Recent results on heavy flavour production at HERA

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on behalf of the H1 and ZEUS collaborations

OUTLINE:

• Heavy flavour production at HERA
• Charm data combination —> charm mass running
• New charm measurements —> new charm data combination
• Beauty measurement —> beauty mass running
• Summary
HERA ep collider (1992-2007) @ DESY

- **HERA**
  - unique lepton-proton collider
  - Operational:
    - 1992-2000 (HERA I)
    - 2003-2007 (HERA II)
  - Ep=460-920 GeV, Ee = 27.6GeV

- **H1 and ZEUS** collected 0.5/fb per experiment

- **Rich Physics Program:**
  - proton structure, EW, QCD, diffraction, BSM searches,…

Kinematic variables

- \( Q^2 = -q^2 = -(k-k')^2 \)  
- \( x = \frac{Q^2}{2p \cdot q} \)  
- \( y = \frac{p \cdot q}{p \cdot k} \)  
  - Photon virtuality
  - Bjorken variable
  - Inelasticity

Two kinematic regimes:

- **Photo-production (PHP):** \( Q^2 < 1 \text{ GeV}^2 \)
- **Deep Inelastic Scattering (DIS):** \( Q^2 > 1 \text{ GeV}^2 \)
Why measure heavy flavour production?

- Heavy Flavour (HF) production: multi-hard scales pose a challenge for pQCD
  - $m_c$, $m_b$, $p_T$, $Q^2$ —> several calculations (schemes) exist
    - Zero-Mass Variable Flavour Number Scheme (ZMVFNS) — massless scheme
    - Fixed Flavour Number Scheme (FFNS) — massive scheme
    - General-Mass Variable Flavour Number Scheme (GM-VFNS) — matched scheme

- HF production cross section factorise as: $\sigma^{HQ} = \text{PDF} \otimes \text{ME} \otimes \text{FF}$

- Measurements of heavy quarks:
  - are sensitive to the gluon PDF
  - are sensitive to the masses of the heavy quarks
  - are sensitive to the fragmentation process of heavy flavour hadrons

- Measurements allow for tests of pQCD:
  - QCD LO + Parton shower Monte Carlo generators:
    - Collinear factorisation, DGLAP evolution (PYTHIA, RAPGAP)
    - kT factorisation, CCFM evolution (CASCADE)
  - QCD NLO calculations

Main process of heavy quark production at HERA is Boson Gluon Fusion
Tagging methods for heavy flavours @ HERA

- Rates at HERA:
  - in PHP regime $\sigma(b) : \sigma(c) \approx O(0.05\%) : O(1\%)$ of $\sigma_{TOT}$
  - in DIS regime $\sigma(b) : \sigma(c) \approx O(1\%) : O(20\%)$ of $\sigma_{TOT}$

- Charm and Beauty Tagging methods:
  - Full reconstruction:
    - yields best signal-to-background ratio for charm production
    - small BR, phase space of charm production is restricted as all products from decay must be measured.
  - Lepton tagging: Use semi-leptonic b/c decay channels
    - profits from high BR$(c,b \rightarrow \text{lepton} + \text{anything})$
    - worse signal-to-background ratio
  - Inclusive life-time info:
    - has the largest phase space coverage
      - life-time tagging: b/c quarks have long lifetimes
      - secondary vertex mass tagging: large masses

Heavy flavour measurements at HERA using different experimental techniques provide complementary handle of systematic uncertainties
HERA Charm Data Combination

- Best precision achieved when measurements are combined:
  - Charm Data Combination: $\chi^2/\text{ndof} = 62/103$
  - 155 data points from 9 different measurements of H1 and ZEUS were combined into 52 points
  - efforts in accounting for correlations of systematic uncertainties between data sets

<table>
<thead>
<tr>
<th>Data Set</th>
<th>Period</th>
<th>Reconstruction</th>
<th>$Q^2$ [GeV$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) H1 Vertex</td>
<td>HERA I + II</td>
<td>displaced vtx</td>
<td>5–2000</td>
</tr>
<tr>
<td>2) H1 $D^*$</td>
<td>HERA I</td>
<td>$D^*$ decay</td>
<td>2–100</td>
</tr>
<tr>
<td>3) H1 $D^*$</td>
<td>HERA II</td>
<td>$D^*$ decay</td>
<td>5–100</td>
</tr>
<tr>
<td>4) H1 $D^*$</td>
<td>HERA II</td>
<td>$D^*$ decay</td>
<td>100–1000</td>
</tr>
<tr>
<td>5) ZEUS $D^*$</td>
<td>96–97</td>
<td>$D^*$ decay</td>
<td>1–200</td>
</tr>
<tr>
<td>6) ZEUS $D^*$</td>
<td>98–00</td>
<td>$D^*$ decay</td>
<td>1.5–1000</td>
</tr>
<tr>
<td>7) ZEUS $D^0$</td>
<td>2005</td>
<td>$D^0$ decay</td>
<td>5–1000</td>
</tr>
<tr>
<td>8) ZEUS $D^+$</td>
<td>2005</td>
<td>$D^0$ decay</td>
<td>5–10000</td>
</tr>
<tr>
<td>9) ZEUS $\mu$</td>
<td>2005</td>
<td>semileptonic</td>
<td>20–10000</td>
</tr>
</tbody>
</table>

- Data combination is performed at the reduced charm cross sections level (as in DIS):
  - they are obtained from xsec in visible phase space and extrapolated to full space

\[
\frac{d^2\sigma^{\text{ee}}}{dx\,dQ^2} = \frac{2\pi\alpha_e^2}{x\,Q^4} Y_+ \sigma^{\text{red}}_{\text{xe}}(x, Q^2, s) \\
\sigma^{\text{ee}}_{\text{red}}(x, Q^2, s) = F_2^{\text{e}}(x, Q^2) - \frac{y^2}{Y_+} F_L^{\text{e}}(x, Q^2) \\
\sigma^{\text{ee}}_{\text{red}, \text{HVQDIS}}(x, Q^2) = \left(\sigma_{\text{vis}} - \sigma_{\text{vis}}^{\text{beauty}}\right) \frac{\sigma^{\text{ee}}_{\text{red}, \text{HVQDIS}}}{\sigma_{\text{vis}, \text{HVQDIS}}} 
\]
HERA Charm Data Combination

- Best precision achieved when measurements are combined:
  - Charm Data Combination: chi2/ndof = 62/103
  - 155 data points from 9 different measurements of H1 and ZEUS were combined into 52 points
  - Efforts in accounting for correlations of systematic uncertainties between data sets
Impact of the Charm Measurements

- Combined data well described by the theory predictions when $M_c$ is taken at its optimal value
- The combined charm data used in NLO QCD fits

**QCD Fits**

**HERA I+charm**

Different calculation schemes prefer different $M_c$

Measurements help reduce uncertainties of predictions for the LHC
Running charm mass $m_c(m_c)$

- Charm combination can also be used in a NLO QCD analysis in FFN scheme to determine the running of charm-quark mass $m_c(m_c)$ in $\overline{\text{MS}}$:

$$m_c(m_c) = 1.26 \pm 0.05_{\text{exp}} \pm 0.03_{\text{mod}} \pm 0.02_{\text{param}} \pm 0.02_{\alpha_s} \text{ GeV}$$

- which is in agreement with the world average extraction:

$$m_c(m_c) = 1.275 \pm 0.025 \text{ GeV}$$

- This has triggered the question:

$\rightarrow$ how about measuring the running of $m_c$?
The running of the charm mass in the $\overline{\text{MS}}$ scheme is measured for the first time from the same HERA combined charm data:

- Extract $m_c(m_c)$ in 6 separate kinematic regions
- Translate back to $m_c(\mu)$ [with $\mu = \sqrt{Q^2 + 4m_c^2}$] using OpenQCDrad [S. Alekhin’s code].

The scale dependence of the mass is consistent with QCD expectations.
Recent charm measurements: $D^*$ in DIS

- The most precise charm DIS measurement from ZEUS from final HERA II data

- Well described by massive NLO QCD predictions.

- The $D^*$ measurements from H1 and ZEUS are combined at the differential level


Precise measurements that can be compared directly to QCD predictions without the need of extrapolations corrections
**D* Combination**

- Good agreement is observed between the H1 and ZEUS measurements —>

- Measurements are compared to NLO QCD theory predictions
  - good agreement is found theory calculations
  - scale variation is dominant uncertainty on predictions
**D* Measurement in photo-production**

- Measurement of D* photo-production at different centre-of-mass energies at HERA
  - $\sqrt{s} = 318$ (HER), 251 (MER) and 225 (LER) GeV
  - D* visible photo-production measurements normalised to the high-statistics measurement at $\sqrt{s} = 318$.

- The cross sections for the MER and LER sample are significantly smaller than the cross section for the HER data.
- The NLO QCD predictions well describe measured energy dependence.
New Charm measurements from LifeTime-Tagging (vtx)

- Independent from D* data: D^+ and secondary vertices + lifetime tag:
- New measurement in the kinematic span of $5 < Q^2 < 1000$ GeV^2 and L=354/pb
  - exploiting the long lifetimes of the weakly decaying b and c hadrons and their large masses
  - The single differential cross sections were obtained vs of $E_T^{\text{jet}}$, $\eta^{\text{jet}}$, $Q^2$ and $x$
- The measurements are compared to HVQDIS NLO QCD and RAPGAP predictions

Good description of the data by the massive NLO QCD predictions.
Charm data from D+, D*, second. vertex comparison

- The new data are precise and independent from the previous combination.
- The new measurements are in agreement with previous measurements at HERA.

\[
\frac{d \sigma^{c\bar{c}}}{dx dq^2} = \frac{2 \pi \alpha^2}{x Q^4} \left[ 1 + (1 - y)^2 \right] \sigma_{\text{red}}^{c\bar{c}}
\]
New Beauty in DIS from LifeTime-Tagging

- New measurement in the kinematic span of $5 < Q^2 < 1000 \text{GeV}^2$ and $L=354/pb$
  - exploiting the long lifetimes of the weakly decaying $b$ and $c$ hadrons and their large masses
  - measurement was not restricted to any particular final state → substantially increased statistics
  - Differential cross sections as functions of $E_T^{\text{jet}}$, $\eta^{\text{jet}}$, $Q^2$ and $x$ were determined.

- beauty enriched sample

Good description of the data by the massive NLO QCD predictions.
New Beauty in DIS from LifeTime-Tagging

- Inclusive jet cross sections in beauty and charm events are used to:
  - The good agreement of the data and NLO calculations in the visible phase (given by the heavy quark tagging) allow to extrapolate to the full phase space and to measure $F_2^{bb}$ (and identical $F_2^{cc}$):

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

- The new measurement is the most precise determination of $F_2^b$ from ZEUS
- Data are in good agreement and well described by fixed-order (massive) and variable-flavour (mixed) NLO and NNLO QCD calculations
Running beauty mass \( m_b(m_b) \)

- The value of the running beauty mass is obtained in a similar manner as for \( m_c(m_c) \):
  - chi2 scan method from QCD fits in FFN scheme to the combined HERA I inclusive data + beauty measurements, beauty-quark mass is defined in the MS scheme.

The extracted MS beauty-quark mass is in agreement with PDG average and LEP results.
Summary

- Most HERA DIS charm data were combined:
  - consistent data sets extracted using different methods
  - data are well described by QCD predictions
  - running charm mass determined: \( m_c(m_c) = 1.26 \pm 0.06 \) GeV

- First measurement of the charm-mass running.

- New charm measurements for D* are combined at the visible phase space level
  - awaiting for theory improvements

- New measurement in photo-production exploiting different centre of mass energy.

- New beauty-jet measurement + lifetime tagging in DIS by ZEUS:
  - one of the most precise beauty measurements at HERA
  - beauty mass measured: \( m_b(m_b) = 4.07 \pm 0.17 \) GeV.

Thank you!
Extra Material
Why measure heavy flavour production?

Multi-hard scales: a challenge for pQCD

- $m_c, m_b, p_T, Q^2 \rightarrow$ several calculations (schemes) exist
  - Zero-Mass Variable Flavour Number Scheme (ZMVFNs) — massless scheme
    - all flavours massless
    - valid at $Q^2 >> m_c^2, m_b^2$
  - Fixed Flavour Number Scheme (FFNS) — massive scheme
    - heavy quark produced perturbatively
  - General-Mass Variable Flavour Number Scheme (GM-VFNs)
    - matched scheme across the heavy quark thresholds
      $\rightarrow$ heavy quarks masses more a tuning parameter.
    - different variants exists (as used in global PDFs: Thorne-Roberts, ACOT, FONLL)
$F_2^{bb}$ and $F_2^{cc}$ contributions to the proton structure function $F_2$

- $F_2$ structure function of the proton:
  
  \[
  \frac{d^2 \sigma}{dx \, dQ^2} = \frac{2\pi \alpha^2}{x \, Q^4} \left[ (1 + (1-y)^2) F_2 - y^2 F_L \right]
  \]

- $F_2^{cc}$ structure function of the proton:
  (identical for $F_2^{bb}$)

  \[
  \frac{d^2 \sigma^{ep}}{dx \, dQ^2} = \frac{2\pi \alpha^2}{x \, Q^4} \left[ (1 + (1-y)^2) F_2^{cc} - y^2 F_L^{cc} \right]
  \]

- The good agreement of the data and NLO calculations in the visible phase (given by the heavy quark tagging) allow to extrapolate to the full phase space and to measure $F_2^{cc}$ (and identical $F_2^{bb}$):

  \[
  F_2^{cc, \text{meas}}(x, Q^2) = \sigma_{\text{vis. \, bin}}^{\text{meas}} \frac{F_2^{cc, \text{model}}(x, Q^2)}{\sigma_{\text{vis. \, bin}}^{\text{model}}}
  \]
Charm Fragmentation Fractions

- $f(c \rightarrow D^0)$
- $f(c \rightarrow D^+)$
- $f(c \rightarrow D^{++})$
- $f(c \rightarrow D_s)$
- $f(c \rightarrow \Lambda_c)$

ZEUS-prel-12-003

- Charm fragmentation universality confirmed.
Running of heavy quark masses

• Quark mass running depends on $\alpha_s$:
  
  - leading order QCD formulae:
  - $m_c(pole) = m_c(mc) \left(1 + \frac{4}{3} \frac{\alpha_s}{\pi}\right) = m_c(Q) \left(1 + \frac{\alpha_s}{\pi} \left(\frac{4}{3} + \ln\left(\frac{Q^2}{m_c^2}\right)\right)\right)$

• Charm mass running not explicitly measured (so far)
Figure 1: Distributions of the decay-length significance, \( S \), for (a) \( 1 < m_{vtx} < 1.4 \text{ GeV} \), (b) \( 1.4 < m_{vtx} < 2 \text{ GeV} \), (c) \( 2 < m_{vtx} < 6 \text{ GeV} \) and (d) no restriction on \( m_{vtx} \). The data are compared to the sum of all MC distributions as well as the individual contributions from the beauty, charm and light-flavour (LF) MC subsamples. All samples were normalised.