Extraction of $F_2^c(x,Q^2)$ from D* cross sections at H1

- Introduction
- D* cross sections
- Fragmentation & Extrapolation
- Extraction of $F_2^c(x,Q^2)$
- Conclusions

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XVII. International Workshop on Deep-Inelastic Scattering and Related Subjects
**D* production: Boson gluon fusion**

**Dominant process: BGF process**

\[ e(k) \rightarrow e(k') \]

- **Matrix element**
  - Calculable in different heavy flavor schemes

- **Fragmentation function**
  - From data

**Proton p.d.f.**

\[ f^B_{i,j,k}(x_2, \mu_f) \]

\[ d\tilde{\sigma}_{i,j \rightarrow kX}(\mu_f) \]

\[ D^H_k(z, \mu_f) \]

**Factorisation ansatz:**

\[ d\sigma = \sum \left[ f^B_{i,j,k}(x_2, \mu_f) \otimes d\tilde{\sigma}_{i,j \rightarrow kX}(\mu_f) \otimes D^H_k(z, \mu_f) \right] \]

- **Kinematic at \( \sqrt{s} \approx 320 \text{ GeV} \):**
  - Photon virtuality: \( Q^2 \)
  - Inelasticity: \( y \)
  - Bjørken \( x \)

- **D* via Fragmentation:**
  - Pseudo-rapidity: \( \eta \)
  - Transverse momentum: \( p_T \)
  - (In)elasticity: \( z \)

**Extraction of \( F_2^c \) from measurement of D* cross sections**

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Theoretical models

Study production mechanism:

Perturbative QCD:
- $Q^2, m_c^2$ or $p_T^2$ provide a hard scale → multiscale problem
- Test of heavy flavor treatment in pQCD

Non-perturbative QCD:
- Parton densities: gluon structure of the proton → test universality
- Fragmentation

Models discussed in the following:

<table>
<thead>
<tr>
<th>CASCADE vs. HVQDIS:</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO($\alpha_s$) + PS ↔ NLO($\alpha_s^2$)</td>
</tr>
<tr>
<td>CCFM ↔ DGLAP</td>
</tr>
<tr>
<td>only gluons ↔ all partons</td>
</tr>
<tr>
<td>Lund frag. ↔ Independent frag.</td>
</tr>
<tr>
<td>massive BGF ↔ massive BGF (FFNS)</td>
</tr>
</tbody>
</table>

Note: RAPGAP + HERACLES used correction of data

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Event selection

Forward directions $\eta > 0$

Backward directions $\eta < 0$

- Scattered electron in backward calorimeter:
  \[ Q^2: 5 - 100 \text{ GeV}^2 \]
  → Summary given here

- OR in main calorimeter:
  \[ Q^2: 100 - 1000 \text{ GeV}^2 \]
  → Talk by M. Brinkmann

Visible range for the $D^*$ cross section:
\[ Q^2 : 5 - 100(0) \text{ GeV}^2 \]
\[ \gamma : 0.02 - 0.70 \]
\[ p_T(D^*) : > 1.5 \text{ GeV} \]
\[ |\eta(D^*)| : < 1.5 \]

$D^*$ reconstructed in golden decay channel:
(with a total BR of 2.57%)

\[ D^{*\pm} \rightarrow D^0 \pi^\pm_{\text{slow}} \rightarrow (K^+\pi^\pm)\pi^\pm_{\text{slow}} \]
Event selection

**Forward directions:** \( \eta > 0 \)

**Backward directions:** \( \eta < 0 \)

- Scattered electron in backward calorimeter:
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- Summary given here

- OR in main calorimeter:
  \[ Q^2: 100 - 1000 \text{ GeV}^2 \]

- Talk by M. Brinkmann

**Visible range for the D* cross section:**
- \( Q^2: 5 - 100(0) \text{ GeV}^2 \)
- \( \gamma: 0.02 - 0.70 \)
- \( p_T(D^*) > 1.5 \text{ GeV} \)
- \( |\eta(D^*)| < 1.5 \)

**D* reconstructed in golden decay channel:**
- \( D^{*\pm} \rightarrow D^0 \pi_{\text{slow}}^{\pm} \rightarrow (K^\mp \pi^\pm) \pi_{\text{slow}}^\pm \)

- **Luminosity:** \( \sim 350 \text{pb}^{-1} \)

- **Extraction of \( F_2^c \) from measurement of D* cross sections**

28\textsuperscript{th} April, 2009

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**D* cross sections in y-Q²**

Considered in cross section:
- Data corrected with RAPGAP → \( \epsilon \sim 60\% \)
- Contribution due to b-quarks not subtracted → but < 2\%
- Correction due to other D⁰ decay channels → 4\%
- Correction for NLO-QED effects using HERACLES → 2\%

More information:
https://www-h1.desy.de/psfiles/confpap/ICHEP08/H1prelim-08-072.ps
and http://www-h1.desy.de/psfiles/theses/h1th-504.pdf

- CASCADE describes the data reasonable
- difficulties to describe the new (lowest) y-bin (→ highest x)

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Extraction of \( F_2^c \) from measurement of D* cross sections
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Error estimation of the NLO-calculation with parameter variation:

- charm mass: $1.3 < m_c < 1.6$ GeV
- renormalization & factorization scale: $0.5 < \mu_{f,r}/\mu_0 < 2$, with $\mu_0^2 = Q^2 + 4m_c^2$
- fragmentation: comes later

More information:
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- Equally good described by HVQDIS (NLO, DGLAP) and CASCADE (LO+PS, CCFM)
- Both have difficulties to describe the new (lowest) $y$-bin ($\rightarrow$ highest $x$)
- Data don't prefer a specific model - use both for the extraction of $F_2^c(x,Q^2)$
Extraction of $F_2^c(x,Q^2)$

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

What is done to measure $F_2^c(x,Q^2)$:

- Double differential cross section measurement in visible phase space
  - Double differential prediction of cross section in visible phase space (DGLAP & CCFM)
  - Prediction of $F_2^c(x,Q^2)$ in full phase space ($\eta, p_T$) (DGLAP & CCFM)

Only at high $y$: This measurement $O(2-3\%) \rightarrow$ negligible
Extraction of $F_2^c(x,Q^2)$

$$\frac{d^2\sigma^{c\bar{c}}(x,Q^2)}{dxdQ^2} = \frac{2\pi\alpha_s^2}{xQ^4} \cdot \left[1 + (1 - y)^2\right] \cdot F_2^{c\bar{c}}(x,Q^2) - y^2 \cdot F_L^{c\bar{c}}(x,Q^2)$$

What is done to measure $F_2^c(x,Q^2)$:

1. Double differential cross section measurement in visible phase space
2. Double differential prediction of cross section in visible phase space (DGLAP & CCFM)
3. Prediction of $F_2^c(x,Q^2)$ in full phase space $(\eta,p_T)$ (DGLAP & CCFM)
4. Extrapolation into not measured region → Fragmentation has an influence

- Extrapolation into not measured region → Fragmentation has an influence

Determine Fragmentation Function (FF) from data !
**Jet method:**

- momentum of $c$-quark approximated by momentum of rec. $D^*$-jet

  \[ Z_{\text{jet}} = \frac{(E+p_L)_{D^*}}{(E+p)_{\text{jet}}} \]

- $k_{\perp}$-clus jet algorithm applied in $\gamma p$-frame ($E_t(D^* \text{jet}) > 3 \text{ GeV}$)

**Hemisphere method:**

- momentum of $c$-quark approximated by momentum of rec. $D^*$-hemisphere

  \[ Z_{\text{hem}} = \frac{(E+p_L)_{D^*}}{\sum_{\text{hem}}(E+p)_i} \]

- $\eta(\text{part}) > 0$ for $p$-remnant suppression

- thrust axis in plane perpendicular to $\gamma$ used for hemisphere division

Analyses based on:
- $D^*$ reconstructed in golden decay
- HERA I data with $L = 47 \text{ pb}^{-1}$
Fragmentation functions (FF)

Jet method:
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Analyses based on:
- $D^*$ reconstructed in golden decay
- HERA I data with $L = 47 \text{ pb}^{-1}$

Differences of the methods:
- Jet method & hemisphere method:
  - Methods are different, i.e. hemisphere method sums more gluon radiation and does not need a hard scale ($E_T$-cut)
  - Hem. method is sensitive to threshold region!
Fragmentation functions (FF)

\[ \frac{1}{\sigma} \frac{d\sigma}{dz_{\text{hem}}} \]

\( z_{\text{hem}} \)

\( R \)

\( \chi^2_{\text{min}} / \text{n.d.f.} = 40/4 \)

\( \alpha = 3.3 + 0.4 \)

\( \alpha = 3.3 - 0.4 \)

\( \alpha = 6.1 + 0.9 \)

\( \alpha = 6.1 - 0.8 \)

\( \alpha = 10.3 + 1.9 \)

\( \alpha = 10.3 - 1.6 \)

\( \alpha = 4.4 \)

-- NLO (HVQDIS) describes D^*-jet sample

-- Extracted FF (hemisphere method) differs by 4\( \sigma \) from FF extracted from jet sample

-- NLO (HVQDIS) fails to describe the no-D^*-jet data

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Extraction of \( F_2^c \) from measurement of D^* cross sections

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**Fragmentation functions (FF)**

- **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 used for extrapolation:**

<table>
<thead>
<tr>
<th>Function</th>
<th>at-threshold:</th>
<th>above-threshold:</th>
</tr>
</thead>
<tbody>
<tr>
<td>HVQDIS</td>
<td>$\alpha = 6.0^{+1.0}_{-0.8}$</td>
<td>$\alpha = 3.3 \pm 0.4$</td>
</tr>
<tr>
<td>CASCADE</td>
<td>$\alpha = 8.2 \pm 1.1$</td>
<td>$\alpha = 4.6 \pm 0.6$</td>
</tr>
</tbody>
</table>

**Threshold position from $S$ (CMS energy of hard subprocess):**

- HVQDIS: $70 \pm 20$ GeV$^2$
- CASCADE: $70 \pm 20$ GeV$^2$
- Fragmentation uncertainty assigned to NLO & CASCADE reweighted
- In visible phase space small influence
- $y-Q^2$ cross sections are used for the extraction of $F_2^c(x,Q^2)$
Extraction of $F_2^c(x,Q^2)$

Extrapolation to full phase space:

$$p_T(D^*) \rightarrow 0 \text{ GeV}$$

$$|\eta(D^*)| \rightarrow 10$$

- CASCADE & HVQDIS used, $f_{avg} \sim 3$
- Ratio CASCADE/HVQDIS within 10%
- BUT at high $x$ differences of up to 80%
  - reason is the restricted phase space
    $\rightarrow$ larger $\eta(D^*)$ range needed!

- Extrapolation uncertainty:
  - charm mass: $1.3 < m_c < 1.6$ GeV
  - renormalization & factorization scale:
    $$0.5 < \mu_{f,r}/\mu_0 < 2, \mu_0^2 = Q^2 + 4m_c^2$$
  - PDF: MRST vs. CTEQ
  - Fragmentation: as discussed...
  - Partial cancellations of uncertainties
F$^c_2$ in NLO DGLAP scheme

- 20x statistics of last Publication
- Extrapolation error: typically 5 - 10%
- Fragmentation: applied to sys. Error of data typically 2 - 7%
- HVQDIS using different proton PDFs describes the $F^c_2$ data reasonable
- Deviations at large x - originating from differences at cross section level

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**$F_2^c$ in CCFM scheme**

- **20x statistics of last Publication**
- **Extrapolation error:**
  - typically 2 - 6%
  - (no factorization scale & PDF variation)
- **Fragmentation:** applied to sys. Error of data
  - typically 2 - 7%
- **CASCADE describes the $F_2^c$ data**
  - reasonable
- **Deviations at large $x$ - originates from differences at cross section level**

More information:
- [http://www-h1.desy.de/psfiles/confpap/ICHEP08/H1prelim-08-172.ps](http://www-h1.desy.de/psfiles/confpap/ICHEP08/H1prelim-08-172.ps)
- [http://www-h1.desy.de/psfiles/theses/h1th-504.pdf](http://www-h1.desy.de/psfiles/theses/h1th-504.pdf)

**Extraction of $F_2^c$ from measurement of $D^*$ cross sections**

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This presentation!

• Most precise HERA measurement so far at $5 < Q^2 < 60$ GeV$^2$
• Good agreement of different data sets (D*, D mesons, displaced tracks)

Talk by P. Thompson

Extraction of $F_2^c$ from measurement of D* cross sections  

28th April, 2009
Conclusions

- Full HERA II data sample for $F_2^c(x,Q^2)$ analysed $L \sim 350\text{pb}^{-1}$
- Most precise $F_2^c(x,Q^2)$ - on the way to final precision!
- Described by DGLAP & CCFM and consistent with other results

Closer look:
- Fragmentation uncertainty from Results of H1 measurement of Fragmentation fcts. estimated
- Larger differences in extrapolation at high $x$ between models corresponds to most forward $\eta(D^*)$
- Extend phase space for cross section measurement towards larger $\eta(D^*)$ and smaller $p_T(D^*)$

Combination with other $F_2^c(x,Q^2)$ measurements possible

Talk by P. Thompson
Backup

Extraction of $F_2^c$ from measurement of D* cross sections

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Result of Study from my Ph.D. Thesis:

- "Fragmentation model" from H1 measurement of FF applied
- Ratio: CASCADE / HVQDIS

More information:

**Backup: The HERA collider**

**ep collisions at** $\sqrt{s} \approx 320$ GeV:

**Collected Data samples:**

- **Protons**: 920 GeV
- **Electrons**: 27.6 GeV

**Two multi-purpose detectors**: H1 & Zeus

**Collected Luminosity**: HERAI + HERAII ~ 0.5 fb$^{-1}$

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Decay: $D^{*\pm} \rightarrow D^0 \pi^\pm \rightarrow (K^\mp \pi^\pm) \pi^\pm$

Higher resolution in mass difference:
\[ \Delta M = M(K\pi\pi) - M(K\pi) \]

Larger phase space with use of electron-Σ-method: lower $y$ of 0.02

Fit asymmetric shape: with ROOFIT

Additional D* cuts:
- $p_T(K) > 0.3$ GeV
- $p_T(\pi) > 0.3$ GeV
- $p_T(\pi_{slow}) > 0.12$ GeV
- $p_T(K) + p_T(\pi) > 2$ GeV
- $|M(D^0)| < 0.080$ GeV

D* sample:
- Stat. Error ~2%
- Syst. Error ~9%

Crystal-Ball:
\[
\begin{align*}
    f(x) &= \begin{cases} 
    \left( \frac{n}{|\alpha|} \right)^n \exp\left( -\frac{1}{2} \alpha^2 \right) & \text{if } \frac{x-m}{\sigma} < -\alpha, \\
    \exp\left( -\frac{1}{2} \left( \frac{x-m}{\sigma} \right)^2 \right) & \text{if } \frac{x-m}{\sigma} \geq -\alpha
    \end{cases}
\end{align*}
\]

Determines in units of $\sigma$ where: Gauss $\rightarrow$ Expo

Background (Granet Parametrisation):
\[
f(x) = p_0 \cdot (x - m_{\text{Cutoff}})^{p_1} \cdot e^{-p_2 x} (-p_3 x^2)
\]

$\sigma_{\text{vis}}^{\text{tot}} = \frac{N_{D^*} \cdot (1 - r)}{\mathcal{L} \cdot \mathcal{B}(D^* \rightarrow K\pi\pi_{\text{slow}}) \cdot \epsilon \cdot (1 - \delta_{\text{rad}})}$
- Good description by NLO calculation
- Small deviations in forward $\eta(D^*)$ with full HERA2 statistics
- differences are located at low transverse momenta
- data shows sensitivity to the proton PDF
- CASCADE describes nicely the shape

https://www-h1.desy.de/psfiles/confpap/ICHEP08/H1prelim-08-072.ps
and http://www-h1.desy.de/psfiles/theses/h1th-504.pdf
In general NLO gives a good description of the data of single & double differential distributions.

Forward $\eta(D^*)$ at low $p_T(D^*)$: data is above the NLO-calculations.

Better precision of the data is needed – more bins in larger phase space.

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Backup: $D^*$ cross sections

Extraction of $F_2^c$ from measurement of $D^*$ cross sections

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**Backup: D* cross sections**

**Total integrated Cross section in Q^2: 5 - 100 GeV^2:**

- **Data:** \((4.85 \pm 0.07\text{ (stat.)} \pm 0.42\text{ (sys.)}) \text{ nb}\)
- **HVQDIS (CTEQ):** \((4.43 \pm 0.69 - 0.47) \text{ nb}\)
- **HVQDIS (MRST):** \((4.17 + 0.59 - 0.37) \text{ nb}\)

**Total integrated Cross section in Q^2: 100 - 1000 GeV^2:**

- **Data:** \((0.24 \pm 0.02\text{ (stat.)} \pm 0.03\text{ (sys.)}) \text{ nb}\)
- **HVQDIS (MRST):** \((0.25 + 0.02 - 0.02) \text{ nb}\)

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Talk by M. Brinkmann

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