Jet production at low Bjorken-$x$ from HERA

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- HERA and low $x$ physics
- Inclusive Forward jets
- Forward jets in multijet configurations
- Azimuthal correlations in dijet system

Low $x \leq 5 \cdot 10^{-3}$
The HERA Collider

HERA-1 (1993-2000) $\sim 120 \text{ pb}^{-1}$
HERA-2 (2003-2007) $\sim 380 \text{ pb}^{-1}$

Last 3 months - low $E_p$ run to measure $F_L^p$
($E_p = 460; 575 \text{ GeV}, \quad \mathcal{L} = 20\text{pb}^{-1}$)

- HERA upgrade: $\mathcal{L} \times 3$, Polarised $e^+/e^-$
  (Exp. improvements: silicon trackers, triggering, ...)

- Final Data samples H1+ZEUS: $2 \times 0.5 \text{ fb}^{-1}$
Small $x$ domain of HERA

- $ep$ DIS: clean QCD laboratory with high resolving power $Q^2 \Rightarrow 0.001\text{fm}$

- Low $x \leq 10^{-3}$: new kinematic domain at HERA
  $\Rightarrow$ any sign of novel parton dynamics?
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- There is a lot of glue in proton at low $x$!
  $\Rightarrow$ gluodynamics in high energy limit of QCD ($W^2 \approx Q^2/x$)
QCD at low $x$

Lots of glue in the proton $\Rightarrow$ long gluon cascade at low $x$. Perturbative expansion of evolution equations $\sim \sum_{mn} A_{mn} \ln(Q^2)^m \ln(1/x)^n$ hard to calculate explicitly

$\Rightarrow$ approximations needed

**DGLAP:** resums $\ln(Q^2)^n$ terms, neglecting $\ln(1/x)^n$ terms

strong $k_T$ ordering in partonic cascade

**BFKL:** resums $\ln(1/x)^n$ terms

no $k_T$ ordering in partonic cascade $\Rightarrow$ more hard gluons are radiated far from the hard interaction vertex

**CCFM:** angular ordered parton emission $\Rightarrow$

reproduces DGLAP at large $x$ and BFKL at $x \to 0$

- How long is partonic cascade at HERA, at small $x$?
- Do the $\ln(1/x)^n$ terms play a major role in parton dynamics as suggested by BFKL?

$\Rightarrow$ Look at (multi)jet final states at low $x$ in different configurations
Low $x$ phenomenology

**Fixed order QCD calculations**

- NLO 2-jet
- NLO 3-jet
- DISENT, NLOJET++, NLOJET++

**LO ME + PS MC models**

- Rapgap Dir
- Rapgap Res
- Cascade
- Lepto (CDM)

- $k_t$-ordered gluon radiation (DGLAP)
- Angular ordering (DGLAP $\leftrightarrow$ BFKL)
- Random walk in $k_t$ (BFKL like)
Forward jets

Strategy

\((E_t^{jet})^2 \approx Q^2 \Rightarrow\) suppress phase space for DGLAP evolution

large \(x_{jet} \gg x_{Bj}\) \(\Rightarrow\) enhance BFKL evolution

Event selection

\(10^{-4} < x < 4 \cdot 10^{-3} \quad 5 < Q^2 < 85 \text{GeV}^2\)

\(E_t^{jet} > 3.5 \text{GeV} \quad 7^\circ < \theta_{jet} < 20^\circ\)

\(x_{jet} > 0.035 \quad 0.5 < (E_t^{jet})^2/Q^2 < 2\)
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- Huge improvement from LO to NLO, but still insufficient at low \(x\)
- Resolved \(\gamma\) component in DGLAP MC helps ("breaks" \(k_t\) ordering)
- CDM and RG(d+r) provide similar description \(\Rightarrow\) inconclusive
Forward jets against CCFM Monte Carlo

- extended forward range
  \( 2 < \eta^{jet} < 4.3 \)
  \( E_t^{jet} > 5 \text{GeV}, x_{jet} > 0.036 \)

- Jet rate is OK, but shapes of the distributions are not described

- Clear sensitivity to uPDF
5 < Q^2 < 80 \text{ GeV}^2 \\
10^{-4} < x < 10^{-2} \\
Jets: \quad E_{t,\text{jet}}^* > 4 \text{ GeV} \\
\quad -1 < \eta < 2.5 \\
\quad N_{\text{jet}} \geq 3 \\

- Gluon radiation is frequent at low $x$ \\
- $O(\alpha_s^3)$ QCD can only predict up to 4 jets \\
- RG d+r (DGLAP type of MC) underestimates high jet multiplicities \\
- CDM (BFKL like MC) is just perfect!
Two and Three Jet production vs NLO QCD

- NLO QCD is OK in this domain ($x > 2 \cdot 10^{-4}, E_t^{j1} > 7\text{GeV}, E_t^{j2(3)} > 5\text{GeV}$)

⇒ Try even higher jet multiplicities and look for specific jet topologies
3-jet samples with different topologies

Central jets:
\[-1 < \eta_{jet} < 1\]

Forward jets:
\[\eta_{fj1} > 1.73\]
\[x_{fj1} > 0.035\]
\[\eta_{fj2} > 1\]

All jets:
\[E^*_{t,jet} > 4 \text{ GeV}\]

- Large deficit at small \(x\) for 2-forward jet topology! There \(\mathcal{O}(\alpha_s^3)\) calculation is insufficient
3- and 4-jet distributions vs LO+PS Monte Carlo

- CDM describes well all distributions except high $p_T$ tail where it is too hard
- DGLAP MC (RG dir+res) fails both in shapes and normalization ($3j \times 1.55$, $4j \times 2.9$)
Collinear factorisation scheme:

jets are back-to-back at LO, hence
\( \Delta \Phi^* < 180^\circ \) are only possible at higher orders

\( k_t \) factorisation scheme:

\( \Delta \Phi^* < 180^\circ \) already at LO

Sensitive to details of parton dynamics

\[ \mathcal{O}(\alpha_s^3) \] calculations describes the data reasonably well
(although with still large scale uncertainty)

ZEUS vs NLO DGLAP

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Azimuthal correlations vs CCFM

H1 data vs CCFM based MC

- Although Cascade fail to describe the shape of $\Delta \Phi^*$, 2 sets of uPDF (both describing HERA $F_2$) essentially cover the data
- Large sensitivity to uPDF

ZEUS data vs CCFM based MC

- "collinear approach" (HERWIG) fails
- Cascade based on $k_t$ factorisation describes data much better
Implications for LHC predictions

- Large part of LHC phase space is at low $x$
- Tevatron is at large $x$

$\Rightarrow$ SM predictions based on fixed order calculations and on DGLAP MC may not work even if tuned to Tevatron data

- Low $x$ dynamics has to be implemented
- CDM and Cascade MC after additional tuning are promising tools for LHC
Summary

- There is a lot of gluon radiation at small $x$. Hard gluons are often radiated forward, with large rapidity separation from hard interaction vertex. This has an important implications for LHC!

- Fixed order QCD predictions based on DGLAP approach give large improvement with every order in $\alpha_s$. Presently available calculations describe basic properties of multijet production in DIS, however it still fails at lowest $x$ and for specific configurations with very forward jets.

- Color Dipole Model gives best description of jet production at HERA down to lowest $x$ while models with $k_t$-ordered gluon radiation fail completely. This provides a substantial indication for unordered gluon radiation at small $x$ as expected from $\ln(1/x)$ terms in evolution equations.

- Forward jet data and azimuthal correlations in dijet system show sensitivity to unintegrated PDFs and therefore can be used for their extraction.
BACKUP SLIDES...
H1 Forward jets: triple differential cross sections

\begin{align*}
5 < Q^2 < 10 & \quad 10 < Q^2 < 20 & \quad 20 < Q^2 < 85 \\
\begin{array}{c|c|c|c}
\text{Region} & \text{Value} & \text{Value} & \text{Value} \\
\hline
5 < Q^2 < 10 & 1.2 < r < 7 & 0.6 < r < 3.5 & 0.1 < r < 1.8 \\
\end{array}
\end{align*}
H1 Forward jets vs NLL BFKL

(C.Royon, DIS-2008)

$\frac{d\sigma}{dx \, dp_T^2} \, dQ^2$ - H1 DATA
Azimuthal correlations: Data vs NLOJET++

- NLO 3-jet is not in agreement with H1 data