Hadronic Final States at HERA

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Outline

★ **Hard QCD:**
  ○ Prompt photons + jets in DIS

★ **Parton dynamics:**
  ○ Transverse momentum spectra

★ **Hadronisation:**
  ○ Production of forward photons
  ○ Fragmentation function
Kinematic variables

- **$Q^2$ exchanged boson virtuality:**
  
  \[ Q^2 = -q^2 = -(k - k')^2 \]

  $k$ - 4-momentum of incoming electron
  $k'$ - 4-momentum of outgoing electron

- **$x$ Bjorken scaling variable:**

  \[ x = \frac{q^2}{2P(k - k')} \]

  $P$ - momentum fraction of the proton carried by the struck quark

**Photoproduction:** $Q^2 < 1\text{GeV}^2$

**DIS:** $Q^2 > 1\text{GeV}^2$
Prompt photons + jets in DIS

Motivation:
- Events with isolated photons provide a clean test of QCD
- Do not undergo the hadronisation process
- Arrive in the detector unchanged after their production
- The requirement for an accompanying jet provides a test of pQCD with two hard scales

- ZEUS 2004-2007, $\int L dt = 326 \text{ pb}^{-1}$
- $10 < Q^2 < 350\text{GeV}^2$
- $E_T^{\text{jet}} > 2.5\text{GeV}, -1.5 < \eta^{\text{jet}} < 1.8$
- jet reconstruction done with inclusive $k_T$-clus algorithm
- photon identification using shower shapes
Production of isolated photons with jets in DIS $ep$ scattering

GKS (A.Gehrmann-De Ridder, G.Kramer and H.Spiesberger): fixed order NLO ($\alpha^3 \alpha_s$) = LL, QQ contributions, LQ interference term; agrees better with the cross sections as function of jet variables, below the data.

BLZ (S.P.Baranov, A.V.Lipatov and N.P.Zotov): QCD $k_T$ factorisation approach; overestimate the data by $\sim 20\%$. 
Transverse momentum of charged particles

Motivation:
- Low-\(x\) dynamics is challenging
- Semi-inclusive measurements \(ep \rightarrow e' hX\) may potentially discriminate between DGLAP and beyond-DGLAP

H1 Preliminary results (H1prelim-11-035)
- H1 2006, \(\int L dt = 88.64\) pb\(^{-1}\)
- \(5 < Q^2 < 100\) GeV\(^2\)
- \(10^{-4} < x < 10^{-2}\)
- Measurements are performed in hadronic centre-of-mass system \((p_T^*, \eta^*)\)

Distributions are normalised to

\[
\frac{1}{N_{\text{event}}} \frac{dn}{dp_T^*}
\]
\( p_T^* \) distribution

- DJANGOH works better in current \( p_T^* \) region
- RAPGAP shows strong deviation at low \( x \) and \( Q^2 \)
- CASCADE describes the data at high \( p_T^* \)
η* distributions

Charged particles with $p_T^* < 1$ GeV:

Strong sensitivity to hadronisation

Charged particles with $p_T^* > 1$ GeV:

Strong sensitivity to parton dynamics
Fragmentation function (FF) for $K^0_s$ and $\Lambda$

Motivation:
- Scaling violations in fragmentation functions
- Universality of fragmentation function
- Test NLO QCD calculations and universality of factorisation theorem

ZEUS JHEP 03 (2012) 020
- ZEUS 2005-2007, $\int L dt = 330 \text{ pb}^{-1}$
- $10 < Q^2 < 40000 \text{ GeV}^2$
- $0.001 < x < 0.75$
- Measurements are performed in current region of Breit frame (similarity with $e^+e^-$)

Observable:
- $x_p \equiv \frac{|p_{h^+}|}{p_{max}} \equiv \frac{2p_h}{Q}$ (Breit frame)
- $\frac{1}{N_{\text{event}}} \frac{dn}{dx_p}$

NLO QCD calculations $\otimes$ FF:
- AKK+CYCLOPS: FFs from fits to $e^+e^-$ data
- DSS: FFs from fits to $e^+e^-$, $ep$ and $pp$ data
**Scaled momentum distributions:** $K^0_s$

- **Scaling violations:** $Q$ increases
  - $\Rightarrow$ more soft gluon radiation
  - $\Rightarrow$ more particles with low $x_p$
- ARIADNE and LEPTO describe the data in most parts of phase space
- QCD NLO predictions fail to describe the data
- Data may constrain further FF
- Similar behaviour for $\Lambda$

**Graphs:**

- $0.0 < x_p < 0.1$
- $0.2 < x_p < 0.3$
- $0.4 < x_p < 0.6$
- $0.1 < x_p < 0.2$
- $0.3 < x_p < 0.4$
- $0.6 < x_p < 1.0$

- Relative $1/N_n(K^0_s)/\Delta x_p$
- $Q^2 (\text{GeV}^2)$
Production of very forward photon in DIS

Motivation:
- Understanding the photon fragmentation
- Testing the hypothesis of limiting fragmentation
- Models tuning, in particular for hadron interaction
  Cosmic Ray models
- Fragmentation of the proton does not feel the hard process


- H1 2006-2007, $\int L dt = 126 \text{ pb}^{-1}$
- $6 < Q^2 < 100 \text{ GeV}^2$
- $0.05 < y < 0.6$
- $\eta_\gamma > 7.9$, $X_L = E_\gamma/E_p > 0.1$
- $\gamma$ is detected in e/m part of Forward Neutron Calorimeter

Main source: $\pi^0 \to \gamma\gamma$

Observable:
- Normalised differential cross sections for leading forward photon:
  \[
  \frac{1}{\sigma_{DIS}} \frac{d\sigma}{dx_L}\]
Production of very forward photon in DIS

- Both CDM and LEPTO (standard high energy MC) models are significantly higher than data.
- Monte Carlo models SIBYLL, EPOS and QGSJET are Cosmic Ray models.
- QGSJET models have steeper behavior than the data, close to data in absolute values except at low $X_L$.
- Cosmic ray doing better in normalisation.
- Similar behavior observed for $p_{T, lead}$.
Production of DIS events with very forward photons

- Test of limiting fragmentation hypothesis (forward particle production insensitive to $Q^2$, $x_{bj}$ and $W$)
- Proton remnant does not "feel" the hard interaction
- Data support the hypothesis of limiting fragmentation
Summary

★ **Hard QCD:**
- Prompt photons + jets in DIS
  - Both theoretical predictions reproduce the shapes of all the measured experimental distributions reasonably well
  - However neither calculation gives a correct normalisation
  - The results can be used to make further improvements in the QCD calculations

★ **Parton dynamics:**
- Transverse momentum spectra
  - CDM is the best in description of charged particle spectra
  - DGLAP is below the data for low $x$ and large $p_T$ of charged particles

★ **Hadronisation:**
- Fragmentation function for $K^0_S$ and $\Lambda$
  - Scaled momentum distributions show the scaling violation
  - NLO QCD calculations fail to describe the data
  - Measurements can be used for further FF fit
- Production of forward photons
  - Models predict higher yield of photons than data
  - Data supports the hypothesis of limiting fragmentation