D* + jets in DIS and photoproduction

Andreas W. Jung (Fermilab) for the H1 collaboration

- Introduction
- D* (+jet) cross sections
- Extraction of $F_2^c(x,Q^2)$
- Combination of $F_2^c(x,Q^2)$
- Conclusions
**D* production: boson-gluon-fusion**

Dominant process for charm-production in ep -scattering:

\[ \gamma (q) \rightarrow c \quad \text{E}(e)=27.5 \text{ GeV} \]

\[ e \rightarrow k \quad k' \]

\[ \text{E}(p)=920 \text{ GeV} \]

\[ p \rightarrow c \quad c \quad X \]

Kinematic at \( \sqrt{s} \approx 320 \text{ GeV} \):

- **Photon Virtuality:**
  \[ Q^2 = -q^2 = - (k - k')^2 \]

  \( Q^2 \sim 0 \text{ GeV}^2 \): Photoproduction

  \( Q^2 > 2 \text{ GeV}^2 \): Deep Inelastic Scattering

- **Inelasticity:**
  \[ y = \frac{q \cdot p}{k \cdot p} \]

- **Bjorken x:**
  \[ x := \frac{Q^2}{2(p \cdot q)} \]

- **D* via Fragmentation:**
  - **Pseudorapidity:**
    \[ \eta = \ln \tan \left( \frac{\theta}{2} \right) \]
  - **Transverse momentum:**
    \[ p_T \]
  - **Elasticity:**
    \[ z = \frac{E(D^*) - p_z(D^*)}{2 \cdot y E_e} \]

**Study production mechanism:**

- \( Q^2, m_c^2 \) or \( p_T^2 \) provides a hard scale for pQCD

- Test of heavy flavor treatment in pQCD

- Parton densities ("gluon structure") in the proton

\[ \rightarrow \text{multiscale problem} \]

\[ \rightarrow \text{test universality} \]
**Theoretical models**

Factorisation ansatz:

\[
d\sigma = \sum_{i,j,k} f_j^B(x_2, \mu_f) \otimes d\hat{\sigma}_{i,j\to k,X}(\mu_f) \otimes D^H_k(z, \mu_f)
\]

- **Parton density functions (PDFs):** from global fits to data
- **Matrix element:** calculable to different orders of \(\alpha_s\)
- **Fragmentation function:** from data

**Many approaches on the market:**

- **LO(\(\alpha_s\)) + PS:**
  - collinear factorization
  - collinear factorization
  - \(k_T\) factorization
  - (all MCs use Lund fragmentation (uds) and Bowler (c))
  - PYTHIA (DGLAP, massive/massless)
  - RAPGAP (DGLAP, massive)
  - CASCADE (CCFM, massive)

- **NLO(\(\alpha_s^2\)):**
  - Collinear factorization
  - HVQDIS (DGLAP, FFNS, massive, independent Fragmentation)
  - ZMVFNS (DGLAP, ZM-VFNS, massless, KKKS08)

- **NLO(\(\alpha_s^2\)) + PS:**
  - collinear factorization
  - MC@NLO (DGLAP, massive, cluster fragmentation)
- Full HERA II sample ($L = 93\text{ pb}^{-1}$)
- Total systematic error: ~9%
- Phase Space cuts:
  \begin{align*}
  p_T(D^*) &> 2.1\text{ GeV} & |\eta(D^*)| &< 1.5 \\
  p_T(\text{jet}) &> 3.5\text{ GeV} & |\eta(\text{jet})| &< 1.5 \\
  |\eta(D^*-\text{jet})| &< 1.5 \\
  -1.5 &< \eta(\text{other-jet}) < 2.9 \\
  \end{align*}
  (other-jet is jet with highest $p_T(\text{jet})$ other than $D^*$-jet)

- Comparison to MC@NLO (CTEQ66)
- Uncertainty band from scale variations
  - MC@NLO too low in normalization
  - Shape fits quite well

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- Longitudinal momentum fraction of the photon carried by the jets:
  - At low $x_\gamma$ significant contribution from resolved (quasi-real) photons:
    → Low $x_\gamma$ sensitive to the photon PDF
  - High $x_\gamma$: direct processes well described by either MCs & MC@NLO
  - Low $x_\gamma$: resolved processes not described by any model, but better by MCs

\[
x_{\gamma} = \frac{\sum_j (E - p_z)_j + \sum_k (E - p_z)_k}{2yE_e}
\]
- $M_X$ invariant mass of the remnant from photon & proton side

$M_X$ not very well described: At high $x_\gamma$ shape reasonably well described but at low $x_\gamma$ the normalization is too low
D* production: medium $Q^2$

Full HERAII statistics: $L = 347 \text{ pb}^{-1}$ yields $N(D^*) \sim 24705$

- Total systematic error is 7.6%!
- Well understood detector allows increased Phase Space:
  
  \[
  p_T(D^*) > 1.25 \text{ GeV and } |\eta(D^*)| < 1.8
  \]

- Data are reasonable described by HVQDIS

Shape comparison via normalized ratio:

\[
R = \frac{1/\sigma_{\text{data}}^{\text{tot,vis}} \cdot \frac{d\sigma_{\text{calc}}}{dY}}{1/\sigma_{\text{calc}}^{\text{tot,vis}} \cdot \frac{d\sigma_{\text{data}}}{dY}}
\]
Theory uncertainty includes scale, mass & fragmentation uncertainty

- HVQDIS describes nicely the $Q^2$ dependency
- Slope in $x$ not very well reproduced!
- Double differential $y-Q^2$ has also been measured, can be used to extract $F_2^c(x,Q^2)$
For comparison with ZM-VFNS: Cut in photon-proton rest frame: $p_T^{*,(D^*)} > 2$ GeV

- ZM-VFNS: Theoretical uncertainty taken from scale variations

- Reasonable description of $Q^2$ by both NLO calculations, HVQDIS is better in shape

- For $x$ ZM-VFNS predicts completely different slope & fails especially at large $x$

Remark: Only the most recent PDF sets consider mass effects!
D* production: high $Q^2$

- Full HERAII statistics ($L = 351 \text{ pb}^{-1}$)
- Total systematic error: 12%

Phase Space:
- $p_T(D^*) > 1.5 \text{ GeV}$ and $|\eta(D^*)| < 1.5$

- MCs fail to describe differential $D^*$ cross sections
- HVQDIS describes the data quite reasonably
Massive FFNS describes cross section over three orders of magnitude!

Massless ZM-VFNS fails to describe high $Q^2$ region.

D*+jets in DIS and photoproduction

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**Experimental method to measure $F_2^c(x,Q^2)$:**

- Measured cross sections

\[
F_2^c \text{ exp} (x, Q^2) = \frac{\sigma_{\text{vis}}^\text{exp} (y, Q^2)}{\sigma_{\text{vis}}^\text{theo} (y, Q^2)} \cdot F_2^c \text{ full} (x, Q^2)
\]

Using NLO (FFNS)

- Extrapolation uncertainty from variations of scale, mass, fragmentation
- At medium $Q^2$ measured $D^*$ cross section covers only 30% if $p_T(D^*) > 1.5$ GeV & $|\eta(D^*)| < 1.5$

Only at high $y$: 2-3% for this measurement negligible
Reasonable agreement between two experimental methods
H1PDF2009 overall slightly above data
Within uncertainty data described by MSTW, ABKM
Comparison of $F_2^c(x,Q^2)$ results

- HVQDIS using different proton PDFs describes the $F_2^c$ data reasonable
- Nice agreement between different experimental methods & experiments
- Details on H1 VTX → (1169, P. Thompson)
- Gain in precision by combining data within one experiment and by combining with ZEUS
Combine D* and lifetime results:
- Gain in precision because of different systematic uncertainties
- Correlation of Systematic uncertainties taken into account
- Typical gain ~25%:

Data are reasonable described
- At low $Q^2$ data can discriminate between models
- For HERA combined results:
  → see Talk by M. Corradi (1159)
Conclusions

Full H1 HERA II data sample analyzed for photoproduction, medium & high $Q^2$ D* production:

- Photoproduction: MCs & MC@NLO dont describe resolved photon domain
- DIS:  
  - HVQDIS describes Data reasonably well
  - ZM-VFNS not able to describe the D* data

Extracted $F_2^c(x,Q^2)$ from D* data & combined with life-time data:

- Gain in precision via combination of data
- Reasonably described by different calculations
The HERA Collider (1994-2007)

-- Two multi-purpose detectors: H1 & Zeus
-- Collected Luminosity: HERAI + HERAII ~ 0.5 fb⁻¹
**Event selection & techniques**

- Fully reconstructed D*: total BR of 2.57%
- Inclusive method using lifetime of charmed mesons
  → More details: Talk by P. Thompson

- **Untagged electron:** $Q^2 \sim 0 \text{ GeV}^2$
  Track based final states:
  - **H1 Fast Track Trigger**

- **Scattered electron in backward calorimeter:** $5 < Q^2 < 100 \text{ GeV}^2$
- OR in main calorimeter: $100 < Q^2 < 1000 \text{ GeV}^2$

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

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D*+jets in DIS and photoproduction
Theoretical models

Factorisation ansatz:

\[ d\sigma = \sum_{i,j,k} f^B_{ij}(x_2, \mu_f) \otimes d\hat{\sigma}_{i,j\rightarrow k} X(\mu_f) \otimes D^H_k(z, \mu_f) \]

- Parton density functions (PDFs): from global fits to data
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- Fragmentation function: from data

Many approaches on the market:

- NLO(\( \alpha_s^2 \)):
  - HVQDIS (FFNS, massive)
  - vs.
  - ZMVFNS (ZM-VFNS, massless)

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D*+jets in DIS and photoproduction
If a hard scale is involved:
- jet- & hemisphere method agree well
- FF also agrees with ZEUS and LEP data

If no hard scale is involved:
- discrepancy at charm production
  threshold in QCD models
- much harder fragmentation

More information:
http://arxiv.org/abs/0808.1003v2

Fragmentation uncertainty from FF values
for charm production:

<table>
<thead>
<tr>
<th></th>
<th>HVQDIS:</th>
<th>CASCADE:</th>
<th>RAPGAP:</th>
</tr>
</thead>
<tbody>
<tr>
<td>at-threshold</td>
<td>$\alpha = 6.0^{+1.0}_{-0.8}$</td>
<td>$\alpha = 8.2 \pm 1.1$</td>
<td>$8.7 &lt; \alpha &lt; 12.2$</td>
</tr>
<tr>
<td>above-threshold</td>
<td>$\alpha = 3.3 \pm 0.4$</td>
<td>$\alpha = 4.6 \pm 0.6$</td>
<td>$3.9 &lt; \alpha &lt; 5.0$</td>
</tr>
</tbody>
</table>

Threshold position from $\hat{s}$ (cms energy of
hard subprocess):
- $70 \pm 20$ GeV$^2$
- Parameters of the MCs & MC@NLO:

<table>
<thead>
<tr>
<th>generator</th>
<th>proton (u)pdfs</th>
<th>photon pdfs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pythia massive</td>
<td>CTEQ 6M NLO</td>
<td>SAS 2D LO</td>
</tr>
<tr>
<td>Pythia massless</td>
<td>CTEQ 6L LO</td>
<td>GRV-G LO</td>
</tr>
<tr>
<td>Cascade</td>
<td>Set A0</td>
<td>–</td>
</tr>
<tr>
<td>MC@NLO</td>
<td>CTEQ 6.6</td>
<td>GRV</td>
</tr>
</tbody>
</table>

- High $x_\gamma$: direct processes well described by MCs
- Low $x_\gamma$: resolved processes not described by any model, especially at high $M_X$
In general described by PYTHIA (CTEQ6) and CASCADE (A0)
As seen in x also in y ZM-VFNS fails completely!
HVQDIS overshoots at low y
z(D*) reasonable described by ZM-VFNS & HVQDIS
Without the additional $p_T(D^*)$ cut HVQDIS fails to describe $z(D^*)$
In general $\eta(D^*)-p_T(D^*)$ cross section reasonable described by HVQDIS

Forward direction: HVQDIS undershoots data located at low $p_T(D^*)$
Massive FFNS describes cross sections reasonably well.

MCs predict different slopes and fail completely to predict the $Q^2$ slope.