H1 Measurements of $F_2$, $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$

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$F_2$ Measurements at low $Q^2$

Measurement of $F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$

Experimental method

Results at medium and high $Q^2$
Deep Inelastic Scattering

Neutral Current

Electron $l$ scattering off proton $p$ produces virtual photon $Q^2$, which interacts with proton to produce final state electron $l'$.

- cms energy $\sqrt{s} = \sqrt{(l + p)^2}$
- $\gamma$ virtuality $Q^2 = -(l - l')^2$
- Bjorken variable $x = \frac{Q^2}{2p \cdot (l - l')}$
- Inelasticity $y \approx \frac{Q^2}{xs}$

$$\frac{d^2\sigma}{dx \, dQ^2} = \frac{2\pi \alpha^2}{x \, Q^4} [(1 + (1 - y)^2) F_2(x, Q^2) - y^2 F_L(x, Q^2)]$$
Accessible Phase Space

- medium-high $Q^2$
  - asymptotic freedom
  - perturbative QCD
- low $Q^2$
  - transition to soft hadronic physics
  - $\alpha_s(Q^2)$ becomes large
  - phenomenological models
The H1 Detector

\[ Q^2 = 2E_e E'_e (1 + \cos \theta_e) \]

standard DIS in LAr Calorimeter:
\[ Q^2 \gtrsim 100 \text{ GeV}^2 \]

SpaCal
\[ 2 \lesssim Q^2 \lesssim 100 \text{ GeV}^2 \]

possibilities to reach lower \( Q^2 \):

- extend to larger polar angles \( \theta_e \)
- use events with lower initial electron energy \( E_e \)
$F_2$ at low $Q^2$: Experimental Techniques

- Initial State Radiation (ISR)
- QED Compton (QEDC)
- Shifted Vertex Runs
  - larger $\theta_e$

Diagram:
- Nominal IP
- Shifted IP
- BST
- SpaCal
- $70\text{ cm}$
Untagged ISR in Shifted Vertex Runs

- $\gamma$ is undetected
- Photoproduction background rejected by BST

- Reconstruction of initial electron energy by $E - p_z$:

$$2E_e = (E - p_z)_{e'} + (E - p_z)_{\text{had}}$$
Untagged ISR in Shifted Vertex Runs: $F_2$

- ISR extends shifted vertex measurement at low $Q^2$ to higher $x$
- Difference between reduced cross section and $F_2$ at low $x$ allows $F_L$ measurement

$\Rightarrow$ ISR extends shifted vertex measurement at low $Q^2$ to higher $x$
Inelastic QED Compton Events

\[ e + p \rightarrow e + \gamma + X \]

- smaller \( \theta \) of the final state electron and photon
- larger \( \theta \) of the intermediate electron \( \Rightarrow \) access to low \( Q^2 \)

- DIS background: \( \pi^0 \) fakes QEDC photon
  - dominates at low \( x \)
Inelastic QED Compton Events: $F_2$

$Q^2 = 0.5 \text{ GeV}^2$

$Q^2 = 2 \text{ GeV}^2$

$Q^2 = 7 \text{ GeV}^2$

⇒ high $x$: overlap with fixed target experiments, good agreement
$F_2^{c\bar{c}}$ and $F_2^{b\bar{b}}$ Measurement

Goal: measure structure function for heavy quarks as inclusively as possible

⇒ use impact parameter of as many tracks as possible

two $Q^2$ regions:

- high $Q^2$: scattered electron in LAr: $Q^2 > 150$ GeV$^2$
  - high beauty fraction ($\sim 3\%$)
  - high $p_t$ of hadronic final state

- medium $Q^2$: scattered electron in Spacal: $3.75 < Q^2 < 60$ GeV$^2$
  experimentally much more difficult!

⇒ details and plots in the following for medium $Q^2$ analysis
\( F_2^{c\bar{c}} \) and \( F_2^{b\bar{b}} \): Experimental Method

Study the signed impact parameter in the \( r\phi \) plane for all tracks with precise measurement from Central Silicon Tracker (CST)

\[
\begin{align*}
\alpha < \pi/2 & \rightarrow \delta = +|\delta| \\
\alpha > \pi/2 & \rightarrow \delta = -|\delta| 
\end{align*}
\]

- **sign** determination needs a reference axis approximating the original quark direction

Events with decays of long-lived **heavy flavour** particles will have large positive impact parameters w.r.t. the primary vertex

Light flavour primary decays will have small negative and positive impact parameters due to resolution effects
The H1 Central Silicon Tracker

- 2 cylindrical layers of double-sided silicon strip detectors surrounding the beam pipe
- radii 5.7 cm and 9.7 cm
- angular coverage: $30^\circ < \theta < 150^\circ$
- hit resolution: 12 $\mu$m in $r\phi$, 25 $\mu$m in $z$
- impact parameter resolution (for central tracks with CST hits in both layers):
  \[ 33 \mu m \oplus \frac{90 \mu m}{p_T} \text{[GeV]} \]
- hit efficiency: 97% for $r\phi$ hits
Determination of Reference Axis: Jets vs. HFS

two possible methods to determine the reference axis:

- jet axis of the highest $p_T$ jet
- four-vector of the Hadronic Final State:
  $\varphi_{\text{ref.axis}}$ approximated by opposite $\varphi$ to electron

jet measurement much more precise than HFS

$\Rightarrow$ jet cuts as low as possible to have high jet fraction

- inclusive $k_T$ algorithm in the lab frame
- $p_T > 4$ GeV
- $15^\circ < \theta < 155^\circ$

low jet fraction at low $Q^2$ due to small $p_T$ of hadrons
Impact Parameter and Significance

- tracks matched to reference axis within $\Delta \varphi_{\text{ref.axis}} < \pi/2$
- for matched tracks, plot impact parameter $\delta$ in $r\varphi$ plane
  cut $|\delta| < 0.1$ cm to remove e.g. $K^0$s
- significance of each track given by $S_i = \delta / \sigma_\delta$

Impact Parameter

![Impact Parameter Graph]

Significance

![Significance Graph]
Significance Distributions

at medium $Q^2$ beauty fraction is smaller than at high $Q^2$

⇒ need 3 distributions to separate $b$, $c$, and $uds$ (2 at high $Q^2$)

- $S_1$ signif. of highest significance track
- $S_2$ signif. of 2nd highest significance track with same sign as $S_1$
- $S_3$ signif. of 3rd highest significance track with same sign as $S_1$ and $S_2$
'Negatively Subtracted' Significance Distributions

subtract bins at negative $S_i$ from the corresponding positive bin
⇒ reduce sensitivity to resolution effects

for each $x - Q^2$ bin fit simultaneously the subtracted $S_i$ distributions and the total number of inclusive events before the CST track selection with 3 parameters:

- $P_c$ scale factor for charm MC (RAPGAP) $P_c = 1.34 \pm 0.06$
- $P_b$ scale factor for beauty MC (RAPGAP) $P_b = 1.43 \pm 0.17$
- $P_l$ scale factor for light quark MC (DJANGO) $P_l = 1.16 \pm 0.01$
Extraction of Cross Section Fractions, $F_{2}^{c\bar{c}}$ and $F_{2}^{b\bar{b}}$

- reduced charm cross section $\tilde{\sigma}^{c\bar{c}}$:
  \[
  \tilde{\sigma}^{c\bar{c}}(x, Q^{2}) = \tilde{\sigma}(x, Q^{2}) \frac{P_{c}N_{c}^{\text{MCgen}}}{P_{c}N_{c}^{\text{MCgen}} + P_{b}N_{b}^{\text{MCgen}} + P_{l}N_{l}^{\text{MCgen}}}
  \]
  $\tilde{\sigma}(x, Q^{2})$ taken from the inclusive H1 measurement

- charm cross section fraction:
  \[
  f^{c\bar{c}} = \frac{\tilde{\sigma}^{c\bar{c}}}{\tilde{\sigma}}
  \]

- charm structure function $F_{2}^{c\bar{c}}$:
  \[
  \tilde{\sigma}^{c\bar{c}} = F_{2}^{c\bar{c}} - \frac{y^{2}}{1+(1-y)^{2}}F_{L}^{c\bar{c}}
  \]
  $F_{L}^{c\bar{c}}$ estimated from the NLO QCD expectation
Charm Structure Function $F_{2}^{c\bar{c}}$

- results consistent with H1 and ZEUS $D^*$ measurements
- consistent with pQCD predictions
- highest $Q^2 F_{2}^{c\bar{c}}$ measurement for H1

theory curves:
MRST04 - Variable FNS
CTEQ6HQ - Variable FNS
CCFM - Massive BGF
Beauty Structure Function $F_2^{b\bar{b}}$

- first $F_2^{b\bar{b}}$ measurement
- lowest $Q^2$ point consistent with zero
- consistent with pQCD predictions
- MRST04 preferred by data

theory curves:
MRST04 - Variable FNS
CTEQ6HQ - Variable FNS
CCFM - Massive BGF
$F_{2cc}^c$ and $F_{2bb}^b$ vs. $Q^2$
Cross Section Fractions $f^{c\bar{c}}$ and $f^{b\bar{b}}$

- $f^{q\bar{q}} = \frac{\sigma^{q\bar{q}}}{\sigma}$
- $c$ and $b$ fractions increase with $Q^2$
- $c$ fraction up to $\sim 30$
- $b$ fraction up to $\sim 3$

theory curves:
MRST04 - Variable FNS
Summary

- phase space for $F_2$ measurements at low $Q^2$ extended by special techniques like untagged ISR in shifted vertex runs and inelastic QEDC scattering

- inclusive measurement of $F_{2c\bar{c}}$ and $F_{2b\bar{b}}$ at medium and high $Q^2$ using impact parameter method
  - first measurement of $F_{2b\bar{b}}$
  - measurements well described by pQCD