Heavy Flavor Production at HERA and the Tevatron

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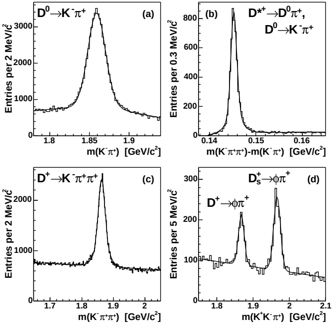
Outline

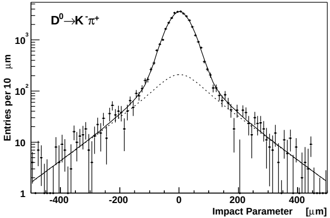
1. c and b Production in $p\bar{p}$
   - CDF: Prompt Charm Meson Production Cross Sections
   - CDF: J/ψ and b-Hadron Production Cross Sections
   - CDF: Inclusive b-Jet Production
   - CDF: $b\bar{b}$-Dijet Production
2. c and b Production in Deep Inelastic Scattering
   - HERA Kinematics
   - H1: Measurement 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 inγp
   - ZEUS: $\gamma p \rightarrow D^* + \mathrm{jet(s)}$
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



Charm Meson Signals. 5.8 pb^{-1}.

- 2$^{\mathrm{nd}}$ level impact param. trigger.
- 2 tracks with impact param. w.r.t beam $> 120\,\mu$m
- decay length $> 200\,\mu$m



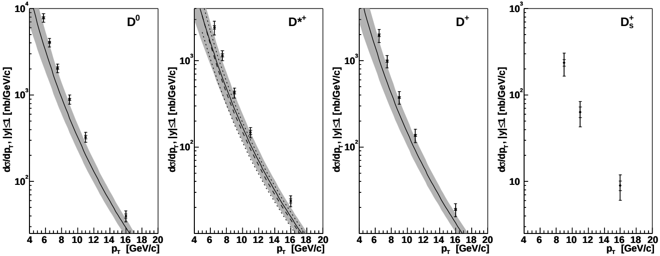
Impact param. of D^0 w.r.t beam

- Comb. background subtracted,
- Dashed curve $= b$ contribution.
- P_t cuts (GeV)

D^0	D^{*+}	D^+	D_s^+
5.5	6	6	8

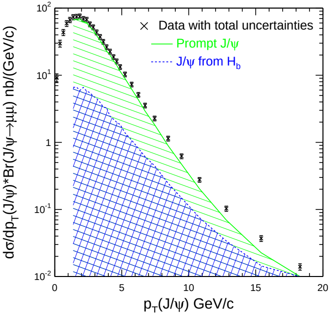
Acosta,*et.al.*, Phys. Rev. Lett. 91, 241804 (2003).

CDF: Prompt Charm Meson Production Cross Sections

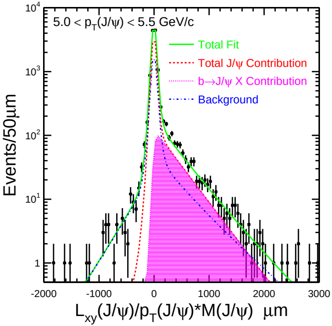


- Prompt charm meson cross sections for $|y| < 1$
- Inner error bars are statistical, outer are systematic (dominates).
  - 3%-4% uncertainty on prompt fraction
  - 8%-14% uncertainty on trigger/reconstruction efficiency
- Theory curves by Cacciari and Nason, J.High Energy Phys. **0309** (2003) p.6.

CDF: J/ψ and b-Hadron Production Cross Sections



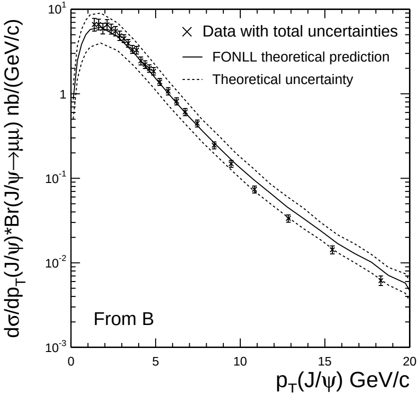
J/Ψ cross section for $|y| < 0.6$.
39.7 pb^{-1}



Extract fraction from B decays by fit to pseudoproper decay time

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

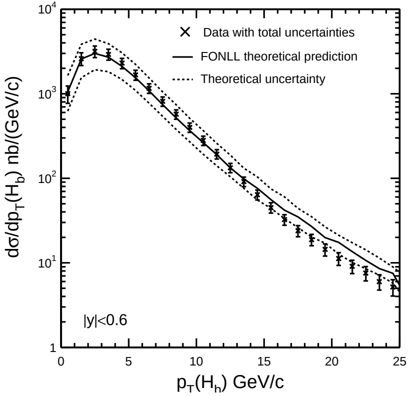
CDF: J/ψ and b-Hadron Production Cross Sections



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/ψ and b-Hadron Production Cross Sections



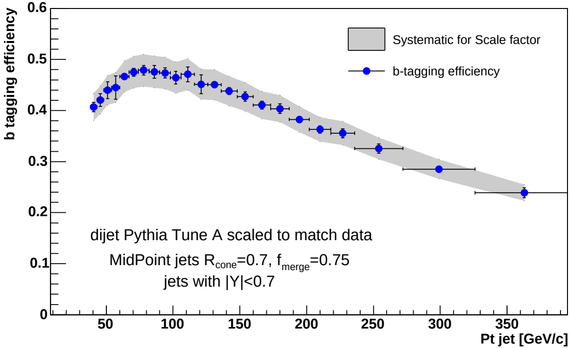
Iterative unfolding of $d\sigma/dP_t(J/\Psi)$ gives $d\sigma/dP_t(H_b)$.

CDF: J/ψ and b-Hadron Production Cross Sections

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

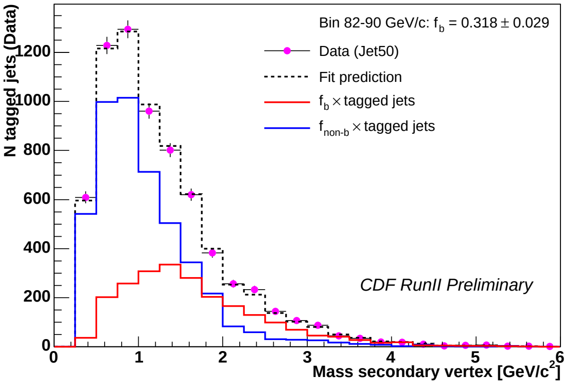
CDF: Inclusive b-Jet Production

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



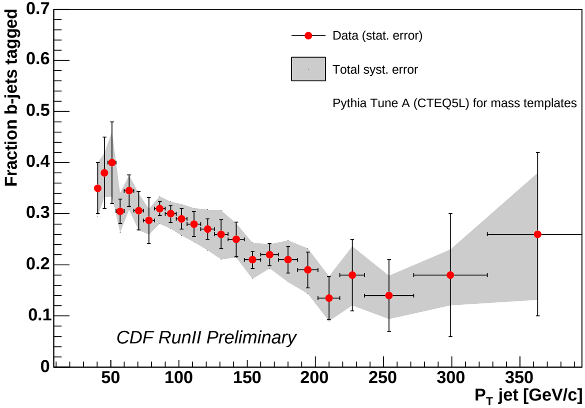
Efficiency to tag b-jets using `SecVtx` algorithm. Simulated efficiency is corrected with efficiency measured in electron sample. Syst. uncertainty$\sim$ 7% Use 300 pb^{-1}.

CDF: Inclusive b-Jet Production



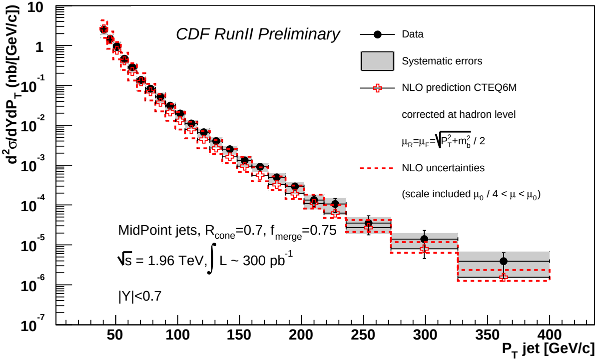
Fraction of b-jets in each P_t bin determined by fit to spectrum of secondary vertex mass. Templates from Pythia. Syst. uncertainty oin b-fraction

CDF: Inclusive b-Jet Production



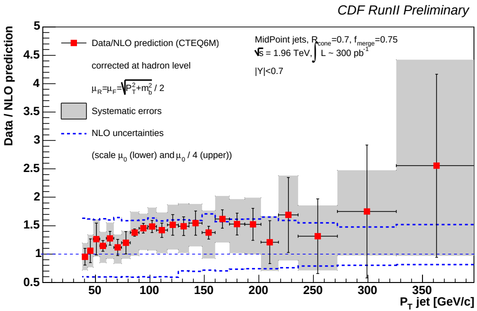
Fraction of b-jets in each P_t bin.

CDF: Inclusive b-Jet Production



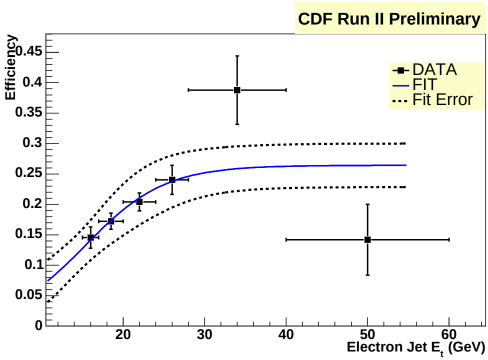
b-jet cross section compared to NLO
(Mangano and Frixione, Nucl. Phys. B483, 321 (1997)).

CDF: Inclusive b-Jet Production



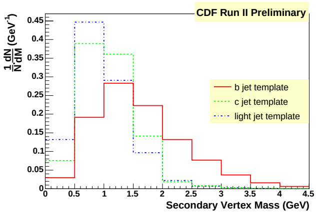
systematic uncertainties	low P_t	high P_t
vary E-Scale by $\pm 3\%$	+10%/-8%	+39%/-22%
Unfolding	$\pm 5\%$	$\pm 15\%$
vary E resolution by $\pm 10\%$	$\pm 6\%$	
Luminosity	$\pm 5.8\%$	

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

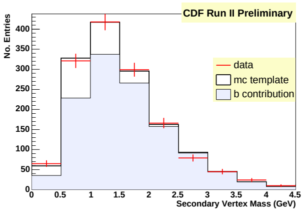


Select events with 2 secondary-vertex tagged jets with $|\eta| < 1.2$, $E_T^1 > 30$ GeV and $E_T^2 > 20$ GeV.
Plot show tagging efficiency measured using electron jet with opp-side secondary vertex tagged jet

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

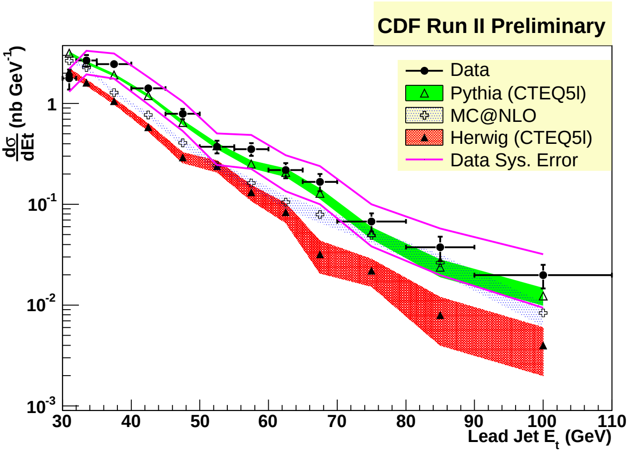


Templates of Secondary Vertex Mass for light flavors, c, and b

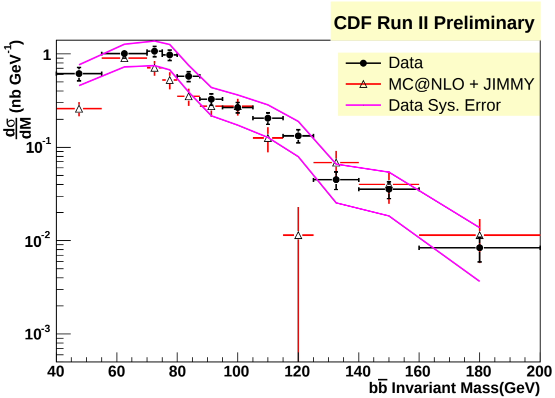


Fit of data for linear combination of templates. $F_b = 0.83 \pm 0.04$. $\sigma_{b\bar{b}}(|\eta| < 1.2, E_t^1 > 30, E_t^2 > 20) = 34.5 \pm 1.8 \pm 10.5\,\text{nb}$

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



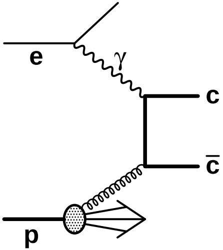
CDF: $b\bar{b}$-Dijet Production



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

HERA Kinematics

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



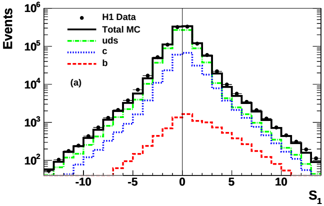
The dominant LO process for $c\bar{c}$ and $b\bar{b}$ production is photon-gluon fusion. $d\sigma/dx \sim g(x)$

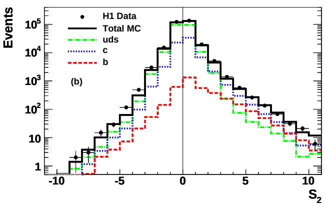
$$\begin{aligned} Q^2 &= -(\gamma \text{ 4-mom})^2 \\ x &= \text{fraction of } p \text{ momentum carried by } g \\ y &= Q^2/(sx) \\ &= \text{fraction of initial-state } E - P_z \\ &\quad \text{transferred to hadronic final state.} \end{aligned}$$

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

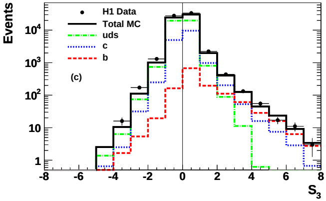
ratio F_2/F_L is calculated by QCD.

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





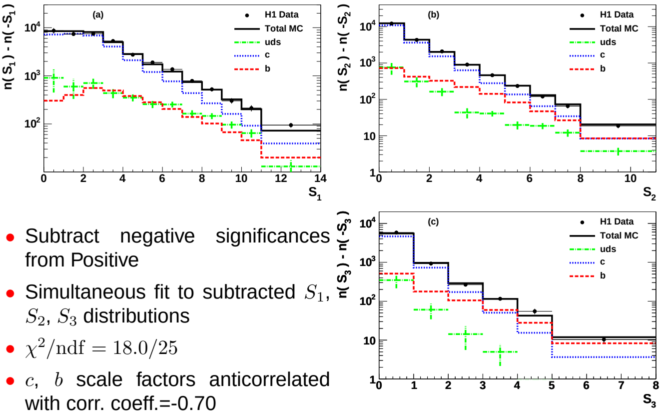
- 57.4 pb^{-1} of e^+p data
- Select DIS Events with
  - $E - P_z > 35$ GeV
  - $6.3 < Q^2 < 120$ GeV^2
  - $0.07 < y < 0.7$
- use CST tracks w/ P_t >0.5 GeV
- plot 1$^{\text{st}}$, 2$^{\text{nd}}$, 3$^{\text{rd}}$ highest impact parameter significance
- fit data with uds+c+b



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

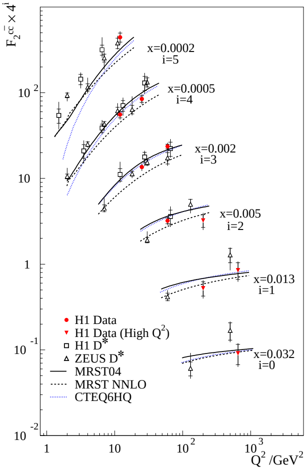
A.Aktas *et al.*, Eur.Phys.J. **C40** (2005) 349,`hep-ex/0411046`

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

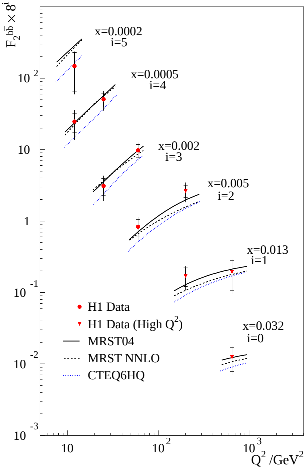


- Subtract negative significances from Positive
- Simultaneous fit to subtracted S_1, S_2, S_3 distributions
- $\chi^2/\mathrm{ndf} = 18.0/25$
- c, b scale factors anticorrelated with corr. coeff.=-0.70
- Apply same procedure in each (x, Q^2) bin

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

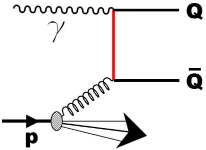


$F_2^{c\bar{c}}$

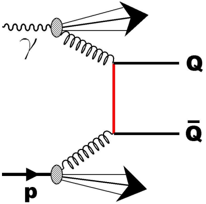


$F_2^{b\bar{b}}$

Photoproduction Processes

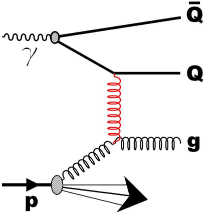


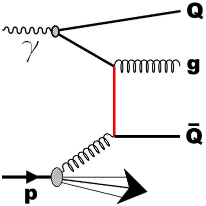
Direct (pointlike) Photoproduction



Resolved Photoproduction

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





Flavor Excitation
(a resolved process)

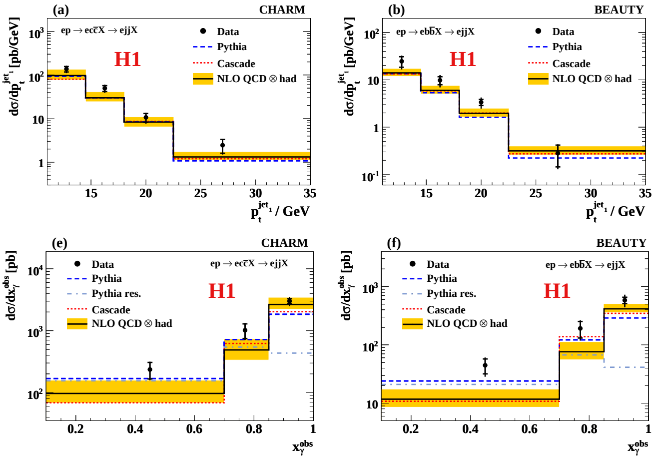
H1: c and b dijet cross sections in γp

- 56.8 pb^{-1}
- 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 $-0.l9 < \eta < 1.3$
  - $P_t^{(1)} > 11$ 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

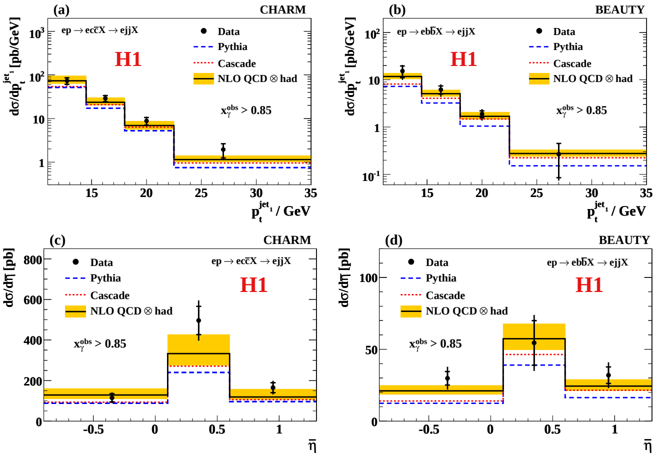
`hep-ex/0605016`
submitted to Euro.J.Phys.**C**

H1: c and b dijet cross sections in γp



Data above NLO, especially for b and for low x_γ

H1: c and b dijet cross sections in γp



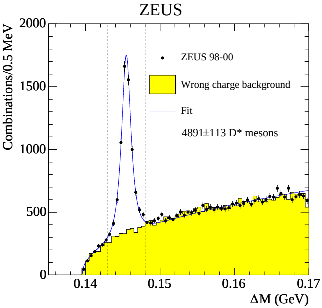
$\bar{\eta} = (\eta^{(1)} + \eta^{(2)})/2$. Better agreement for $x_\gamma > 0.85$ (direct).

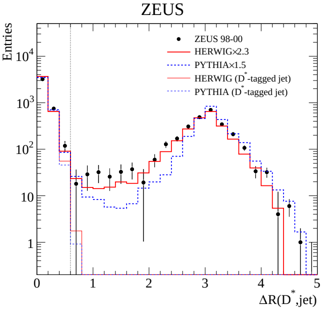
H1: c and b dijet cross sections in γp

	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 $Q^2 < 1$ GeV^2, $0.15 < y < 0.8$, $p_t^{\text{jet}_{1(2)}} > 11(8)$ GeV and $-0.9 < \eta^{jet_{1(2)}} < 1.3$ in comparison to predictions in NLO QCD (FMNR) and from the Monte Carlo programs PYTHIA and CASCADE.

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



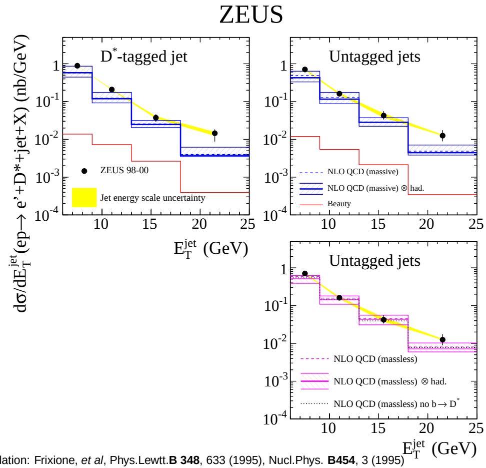


- Integrated Luminosity = 78.6 pb^{-1}
- γp events w/ $130 < W < 280$ GeV
- D^* with $P_t > 3$ GeV and $|\eta| < 1.5$

Nuclear Physics B 729 (2005) 492-525.

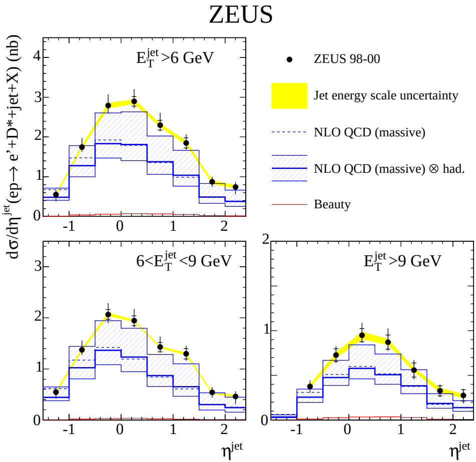
- Use k_t cluster jet algorithm
- Require $>= 1$ jet with $E_t > 6$ GeV and $-1.5 < \eta < 2.4$
- For dijet events require 2 such jets, one with $E_t > 7$ GeV
- Tagged if $\Delta R(D^*, \mathrm{jet}) < 0.6$

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

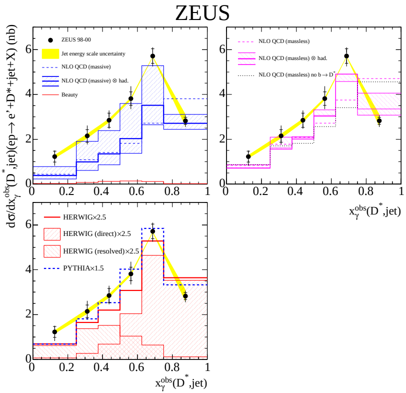


Massive Calculation: Frixione, *et al*, Phys.Lewtt.**B 348**, 633 (1995), Nucl.Phys. **B454**, 3 (1995)
Massless Calculation: Binnewies, Kniehl, Kramer, Z.Phys. **C 76**, 677 (1997), Kniehl, Kramer, Spira, Z.Phys. **C 76**, 689 (1997)

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

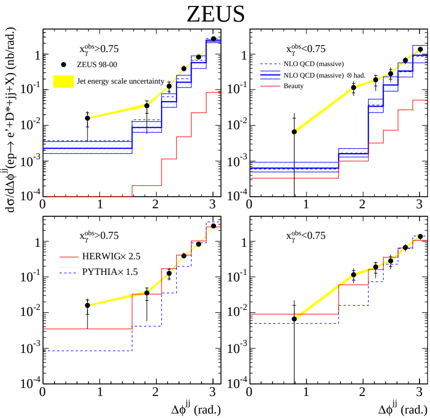


ZEUS: $\gamma p \rightarrow D^* + \mathrm{jet(s)}$



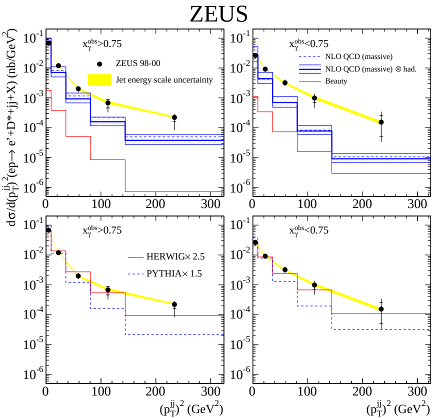
- $x_\gamma^{\text{obs}}(D^*, \text{jet})$ = fraction of incoming γ $E - P_z$ transferred to the hadronic final state
- For direct (pointlike) photoproduction $x_\gamma^{\text{obs}}(D^*, \text{jet}) = 1$
- Excess of data over NLO is greater for resolved γp ($x_\gamma^{\text{obs}}(D^*, \text{jet}) < 0.75$)

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



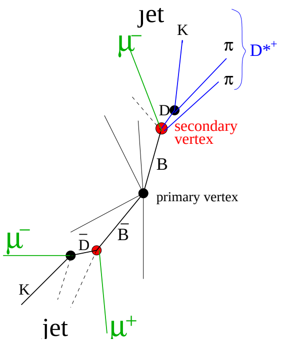
NLO calculation does not describe non-back-to-back configurations, especially for $x_\gamma^{\text{obs}} < 0.75$ (resolved photon). HERWIG does a reasonable job.

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



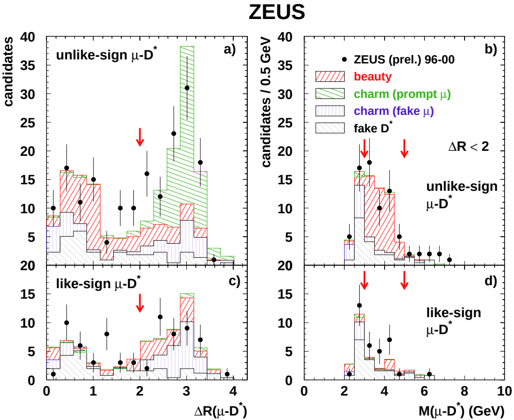
Again NLO calculation does not describe jet pairs with a net P_t, especially for $x_\gamma^{\rm obs} < 0.75$ (resolved photon). HERWIG does a reasonable job. For precise description, we need a program to match parton showers to NLO.

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



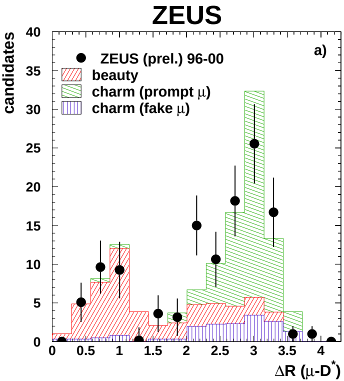
- 114 pb^{-1}
- Low Branching Ratio, High Purity
  - $BR(b \to D^{*\pm})\cdot$
    $BR(D^*+ \to D^0\pi^+)\cdot$
    $BR(D^0 \to K^-\pi^+) = 0.45 \pm 0.05\%$
    ($86 \pm 3\%$ to D^{*+})
  - $BR(b \to \mu^+) = 8.3 \pm 0.4\%$
  - $BR(b \to \mu^-) = 13.2 \pm 0.6\%$
- Sensitive to low-P_t b production
-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

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



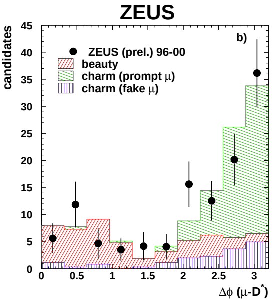
High b-fraction at low ΔR. For $\Delta R < 2$, require $3 < M(\mu, D^*) < 5\,$GeV

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



ΔR spectrum after subtracting fake D^*'s and requiring $3 < M(\mu, D^*) < 5$ 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 $\sigma(ep \to eb\bar{b}X \to eD^*\mu X')$:

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

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

photoproduction only $Q^2 < 1$ GeV^2, $0.05 < y < 0.85$

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

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

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

$\sigma(ep \to bX)$

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

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

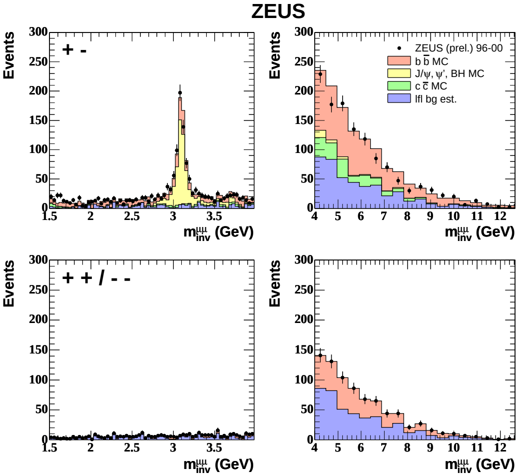
NLO calculations from Cacciari,Frixione, and Nason, JHEP **0103**, (2001) p.6

ZEUS: Beauty production from dimuon events

- 121 pb^{-1}
- require 2 μ's with $-2.2 < \eta < 2.5$
- One μ with $P_t > 1.5$ GeV
- 2$^{\rm nd}$ μ with $P_t > 0.75$ GeV
- $c\bar{c}$ background estimated from $D^*\mu$ analysis
- Apply non-isolation requirement to supress J/Ψ and $\gamma\gamma \to \mu^+\mu^-$ backgrounds
- Normalize J/Ψ and $\gamma\gamma \to \mu^+\mu^-$ backgrounds using isolated $\mu^+\mu^-$ pairs
- Fake $\mu\mu$ background $\sim$ same for same sign and opposite sign

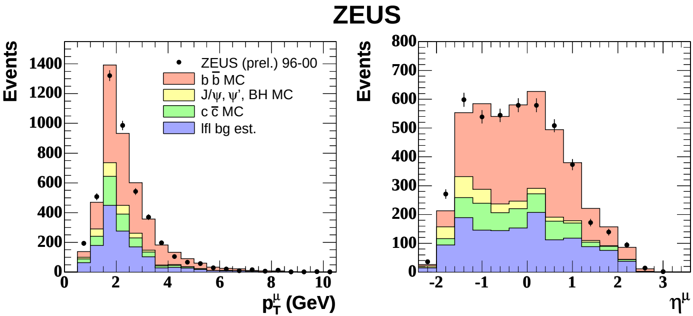
$$N_{b\bar{b}} = \left(N^{+-}_{\rm data} - N^{++,--}_{\rm data} - N_{c\bar{c}} - N_{J/\Psi} - N_{\gamma\gamma}\right) \times \left(\frac{N^{+-}_{b\bar{b}} + N^{++,--}_{b\bar{b}}}{N^{+-}_{b\bar{b}} - N^{++,--}_{b\bar{b}}}\right)_{\rm MC}$$

ZEUS: Beauty production from dimuon events



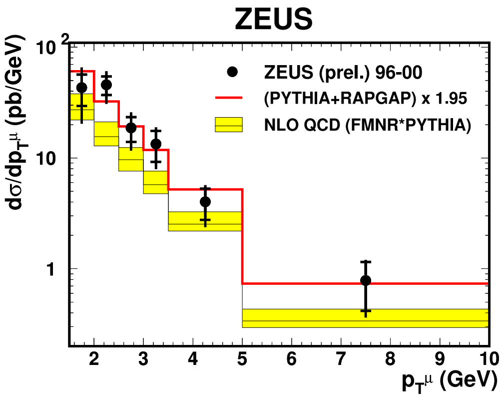
$\mu\mu$ mass spectra before non-isolation requirement

ZEUS: Beauty production from dimuon events



Unlike sign sample after non-isolation requirement

ZEUS: Beauty production from dimuon events



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

ZEUS: Beauty production from dimuon events

visible $\sigma(ep \to eb\bar{b}X \to \mu\mu X')$:

Two muons, both with $-2.2 < \eta < 2.5$
1st muon: $P_t > 1.5$ GeV
2nd muon if $\eta < 0.6$: $P_t > 0.75$ GeV AND $P > 1.8$ GeV
2nd muon if $\eta > 0.6$: ($P_t > 0.75$ GeV AND $P > 2.5$ GeV) OR $P_t > 1.5$ GeV

ZEUS:	$\sigma_{\mathrm{vis}} =$	63	± 7 (stat)	$^{+20}_{-18}$ (syst) pb
NLO+Pythia:	$\sigma_{\mathrm{vis}} =$	30	$^{+9}_{-6}$ (NLO)	$^{+5}_{-3}$ (frag+br) pb

$\frac{\mathrm{Data}}{\mathrm{NLO}} = 2.1^{+0.8}_{-1.0}$

$\sigma(ep \to bX)$

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

ZEUS:	$\sigma_b =$	16.1	± 1.8 (stat)	$^{+5.3}_{-4.8}$ (syst) nb
NLO(FMNR):	$\sigma_b =$	7.0	$^{+3.0}_{-1.7}$ nb	

$\frac{\mathrm{Data}}{\mathrm{NLO}} = 2.3^{+1.0}_{-1.2}$

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

Summary

- CDF c cross sections exceed NLO by $\sim 50 - 100\%$
- CDF b-hadron cross sections from J/Ψ 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 diject cross sections described by NLO, for resolved data exceeds theory
- ZEUS D^*+jets in γp 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 4-8 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).