Review of H1 results on the hadronic final state at HERA

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- QCD tests with the hadronic final states
- Azimuthal correlation of forward jets in DIS
- Hadroproduction in DIS
- Summary

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Deep inelastic scattering at HERA

**HERA (1992 – 2007):** electron (positron) – proton collider at DESY, Hamburg

- **e^+ / e^-**
- **p**

- **E_e = 27.6 GeV**
- **E_p = 920, 820, 575, 460 GeV**

Centre-of-mass energy up to $\sqrt{s} \sim 320$ GeV

Total lumi: $\sim 0.5$ fb$^{-1}$ per H1 and ZEUS experiment

**Standard DIS variables:**

- **$Q^2$** |virtuality| of the exchanged boson
- **$x$** fraction of proton momentum carried by struck quark in Quark Parton Model
- **$y = Q^2 / x \sigma$** inelasticity, fraction of lepton energy transferred in the proton rest frame
Measurements of the HFS in DIS are complementary to inclusive measurements
(structure of the proton, parton distribution functions PDF ...)

- Information on the gluon density in the proton
- Determination of $\alpha_S$
- Search for effects of parton dynamics beyond the standard DGLAP approach
- Mechanisms of hadroproduction ...
QCD dynamics at low Bjorken-x

HERA: DIS at low Bjorken-x down to $10^{-5}$ → energy in $\gamma^* p$ cms is large ($W_{\gamma^* p} \approx Q^2 / x$)

- long gluon cascades exchanged between the proton and the photon
- pQCD – multiparton emissions described only with approximations:
  - DGLAP evolution: resums terms $\sim (\alpha_S \ln Q^2)^n$
    Assumes strong ordering of parton $k_T$
  - BFKL evolution: resums terms $\sim (\alpha_S \ln(1/x))^n$
    No ordering in $k_T$, strong ordering in $x_i$
    Transition from DGLAP to BFKL scheme expected at low $x$
  - CCFM evolution: emitted partons are ordered in angles
    reproduces DGLAP at large $x$ and BFKL at $x \to 0$

Search at HERA for effects of parton dynamics beyond the standard DGLAP approach

- Strong rise of the proton structure function $F_2(x, Q^2)$ with decreasing $x$
  - well described by NLO DGLAP over a large range of $Q^2$
  $F_2$ measurement too inclusive to discriminate between different QCD evolution schemes
- Look at hadronic final states – reflecting kinematics, structure of gluon emissions
Low x phenomenology: Monte Carlo models with different QCD dynamics

**RAPGAP, Herwig++, DGLAP**

LO QCD matrix elements + HO modelled by leading log parton showers

**DJANGOH**

Colour Dipole Model

CDM: QCD radiation from the colour dipole formed by the struck quark and the proton remnant.

Chain of independently radiating dipoles formed by the emitted gluons.

**CASCADE - CCFM**

Off-shell QCD ME + parton emissions based on the CCFM equation

$k_t$ – factorisation

**Random Walk in $k_T$**

Angelic ordering of parton emissions

 Hadronisation parameters tuned to $e^+e^-$ data (ALEPH tune)
Mueller – Navelet jets in DIS (1990):

BFKL – more hard partons emitted close to the proton

Study high transverse momentum and high energy jets produced close to the proton (forward region in LAB)

Suppress standard DGLAP evolution in $Q^2$:

\[ p^2_{T,\text{fwdjet}} \approx Q^2 \]

Enhance BFKL evolution in $x$:

\[ x_{\text{fwdjet}} = \frac{E_{\text{fwdjet}}}{E_p} > 0.035, 0.5 < \frac{p^2_{T,\text{fwdjet}}}{Q^2} < 6.0 \]

H1 experiment, $L = 38.2$ pb$^{-1}$

<table>
<thead>
<tr>
<th>DIS selection</th>
<th>Jets reconstructed in the Breit frame and boosted to LAB, all cuts in LAB</th>
<th>η = - ln tan(θ/2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 &lt; y &lt; 0.75, 5 &lt; $Q^2$ &lt; 85 GeV$^2$</td>
<td>$p_{T,\text{fwdjet}} &gt; 6$ GeV, $1.73 &lt; \eta_{\text{fwdjet}} &lt; 2.79$</td>
<td>θ with respect to proton beam direction</td>
</tr>
<tr>
<td>0.0001 &lt; x &lt; 0.004</td>
<td>$x_{\text{fwdjet}} = \frac{E_{\text{fwdjet}}}{E_p} &gt; 0.035, 0.5 &lt; \frac{p^2_{T,\text{fwdjet}}}{Q^2} &lt; 6.0$</td>
<td></td>
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Measurement of the azimuthal angle difference $\Delta \phi$ between the scattered positron and the forward jet as a function of the rapidity distance $Y$ between them.
At higher Y corresponding to lower x the forward jet is more decorrelated from the scattered positron.

\[ Y = \ln \left( \frac{x_{\text{fwd jet}}}{x} \right) \] rapidity distance between the most forward jet and the scattered positron.

Cross sections best described by BFKL-like model CDM:
- DGLAP predictions below the data
- CCFM (set A0) as good description as CDM at large Y

The shapes of the \( \Delta \phi \) distributions are described equally well by all MC models.

\[ R = \left( \frac{1}{\sigma_{\text{MC}}} \frac{d\sigma}{d\Delta \phi} \right) / \left( \frac{1}{\sigma_{\text{data}}} \frac{d\sigma}{d\Delta \phi} \right) \]
Forward jet azimuthal correlations

Different splitting functions used in unintegrated gluon density function (uPDF):

- set A0 – only singular terms of the gluon splitting function
- set 2 – includes also non-singular terms

- Cross sections strongly depend on uPDF
- Shape of $\Delta \phi$ distributions
  - at low Y shows sensitivity to uPDF
  - well described by the set A0

Predictions of the CCFM model depend on the choice of uPDF
Dijet production at parton level in DIS at NLO($\alpha_S^2$)
Charged particle densities in DIS

The underlying dynamics of hadron production in high energy particle interaction is still not fully understood.

PDF  parton dynamics  hadronisation  →  hadronic final state

Different kinematic regions sensitive to different effects:

- low $p_T$ region  →  hadronisation effects dominate
- high $p_T$ region  →  sensitivity to parton evolution effects

Recent H1 results on charged particle spectra:

Charged particle density: test of QCD dynamics at low $x$

**DIS selection**
- $0.05 < y < 0.6$
- $5 < Q^2 < 100 \text{ GeV}^2$
- $0.0001 < x < 0.01$

**Charged particles**
- LAB frame: $-2 < \eta < 2.5$
  - $p_T > 150 \text{ MeV}$
- $\gamma^*p$ frame: $0 < \eta^* < 5$
  - $0 < p_T^* < 10 \text{ GeV}$

**Observables:**
- Charged particle densities vs. pseudorapidity $\eta^*$ and transverse momentum $p_T^*$

- $p_T^*$ dependence studied in two $\eta^*$ intervals:
  - $0 < \eta^* < 1.5$ central region $\rightarrow$ test of parton shower models
  - $1.5 < \eta^* < 5$ current region $\rightarrow$ large sensitivity to the hard scatter

- Target region $\eta^* < 0$ not accessible


Analysis in the virtual photon – proton ($\gamma^*p$) rest frame
measurements for two $p_T^*$ regions:

- $p_T^* < 1$ GeV
- $1 < p_T^* < 10$ GeV

First focus on the low and high $p_T$ regions for understanding the influence of hadronisation and parton evolution effects
Charged particle density: sensitivity to QCD dynamics

All models, except CASCADE (CCFM), describe the data within PDF uncertainties.

DJANGOH (CDM) provides the best description of the data.

Strong sensitivity to QCD dynamics at high transverse momentum $p_T^*$

EPJ C73 (2013) 2406
Charged particle density: DGLAP predictions for different PDFs

- All predictions are close to the data
- RAPGAP (LO ME + LL parton shower) with different NLO PDFs predicts similar results
- None of the predictions describe the data
- CTEQ6L(LO) is closest to the data

EPJ C73 (2013) 2406
Charged particle density: sensitivity to hadronisation schemes

- Sensitivity to the tuning of hadronisation parameters
- Data are best described by the ALEPH tune (e^+e^-)
- Little sensitivity to hadronisation
- None of the tunes describe the data
Study the effect from parton showers (central region) and from the hard scatter (current region).

- Predictions are sensitive to different parton shower dynamics at high $p_T^*$
- DJANGOH (CDM) provides a reasonable description of the data, other models fail $\rightarrow$ deviations are strongest in the central region
Charged particle $p_T^*$ spectra in bins of $Q^2$ and $x$

1.5 $< \eta^* < 5$

at high $Q^2$ RAPGAP (based on DGLAP) is almost as good as DJANGOH (CDM) at large $p_T^*$

the region most sensitive to the hard scatter
Summary

Azimuthal correlation of forward jets in DIS at HERA

- Cross sections as a function of $\Delta \phi$ and rapidity separation between the forward jet and the scattered positron are best described by the BFKL – like model CDM
- The shapes of the $\Delta \phi$ distributions are equally well described by LO MC models with different QCD evolution schemes
- NLO DGLAP predictions are in general below the data, but still in agreement within the large theoretical uncertainties

Measurements of charged particle spectra in DIS at HERA

- Transverse momentum and pseudorapidity distributions in the hadronic centre-of-mass system were measured in $ep$ collisions at low $Q^2$ for $\sqrt{s} = 319 \text{ GeV}$
- The data are compared to QCD models with different parton evolution dynamics (DGLAP, CDM, CCFM) and with different hadronisation schemes
- DGLAP-based models are below the data especially at high $p_T^*$ and low $\eta^*$
- CDM provides a reasonable description of the data
backup
Forward and central jet cross sections $d\sigma / d\Delta \phi$

- Subsample of events with forward jet + additional central jet
  
  $p_{T,cenjet} > 4 \text{ GeV}, \quad -1 < \eta_{cenjet} < 1$
  
  $\Delta \eta = \eta_{fwdjet} - \eta_{cenjet} > 2$ (enhance radiation between the forward and central jet)

- $\Delta \phi$ still between the forward jet and the scattered positron

**NLO $O(\alpha_s^2)$ predictions**

- at low $Y$ reasonable description of the data
- at high $Y$, central value to small but still within theory uncertainty
- large scale uncertainty (of up to 40%) indicates importance of higher order contributions

**NLOJET++**

PDF : CTEQ6.6, $\alpha_s(M_Z) = 0.118$

$\mu_r^2 = \mu_f^2 = (\langle p_T^2 \rangle + Q^2) / 2$

$\langle p_T \rangle = 0.5 \left( p_{T,\ fwdjet} + p_{T,\ cenjet} \right)$
Forward jet production at NLO BFKL


BFKL kernel at NLO accuracy, jet vertex & photon impact factor using LO approximation

\[ <\cos 2\Delta \phi> \]

Results for forward jets with ZEUS cuts

\[
\begin{align*}
20 &< Q^2 < 100 \text{ GeV}^2 \\
0.05 &< y < 0.7 \\
4 \times 10^{-4} &< x_{\text{Bj}} < 5 \times 10^{-3} \\
0.5 &< \frac{p_t^2}{Q^2} < 2.0
\end{align*}
\]

\[ \Delta \phi = \phi_{\text{el}} - \phi_{\text{fwdjet}} \]

\[ Y = \ln \left( \frac{x_{\text{jet}}}{x_{\text{BJ}}} \right) \] – evolution length in BFKL formalism

- The forward jet is more decorrelated from the scattered lepton for larger rapidity difference \( Y \) (center of mass energy)
- The azimuthal angle correlations increase when HO corrections are included for a fixed value of \( Y \)
Mueller-Navelet jets at LHC – complete NLL BFKL calculations

Colferai, Schwennsen, Szymanowski & Wallon, JHEP 12(2010)026

next-to-leading corrections to the Green’s function and to the Mueller-Navelet vertices

LHC $\sqrt{S} = 14$ TeV, $p_{T,\text{jet}1} = 35$ GeV, $p_{T, \text{jet}2} = 50$ GeV

Azimuthal correlation $<\cos 2\phi> = <\cos(2 \cdot (\phi_{\text{jet}1} - \phi_{\text{jet}2} - \pi))>$

- importance of NLL vertex corrections
- no significant difference between NLL BFKL and NLO DGLAP

H1 measurements $\rightarrow$
the electron-forward jet decorrelation in DIS does not discriminate between different evolution schemes