F$_2^{cc}$ Measurements in D* Analysis in DIS

Outline

- HERA and DIS kinematics
- Heavy flavour physics
- Charm production
- Charm fragmentation
- Analysis plans
- Summary

DESY Student Seminar
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**HERA Super-microscope at DESY (Hamburg)**

World-only ep machine to study the proton structure

Until June 2007:
- collisions at $\sqrt{s} = 318$ GeV
- collider experiments H1 and ZEUS
- integrated Luminosity $\sim 0.5$ fb$^{-1}$/ experiment
**Deep Inelastic Scattering @ HERA**

Kinematics:

\[
\begin{align*}
    s &= (k + P)^2 \\
    Q^2 &= -q^2 = -(k - k')^2 \\
    x &= \frac{Q^2}{2P \cdot q} \\
    y &= \frac{p \cdot q}{p \cdot k} \\
    W_{\gamma p} &= y \cdot s - Q^2 \\
    \eta &= -\ln \tan \frac{\theta}{2}
\end{align*}
\]

DIS: \( Q^2 > 5 \text{ GeV}^2 \)

Purpose of HERA: precision measurement of the proton structure
tests of perturbative Quantum Chromodynamics (pQCD)
Heavy Flavour Physics @ HERA Motivation

- pQCD requires the presence of a large scale (large $Q^2$ virtualities, large $p_T$, large particle masses)

- Large masses of heavy quarks: $m_c = 1.6$ GeV
  $m_b = 4.7$ GeV

- Studying heavy quark production mechanism is a testing ground for pQCD, even at small $p_T$ and low $Q^2$
Heavy quark contribution to the total DIS cross section is significant: ~ 30%

- At low $q^2$ – suppression of the $\sigma_b$ is given by the mass term
- At very high $q^2$ – suppression of the $\sigma_b$ is given by the charge coupling

\[ \sim \frac{1}{\text{charge}^2_{\text{quark}}} \]
Charm Production at HERA

Dominant production mechanism: **Boson Gluon Fusion (BGF)**

- Offers direct access to the gluon
- Charm quark cross section:

\[
\frac{d^2\sigma^c}{dx dQ^2} = \frac{2\pi\alpha^2_{em}}{Q^4 x} (1 + (1 - y)^2) F_{2c\bar{c}}(x, Q^2)
\]

Charmed meson cross section can be decomposed into:

\[
\sigma_{\text{charmed meson}} = \text{PDFs} \otimes \text{ME} \otimes \text{fragmentation}
\]
There are several methods used for studying charm production in DIS:

- **lifetime tag method** – exploits the longer lifetime of charmed mesons (arXiv: 0907.2643)
- **muon tag method** – tags the muons coming from semileptonic decays of the charm meson (arXiv: 0904.3487)
- **charmed meson tag** method – tags the charm meson (arXiv:0808.1003)

Used in my analysis
Charm tagging via $D^*$

$D^{*\pm}(2010)$ is reconstructed in decay:

$$D^{*\pm} \rightarrow D^0 \pi^{\pm} \rightarrow K^{\mp} \pi^{\pm} \pi_s^{\pm}$$

- Simple 2-body kinematics
- Lower combinatorial background

$$dm = M(K\pi\pi_s) - M(K\pi)$$

- Resolution given by $\pi_s$ – large curvature
• Wide range of Q2 is covered
• Data well described by the NLO QCD calculation
Charm structure function

Charm contribution $F_2^{cc}$ to the proton structure function $F_2$:

$$F_2^{cc} = \frac{Q^2 \alpha_s}{4 \pi \mu^2} \int_{x_{min}}^{1} \frac{dx'}{x'} e_c g(x, \mu^2) C_{2,g}(\frac{x}{x'}, Q^2, m_c^2, \mu^2).$$

Direct connection to the gluon distribution in the proton

Most recent HERA result on $F_2^{cc}$:

Theory uncertainties dominate mostly
**Extraction of $F_2^c$ from meson cross section**

$$F_2^{c\bar{c}} \text{(exp)} = \frac{\sigma_{\text{vis}} \text{(exp)}}{\sigma_{\text{vis}} \text{(theory)}} F_2^{c\bar{c}} \text{(theory)}$$

Visible cross section: \( p_T(D^*) > 1.5 \text{ GeV}, |\eta(D^*)| < 1.5 \)

\( 0.02 < y < 0.7, 5 < Q^2 < 1000 \text{ GeV}^2 \)

Problem: detector sees only 40% of the phase space for $c \rightarrow D^*$

→ strong model dependence due to large extrapolation factors

**Extrapolation problems:**

➢ Different extrapolation models

➢ Unknown parameters within a single model:
  - mass of charm quark, renormalisation/factorisation scales,
  - fragmentation model → experimentally measurable: see next slides
Charm fragmentation in $e^+e^-$ collisions

- Fragmentations functions: dimensionless functions that describe the final-state single-particle energy distributions in hard scattering processes

- Fragmentation variable:
  \[ Z_h = \frac{E_h + |\vec{p}_h||q|c}{E_q + |\vec{p}_q|c} \]

**Fragmentation in $e^+e^-$ annihilation**

- Charm production via s-channel

- In LO, the laboratory frame is the center of mass of the $c\bar{c}$ system – each quark takes half of CMS energy

- $Z_D$ is approximated either by $x_{pD}$ or $x_{ED}$:
  \[ x_{pD} = \frac{|\vec{p}_D|}{|\vec{p}_{Dmax}|} \quad x_{ED} = \frac{E_D}{E_{beam}} \]
**Measurement of charm fragmentation in ep collisions**

Methods to reconstruct the energy of the parent quark:

- Jet containing D*: problem: only small region of phase space accessible
  - significant contribution only from $\hat{s} > 100$ GeV$^2$ (much above threshold)
  - $\hat{s}$: center of mass energy of ccbar pair, threshold $4m_c^2$

- Hemisphere containing D*:
  - experimental setup similar to $e^+e^-$, works at threshold, $\hat{s} \approx 4m_c^2$

\[ \gamma \text{ p-system} \]

- take all particles towards $\gamma$
- project onto the plane $\perp$ to the $\gamma$
- get Thrust axis
- $\sum$ momenta of all particles in the D* hemisphere
**Measurement of charm fragmentation in DIS**

Data: H1 HERA I, \( L = 75 \text{ pb}^{-1} \) both methods used:

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

Differences between the methods:

- Hemisphere method should include more final state gluon radiation than jet method

⇒ Measured distributions of the fragmentation variable should be different

⇒ Extracted fragmentation functions (FF) should agree

- Measure in the common phase space: require presence of a D* jet
- Extract parameters for FF using MC/ NLO calculation
- Expect: parameters agree for different methods, different for MCs and NLO
- Any differences at the threshold (absence of a D*-jet)?
Fragmentation measurement: $D^*$ - Jet sample

RAPGAP MC:

Hemisphere method

Jet method

- Distributions on hadron level look different (as expected)
- MC (Rapgap) with FF yield reasonable description of data
- Extracted FF parameters from $z_{\text{hem}}$ and $z_{\text{jet}}$ agree for MC ($\alpha = 4.5\pm0.6$ for hemisphere method and $\alpha = 4.3\pm0.4$ for jet method)
Fragmentation measurement: $D^*$ - Jet sample

NLO:

- Extracted FF parameters from $z_{\text{hem}}$ and $z_{\text{jet}}$ agree for NLO ($\alpha = 3.3 \pm 0.4$ for hemisphere method and $\alpha = 3.8 \pm 0.3$ for jet method)
Fragmentation measurement: No $D^* - Jet$ sample

MC: Extracted parameters ($\alpha = 10.3^{+1.7}_{-1.6}$) inconsistent with jet-sample ($\alpha = 4.5\pm0.6$)

NLO: “no jet” ($\alpha = 6.0^{+1.0}_{-0.8}$) inconsistent with jet-sample ($\alpha = 3.3\pm0.4$)

Fragmentation at threshold significantly harder than expected from the jet-sample

Treatment in extrapolation models: $\hat{s}$-dependent fragmentation
Aim: measure the D* cross-section and fragmentation function as a function of ccbar center of mass energy $\hat{s}$

Two ways to reconstruct $\hat{s}$ experimentally:
- using the $p_T$ of the D*:
  \[
  \hat{s}(p_{\perp}^{D^*}) = \frac{p_{\perp}^2(D^*) + m_c^2}{Z_{D^*}(1 - Z_{D^*})}
  \]
  \[Z_{D^*} = \frac{(E - p_z)^{D^*}}{2yE_{beam}}\]
  D* inherits most of the c quark momentum
  $p_T(D^*)$ is calculated in $\gamma p$ frame

- using the hemisphere variables:
  \[
  \hat{s}_{hemi} = W^2 exp(-\eta_{D^*hemi} - \eta_{opp hemi})
  \]
  The hemispheres approximate better the ccbar system

- Combination of both methods
Summary

- Study of charm production at HERA provides test of pQCD
- Measurement of D* production elegant way of charm tagging
- Charm contribution to total DIS cross section high
- Charm Fragmentation is a key issue in measuring $F_{2}^{cc}$
- Fragmentation in ep collisions is both a theoretical and an experimental challenge
- HERA I measurement: different behavior of the fragmentation close and above the threshold
- In the HERA II data set good statistics is available: study fragmentation as a function of \( \hat{s} \)
- Understanding fragmentation better should reduce systematic uncertainty in $F_{2}^{cc}$
Backup slides
The relation between the DIS neutral current cross section and structure functions:

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

In naïve Quark Parton Model, \( F_2 \) is:

\[
F_2(x) = \sum_{i=1}^{n_f} e_i^2 x \left( q_i(x) + \bar{q}_i(x) \right)
\]

If full QCD is taken into account, scaling violations appear.

Factorization theorem for \( F_2 \) in perturbative QCD:

\[
F_2(x, Q^2) = \text{hard interaction part} \otimes \text{parton distribution function}
\]
Parton Distribution Functions

- Structure functions are used to extract parton flavours distributions

- The lower the $x$, the higher the gluon contribution

- At low $x$, the proton is “seen” to be made only from gluons – see the scaling factor of 20
• Inclusive $F_2$ measurements – all processes with a scattered electron in the final state

• In QPM DIS, at high incident particle momentum and high momentum transfer, quarks are seen as free (non-interacting) $\Rightarrow$ scaling of $F_2$

• At high $Q^2$ QCD subprocesses are “visible” $\Rightarrow$ scaling violations appear

Proton Structure Function $F_2$
Evolution schemes

Dokshitzer Gribov Lipatov Altarelli Parisi evolution scheme
- applicable at large $x$
- the gluon ladder is ordered in $Q^2$:
  \[
  q_n^2 \gg q_{n-1}^2 \gg \ldots \gg q_1^2 \gg q_0^2
  \]
  Small $x$
  \[
  k_{T,n}^2 \gg k_{T,n-1}^2 \gg \ldots \gg k_{T,1}^2 \gg k_{T,0}^2
  \]
- Effectively integration over $k_T$

Balitsky Fadin Kuraev Lipatov evolution scheme
- applicable at small $x$ and small $Q^2$
- Gluon ladder ordered by $x$
- uses unintegrated parton distributions with:

\[
x g (x, Q^2) = \int_0^{Q^2} \mathcal{F} (x, k_{\perp}^2, Q_0^2) \frac{dk_{\perp}^2}{k_{\perp}^2}
\]

Ciafaloni Catani Fiorani Marchesini evolution scheme
- general Ansatz with border cases DGLAP and BFKL
- also unintegrated parton densities used
- gluon ladder ordered by angles of emitted gluons
DGLAP evolution of $F_2$

\[
\frac{\partial q_i(x, Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int x \frac{d\xi}{\xi} \left[ P_{qq} \left( \frac{x}{\xi} \right) q_i(\xi, Q^2) + P_{qg} \left( \frac{x}{\xi} \right) g(\xi, Q^2) \right],
\]

\[
\frac{\partial g(x, Q^2)}{\partial \ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int x \frac{d\xi}{\xi} \left[ \sum_i P_{gq} \left( \frac{x}{\xi} \right) q_i(\xi, Q^2) + P_{gg} \left( \frac{x}{\xi} \right) g(\xi, Q^2) \right].
\]

- The $Q^2$ dependence of the PDFs can be calculated using the DGLAP evolution scheme ($\alpha_s(Q^2)\ln(1/x)<<1$)
- $P_{qq}$, $P_{qg}$, $P_{gq}$, $P_{gg}$ are functions which model the splitting of a parton in another 2 partons

Physical processes behind splitting functions:

Evolution of PDF from $Q_0^2$ to $Q^2 > Q_0^2$ by integration
FraAGMENTATION FRACTIONS

\[ f (c \rightarrow \mu) = 0.096 \pm 0.004 \]
\[ f (c \rightarrow D^*) = 0.255 \pm 0.017 \]
\[ f (c \rightarrow D^0, \text{no } D^*) = 0.45^{+0.04}_{-0.03} \]
\[ f (c \rightarrow D^{\pm}) = 0.216^{+0.029}_{-0.021} \]
### Charm production models

#### Massive approach:

- $u,d,s$ in proton PDF + massive charm produced in pQCD
- Fixed number of flavours (Fixed Flavour Number Scheme): $n_f = 3$
  - Valid for $Q^2 \approx m_c^2 c^4$
  - Dominant process
  - BGF

#### Massless approach:

- $u,d,s +$ massless $c$ in proton PDF – initiates hard scattering (charm excitation)
- FFNS: $n_f = 4$
  - Valid for $Q^2 \gg m_c^2 c^4$

#### Variable flavour number scheme approach (VFNS):

- Mixture of massive and massless approach
Charm production MC models

LO in $\alpha_s$

**RAPGAP**
- Charm produced via LO BGF
- Higher orders approximated with parton showers
- Uses DGLAP evolution scheme for proton PDF

**CASCADE**
- LO charm production
- Higher orders approximated with parton showers
- Uses CCFM evolution scheme

NLO in $\alpha_s$

**HVQDIS**
- Charm production in massive approach up to NLO
- FFNS: $n_f = 3$
- Uses Peterson fragmentation function
Several phenomenological models of fragmentation exist:

- **Peterson parametrization:**
  \[
  D_Q^H(z) = \frac{N}{z[1 - \frac{1}{z} - \frac{\varepsilon_Q}{1-z}]^2}
  \]

- **Bowler parametrization:**
  \[
  D_Q^H(z) \propto \frac{1}{z^{1+r_Qb_Q^2}}(1 - z)^\alpha \exp\left(-\frac{bM_T^2}{z}\right)
  \]

- **Kartvelishvili parametrization:**
  \[
  D_Q^H(z) \propto z^\alpha(1 - z)
  \]