Transverse momentum of charged particles at low $Q^2$ at HERA

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Outline

- Introduction and motivation
- Analysis details
- Results
- Summary
**Evolution equations**

- **DGLAP (RAPGAP)**
  - DGLAP model: $Q_0^2 \ll k_{T1}^2 \ll \cdots \ll k_{Tn}^2 \ll Q^2$
  - DGLAP works when $Q^2$ is large, but $x$ is not too small

- **CDM (Color Dipole Model)**
  - CDM = non-DGLAP
  - Random walk in transverse momentum (ordering in angle)

- **CCFM (CASCADE)**
  - CCFM = non-DGLAP
  - Random walk in transverse momentum

**beyond-DGLAP models** (random walk in $k_T$)

- **CDM (Color Dipole Model)**
  - (not evolution equation, but gives BFKL-like final state)
  - works for small $x$ and $Q^2$ is not large

- **CCFM**
  - Valid for both, small and large $x$
HFS as an access to the dynamics of the cascade

\( F_2(x, Q^2) \) has little sensitivity to discriminate between DGLAP and beyond-DGLAP. Semi-inclusive measurements \( ep \rightarrow e' hX \) are believed to possess higher discriminating power.

**The observables for physics beyond DGLAP at HERA:**

- Transverse energy flow
- Forward jets with \( p_{Tjet}^2 \sim Q^2 \)
- Transverse momentum spectra:

Low \( p_T \) region:
hadronisation effects are expected to play a role.
Small sensitivity to different parton dynamic models.

Hadrons at large \( p_T \):
disfavoured by the strong \( p_T \) ordering \( \rightarrow \) difference between different parton dynamics
Experimental setup and reconstruction

- HERA beam energies: $E_e = 27.6$ GeV, $E_p = 920$ GeV
- Data 2006e+: $L = 88.64$ pb$^{-1}$

**Scattered electron**

Information from scattered positron ($E'_e, \theta'_e$) and hadronic final state is used to reconstruct the kinematics:

\[
Q^2_e = 4E_e E'_e \cos^2 \frac{\theta'_e}{2}
\]

\[
ye\Sigma = 2E_e \frac{\Sigma_h}{\Sigma^2}
\]

\[
\Sigma_h = \sum_h (E_h - p_{z,h}) ; \quad \Sigma = \Sigma_h + \Sigma_e
\]

In this analysis:

$5 < Q^2 < 100$ GeV$^2$, $0.05 < y < 0.6$

$10^{-4} < x < 10^{-2}$

For *charged particles*

Extension to the forward region is performed. Track selection:

$p_T > 0.15$ GeV, $10^\circ < \theta < 155^\circ$, (last preliminary results $20^\circ < \theta < 155^\circ$)
Reference frames

- **Laboratory frame:**

\[ \eta = - \ln \tan \left( \frac{\theta}{2} \right) \]
\[ \theta - \text{with respect to proton direction} \]
\[ \eta > 0 \Leftrightarrow \text{proton direction} \]

- **Hadronic centre-mass system (HCM):**

\[ \eta^* = - \ln \tan \left( \frac{\theta^*}{2} \right) \]
\[ \theta^* - \text{with respect to virtual photon direction} \]
\[ \eta^* < 0 \Leftrightarrow \text{proton direction} \]

\[ p_T^* \text{ distribution is studied in } 0 < \eta^* < 1.5 \text{ and } 1.5 < \eta^* < 4 \text{ region} \]
$p_T^*$ spectra: DATA vs. DJANGOH/RAPGAP/CASCADE

**Central region ( $0 < \eta^* < 1.5$, $10^\circ < \theta_{\text{lab}} < 155^\circ$ )**

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

RAPGAP(DGLAP) is below the data for $p_T^* > 1$ GeV (especially in the forward region)

In contrast, CASCADE(CCFM) is systematically above the data (except high $p_T^*$)

**Current region ( $1.5 < \eta^* < 4$, $16^\circ < \theta_{\text{lab}} < 155^\circ$ )**
$p_T^*$ distribution in bins of $(x, Q^2)$; central region

**Results**

- $5 < Q^2 < 10 \text{ GeV}^2$
- $0.0001 < x < 0.00024$
- $0.0024 < x < 0.0005$
- $0.0005 < x < 0.002$

- $10 < Q^2 < 20 \text{ GeV}^2$
- $0.0002 < x < 0.00052$
- $0.00052 < x < 0.0011$
- $0.0011 < x < 0.0037$

- $20 < Q^2 < 100 \text{ GeV}^2$
- $0.0004 < x < 0.0017$
- $0.0017 < x < 0.01$

**H1 Preliminary**

- $0 < \eta^* < 1.5$
- $10^\circ < \theta_{lab} < 155^\circ$

- RAPGAP(DGLAP) is substantially below the data at lowest $x$ and $Q^2$ region at large $p_T^*$
$p_T^*$ distribution in bins of $(x, Q^2)$; current region region

**Results**

- H1 Preliminary
  - $1.5 < \eta^* < 4$
  - $16^\circ < \theta_{lab} < 155^\circ$
  - H1 data (prelim.)

- RAPGAP (DGLAP) provides better description of the data compared to the forward region
**Results**

- **η*** - distributions

**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:

- Strong sensitivity to different parton dynamics.
- Weak sensitivity to hadronisation parameters.
**$\eta^*$ distribution in bins of $(x, Q^2)$ for $p_T^* < 1$ GeV**

DJANGOH(CDM) provides reasonable description of the data for all $(x, Q^2)$-bins. RAPGAP(DGLAP) is slightly above the data for lowest $x$. 

**H1 Preliminary**

$p_T^* < 1$ GeV

$10^\circ < \theta_{lab} < 155^\circ$

- **H1 data (prelim.)**
- **RAPGAP**
- **DJANGOH**
- **CASCADE**
\( \eta^* \) distribution in bins of \((x, Q^2)\) for \(p_T^* > 1\) GeV;

\[
\begin{align*}
5 < Q^2 < 10 \text{ GeV}^2 & : \\
0.0001 < x < 0.00024 & : & 0.00024 < x < 0.0005 & : & 0.0005 < x < 0.002
\end{align*}
\]

\[
\begin{align*}
10 < Q^2 < 20 \text{ GeV}^2 & : \\
0.0002 < x < 0.00052 & : & 0.00052 < x < 0.0011 & : & 0.0011 < x < 0.0037
\end{align*}
\]

\[
\begin{align*}
20 < Q^2 < 100 \text{ GeV}^2 & : \\
0.0004 < x < 0.0017 & : & 0.0017 < x < 0.01
\end{align*}
\]

- RAPGAP(DGLAP) is below the data for almost all \((x, Q^2)\)-bins.
- The difference is more pronounced in proton direction \((\eta^* < 2)\)
Transverse momenta and rapidity spectra were measured with H1 detector at HERA (2006 e^+p data)

- **Low \( p_T^* \) region (\( p_T^* < 1 \) GeV):
  - Sensitivity to the fragmentation parameters
  - Both RAPGAP(DGLAP) and DJANGOH(CDM) provide reasonable description of the data for both \( p_T^* \) and \( \eta^* \) distributions

- **Hard \( p_T^* \) region (\( p_T^* > 1 \) GeV):
  - Sensitivity to the different parton dynamic models
  - DJANGOH(CDM) is better than RAPGAP(DGLAP) in describing both, \( p_T^* \) and \( \eta^* \) measured spectra, especially at low \( x \)

→ data are in favour of CDM (Colour Dipole Model) model