

# Heavy Flavor Production at HERA and the Tevatron

Bruce Straub, University of Oxford

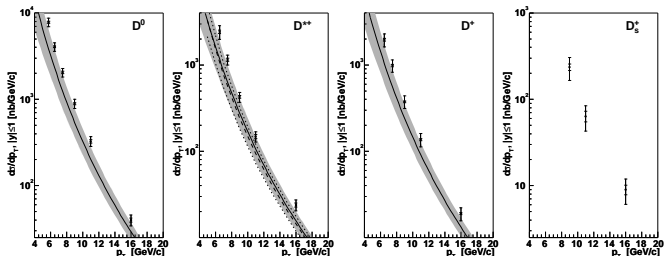
Physics in Collision, Buzios, Brazil , 5-9 July 2006

## Outline

- 1 c and b Production in  $p\bar{p}$ 
  - CDF: Prompt Charm Meson Production Cross Sections
  - CDF:  $J/\psi$  and b-Hadron Production Cross Sections
  - CDF: Inclusive b-Jet Production
  - CDF:  $b\bar{b}$ -Dijet Production
- 2 c and b Production in Deep Inelastic Scattering
  - HERA Kinematics
  - H1: Measurement of  $F_2^{c\bar{c}}$  and  $F_2^{b\bar{b}}$
- 3 Photoproduction of c and b
  - Photoproduction Processes
  - H1: c and b dijet cross sections in  $\gamma p$
  - ZEUS:  $\gamma p \rightarrow D^* + \text{jet}(s)$
- 4 b Production at HERA
  - ZEUS: Beauty production using a  $D^* \mu$  tag
  - ZEUS: Beauty production from dimuon events
- 5 Conclusions

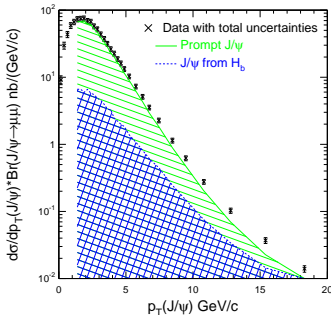


## CDF: Prompt Charm Meson Production Cross Sections

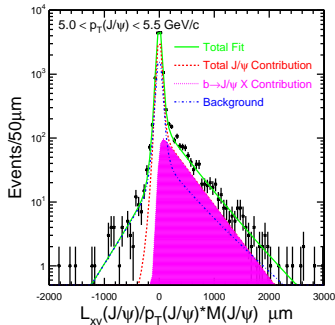


- Prompt charm meson cross sections for  $|y| < 1$
- Inner error bars are statistical, outer are systematic (dominates).
  - 3%-4% uncertainty on prompt fraction
  - 8%-14% uncertainty on trigger/reconstruction efficiency
- Theory curves by Cacciari and Nason, J.High Energy Phys. **0309** (2003) p.6.

# CDF: $J/\psi$ and $b$ -Hadron Production Cross Sections



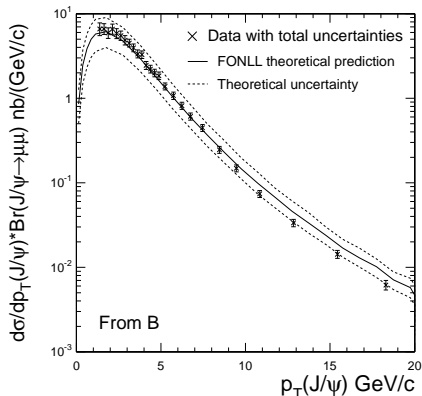
$J/\psi$  cross section for  $|y| < 0.6$ .  
 $39.7 \text{ pb}^{-1}$



Extract fraction from  $B$  decays by fit to pseudoproper decay time

Acosta, et al., Phys. Rev. D **71**, 032001 (2005).

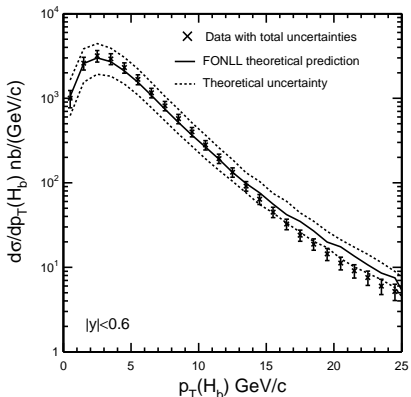
# CDF: $J/\psi$ and $b$ -Hadron Production Cross Sections



Theory curves are fixed-order with resummation of next-to-leading logs in  $P_t/m_b$ . Matched to NLO for massive quarks.

Cacciari, *et al.*, J.High Energy Phys. 07 (2004) p.33.

# CDF: $J/\psi$ and *b*-Hadron Production Cross Sections



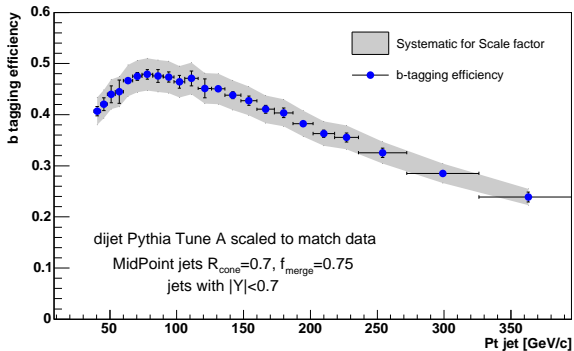
Iterative unfolding of  $d\sigma/dp_T(J/\Psi)$  gives  $d\sigma/dp_T(H_b)$ .

## CDF: $J/\psi$ and $b$ -Hadron Production Cross Sections

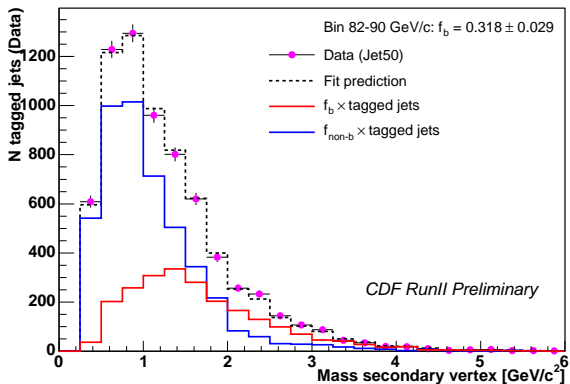
- single  $b$ -hadron cross section for  $|y| < 0.6$ 
  - $\sigma^{\text{FONLL}} = 16.8_{-5}^{+7} \mu\text{b}$
  - $\sigma^{\text{CDF}} = 17.6 \pm 0.4_{-2.3}^{+2.5} \mu\text{b}$
- compare  $\sigma(p\bar{p} \rightarrow H_b X) \cdot \text{Br}(H_b \rightarrow J/\Psi) \cdot \text{Br}(J/\Psi \rightarrow \mu^+ \mu^-)$ 
  - for  $P_t(J/\Psi) > 5 \text{ GeV}$  and  $|\eta(J/\Psi)| < 0.6$
  - $\sigma^{\text{runI}} = 3.23 \pm 0.05 \pm 0.30 \text{ nb}$
  - $\sigma^{\text{runII}} = 2.75 \pm 0.04 \pm 0.20 \text{ nb}$
  - run II  $\sigma$  should be 10% higher

CDF: Inclusive *b*-Jet Production

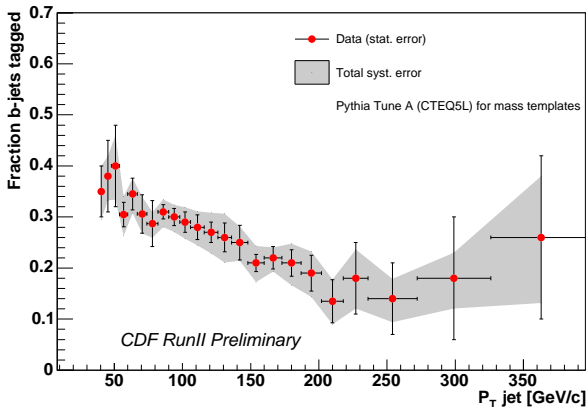
*b*-jet cross section less sensitive to hadronization than *b*-hadron cross-section.



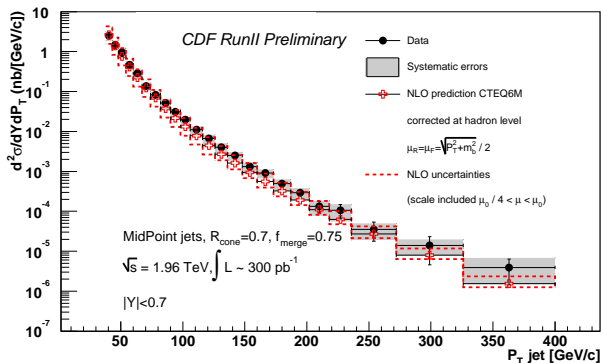
Efficiency to tag *b*-jets using  $SecVTx$  algorithm. Simulated efficiency is corrected with efficiency measured in electron sample. Syst. uncertainty  $\sim 7\%$   
Use  $300 \text{ pb}^{-1}$ .

CDF: Inclusive *b*-Jet Production

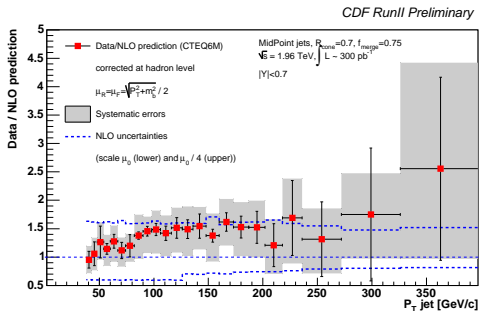
Fraction of *b*-jets in each  $P_t$  bin determined by fit to spectrum of secondary vertex mass. Templates from Pythia. Syst. uncertainty on *b*-fraction

CDF: Inclusive  $b$ -Jet Production

Fraction of  $b$ -jets in each  $P_t$  bin.

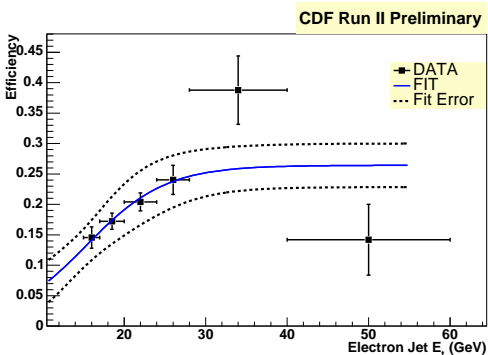
CDF: Inclusive  $b$ -Jet Production

$b$ -jet cross section compared to NLO  
(Mangano and Frixione, Nucl. Phys. B483, 321 (1997)).

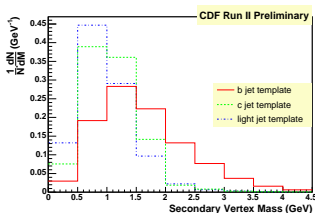
CDF: Inclusive  $b$ -Jet Production

systematic uncertainties	low $P_t$	high $P_t$
vary $E$ -Scale by $\pm 3\%$	+10%/-8%	+39%/-22%
Unfolding	$\pm 5\%$	$\pm 15\%$
vary $E$ resolution by $\pm 10\%$	$\pm 6\%$	
Luminosity	$\pm 5.8\%$	

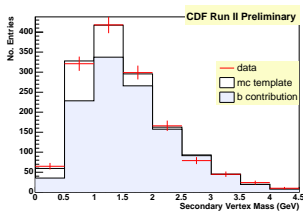
# CDF: $b\bar{b}$ -Dijet Production



Select events with 2 secondary-vertex tagged jets with  $|\eta| < 1.2$ ,  $E_T^1 > 30$  GeV and  $E_T^2 > 20$  GeV.  
 Plot show tagging efficiency measured using electron jet with opp-side secondary vertex tagged jet

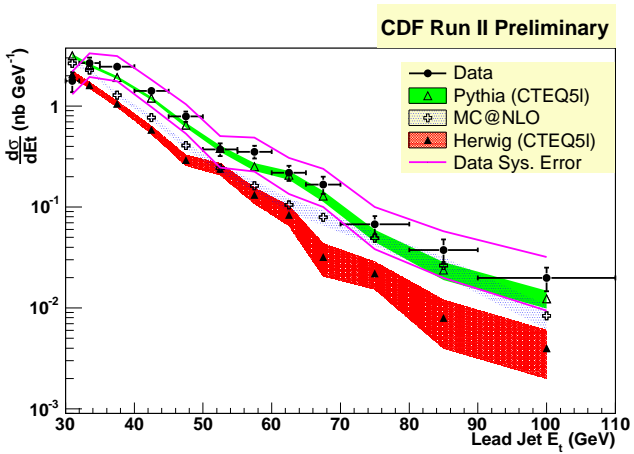
CDF:  $b\bar{b}$ -Dijet Production

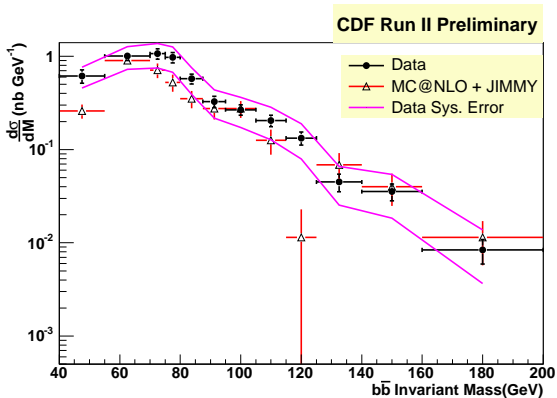
Templates of Secondary Vertex Mass for light flavors, *c*, and *b*



Fit of data for linear combination of templates.  $F_b = 0.83 \pm 0.04$ .  
 $\sigma_{b\bar{b}}(|\eta| < 1.2, E_t^1 > 30, E_t^2 > 20) = 34.5 \pm 1.8 \pm 10.5 \text{ nb}$

# CDF: $b\bar{b}$ -Dijet Production

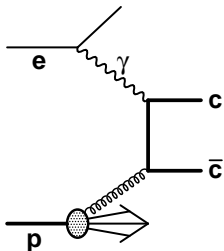


CDF:  $b\bar{b}$ -Dijet Production

Agreement with MC@NLO is improved by using JIMMY to model the underlying event.

## HERA Kinematics

- $E_e = 27.6 \text{ GeV}$
- $E_p = 920 \text{ GeV}$
- $\sqrt{s} = 319 \text{ GeV}$
- $z = \text{proton direction}$



The dominant LO process for  $c\bar{c}$  and  $b\bar{b}$  production is photon-gluon fusion.  $d\sigma/dx \sim g(x)$

$$Q^2 = -(\gamma \text{ 4-mom})^2$$

$x = \text{fraction of } p \text{ momentum carried by } g$

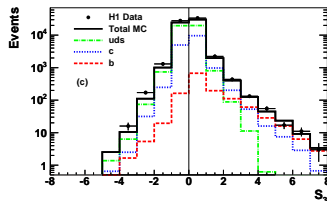
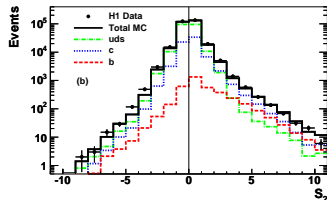
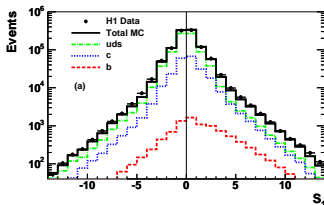
$$y = Q^2/(sx)$$

$= \text{fraction of initial-state } E - P_z$

transferred to hadronic final state.

$$\frac{d^2\sigma^{c\bar{c}}(x, Q^2)}{dx dQ^2} = \frac{2\pi\alpha^2}{xQ^4} \{ [1 + (1-y)^2] F_2^{c\bar{c}}(x, Q^2) - y^2 F_L^{c\bar{c}}(x, Q^2) \}$$

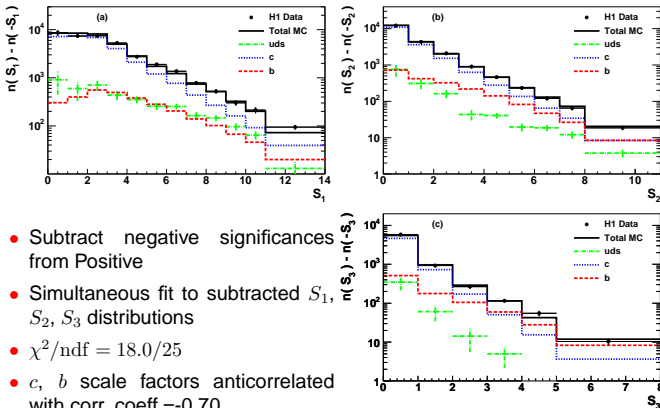
ratio  $F_2/F_L$  is calculated by QCD.

H1: Measurement of  $F_2^{c\bar{c}}$  and  $F_2^{b\bar{b}}$ 

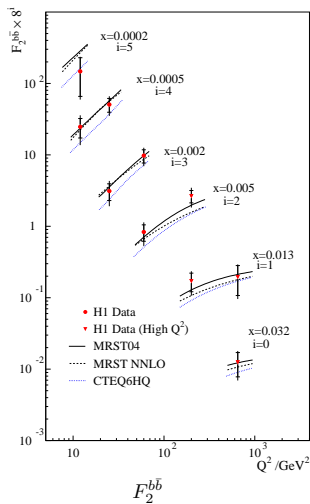
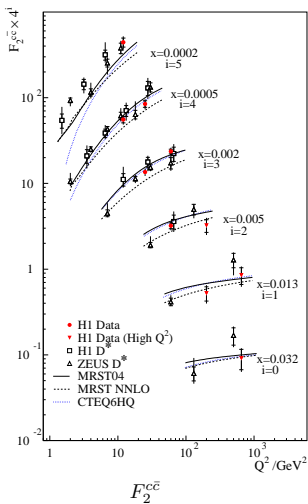
- 57.4 pb<sup>-1</sup> of  $e^+p$  data
- Select DIS Events with
  - $E - P_z > 35$  GeV
  - $6.3 < Q^2 < 120$  GeV<sup>2</sup>
  - $0.07 < y < 0.7$
- use CST tracks w/  $P_t > 0.5$  GeV
- plot 1<sup>st</sup>, 2<sup>nd</sup>, 3<sup>rd</sup> highest impact parameter significance
- fit data with  $uds+c+b$

A.Aktas *et al.*, Eur.Phys.J. **C45** (2006) 23, hep-ex/0507081A.Aktas *et al.*, Eur.Phys.J. **C40** (2005) 349, hep-ex/0411046

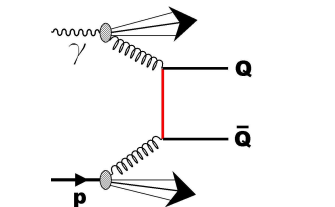
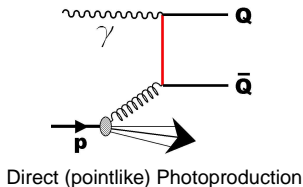
# H1: Measurement of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$



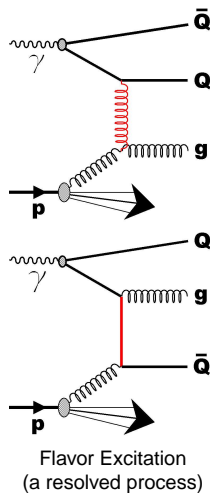
- Subtract negative significances from Positive
- Simultaneous fit to subtracted  $S_1$ ,  $S_2$ ,  $S_3$  distributions
- $\chi^2/\text{ndf} = 18.0/25$
- $c$ ,  $b$  scale factors anticorrelated with corr. coeff.=-0.70
- Apply same procedure in each  $(x, Q^2)$  bin

H1: Measurement of  $F_2^{c\bar{c}}$  and  $F_2^{b\bar{b}}$ 

# Photoproduction Processes



Resolved Photoproduction  
 $x_\gamma =$  fraction of  $(E - P_z)_\gamma$  carried by interacting parton. Remaining partons produce the 'photon remnant'.

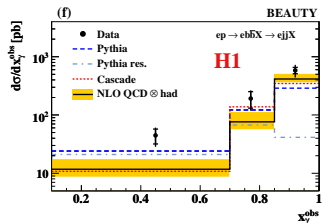
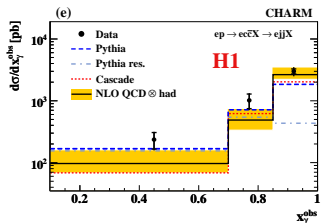
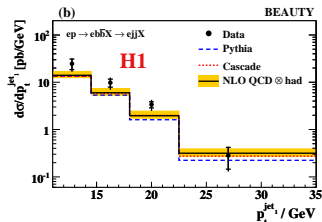
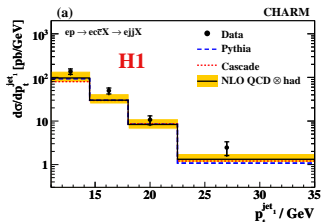


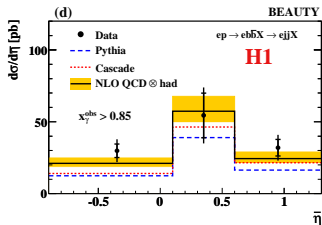
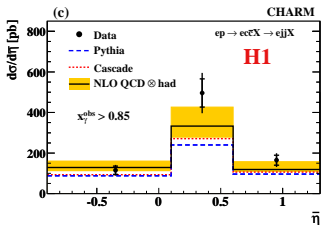
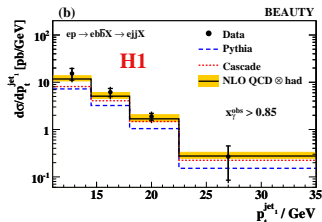
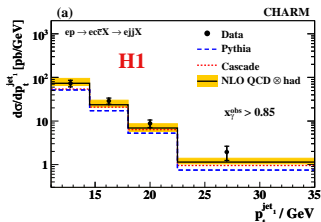
H1:  $c$  and  $b$  dijet cross sections in  $\gamma p$ 

- 56.8 pb<sup>-1</sup>
- Use same method as for DIS
  - Fit reflection-subtracted  $S_1$  and  $S_2$  distributions to get  $c$ ,  $b$ , and light quark fractions.
- $0.15 < y < 0.8$
- Require 2 jets
  - inclusive  $k_t$  algorithm in the  $p_t$  recombination scheme
  - jets lie within  $-0.19 < \eta < 1.3$
  - $P_t^{(1)} > 11$  GeV
  - $P_t^{(2)} > 8$  GeV
- Dominant Systematics
  - Vary Impact Parameter Resolution: 7% ( $c$ ), 10% ( $b$ )
  - Vary resolved fract.,  $P_t$  spectrum in Pythia: 7% ( $c$ ), 14% ( $b$ )
  - $uds$  asymmetry: 1% ( $c$ ), 6% ( $b$ )
  - Jet  $E$ -Scale: 6% ( $c$ ), 5% ( $b$ )
  - Trigger Efficiency: 5%
- Use Pythia or Cascade to calculate acceptance.
- NLO QCD predictions with FMNR
  - CTEQ5F3 proton pdf
  - GRV-G HO photon pdf

hep-ex/0605016

submitted to Euro.J.Phys.C

H1:  $c$  and  $b$  dijet cross sections in  $\gamma\gamma$ Data above NLO, especially for  $b$  and for low  $x_\gamma$

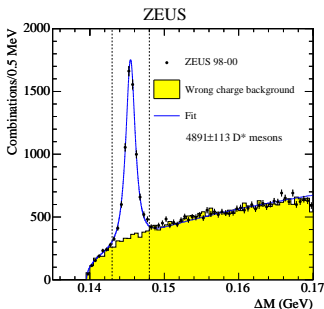
H1:  $c$  and  $b$  dijet cross sections in  $\gamma\gamma$ 

$\bar{\eta} = (\eta^{(1)} + \eta^{(2)})/2$ . Better agreement for  $x_\gamma > 0.85$  (direct).

H1:  $c$  and  $b$  dijet cross sections in  $\gamma p$ 

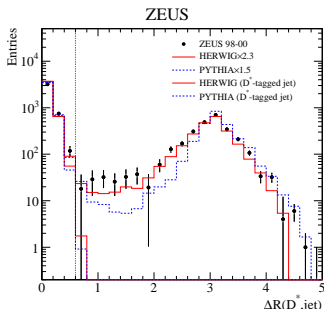
	Charm [pb]	Beauty [pb]
Data	$702 \pm 67(stat.) \pm 95(syst.)$	$150 \pm 17(stat.) \pm 33(syst.)$
FMNR	$500^{+173}_{-99}$	$83^{+19}_{-14}$
PYTHIA	484	76
CASCADE	438	80

The measured charm and beauty photoproduction dijet cross sections in the kinematic range  $Q^2 < 1 \text{ GeV}^2$ ,  $0.15 < y < 0.8$ ,  $p_t^{\text{jet}_{1(2)}} > 11(8) \text{ GeV}$  and  $-0.9 < \eta^{\text{jet}_{1(2)}} < 1.3$  in comparison to predictions in NLO QCD (FMNR) and from the Monte Carlo programs PYTHIA and CASCADE.

ZEUS:  $\gamma p \rightarrow D^* + \text{jet}(s)$ 

- Integrated Luminosity =  $78.6 \text{ pb}^{-1}$
- $\gamma p$  events w/  $130 < W < 280 \text{ GeV}$
- $D^*$  with  $P_t > 3 \text{ GeV}$  and  $|\eta| < 1.5$

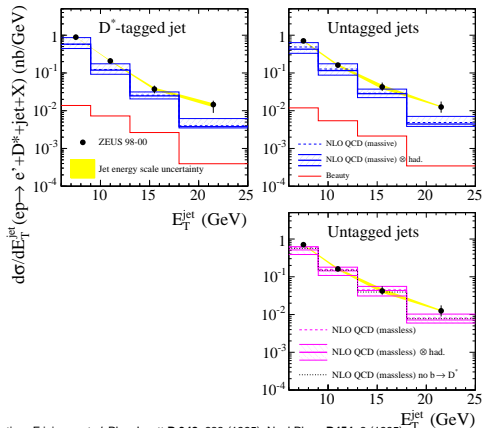
Nuclear Physics B 729 (2005) 492-525.



- Use  $k_t$  cluster jet algorithm
- Require  $\geq 1$  jet with  $E_t > 6 \text{ GeV}$  and  $-1.5 < \eta < 2.4$
- For dijet events require 2 such jets, one with  $E_t > 7 \text{ GeV}$
- Tagged if  $\Delta R(D^*, \text{jet}) < 0.6$

ZEUS:  $\gamma p \rightarrow D^* + \text{jet}(s)$ 

## ZEUS

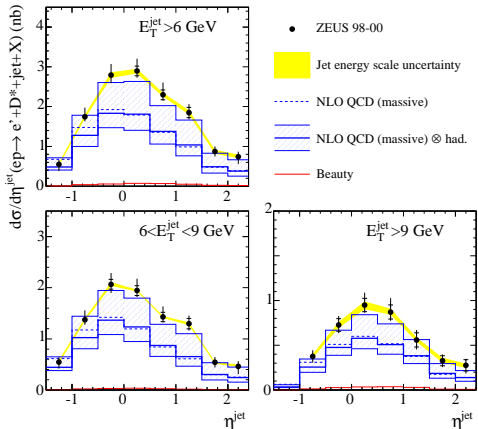


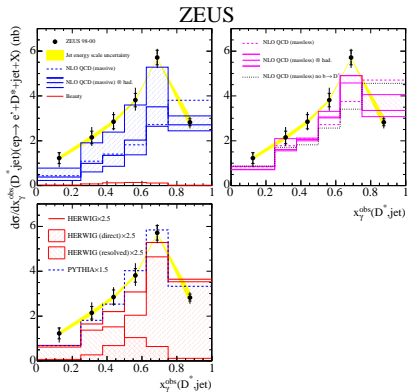
Massive Calculation: Frixione, *et al*, Phys.Lett.**B 348**, 633 (1995), Nucl.Phys. **B454**, 3 (1995)

Massless Calculation: Binnewies, Kniehl, Kramer, Z.Phys. **C 76**, 677 (1997), Kniehl, Kramer, Spira, Z.Phys. **C 76**, 689 (1997)

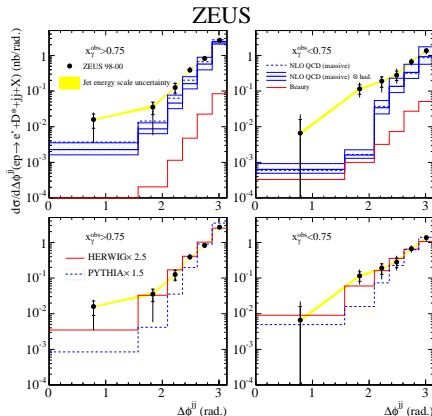
# ZEUS: $\gamma p \rightarrow D^* + \text{jet}(s)$

## ZEUS

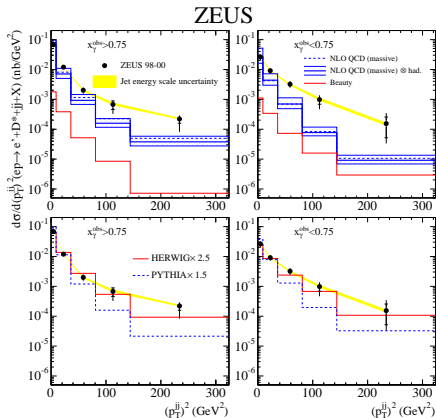


ZEUS:  $\gamma p \rightarrow D^* + \text{jet}(s)$ 

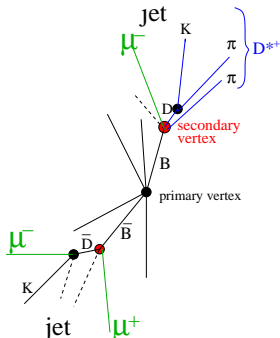
- $x_\gamma^{\text{obs}}(D^*, \text{jet}) =$  fraction of incoming  $\gamma$   $E - P_z$  transferred to the hadronic final state
- For direct (pointlike) photoproduction  $x_\gamma^{\text{obs}}(D^*, \text{jet}) = 1$
- Excess of data over NLO is greater for resolved  $\gamma p$  ( $x_\gamma^{\text{obs}}(D^*, \text{jet}) < 0.75$ )

ZEUS:  $\gamma p \rightarrow D^* + \text{jet}(s)$ 

NLO calculation does not describe non-back-to-back configurations, especially for  $x_\gamma^{\text{obs}} < 0.75$  (resolved photon). HERWIG does a reasonable job.

ZEUS:  $\gamma p \rightarrow D^* + \text{jet}(s)$ 

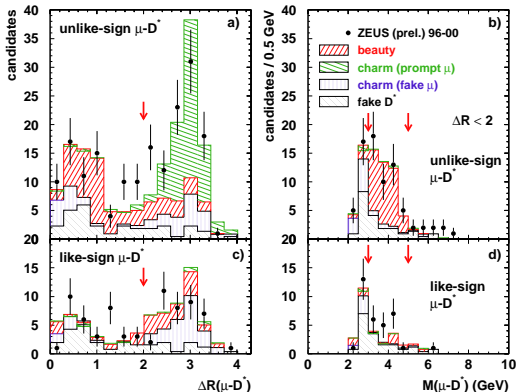
Again NLO calculation does not describe jet pairs with a net  $P_t$ , especially for  $x_\gamma^{\text{obs}} < 0.75$  (resolved photon). HERWIG does a reasonable job. For precise description, we need a program to match parton showers to NLO.

ZEUS: Beauty production using a  $D^*\mu$  tag

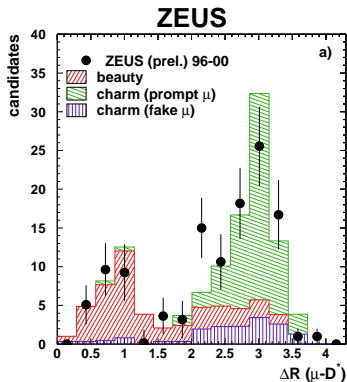
- $114 \text{ pb}^{-1}$
- Low Branching Ratio, High Purity
  - $BR(b \rightarrow D^{*\pm})$ .
  - $BR(D^{*+} \rightarrow D^0\pi^+)$ .
  - $BR(D^0 \rightarrow K^-\pi^+) = 0.45 \pm 0.05\%$   
( $86 \pm 3\%$  to  $D^{*+}$ )
  - $BR(b \rightarrow \mu^+) = 8.3 \pm 0.4\%$
  - $BR(b \rightarrow \mu^-) = 13.2 \pm 0.6\%$
- Sensitive to low- $P_t$  b production
- $D^*, \mu$  from same b have opposite charge
- $D^*, \mu$  from different b's may have like or unlike charge
- $\mu, D^*$  from  $c\bar{c}$  have opposite charge
- Fake  $D^*$  background estimated from data

ZEUS: Beauty production using a  $D^* \mu$  tag

## ZEUS

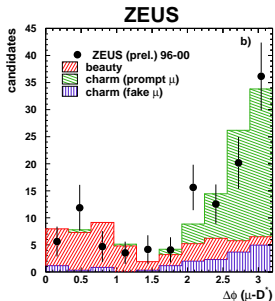


High  $b$ -fraction at low  $\Delta R$ . For  $\Delta R < 2$ , require  $3 < M(\mu, D^*) < 5$  GeV

ZEUS: Beauty production using a  $D^*\mu$  tag

$\Delta R$  spectrum after subtracting fake  $D^*$ 's and requiring  $3 < M(\mu, D^*) < 5 \text{ GeV}$  for  $\Delta R < 2$ .  
Fit to this plot yields:

$$f_b = 0.363 \pm 0.084(\text{stat}).$$



As a check, fit the  $\Delta\phi$  distribution to get:

$$f_b = 0.348 \pm 0.080(\text{stat}).$$

# ZEUS: Beauty production using a $D^*\mu$ tag

visible  $\sigma(ep \rightarrow e\bar{b}bX \rightarrow eD^*\mu X')$ :

$P_t(D^*) > 1.9 \text{ GeV}$ ,  $|\eta(D^*)| < 1.5$ ,  $P_t(\mu) > 1.4 \text{ GeV}$ ,  $-1.75 < \eta(\mu) < 1.3$

<b>ZEUS:</b>	$\sigma_{\text{vis}} = 214 \pm 52 \text{ (stat)}$	$^{+96}_{-84} \text{ (syst) pb}$	$\frac{\text{Data}}{\text{NLO}} = 3.0^{+1.6}_{-1.7}$
<b>NLO+Pythia:</b>	$\sigma_{\text{vis}} = 72$	$^{+20}_{-13} \text{ (NLO)}$ $^{+14}_{-10} \text{ (frag+br) pb}$	

photoproduction only  $Q^2 < 1 \text{ GeV}^2$ ,  $0.05 < y < 0.85$

<b>ZEUS:</b>	$\sigma_{\text{vis}} = 159 \pm 41 \text{ (stat)}$	$^{+68}_{-62} \text{ (syst) pb}$	$\frac{\text{Data}}{\text{NLO}} = 2.8^{+1.5}_{-1.6}$
<b>NLO+Pythia:</b>	$\sigma_{\text{vis}} = 57$	$^{+16}_{-10} \text{ (NLO)}$ $^{+11}_{-9} \text{ (frag+br) pb}$	

H1 Cuts:  $P_t(D^*) > 1.5 \text{ GeV}$ ,  $|\eta(D^*)| < 1.5$ ,  $P_t(\mu) > 2.0 \text{ GeV}$ ,  $|\eta(\mu)| < 1.735$

<b>ZEUS:</b>	$\sigma_{\text{vis}} = 186 \pm 48 \text{ (stat)}$	$^{+80}_{-73} \text{ (syst) pb}$
<b>H1:</b>	$\sigma_{\text{vis}} = 206 \pm 53 \text{ (stat)}$	$\pm 35 \text{ (syst) pb}$

$\sigma(ep \rightarrow bX)$

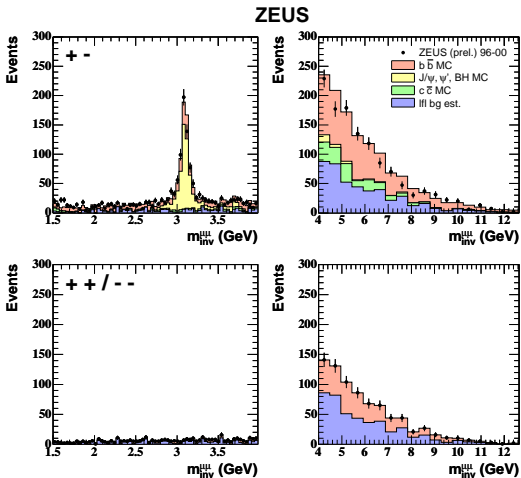
Use Pythia to extrapolate to  $y_{\text{rapidity}}(b) < 1$ ,  $Q^2 < 1 \text{ GeV}^2$ ,  $0.05 < y < 0.85$

<b>ZEUS:</b>	$\sigma_b = 15.1 \pm 3.9 \text{ (stat)}$	$^{+3.8}_{-4.7} \text{ (syst) nb}$	$\frac{\text{Data}}{\text{NLO}} = 3.0^{+1.3}_{-1.6}$
<b>NLO(FMNR):</b>	$\sigma_b = 5.0$	$^{+1.7}_{-1.1} \text{ nb}$	

NLO calculations from Cacciari, Frixione, and Nason, JHEP **0103**, (2001) p.6

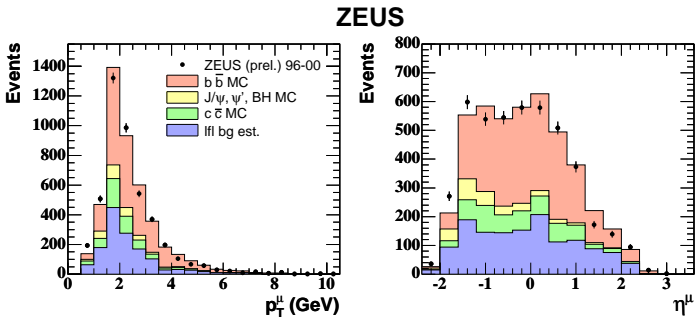


# ZEUS: Beauty production from dimuon events



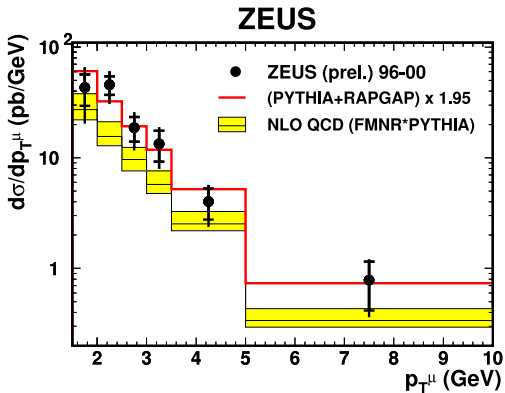
$\mu\mu$  mass spectra before non-isolation requirement

# ZEUS: Beauty production from dimuon events



Unlike sign sample after non-isolation requirement

## ZEUS: Beauty production from dimuon events



$d\sigma/dP_t^\mu$  for  $\mu$  from  $b$  decays in  $\mu\mu$  events with  $P_t^\mu > 1.5$  GeV and  $-2.2 < \eta^\mu < 2.5$



## Summary

- CDF  $c$  cross sections exceed NLO by  $\sim 50 - 100\%$
- CDF  $b$ -hadron cross sections from  $J/\psi$  in good agreement with FONLL
- CDF  $b$ -jet cross sections agree at low  $P_t$ , higher (within errors) at high  $P_t$
- CDF  $b\bar{b}$  dijet cross sections above MC@NLO, agreement improved by including underlying event
- H1  $F_2^{c\bar{c}}$  and  $F_2^{b\bar{b}}$  agree with QCD fits. Precision comparable to  $D^*$  measurements
- H1 direct  $c$ ,  $b$  dijet cross sections described by NLO, for resolved data exceeds theory
- ZEUS  $D^*$ +jets in  $\gamma p$  agrees with NLO, except for non-back-to-back topologies
- ZEUS measures  $b$  production 2-3 times above theory, with large uncertainties.

## Outlook

- All results shown today use only a small part of the on-tape luminosity for the Tevatron and HERA.
- The Tevatron can expect  $4\text{-}8\text{ fb}^{-1}$ .
- HERA experiments have  $\sim 250\text{ pb}^{-1}$  of useable luminosity on tape.
- Should be  $\sim 450\text{ pb}^{-1}$  when running ends in June 2007.
  - Hopefully a flood of HERA II results next summer
  - Rapid understanding of ZEUS Micro Vertex Detector
- Many (most) results shown were systematics limited
  - Much hard work ahead.
- Theoretical errors are quite large (often a factor of 2).