Heavy Quark Production at HERA

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On behalf of the H1 and ZEUS Collaborations

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Outline

- Introduction
- Charm via D* 
- Beauty via semileptonic decays to $\mu$
- Charm and Beauty via semileptonic decays to e 
- Beauty correlations 
- $F_{2}^{bb}$, $F_{2}^{cc}$
- Conclusions & Outlook
Boson-gluon fusion (BGF) is main production mechanism

Concentrate on studies of production mechanism:
- Test QCD (different hard scales, $m_Q$, $p_T$, $Q^2$)
- Gluon Parton Density Function?
Life (QCD) is not quite so simple 😞
Heavy Flavour Production at HERA

- HERA (ep):
  - $p$: 920 (820) GeV
  - $e$: 27.5 GeV
- $Q^2 = -q^2 = (k-k')^2$
- $Q^2 < 1 \text{ GeV}^2$
  - Photoproduction
- $Q^2 > 1 \text{ GeV}^2$
  - DIS
Methods to tag HF:
- Reconstruct D* (or other D mesons)
- Tag semileptonic decay to e, \( \mu \)
- Use long B,D hadron lifetime
- Jet properties

Different tags probe different kinematic regions
The Theory

- QCD Leading Order + Parton Shower Monte Carlo
  - PYTHIA, RAPGAP, HERWIG, CASCADE
    - Massless & massive matrix elements for charm
    - Massive for beauty
    - Used for acceptance corrections

- QCD NLO programs
  - Weighted events
  - Do not include parton shower
  - FMNR for Photoproduction
  - HVQDIS for DIS
  - Usually compare with experiment by applying hadronic corrections from LO Monte Carlo
Luminosity & Detectors

HERA I 1996-2000
HERA II 2004-2007

Integrated luminosity on tape
~0.5 fb$^{-1}$ per experiment

Forward
$\eta = -\ln \tan \theta/2 > 0$
Charm Production

- HERA II data
- Two recent H1 analyses using new Fast Track Trigger
  - Photoproduction
    - 93 pb$^{-1}$ (2006/7)
  - DIS at low $Q^2$
    - 247 pb$^{-1}$ (2004-7)

“Golden” Decay of $D^*$

$D^{*-} \rightarrow \bar{D}^0 \pi^- \rightarrow K^+ \pi^- \pi^-$
Charm Production

- Earlier ZEUS measurements include very low $Q^2$
- Single function to describe $\gamma p$ cross-section over full $Q^2$ range

HVQDIS describes data over 5 orders of magnitude cross-section variation.
Charm Production

- **Photoproduction:**
  - $Q^2 < 2 \text{ GeV}^2$

- **DIS:**
  - $Q^2 > 5 \text{ GeV}^2$

\[ D^{*-} \rightarrow \bar{D}^0 \pi^- \rightarrow K^+ \pi^- \pi^- \]
Charm Production

- Cross-section as a function of
  - $Q^2$
  - $P_T$, $\eta$ of $D^*$
- Photoproduction:
  - $W$ ($\gamma p$ CM energy)
- DIS
  - $y$ (inelasticity)
- Compared to MC and NLO predictions

Different PDFs show very similar $Q^2$ behaviour

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Charm in DIS

- **Compare with MC**
  - Significant changes for different PDFs
  - Cascade agrees very well with data

- **Compare with NLO**
  - Data overshoot prediction at large $\eta$
  - Some sensitivity to gluon: MRST vs CTEQ
**Charm in Photoproduction**

- **Compare with MC**
  - **D* in Photoproduction**
  - **H1 Preliminary HERA II**
  - **MC scaled by**
    - $\frac{d\sigma}{d\eta}$
    - $\frac{d\sigma}{d\eta}$

  - **Data overshoot prediction at large $\eta$**

  - **Significant changes for different MCs**
    - Pythia with massless charm agrees very well with data

- **Compare with NLO**
  - **D* in Photoproduction**
  - **H1 Preliminary HERA II**
  - **MC scaled by**
    - $\frac{d\sigma}{d\eta}$
    - $\frac{d\sigma}{d\eta}$

  - **Data overshoot prediction at large $\eta$**

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Beauty in Photoproduction

- HERA II data
  - 124 pb\(^{-1}\) (2005)
- Photoproduction
- Dijet events
  - \(P_T^{\text{jet}} > 7(6)\) GeV
- Semileptonic decays to muons (\(p_T^{\mu} > 2.5\) GeV)
- Include lifetime information
Beauty in Photoproduction

- $p_T^{\text{rel}}$

- Impact parameter

![Diagram showing Beauty in Photoproduction with $p_T^{\text{rel}}$ and impact parameter](image-url)
Beauty in Photoproduction

\[ \sigma_{\text{vis}} = 46.8 \pm 4.0 \text{ (stat.)}^{+6.1}_{-7.2} \text{ (syst.)} \text{ pb} \]

\[ \sigma_{\text{NLO}} = 41.5^{+13.9}_{-8.9} \text{ pb} \]

Renormalisation/factorisation scales

Renormalisation/factorisation scales

Good agreement between HERA I and HERA II cross-sections

\[ P_T^\mu > 2.5 \text{ GeV} \]
b & c in Photoproduction

- HERA I data
  - 120 pb\(^{-1}\) (1996-2000)
- Dijet photoproduction events
  - \(E_T^{\text{jet}} > 7(6)\) GeV
- Semileptonic decays to electrons (\(p_T^e > 0.9\) GeV)
- Look for more variables to determine b and c quark fractions separately
b & c in Photoproduction

- Use a likelihood ratio method to separate b, c and light flavour

- Visible cross-section

![Graph showing the visible cross-section for b and c in Photoproduction](attachment:graph.png)
b & c in Photoproduction

- LO Monte Carlo scale factors:
  - $b \times 1.75$
  - $c \times 1.28$
- NLO absolute predictions

$P_T^e > 0.9$ GeV
**b\bar{b} Production**

- Double tag events
  - Low background 😊
  - Larger kinematic range 😊
  - Low statistics 😞
- \(E_T > 8\) GeV
- Two identified muons
- PhP + DIS
- Measure b\bar{b} correlations
  - Probe NLO effects
b\bar{b} Production

- $\Delta \phi$ between muons from different quarks
- Correlations reasonably well described

$m_{\mu\mu} > 4$ GeV
Summary of b Photoproduction

No sign of large excess seen in first b production measurements

Plot actually shows ratio of measurement to FMNR prediction

$Q^2<1\text{GeV}^2$, $0.2<y<0.8$, $|\eta^b|<2$
- HERA II data
- 54 pb$^{-1}$ (2006)
- DIS
  - $Q^2 > 12$ GeV$^2$
- Use lifetime information
b & c in DIS

- **Significance:** \( \delta / \sigma_\delta \)
  - \( S_1 \) highest
  - \( S_2 \) 2\(^{nd} \) highest

- **Subtracted significance**

**Measurement of \( F_2^{c\bar{c}} \) and \( F_2^{b\bar{b}} \)**

- H1 Data (Prel.)
- Total MC
- uds
- c
- b

Reject events when \( S_1 \) and \( S_2 \) have opposite sign

**Measurement of \( F_2^{c\bar{c}} \) and \( F_2^{b\bar{b}} \)**

- H1 Data (Prel.)
- Total MC
- uds
- c
- b

Dominated by charm

More beauty at high significance
Split data into $Q^2 - x$ (Bjorken) bins

Extract $F_2$ from reduced cross-sections:

$$\bar{\sigma}^{c\bar{c}}(x, Q^2) = F_2^{c\bar{c}} - \frac{y^2}{(1 + (1 - y)^2)} F_L^{c\bar{c}}$$

Combine HERA I & HERA II measurements
b & c in DIS
Conclusions

- Small selection of HERA heavy flavour measurements presented:
  - D* production
  - Beauty production via semileptonic decays to e,\(\mu\)
  - Double \(\mu\) tags
  - \(F_{2}^{cc}, F_{2}^{bb}\)
- General agreement with NLO QCD predictions
- LO Monte Carlos usually describe shape well
- Data often overshoot predictions in forward direction

MC@NLO for HERA?
Outlook

- Several HERA I measurements still to be published
- Expand kinematic region:
  - Double tags
  - Semileptonic decays to electrons
  - Lifetime tags
  - Combine tags
- Go forward! (sensitivity to gluon PDF)
  - Use improved HERA II forward tracking
- Many results with complete HERA II dataset still to come
Backup
dE/dx in ZEUS
b & c in Photoproduction

- Electron identification variables

Graphs showing distributions in arbitrary units for different processes:

- $b \rightarrow e X$
- $c \rightarrow e X$
- Bkg
b & c in Photoproduction

- LO Monte Carlo scale factors:
  - b x 1.75
  - c x 1.28
- NLO absolute predictions
b\bar{b} Production

- Split into different charge combinations
- Also use $\mu\mu$ invariant mass to separate signal and background
- Most of background can be estimated from the data
Significance (1 track events)

Significance (2\textsuperscript{nd} highest significance track)

Reject events when $S_1$ and $S_2$ have opposite sign
b & c in DIS

Subtracted significance distributions

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

- H1 Data (Prel.)
- Total MC
- uds
- c
- b

H1
Reduced Cross-Section

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

\[ \tilde{\sigma}^{c\bar{c}}(x, Q^2) = \tilde{\sigma}(x, Q^2) \frac{P_c N_c^{MC gen}}{P_c N_c^{MC gen} + P_b N_b^{MC gen} + P_{LF} N_{LF}^{MC gen}} \]

\[ \tilde{\sigma}^{c\bar{c}}(x, Q^2) = F_2^{c\bar{c}} - \frac{y^2}{(1+(1-y)^2)} F_L^{c\bar{c}} \]