Heavy flavour production at HERA

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On behalf of the H1 and ZEUS collaborations

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Outline

- Introduction
- Charm combination
- Charm quark mass measurement
- Beauty production and beauty quark mass measurement
- Recent charm measurements and combination of D* production results
- Summary
The HERA $ep$ collisions experiments

- HERA accelerator is unique lepton-proton collider
- Was in operation 1992-2007
- $e^\pm$ and $p$ were brought to collision with $E_p=460-920$ GeV (period dependent) and $E_e = 27.6$ GeV

- H1 and ZEUS detectors
- H1 and ZEUS experiments collected 0.5 $fb^{-1}$ per experiment
Deep Inelastic Scattering diagram.

$Q^2 = -(k - k')^2$ – photon virtuality,

$x = \frac{Q^2}{2P \cdot (k - k')}$ – Bjorken $x$

$y = \frac{P \cdot (k - k')}{P \cdot k}$ – inelasticity

Deep Inelastic Scattering

$Q^2 > 1 \text{GeV}^2$ : DIS;
At HERA heavy quarks mainly produced by boson-gluon fusion (sensitive to the gluon density in the proton)

Process involves multiple hard scales \(m_q, p_t, Q^2\) that results in different approaches to heavy flavours in QCD

Contribution to total DIS cross section – charm up to 30% and beauty up to 3%.
Charm tagging techniques
Reduced cross section definition

Relation between heavy quarks production cross-section and reduced cross-section is the following:

\[
\frac{d\sigma^{q\bar{q}}(e^\pm p)}{dx dQ^2} = \frac{2 \pi \alpha^2}{x Q^4} \left[ 1 + (1 - y)^2 \right] \sigma^{q\bar{q}}_{\text{red}}(Q^2, x)
\]

The heavy quarks measurements are presented in terms of the reduced cross sections that in Neutral Current DIS can be written in term of two structure functions:

\[
\sigma^{q\bar{q}}_{\text{red}} = F_2^{q\bar{q}} - \frac{y^2}{1 + (1 - y)^2} F_L^{q\bar{q}}
\]

Most measurements are actually measuring visible cross sections with restricted phase space. The extrapolation to full phase space is required using theory (e.g., momentum of D* meson):

\[
\sigma^{q\bar{q}}_{\text{red}}(x, Q^2) = \sigma^{q\bar{q}}_{\text{vis}, \text{bin}} \frac{\sigma^{q\bar{q}, \text{th}}_{\text{red}}(x, Q^2)}{\sigma^{q\bar{q}, \text{th}}_{\text{vis}, \text{bin}}}
\]
155 data points from 9 different measurements were combined to 52 points.
HERA Charm Data combination : Results

With precision about 6% at medium $Q^2$
Different Heavy Quark Schemes

Heavy Quark Scheme in QCD Analysis defines treatment of heavy flavours in perturbative expansion.

- Zero Mass Variable Flavours Number Scheme (ZMVFMS): all flavours are massless. Fails near $Q^2 = m_{HQ}^2$
- Fixed Flavour Number Scheme (FFNS) (ABM): heavy quarks are massive, produced in processes equivalent to boson-gluon fusion.
- Generalized Mass VFNS (CTEQ, MSTW, HERAPDF): number of active flavours depends on $Q^2$, matching at switching points different for different PDF groups implementations.

Heavy flavours treatment and quarks masses are crucial for QCD analysis.
Good agreement with data

HERAPDF1.5 obtained with DIS inclusive data only in RT (VFNS) heavy flavour scheme

Error band mostly corresponds to $M_c$ variation from 1.35 to 1.6 GeV (central value 1.4 GeV) -> data may be used to determine $M_c$
Testing different heavy quarks schemes: $m_c$ scan

Adding charm data to HERA inclusive data gives sensitivity to $M_c$ parameter.

Optimal $M_c$ can be measured with uncertainties determined using $\Delta \chi^2 = 1$
Due to multiple scale problems there are different heavy flavours schemes. They have significant different predictions with given $M_c$ value for example for $W^\pm$, $Z$ production at LHC. (difference due to scheme about 7% !)
Testing different heavy quarks schemes: motivation

- **Optimal** $M_c$ value is different for different schemes.
- Uncertainties on W and Z production due to the charm mass using optimal $M_c$ reduced to 1%
Charm data reduces uncertainty on gluon and light sea due to better constrained charm-quark mass.
Good description of data for both NLO and NNLO variants

Using $\bar{\mathcal{M}}S$ mass definition

Allows to determine $m_c(m_c)$
Charm mass measurement

- FFNS gives possibility to determine running charm mass $m_c(m_c)$ in $\bar{MS}$
- Result:

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

in good agreement with the world average:

$$m_c(m_c)_{PDG} = 1.275 \pm 0.025 \text{ GeV}$$
The running of the charm mass in $\bar{\tilde{M}}S$ scheme is measured for the first time, found to be consistent with expectations from QCD.
$F_2^{b\bar{b}}$ structure function (arXiv:1405.6915v1)

- $5 < Q^2 < 1000$ GeV$^2$
- $1.5 \times 10^{-4} < x < 0.035$

At least 1 jet with invariant mass of charged tracks associated with secondary vertices and decay-length significance.
NLO FFNS fit used to extract the b quark mass in $\overline{\text{MS}}$ scheme

ZEUS: $m_b(m_b) = 4.07 \pm 0.14 \, ^{+0.01}_{-0.07} \, \text{(mod.)} \, ^{+0.05}_{-0.00} \, \text{(param.)} \, ^{+0.08}_{-0.05} \, \text{(theo.)}$

PDG: $m_b(m_b) = 4.18 \pm 0.03 \, \text{GeV}$
Recent charm measurements

Two new measurements from ZEUS were published recently: $D^+$ (JHEP 05 (2013) 023) and $D^*$ (JHEP 05 (2013) 097) – good agreement with combination of HERA data.
Combined $D^*$ differential cross sections (H1prel-13-171, ZEUS-prel-13-00)

Visible cross sections from new $D^*$ measurement were combined with H1 results for single-differential and double-differential cross-sections to reduce uncertainties, especially systematics.
Recently combined H1 and ZEUS measurements of visible $D^*$ production cross-sections gives possibility to use them for fragmentation models study and further theory constraints.

Predictions were obtained in NLO QCD (HVQDIS) with Kartvelischwili fragmentation using HERAPDF 1.0 FFNS.
Summary

HERA providing new heavy flavour results using all measured data to test QCD and constraint it

- Optimal charm mass parameter in PDF for different VFNS determined, improves predictions of $W^\pm$ and $Z$ cross sections at the LHC
- Charm data reduces uncertainties on gluon and sea quarks PDFs
- Running mass of charm quark in $\bar{MS}$ determined in FFNS at NLO, in good agreement with PDG world average
- Consistency check of charm quark mass running performed
- New precise measurements of beauty production in DIS with high statistics using secondary vertices. Measured b quark mass in $\bar{MS}$ scheme showed good agreement with PDG value
- Differential cross sections of $D^*$ mesons at HERA combined, challenge to the theory and fragmentation models
Testing different PDFs

Having such precise combined data gives a possibility to test different available PDFs on a market.

<table>
<thead>
<tr>
<th>Theory</th>
<th>Scheme</th>
<th>Ref.</th>
<th>$F_{2(L)}$</th>
<th>$m_c$ [GeV]</th>
<th>Massive ($Q^2 \lesssim m_c^2$)</th>
<th>Massless ($Q^2 \gg m_c^2$)</th>
<th>$\alpha_s(m_Z)$ ($n_f = 5$)</th>
<th>Scale</th>
<th>Included charm data</th>
</tr>
</thead>
<tbody>
<tr>
<td>MSTW08 NLO</td>
<td>RT standard</td>
<td>[28]</td>
<td>$F_{2(L)}^c$</td>
<td>1.4 (pole)</td>
<td>$\mathcal{O}(\alpha_s^2)$ approx-$\mathcal{O}(\alpha_s^3)$</td>
<td>$\mathcal{O}(\alpha_s)$</td>
<td>0.12108</td>
<td>$Q$</td>
<td>[1, 4–6, 8, 9, 11]</td>
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<tr>
<td>MSTW08 NNLO</td>
<td>RT standard</td>
<td>[31]</td>
<td>$F_{2(L)}^c$</td>
<td>1.4 (pole)</td>
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<td>$\mathcal{O}(\alpha_s)$</td>
<td>0.11707</td>
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<tr>
<td>MSTW08 NLO (opt.)</td>
<td>RT optimised</td>
<td>[32]</td>
<td>$F_{2(L)}^c$</td>
<td>1.4 (pole)</td>
<td>$\mathcal{O}(\alpha_s^2)$ approx-$\mathcal{O}(\alpha_s^3)$</td>
<td>$\mathcal{O}(\alpha_s)$</td>
<td>0.12108</td>
<td>$Q$</td>
<td></td>
</tr>
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<td>HERAPDF1.5 NLO</td>
<td>RT standard</td>
<td>[55]</td>
<td>$F_{2(L)}^c$</td>
<td>1.4 (pole)</td>
<td>$\mathcal{O}(\alpha_s^2)$ approx-$\mathcal{O}(\alpha_s^3)$</td>
<td>$\mathcal{O}(\alpha_s)$</td>
<td>0.1176</td>
<td>$Q$</td>
<td>HERA inclusive DIS only</td>
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<tr>
<td>NNPDF2.1 FONLL A</td>
<td>FONLL A</td>
<td>[30]</td>
<td>$F_{2(L)}^c$</td>
<td>$\sqrt{2}$ (pole)</td>
<td>$\mathcal{O}(\alpha_s)$</td>
<td>$\mathcal{O}(\alpha_s)$</td>
<td>0.119</td>
<td>$Q$</td>
<td>[4–6, 12, 13, 15, 18]</td>
</tr>
<tr>
<td>NNPDF2.1 FONLL B</td>
<td>FONLL B</td>
<td>n.a.</td>
<td>$F_{2(L)}^c$</td>
<td>$\sqrt{2}$ (pole)</td>
<td>$\mathcal{O}(\alpha_s)$</td>
<td>$\mathcal{O}(\alpha_s)$</td>
<td>0.119</td>
<td>$Q$</td>
<td>[4–6, 12, 13, 15, 18]</td>
</tr>
<tr>
<td>NNPDF2.1 FONLL C</td>
<td>FONLL C</td>
<td>n.a.</td>
<td>$F_{2(L)}^c$</td>
<td>$\sqrt{2}$ (pole)</td>
<td>$\mathcal{O}(\alpha_s)$</td>
<td>$\mathcal{O}(\alpha_s)$</td>
<td>0.119</td>
<td>$Q$</td>
<td>[4–6, 12, 13, 15, 18]</td>
</tr>
<tr>
<td>CT10 NLO</td>
<td>S-ACOT-χ</td>
<td>[22]</td>
<td>n.a.</td>
<td>1.3 (pole)</td>
<td>$\mathcal{O}(\alpha_s)$</td>
<td>$\mathcal{O}(\alpha_s)$</td>
<td>0.118</td>
<td>$\sqrt{Q^2 + m_c^2}$</td>
<td>[4–6, 8, 9]</td>
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<tr>
<td>CT10 NNLO (prel.)</td>
<td>S-ACOT-χ</td>
<td>[56]</td>
<td>n.a.</td>
<td>1.3 (pole)</td>
<td>$\mathcal{O}(\alpha_s)$</td>
<td>$\mathcal{O}(\alpha_s)$</td>
<td>0.118</td>
<td>$\sqrt{Q^2 + m_c^2}$</td>
<td>[4–6, 8, 9]</td>
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<tr>
<td>ABKM09 NLO</td>
<td>FFNS</td>
<td>[57]</td>
<td>$F_{2(L)}^c$</td>
<td>1.18 (MS)</td>
<td>$\mathcal{O}(\alpha_s^2)$ approx-$\mathcal{O}(\alpha_s^3)$</td>
<td>-</td>
<td>0.1135</td>
<td>$\sqrt{Q^2 + 4m_c^2}$</td>
<td>for mass optimisation only</td>
</tr>
</tbody>
</table>

Available predictions differs by many parameters such as :heavy flavour scheme, perturbative order, masses, PDF assumptions, values of $\alpha_s(M_Z)$.
# HERA Charm Data combination: datasets

9 different charm reduced cross sections measurements were combined:

<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>5–1000</td>
</tr>
<tr>
<td>9) ZEUS $\mu$</td>
<td>2005</td>
<td>semileptonic</td>
<td>20–10000</td>
</tr>
</tbody>
</table>

Full references in the paper.