Charm final states at HERA

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Motivation to measure heavy flavour production

- Charm and Beauty quarks at HERA are mainly produced in Boson-Gluon-Fusion.

- Event kinematics:
  - Photon virtuality: $Q^2 = -q^2 = -(k-k')^2$
  - Inelasticity: $y = (q \cdot p) / (k \cdot p)$
  - Bjorken x: $x = Q^2 / (2 p \cdot q)$

- Two kinematic regimes:
  - Photoproduction: $Q^2 \approx 0 \text{ GeV}^2$
  - Deep Inelastic Scattering: $Q^2 > 1 \text{ GeV}^2$
    (scattered electron detected)
Motivation to measure heavy flavour production

- Heavy Flavour cross sections can be calculated via the factorisation ansatz:

\[ d\sigma = \sum_{ijk} f_j^B(x, \mu_f) \otimes d\sigma_{ij \rightarrow kX} \otimes D_k^H(\mu_f) \]

- Interpretation of heavy flavour measurements:
  - Use the pQCD calculations and constrain the gluon density of the proton.
  - Take the gluon density from elsewhere and test the consistency of the pQCD calculation.
QCD models

QCD scheme:
- Massive scheme – Fixed Flavour Number Scheme (FFNS):
  - c and b quarks generated dynamically via boson-gluon-fusion.
  - c and b quarks treated massive.
  - Expected to be valid for small scales $\mu^2 \approx m_{b,c}^2$

QCD predictions:
- QCD LO + Parton shower Monte Carlo generators:
  - Collinear factorisation, DGLAP evolution (PYTHIA).
  - $k_T$ factorisation, CCFM evolution (CASCADE).
  - Used for data corrections and model comparisons.

- QCD NLO calculations:
  - Massive scheme, NLO($\alpha_s^2$):
    - HVQDIS
  Used for comparisons and small phase space corrections.
D* combination in visible phase space in DIS

- Combination of most precise D* measurements from H1 and ZEUS within visible phase space.
- Minimal extrapolation factors to common phase space → minimal theory related uncertainties.
- Good agreement between measurements: $\chi^2$ probability between 0.15 and 0.86.
- Uncorrelated systematics and larger statistics → improved experimental precision of typically 5%.

H1-prelim-13-171, ZEUS-prel-13-002
Most precise D* measurement in DIS within visible phase-space.
NLO QCD predictions describe data well; theory uncertainties are typically larger than data precision.
D* in photoproduction at different CMS energies

- Exploit low energy runs of HERA, with reduced proton energy.
- Look at ratio of visible D* cross section $R_\sigma$ from reduced CMS energy to D* cross sections from nominal CMS energy.

Measured D* cross section increases with higher CMS energy.
- Behavior predicted by NLO QCD.

DESY-14-082, ZEUS Collaboration; to be published in JHEP
Inelastic $J/\psi$ and $\psi'$ in photoproduction

- Differential measurement of $\psi'$ to $J/\psi$ ratio.
- Differential $J/\psi$ cross sections as a function of:
  - $p_T^2$
  - Inelasticity $z$, $z = \frac{P \cdot p_{\psi}}{P \cdot q}$

- Theory comparisons to
  - non-relativistic QCD, based on CS and CO model.
  - $k_T$-factorisation + CS.

Color Singlet (CS)

$\rightarrow$ radiation of hard gluon

Color Octet (CO)

$\rightarrow$ radiation of soft gluons

$z < 0.9 \rightarrow$ no diffraction, high track multiplicity.

DESY-12-226, ZEUS Collaboration; JHEP 02 (2013) 071
Inelastic $J/\psi$ and $\psi'$ in photoproduction

- Differential $J/\psi$ cross section compared to NRQCD:
  - rough description by CS+CO predictions.

- $\psi'$ to $J/\psi$ ratio agrees to LO CS prediction:

- Very high precision of the data, compared to the uncertainties of the NLO predictions.
- Prediction in general show a reasonable agreement.
Charm fragmentation fraction

- Is the charm fragmentation fraction $f$ universal?

$f \rightarrow$ Probability of $c$-quark to hadronise into particular charm meson:

**Analysed channels:**
- $D^+ \rightarrow K^+ \pi^+ \pi^+$
- $D_s^+ \rightarrow K^+ \pi^+$
- $D_s^+ \rightarrow K^+ K^+ \pi^+$
- $\Lambda_c^+ \rightarrow pK^+ \pi^+$

**DESY-13-106,**
**ZEUS Collaboration;**
**JHEP 09 (2013) 058**

Michel Sauter
Charm fragmentation fraction

- Universality of charm fragmentation confirmed.
Excited charm mesons $D_1$ and $D_2^*$

- Exploit large samples of “D-ground states” to reconstruct excited charm states $D_1(2420)^0$, $D_2^*(2460)^0$, $D_1(2420)^+$, $D_2^*(2460)^+$.

  - Look at invariant mass distributions of
    - $M(D_1^{*+}\pi) \Rightarrow D_1^0, D_2^*$
    - $M(D^+\pi) \Rightarrow D_2^*$
    - $M(D^0\pi) \Rightarrow D_1^+, D_2^{*+}$

  - Measurement of masses, widths, angular distributions and fragmentation fractions of excited charm states.

DESY-12-144, ZEUS Collaboration; Nuclear Phys. B 866 (2013) 229-254

$D^{*+} \rightarrow K\pi\pi_S$

\begin{figure}[h!]
\centering
\includegraphics[width=0.4\textwidth]{fig1a.pdf}
\end{figure}

\begin{figure}[h!]
\centering
\includegraphics[width=0.4\textwidth]{fig1b.pdf}
\end{figure}

\begin{align*}
&\sim 90000 \ D^{*+} \\
&\sim 40000 \ D^+ \\
&\sim 150000 \ D^0
\end{align*}
Excited charm mesons $D_1$ and $D^*_2$

- **Neutral excited states:**

<table>
<thead>
<tr>
<th></th>
<th>HERA-II (this)</th>
<th>HERA-I</th>
<th>PDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M(D_1^0)$, MeV</td>
<td>2423.1 ± 1.5$^{+0.4}_{-1.0}$</td>
<td>2420.5 ± 2.1 ± 0.9</td>
<td>2421.3 ± 0.6</td>
</tr>
<tr>
<td>$\Gamma(D_1^0)$, MeV</td>
<td>38.8 ± 5.0$^{+1.9}_{-5.4}$</td>
<td>53.2 ± 7.2$^{+3.3}_{-4.9}$</td>
<td>27.1 ± 2.7</td>
</tr>
<tr>
<td>$h(D_1^0)$</td>
<td>7.8$^{+6.7+4.6}_{-2.7-1.8}$</td>
<td>5.9$^{+3.0+2.4}_{-1.7-1.0}$</td>
<td></td>
</tr>
<tr>
<td>$M(D_2^{*0})$, MeV</td>
<td>2462.5 ± 2.4$^{+1.3}_{-1.1}$</td>
<td>2469.1 ± 3.7$^{+1.2}_{-1.3}$</td>
<td>2462.6 ± 0.7</td>
</tr>
<tr>
<td>$\Gamma(D_2^{*0})$, MeV</td>
<td>46.6 ± 8.1$^{+5.9}_{-3.8}$</td>
<td>43 fixed</td>
<td>49.0 ± 1.4</td>
</tr>
<tr>
<td>$h(D_2^{*0})$</td>
<td>−1 fixed</td>
<td>−1 fixed</td>
<td></td>
</tr>
</tbody>
</table>

- **Charged excited states:**

<table>
<thead>
<tr>
<th></th>
<th>HERA-II (this)</th>
<th>PDG</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M(D_1^+)$, MeV</td>
<td>2421.9 ± 4.7$^{+3.4}_{-1.2}$</td>
<td>2423.4 ± 3.1</td>
</tr>
<tr>
<td>$\Gamma(D_1^+)$, MeV</td>
<td>25 fixed</td>
<td>25 ± 6</td>
</tr>
<tr>
<td>$h(D_1^+)$</td>
<td>3 fixed</td>
<td></td>
</tr>
<tr>
<td>$M(D_2^{*+})$, MeV</td>
<td>2460.6 ± 4.4$^{+3.6}_{-0.8}$</td>
<td>2464.4 ± 1.9</td>
</tr>
<tr>
<td>$\Gamma(D_2^{*+})$, MeV</td>
<td>37 fixed</td>
<td>37 ± 6</td>
</tr>
<tr>
<td>$h(D_2^{*+})$</td>
<td>−1 fixed</td>
<td></td>
</tr>
</tbody>
</table>

- Accurate measurement of $D_1$ and $D^*_2$ spectroscopy and fragmentation (not shown) parameters.
- All values consistent with PDG values.
Summary

- H1 and ZEUS combined D* cross sections in DIS:
  - High data precision in visible phase space (→ negligible theory uncertainty).
  - Test pQCD at various variables.

- D* cross sections rises with CMS energy, as predicted by pQCD.

- New precise measurement of inelastic J/ψ production.

- Confirmation of charm fragmentation universality.

- Spectroscopy and fragmentation parameters of excited charm states.
• “Combination of D* Differential Cross Section Measurements in Deep-Inelastic ep Scattering at HERA”
  H1-prelim-13-171, ZEUS-prel-13-002

• “Measurement of D* photoproduction at three different centre-of-mass energies at HERA”
  DESY-14-082, ZEUS Collaboration; to be published in JHEP

• “Measurement of Inelastic J/ψ and ψ' photoproduction at HERA“
  DESY-12-226, ZEUS Collaboration; H. Abramowicz et al., JHEP 02 (2013) 071

• “Measurement of Charm Fragmentation Fractions in Photoproduction at HERA”
  DESY-13-106, ZEUS Collaboration; H. Abramowicz et al., JHEP 09 (2013) 058

• “Production of the excited charm mesons D_1 and D^*_2 at HERA”
  DESY-12-144, ZEUS Collaboration; H. Abramowicz et al., Nuclear Phys. B 866 (2013) 229-254
The HERA ep collider (1992 – 2007) at DESY in Hamburg

- ep collider:
- $e^\pm$ energy: 27.6 GeV
- p energy: 920 GeV
- Centre of mass energy: 319 GeV
- 2 collider experiments: H1 and ZEUS
- Integrated luminosity: $\sim0.5$ fb$^{-1}$ (per experiment)
Tagging methods for heavy flavours at HERA

- Rates at HERA behaved like $\sigma(b) : \sigma(c) : \sigma(uds) \approx 1 : 50 : 2000$
- Charm and beauty enrichment is possible with:

1) Full reconstruction
   - Only possible for charm at HERA, e.g. $D^* \rightarrow K\pi\pi$.

2) Lepton tagging: Use semileptonic $b/c$ decay channels
   - look for $\mu$ or $e$, high BR($c, b \rightarrow $ lepton + anything)

3) $p_T^{\text{rel}}$ tagging: $b/c$ quark have large masses
   - look for decay leptons with a high transverse momentum w.r.t the $b$ quark flight direction.

4) Lifetime tagging: $b/c$ quark have long lifetimes:
   - look for displaced vertices.
   - look for tracks with large impact parameters $\delta$.

5) Secondary vertex mass tagging: long lifetime and large masses
   - look for high secondary vertex masses.