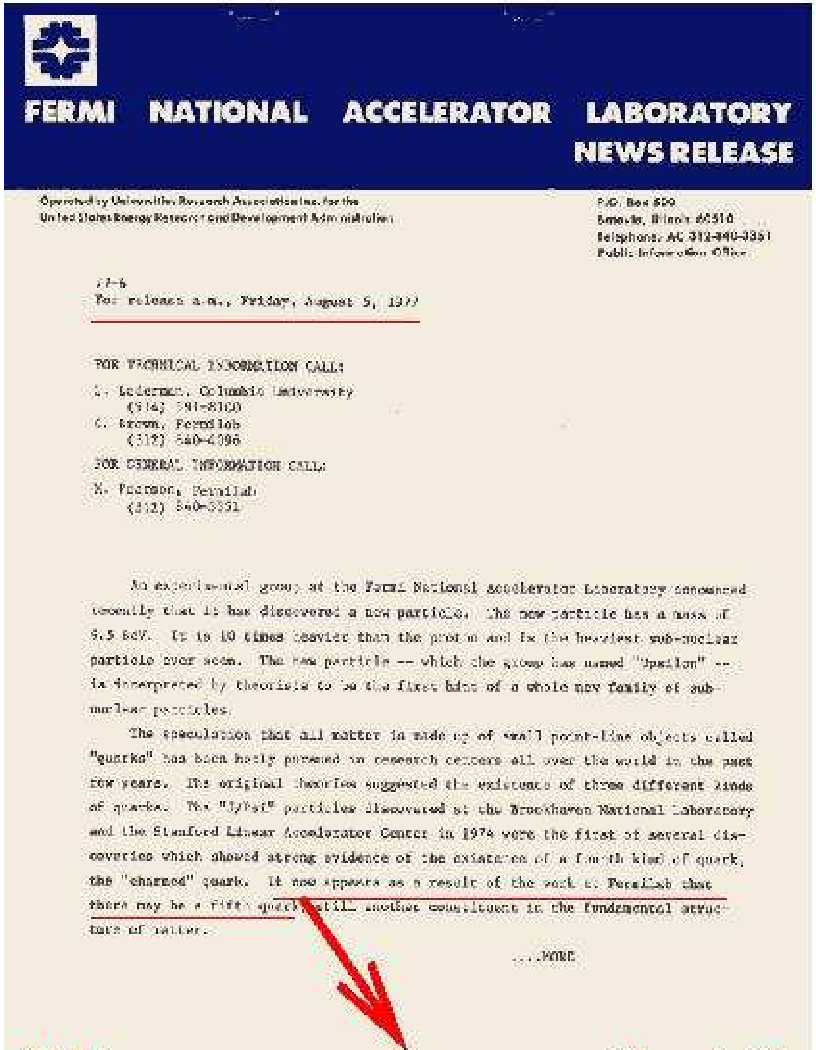
Beauty and Charm Production *at CDF*

Mary Bishai

bishai@fnal.gov

Brookhaven National Laboratory

b quark discovered - 1977



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77-6
For release a.m., Friday, August 5, 1977

FOR TECHNICAL INFORMATION CALL:

L. Lederman, Columbia University
(914) 591-8100
C. Brown, Fermilab
(312) 840-4096

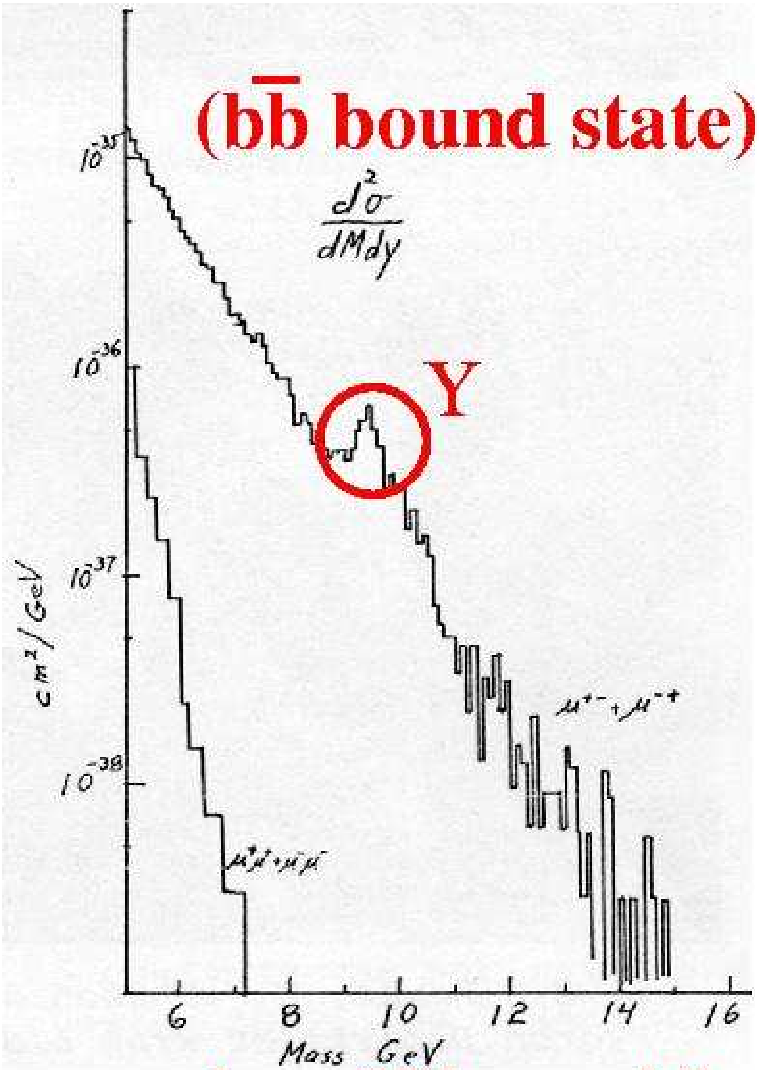
FOR GENERAL INFORMATION CALL:

M. Peterson, Fermilab
(312) 840-3351

An experimental group at the Fermi National Accelerator Laboratory announced recently that it has discovered a new particle. The new particle has a mass of 9.5 GeV. It is 10 times heavier than the proton and is the heaviest sub-nuclear particle ever seen. The new particle -- which the group has named "Upsilon" -- is interpreted by theorists to be the first hint of a whole new family of sub-nuclear particles.

The speculation that all matter is made up of small point-like objects called "quarks" has been hotly pursued in research centers all over the world in the past few years. The original theories suggested the existence of three different kinds of quarks. The "J/Psi" particles discovered at the Brookhaven National Laboratory and the Stanford Linear Accelerator Center in 1974 were the first of several discoveries which showed strong evidence of the existence of a fourth kind of quark, the "charmed" quark. It now appears as a result of the work at Fermilab that there may be a fifth quark, still another constituent in the fundamental structure of matter.

....MORE

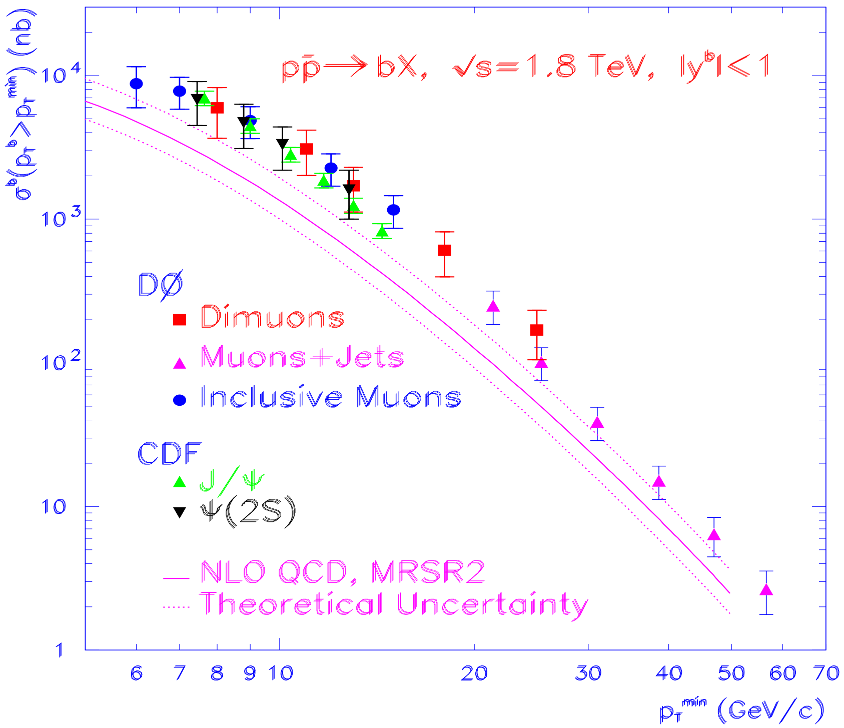


"It now appears .... that there may be a fifth quark"

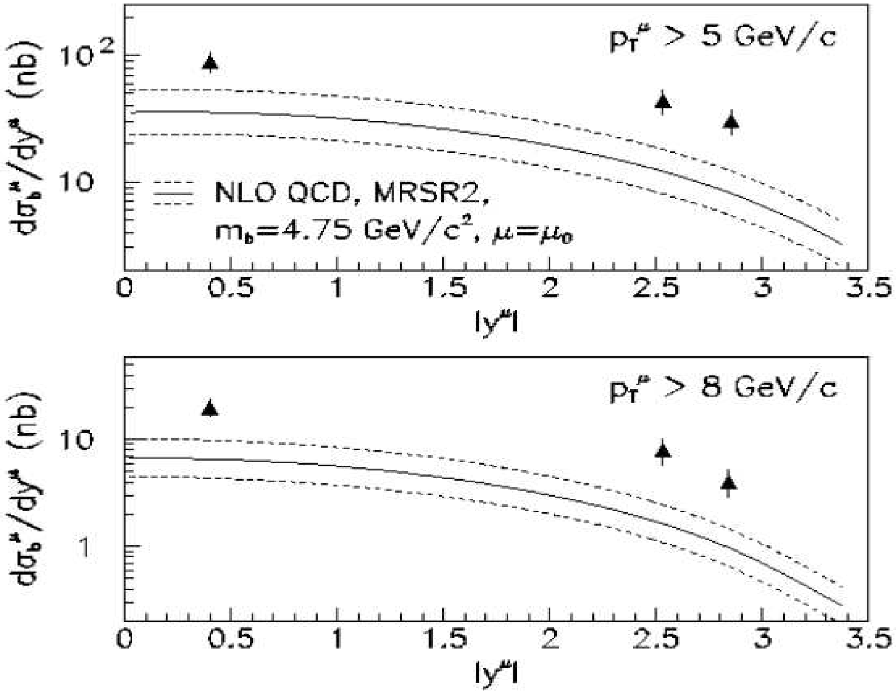
20 years later.....

- In 1997, b production cross-sections were still $> 2\times$ larger than QCD predictions. At that time only a small portion of the b hadron inclusive cross-section, $p_T > 6.0$ GeV/c, had been measured.

$\sigma(p\bar{p} \to bx)$ for $(p_T > p_T^{min})$



$d\sigma/dy$ vs y^μ (inclusive μ from D0)



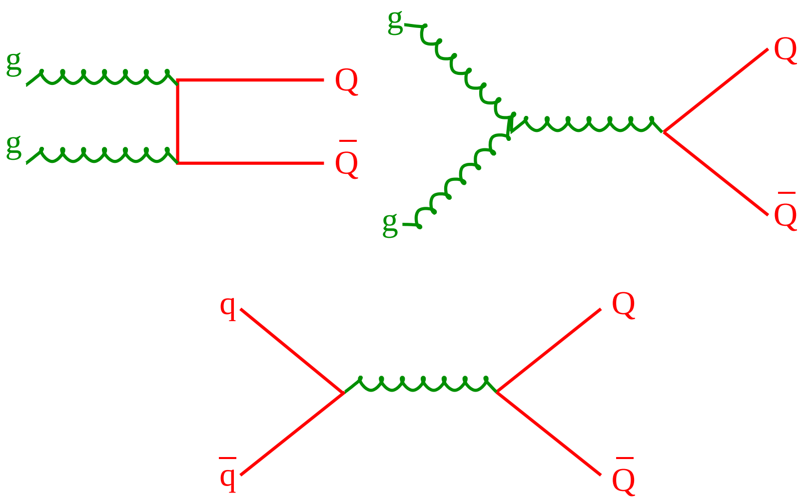
Is this a *shape* or *normalization* problem? What about *charm*?

Outline

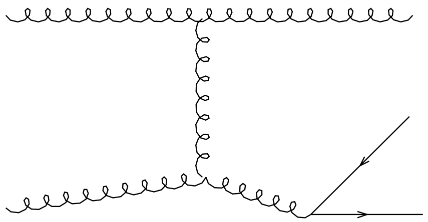
- Recent advances in the theory of heavy quark production cross-sections in $p\bar{p}$ collisions.
- Run II inclusive J/ψ production cross-sections.
- Run II inclusive b-hadron production cross-sections.
- Run II charm production cross-sections.
- *Quarkonia production (including diffractive!)*

THE THEORY

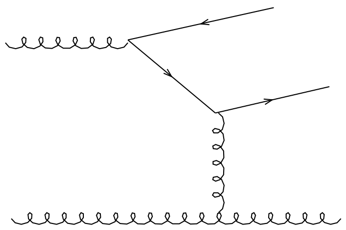
Heavy Quark Production in $p\bar{p}$



LO Heavy Quark Production



NLO: Gluon splitting



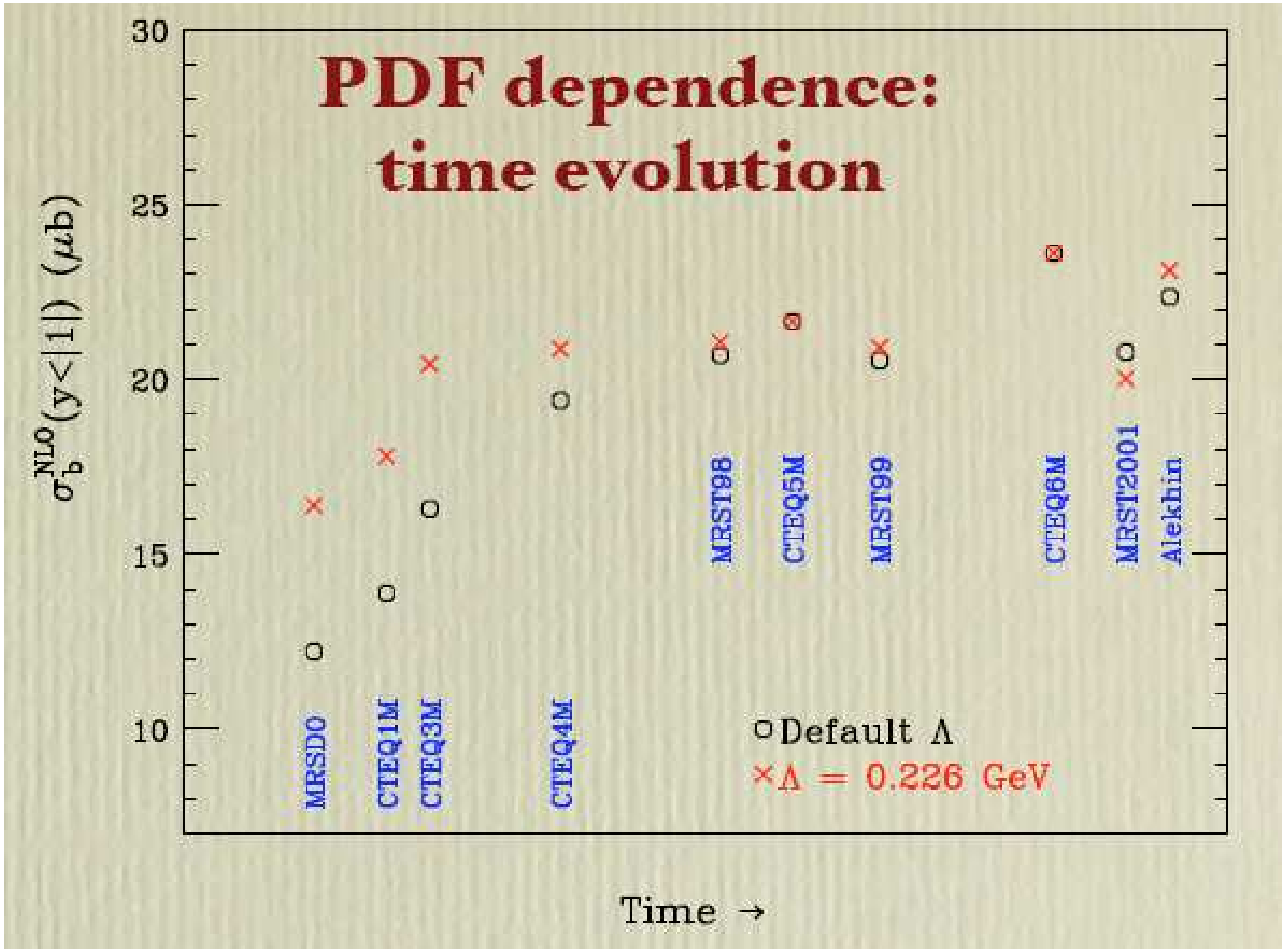
NLO: Flavour excitation

Factorization theorem: factorize physical observable into a calculable part and a non-calculable but universal piece:

$$\underbrace{\frac{d\sigma(qq/gg/qg \rightarrow bX)}{dp_T(b)}}_{\text{NLO/NNLO QCD}} \otimes \underbrace{f^{p,\bar{p}}}_{\text{Proton structure}} \otimes \underbrace{D^{b\rightarrow B}}_{\text{fragmentation}} = \underbrace{\frac{d\sigma(p\bar{p} \rightarrow BX)}{dp_T(B)}}_{\textit{observed}}$$

Evolution of PDFs

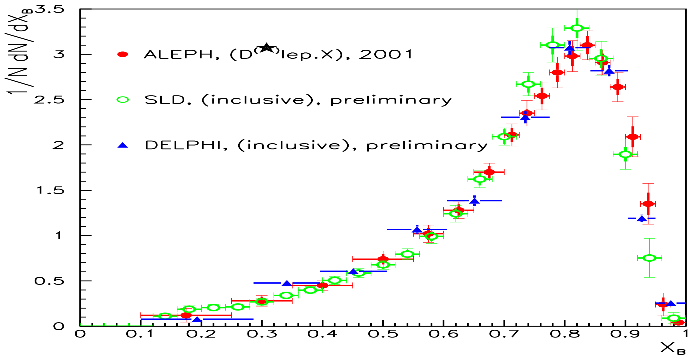
By 2004, recalculating the cross-section with updated PDFs increases theoretical value by almost 2X!



New Fragmentation Functions $D^{b\to B}$

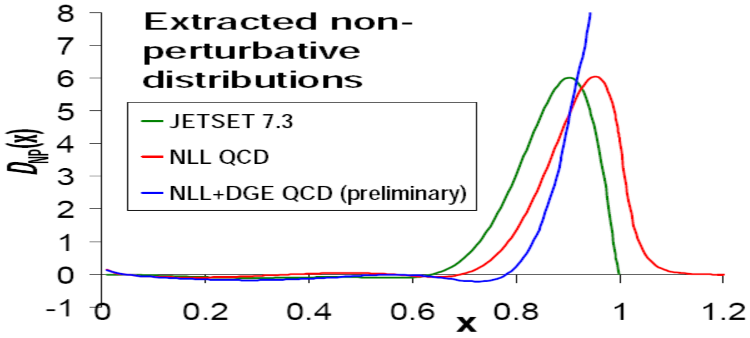
$$D^{meas}(x) = \int \underbrace{D^{pert}(x')}_{pQCD/MC} \otimes \underbrace{D^{non-pert}(x')}_{Parameterized/MC} dx'$$

- **Next-to-leading-log resummation:** In pQCD, powers of $\alpha_s \log p_T/m_Q$ modify shape of fragmentation function: $p_T >> m_Q$ = Large corrections



$D(x)$ Measured

- **Moment analysis (2002):** Mellin transformation into moment space $\tilde{D}(N) = \int x^{N-1} D(x) dx$



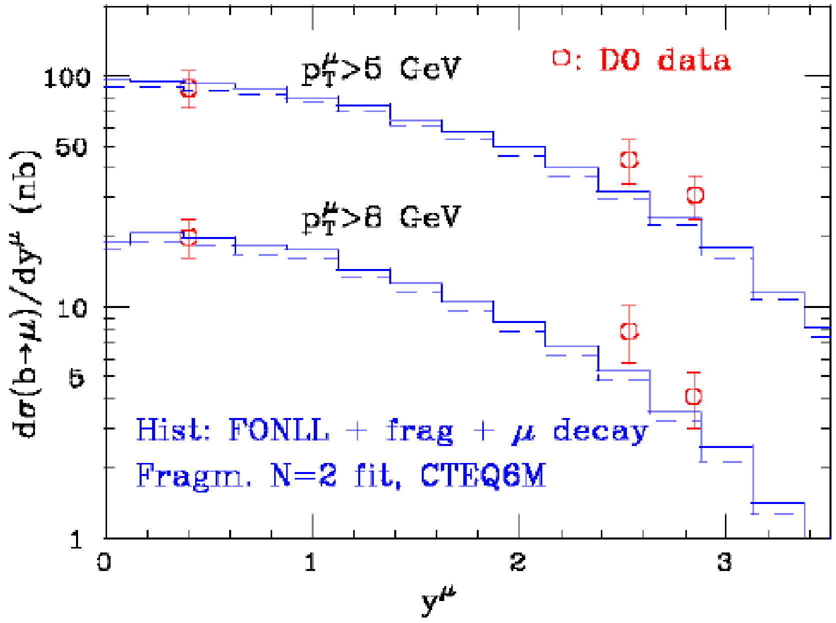
$$\tilde{D}^{meas}(N) = \underbrace{\tilde{D}^{pert}(N) \times \tilde{D}^{non-pert}(N)}_{\text{A product}}$$

$D^{non-pert}(x')$ Extracted

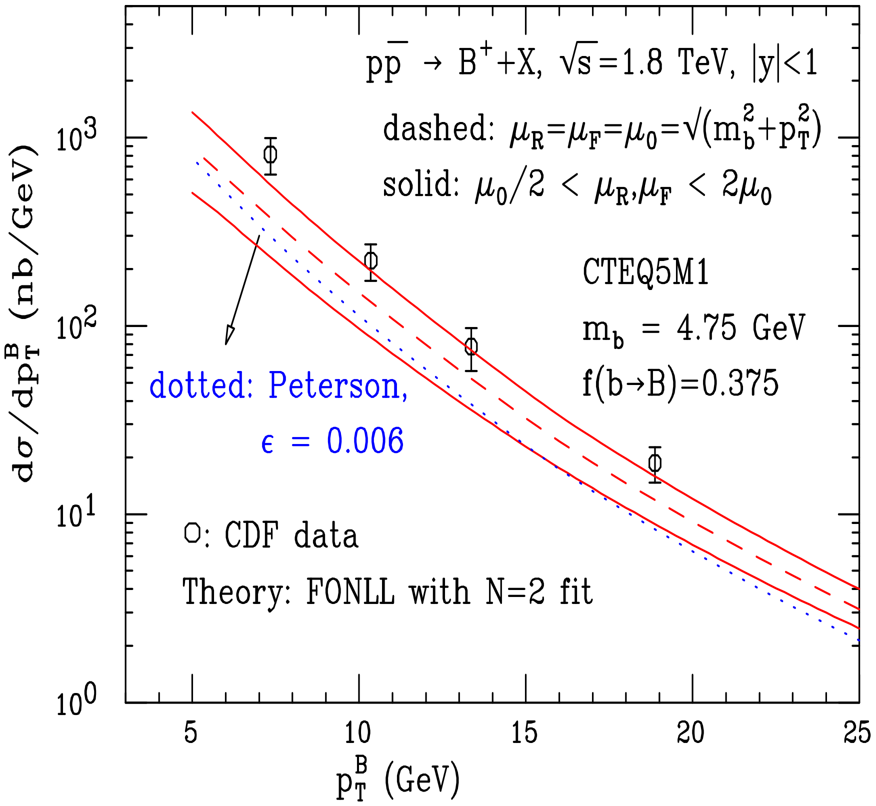
Non-perturbative functions used must match perturbative assumptions

Comparison with Run I Data - NLL

Fixed order (FO) QCD NLO calculation + Resummation of next-to-leading logs (NLL). Method of moments instead of a fragmentation model $\Rightarrow$ *Better agreement with CDF and D0 Run I data*



$d\sigma(p\bar{p} \to B^+X)/dp_T$ vs $p_T(B^+)$ (CDF)



$p_T(B^+)$ GeV/c

Cacciari, Nason hep-ph/0204025 (Run I)

Theory Summary

- Agreement with the Run I b cross-section data for $p_T > 5.0$ GeV/c has greatly improved without the need to invoke exotic sources of excess b quarks. Most of the improvement is due to improved treatment of experimental inputs.
- BUT: Different theoretical approaches: different factorization schemes, FONLL calculations, new methods to extract the non-perturbative part of fragmentation function. Which is the correct approach?

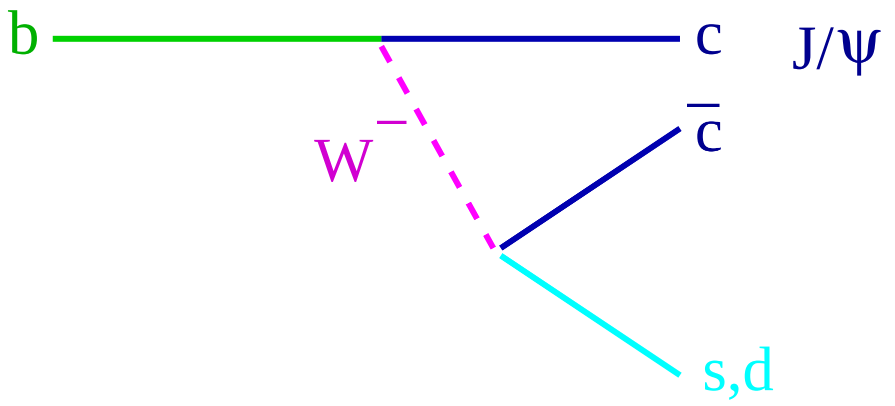
Total cross-sections do not depend on the fragmentation model!

= powerful experimental test of QCD calculations.

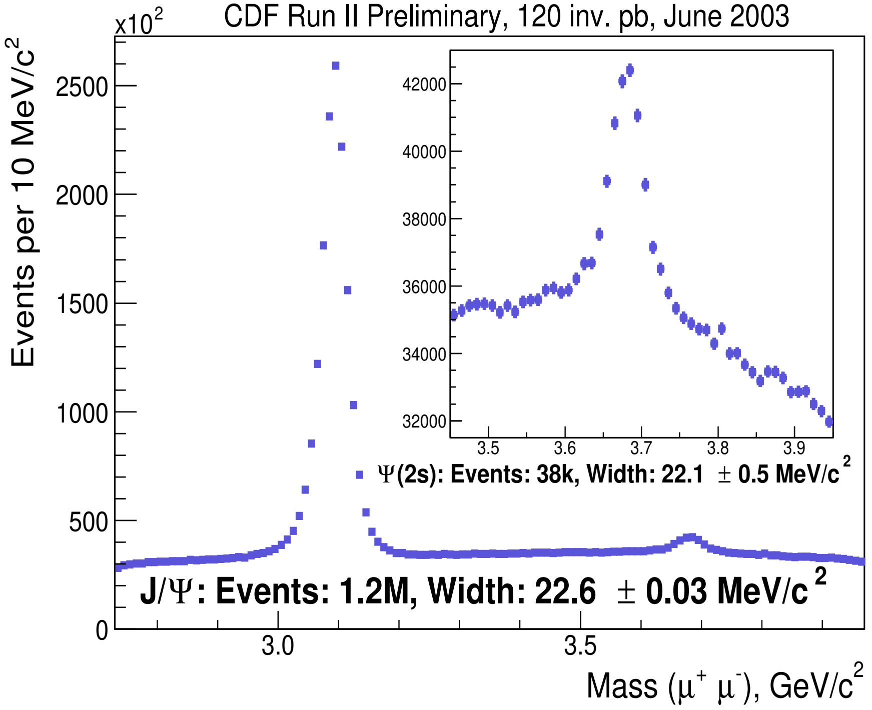
Charm quark mass and production cross-sections are close to b-quark

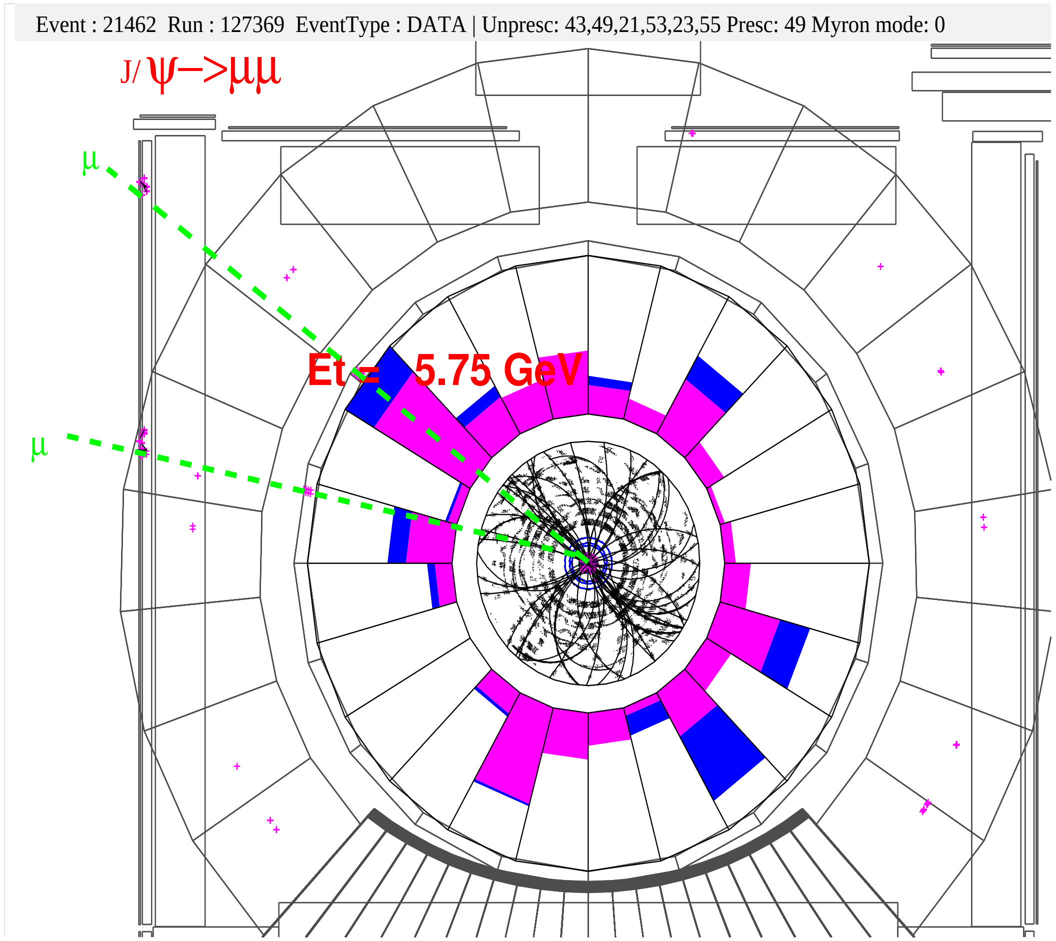
but fragmentation is very different - test theory predictions

RUN II MEASUREMENTS OF THE J/ψ AND b-HADRON INCLUSIVE CROSS-SECTIONS



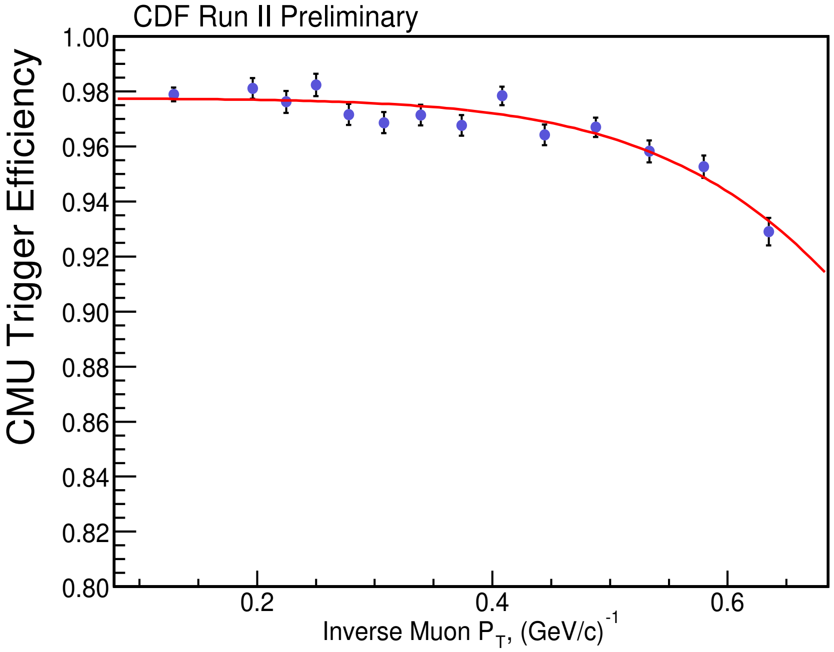
$J/\psi \to \mu\mu$ signals



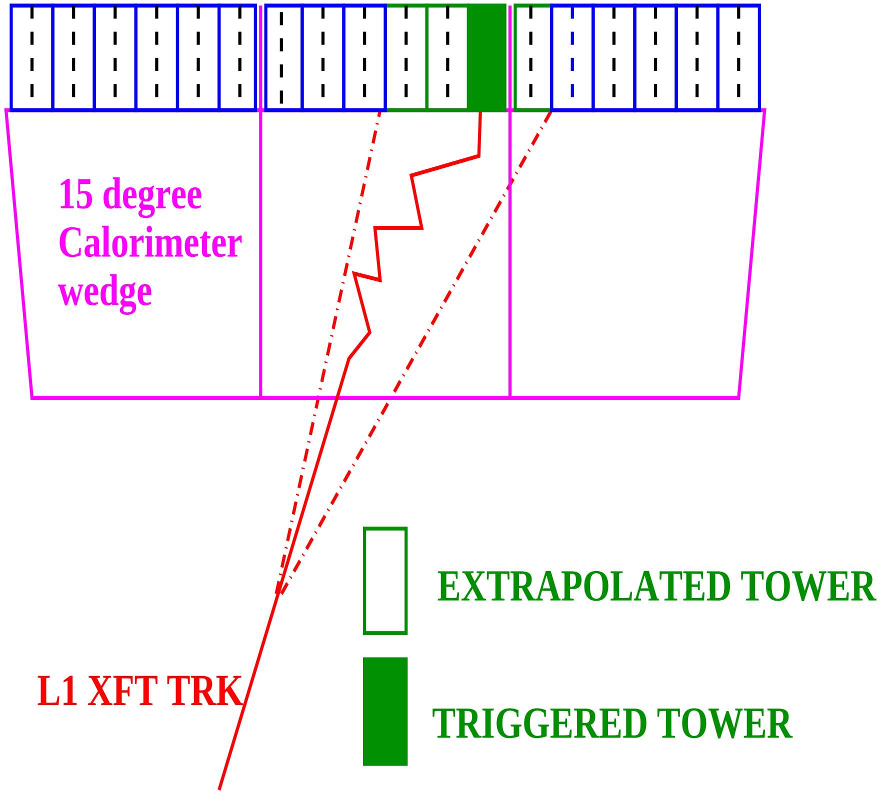


L1 Muon triggers (CDF)

Tracks are reconstructed in the COT by the Level 1 Trigger eXtra Fast Tracker (XFT). A match is made to hits in the Muon Chambers. (Offline $\epsilon = 0.986 \pm 0.010$)



L1 muon trigger efficiency .vs. $1/p_T$



- *lower p_t reach:*

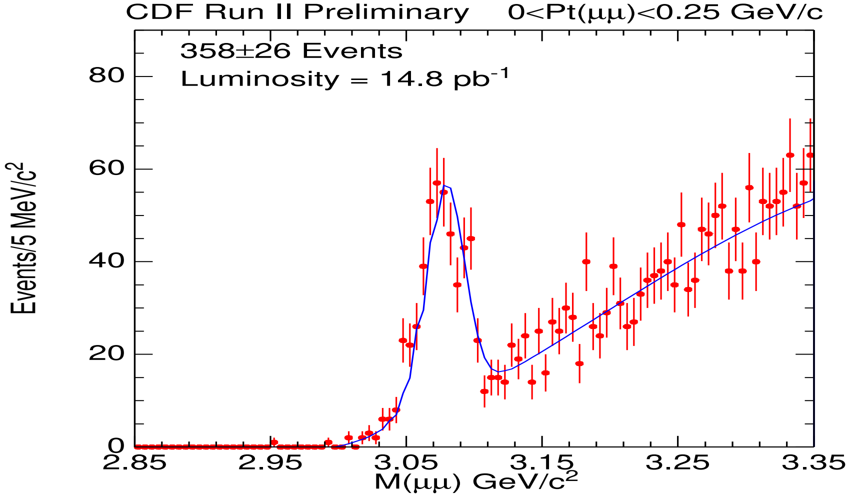
  $p_t(\mu) > 1.5(|\eta| < 0.6)$.

  $p_t(\mu) > 2.0(0.6 < |\eta| < 1.0)$

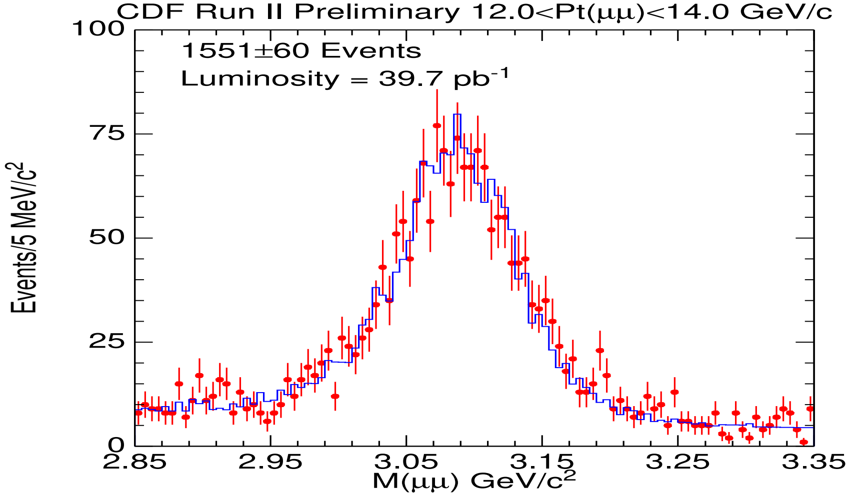
Can now reach $p_t(J/\psi) = 0$ GeV/c.

Counting J/ψs ($p_T = 0$ to 20 GeV/c)

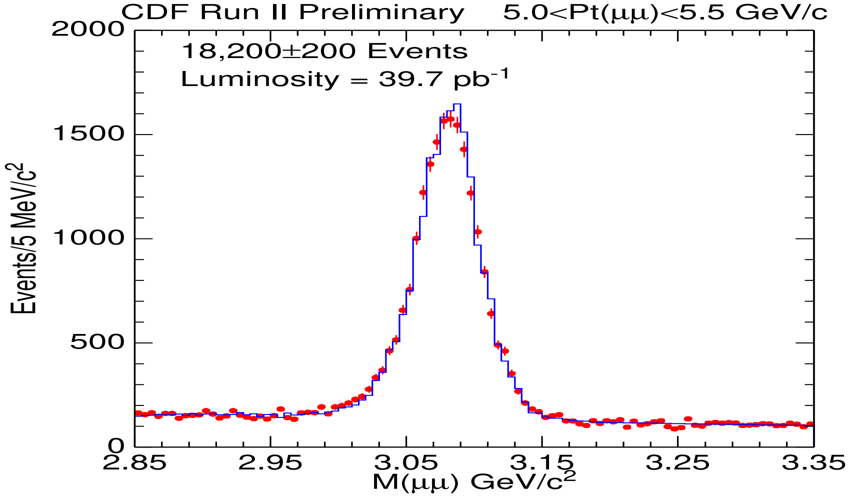
$0 < p_T(J/\psi) < 0.25 GeV/c$



$12 < p_T(J/\psi) < 14 GeV/c$



$5 < p_T(J/\psi) < 5.5 GeV/c$

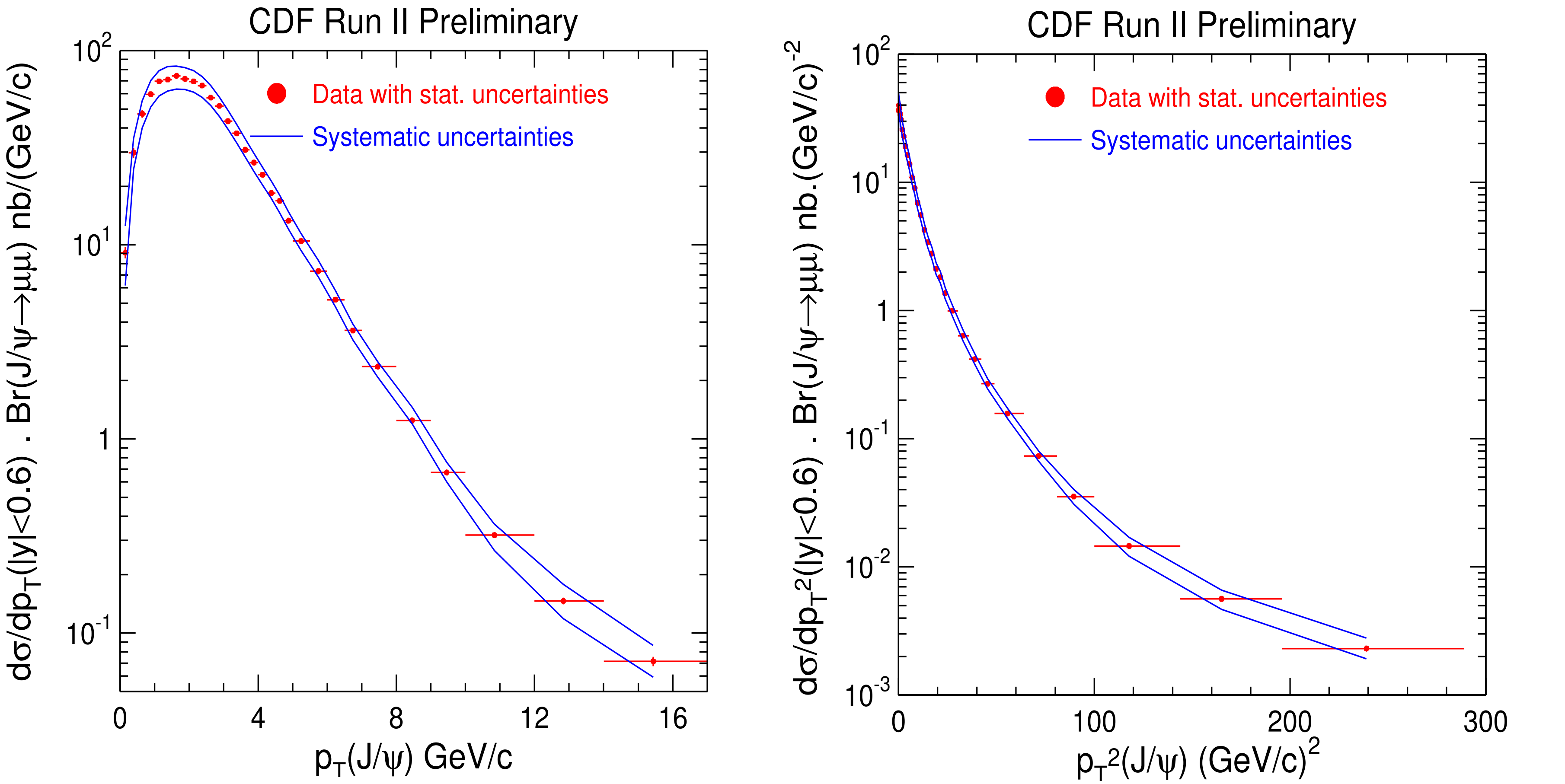


- Transverse momentum resolution: $\delta(p_T)/p_T = 0.003 p_T$
- A detector simulation is used to model the expected shape of the J/ψ signal.

J/ψ Cross-sections - Run II

$$\frac{d\sigma(p\bar{p}\to J/\psi X)}{dp_T(J/\psi)} = \frac{\text{Number of } J/\psi}{\text{luminosity}\times\text{acceptance}\times\text{efficiency}\times\Delta p_T}$$

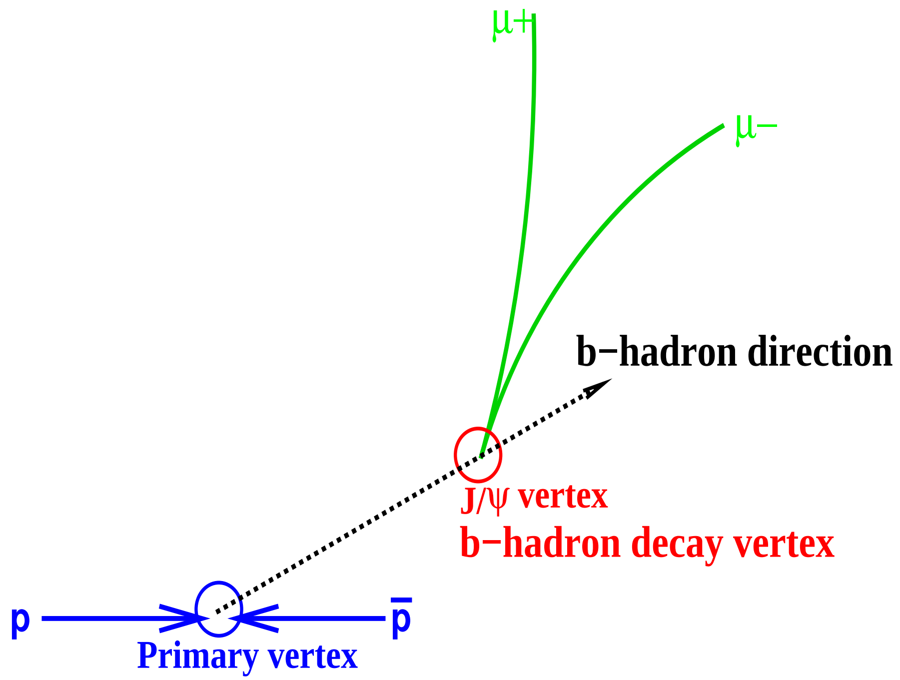
$\sigma(p\bar{p} \to J/\psi X, |y| < 0.6)$ vs $p_T(J/\psi)$ $\sigma(p\bar{p} \to J/\psi X, |y| < 0.6)$ vs $p_T^2(J/\psi)$



$$\sigma(p\bar{p} \to J/\psi X, |\, y(J/\psi)\,| < 0.6) = 4.08 \pm 0.02(stat)^{+0.60}_{-0.48}(syst)\ \mu\text{b}$$

Separate $H_b \to J/\psi X$ from Total

- The J/ψ inclusive cross-section includes contributions from
  - Direct production of J/ψ
  - Indirect production from decays of excited charmonium states such as $\psi(2S) \to J/\psi\pi^+\pi^-$
  - Decays of b-hadrons such as $B \to J/\psi X$

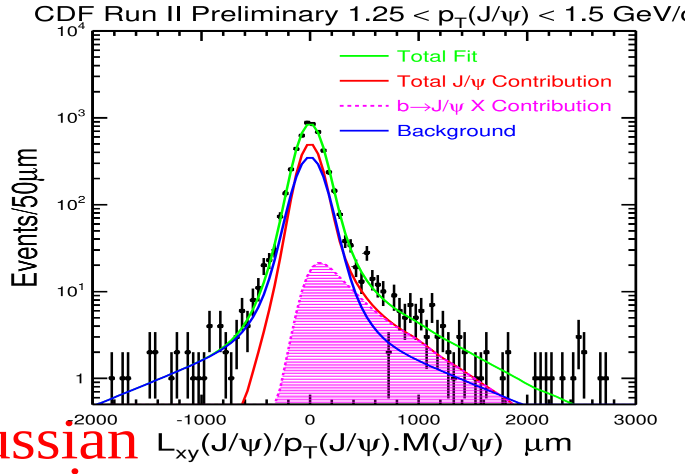


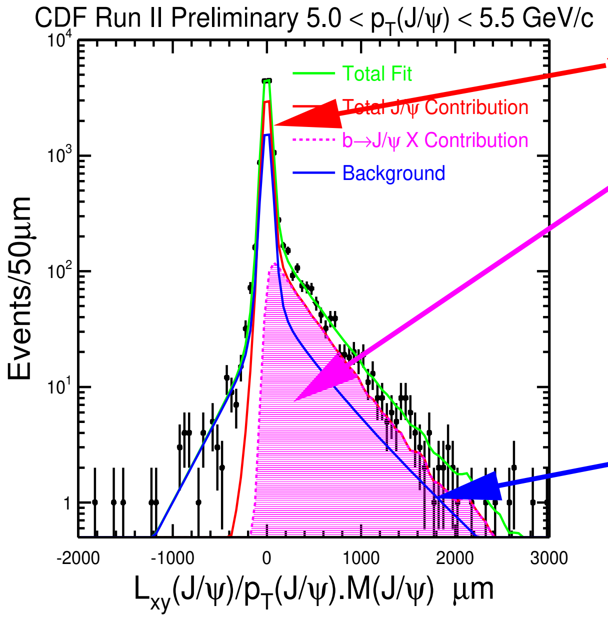
- b-hadrons have long life-times, J/ψ from $H_b \to J/\psi X$ will be displaced.

Extracting the b-fraction

- A maximum likelihood fit to the flight path of the J/ψ in the $r-\phi$ plane, L_{xy} is used to extract the b-fraction.

$1.25 < p_T < 1.5$ GeV/c, $f_b = 9.7\%$



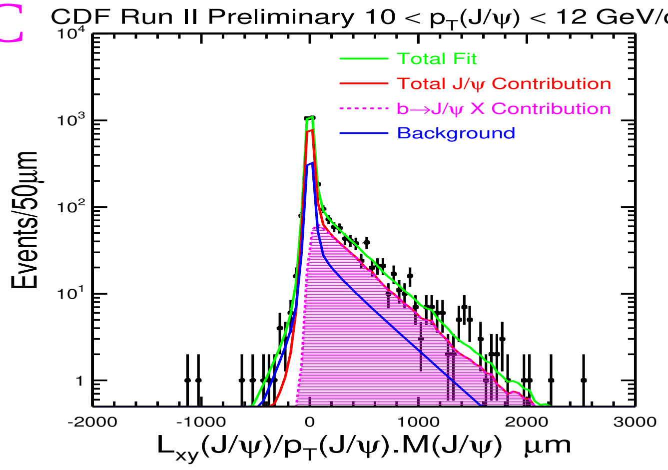


Prompt J/Ψ is a double Gaussian = resolution function

b−>J/ψ X shape from MC template

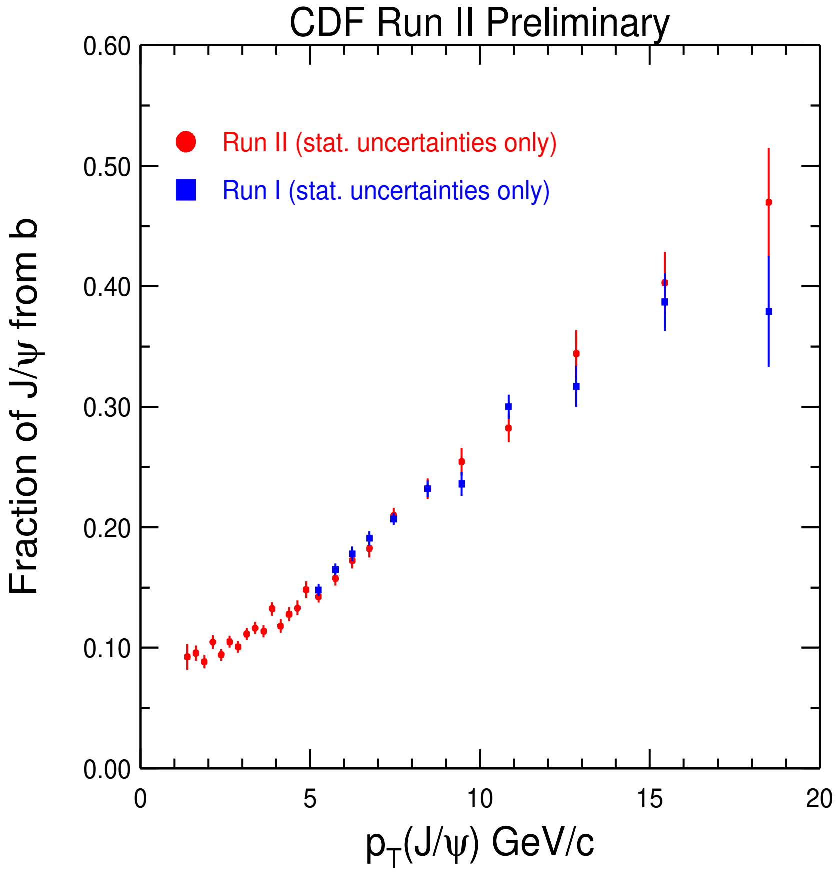
Parameterized background

$10 < p_T < 12$ GeV/c, $f_b = 28\%$

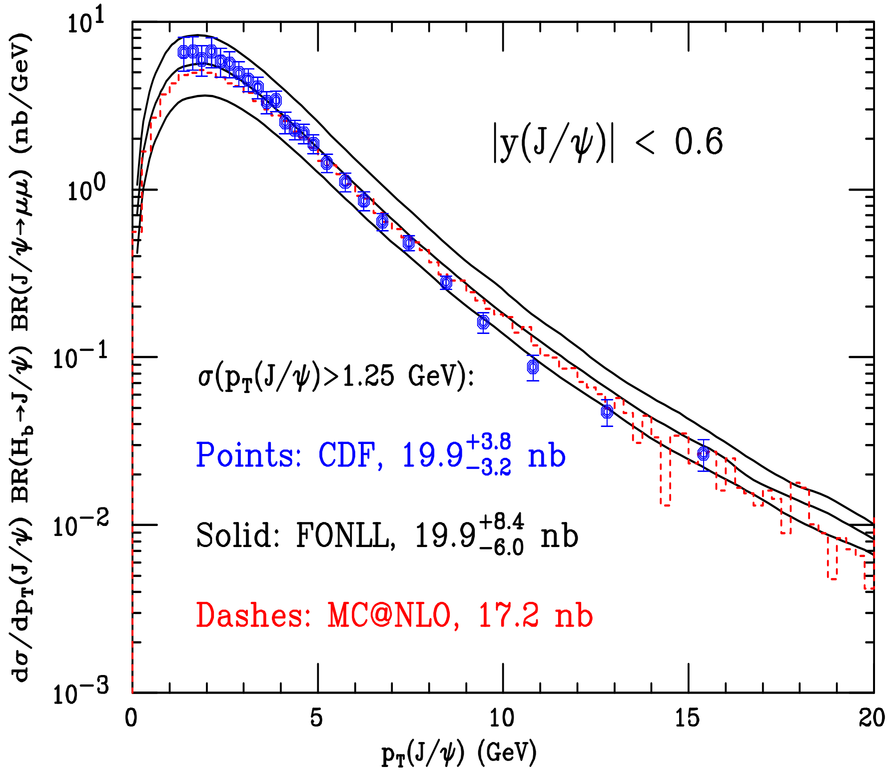


$d\sigma(p\bar{p} \to H_b X)/dp_T(J/\psi)$

Fraction of J/ψs from H_b



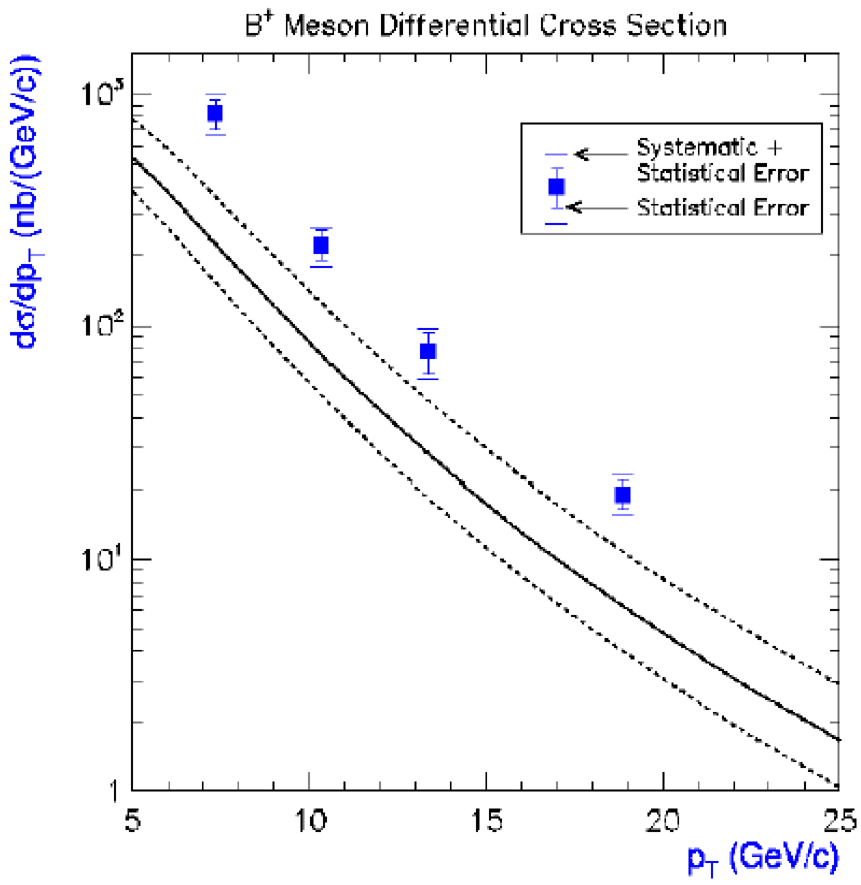
$d\sigma(p\bar{p} \to H_b X, H_b \to J/\psi X)/dp_T(J/\psi)$



Theory: M.Cacciari, S. Frixione, M.L. Mangano, P. Nason. G. Ridolfi (Dec, 2003)

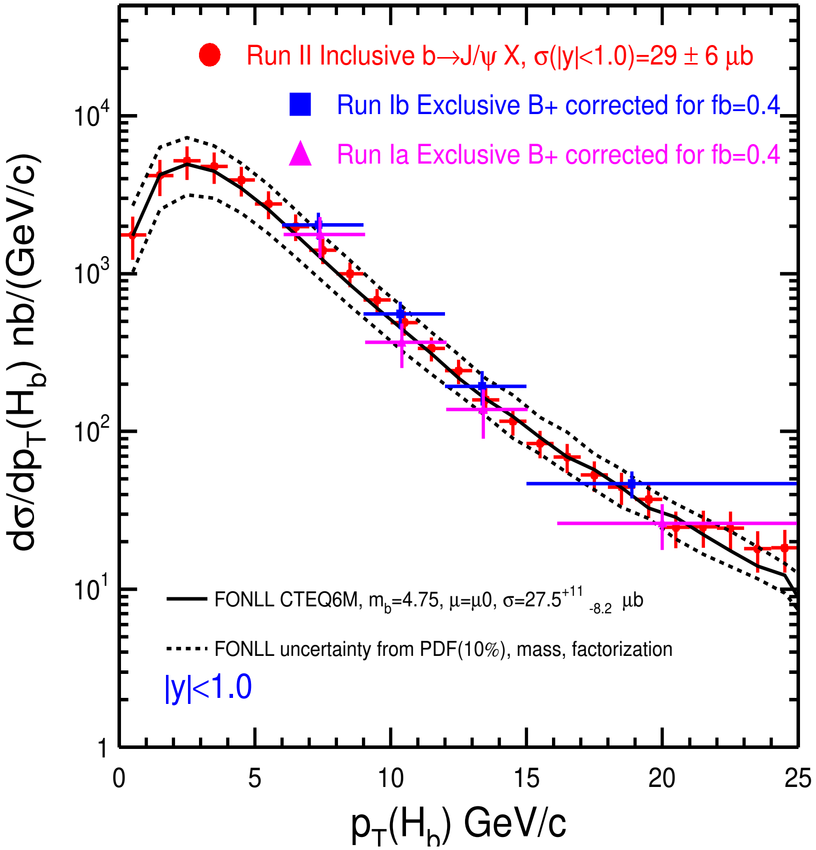
b-Production cross-section

$\sigma(p\bar{p} \to B^+X)$ vs $(p_T(B^+))$



1997

$\sigma(p\bar{p} \to bx)$ versus $(p_T(H_b))$

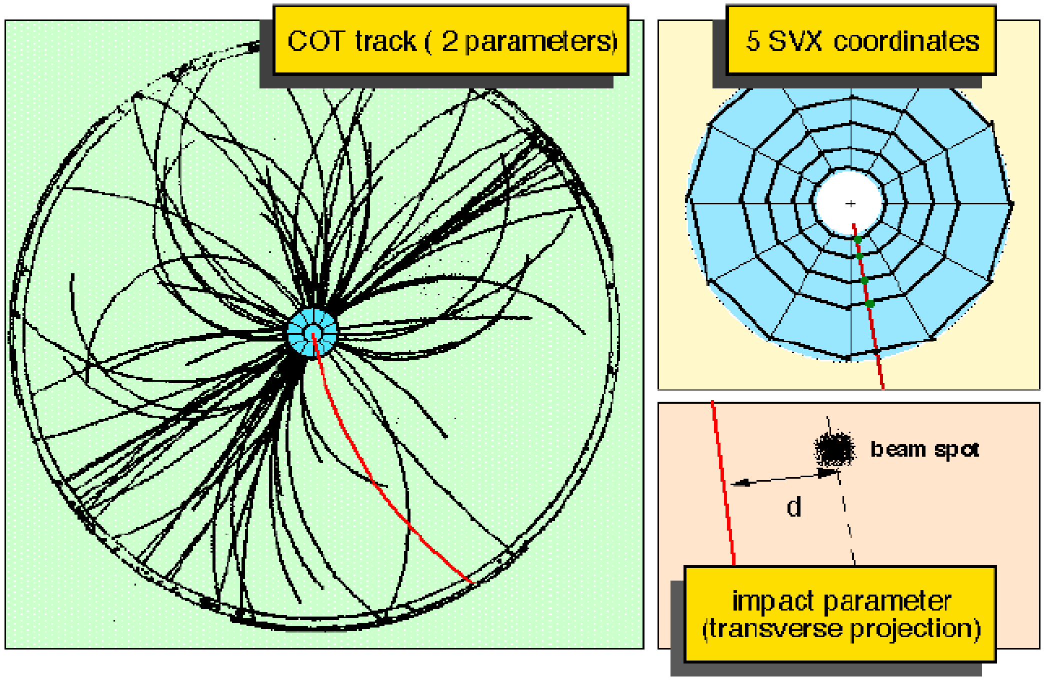


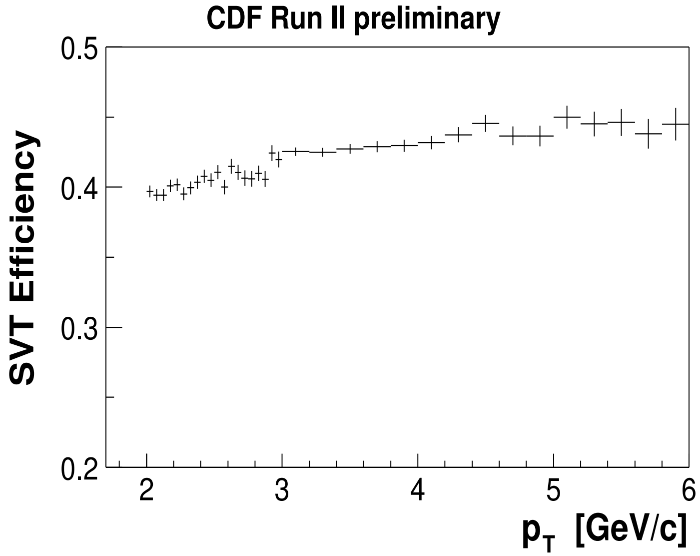
2003

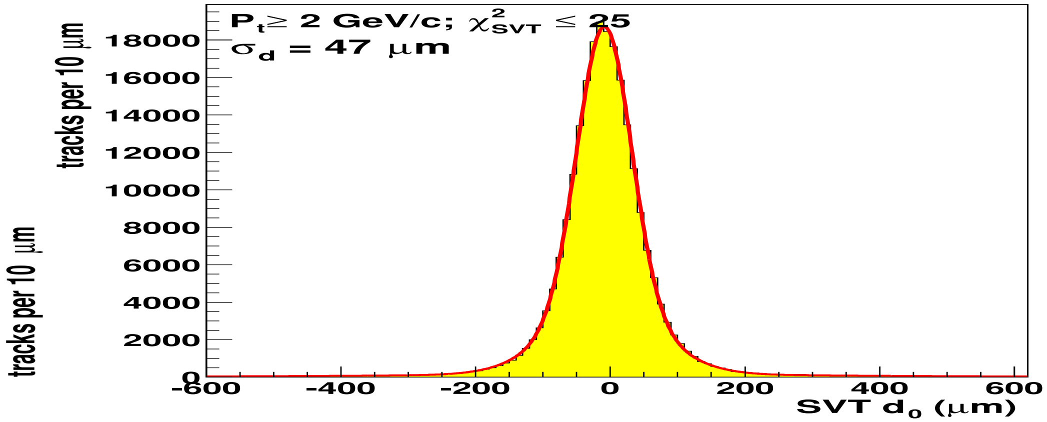
Data: $\sigma = 29 \pm 6\mu$b, FONLL: $\sigma = 27.5\mu$b (CTEQ6M, $m_b = 4.75$, $\mu = \mu_0$)

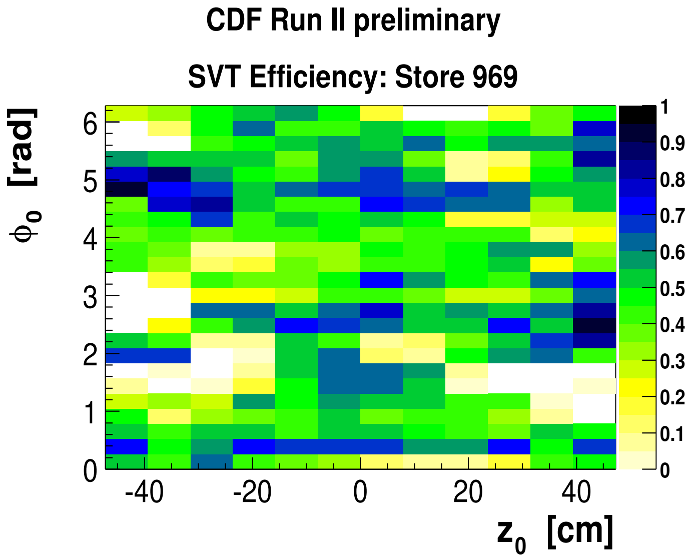
CHARM MESON CROSS-SECTIONS

L2 Silicon Vertex Trigger (CDF)

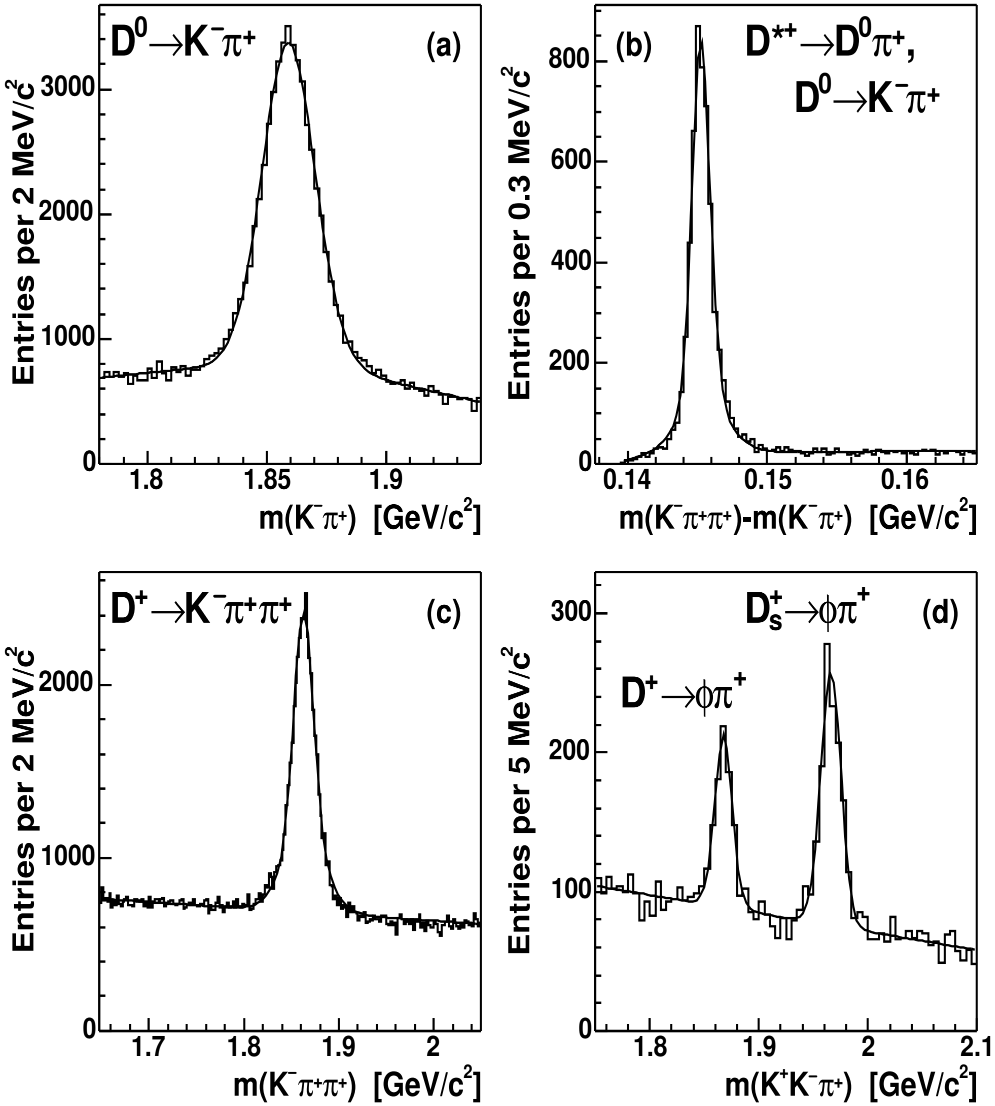








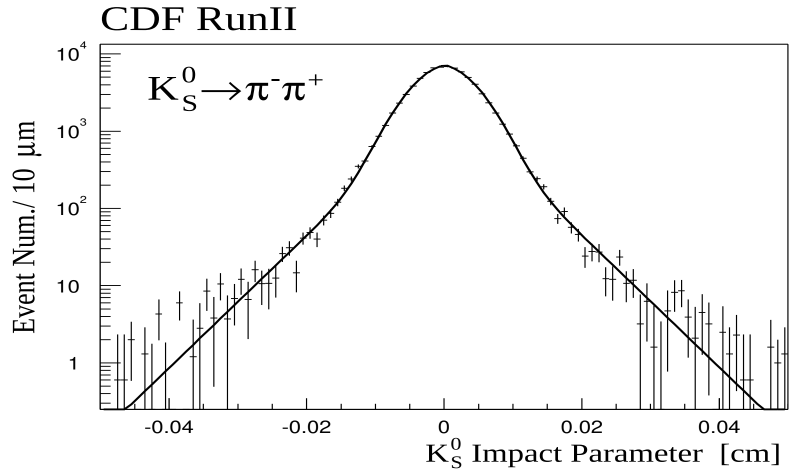
Charm Production in Run II



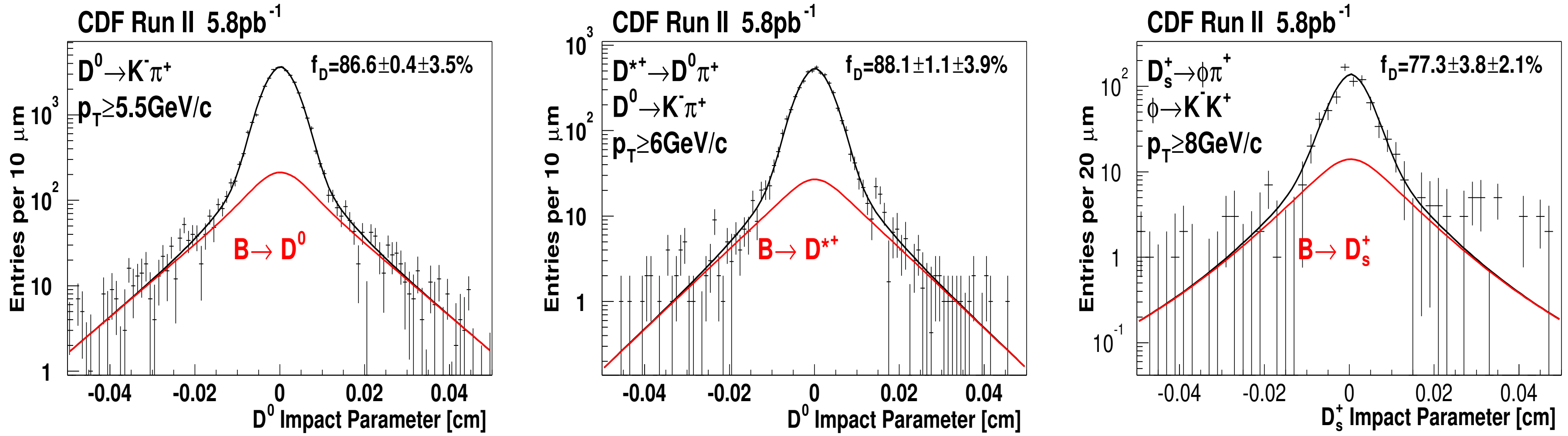
- Analysis uses 5.8pb $^{-1}$ of early 2002 data.
- Challenges: SVT not fully efficient at the time.
- Efficiency is a complex function of $p_T, z, \cot(\theta)$ and time.

Direct Charm Production Run II

Use impact parameter of reconstructed charm mesons $F_D(d_0)$ *to distinguish directly produced charm from* $B \to DX$, $F_B(d_0)$

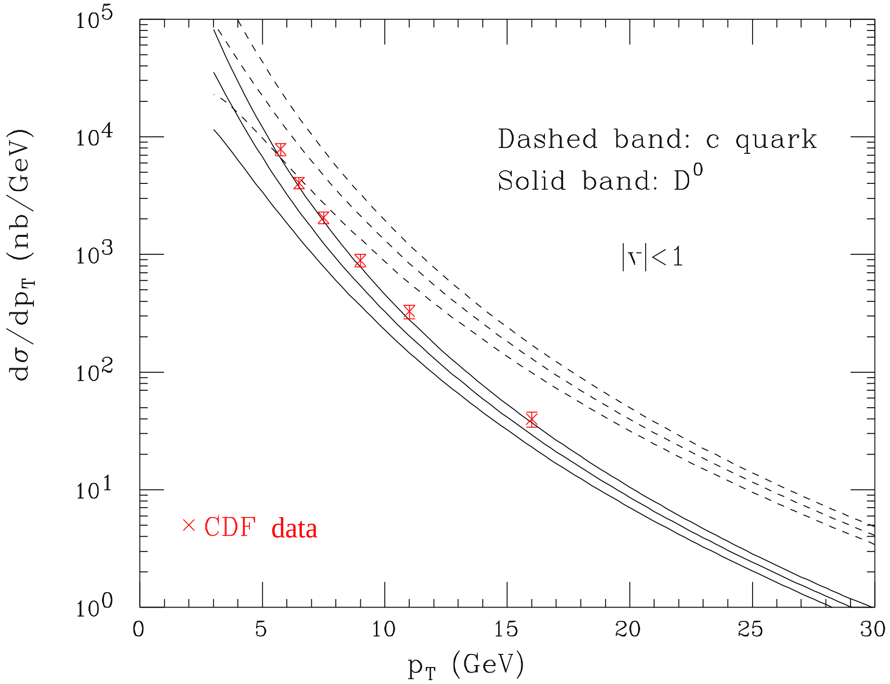


From $K_s \to \pi\pi$ data we find $F_D(d_0)$ = Gaussian + exp tails. From $B \to DX$ MC : $F_B(d_0)$ = a double exponential.

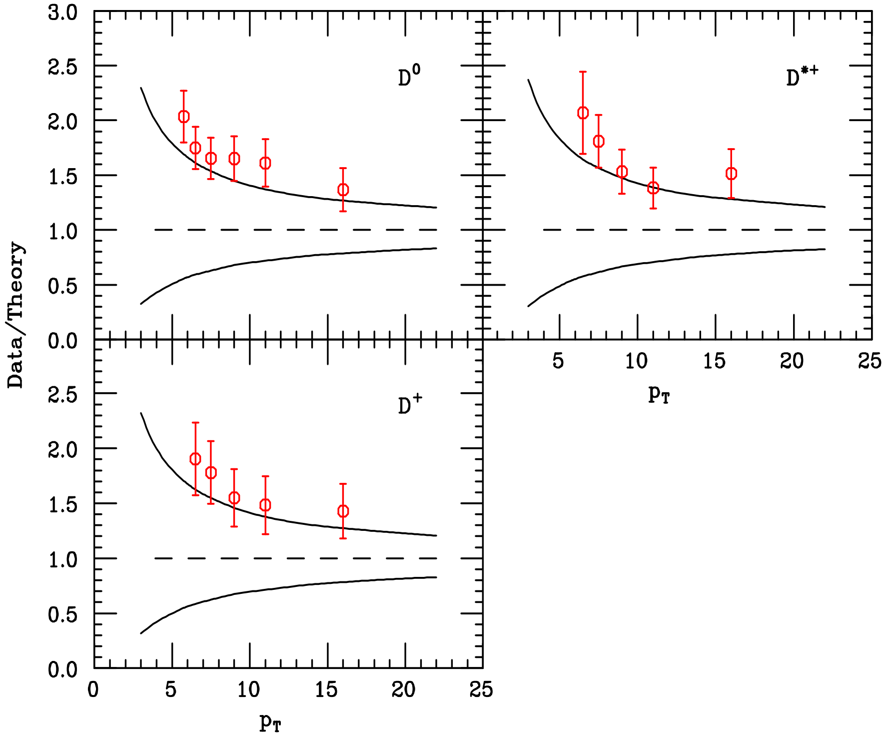


Charm cross-sections

D^0 Meson Differential Cross-section



D Meson Cross-sections Data/Theory



M. Cacciari, P. Nason. hep-ph/0306212.

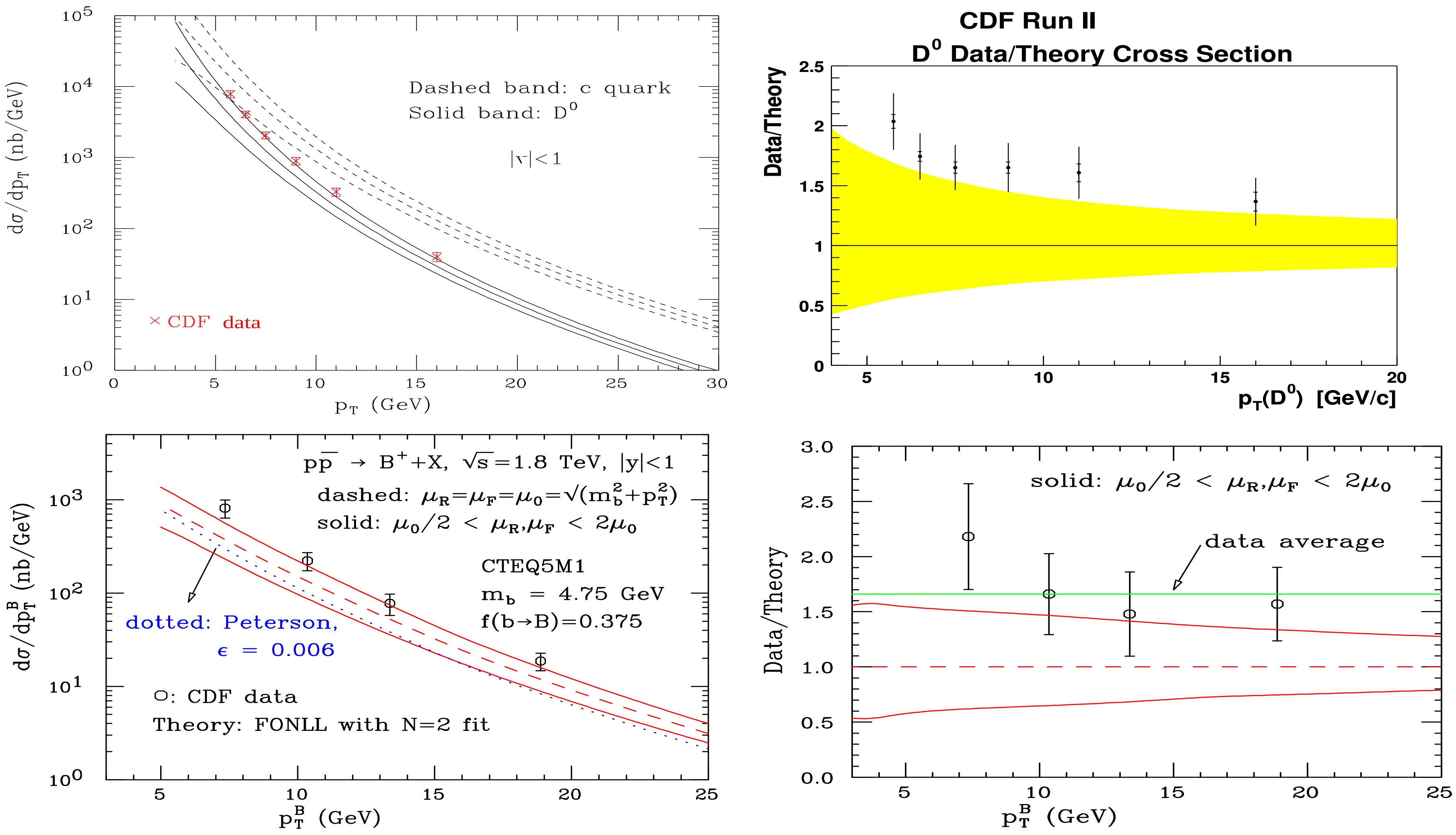
$\sigma(p\bar{p} \rightarrow D^0 X, |\, y \,| < 1.0, p_T > 5.5 \text{ GeV/c}) = 13.3 \pm 0.2(stat) \pm 1.5(syst)\ \mu\text{b}$

$\sigma(p\bar{p} \rightarrow D^+ X, |\, y \,| < 1.0, p_T > 6.0 \text{ GeV/c}) = 4.3 \pm 0.1(stat) \pm 0.7(syst)\ \mu\text{b}$

$\sigma(p\bar{p} \rightarrow D^{*+} X, |\, y \,| < 1.0, p_T > 6.0 \text{ GeV/c}) = 5.2 \pm 0.1(stat) \pm 0.8(syst)\ \mu\text{b}$

$\sigma(p\bar{p} \rightarrow D_s X, |\, y \,| < 1.0, p_T > 8.0 \text{ GeV/c}) = 0.75 \pm 0.05(stat) \pm 0.22(syst)\ \mu\text{b}$

Charm .vs. Beauty (FONLL)



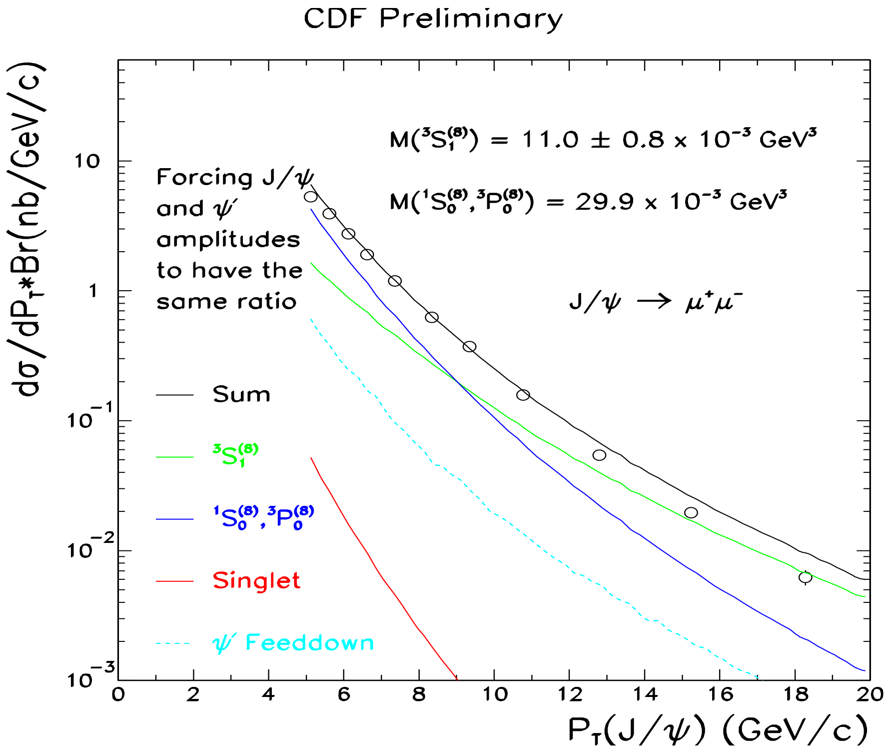
Charm and Beauty meson crossection predictions are consistent

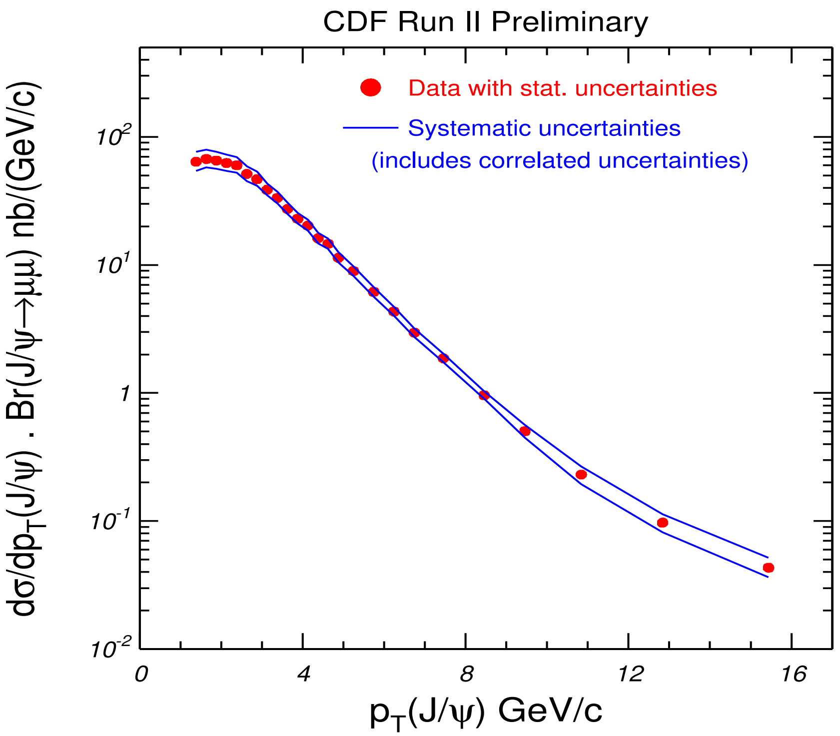
QUARKONIA PRODUCTION

Prompt Quarkonia Production

Quarkonia bound states are non-relativistic. NRQCD LO perturbative expansion is $\mathcal{O}(\alpha_s^3 v^0)$ *as in the color singlet model (CSM) + higher order* $\mathcal{O}(\alpha_s^3 v^4)$.

Fragmentation processes $\propto$ *color octet matrix element dominate. CO matrix elements extracted from fits to data - agree well with Run I data at high* p_t.

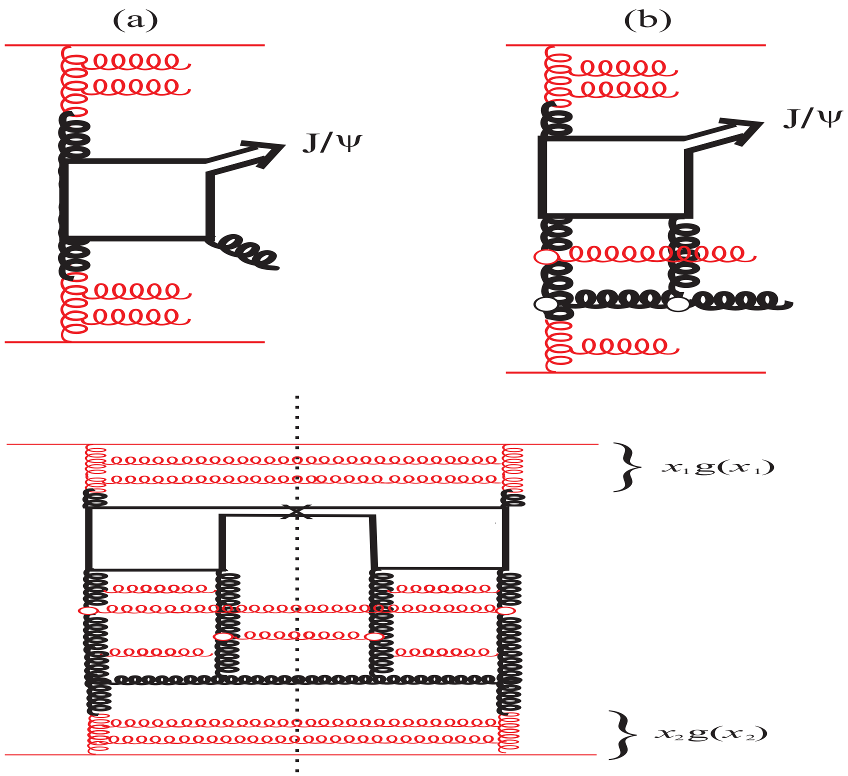


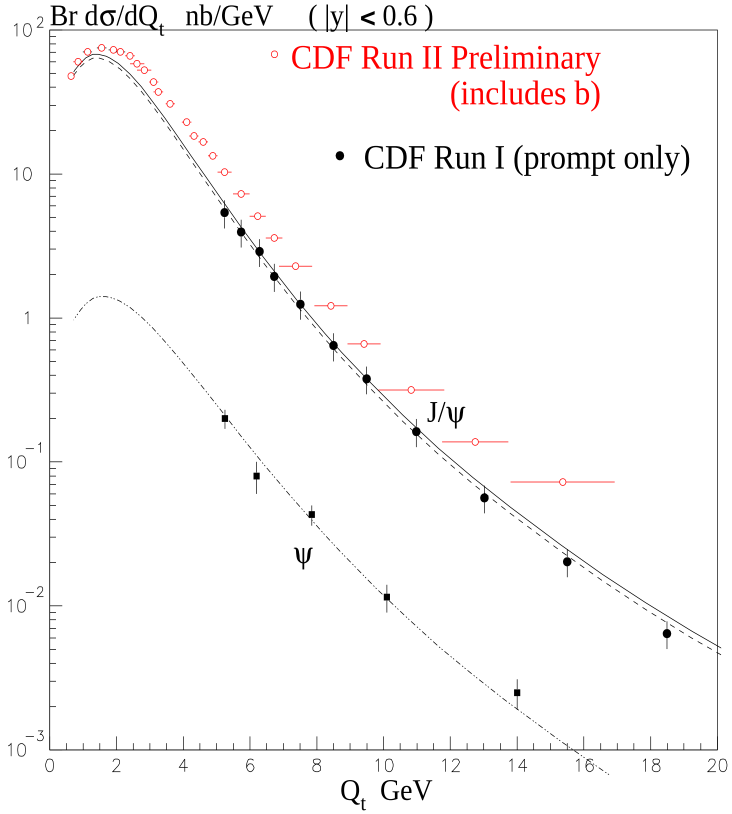


Prompt J/ψ production (Run I)   Prompt J/ψ production (Run II)

NEW: Fusion of color-octet + g

hep-ph/0410020 (Oct 2004), avoids the need to invoke non-perturbative CO contributions as in NRQCD. Studies yet another pQCD contribution and finds out its dominant





$\sigma(p\bar{p} \to J/\psi X, \mid y(J/\psi) \mid < 0.6) = 4.08 \pm 0.02(stat)^{+0.60}_{-0.48}(syst)\ \mu$b (includes $\sim 10\%\ b$)

$\sigma(p\bar{p} \to J/\psi(prompt)X, \mid y(J/\psi) \mid < 0.6) \sim 2.7\mu$b (pQCD). Uncertainty is $\pm$ factor of 2-3

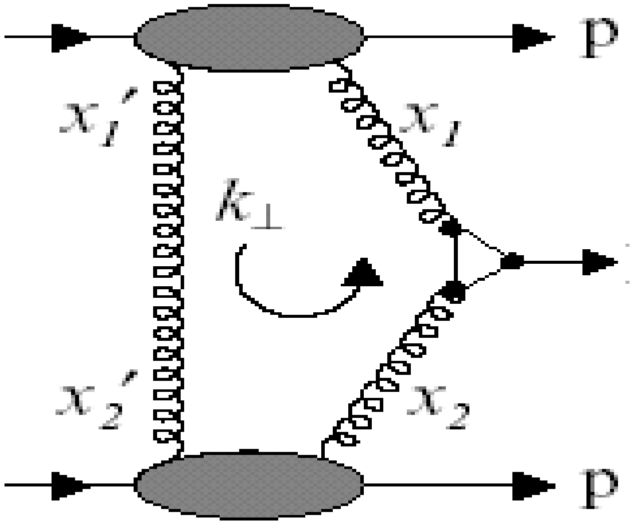
Diffractive production of χ_c

- At LHC SM Higgs boson could be produced by exclusive production with NOTHING else in the interaction ($\sigma \sim 40$ fb ?):

$$p + p \rightarrow p + H + p$$

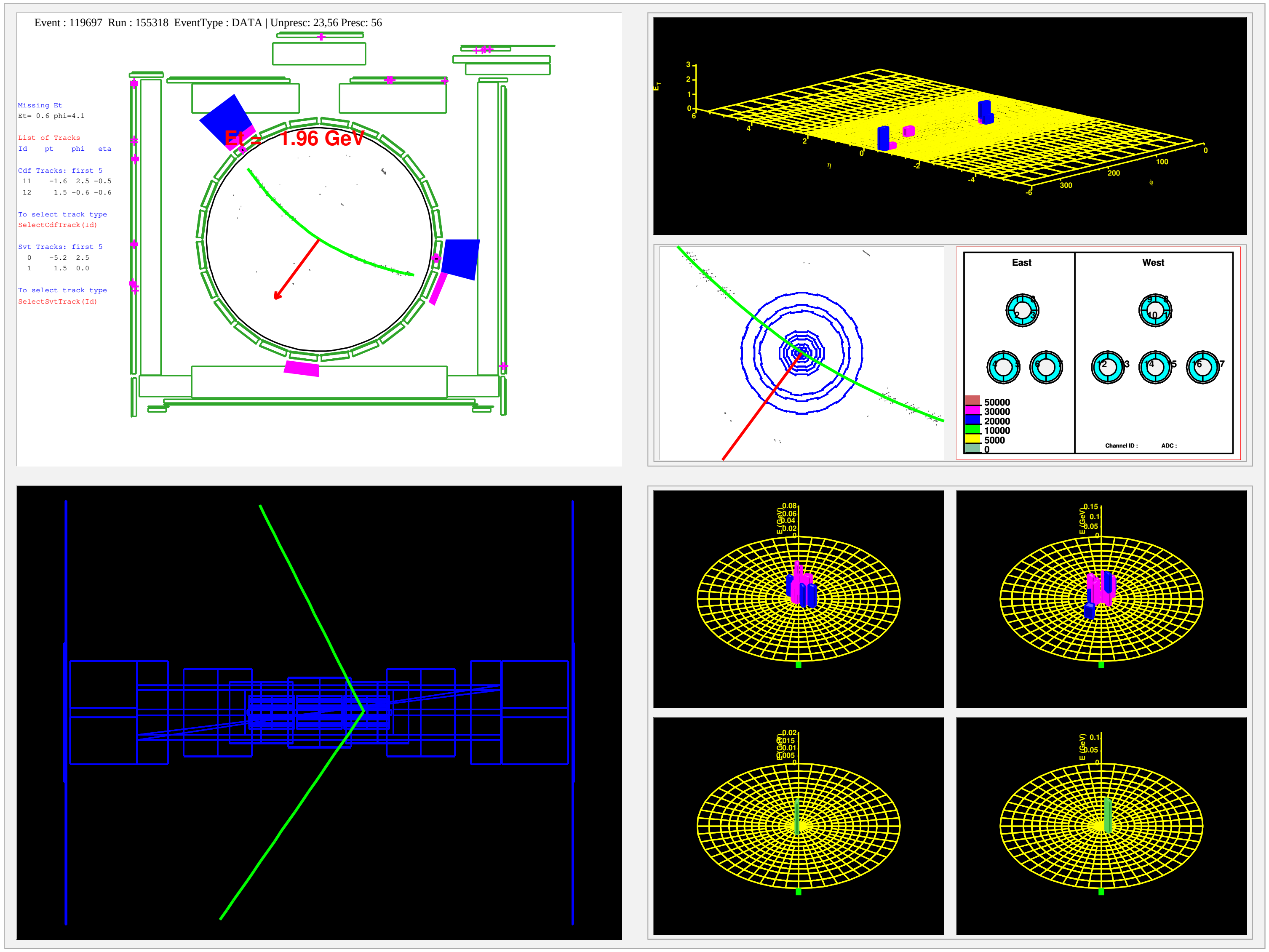
- To test prediction, search for a similar process at the Tevatron:

$$p + \bar{p} \rightarrow p + \chi_c^0 + \bar{p} \rightarrow p + J/\psi\gamma + \bar{p}$$

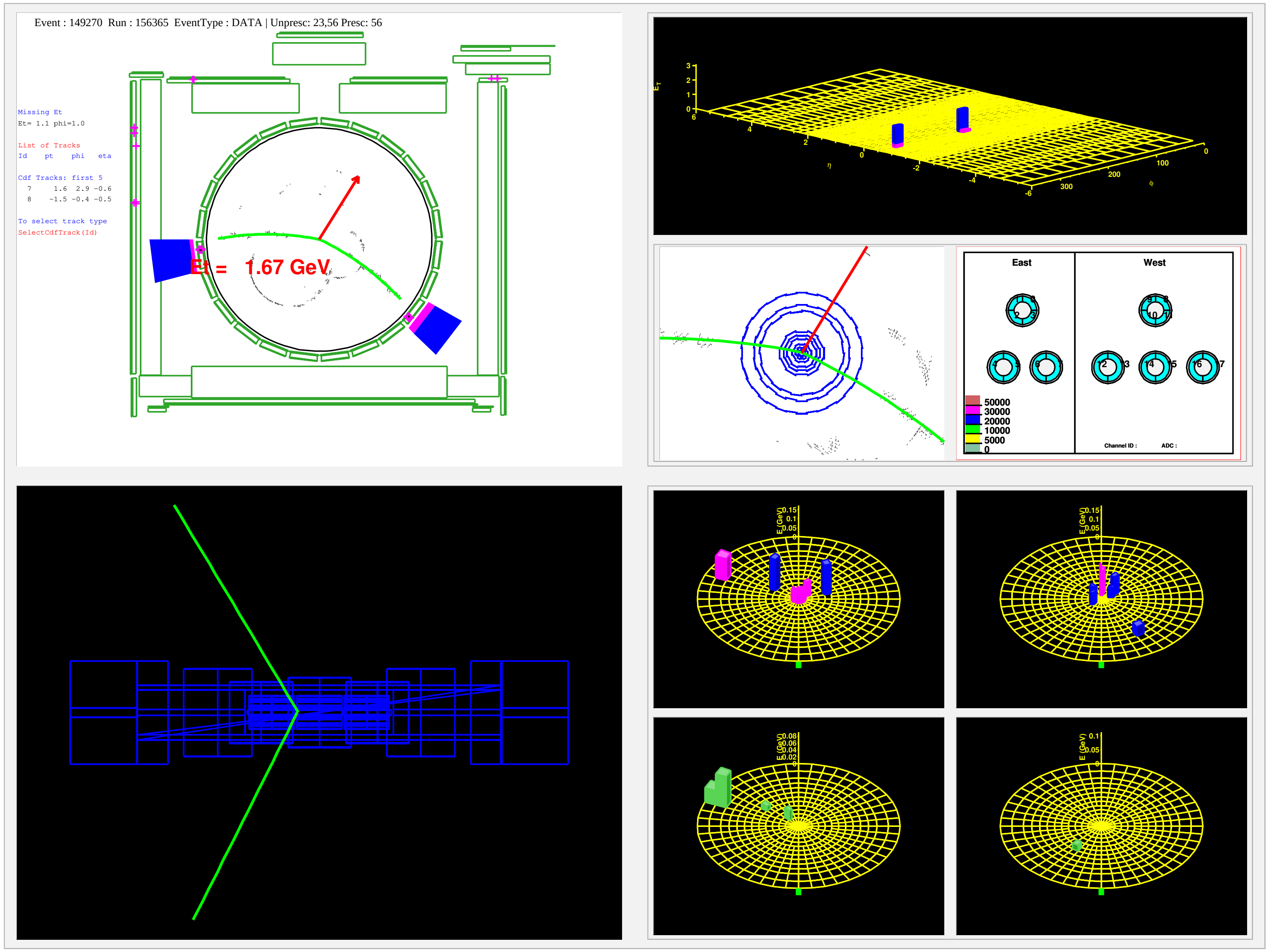


c–loop:χ_c
b–loop:χ_b
t–loop: H

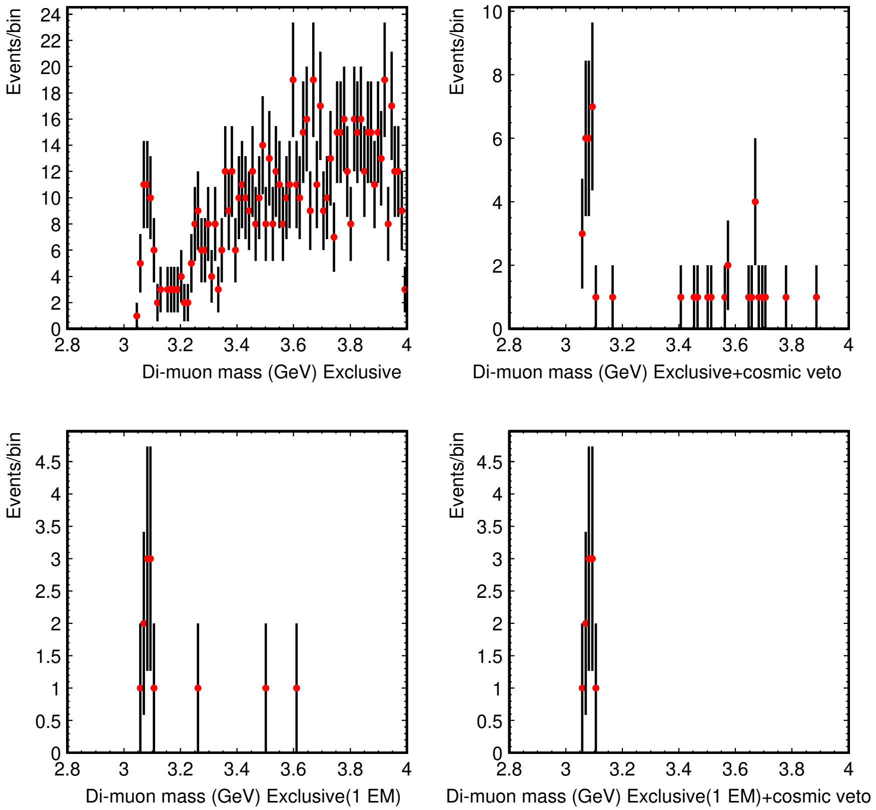
Exclusive χ_c candidate 1

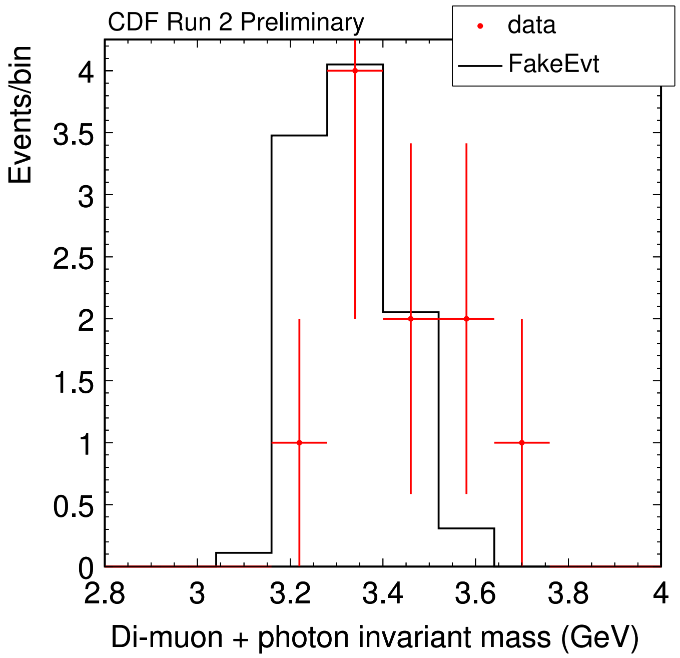


Exclusive χ_c candidate 2



Analysis of exclusive events





Exclusive χ_c candidates

Need to understand backgrounds!. IF all 10 events are signal

then: $\sigma(p\bar{p} \rightarrow p\bar{p}\mu\mu\gamma, |y| < 0.6) = 49 \pm 18(stat) \pm 39(syst)$ pb

Prediction: $\sigma =\sim 200$ pb hep-ph/0011393

Summary

Studies of heavy quark production are precision tests of NLO pQCD.

- NEW: Run II measurements of heavy flavor production:
  - Quarkonia: New measurements of the inclusive J/ψ cross-sections down to $p_T = 0$ GeV/c. Diffractive production of exclusive $\mu\mu\gamma$ candidates observed.
  - b-hadron cross-sections measured down to $p_T = 0$.
  - $D^{+,0,*}$, D_s cross-sections published.
  - Exotic Spectroscopy: X(3872) confirmed at $p\bar{p}$. CDF observes no pentaquark candidates.
- Recent theory advances in PDF fits, factorization schemes and new and improved treatments of heavy quark fragmentation.

Conclusions

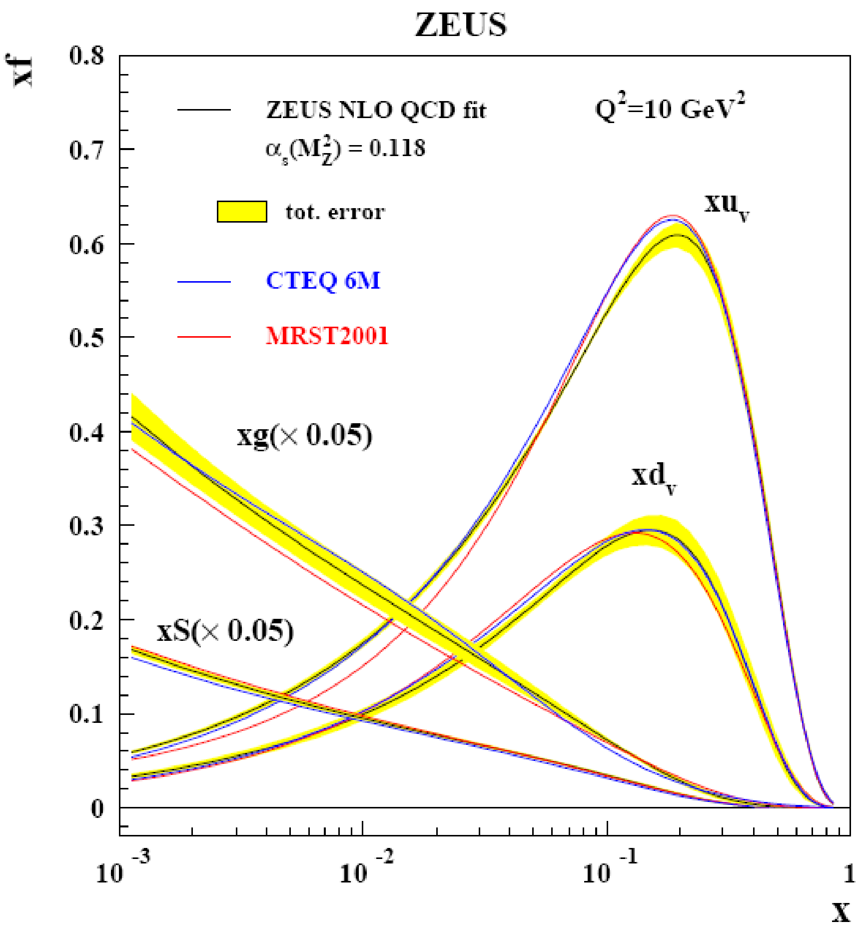
Total inclusive b-hadron cross-sections are in agreement with theoretical predictions within uncertainties.

Charm cross-sections in reasonable agreement with theory and consistent with beauty meson results.

Mysteries: Quarkonia production/polarization, X(3872), Θ

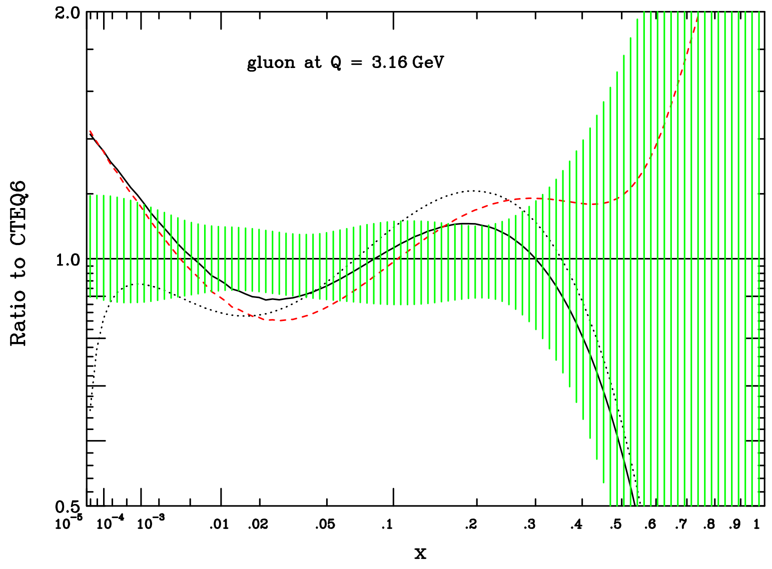
BACKUP

Parton Density Functions (PDF)



New PDFs with uncertainties extracted from fits to the data

- *The uncertainties from one PDF fit do not always cover differences with other fits:*

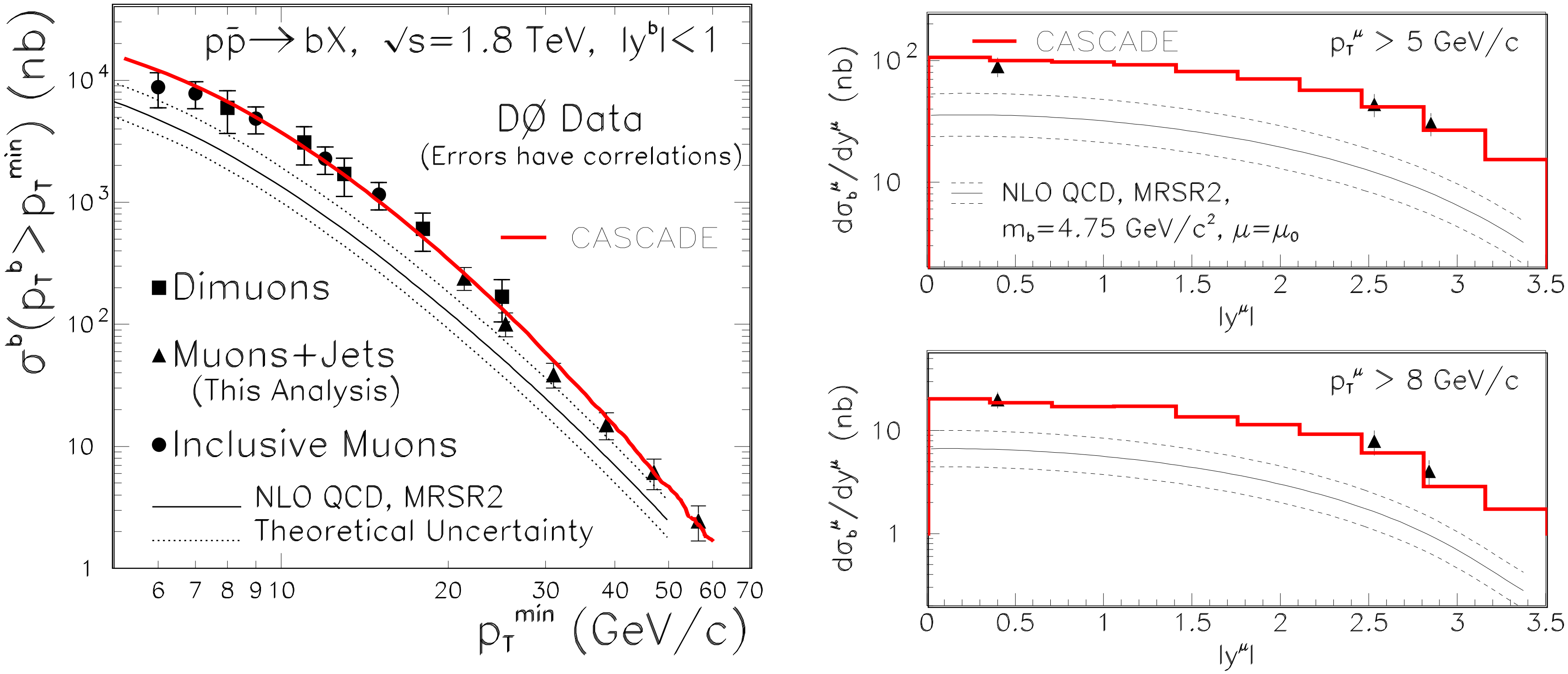


Uncertainties on gluonic function

2001: k_T Factorization Scheme

Standard PDFs are functions of x, the fraction of the momentum carried by the parton longitudinal to the hadron direction. Partons also have a small transverse momentum component:

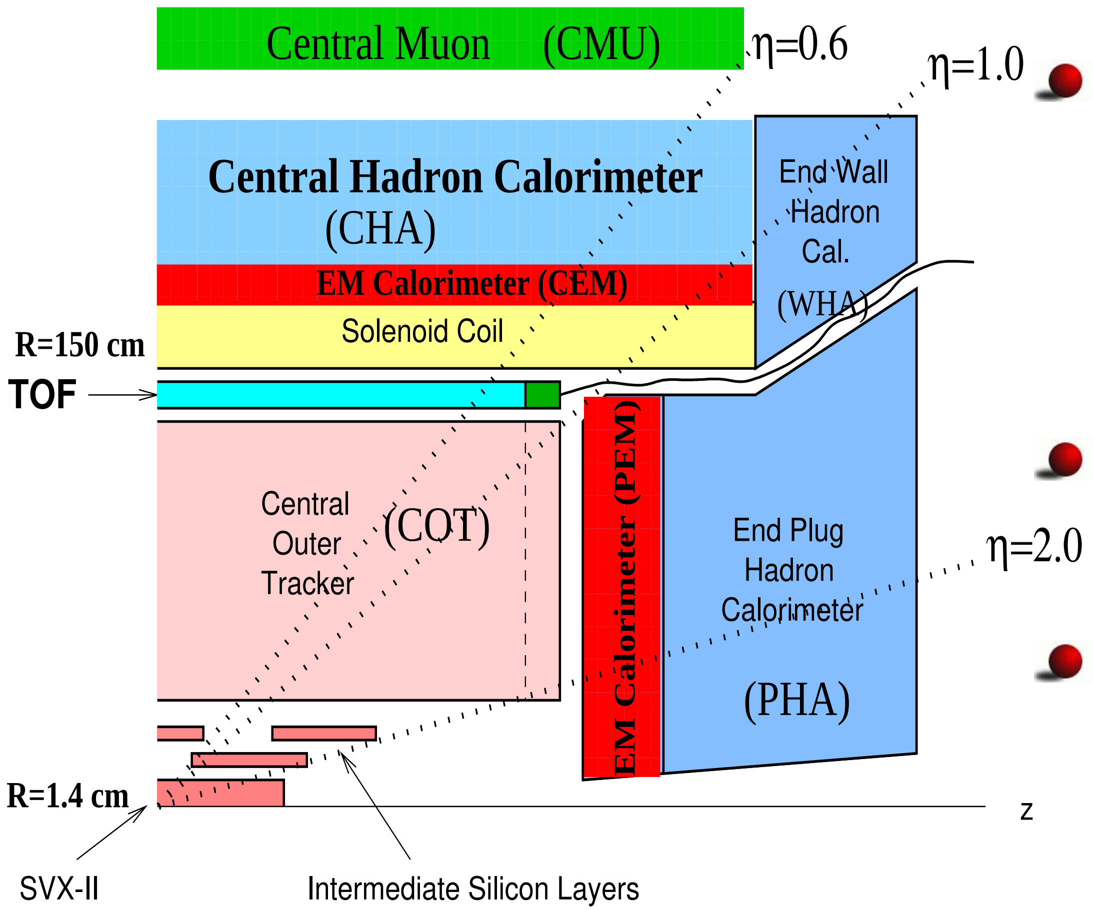
k_T factorization : $f(x) \rightarrow f(x, k_T)$, $\sigma(x, s) \rightarrow \sigma(k_T, x, s)$



H.Jung, hep-ph/0110034

CDF Run II - Overview

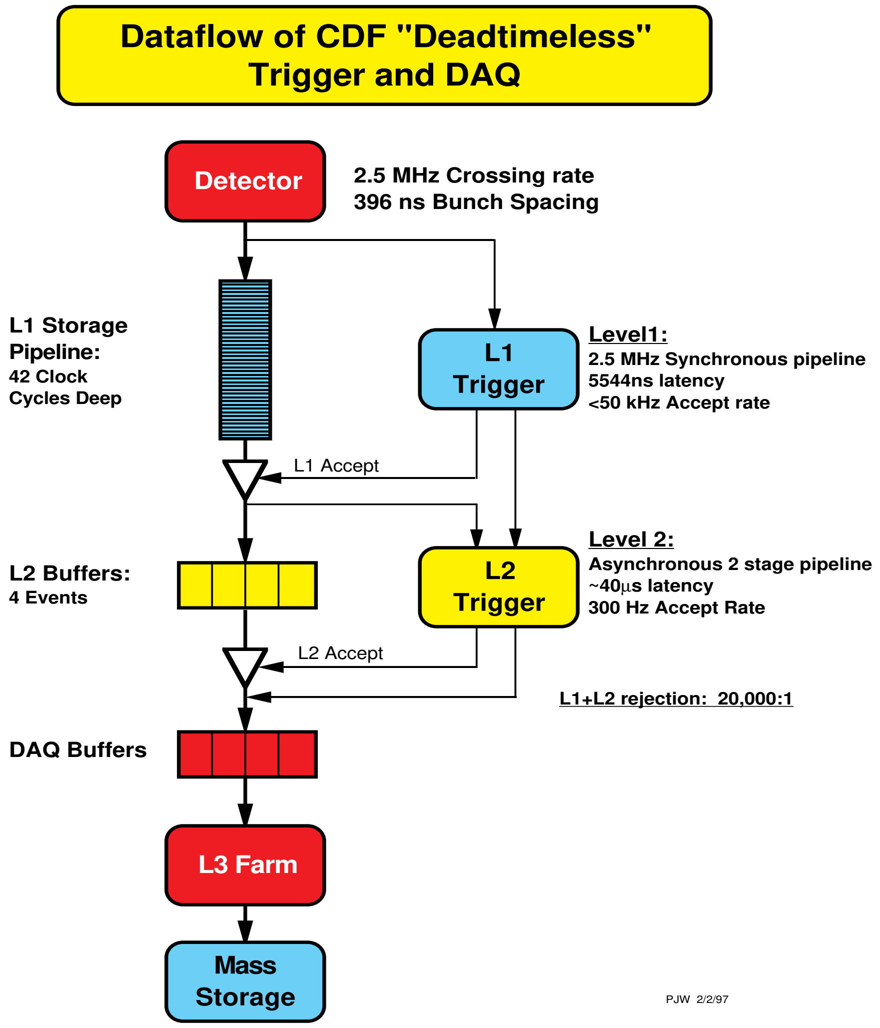
Signals: $J/\psi \to \mu\mu$, $D \to K\pi$, displaced b vertices



$$\eta = -1/2 \ln \tan \theta/2$$

- *Central Muon detector*: Prop. chambers outside central calor. $\sim 5\pi$ interaction lengths.
- 96 layer COT: $\sigma(p_t)/p_t = 0.002p_t$
- Silicon vertex detector: 8 Layers of 3-D Silicon up to $|\eta| = 2$, 700,000 readout channels, $\sigma(d_0) \sim 30\mu m$

CDF Data Flow



250 pb $^{-1}$ $\Rightarrow$ 480TB on tape

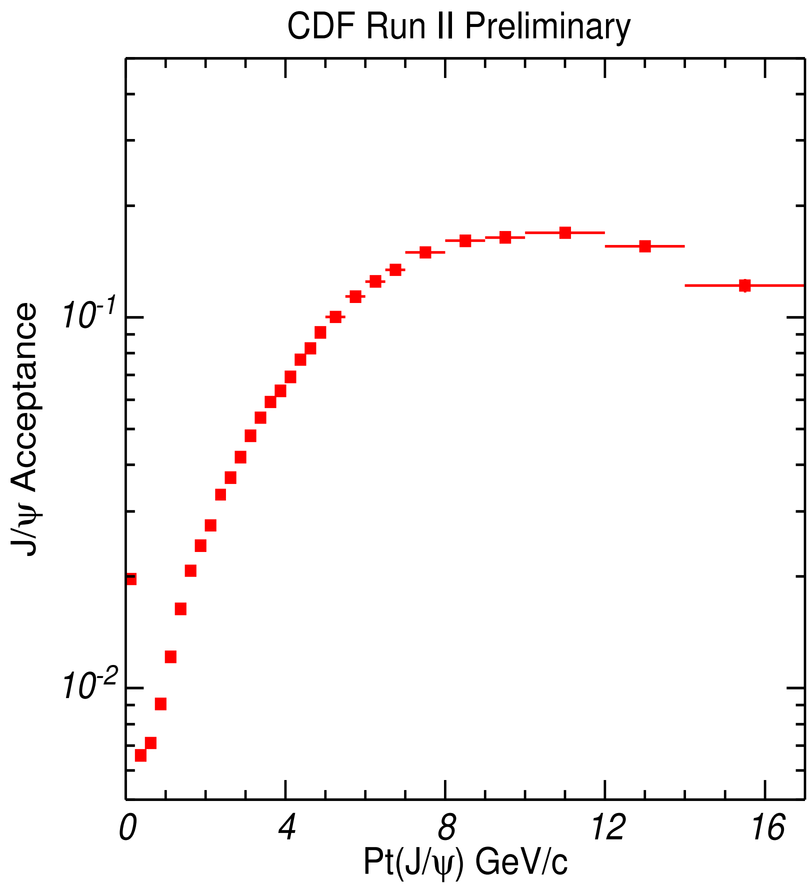
L1 latency: Pipeline depth = L1 processing time $\sim$ 5μsecs. *The SVXII detector is readout on L1 Accept*.

L2 processing time: The Silicon Vertex Trigger is in L2 $\Rightarrow$ *readout of the Silicon takes place in $\sim 15\mu$secs + $\sim 15\mu$secs SVT processing time*

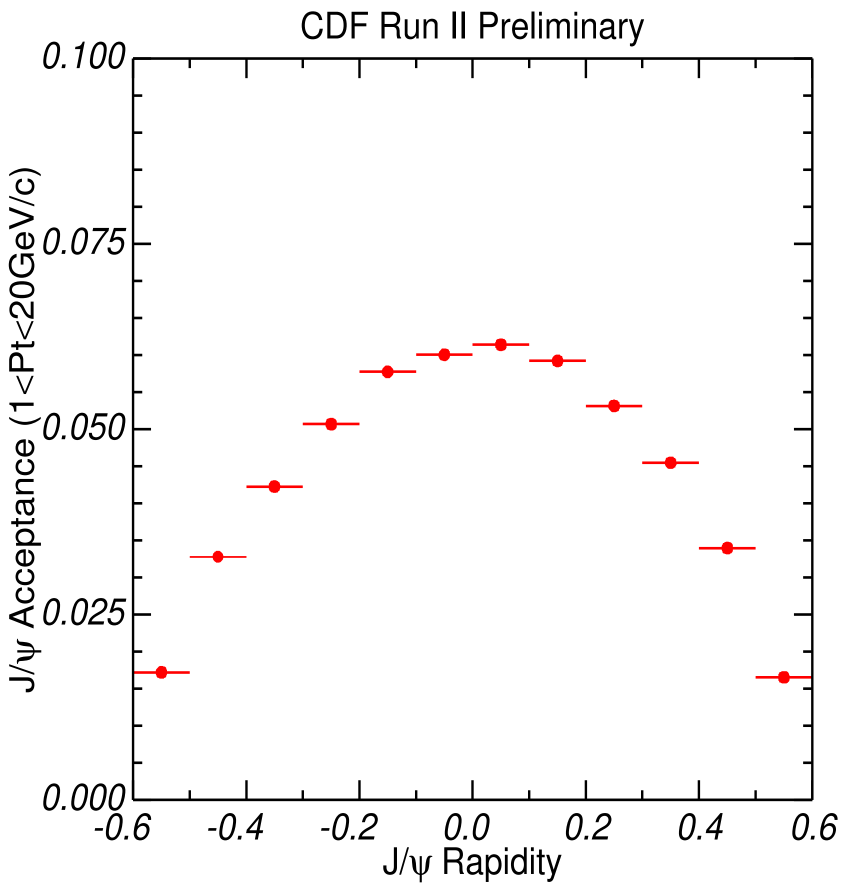
Data logging rate: sustained rate of 18MB/s (150-200 KB/event)

Detector Acceptance (CDF)

A detector simulation is used to estimate acceptance:



Transverse momentum



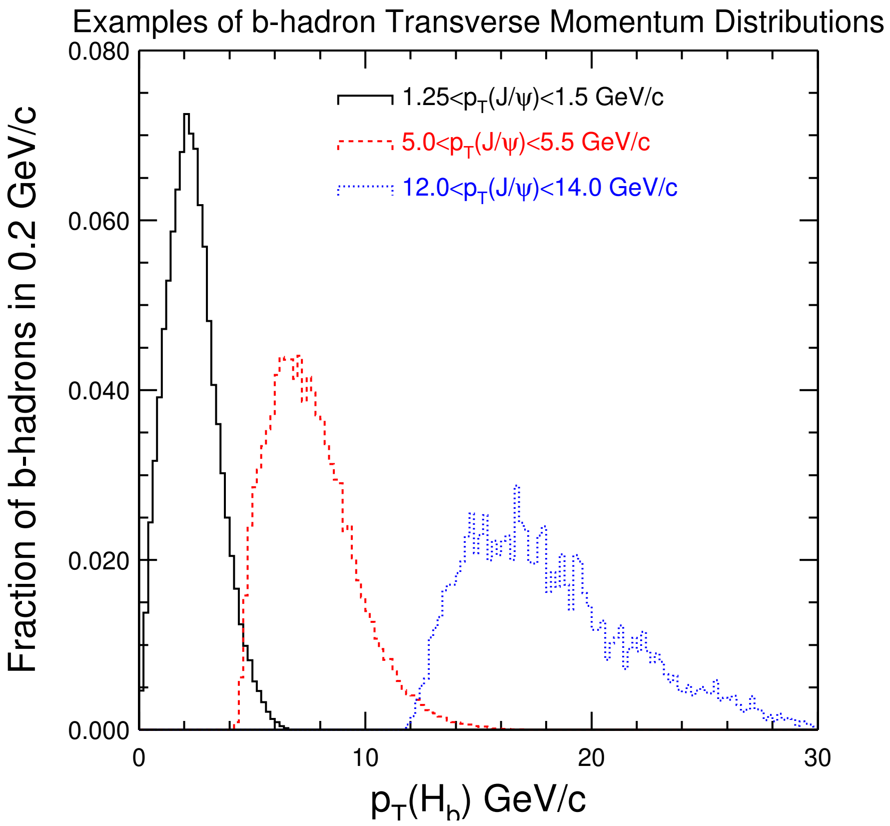
Rapidity

Algorithm to extract $d\sigma/dp_T(H_b)$

- Count the observed number of b-hadrons in a given $p_T(H_b)$ bin

$$N_i^b = \sum_{j=1}^{N} w_{ij} N_j^{J/\psi}$$

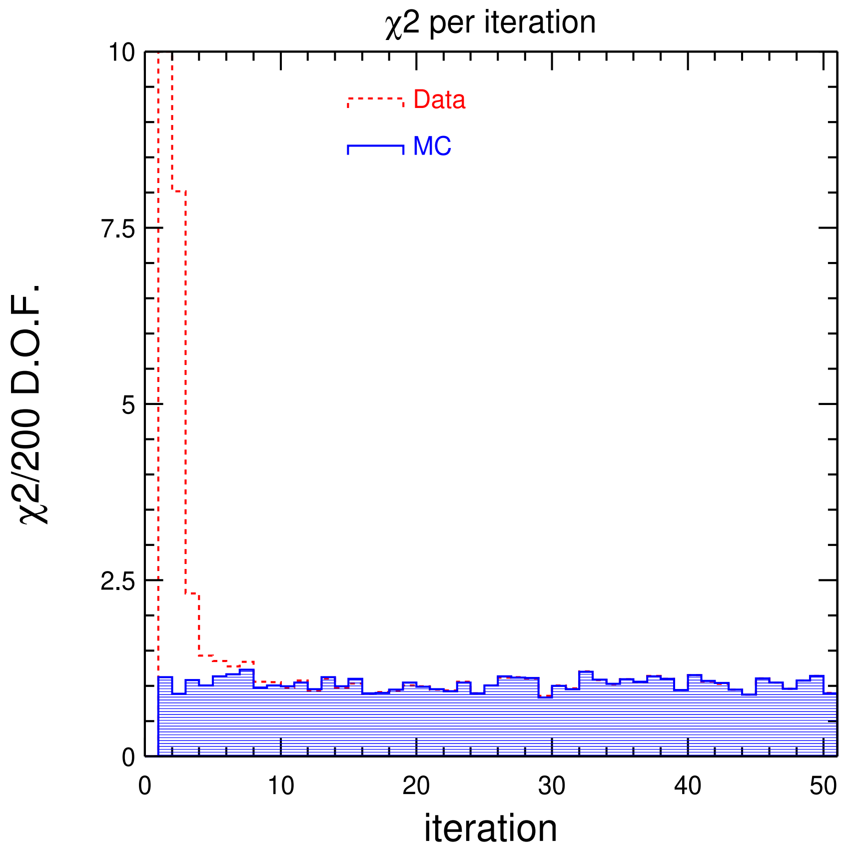
w_{ij} is the fraction of b events in the i^{th} $p_T(H_b)$ from the j^{th} $p_T(J/\psi)$ bin obtained from MC.



- Correct the observed number of b-hadrons for the kinematic acceptance

Iterating...

- *After a $d\sigma/dp_T(H_b)$ spectrum is obtained, the MC weights w_{ij} are recomputed using the new spectrum and the algorithm repeated.*
- A χ^2 test is performed on the input and output spectra until no difference is seen.

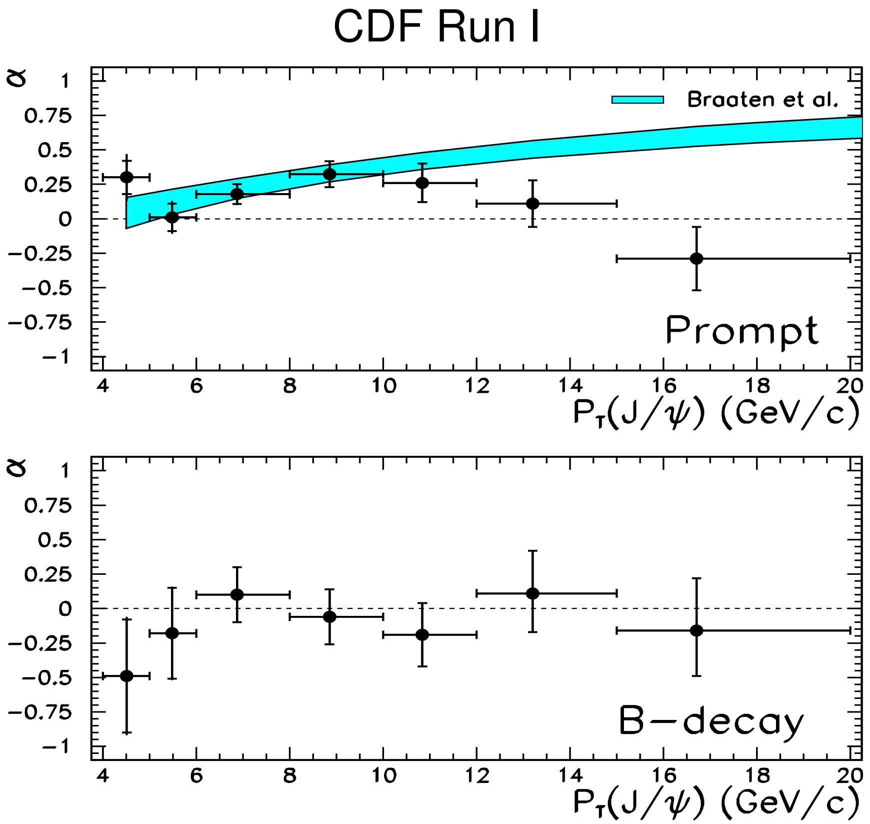


Charmonium Polarization Mystery

BUT Inclusion of color octet in NRQCD leads to a prediction of increasing transverse polarization of charmonium at high p_t.

Method: Fit the production angle, $\cos\theta*$, distribution to MC distribution which is a mixture of transverse and longitudinal polarizations. Use lifetime fit method to separate prompt and $b \to J/\psi X$

$dN/d\cos\theta^* \propto (1 + \alpha\cos^2\theta^*)$



Run II :Need more precise measurements

N.B. Accurate measurements needed to reduce systematic uncertainty on detector acceptance