Measurements of the Proton Structure Function $F_2$ at Low $Q^2$ at HERA

- Deep Inelastic Scattering at HERA
- Initial State Radiation Events
- QED Compton Scattering

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Deep Inelastic Scattering

Neutral Current

\[ l \rightarrow l' \]
\[ \gamma^* \rightarrow xp \]

Electron
Proton

\[ Q^2 = -(l - l')^2 \]

Bjorken variable
\[ x = \frac{Q^2}{2p \cdot (l - l')} \]

Inelasticity
\[ y \approx \frac{Q^2}{xs} \]

Invariant mass of the hadronic final state
\[ W = \sqrt{\frac{Q^2}{x} \frac{1 - x}{x} + m_p^2} \]

\[ \frac{d^2\sigma}{dx dQ^2} = \frac{2\pi\alpha^2}{Q^4x} (Y_+ F_2(x, Q^2) - y^2 \cdot F_L(x, Q^2)) \]

\[ Y_+ = 1 + (1 - y)^2 \]

\( \text{cms energy} \quad \sqrt{s} = \sqrt{(l + p)^2} \approx 300/320 \text{ GeV} \)
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
Accessible Phase Space

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Experimental Techniques to Access Low $Q^2$

Possibilities to access lower $Q^2$:

- larger polar angles
- lower initial electron energy

$$Q_e^2 = 2E_e E'_e (1 + \cos \theta_e)$$

- standard DIS in main detector:
  $$Q^2 > 2 \text{ GeV}^2$$
Experimental Techniques to Access Low $Q^2$

A

Nominal IP

Shifted IP

BST

SpaCal

$70 \text{ cm}$

Shifted Vertex Runs

larger $\theta_e$

B

Initial State Radiation (ISR)

$E_e \rightarrow E_e - E_\gamma$

C

QED Compton (QEDC)

$X$

larger $\theta_e$

$p$  
l

$p'$

$q$

$k$

$l$
**Inelastic QED Compton Events**

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

- smaller polar angle of final state e and \( \gamma \)
- larger polar angle of the intermediate e

\[ \Rightarrow \text{access to low } Q^2 \]

- DIS background: \( \pi^0 \) fakes QEDC \( \gamma \)
  - dominates QEDC signature at low x
Medium - high $x$ are measured

- understanding of hadronic final state at low $W$
- use of SOPHIA Monte Carlo model
F_2 Measurement with QEDC Events

\begin{itemize}
  \item good agreement with fixed target experiments
\end{itemize}
Initial State Radiation (ISR)

• $\gamma$ is radiated from incoming $e$
• equivalent to inclusive DIS at reduced $s = 4(E_e - E_\gamma)E_p$
• $Q^2 = sxy$
  $\Rightarrow$ larger $x$ at fixed $Q^2$

Previous ISR measurements:
• $\gamma$ directly detected
Untagged ISR in Shifted Vertex (H1)

Kinematics:

• $E - p_z$ is used to determine initial electron energy

\[ 2(E_e - E_\gamma) = (E - p_z)_{\text{had}} + (E - p_z)_{e'} \]

• $\gamma$ is undetected
• $\gamma p$ background rejected by BST
F₂ in Shifted Vertex ISR

\[ \sigma = F_2 - y F_L \]

\( Q^2 = 0.35 \text{ GeV}^2 \)
\( Q^2 = 0.5 \text{ GeV}^2 \)
\( Q^2 = 0.65 \text{ GeV}^2 \)
\( Q^2 = 0.85 \text{ GeV}^2 \)

- H1 svtx00 ISR prel.
- ZEUS BPT97
- NMC
- H1 QEDC97
- H1 svtx00 prel.

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shifted vertex measurement extended to larger x
Improved Extraction of $\lambda(Q^2)$

- rise of $F_2$ for $x < 0.01$ well parameterised by:
  $$F_2(x, Q^2) = c(Q^2)x^{-\lambda(Q^2)}$$

- at $Q^2 \gtrsim 3 \text{GeV}^2$
  $$\lambda \propto \ln Q^2, \ c \approx \text{const}$$
  partonic degrees of freedom

- at $Q^2 \lesssim 0.5 \text{GeV}$
  $$\lambda(Q^2) \rightarrow 0.08$$
  hadronic degrees of freedom

new data cover transition region
Summary

New measurements of $F_2$ at low $Q^2$
which extend the accessible phase space towards larger $x$

Inelastic QEDC scattering

$0.5 < Q^2 < 7 \text{ GeV}^2$
$2 \cdot 10^{-3} \lesssim x \lesssim 0.1$

- good agreement with fixed target data
- better modelling of the hadronic final state

Untagged ISR in shifted vertex

$0.35 < Q^2 < 0.85 \text{ GeV}^2$
$10^{-4} \lesssim x \lesssim 5 \cdot 10^{-3}$

- improved extraction of $\lambda(Q^2)$
Backup Transparencies
Previous Results at low $Q^2$

$Q^2 = 0.35$ GeV$^2$, $Q^2 = 0.5$ GeV$^2$, $Q^2 = 0.65$ GeV$^2$

$Q^2 = 0.85$ GeV$^2$, $Q^2 = 1.2$ GeV$^2$, $Q^2 = 1.5$ GeV$^2$

$Q^2 = 2$ GeV$^2$, $Q^2 = 2.5$ GeV$^2$, $Q^2 = 3.5$ GeV$^2$

- H1 svtx00 prelim.
- H1 99 prelim.
- H1 97
- NMC
- ZEUS BPT97

Fractal Fit
ALLM97
H1 QCD Fit
$Q^2_{\text{min}} = 3.5$ GeV$^2$
Rise of $F_2$ at Low $x$

- derivative independent of $x$ for $x < 0.01$
- rise of $F_2$ well parameterised by

$$F_2(x, Q^2) = c(Q^2)x^{-\lambda(Q^2)}$$