Recent Tevatron Results on b-Quark Production

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OUTLINE

- **Open b-Quark**
- **Central and Forward Open b-Quark Production Cross Section [CDF, DØ]**
- **b Production vs. Rapidity [DØ]**
- **Correlated $b\bar{b}$ Production**
  - correlation in azimuthal angle [DØ]
  - correlation in rapidity [CDF]
- **Bound States**
- **$\Upsilon(1S)$ from χ_b Decays [CDF]**
- **$\psi(2S)$ Polarization - Color Octet Model [CDF]**
- **Conclusions**

Extraction of b-Quark Cross-Section from Data

- Data samples with e or μ and/or jets in final state:
  * inclusive e/μ: $p\overline{p} \rightarrow b\,\overline{b}\,X$

    e/μ
  * muon + jet: $p\overline{p} \rightarrow b\,\overline{b}\,X$

    μ + jet
  * dimuon + jets: $p\overline{p} \rightarrow b\,\overline{b}\,X$

    μ + jet

    μ + jet
  * J/Ψ (Ψ'): $p\overline{p} \rightarrow b\,\overline{b}\,X$

    $J/\Psi\,X$

    $\mu^+\,\mu^-$

- b-quarks can be efficiently detected through semi-leptonic decays into high p_T non-isolated muons
  - reducing uncertainties due to jet algorithm and underlying event, branching ratios and decay kinematics are well measured, momentum smearing due to decay partially accounted for by measuring integrated cross-section

  full reconstruction of decays into exclusive final states: $B^{\pm} \rightarrow J/\Psi + K^{\pm}$ and $B^0 \rightarrow J/\Psi + K^{*0}$
  - complementary to above measurements which require unfolding c-quark contribution

Method of Extracting b-Quark Cross-Section

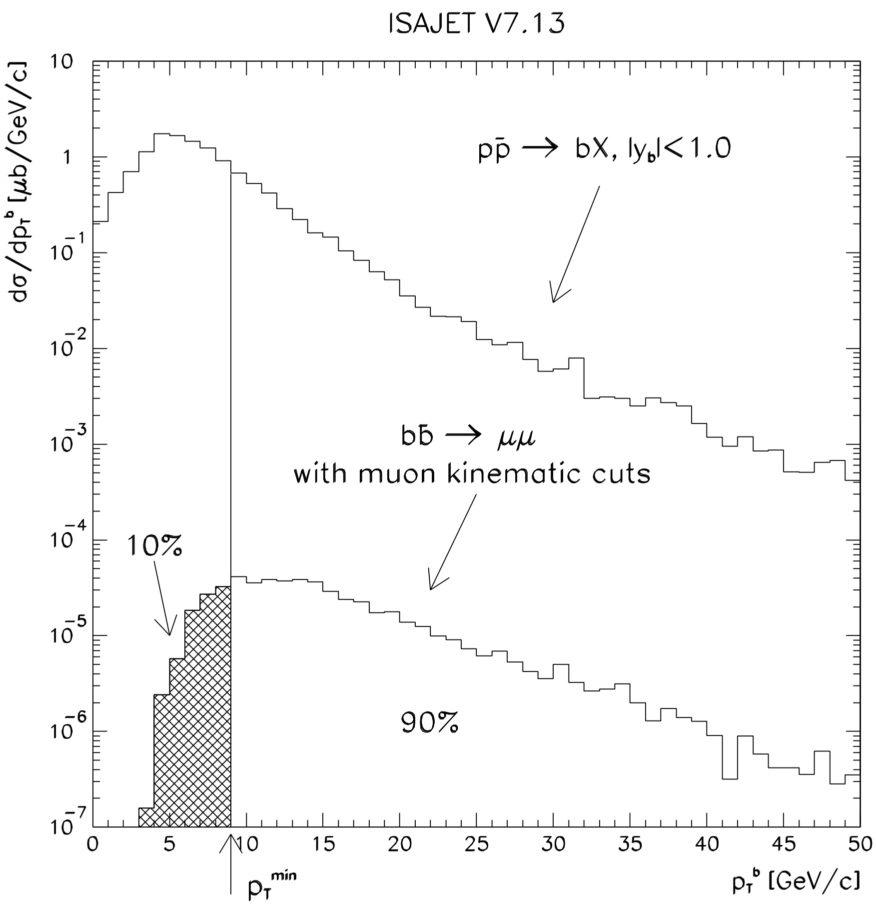
Example: Inclusive Muon Data

- Measure inclusive muon cross section:
  $d\sigma/dp_T^\mu$ ($|\ \eta^\mu\ | < 0.8$ (DØ) 0.6 (CDF))
  - includes backgrounds from
    - charm quark decays: $c \to \mu X$
    - in-flight decays: $\pi/K \to \mu\nu$
    - vector boson decays: $W \to \mu\nu$, $Z \to \mu\mu$
- Determine fraction of muons from b-decays:
  $d\sigma/dp_T^\mu$ $(b \to \mu X)$
  - subtract backgrounds:
    - c, π/K contributions using decay kinematics
      - $p_T^{rel} = p_\mu \sin\theta$ distributions
      - $z = p_\mu \cos\theta/(p^{\text{jet}} \cdot E_T^{\text{jet}})$ distributions
      - d (impact parameter) $= |\ \beta\gamma c\tau\ sin(\delta)\ |$ distributions
    - W/Z contribution using Monte Carlo calculations
  - correct for muon momentum resolution effects
- Extract integral b-quark cross section:
  $\sigma(p_T^b > p_T^{\text{min}}, |\ y_b\ | < 1)$
  - account for branching ratio $b \to \mu \approx 10\%$
  - use Monte Carlo techniques to correct for fragmentation effects and acceptance ($|\ \eta^\mu\ | \longrightarrow |\ y_b\ | < 1$)

- $\sigma_b\ (p_T^b > p_T^{\min},\ |\ y^b\ |< 1) =$

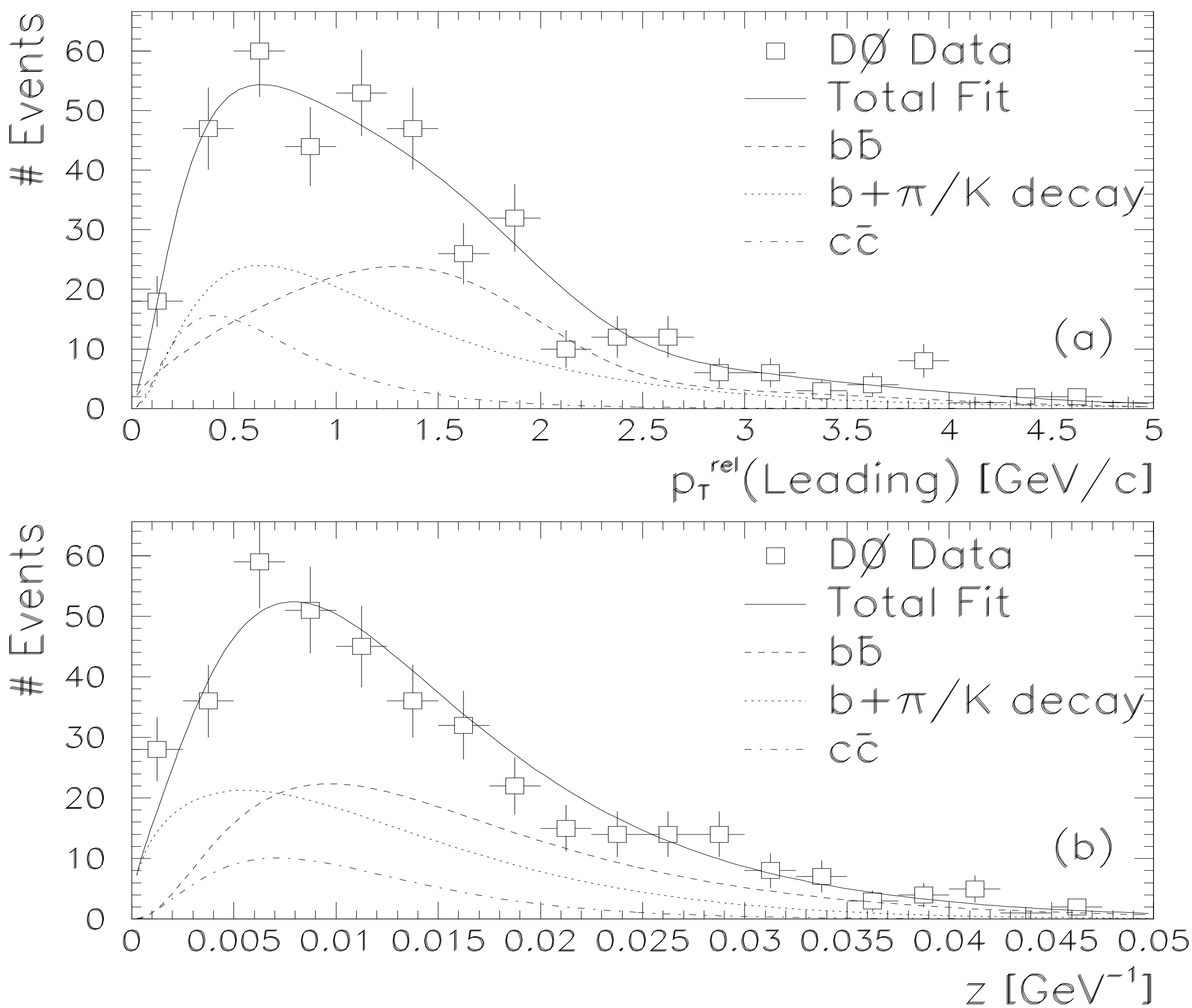
$$\frac{1}{2} \cdot \frac{d\sigma^\mu}{dp_T^\mu} \cdot \frac{\sigma_b^{\rm MC}(p_T^b > p_T^{\min})}{\sigma_b^{\rm MC}(p_T^\mu \ \text{bin})}$$

- $p_T^{\min} = p_T^b$ for which 90% of events in p_T^μ bin come from b quarks with $p_T^b > p_T^{\min}$



$b\,\overline{b} \rightarrow \mu\;\mu\;X$

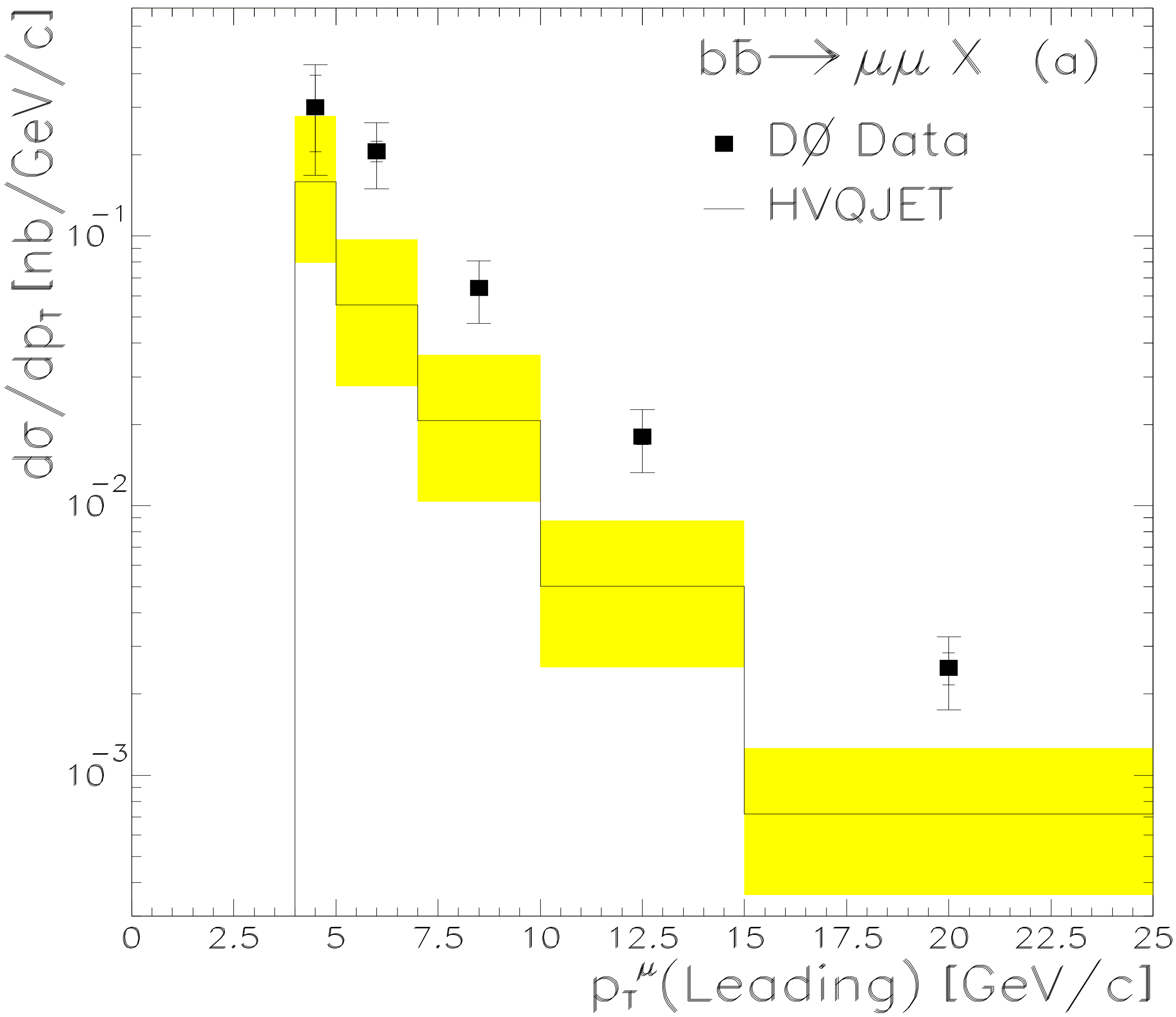
- DØ using muon pairs from $\int \mathcal{L} dt = 6.5\ pb^{-1}$
  $4 < p_T^\mu < 25$ GeV/c, $|\ \eta^\mu\ | < 0.8$, $6 < M_{\mu\mu} < 35$ GeV/c^2
- Require associated jet ($E_T > 12$ GeV) with each muon and use p_T^{rel} to determine $b\,\overline{b}$ fraction



Source	Fraction	Source	Fraction
$b\overline{b}$	0.44 ± 0.06	$c\overline{c}$	0.14 ± 0.04
$b + \pi/K$	0.38 ± 0.06	Cosmic	0.03 ± 0.02

$b\,\bar{b} \to \mu\,\mu\,X$

DØ – Preliminary



- MC error band: $^{+74}_{-50}\%$
  - m_b (4.5 – 5.0 GeV/c^2), μ ($\mu_0/2$ – $2\mu_0$): $^{+67}_{-38}\%$
  - PDF (MRSR2 – MRSA'): ±20%
  - $B \to \mu$ decay spectrum: ±20%
  - ϵ (Peterson): ±8%, Branching fractions: ±7%

HVQJET Monte Carlo Event Generator

Marc Baarmand and Frank Paige

- Monte Carlo event generator based on $\mathcal{O}(\alpha_s^3)$ calculations of $p\overline{p} \to Q\overline{Q}X$ by Mangano, Nason and Ridolfi (MNR).

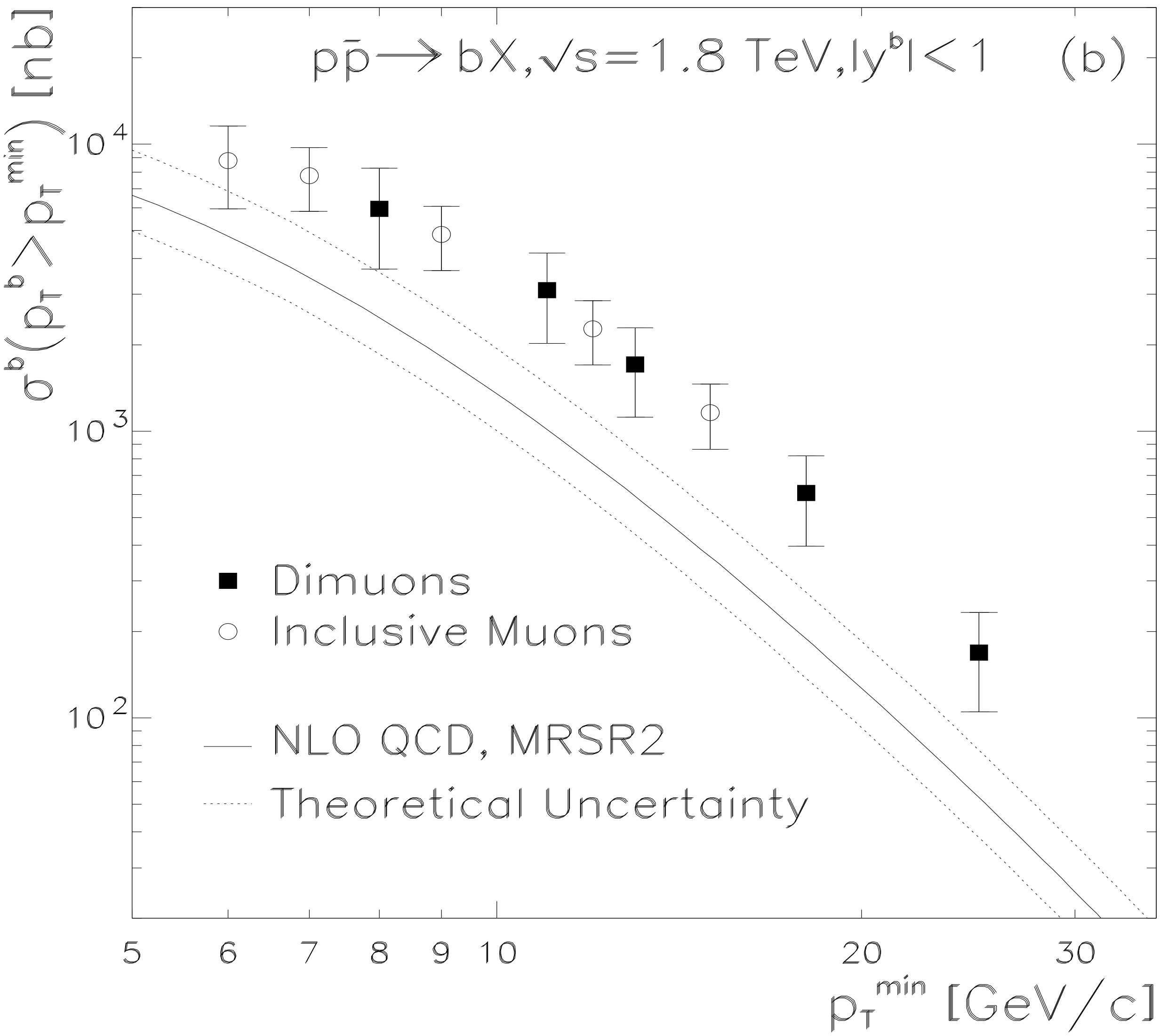
- MNR calculation produces weighted partonic events for $gg \to Q\overline{Q}g$, $gq \to Q\overline{Q}q$, $g\overline{q} \to Q\overline{Q}\overline{q}$ and $q\overline{q} \to Q\overline{Q}g$ subprocesses.

- HVQJET Cancellation Algorithm systematically combines topologically similar events with positive and negative weights within NLO, and then between NLO and LO partonic events. Similarity is measured using a χ^2 formed from p_T, y and $\Delta\phi$ of Q and $\overline{Q}$.

- ISAJET model is used to simulate initial and final state gluon radiation. Gluon radiation is limited such that no infrared-safe distributions of partons is altered. Peterson function and CLEO decay table are used to fragment Q-quarks and to decay Q-hadrons. ISAJET is also used to simulate interaction of spectator quarks (underlying event).

b-Quark Production in Central Region (DØ)

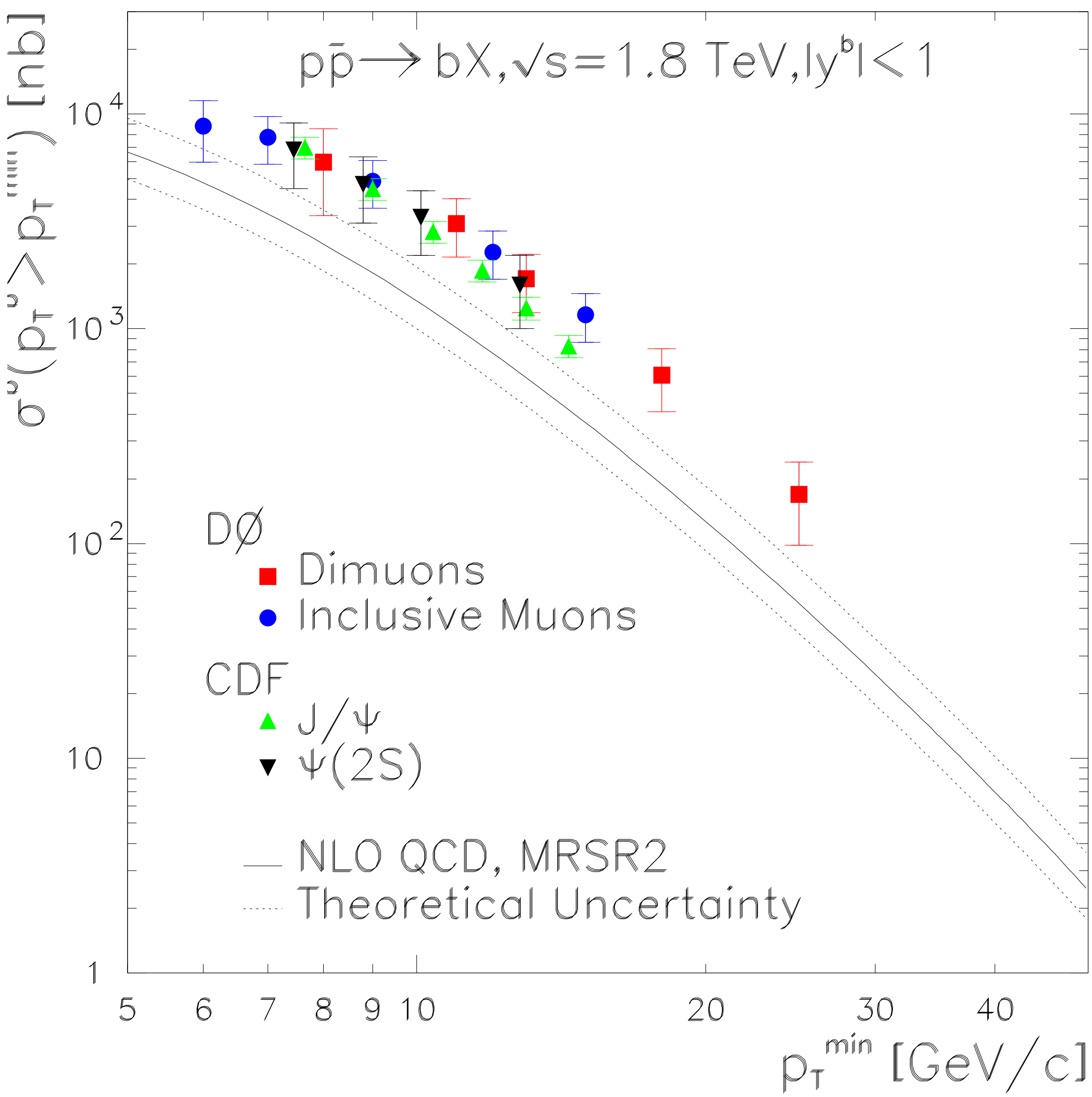
DØ – Preliminary



- Published inclusive muon results were revised:
  - Updated B meson decays, improved Monte Carlo (HVQJET) for converting μ to b cross section
  - Excluded $p_T^\mu > 12$ GeV/c data (cosmic ray background)

b-Quark Production in Central Region

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

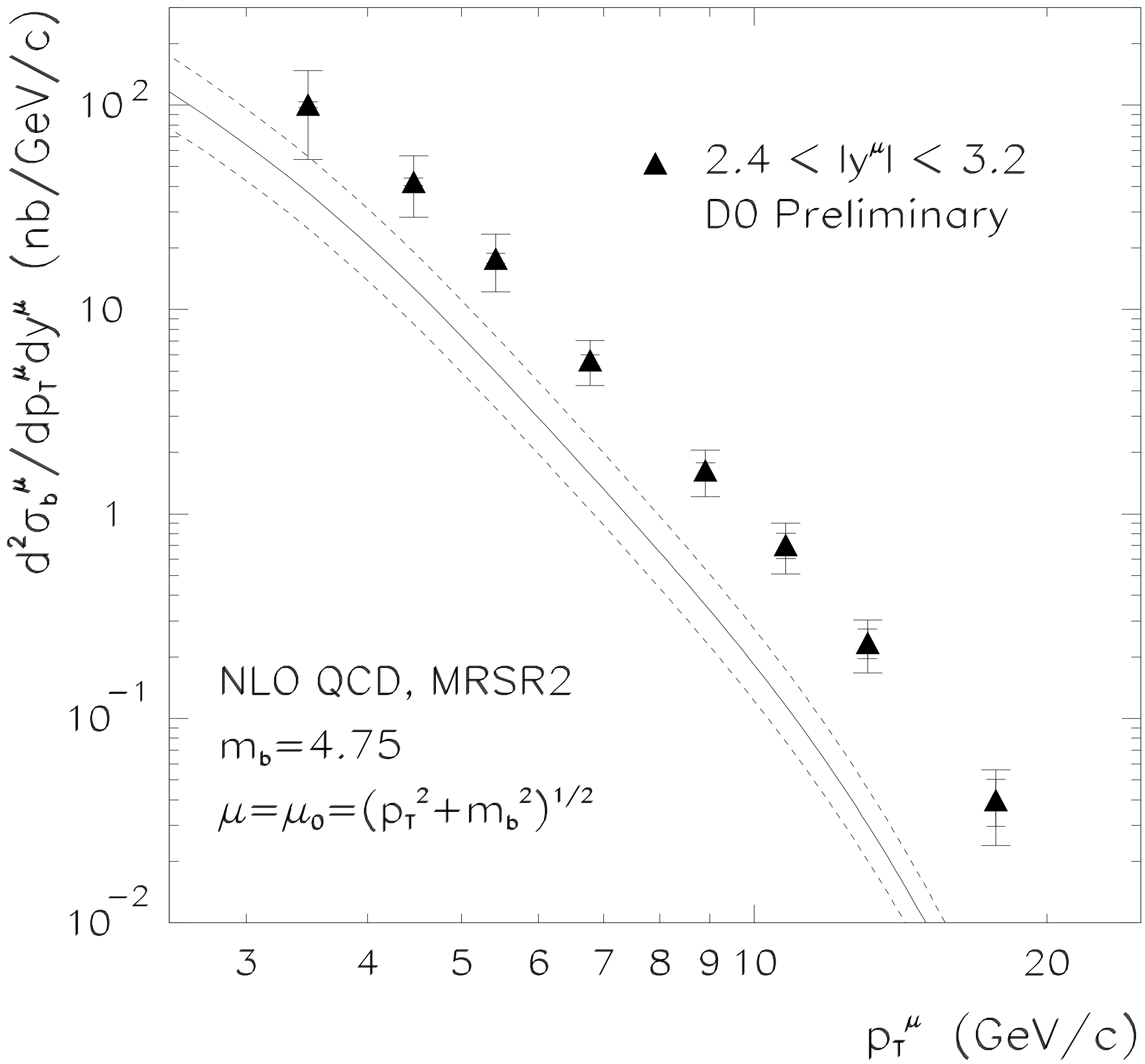


- Good agreement between different measurements

⇒ Data/Theory ≈ 2.5

Inclusive Forward *b* Production (DØ)

- Small Angle Muon System: $2.2 < |\eta^\mu| < 3.3$
- $p_T^\mu > 2$ GeV/c, 94-95 Runs, $\int \mathcal{L}dt = 111$ nb^{-1}
- *b*-produced muon cross section compared to NLO QCD prediction (HVQJET)

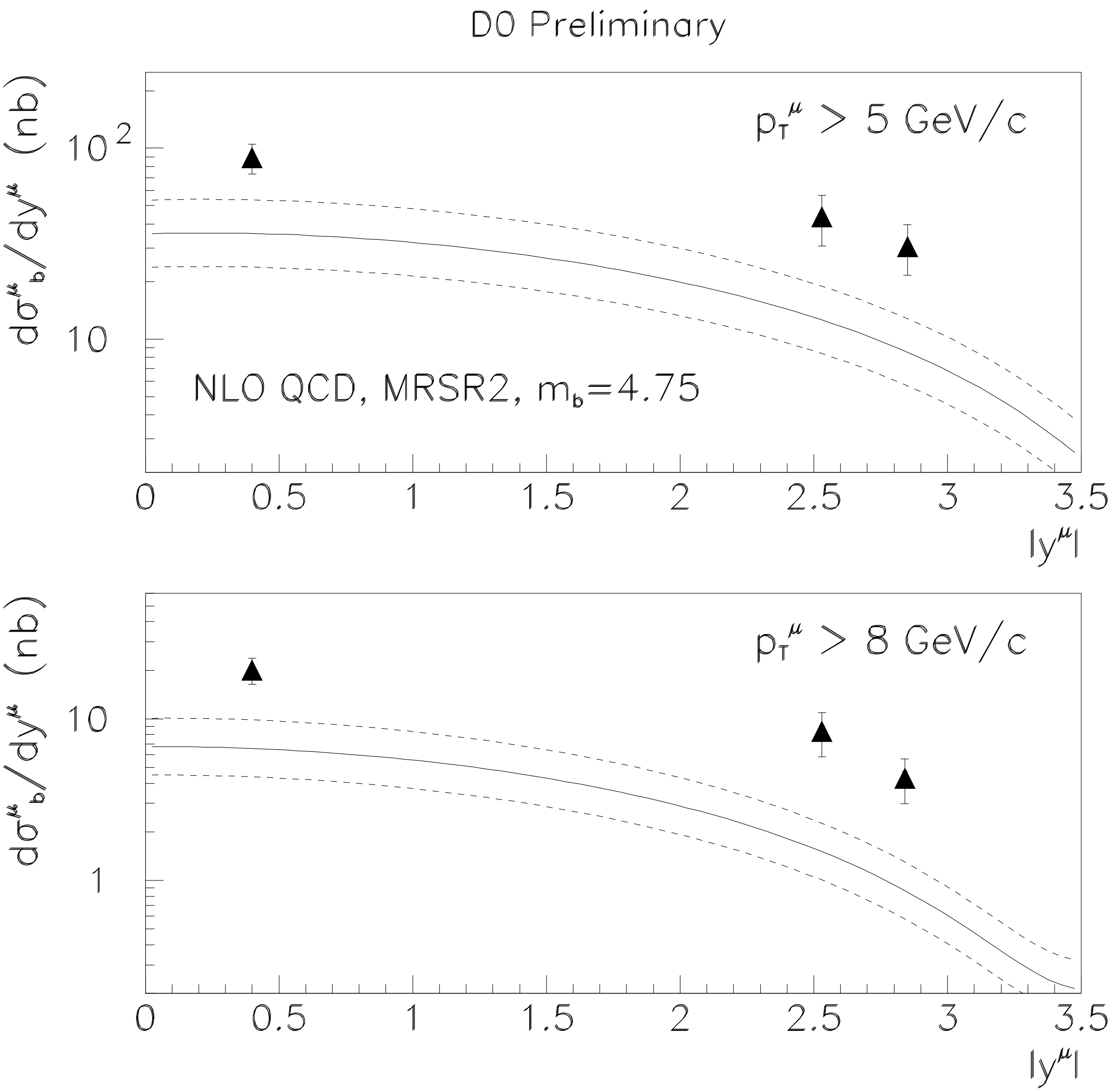


⇒ Data/Theory ≈ 4

- Systematic errors: $29 - 46\%$

Rapidity Dependence

- ***b*-produced muon cross section vs. rapidity**



⇒ **Data/Theory ($p_T^{\mu} > 5$ GeV/c):**

2.5 ± 0.4 $\quad |y^{\mu}| < 0.8$

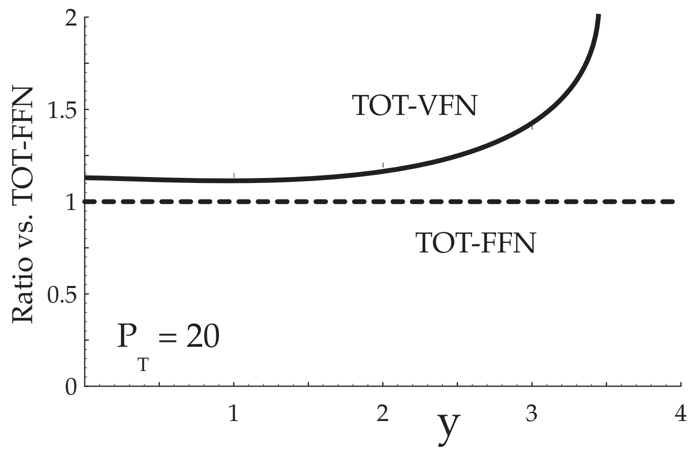
3.6 ± 0.8 $\quad 2.4 < |y^{\mu}| < 3.2$

Recent Theoretical Developments

- “Variable Flavor Number” scheme

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

  – Enhanced cross section for b production
  – Broader rapidity distribution



- Hadronization of heavy quark

  Harder $b \to B$ fragmentation than Peterson
  Colangelo–Nason fragmentation function:

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

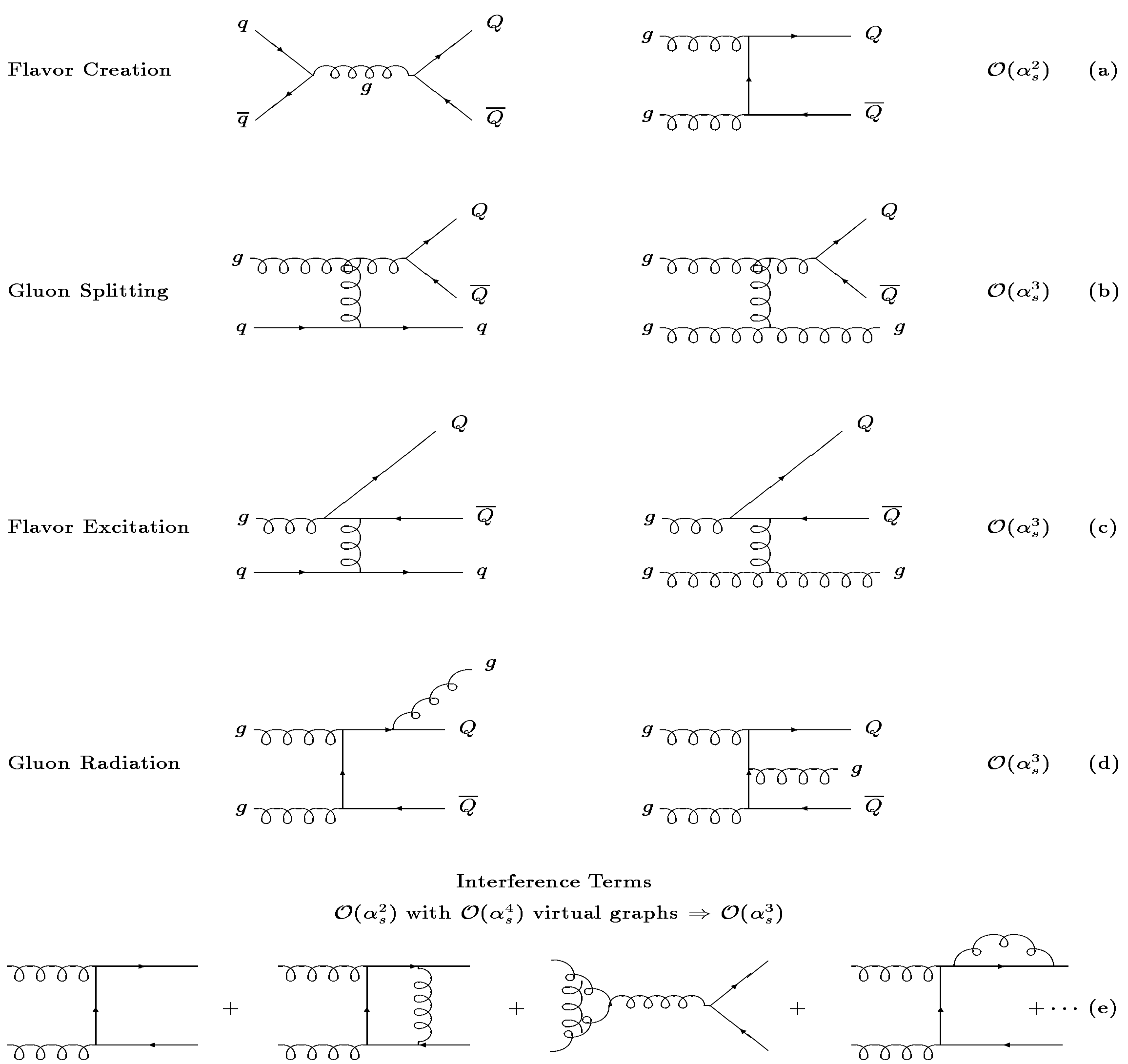
$\approx$ 30% (40%) higher B cross section
in the central (forward) region

Correlated $b - \bar{b}$ Production

- Further test of pQCD through observation of b and $\bar{b}$ angular and rapidity correlations
- Moreover:

  $d\sigma/d\Delta\Phi \Rightarrow$ contribution of NLO processes

  $d^2\sigma/dy_1 dy_2 \Rightarrow$ PDFs (gluon distribution at large x)

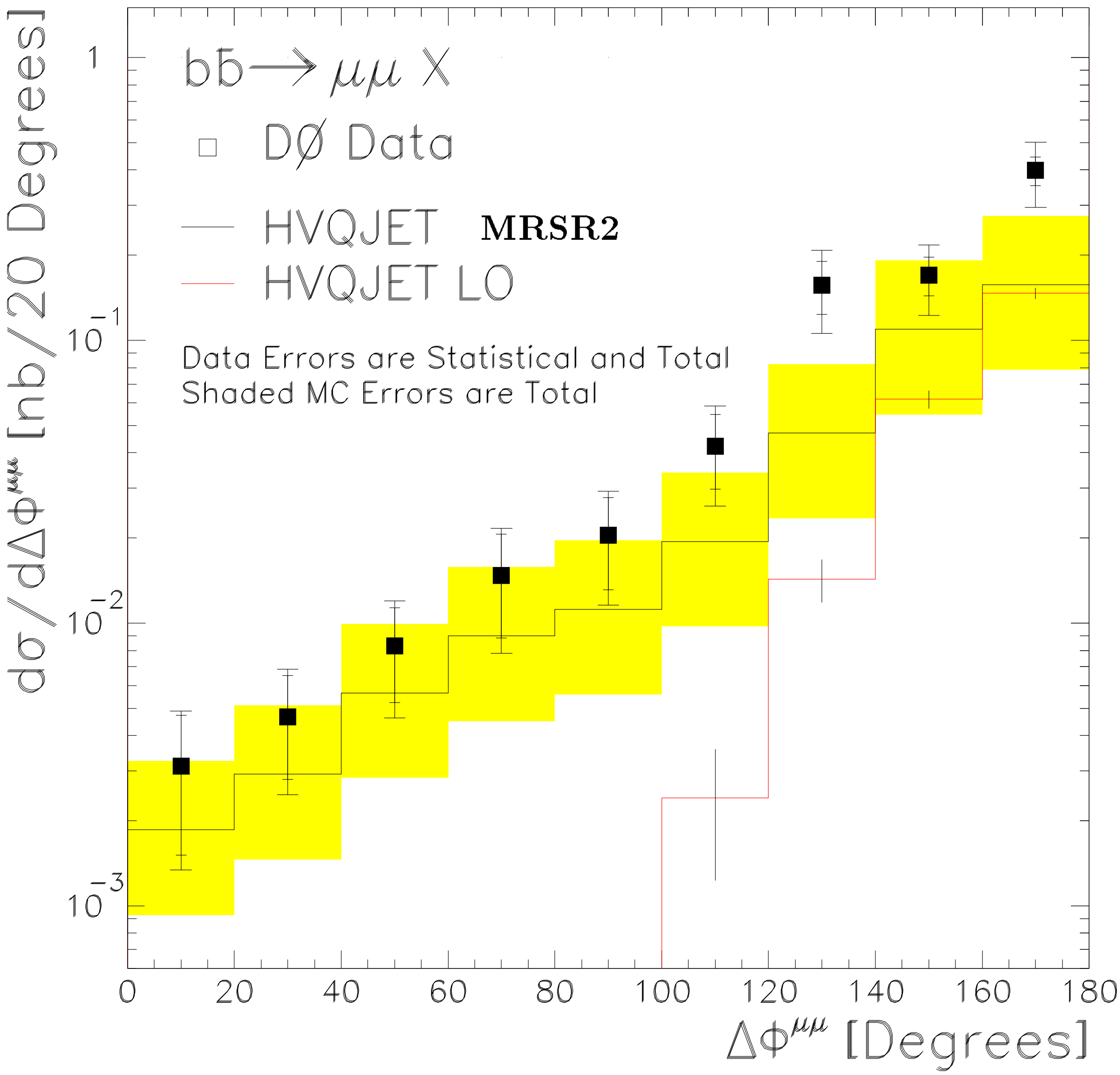


$b - \bar{b}$ Angular Correlations (DØ)

Muon pairs from $\int \mathcal{L} dt = 6.5\ pb^{-1}$

$4 < p_T^\mu < 25$ GeV/c, $\mid \eta^\mu \mid < 0.8$, $6 < M_{\mu\mu} < 35$ GeV/c^2

DØ – Preliminary

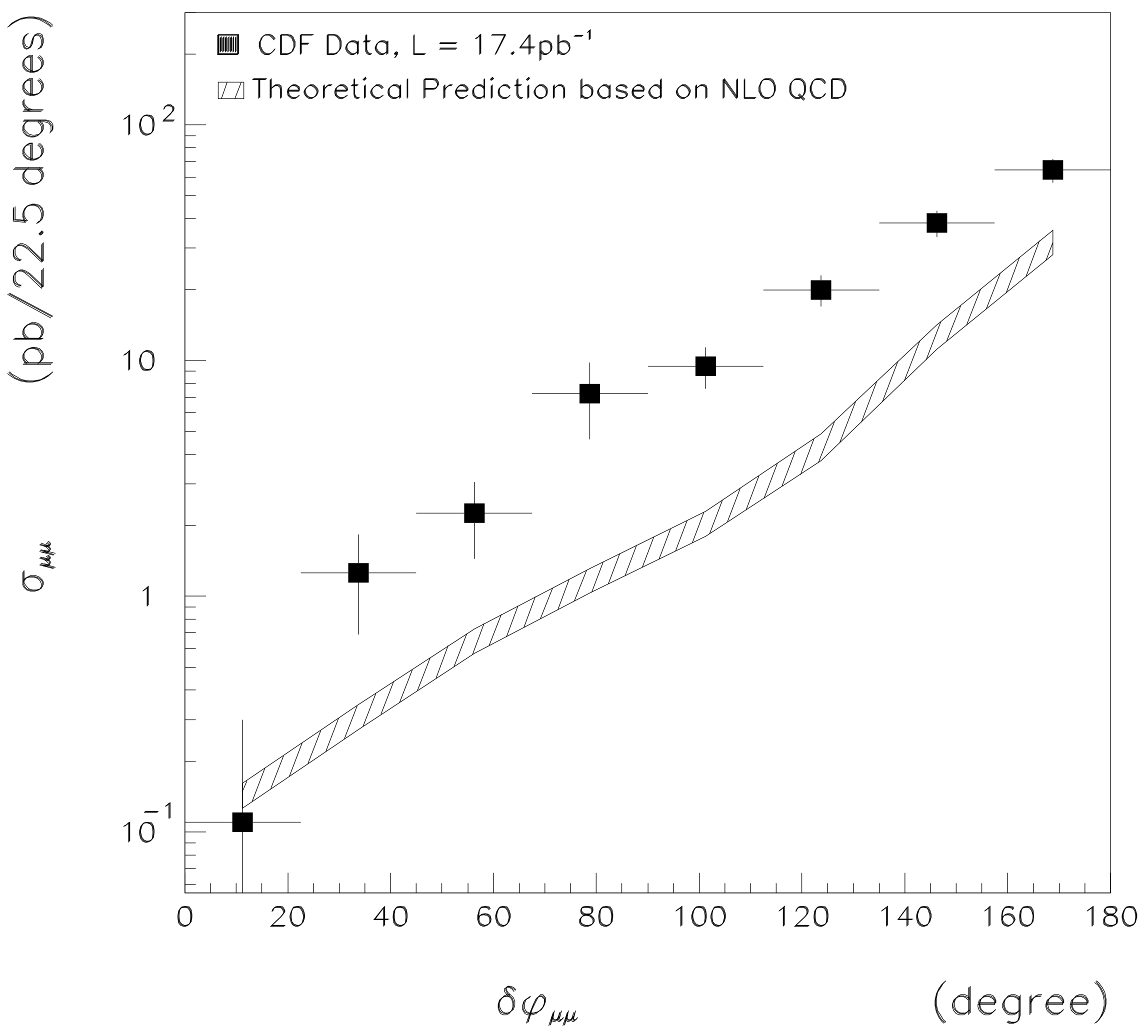


⇒ **Data / Theory ≈ 2.0**

⇒ **Sizeable contribution from NLO processes**

$b - \bar{b}$ Angular Correlations

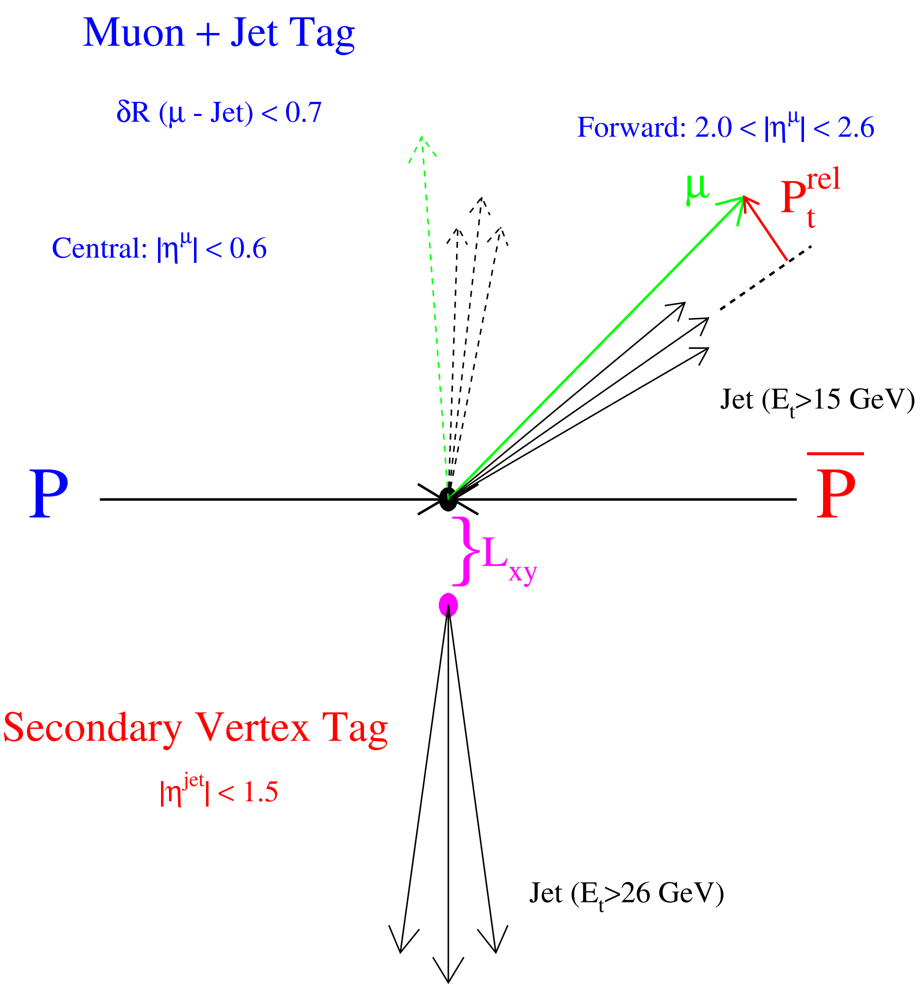
- CDF using high mass dimuons ($M_{\mu\mu} \geq 5$ GeV$/c^2$) from $\int \mathcal{L}dt = 17.4\ pb^{-1}$
- SVX impact parameter for each μ is used to determine $b\,\bar{b}$ content



- Theory band from efficiencies, $B(B \rightarrow \mu X)$, b fragmentation

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

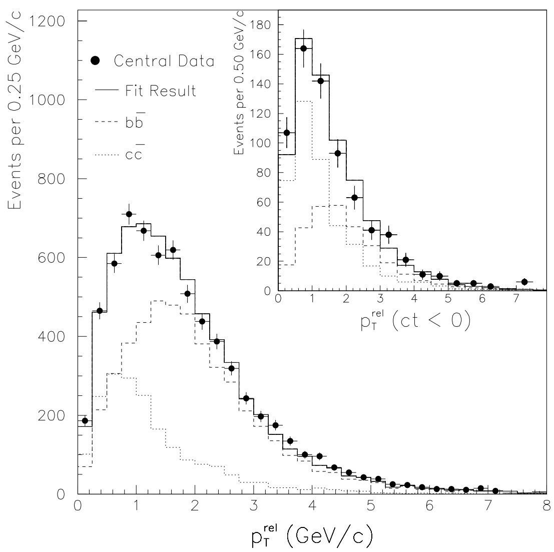
- **Event selection:**
  - Central b jet ($|\eta^{\text{jet}}| < 1.5$) with displaced secondary vertex
  - Second b decaying to muon+jet in central ($|\eta^{\mu}| < 0.6$) or forward ($2.0 < |\eta^{\mu}| < 2.6$) rapidity region



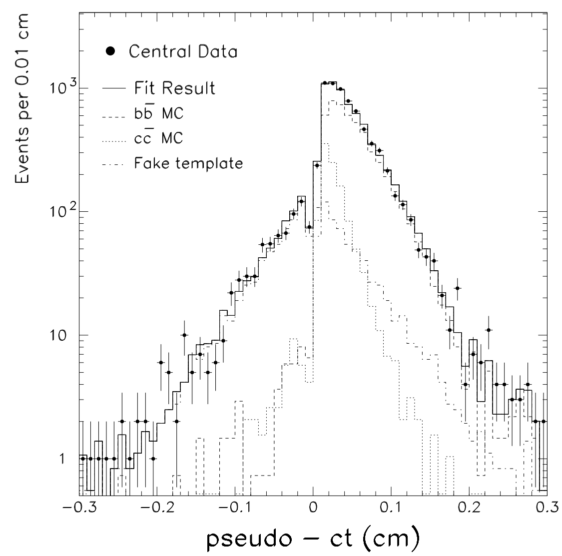
- **1994–95 Tevatron run ($\int \mathcal{L}dt = 77\ \text{pb}^{-1}$)**

  $\Rightarrow$ **382 forward–central events**
  7544 central–central events

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



p_T^{rel}



pseudo – $c\tau$

- Fitted fractions for each source:

(SVX-tag – μ-tag)	forward-central	central-central
b / b	0.815 ± 0.060	0.617 ± 0.017
c / c	0.083 ± 0.051	0.148 ± 0.014
b / fake	$0.000^{+0.059}_{-0.000}$	0.066 ± 0.021
fake / b	$0.017^{+0.047}_{-0.017}$	0.070 ± 0.010
fake / c	$0.086^{+0.035}_{-0.046}$	0.099 ± 0.010

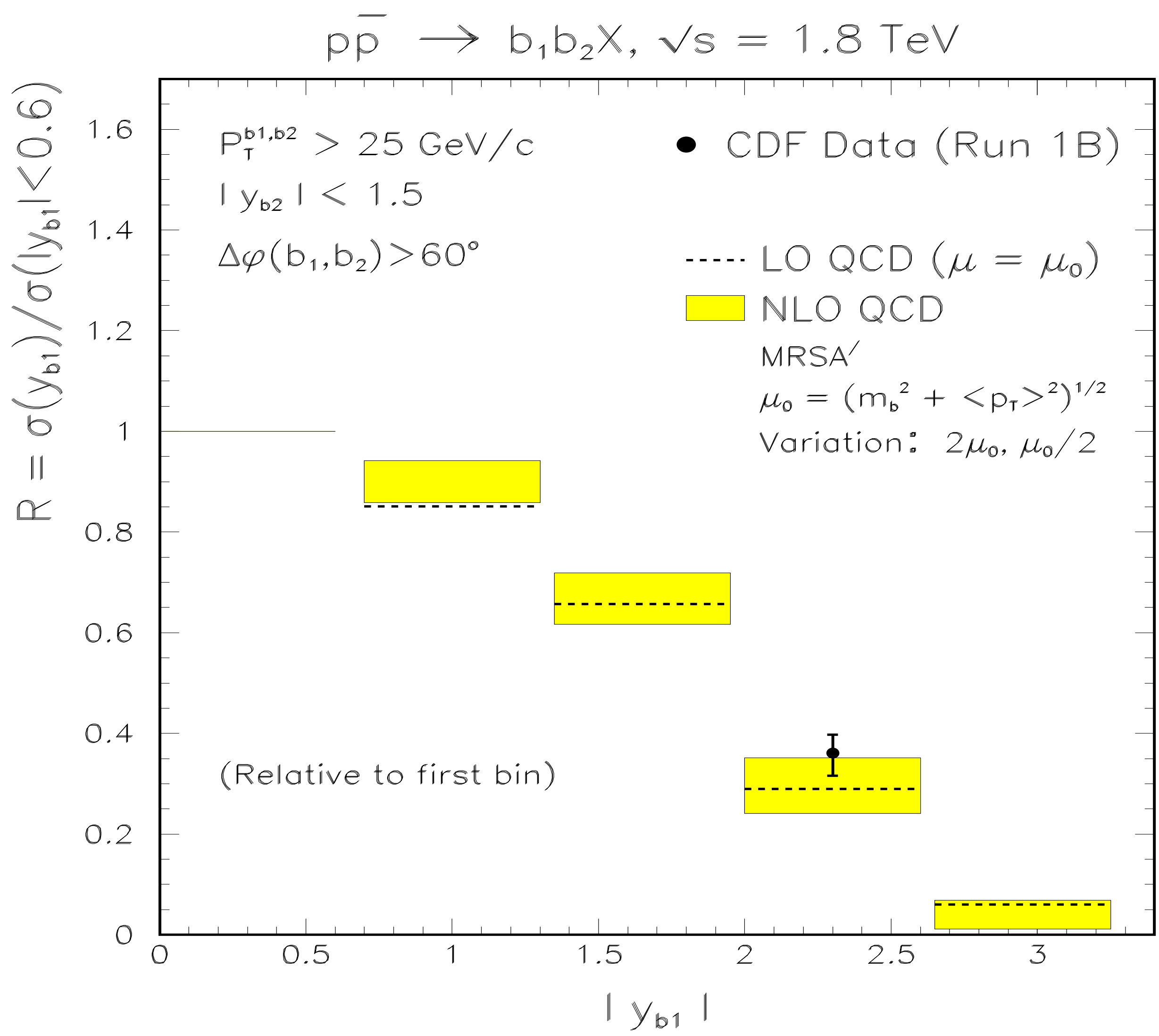
- Take $\sigma_{b\bar{b}}(forward - central)/\sigma_{b\bar{b}}(central - central)$ to reduce systematic errors

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

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

$$\boxed{R_{\text{expt}} = 0.361 \pm 0.033(\text{stat})^{+0.015}_{-0.031}(\text{syst})}$$

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

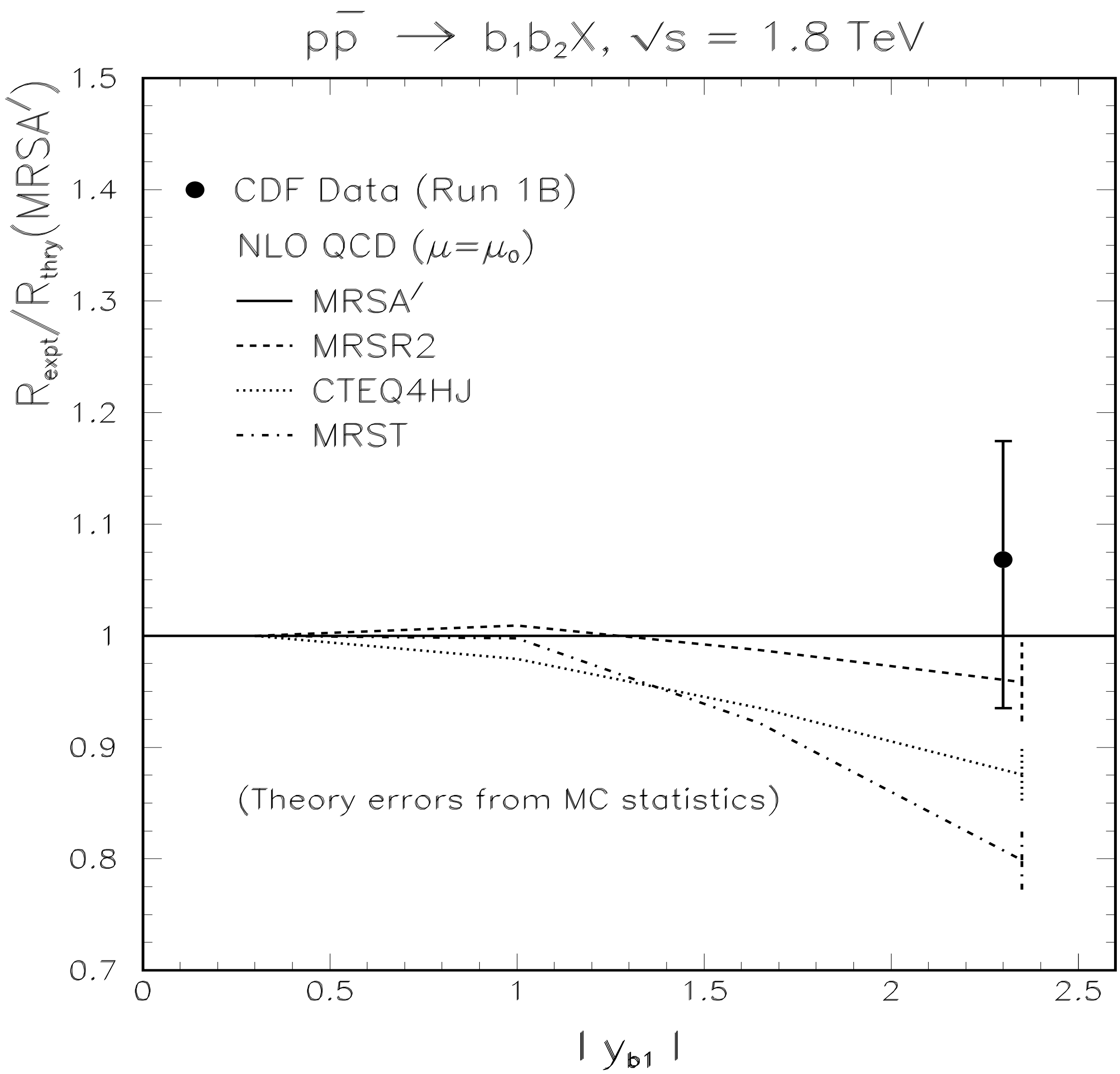


Probing Gluon Distribution in Proton

- Forward–central events correspond to

  low − x parton $\bar{x} \approx 0.025$ ***high − x parton*** $\bar{x} \approx 0.25$

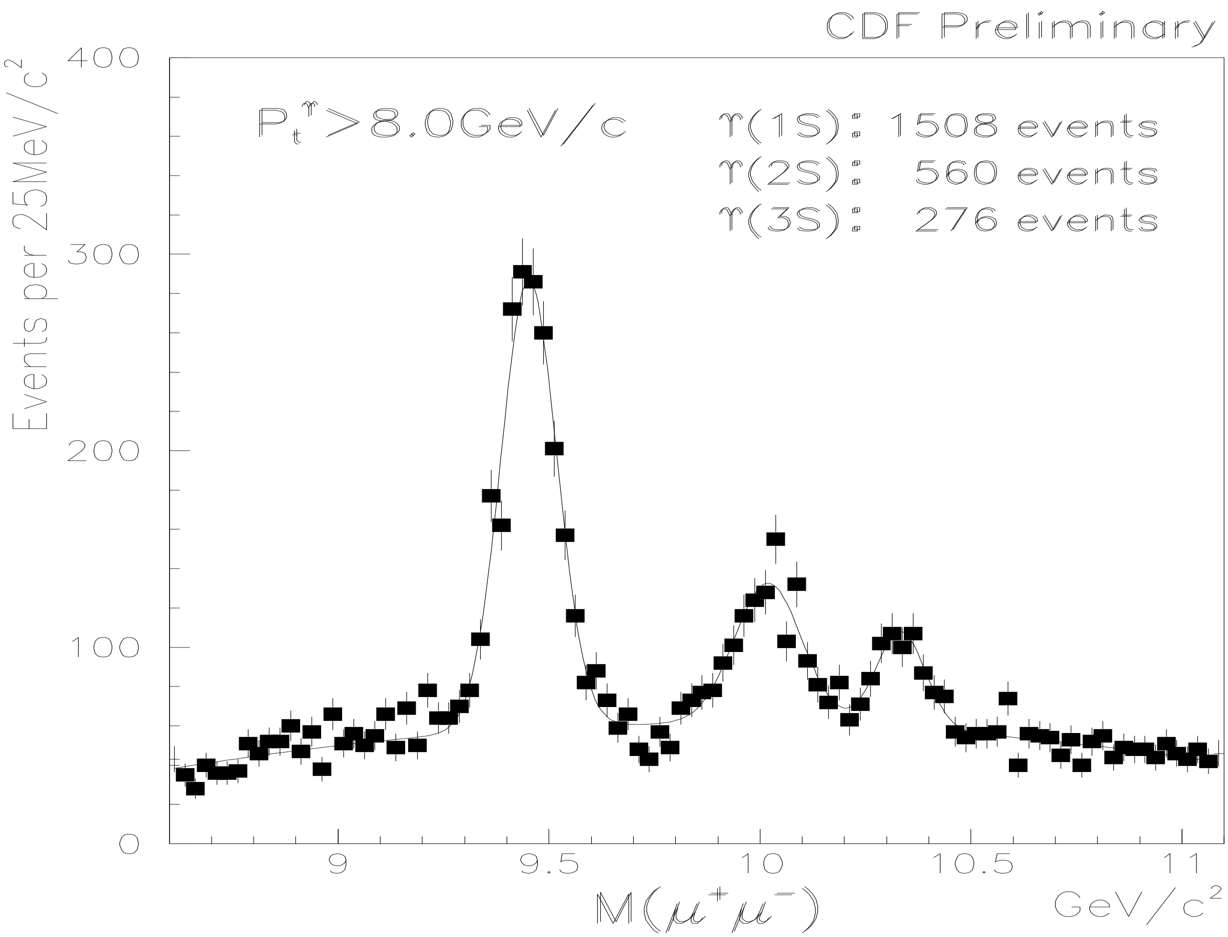
- R sensitive to $G(x, Q^2)$ at large x values
- $R_{\mathrm{expt}}/R_{\mathrm{thry}}$ for various PDFs



NB: Harder b fragmentation would lower R_{expt} !

$\Upsilon(1S)$ from χ_b Decays (CDF)

- CDF can observe $\Upsilon(1S)$ $\Upsilon(2S)$ $\Upsilon(3S)$



- Determine Direct Production of $\Upsilon(1S)$ from measurement of $\Upsilon(1S)$ from χ_b decays

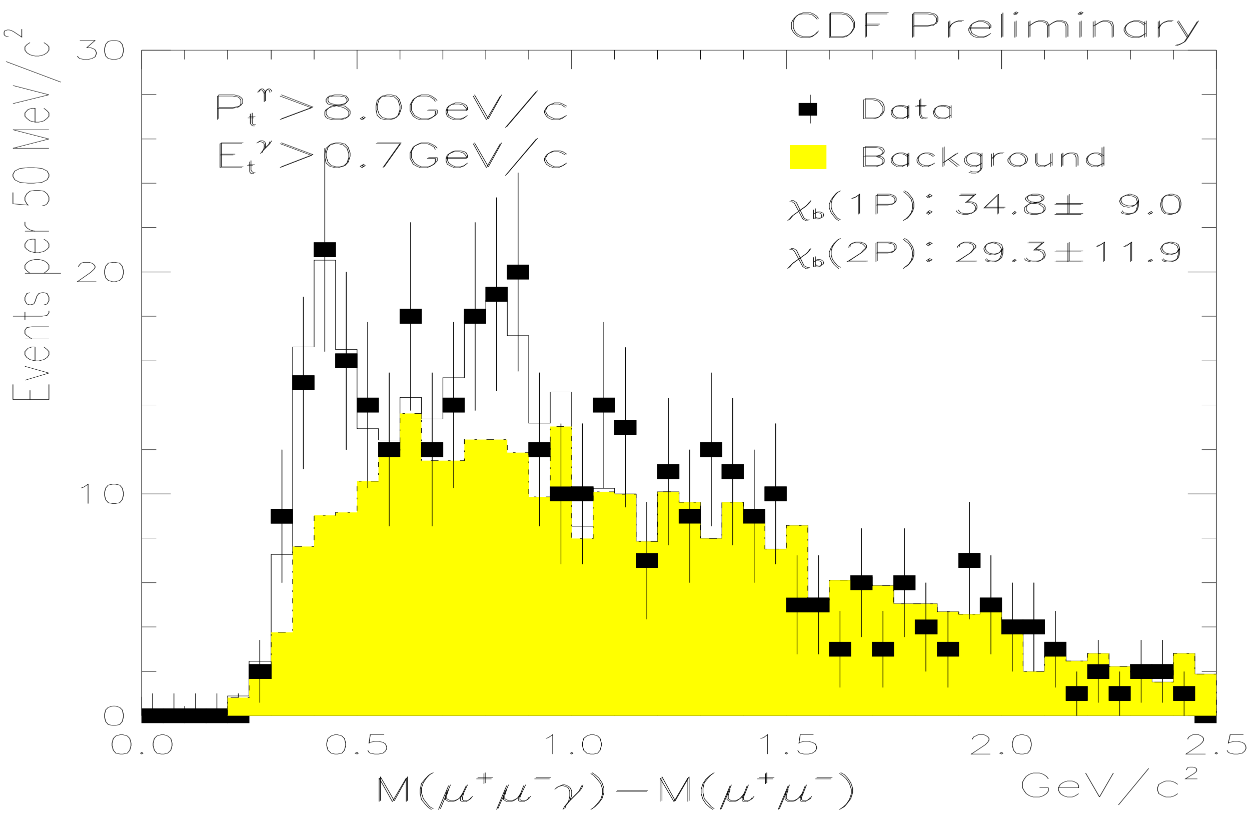
  NB: Inclusive Υ cross section alone not enough to extract Color Octet Model matrix elements

- $\chi_b(1P)$ and $\chi_b(2P)$ below $b\,\bar{b}$ threshold

  $\Rightarrow \chi_b(1P) \rightarrow \Upsilon(1S)\,\gamma \quad \Delta M = 443$ MeV$/c^2$

  $\Rightarrow \chi_b(2P) \rightarrow \Upsilon(1S)\,\gamma \quad \Delta M = 802$ MeV$/c^2$

- CDF uses dimuons from Run 1B $\int \mathcal{L} dt = 90$ pb^{-1}
- Reconstruct χ_b - $\mu\mu$ ($p_T^{\mu} > 2$; $p_T^{\mu\mu} > 8$ GeV/c) in $\Upsilon(1S)$ signal region and γ ($E_T^{\gamma} > 0.7$ GeV)



- Fitting ΔM to two gaussians and background

$\Rightarrow F[\chi_b(1P) \to \Upsilon(1S) \;\; p_T^{\Upsilon} > 8 \text{ GeV}/c] = 26.7 \pm 6.9 \pm 4.3$ %

$\Rightarrow F[\chi_b(2P) \to \Upsilon(1S) \;\; p_T^{\Upsilon} > 8 \text{ GeV}/c] = 10.8 \pm 4.4 \pm 1.3$ %

- From measured $\Upsilon(2S)$ cross section

$\Rightarrow F[\Upsilon(2S) \to \Upsilon(1S)\pi\pi \;\; p_T^{\Upsilon} > 8 \text{ GeV}/c] = 10.7 \pm 2.5^{+7.4}_{-4.3}$ %

NB: $\Upsilon(3S) \to \Upsilon(1S)$ negligible

$$\boxed{F[DIRECT\ \Upsilon(1S);\ p_T^{\Upsilon} > 8 \text{ GeV}/c] = 51.8 \pm 8.2^{+9.0}_{-6.7} \text{ \%}}$$

$\psi(2S)$ Polarization (CDF)
A Test of Color Octet Model

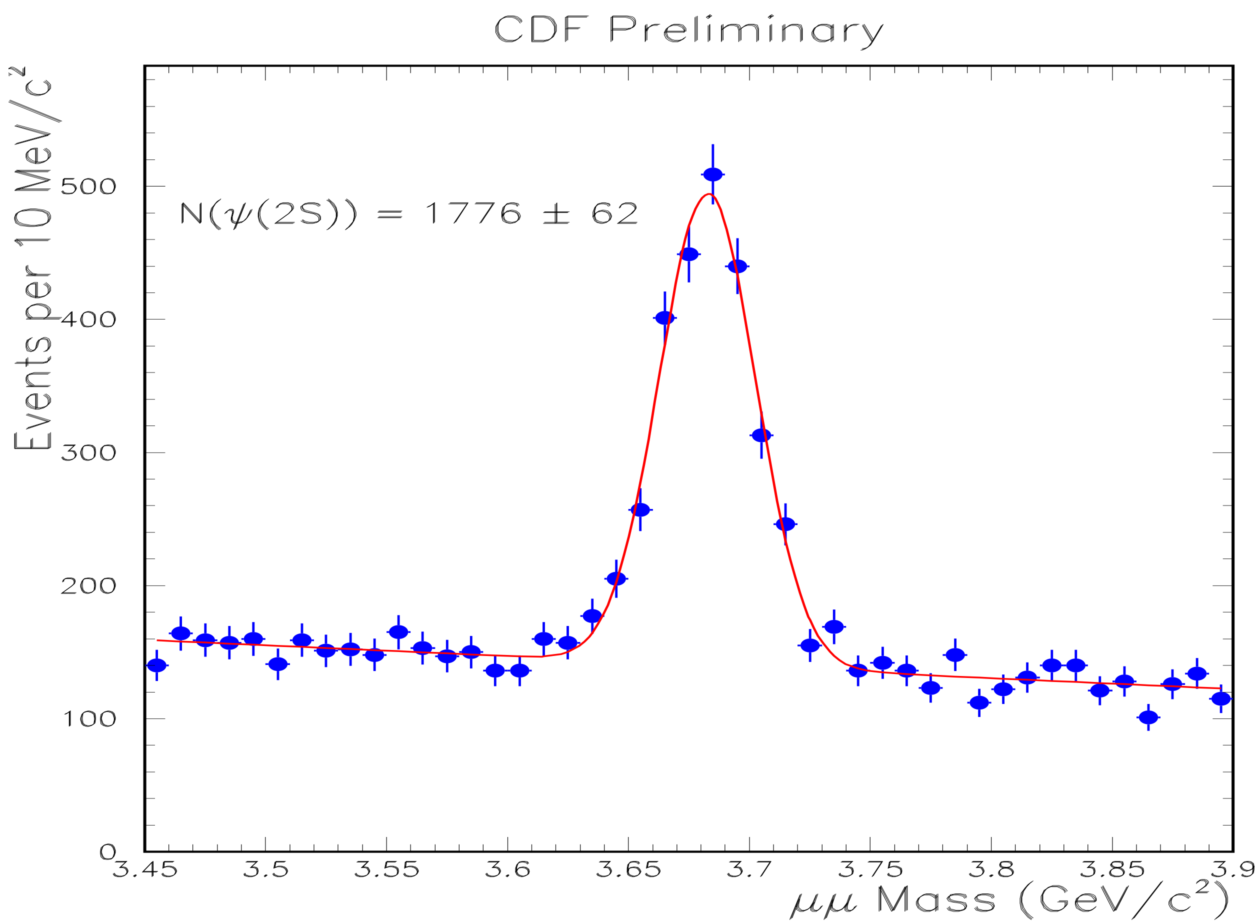
- Recall: Direct $\psi(2S)$ (J/ψ) production in $p\bar{p}$ collisions is $\approx$ 50 (6) times higher than Color Singlet Model predictions !
- Color Octet Model describes this anomalously high cross section by including color-octet $c\bar{c}$ states in gluon fragmentation
- At high p_T ($p_T \gg m_c$) fragmenting gluon is transversely polarized
  C O M $\Rightarrow$ At high p_T direct J/ψ and $\psi(2S)$ approach 100% transverse polarization
- Displaced $\psi(2S)$ vertex allows separation of direct production from B decays. Direct $\psi(2S)$ is cleaner than direct J/ψ - not contaminated with $\chi_c \to J/\psi\gamma$
- Angular distribution in $\psi(2S) \to \mu^+\mu^-$:

$$w(\theta) = \frac{3}{2(\alpha + 3)}(1 + \alpha\ cos^2\theta)$$

θ angle between p_{μ^+} in $\psi(2S)$ rest frame and p_ψ in lab frame

α polarization; $+1$ transverse, -1 longitudinal

- CDF uses dimuons from 1992-95 $\int \mathcal{L} dt = 110\ \mathrm{pb}^{-1}$
- Reconstruct $\psi(2S)$ - $\mu\mu$ ($p_T^{\mu} > 2$; $p_T^{\mu\mu} > 5.5$ GeV/c)
  Fit a gaussian plus linear background

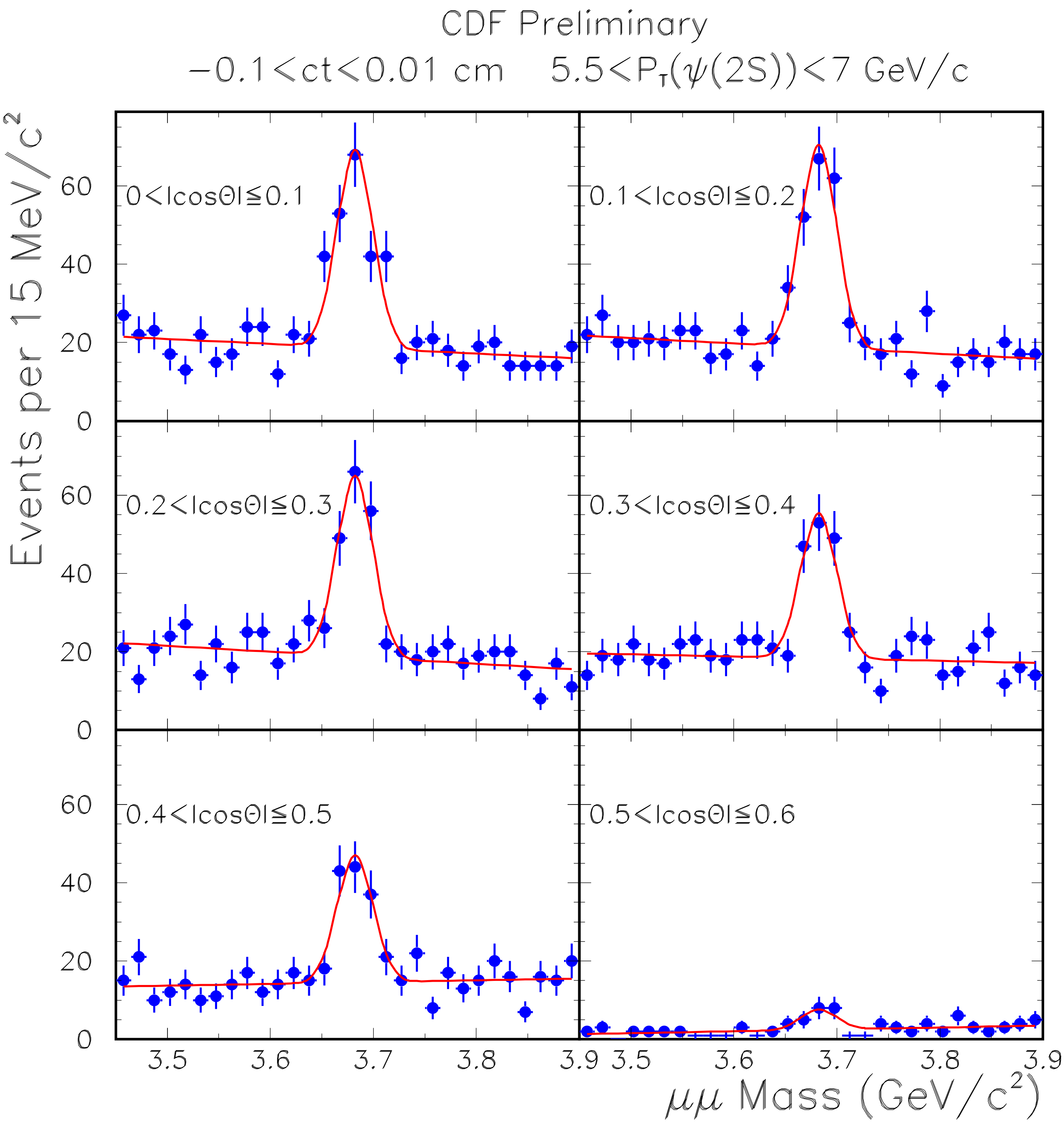


- Data sample divided into bins of
  p_T : $5.5 - 7.0$; $7.0 - 9.0$; $9.0 - 20.0$ GeV/c
  $ct = \dfrac{m\ L_{xy}}{F_c\ p_T}$:

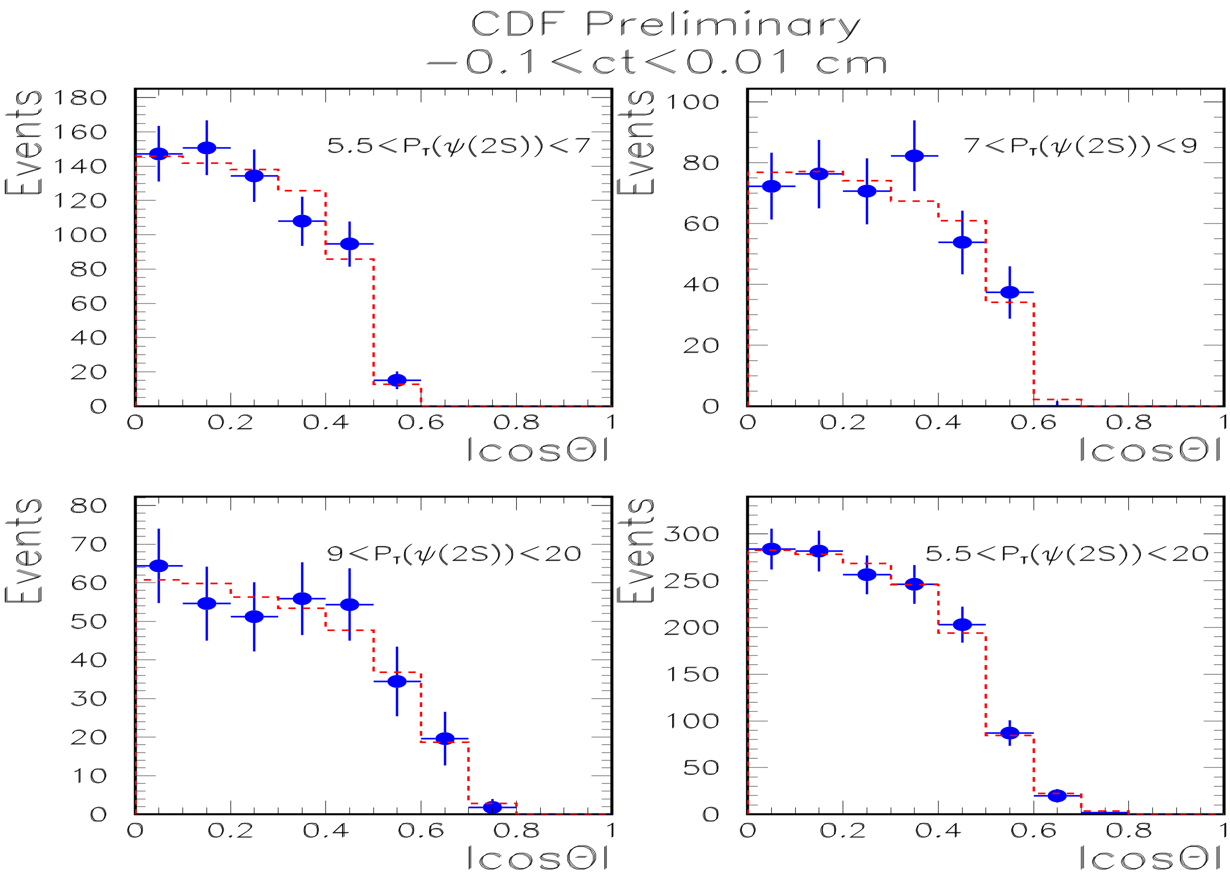
  Direct $\psi(2S)$: $-0.1 < ct < 0.01\ cm$

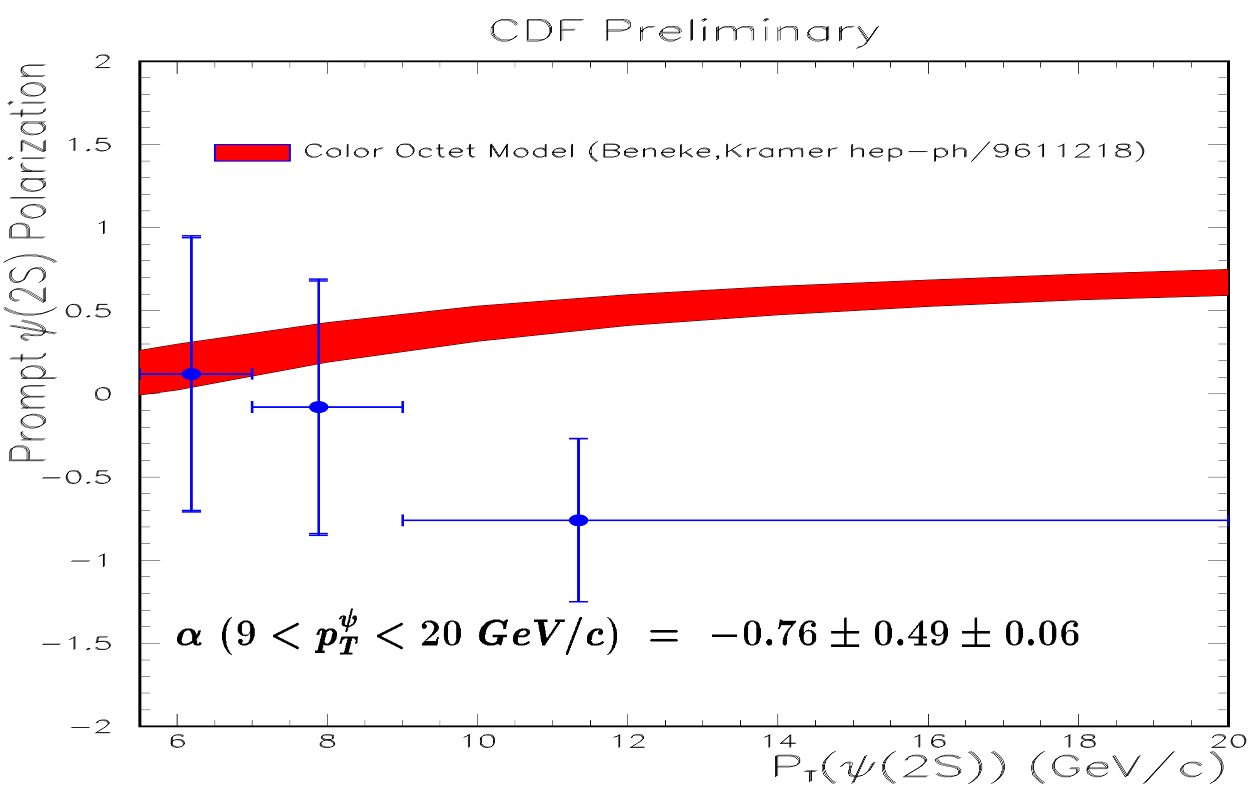
  $\psi(2S)$ from B decays : $ct > 0.01\ cm$

- **Calculate *cos θ* for events - fit *μμ* mass to a gaussian plus linear background to extract signal event yield per *cos θ* bin**



- $\cos\theta$ **distributions, fit results for direct** $\psi(2S)$





Data (large statistical errors) do not support COM !

CONCLUSIONS

- Several different CDF and DØ data sets give consistent measurements of b-quark production cross section in $p\,\bar{p}$ collisions at $\sqrt{s} = 1800$ GeV

- NLO QCD calculations describe the shape but underestimate b-quark production by

  a factor of 2.5 ± 0.4 in central rapidity region

  a factor of 3.6 ± 0.8 in forward region

- Results on $b\,\bar{b}$ angular correlations indicate:
  - Shape of $d\sigma/d\Delta\Phi_{\mu\mu}$ in agreement with NLO QCD
    $\Rightarrow$ Sizeable contribution from NLO processes
  - Normalization off by a factor of ≈ 2

- First measurement of $b\,\bar{b}$ rapidity correlations indicates Strong correlation:
  Ratio of forward $(2.0 <|\,y\,|< 2.6)$ to central $(|\,y\,|< 0.6)$ $b\,\bar{b}$ production $R = 0.36$ in agreement with NLO QCD
  - Normalization off by a factor of ≈ 2
  - R sensitive to $G(x, Q^2)$ in proton for $x > 0.15$
    Need more data to distinguish between PDFs

CONCLUSIONS

- Different sources of $\Upsilon(1S)$ production in $p\,\overline{p}$ collisions are separated:

  $F[\chi_b(1P) \rightarrow \Upsilon(1S)\;\; p_T^{\Upsilon} > 8\ \mathrm{GeV}/c] = 26.7{\pm}6.9{\pm}4.3\ \%$

  $F[\chi_b(2P) \rightarrow \Upsilon(1S)\;\; p_T^{\Upsilon} > 8\ \mathrm{GeV}/c] = 10.8{\pm}4.4{\pm}1.3\ \%$

  $F[\Upsilon(2S) \rightarrow \Upsilon(1S)\pi\pi\;\; p_T^{\Upsilon} > 8\ \mathrm{GeV}/c\,] = 10.7{\pm}2.5^{+7.4}_{-4.3}\ \%$

  $F[DIRECT\ \Upsilon(1S);\;\; p_T^{\Upsilon} > 8\ \mathrm{GeV}/c\,] = 51.8{\pm}8.2^{+9.0}_{-6.7}\ \%$

- A preliminary measurement of $\psi(2S)$ polarization from direct production gives

  $\alpha\ (9 < p_T^{\psi} < 20\ GeV/c)\ =\ -0.76 \pm 0.49 \pm 0.06$

  The measurement does not support the Color Octet Model prediction that $\psi(2S)$ is transversely polarized - although the data are limited in statistics