Heavy Flavour Production at the Fermilab Tevatron

Heavy Flavour Productions and Hot/Dense Quark Matter, 2005

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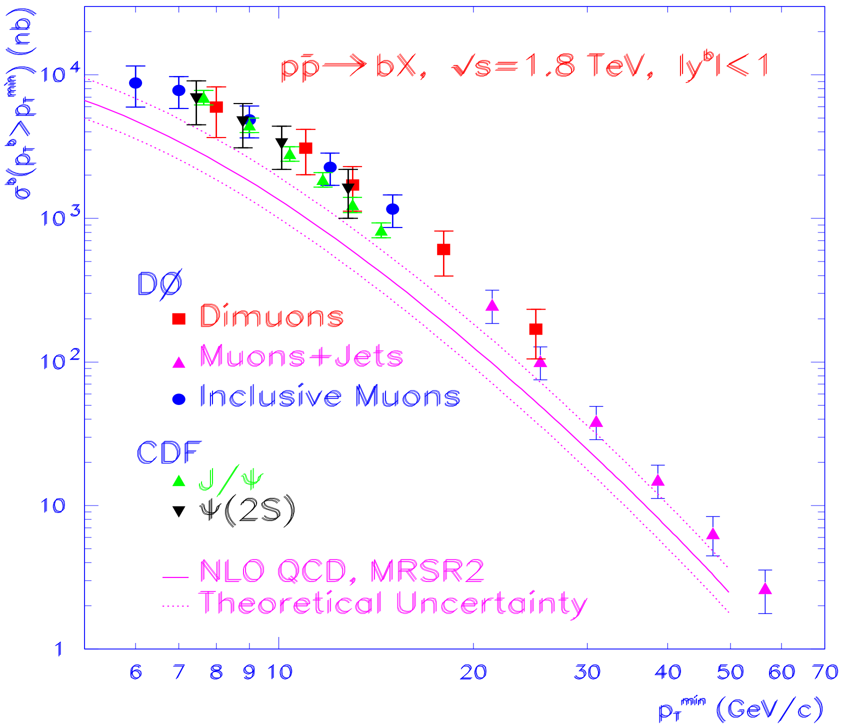
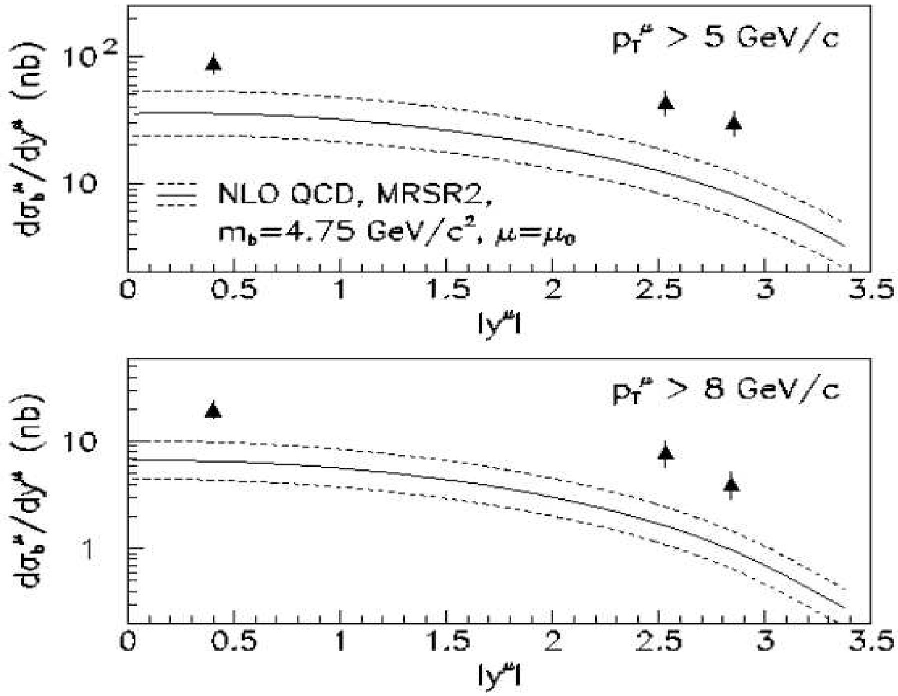
b Production Xsec - history

- <u>In 1997</u>, b production cross-sections in $p\bar{p}$ collisions 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)



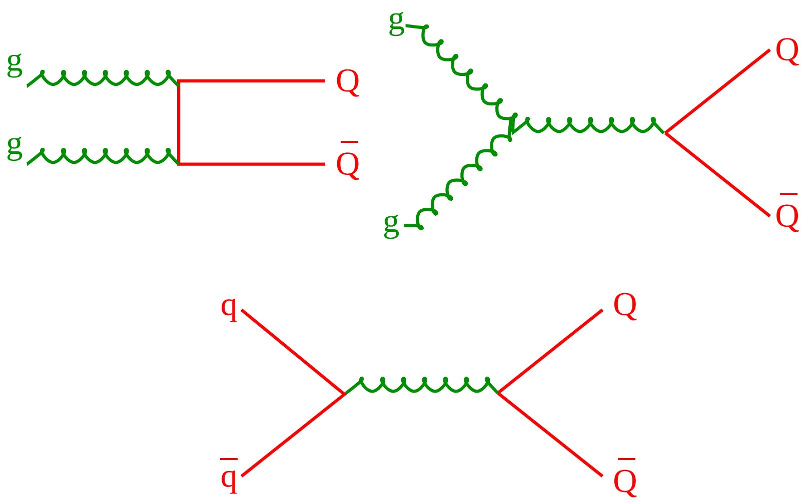
Is this a <u>*shape*</u> or <u>*normalization*</u> problem? What about *charm*?

Outline

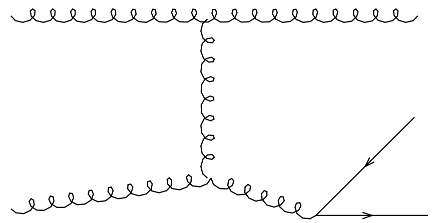
- Recent advances in the theory of heavy quark production cross-sections in $p\bar{p}$ collisions.
- Description of the Run II CDF and D0 detectors at the Tevatron.
- Tevatron Run II results on beauty and charm hadron production cross-sections.
- Heavy flavour jet production.
- *Quarkonia production (including diffractive!)*
- Summary and conclusions.

THE THEORY

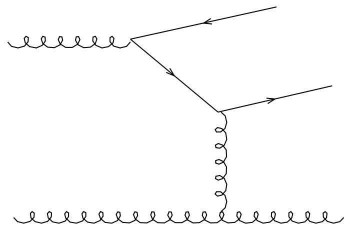
Heavy Quark Production in $p\bar{p}$



LO Heavy Quark Production



NLO: Gluon splitting

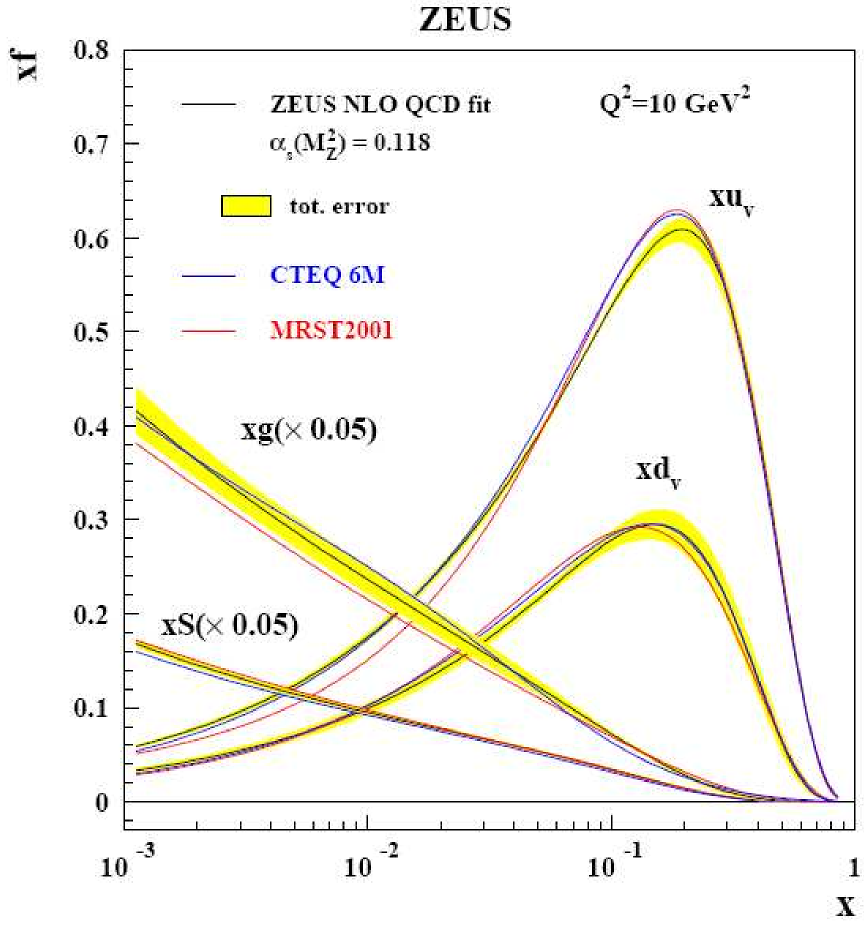


NLO: Flavour excitation

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

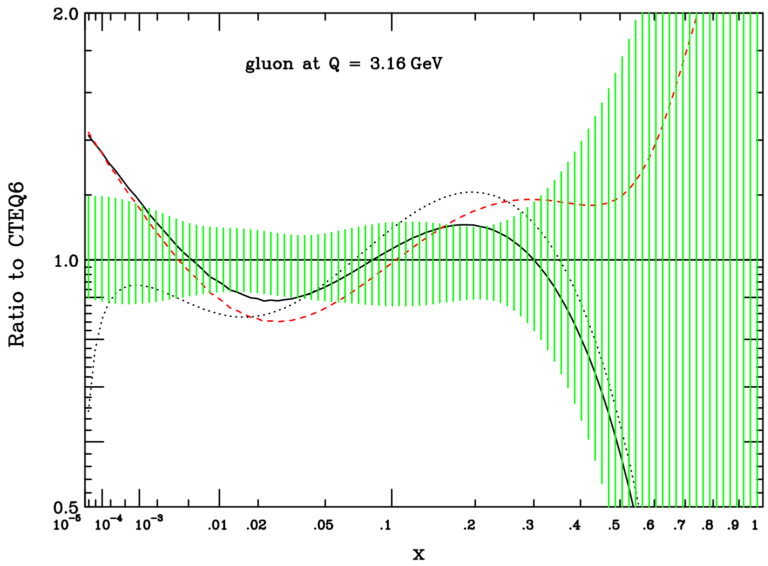
$$\underbrace{\frac{d\sigma(qq/gg/qg \to bX)}{dp_T(b)}}_{\text{NLO/NNLO QCD}} \otimes \underbrace{f^{p,\bar{p}}}_{\text{Proton structure}} \otimes \underbrace{D^{b\to B}}_{\text{fragmentation}} = \underbrace{\frac{d\sigma(p\bar{p} \to BX)}{dp_T(B)}}_{\textit{observed}}$$

Parton Density Functions (PDF)



New PDFs with uncertainties extracted from fits to the data

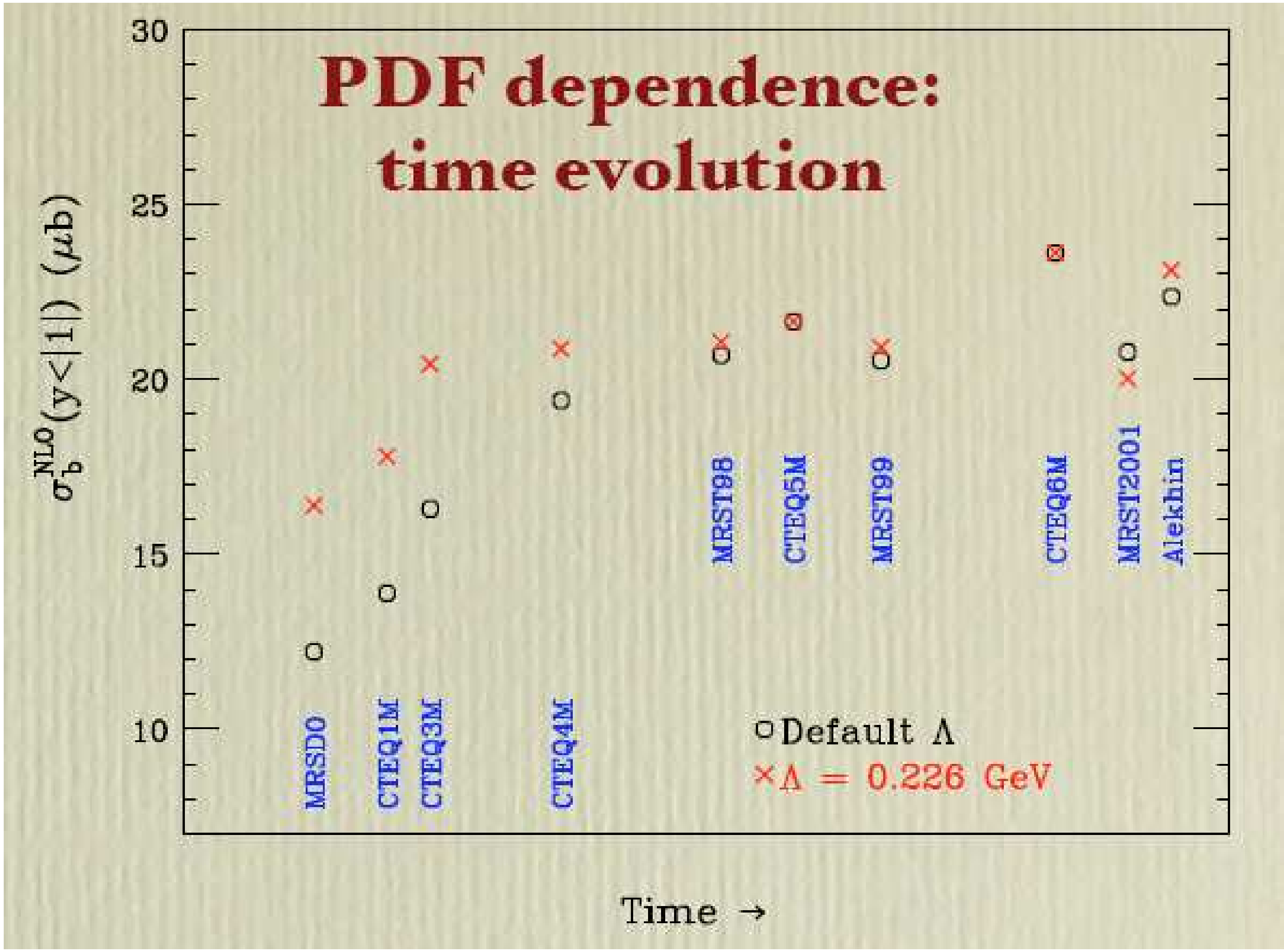
- *The uncertainties from one PDF fit do not always cover differences with other fits:*



Uncertainties on gluonic function

Evolution of PDFs

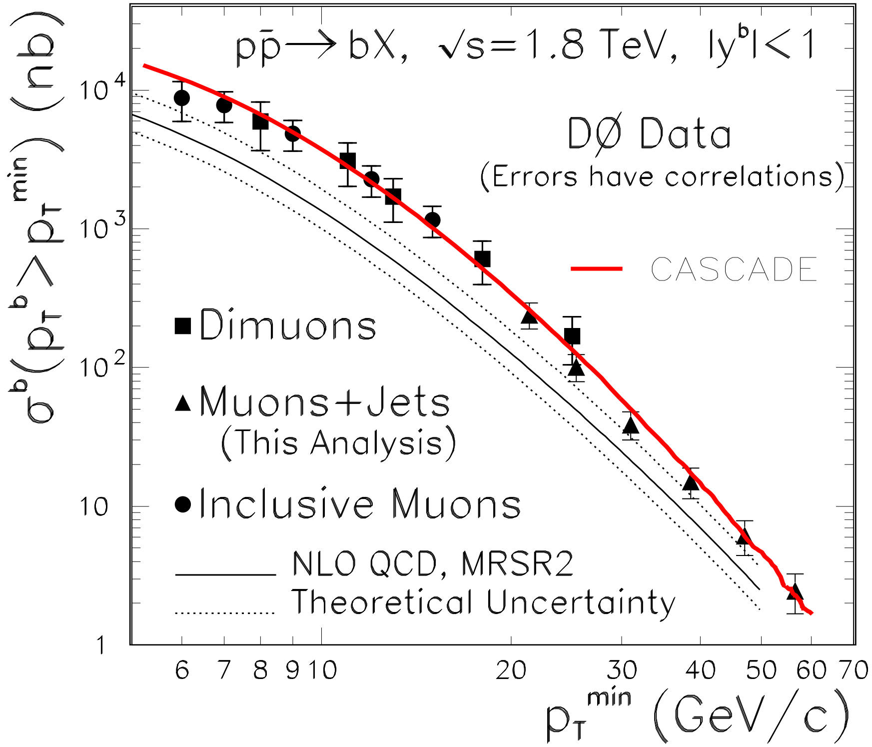
By 2004, recalculating the cross-section with updated PDFs increases theoretical value by almost 2X!

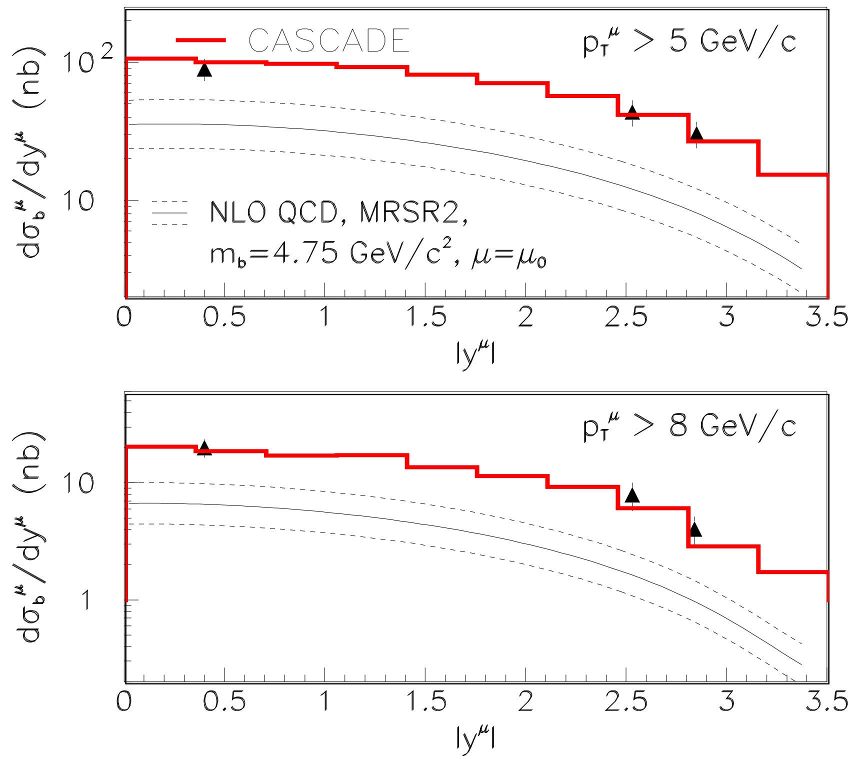


2001: k_T Factorization Scheme

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

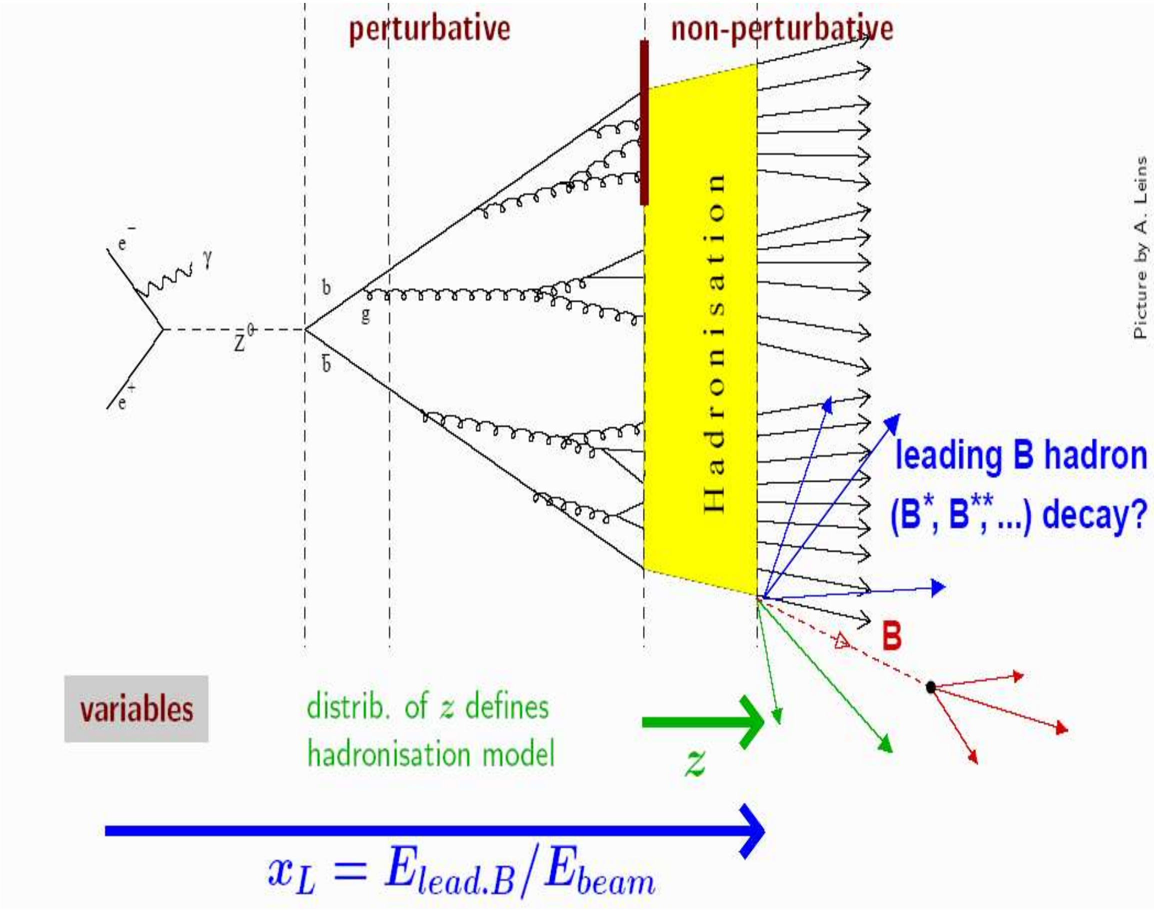




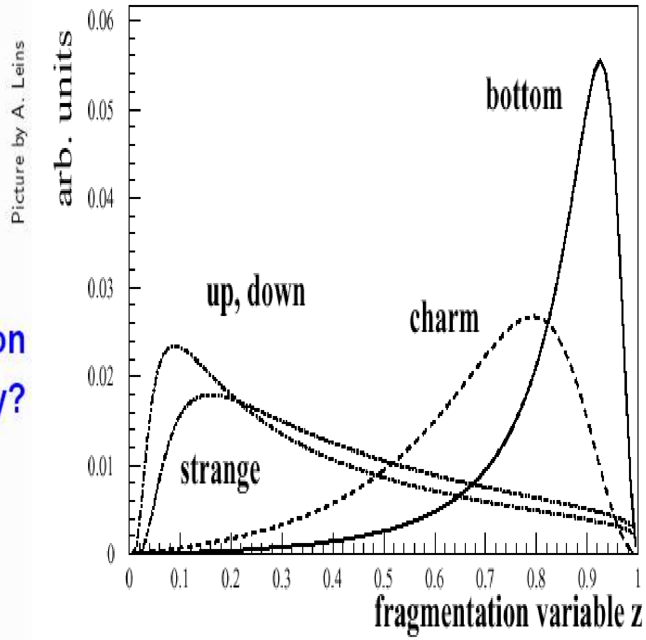
H.Jung, hep-ph/0110034

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

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



Peterson parameterization

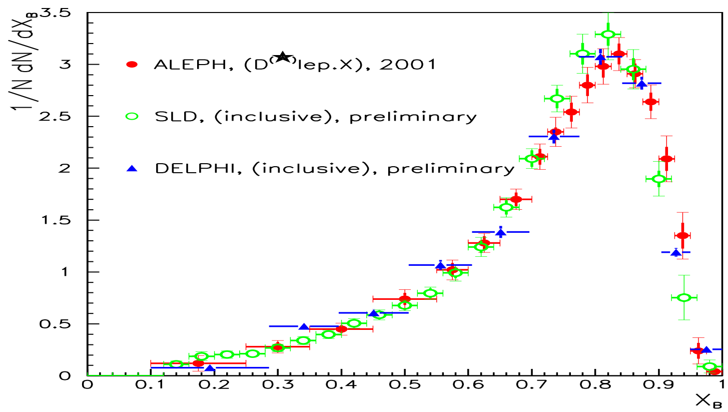


$$z = \frac{(E+p_{||})_{hadron}}{(E+p)_{quark}}$$

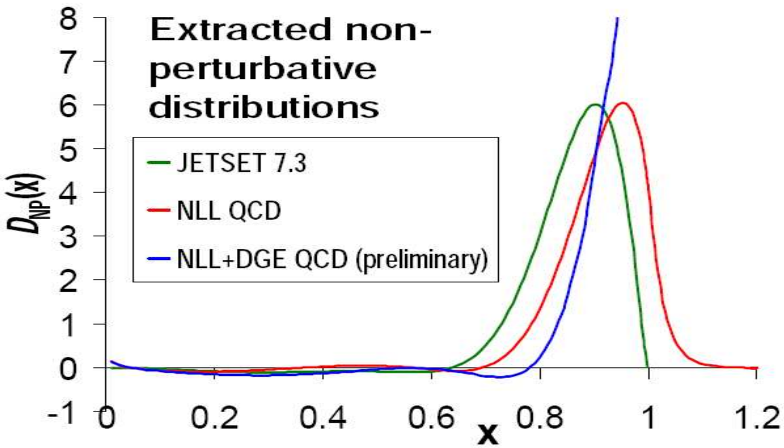
Recent Theory Advances

- Next-to-Leading-log resummations (2001): In pQCD calculations powers of $\alpha_s \log p_T/m_Q$ modify shape of fragmentation function: $p_T >> m_Q$ = Large corrections
- Moment analysis (2002): Mellin transformation into moment space $\tilde{D}(N) = \int x^{N-1} D(x) dx$

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



$D(x)$ Measured

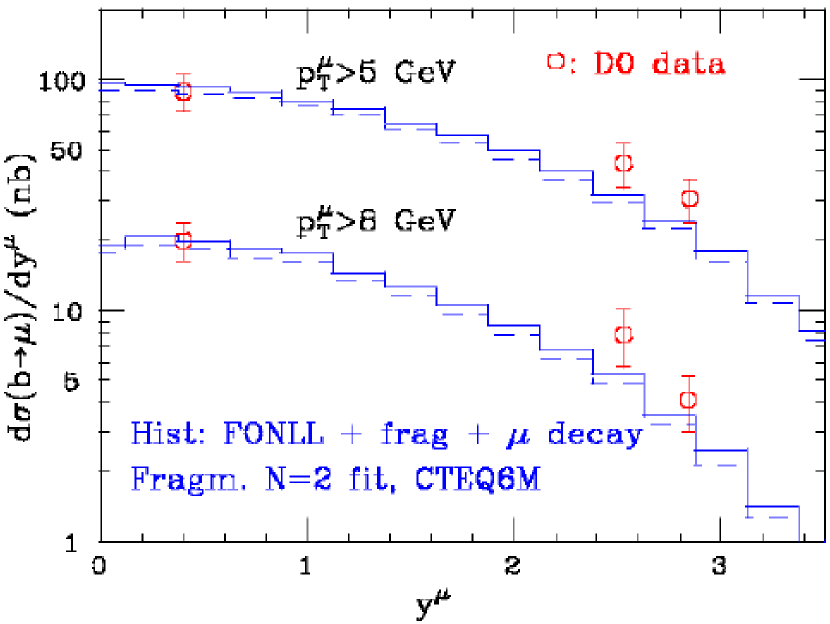


$D^{non-pert}(x')$ Extracted

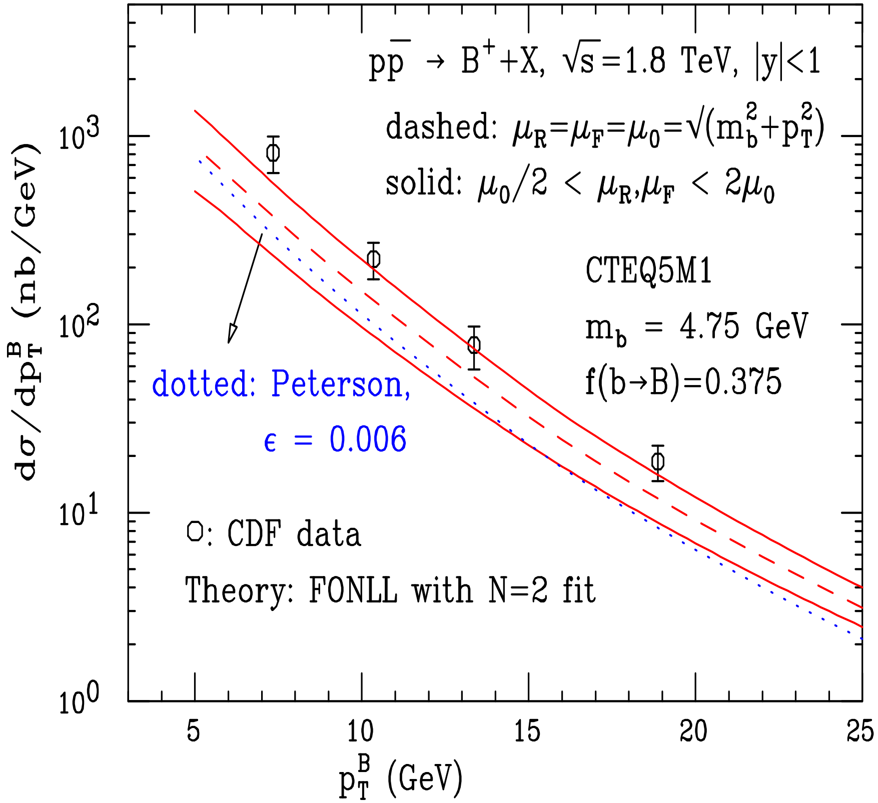
Non-perturbative functions used must match perturbative assumptions

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?

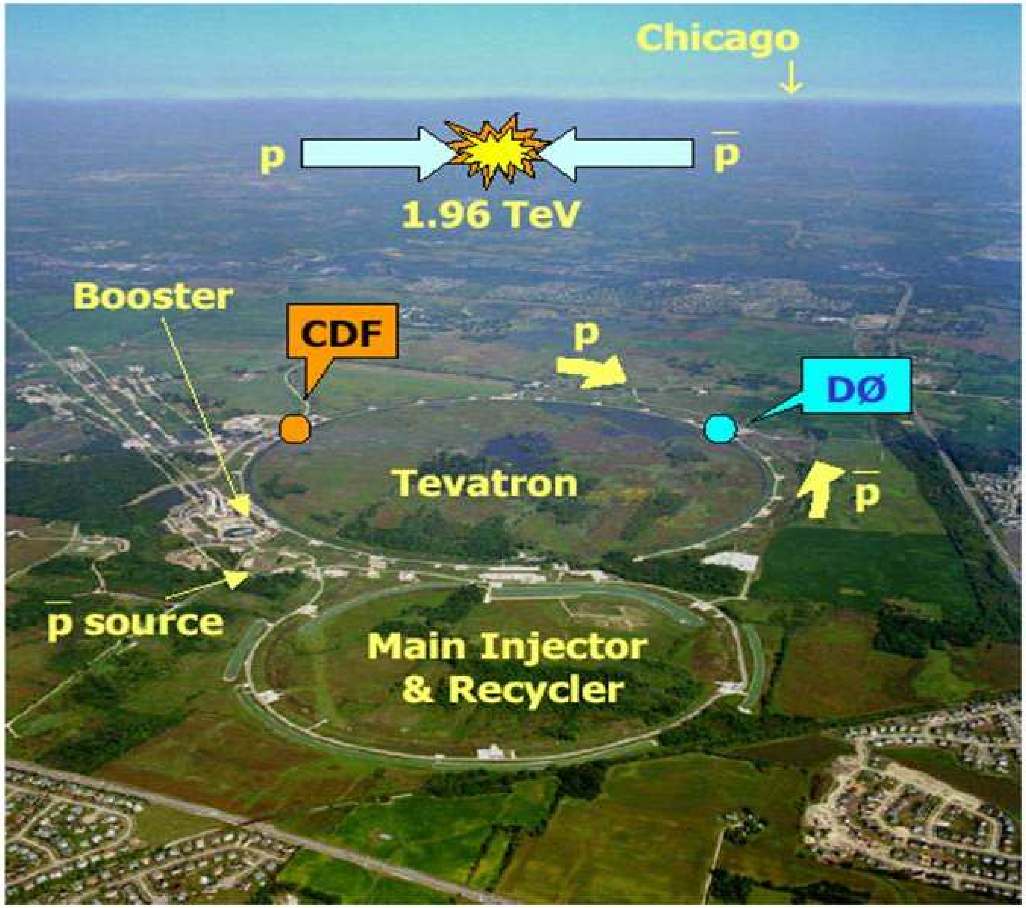
Total cross-sections do not depend on the fragmentation model!

= 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

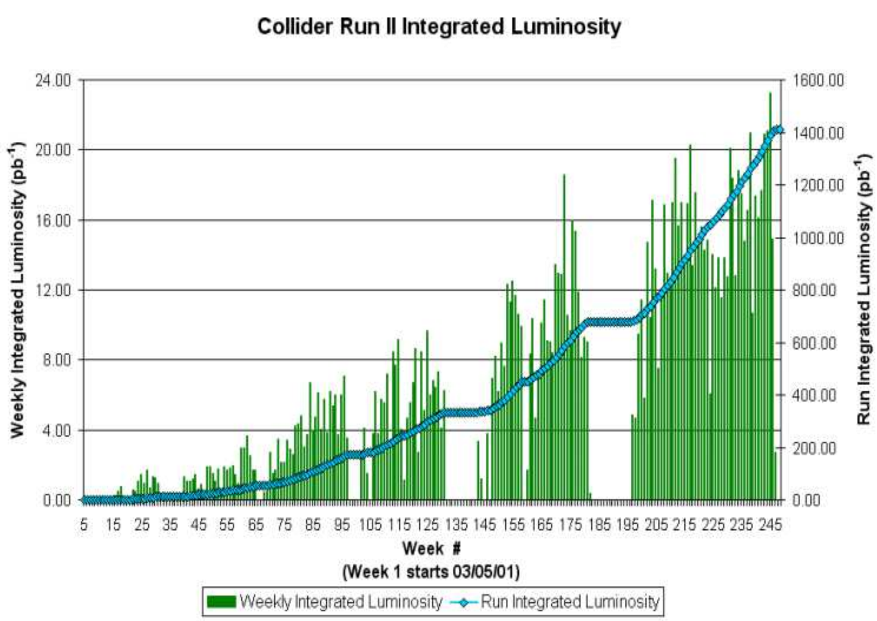
THE EXPERIMENTS

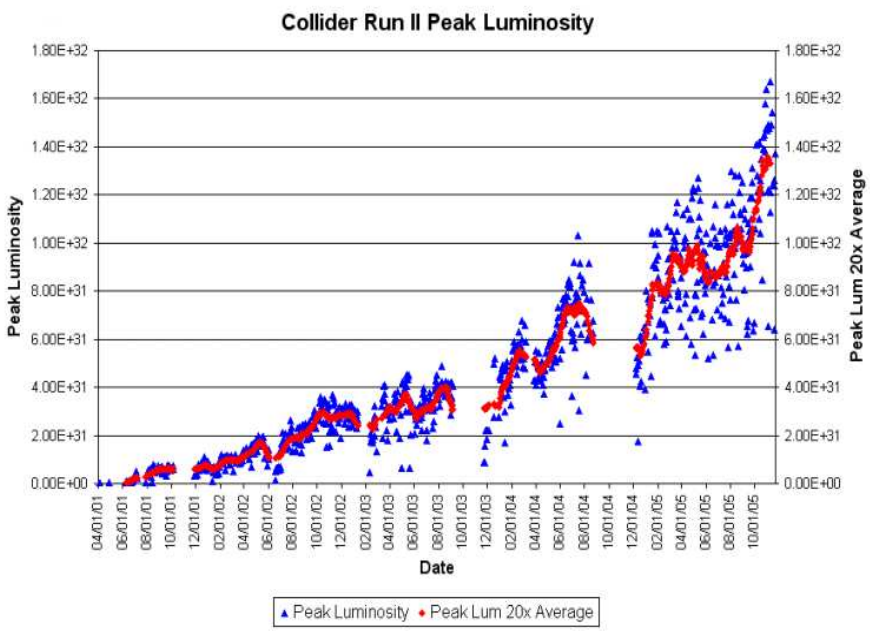


The Tevatron Today

- 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 $\mathcal{L}^{typical} = 1.6 \times 10^{31}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

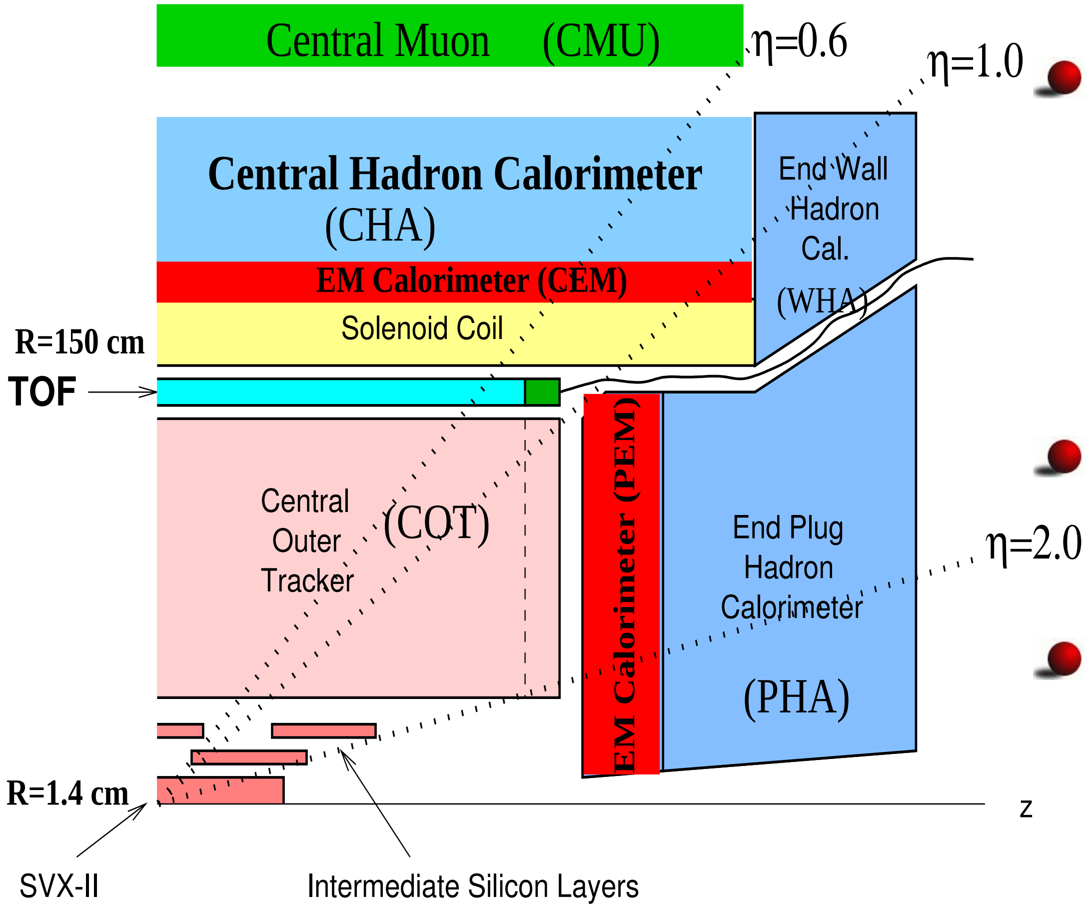
Run II : Summer 2001 - present - > 1 fb^{-1}





CDF Run II - Overview

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

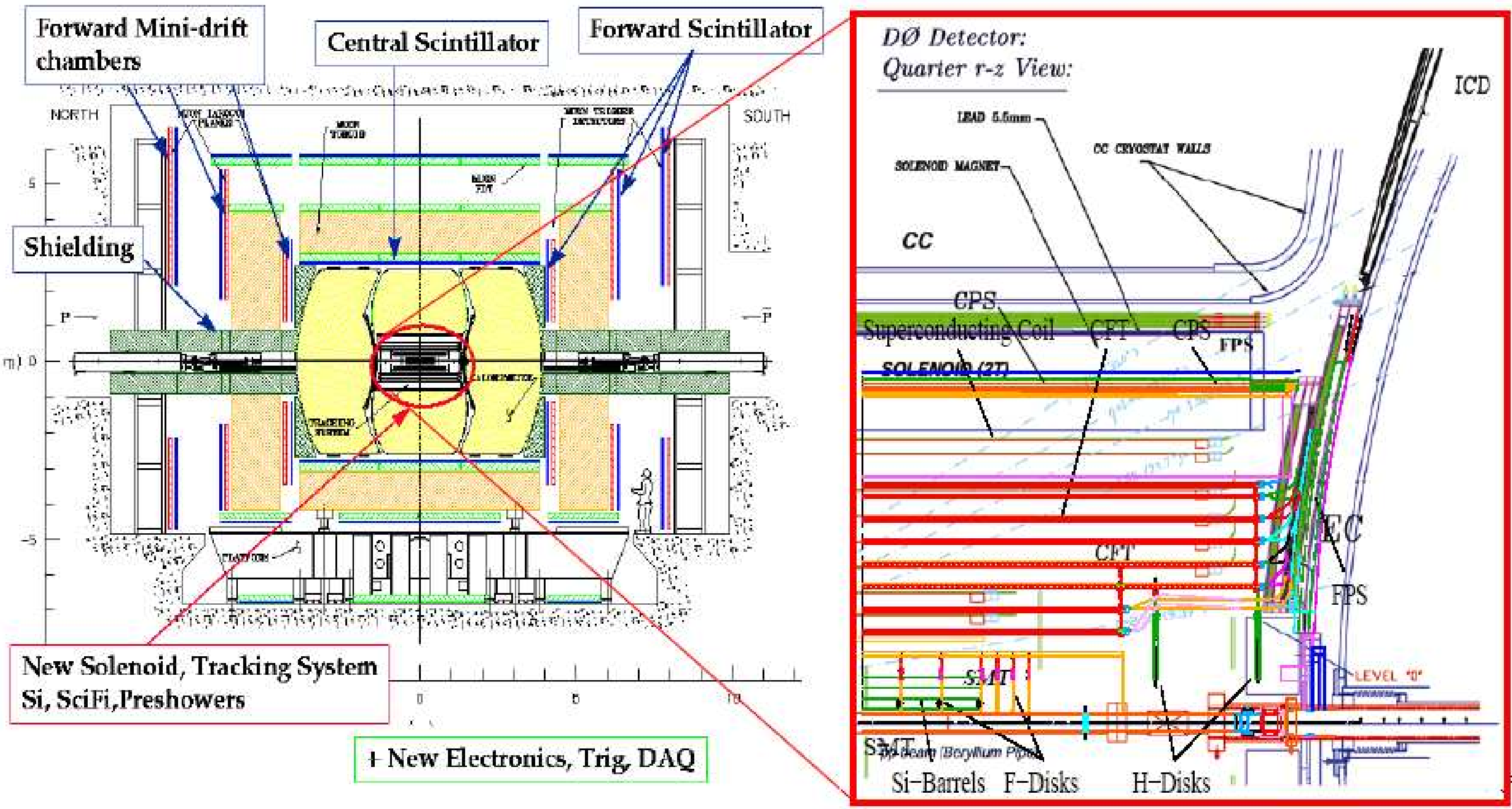


$$\eta = -1/2 \ln \tan \theta/2$$

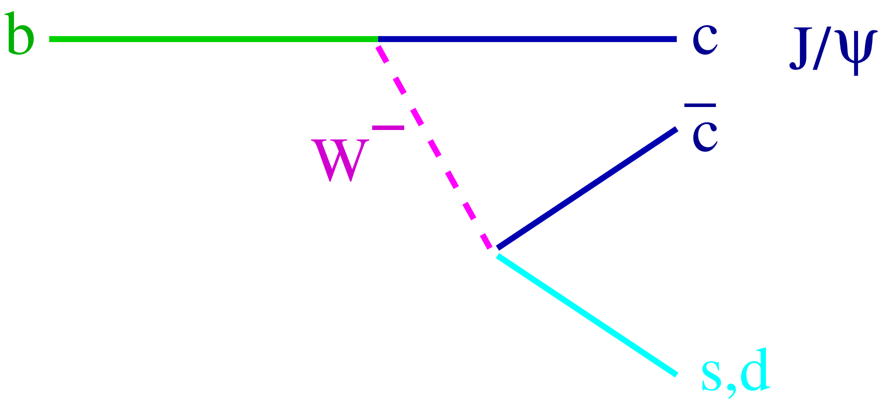
- *Central Muon detector*: Prop. chambers outside central calor. $\sim 5\pi$ interaction lengths.
- 96 layer COT: $\sigma(p_t)/p_t = 0.002 p_t$
- Silicon vertex detector: 8 Layers of 3-D Silicon up to $|\eta| = 2$, 700,000 readout channels, $\sigma(d_0) \sim 30\mu m$

D0 Run II - Overview

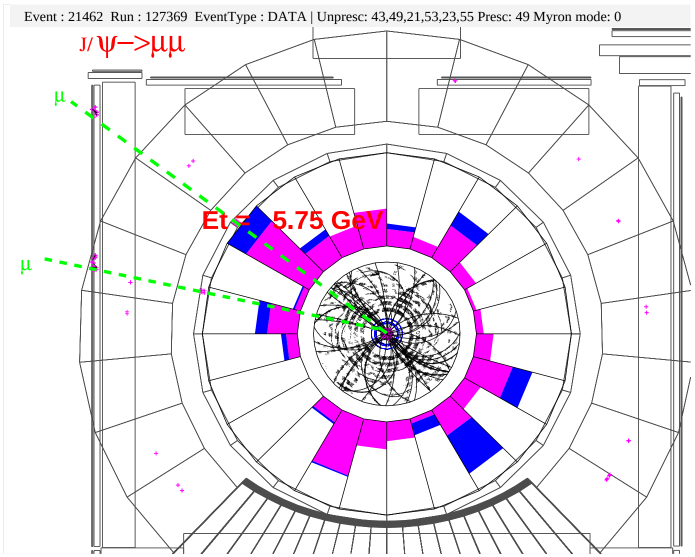
- New forward muon system with $|\eta| < 2$ and good shielding
- 16 layer Fiber Trackers in 2T
- 4 layer Silicon, $\sigma(d_0) = 54\mu$m at 1 GeV/c

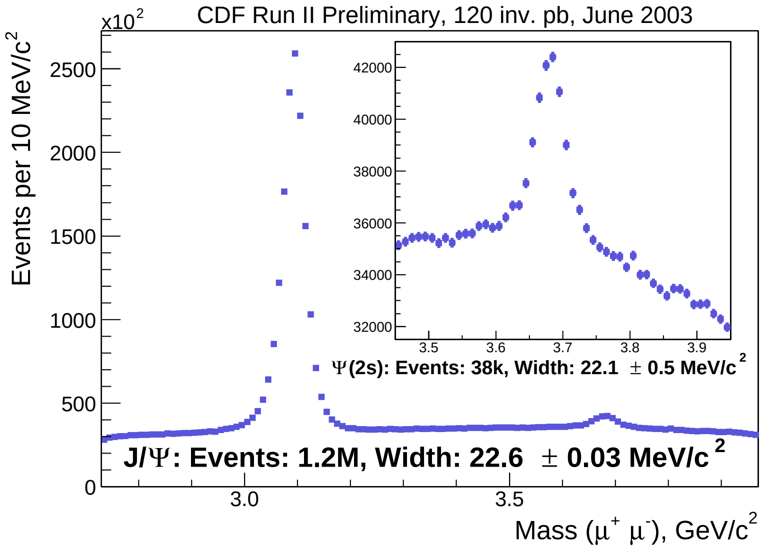


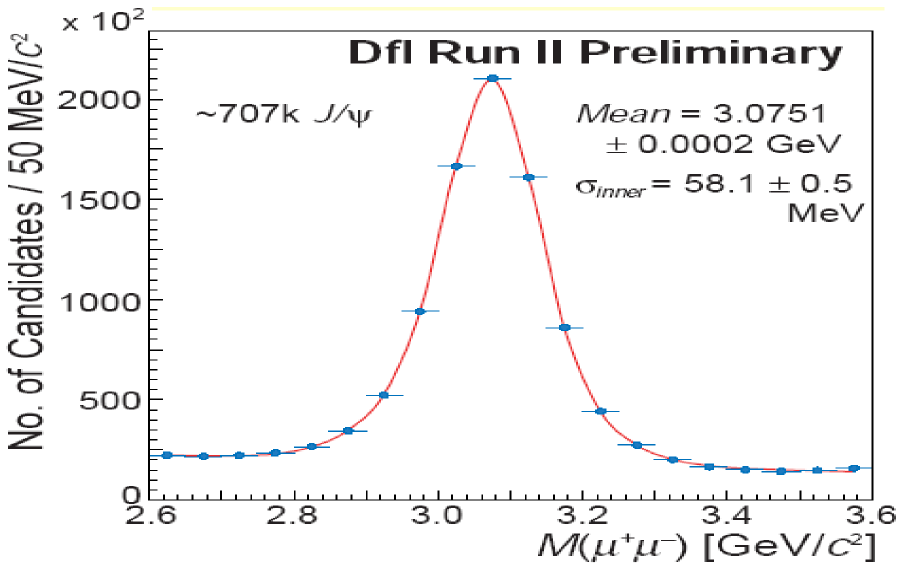
RUN II MEASUREMENTS OF THE J/ψ AND b-HADRON INCLUSIVE CROSS-SECTIONS



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

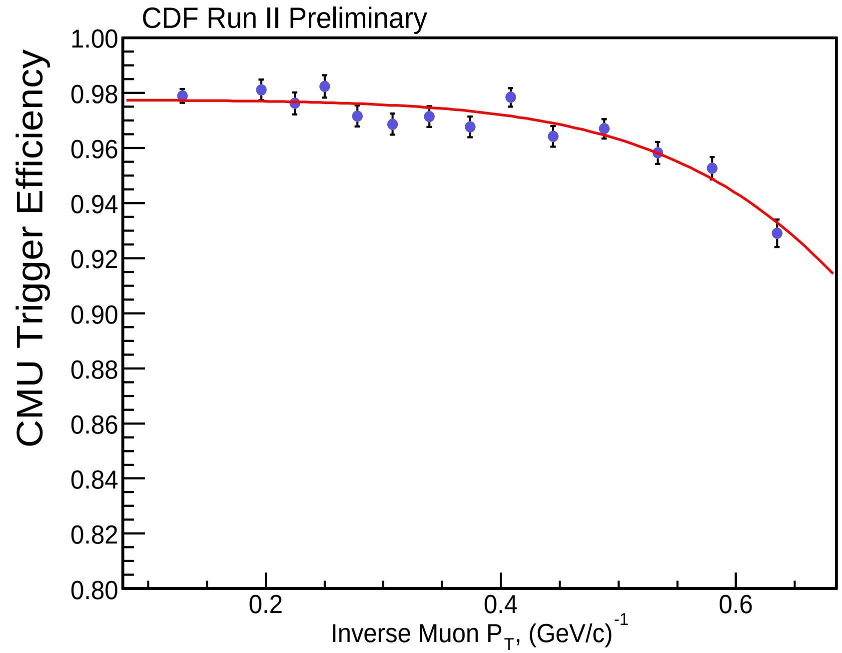




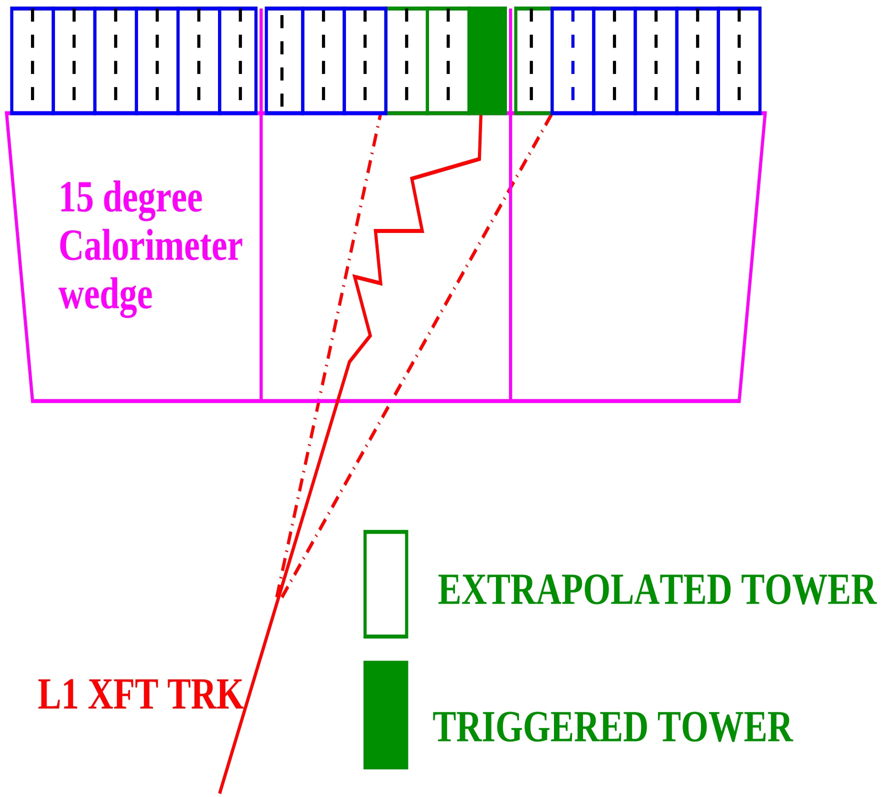


L1 Muon triggers (CDF)

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:*

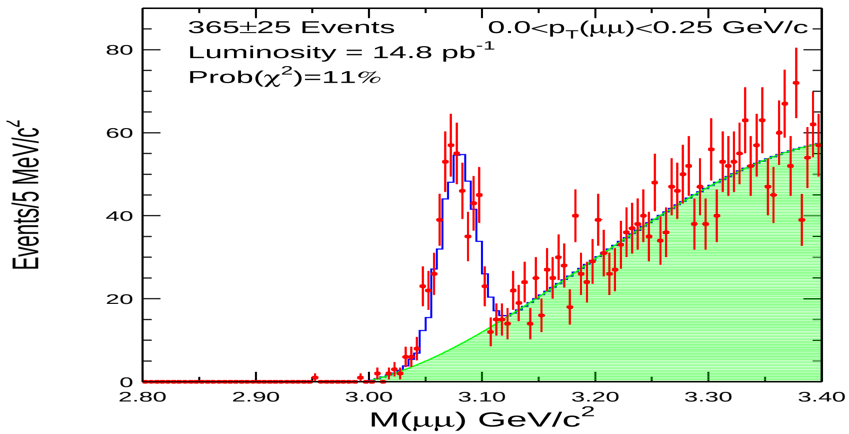
  $p_t(\mu) > 1.5(|\eta| < 0.6)$.

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

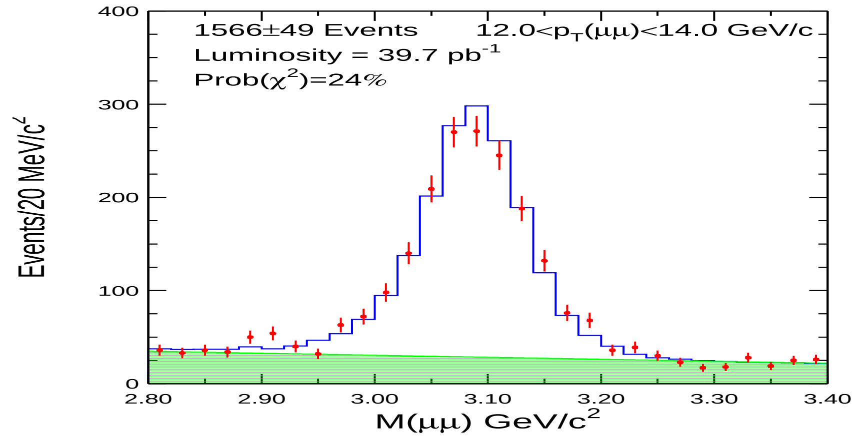
Can now reach $p_t(J/\psi) = 0$ GeV/c.

Counting J/ψs ($p_T = 0$ to 20 GeV/c)

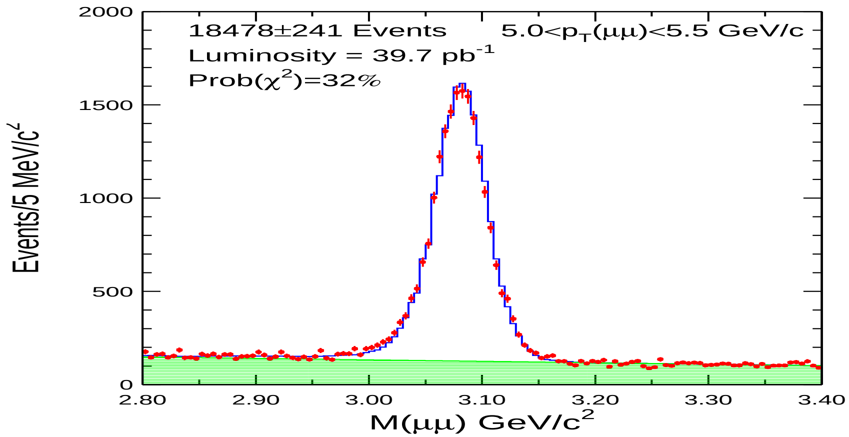
$0 < p_T(J/\psi) < 0.25 GeV/c$



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



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



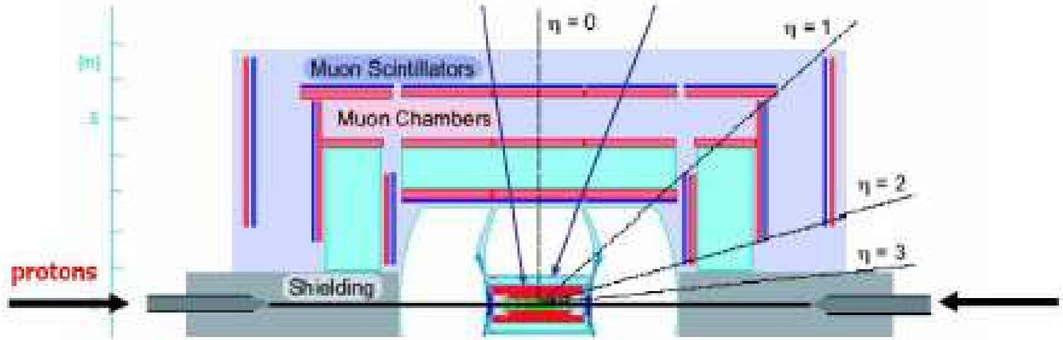
- Transverse momentum resolution: $\delta(p_T)/p_T = 0.003 p_T$
- A detector simulation is used to model the expected shape of the J/ψ signal.

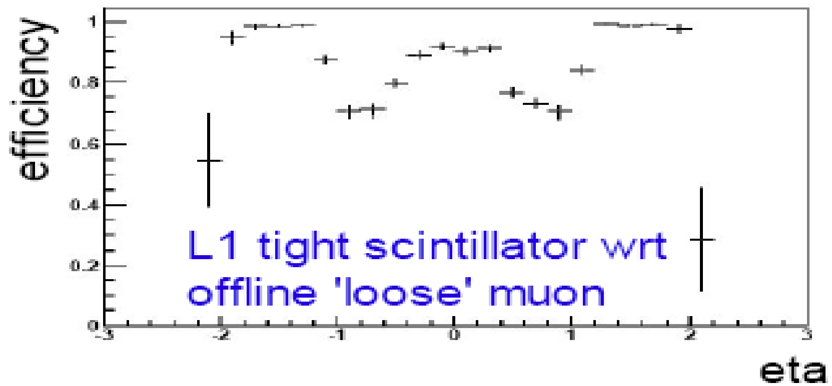
Muon triggers (D0)

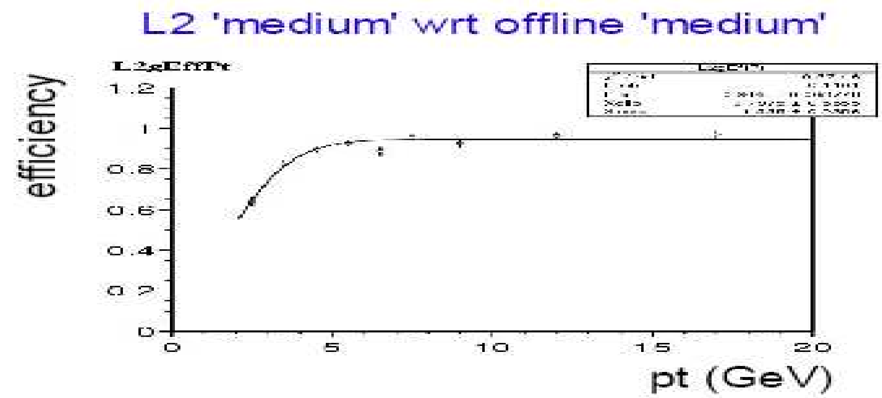
- *Large rapidity coverage up to* $|\eta| < 2.0$
- Offline reco eff:

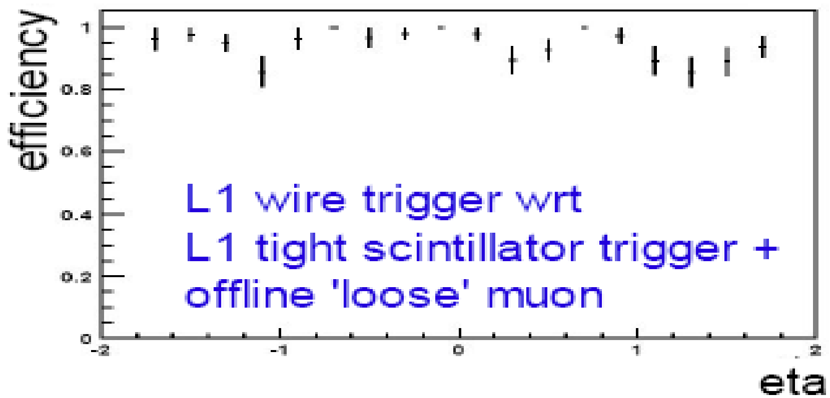
loose $\epsilon = 0.905 \pm 0.0033$

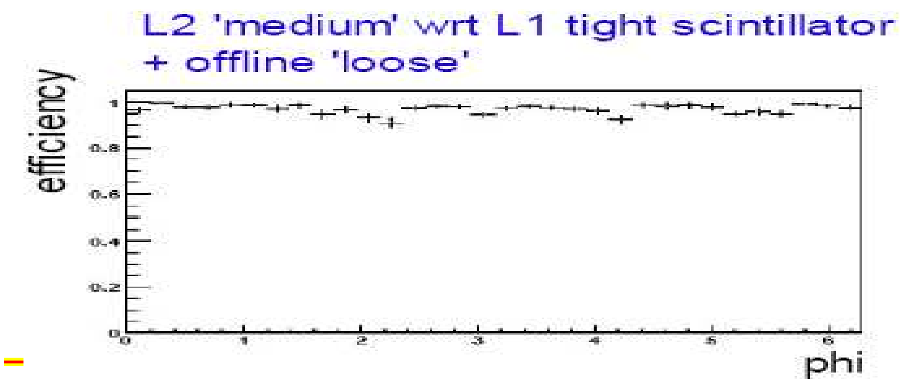
medium $\epsilon = 0.8 \pm 0.0045$







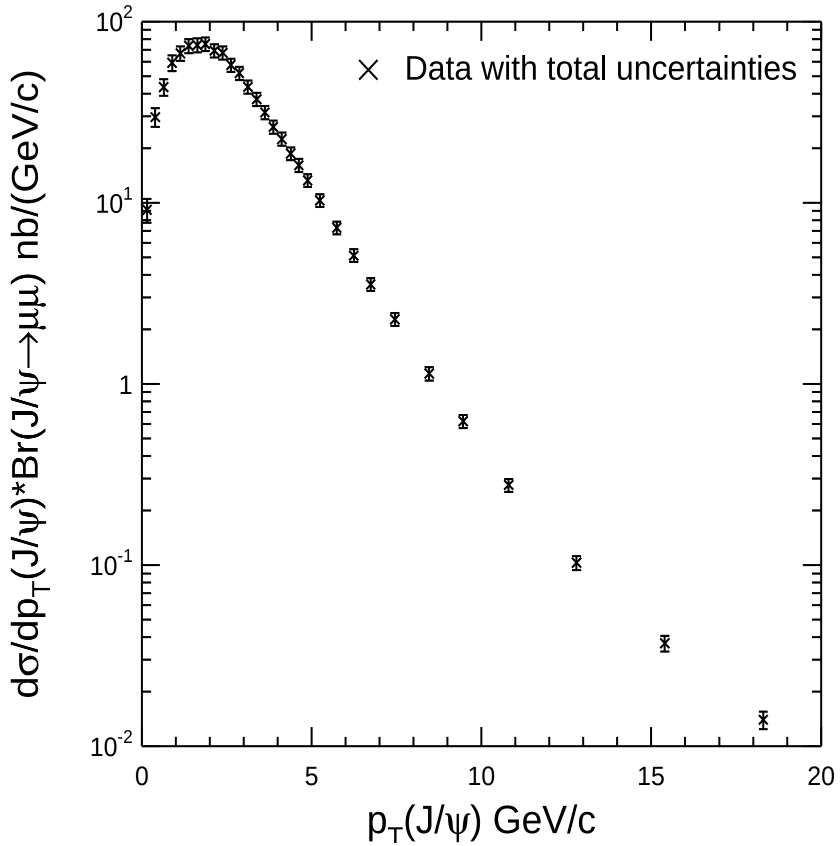




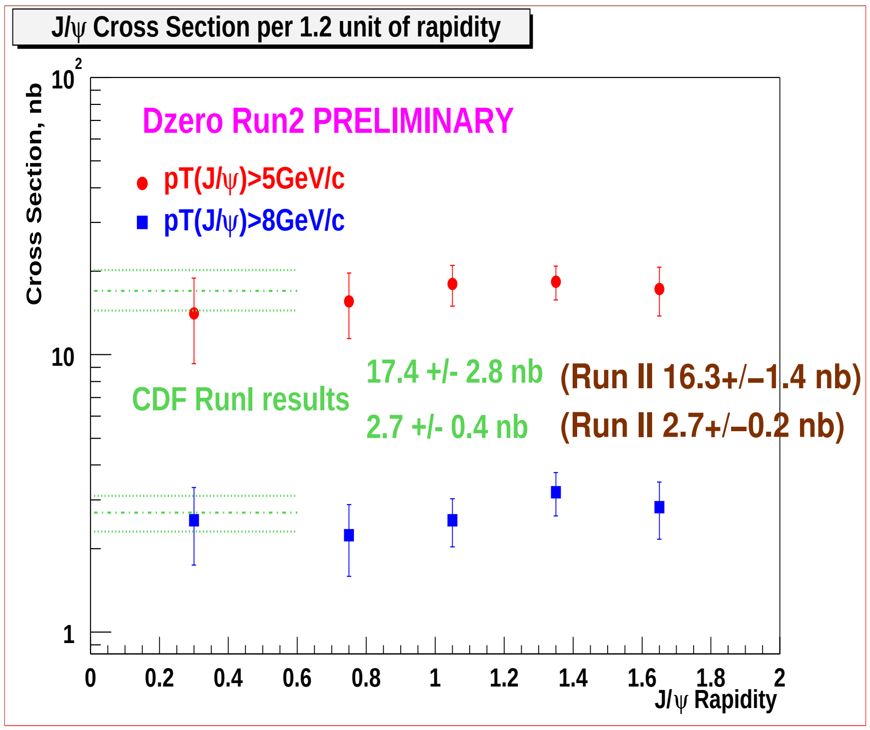
J/ψ Cross-sections - Run II

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

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



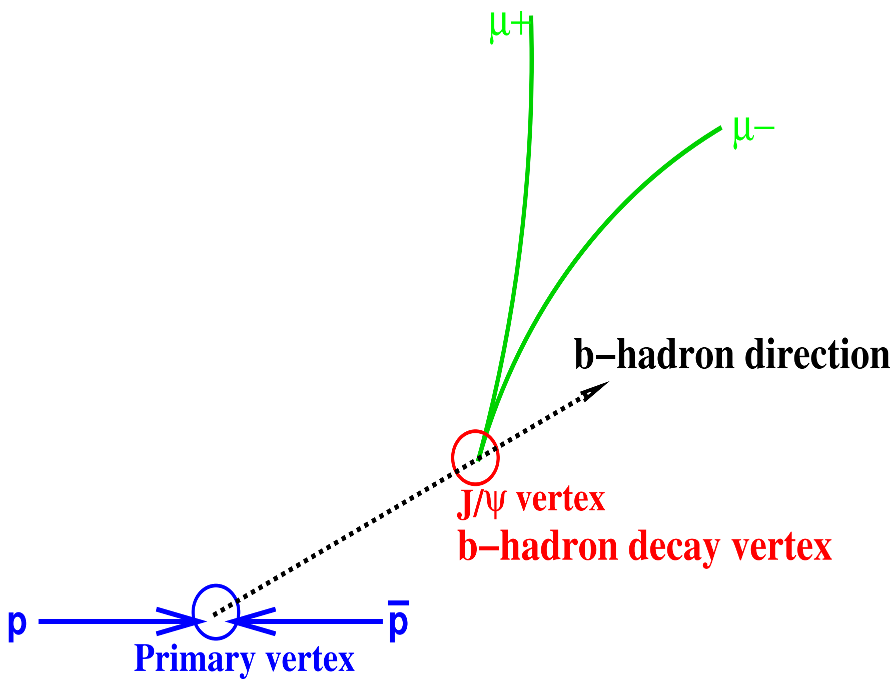
$\sigma(p\bar{p} \rightarrow J/\psi X, p_T > 5, 8GeV/c)$ vs $y(J/\psi)$



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

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 $B \to J/\psi X$

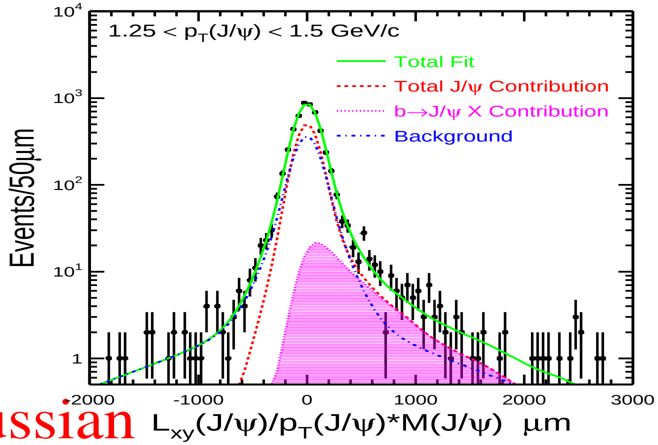


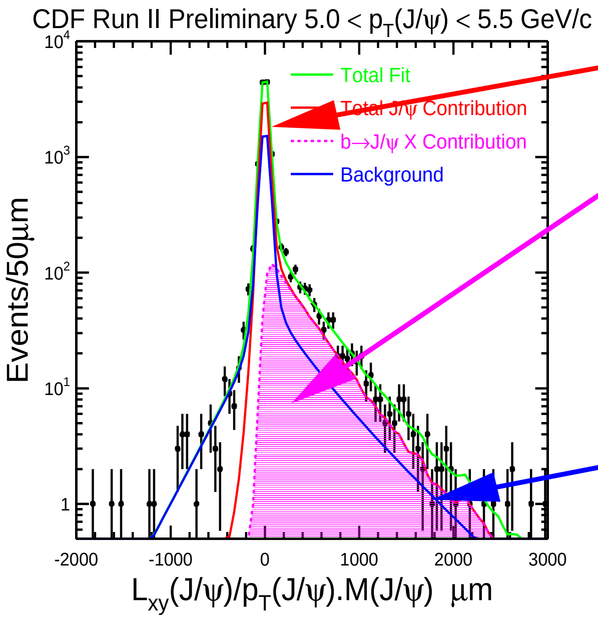
- b-hadrons have long life-times, J/ψ from $H_b \to J/\psi X$ will be displaced.

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, $f_b = 9.4\%$



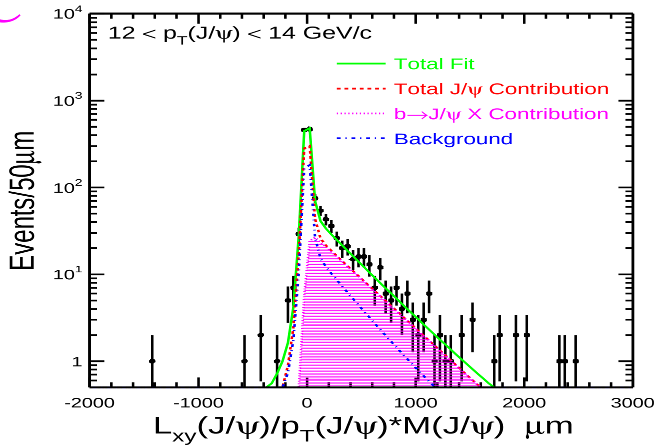


Prompt J/Ψ is a double Gaussian = resolution function

b–>J/Ψ X shape from MC template

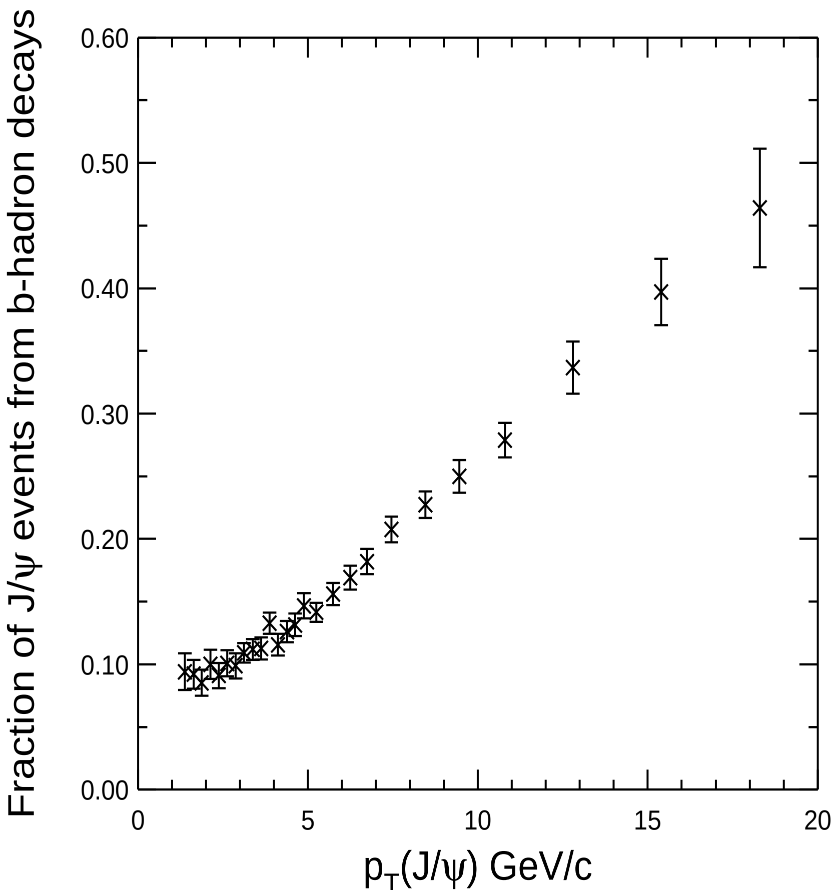
Parameterized background

$12 < p_T < 14$ GeV/c, $f_b = 34\%$

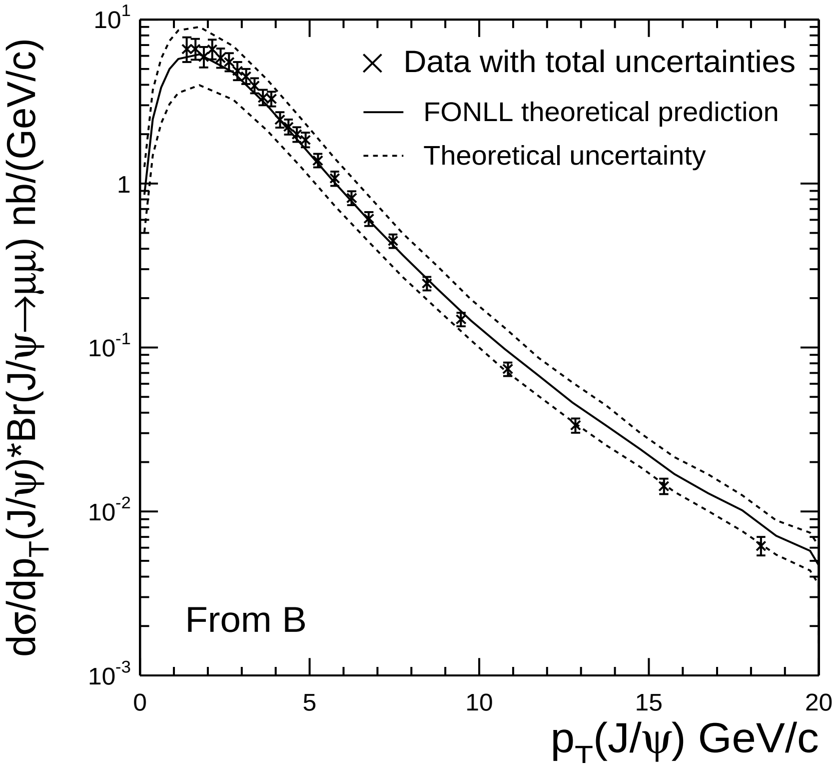


$d\sigma(p\bar{p} \to H_b X)/dp_T(J/\psi)$

Fraction of J/ψs from H_b



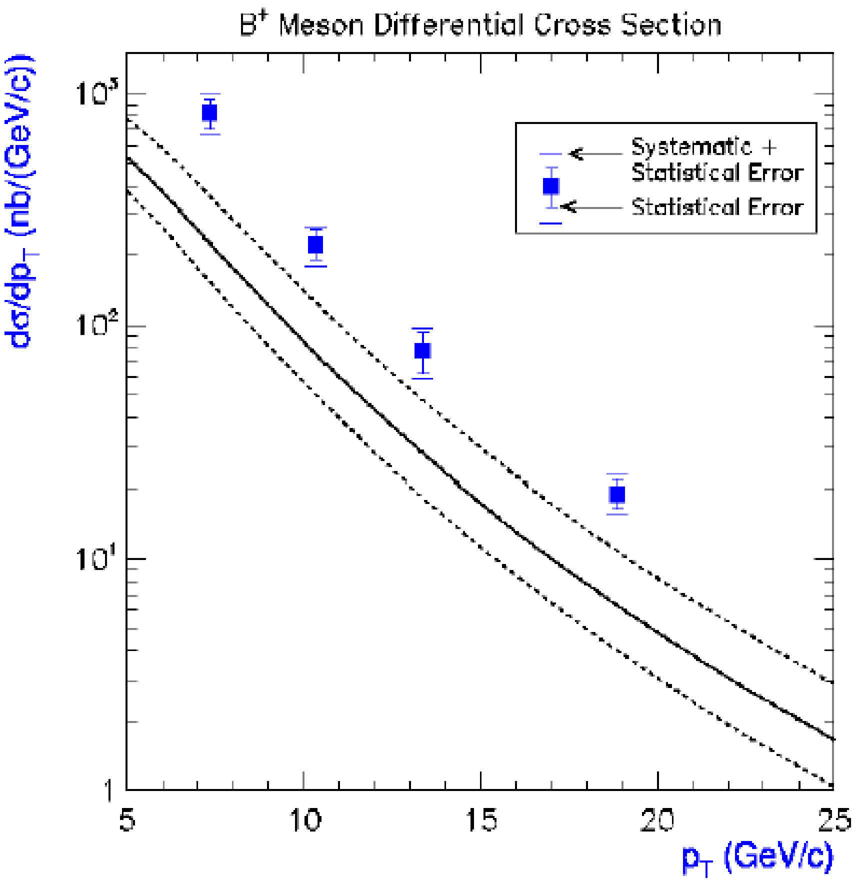
$d\sigma(p\bar{p} \to H_b X, H_b \to J/\psi X)/dp_T(J/\psi)$



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

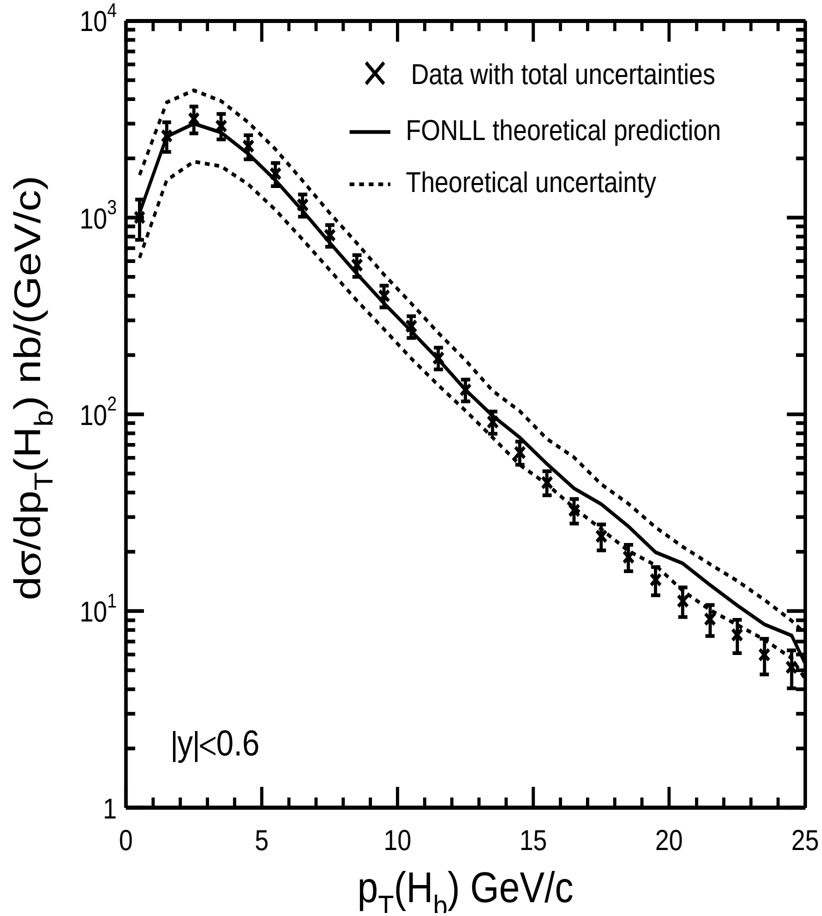
b-Production cross-section

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



1997

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

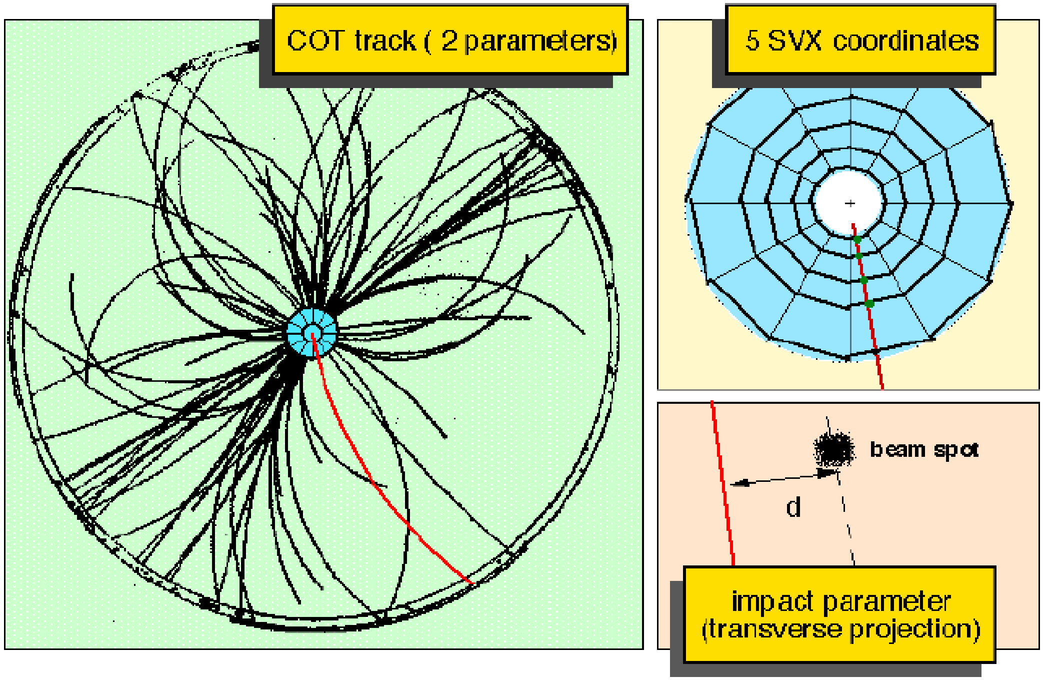


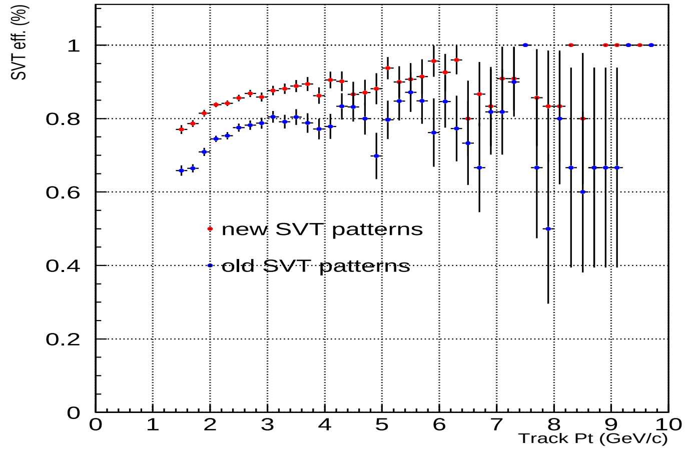
2003

$\sigma_{\text{CDF}} = 17.6 \pm 2.5\mu$b, $\sigma_{\text{FONLL}} = 16.8^{+7.0}_{-5.0}\mu$b (CTEQ6M, $m_b = 4.75$, $\mu = \mu_0$)

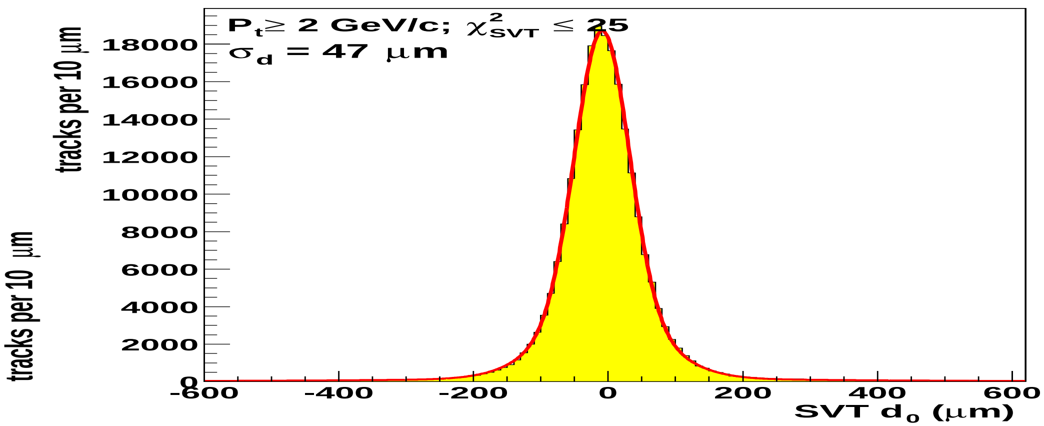
CHARM MESON CROSS-SECTIONS

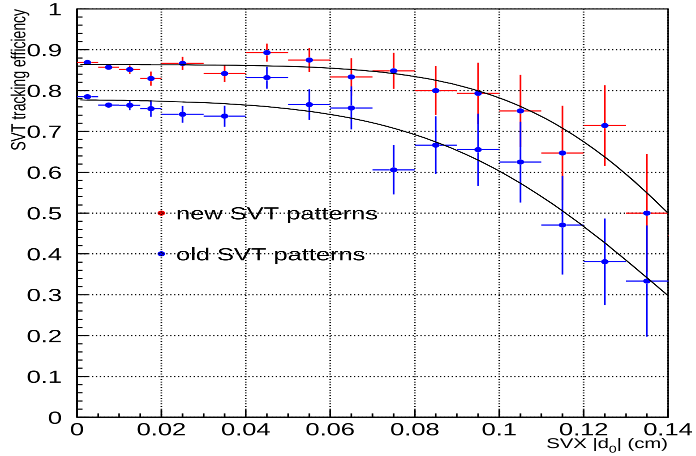
L2 Silicon Vertex Trigger (CDF)





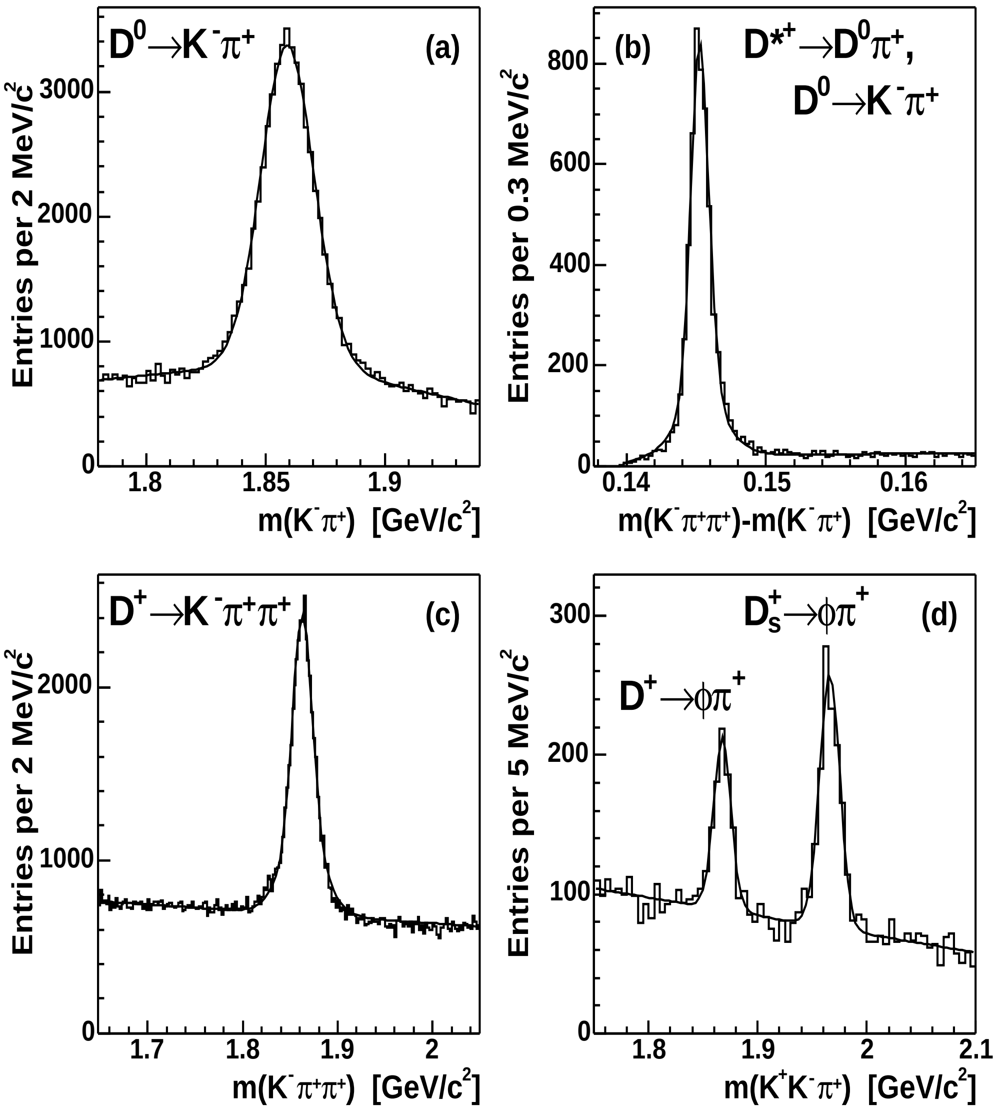
Eff. vs track p_t





SVT Eff. vs track d_0

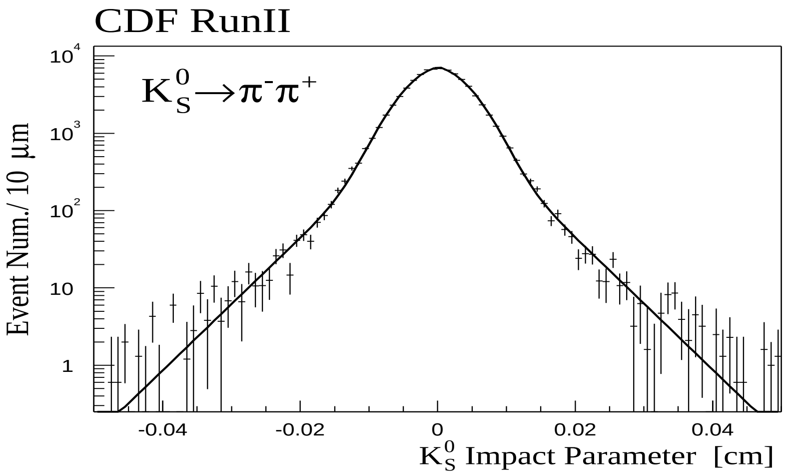
Charm Production in Run II



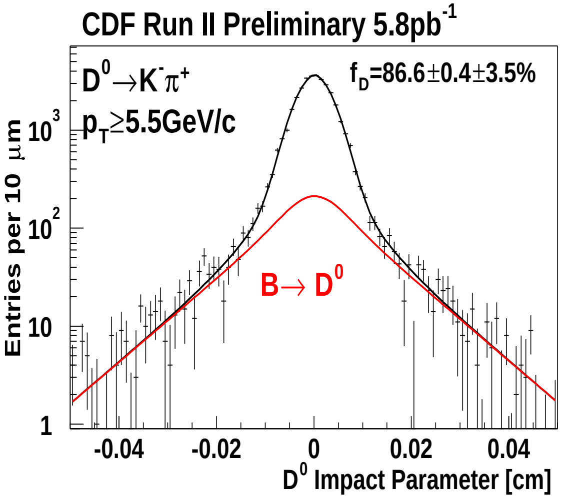
- Analysis uses 5.8pb $^{-1}$ of early 2002 data.
- Challenges: SVT not fully efficient at the time. Efficiency is a complex function of $p_T, z, \cot(\theta)$ and time.

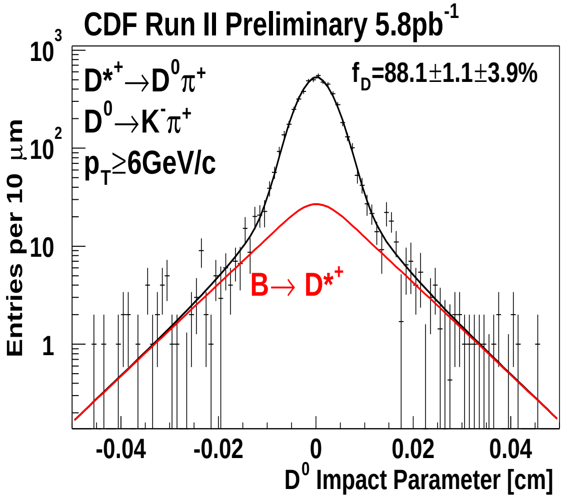
Direct Charm Production Run II

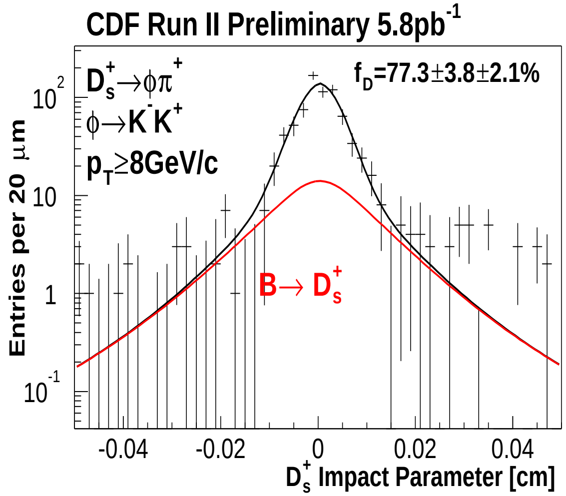
Use impact parameter of reconstructed charm mesons $F_D(d_0)$ *to distinguish* *directly* *produced charm from* $B \to DX$, $F_B(d_0)$



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.

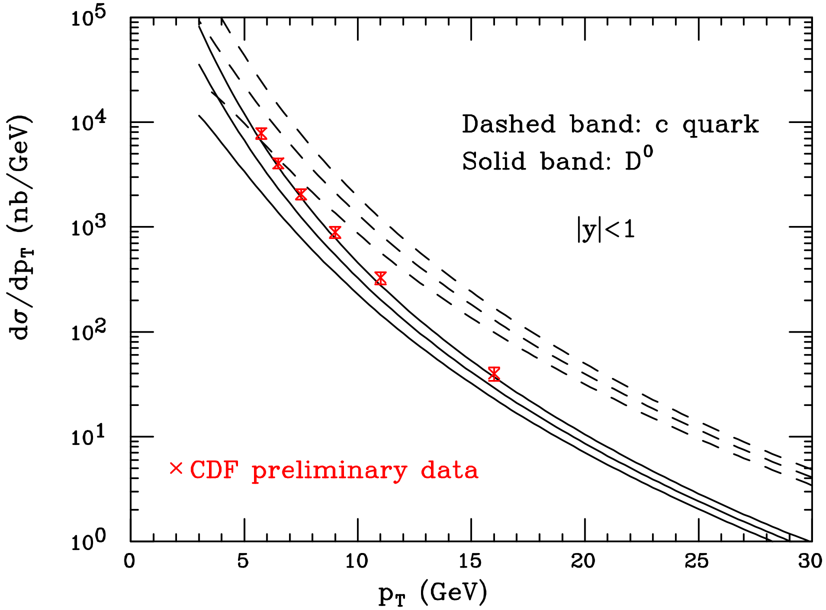




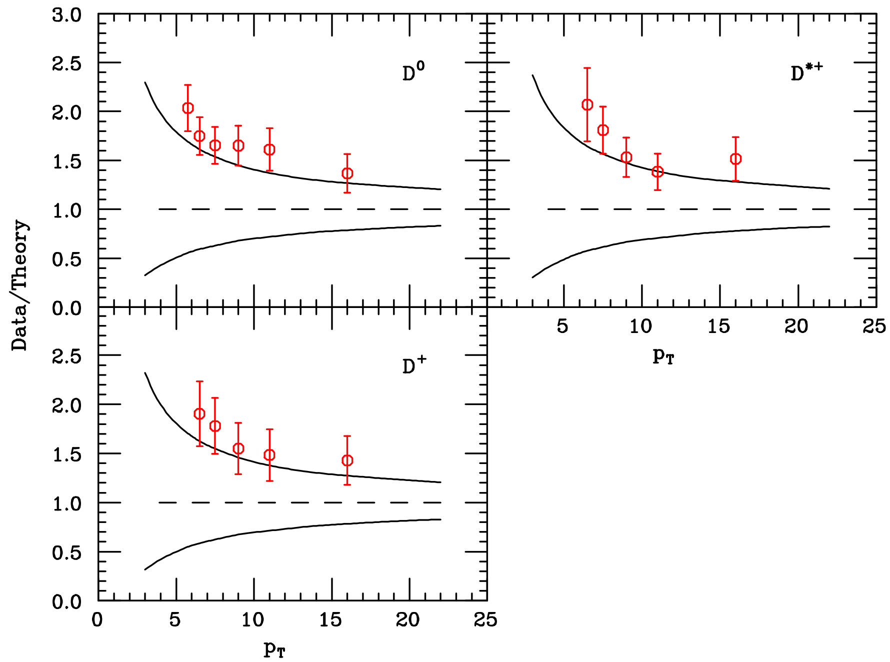


Charm cross-sections

D^0 Meson Differential Cross-section



D Meson Cross-sections Data/Theory



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

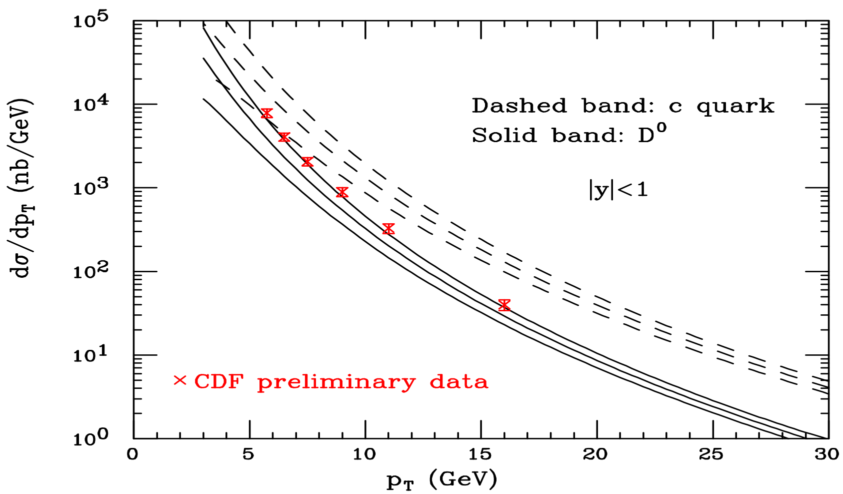
$\sigma(p\overline{p} \rightarrow D^0 X, \mid y \mid < 1.0, p_T > 5.5\ \mathrm{GeV/c}) = 13.3 \pm 0.2(stat) \pm 1.5(syst)\ \mu\mathrm{b}$

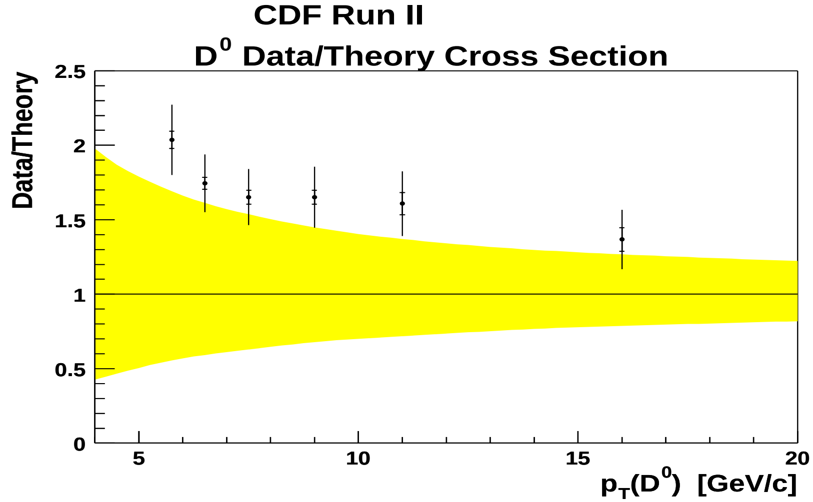
$\sigma(p\overline{p} \rightarrow D^+ X, \mid y \mid < 1.0, p_T > 6.0\ \mathrm{GeV/c}) = 4.3 \pm 0.1(stat) \pm 0.7(syst)\ \mu\mathrm{b}$

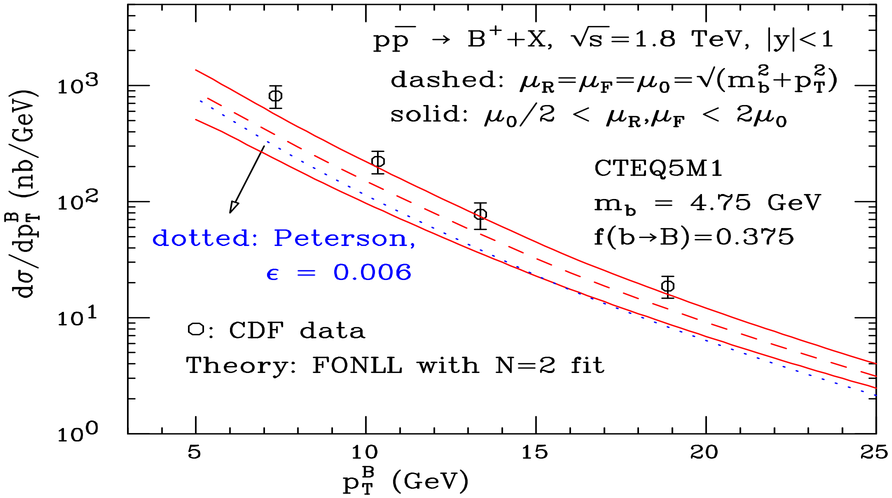
$\sigma(p\overline{p} \rightarrow D^{*+} X, \mid y \mid < 1.0, p_T > 6.0\ \mathrm{GeV/c}) = 5.2 \pm 0.1(stat) \pm 0.8(syst)\ \mu\mathrm{b}$

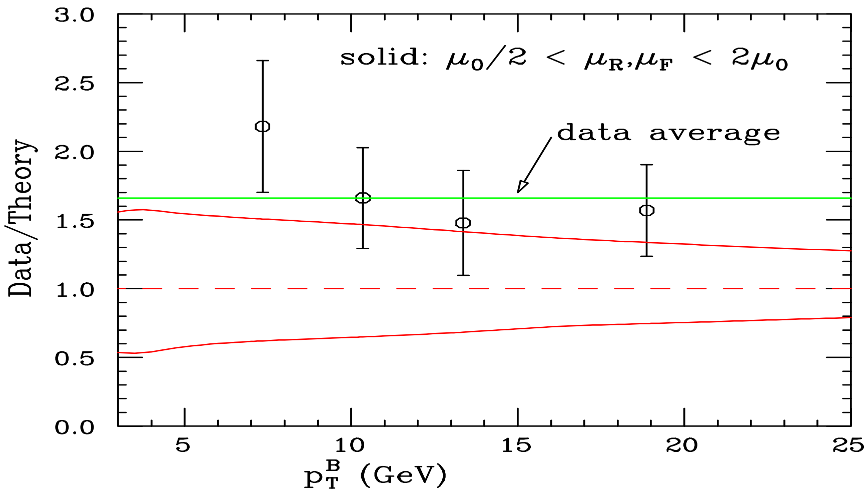
$\sigma(p\overline{p} \rightarrow D_s X, \mid y \mid < 1.0, p_T > 8.0\ \mathrm{GeV/c}) = 0.75 \pm 0.05(stat) \pm 0.22(syst)\ \mu\mathrm{b}$

Charm .vs. Beauty (FONLL)









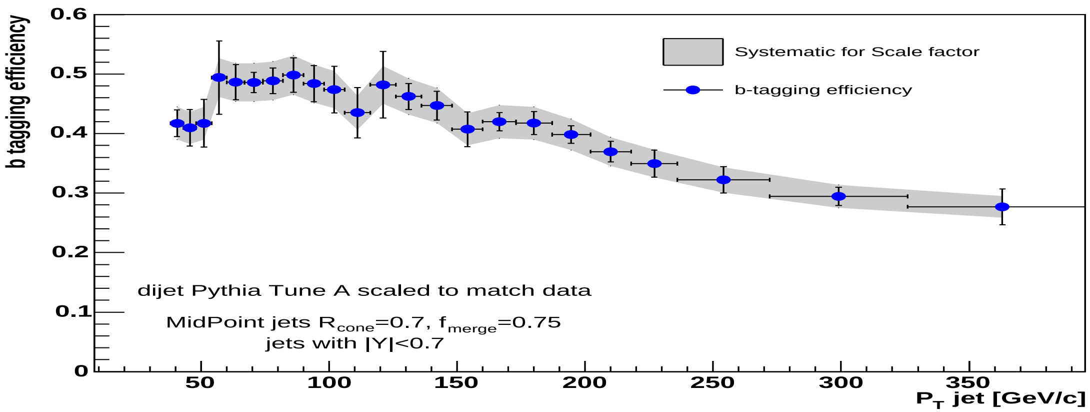
Charm and Beauty meson crossection predictions are consistent

HEAVY FLAVOUR JET PRODUCTION

High p_T b-Jet Production (CDF)

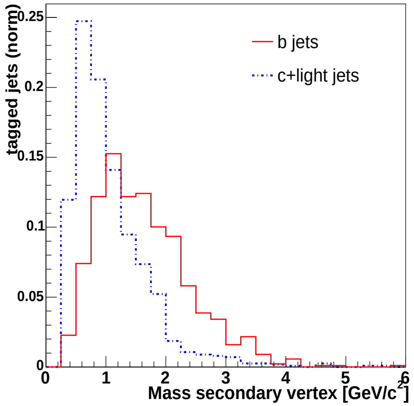
Heavy flavour jets include much of the quark fragmentation remnants $\Rightarrow$ jet cross-sections have small dependence on fragmentation. Good test of QCD at high p_T.

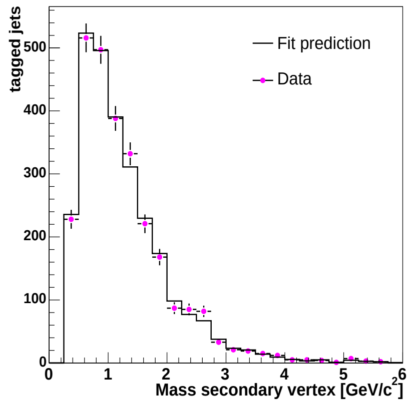
- At CDF, heavy flavour jets are tagged using detached vertices in a jet $L_{xy} > 0$.
- the b-flavor tagging efficiency at very high p_T is measured from MC normalized to data from the 8 GeV inclusive lepton triggers.

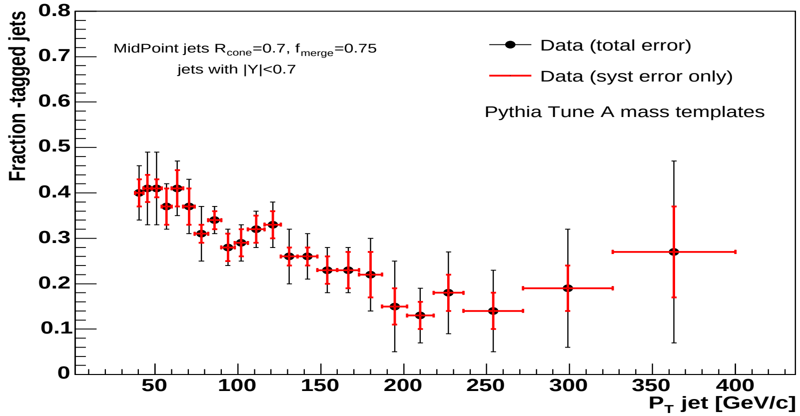


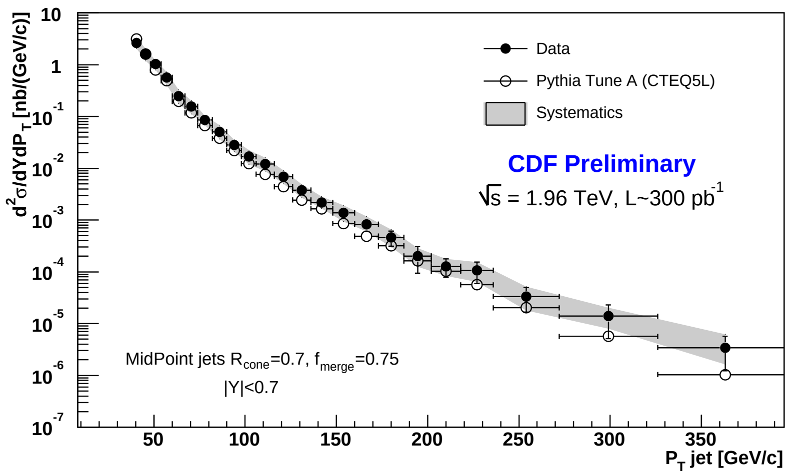
High p_T b-Jet Production (CDF)

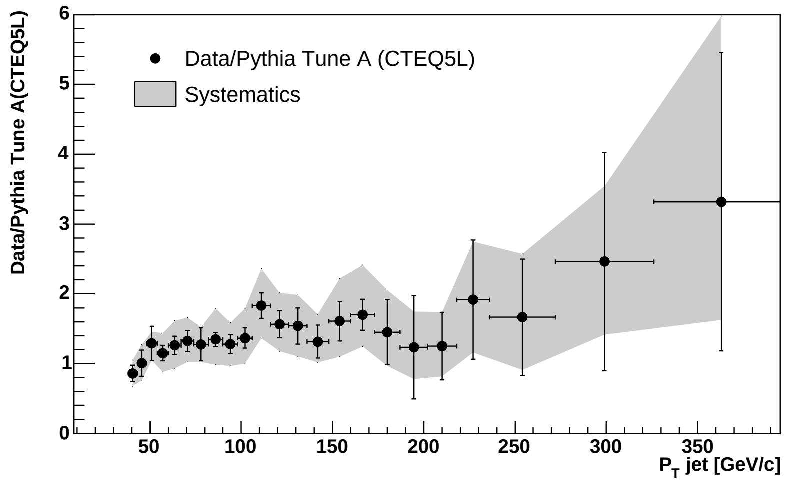
- b/c jet? = fit to the secondary vertex mass:







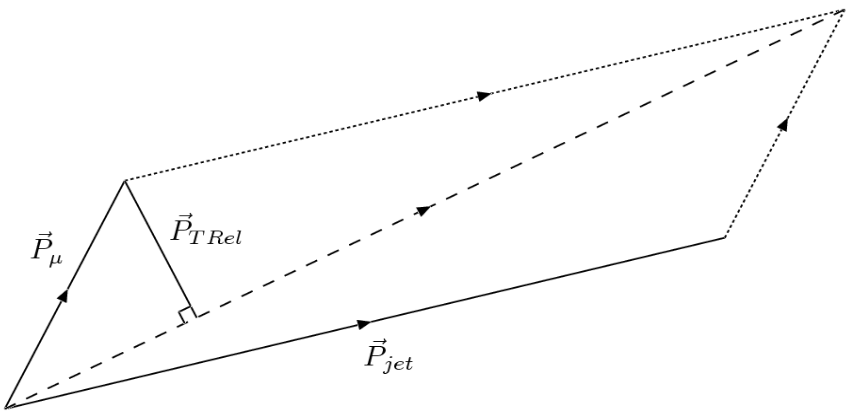


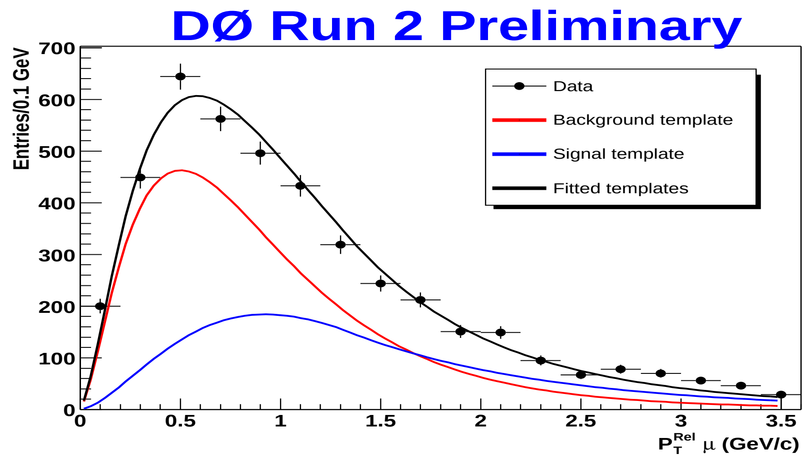


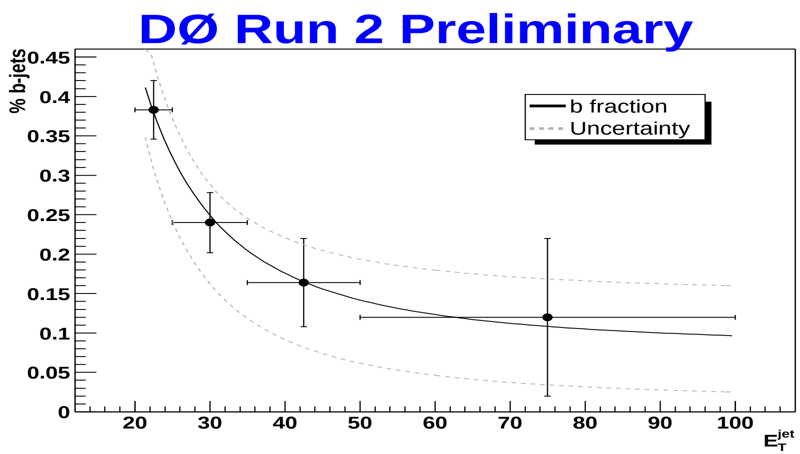
b-jet xsecs: good agreement with Pythia (LO QCD) at high p_T.

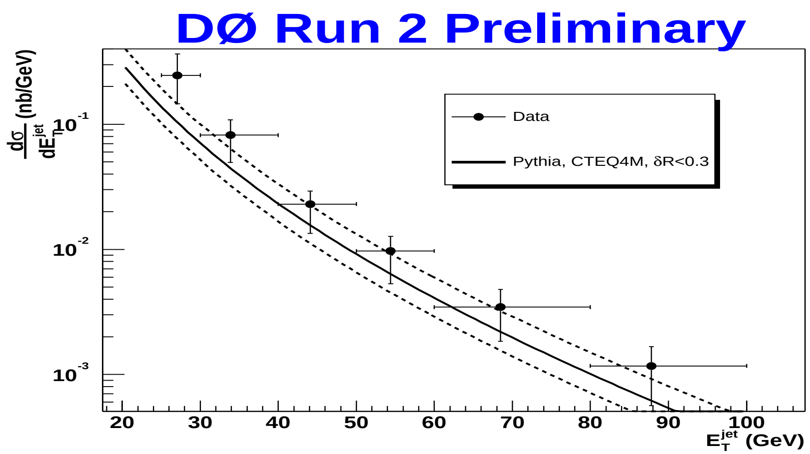
High p_T b-Jet Production (D0)

- Initial D0 analysis using the Run I lepton-jet relative p_T method also indicates good agreement with LO QCD.

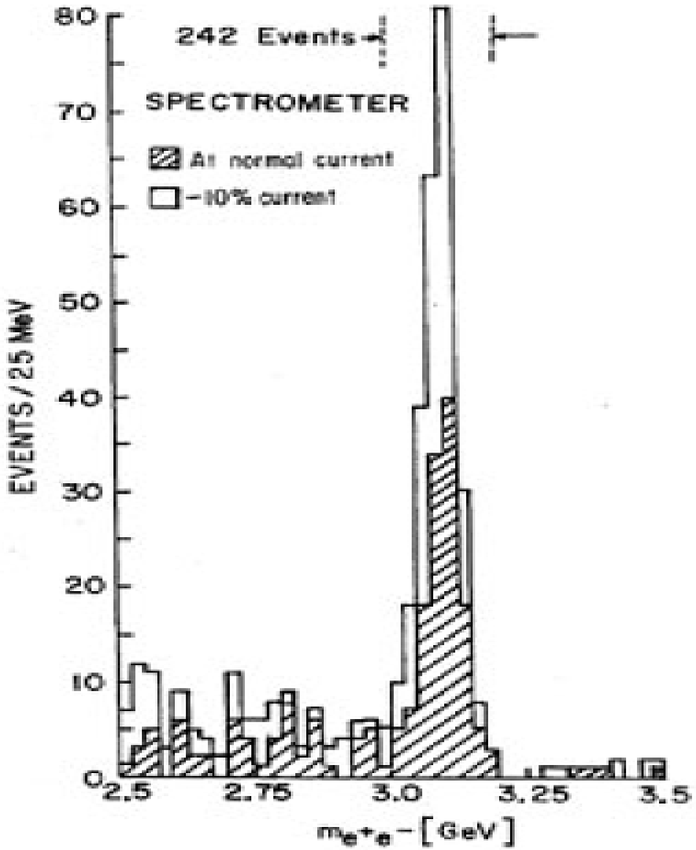








QUARKONIA PRODUCTION

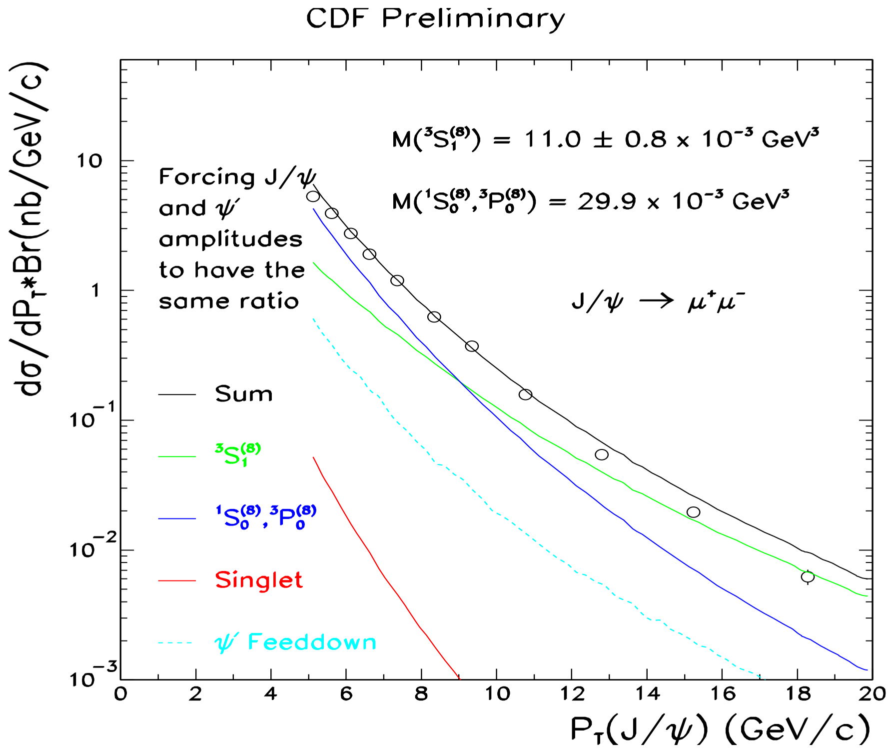


Quarkonia = discovery. J/ψ signal at Brookhaven in 1974

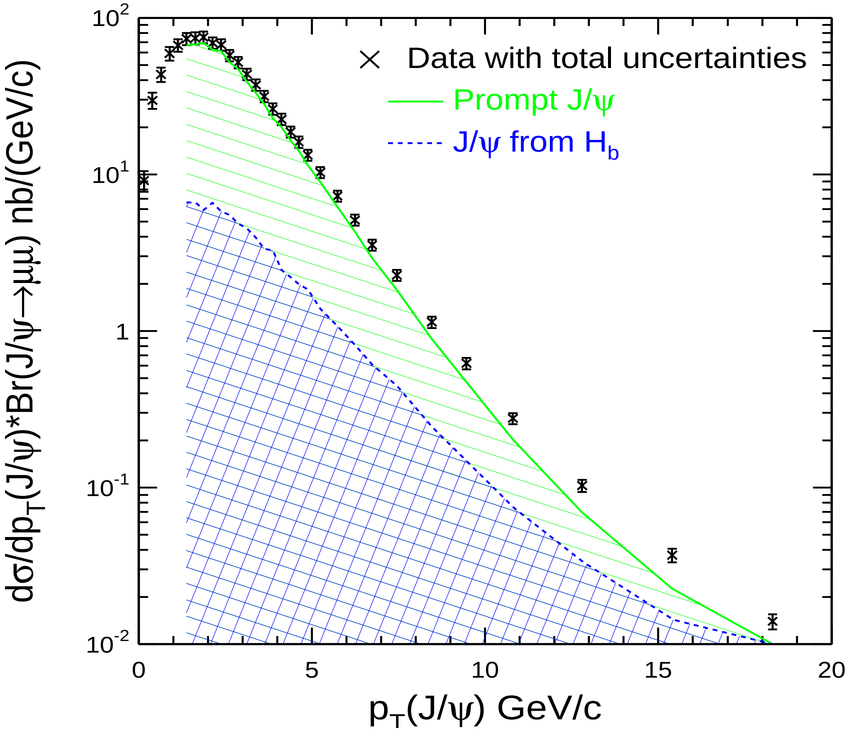
Prompt Quarkonia Production

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)

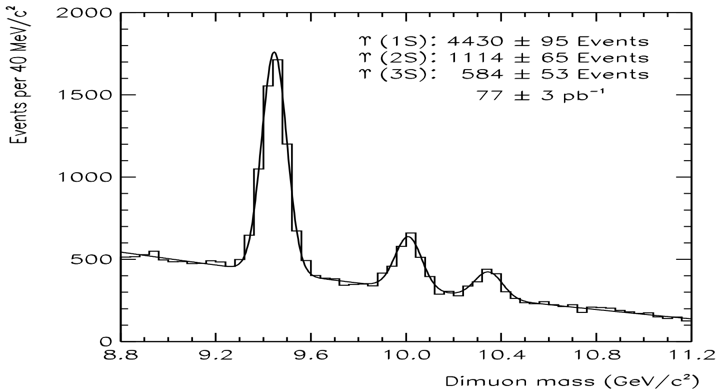


J/ψ production (Run II)

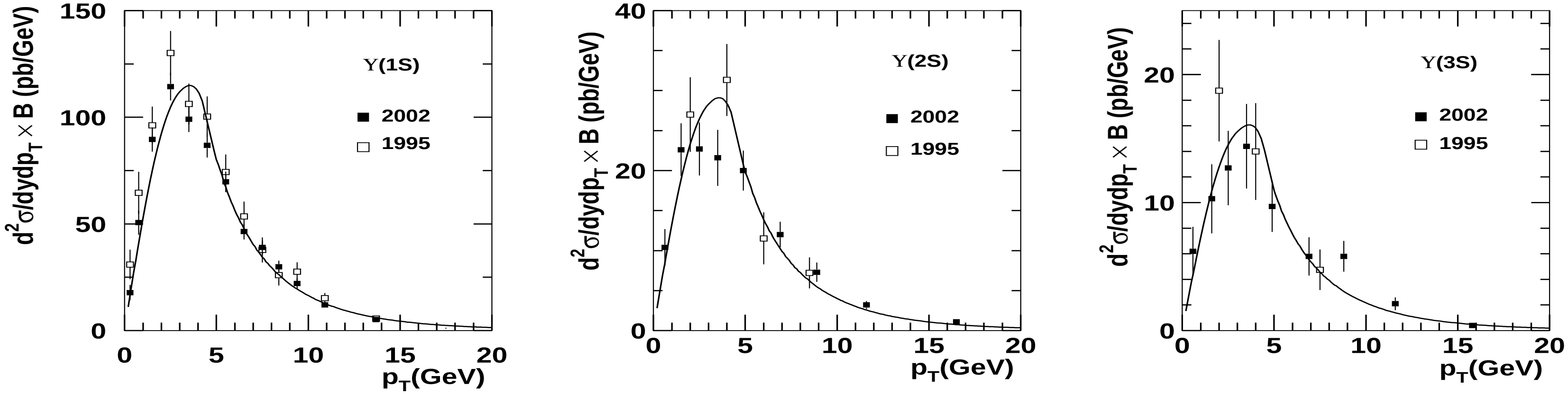
Υ production at $\sqrt{s} = 1.8$ TeV

CDF Run I Υ signals from 77 pb^{-1}

PRL 88, 161802 (2002).



At lower p_t NRQCD non-fragmentation diagrams from other octet matrix elements are important. 2004: Resummation of soft gluon effects $\Rightarrow$ reliable predictions at low p_T (Berger et. al. hep-ph/041108). CDF Run I measurements/theory



Also good agreement with CEM models + k_T kick (R. Vogt).

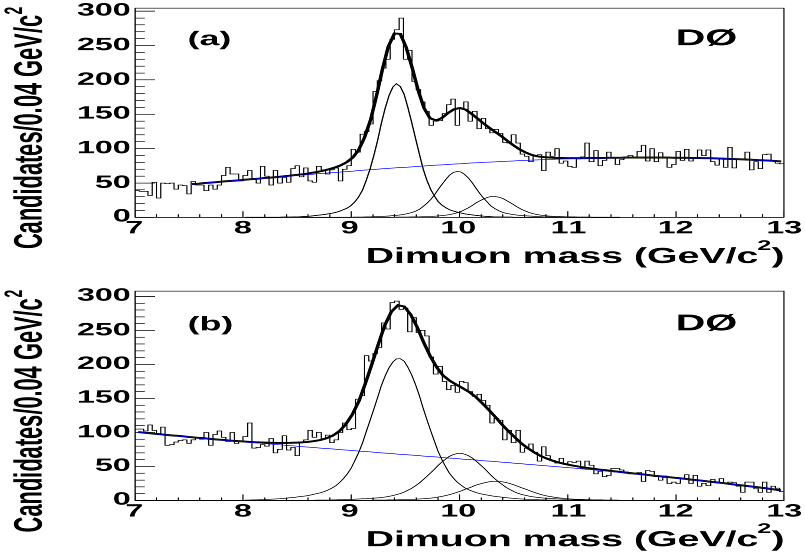
Υ production at $\sqrt{s} = 1.96$ TeV

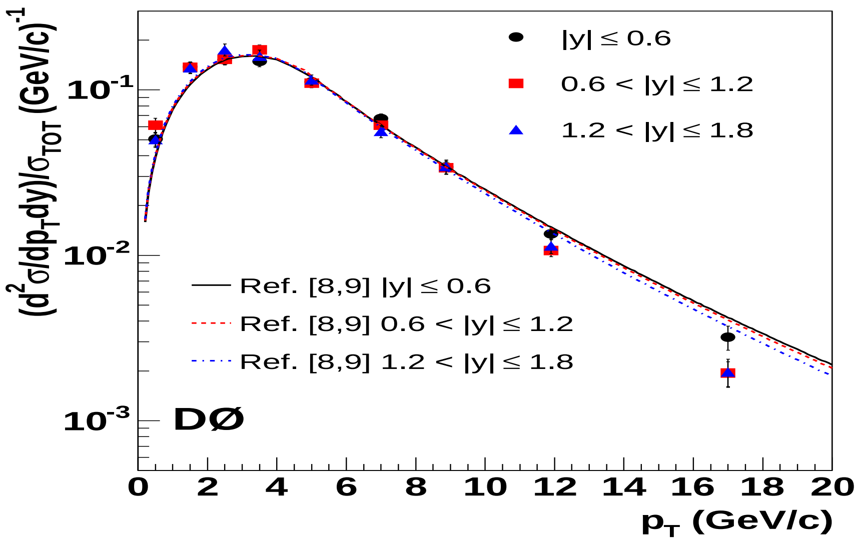
D0 Run II measurements of the Υ cross-sections from 160 pb^{-1}.

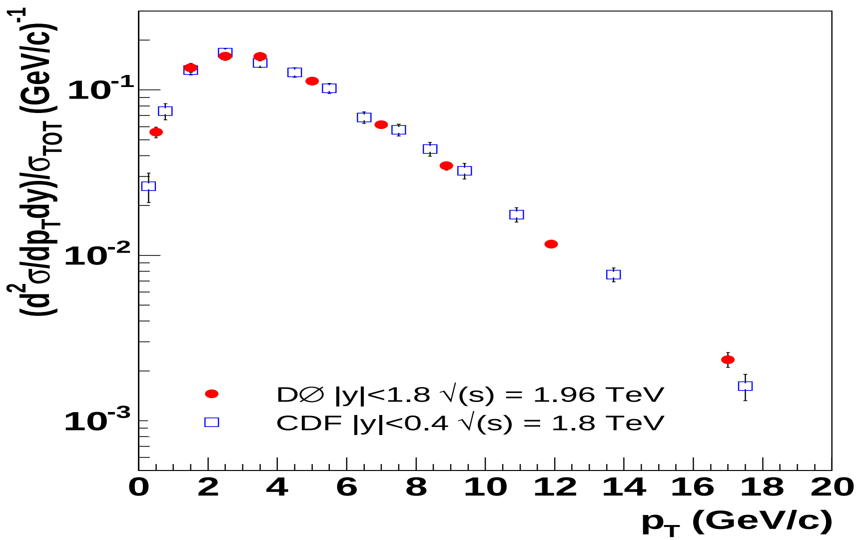
PRL 94, 232001 (2005).

(a) $|y^{\Upsilon}| \leq 0.6$

(b) 1.2 < $|y^{\Upsilon}| \leq 0.6$ < 1.8







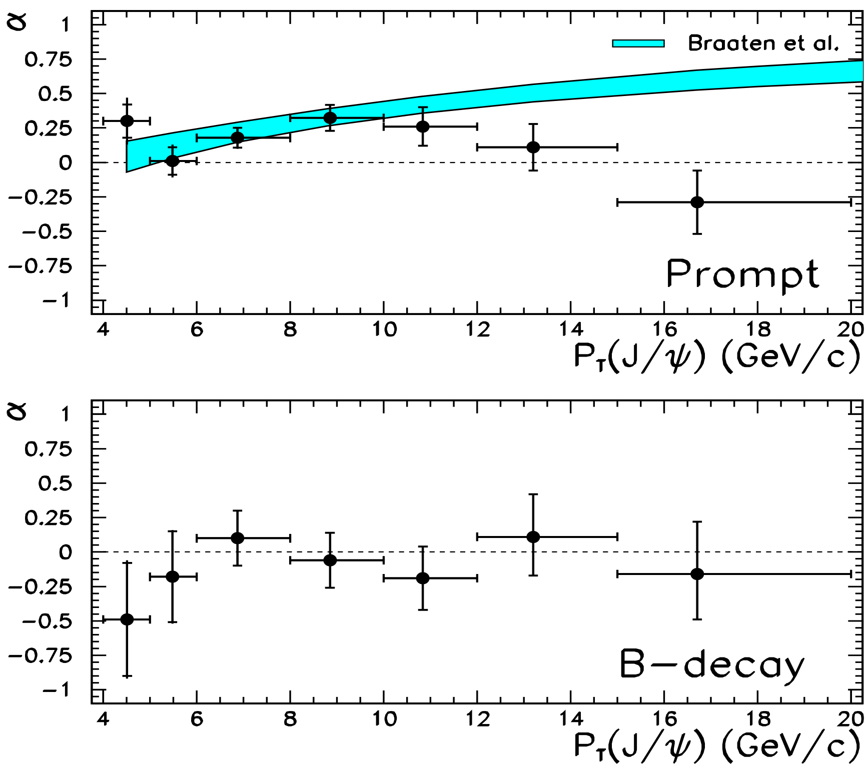
Charmonium Polarization Mystery

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 $b \rightarrow J/\psi X$

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

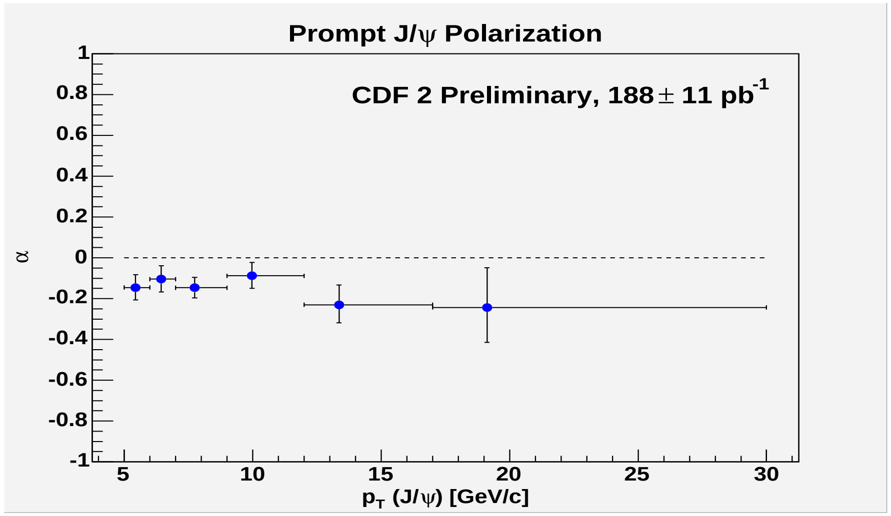
CDF Run I



Is this fatal for the COM?

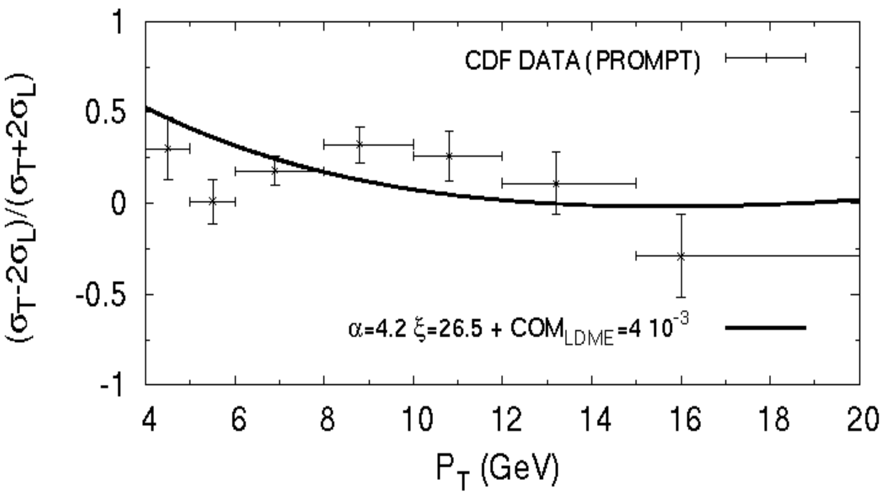
Polarization: new data, theory

CDF Run II measurement of the prompt J/ψ polarization at $\sqrt{s} = 1.96$ TeV. 188 ± 11 pb^{-1}. Both Run I and Run II show increasing longitudinal polarization at higher p_T.



CDF Run II

Lansberg, hep-ph/0507175 (July 2005). *Introduced non-static relativistic effects to the hadroproduction of quarkonia ⇒ contributions which produce only longitudanlly polarized quarkonia.*



CDF Run I

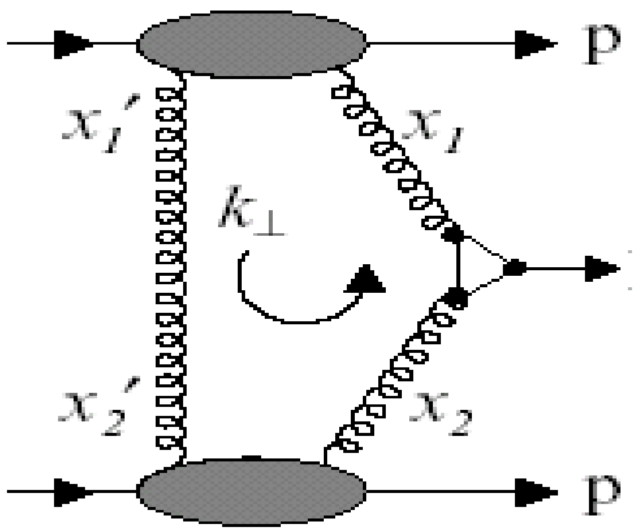
Diffractive production of χ_c

- 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:

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

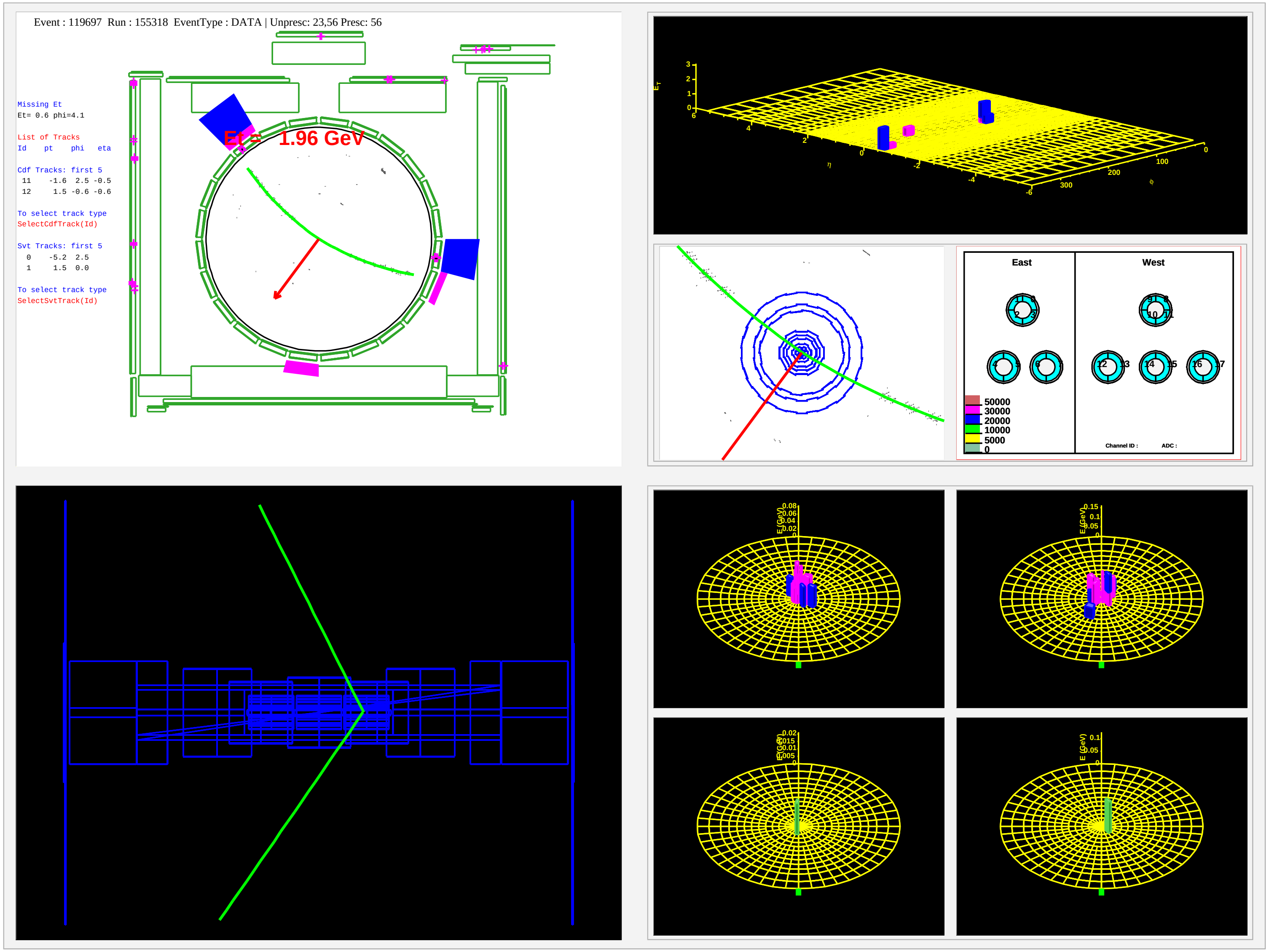


c–loop: χ_c

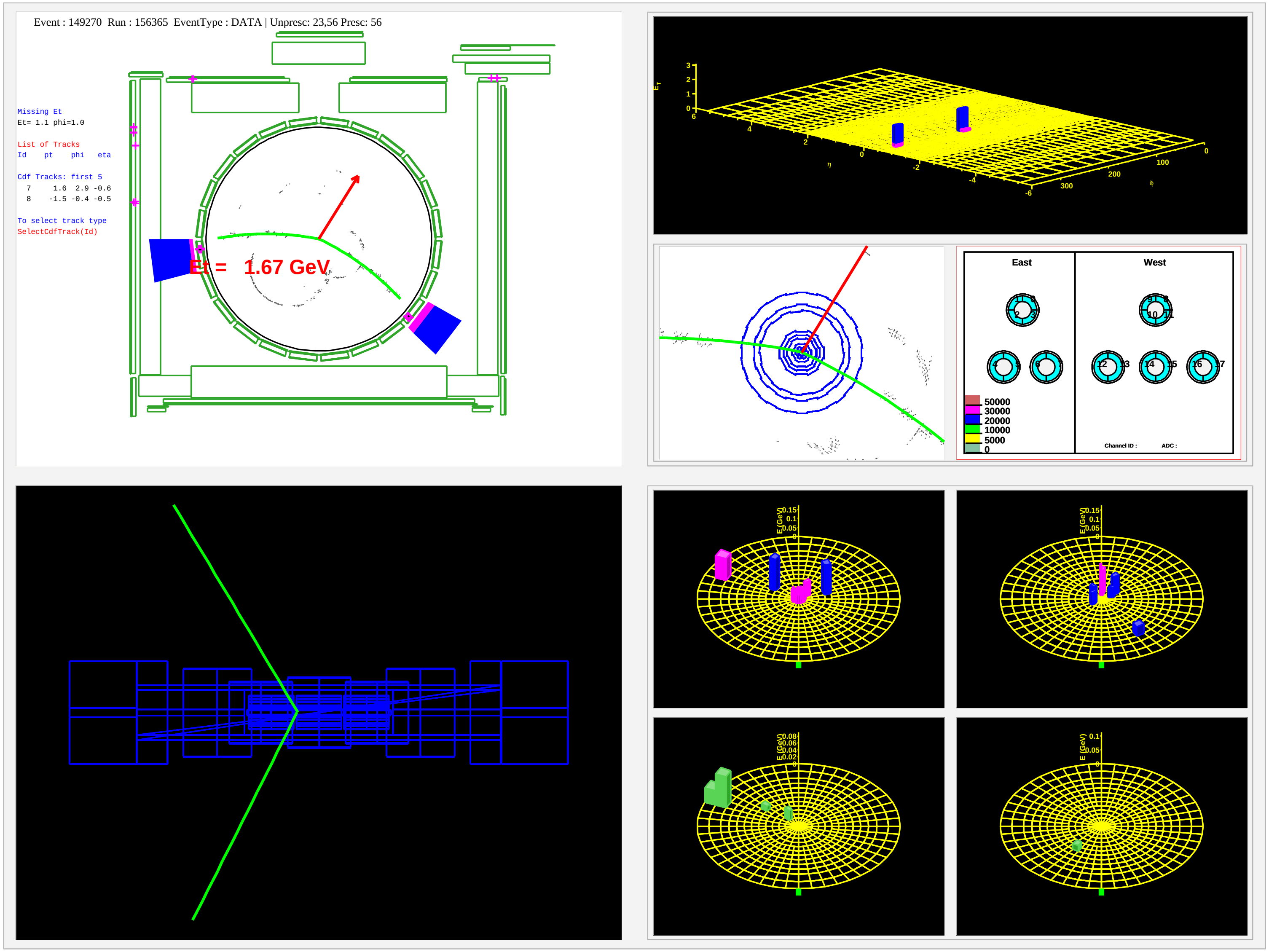
b–loop: χ_b

t–loop: H

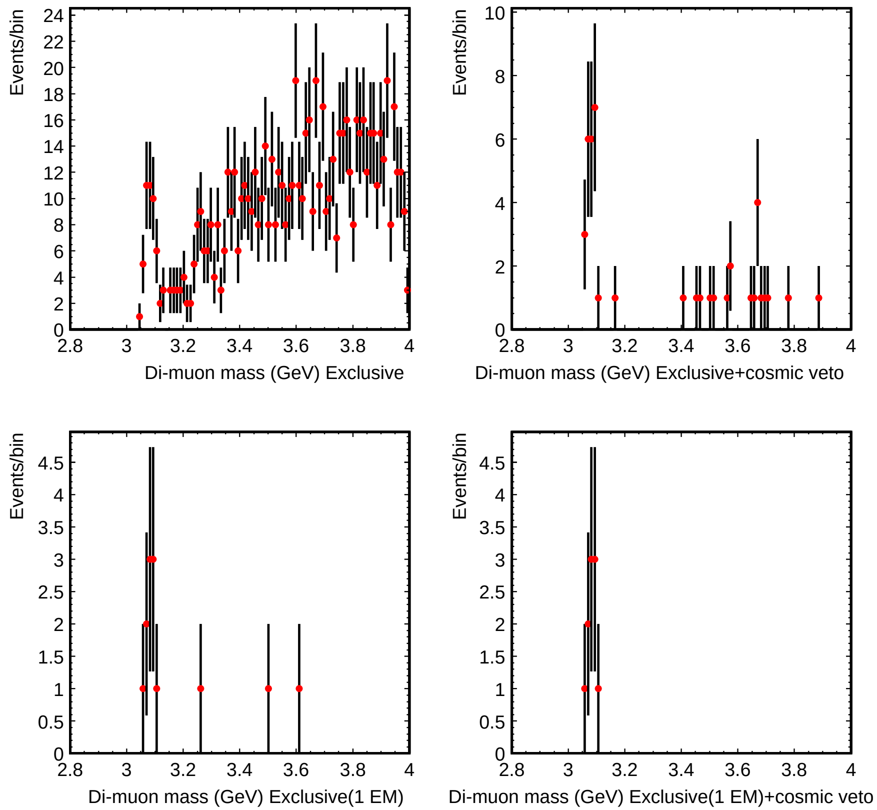
Exclusive χ_c candidate 1

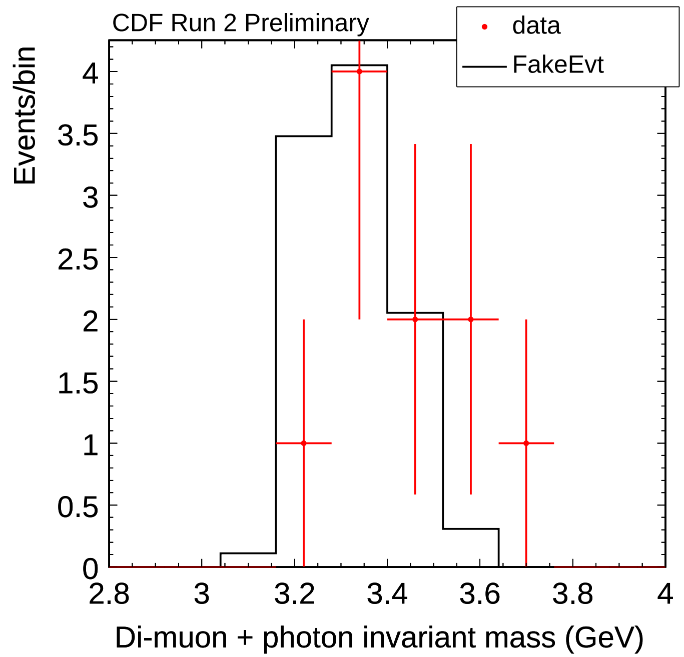


Exclusive χ_c candidate 2



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 at the Tevatron:
  - Quarkonia: New measurements of the inclusive J/ψ cross-sections down to $p_T = 0$ GeV/c (CDF) and $|y| < 2.0$ (D0). New Υ cross-sections (D0). Measurement of J/ψ polarization at $\sqrt(s) = 1960$ GeV (CDF). Diffractive production of exclusive $\mu\mu\gamma$ candidates observed (CDF).
  - Measurement of the central b-hadron cross-sections over all p_T (CDF) and b-jet cross-sections at $\sqrt(s) = 1960$ GeV (CDF/D0)
  - $D^{+,0,*}$, D_s cross-sections published (CDF).

- Lots of theory advances:
  - New PDF fits to proton structure data and better understanding of uncertainties.
  - New factorization schemes: k_T
  - Resummation of NLL for factorization schemes where quarks are massive - now valid for all p_T
  - Improved treatments of heavy quark fragmentation
  - New calculations of low p_T quarkonia production and charmonium polarization.

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.