Scaled momentum spectra in Deep Inelastic Scattering at HERA

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1 Introduction
   - Deep Inelastic Scattering (DIS)
   - Motivation

2 Review of data
   - $e^+ e^-$ experiment
   - $ep$ experiment

3 Analysis
   - DIS selection
   - Comparison with theoretical models
   - Comparison between $ep$ and $e^+ e^-$

4 Summary
The Breit frame is defined by two conditions:

- proton and virtual photon are moving collinearly;
- virtual photon doesn’t carry the energy, only momentum.

**Brick wall**

- before scattering: $xP = \left( \frac{Q}{2}, 0, 0, \frac{Q}{2} \right)$
- after scattering: $xP = \left( \frac{Q}{2}, 0, 0, -\frac{Q}{2} \right)$

**DIS variables**

- $Q^2 = -q^2$, where $q$ is the 4-momentum of photon
- $xP$ is 4-momentum of parton from proton
Definition of $x_p$ and $\xi$

**Definitions**

\[ x_p = \frac{2P^{Breit}}{Q} \]

\[ \xi = \ln\left(\frac{1}{x_p}\right) \]

- $x_p$ is the particle momentum measured in the Breit frame scaled by $\frac{Q}{2}$ so by max available momentum (effects connected with internal $k_T$ of quark in proton are ignored)

Momentum space in the Breit frame
Measurements of $x_p$ distribution as a test of QCD

Quantum Chromodynamics

- QCD predictions for $x_p$ distributions are based on:
  \[ f(x, Q^2) \otimes \sigma_{NLO} \otimes D(x_p, Q^2) \]
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### Quantum Chromodynamics

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- $f(x, Q^2)$ – proton parton density
- $\sigma_{NLO}$ – hard-scattering cross section
- $D(x_p, Q^2)$ – fragmentation function (FF), which describes probability for a parton to fragment into a hadron carrying a given fraction of the parton’s energy, $x_p$
Comparison $ep$ and $e^+e^-$

Current region in the Breit frame in $ep$ is similar to the one of the hemispheres in $e^+e^-$. 
Distributions for charged particles are investigated in the wide $Q = \sqrt{s}$ range.

- 14 GeV < $\sqrt{s}$ < 202 GeV comes from 3 $e^+e^-$ experiments
- 4 GeV < $Q$ < 170 GeV new ZEUS data (from one experiment only)
ZEUS Collaboration – published results

Old data
- Luminosity 38 pb\(^{-1}\)
- Uncertainty related to the massless assumption in FF:
  \[ \sim 1/(1 + (m/Qx)^2), \quad 0.1 < m < 1.0 \]

Aim of new studies
- Update this result using \( \sim 0.44 \) fb\(^{-1}\)
- Concentrate on \( Q^2 > 160 \) GeV\(^2\) region
DIS and particle selection

**Experimental data**
- collected in 1996 - 2007 (≈ 0.44 fb\(^{-1}\))
- central tracking detector used, \(P_T > 0.15 \text{ GeV}, |\eta| < 1.75\)

**Monte Carlo**
- ARIADNE 4.12 and LEPTO 6.5
- All the particles with a lifetime larger than 0.01 ns (0.3 cm)
- Treated as stable particles: \(\Lambda, \Sigma^+_u, \Sigma^+_d, \Omega, K_s\)
Sample preparation

Samples were prepared using formula:

\[ 10 \times 2^n < Q^2 < 10 \times 2^{n+1}, \text{ where } n = 0, 1, 2, \ldots \]

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Good agreement with the published HERA results.

The mean charged multiplicity is given by the integral of distributions.

The peak moves to larger $\ln(1/x_p)$ with increasing $Q^2$.

Both LEPTO and ARIADNE should be improved at higher $Q^2$. At medium $Q^2$ LEPTO overestimates the data. At low $Q^2$ ARIADNE underestimates the data.
MLLA QCD

- Modified Leading Log Approximation (MLLA):
  - describes parton production in terms of a shower evolution
  - includes colour coherence and gluon interference effects

- According to MLLA predictions, function $D(\xi(x_p))$ is roughly Gauss distribution.

- LEP data have been fitted with 2 free parameters: $\Lambda_{\text{eff}} = Q_0$ and $K_h$.

- From LEP I – LEP II fits:
  - $\Lambda_{\text{eff}} = 270 \pm 20$ MeV
  - $K_h = 1.31 \pm 0.03$

Parameters used from LEP fits (MLLA + LPHD).

Λ_{eff} value agrees with the value Λ_{eff} = 275 \pm 4(stat.)^{+4}_{-8}(syst.)\ MeV deduced from a ZEUS analyses of scaled momenta in dijet photoproduction.

The long tails come from mass corrections.

low Q^2 – large differences; medium Q^2 – small differences although BGF contribution is big; high Q^2 – large differences again (unexpected);
Scaling violation is observed.

The data are generally well reproduced by LEPTO and ARIADNE in the lowest bins in $Q^2$.

At high $Q^2$ and medium $x_p$ both MCs underestimate the data.

At high $Q^2$ and large $x_p$ ARIADNE is above the data whereas LEPTO is below it.
NLO predictions

Used FF

- "Kretzer FF" (2000)
  - $Z^0$-pole data from ALEPH, SLD and low-energy TPC data
  - fitted both identified hadrons ($\pi$, K) and inclusive spectra

- "KKP FF" (Kniehl, Kramer, Pötter) (2000)
  - $Z^0$-pole data from ALEPH, SLD, TPC + DELPHI, OPAL three-jet data

- "AKK FF" (Albino, Kniehl, Kramer) (2005)
  - update of KKP FF + OPAL results on light-quark tag used to constrain individual light-quark FF ($d, s \rightarrow K^{+-}$)
NLO+FF cannot fully describe the data for the entire $x_p$ range.

Scaling violation larger than predicted.
**ZETUS**

- **ZEUS 38 pb$^{-1}$**
- **ZEUS 440 pb$^{-1}$**
- **H1 44 pb$^{-1}$**
- **$e^+e^-$**

$Q$ (GeV): $10^{-2}$ to $10^2$

- $x_p$ range
  - $0.0 - 0.02$ (x30)
  - $0.02 - 0.05$ (x5)
  - $0.05 - 0.1$ (x2)
  - $0.1 - 0.2$
  - $0.2 - 0.3$
  - $0.3 - 0.4$
  - $0.4 - 0.5$
  - $0.5 - 0.7$
  - $0.7 - 1.0$

**ep data compared with $e^+e^-$ annihilation data and H1 experiment**

**the agreement supports fragmentation universality**
DIS selection
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$ep$ data compared with $e^+e^-$ annihilation data and H1 experiment
Some differences between $ep$ and $e^+e^-$ are visible.
Conclusions

- HERA provides high-precision data FFs with large coverage in energy scale $10 < Q^2 < 41000$.
- Scaling violation is demonstrated using data from one experiment only ($440 \text{ pb}^{-1}$).
- The measurements broadly support the concept of quark fragmentation universality.
- MC and analytical MLLA+LPHD QCD calculations cannot reproduce the data in the entire range of $x_p$ and $Q^2$. 
Thank you for your attention