Heavy Flavours in High Energy $ep$ Collisions

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on behalf of the H1 and ZEUS collaborations

XXXV International Symposium on Multiparticle Dynamics
Kroměříž, Czech Republic
August 2005
1 Introduction

2 Charm production

3 Beauty production

4 Summary
1 Introduction

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Colliding experiments at HERA

<table>
<thead>
<tr>
<th></th>
<th>$E_e$</th>
<th>$E_p$</th>
<th>$\sqrt{s}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>94-98</td>
<td>27.5 GeV</td>
<td>820 GeV</td>
<td>300 GeV</td>
</tr>
<tr>
<td>99-</td>
<td>27.5 GeV</td>
<td>920 GeV</td>
<td>318 GeV</td>
</tr>
</tbody>
</table>

$e^\pm \to p$  

$Q^2$ exchanged boson virtuality

$x$ proton’s fractional momentum carried by struck parton

0 $\xrightarrow{\text{photoproduction}(\gamma p)}$ $Q^2(\sim 1 \text{GeV}^2)$ $\xrightarrow{\text{deep inelastic scattering}(DIS)}$ $\infty$
Heavy flavours in QCD

Factorisation: Parton densities $\otimes$ pQCD $\otimes$ Fragmentation

\[ e(k) \rightarrow e(k') \]

$\gamma^* (-Q^2)$

\[ p(P) \rightarrow \phi_{q/p}(\xi P) \]

$\hat{\sigma}$: Partonic cross section

Hard scales: $m_{c,b}, p_T, Q^2$

$D_{H/h}$: fragmentation function of quark $h$ to hadron $H$

$z$: fractional momentum of $H$ relative to $h$

$\phi_{q/p}$: probability density of finding parton $q$ in proton, carrying momentum $\xi P$
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Previous measurements of inclusive charm production have shown general agreement with NLO QCD predictions.

Recent measurements:
- Exclusive $charm + jet$ photoproduction to understand photon’s hadronic behaviour
- Charm production in DIS to constrain gluon density in the proton
- Charmed hadrons production to confirm charm fragmentation universality
$D^* + jet$ photoproduction

- $Q^2 < 1 \text{ GeV}^2$
- $130 < W < 280 \text{ GeV}$
- $p_T^{D^*} > 3 \text{ GeV}$
- $|\eta^{D^*}| < 1.5$
- $E_T^{jet} > 6 \text{ GeV}$
- $-1.5 < \eta^{jet} < 2.4$

- Consistent with NLO massive and massless calculations
- No excess in the forward direction
**Dijet correlation**

\[ \Delta \phi_{jj} \rightarrow \text{sensitive to higher-order topologies} \]

**ZEUS**

\[ \frac{d\sigma}{d\Delta \phi_{jj}}(e^+e^- \rightarrow e^+D^*+jj+X) \text{ (nb/rad.)} \]

- \( x_T^{obs}>0.75 \)
- \( x_T^{obs}<0.75 \)

**Jet energy scale uncertainty**

\[ E_T^{jet_1} > 7 \text{ GeV} \quad E_T^{jet_2} > 6 \text{ GeV} \]

\[ x_{\gamma}^{obs} = \sum_{i=1,2} \frac{E_T^{jet_i} e^{\eta^{jet_i}}}{2yE_e} \]

**NEEDS:**
higher-order calculations or additional parton showers in current NLO calculations!
Jet shape in charm + dijet photoproduction

Tag charm jet by muon and look at the other jet

\[ \psi(r) \equiv \frac{p_T^{\text{jet}}(r' < r)}{p_T^{\text{jet}}(r' < R)} \]

\[ \langle \psi(r) \rangle = \frac{\sum_{\text{jets}} \psi(r)}{N_{\text{jets}}} \]

PYTHIA:
- excitation \( \sim 35\% \)
- proton: CTEQ5L
- photon: GRV-LO

DATA: fewer gluon jets at low \( x_\gamma \)
Exploiting low $Q^2$ region

$\frac{d\sigma}{dQ^2}$ (nb/GeV$^2$)

- ZEUS DIS BPC D* (prel.) 98-00
- ZEUS DIS D* 98-00
- HVQDIS, $M_c=1.35$ GeV, ZEUS NLO pdf fit

$0.05 < Q^2 < 0.7$ GeV$^2$

$0.02 < y < 0.085$

$p_T^{D*} > 1.5$ GeV

$|\eta^{D*}| < 1.5$

NLO QCD: well over 4 orders of magnitude in $Q^2$
First charm result from HERA II

<table>
<thead>
<tr>
<th>Year</th>
<th>$L/(\text{pb}^{-1})$</th>
<th>$e^-p$</th>
<th>$e^+p$</th>
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</thead>
<tbody>
<tr>
<td>98-00</td>
<td>17</td>
<td>65</td>
<td></td>
</tr>
<tr>
<td>03-05</td>
<td>33</td>
<td>40</td>
<td></td>
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</table>

$5 < Q^2 < 1000 \text{ GeV}^2$
$0.02 < y < 0.7$
$1.5 < p_T^{D^*} < 15 \text{ GeV}$
$|\eta^{D^*}| < 1.5$

\[ \frac{\sigma(e^-p \rightarrow e^-D^*X)}{\sigma(e^+p \rightarrow e^+D^*X)} \]

excess in the previous measurement NOT confirmed
Probing gluon density in the proton

ZEUS

HERA, D* in DIS

\[ \frac{d\sigma}{dp_T}(D^*) \text{ (nb/GeV)} \]

\[ \frac{d\sigma}{d\eta}(D^*) \text{ (nb)} \]

- ZEUS 98-00
- HVQDIS \( m_c = 1.35 \text{ GeV} \)
- ZEUS NLO QCD fit
- HVQDIS \( m_c = 1.3 \text{ GeV} \)
- CTEQ5F3
- HVQDIS \( m_c = 1.35 \text{ GeV} \)
- ZEUS + AROMA

\[ \frac{\sigma}{\sigma(\text{theory})} \]

- H1 (prel.) 99-00
- ZEUS 98-00
- HVQDIS \( m_c = 1.35 \text{ GeV} \)
- ZEUS NLO QCD fit
- HVQDIS \( m_c = 1.3 \text{ GeV} \)
- CTEQ5F3

\[ p_T(D^*) \text{ (GeV)} \]

\[ \eta(D^*) \]

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Precise measurements of $F_2^{c\bar{c}}$ at HERA
Charm fragmentation function

Spectra similar in shape despite different definitions
Charm fragmentation ratios and fractions

\[ R_{u/d} = \frac{c\bar{u}}{c\bar{d}} \approx 1 \Rightarrow \text{isospin invariance} \]

\[ \gamma_s = \frac{2c\bar{s}}{c\bar{d}+c\bar{u}} \approx \frac{1}{4} \Rightarrow s \text{ suppression} \]

\[ P_V = \frac{V}{V+PS} \neq \frac{3}{4} \Rightarrow \text{NOT naïve spin counting} \]

Consistent with fragmentation universality

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$m_b > m_c$: pQCD calculations more reliable

But, suppression $\Rightarrow \sigma_{uds} : \sigma_c : \sigma_b \sim 2000 : 200 : 1$

Anyway, beauty “puzzle” seems to be over...
Beauty photoproduction: $\mu + dijet$

**NLO: describing data well**

**H1: excess at low $p_T^\mu$**
Introduction Charm Beauty Summary

Production $F_2^{bb}$ Latest

Beauty production in DIS: $\mu + \text{jet}$

- H1 and ZEUS: good agreement
- NLO: describing DATA well except at low $p_T^\mu$ and high $\eta^\mu$

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Total beauty production

Excess confirmed by integrated cross section measurements

H1 D*µ
σ_{vis}(ep \rightarrow bb \rightarrow D*µX)
Q^2<1GeV^2, 0.05<y<0.75
p_µ>2GeV, p_(D*)>1.5GeV

ZEUS (prel.) D*µ
σ(ep \rightarrow b or bX)
Q^2<1GeV^2, rap.ζ<1, 0.05<y<0.85

ZEUS (prel.) D*µ
σ(ep \rightarrow b or bX)
Q^2>2GeV^2, rap.ζ<1, 0.05<y<0.7

ZEUS (prel.) µµ
σ_{tot}(ep \rightarrow bbX)

NLO (FNMR+HVQDIS): too small?
First measurement of $F_{2}^{b\bar{b}}$

Inclusive impact parameters ($\delta$) of tracks

Two VFNS NLOs and one NNLO reasonably describing data
Heavy flavour contributions to $ep$ cross section

Charm: increasing slightly with $Q^2$, roughly 24% on average

Beauty: increasing rapidly with $Q^2$, 0.4% at $Q^2 = 12\ GeV^2$
3% at $Q^2 > 150\ GeV^2$

NLO QCD predictions of MRST describing data reasonably well
... many new points — large excess of early measurements NOT confirmed,
although NLO calculation still consistently below data.
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Some recent heavy flavour measurements at HERA were reviewed. NLO calculations are in general agreement with the data. There are still problematic regions at small $Q^2$ and $p_T$, and in the forward direction. Improved models needed!

Outlook — HERA II results!
- Higher luminosity
- Improved detector