Heavy quark photoproduction at HERA

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Motivation to measure heavy flavour production

- Charm and beauty quarks at HERA are mainly produced in Photon-Gluon-Fusion → sensitive to the gluon in the proton.

- Hard scales for perturbative QCD:
  - $m_{c,b}^2$, $p_T^2$, $Q^2$
    - multi-scale problem, for example combined to
      $\mu_0 = \frac{1}{2} \sqrt{(m_{b,c}^2 + p_T^2)}$

- 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.

Two kinematic regimes:

- Photoproduction: $Q^2 \approx 0 \text{ GeV}^2$
- Deep Inelastic Scattering: $Q^2 > 1 \text{ GeV}^2$
  (scattered electron detected)
**QCD schemes:**

- 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 factorization, DGLAP evolution (PYTHIA).
  - $k_T$ factorization, CCFM evolution (CASCADE).
  - Used for data corrections and model comparisons.

- QCD NLO calculations:
  - Massive scheme, NLO($\alpha_s^2$):
    - FMNR
    - MC@NLO
  Used for comparisons and extrapolations to full phase space of beauty production.
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, eg. $D^* \rightarrow K\pi\pi$.
  2) Lepton tagging: Use semileptonic b/c decay channels
     - look for $\mu$ or $e$, high BR(c,b→ lepton + anything)
  3) $p_T^{rel}$ 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.

Methods used in the analyses discussed today:
- D* analysis: D* reconstruction.
- Low $p_T$ analysis: 2 electrons.
- Muon analysis: 1 $\mu$ for $p_T^{rel}$ tag, lifetime with large impact parameters $\delta$.
- Inclusive analysis: lifetime with displaced vertices, large secondary vertex masses.
Photoproduction of $D^*$

Data sample: $\mathcal{L}=93$ pb$^{-1}$

Phase Space
$Q^2 < 2$ GeV$^2$, $p_T^{D^*} > 1.8$ GeV

Charm tagging
$D^*$ meson reconstruction via:

$D^{*\pm} \rightarrow D^0 \pi^\pm_{\text{slow}} \rightarrow K^{\mp} \pi^\pm \pi^\pm_{\text{slow}}$

- Very high precision of the data, compared to the uncertainties of the NLO predictions.
- NLO predicted shapes less sensitive to theoretical uncertainties, generally show a reasonable agreement with the data.


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Photoproduction of D* and two jets

**Data sample:** $\mathcal{L}=93$ pb$^{-1}$

**Phase Space**

$Q^2 < 2\text{GeV}^2$, $p_T^{D*} > 2.1\text{GeV}$

2 jets with: $p_T^{\text{jet}} > 3.5\text{ GeV}$

- Azimuthal correlation between the two jets, $\Delta\Phi$:

- Fraction of the photon energy entering the hard interaction (direct vs resolved), $x_\gamma^{\text{obs}}$:

$$x_\gamma^{\text{obs}} = \frac{\sum_{\text{jet1}}(E - p_z) + \sum_{\text{jet2}}(E - p_z)}{\sum_h(E - p_z)}$$

**MC@NLO predictions below the data for resolved photons, direct contribution reasonably well-described in normalization, shape not well described.**


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Heavy quark photoproduction at HERA

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Focus of the measurement:
- Low $p_T(b)$ momentum
- Low experimental thresholds
- Extraction of the $b$-cross section from two low $p_T$-electrons, $p_T(e) \geq 1$ GeV

Offline Electron Identification:
Combination of:
- calorimeter shower profiles
- $dE/dx$ measured in the tracker
- $\sim 90\%$ efficiency at a rejection of $\sim 99\%$

Trigger for low $p_T$-Electrons:
Combination of calorimeter (Jet Trigger) and tracker (Fast Track Trigger):
- Topological match
- Cut on $E_{T,\text{JT}}/p_{T,\text{FTT}}$

Data sample: $\mathcal{L} = 48$ pb$^{-1}$

Heavy Flavour Tagging

- Exploit di-electron correlations:
  - Invariant mass $m_{ee}$
  - Azimuthal angle $\Delta \phi_{ee}$
  - Charge product $q(e_1) \cdot q(e_2)$
Heavy Flavour Tagging

- Exploit di-electron correlations:
  - Invariant mass $m_{ee}$
  - Azimuthal angle $\Delta\phi_{ee}$
  - Charge product $q(e_1)\cdot q(e_2)$
- An additional background region (open electron identification cuts) constrains uds.
- Matrix unfolding of the differential beauty cross section (similar to 2d template fit).

\[ J/\psi \rightarrow e^+ e^- \text{ mass peak} \]
Beaut in photoproduction at low $p_T(b)$

- Differential beauty cross section as function of the mean $b$ quark momentum.
- Access to lowest $p_T(b)$ values ever measured in ep.
- Data in agreement with the NLO calculation, but slightly below.

DESY-12-072, Submitted to EPJC
Photoproduction of b- and c-jets with muons

Data sample: $\mathcal{L}=179$ pb$^{-1}$

Phase Space
Events with:
- 1 muon, $p_T^\mu > 2.5$ GeV
- 2 jets, $p_T^{\text{jet 1(2)}} > 7$ (6) GeV

Heavy Flavour Tagging
- Momentum relative to $\mu$ jet, $p_T^{\text{rel}}$.
- Impact parameter $\delta$.
- 2d template fit.
Photoproduction of b- and c-jets with muons

- Simultaneous measurement of differential charm and beauty jet cross sections.
- Azimuthal angle difference of jets $\Delta \phi_{jj} \rightarrow$ sensitive to higher orders.

The data are in agreement with NLO calculation (MC@NLO).

$\Delta \phi_{jj}$ described by all models (LO, NLO).
Data sample: $\mathcal{L}=130 \text{ pb}^{-1}$

Phase Space
Events with at least 2 jets with:
$\mathbf{p}_T^{\text{jet 1(2)}> 7 (6) \text{ GeV}}$

Heavy Quark tagging
Reconstruction of secondary vertices:
- Decay length significance $S = \text{DL} / \sigma(\text{DL})$
- Mass of tracks associated with the secondary vertex, $m_{\text{vtx}}$

Flavour separation: Fit MC templates for mirrored DL significance to data
Inclusive heavy quark jets in photoproduction

- Inclusive differential heavy flavour cross sections as function of $p_T^{\text{jet}}$ and $\eta^{\text{jet}}$.

- Good agreement between the data the LO MC (Pythia) and the NLO prediction (FMNR).


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Heavy quark photoproduction at HERA  
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Many measurements agreeing with each other over a wide $p_T(b)$ range.

General NLO calculation (FMNR) consistent with data.
Summary

- Heavy flavour production at HERA allows to test QCD at different scales.
- Four new heavy flavour photoproduction measurements of ZEUS and H1 using different experimental techniques and having different systematics are in good agreement.
- The data is in general in agreement with NLO pQCD predictions.
Heavy Flavor Measurements discussed in this talk:

- “Measurement of Inclusive and Dijet D* Meson Cross Sections in Photoproduction at HERA”

- “Measurement of heavy-quark jet photoproduction at HERA”

- “Measurement of Beauty and Charm Photoproduction using Semi-muonic Decays in Dijet Events at HERA”
  DESY-12-059, H1 Collab., F.D. Aaron et al., Accepted by EPJC

- “Measurement of Beauty Photoproduction near Threshold using Di-electron Events with the H1 Detector at HERA”
  DESY-12-072, H1 Collab., F.D. Aaron et al., Submitted to EPJC
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: $\sim0.5 \text{ fb}^{-1}$ (per experiment)
Heavy Flavour Tagging

- An additional background region (open electron identification cuts) constrains uds.
- Electrons are identified by
  - Electron discriminator, $D_{\text{ele}}$
  - Isolation criterion, $R_{E,\text{cone}}$
- Definition of the background region:

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<th>$R_{E,\text{cone}}$</th>
<th>$D_{\text{ele}}$</th>
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<tbody>
<tr>
<td>$150 - 350%$</td>
<td>$0.825 - 0.875$</td>
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<tr>
<td>$0 - 150%$</td>
<td>$0.875 - 1.0$</td>
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Open cut

Background templates