Azimuthal asymmetries, Subjets and Event shapes in DIS at HERA

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on behalf of

- Hadronic final states in NC DIS
- Azimuthal asymmetries and subjet distributions
- Event shape analysis
- Summary
The hadronic final state in NC DIS

Rich final states which reflect underlying QCD dynamics

- Particle spectra and $E$-flow
  - high statistics, large hadronisation effects
  - pQCD + phenomenological hadr.corr. (MC)

- High $E_T$ jets
  - limited statistics and phase space
  - pQCD; hard.corr. are small

- Event shapes
  - large statistics and phase space
  - pQCD + PC ($O(1/Q)$)
  (analytical approach to confinement from first principles)
Asimutual asymmetry in NC DIS

\[ \frac{d\sigma}{d\phi} = 2A\left( \frac{1}{2} + B \cos \phi + C \cos 2\phi + D \sin \phi + E \sin 2\phi \right) \]

\[ \langle \cos \phi \rangle = \frac{B}{2A} \quad \langle \sin \phi \rangle = \frac{D}{2A} \]

\[ \langle \cos 2\phi \rangle = \frac{C}{2A} \quad \langle \sin 2\phi \rangle = \frac{E}{2A} \]

Data \quad \mathcal{L} = 45 \text{ pb}^{-1}

100 < Q^2 < 8000 \text{ GeV}^2

0.2 < y < 0.8

0.01 < x < 0.1

\textbf{E-flow method} is used:

\[ \langle F(n\phi) \rangle = \frac{\sum_i E_{T,i} F(n\phi)}{\sum_i E_{T,i}} \]

★ The NLO is closer to the data as compared to LO Monte Carlo programs
Subjet distributions

$k_T$ alg. in Lab frame

$$E_T^{\text{jet}} > 14 \text{ GeV}$$

$$d_{\text{cut}} = y_{\text{cut}} \cdot (E_T^{\text{jet}})^2$$

$$y_{\text{cut}} = 0.05, n_{sj} = 2$$

**Aim:** study QCD parton radiation and transition from partons to jets of hadrons

★ NLO (DISENT) predictions describe all features of the data within $\pm 10\%$
Inclusive jets in the Breit frame are $\mathcal{O}(\alpha\alpha_s)$ at lowest order (current quark has no $E_T$).

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

In this analysis sums extend over all particles in current hemisphere of the Breit frame (for $K_{out}$ the region extended to $\eta < 3$).

Event shape variables

\[ \tau = 1 - T_\gamma \text{ with } T_\gamma = \frac{\sum_h |\vec{p}_{z,h}|}{\sum_h |\vec{p}_h|} \]

\[ \tau_C = 1 - T_C - \text{thrust along the axis maximising } T \text{ (like in } e^+e^-) \]

\[ B = \frac{\sum_h |\vec{p}_{h,h}|}{2 \sum_h |\vec{p}_h|} - \text{ Jet Broadening} \]

\[ \rho = \frac{(\sum_h E_h)^2 - (\sum_h \vec{p}_h)^2}{(2 \sum_h |\vec{p}_h|)^2} - \text{ Jet inv. mass} \]

\[ C = \frac{3}{2} \frac{\sum_{h,h'} |\vec{p}_h||\vec{p}_{h'}| \sin^2 \theta_{h,h'}}{\left( \sum_h |\vec{p}_h| \right)^2} \]

\[ K_{out} = \sum_h |p_h^{out}| \]

\[ \chi = \sum_{h,i} (\pi \cdot |\phi_h - \phi_i|) \]

\[ F \to 0 \text{ for Born level, } \]
\[ F > 0 \text{ in case of multijets } \]
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 \( \mu_I = 2\text{GeV} \))

(\text{theory predicts universal } \alpha_0 \simeq 0.5 \text{ )}

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

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

★ 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 \( F \) (\( F \leq a_F P \sim \mu_1/Q \)) 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 \( \alpha_s(M_Z) \)
• H1 and ZEUS data are in agreement, but somewhat different fit range used
• Not all points are used in the NLO+NLL+PC fit: theory has limited range of applicability
\(\alpha_s\) and \(\alpha_0\) from the fits to distributions

(1\(\sigma\) contours denote experimental errors alone; not shown are theoretical errors, \(\sim 10\%\), which dominate)

\[
\begin{align*}
\alpha_s(M_Z) &= 0.1198 \pm 0.0013 \text{(exp)} \pm 0.0056 \text{(th)} \\
\alpha_0 &= 0.476 \pm 0.008 \text{(exp)} \pm 0.018 \text{(th)}
\end{align*}
\]

- different error treatment in case of H1 and ZEUS
- extracted values of \(\alpha_s\) are in good agreement with world average (shown by yellow band)
\( \alpha_s \) and \( \alpha_0 \) from the fits to mean values

(Note different scales in case of H1 and ZEUS plots)

- Bigger spread in \( \alpha_s \) as compared to fits to distributions \( \Rightarrow \)
  indirect indication of the success of resummed theory

- With exception of thrust, H1 and ZEUS results display similar pattern:
  universal \( \alpha_0 \) within \( \pm 10\% \)
3-jet event shape observables

\[ K_{\text{out}} = \sum_h |p_h^{\text{out}}| \quad \chi = \sum_{h,i} (\pi - |\phi_h - \phi_i|) \]

In LO appear only due to non-perturbative effects, hence large sensitivity to NLO and to PC

★ No complete theoretical calculations for these variables available yet
★ MC models give fair description in the bulk of the phase space
High statistics HERA data on HFS in DIS provide stringent tests of pQCD.

- In most of the observables NLO effects give sizeable contribution.
- In many cases the dominant systematics comes from theory ⇒ need for NNLO.

Event shape means and distributions have been measured and analysed by both H1 and ZEUS collaborations.

- The measurements themselves are in good agreement between the experiments
- Obtained values of $\alpha_s(M_Z)$ are in agreement with world average
- 3-jet event shapes, sensitive to higher orders and non-perturbative effects, have been measured as well and are waiting for theoretical calculation.

★ The observed universality of $\alpha_O$ gives strong support for the concept of power corrections.
BACKUP SLIDES...
Fits to mean values

- Reminder: resummation is not applicable, as means contain ‘forbidden’ regions
- Significant positive PC values for all observables (except thrust along $\gamma^*$ axis in case of ZEUS)
Running $\alpha_s(Q)$

NLO($\alpha_s^2$)+NLL+PC
fits to DISTRIBUTIONS

$\alpha_s(m_Z)=0.1178$

$\alpha_s(M_Z) = 0.1178 \pm 0.0015^{+0.0081}_{-0.0061}(\text{theo})$
$(\alpha_s, \alpha_0)$ from fits to distributions in different matching schemes