B Production and ONIUM Production at the Tevatron

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Outline (B Production)

- Introduction
- Brief Summary of "old" Results
- Forward μ and b-Quark Production (DØ)
  - Analysis procedure
  - Inclusive μ cross section
  - b-produced μ cross section
  - Rapidity dependence
- $b\bar{b}$ Rapidity Correlations (CDF)
  - Analysis procedure
  - Ratio forward–central / central–central
  - Probing the gluon distribution
- Outlook

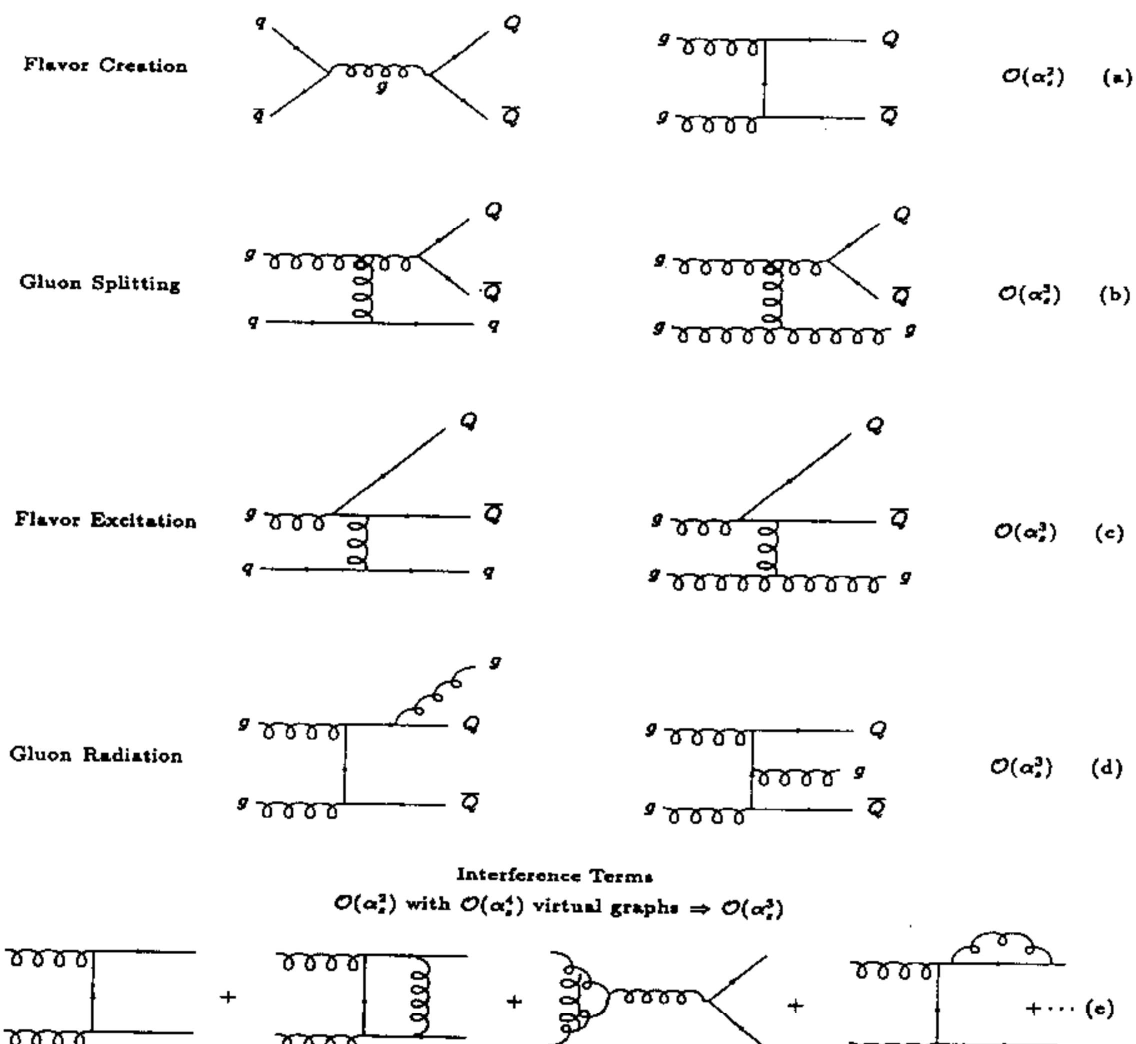
$b\bar{b}$ production in pQCD

$$O(\alpha_s^3) \sim O(\alpha_s^2)$$

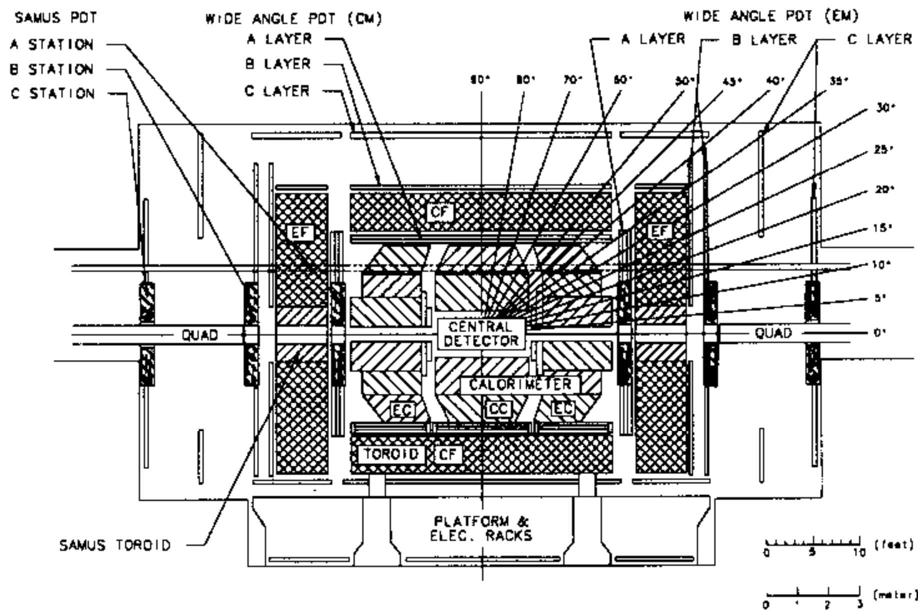
$O(\alpha_s^2) \rightarrow$

$O(\alpha_s^3) \rightarrow$

$\downarrow$



DØ Muon Spectrometer



- Wide Angle Muon System (WAMUS)
  - Coverage: $\mid \eta^\mu \mid < 2.4$ $\qquad \eta = -\ln(\tan(\theta/2))$
    - in these analyses: $\mid \eta^\mu \mid < 0.8$
  - Momentum resolution:
    $\Delta p/p = \sqrt{(0.18)^2 + (0.008p)^2} \quad (p \text{ in GeV/c})$
- Small Angle Muon System (SAMUS)
  - Coverage: $1.7 < \mid \eta^\mu \mid < 3.3$
    - in these analyses: $2.4 < \mid \eta^\mu \mid < 3.2$
  - Momentum resolution:

$$\begin{aligned} \Delta p/p &= 19\% \text{ at } p = 20\,\text{GeV/c} \\ &= 25\% \text{ at } p = 100\,\text{GeV/c} \end{aligned}$$

Beauty Production in Hadron Collisions

Motivation

- Test of perturbative QCD
  - *b* production has been calculated in pQCD to next-to-leading order ($\mathcal{O}(\alpha_s^3)$):
    * P. Nason, S. Dawson and R. K. Ellis
    * W. Beenakker, W. L. van Neerven, R. Meng, G. A. Schuler and J. Smith
    * M. Mangano, P. Nason, G. Ridolfi
  - NLO $\sim$ LO
  - (running) α_s measurement

- Probe gluon densities [redacted]

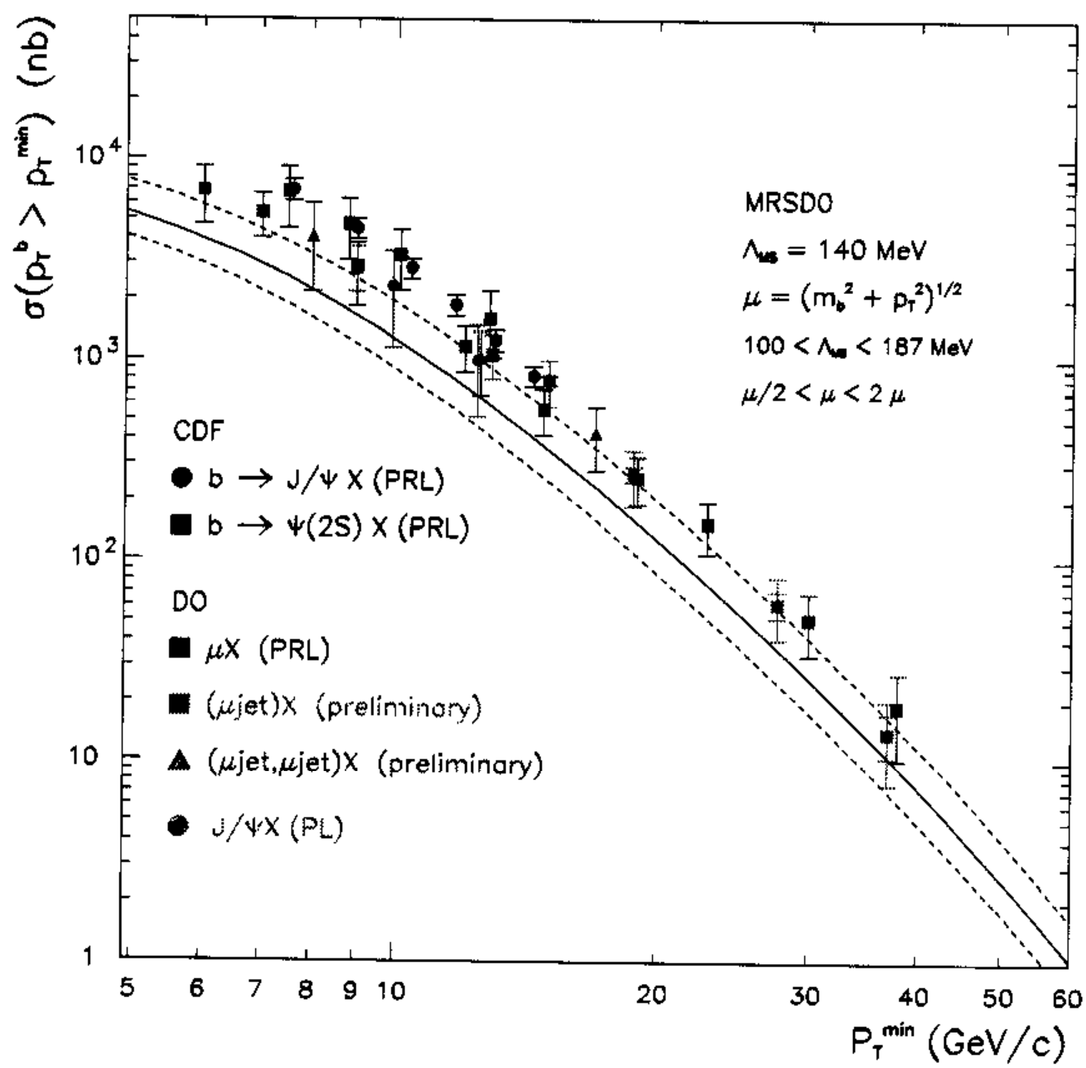
- Heavy quarkonium production mechanisms

- Gluon fragmentation (μ's in jets)

- Reliable predictions of *b* cross-section for future experiments (CP violation, B_s mixing, rare decays)

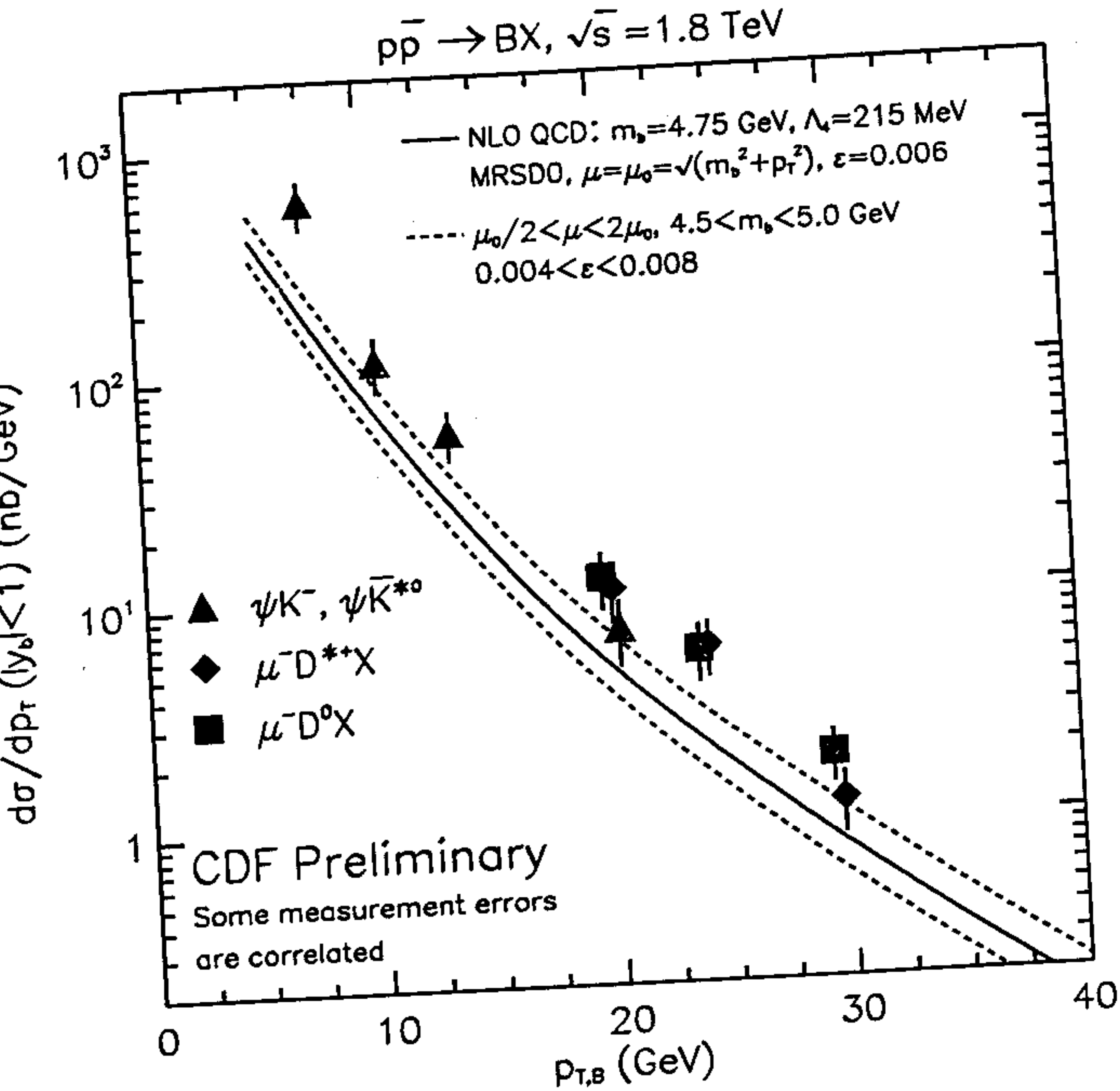
b-Quark Production in Central Region

- **Inclusive *b*-Quark production cross section at $\sqrt{s} = 1.8$ TeV for $| y^b | < 1$:**



⇒ **Data/Theory:**

- ≈ **2.1** **DØ** ⇒ (≈ **2.5 with ISAJET 7.37**)
- ≈ **2.8** **CDF**



pp̄ → BX, √s = 1.8 TeV
NLO QCD: m_b=4.75 GeV, Λ_4=215 MeV
MRSD0, μ=μ_0=√(m_b²+p_T²), ε=0.006
μ_0/2<μ<2μ_0, 4.5<m_b<5.0 GeV
0.004<ε<0.008
ψK⁻, ψK̄*⁰
μ⁻D*⁺X
μ⁻D⁰X
CDF Preliminary
Some measurement errors
are correlated
dσ/dp_T (|y_b|<1) (nb/GeV)
p_T,B (GeV)

Inclusive Forward *b* Production (DØ)

- Analysis based on Small Angle Muon System (SAMUS).

  - 3 layers of drift tubes
  - Toroidal magnet between first and second layer
  - Coverage: $2.2 < |\eta^\mu| < 3.3 \quad \eta = -\ln(\tan(\theta/2))$
  - Momentum resolution (p in GeV/*c*):

$$\Delta p/p = \sqrt{(0.25\,\frac{p-5.3}{p})^2 + (0.21\,p)^2}$$

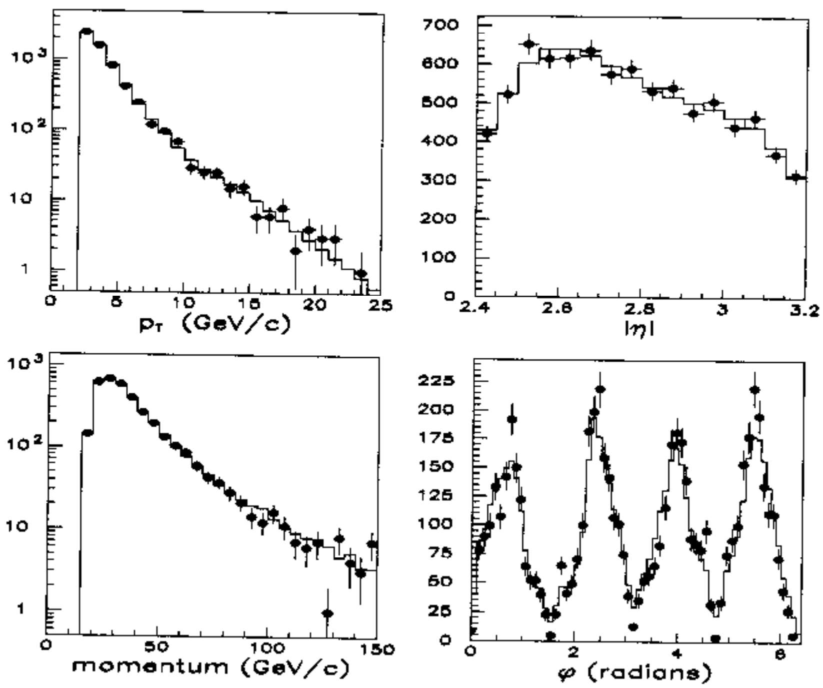
- Special 1994-95 runs — $\int \mathcal{L} dt = 111 \pm 6\ \text{nb}^{-1}$

  - $2.4 < |\eta^\mu| < 3.2$
  - $p_T^\mu > 2$ GeV/c
  - $p^\mu < 150$ GeV/c
  - Quality cuts
  - Calorimeter confirmation
  - Single interaction events

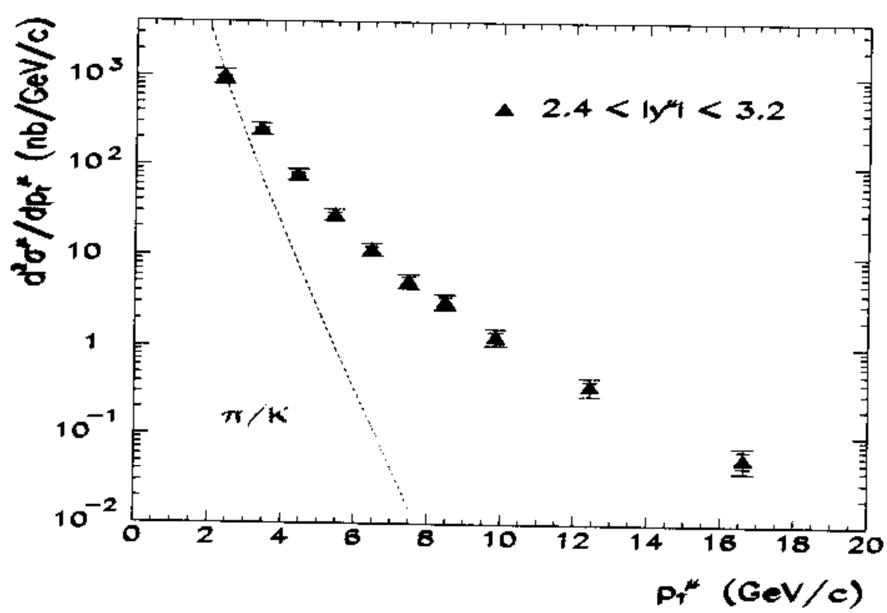
$\Rightarrow$ 6709 events

Inclusive Muon Cross Section

- **Muon detection efficiencies determined with MC**
- **Reconstructed MC distributions match data:**



- **Unfolded p_T spectrum of forward muons:**

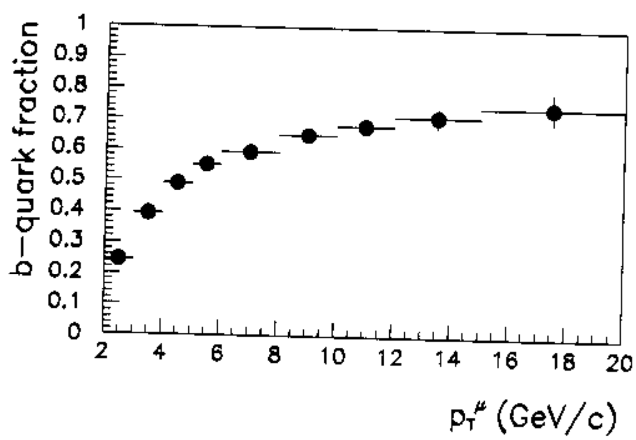


Extraction of *b*-Quark Contribution

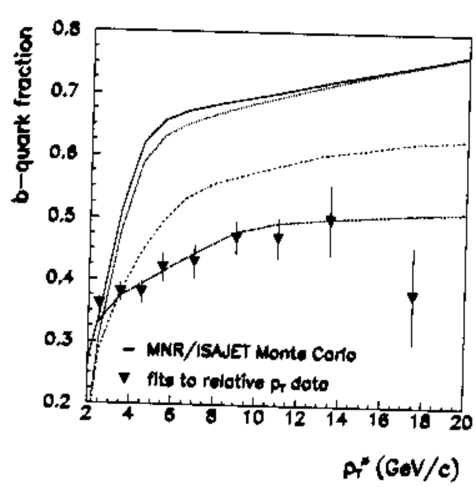
- Contribution from $\pi/K \to \mu$ taken from ISAJET.
- Use fraction of muons due to *b*-quark decays

$$f_b = \frac{\sigma(b \to \mu)}{\sigma(b \to \mu) + \sigma(c \to \mu)}$$

as predicted by NLO QCD (MNR).



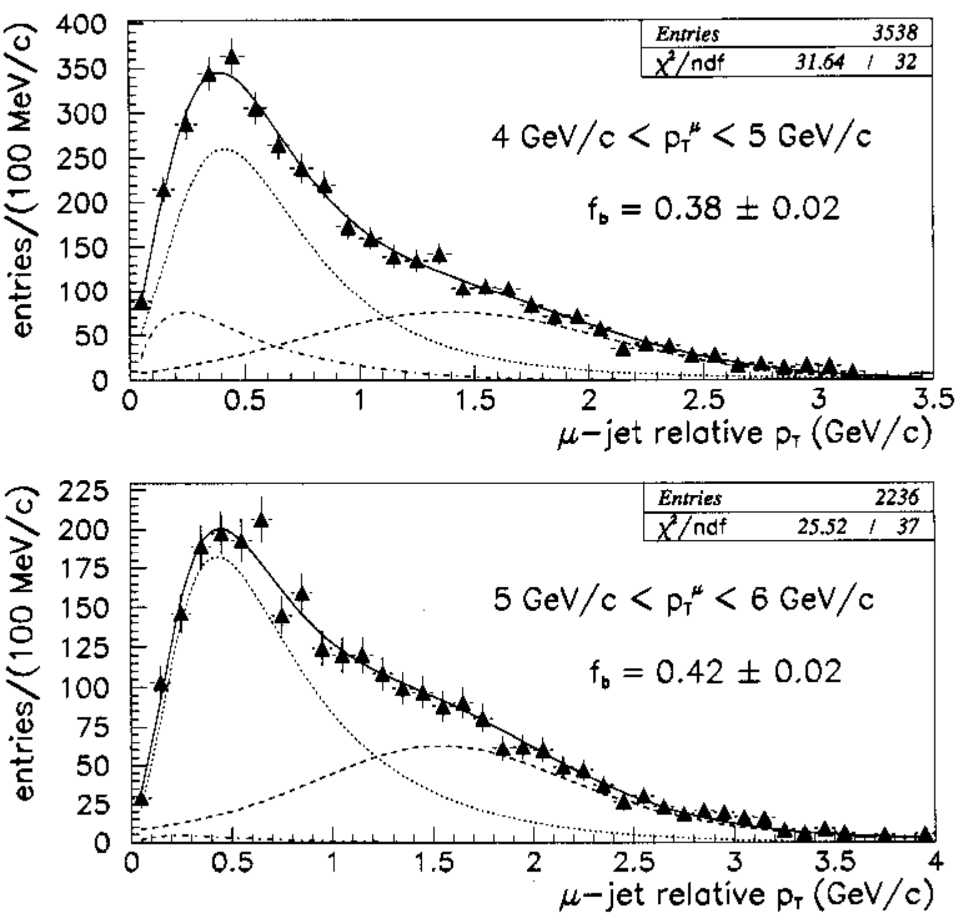
- f_b for muon+jet events using $p_T^{\rm rel}$ fits.



⇒ Good agreement between data and QCD predictions.

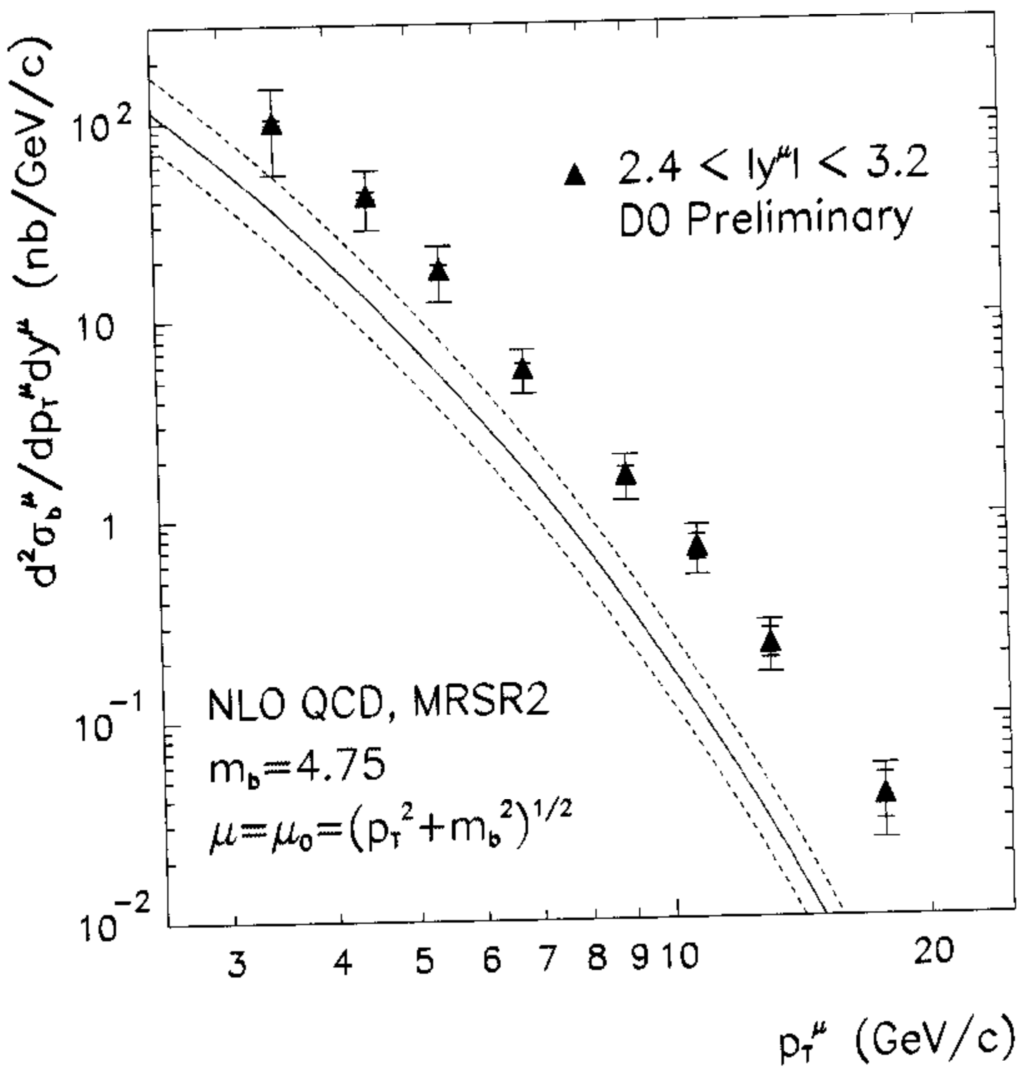
b-Fraction Cross Check

- **Determine f_b for events with a reconstructed associated jet (7% of the muon sample):**
  - **Use all Run 1B data — $\int \mathcal{L} dt = 90$ pb^{-1}**
  - **no trigger requirement ⇒ 20,000 events.**
  - **Shape of $p_T^{\rm rel}$ distributions obtained from real data (π/K) or ISAJET (*b* and *c* quarks).**
  - **Muons from $b \to c \to \mu$ included in the *c*-quark sample.**
  - **$p_T^{\rm rel}$ fits for p_T^{μ} bins.**



b-Produced Muon Cross Section

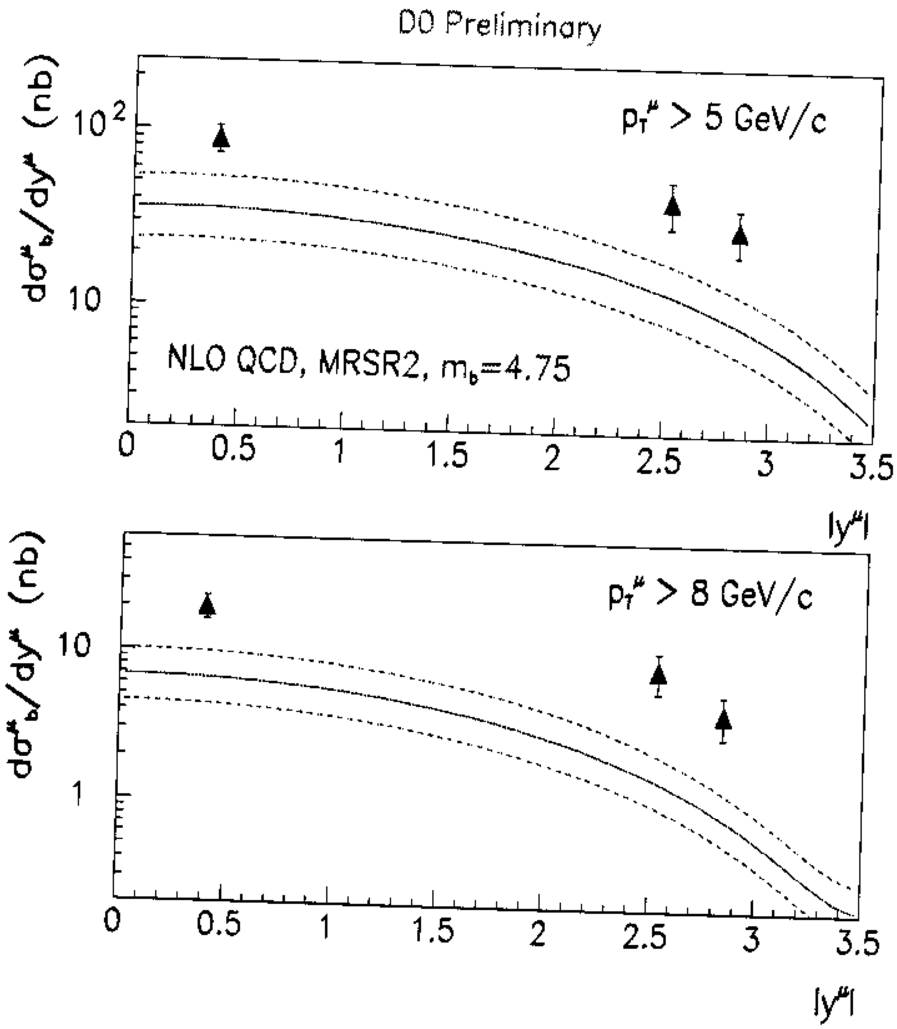
- p_T spectrum of forward muons from *b* decays compared to NLO QCD prediction (HVQJET).



⇒ Measured cross section ≈ 4 times higher than NLO QCD prediction.

Rapidity Dependence

- *b*-produced muon cross section *vs.* rapidity compared to the NLO QCD prediction:



$\Rightarrow$ Ratio Data/Theory ($p_T^\mu > 5$ GeV/c):

- 2.5 ± 0.5 $\quad | y^\mu | < 0.8$
- 3.6 ± 0.9 $\quad 2.4 < | y^\mu | < 3.2$

Recent Theoretical Studies

- "Variable Flavor Number" scheme

  (F.I Olness, R.J. Scalise, and Wu-Ki Tung, hep-ph/9712494)

  - Usual QCD parton formalism: $m_Q = 0$ when $p_T > m_Q \Rightarrow$ *zero-mass variable-flavor-number* scheme

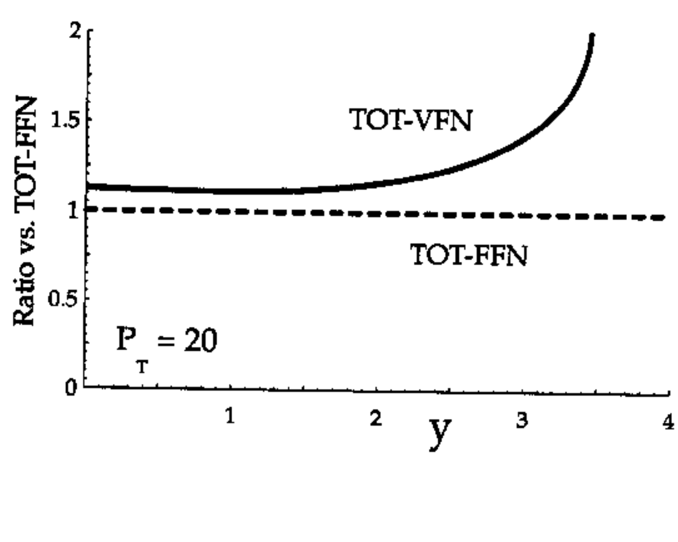
  - NLO QCD calculations: Q is always a heavy particle $\Rightarrow$ *fixed-flavor-number* scheme (FFN)

  - New development: retains the m_Q dependence at all energy scales $\Rightarrow$ *general-mass variable-flavor-number* scheme (VFN).

    Initial- and final-state mass singularities associated with heavy quark mass resummed into parton distributions, without taking the zero mass limit on the hard cross section.

Implications:

- Enhanced cross section for *b* production
- Broader rapidity distribution



Recent Theoretical Studies — cont.

- Hadronization of the heavy quark

  $b \to B$ fragmentation function used with NLO evaluation of the b cross section should be harder than the commonly used Peterson f.f. with ϵ_b =0.006.

  Example: Colangelo–Nason fragmentation function:

$$f(z) \propto (1-z)^{\alpha}\, z^{\beta}$$

  Implications:

  - $\approx$ 30% (40%) higher predicted B cross section in the central (forward) region.

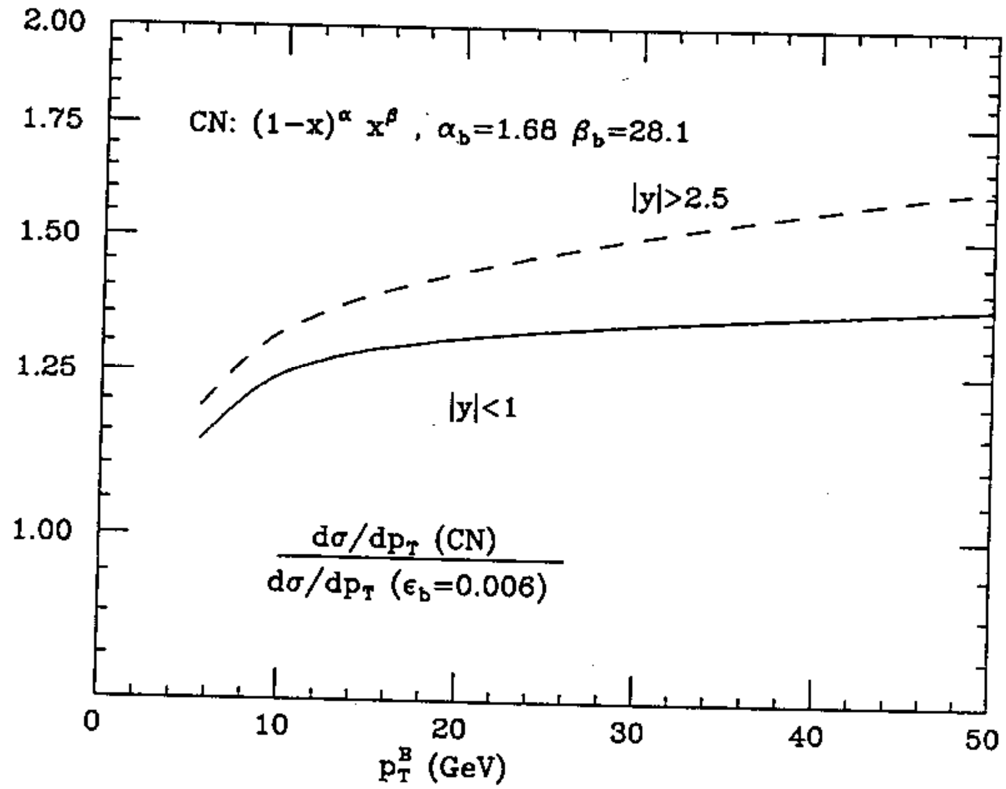


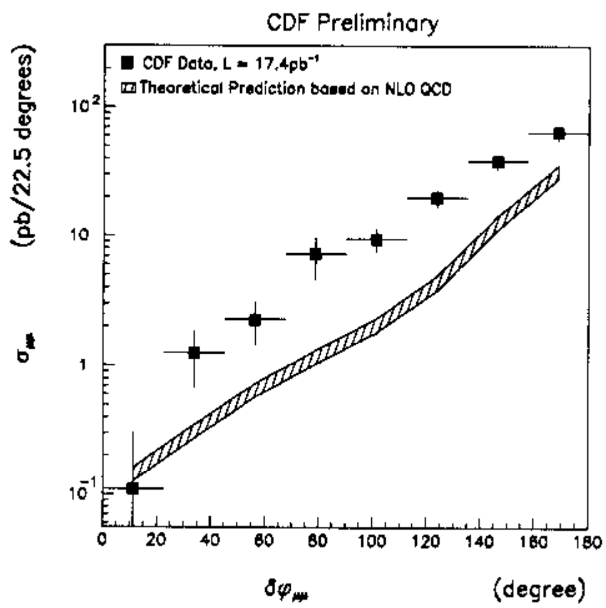
Figure 24: *Ratio of the B-meson p_T distribution using the Colangelo-Nason fragmentation function (with the parameters α and β fitted at NLO), relative to that obtained by using the Peterson fragmentation function and $\epsilon_c = 0.06$. Central production (solid) and forward production (dashes).*

$\epsilon_b = 0.006$

M. Mangano et al.

$b\bar{b}$ Rapidity Correlations (CDF)

- Study of $b\bar{b}$ correlation is fundamental to test NLO QCD predictions.
- Previous studies based on $\Delta\phi_{b\bar{b}}$ or $\Delta\phi_{\mu\mu}$:



- CDF measurement of correlated central–forward $b\bar{b}$ production:

$$\sigma(p\bar{p} \to b\bar{b}) = 6.49 \pm 0.63(\text{stat})^{+1.43}_{-1.23}(\text{syst})\ \text{nb}$$

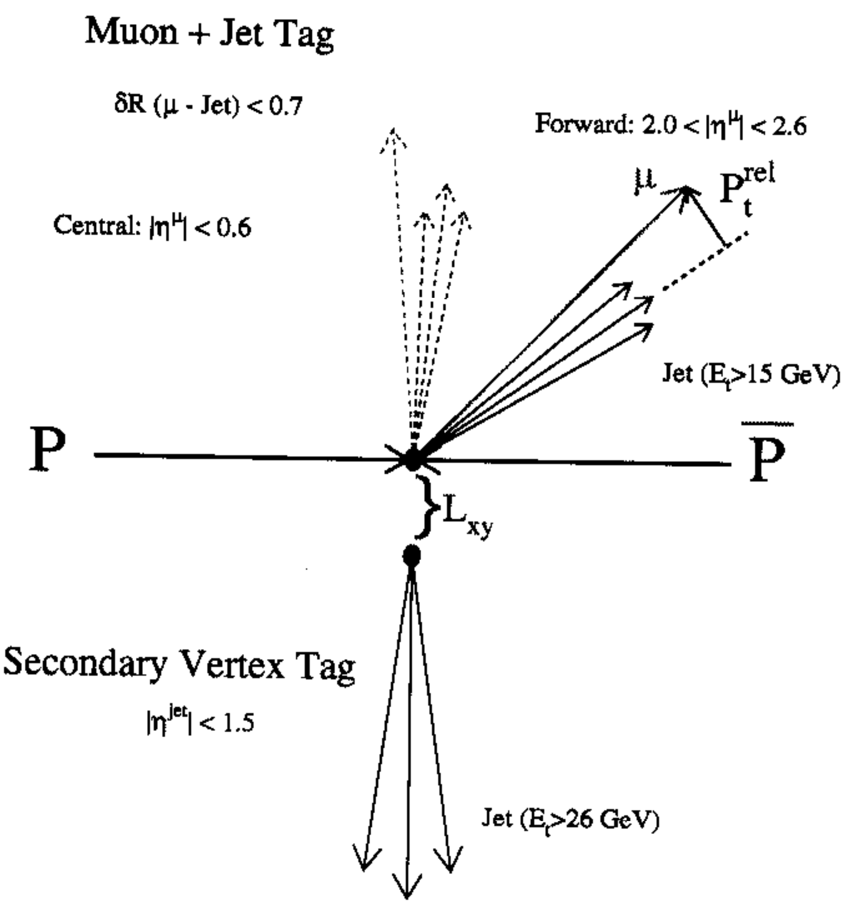
with $p_T(b, \bar{b}) > 25$ GeV/c
$\mid \eta(b_1) \mid < 1.5$
$1.8 < \mid \eta(b_2) \mid < 2.6$

- Data / NLO QCD ≈ 2.4.
- This analysis:

$$\frac{\sigma_{b\bar{b}}(\text{central} - \text{forward})}{\sigma_{b\bar{b}}(\text{central} - \text{central})}$$

Analysis Method

- **Select events with:**
  - central *b*-quark jet ($\mid \eta^{jet} \mid < 1.5$) with a displaced secondary vertex.
  - second *b*-quark decaying to muon+jet and produced in the central ($\mid \eta^{\mu} \mid < 0.6$) or forward ($2.0 < \mid \eta^{\mu} \mid < 2.6$) rapidity regions.

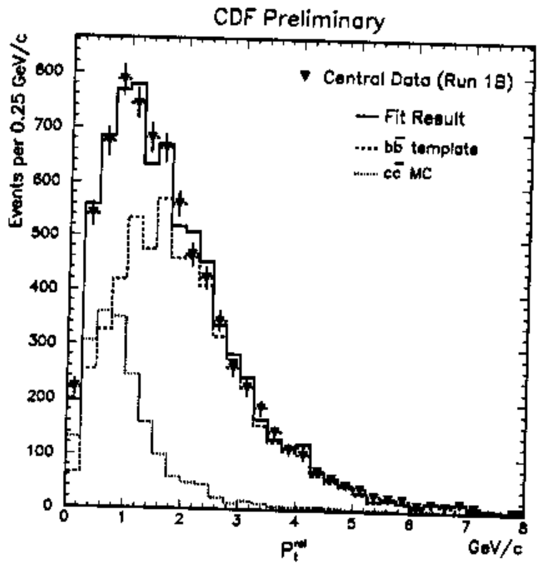


- **1994–95 Tevatron run** ($\int \mathcal{L} dt = 80\ pb^{-1}$)

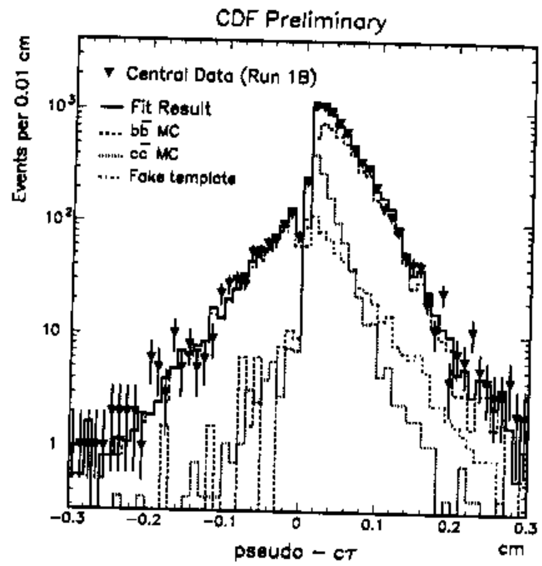
  ⇒ **382 forward–central events**
  7544 central–central events

Signal Extraction

- Signal fraction extracted by simultaneous fits of the p_T^{rel} of the muon and the pseudo-$c\tau$ of the b-jet.
- Central–central events:



p_T^{rel} distribution



pseudo − $c\tau$ distribution

Source (b-tag/μ-tag)	forward-central	central-central
Real b / Real b	0.739 ± 0.073	0.582 ± 0.021
c / $\bar{c}$	0.123 ± 0.089	0.169 ± 0.021
Real b / Fake	$0.034^{+0.087}_{-0.034}$	0.085 ± 0.026
Fake / Real b	0.104 ± 0.030	0.165 ± 0.009

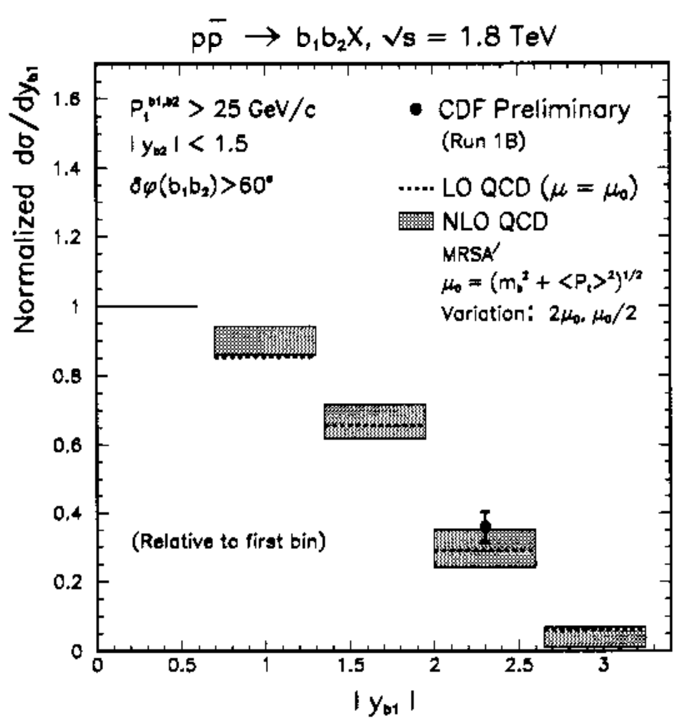
Cross Section Ratio

$$R_{\text{data}} = \frac{\sigma(p\bar{p} \to b_1 b_2 X;\ 2.0 <|\ y_{b_1}\ |< 2.6)}{\sigma(p\bar{p} \to b_1 b_2 X;\ |\ y_{b_1}\ |< 0.6)}$$

where: $p_T(b_1, b_2) > 25$ GeV/c,
$|\ y_{b_2}\ |< 1.5$,
$\delta\phi(b\bar{b}) > 60^\circ$.

$$\boxed{R_{\text{data}} = 0.361 \pm 0.041(\text{stat})^{+0.011}_{-0.023}(\text{syst})}$$

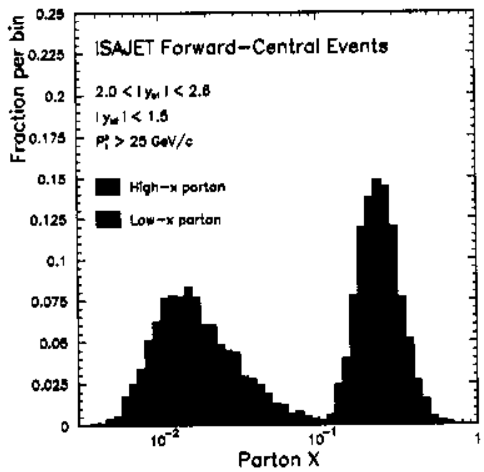
$$\boxed{R_{\text{theory}} = 0.338^{+0.014}_{-0.097}}$$



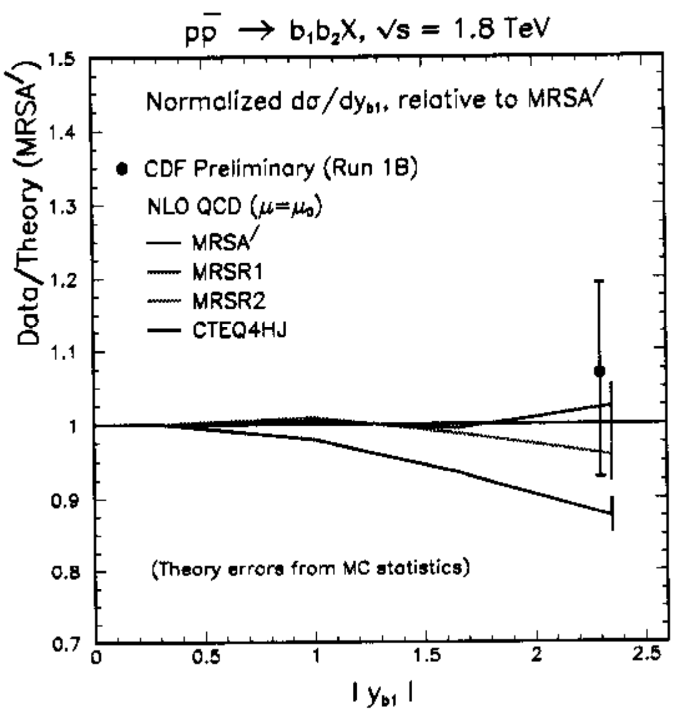
Probing the Gluon Distribution

- **Forward–central events correspond to**

$$x_{\rm low} \approx 0.025 \qquad x_{\rm high} \approx 0.25$$



- **Sensitivity to $G(x, Q^2)$ at large x values.**
- **Comparison of $R_{\rm data}$ with $R_{\rm theory}$ obtained from various parton distribution functions.**



Overview of Quarkonium Production

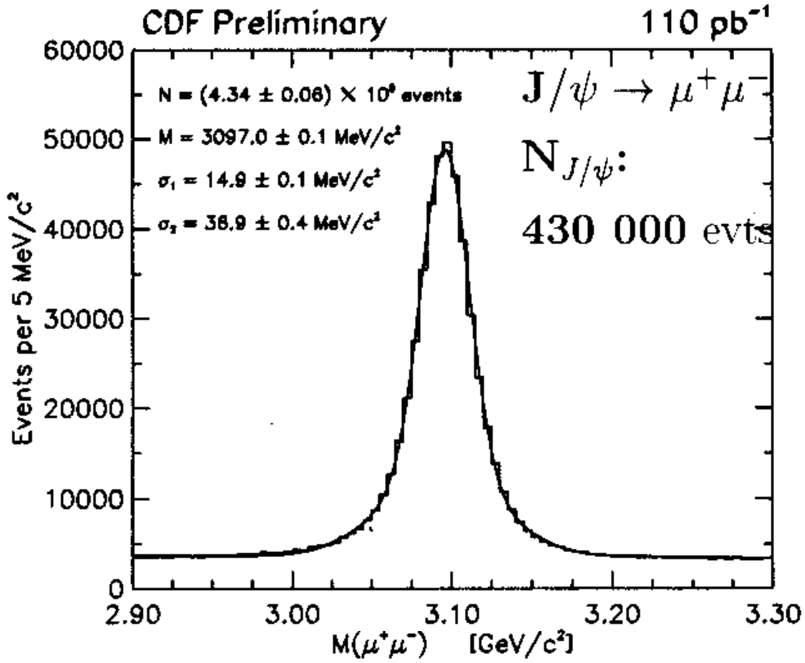
- Provides insight into the nature of strong interactions. Window on the boundary region between perturbative and non-perturbative QCD.

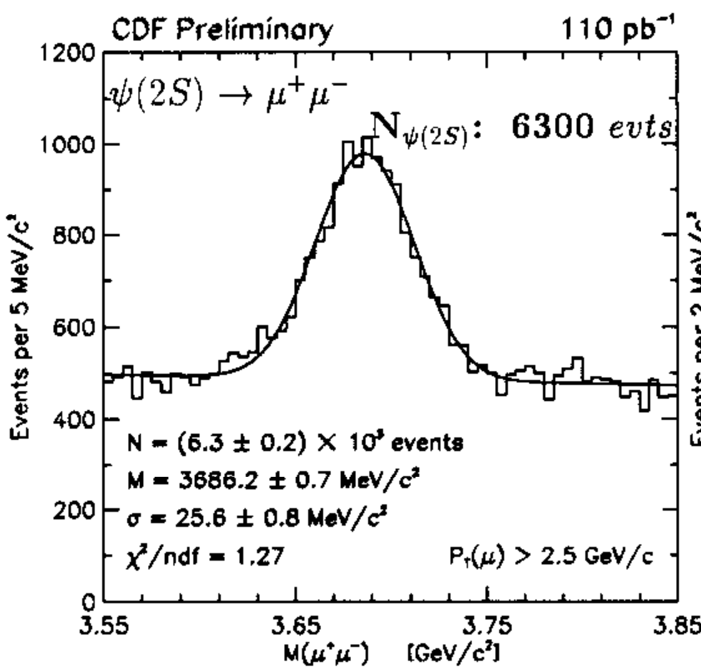
- Processes involved:
  - Prompt production: (primary vertex):
    - direct
    - indirect e.g. $\chi_c \rightarrow J/\psi\gamma$
  - b-quark decays (secondary vertex)

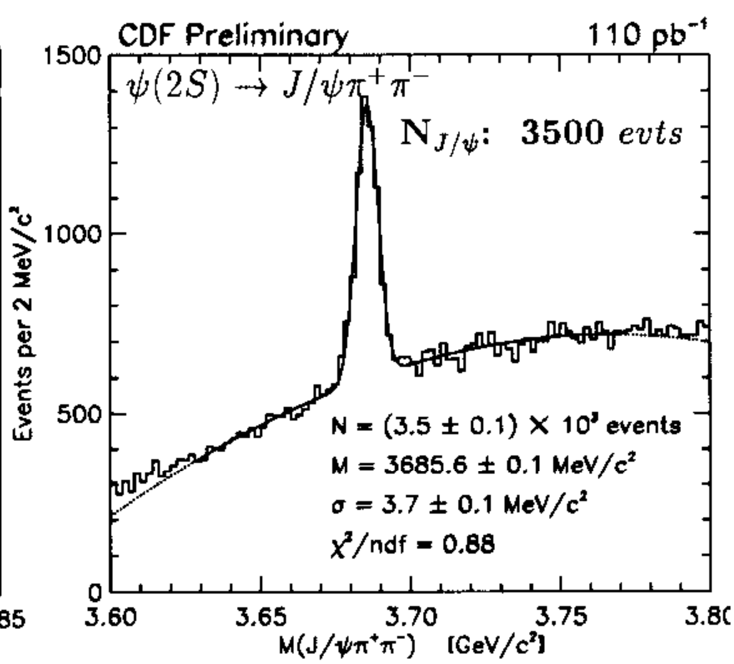
- Recently Published/Available Results on ONIA Production::
  - Υ cross section (CDF)
    PRL 75, 4358 (1995).
  - Central J/ψ cross section, f_b, f_χ (DØ),
    PL B370, 239(1996).
  - Central J/ψ, $\psi(2s)$ cross section, f_b (CDF),
    PRL 79, 572(1997).
  - Production of J/ψ from χ_c (CDF),
    PRL 79, 578(1997).
  - Forward J/ψ Production ((DØ);
    submitted to PRL
  - Measurement of the Ratio of Production of χ_{c1} to χ_{c2} (CDF) - preliminary

Charmonium Production at CDF

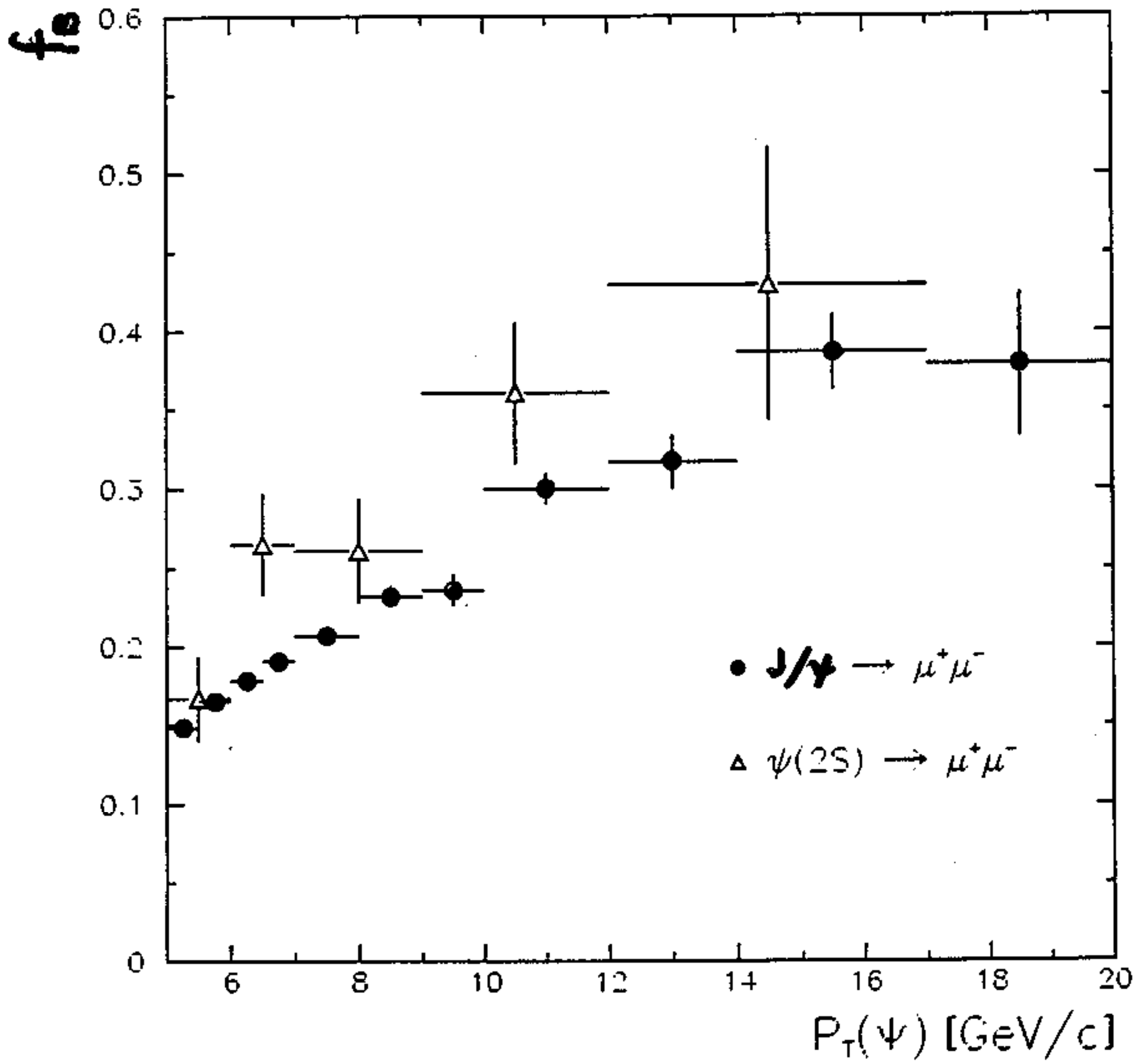
- Full Run I charmonium statistics.







CDF, PRL 79



The fractions of J/ψ and $\psi(2s)$ originating from b-hadron decays

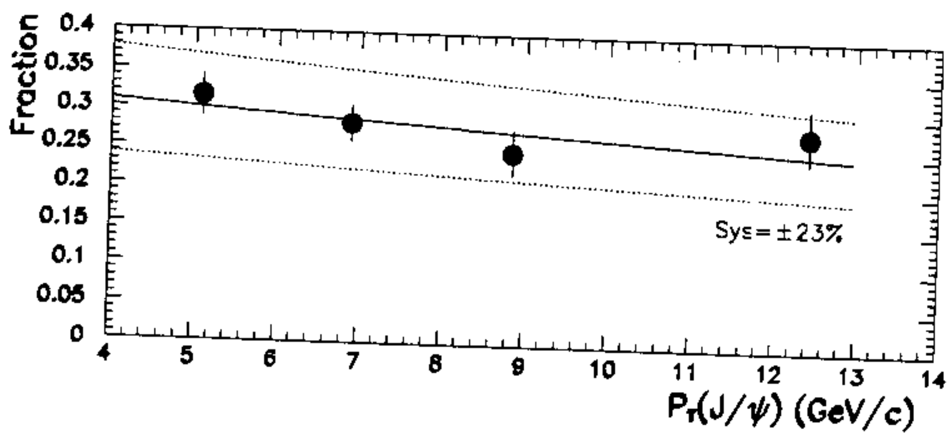
χ_c Production at CDF

- **Removing B $\to J/\psi$ X and B $\to \chi_c$ X**

  - Analysis of the Transverse Decay Length;
  - Fractions of χ_c from $B \to J/\psi$ and J/ψ from B.

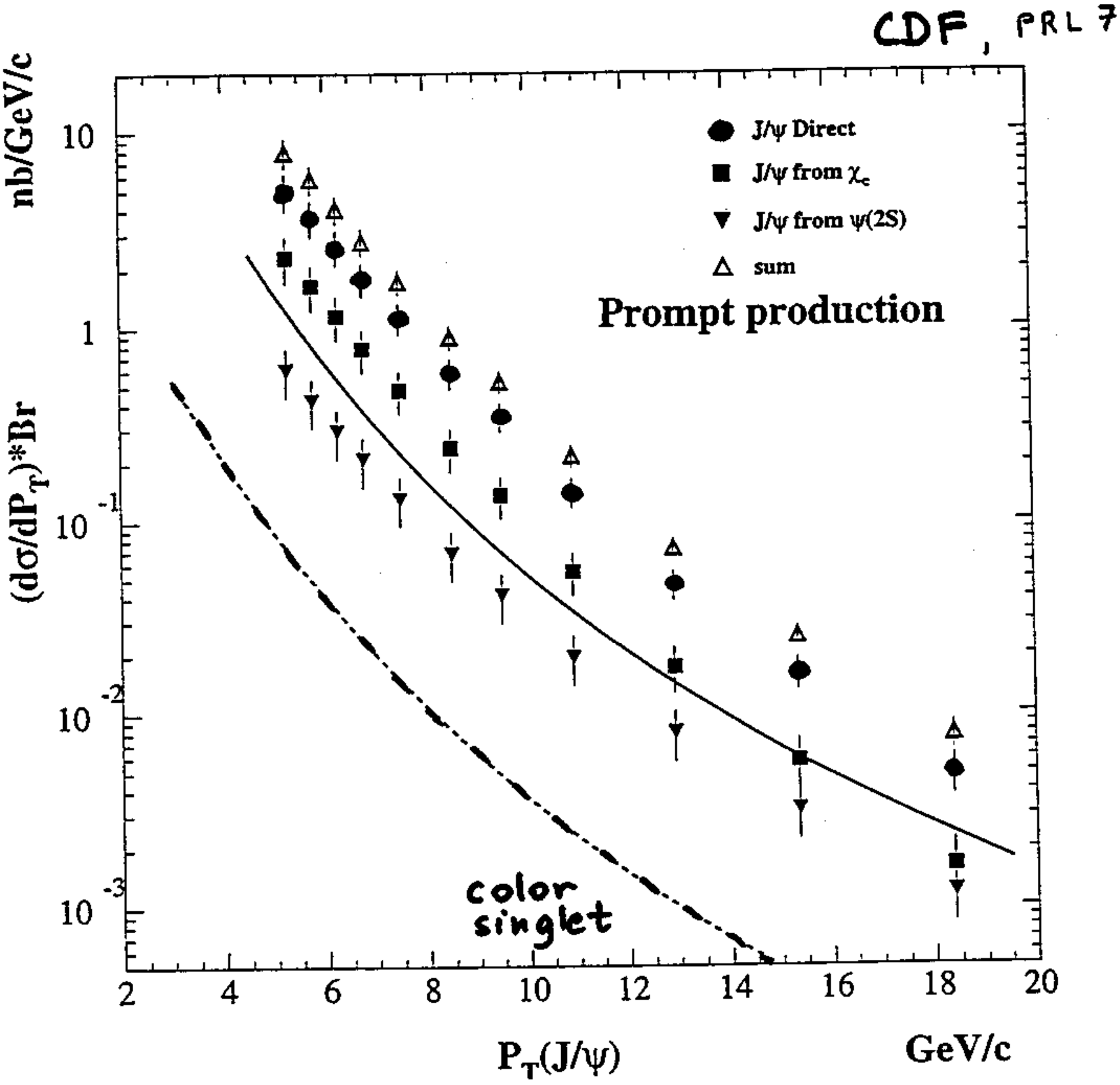
$$F(No\ b)^{\psi}_{\chi} = F^{\psi}_{\chi} \cdot \frac{1 - F^{\chi}_{b}}{1 - F^{\psi}_{b}} = F^{\psi}_{\chi} \cdot (1.085 \pm 0.04)$$

CDF [redacted] PRL 79



Fraction vs p_T^{ψ}

$p_T^{\psi} > 4.0$	**0.32±0.02±0.09**
$4.0 < p_T^{\psi} < 6.0$	**0.33±0.03±0.09**
$6.0 < p_T^{\psi} < 8.0$	**0.31±0.03±0.08**
$8.0 < p_T^{\psi} < 10.0$	**0.26±0.04±0.07**
$p_T^{\psi} > 10.0$	**0.27±0.05±0.08**

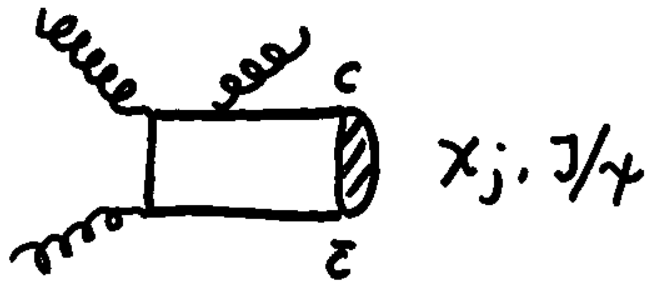


CDF, PRL 79
nb/GeV/c
$(d\sigma/dP_T)*Br$
J/ψ Direct
J/ψ from χ_c
J/ψ from ψ(2S)
sum
Prompt production
color singlet
$P_T(J/\psi)$
GeV/c
10
1
10^{-1}
10^{-2}
10^{-3}
2
4
6
8
10
12
14
16
18
20

Charmonium production Models

• Color Evaporation (local-duality)

H. Fritzsch PL 67B, 217(1977), R. Gavai *et al.* IJ of MP A10, 3043(1995), J. Amundson *et al.* PL B390, 323 (1997).

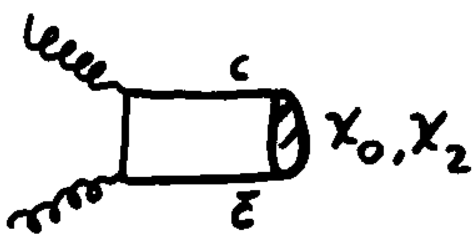


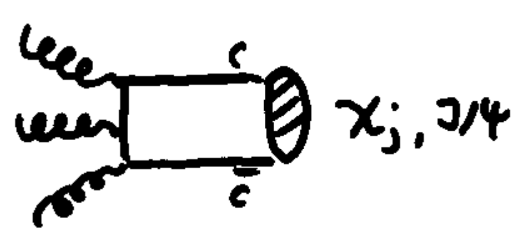
directly produced charmonium meson is not constrained to the same J^{PC} state as the $c\bar{c}$ pair produced in the hard scatter

• Color Singlet Model

R. Baier, R. Ruckl, ZP C19, 251(1983),

M. Vanttinen *et al.*, PR D51, 3332(1995); G. Schuler CERN-TH.7170/94.

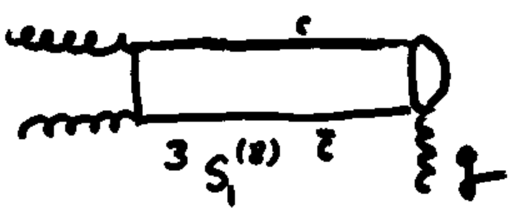


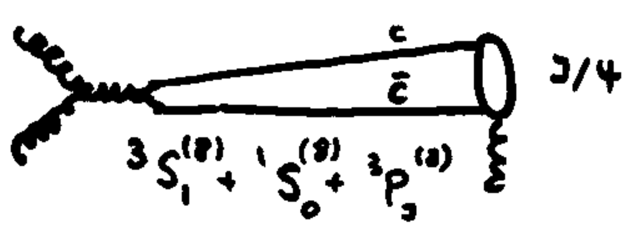


charmonium meson retains the quantum numbers of the $c\bar{c}$ pair

• Color Octet Model

E. Braaten and S. Fleming PRL 74, 3327 (1995); P. Cho, A. Leibovitch PR D53 150(1996); 6203(1996)

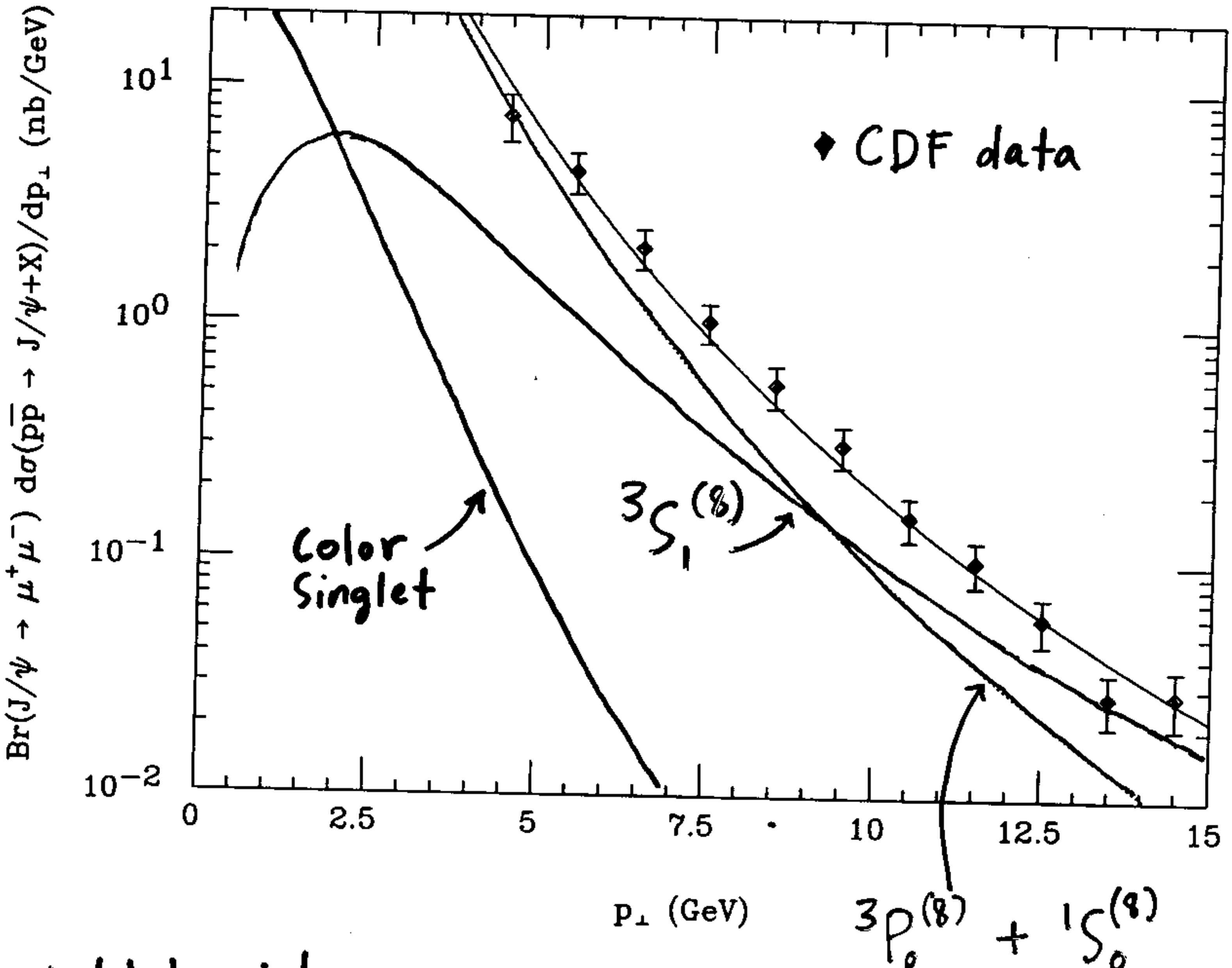




takes into account the production of $c\bar{c}$ pairs in a color-octet configuration ac- $c\bar{c}$ pair emits a long wavelength gluon far away from the collision point

Direct J/ψ

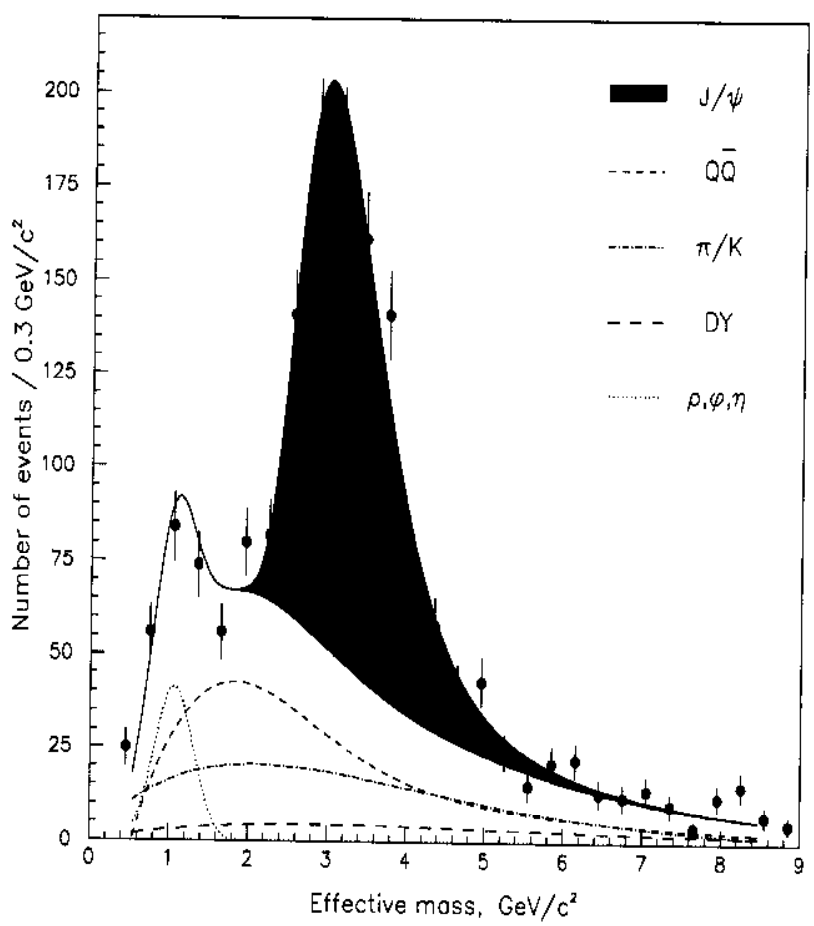
χ's removed
b's removed



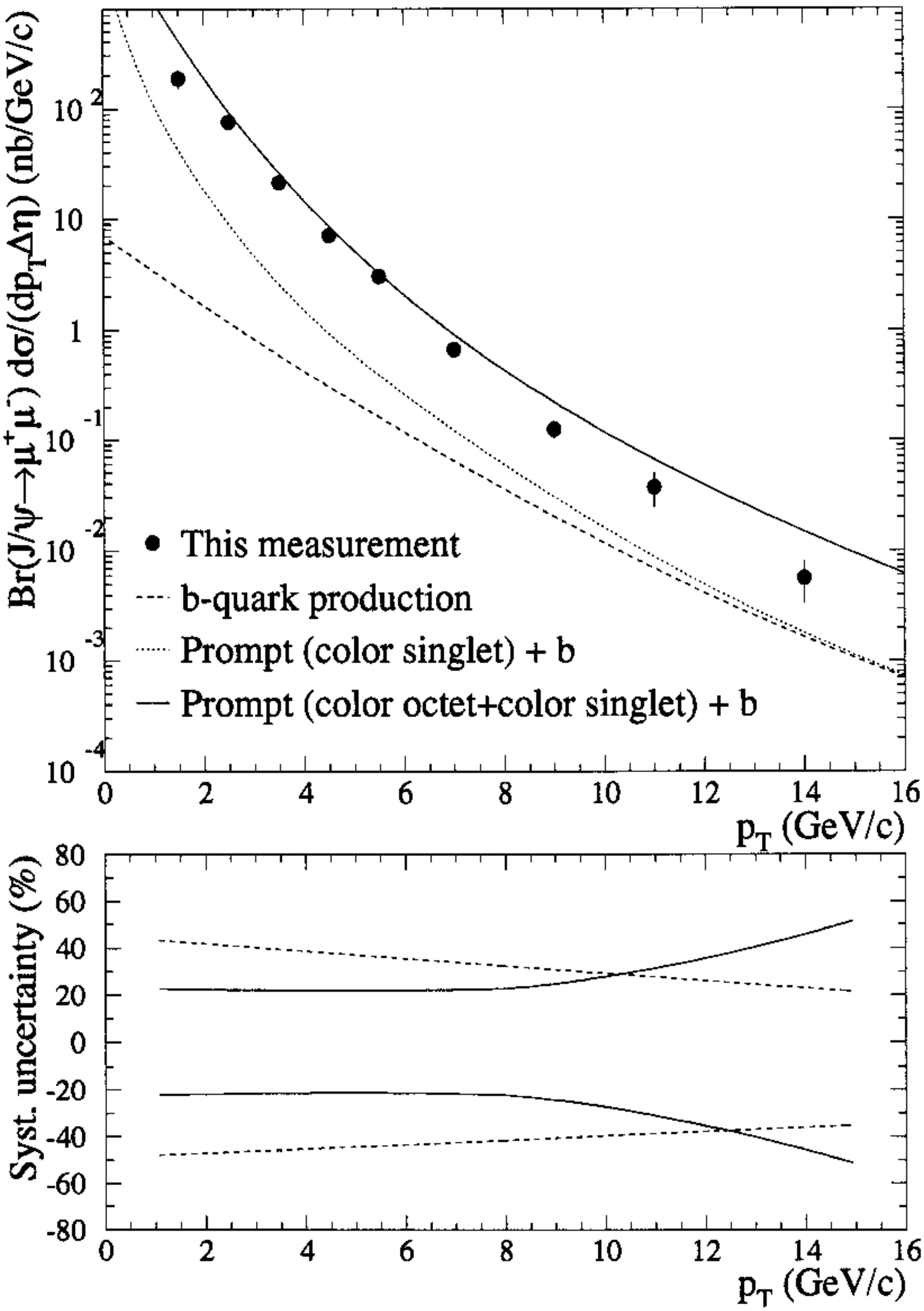
Cho + Liebovich
PRD 53 6203 (1996)

Inclusive Forward J/ψ Production (DØ)

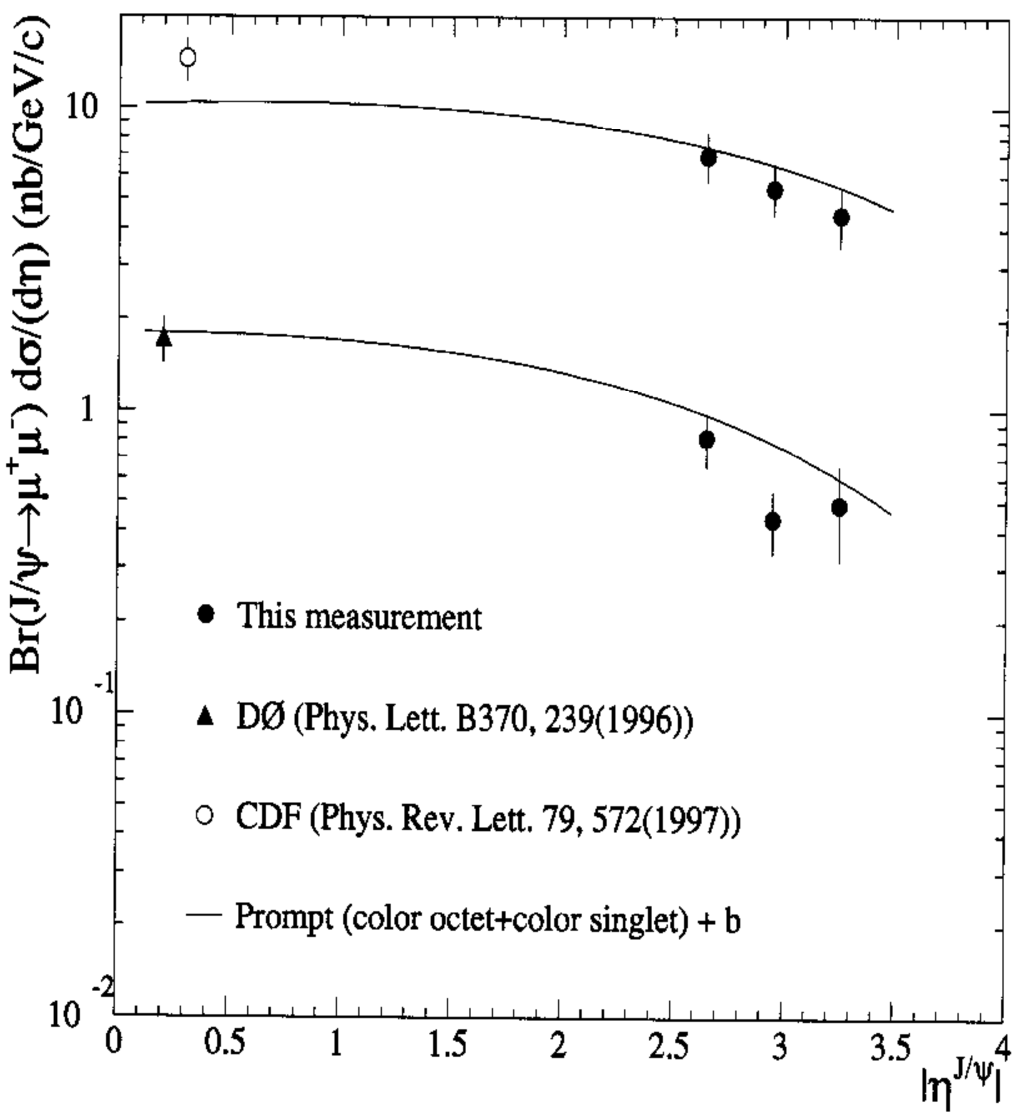
- **Analysis based on Small Angle Muon System (SAMUS)**
- **1994-95 data (prescaled diμ triggs) - $\int \mathcal{L}dt = 9.8 \pm 0.5$ pb^{-1}**
- **Data selection:**
  - **Level1 hit multiplicity cut (ϵ from the data)**
  - **Single interaction events**
  - **$2.4 <| \eta^{\mu} |< 3.2$**
  - **leading μ with $p_T^{\mu} > 3$ GeV/c; $p^{\mu} < 150$ GeV/c**
  - **Quality cuts; >14 hits/track (max: 18)**
- **$\Rightarrow$ 1779 $\mu^+\mu^-$; 281 $\mu^{\pm}\mu^{\pm}$events**
- **Fitted J/ψ events: 740 $\pm$ 80 $(2.5<| \eta^{J/\psi} |< 3.7)$**



p_T Dependence of Forward J/ψ Production



Rapidity Dependence of Forward J/ψ Production



- Color octet model predictions agree with the data.

Conclusions (ONIA Production)

- CDF published results on the central ($|\eta^{J/\psi}| < 0.6$) J/ψ and $\psi(2s)$ production:
  - fraction of J/ψ and $\psi(2s)$ orginating from b hadrons increases with p_T from 15% ($p_T(J/\psi)$ =5 GeV/c) to 40% ($p_T(J/\psi)$ =18 GeV/c)
  - $B \to J/\psi + X$ production consistent with other CDF and DØ B cross section results
  - fraction of J/ψ originating from χ_c decays is 29.7±1.7 ±5.7 % ($p_T(J/\psi) >$4 GeV/c)
  - DØ cross section, f_b and f_χ measurements are consistent with the CDF results.
  - direct J/ψ and $\psi(2s)$ productions are in excess of the predictions of the Color Singlet Model by a factor $\approx$ 50
  - Color Octet Model can fit the CDF data
- Rapidity Dependence of J/ψ Production (DØ)
  - color octet model, with matrix elements fitted to the CDF data for the central J/ψ production, describes the data in the ($2.5 < |\eta^{J/\psi}| < 3.7$) range.
- Work in Progress
  - J/ψ and $\psi(2s)$ polarization measurements (CDF)

Conclusions (B Production)

- Measured b cross section at $|y_b| < 1$ exceeds NLO QCD predictions by $\times$ 2.5 - 3.
- Measured (preliminary) b cross section at $|y_b| \approx 3$ is $\approx$ 3 - 4 times higher than NLO QCD prediction (DØ)
- Measured (preliminary) $b\bar{b}$ cross section at ($|\eta_{b1}| < 1.5$, $1.8 < |\eta_{b2}| < 2.6$) is $\approx$ 2.4 times higher than NLO QCD prediction (CDF).
- CDF measurement of central–forward to central–central cross section ratio:

$$R_{\rm data} = 0.361 \pm 0.041({\rm stat})^{+0.011}_{-0.023}({\rm syst})$$

  in agreement with NLO QCD prediction:

$$R_{\rm theory} = 0.338^{+0.014}_{-0.097}$$

- Result sensitive to gluon distribution in the proton for $x > 0.15$ but higher statistics needed to distinguish between various parton distribution sets.