Experimental Status of Open Beauty Production

Marc M. Baarmand
SUNY - Stony Brook

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OUTLINE

- Introduction

- Inclusive and differential b-quark production cross-section in $p\,\bar{p}$ Collisions at $\sqrt{s} = 1800$ and 630 GeV CDF and DØ data:
  - inclusive electron or muon
  - muon + jet
  - non-resonant dimuon
  - $J/\Psi, \Psi' \rightarrow \mu\mu$

- $b\,\bar{b}$ correlations

- Summary and conclusions

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 at small x, below DIS x-range

- 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)

Beauty Production Cross-Section Calculation

- Description of experimentally observed b-hadron production and decay:
  - Production of b-quark in hadron collisions
    - calculable in parton model - strong production of b in association with a $\bar{b}$
  - Fragmentation of b-quark into a b meson or baryon
    - not calculable in perturbation theory - factorized out as a phenomenalogical "fragmentation function" in pQCD
  - Decay of b-hadron into ordinary hadrons and leptons with measured branching ratios
- Fixed-order QCD calculations:
  - b cross-section is a convolution of parton-parton scattering with parton distribution functions:

$$\sigma(s, m, Q^2) = \Sigma_{ij} \int dx_1 \int dx_2 \; f_i(x_1, Q^2) f_j(x_2, Q^2) \hat{\sigma}_{ij}(\hat{s}, m, Q^2)$$

  - f_i, f_j and $\hat{\sigma}_{ij}$ are expanded in perturbation series in α_s and calculated to LO or NLO
  - No real physical criterion for choosing the scale Q^2 - reduce sensitivity to choice of Q^2 by calculating NLO corrections to LO
  - NLO corrections are particularly important to b (heavy quark) production because of initial and final state gluon splitting in $g + g \rightarrow g + g$

Extraction of b-Quark Cross-Section from Data

- Data samples with e or μ and/or jets in final state:
  - * inclusive e/μ: $p\bar{p} \rightarrow b\bar{b}X$ → e/μ
  - * muon + jet: $p\bar{p} \rightarrow b\bar{b}X$ → μ + jet
  - * dimuon + jets: $p\bar{p} \rightarrow b\bar{b}X$ → μ + jet, μ + jet
  - * J/Ψ (Ψ'): $p\bar{p} \rightarrow b\bar{b}X$ → $J/\Psi X$ → $\mu^+\mu^-$
- 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

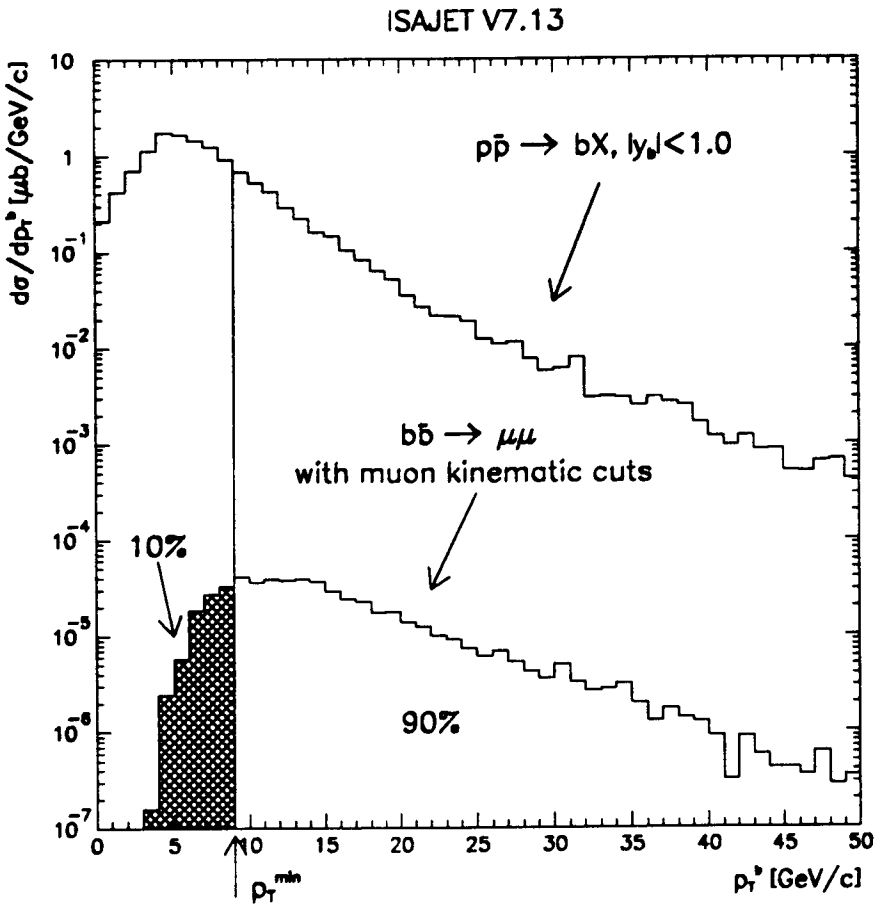
Example: Inclusive Muon Data

- 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
      - $z' = p_\mu \cos\theta/(p^{jet} \cdot E_T^{jet})$ 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:
  $\sigma(p_T^b > p_T^{min}, |y_b| < 1)$
  - account for branching ratio $b \to \mu \approx 11\%$
  - 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 $p_T^b > p_T^{\min}$



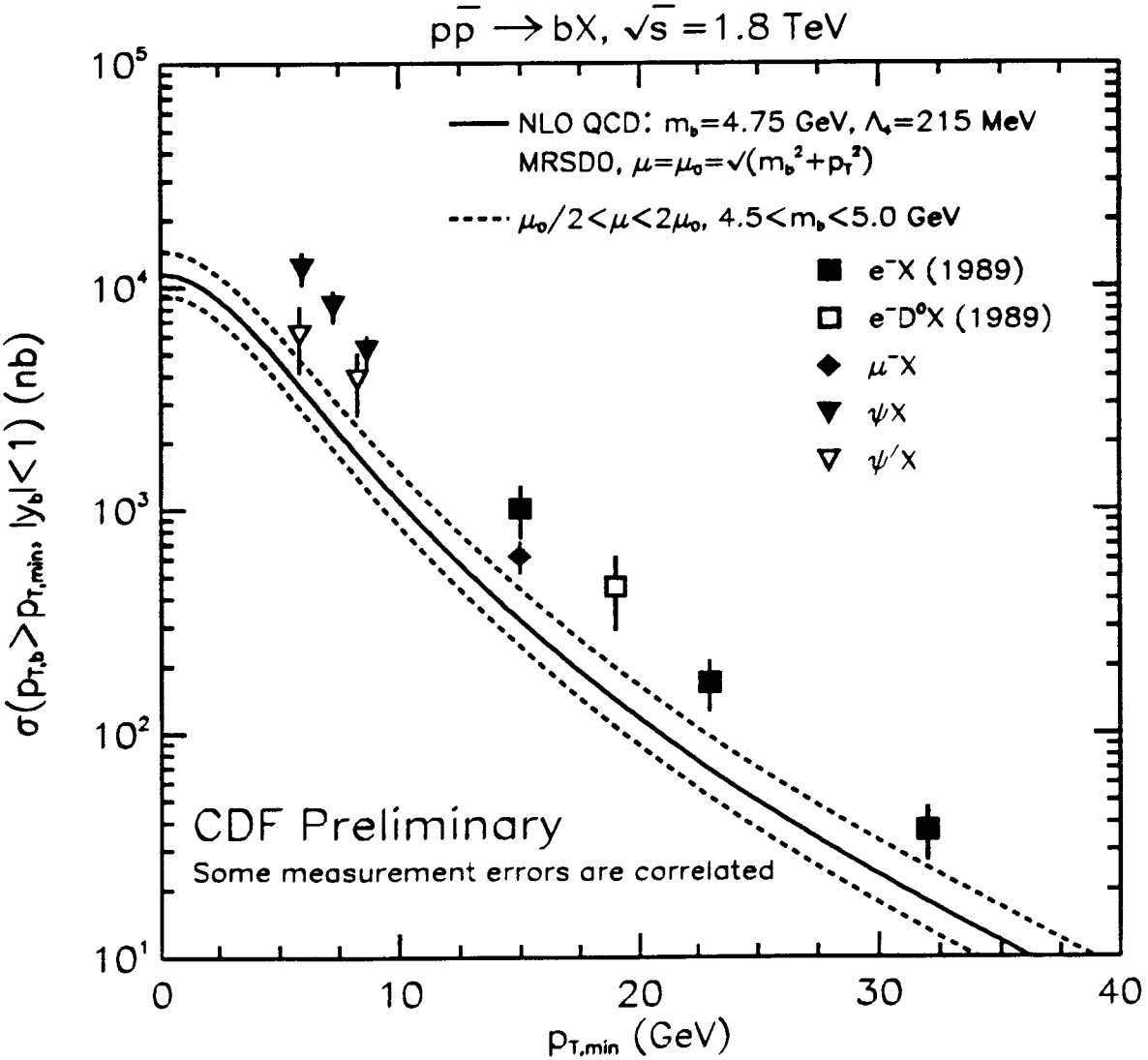
Inclusive b-quark Production Cross-Section

- CDF measurements at $\sqrt{s} = 1.8$ TeV
- $\sigma(p_T^b > p_T^{min})$ for $| y^b | < 1$
- NLO calculations:

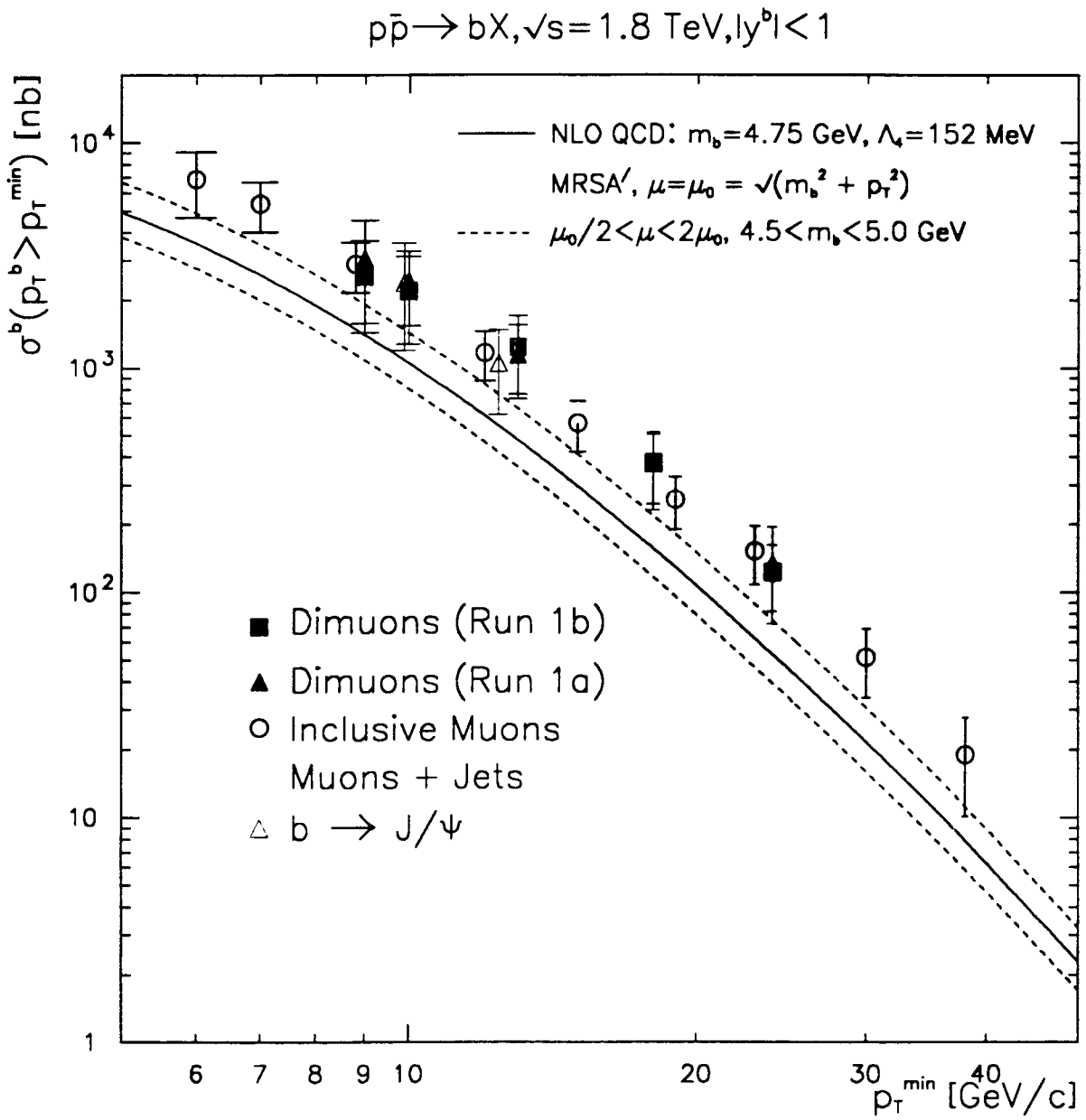
P. Nason *et al.*, Nucl. Phys. B327 (1989) 49, B335 (1990) 260

W. Beenakker *et al.*, Nucl. Phys. B351 (1991) 507

M. Mangano *et al.*, Nucl. Phys. B373 (1992) 295



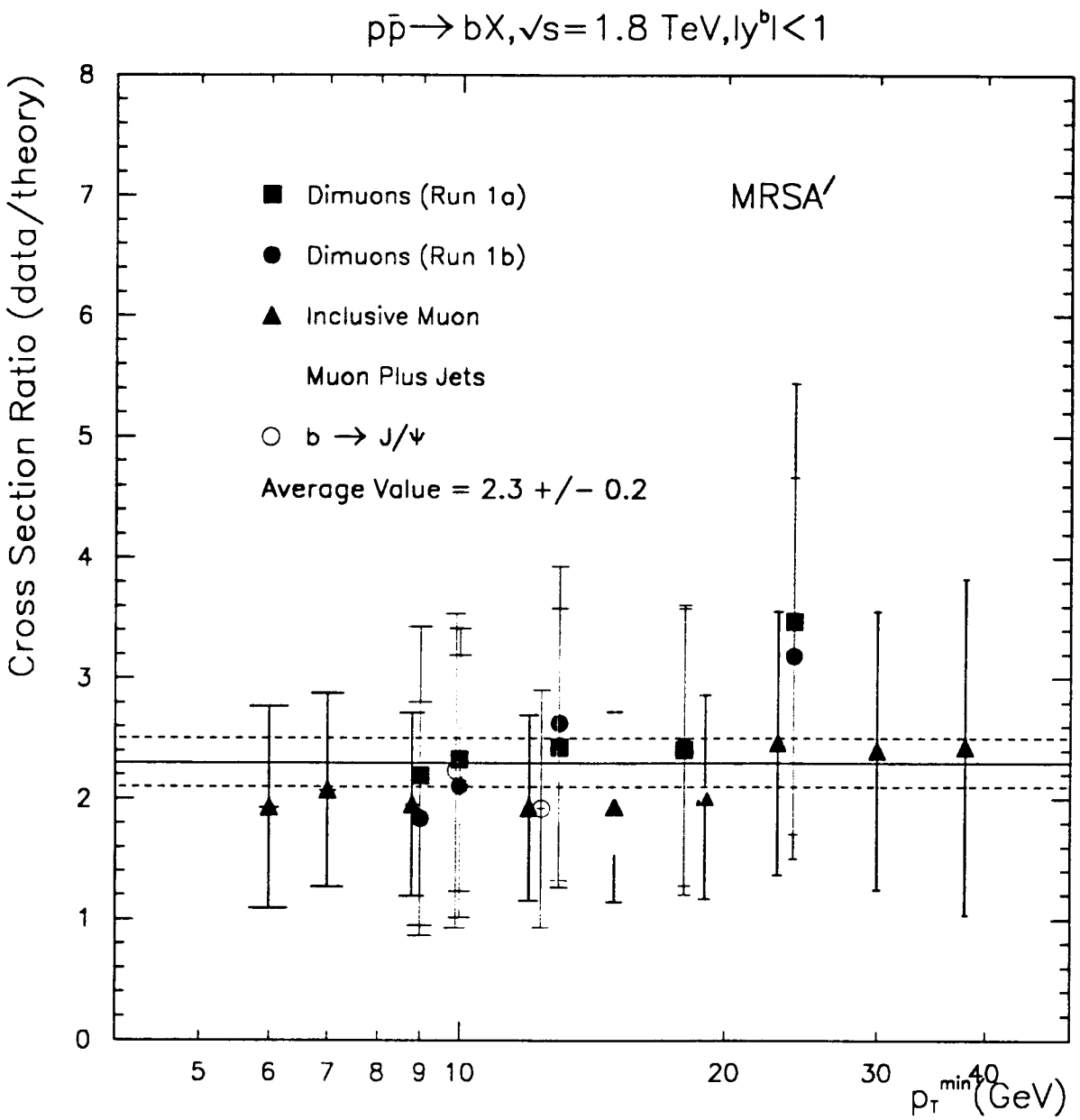
DØ measurements at $\sqrt{s} = 1.8$ TeV



- **Good agreement between measurements**
- **Data at upper edge of NLO QCD**

b-Quark Production: Comparison to Theory

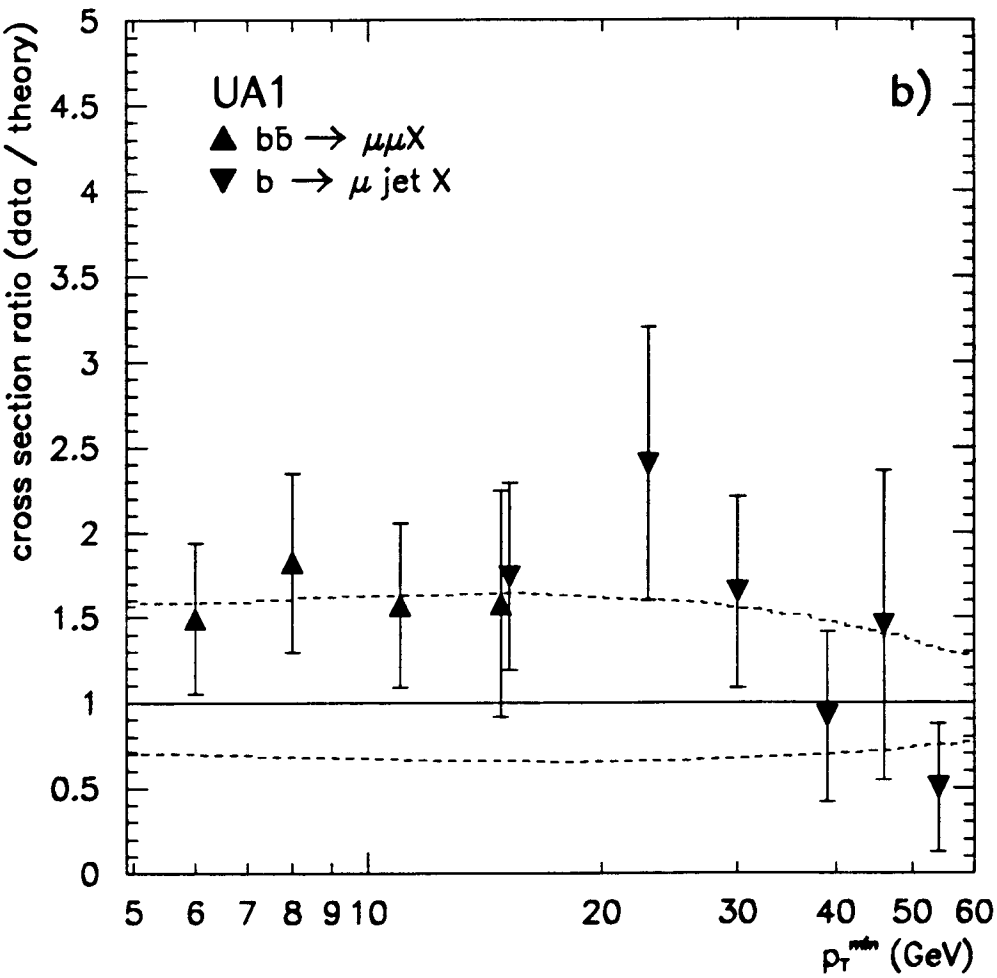
- **DØ Measurements**



- **Ratio Data/Theory = 2.3 ± 0.2**

Previous Measurements of b Cross-Section

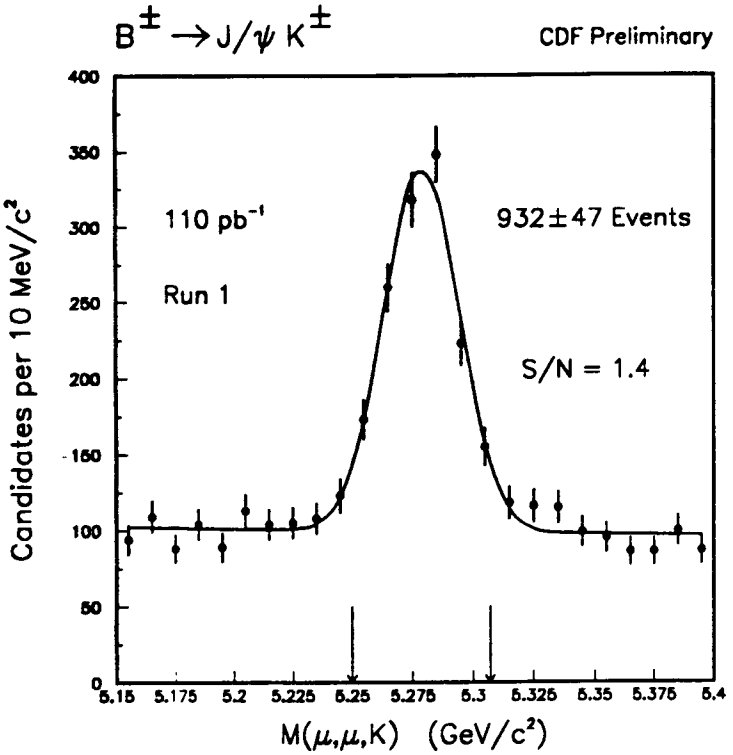
- UA1 measurements at $\sqrt{s} = 630$ GeV
- $\sigma(p_T^b > p_T^{min})$ for $\mid y^b \mid < 1.5$ from $\int \mathcal{L}dt = 4.7$ pb^{-1}
- NLO calculations using MRSD0 (UA1 used DFLM)

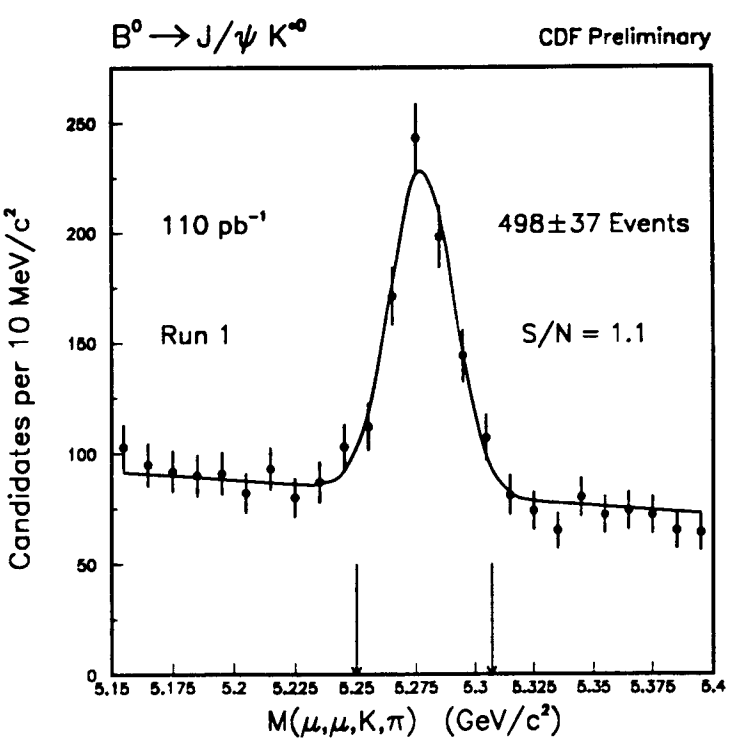


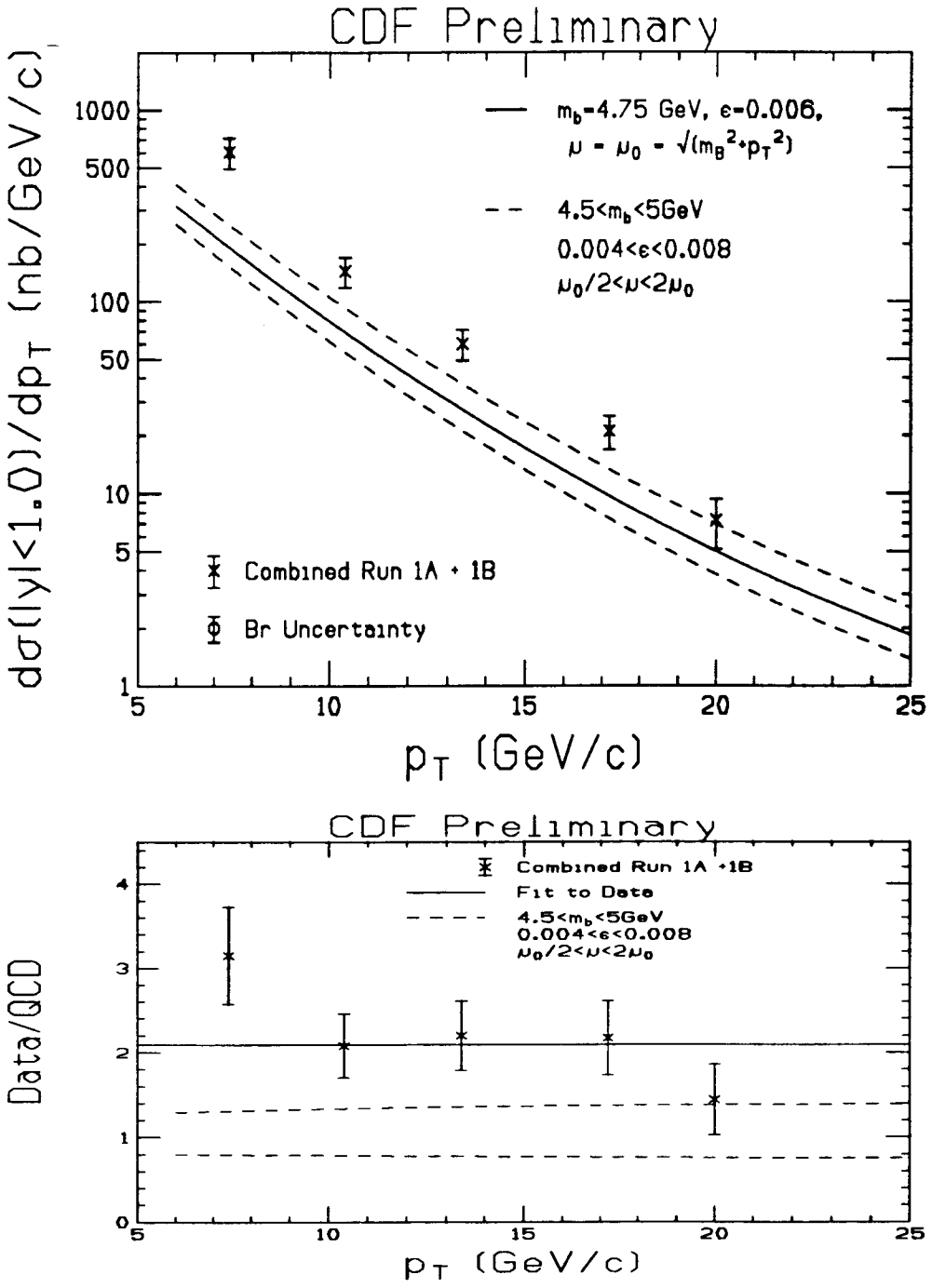
- Ratio Data/Theory ≈ 1.5
- $\sigma(p\bar{p} \to bX, \mid y^b \mid < 1.5) = 13.0 \pm 2.8 + 6.9 - 4.3$ μb

B Meson Differential Cross-Section

- CDF measurement from $\int \mathcal{L}dt = 74\ \mathrm{pb}^{-1}$
- $d\sigma/dp_T$ ($|\ y_b\ | < 1$) for $p_T(B) > 6.0$ GeV/c
- Full reconstruction of
  $B^{\pm} \rightarrow J/\Psi + K^{\pm}$
  $B^0 \rightarrow J/\Psi + K^{*0}$
  where $J/\Psi \rightarrow \mu^+\mu^-$ and $K^{*0} \rightarrow K^+\pi^-$
- $\sigma^B_{tot}(p_T(B) > 6.0\ \mathrm{GeV/c}) = 2.54 \pm 0.22 \pm 0.53\ \mu b$







- **Ratio Data/QCD = $2.1 \pm 0.2 \pm 0.3$**
- **NLO calculations:**

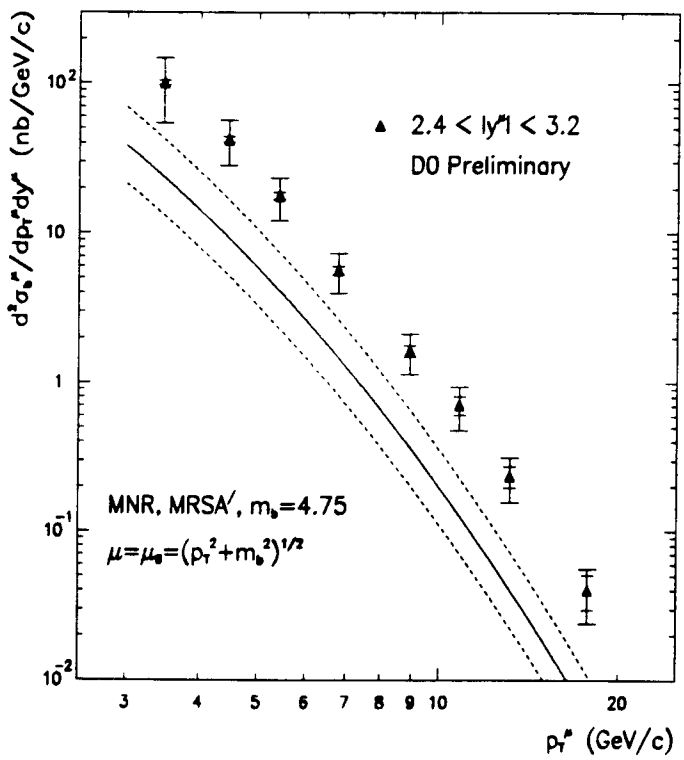
P. Nason *et al.*, Nucl. Phys. B327 (1989) 49

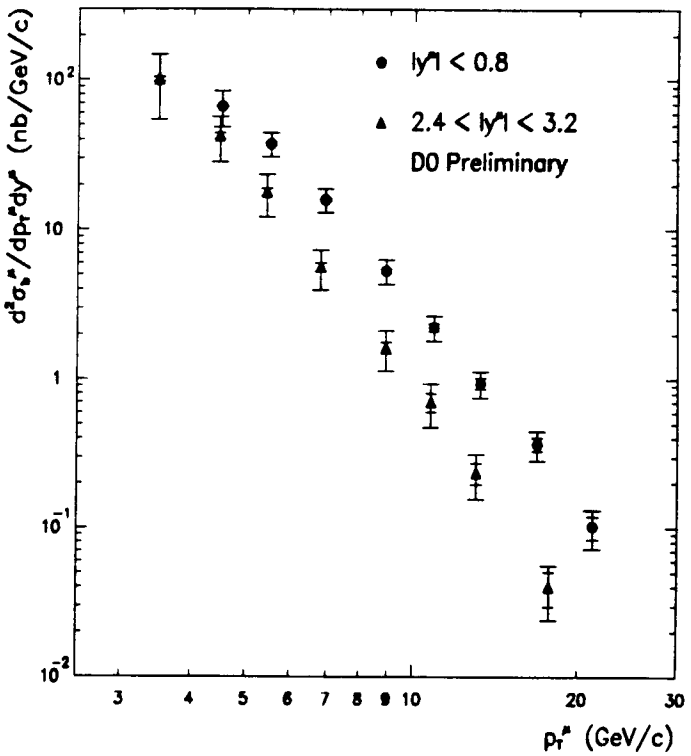
M. Mangano *et al.*, Nucl. Phys. B373 (1992) 295

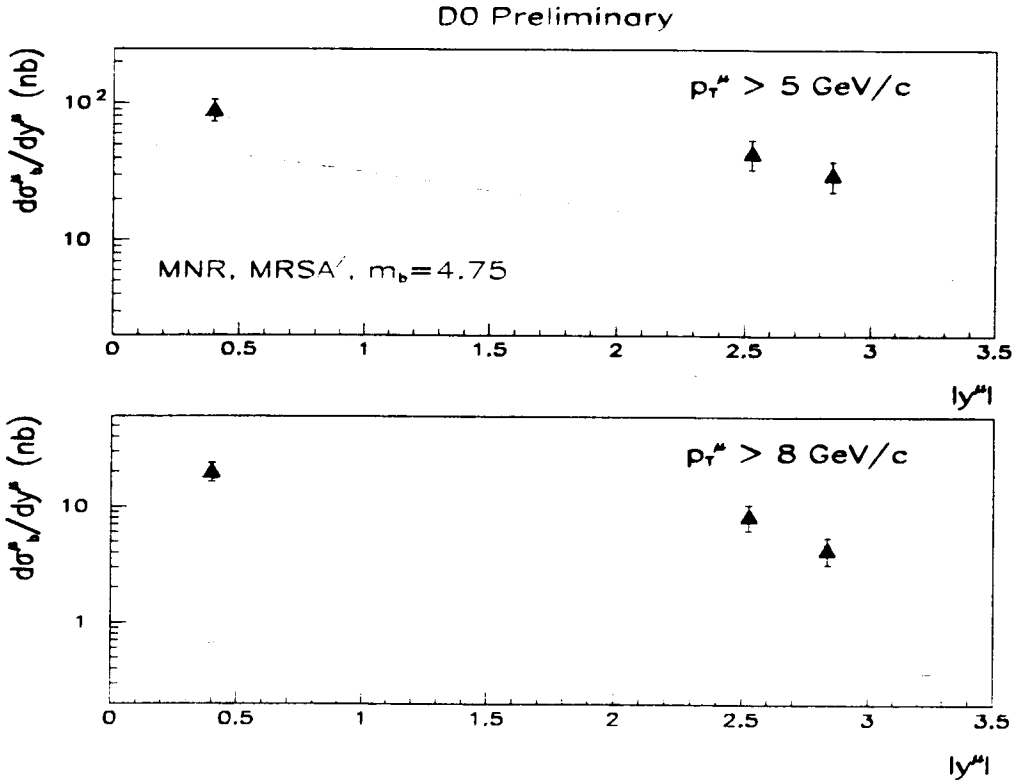
75% of *b* quarks assumed to fragment in equal amounts to charged B and B^0

Differential Muon Cross-Section

- DØ : First measurement of $d^2\sigma_b^\mu / dp_T^\mu \, dy^\mu$ in $2.4 < |y^\mu| < 3.2$ (SAMUS) from $\int \mathcal{L}dt = 60$ nb^{-1}







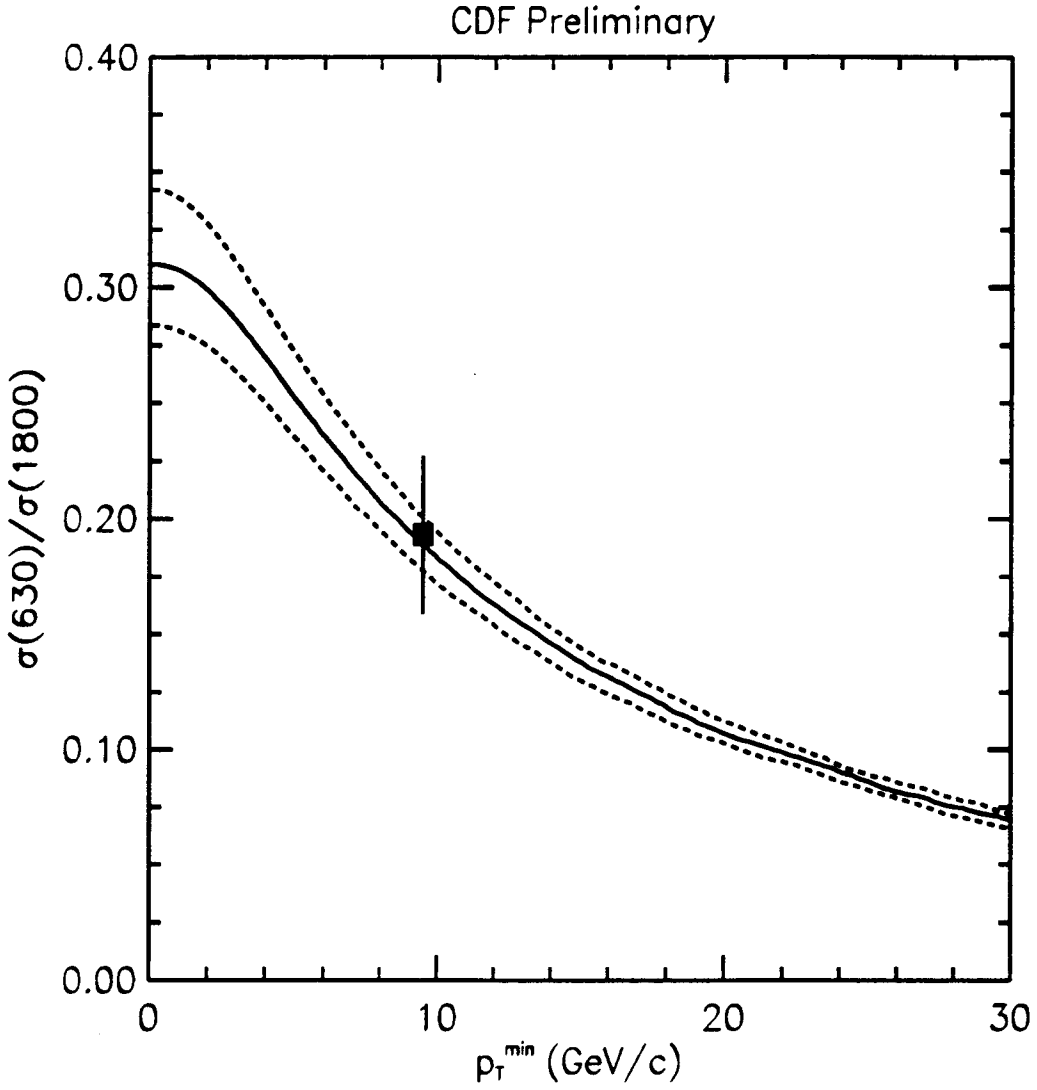
b-quark Cross-Section vs. $\sqrt{s}$

- Ratio $= \sigma_b(\sqrt{s} = 630 \text{ GeV})/\sigma_b(\sqrt{s} = 1800 \text{ GeV})$

  reduced theoretical uncertainties

  reduced experimental errors when a common signature used

- CDF muons associated with secondary vertices
  $\sqrt{s} = 630$ GeV $\int \mathcal{L}dt = 0.46\ pb^{-1}$, 1800 GeV $1.89\ pb^{-1}$

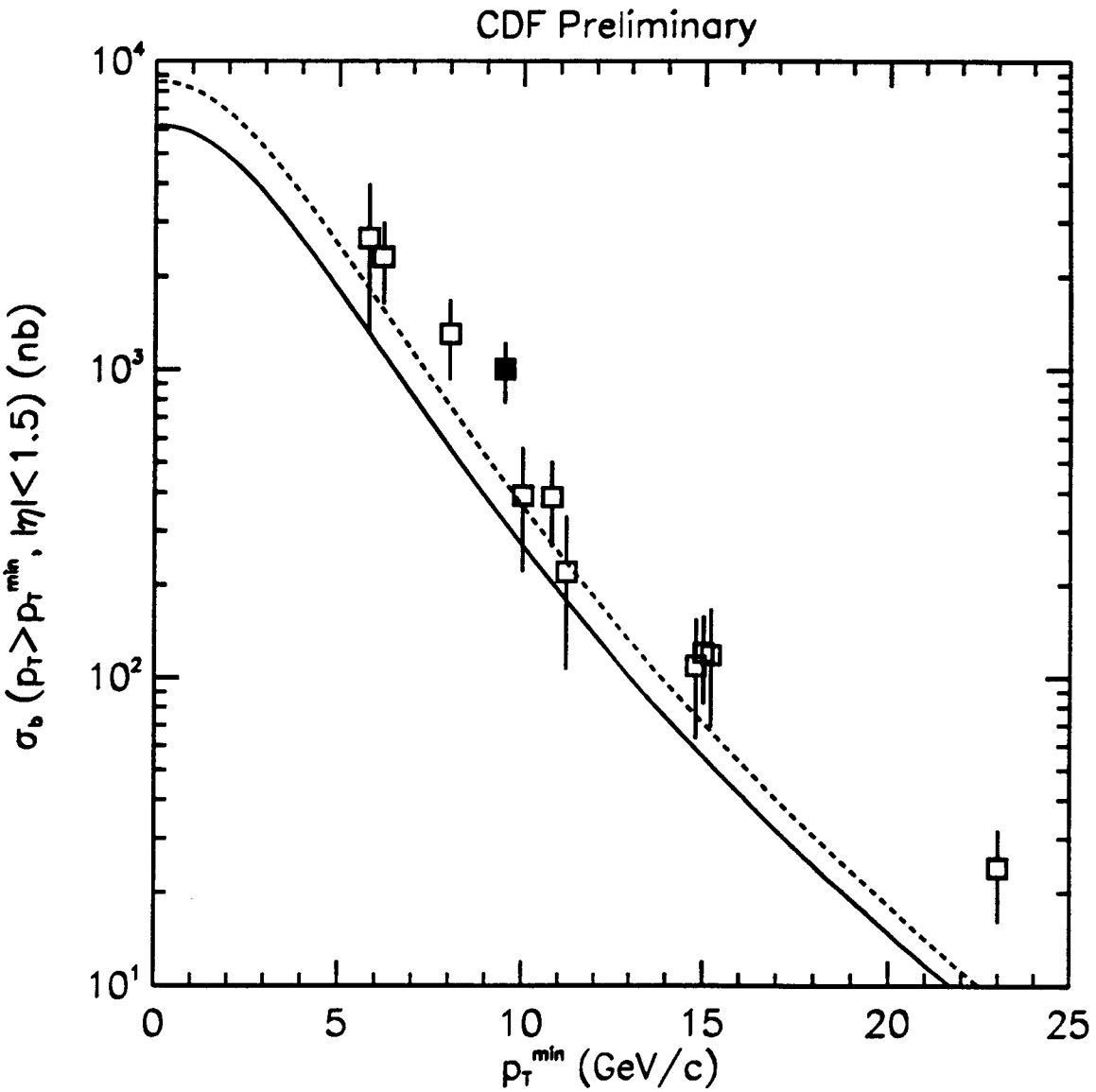


- $\mu = \mu_0 = \sqrt{(m_b^2 + p_T^2)}, m_b = 4.75$ GeV, MRSA'

b-quark Cross-Section at $\sqrt{s} = 630$ GeV

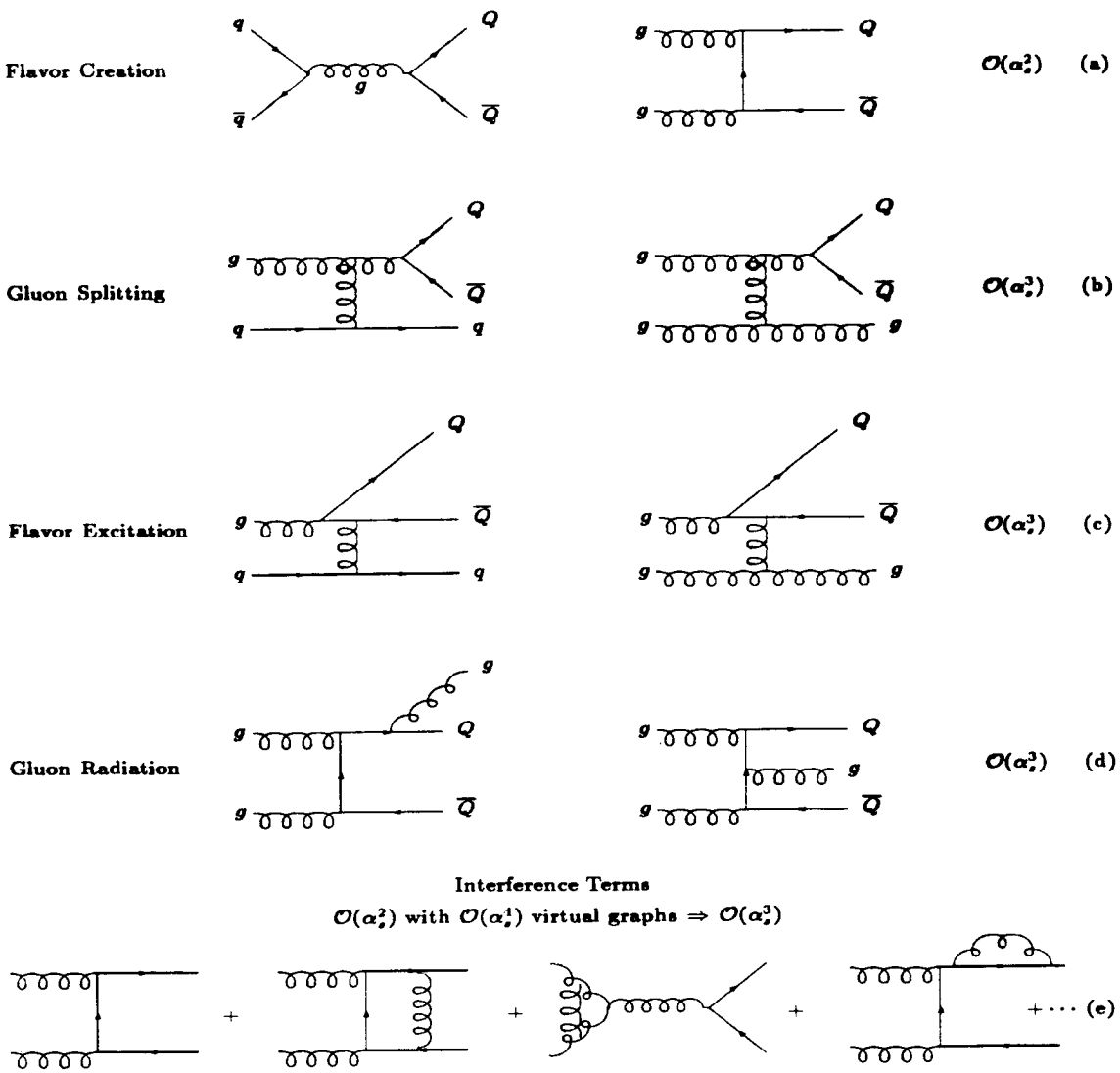
- CDF using the ratio and $\sigma(b \to J/\psi\ X, \sqrt{s} = 1800)$

- $\sigma_b(p_T^b > 9.5, |\ y^b\ | < 1.5, \sqrt{s} = 630\ \text{GeV})$
  $= 1.01 \pm 0.12 \pm 0.18 \mu b$



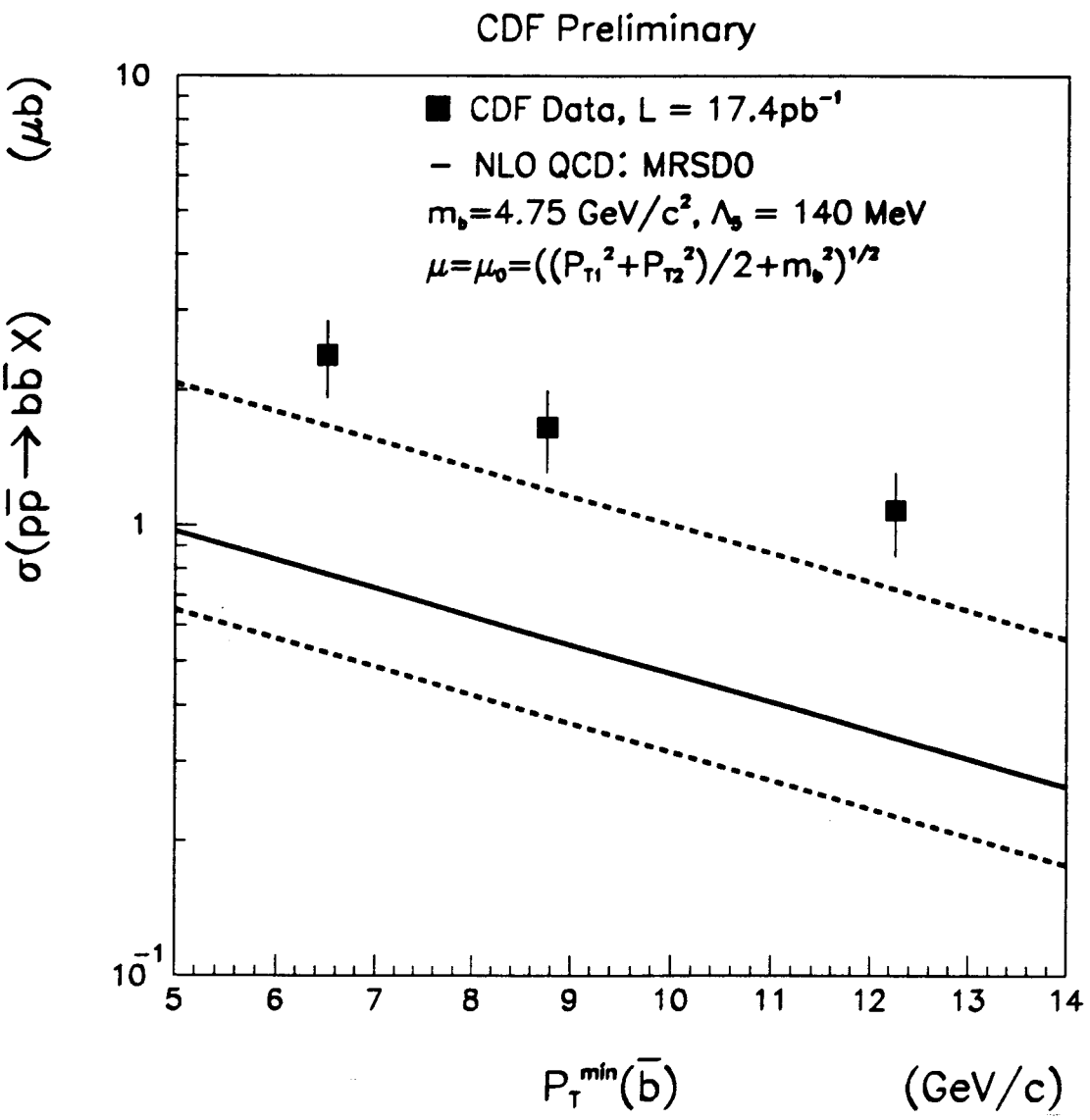
$b - \bar{b}$ Correlation Measurements

- **Further test of pQCD through observation of angular correlations between b and $\bar{b}$ quarks**
- Topology of b $\bar{b}$ pair allows separation of different QCD production mechanisms and determination of NLO contribution to total cross section

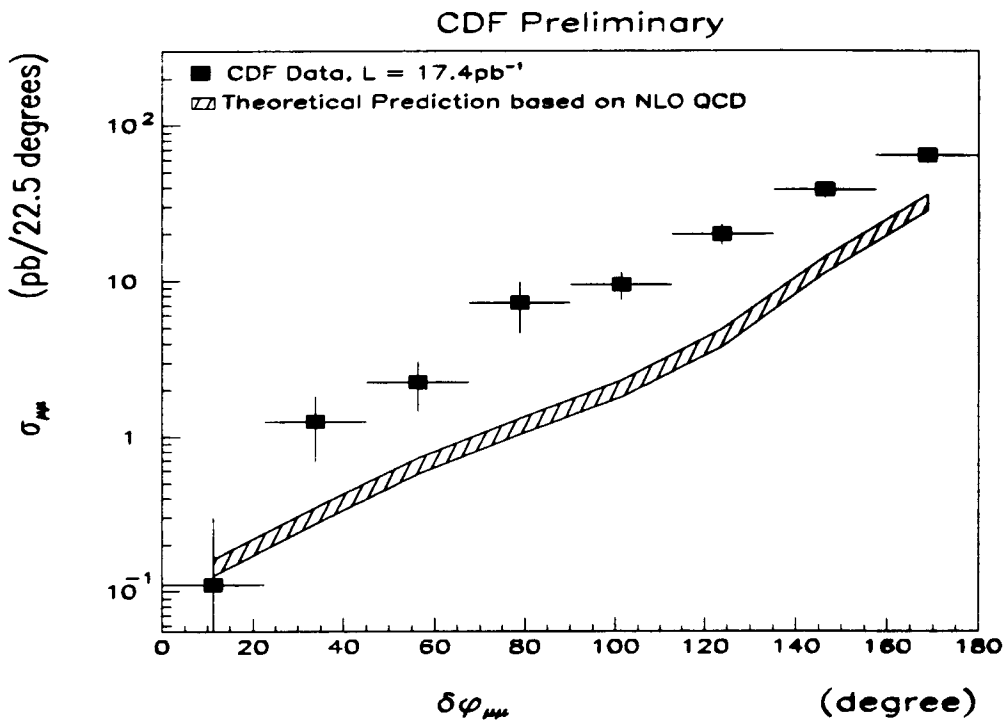


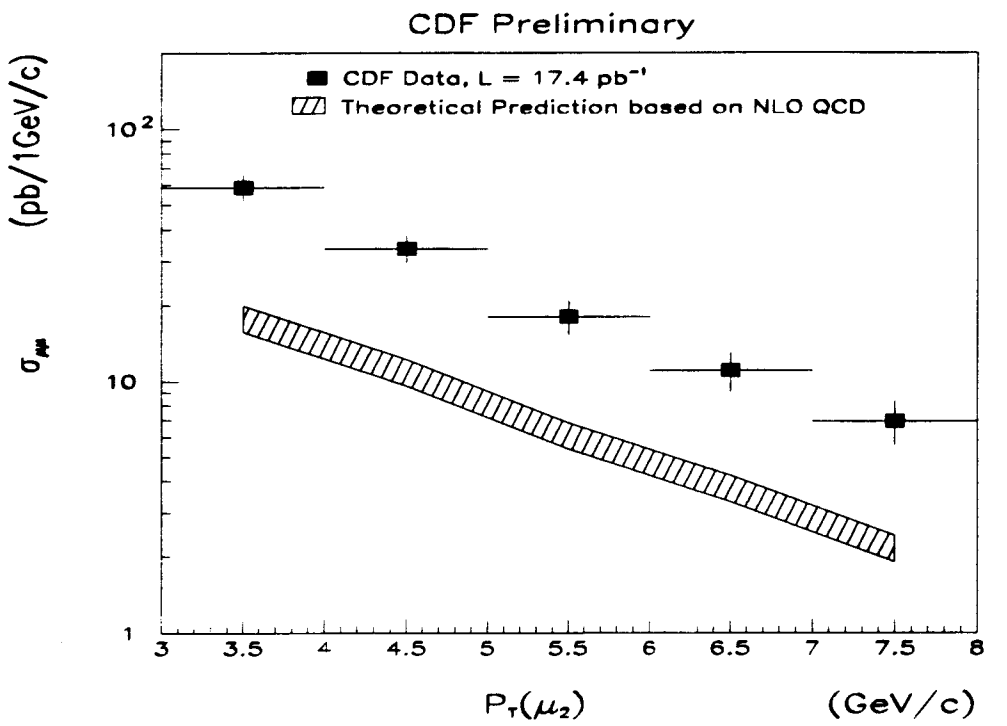
Correlated $b - \bar{b}$ Production

- CDF using high mass dimuons ($M_{\mu\mu} \geq 5$ GeV) from $\int \mathcal{L}dt = 17.4\ pb^{-1}$
- SVD impact parameter for each μ is used to determine $b\ \bar{b}$ content
- $\sigma_{b\ \bar{b}}$ ($p_T^b \geq 6.5$ GeV, $p_T^{\bar{b}} \geq p_T^{min}$, $|\ y^b, y^{\bar{b}}\ | \leq 1$)



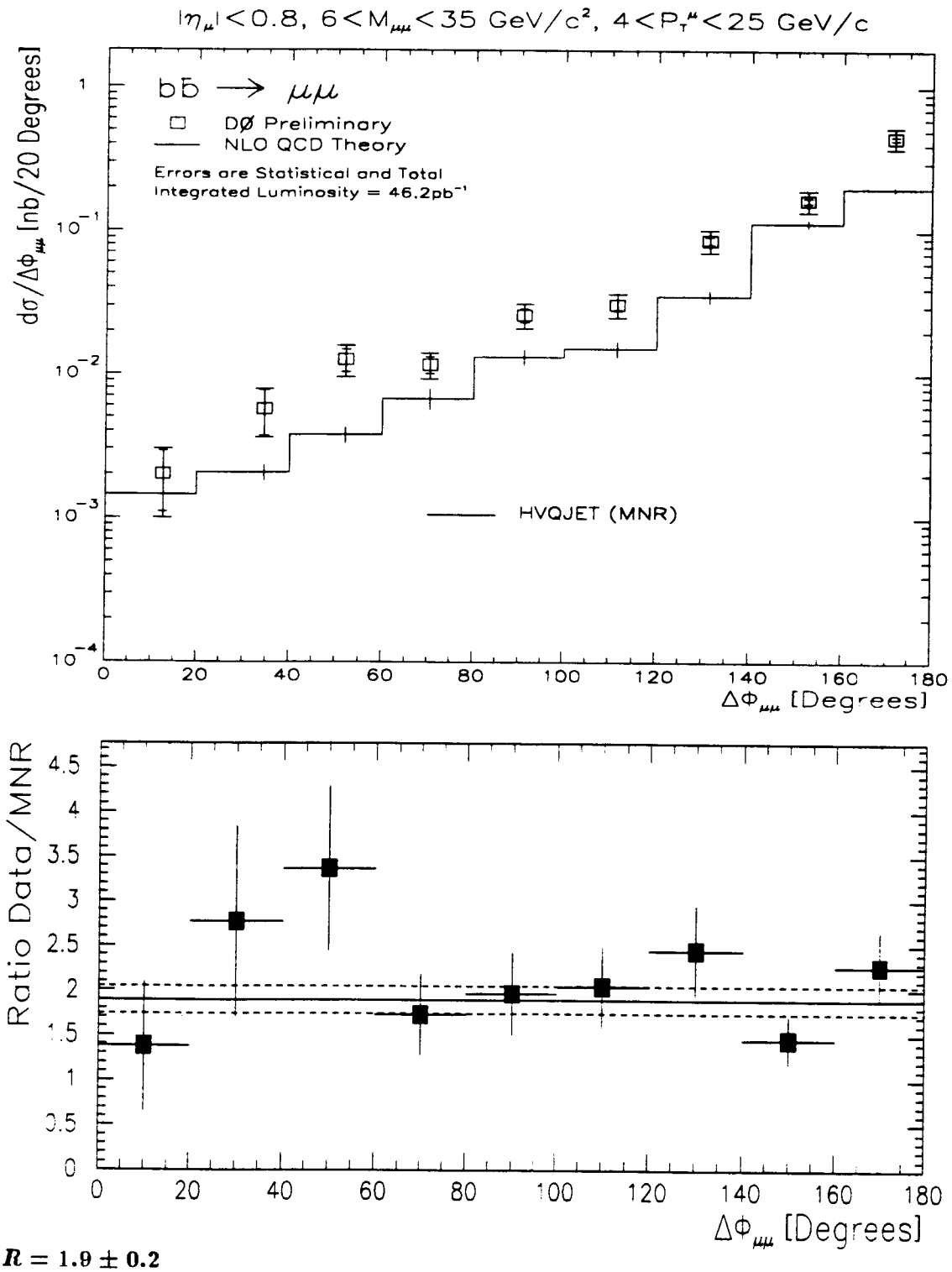
Geometrical and kinematic Correlations





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

DØ Measurements



- $R = 1.9 \pm 0.2$

HVQJET Monte Carlo Event Generator

Marc Baarmand, Frank Paige and John Smith

- Monte Carlo event generator based on $\mathcal{O}(\alpha_s^3)$ calculations of $p\bar{p} \to Q\bar{Q}X$ by Mangano, Nason and Ridolfi (MNR).
- MNR produces weighted partonic events (large positive and negative weights) for $gg \to Q\bar{Q}g$, $qg \to Q\bar{Q}q$ and $q\bar{q} \to Q\bar{Q}g$ subprocesses.
- HVQJET Algorithm systematically combines topologically similar events with positive and negative weight 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 $\bar{Q}$.
- ISAJET is used to simulate initial and final state gluon radiation, fragmentation and underlying event. Gluon radiation is limited so that no infrared-safe distributions of partons (e.g. $d\sigma/d\Delta\phi$) is altered.
- End product: A Monte Carlo event generator that is a direct implementation of an $\mathcal{O}(\alpha_s^3)$ calculation of correlated $Q\bar{Q}$ production in hadron collisions.

Conclusions

- **Several different CDF and DØ data sets give consistent measurements of the b-quark production cross-section in $p\,\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV**
- **NLO QCD calculations describe the shape but underestimate b production**
  - a factor of ≈ 2 **in central rapidity region**
  - a factor of ≈ 4 **in forward region**
- **Same trend observed with 0.63 TeV CDF and UA1 data, although $\sqrt{s}$ dependence of b production seems to be well described by QCD**
- **Results on $b\,\bar{b}$ angular correlations indicate:**
  - **Shape of $d\sigma/d\Delta\Phi_{\mu\mu}$ is in agreement with NLO QCD $\Rightarrow$ sizeable contribution from higher order QCD processes**
  - Normalization off by $\approx$ 2-3
- **More tests of QCD with existing data are under way heavy flavor content of jet, $b\bar{b}$ mass spectroscopy, running α_s, etc.**
- QUESTIONS: Does the observed disagreement imply a breakdown of truncated perturbation calculation - providing only a poor approximation - at Tevatron energies?! Small-x effects?! What about LHC?!....