Scaled momentum spectra in Deep Inelastic Scattering at HERA

B. Brzozowska
University of Warsaw

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   - Motivation
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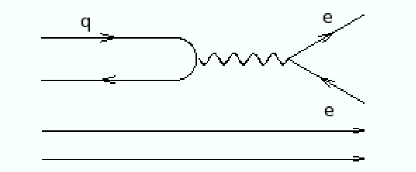
   - e^+e^- experiment
   - ep experiment
3. Analysis
   - DIS selection
   - Comparison with theoretical models
   - Comparison between ep and e^+e^-
4. Summary

Breit frame

The Breit frame is defined by two conditions:

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

current region



target region

Brick wall

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

DIS variables

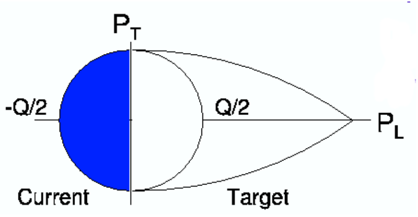
- $Q^2 = -q^2$, where q is the 4-momentum of photon
- xP is 4-momentum of parton from proton

Definition of x_p and ξ

Definitions

$$x_p = \frac{2P^{Breit}}{Q}$$

$$\xi = \ln(\frac{1}{x_p})$$



Momentum space in the Breit frame

- 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)

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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- σ_{NLO} – hard-scattering cross section

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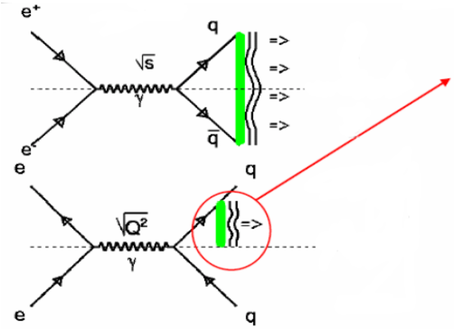
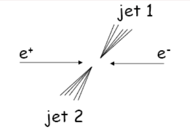
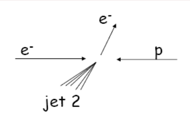
- $f(x, Q^2)$ – proton parton density
- σ_{NLO} – hard-scattering cross section
- $D(x_p, Q^2)$ – fragmentation function (FF), which describes probability for a parton to fragment into a hadron carrying a given fraction of the parton's energy, x_p

Comparison ep and e^+e^-

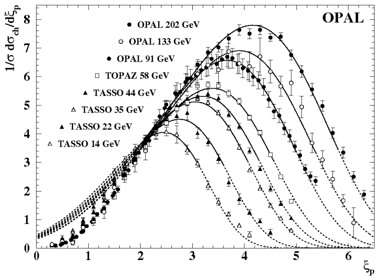


Current region in the Breit frame in ep is similar to the one of the hemispheres in e^+e^-.





OPAL Collaboration

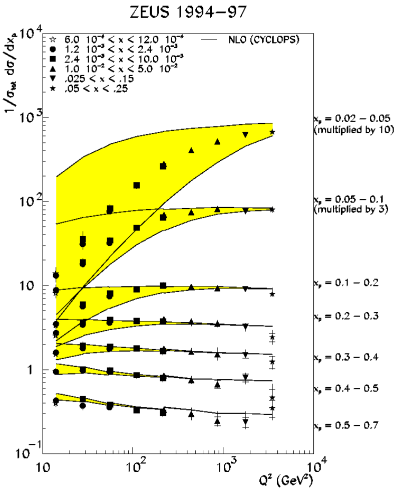


Distributions of $\xi_p = \ln(\frac{1}{x_p})$

- 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 $\sim 0.44\ \mathrm{fb}^{-1}$
- Concentrate on $Q^2 > 160\ \mathrm{GeV}^2$ region

DIS and particle selection

Experimental data

- collected in 1996 - 2007 ($\sim 0.44\ \mathrm{fb}^{-1}$)
- central tracking detector used, $P_T > 0.15\ GeV$, $|\eta| < 1.75$

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: Λ, Σ_u^+, Σ_d^+, Ω, K_s

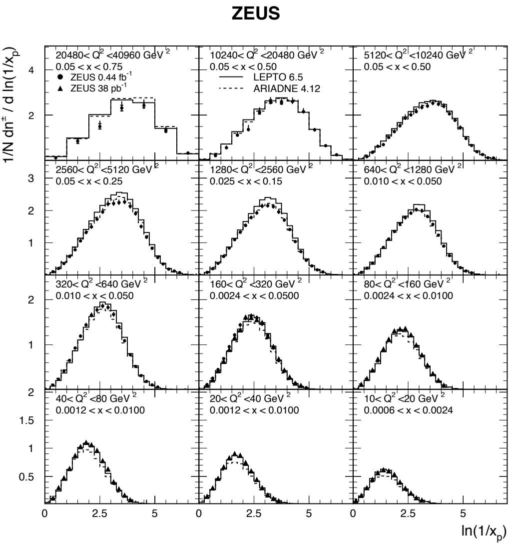
Sample preparation

Published (94-97)

Bin	Q2 min	Q2 max	X min	X max
1	10	20	0.0006	0.0024
2	20	40	0.0012	0.0100
3	40	80	0.0012	0.0100
4	80	160	0.0024	0.0100
5	160	320	0.0024	0.0500
6	320	640	0.0100	0.0500
7	640	1280	0.0100	0.0500
8	1280	2560	0.0250	0.1500
9	2560	5120	0.0500	0.2500
10	5120	10240	0.0500	0.5000
11	10240	20480	0.0500	0.5000
12	20480	40960	0.0500	0.7500

This analysis

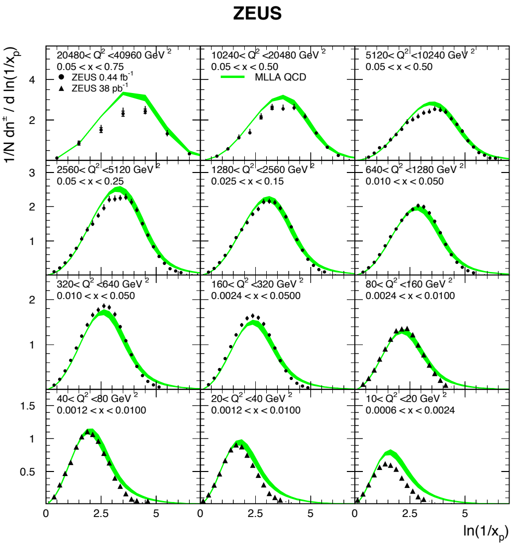
Samples were prepared using formula:
$10 \times 2^n < Q^2 < 10 \times 2^{n+1}$, where $n = 0, 1, 2, \ldots$



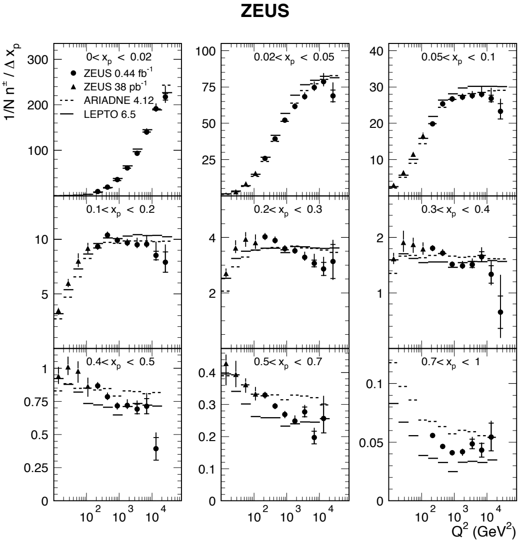
- Good agreement with the published HERA results.
- The mean charged multiplicity is given by the integral of distributions.
- The peak moves to larger $ln(1/x_p)$ with increasing Q^2.
- Both LEPTO and ARIADNE should be improved at higher Q^2. At medium Q^2 LEPTO overestimates the data. At low Q^2 ARIADNE 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: $\Lambda_{eff} = Q_0$ and K_h.
- **From LEP I – LEP II fits:**
  – $\mathbf{\Lambda_{eff} = 270 \pm 20}$ MeV
  – $\mathbf{K_h = 1.31 \pm 0.03}$
  V.Khoze, S.Lupia, W.Ochs (Phys.Lett. B386 (1996) 451-457)



- Parameters used from LEP fits (MLLA + LPHD).
- Λ_{eff} value agrees with the value $\Lambda_{eff} = 275 \pm 4(stat.)^{+4}_{-8}(syst.)$ 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.

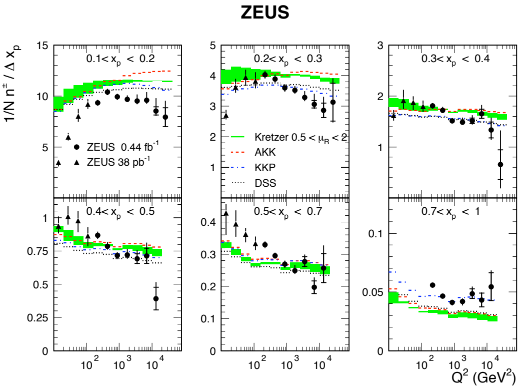
At high Q^2 and medium x_p both MCs underestimate the data.

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

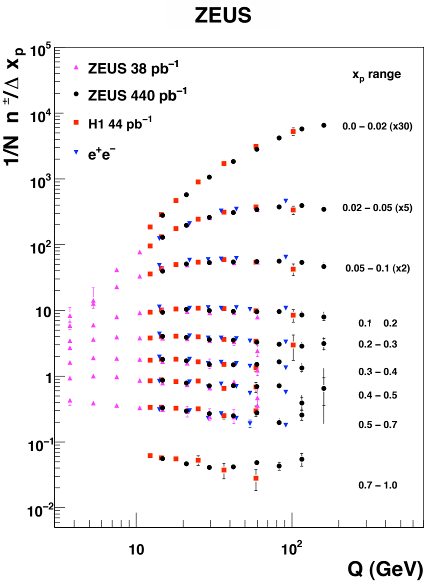
NLO predictions

Used FF

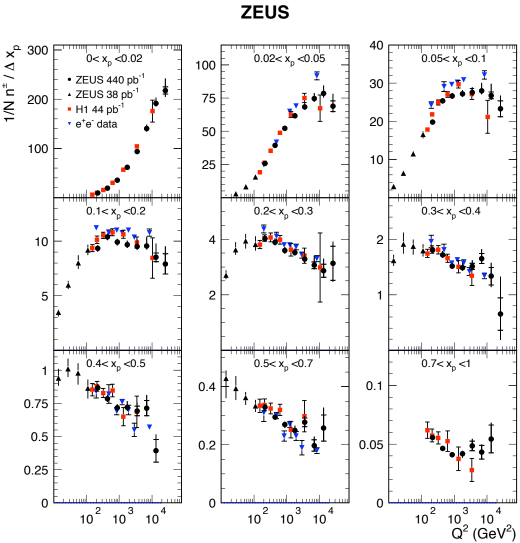
- "Kretzer FF" (2000)
  – Z^0-pole data from ALEPH, SLD and low-energy TPC data
  – fitted both identified hadrons (π, K) and inclusive spectra
- "KKP FF" (Kniehl, Kramer, Pötter) (2000)
  – Z^0-pole data from ALEPH, SLD, TPC + DELPHI, OPAL three-jet data
- "AKK FF" (Albino, Kniehl, Kramer) (2005)
  – 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.



- ep data compared with e^+e^- annihilation data and H1 experiment
- the agreement supports fragmentation universality



- *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 ($440\ \mathrm{pb}^{-1}$).
- 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