Inclusive Properties of Hadronic Final States at HERA

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Presented Results

Measurement of Azimuthal Asymmetries in NC DIS.
hep-ex 0608053 (Zeus Collab., S. Chekanov et al., Eur. Phys. J. C51 (2007) 289-299)

Measurement of Event Shape Variables in DIS.
hep-ex 0512014 (H1 Collab., A. Aktas et al., Eur. Phys. J. C46 (2006) 343-356)

Charged Particle production in High Q2 DIS.
hep-ex 0706.2456

Scaled Momentum Spectra in the Current Region of the Breit Frame. (ZEUS Preliminary)
Phase Space

Similar phase space for all analyses

Azimuthal Asymmetries
100 < $Q^2$ < 8,000 GeV$^2$
0.2 < $y$ < 0.8
0.01 < $x$ < 0.1
Energy Flow Objects
$P_t > 0.15$ GeV, $\theta > 8^\circ$.

Event Shapes
196 < $Q^2$ < 40,000 GeV$^2$
0.1 < $y$ < 0.7
Energy Flow
$4^\circ < \theta < 177^\circ$

calo + tracks

Scaled Momentum (H1)
100 < $Q^2$ < 20,000 GeV$^2$
0.05 < $y$ < 0.6
Charged Particles
$P_t > 0.12$ GeV, $20^\circ < \theta < 165^\circ$

Scaled Momentum (ZEUS)
160 < $Q^2$ < 40,960 GeV$^2$
0.0024 < $x$ < 0.75
Charged Particles
$P_t > 0.15$ GeV, $20^\circ < \theta < 164^\circ$

High $Q^2$ (>100 GeV$^2$), reasonably large $x$
→ single large scale “Q”, good place to test pQCD
Phenomenology

Monte-Carlo (LO ME)

LEPTO (Parton Showers + String)
ARIADNE (Colour Dipole Model + String)

NLO pQCD

Azimuthal Asymmetries

NLO - DISENT
phenomenological had corr (MC)

Event shapes
NLO - DISASTER + DISPATCH
NLL resummation - DISRESUM
analytical Power Corrections

Scaled Momentum
NLO - CYCLOPS
Fragmentation Functions - e^+e^- fits
\[
\frac{d\sigma^{ep\rightarrow ehX}}{d\phi} = A + B \cos \phi + C \cos 2\phi + D \sin \phi + E \sin 2\phi
\]

\[
< \cos \phi > = \frac{B}{2A} \quad < \sin \phi > = \frac{D}{2A}
\]

\[
< \cos 2\phi > = \frac{C}{2A} \quad < \sin 2\phi > = \frac{E}{2A}
\]
The ZEUS Collaboration: Measurement of azimuthal asymmetries in neutral current deep inelastic scattering

Fig. 3. The ZEUS Collaboration measured azimuthal asymmetries in neutral current deep inelastic scattering. The plots show the dependence of the asymmetries on the HCM (hadron center of mass) variable for different ranges in pseudorapidity ($\eta$) and azimuthal angle ($\phi$). The data points are compared with predictions from various theoretical models, including NLO + hadr. corr., LEPTO, and ARIADNE.
Born Level ($\alpha_s^0$), current quark has no $E_T$
Jets in the Breit frame are $O(\alpha_s)$

Provides clearest separation between particles from hard scattering and proton remnant.
Allows for easy comparison with $e^+e^-$ data

current region energy scale is $Q$

\[ \tau = 1 - T_\gamma \text{ with } T_\gamma = \frac{\sum_h |\vec{p}_{z,h}|}{\sum_h |\vec{p}_h|} \]
\[ \tau_C = 1 - T_C \text{ - thrust along the axis maximising } T \text{ (like in } e^+e^-) \]
\[ B = \frac{\sum_h |\vec{p}_{h,h}|}{2 \sum_h |\vec{p}_h|} \text{ - Jet Broadening} \]
\[ \rho = \frac{(\sum_h E_h)^2 - (\sum_h \vec{p}_h)^2}{(2 \sum_h |\vec{p}_h|)^2} \text{ - Jet inv. mass} \]
\[ C = \frac{3}{2} \frac{\sum_{h,h'} |\vec{p}_h||\vec{p}_{h'}| \sin^2 \theta_{h,h'}}{(\sum_h |\vec{p}_h|)^2} \]

sums extend over all particles (energy flow) in current hemisphere of the Breit frame

$\rightarrow 0$ for Born Level
$> 0$ for higher orders
H1 Data

- $<Q> = 15$ GeV ($\times 20^5$)
- $<Q> = 18$ GeV ($\times 20^5$)
- $<Q> = 24$ GeV ($\times 20^5$)
- $<Q> = 37$ GeV ($\times 20^5$)
- $<Q> = 58$ GeV ($\times 20^5$)
- $<Q> = 81$ GeV ($\times 20^5$)
- $<Q> = 116$ GeV ($\times 20^5$)

- NLO($\alpha_s^2$)+NLL+PC (fitted)
- NLO($\alpha_s^2$)+NLL+PC (extrapolated)
Event Shapes

Fit of NLO+NLL+PC to data
Theory has limited range of applicability

Extrapolation of fit to “unsafe” regions seems to work

Except for highest Q bin experimental errors really small.

$\tau_c = 1 - T_c$ : Thrust along the axis Maximising $T$
\( \alpha_0: \) effective non-perturbative coupling from power corrections. Theory expects \( \approx 0.5 \)

\[
\alpha_0 = 0.476 \pm 0.008 \text{(exp)} + 0.018 \text{(theo)}
\]

\( \alpha_0 \) universal to about \( \pm 10\% \)

\[
\alpha_s(m_Z) = 0.1198 \pm 0.0013 \text{(exp)} + 0.0056 \text{(theo)},
\]
Scaled Momentum

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

\[ D(x_p) = \frac{1}{N_{\text{event}}} \frac{dn}{dx_p} \]

- \( x_p = \) scaled momentum variable
- \( Q/2 = \) Scale in current region of Breit Frame
- \( p_h = \) momentum of charged particle in current region of Breit frame
- \( D(x_p) = \) event normalised, charged particle, scaled momentum distribution

As \( Q \) increases \( D(x_p) \) gets softer, i.e. more tracks with small share of initial scale.
Pretty good agreement between ep and e^+e^-!

High $Q^2$ and small $x_p$.

Reason unclear.

Low $Q^2$, mid $x_p$.

Expected to be due to BGF kinematics producing empty current region.

NB: suppressed zeros.
Pretty good agreement between ep and e⁺e⁻!

high Q² and small xₚ, reason unclear

low Q², mid xₚ, expected to be due to BGF kinematics producing empty current region

NB: suppressed zeros
Scaled Momentum

Pretty good agreement between ep and e^+e^-!

high Q^2 and small x_p
reason unclear

low Q^2, mid x_p.
expected to be due to
BGF kinematics
producing empty
current region

NB: suppressed zeros
Scaled Momentum

Fragmentation functions (KKP, KRETZER, AKK) taken from fits to $e^+e^-$ data

Scale and PDF errors small

Sensitivity to different FF

NLO theory does not describe the scaling violations seen in data
**Scaled Momentum**

**ZEUS**

- **0.1 < x_p < 0.2**
- **0.2 < x_p < 0.3**
- **0.3 < x_p < 0.4**
- **0.4 < x_p < 0.5**
- **0.5 < x_p < 0.7**
- **0.7 < x_p < 1**

- Green curve: Kretzer 0.5 < \mu_R < 2
- Red line: AKK
- Blue line: KKP

**Q^2 (GeV^2)**

- **0 < x_p < 0.02**
- **0.05 < x_p < 0.1**
- **0.1 < x_p < 0.15**
- **0.15 < x_p < 0.2**
- **0.2 < x_p < 0.25**
- **0.25 < x_p < 0.3**
- **0.3 < x_p < 0.4**
- **0.4 < x_p < 0.5**
- **0.5 < x_p < 0.7**
- **0.7 < x_p < 1**

**Analysis:**
- Red points: old low Q^2 analysis
- Black points: new High Q^2 analysis
- Stats: ~0.5 fb^{-1}

**Similar picture as seen by H1**
Summary:
- Published H1 results
- Preliminary ZEUS data
- Selected $e^+e^-$ results
• HERA provides a rich source of data for studies of the hadronic final state.

• Azimuthal Asymmetries: NLO better than MC at describing data but still fails to describe the magnitude of the asymmetries.

• Event shapes: NLO + NLL + PC describe the data well. Power corrections give universal $\alpha_0$. Competitive value of $\alpha_s$ extracted, running of $\alpha_s$ also shown.

• Scaled Momentum: Broadly supports quark fragmentation universality between $e^+e^-$ and $ep$. NLO fails to describe the scaling violations seen in the data.
Backup
Event shapes in Breit Frame

- Event shapes $F$ are defined such that $F \rightarrow 0$ for pencil-like hadron configurations aligned with $z$-axis.
- Born level quark in Breit Frame has $p_T=0$ so its fragments produce $F \approx 0$
- Multijet configurations produce $F > 0$ in extreme $F \approx 1$

$$
\tau = 1 - \frac{\sum_{h} |\vec{p}_{z,h}|}{\sum_{h} |\vec{p}_{h}|}
$$

$B = \frac{\sum_{h} |\vec{p}_{t,h}|}{2 \sum_{h} |\vec{p}_{h}|}$

- $\tau$ : thrust $a \ la$ e$^+e^-$; $z$-axis maximizing thrust
- $B$ : Jet broadening
- $\rho$ : Jet invariant mass
- $C$ : C-parameter, hadron-hadron correlation

$$
C = \frac{3}{2} \frac{\sum_{h,h'} \vec{p}_h \cdot \vec{p}_{h'} \sin^2 \theta_{h,h}}{(\sum_{h} |\vec{p}_{h}|)^2}
$$

All event shapes are normalized to total momentum - less sensitive to uncertainty of hadronic calorimeter scale!

J. Turnau  Event Shapes
Power correction approach

★ Introduce effective non-pert. coupling $\alpha_0 = \frac{1}{\mu_I} \int_0^{\mu_I} \alpha_{\text{eff}}(k) dk$ ($\alpha_0 = \alpha_s$ at $\mu_I = 2\text{GeV}$)

 theory predicts universal $\alpha_0 \approx 0.5$

★ PC (Dokshitzer at al.): non-pert. corrections (suppressed by powers of $1/Q$) obtained from first principles

- for distributions $\frac{1}{\sigma} \frac{d\sigma(F)}{dF} = \frac{1}{\sigma} \frac{d\sigma^{\text{PQCD}}(F-a_F \mathcal{P})}{dF}$
- for mean values $\langle F \rangle = \langle F \rangle^{\text{PQCD}} + a_F \mathcal{P}$ (with universal PC term $\mathcal{P}$)

★ Complete description for $F$: NLO+NLL+PC

Recent progress in theory (as compared to previous round of event shape analyses in DIS) – resummation of large log terms and matching it to fixed order NLO (DISRESUM package by Dasgupta and Salam, 2002)

★ Limitations: very low $F$ ($F \leq a_F \mathcal{P} \sim \mu_I/Q$) and very high $F$ (substantial HO corr.)

Main aim of the analysis: check the validity of PC concept and universality of $\alpha_0$

By product: yet another method/observables to extract $\alpha_s(M_Z)$
\begin{align*}
\text{Scaled Momentum} \\
\text{(a)} & \quad Q_1 E^* (\text{GeV}) \\
\text{(b)} & \quad Q (\text{GeV})
\end{align*}
Scaled Momentum

\[
\frac{1}{N} \frac{dN}{dx_p} = f(Q) \quad \text{for} \quad 0 < x_p < 0.02
\]

\[
\frac{1}{N} \frac{dN}{dx_p} = f(Q) \quad \text{for} \quad 0.05 < x_p < 0.1
\]

\[
\frac{1}{N} \frac{dN}{dx_p} = f(Q) \quad \text{for} \quad 0.1 < x_p < 0.2
\]

\[
\frac{1}{N} \frac{dN}{dx_p} = f(Q) \quad \text{for} \quad 0.2 < x_p < 0.3
\]

\[
\frac{1}{N} \frac{dN}{dx_p} = f(Q) \quad \text{for} \quad 0.3 < x_p < 0.4
\]

\[
\frac{1}{N} \frac{dN}{dx_p} = f(Q) \quad \text{for} \quad 0.4 < x_p < 0.5
\]

\[
\frac{1}{N} \frac{dN}{dx_p} = f(Q) \quad \text{for} \quad 0.5 < x_p < 0.7
\]

\[
\frac{1}{N} \frac{dN}{dx_p} = f(Q) \quad \text{for} \quad 0.7 < x_p < 1.0
\]
Scaled Momentum

**ZEUS**

- $0 < x_p < 0.02$
- $0.02 < x_p < 0.05$
- $0.05 < x_p < 0.1$
- $0.1 < x_p < 0.2$
- $0.2 < x_p < 0.3$
- $0.3 < x_p < 0.4$
- $0.4 < x_p < 0.5$
- $0.5 < x_p < 0.7$
- $0.7 < x_p < 1$

**Graphs:**
- $1/\sigma d\sigma/dx_p$
- $Q^2 (\text{GeV}^2)$
- Data and predictions from different experiments:
  - ZEUS (prel.) 0.5 fb$^{-1}$
  - ZEUS 38 pb$^{-1}$
  - ARIADNE 4.12
  - LEPTO 6.5
Scaled Momentum

ZEUS

\[ \frac{1}{\sigma} \frac{d\sigma}{d \ln(1/x_p)} \]

- \(20480 < Q^2 < 40960 \text{ GeV}^2\)
- ZEUS (prel.) 0.5 fb\(^{-1}\)
- ZEUS 38 pb\(^{-1}\)
- MLLA QCD

- \(10240 < Q^2 < 20480 \text{ GeV}^2\)

- \(5120 < Q^2 < 10240 \text{ GeV}^2\)

- \(2560 < Q^2 < 5120 \text{ GeV}^2\)

- \(1280 < Q^2 < 2560 \text{ GeV}^2\)

- \(640 < Q^2 < 1280 \text{ GeV}^2\)

- \(320 < Q^2 < 640 \text{ GeV}^2\)

- \(160 < Q^2 < 320 \text{ GeV}^2\)

- \(80 < Q^2 < 160 \text{ GeV}^2\)

- \(40 < Q^2 < 80 \text{ GeV}^2\)

- \(20 < Q^2 < 40 \text{ GeV}^2\)

- \(10 < Q^2 < 20 \text{ GeV}^2\)