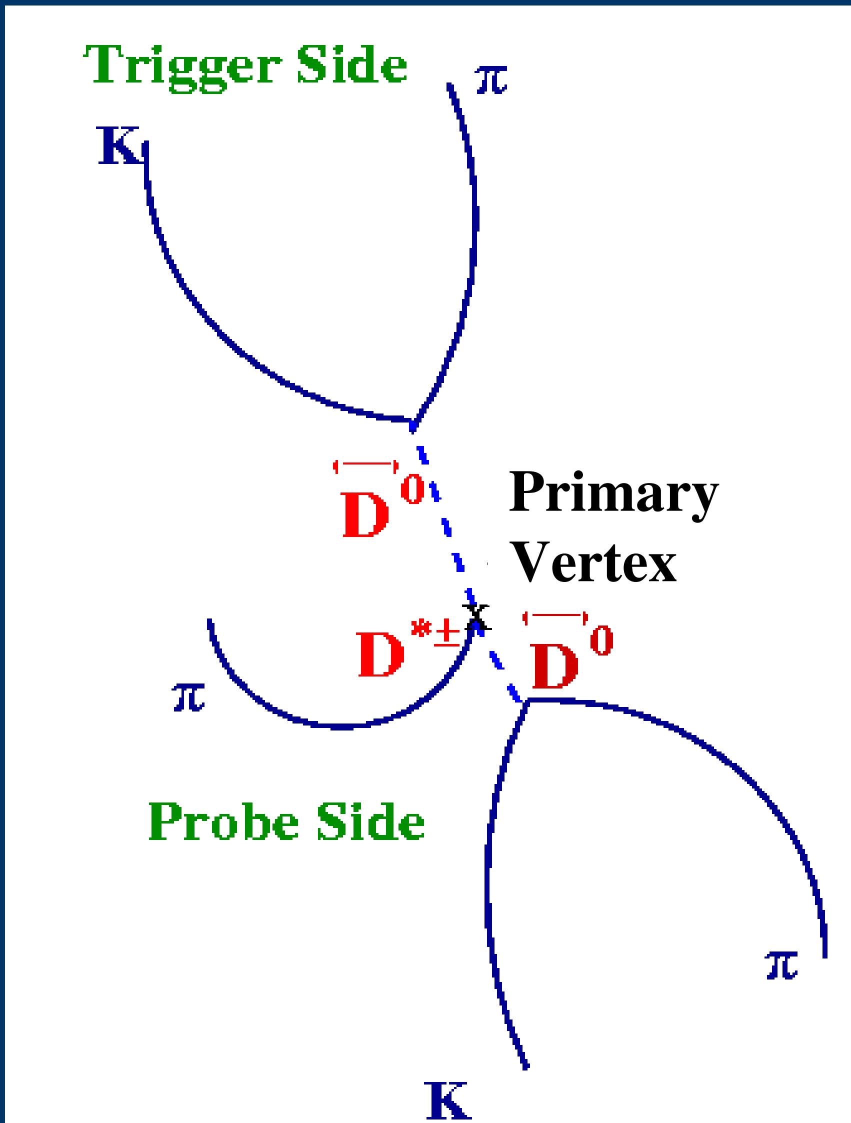






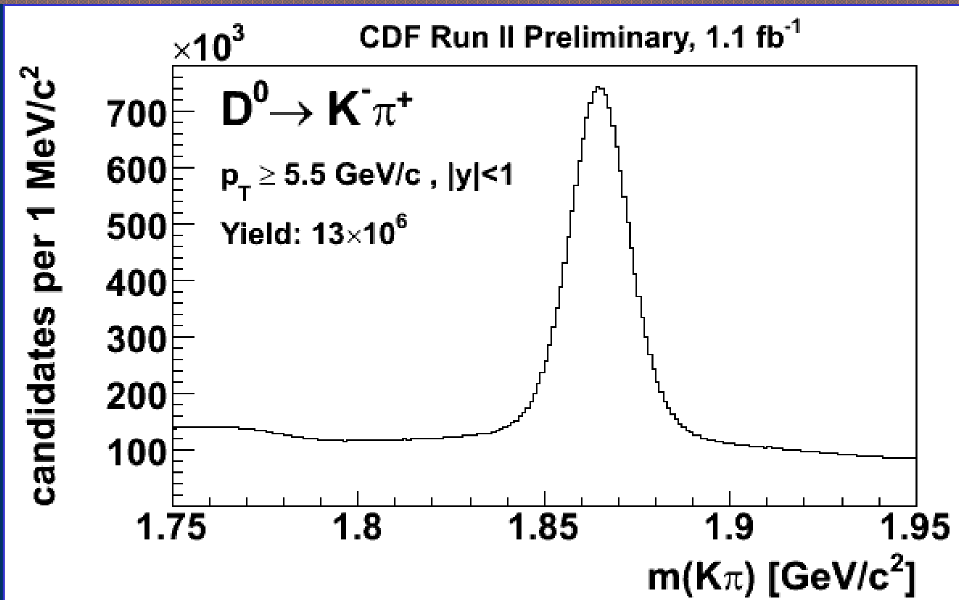
- Search for second charm particle in the event
- Correlations between first and second charm particle give access to detailed understanding of the underlying production mechanism

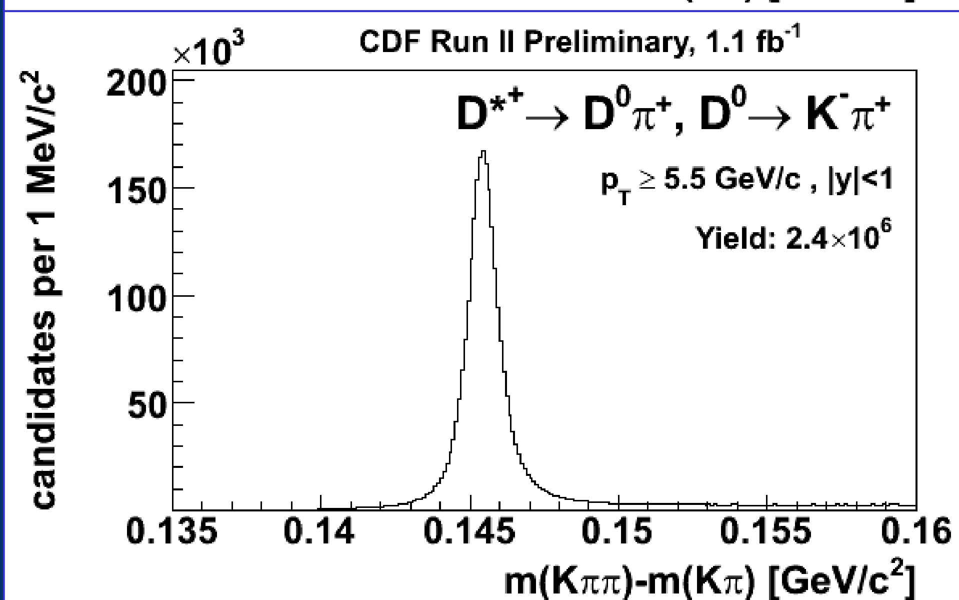
Charm Meson Pair Analysis Approach



- Simple experimental approach
- Find triggered charm meson D^0, D^+, D^{*+}, D_s^+,
- Look for second charm meson probe D^{*+}
- Correlation variable $\Delta\phi$ gives access to underlying production mechanism
- Measured inclusive cross section provides normalization

Inclusive Charm Mesons: D^0&$D^{*\pm}$



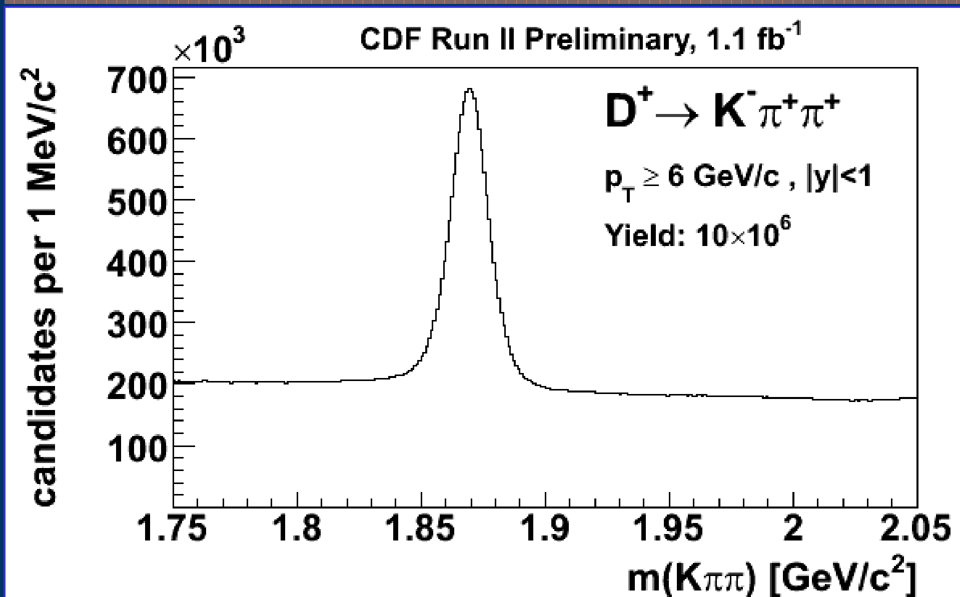


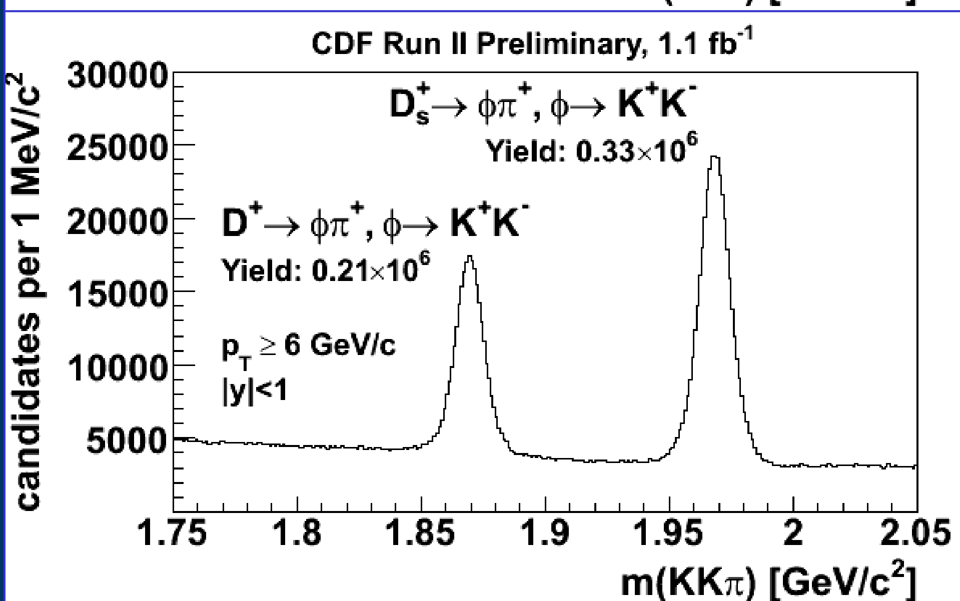
Inclusive triggered D Mesons reconstruction as in inclusive *Charm Meson Analysis*

- **Trigger $D^0 \to K\pi$:**
  $p_T(K,\pi) > 2GeV/c$,
  flight distance: $L_{xy} \geq 500\mu m$,
  impact parameters: $d_0(K)\cdot d_0(\pi)<0$

- **Trigger $D^{*+} \to (K\pi)D^0\pi^*$** :
  add π^* (p_T>0.4GeV/c)
  to triggered D^0
- **Probe** $D^{*+} \to (K\pi)_{D^0}\pi^*$:
  Keep selection simple:
  $p_T(k,\pi)$ >1GeV/c, $L_{xy}(D^0)$>0,
  Δm provides handle for clean up

Inclusive Charm Mesons: D^+ & D_s^+





selection as in inclusive Charm Meson Analysis, with some improvements:

Trigger side $D^+ \to K\pi\pi$:

$p_T(K,\pi_1) > 2GeV/c$, $p_T(\pi_2) > 0.4GeV/c$

$d_0 d_0(\max\Delta\phi \text{ tracks})<0$

$L_{xy} >1000\mu m$

veto D^{*+}:$m(K\pi\pi)-m(K\pi)<0.18\ GeV/c^2$

Trigger side $D_s^+ \to (KK)_\phi\pi$:

$p_T(K_1,\pi) > 2GeV/c$, $p_T(K_2) > 0.4GeV/c$

$d_0(K^+)d_0(\pi^-)<0$

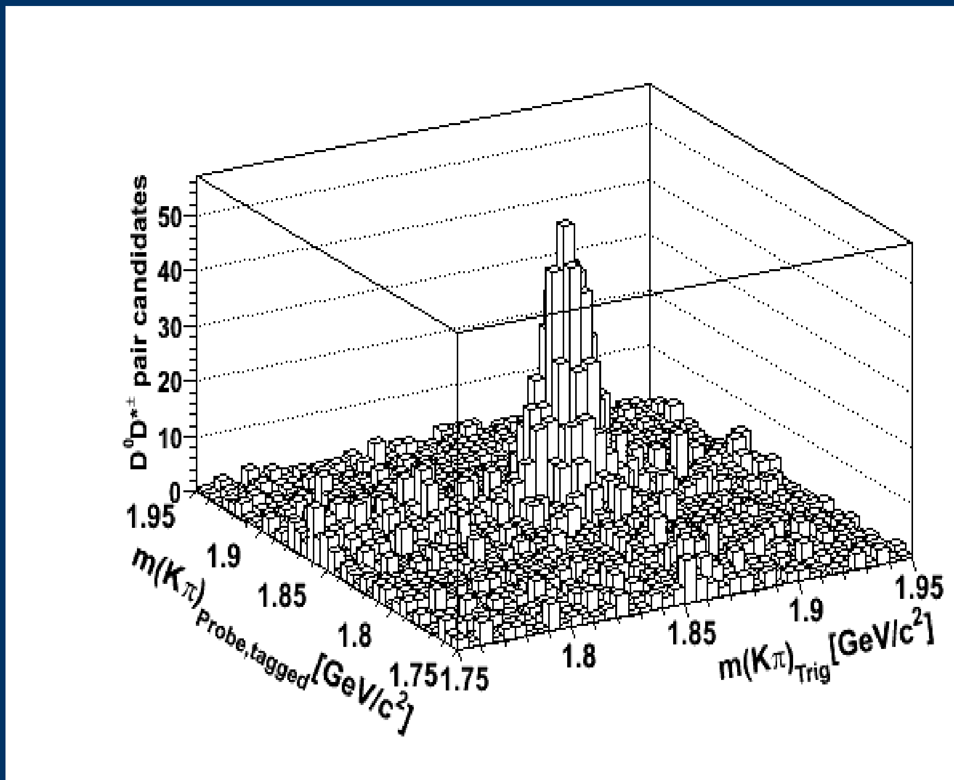
$L_{xy} \geq 500\mu m$

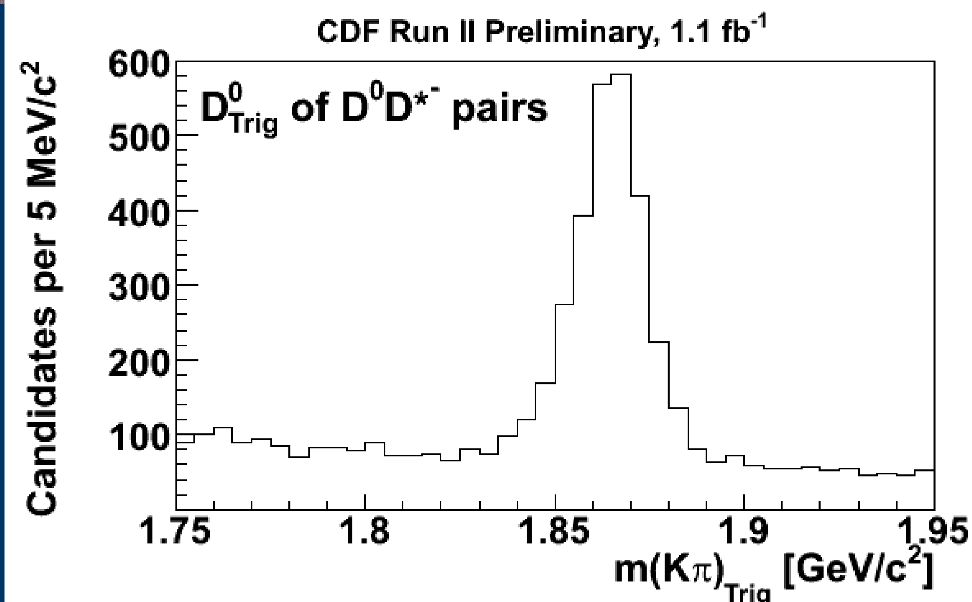
$m(K_{Tr},K_{Tr})raw < 1.06GeV/c2$

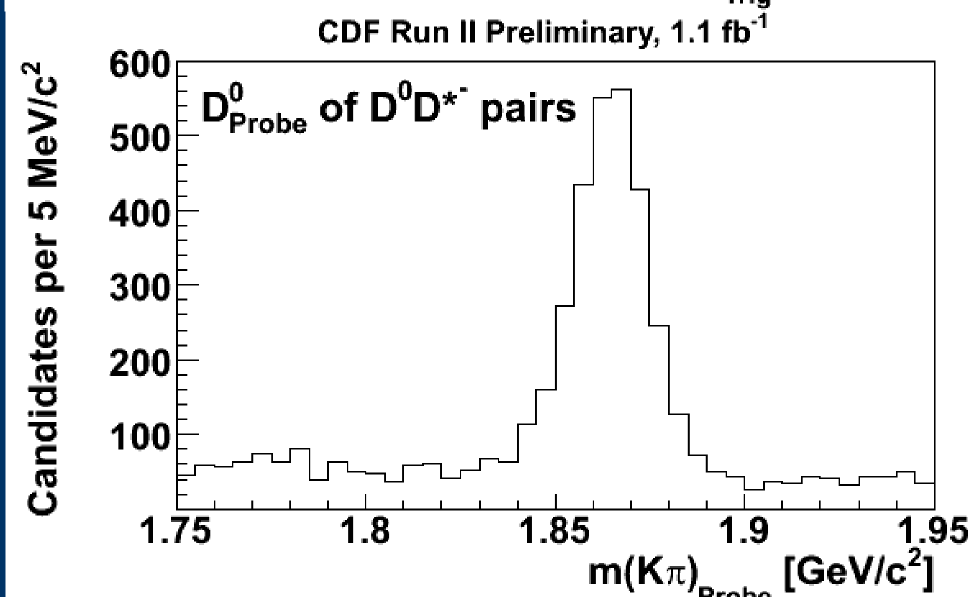
(veto $K_s \to \pi\pi$, π's fake K's)

tight $m(\phi)$ window

$D^0_{Trig} D^{*\pm}_{Probe}$ Pairs

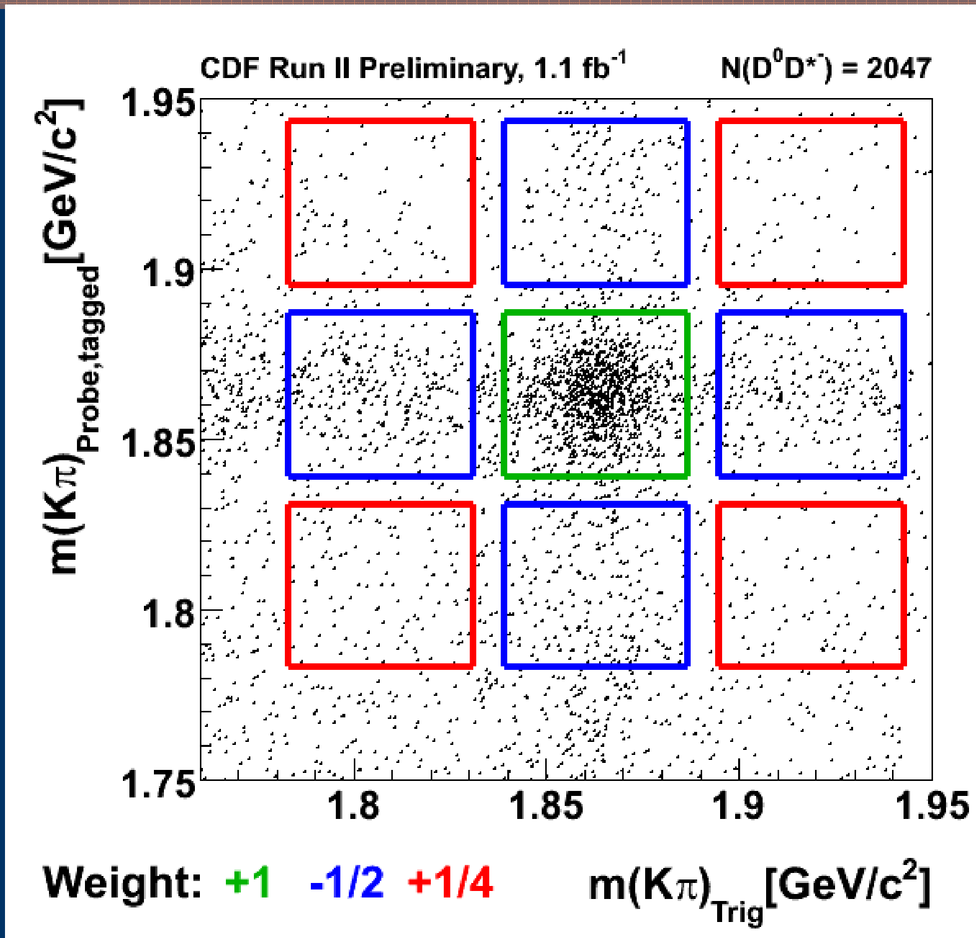


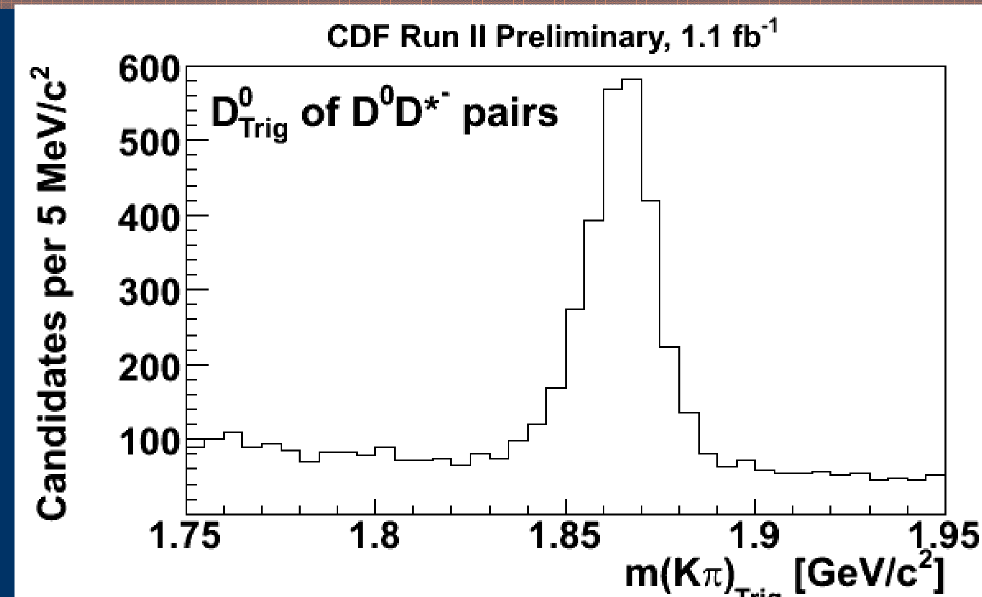


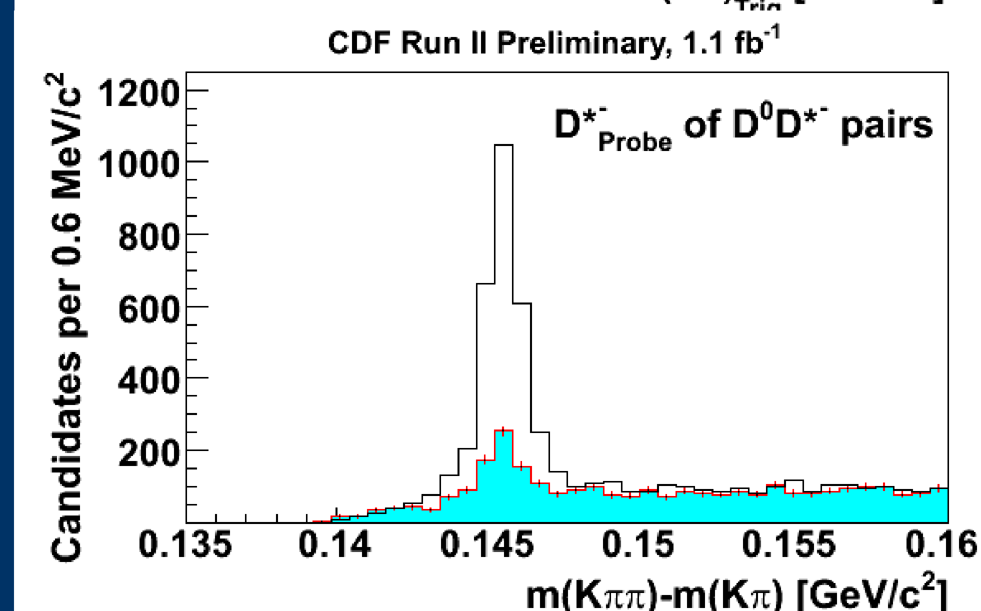


2dim SB-subtraction by weighting events
In mass plane of **Trigger D** and
soft π tagged **Probe D^0**

$D^0_{Trig} D^{*\pm}_{Probe}$ Yields





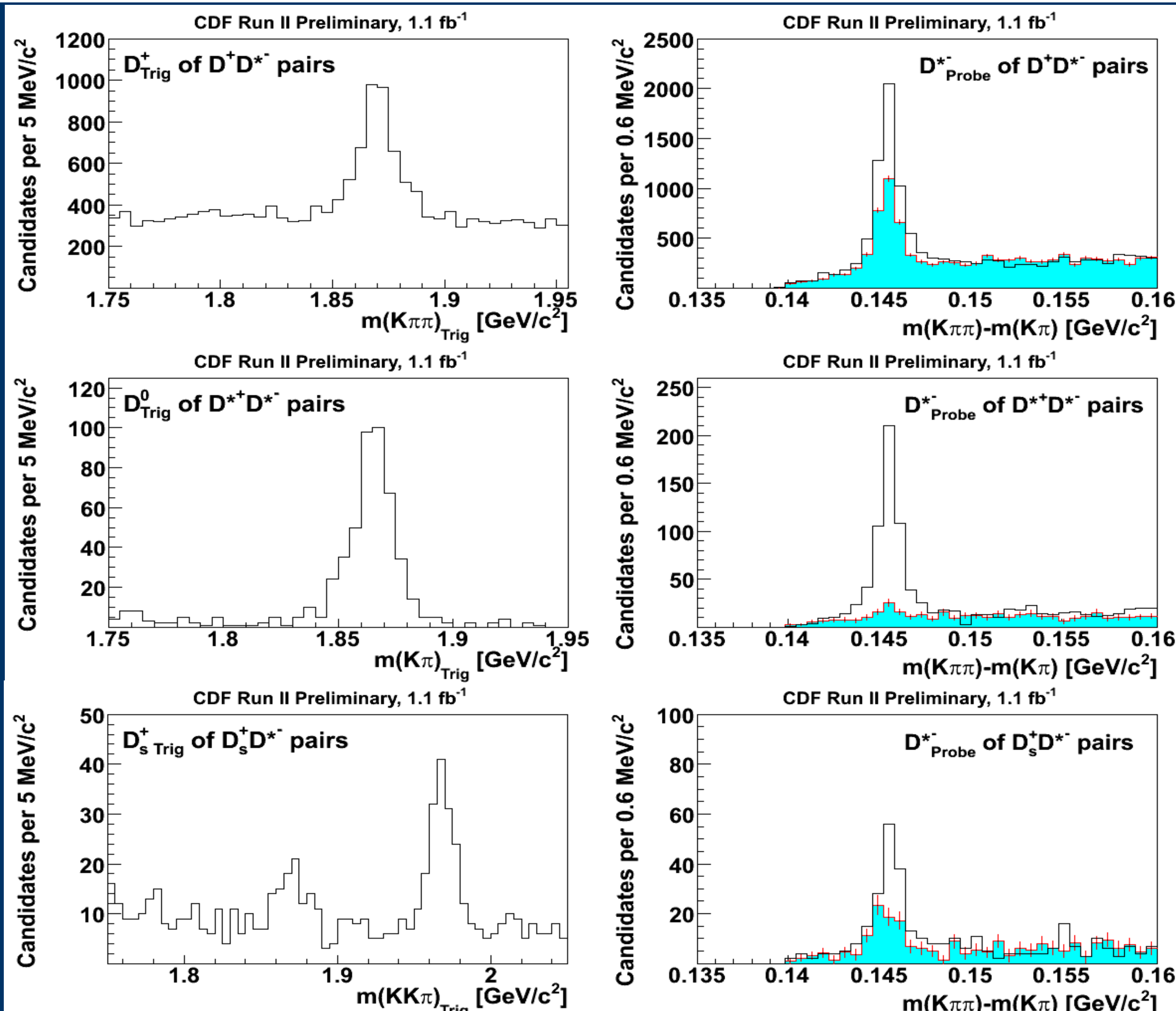


2dim SB-subtraction by weighting events
In mass plane of **Trigger D** and
soft π tagged **Probe D^0**

D^+D^{*-}

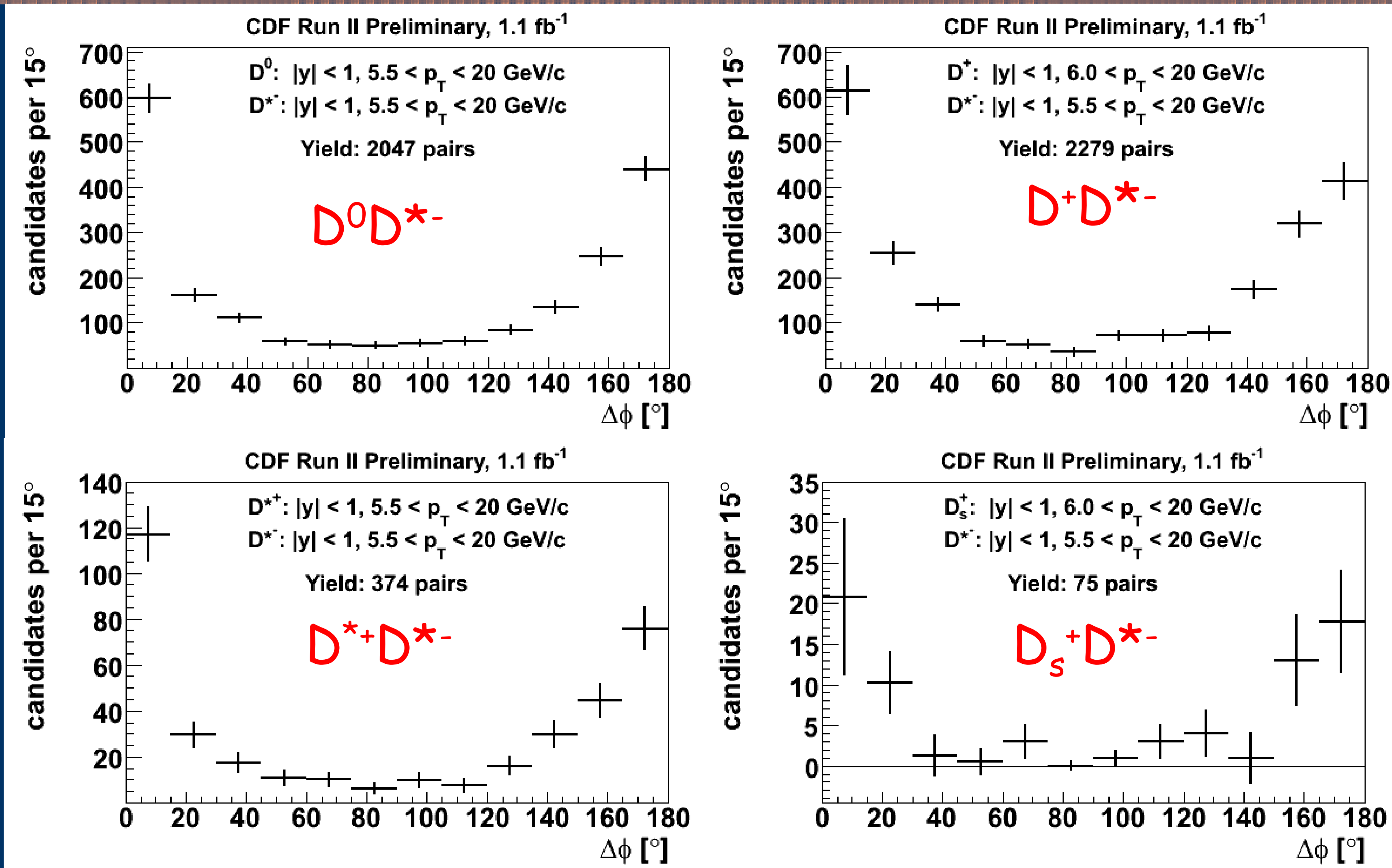
$D^{*+}D^{*-}$

$D_s^+D^{*-}$



CDF Run II Preliminary, 1.1 fb⁻¹
D⁺Trig of D⁺D*⁻ pairs
Candidates per 5 MeV/c²
m(Kππ)Trig [GeV/c²]
D*⁻Probe of D⁺D*⁻ pairs
Candidates per 0.6 MeV/c²
m(Kππ)-m(Kπ) [GeV/c²]
D⁰Trig of D*⁺D*⁻ pairs
m(Kπ)Trig [GeV/c²]
D*⁻Probe of D*⁺D*⁻ pairs
D⁺s Trig of D⁺sD*⁻ pairs
m(KKπ)Trig [GeV/c²]
D*⁻Probe of D⁺sD*⁻ pairs

Charm Meson Pairs vs. $\Delta\phi$ (Raw Yields)



Challenges of the Charm Meson Correlation analysis

- Convert raw $\Delta\phi$ yields into a cross section
  - Correct for physics background: DD*- pairs from B hadron decays
  - Correct for detector acceptance and efficiency effects
  - Control systematic effects over a data taking period of 4 years
- Technical challenge: efficient analysis of huge inclusive D samples

Prompt Charm Production Cross Sections

- Inclusive production (already measured by CDF):

$$\sigma^i = \left.\frac{d\sigma^D}{dP_T^i}\right|_{|y|<1} = \frac{N^i \cdot f_p^D}{\int \mathcal{L}dt \cdot \varepsilon^i \cdot B}$$

- Pair production cross section:

$$\sigma^{ij} = \left.\frac{d^2\sigma^{D_1D_2}}{dP_T^i dP_T^j}\right|_{|y_{1,2}|<1} = \frac{N^{ij} \cdot f_P^{DD}}{\int \mathcal{L}dt \cdot \varepsilon^{ij} \cdot B_1 B_2}$$

- Relative pair Cross section:

$$\frac{\sigma^{ij}}{\sigma^i} = \frac{N^{ij}}{N^i} \cdot \frac{f_P^{DD}}{f_P^D} \cdot \frac{1}{\varepsilon^j B_2}$$

- uses

$\varepsilon^{ij} = \varepsilon^i \cdot \varepsilon^j$ (MC study: valid better than 2.5%)

N^i: Number of observed charm mesons in i^{th} P_T-bin

N^{ij}: Number of observed charm meson pairs with D_1 in i^{th} P_T-bin and D_2 in j^{th} P_T-bin

f_P^D: fraction of prompt D mesons

f_P^{DD}: fraction of prompt pairs

e^i: trigger and reconstruction efficiency

e^{ij}: pair trigger and reconstruction efficiency

e^j: probe-side reconstruction efficiency

$\int\mathcal{L}dt$: integrated luminosity

B: branching fraction e.g. $D^0 \to K\pi$

Measurement of Pair Cross Section

develop methods to extract these numbers

published CDF measurements of inclusive cross sections

2d sideband subtraction

$$\sigma^{DD} = \frac{N^{ij}}{N^{i}} \cdot \frac{f_{\mathrm{Pr}}^{DD}}{f_{\mathrm{Pr}}^{D}} \cdot \frac{\sigma^{D}}{\varepsilon^{j} Br_{\mathrm{Probe}}}$$

binned log likelihood fit

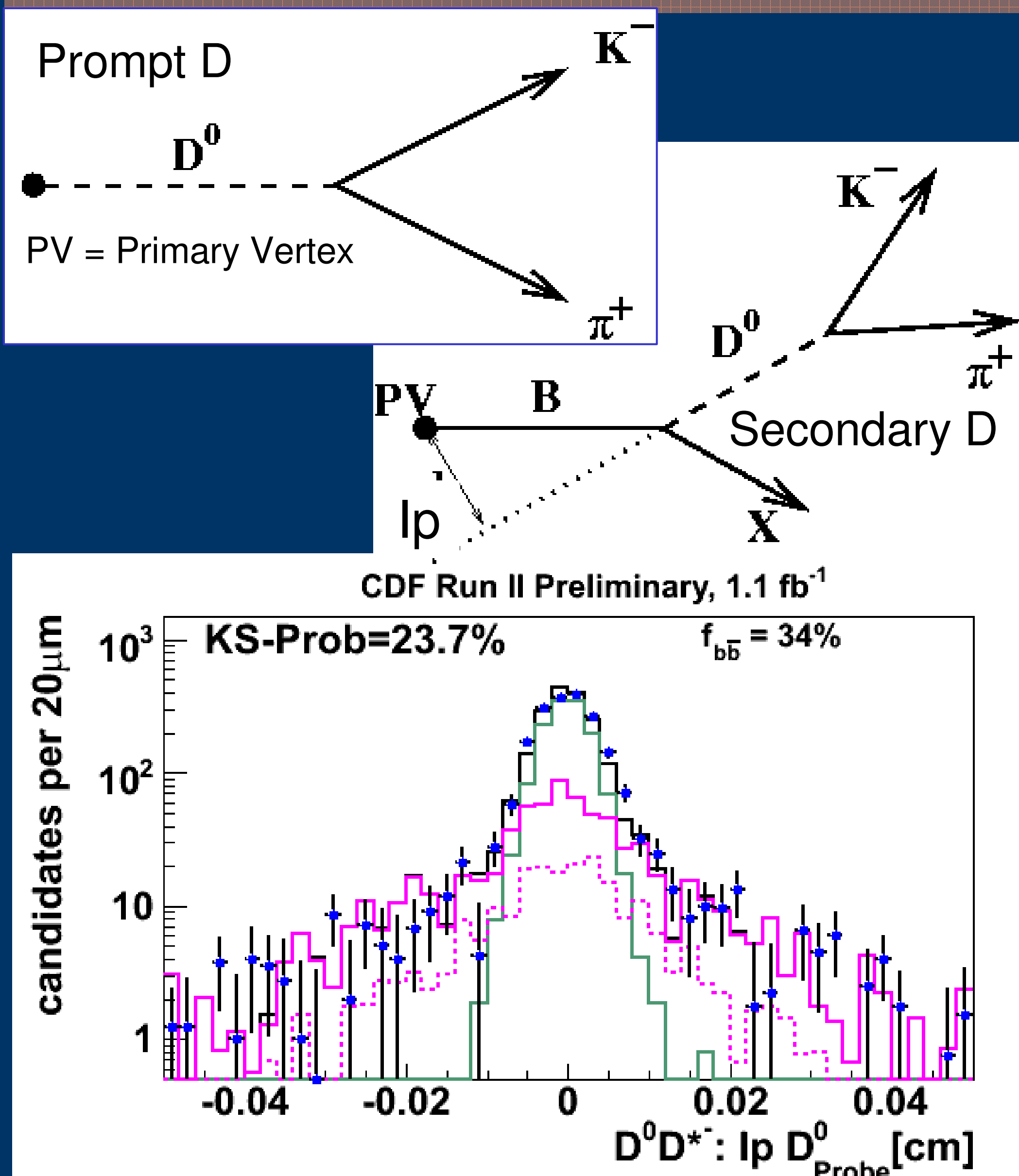
Full detector simulation

branching fraction from PDG

apply methods developed for inclusive cross section measurements to extract these numbers

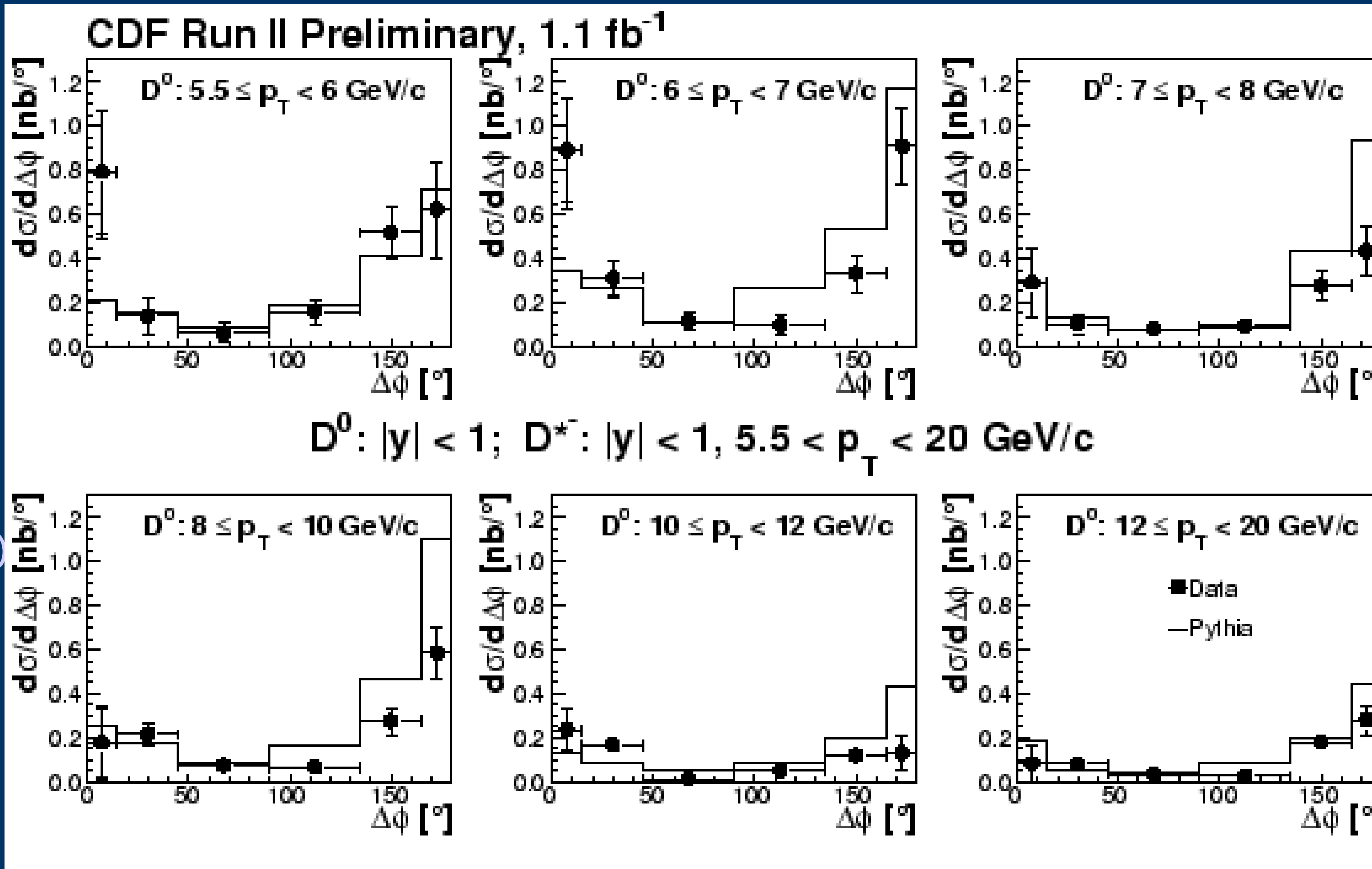
obtain parameterization from simulation

Extraction of Prompt D Production



- Extract prompt and secondary D meson fractions from their impact parameter (Ip) distributions
- Inclusive D^0, D^+: f_b^{D} =10-20%
- DD Pairs using tagged probe side D^0: f_b^{DD} = ~30%
- Cross checks : Ip, L_{xy} of trigger D, probe D and DD*- pair

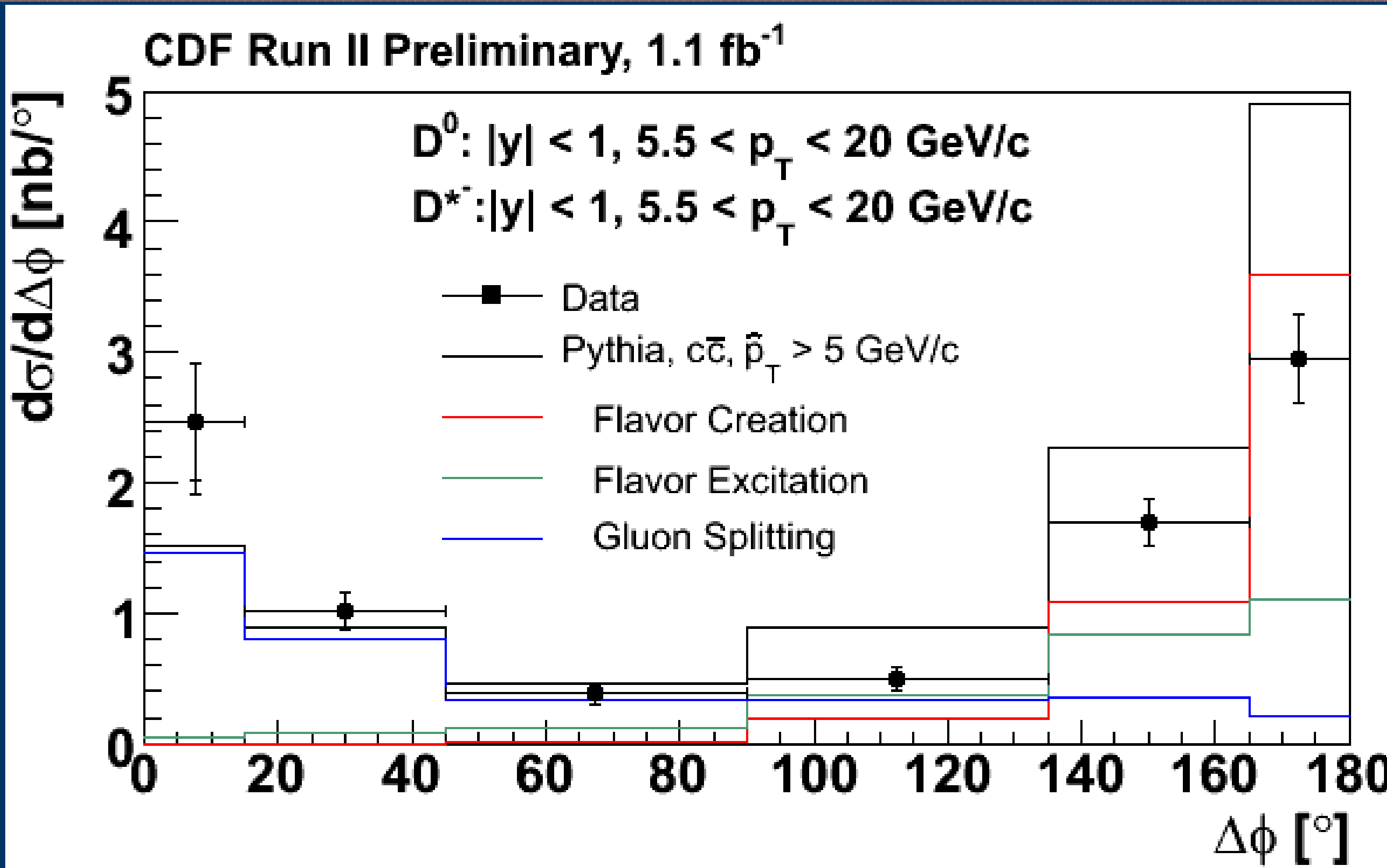
D^0D^{*-} Pair Cross Section binned in P_T(Trig)



Error: stat⊕sys(f_b)

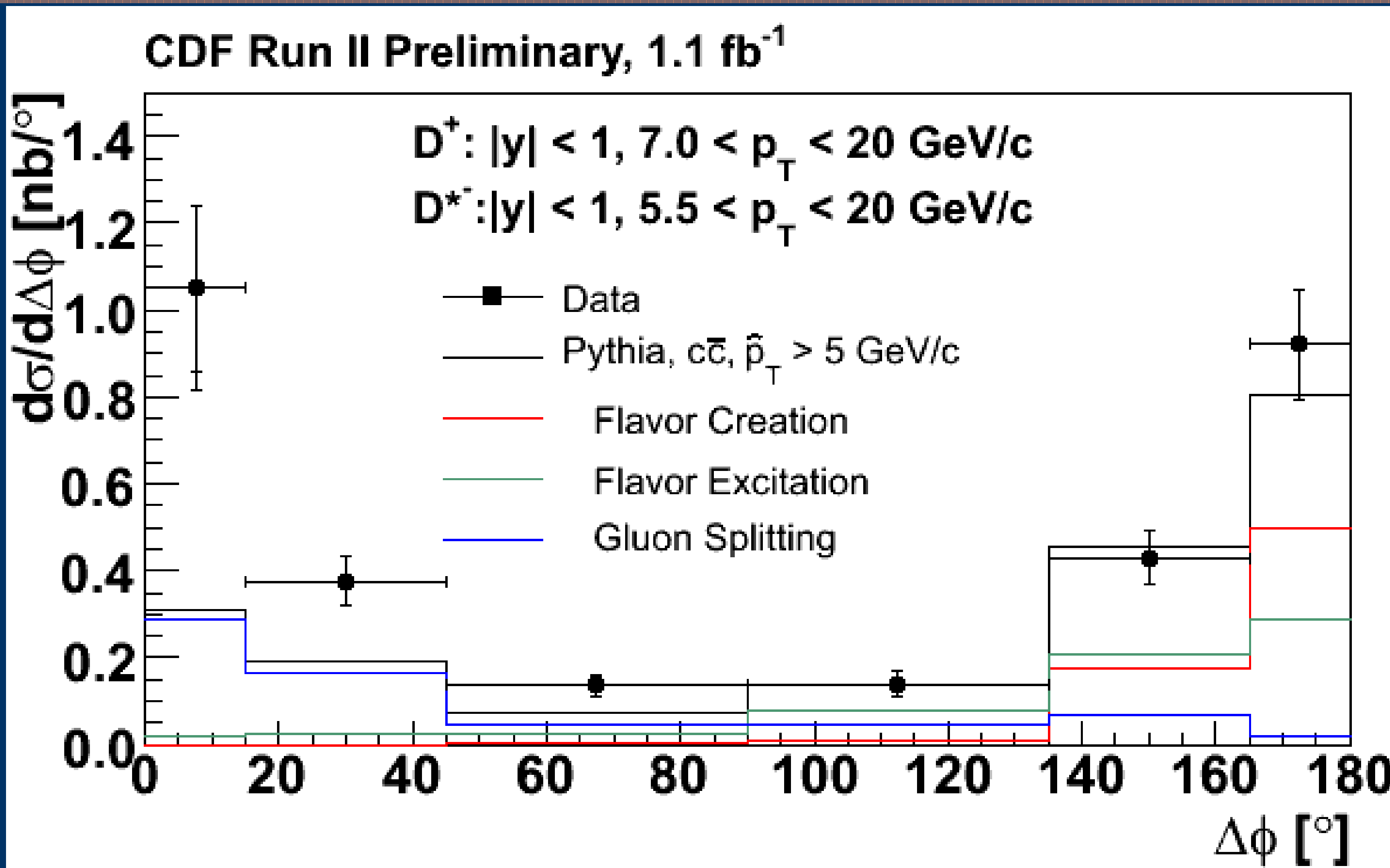
Common Syst. Error: δ~15%

D^0D^{*-} Cross Section



- Magnitude of D^0D^{*-} cross section in Pythia is about right,
- Collinear production as important as back-to-back production
- Pythia under estimates collinear (over estimates back-to-back)

D^+D^{*-} Cross Section



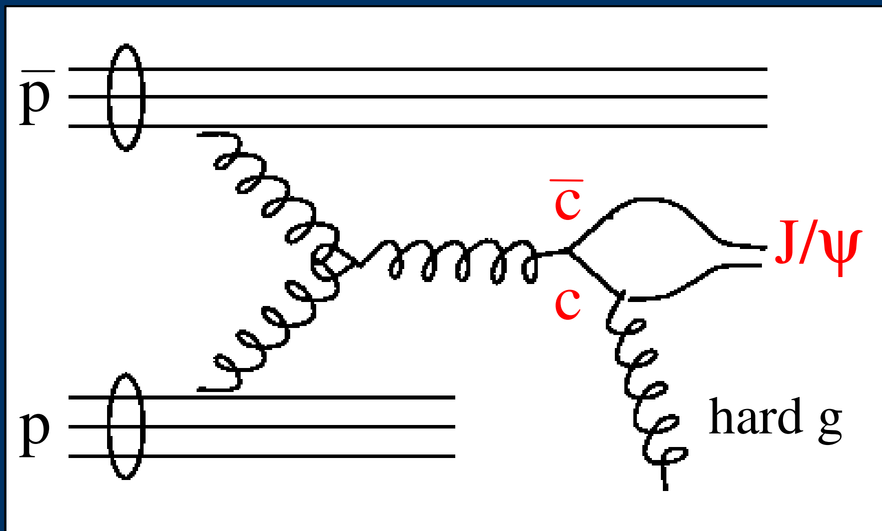
Error: stat⊕sys(f_b)

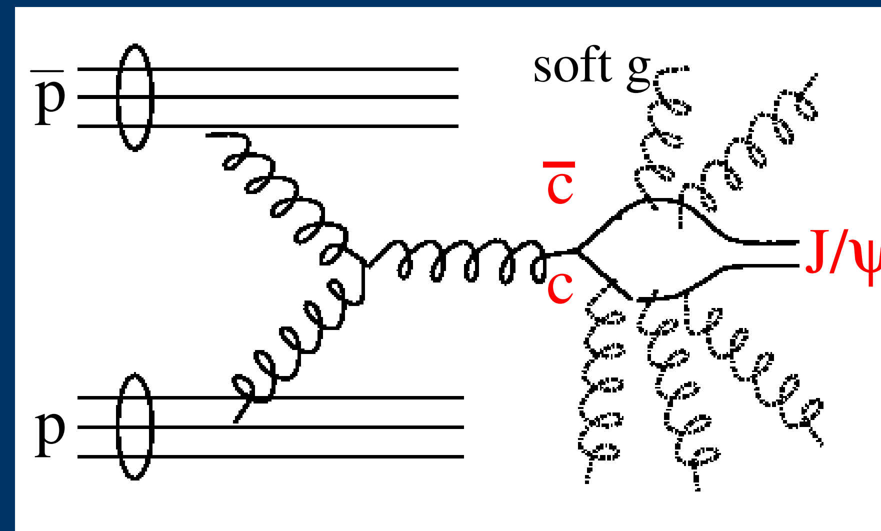
Common Syst. Error: δ~19%

Significant shape discrepancy consistent for both D^0D^{*-} and D^+D^{*-}

Charmonium Production

Color Singlet & Color Octet models





Color Singlet Model:

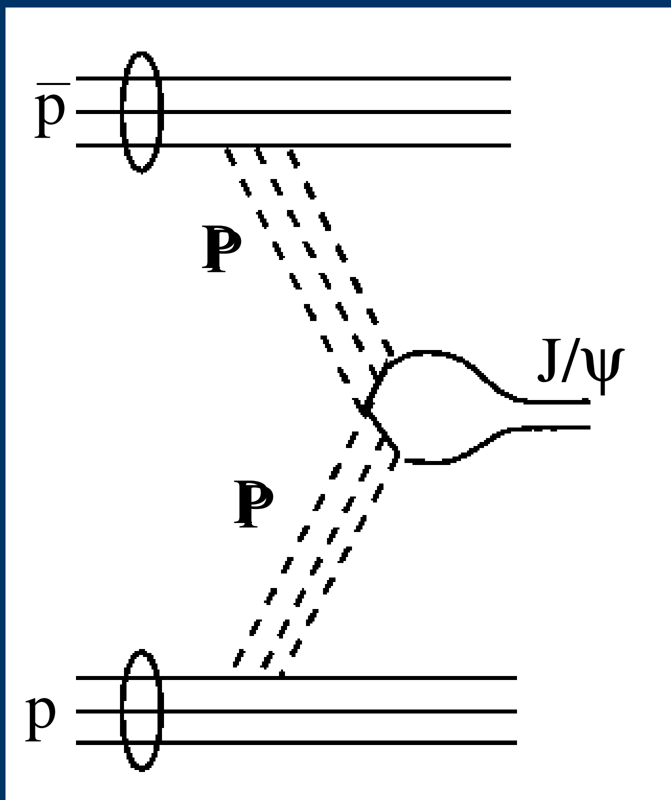
- cc pair is "bleached" by radiating off a hard gluon
- Underestimates J/ψ (1/10) and ψ' (1/50) production
- Feed down from χ_{cj} dominates (>90%) J/ψ production (CDF Run I finds 30%)
- PT spectrum does not match data

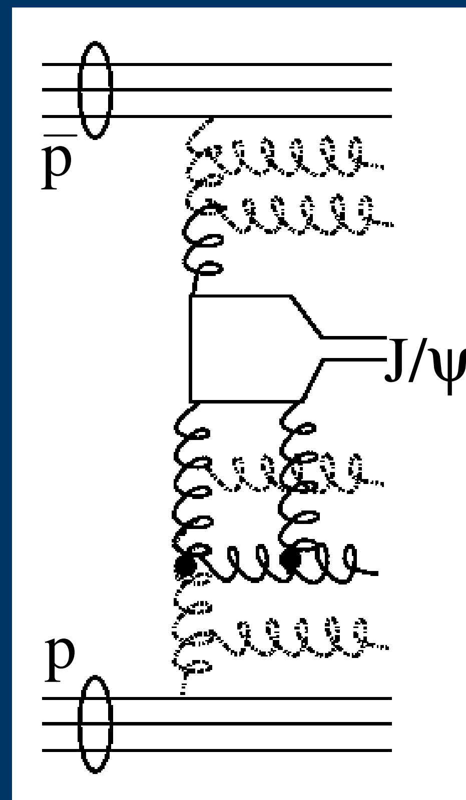
Non relativistic QCD introduces Color Octet Mechanism:

- Soft gluon radiation
- Adjustable hadronization parameter allows to match the observed PT spectra and production cross sections
- Predicts transverse polarization for J/ψ, deviates from data

"Pomeronic Idea"

Pomeron picture ⟶ pQCD





Emission of ℙomerons

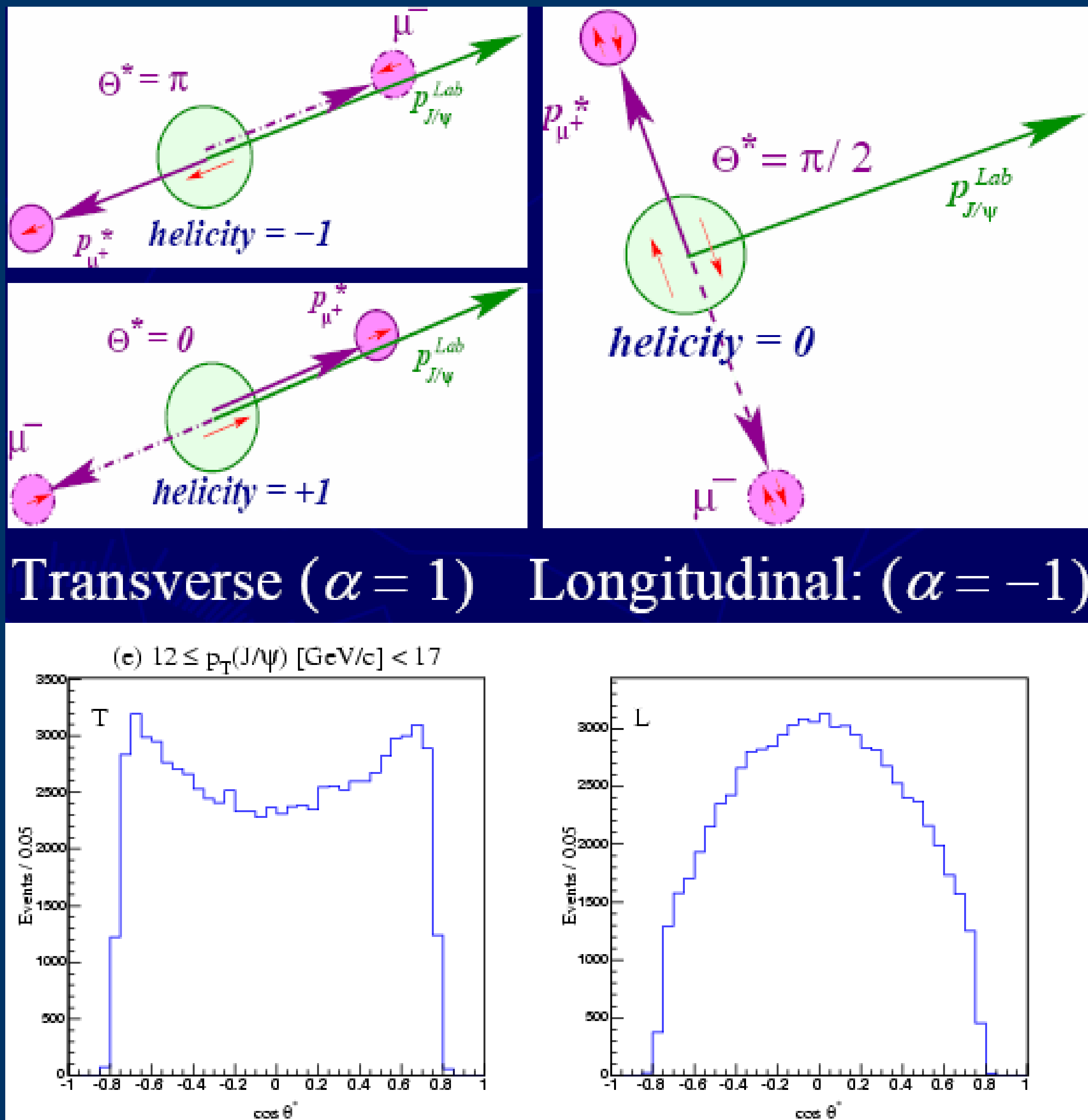
ℙomerons have vacuum Quantum numbers $J^P = 0^0$

Recent idea by V.A. Khoze, A.D. Martin, M.G. Ryskin and W.J. Sterling hep-ph/0410020

Fusion of a symmetric color octet state and a gluon

- Cross sections calculated in LO pQCD consistent with data
- PT spectra match data
- Predicts longitudinal polarization of J/ψ increasing with p_T

Polarization of J/ψ



$$\frac{d\Gamma}{d\cos\theta^*} \propto 1 + \alpha \cdot \cos^2\theta^*$$

$$\text{with} \quad (-1 \le \alpha \le 1)$$

θ^* angle between μ^+ in J/ψ rest frame and J/ψ in lab frame

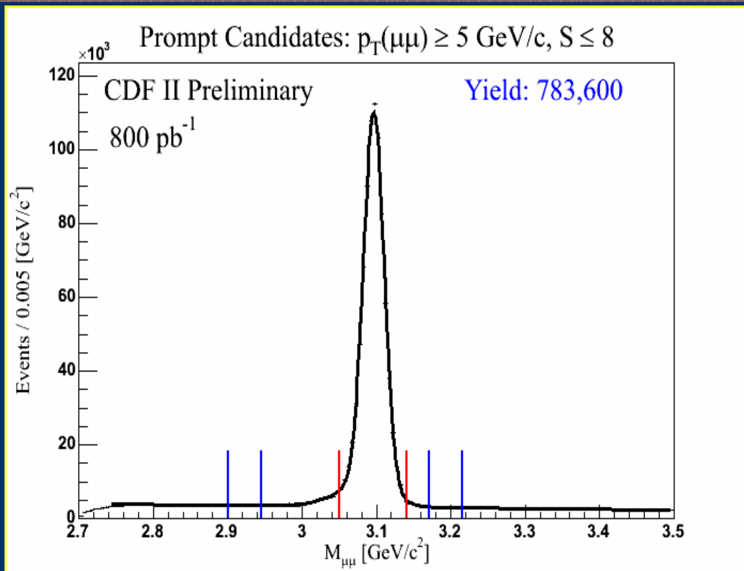
α polarization parameter

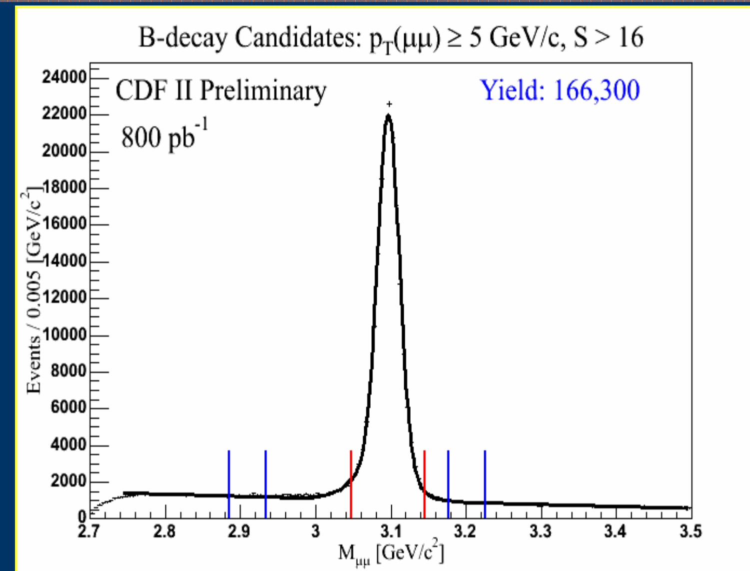
α=0 all 3 helicity states are equally populated

← MC polarization templates

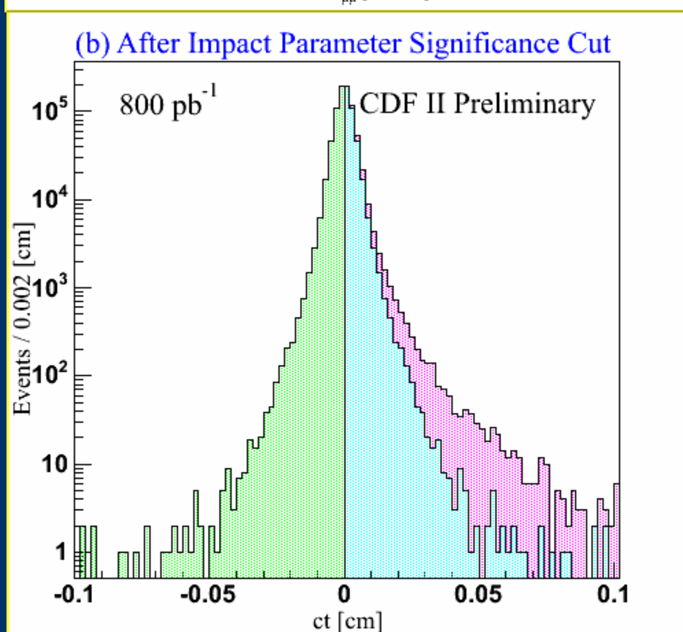
(trigger efficiency from data)

J/ψ Yields and Separation of Prompt and Secondary J/ψ



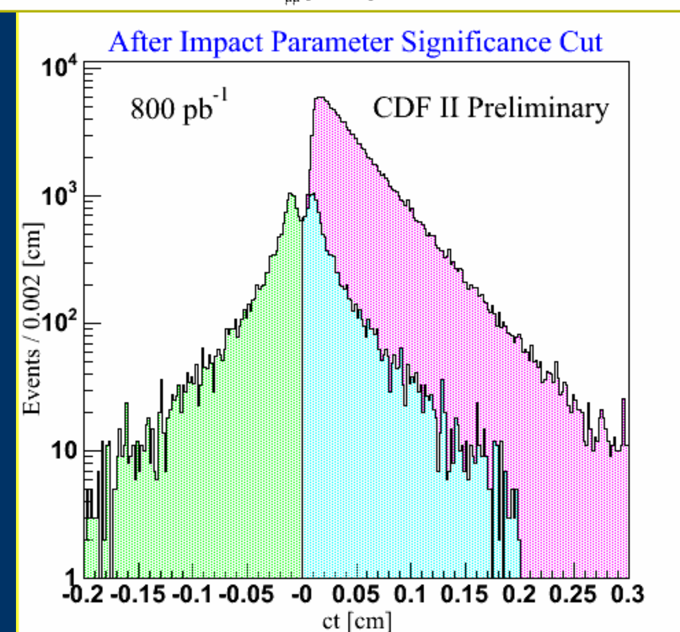


J/ψ selection
Central: $|y|<0.6$
$5<P_T<30$GeV/c

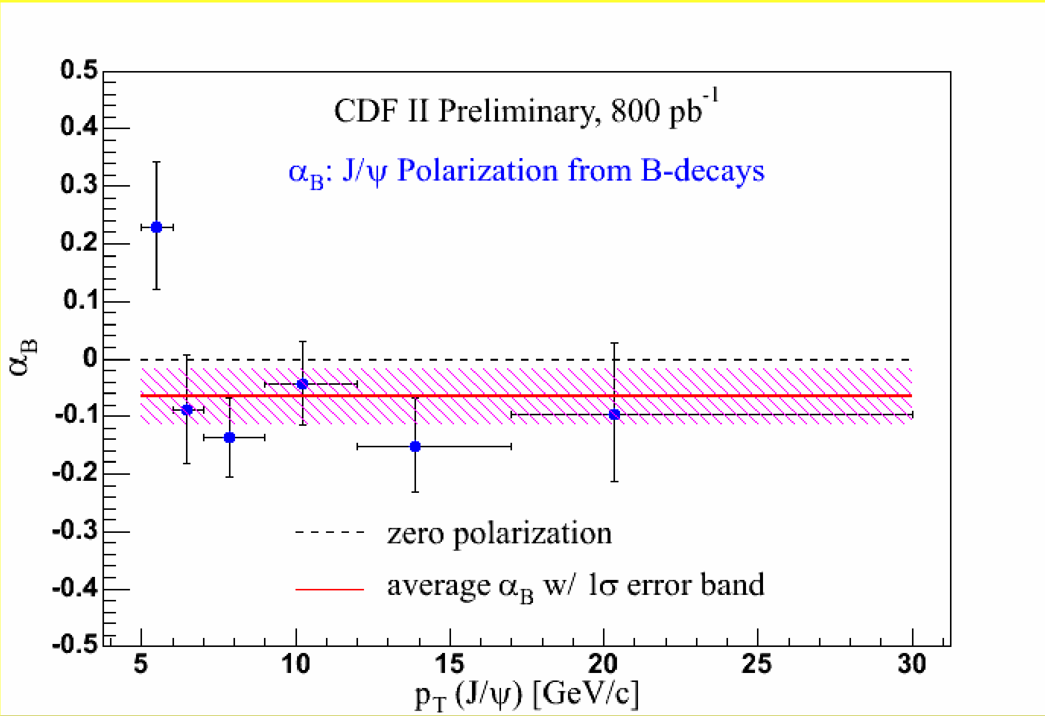


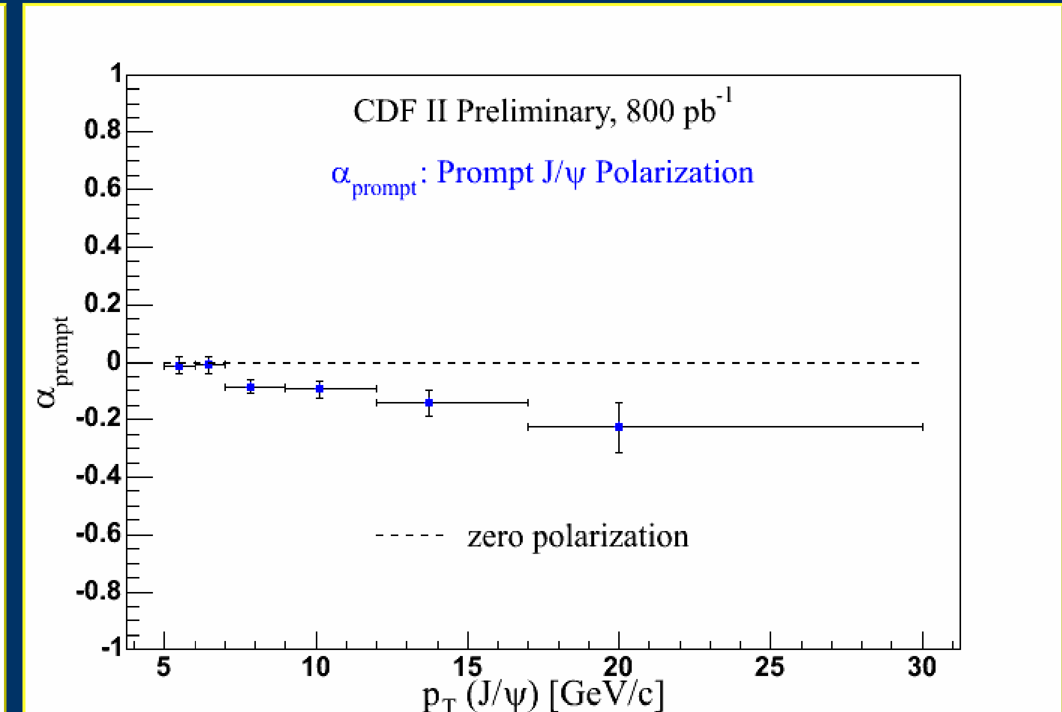
Use $\mu^+\mu^-$ combined impact parameter significance to separate prompt $S\leq 8$ and secondary $S>16$

$$S \equiv \left(\frac{d_0(\mu^+)}{\sigma_{d_0(\mu^+)}}\right)^2 + \left(\frac{d_0(\mu^-)}{\sigma_{d_0(\mu^-)}}\right)^2$$



Polarization of J/ψ Mesons





Polarization of J/ψ from B decays

- independent of P_T
- $\alpha_B = -0.066 \pm 0.050$
- Consistent with BaBar
  ($\alpha_B = -0.129 \pm 0.009$)

CDF result includes B_s and B baryons

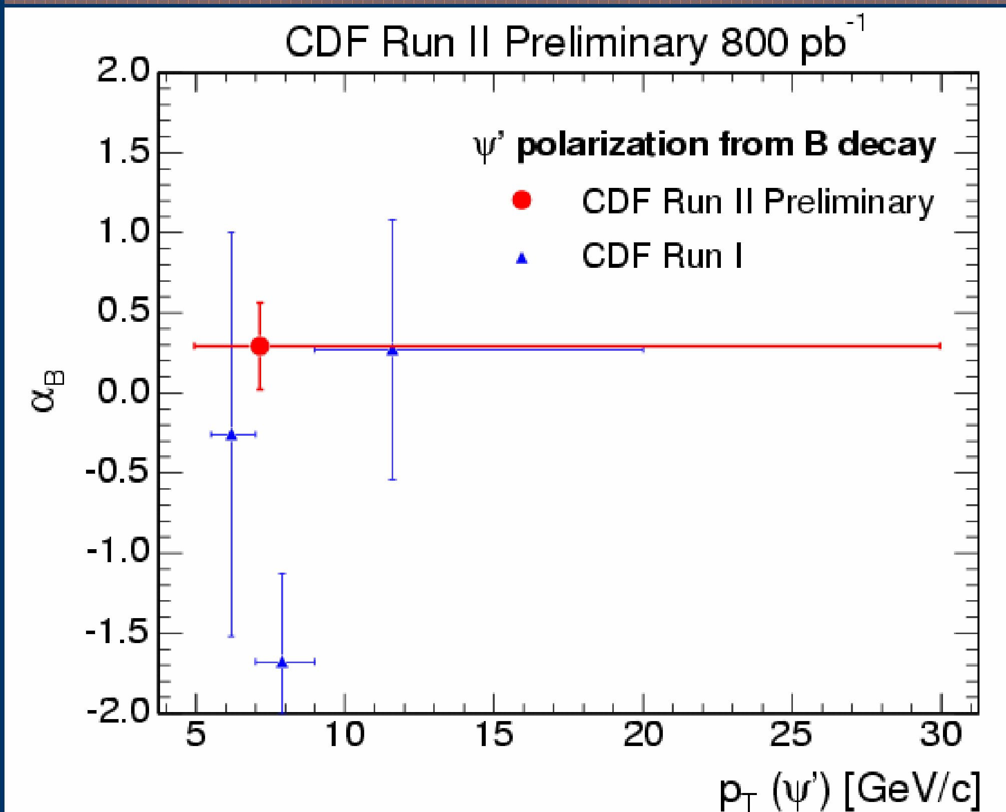
Polarization of prompt J/ψ

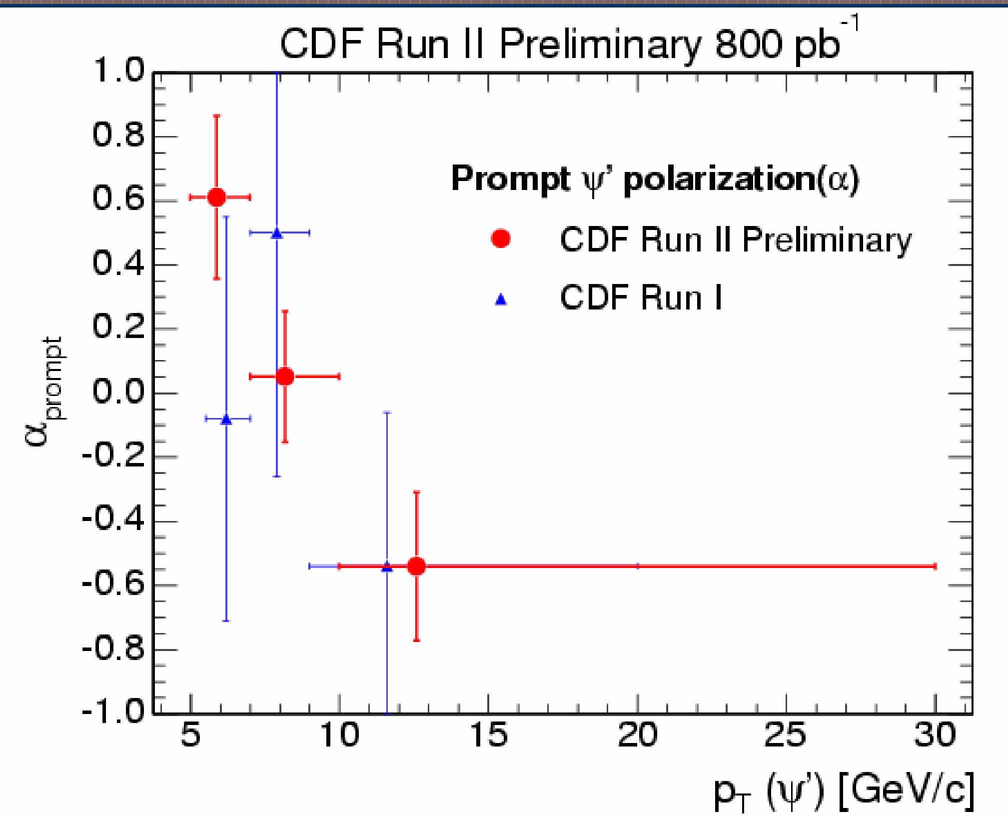
- Corrected for residual secondary J/ψ
- $\alpha<0$: longitudinal polarization

ψ' Polarization

- Same theoretical framework applies to prompt ψ' and J/ψ production
- no contribution from feed down from higher states therefore ψ' is a cleaner system to test direct charmonium production
- ψ' uses analysis approach as just described for J/ψ

ψ' Polarization Results





Polarization in B decays

- First measurement of α_B for ψ'
- $\alpha_B = 0.28 \pm 0.27 \pm 0.03$ (consistent with J/ψ within stat.)

Polarization of prompt ψ'

- Longitudinal polarization at high p_T, just as for J/ψ

Final Conclusion

New “Charming” results:

- First measurement of charm meson pair cross section in an hadron collider environment probes open charm production: →collinear charm production underestimated
- Polarization measurements of J/ψ and ψ' instigates new theory approach to charmonium production

We, CDF@Tevatron, continue to learn more about Heavy Quark Production in proton anti-proton collisions

Lessons from the Tevatron for LHC

- Current understanding of QCD heavy flavour production is limited: e.g. uncertainties of cross section ±50%
- Production models (cross section, p_T-spectra, polarization) for important calibration signals, e.g. J/ψ, are still pretty uncertain. How reliable is the extrapolation into new center-of-mass regime?
- Commonly used Leading Order MCs (e.g. Pythia) does not describe standard model heavy quark production in some aspects.
  Warning: This may become a problem when relying on MC to optimize search strategies for Higgs, Susy, etc..

Acknowledgements

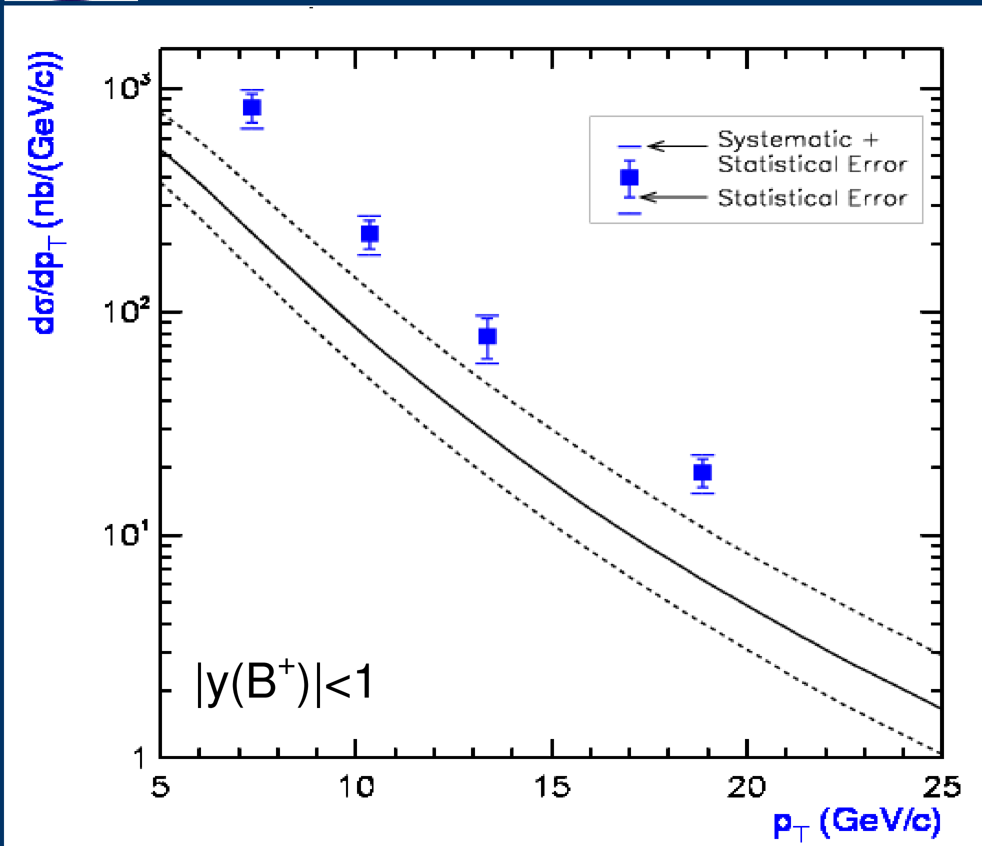
Contact persons for the presented CDF analyses:

- Charm meson pair cross Sections
  Burkard Reisert, reisert@fnal.gov
- J/ψ and ψ' polarization
  Min-Jeong Kim mjkim@fnal.gov
  Kwangzoo Chung kchung@andrew.cmu.edu
- Relative χ_{c1} χ_{c2} production
  Patrick Lukens ptl@fnal.gov

Beauty Cross Sections at the Tevatron

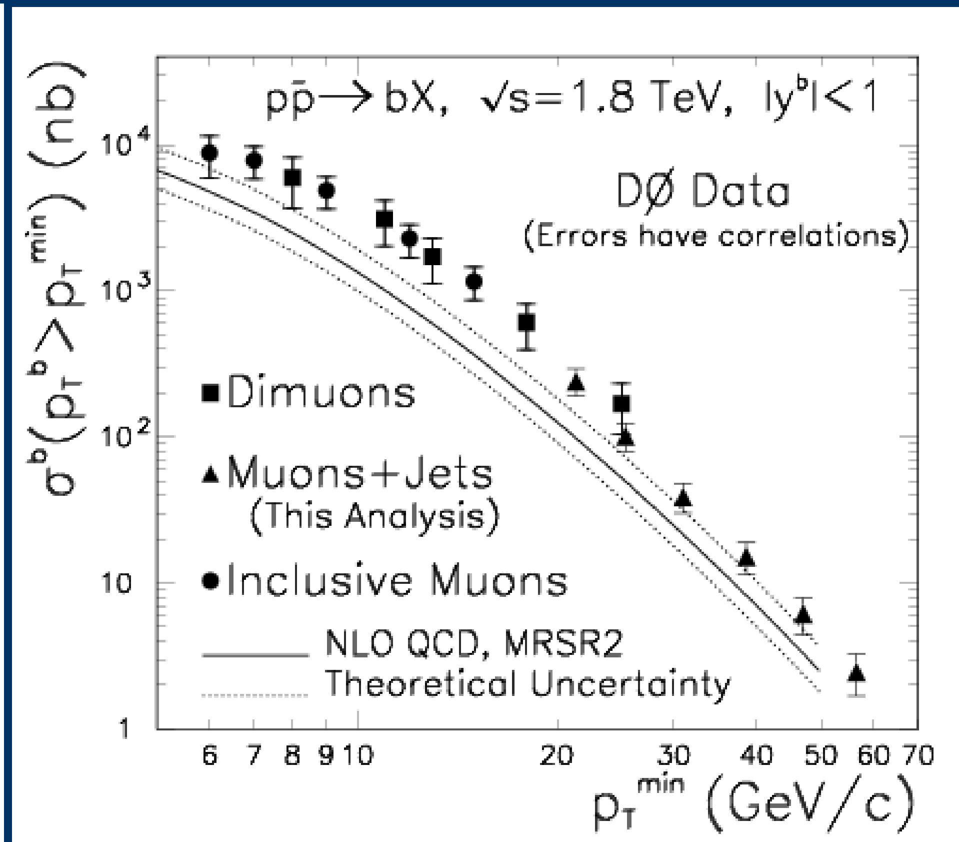
hep-ph/0111359

B^+ Meson
Differential Cross Section



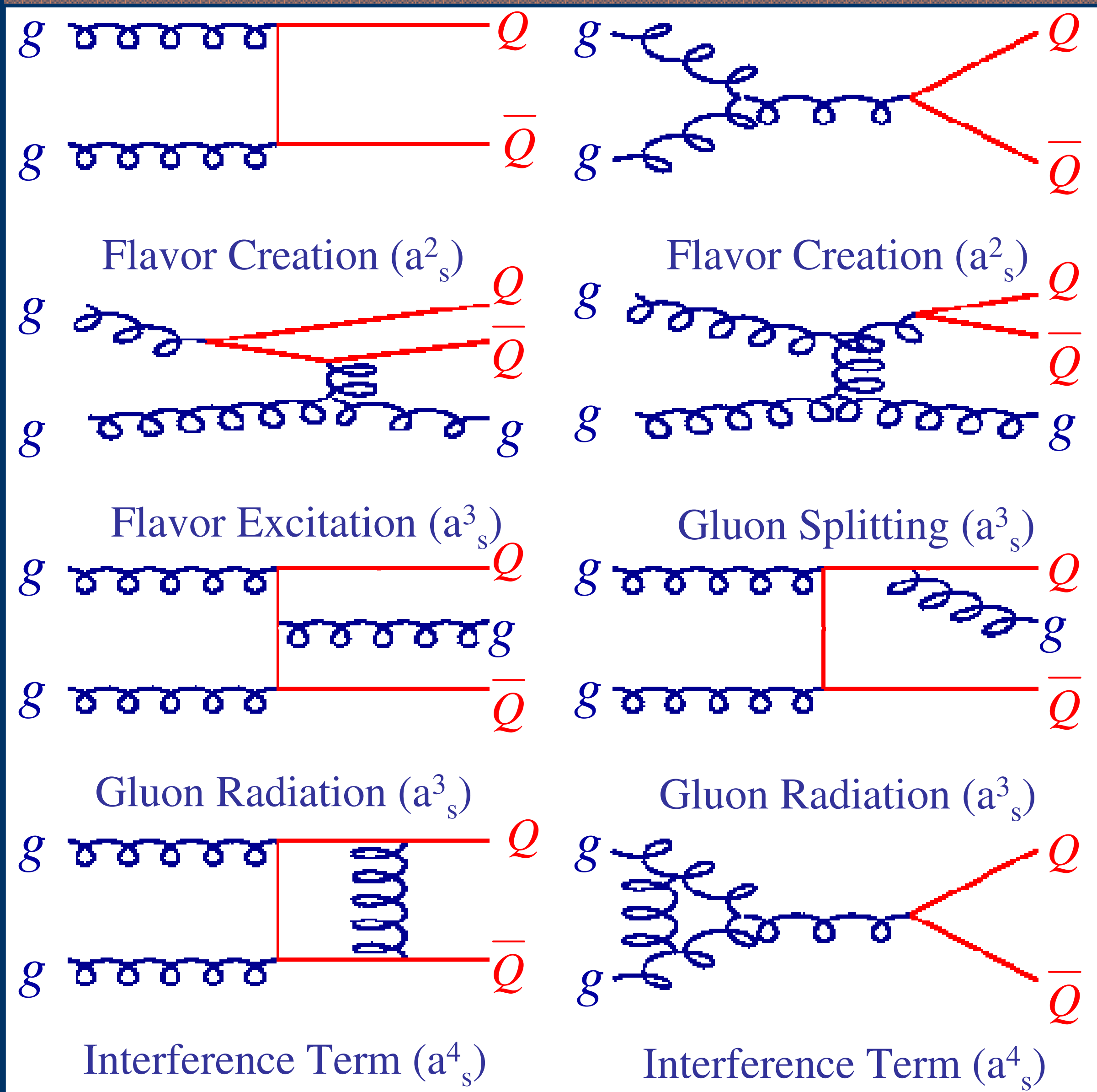
Integrated Cross Section for b-Quark Production

hep-ex/0008021



- Measurements in many channels lower than original theoretical predictions
- Instigated improved understanding of b fragmentation, now data & theory agree

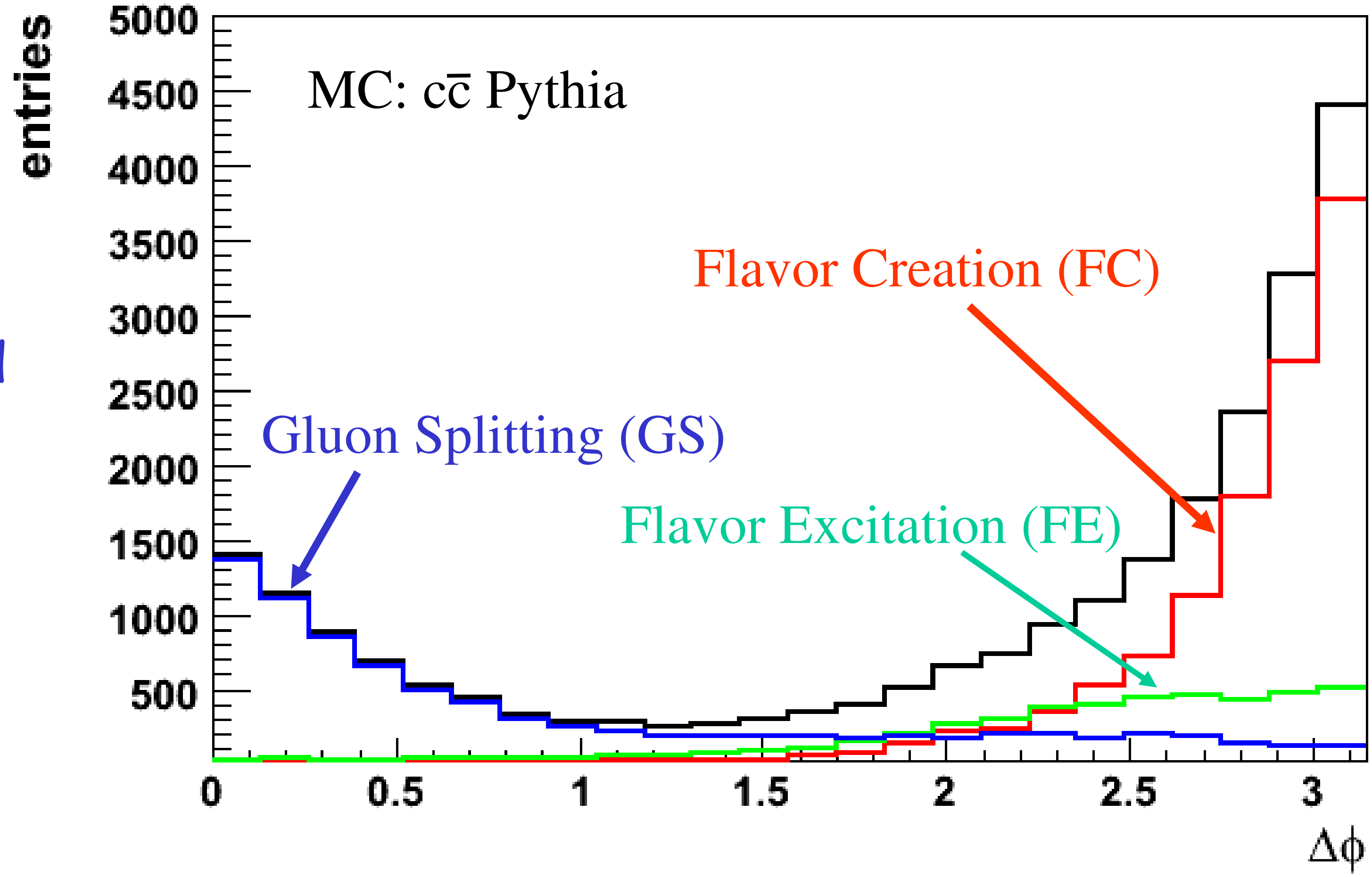
Open Charm Production



- Example Feynman Diagrams
- Calculations with massive quarks
  - incoming charm
  - charm in final state
  - parton shower
- All shown example graphs can be interpreted as higher order flavor creation

Leading Order Generator Level Study

$\Delta\phi<\pi/2$:
Gluon Splitting dominated region ("toward side")

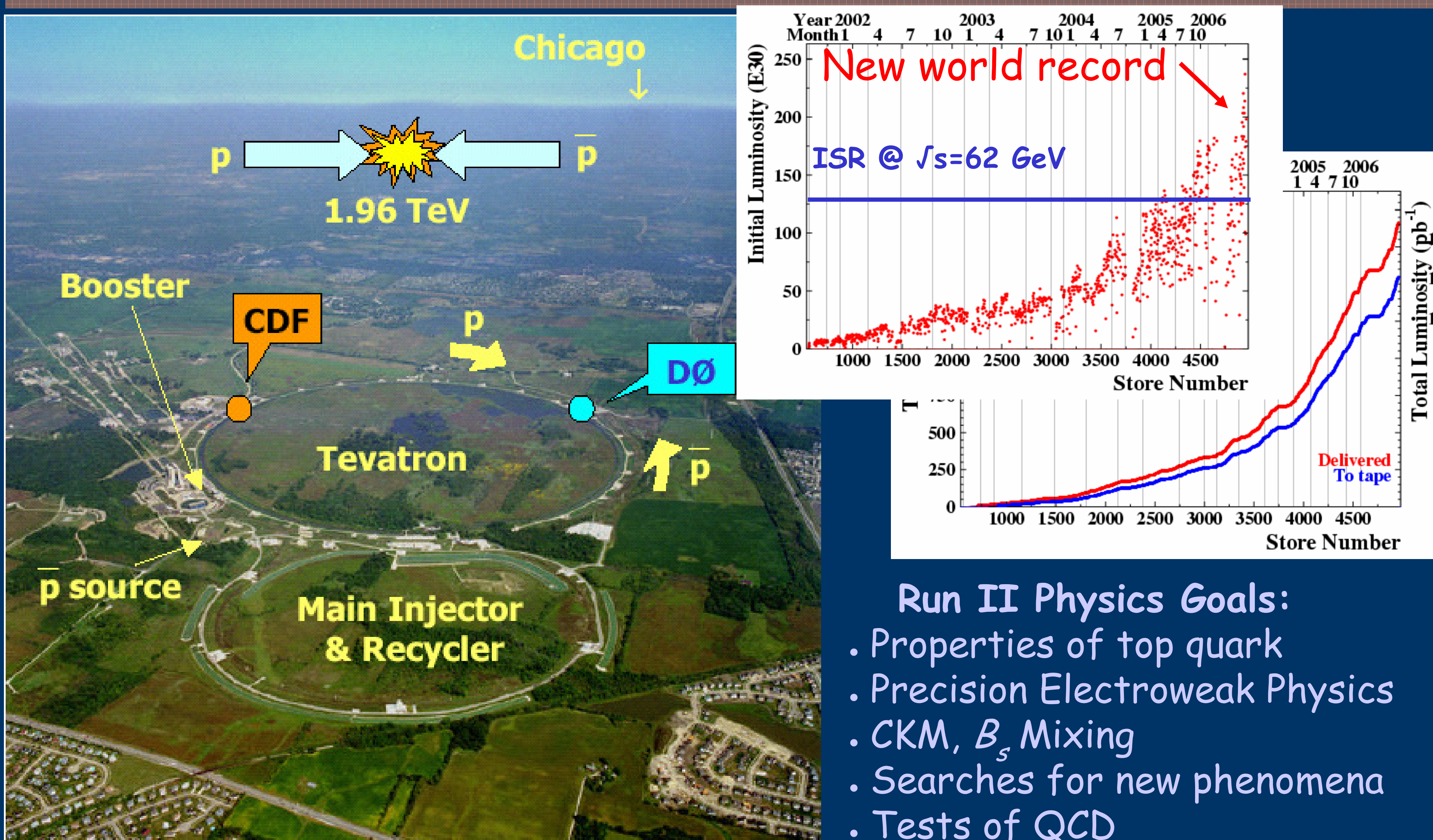


$\Delta\phi>\pi/2$:
Flavor Creation dominated region ("away side")

Pair selection on Generator (Pythia) level with "realistic cuts":

- Trigger-side D^0: P_T>5.5 GeV/c, $|y_D| < 1$, $P_T(K,\pi) > 2$GeV/c, $\Sigma_{K,\pi}P_T$>5.5GeV/c
- Probe-side $D^{*\pm}$: P_T>4.5 GeV/c, $|y_D| < 1$, $P_T(K,\pi) > 1$ GeV/c, $P_T(\pi^*) > 0.4$GeV/c

Tevatron

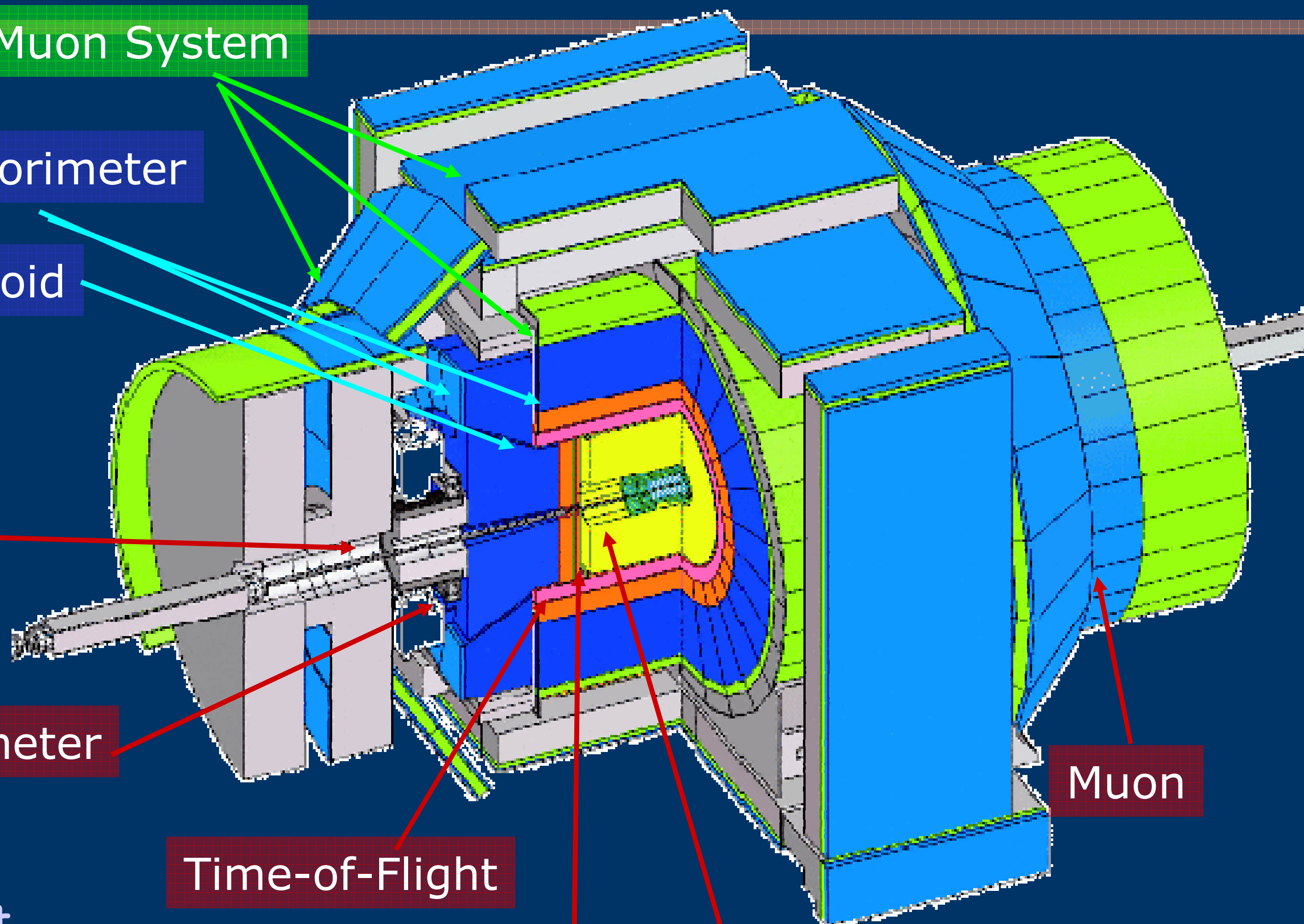


Run II Physics Goals:

- Properties of top quark
- Precision Electroweak Physics
- CKM, B_s Mixing
- Searches for new phenomena
- Tests of QCD

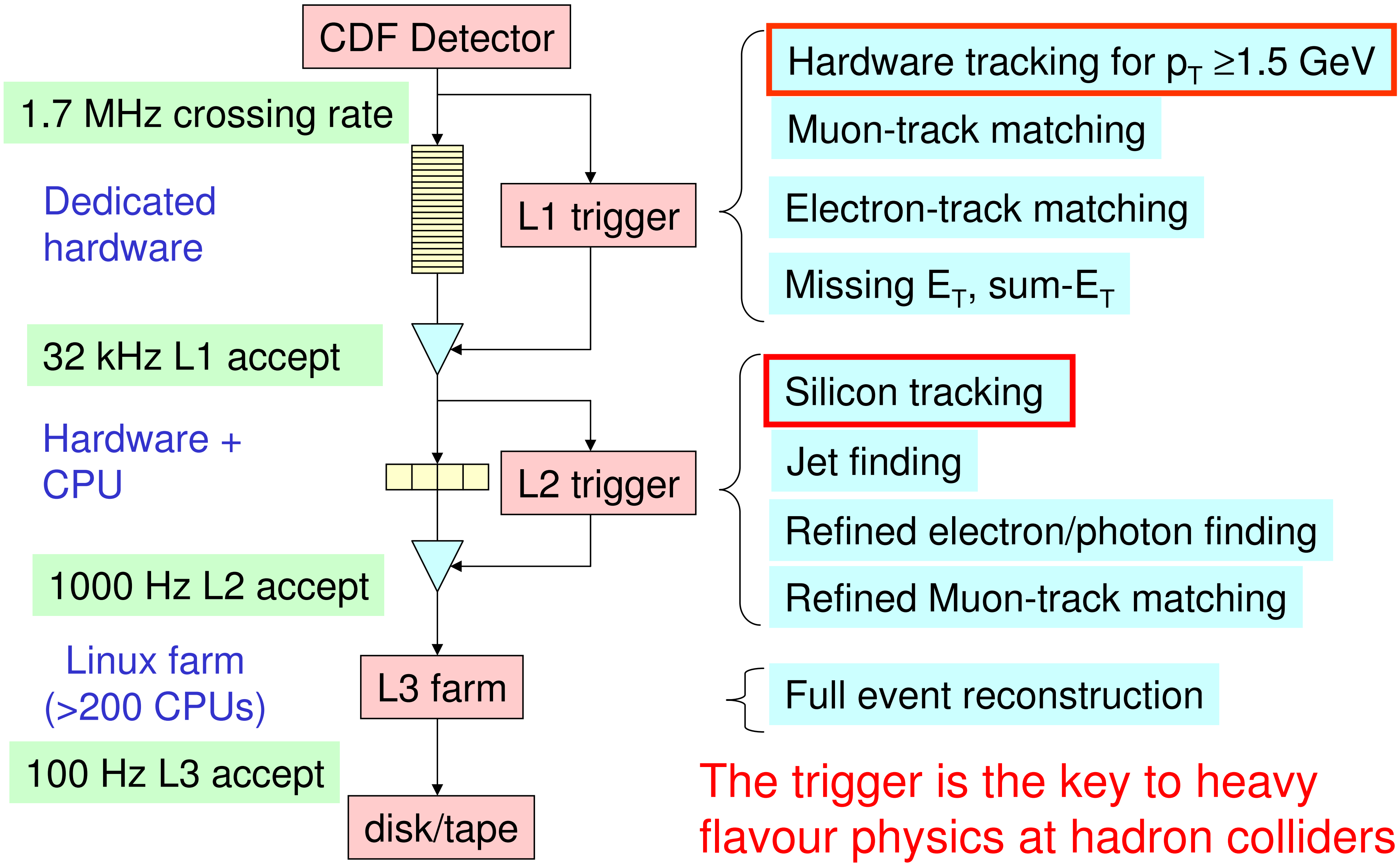
Collider Detector at Fermilab

New
Old
Partially New



CDF has
- Tracking with excellent momentum and impact parameter resolution
- High-bandwidth trigger

CDF Trigger & DAQ System



The trigger is the key to heavy flavour physics at hadron colliders

Triggers for Beauty & Charm Physics

Di-Muon (J/ψ)
$P_T(\mu) > 1.5$ GeV

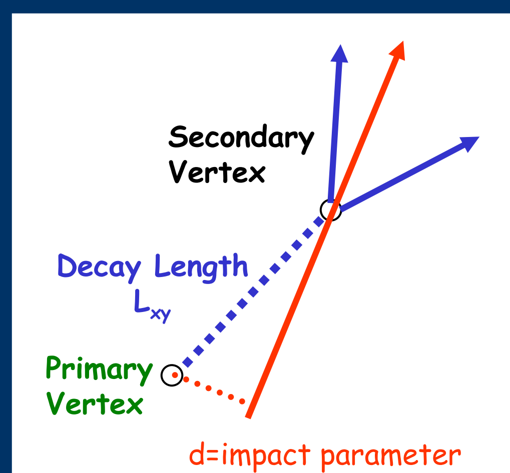
J/ψ, $\psi(2S)$ modes
Down to low $P_T(J/\psi)$ (~ 0 GeV)

- $\psi(2s)$, $X(3872) \rightarrow J/\psi pp$ (quarkonia)
- $B_s \rightarrow J/\psi\phi$, $B_{u,d}$ $J/\psi K_s^{(*)}$ $L_b \rightarrow J/\psi\Lambda$ (masses, lifetimes, mixing calibration)
- $B_{s,d} \rightarrow \mu\mu$ (rare decays)
- B_c(lifetime $B \rightarrow J/\psi lX$, mass $B \rightarrow J/\psi p$)

Displaced track(s) + lepton (e, μ)
IP(trk)>120 μm
P_T(lepton) >4GeV

Semileptonic modes

- B_s mixing (semileptonic)
- Tagging, lifetime

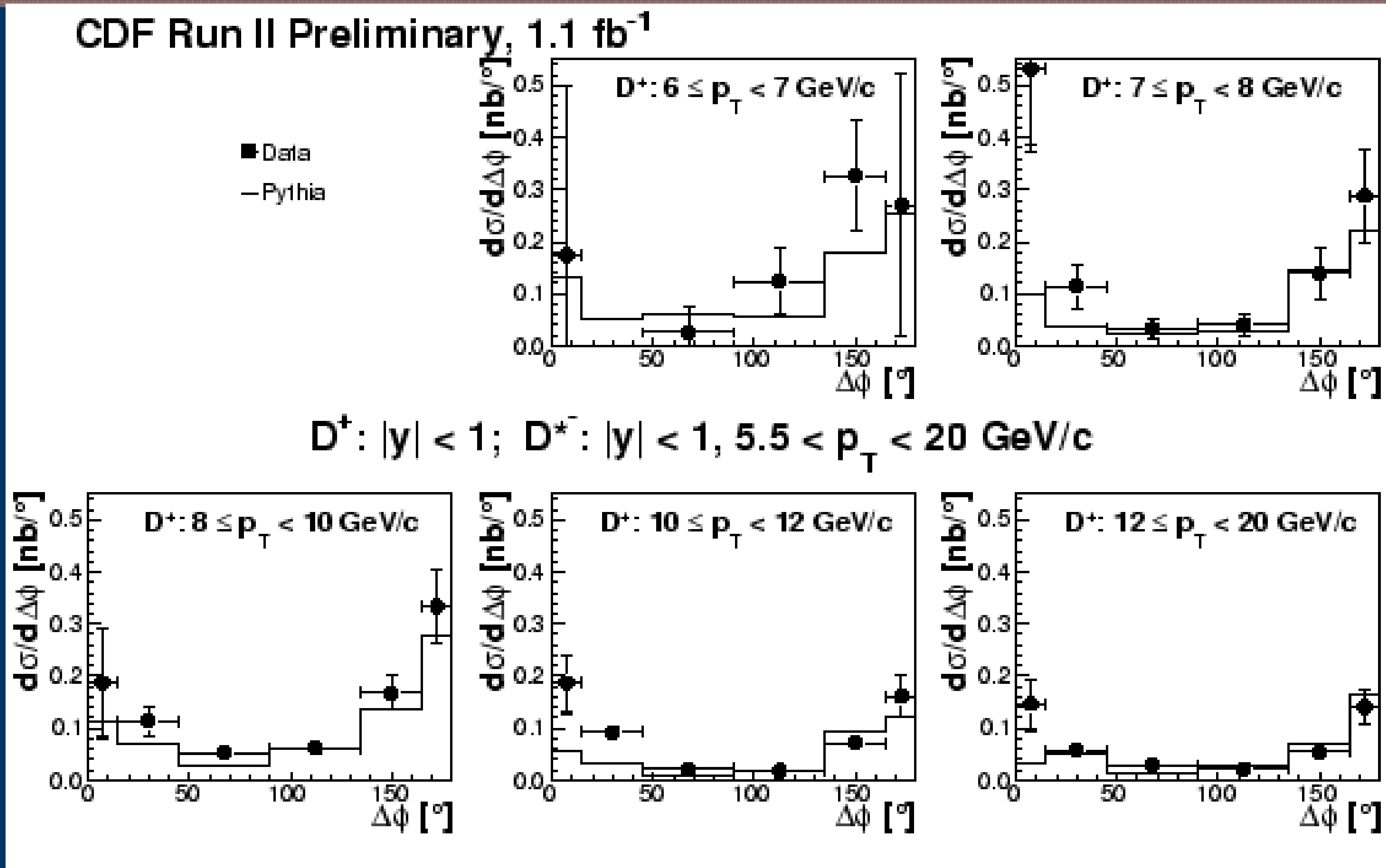


Two Track Trigger
P_T(trk)>2 GeV
IP(trk) >100 μm

Fully hadronic modes

- 2-body charmless decays (B^0,B_s,Λ_b)
- B_s mixing (hadronic)
- Charm physics
  - inclusive cross sections
  - $D^0 \rightarrow K\pi,\pi\pi,KK$
- Heavy quark production

D^+D^{*-} Pair Cross Section binned in P_T(Trig)



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Common Syst. Error: δ~19%

Conclusion on Charm Meson Pairs

The unprecedented integrated luminosity delivered by the Tevatron in conjunction with CDF's high bandwidth trigger allows us to perform a detailed study of charm production

- First measurement of charm meson pair cross section in a hadron collider environment probes open charm production
- We find collinear production to be as important as back-to-back production,
- Same result is seen consistently in 2 different modes
- Expectation from Pythia has significantly different shape

- Interesting new result on Open Charm Production

- News on Charmonium (i.e. hidden Charm) Production
  → second part of this talk

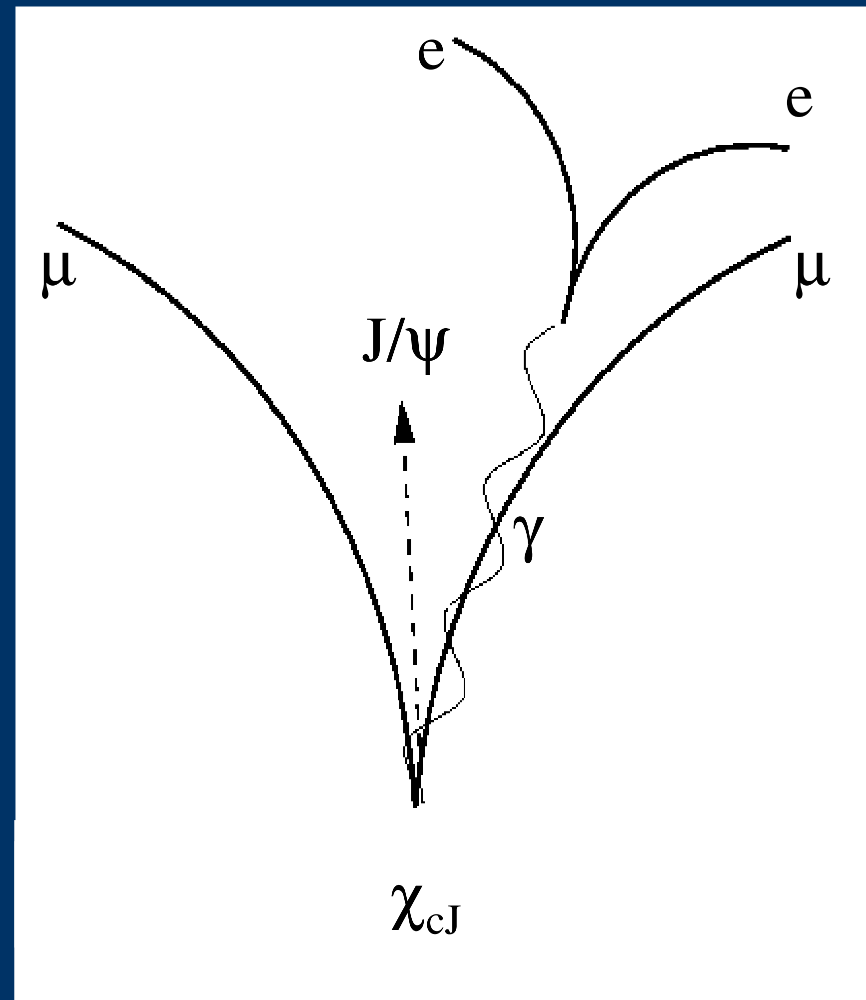
χ_{cJ} Production

- Models of prompt charmonium production in hadron collisions always contain significant χ_{cJ} contributions

- The measurement of $\sigma(\chi_{c2})/\sigma(\chi_{c1})$ has been performed at several energies and beam types over the years.
  - Best measurements have ~100 events, 30% statistical uncertainty on the cross section ratio.
  - Results like 1.0 ± 0.3 are consistent with most models.

Measurement of $\sigma(\chi_{c2})/\sigma(\chi_{c1})$

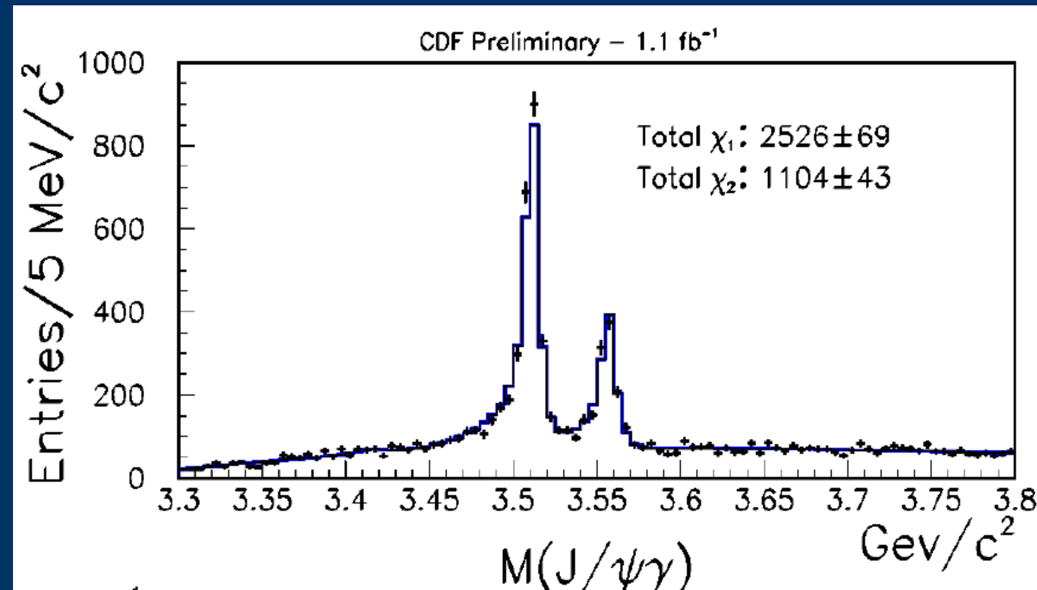
- Measurement of properties of χ_{cJ} production has always been an experimental challenge
- Low energy photon from $\chi_{cJ} \rightarrow J/\psi\gamma$ is difficult to measure (~400 MeV in χ_{cJ} rest frame)
- Calorimeter measurements have good efficiency but poor resolution and high background in a hadron collider environment
    - Conversion measurement
      - good resolution
      - poor efficiency
      (now compensated L=1fb^{-1})

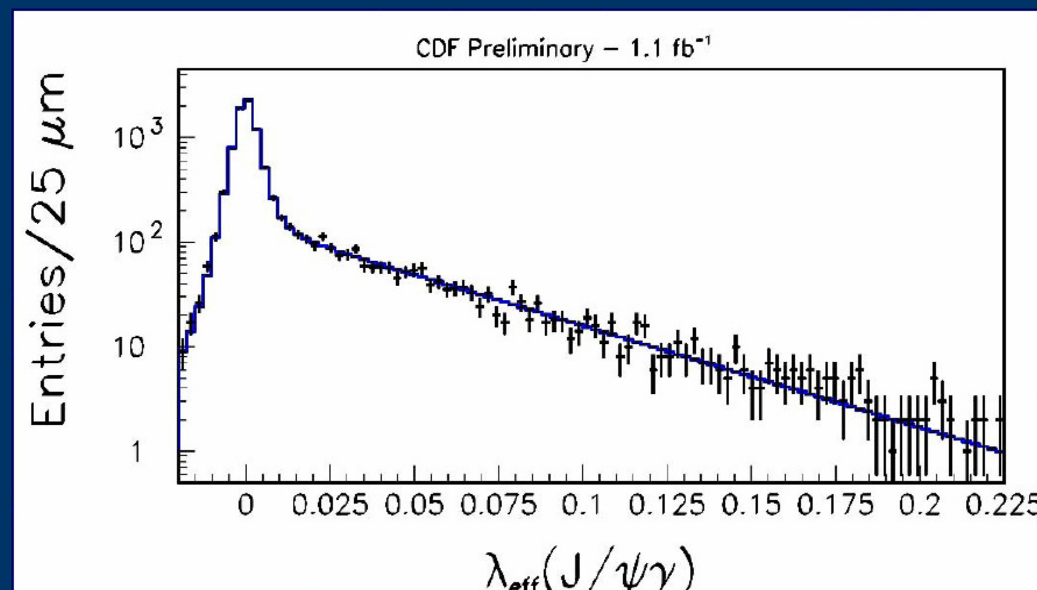


χ_{cJ} Data Set

Here we reconstruct:
$\chi_{cJ} \rightarrow J/\psi\gamma$, $J/\psi \rightarrow \mu^+\mu^-$, $\gamma \rightarrow e^+e^-$

- J/ψ selection as polarization analysis
- Photon conversion gives excellent energy (mass) resolution.
- Prompt and B-decays are easily separated

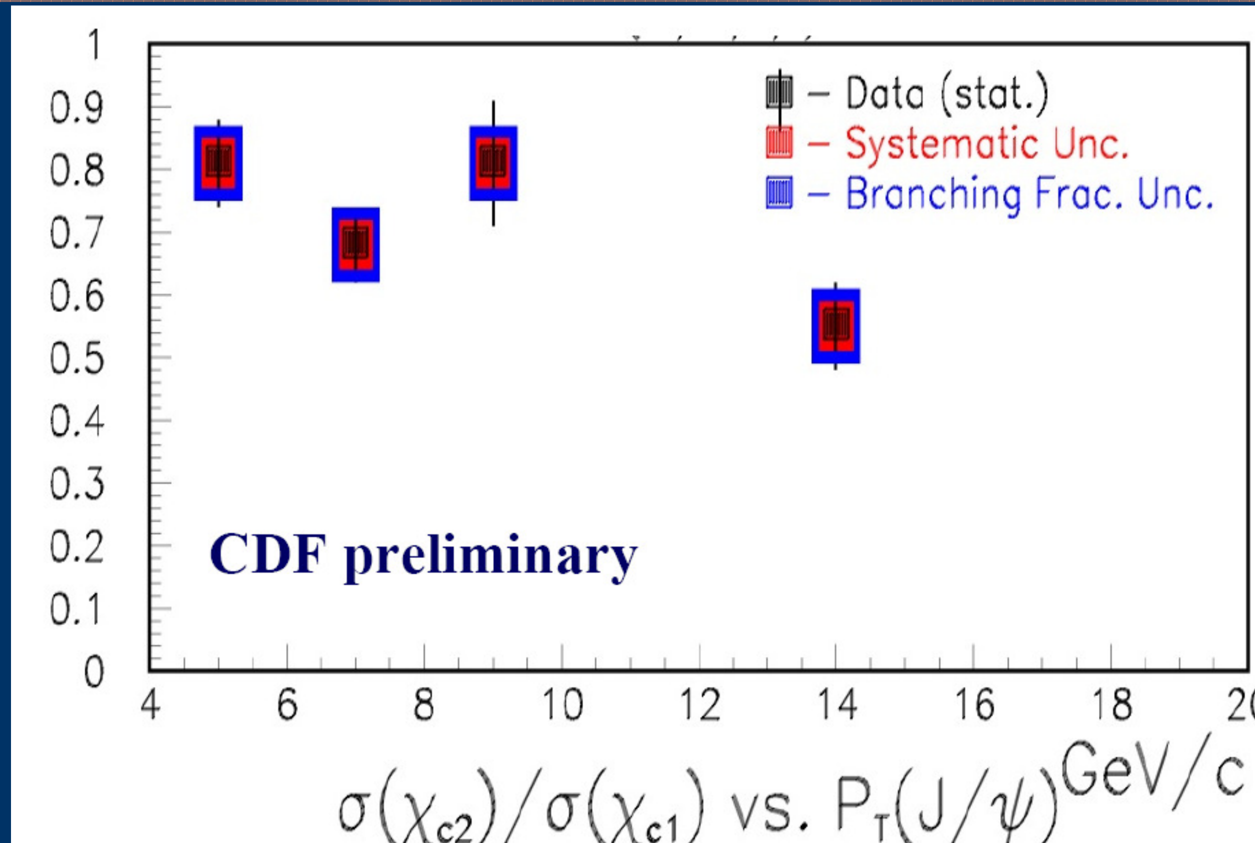




Simultaneous fit to the mass and flight distance distributions is used to extract the relative yields for both prompt χ_{cJ} and χ_{cJ} from *B* decays

Results on $\sigma(\chi_{c1})/\sigma(\chi_{c2})$

- New level of precision for measurement of $\sigma(\chi_{c1})/\sigma(\chi_{c2})$
- Should provide nice constraint on models of production mechanisms



- Result for prompt χ_{cJ}:

$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = 0.70 \pm 0.04(stat.) \pm 0.03(syst.) \pm 0.06(B.F.)$$

for $4 < p_T(\chi_{cJ}) < 20$ GeV/c

- Color Octet predicts 5/3 (counting of Spin states)