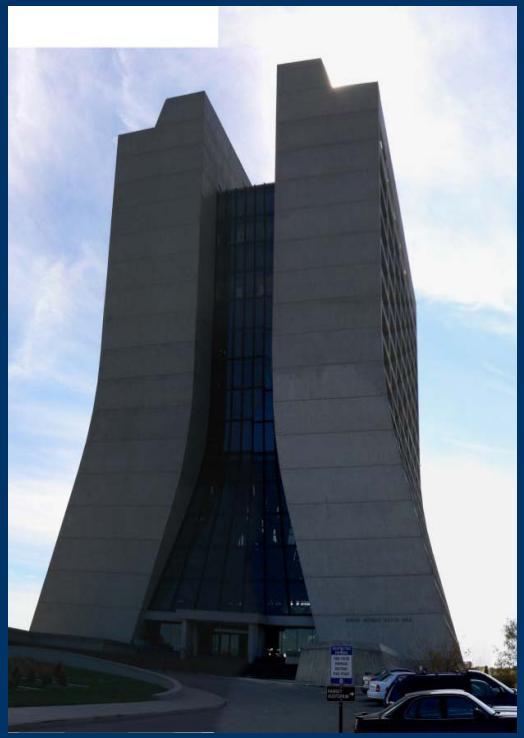
Charm and Beauty Production at the Tevatron

Burkard C. Reisert



- Heavy Quark Production
- Tevatron & Detectors
- Plethora of New Results:
  Open charm and charmonium production, B cross sections, events with b-tagged jets

Motivation

Heavy Quark Production:

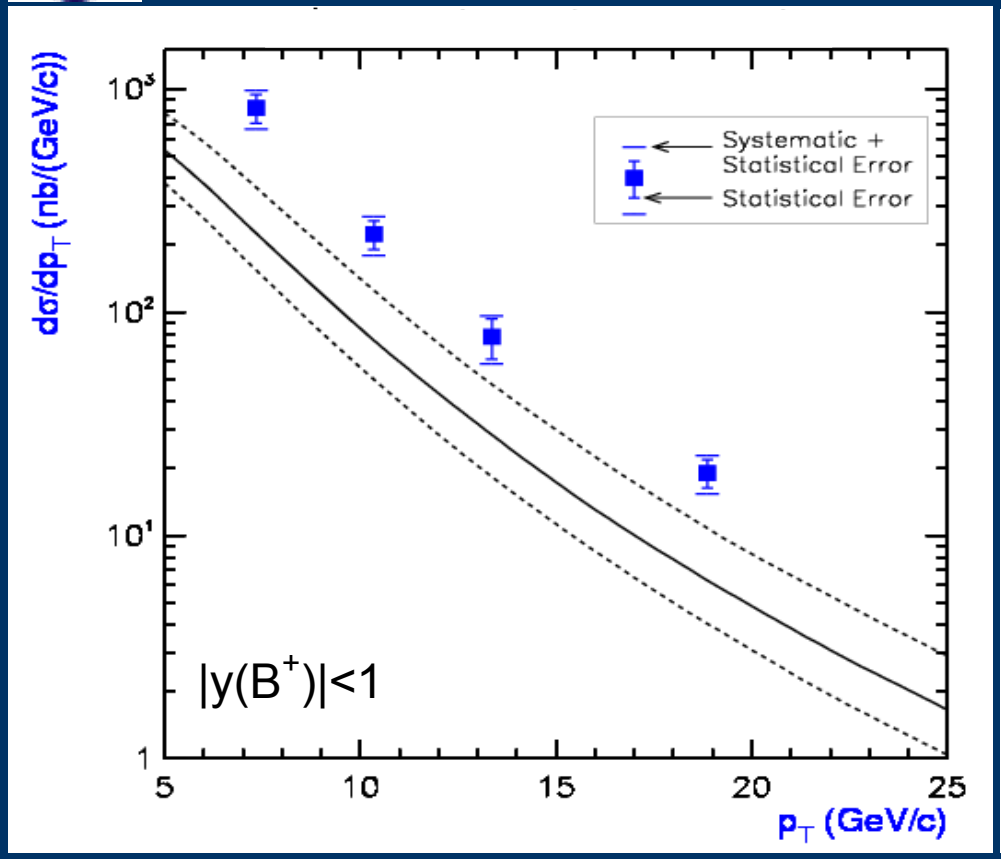
- Test of Quantum Chromodynamics at the transition from perturbative to non-perturbative regime
  masses of *c*, *b* quarks provide hard scale for QCD calculations, $m_Q > \Lambda_{QCD}$
  ➔heavy quark production should be well predictable

- Beauty and charm cross sections in pp collisions were measured to be larger than expected in early Tevatron data.

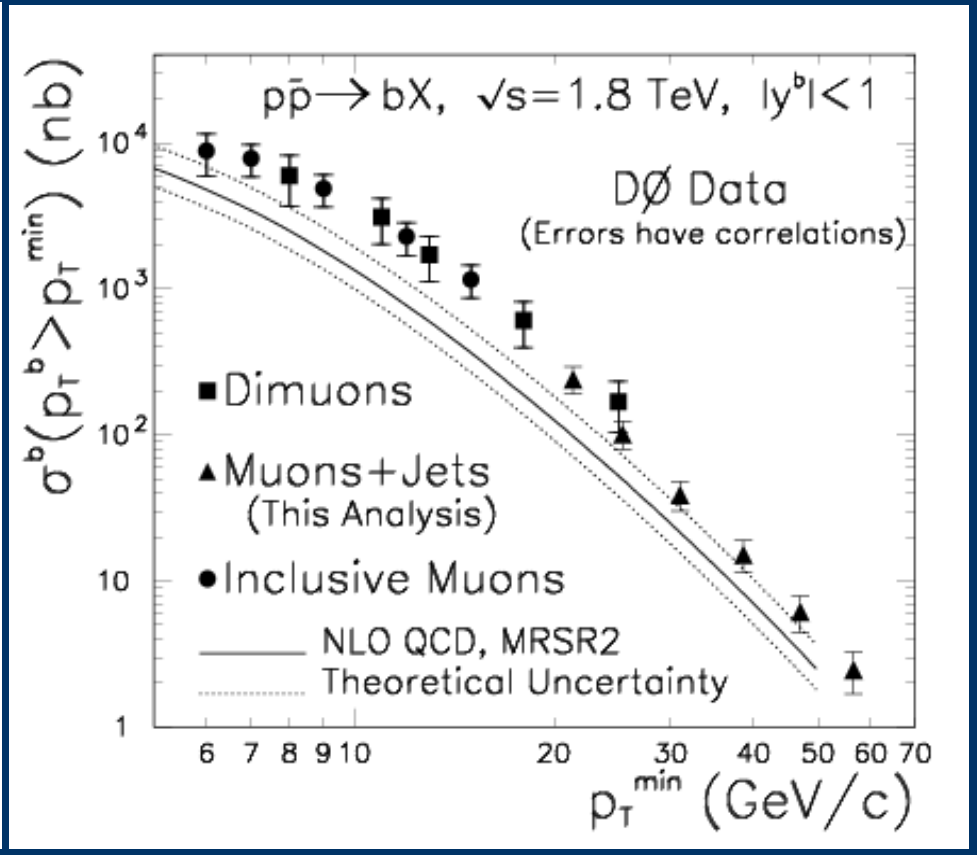
Reminder: B Cross Section "Crisis" in Tevatron Run I

hep-ph/0111359

B^+ Meson
Differential Cross Section



Integrated Cross Section for
b-Quark Production



hep-ex/0008021

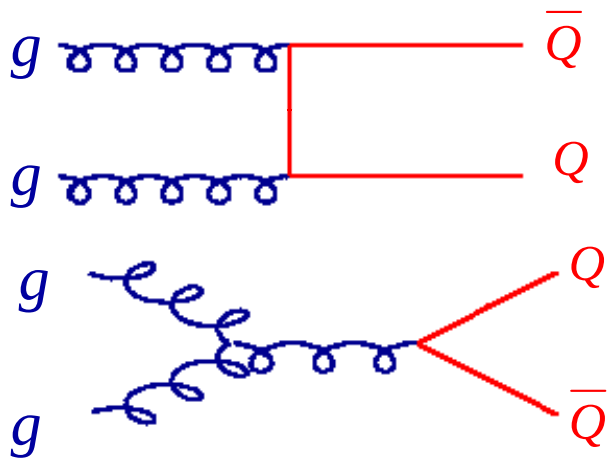
- Measurements in many channels higher than original theoretical predictions

Charm and Beauty Production

- This crisis instigated better theoretical understanding and improved measurements, now data & theory are in much better agreement
- Resummation schemes are active field of research
- Calculations in FONLL are available

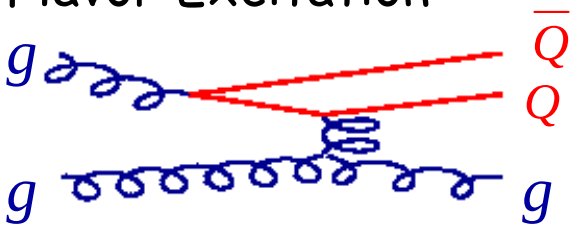
Leading Order:

Flavor Production

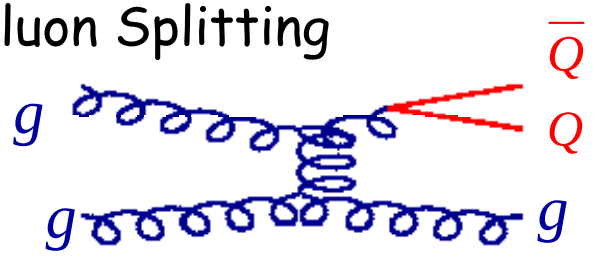


Next-to-leading Order:

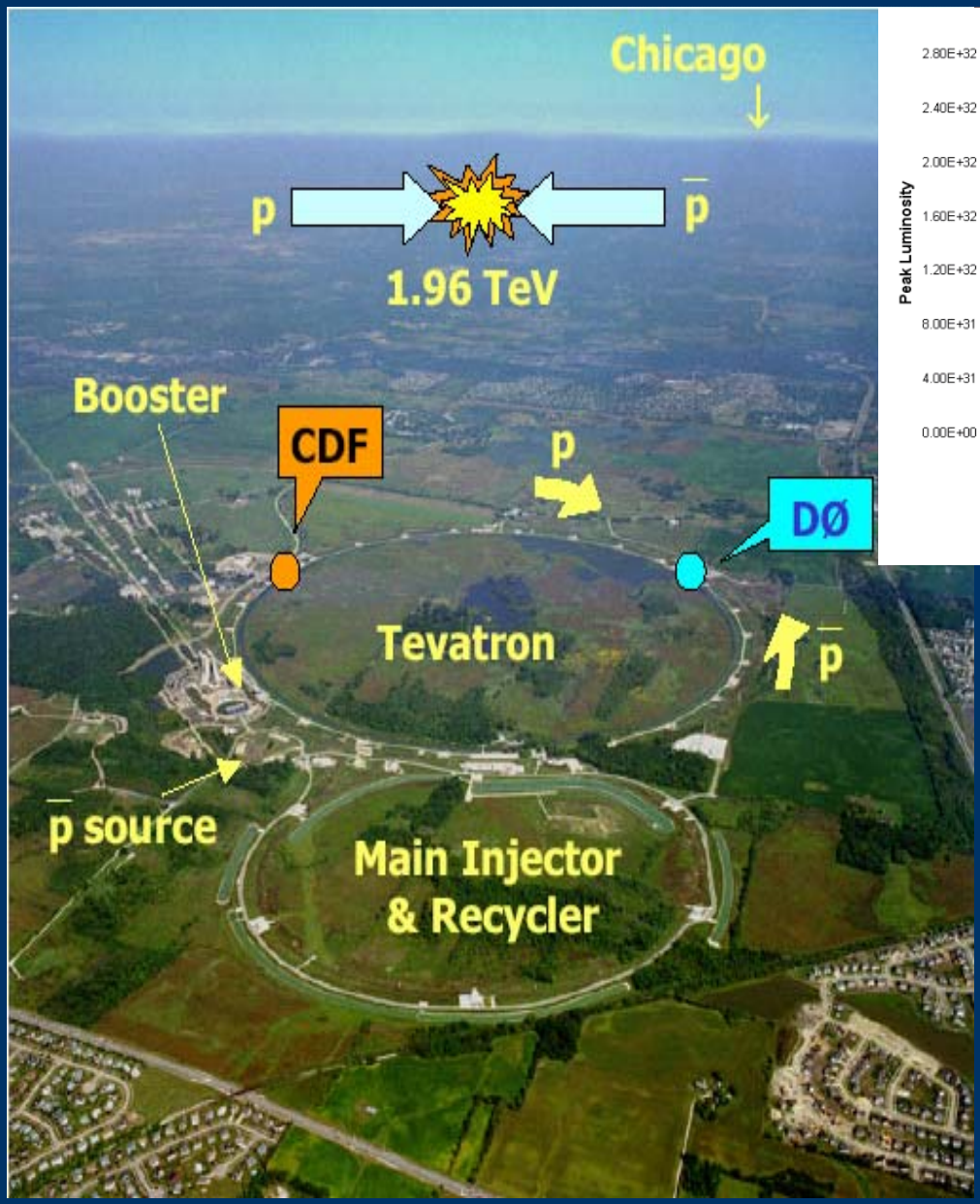
Flavor Excitation

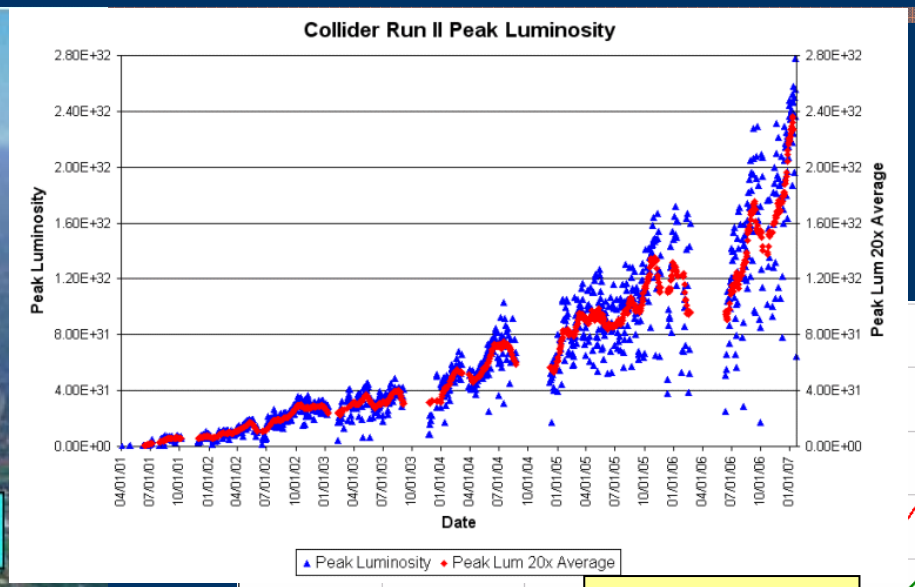


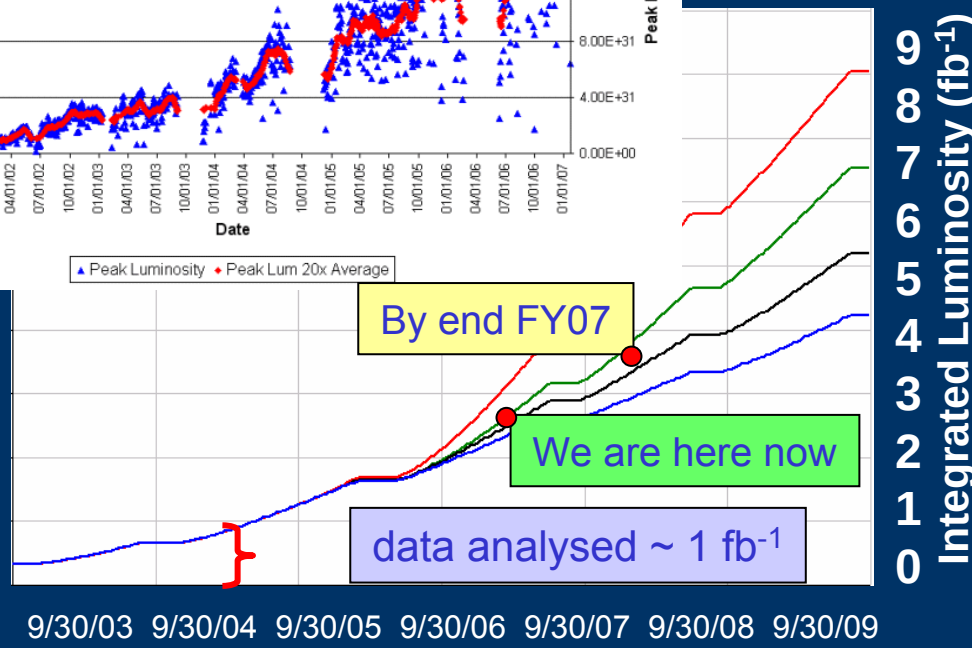
Gluon Splitting



The Tevatron
Largest Hadron Collider in Operation (still)

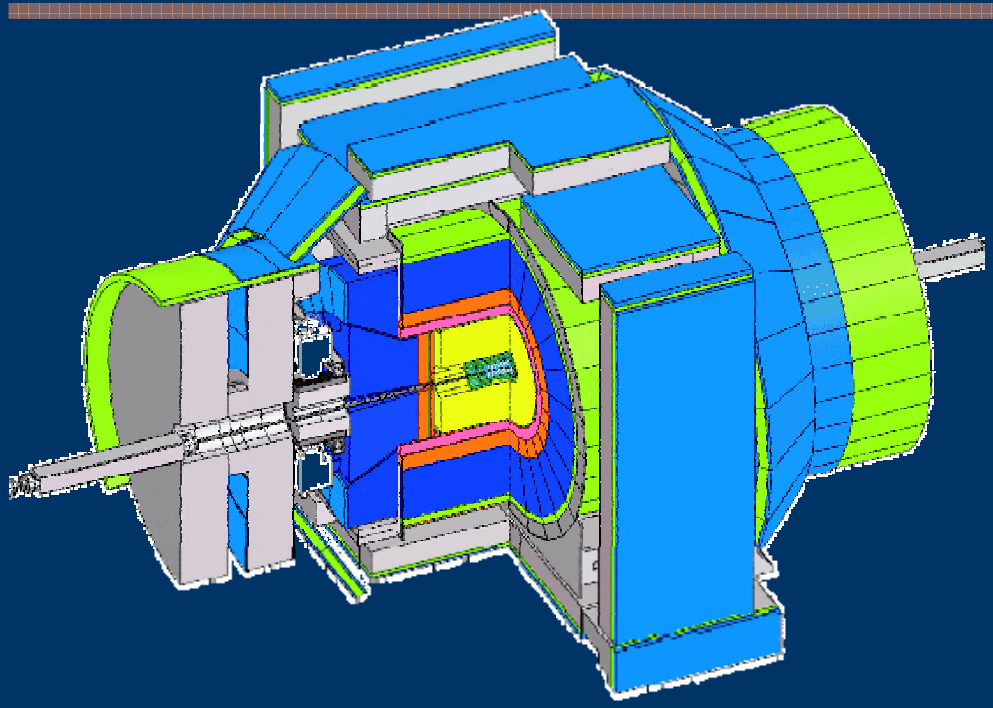


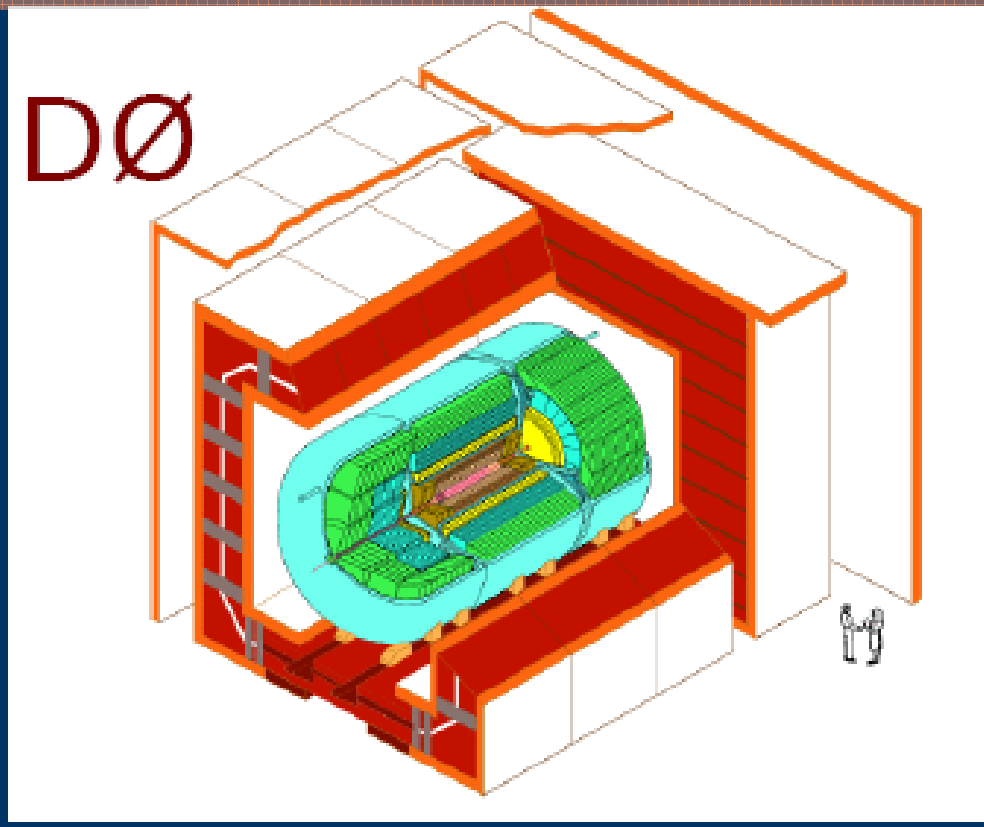




- Highest initial luminosity: 290 10^{30}
- More than 2fb^{-1} per experiment collected
- Best int. Lum. in 1 month: 165pb-1 (01/07)
- ~26 month of data taking until 10/09

Detectors





Excellent mass resolution & particle ID (large tracking volume, silicon vertex detector, ToF system)

Displaced vertex trigger: fast track trigger at Level1, add Silicon at Level2

Strength: Hadronic & semileptonic modes

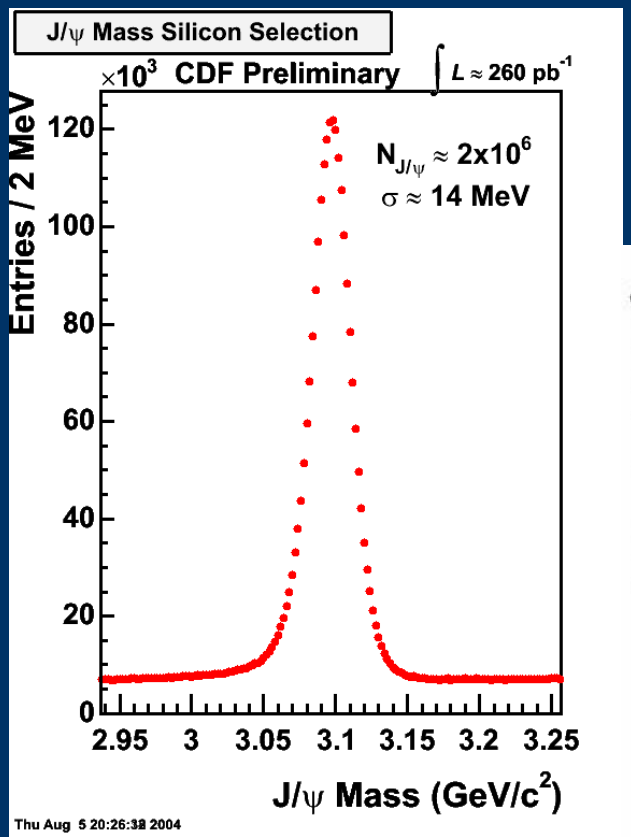
Good muon coverage (η<2) and forward tracking → high rapidities, high yields

Strength: Di-muon & semileptonic modes

Triggers for Beauty & Charm Physics

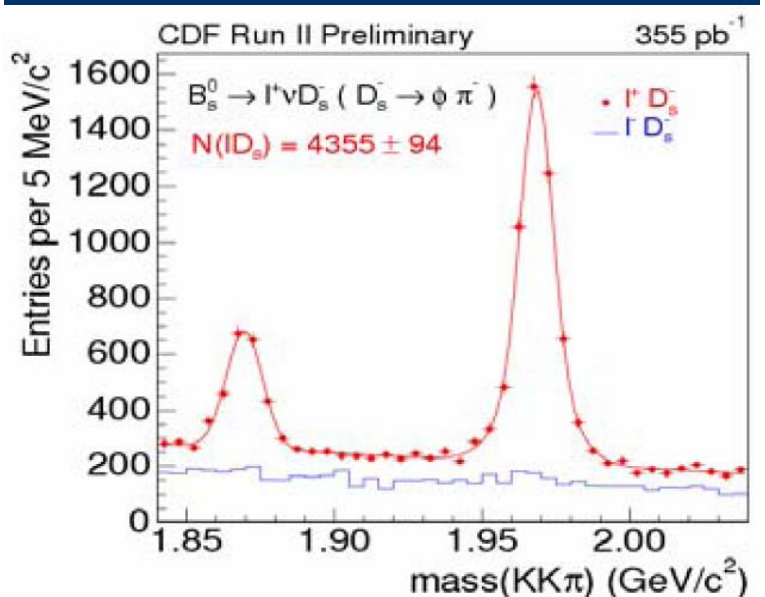
"Classic" Run I Trigger

Di-muon
$J/\psi \to \mu\mu$
$B \to \mu\mu(X)$
Two muons with:
$p_T(m) > 1.5$ GeV/c



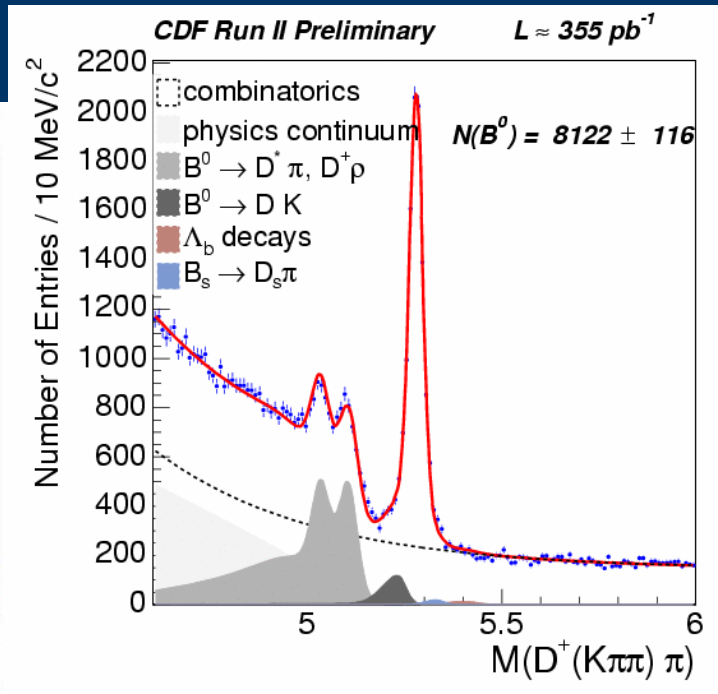
Improved (wrt. Run I) semileptonic trigger

One displaced track + lepton (e, m)
$B \to l\nu X$
Lepton:
$p_T(l) > 4.0$ GeV/c
Track:
$p_T > 2.0$ GeV/c,
$d_0 > 120$ mm



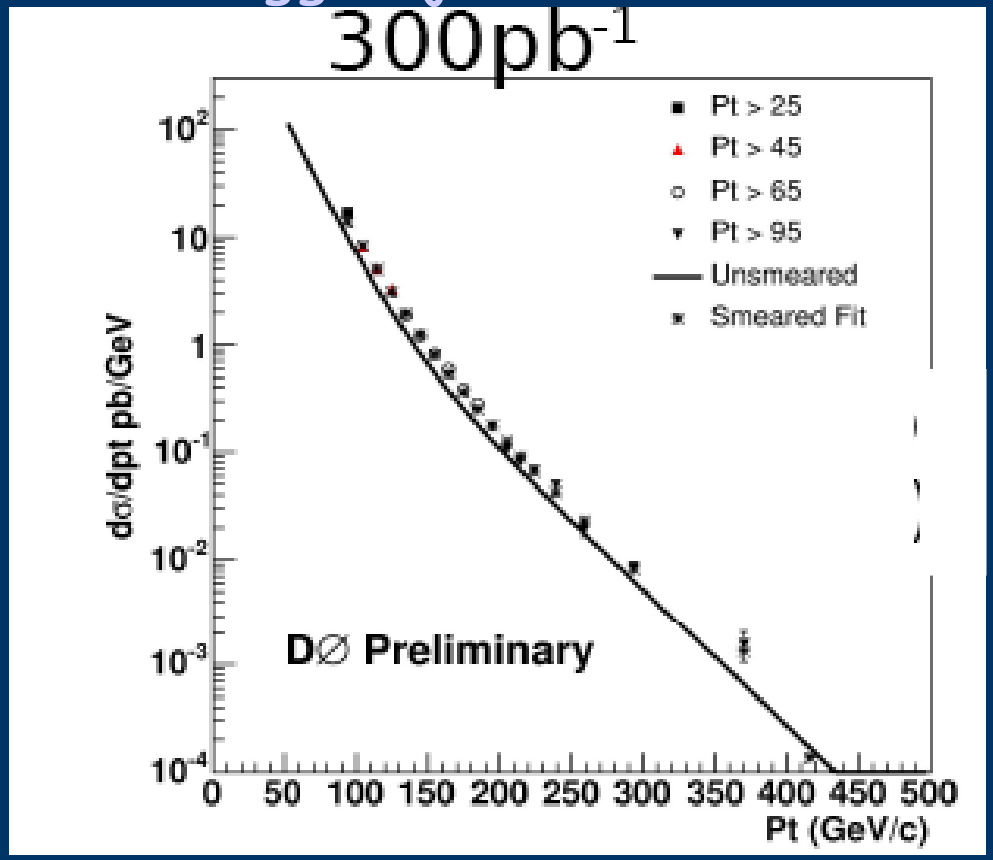
Completely new trigger

Two displaced tracks
$B \to hh$
$D \to hh$
Two tracks with:
$p_T > 2.0$ GeV/c
$\Sigma p_T > 5.5$ GeV/c
$d_0 > 100$ mm



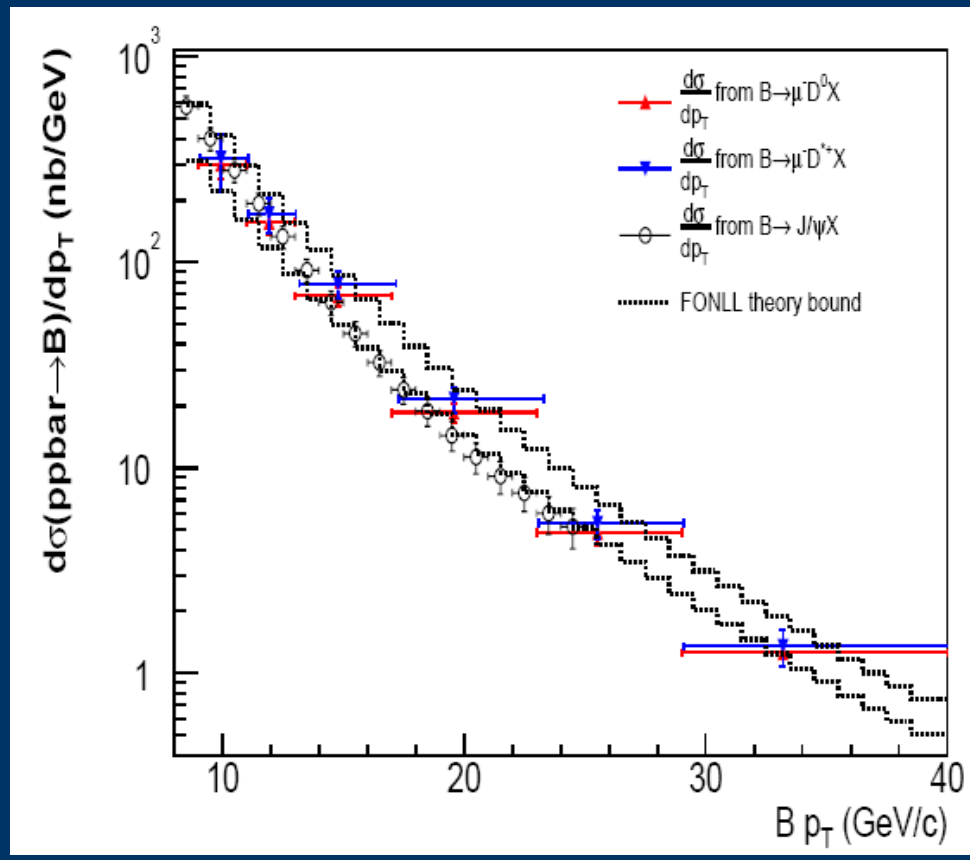
Inclusive B Cross Sections

- DO: new measurement of muon tagged jet cross sections



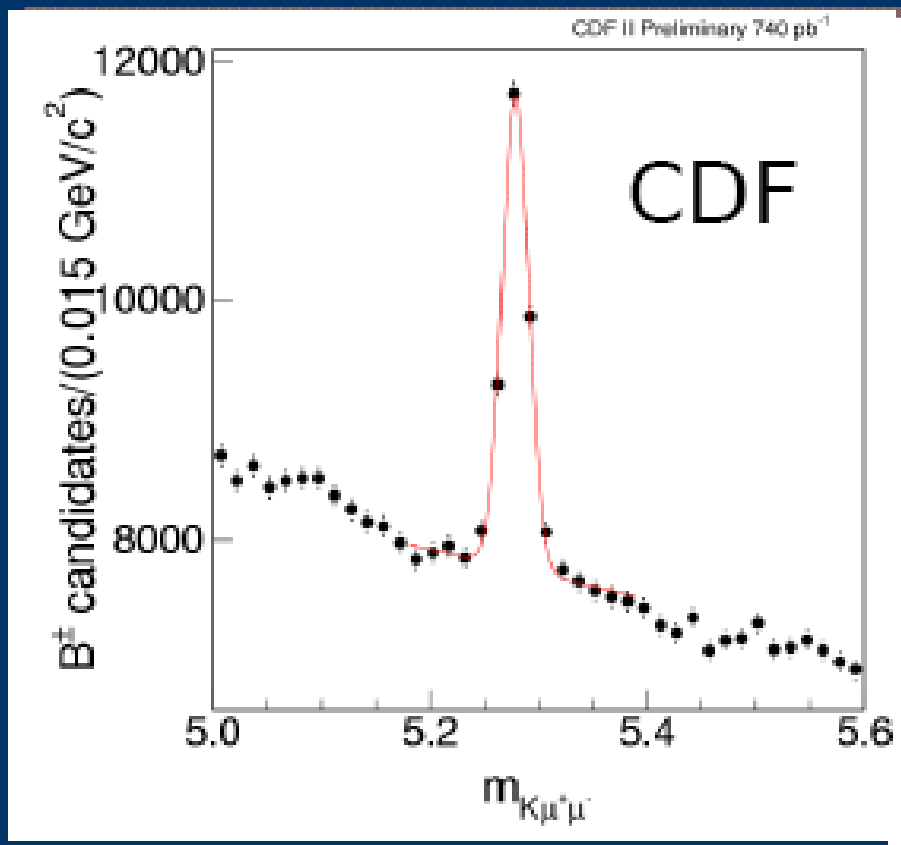
- Measured cross section still higher than theory predicts
- Unfolding uncertainty

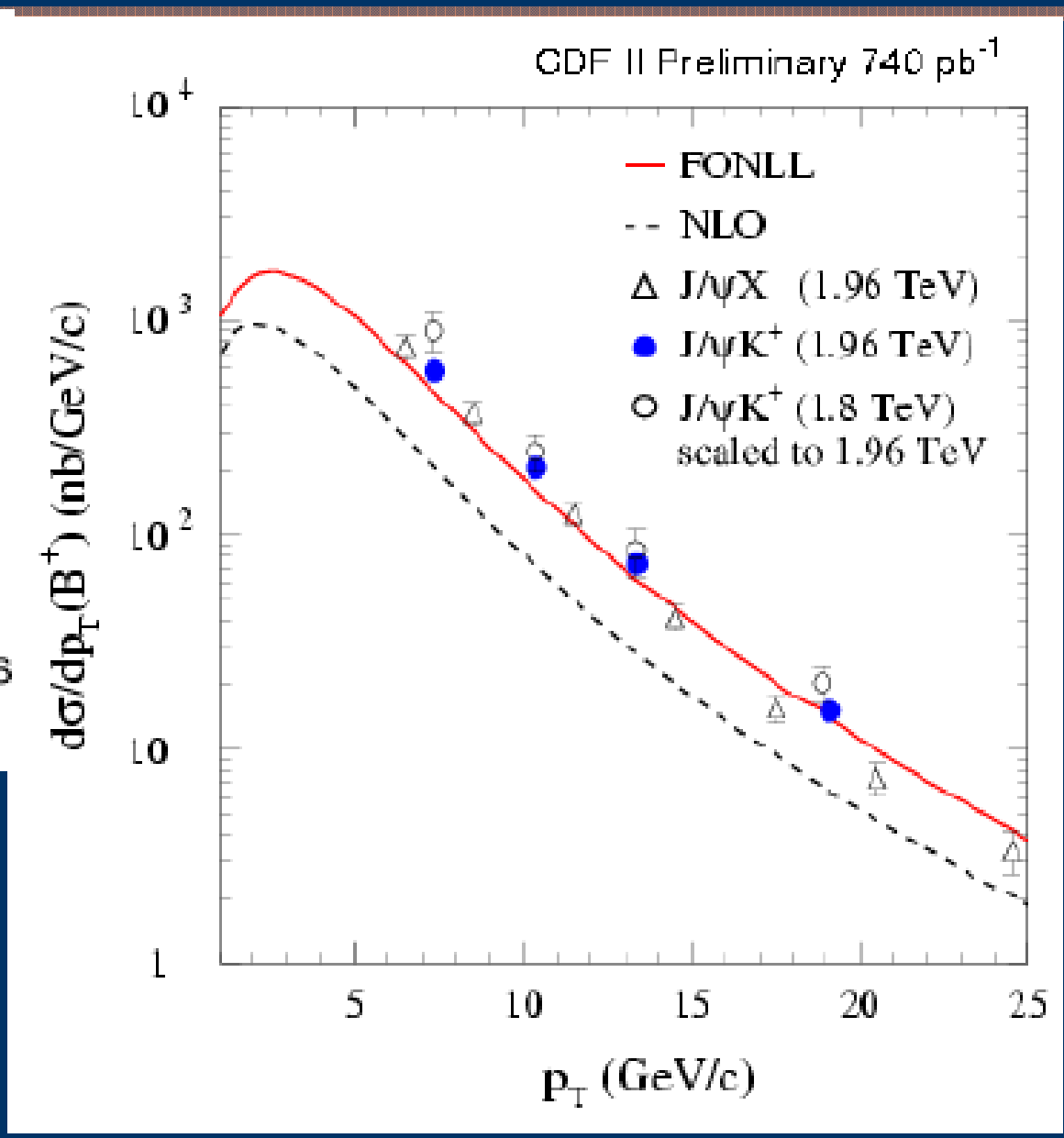
- CDF measurement of inclusive B cross section



- CDF new modes B-> $l\nu D^0/D^*X$ consistent with B->$J/\psi X$ within uncertainty of FONLL

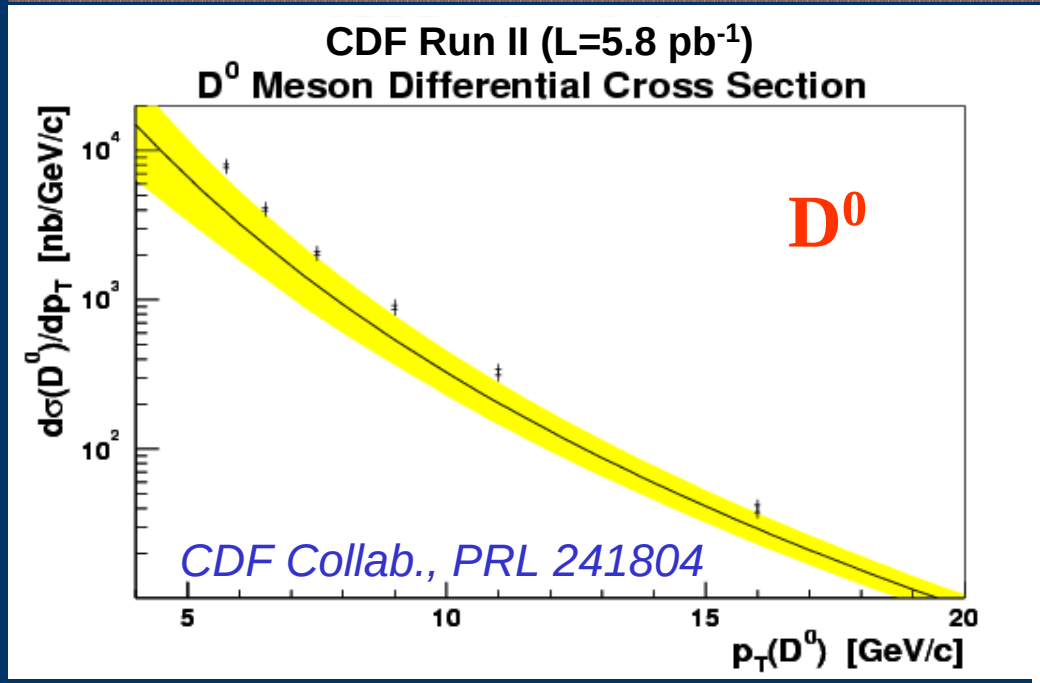
B+ Production Cross Section

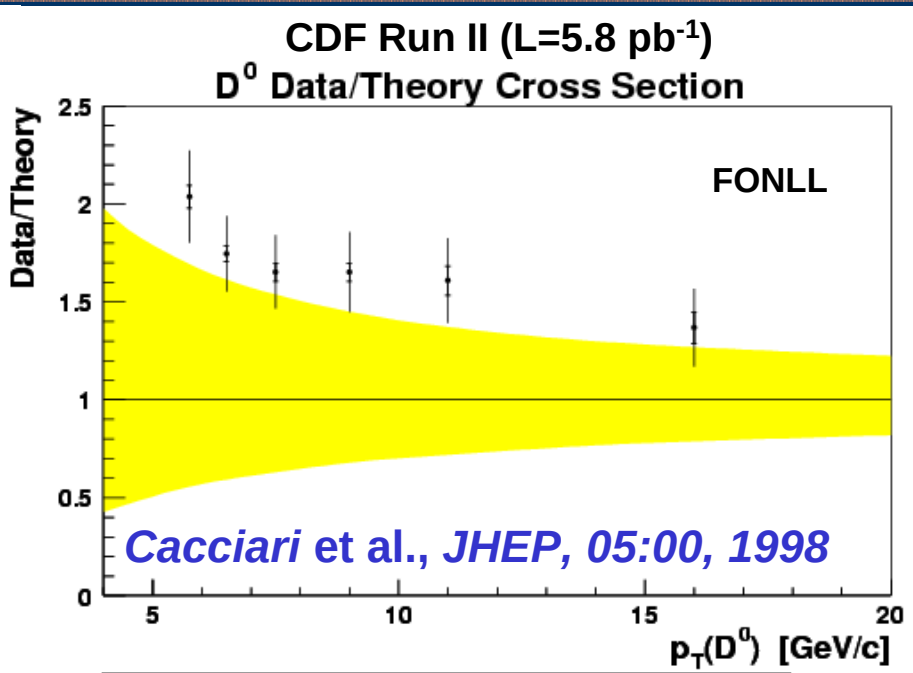


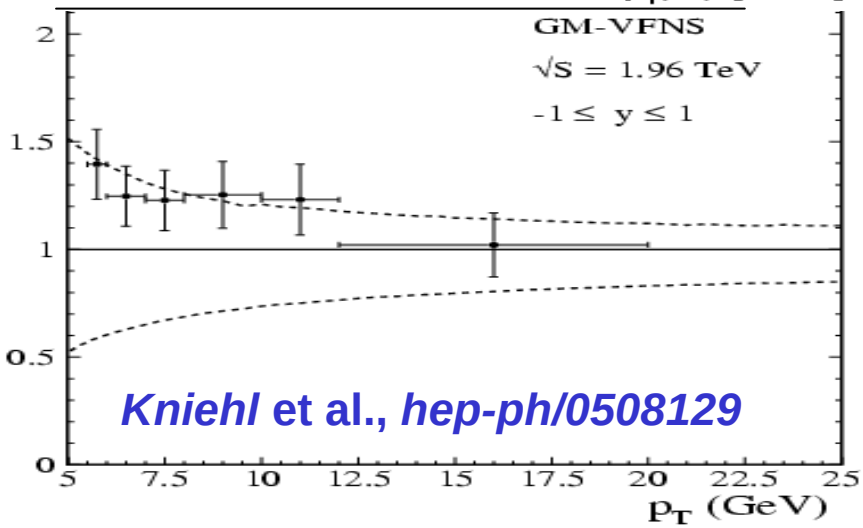


- Fully reconstructed decays $B \to J/\Psi K \to K\mu\mu$
- 8197±239 candidates in 0.74fb^{-1}
- Di muon Trigger, no lifetime bias
- Data slightly higher than FONLL

Inclusive Charm Cross Sections





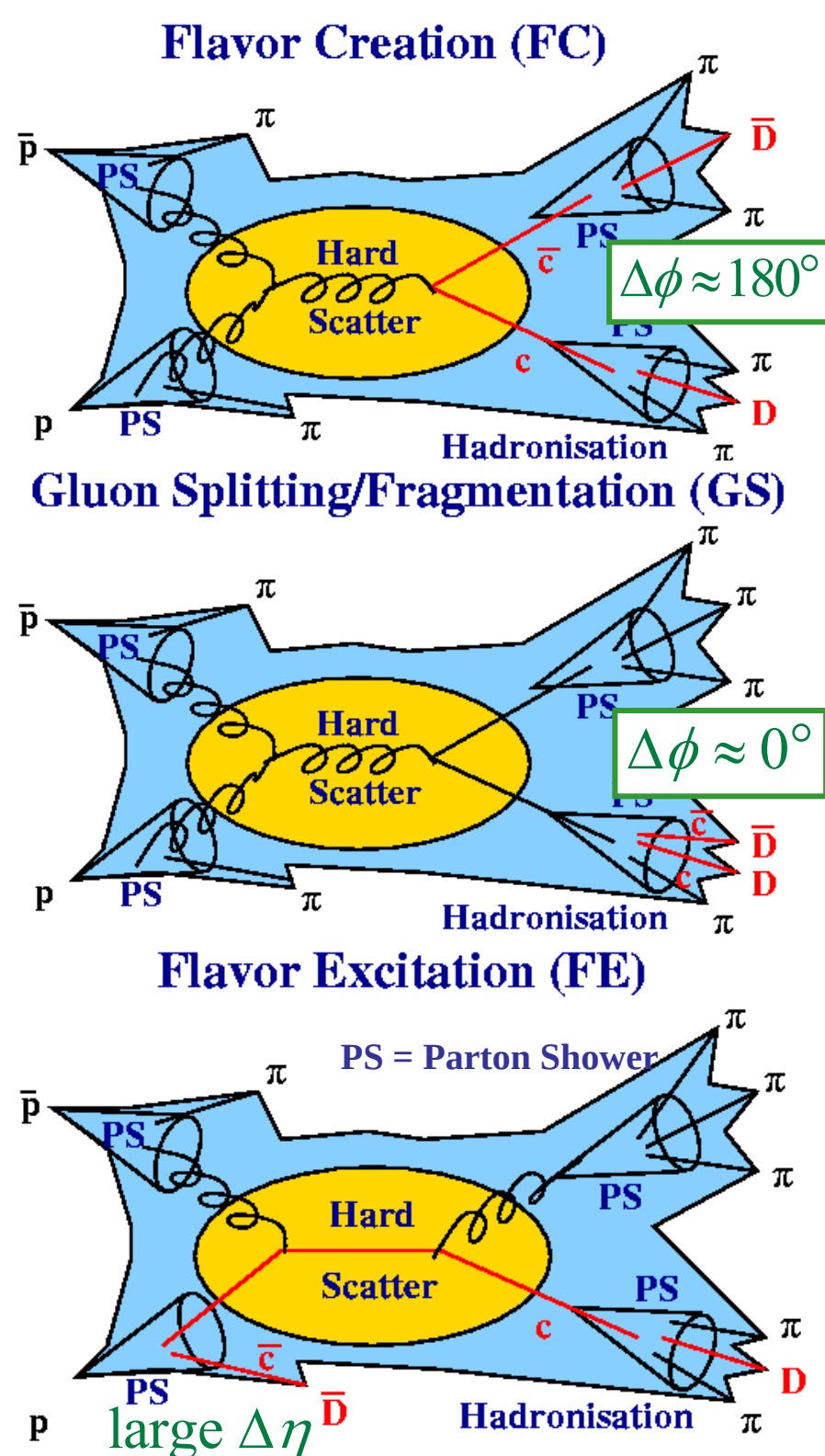


Inclusive charm (D^0, $D^{*\pm}$, D^+, D_s^+) cross sections was one of the first CDF Run II results

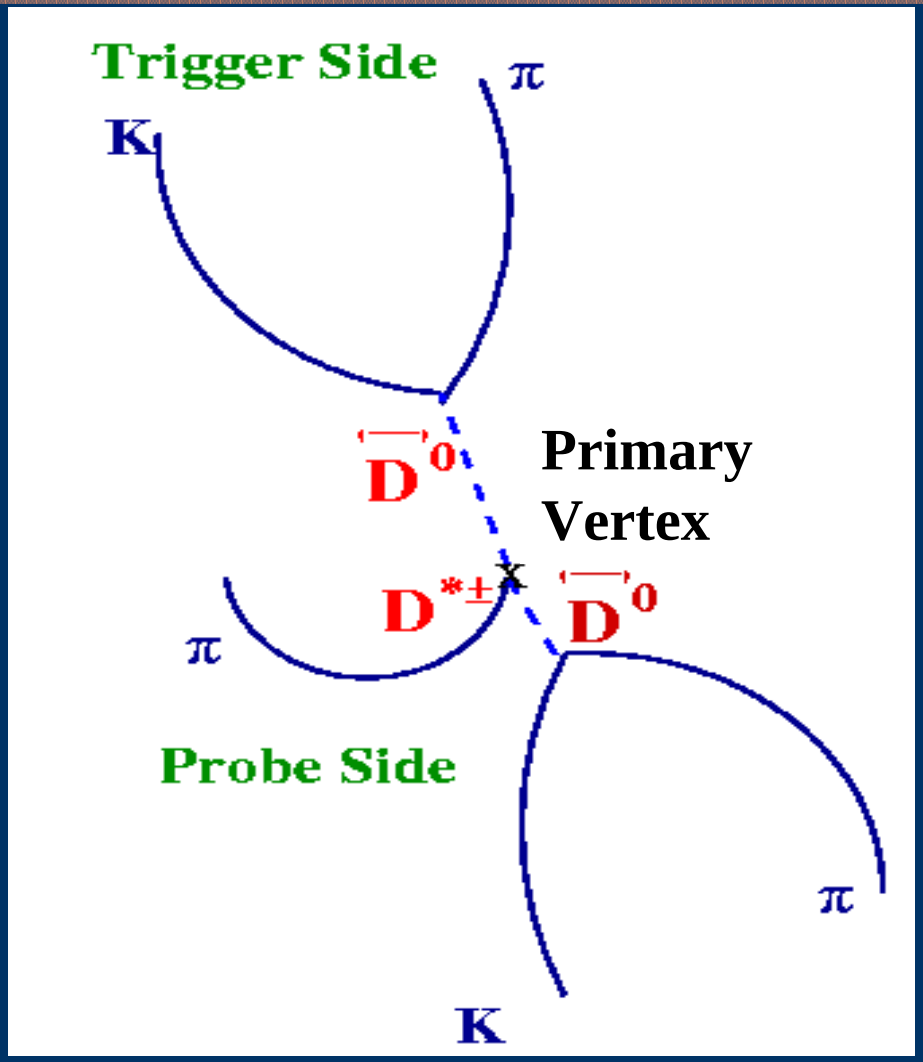
- factor ~2 higher than expected
- progress in theory reduced deviation
- measurement systematically limited

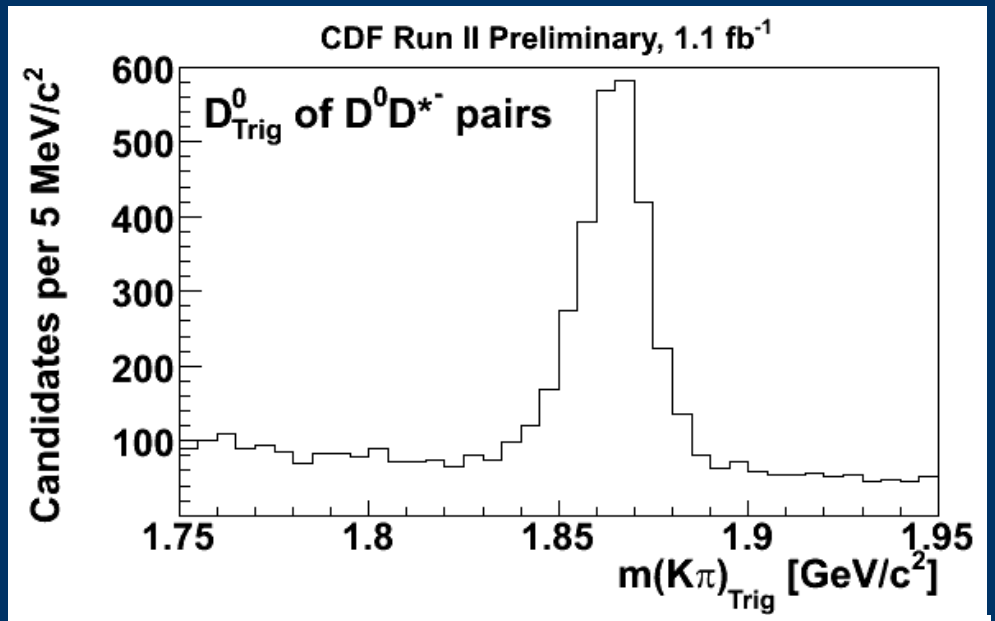
Charm-Charm-Correlation

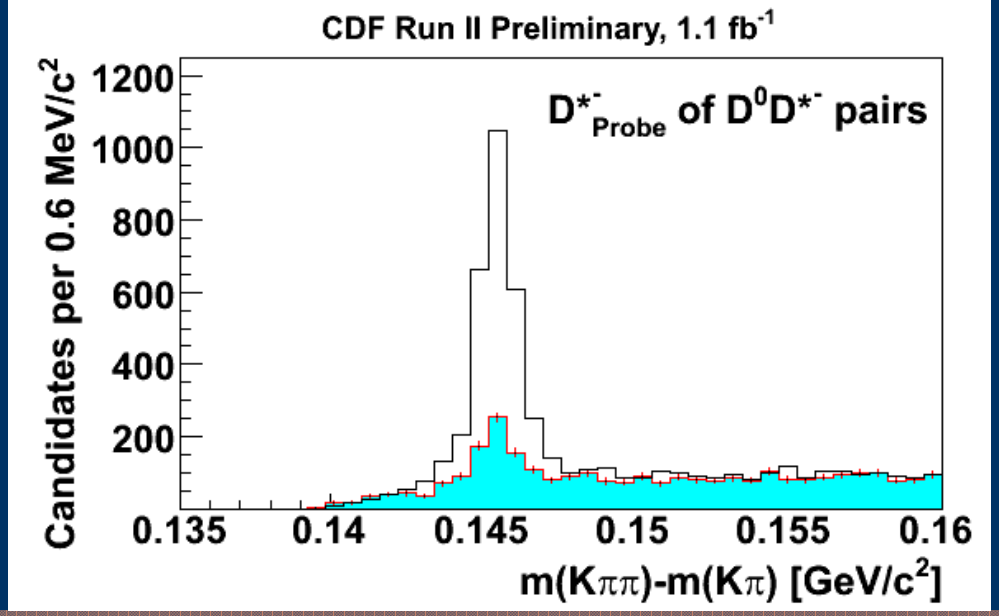
- Study of fully reconstructed charm mesons
- Angular correlation: access to underlying production process
  - Flavor creation: large opening angle $\Delta\phi$
  - Gluon splitting: collinear charm particles
  - Flavor excitation: large opening pseudo rapidity $\Delta\eta$
- Experimental approach:
  - Select triggered charm mesons
  - Look for second, Probe charm meson



Charm Pair Production

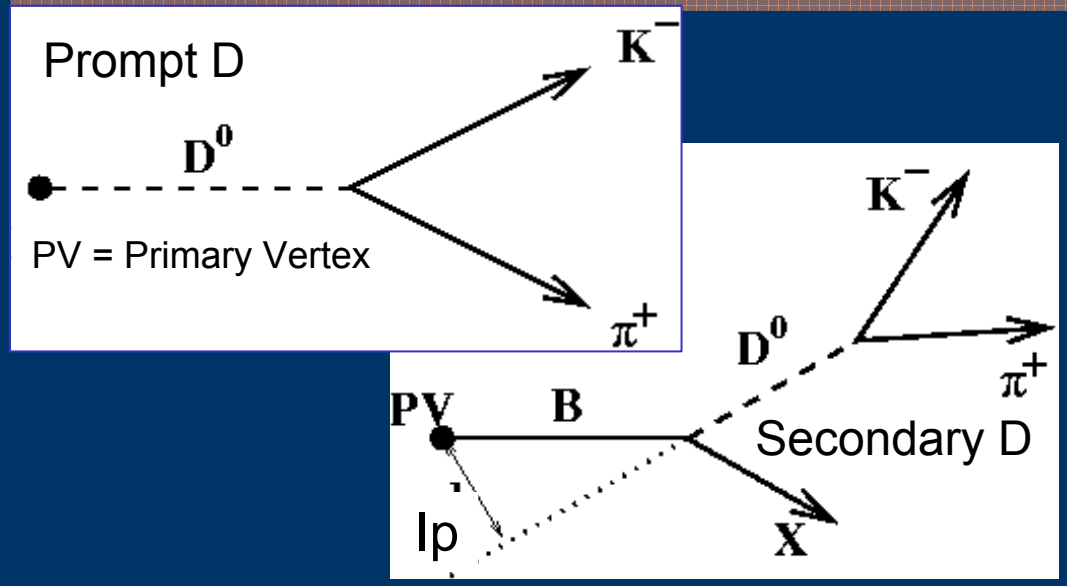


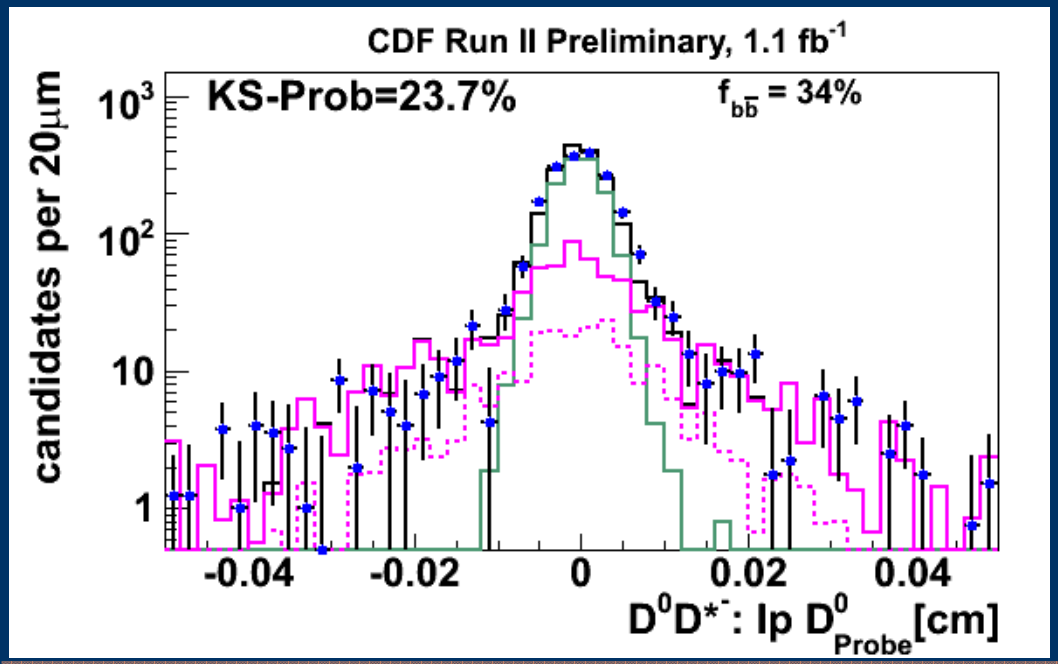




- Background subtraction using sidebands in 2-dim $m_{K\pi}$-$m_{K\pi}$

Prompt and Secondary D's





- 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} = 34%
- Cross checks : Ip, L_{xy} of trigger D, probe D and DD*- pair

D^0D^{*-} Cross Section

- 1.1fb^{-1} analysis

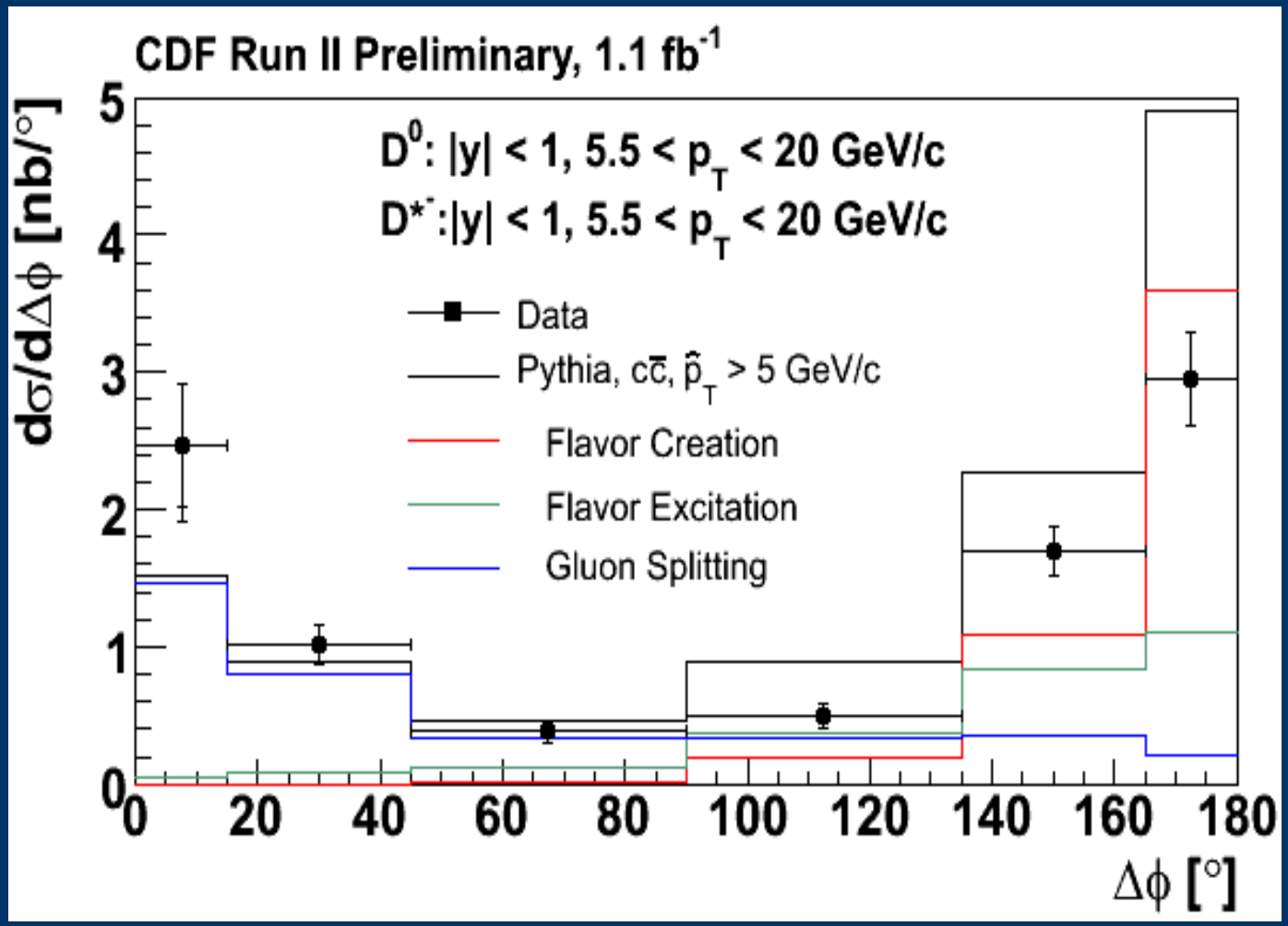
- Collinear production as important as back-to-back production

- Monte Carlo: Pythia Tune A

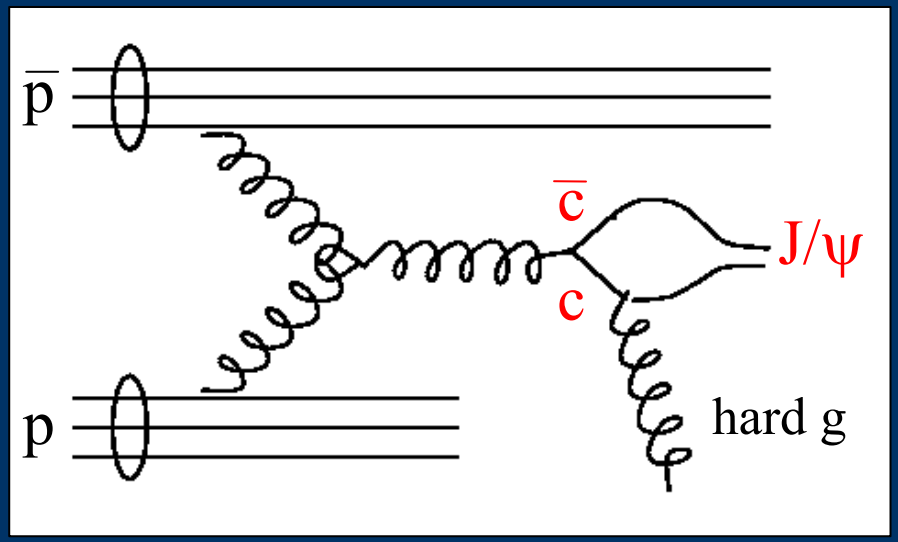
- Pythia under estimates collinear (over estimates back-to-back) production

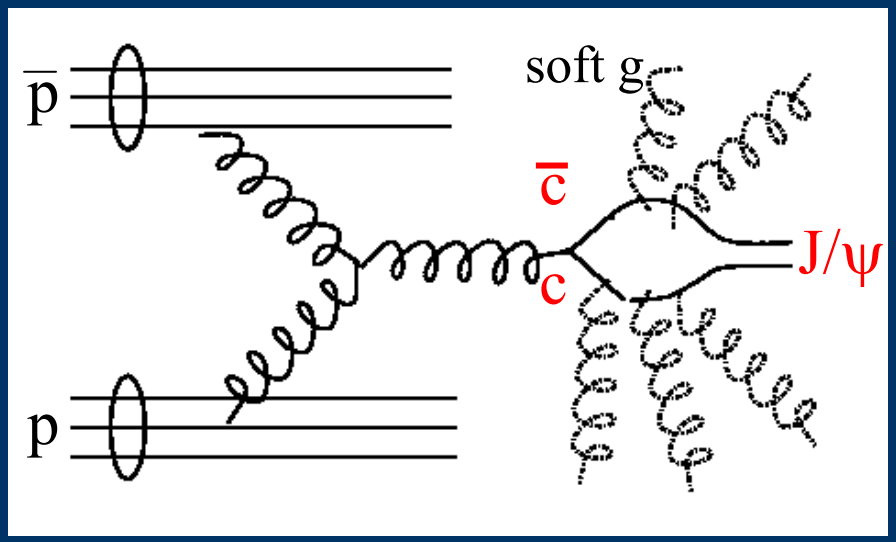
- Error: stat + syst ~15%

- Similar result for D+D*-



Quarkonia Production





Color Singlet Model:

- $c\bar{c}$ 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%)
- P_T spectrum does not match data

Non relativistic QCD introduces

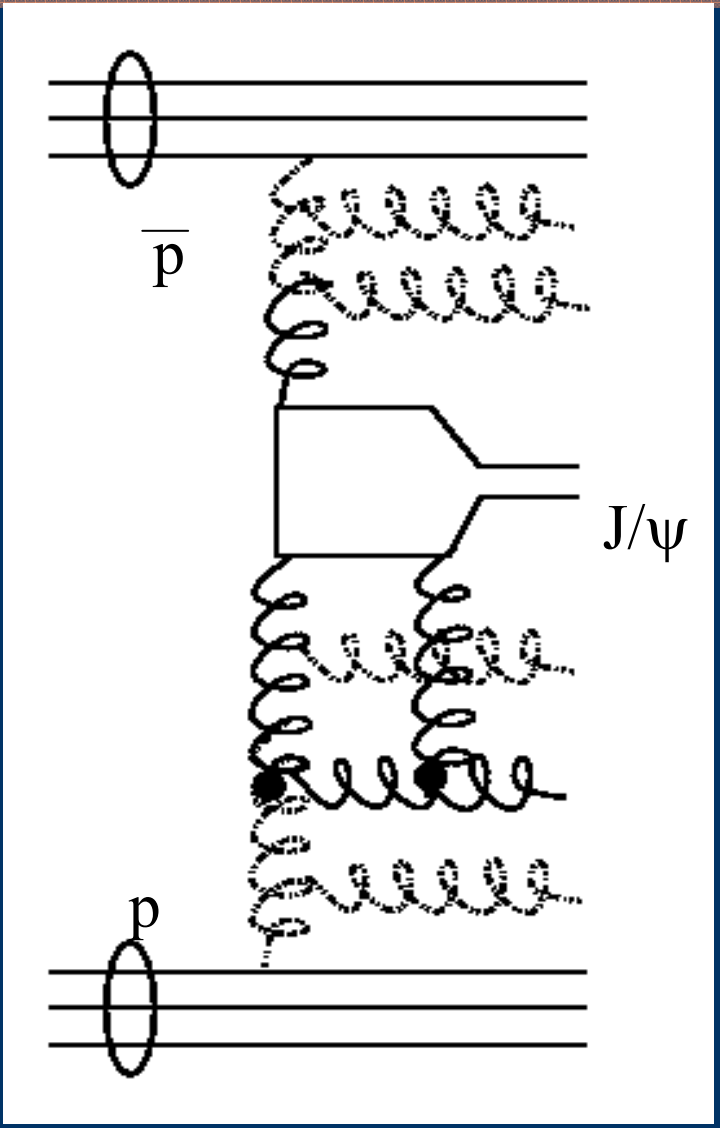
Color Octet Mechanism:

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

Quarkonium Production

New pomeron inspired idea:

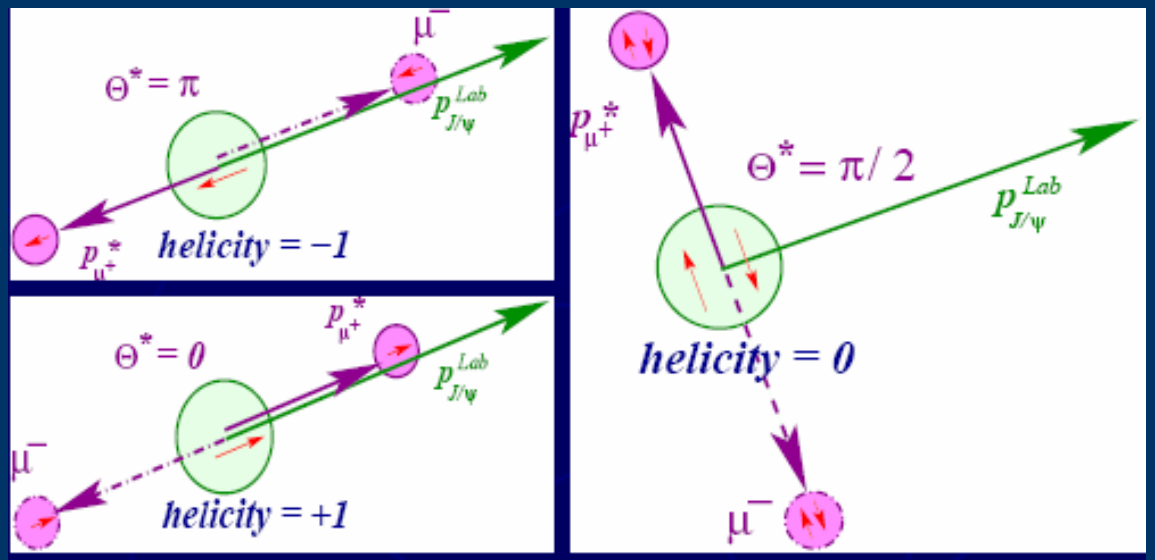
- Fusion of a symmetric color octet state and a gluon
- Predicted cross sections and P_T spectra match data (calculation in LO pQCD)
- P_T spectra match data
- Expect longitudinal polarization of prompt J/ψ increasing with p_T



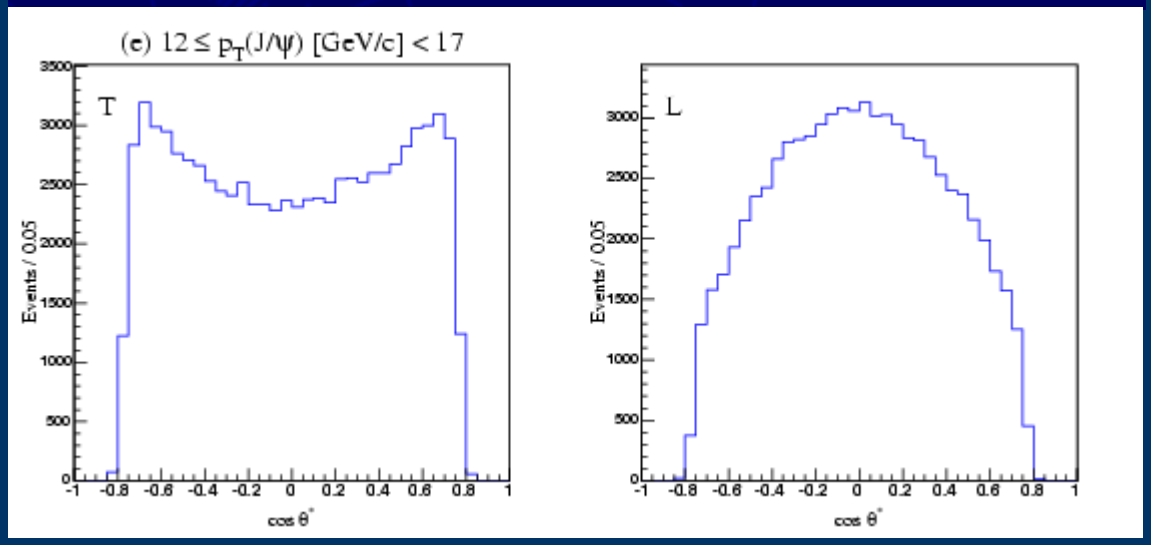
Pomeron ➔Gluon ladder

V.A. Khoze, A.D. Martin, M.G. Ryskin and W.J. Sterling hep-ph/0410020
E.L. Berger, J. Qiu, Y. Wang hep-ph/0411026

Polarization of J/ψ



Transverse ($\alpha = 1$) Longitudinal: ($\alpha = -1$)



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

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

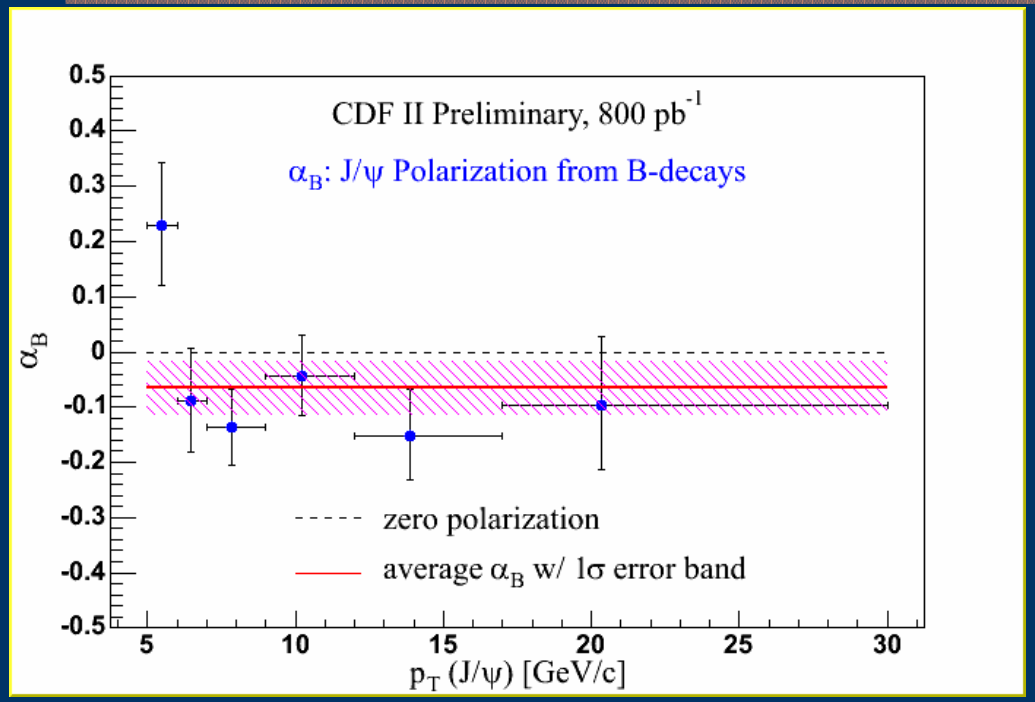
θ^* angle between μ^+ in J/ψ rest frame and J/ψ in lab

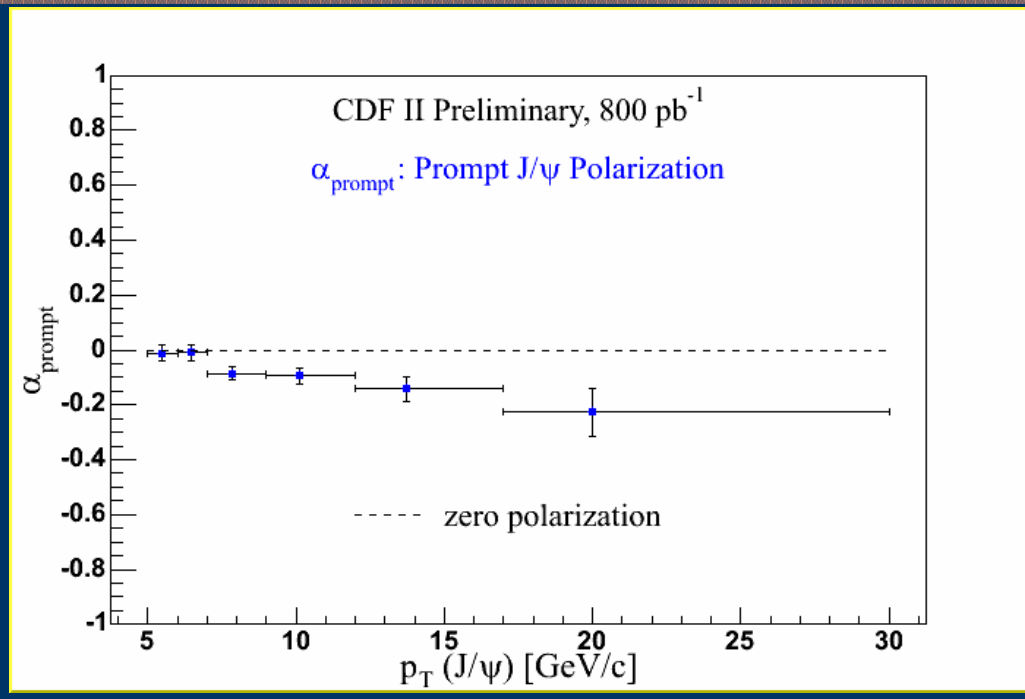
α polarization parameter
α=0 all 3 helicity states are equally populated

← MC polarization templates (trigger efficiency from data)

Separate prompt and secondary J/ψ using the impact pararm. of both μ

Polarization of J/ψ Mesons





Polarization of J/ψ from B decays

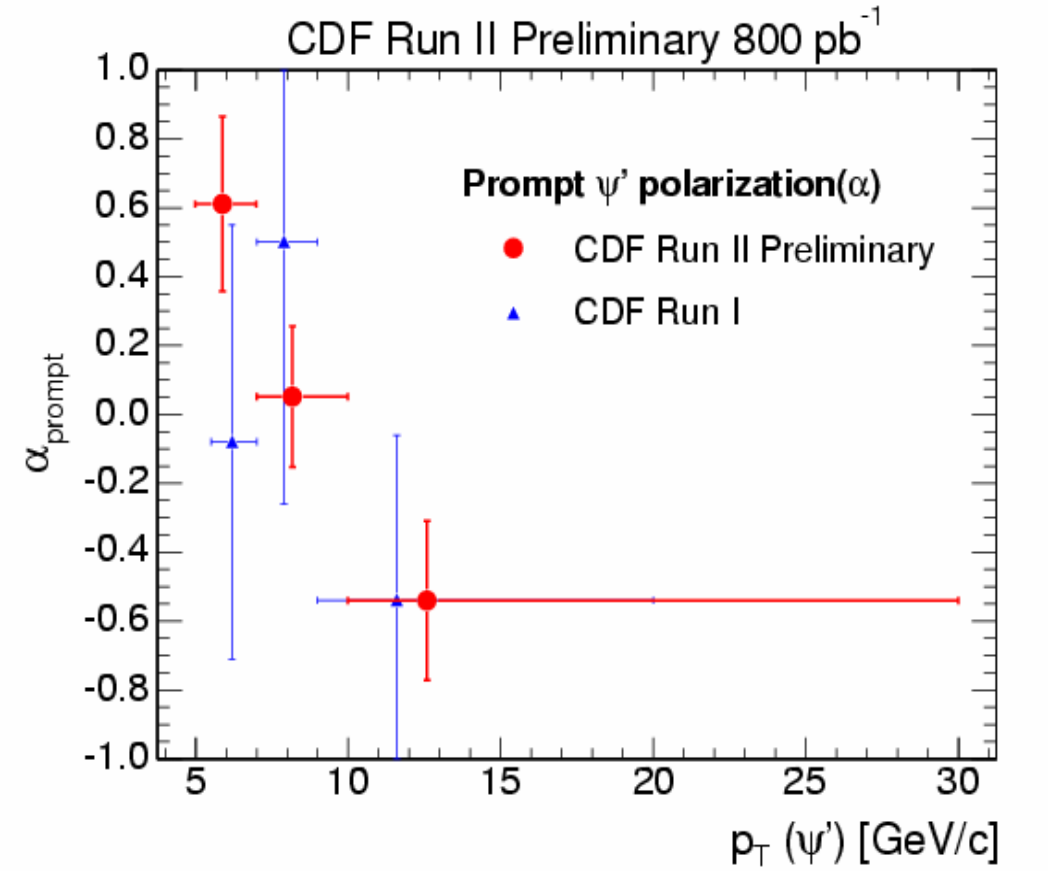
- independent of P_T
- a_B = -0.066±0.050
- Consistent with BaBar (a_B = -0.129±0.009)
  CDF result includes
  B_s and B baryons

Polarization of prompt J/ψ

- Corrected for residual secondary J/y
- a<0: longitudinal polarization

ψ' Polarization

- Analysis analogous to J/Ψ
- Same theory framework applies to prompt ψ' and J/ψ production
- no contribution from feed down from higher states
  ➔ ψ' is a cleaner system to test direct charmonium production



Polarization in B decays

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

Polarization of prompt ψ'

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

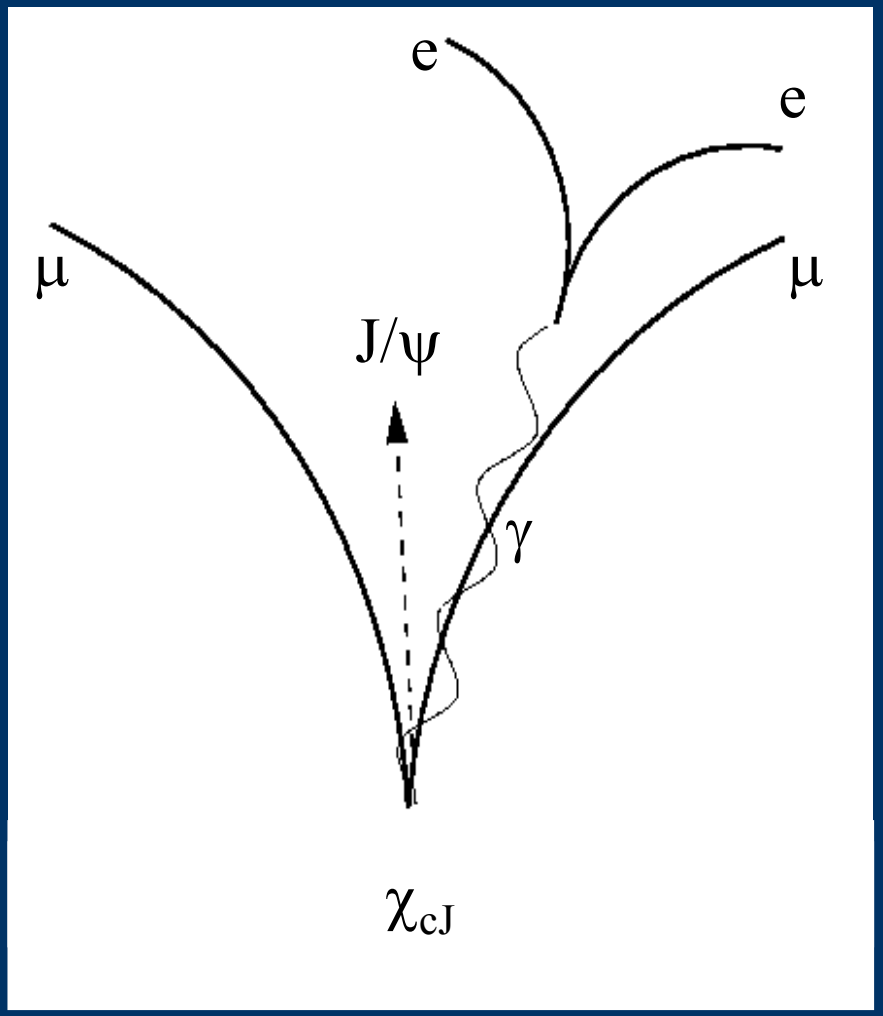
χ_{cJ} Production

- 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 $L=1fb^{-1}$)

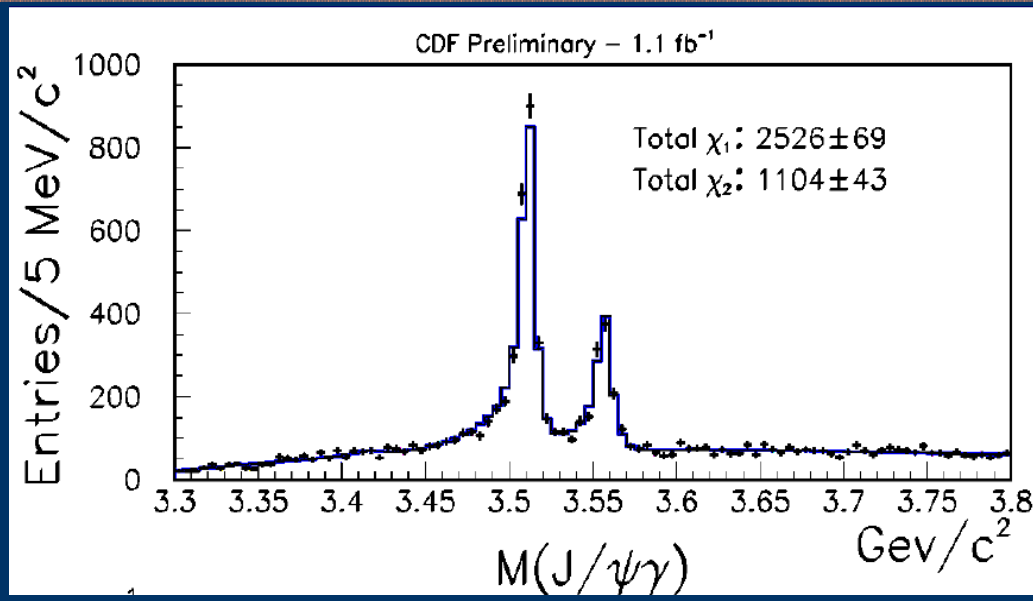


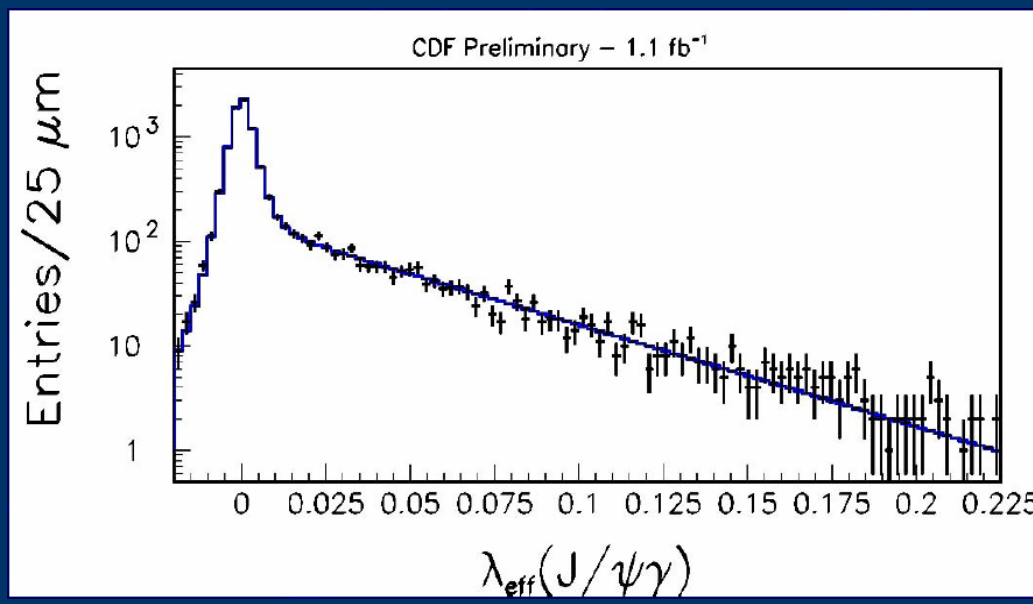
χ_{cJ} Data Set

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

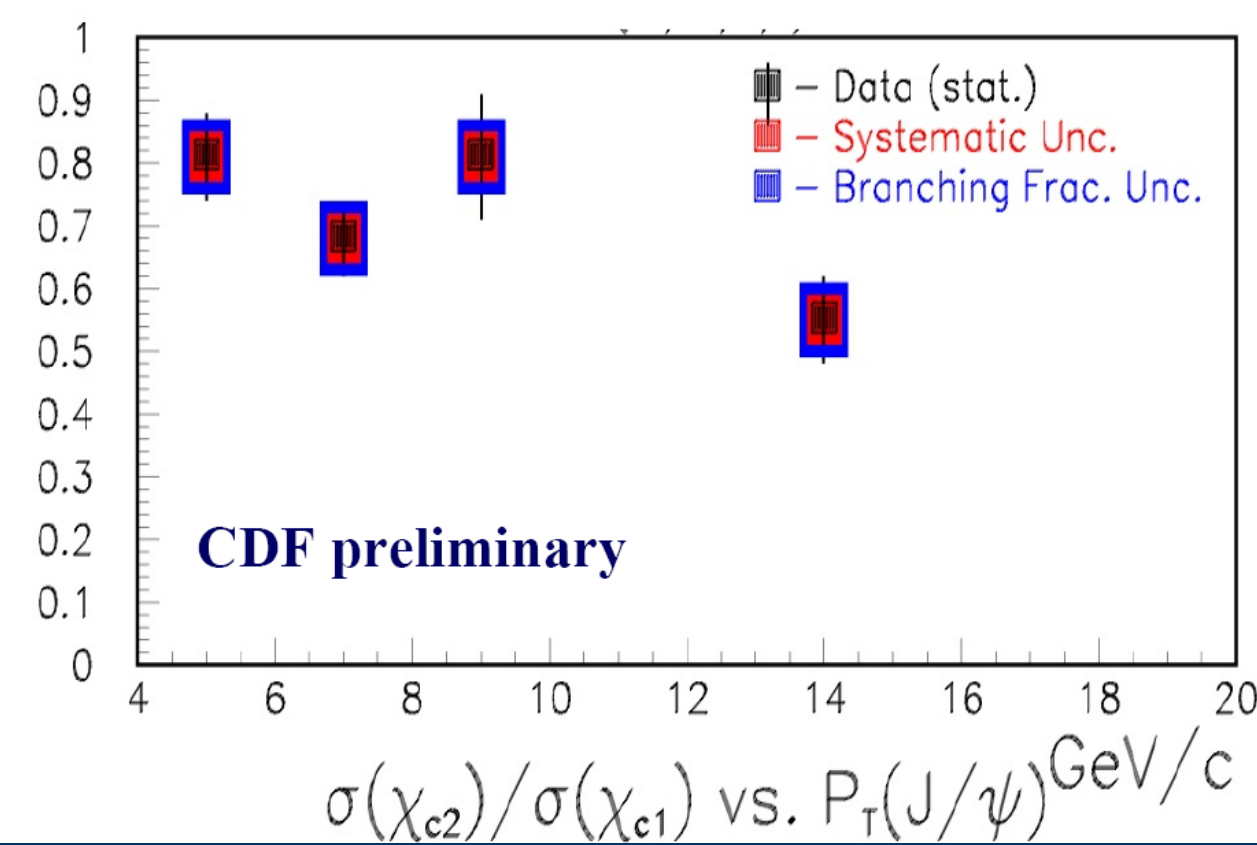
Simultaneous fit to the mass and Flight distance distributions is used to extract the relative yields for prompt χ_{cJ} and χ_{cJ} from *B* decays





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}:



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

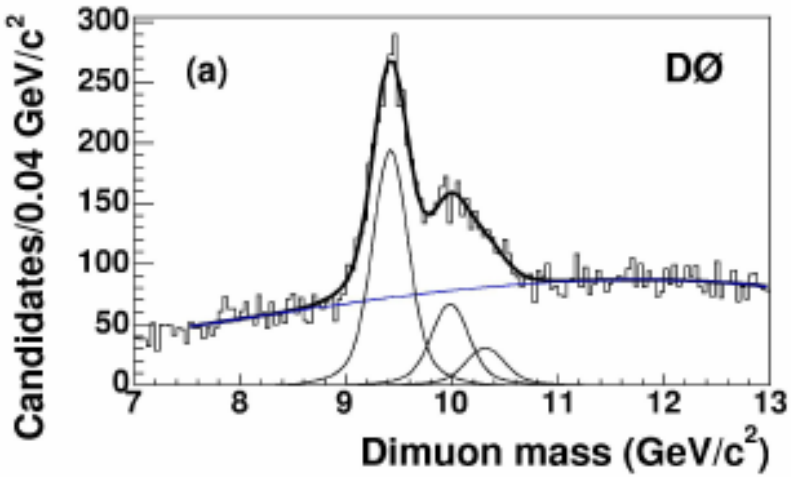
for $4 < p_T(\chi_{cJ}) < 20$ GeV/c

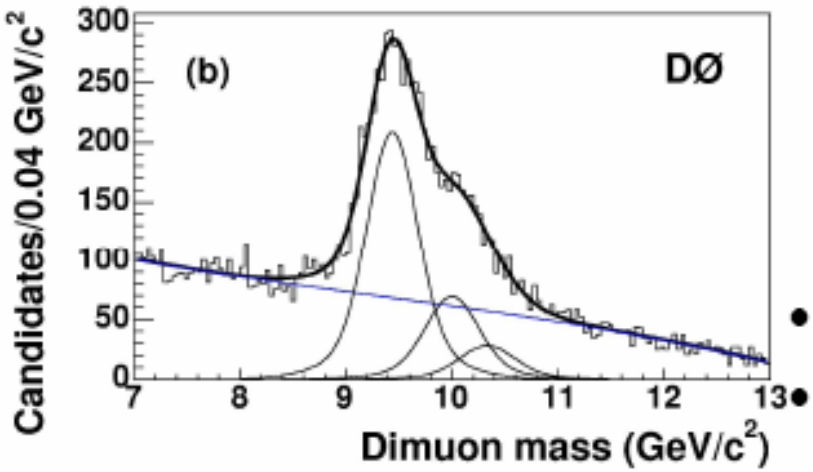
- Color Octet predicts 5/3 (counting of Spin states)

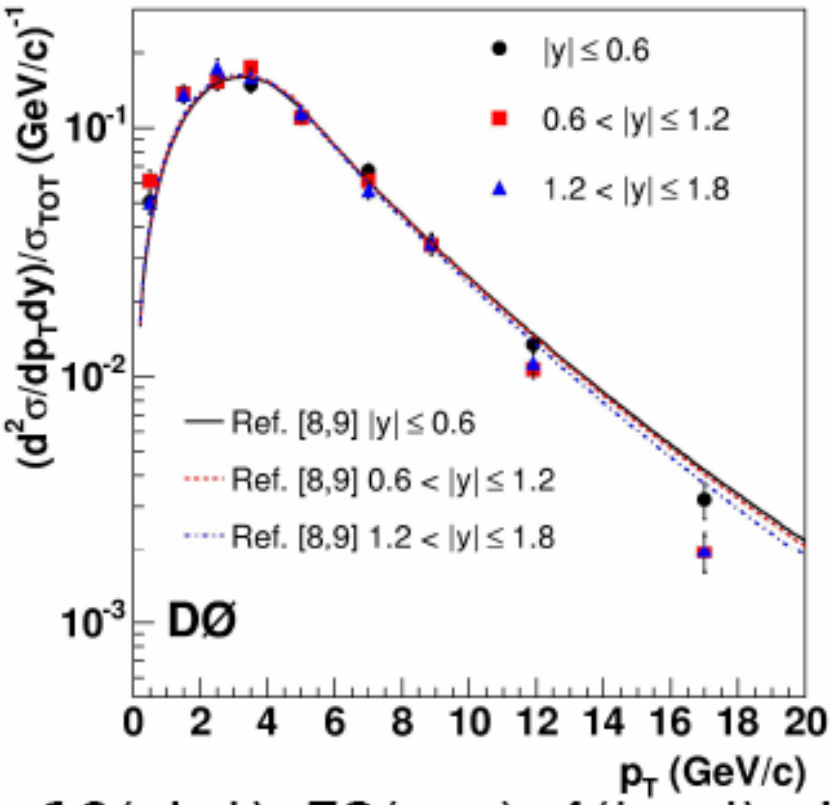
Bottomium

Y(1S),Y(2S),Y(3S)

PRL 94, 232001 (2005)







- σ=732±19(stat)±73(sys)±4(lumi) pbarn
- Differential in p_T and η

Analysis in progress: Measurement of Υ Polarization (differential in P_T)

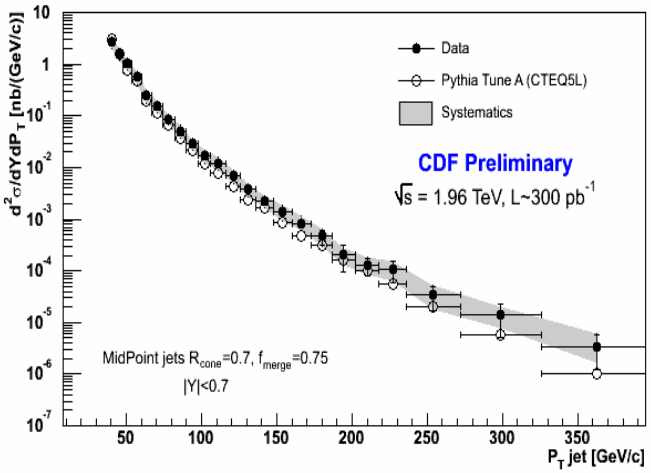
Measurements with b-Jets

- Inclusive b-Tagged Jets
- b-Tagged Di-Jets
- b-Tagged Jet + Photon Events

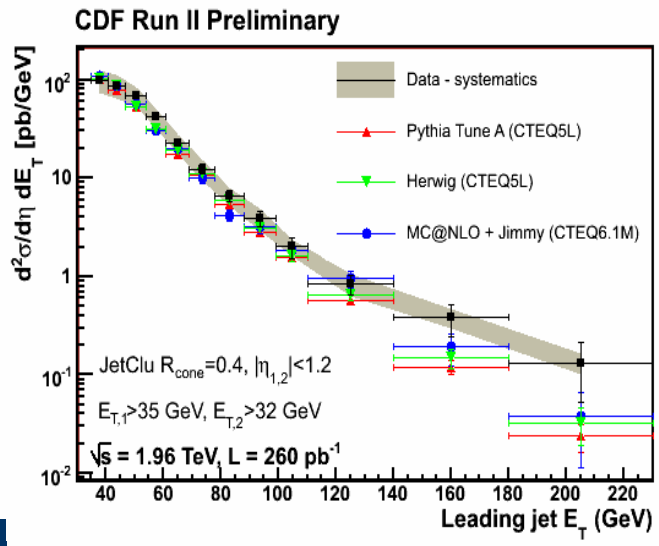
See also talk by Sofia Vallecorsa in QCD parallel session

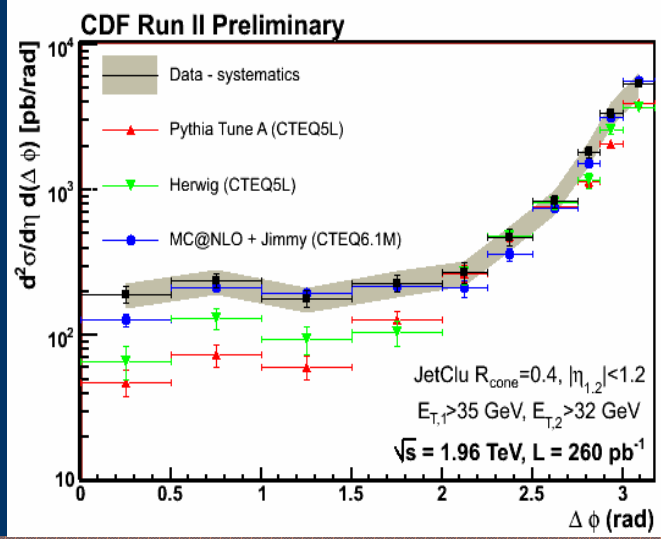
Overview of b-Jet Analyses

Inclusive Jets

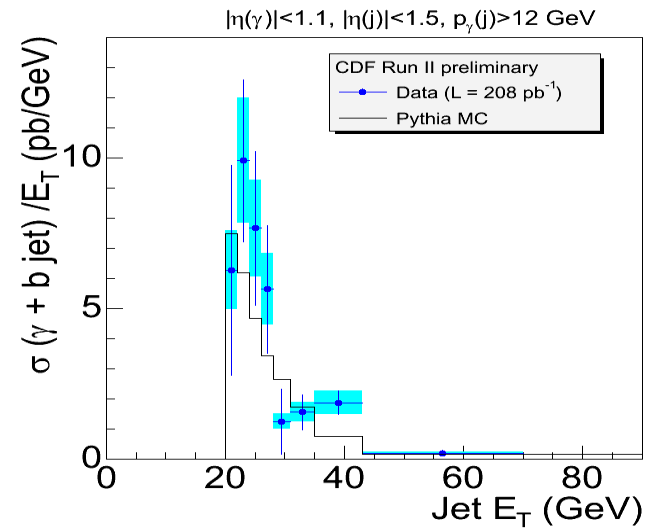


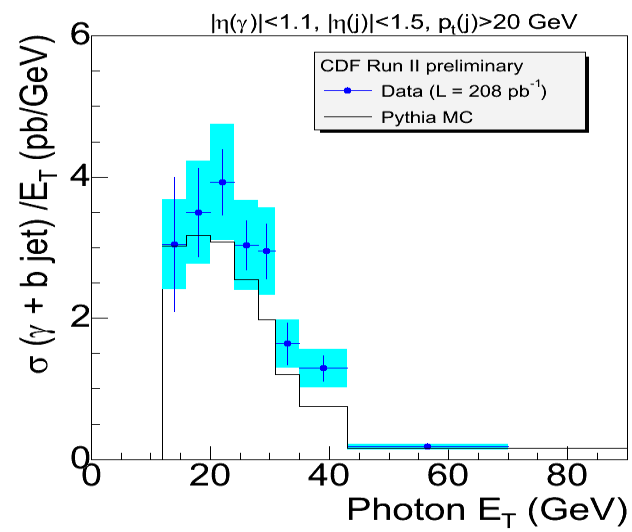
Di-Jets





Jets + Photon





Common to all b-Jet Measurements:

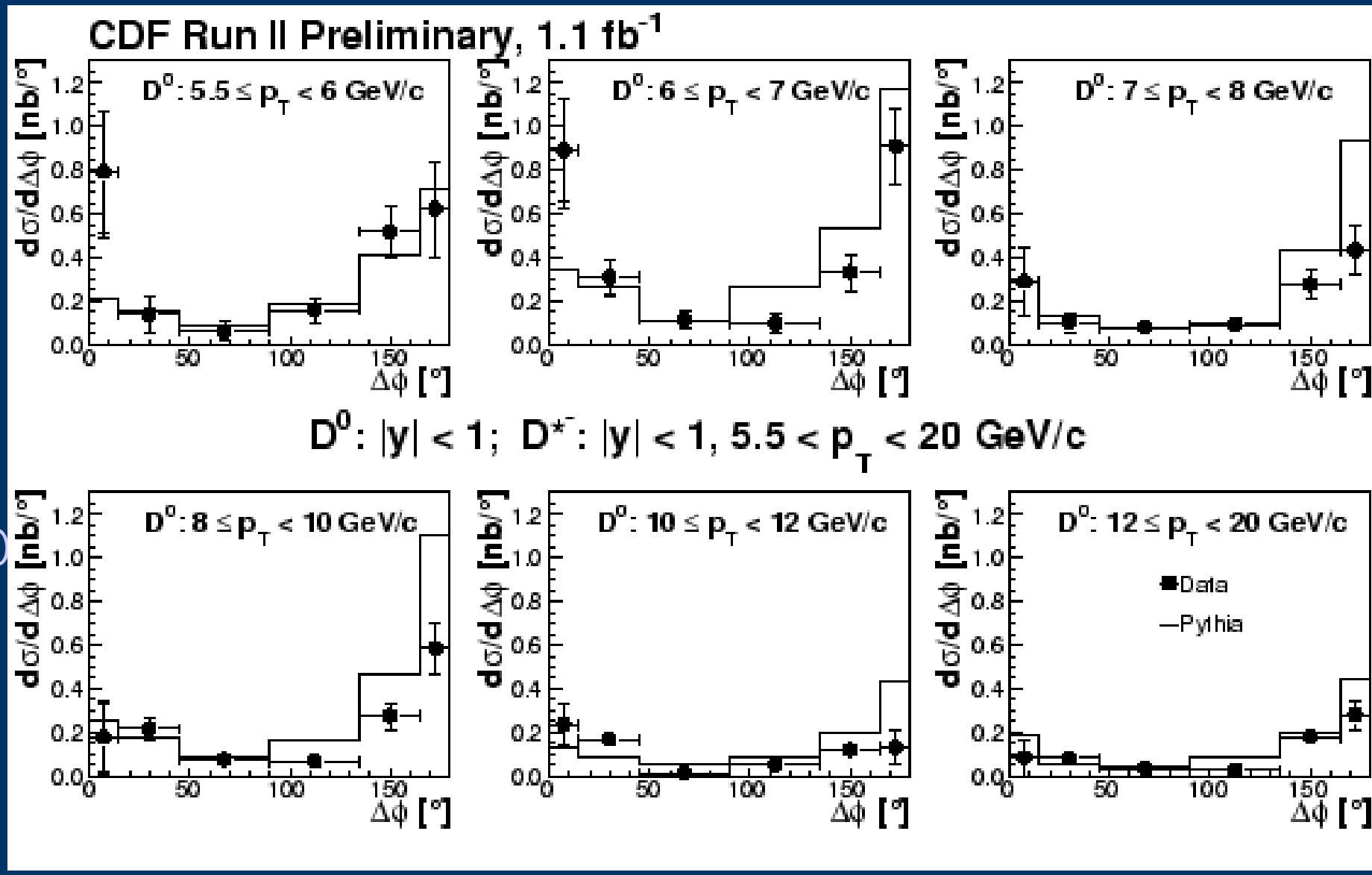
- Theroy matches data within uncertainties
- All measurement are a bit higher than expectation

Summary

- Heavy flavor production is an important topic at the Tevatron
- Theory improves but still does not match data perfectly
- Improved statistics of Tevatron Run II, thanks to larger integrated luminosity and improved triggers, allows detailed studies of heavy production:
  - Cross sections of fully reconstructed B mesons,
  - Charm-charm correlations: access to production mechanisms
  - Cross section and polarization in Quarkonium production is described by new ansatz
- Many new and interesting results. Sorry it has just been impossible to do justice to all of them.
- Future measurements (6-8 fb^{-1}) will allow an even more precise look into the details of heavy quark production in proton anti-proton
- Will impact our understanding of heavy quark production at the startup of the LHC.

Backup

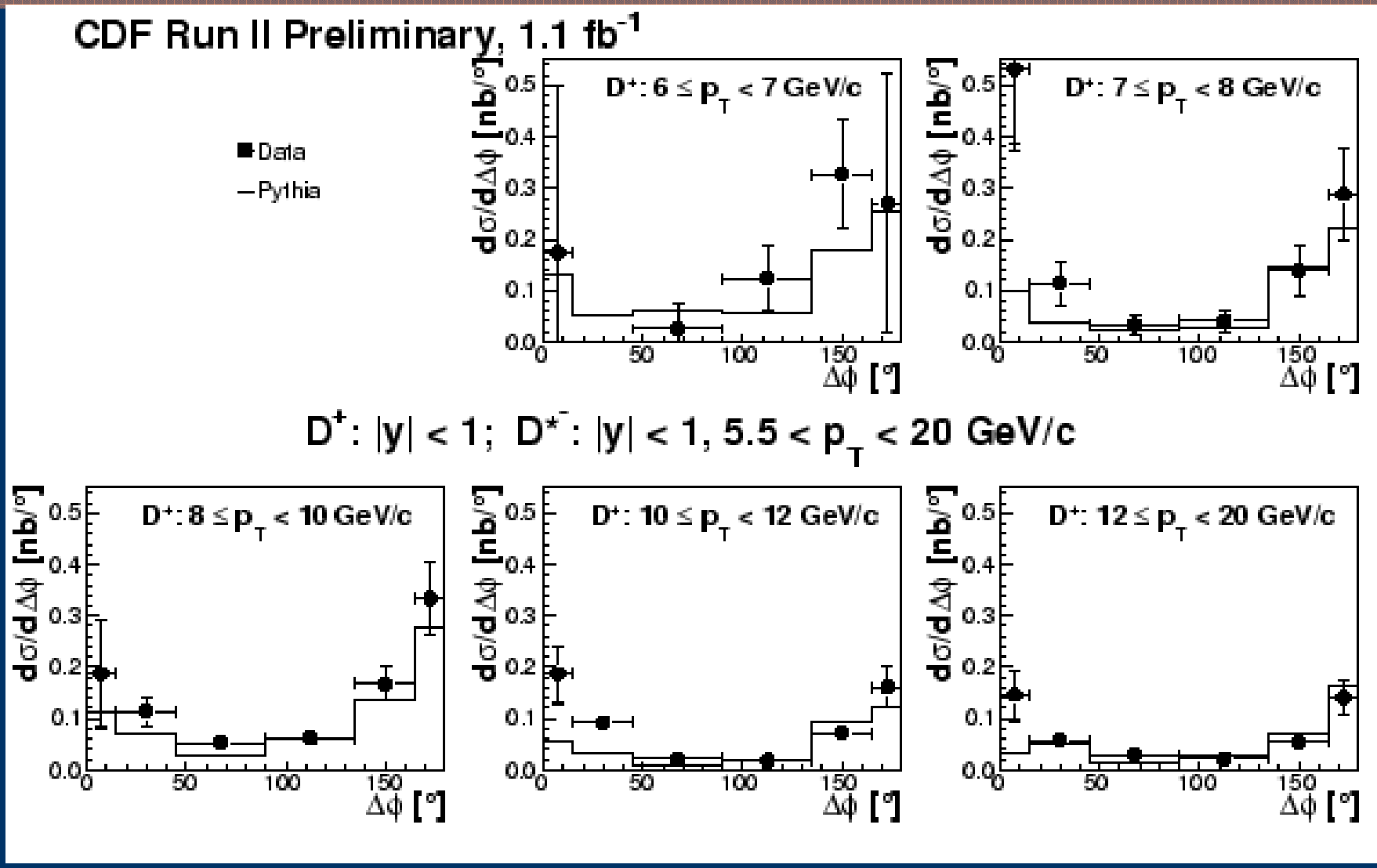
D^0D^{*-} Pair Cross Section binned in P_T(Trig)



Error: stat⊕sys(f_b)

Common Syst. Error: δ~15%

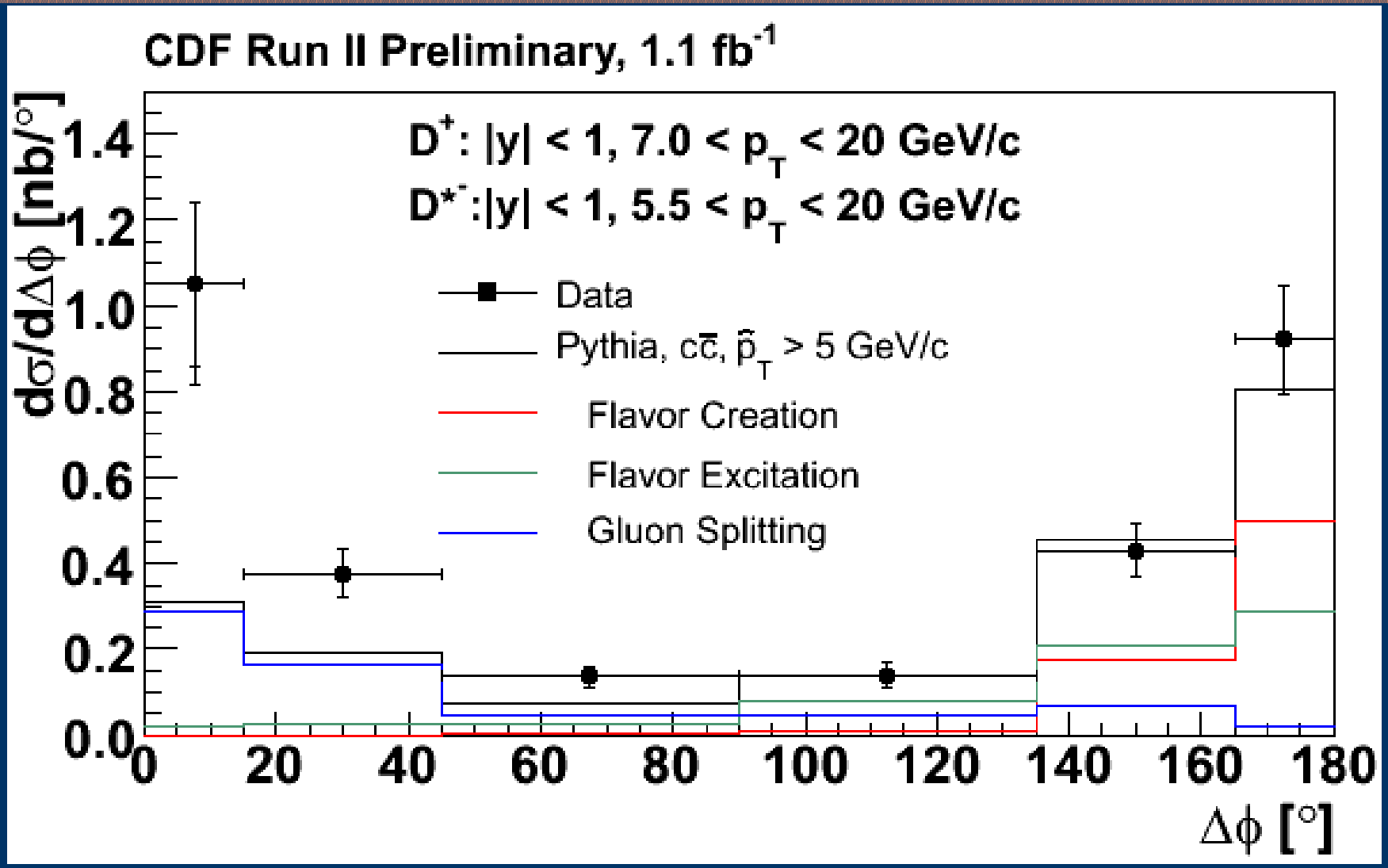
D^+D^{*-} Pair Cross Section binned in P_T(Trig)



Error: stat$\oplus$sys(f_b)

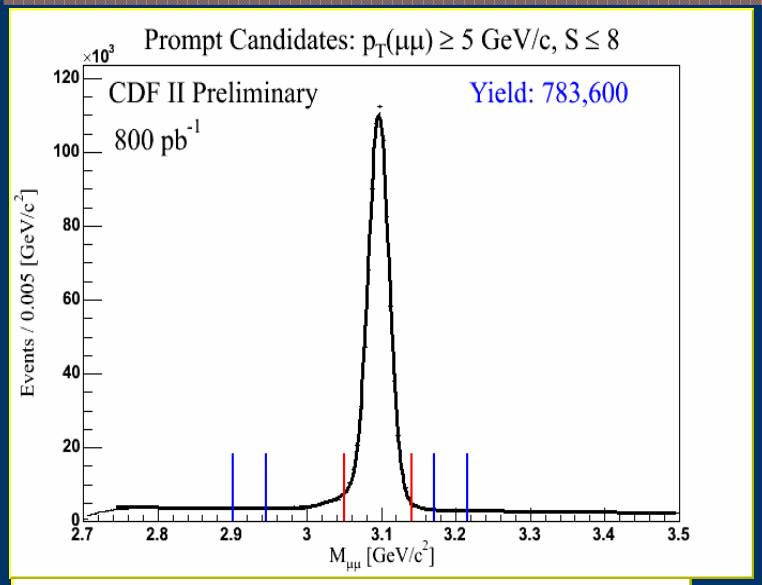
Common Syst. Error: δ~19%

D^+D^{*-} Cross Section

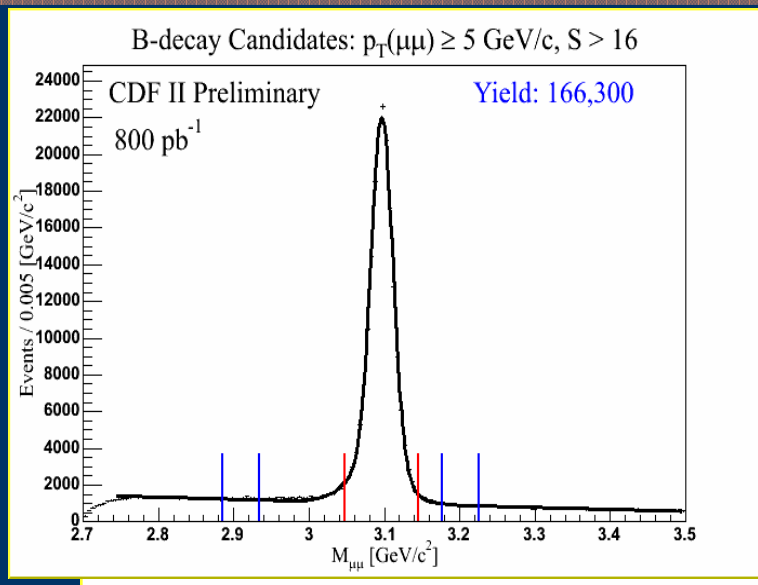


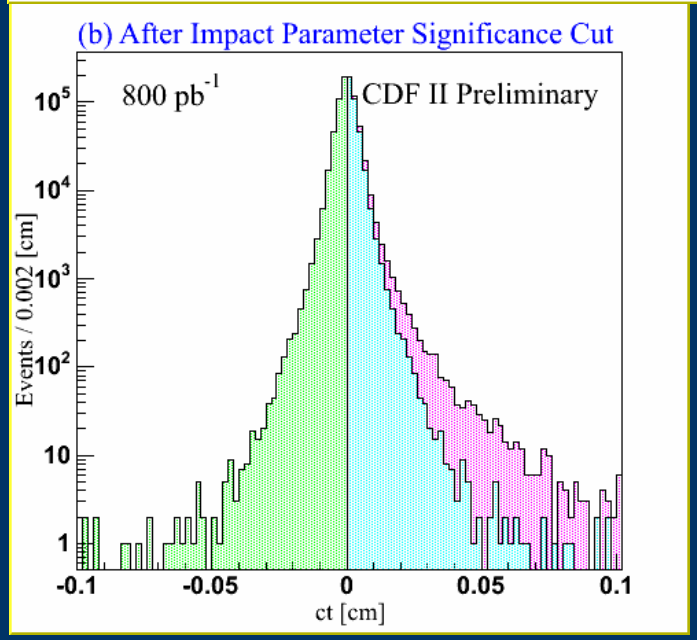
Significant shape discrepancy consistent for both D^0D^{*-} and D^+D^{*-}

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



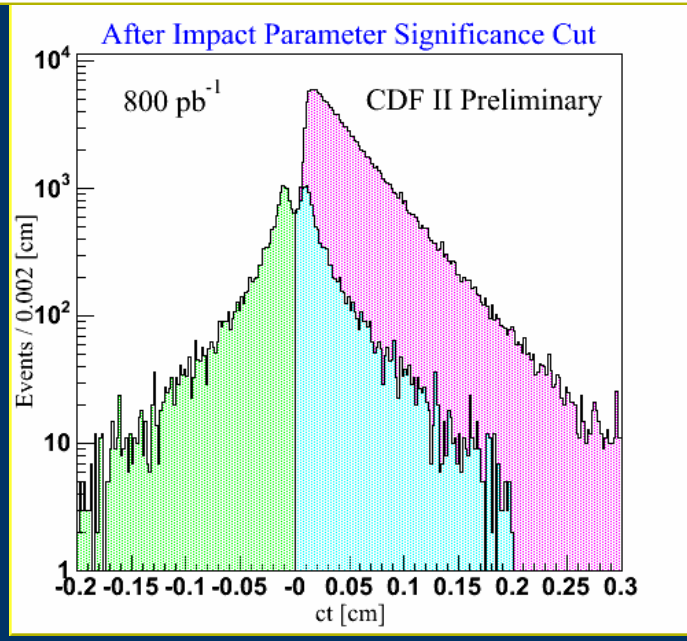
J/ψ selection
Central: |y|<0.6
$5<P_T<30$GeV/c





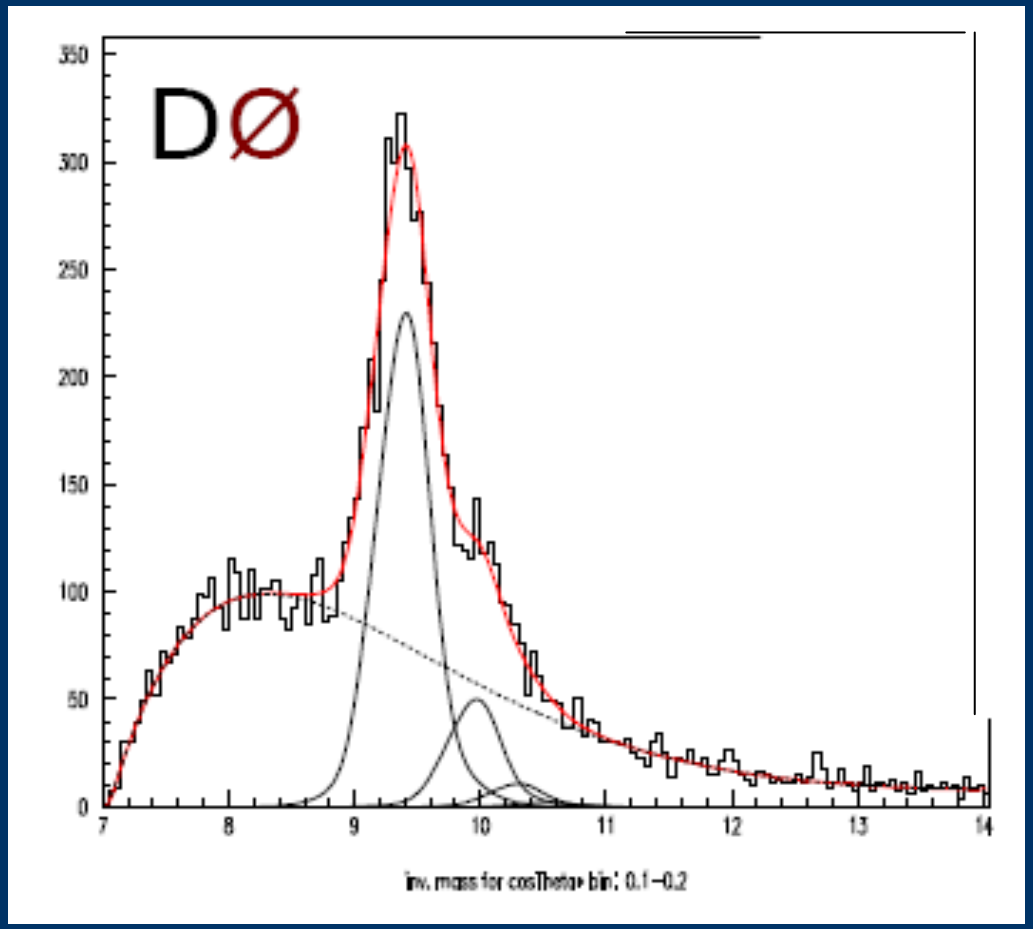
Use $\mu^+\mu^-$ combined impact parameter significance to separate prompt $S \leq 8$ and secondary $S>16$

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



Bottomium Polarization

Updated sample with full statistic



Analysis in progress:

Measurement of Υ Polarization Differential in P_T