Charged Particle Distributions in DIS and Photoproduction at HERA

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Scaled Momentum Spectra in deep inelastic Scattering at HERA
(ZEUS, DESY-09-229 accepted by JHEP)

Observation of the Hadronic Final State Charge Asymmetry in High Q^2 Deep-Inelastic Scattering at HERA

Scaled momentum distributions of charged particles in dijet photoproduction at HERA
(JHEP08(2009)077)

Transverse Momentum of Charged Particles at low Q^2 at HERA
(H1prelim-10-035)
Motivation

• Tests of factorisation and the universality of fragmentation by
  • direct tests: Compare the same measurements (e.g. Fragmentation functions) from different experiments (Zeus, H1, CDF, OPAL, etc...) with each other.
  • Indirect tests: Compare a variety of measurements with the same theory (Monte Carlo, MLLA, NLO+FF). Monte Carlo and NLO Fragmentation function parameterisations fitted to $e^+e^-$ annihilation data. MLLA parameters taken from global fit to all data.

• Non DGLAP behaviour of parton dynamics
  • Go to area of phase space that is expected to be sensitive to DGLAP / BFKL / CCFM differences (low $Q^2$, low $x$ DIS) and compare data to different model predictions.
Usable luminosity per experiment ~500 pb\(^{-1}\)

H1 and ZEUS are general purpose detectors with extensive tracking and calorimetry coverage.

Usable luminosity per experiment ~500 pb\(^{-1}\)
Inclusive Deep Inelastic Scattering (DIS)

\[ Q^2 > 1 \text{ GeV}^2 \]

- "virtuality" 
  \[ Q^2 = -q^2 \]
- "inelasticity" 
  \[ y = E_Y/E_e \]
- relationship 
  \[ Q^2 = s x_{Bj} y \]

\[ \sqrt{s} = 318 \text{ GeV} \]

Dijet Photoproduction (\(\gamma p\))

\[ Q^2 \approx 0 \text{ GeV}^2 \]

The dijet system used to characterises the event kinematics
Inclusive Deep Inelastic Scattering (DIS)

Breit Frame

\[ ep \rightarrow eX \]

\[ e^+e^- \rightarrow q\bar{q} \]

\[ x_p = \frac{2P_h}{Q} \]

- Virtual photon doesn't carry any energy only longitudinal momentum \((P_z)\)
- Provides clearest separation between particles from hard scattering and proton remnant. Allows for easy comparison with \(e^+e^-\) data
- \(x_p\) is the particle momentum in the Breit frame scaled by the energy scale in current region \((Q/2)\).

As \(Q\) increases distribution gets softer, i.e. more tracks with small share of initial scale.
Inclusive Deep Inelastic Scattering (DIS)

**ZEUS**

![Graphs showing data for different x_p ranges](image)

- **Data**
  - 0.44 fb^{-1}
  - Event Selection:
    - $10 < Q^2 < 41,000$ GeV^2
    - $y > 0.04$

- **Detector Track Selection**
  - $|\eta| < 1.75$
  - $p_{t,lab} > 0.15$ GeV

On the whole the comparison with H1 data and with e^+e^- results supports fragmentation universality.

Significant differences at high $Q^2$ and low $x_p$ between ep and e^+e^-.

Due to Breit frame boost ep experiments can measure the $x_p$ spectra down to 0.

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Inclusive Deep Inelastic Scattering (DIS)

Full perturbative NLO QCD calculation combined with NLO Fragmentation functions which are parameterisations of $e^+e^-$. NLO calculations do not provide a good description of the data. Slope of the $Q^2$ dependence, scaling violation, are too small in theory!
Inclusive Deep Inelastic Scattering (DIS)

Fragmentation effects dominate at low $x_p$. Hadrons at large $x_p$ expected come from the hard interaction.

At high $Q^2$ and high $x_{\text{BJ}}$ significant contribution from valence quarks. Expect charge asymmetry in quarks from hard interaction. Is it visible after hadronisation?

$$A(x_p) = \frac{D^+(x_p) - D^-(x_p)}{D(x_p)}$$

Charge asymmetry observed, increasing with $x_p$ (also with $Q^2$, not shown)

Asymmetry described by Monte Carlo models

The results are consistent with the expectation that at high $x_p$ the asymmetry is directly related to the valence quark content of the proton.
Dijet Photoproduction (γp)

Data
~23,000 events
L=359 pb⁻¹

Event Selection
E_{Tjet1,2} ≥ 17 GeV
|η_{Jet1,2}| < 1.0
E_{Tjet1}/E_{Tjet2} ≥ 0.8
0.9π ≤ |Φ_{Jet1}-Φ_{Jet2}|
E_{Tjet3} ≤ 6 GeV
|η_{Jet3}| ≤ 2.4
0.2 ≤ y ≤ 0.8
Q² ≤ 1 GeV²
x_{γ} ≥ 0.75

Detector Track Selection
P_T ≥ 0.15 GeV
|η| ≤ 1.7

Select back to back dijets, suppress 3rd jet.
energy scale E_{jet} = M_{jj}/2

\[ ξ = ln\left(\frac{E_{jet}}{|p_{track}|}\right) \]

Opening angle around jet axis (θ_c) links tracks to a particular jet (only results with θ_c = 0.23 considered here)

Fit the ξ distribution with;
Gaussian around mean or full MLLA+LPHD theory.

Compare results from e^+e^-, ep, γp and p\overline{p}

Jets found with kT algorithm, longitudinal invariant inclusive mode, R=1

\( θ_c = 0.23 \)
Dijet Photoproduction ($\gamma p$)

MLLA approximation to pQCD is a resummation approach where a subset of dominant terms in $\alpha_s$ are used to predict the shape of $\xi$

$\Lambda_{\text{eff}}$ scale cut off independent of process considered!

$\kappa_{\text{ch}}$ - normalisation factor to take into account fraction of neutral hadrons - independent of process considered

Fit Gaussian $\pm 1$ around peak.
For each $E_{\text{jet}}$ interval extract the peak position.

$$\Lambda_{\text{eff}} = \frac{E_{\text{jet}} \sin(\theta_c)}{\exp(\sqrt{0.87 + 2\xi_{\text{peak}} - 0.54})^2} \quad @\text{LO}$$

or fit MLLA equation to all 5 energy points and extract $\Lambda_{\text{eff}}$
When MLLA theory is used to extract a value for $\Lambda_{\text{eff}}$, the extracted values of $\Lambda_{\text{eff}}$ using only ZEUS data are not consistent with the global fit.

A linear fit using ZEUS data only produces a result that is consistent with the global fit to all data.

$\xi_{\text{peak}} = \frac{1}{2} Y + \sqrt{cY} - c, \ Y = \ln \left( \frac{\mu \sin \theta_c}{\Lambda_{\text{eff}}} \right)$

$c = 0.29, \ \Lambda_{\text{eff}} = 246 \pm 3 \text{ MeV}$

$\chi^2 / \text{dof} = 2.20$

$\xi_{\text{peak}} = A \ln(\mu \sin(\theta_c)) + B$

$A = 0.682 \pm 0.007$

$B = 1.009 \pm 0.019$

$\chi^2 / \text{dof} = 0.77$

Characteristic energy scale = $\mu$

Approximately linear relationship expected between $\xi_{\text{peak}}$ and $\ln(\mu \sin(\theta_c))$
Dijet Photoproduction (γp)

**ZEUS**

- ZEUS γp, $\theta_c = 0.23$
- ZEUS ep, $\theta_c = \pi/2$
- CDF pp, $\theta_c = 0.28$
- OPAL ee, $\theta_c = \pi/2$
- L3 ee, $\theta_c = \pi/2$

**Extract energy dependence of $\Lambda_{\text{eff}}$ for data points**

$\frac{\mu}{2} \sin \theta_c = \frac{1}{2} Y + \sqrt{c Y - c}$, $Y = \ln \frac{\mu}{\Lambda_{\text{eff}}}$

**ZEUS γp data shows no dependence on $\mu$, there is a small dependence on $\theta_c$ (not shown)**

A weak dependence on $\mu$ and on $\theta_c$ is reported for the CDF data. This could explain the failure of global fit to match ZEUS data only fit.

$\theta_c$: Opening angle around jet axis.
DGLAP: \( Q_0^2 \ll k_{T1}^2 \ll \ldots \ll k_{Tn}^2 \ll Q^2 \)

Strong ordering in \( k_T \) of emitted partons, works when \( Q^2 \) is large and \( x \) not too small. Implemented in RAPGAP Monte Carlo.

CDM (Colour Dipole Model): Produces weak ordering in parton \( k_T \) emission. Not evolution equation but gives BFKL like final state, works for small \( x \). Used in DJANGOH Monte Carlo.

CCFM: random “walk” in \( k_T \) of emitted partons. Valid for both small and large \( x \). Used in the CASCADE Monte Carlo.
Beyond DGLAP (DIS)

H1 Preliminary

- H1 data (prelim.)
- RAPGAP
- DJANGO
- CASCADE

Djangoh (CDM) describes new data for whole $p_T^*$ spectra.

Rapgap (DGLAP) is below the data $p_T^* > 1$ GeV.

Cascade (CCFM) is systematically above the data.

$p_T^*$ in hadronic centre of mass frame
Beyond DGLAP (DIS)

Charged particles with $p_T^* < 1$ GeV

Strong sensitivity to hadronisation parameters.
Weak sensitivity to different parton dynamics.

Charged particles with $p_T^* > 1$ GeV

Weaker sensitivity to hadronisation parameters.
Stronger sensitivity to different parton dynamics.

$\eta^*$ in hadronic centre of mass frame
Beyond DGLAP (DIS)

Charged particles with $p_T^* > 1$ GeV

Rapgap (DGLAP) is below the data for most of the phase space.

Djangoh (CDM) gives a better description of the data at low $Q^2$ and low $x$

$\eta^*$ in hadronic centre of mass frame
Summary

• Charged particle spectra have been measured in DIS and photoproduction at HERA.

• In general the results are found to support the concept of quark fragmentation universality. However, there exists significant differences when comparing NLO QCD predictions to the data.

• The observed charge asymmetry is consistent with that expected from the valence quarks in the proton.

• At low x DIS, the CDM model is found to provide a better description of parton dynamics indicating that the emission of partons is not strongly ordered in $k_T$. 
Backup
Central Tracking Detector
15° < θ < 164°
microvertex detector
7° < θ < 150°

Uranium Scintillator Calorimeter (Electromagnetic and Hadronic)
2.2° < θ < 176.5°

Central Drift Chamber
20° < θ < 165°
silicon vertex detector
30° < θ < 150°

LAr Calorimeter
-1.4 < η < 3.4

SpaCal Calorimeter
153° < θ < 178°

convert to angle!
Frame of reference

In the Breit frame, QCD radiation generates $E_T$

In the Breit frame, QCD radiation generates $E_T$

No jets in Breit frame!

No jets in Breit frame!

No $E_T$, No jets in Breit frame!

No $E_T$, No jets in Breit frame!

0'th order $\alpha_s$

0'th order $\alpha_s$

no hard QCD radiation

no hard QCD radiation

One jet in Lab frame

One jet in Lab frame

$\frac{Q^2}{x}$

$\frac{Q^2}{x}$

Born level

Born level

LAB

LAB

order $\alpha_s^2$, NLO pQCD

order $\alpha_s^2$, NLO pQCD

$e^+$

$e^+$

$\xi p$

$\xi p$

$\alpha_s$

$\alpha_s$

$\alpha_s$

$\alpha_s$

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At low $Q^2$ (low $x_{Bj}$) all $x_p$, asymmetry $\sim 0$

As $Q^2$ increases asymmetry develops at high $x_p$, low $x_p$ it remains $\sim 0$

Monte Carlo models are able to describe the magnitude and evolution of the asymmetry
The Gaussian fit method

Peak position, $\xi_{\text{peak}}$
- Fit Gaussian $\pm 1$ around mean.
- $\forall \, \xi$, independently measure $\xi_{\text{peak}}$.

$$\Lambda_{\text{eff}} = \frac{E_{\text{Jet}} \sin(\theta_c)}{e^{\left(\sqrt{0.87 + 2\xi_{\text{peak}} - 0.54}\right)^2}} \quad (@ \, \text{LO})$$

Measuring $\Lambda_{\text{eff}}$
- Only use $\theta_c = 0.23$ energy points:
  - Different $\theta_c$ values are correlated;
  - MLLA looses validity at large $\theta_c$.
- Fit equation to all 5 energy points.

$$\Lambda_{\text{eff}} = 275 \pm 4 \, \text{(stat.)}^{+4}_{-8} \, \text{(syst.) MeV}$$
The MLLA + LPHD fit method

Momentum distribution of partons from a gluon is given by:

\[ \lim_{x \to 0} D_{g-Jet} \left( \ln \left( \frac{1}{x_p} \right), Y \right) = \frac{4 C_f}{b} \Gamma(B) \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} e^{-B \alpha} \left[ \frac{\cosh \alpha + (1 - 2\zeta) \sinh \alpha}{4 N_c} \frac{Y}{\sinh \alpha} \right]^{B/2} \]

\[ \cdot I_B \left( \sqrt{\frac{16 N_c}{b}} Y \frac{\alpha}{\sinh \alpha} \left[ \cosh \alpha + (1 - 2\zeta) \sinh \alpha \right] \right) \frac{d\tau}{\pi} \]

Valid for: \( \ln \left( \frac{1}{x_p} \right) \leq \ln \left( \frac{1}{x_p} \right) \leq \ln \left( \frac{M_{2j}}{2P_0} \right) \) \( P_0 \) = Upper bound

For number of flavours, \( N_f = 3 \), and number of colours, \( N_c = 3 \)

- \( C_f = \frac{9}{4}, b = 9, B = 1.247 \).
- \( I_B \) is the modified Bessel function of order \( B \).
- \( \alpha = \alpha_0 + i \tau \), where \( \alpha_0 \) is determined by \( \tanh \alpha_0 = 2\zeta - 1 \).
- \( \zeta = 1 - \frac{\ln \left( \frac{1}{x_p} \right)}{Y} \) and \( Y = \ln \left( \frac{E_{Jet} \sin(\theta_c)}{\Lambda_{eff}} \right) \)

\[ \lim_{q \to Jet} D_{q-Jet} = \frac{1}{r} \lim_{g \to Jet} D_{g-Jet} \]