# Scaled momentum spectra in the current region
## of the Breit frame at HERA

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on behalf of the ZEUS Collaboration

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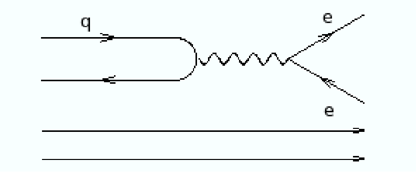
# Breit frame

**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**

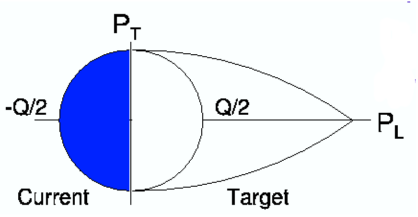
– $Q^2 = -q^2$, where $q$ is the 4-momentum of photon
– $xP$ is 4-momentum of parton from proton

# Definition of $x_p$ and $\xi$

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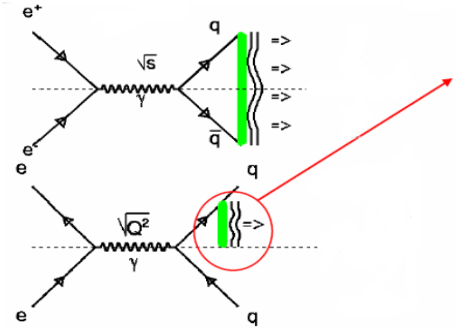
- $f(x, Q^2)$ – proton parton density
- $\sigma_{NLO}$ – hard-scattering cross section
- $D(x_p, Q^2)$ – fragmentation function (FF), which describes probability for a parton to fragment into a hadron carrying a given fraction of the parton's energy

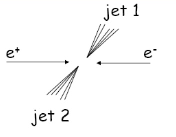
# NLO QCD + FF

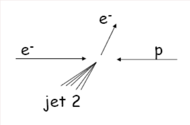
- Like parton densities, fragmentation functions can be evolved with the hard scale using DGLAP from a starting distribution. Experimental input at low scale is necessary.
- Factorization theorem guarantees that FF are independent of the process.
- $\alpha_s$ can be determined from scaling violations expressed as the $Q^2$ evolution of the $x_p$ spectra.
  - It was already done in $e^+e^-$. It was not done at HERA.
  - It is not plagued by uncertainties associated with jet algorithms and PDF uncertainties.
  - It is essential to know FF.

# Comparison $ep$ and $e^+e^-$

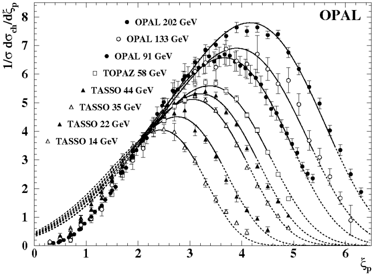



Current region in the Breit frame in $ep$ is similar to the one of the hemispheres in $e^+e^-$.



# OPAL Collaboration

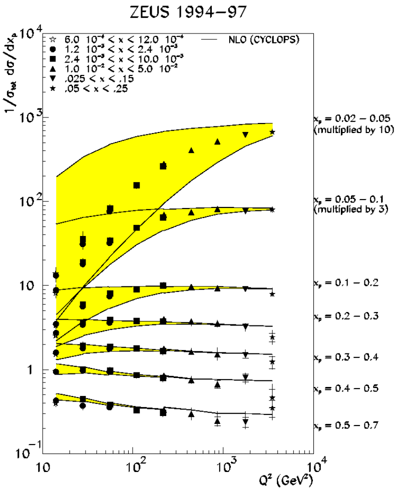



Distributions of $\xi_p = \ln(\frac{1}{x_p})$

- Distributions for charged particles can be investigated in the wide $Q^2$ range.
- 14 GeV$< E^* <$ 202 GeV describes data from three experiments

5 GeV$< E^* = Q <$ 170 GeV
new ZEUS data
(from one experiment only)

# ZEUS Collaboration – published results




## Old data

- Luminosity 38 $\mathrm{pb}^{-1}$
- 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 $\sim 0.5\ \mathrm{fb}^{-1}$
- Concentrate on $Q^2 > 160\ \mathrm{GeV}^2$ region

# DIS and particle selection

## Experimental data

- collected in 1996 - 2007 ($\sim$ 0.5 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: $\Lambda$, $\Sigma_u^+$, $\Sigma_d^+$, $\Omega$, $K_s$

# Corrections

## Detector corrections

- increasing with $Q^2$
- very large for soft particles, i.e.for large $\ln(\frac{1}{x_p})$ - (do not care, no events)

## QED corrections

- for $\ln(\frac{1}{x_p})$ and $x_p$ distributions around 1

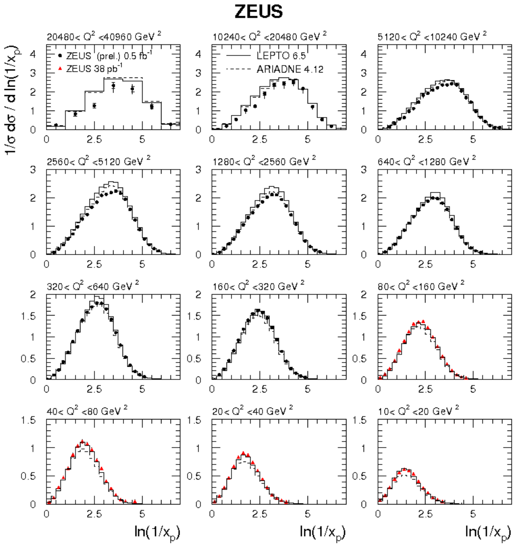
# Sample preparation

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

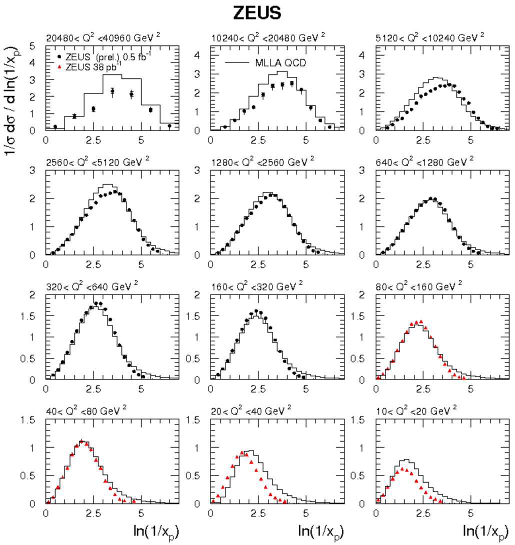
Samples were prepared using formula:
$10 \times 2^n < Q^2 < 10 \times 2^{n+1}$, where $n = 0, 1, 2, \ldots$



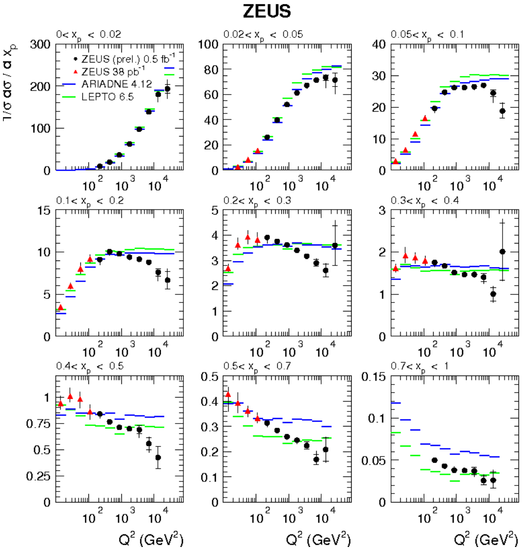

- Good agreement with the published HERA results.
- Both LEPTO and ARIADNE should be improved esp. at higher $Q^2$.

# MLLA QCD

- Modified Leading Log Approximation (MLLA):
  – calculates inclusive characteristics up to $\alpha_s^{1/2}$
  – contains free parameters: $\Lambda_{eff}$ and $Q_0$ cut-off
- According to MLLA predictions function $D(\xi(x_p))$ should be described by Gauss distribution.
- In the past, LEP data have been fitted with 2 free parameters: $\Lambda_{eff} = Q_0$ and $K_h$.
- **From LEP I – LEP II fits:**
  – $\mathbf{\Lambda_{eff} = 270}$ **MeV**
  – $\mathbf{K_h = 1.31}$
  V.Khoze, S.Lupia, W.Ochs (Phys.Lett. B386 (1996) 451-457)




- Parameters used from LEP fits (MLLA + LPHD).
- The limiting spectrum calculations fail to describe the data entire $\frac{Q}{2}$ range.
  1) Low energy: migrations of particles to the target region of the Breit frame.
  2) High energy: $K_h$ is energy dependent.

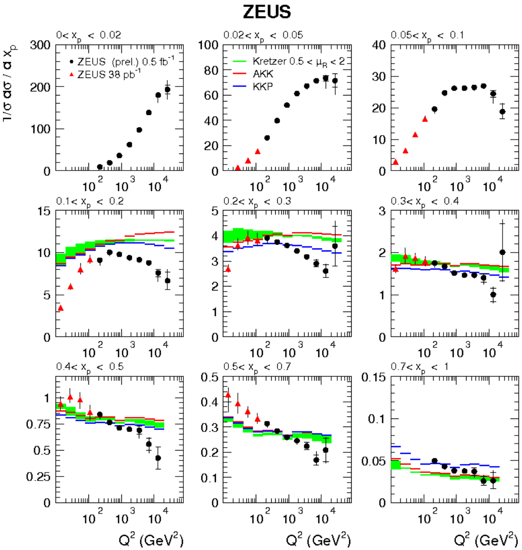



MCs fail to describe the data.

# 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

## Conclusions

- HERA provides high-precision data FFs with large coverage in energy scale from 2 to 90 GeV

$$(< Q^2 > \sim 15 \text{ - } 26\,000 \; GeV^2 ).$$

- MC and analytical MLLA+LPHD QCD calculations cannot reproduce the data in the entire range of $x_p$ and $Q^2$.
- NLO+FF predictions do not describe the $x_p$ momentum distributions as function of $Q^2$:
  - Description does not improve even at $x_p > 0.3$, where the theory should be reliable.
  - Small differences between different FFs.

## Thank you for your attention