Heavy Flavor Production at the Tevatron

Results from DØ and CDF

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Representing the DØ and CDF Collaborations

Outline of Talk

- Introduction
  - Data sets
  - Overview of heavy quark production
- b-production results
  - CDF-DØ Central production cross section
  - CDF-DØ Azimuthal correlations
  - DØ forward production cross section
- c-production results
  - DØ forward J/ψ production
- t-production results
  - CDF-DØ cross sections
  - CDF p_T distribution
  - DØ spin correlations
  - CDF-DØ single top production
- Summary and Run II prospects

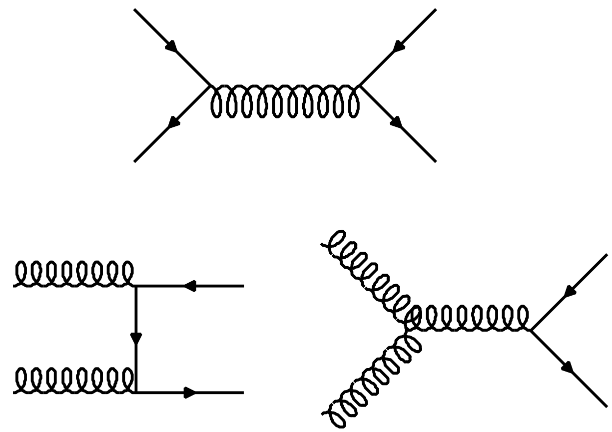
Introduction

- Data taken at the Fermilab Tevatron
  - $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV
  - Integrated luminosity
    - Run Ia $\int \mathcal{L}dt \approx 10$ pb^{-1}
    - Run Ib $\int \mathcal{L}dt \approx 90$ pb^{-1}

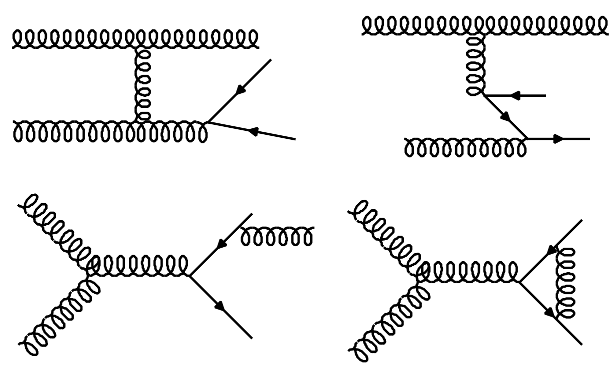
- Heavy flavor production provides a test of QCD calculations
  - NLO calculations available
  - Wide range of mass scales tested
    - $m_c \approx 1.5$ GeV, $m_b \approx 5$ GeV, and $m_t \approx 175$ GeV
    - $m_Q \gg \Lambda_{\rm QCD}$

Heavy Flavor Production—*Overview*

- Born level diagrams
  - $q\bar{q}$ annihilation dominates at threshold
    - $\approx 90\%$ of $t\bar{t}$ at Tevatron
    - Dominates high p_T b and c
  - For $s \gg m_Q$ gluons dominate
    - Dominates low p_T b and c

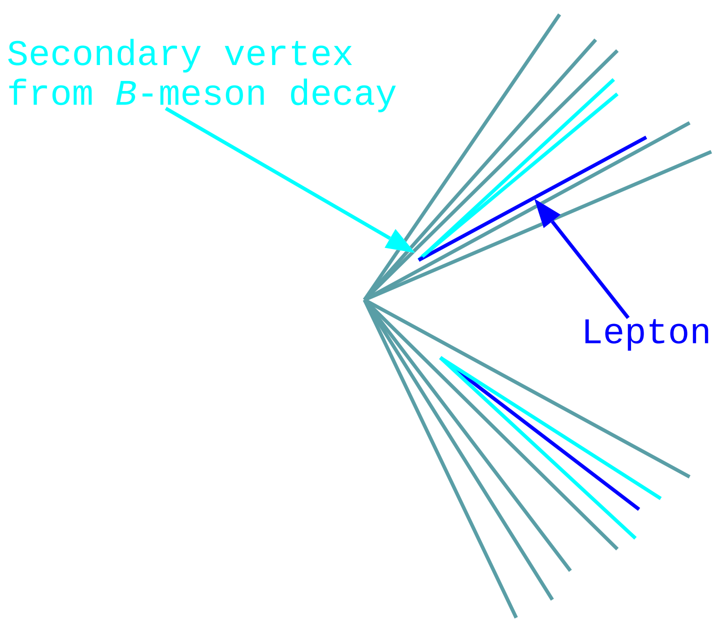


- NLO important
  - Gluon splitting
  - Flavor excitation
  - Loop corrections
  - Gluon radiation



b Cross section analysis
Overview

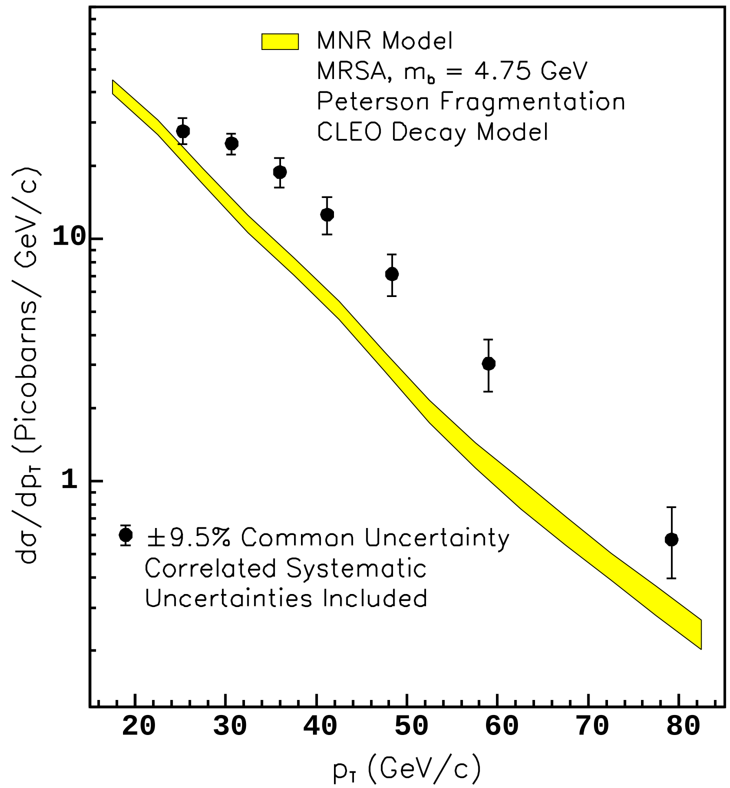
- In general, b identified through a jet tagged by:
  - Associated lepton (e or μ)
  - Secondary vertex in jet



- CDF $\mu + b$-jet analysis
  - Jet requires secondary vertex
  - $\Delta R^{\mu\text{-jet}} > 1$ μ & jet unassociated
  - p_T^b from $E_T^{b\text{-jet}}$ correlation
- DØ analysis
  - Single μ and di-μ
    - Muons require associated jet
      - $\Delta R^{\mu\text{-jet}} < 0.8$
      - Use p_T^μ-p_T^b correlation
  - b-jet
    - Jet requires associated μ
      - $\Delta R^{\mu\text{-jet}} < 0.7$
      - Use E_T^{jet} corrected by muon

CDF $\mu + \bar{b}$ Result

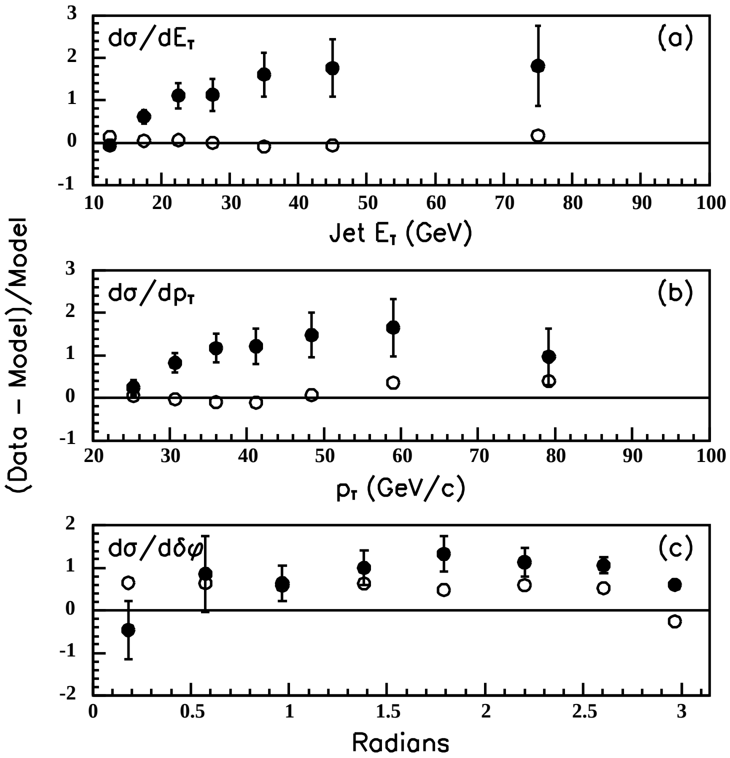
- Kinematic region covered:
  - $p_T^\mu > 9$ GeV, $|\eta^\mu| < 0.6$, $E_T^{\text{jet}} > 10$ GeV, $|\eta^b| < 1.5$
- QCD calculation compared with:
  - Use NLO calculation of Mangano, Nason, and Ridolfi Nucl. Phys. **B373**, 295, 1992
  - Structure functions MSRA
  - $m_b = 4.75$ GeV
  - Renormalization scale equals factorization scale
    - $\mu_0 = \sqrt{m_b^2 + (p_{b,T}^2 + p_{\bar{b},T}^2)/2}$



Uncertainty in theory curve, from muonic fraction and fragmentation model.

CDF $\mu + \bar{b}$ Result—*cont.*

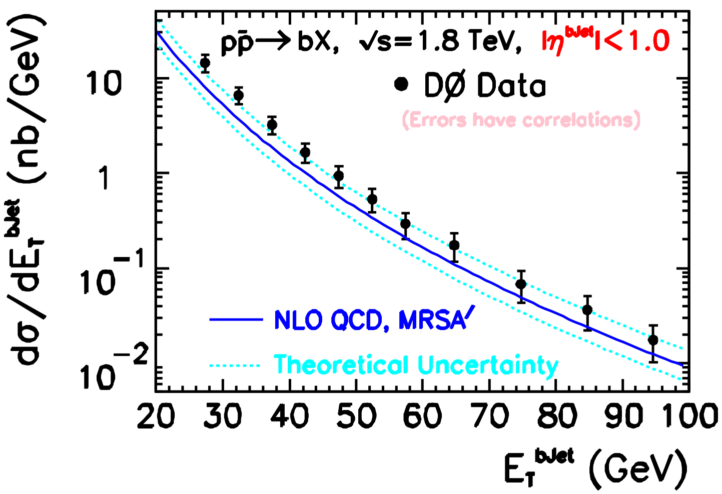
Variation of Renormalization-Factorization Scale

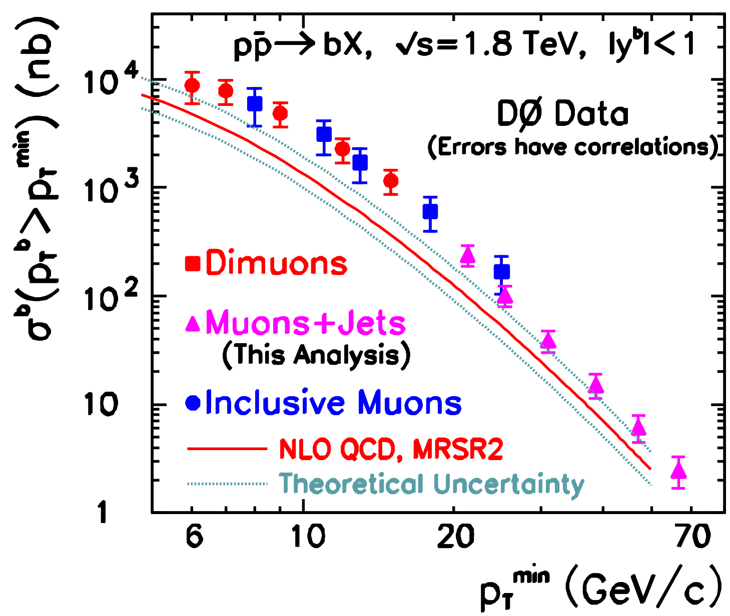


Closed circles μ_0

Open circles $\mu_0/2$

DØ b-quark Results



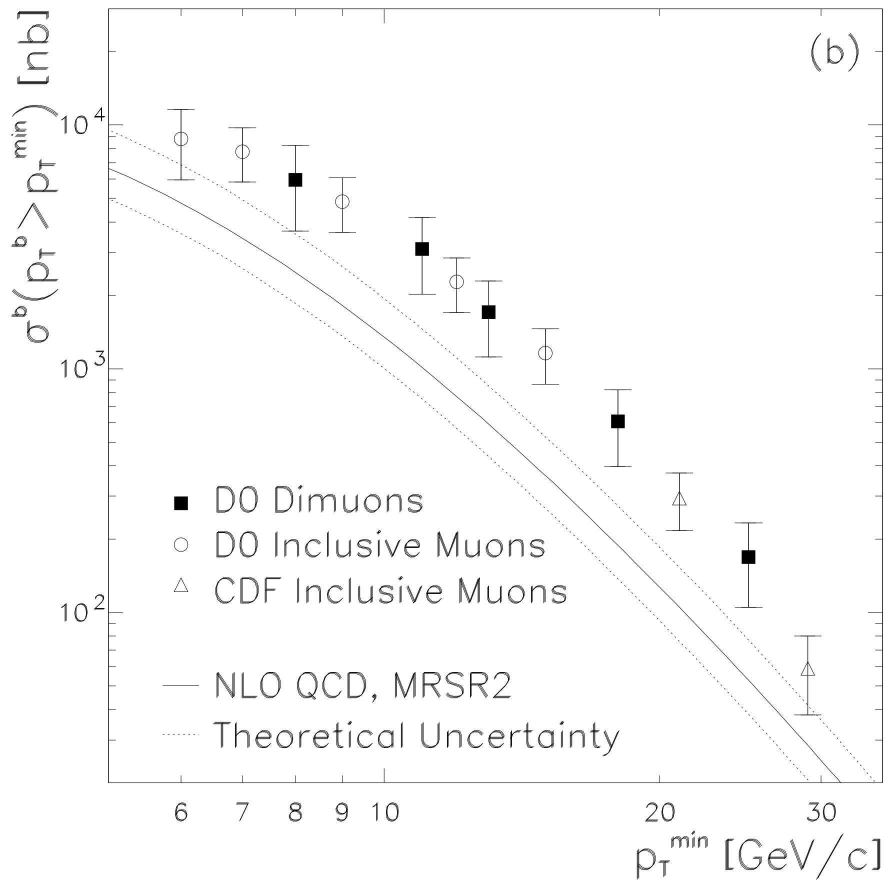


- $E_T^{b\text{-jet}}$ is jet E_T^{jet} corrected by muon
- $m_b = 4.75$ GeV
- Renormalization and Factorization scales set equal to each other
  - $\mu = \sqrt{E_T^2 + m_b^2}$ varied: $\mu/2$ to 2μ

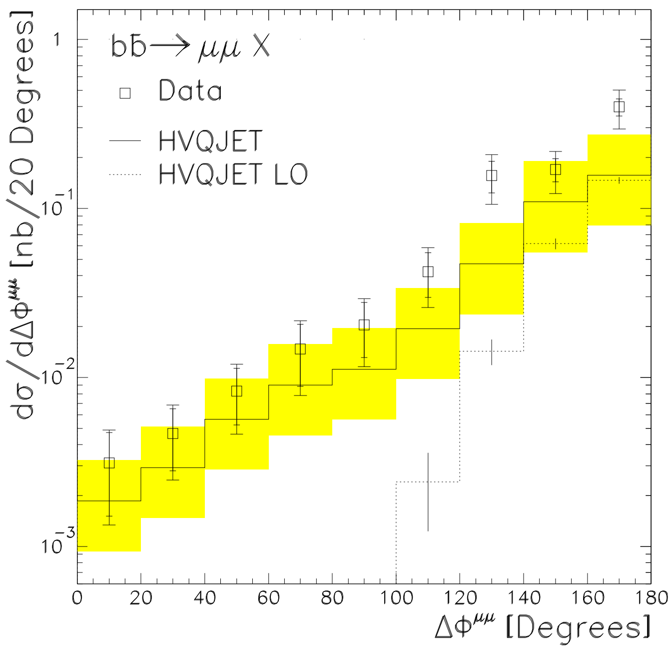
- Use correlation between p_T^μ and p_T^b
- p_T^{min} corresponds p_T^b where $> 90\%$ of events found under specific kinematic cuts including p_T^μ

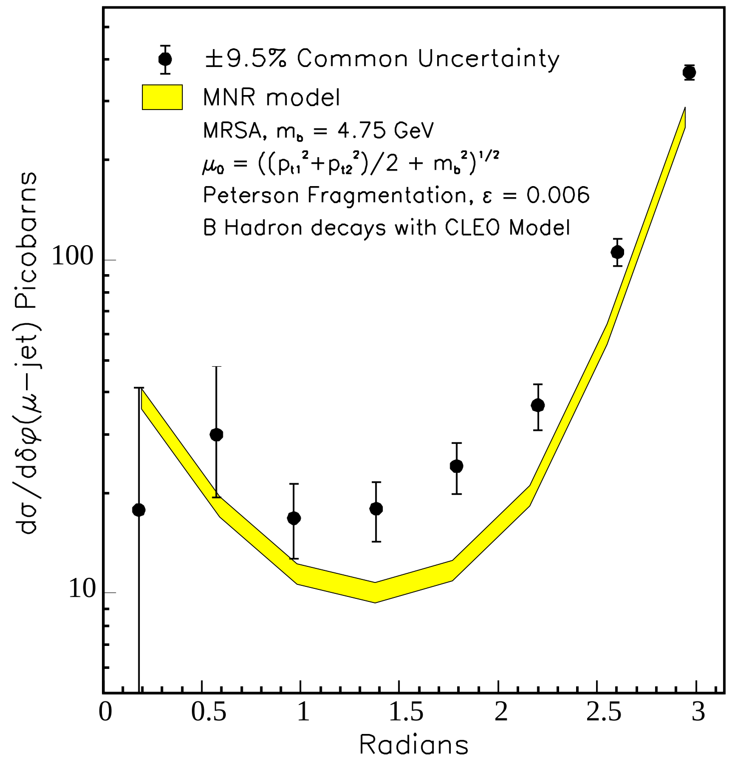
Theoretical uncertainty due to variation in scales.

Comparison of DØ and CDF Muon Data



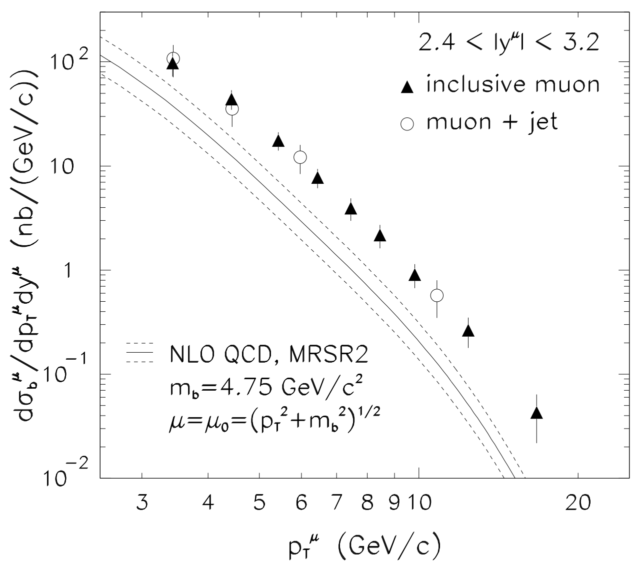
Azimuthal Correlations

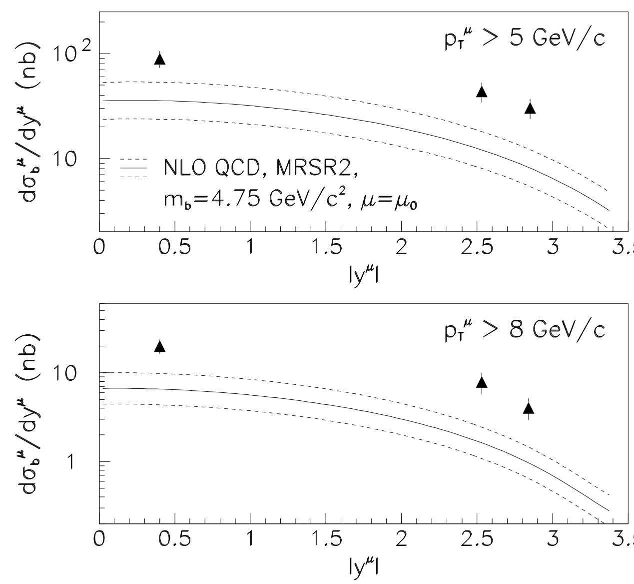




Forward Production of b-quark

DØ Result





CDF Result

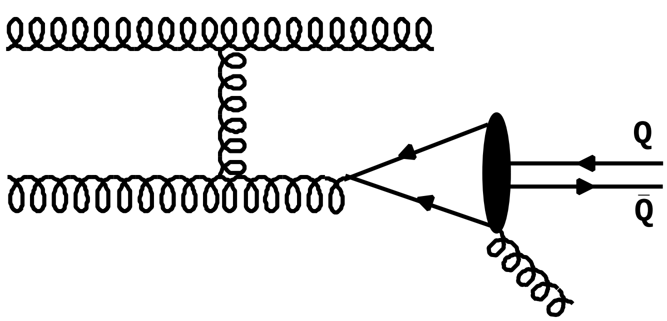
- Forward to Central production ratio $R = 0.361 \pm 0.033^{+0.015}_{-0.031}$
  - $\sigma(2.0 < |\eta_{b_1}| < 2.6)/\sigma(|\eta_{b_1}| < 0.6)$ for $|\eta_{b_2}| < 1.5$
- QCD calculation $R = 0.338^{+0.014}_{-0.097}$ uncertainty from variation in scale $\mu/2$ to 2μ

J/ψ Production—*Theory*

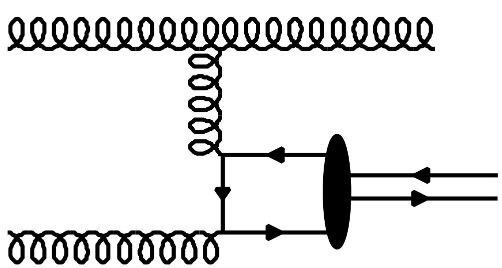
- Charmonium production mechanism
  - From B-meson decay
  - Color singlets production
  - Color octet production
    - NRQCD terms (11) fit to CDF data *central production*

Example of Production Diagrams

Color Octet



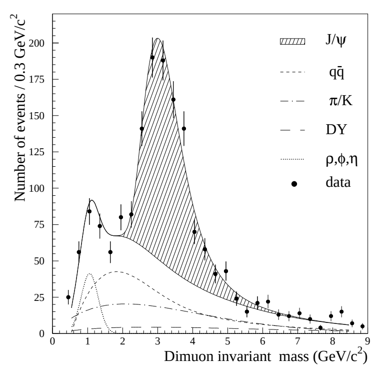
Color Singlet



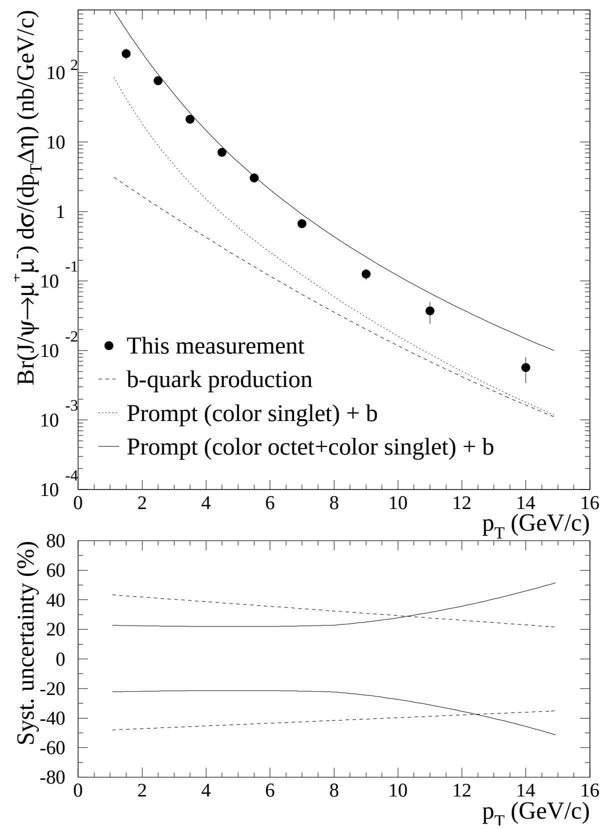
DØ Forward J/ψ Production

Selection Criteria

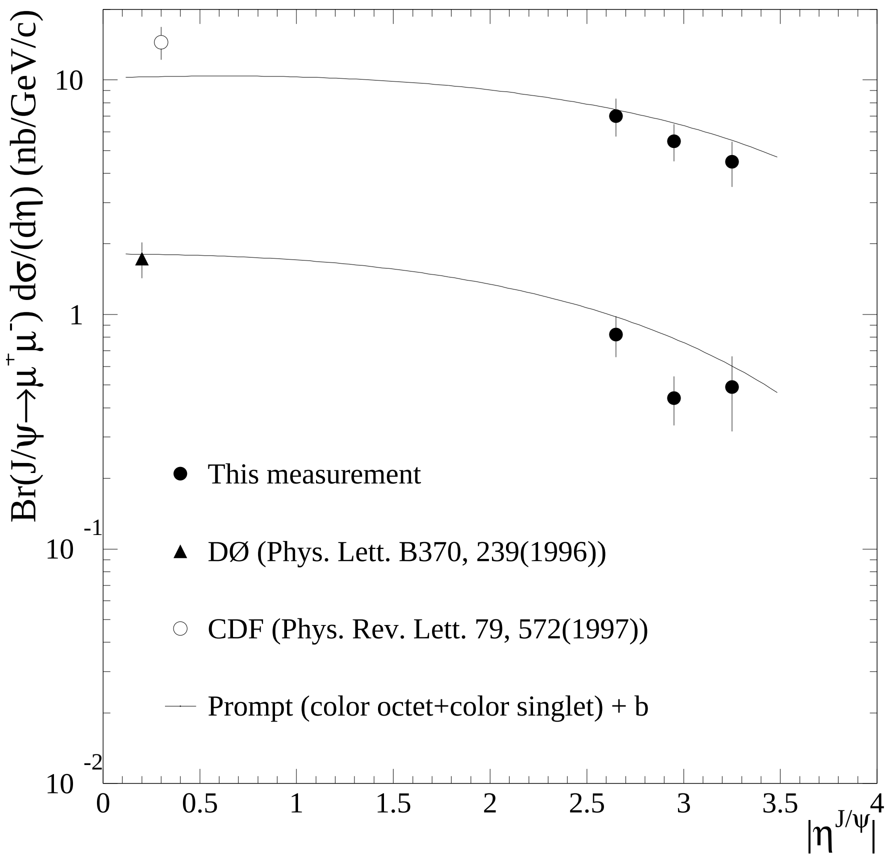
- Single or di muon trigger
- $p_T^\mu \leq 150$ GeV and $\int B d\ell \geq 1.2$ T-m
- $\geq$ 1.5 GeV energy deposited in calorimeter
- $2.5 \leq |\eta^{\mu\mu}| \leq 3.7$



J/ψ Forward Cross Section



CDF DØ J/ψ Production



upper data $p_T^{\psi} > 5$ GeV

lower data $p_T^{\psi} > 8$ GeV

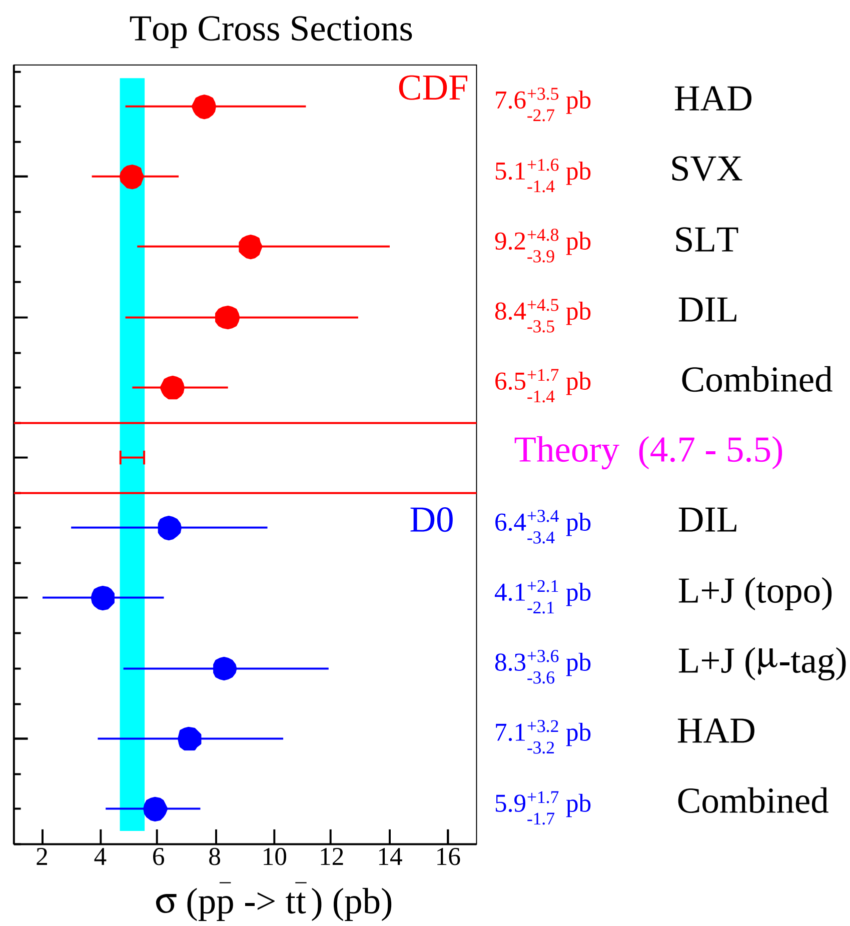
t-quark Production Cross Section

- Event characteristics
  - Dominant decay $t \to Wb$
    - $W \to q\bar{q}'$ $\quad W \to \ell\nu_\ell$
  - $t\bar{t}$ event characteristics
    - 2 b-jets + 4 jets
    - 2 b-jets + 2 ℓ + $\not\!\!E_T$
    - 2 b-jets + 2 jets + ℓ + $\not\!\!E_T$

- Search criteria
  - b-tag
    - CDF displaced vertex in jet
    - DØ jet with associated μ
  - $\not\!\!E_T$ for lepton modes

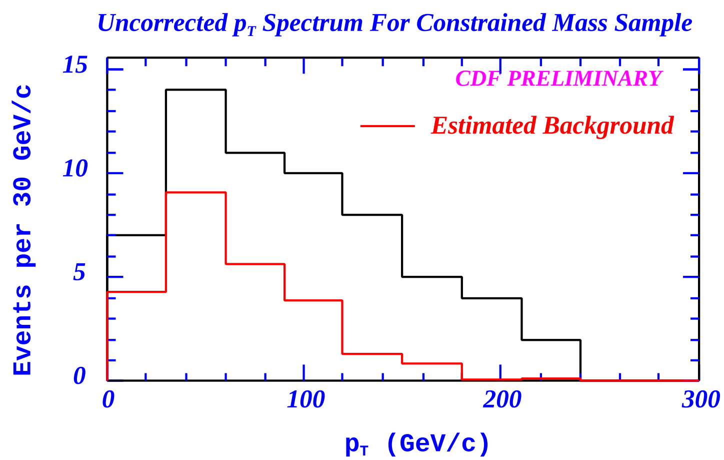
- Search criteria—*cont.*
  - All jets
    - CDF ≥ 5 jets, b jet tag, and sum of scalar E_T
    - DØ Neural Networks—2 NN, w/ $10 + 3$ inputs

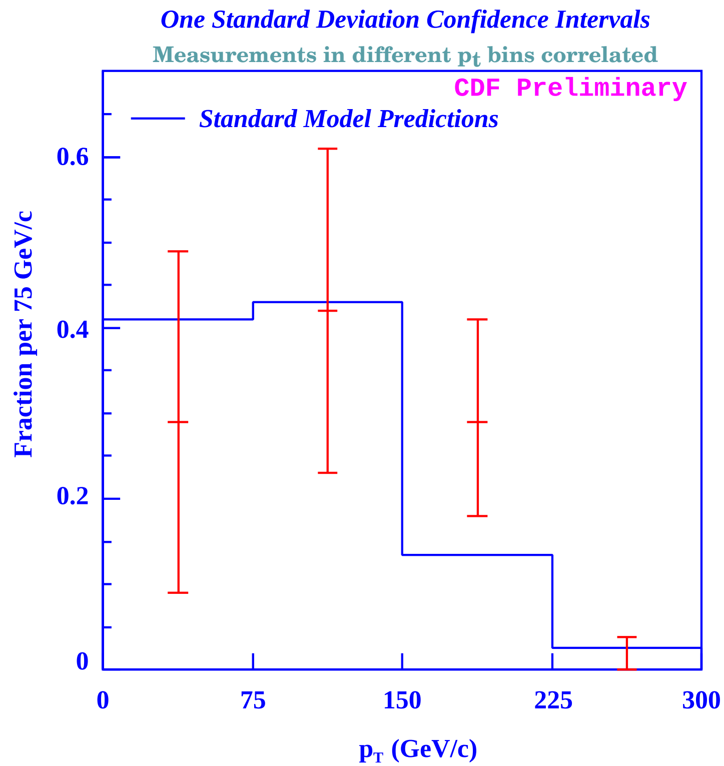
t-quark Production Cross Section



CDF t-quark $d\sigma/dp_T$

- Test of QCD calculations
- Sensitive to new phenomena
- Data sample used
  - Lepton plus jets 61 events
    - Background: 24.6 ± 5.8 events
  - Mass constraint: $m_t = 175$ GeV





DØ t-quark Spin Correlations

- t-quark decays rapidly
  - $t\bar{t}$ Spin correlation remains
  - In the Standard Model

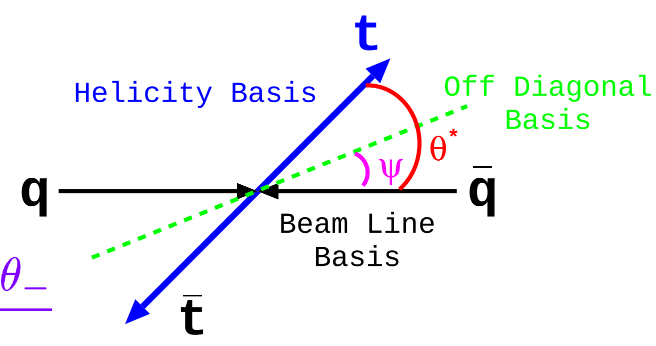
$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+ dcos\theta_-} = \frac{1+\kappa\cos\theta_+\cos\theta_-}{4}$$

with $\kappa \approx 0.9$

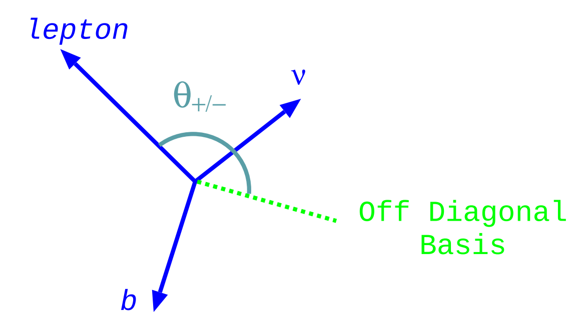
  - Axis of Off-diagonal basis relative to beamline

$$\tan\psi = \frac{\beta^{*2}\sin\theta^*\cos\theta^*}{1-\beta^{*2}\sin^2\theta^*}$$

β^* t velocity in $t\bar{t}$ rest frame

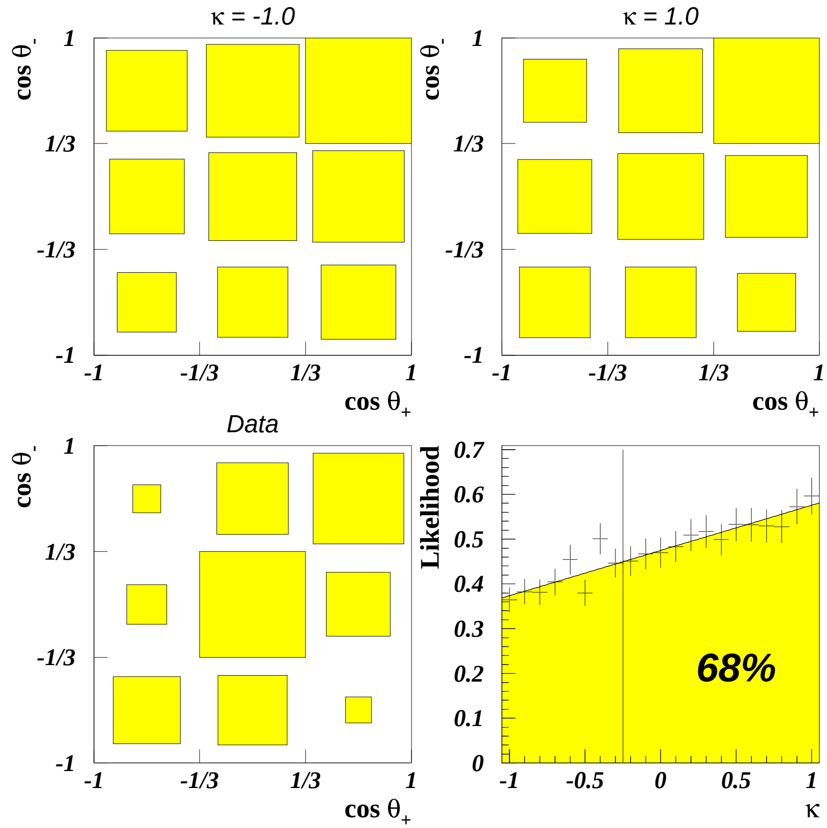


$q\bar{q}$ Center of Mass Frame



$t\bar{t}$ rest frame

DØ t-quark Spin Correlations



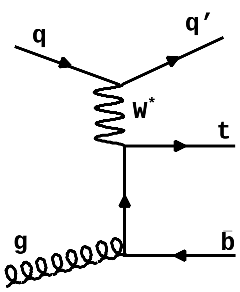
$\kappa > -0.25$ at 68% CL

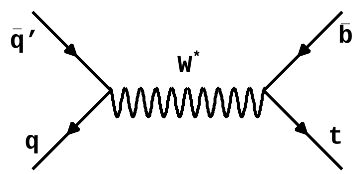
Single top Production

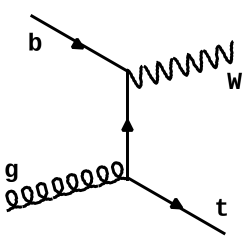
- Three processes contribute

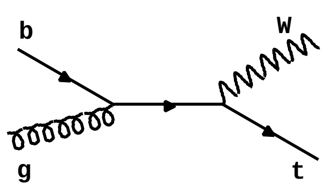
For $m_t = 174.3 \pm 5.1$ GeV

$qg \to q'tb$	$\sigma = 1.47 \pm 0.22$ pb
$q\bar{q} \to t\bar{b}$	$\sigma = 0.75 \pm 0.12$ pb
$bg \to tW$	$\sigma = 0.15$ pb









- Topological signatures for dominant modes
  - W plus 2 or 3 jets
  - Two b-quarks per event
    - For $qg \to q'tb$ one central high E_T one soft
    - For $q\bar{q} \to t\bar{b}$ both central high E_T

Single top Production

CDF Analysis

- Uses likelihood method; scalar sum of E_T^{ℓ}, E_T^{jet}, and $\not\!\!E_T$
  - Relies on $W \to \ell + \nu_\ell$ decays
  - 1 to 3 jets with $\Delta R = 0.4$ cone
  - ≥ 1 b-tagged jet
  - $M_{\ell\nu b}$ close to m_t

DØ Analysis

- Uses Neural Networks
  - Four channels, $e+$ jet and $\mu+$ jets with and without jet μ tag
  - 2 signal processes; s and t channel
  - 5 NN, average 14 input variables each channel and process

Limits 95% **CL**

	CDF *preliminary*	DØ *submitted*
$qg \to q'tb$	$\sigma < 13$ pb	$\sigma < 22$ pb
$q\bar{q} \to tb$	$\sigma < 18$ pb	$\sigma < 17$ pb
Combined	$\sigma < 14$ pb	

Summary

- Tevatron has produced large number of results on heavy flavours
  - Both production and decay
- b cross sections continue to be high compared with QCD calculations
- t cross sections agree with QCD calculations
- Run II starting
  - $\sqrt{s} = 2$ TeV
  - Run IIa expect $\int \mathcal{L}\, dt = 2\ \mathrm{fb}^{-1}$
  - Run IIb expect $\int \mathcal{L}\, dt = 15\ \mathrm{fb}^{-1}$
  - Continue study of all aspects of heavy flavors