Charm and Beauty Production

at the Fermilab Tevatron

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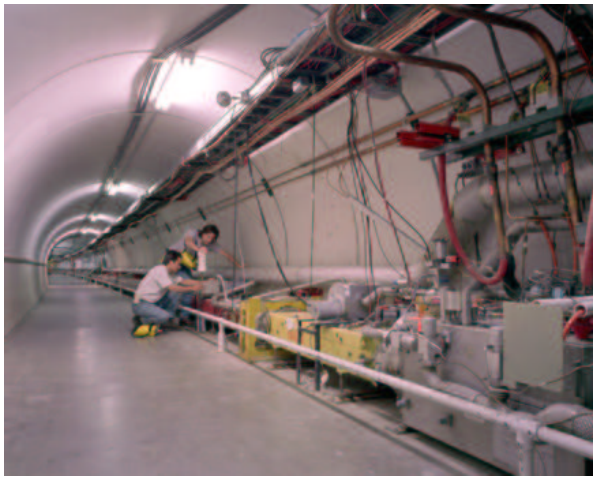
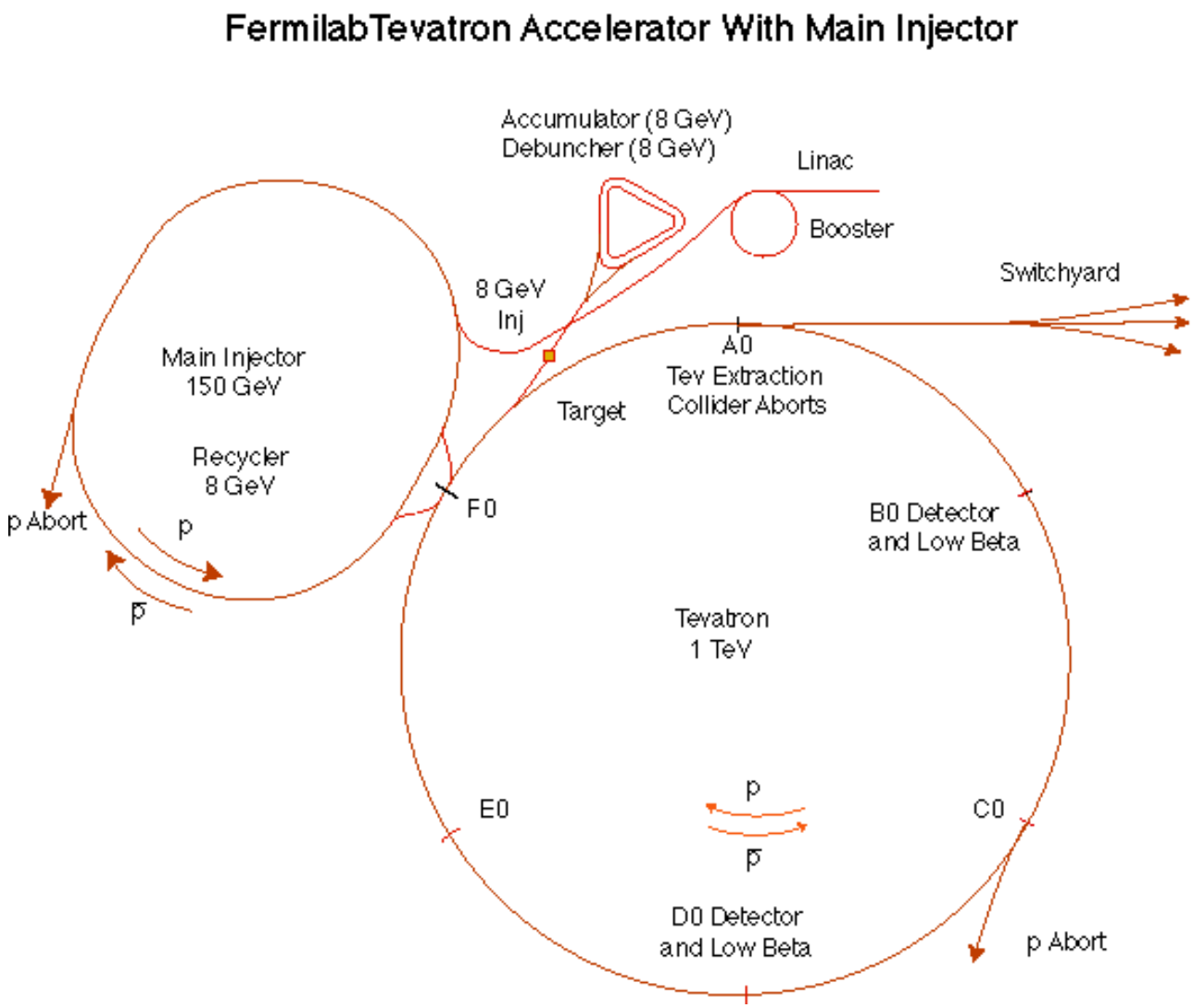
The Tevatron

The highest energy $p\bar{p}$ collider currently in operation $\sqrt{s} = 1.96$ TeV.



Tevatron Tunnel

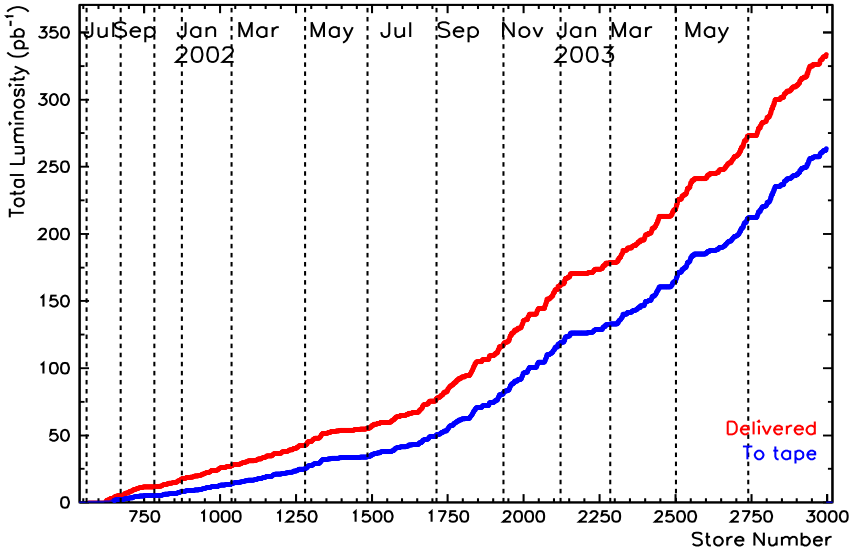
Tevatron Collider Overview

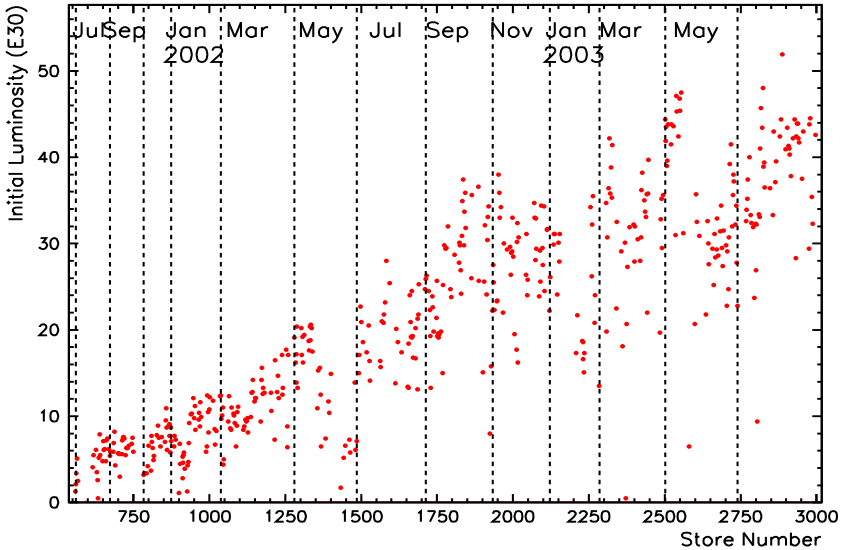


Tevatron Performance

- In 1985, Tevatron collider begins operating @$\sqrt{s} = 1.6$ TeV
- Run I of the Tevatron collected collider data at $\sqrt{s} = 1.8$ TeV from 1992-1995. ~ 109 pb $^{-1}$ of data was collected by the 2 collider detectors with $\mathcal{L}^{typical} = 1.6 \times 10^{31} \mathrm{cm}^{-2} \mathrm{s}^{-1}$

Run II : Summer 2001 - present. 2.5X more data already!

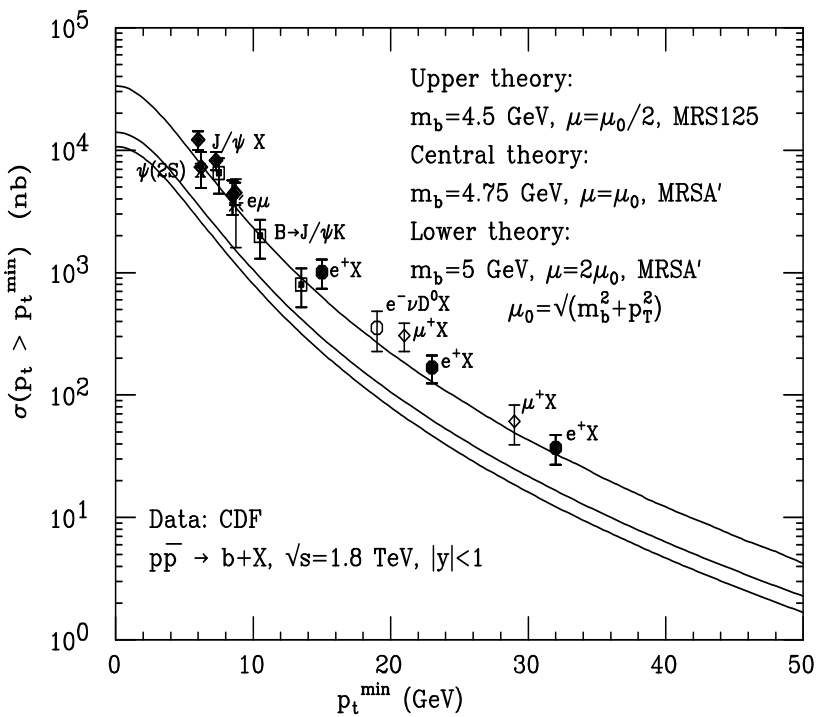




Motivation: Inclusive b x-sections

- In Run I only a small portion of the b hadron inclusive cross-section, $p_T > 6.0$ GeV/c, was measured.

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



- *Initially, b production cross-sections did not agree with NLO QCD calculations with default parameters.*
- Theory and data could be forced to agree by using extreme values of renormalization and factorization scales.

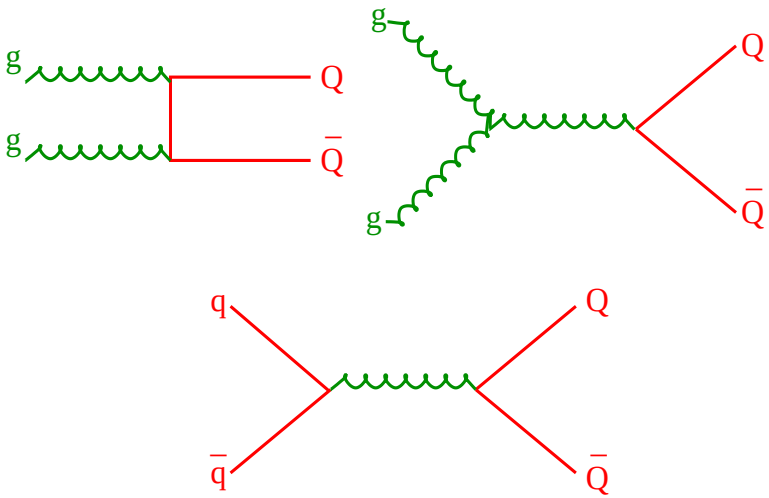
Is this a *shape* or *normalization* problem? What about *charm*?

Outline

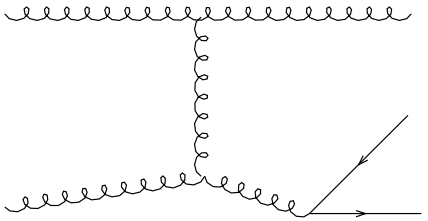
- Overview of the theoretical basis of heavy quark production cross-sections in $p\bar{p}$ collisions.
- Description of the Run II CDF detector at the Tevatron.
- Run II measurement of the *inclusive central* J/ψ cross-section down to $p_T = 0$.
- Run II measurement of the *inclusive central* b*-hadron* cross-section *using* $b \to J/\psi X$ down to $p_T = 0$.
- Run II measurement of the charm meson cross-sections.
- Other Run II production tit-bits: *confirmation of Belle's* $X(3870) \to J/\psi\pi\pi$.
- Quarkonia production basics.

THE THEORY

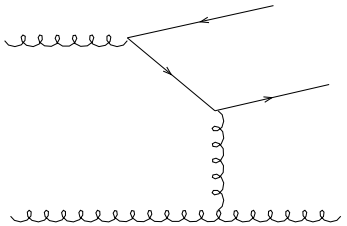
Heavy Quark Production in $p\bar{p}$



LO Heavy Quark Production



NLO: Gluon splitting

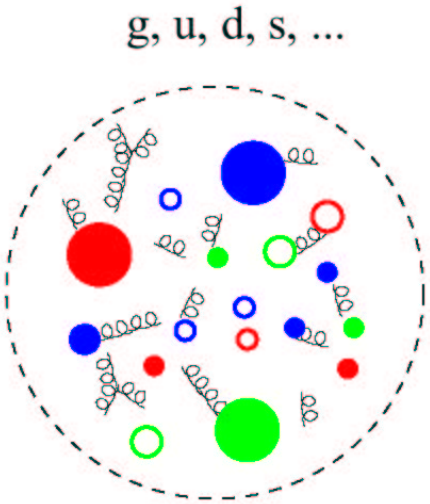


NLO: Flavour excitation

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

Modeling proton structure

- Quark production cross-sections in $p\bar{p}$ collisions depend on quark/gluon/sea distributions in the proton.



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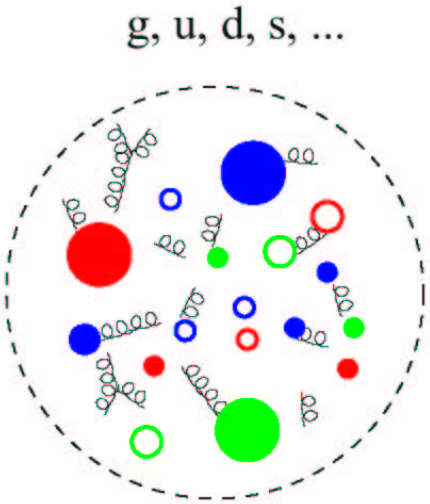
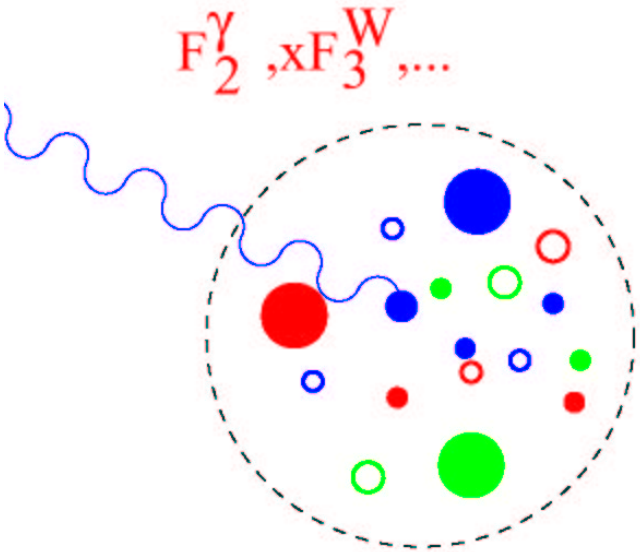


- Proton structure needs to be probed experimentally.



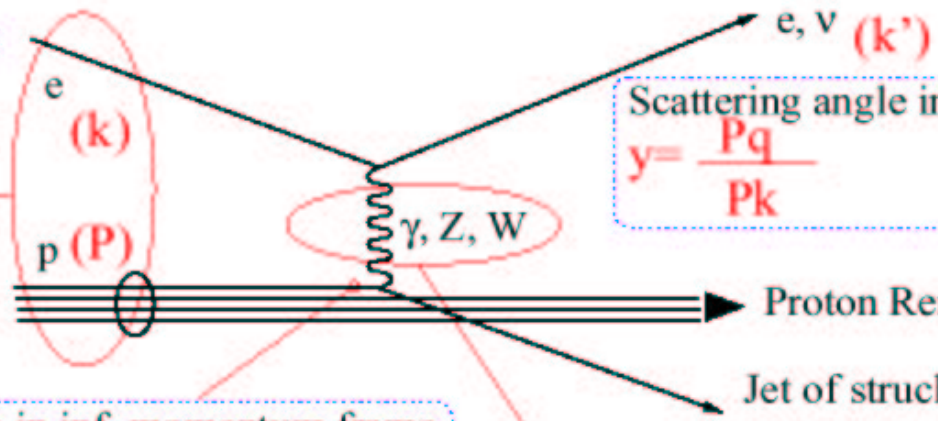
Probing proton structure

$e/\mu/\nu$ used to probe *Proton Structure:*

Reactions:

NC: e + p –> e + X
CC: e + p –> ν+ X

Lorentz invariants:



e p–c.m.–energy: $\sqrt{s}$

$s=(P+k)^2$

Scattering angle in eq–c.m. frame

$y=\frac{Pq}{Pk}$

Quark momentum in inf. momentum frame

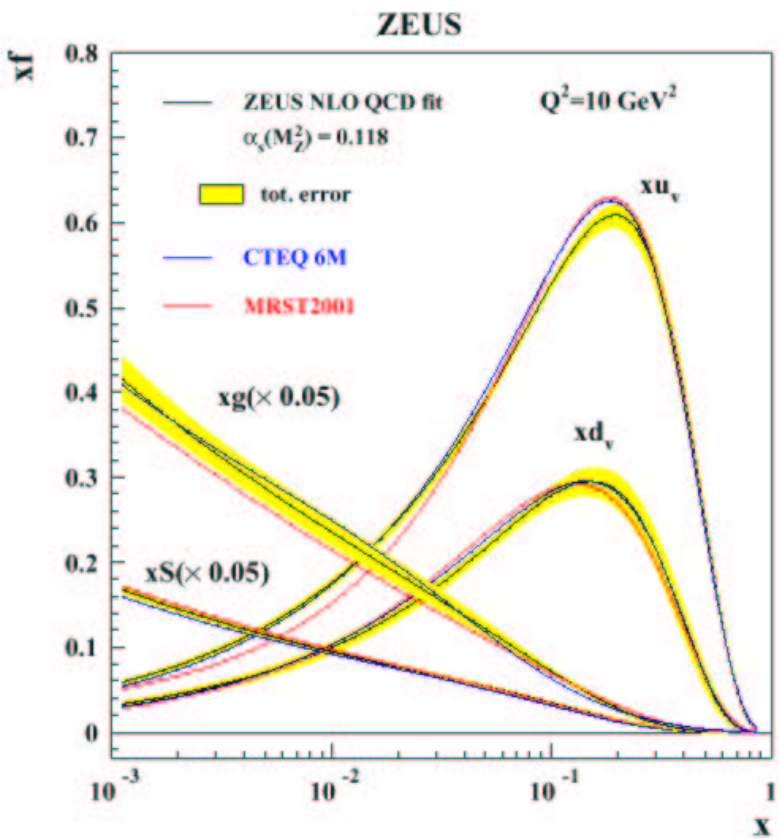
$x=\frac{Q^2}{2Pq}$

1/Momentum transfer^2 ~Resolved dist.

$Q^2=-q^2=-(k-k')^2$

Relation: $Q^2=s\,x\,y$ $(M_p << P)$

Parton Density Functions (PDF)

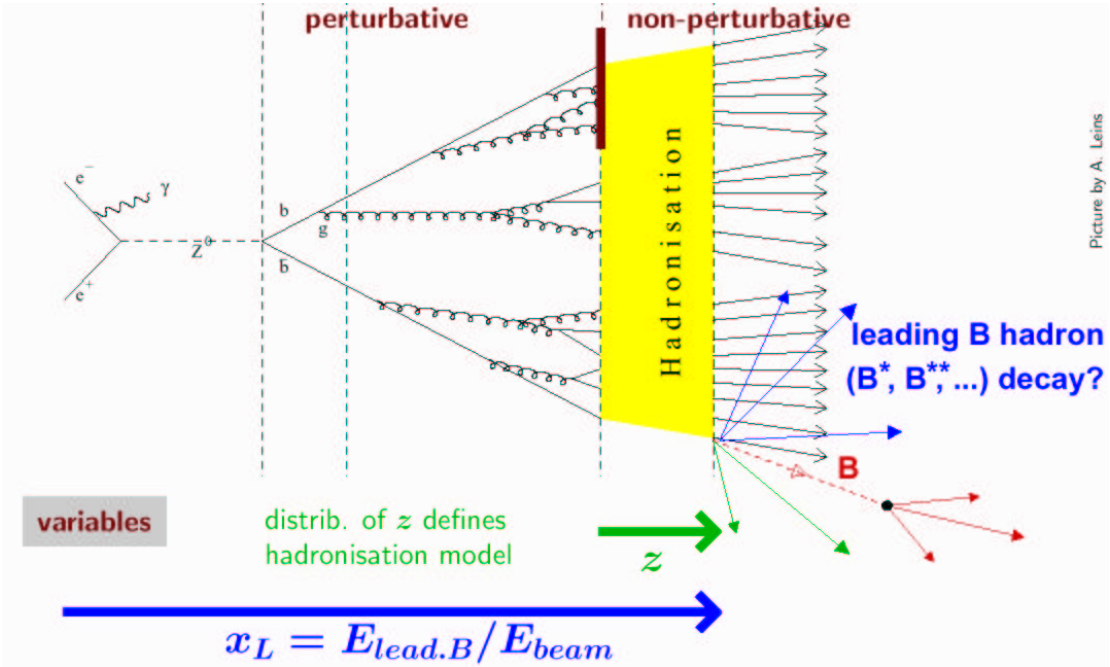


Parton densities with errors extracted from fits to the data

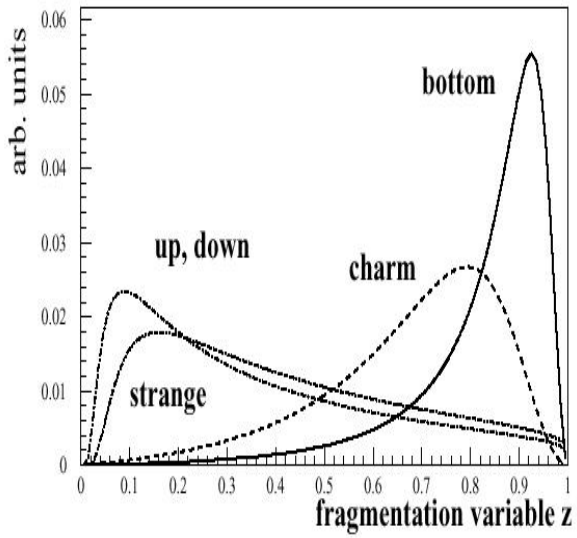
- *Proton Structure Functions* depend on the measuring process. Different experiments probe different ranges of x, different partons...etc
- *PDFs* ($xf(x, Q^2)$ are global fits to data on proton structure that are independent of the measurement process but *depend on factorization scheme chosen*.

Fragmentation Functions

- b/c - quarks fragment to hadrons, H_b.
- $$D^{meas}(x) = \int \underbrace{D^{pert}(x')}_{pQCD/MC} \otimes \underbrace{D^{non-pert}(x')}_{Parameterized} dx'$$



Peterson parameterization



$$z = \frac{(E+p_{||})_{hadron}}{(E+p)_{quark}}$$

Recent Theory Advances

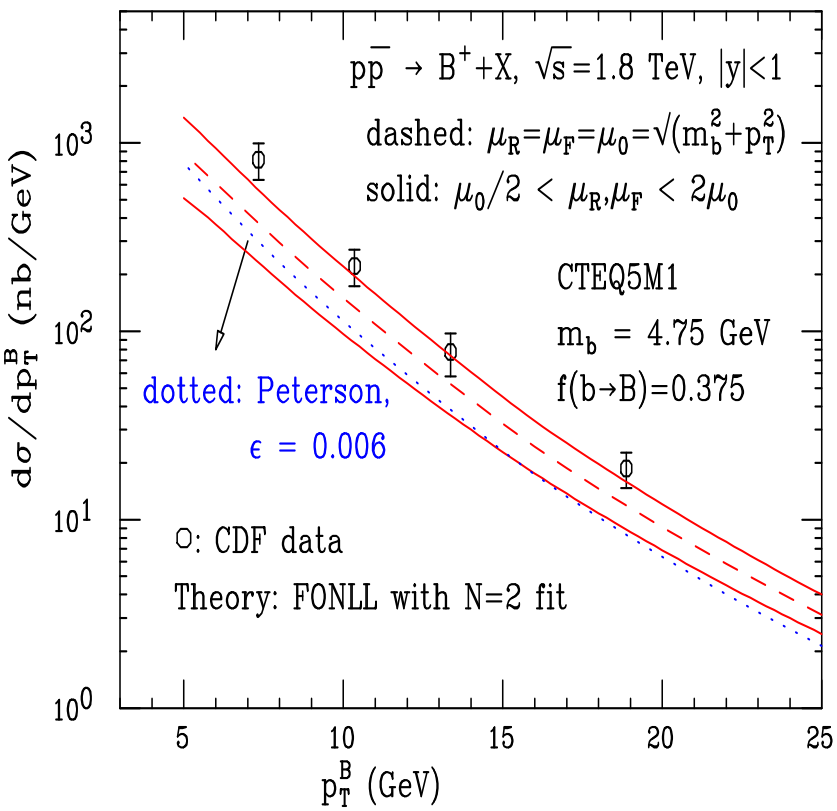
- In pQCD calculation, powers of $\alpha_s \log p_T/m_Q$ modify shape of fragmentation function. When $p_T >> m_Q$ logarithms large $\Rightarrow$ large corrections needed. Next-to-Leading-log resummations performed in 2001. *Important for predicting Tevatron heavy quark cross-section shapes at high p_T*.
- New approach: Moment analysis (Cacciari *et. al.* - 2002)
  - Transformation: $\tilde{D}(N) = \int x^{N-1} D(x) dx \rightarrow$ moment space
  - $\tilde{D}^{meas}(N) = \underbrace{\tilde{D}^{pert}(N) \times \tilde{D}^{non-pert}(N)}_{\text{A product}}$

Comparison with Run I Data

Resummation of next-to-leading logs merged with the QCD NLO using the method of moments instead of a fragmentation model $\Rightarrow$ *Better agreement with CDF Run I data on* B *meson cross-sections (for* $p_T > 5.0$ *GeV/c).*

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

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



$p_T(B^+)$ GeV/c

Theory Summary

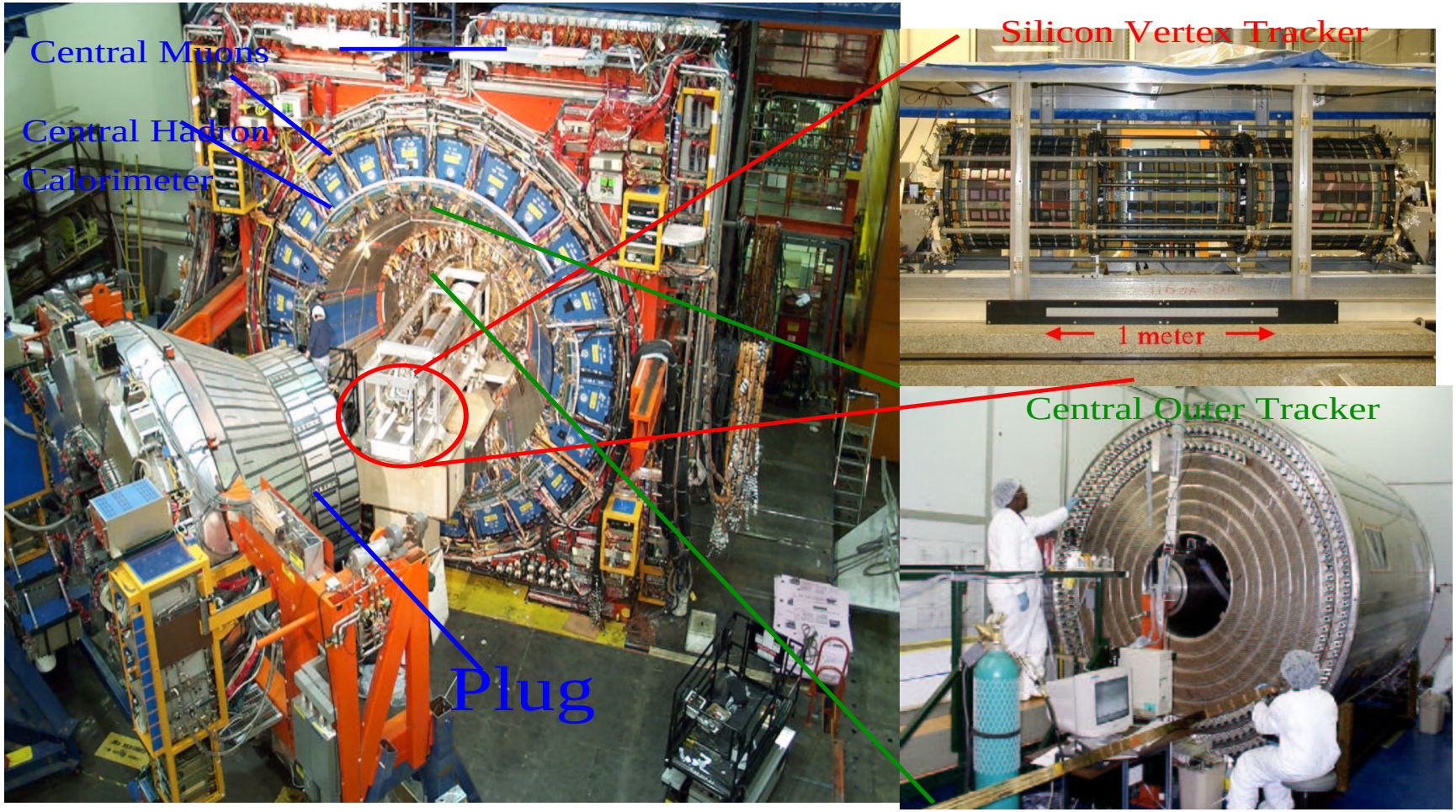
- Parton distribution functions and fragmentation functions based on fits to experimental data are needed in addition to NLO QCD calculations to determine b cross-sections.
- Phenomenological fits to the non-pertubative part of the fragmentation function must be done in a manner consistent with the QCD calculation of the perturbative part.
- Agreement with the Run I spectrum for $p_T > 5.0$ GeV/c has improved mainly due to advances in the theoretical modeling of the b fragmentation.

Total cross-sections do not depend on the fragmentation model! = powerful experimental test.

THE DETECTOR

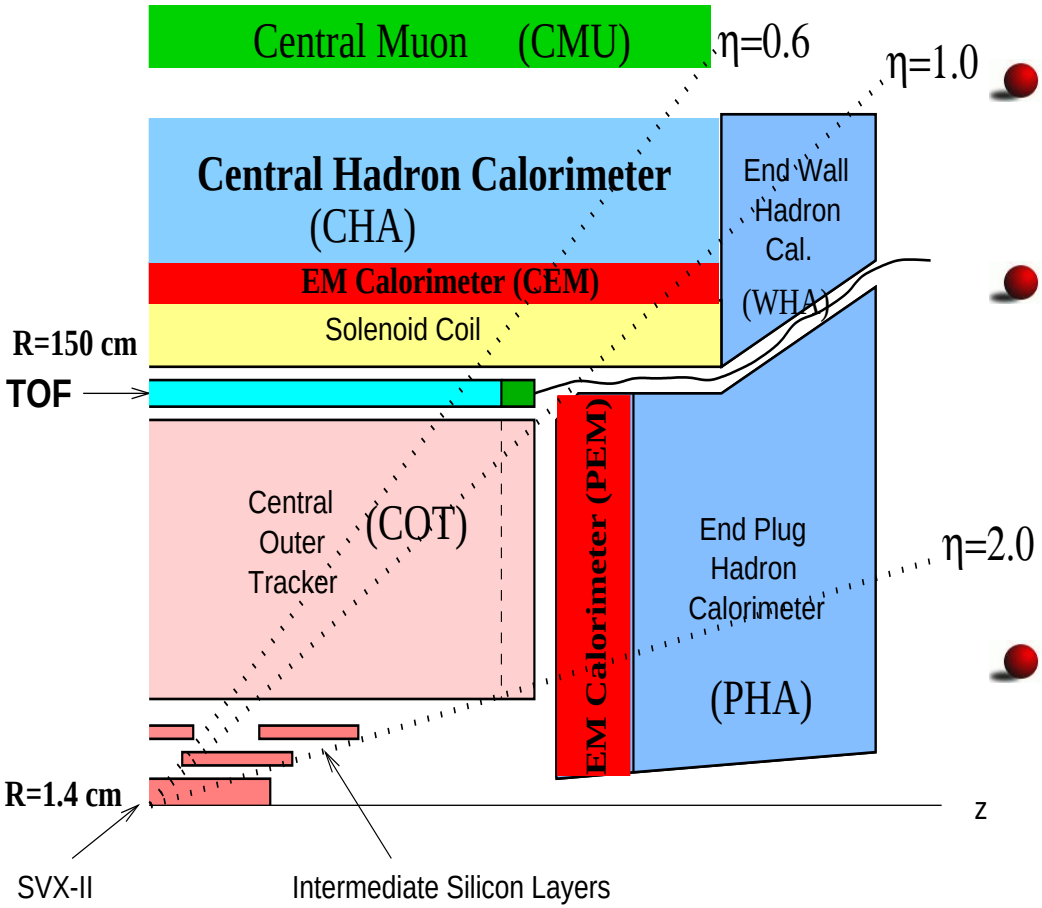
The Collider Detector at Fermilab

Run II: 788 collaborators, 62 institutions, 12 countries



CDF Run II - Overview

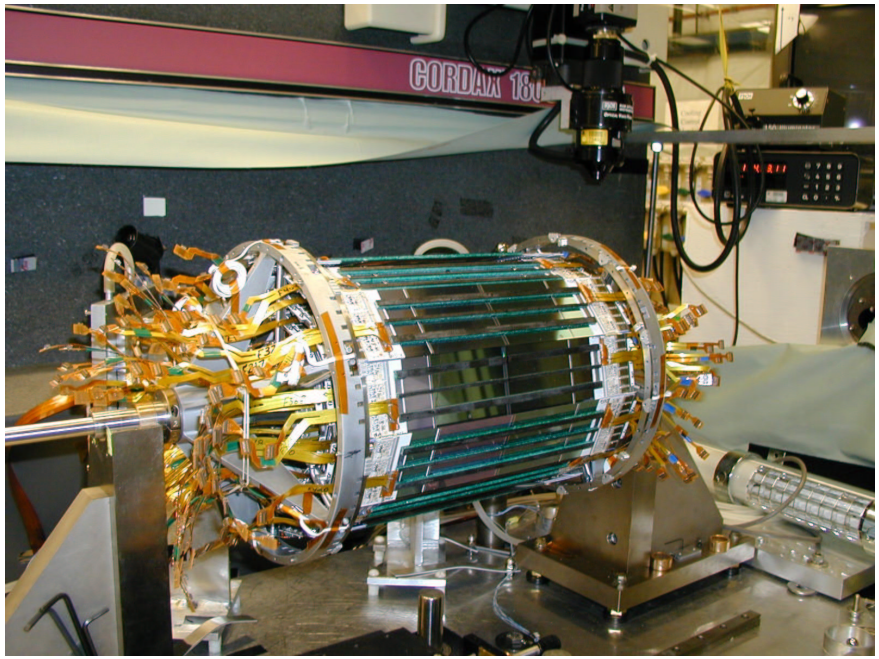
Signals: $J/\psi \rightarrow \mu\mu$, $D \rightarrow K\pi$, displaced b vertices

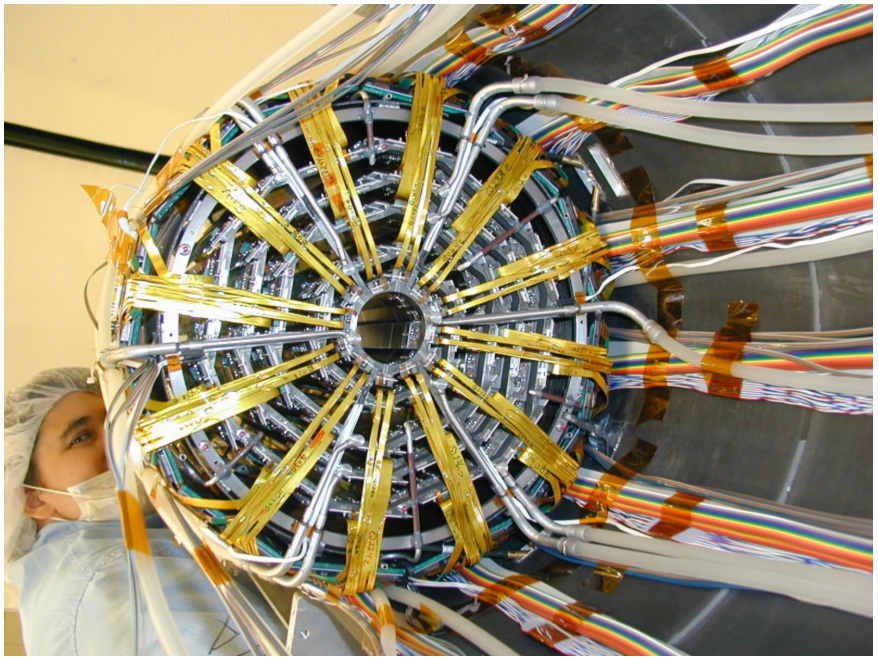


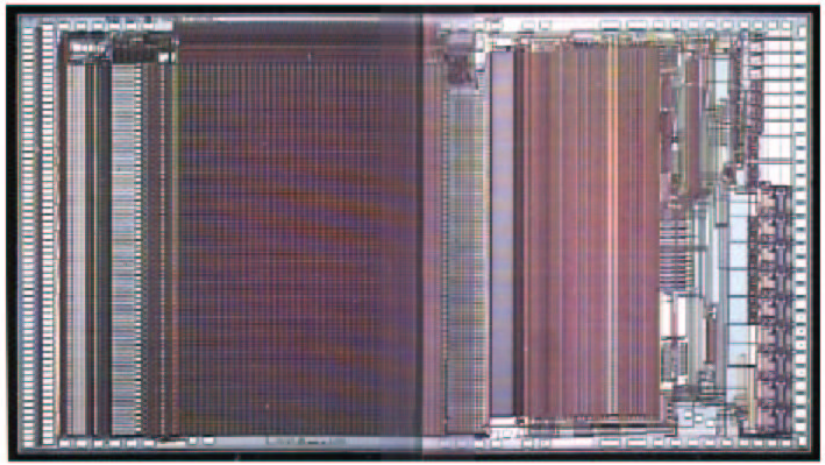
$$\eta = -1/2 \ln \tan \theta/2$$

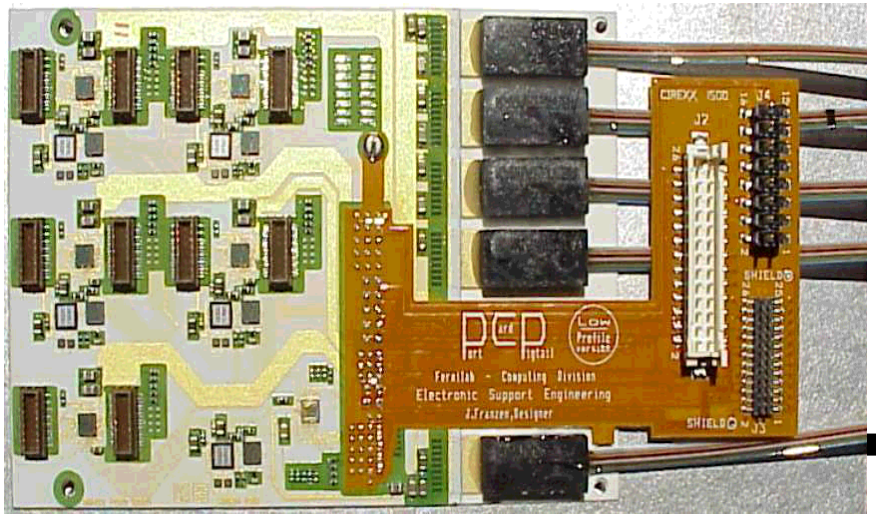
- 96 layer COT: $\sigma(p_t)/p_t = 0.003 p_t$
- Silicon vertex detector: 8 Layers of 3-D Silicon up to $|\eta| = 2$, 700,000 readout channels, $\sigma(d_0) \sim 20\mu m$
- *Central Muon detector*: Prop. counters outside central calor. 5.5 π interaction lengths.

The Silicon Vertex Detector

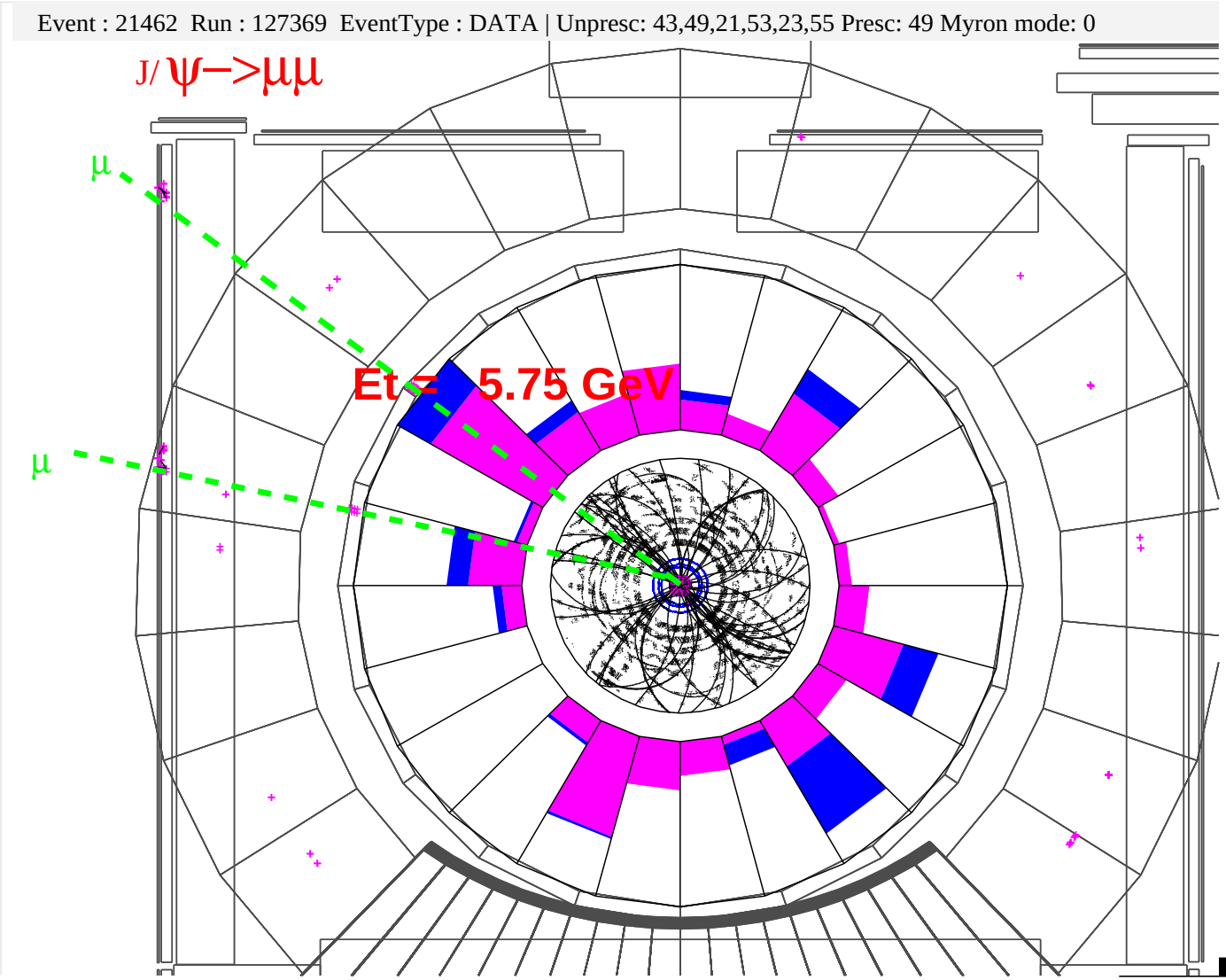




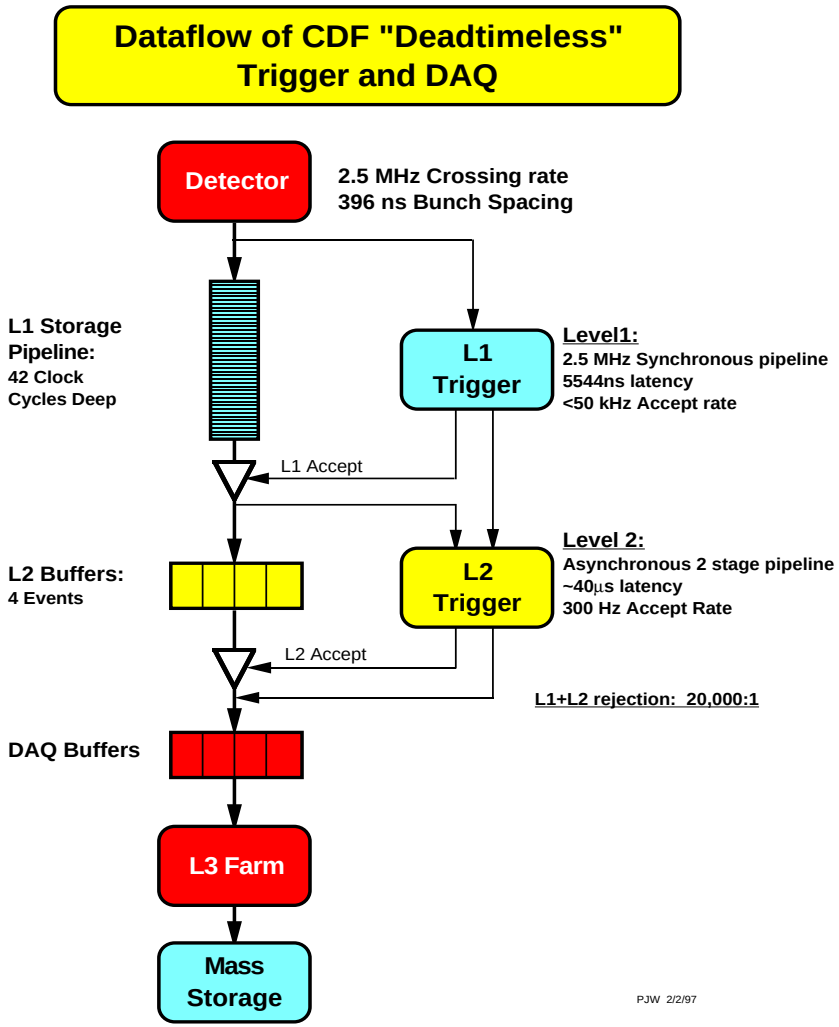




Event Snapshot - $J/\psi \rightarrow \mu\mu$



CDF Data Flow



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

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

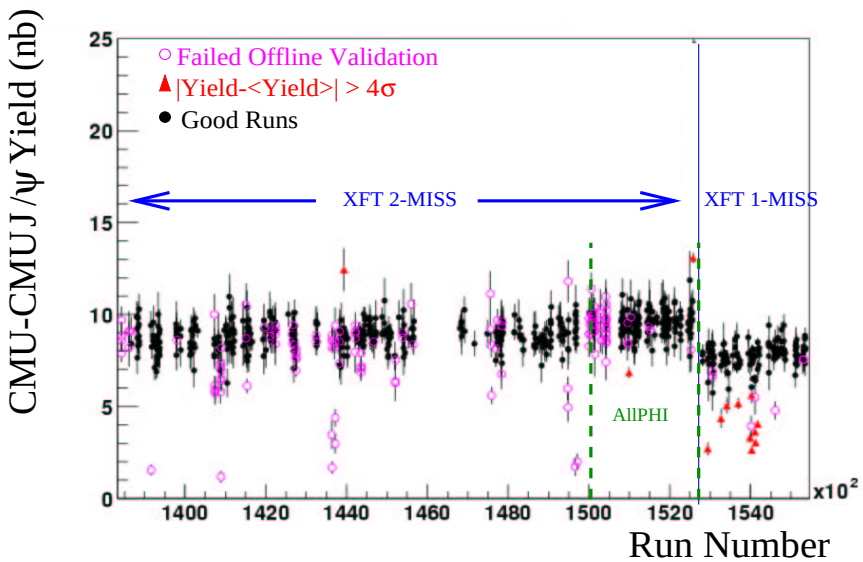
L2 processing time: The Silicon Vertex Trigger is in L2 $\Rightarrow$ *readout of the Silicon takes place in* $\sim 15\mu$*secs* + $\sim 15\mu$*secs SVT processing time*

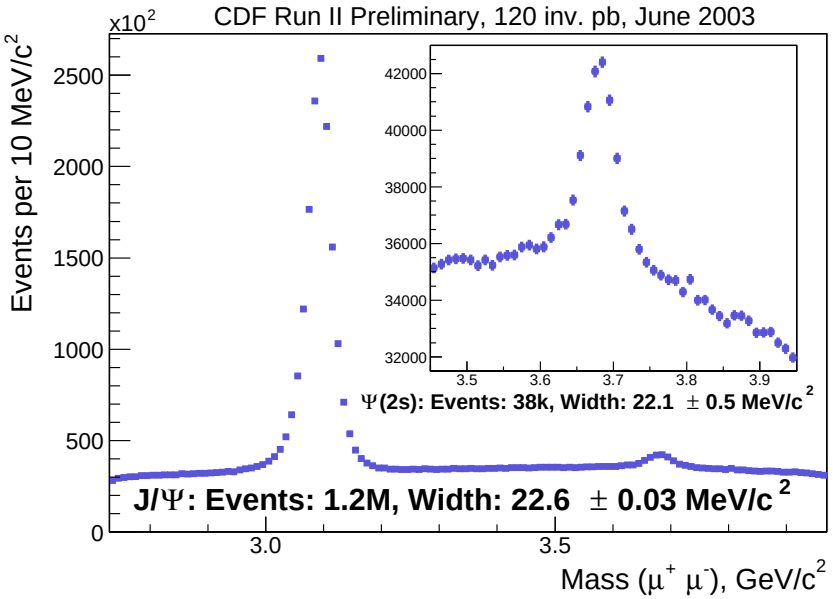
Data logging rate: sustained rate of 18MB/s

RUN II MEASUREMENT OF THE J/ψ and b-hadron inclusive cross-sections

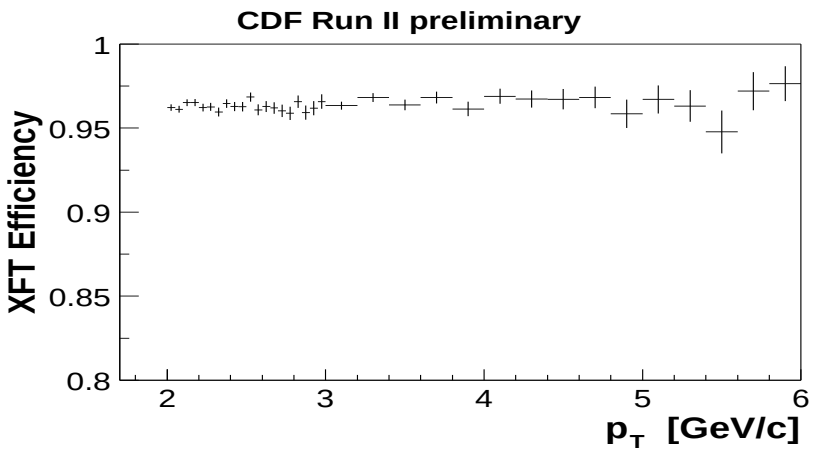
L1 Muon triggers (CDF)

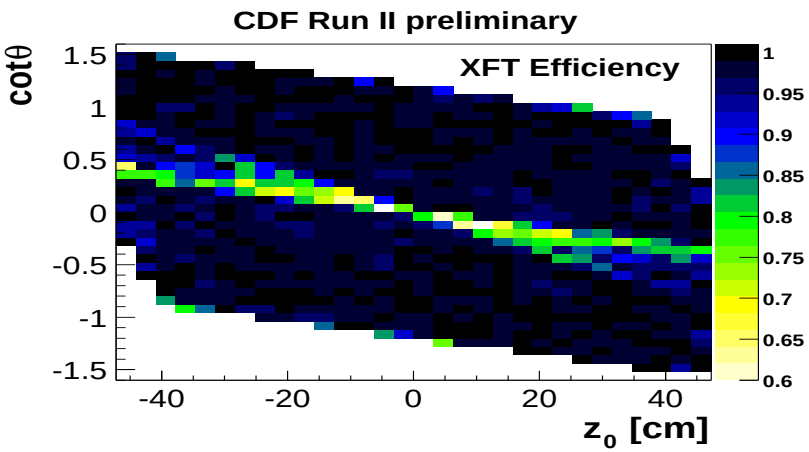
- Tracks are reconstructed in the COT by the Level 1 Trigger eXtra Fast Tracker (XFT). A match is made to hits in the Central Muon Chambers.
- *lower* p_t *reach:* $p_t(\mu) > 1.5(|\eta| < 0.6), 2.0(0.6 < |\eta| < 1.0)$ $\rightarrow p_t(J\psi) = 0$ *GeV/c* $\rightarrow$ TOTAL cross-sections in $|y| < 0.6$.





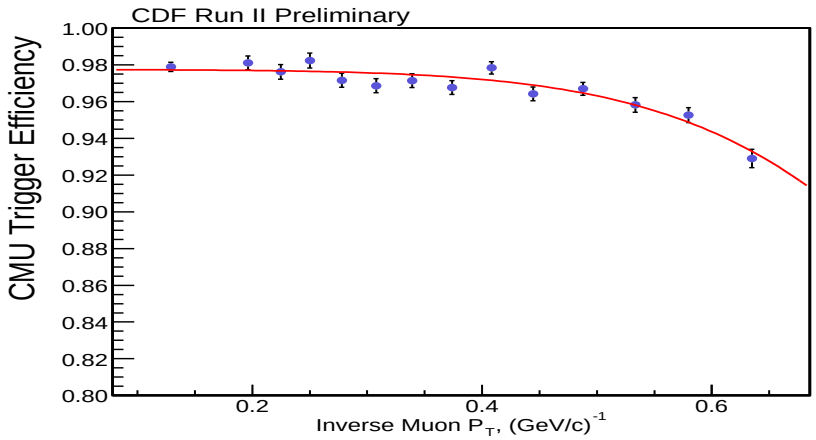
L1 Muon Trigger performance

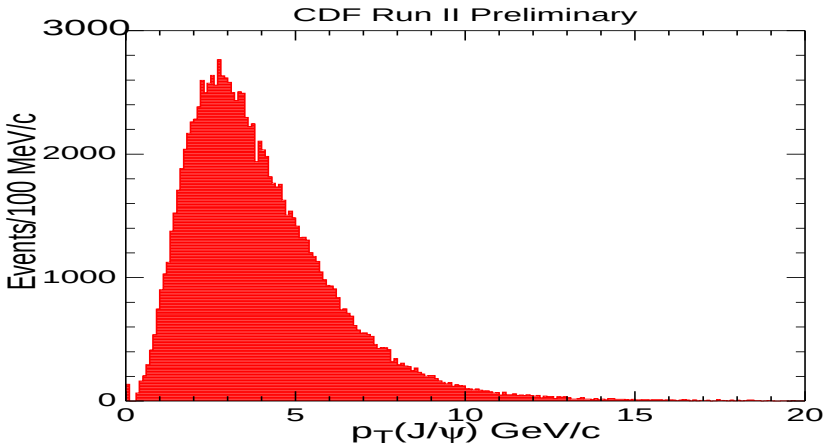




L1 track trigger (XFT) efficiency.

Inefficient near center of wire planes



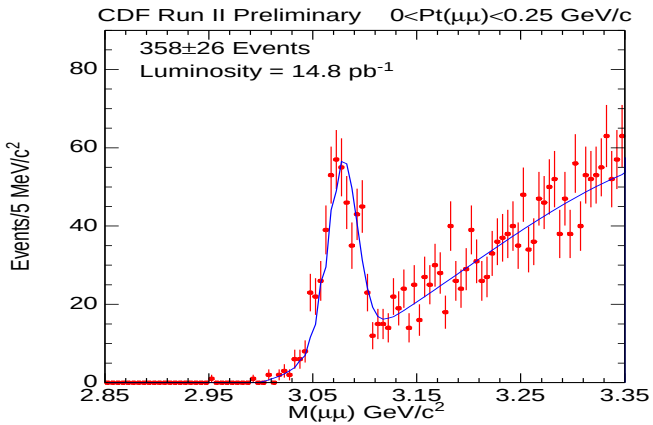


L1 μ trigger eff.

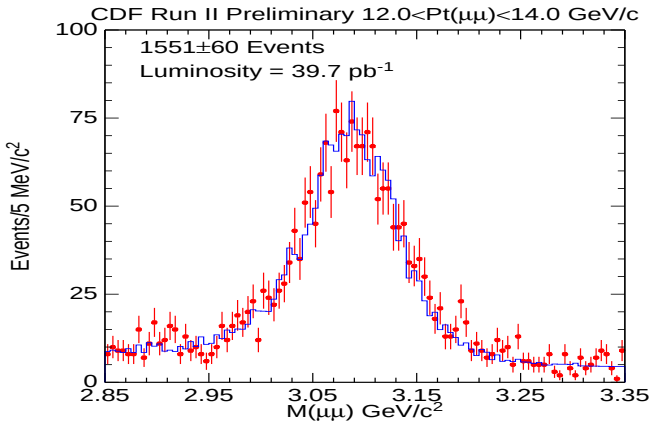
J/ψ momentum spectrum

J/ψ Reconstruction - CDF

Invariant Mass Distributions

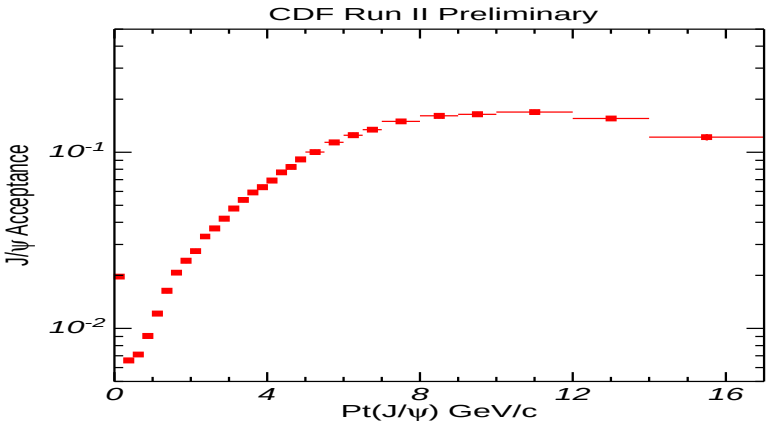


$0 < p_T(J/\psi) < 0.25 GeV/c$

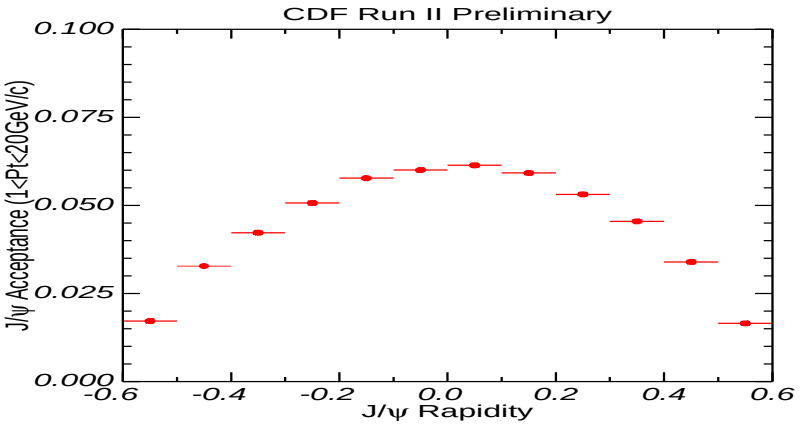


$12 < p_T(J/\psi) < 14 GeV/c$

Detector acceptance (MC)



Transverse momentum

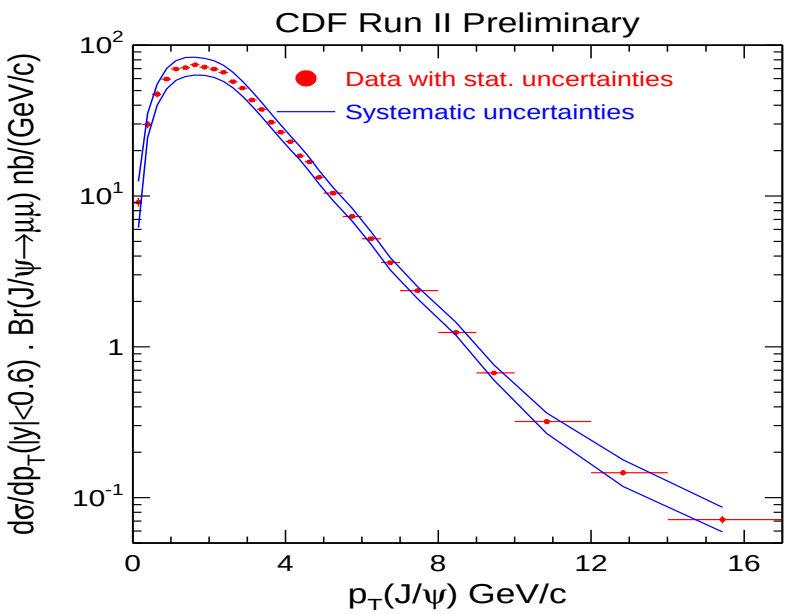


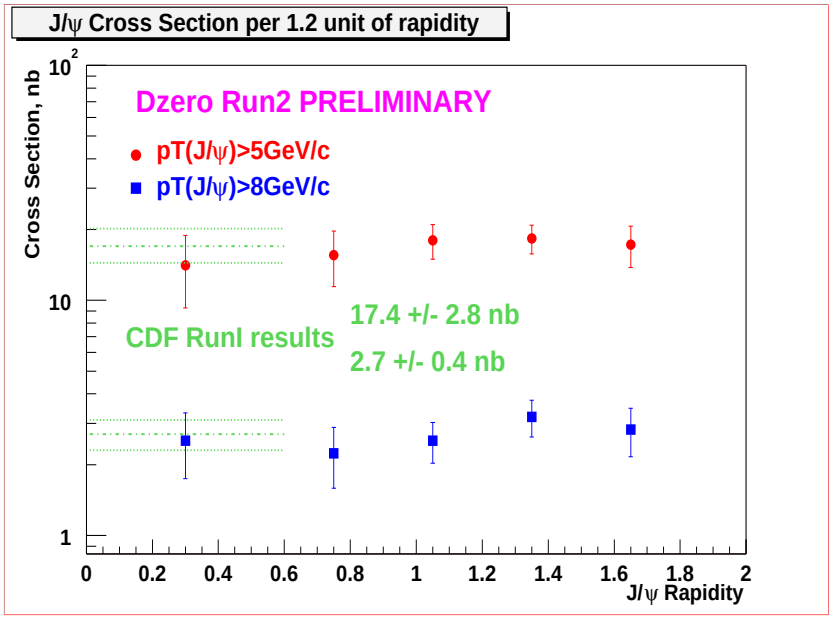
Rapidity

J/ψ Cross-sections - Run II

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

$\sigma(p\bar{p} \rightarrow J/\psi X, |y| < 0.6)$ vs $p_T(J/\psi)$ $\quad$ $\sigma(p\bar{p} \rightarrow J/\psi X, p_T > 5,8GeV/c)$ vs $y(J/\psi)$

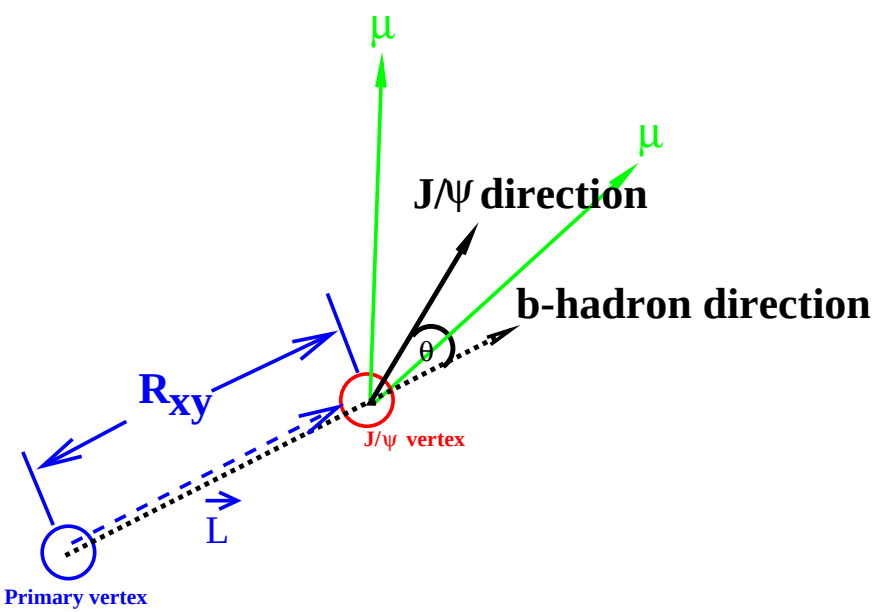




$$\sigma(p\bar{p} \rightarrow J/\psi X, \mid y(J/\psi) \mid < 0.6) = 4.08 \pm 0.02(stat)^{+0.60}_{-0.48}(syst)\ \mu\text{b}$$

Separate $H_b \rightarrow J/\psi X$ 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 $\psi(2S) \rightarrow J/\psi(1S)\pi^+\pi^-$
  - Decays of b-hadrons such as $B \rightarrow J/\psi X$



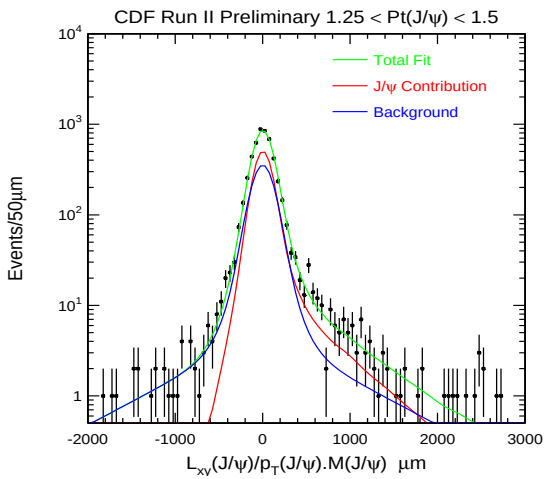
- b-hadrons have long life-times, J/ψ from $H_b \rightarrow J/\psi X$ will be displaced.

Extracting the J/ψ b-fraction

- A maximum unbinned likelihood fit to the flight path of the J/ψ in the $r-\phi$ plane, L_{xy} is used to extract the b-fraction.
- A MC simulation is used to model the L_{xy} distribution from $H_b \to J/\psi X$

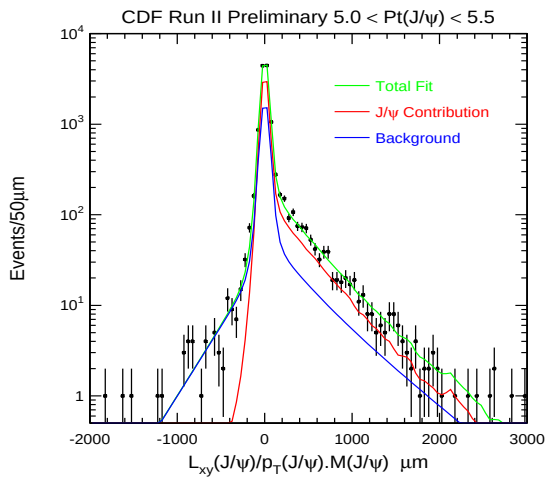
$1.25 < p_T < 1.5$ GeV/c

$f_b = 0.097 \pm 0.010^{+0.012}_{-0.010}$



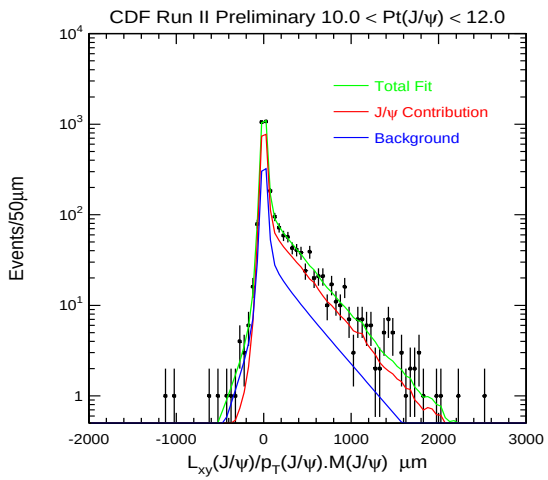
$5.0 < p_T < 5.5$ GeV/c

$f_b = 0.143 \pm 0.005^{+0.006}_{-0.006}$



$10 < p_T < 12$ GeV/c

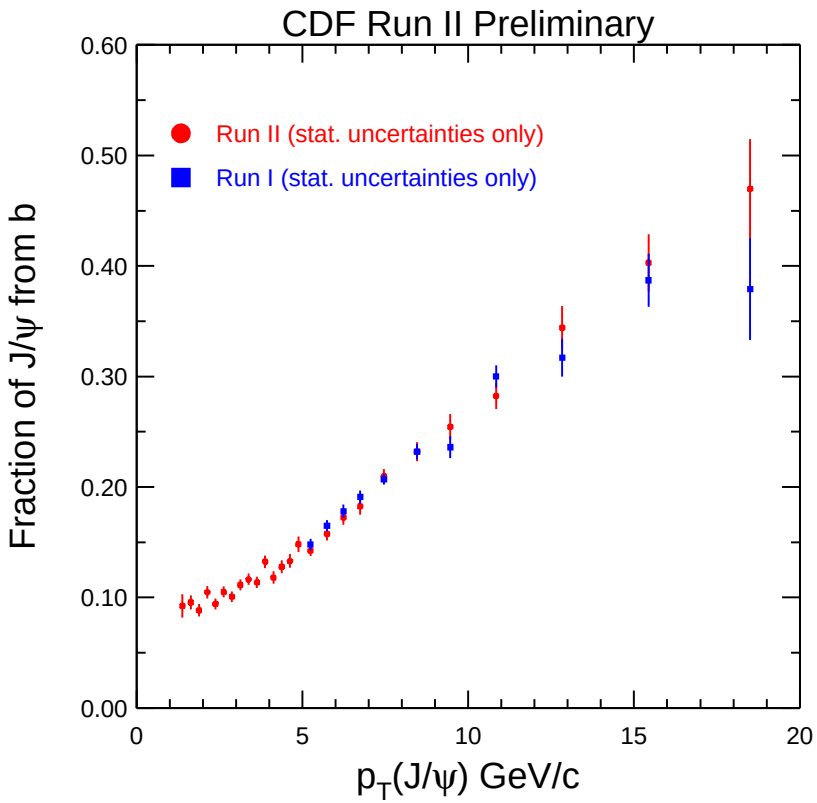
$f_b = 0.279 \pm 0.012^{+0.008}_{-0.007}$



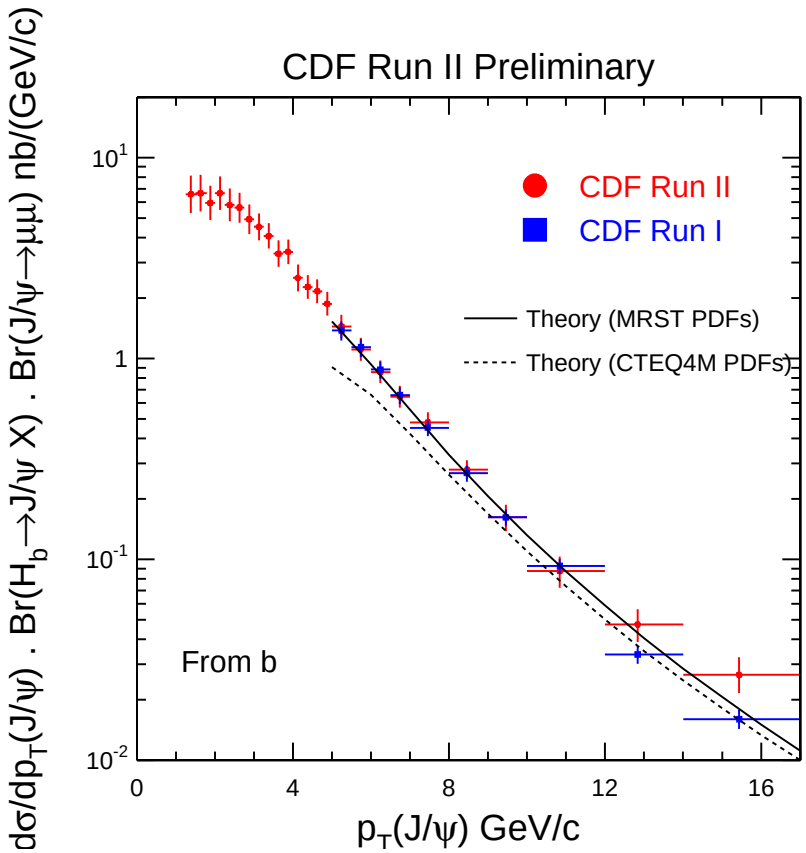
$L_{xy}(J/\psi) \cdot M(J/\psi)/p_T(J/\psi)$ μm

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

Fraction of J/ψs from H_b



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



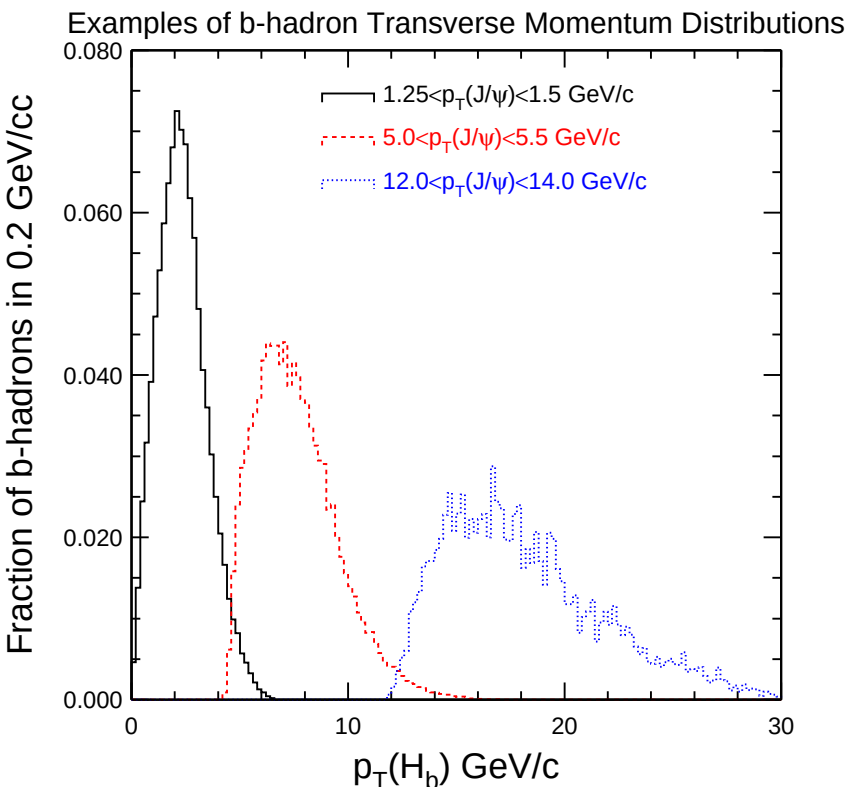
Theory: J. Binnewies, Bernd A. Kniehl and G. Kramer, Phys. Rev. D58 034016 (1998).

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

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

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

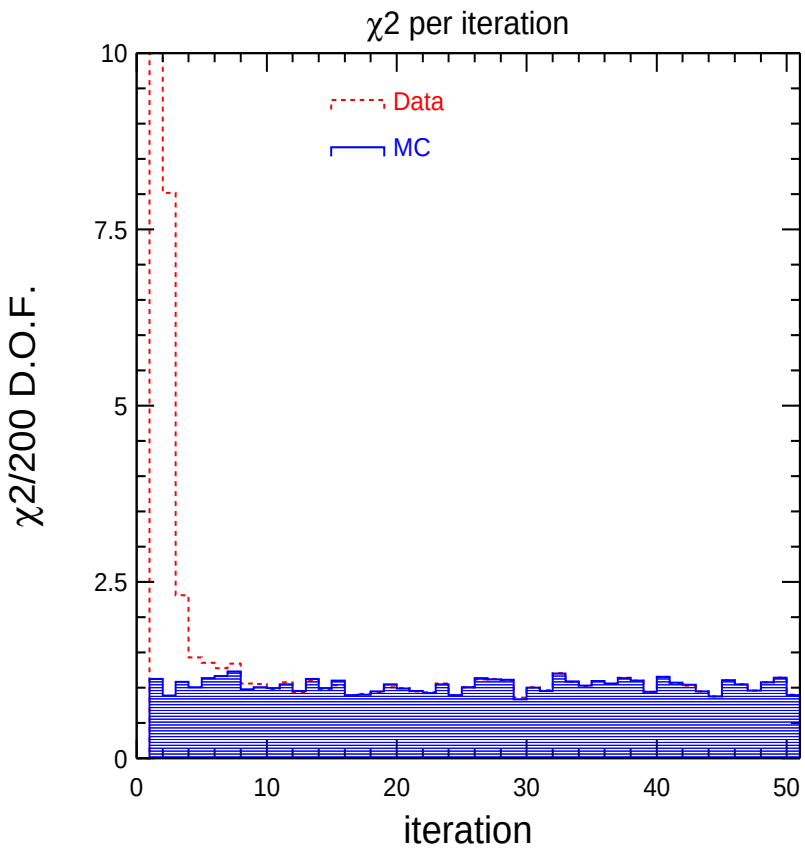
w_{ij} is the fraction of b events in the ith $p_T(H_b)$ from the jth $p_T(J/\psi)$ bin obtained from MC.



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

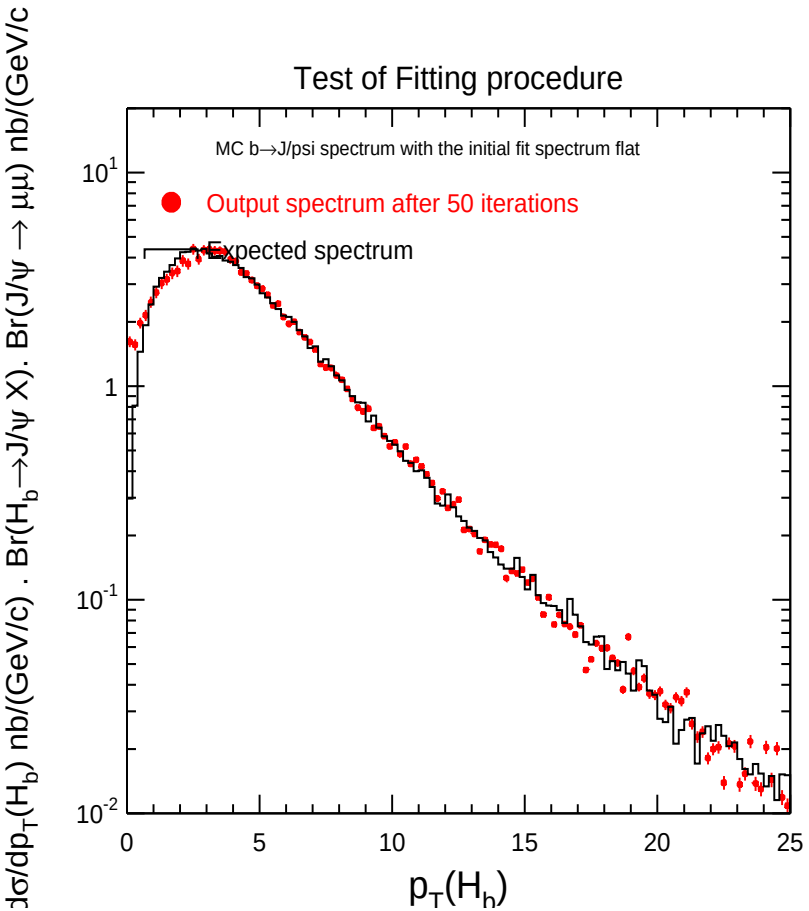
Iterating...

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



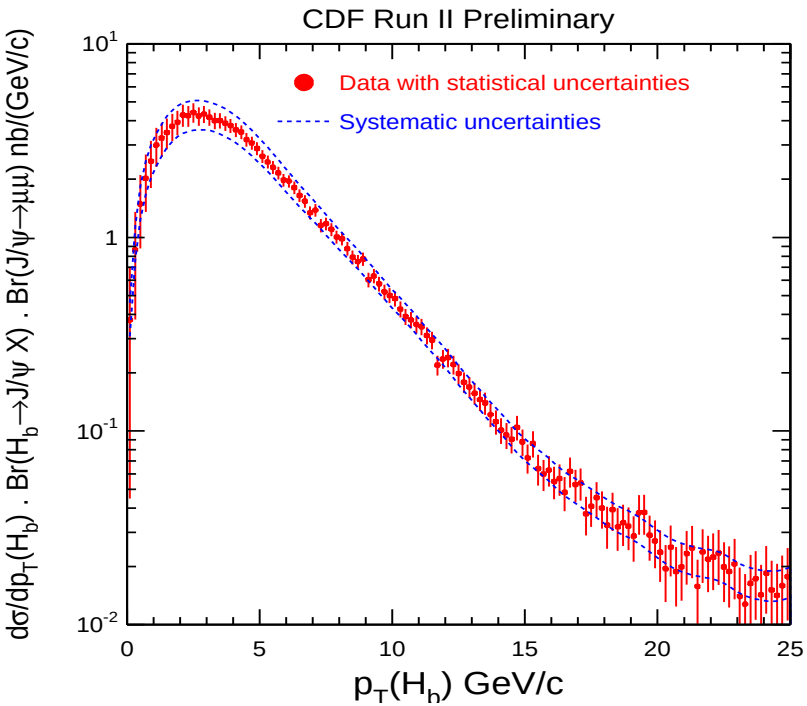
Test of Procedure

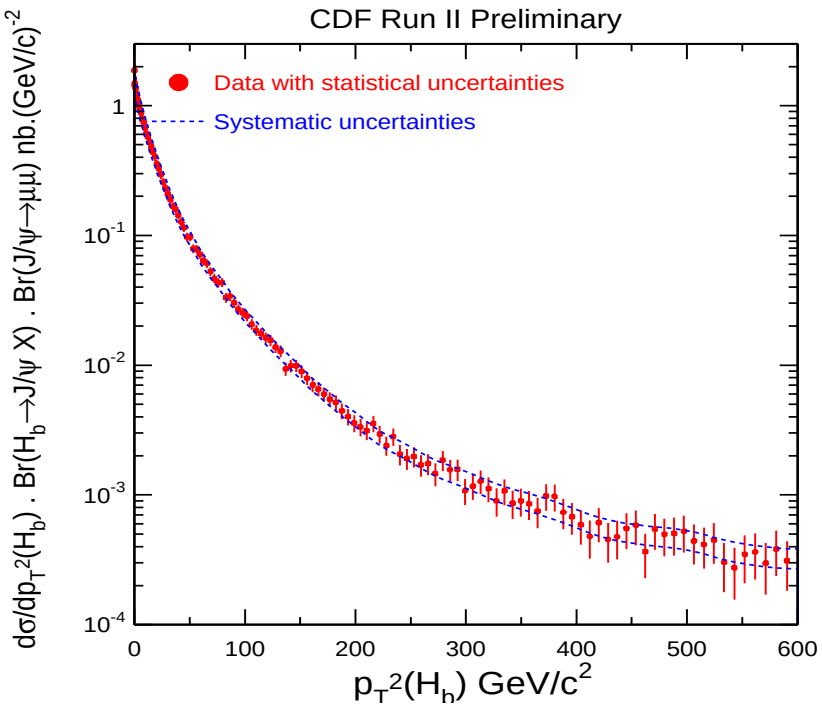
- We test the algorithim using the $d\sigma/dp_T(J/\psi)$ distribution from a MC sample with a *known* distribution of $d\sigma/dp_T(H_b)$ similar to the data.
- An *independent* MC sample, generated with a flat $d\sigma/dp_T(H_b)$ spectrum, is used to compute the weights w_{ij}



The correct spectrum is extracted.

The inclusive H_b cross-section





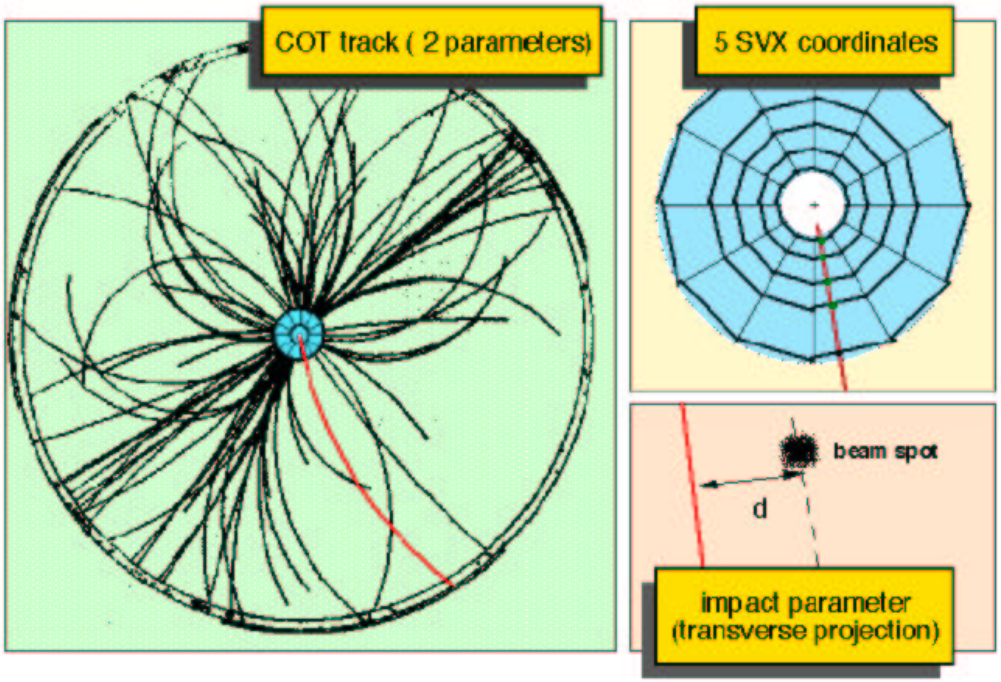
Since each H_b contains a bottom quark, correcting for branching fractions

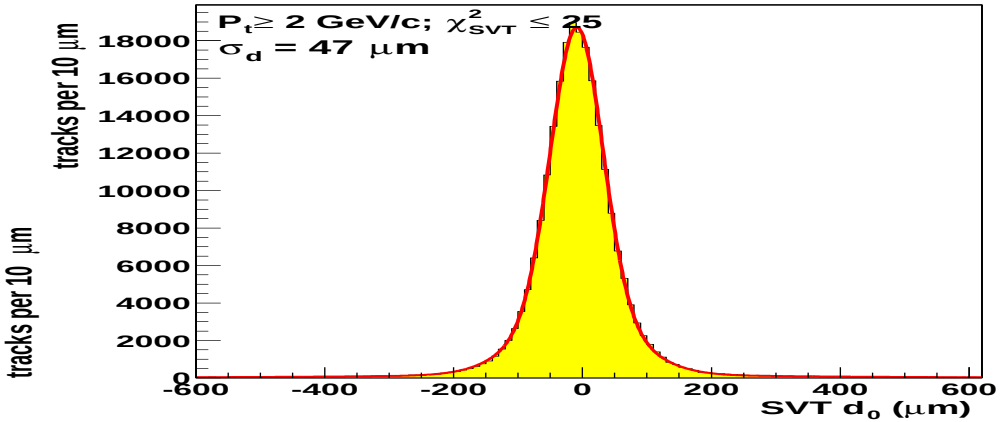
we get: $\sigma(p\bar{p} \to \bar{b}X, |y| < 1.0) = 29.4 \pm 0.6(stat) \pm 6.2(syst)\mu$b

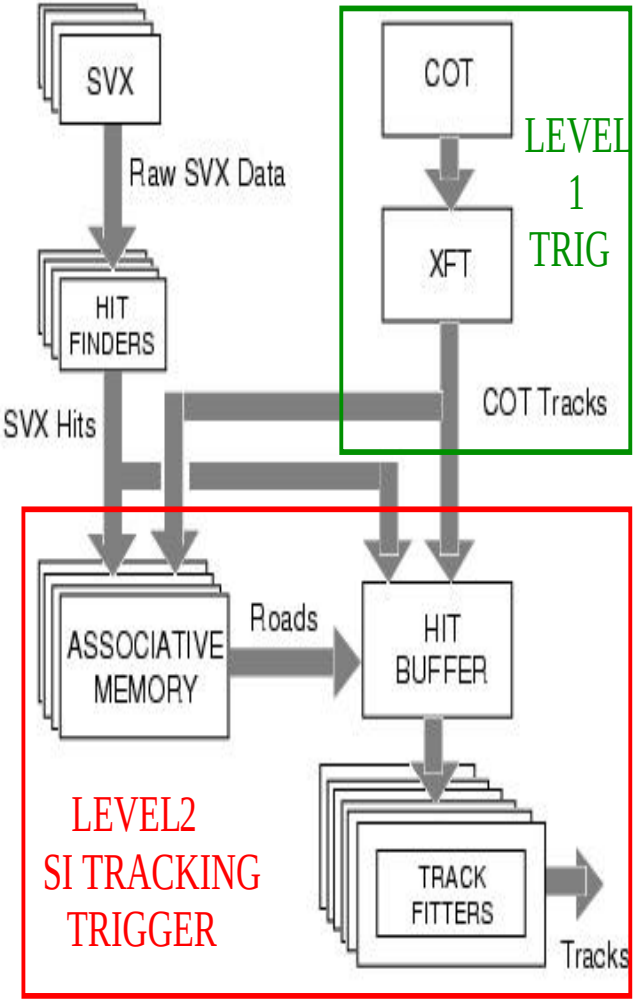
QCD NLO $\otimes$ MRST 2000 $= 20^{+8}_{-5}\mu$b

CHARM MESON CROSS-SECTIONS

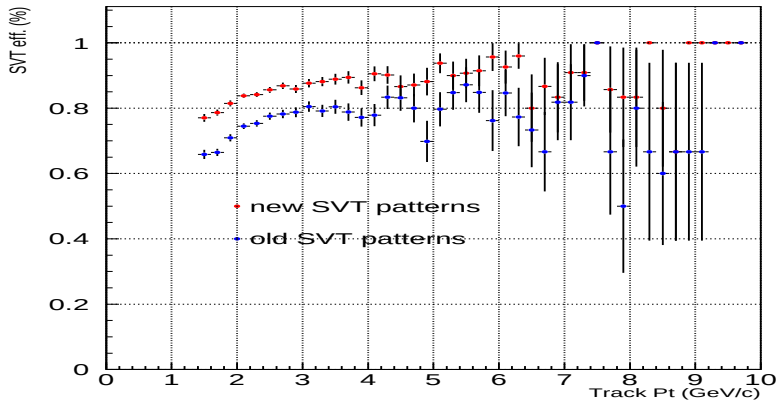
L2 Silicon Vertex Trigger (CDF)



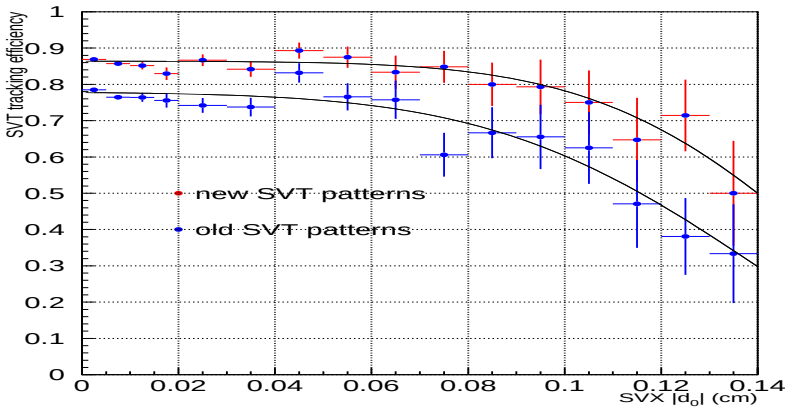




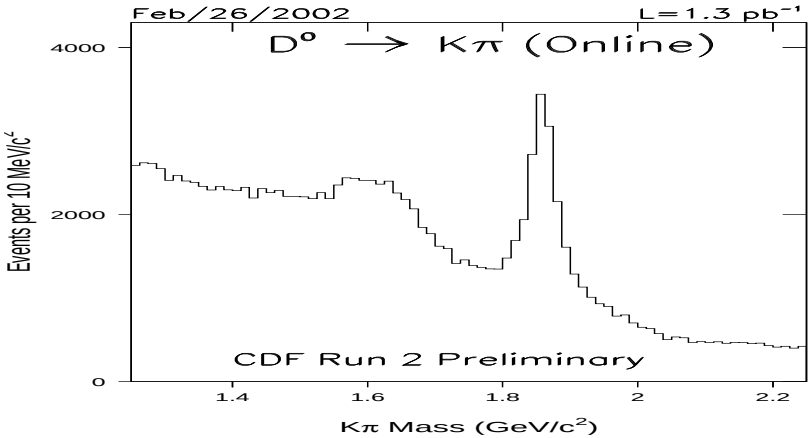
SVT Triggers on Charm



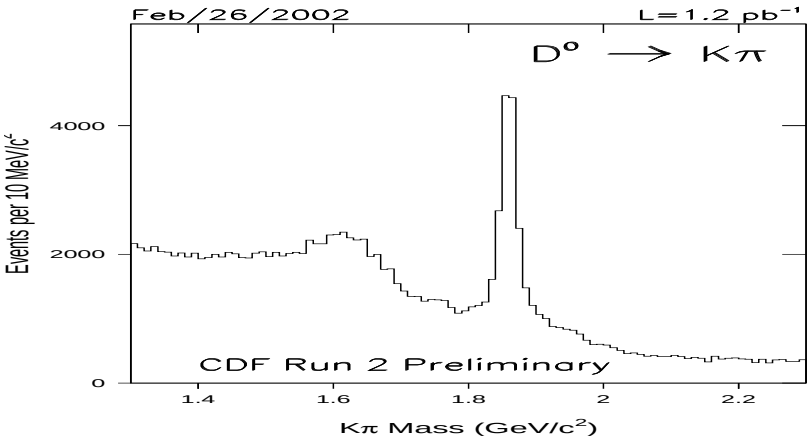
Eff. vs track p_t



SVT Eff. vs track d_0



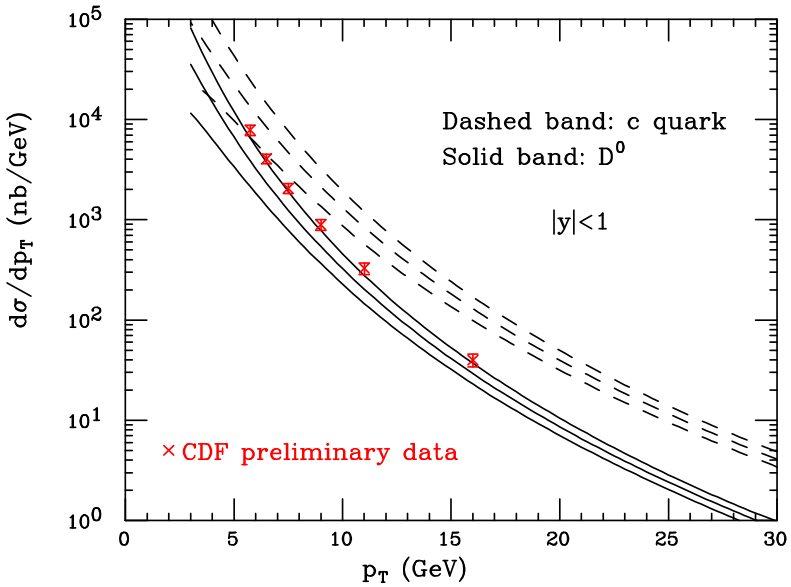
SVT + trigger info



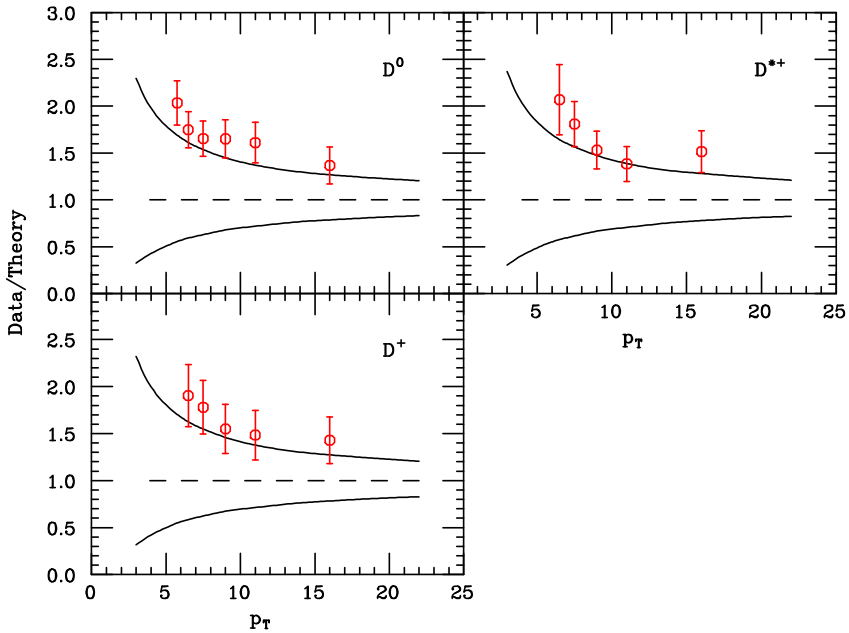
Offline reconstruction

Charm cross-sections

D^0 Meson Differential Cross-section



D Meson Cross-sections Data/Theory



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

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

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

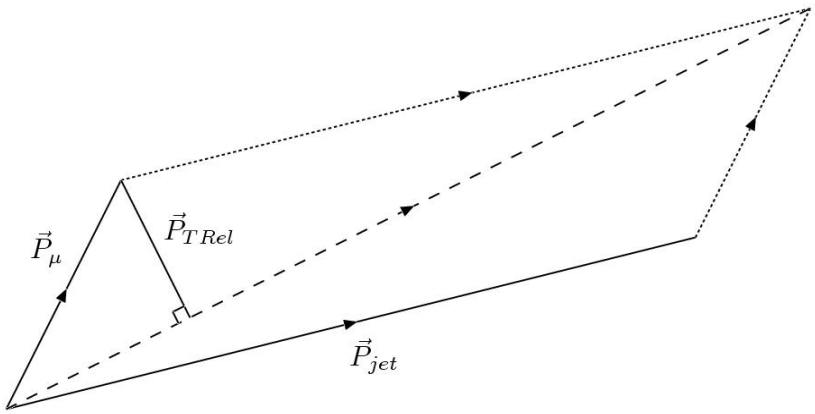
$$\sigma(p\overline{p} \rightarrow D^{*+} X, \mid y \mid < 1.0, p_T > 6.0 \text{ GeV/c}) = 5.2 \pm 0.1(stat) \pm 0.8(syst)\ \mu\text{b}$$

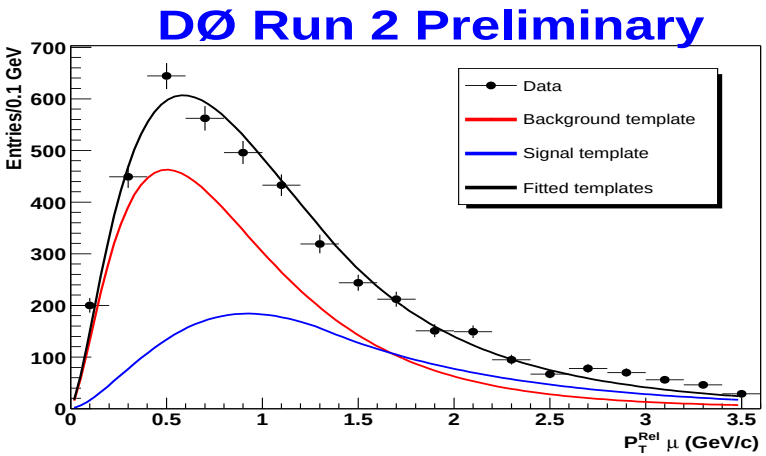
$$\sigma(p\overline{p} \rightarrow D_s X, \mid y \mid < 1.0, p_T > 8.0 \text{ GeV/c}) = 0.75 \pm 0.05(stat) \pm 0.22(syst)\ \mu\text{b}$$

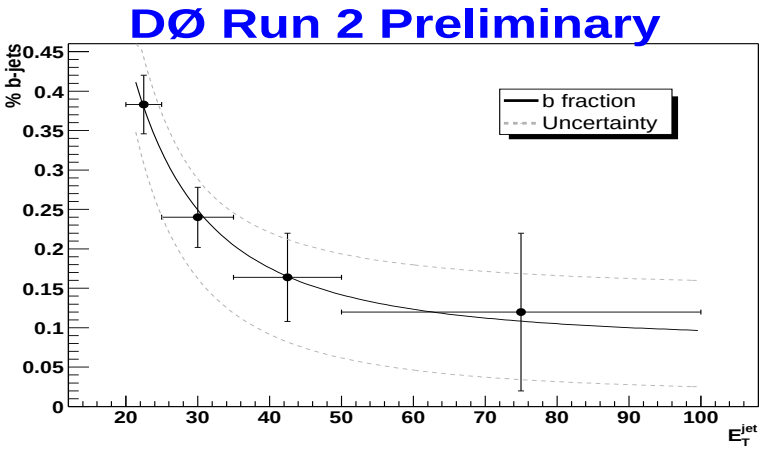
OTHER INTERSTING PRODUCTION TIT-BITS

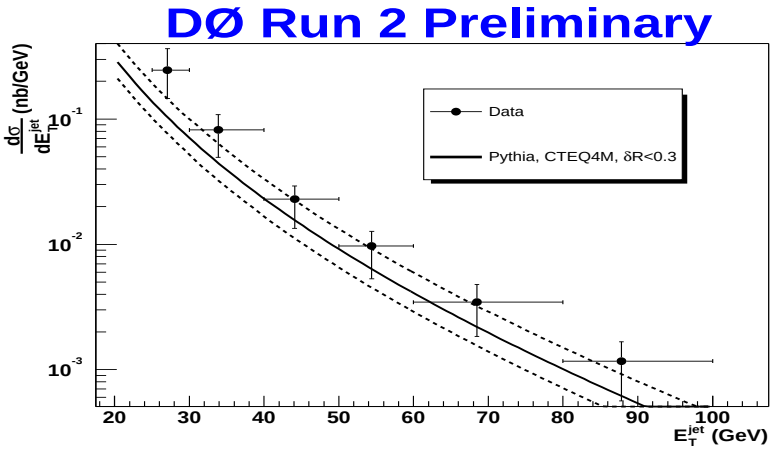
High p_T b-Jet Production

- b-jets include much of the quark fragmentation remnants $\Rightarrow$ jet cross-sections have small dependence on fragmentation.



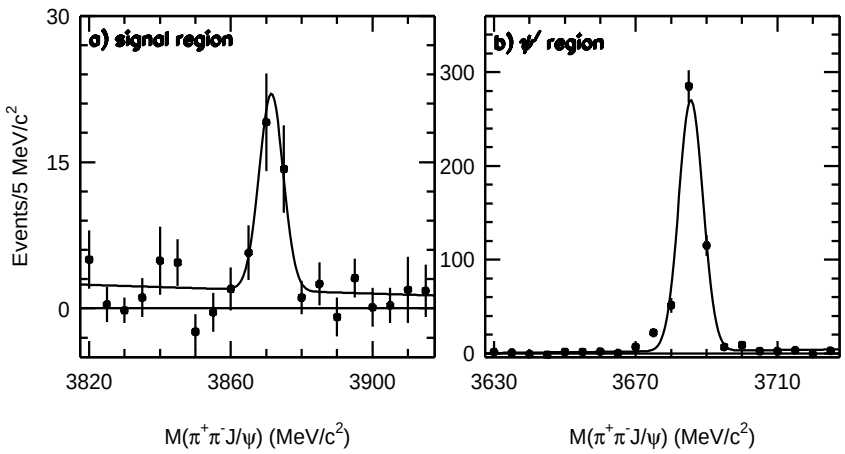




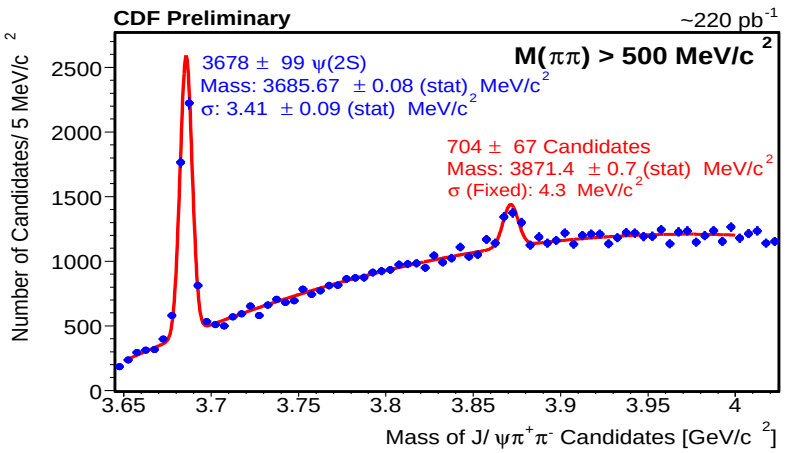


NEW: $X(3870) \to J/\psi\pi\pi$ Confirmed

- At LP 2003, the Belle collaboration announced the observation of a new state decaying into $J/\psi\pi\pi$ from analysis of B decays.



Belle



CDF

Is this a DD^* molecule?

Can CDF determine production mechanism?

Conclusions

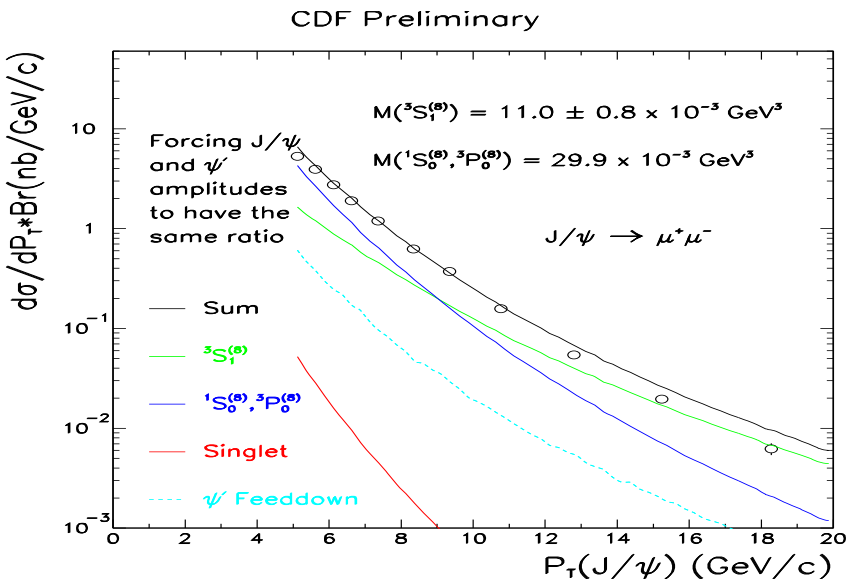
- Studies of heavy quark production at the Tevatron are now precision tests of QCD at NLO.
- In 2003, new mesurements of the inclusive central J/ψ cross-sections and the inclusive central b cross-sections down to $p_T = 0$ GeV/c have been carried out at CDF. *These are the first measurements down to $p_T = 0$ GeV/c at a hadron collider*.
- Phenomenological fits to PDFs and the fragmentation functions from many different experiments have improved theoretical agreement with Tevatron data.
- BUT: Cross-sections are still higher than predicted. Data indicates there may be other effects independent of fragmentation functions.

BASICS OF QUARKONIA PRODUCTION

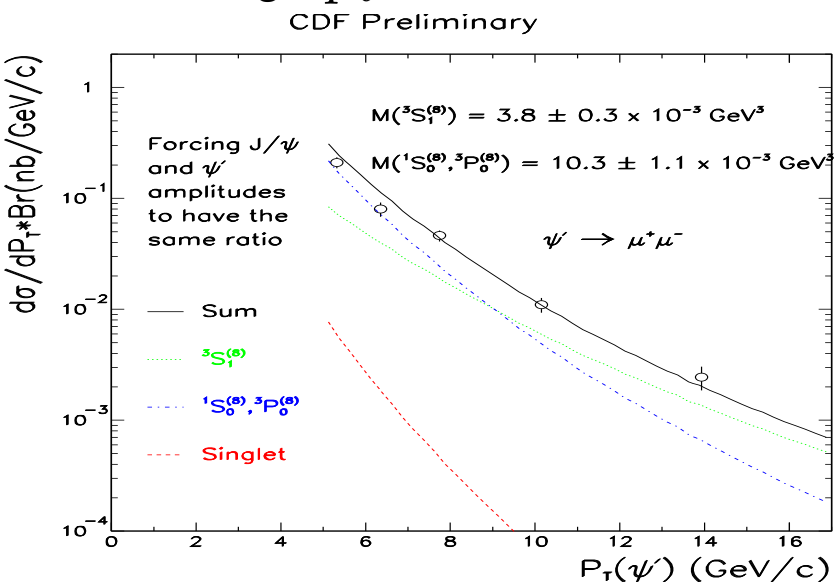
Quarkonia Production - Theory

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.*

Predictions agree well with data at the Tevatron at high p_t.



Direct J/ψ production (Run I)



ψ' production (Run I)

Quarkonia Production - contd

At lower p_t NRQCD non-fragmentation diagrams from other octet matrix elements are important, soft gluon effects cause rates to diverge.

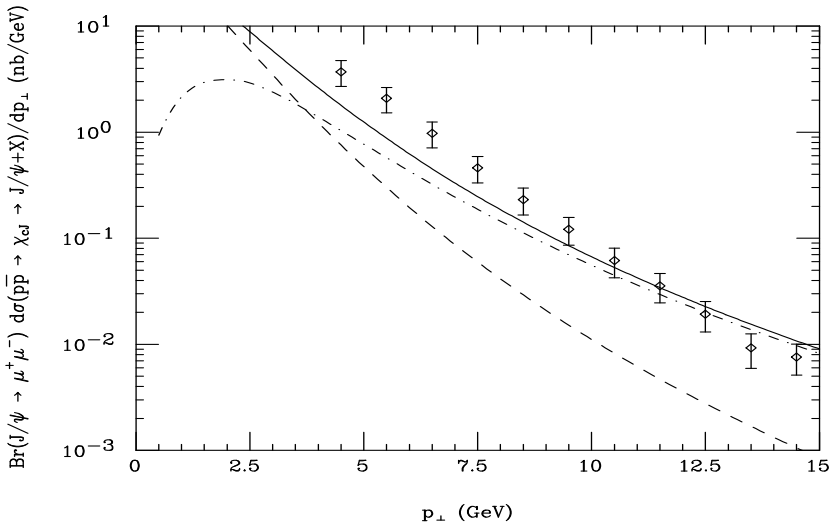
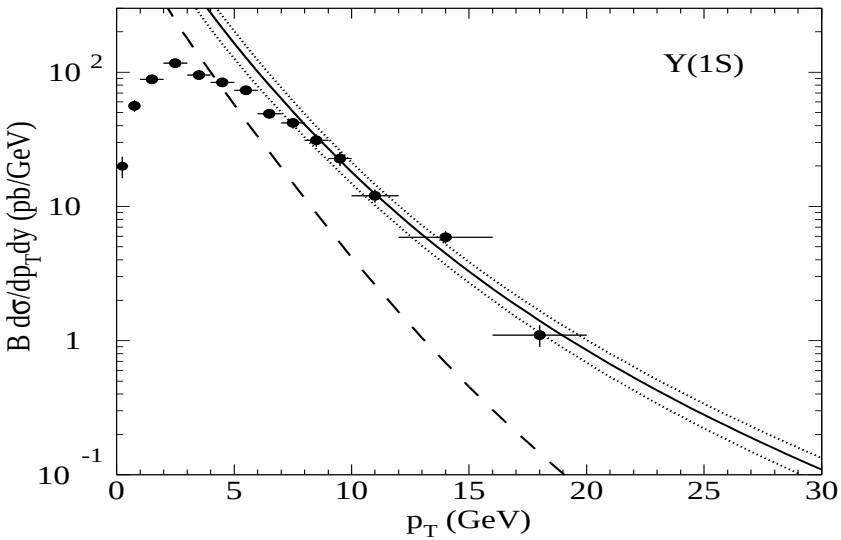


Figure 7

Direct χ_c production



$\Upsilon(1S)$ production

Recent theoretical advances in the resummation of the soft gluon effects of the color octet matrix elements for $e^+e^- \to J/\psi X$.

No new theoretical predictions for low p_T quarkonium at $p\bar{p}$.

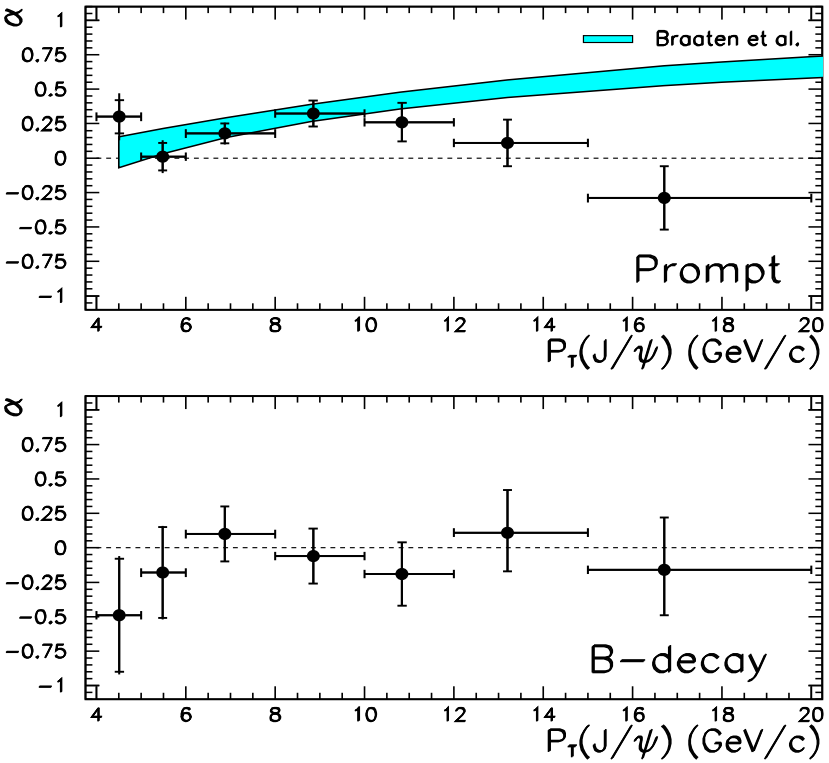
Charmonium Polarization Mystery

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 $b \to J/\psi X$

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

CDF Run I



Run II :Need more precise measurements