H1 and ZEUS Results on $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$

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- Introduction
- Previous measurements of $c$ and $b$
- Motivation for inclusive analyses
- Results
Heavy Flavour Production at HERA

- Heavy flavours directly sensitive to gluon of proton and photon. Understand production mechanisms and constrain PDFs.
- Charm and beauty contributions $F_2^{cc}$ and $F_2^{bb}$
- Low $Q^2$ DIS $Q^2 \geq 1 \text{ GeV}^2$.
- High $Q^2$ DIS $Q^2 \geq 100 \text{ GeV}^2$
NLO QCD Treatments for Inclusive Cross Section

“massive” - Fixed Flavour Number Scheme

\[ \sigma_{e p \to HX} = \sum_{a = \text{light partons only}} f_p^a(x_a, \mu) \otimes \hat{\sigma}_{ea \to HX}^{FNS} (\hat{s}, Q, m_H, \mu) \]

“massless” - Zero Mass Variable Flavour Number Scheme

\[ \sigma_{e p \to CX} = \sum_{a = \text{all active partons}} f_p^a(x_a, \mu) \otimes \hat{\sigma}_{ea \to CX}^{MS} (\hat{s}, Q, \mu) \left|_{m_a = 0} \right. \]

Variable FNS: Interpolate between massive \((Q^2 \sim M^2)\) and massless \((Q^2 \gg M^2)\) avoiding double counting etc. ACOT(CTEQ), MRST.
Charm Production

- At HERA, measurements mainly from $D^* \rightarrow K\pi\pi_s$
  Branching fraction $f(c \rightarrow K\pi\pi) < 1\%$
- Charm production in DIS at HERA generally well described by massive NLO QCD (BGF)

For more details on latest charm results see talk from Manuel Zambrana.
Extraction of $F^c\bar{c}_2$

$$F^c\bar{c}_2 \text{meas}(x, Q^2) = \frac{\sigma_{\text{meas}}(ep \to D^* X)}{\sigma_{\text{theory}}(ep \to D^* X)} F^c\bar{c}_2 \text{theory}(x, Q^2)$$

- Extraction of $F^c\bar{c}_2$ from measured cross section to full phase space using consistent ‘massive’ NLO QCD scheme (HVQDIS program).
- Extrapolation factors $(4.7 - 1.5)$ in $p_T$ and $\eta$ decreasing with $Q^2$.
- Uncertainties in extrapolation due to fragmentation, charm mass, PDF are typically around 10% ($< 20\%$).
At HERA beauty cross section measurements made using exclusive final state (typically with high $p_T$ lepton $\mu, c$ and a jet).

Reasonable agreement between different methods, H1 and ZEUS.

Comparisons with ‘massive’ NLO QCD calculations using CTEQ5F PDF. Data tend to be somewhat higher than theory.

For more details on latest HERA beauty measurements see talk from C. Grab
Motivation for Inclusive Analysis

- Exclusive method e.g. $D^*$, $\mu$ limited by statistics at high $Q^2$


- The technique uses fact that the lifetime of heavy flavours is largely model independent, reducing model uncertainties.

- Using inclusive quantities of all tracks at low $p_T$ means there are smaller extrapolations in $p_T,\eta$.

- Acceptance for at least 1 generated charged track in central acceptance $> 82\%$ for $c$ and $> 96\%$ for $b$. 
• Hit resolutions of 12 μm in $r$–$\phi$ and 25 μm in $z$.
• Momentum resolution $33 \, \mu m \oplus 90 \, \mu m / p_T [GeV]$
• Around 75% efficiency for a Jet Chamber track to be fitted to CST hits in both layers.
Technique

Look at the signed impact parameter for all tracks with precise measurement from central silicon tracker (CST)

\[ \alpha < 90^\circ \rightarrow \delta = +|\delta| \]

\[ \alpha > 90^\circ \rightarrow \delta = -|\delta| \]

- Events with secondary vertex decays from heavy flavour particles will have large positive impact parameter w.r.t. primary vertex
- Light flavour primary decays will have small negative and positive impact parameter due to resolution effects
- Jet direction given by direction of jet or estimate of struck quark direction. Restrict to regions with high jet fractions (> 80%).
- Match tracks to jet axis in \( \phi \) or \( \eta - \phi \) depending on low/high \( Q^2 \).
For each track within each jet, plot DCA to primary vertex in $r\phi$ plane ($\delta$)

Tracks required to have $|\delta| < 1$ mm (remove e.g. $K^0$s).
Significance Distributions \( S_i = \frac{\delta}{\sigma(\delta)} \)

Define 3 significance distributions as:

- \( S_1 \) - highest significance track
- \( S_2 \) - 2\(^{nd}\) highest absolute significance track
- \( S_3 \) - 3\(^{rd}\) highest absolute significance track

Further reduce light quark background

→ Only consider \( S_2 \) events if they have the same significance sign as \( S_1 \).
→ Only consider \( S_3 \) events if they have the same significance sign as \( S_1, S_2 \)

Similar technique used at high \( Q^2 \) with \( S_1 \) and \( S_2 \) only due to higher \( b \) fraction.
Separation improved
Could fit these distributions but would be sensitive to systematic uncertainties in resolution from dominating uds contribution.
Negative Subtraction for $S_i$

Subtract the negative $S_i$ bins from the positive for both data and MC to reduce sensitivity to resolution of light quarks

Small reduction in statistical accuracy for $c$ and $b$
Fitting Method

Three parameter fit

- MC scale factor $c$ - $P_c$
- MC scale factor $b$ - $P_b$
- MC scale factor $uds$ - $P_l$

to

- $S_1, S_2$ and $S_3$
- All events in each $x, Q^2$ bin ($N_{\text{data TOT}}, N_{\text{MC uds TOT}}, N_{\text{MC c TOT}}, N_{\text{MC b TOT}}$)

$$\frac{d\sigma^{c\bar{c}}}{dx \, dQ^2} = \frac{d\sigma}{P_c N_c^{\text{MC gen}}} + \frac{P_c N_c^{\text{MC gen}}}{P_b N_b^{\text{MC gen}}} + \frac{P_b N_b^{\text{MC gen}}}{P_l N_l^{\text{MC gen}}}$$

'Reduced' cross section

$$\bar{\sigma}^{c\bar{c}}(x, Q^2) = \frac{d^2\sigma^{c\bar{c}}}{dx \, dQ^2} \frac{x Q^4}{2\pi \alpha^2 (1 + (1 - y)^2)}$$
Consistent results with H1 and ZEUS $D^*$ measurements.

Consistent with QCD predictions.

MRST04 - NLO QCD Variable FNS

CTEQ6HQ - NLO QCD Variable FNS

CCFM - Cascade MC
First measurements of inclusive $b\bar{b}$ cross section
Large differences in NLO QCD predictions at low $Q^2$.
Threshold treatments? Gluon density?
Data errors consistent with all QCD predictions.
MRST04 - NLO QCD Variable FNS
CTEQ6HQ - NLO QCD Variable FNS
CCFM - Cascade MC
In this kinematic range:

Charm contributes around 15 – 30% of the total cross section.

Beauty contributes 0.3 – 3.5%.

Threshold effect!

Reasonable description by NLO QCD
Conversion to $F_{2}^{c\bar{c}}$ and $F_{2}^{b\bar{b}}$

$$\frac{d\sigma^{c\bar{c}}}{dxdQ^2} = \frac{2\pi\alpha^2}{xQ^4}((1 + (1 - y)^2)F_{2}^{c\bar{c}} - y^2F_{L}^{c\bar{c}}),$$

Use NLO QCD expectation for small contribution of $F_{L}^{c\bar{c}}$. For lower $x$ i.e. higher $y$ bins 3% (5%) correction for $c(b)$.

**Bin centre Correction**

Bin centre correction using NLO fit. Corrections 2% – 3%.
$F_2^{q\bar{q}}$ vs $Q^2$

**HERA $F_2^{c\bar{c}}$**

![Graph showing $F_2^{c\bar{c}}$ vs $Q^2$](image)

- $x = 0.00003 \times 4^{26}$
- $x = 0.00005 \times 4^{19}$
- $x = 0.00007 \times 4^{16}$
- $x = 0.00013 \times 4^{17}$
- $x = 0.00018 \times 4^{16}$
- $x = 0.0003 \times 4^{15}$
- $x = 0.00035 \times 4^{14}$
- $x = 0.0005 \times 4^{13}$
- $x = 0.001 \times 4^{12}$
- $x = 0.0008 \times 4^{11}$
- $x = 0.00015 \times 4^{10}$
- $x = 0.0012 \times 4^{9}$
- $x = 0.0006 \times 4^{8}$
- $x = 0.003 \times 4^{7}$
- $x = 0.0004 \times 4^{6}$
- $x = 0.006 \times 4^{5}$
- $x = 0.008 \times 4^{4}$
- $x = 0.012 \times 4^{3}$
- $x = 0.006 \times 4^{2}$
- $x = 0.032 \times 4^{0}$

**Comparison with NNLO calculation**

The charm data more precise than spread of predictions.
Reasonable agreement between experimental methods
Large difference in predictions from different QCD calculations for inclusive predictions.
Perhaps improves agreement for final state calculations?
As yet no final state NLO program that works with VFNS-PDFs available.
Summary

- Measurements of $F_{2}^{c\bar{c}}$ and $F_{2}^{b\bar{b}}$ at HERA
- Measurement of Inclusive $c$ and $b$ cross sections using technique based on lifetime of the heavy quark decay products presented
- New $F_{2}^{c\bar{c}}$ results compatible with $D^*$ method
- $F_{2}^{c\bar{c}}(x, Q^2)$ measurements more precise than spread in NLO QCD predictions.
- Large differences in predictions for $F_{2}^{b\bar{b}}(x, Q^2)$. We require final state predictions using latest theory!
- HERA-II. Improve statistical precision, especially at high $Q^2$. 