Beauty photoproduction at ZEUS

on behalf the ZEUS collaboration
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CERN

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The HERA Collider

**Heavy Flavour
Beauty at HERA**

**Summary**

**backup**

**HERA**

The HERA Collider

\[ E_p = 920 \text{ GeV}, \quad E_e = 27.6 \text{ GeV} \quad \rightarrow \quad \sqrt{s} = 320 \text{ GeV} \]

\[
\begin{align*}
96/00 (\text{HERA I}): & \quad e^\pm p \sim 130 \text{pb}^{-1} \\
03/07 (\text{HERA II}): & \quad e^\pm p \sim 380 \text{pb}^{-1}
\end{align*}
\]

End of HERA program: June 2007

(last 3 months low energy running \rightarrow F_L)
Dominant production process in $ep$-collisions: **Boson Gluon Fusion**

Kinematic variables:
- $Q^2 = -q^2$ photon virtuality, squared momentum transfer
- $x = \frac{Q^2}{2pq}$ Bjorken scaling variable
- $x_{\gamma}^{jet} = \frac{\Sigma_{j1,j2}(E - P_Z)}{\Sigma_h(E - P_Z)}$

Multiple scales involved:
- $M_b \sim 5$ GeV, $M_c \sim 1.4$ GeV
- $Q^2 \sim 0$ GeV$^2$ (photoproduction - $\gamma p$)
- $Q^2 > \sim 1$ GeV$^2$ (deep inelastic scattering - DIS)
- $P_{t,c}^{c,b}$ few GeV

Powerful tool for testing $p$ structure and $pQCD$
NLO corrections for HQ production in $ep$ collisions known since '90s.

- **FMNR** program available for PHP (massive scheme FFNS, Weizsäcker-Williams approximation used, resolved-photon included).

- NLO corrections significant $\rightarrow \sigma_{\text{NLO}}/\sigma_{\text{LO}} \sim 1.4$ (main contribution from Flavor Excitation-like diagrams).

### Perturbative uncertainties on $\sigma_{\text{PHP}}$ from FMNR:
- Up to $\sim 30\%$ for $m_b = 4.75 \pm 0.25$ GeV.
- $\sim 20\%$ for $\mu_r = \mu_f = 2^{0\pm1}m_T$.
- $\sim 3\%$ for PDFs.

### Non-perturbative uncertainties (coming from fragmentation, hadronization etc.) are overall smaller than perturbative ones.
Beauty measurements difficult at HERA → $\sigma_{b\bar{b}}/\sigma_{tot} \sim 0.1\%$

- increases to $\sim 6\%$ for high-$p_T$ jets
- increased to $\sim 20\%$ for two jets and a high-$p_T$ lepton (beauty and charm are main sources)

**Beauty results at ZEUS**

- events with 2 jets + 1$\mu$ (PRD 70 (2004) 012008, DESY-08-210 (2008))
- events with 1 $D^*$ + 1$\mu$ (EPJ C 50 (2007) 299-314)
- events with 2$\mu$s (JHEP02 (2009) 032)
- events with 2 jets + vertex (DIS2009: ZEUS-prel-09-005)
Final result DESY-08-210, accepted by JHEP, $\mu$ channel:

- ID based on muon chambers
- Background from $c$ and “fake” muons (decays of $K$, $\pi$, punch-through)

Beauty content extracted statistically from fits to discriminant variables:

- $p_T$ of muon relative to the jet axis ($p_T^{rel}$): exploits large B mass
- Muon impact parameter ($\delta$): exploits long B lifetime
**b → µ**

**HERA II data** (2005 $e^+ p$), $\mathcal{L} = 125$ pb$^{-1}$

- **PHP selection**: veto on scattered $e^+$, $0.2 < y_{JB} < 0.8$

- **Jets**: $k_T$ clustering (massive), $N_{jets} \geq 2$, $p_T > 7(6)$ GeV, $|\eta| < 2.5$

- **µ selection**: $p_T^\mu > 1.5$ GeV, $-1.6 < \eta < 2.3$
Combined $p_T^{rel}$-$\delta$ fit

- 3-components fit
- $p_T^{rel}$ fit alone able to distinguish $b$ from $bkg$ ($c$ and $lf$)
- $\delta$ fit alone able to well separate light from heavy flavours
- here not necessary to constrain charm fraction from other measurements (HERA I)
FMNR NLO QCD predictions:

- \( \mu = \mu_0 = \sqrt{\frac{1}{2}((p_T^b)^2 + (p_T^\bar{b})^2) + m_b^2} \),
- \( 0.5\mu_0 < \mu < 2\mu_0 \)
- \( m_b = 4.75 \text{ GeV}, 4.5 \text{ GeV} < m_b < 5 \text{ GeV} \)
- PDF(P) = CTEQ5M, PDF(\( \gamma \)) = GRVG-HO
- Hadronization corrections from PYTHIA

New lower \( p_T^\mu \) bin (1.5-2.5 GeV)!

Results:

- Good agreement with NLO QCD
- Good agreement with previous HERA I results (\( p_T^{rel} \) only)

\[ p_T^\mu > 2.5 \text{GeV} \]
Results:

- Good agreement with NLO QCD

\[ \sigma_{\text{vis}}(e p \rightarrow e b \bar{b} \rightarrow e j j \mu X') = 38.6 \pm 3.5(\text{stat.})^{+4.6}_{-4.9}(\text{syst.}) \text{ pb} \]

\[ \sigma_{\text{NLO}}(e p \rightarrow e b \bar{b} \rightarrow e j j \mu X') = 37.0^{+11.9}_{-7.5} \text{ pb} \]
Low \( x_{\gamma}^{obs} \) region dominated by resolved-\( \gamma \) and multijet topologies

- \( x_{\gamma}^{jet} = \frac{\Sigma_{j1,j2}(E - P_Z)}{\Sigma_h(E - P_Z)} \)
- at LO QCD \( x_{\gamma} \) is the fraction of photon’s energy entering the hard interaction
- \( x_{\gamma}^{obs} \) has been measured by most of the dijets analyses
- No serious discrepancy within the present data/theory description

\[ gg \rightarrow bb \]
\[ b \text{-excitation: } bg \rightarrow gb \]
Dijet angular correlations particular sensitive to higher-order effects

- At LO 2 jets in the event produced back-to-back ($\Delta\phi^{jj} = \pi$)
- additional soft-radiation $\rightarrow$ small azimuthal decorrelation
- $\Delta\phi^{jj} << \pi$ $\rightarrow$ additional hard radiation
- for beauty NLO QCD agrees well with measurements
- Inclusive sample, no lepton request (DIS2009: ZEUS-prel-09-005)
- Fraction of $b$ extracted from decay length significance ($S = \frac{\Delta}{\sigma(\Delta)}$) after reconstructing the decay vertices of $B$ hadrons
- Invariant mass of the decay vertices ($m_{vtx}$) used to distinguish beauty-enriched regions
- Advantage: higher statistics and purity w.r.t. $D^*$ or lepton analysis
lifetime tagging

06-07 $e^\pm p$ data: $\mathcal{L} = 128 \text{ pb}^{-1}$

- **PHP selection**: veto on scattered $e^\pm$, $0.2 < y_{JB} < 0.8$
- **Jets**: $k_T$ clustering (massive), $N_{jets} \geq 2$, $p_t > 7(6) \text{ GeV}$, $|\eta| < 2.5$
- **track selection**: $p_t > 0.5 \text{ GeV}$
- if $\geq 2$ tracks associated to a jet $\rightarrow$ secondary vertex is fitted
- $-1.6 < \eta_{jet} < 1.3$ for vertex-tagged jet
- decay length significance divided in 3 mass bins
- since tails not yet fully described mirrored distribution fitted (reduce systematic effects)
- simultaneous fit over 3 mass bins to extract \( b \), \( c \) and \( lf \) contributions
Control plots of beauty-enriched region

Possibility to select an almost pure beauty sample

- $m_{vtx} > 2$ GeV
- $S^+ - S^- > 8$
FMNR NLO QCD predictions:
- $\mu = \frac{\mu_0}{2}, \frac{\mu_0}{4} < \mu < \mu_0$
- $m_b = 4.75 \text{ GeV}, 4.5 \text{ GeV} < m_b < 5 \text{ GeV}$
- PDF(P) = CTEQ5, PDF($\gamma$) = GRVG-HO
- $\epsilon_b = 0.0035$

Results:
- Good agreement with NLO QCD
Results:

- Good agreement with NLO QCD
- Agreement within the errors with previous HERA I results (DESY-03-212)
- Completely different tagging technique, much smaller errors!
Results obtained with different methods and by different experiments in good agreement

- New scale choice (A. Geiser DIS 2007). Older central value $\mu = \mu_0$

- More precise theory needed
$d\sigma/dp_T^{b}(ep \rightarrow e b X)$

$Q^2 < 1 \text{GeV}^2$, $0.2 < y < 0.8$, $|\eta^b| < 2$

NLO QCD (FMNR)

$\mu^2 = 1/4 (m^2 + p_T^2)$

$\mu^2 = m^2 + p_T^2$

**Data Points**:
- H1 99-00 b jet
- H1 99-00 b → $\mu$ jet
- ZEUS 96-00 b → $\mu$ jet
- ZEUS 05 b → $\mu$ jet
- H1 (prel) 06/07 b → $\mu$ jet
- ZEUS 96-97 b → e
- ZEUS 120 pb$^{-1}$ b → e
- H1 97-00 b → $D^*$\,$\mu$
- ZEUS 96-00 b → $D^*$\,$\mu$
- ZEUS 114 pb$^{-1}$ $b b \rightarrow \mu \mu$
- ZEUS (prel) 128 pb$^{-1}$ b jet
first ZEUS dijet inclusive measurement of beauty has been presented

many new beauty measurements became available. Results in agreement with NLO QCD and between them.

experimental precision comparable or better than theory

HERA II data are still being analysed. More precise and interesting measurements to come...
**Prediction:**

| LO+PS: PYTHIA, HERWIG (DGLAP) | Describes: |
| RAPGAP (DGLAP) | γp |
| CASCADE (CCFM) | DIS |

**NLO:**

| FMNR | γp |
| HVQDIS | DIS |

**MONTE CARLO**

- leading order + parton shower models available, including flavour excitation, DGLAP evolution (*PYTHIA, HERWIG*)
- CCFM evolution with $k_t$ factorisation (*CASCADE*)

**THEORETICAL CALCULATIONS**

- full NLO calculation (*FMNR, HVQDIS*) available
- massive scheme FFNS (heavy quark dynamically generated in the hard process)
Inclusive vertex significance:
Systematics for inclusive jet+vtx measurement

- Luminosity
- MVD hit efficiency
- CAL hadronic energy scale
- Variation of the fit range
- $P_T^{\text{jet}}$ and $\eta^{\text{jet}}$ reweighting
- Uncertainty of HFL5 trigger efficiency
- Decay length smearing $\rightarrow$ DOMINANT!
ZEUS PHP dijets correlations
massive scheme
- \( c, b \) massive
- neglects terms \((\alpha_s \ln(Q^2/m_{c,b}^2))^n\)
- scales \( m_b, m_c \)

\(\rightarrow c, b \) produce perturbatively (not part of the photon or proton)

massless scheme
- \( c, b \) massless
- resums terms \((\alpha_s \ln(Q^2/m_{c,b}^2))^n\)
- scales \( Q^2, p_t \)

\(\rightarrow c, b \) also in proton and photon

variable flavour number scheme
- massive at small \( Q^2 \)
- massless at large \( Q^2 \)
Gluon dens.

main reason for beauty suppression: phase-space factor

- kinematic threshold for $b$ production due to its mass
- $x_g \geq \frac{m^2}{E_\gamma \times 920 \text{ GeV}}$ ($x_g$ fraction of four-momentum of the proton carried by the gluon participating in the hard interaction)
- for charm $x_g \geq 10^{-4}$, for beauty $x_g \geq 10^{-3}$