Forward Jets and Particles in ep collisions and parton dynamics

On behalf of H1 and ZEUS Collaborations

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• Parton dynamics at high energies
• Central region
• Forward Jets
• Forward $\pi^0$
• Conclusions

$ep$ (27.5 + 820 GeV) collisions
QCD Evolution at low $x$

At low $x$ scattered parton usually descends from long cascade of parton branchings.

$$\Delta \tau_{g1} \geq \Delta \tau_{g2} \geq \Delta \tau_{g3} \geq \ldots \Delta \tau_{gn}$$

$$\Delta \tau_g \sim \frac{1}{\Delta E} \sim \frac{2xp}{k_T^2}$$

$$k_{T1} \leq k_{T2} \ldots \leq k_{Tn}$$

$$x_{g1} \geq x_{g2} \geq \ldots \geq x_{gn}$$

$$\theta_1 \leq \theta_2 \leq \ldots \leq \theta_n$$

DGLAP  BFKL  CCFM
Comparison of the data to MC models with different QCD dynamics

\[ E_T < Q \]

- \( k_t \) ordered initial state radiation
- RAPGAP DIR

\[ E_T > Q \]

- No \( k_t \) ordering in initial state radiation
- Resolved photon
- RAPGAP RES at scale \( Q^2 + p_t^2 (\text{jets}) \) or \( Q^2 + 4p_t^2 (\pi^0) \)
- CCFM evolution equation

\[ E_T \approx Q \]

- \( k_t \) - factorization
- CASCADE 1.0
DGLAP description gradually deteriorates when going from backward to forward direction.

Forward region:
- huge NLO correction
- large deviations at small $Q^2$ & $E_T$

Moral: NNLO may be important in forward region

Inclusive Jets in DIS

$5 < Q^2 < 100 \text{ GeV}^2$, $0.2 < y < 0.6$

incl. $k_T$ algorithm in Breit frame
Forward jets: forward region under special scrutiny

Large $x_{jet}/x_{bj}$ to enhance phase space for BFKL evolution

$E_{Tjet}^2 \approx Q^2$ to suppress DGLAP evolution

Diagram: Graph showing phase space evolution from large to small $x$.
Forward Jets

\[ 5 < Q^2 < 75 \text{ GeV}^2 \]

Forward jet (incl. \( k_t \) algo.)

\[ 7.0^\circ < \theta_{\text{jet}} < 20.0^\circ \]

\[ x_{\text{jet}} > 0.035 \]

\[ 0.5 < \frac{p_{t\text{jet}}^2}{Q^2} < 2.0 \]

- DGLAP direct: too low
- CCFM: too high
- DGLAP (DIR+RES): OK

\[ \mu^2 = Q^2 + p_T^2 \]

Similar pattern of agreement/disagreement for \( x_{\text{jet}} \) \( p_{T\text{jet}} \)
Forward jets are experimentally difficult:

- Interference with proton remnant
- Hadronic corrections strongly model dependent at small $x$
Forward jets $\leftrightarrow$ forward particles ($\pi^0$)

Forward particle detection $\pi^0$

- fragmentation effects more significant
- smaller rate

Jet measurements

- better parton correlation
- higher rates
- ambiguities of jet algorithms
- exp. difficult in very forward ($p$) region

+ identification possible in more forward region

There is another interesting aspect of bringing particle into the game - later.
Forward $\pi^0$ cross section: $x$ dependence

Best description:
direct + resolved at scale $\mu^2 = Q^2 + 4p_T^2$

DGLAP direct: too low

CCFM too low at small $x$

Mod. LO BFKL tuned to H1 1997 data + recent FF describes the data

Similar pattern of agreement/disagreement for other distributions
## Overview of description of jet/particle x-sections

<table>
<thead>
<tr>
<th>Evolution scheme</th>
<th>Renor. &amp; factor.scale</th>
<th>Fragmentation scheme</th>
<th>Fragmentation scale</th>
<th>Forward jets</th>
<th>Forward $\pi^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>DGLAP (dir+res) RAPGAP</td>
<td>$\mu^2=Q^2+p_t^2$ Up to $\mu^2=Q^2+4p_t^2$</td>
<td>JETSET 7.4 (Lund model)</td>
<td>String inv. mass</td>
<td>OK</td>
<td>OK at upper limit of renor. scale</td>
</tr>
<tr>
<td>CCFM CASCADE</td>
<td>$\mu^2=Q^2+4m_Q^2$</td>
<td>PYTHIA 6.2 (Lund model)</td>
<td>String inv. mass</td>
<td>too high</td>
<td>too low</td>
</tr>
<tr>
<td>Mod. LO BFKL</td>
<td>$\mu^2=k_{Tjet}^2$</td>
<td>LO KKP FF</td>
<td>$z_{pi}^*Q^2$</td>
<td>OK</td>
<td>OK</td>
</tr>
</tbody>
</table>

Something wrong either in mod. LO BFKL (KMO) or CASCADE
Transverse energy flow associated with forward $\pi^0$

In hadronic CMS:

- $\pi^0$ close to proton (most forward)
- $\pi^0$ towards to photon (less forward)
SUMMARY AND CONCLUSIONS

Forward jets at HERA: after ~10 years description still difficult.

- NLO DGLAP not enough to describe forward jet data
- DGLAP direct + resolved describes the fwd jet & $\pi^0$ data
- Energy flow pattern slightly favors DGLAP direct + resolved in comparison with other schemes
- Mod. LO BFKL tuned to jet data describes $\pi^0$ data
- CCFM slightly overshoots jet data and underestimates $\pi^0$ data
- There seems to be contradiction between last two points: something must be wrong...
Forward jets and BFKL

Modified LO BFKL calculation

Kwiecinski, Martin Outhwaite hep-ph/9903439

Normalization very sensitive to infrared cut-off $k_0$ and scale for $\alpha_S$
Modified LO BFKL calculation

Kwiecinski, Martin Outhwaite hep-ph/9903439

\[ \sigma(jet) \approx \frac{\alpha_s}{k_{jT}^4} \Phi\left( \frac{x}{x_j}, k_{jT}^2, Q^2 \right) \otimes F_2(x_j, k_{jT}^2) \]

\[ \sum_a f_a(x_{jet}, k_{Tjet}) \]
Particle production in central region e.g. $K_s$ in photoproduction

Photoproduction of jets with $K_0 \rightarrow \pi^+\pi^-$

Large $E_T$ central $\eta_{lab}$ region well described by:
- LO Monte Carlo PYTHIA/HERWIG
- based on DGLAP
- including fragmentation

Particle Production well understood !!!
## Forward Jets

<table>
<thead>
<tr>
<th>Parameter</th>
<th>H1 cuts</th>
<th>ZEUS cuts</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E'_e$</td>
<td>$&gt; 11$ GeV</td>
<td>$&gt; 10$ GeV</td>
</tr>
<tr>
<td>$y_e$</td>
<td>$&gt; 0.1$</td>
<td>$&gt; 0.1$</td>
</tr>
<tr>
<td>$E_{T,jet}$</td>
<td>$&gt; 3.5$ (5) GeV</td>
<td>$&gt; 5$ GeV</td>
</tr>
<tr>
<td>$\eta_{jet}$</td>
<td>$1.7 - 2.8$</td>
<td>$&lt; 2.6$</td>
</tr>
<tr>
<td>$E_{T,jet}/Q^2$</td>
<td>$0.5 - 2$</td>
<td>$0.5 - 2$</td>
</tr>
<tr>
<td>$x_{jet}$</td>
<td>$&gt; 0.035$</td>
<td>$&gt; 0.036$</td>
</tr>
<tr>
<td>$p_{z,jet}^{\text{Breit}}$</td>
<td></td>
<td>$&gt; 0$ i.e. TF</td>
</tr>
<tr>
<td>$x$</td>
<td>$0.0001 - 0.004$</td>
<td>$0.00045 - 0.045$</td>
</tr>
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