Low $x$ Hadronic Final State Studies at H1

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Overview

- Quick Introduction to the low x issue.
- New results from H1.
- Implications for the LHC.
Parton Evolution

Standard DGLAP approximation, large $Q^2$: sums terms $\sim \alpha_s \log Q^2$, strong ordering in $k_T$ of parton emission (collinear factorisation).

BFKL evolution equation, low $x$: sums terms $\sim \alpha_s \log (1/x)$, strong ordering in $x_i$, no ordering in $k_T$, ($k_T$ factorisation).

CCFM equation applicable at all $x$ and $Q^2$: includes both $\alpha_s \log Q^2$ and $\alpha_s \log (1/x)$ terms. implements angular ordering resulting from QCD interference effects.

Inclusive $F_2$ measurement not able to discriminate between different QCD approaches. Study Hadronic final state.

non DGLAP effects expected to produce a significant enhancement of gluon radiation

Inclusive $F_2$ measurement not able to discriminate between different QCD approaches. Study Hadronic final state.
Possibility of non DGLAP behaviour of the parton evolution at HERA

What does this mean for the LHC?
DIS and HERA
Kinematic Variables:

\[ Q^2 = -q^2 = -(k - k')^2 \]

Momentum transfer

\[ x = \frac{Q^2}{2p \cdot q} \]

Fraction of the proton’s momentum that participates in the hard scatter

\[ y = \frac{p \cdot q}{p \cdot k} \]

Fraction of the electron’s energy available in the proton’s rest frame

\[ Q^2 = sxy \]

s = center of mass energy squared
Monte Carlos for DIS

- Rapgap (dir)
  - Strong ordering in $k_t$ of emitted partons
- Rapgap (dir+res)
- Cascade
  - CCFM resumes both $\log(Q^2)$ and $\log(1/x)$ angular ordering
- Ariadne
  - Dipoles radiate independently

as is PYTHIA and HERWIG
NLO QCD Calculations

NLO Models and NLO Calculations

NLOJET++, DISENT

NLO 2-jet

NLO 3-jet

Scale $\mu_r = \mu_f = Q$ or $E_t$ or some similar combination

Scale Uncertainty $1/2 \mu_{r,f} < \mu_{r,f} < 2\mu_{r,f}$, changing both scales simultaneously

PDF: CTEQ, MRST, H1, ZEUS

Hadronisation correction from Monte Carlo
H1

\( x_{bj} = 1.7 \times 10^{-4} \)

\( Q^2 = 8.7 \text{ GeV}^2 \)

Jets measured by tracking and calorimeters

\(-1 < \eta_{\text{jet}} < 2.8\)
Forward Jets in DIS
Forward Jet Production

Test QCD at small $x$ and look for parton dynamics beyond DGLAP

Suppress DGLAP ($p_{t, fwd\, jet}^2 \sim Q^2$)
Enhance BFKL ($x_{bj} \ll x_{jet}$)

Forward jets = jets away from hard interaction.

DGLAP (ordered $kt$) - soft parton emissions
BFKL (non-ordered $kt$) - more (harder) jets
Forward Jet Production

Kinematic selection:
5 < Q^2 < 85 GeV^2
0.1 < y < 0.7
0.0001 < x_{bj} < 0.004

1997 data L=13.7 pb^{-1}
E_p=820, E_e=27.6
\sqrt{s} \approx 300 GeV

Forward jet selection:
Inclusive kt-algorithm in Breit frame
1.75 < \eta_{jet} < 2.8
P_{t,jet,lab} > 3.5 GeV
x_{jet} = E_{jet}/E_p > 0.035
0.5 < p_{t,jet}^2/Q^2 < 5
if N_{jet}>1, choose highest \eta_{jet}
Forward Jet Production

DISENT LO ($\alpha_s$) and NLO ($\alpha_s^2$):

\[
\mu_r^2 = p_t^2 \\
\mu_f^2 = \langle p_{t,\text{fwdjet}}^2 \rangle = 45 \text{ GeV}^2 \\
0.25 \mu_{r,f}^2 < \mu_{r,f}^2 < 4 \mu_{r,f}^2 \\
(1+\delta_{\text{HAD}})
\]

NLO below data

LO $\ll$ NLO

large difference between LO and NLO: scale error underestimated? Is this really an inclusive cross section?

H1 forward jet data

NLO better here
Forward Jet Production

RAPGAP direct fails, addition of resolved photon processes improves description. CDM prediction also better.

CASCADE fails to describe spectrum.

Differences between different updfs.

Harder spectrum (only gluon initiated processes?)
Three Jets in DIS
Three Jet Production

For events with three or more jets, at least one jet should come from gluon radiation

Should be sensitive to the dynamics of gluon radiation

Provides a more testing environment to compare with theory
Three Jet Production

Kinematic selection:
\[ 10^{-4} \leq x_{bj} \leq 10^{-2} \]
\[ 5 \leq Q^2 \leq 80 \text{ GeV}^2 \]
\[ 0.1 < y < 0.7 \]

99/2000 data \( L = 44.2 \text{ pb}^{-1} \)
\( E_p = 920, E_e = 27.6 \)
\( \sqrt{s} \approx 318 \text{ GeV} \)

Three Jet Selection:
Inclusive kt-algorithm in \( \gamma^* p \) rest frame
\( E_{\perp, \text{jet}} > 4 \text{ GeV} \)

\( -1 < \eta_{\text{jet,lab}} < 2.5 \)
\( N_{\text{jet}} \geq 3 \)
\( E_{\perp 1} + E_{\perp 2} > 9 \text{ GeV} \)

one jet in range \( -1 < \eta_{\text{jet,lab}} < 1.3 \)
Three Jet Production

NLO prediction

scale uncertainty
(variation *2 resp. *.5)

+ normalisation uncertainty
(20%, not shown)

statistical error
correlated

uncertainty
stat + uncorr.
data point

\[ O(\alpha^2) \rightarrow O(\alpha^3) \]

up to 3 jets
\times 3.3
at low \( x_{bj} \)

up to 4 jets
\times 1.7

Improvement in description especially at low \( x_{bj} \)
For 3 jets $O(\alpha^3) = \text{data}$

$O(\alpha^3)$ misses $\sim$20% of events with 4 or more jets

CDM gives excellent description

RAPGAP fails even for 3 jets
Main discrepancies at low $x$ and large $\eta$ (forward region)

Other distributions are well described apart from $\sim 20\%$ normalisation difference
Three Jet Production

Two central jets

Forward jet selection:
\( \eta_{\text{jet}} > 1.75, x_{\text{jet}} > 0.035 \)

Two forward jets
Three Jet Production

Two central jets
reasonably well described

Two forward jets
Data $= O(\alpha^2) \times 10$
Data $= O(\alpha^3) \times 3.5$
Three Jet Production

Two forward jets

compare shapes:
$O(\alpha^2), O(\alpha^3) \times 1.34$
Rapgap $\times 1.74$
CDM $\times 1.08$

3–jet rest frame
\[ e+p \rightarrow 1+2+3 \]

\[ E'_1 > E'_2 > E'_3 \]

\[ \text{hep-ph/9510351} \]
Dijet Azimuthal Correlations in DIS
Dijet Azimuthal Correlations

DGLAP:
In LO gluon collinear with proton
\( k_{t,g} = 0 \), Jets back-to-back in HCM, \( \Delta \phi^* = 180^\circ \)
Higher order QCD radiation
\( k_{t,g} \neq 0, \Delta \phi^* < 180^\circ \)
Gluon emissions ordered in virtuality
\( k_{t,g} \) ordered

BFKL, CCFM:
unordered \( k_{t,g} \)
Broader \( \Delta \phi^* \) compared to DGLAP
sensitive to unintegrated (u)PDF
\( \Delta \phi^* < 180^\circ \) at LO!

Sensitive to different parton dynamics
Sensitive to unintegrated gluon density
Dijet Azimuthal Correlations

Kinematic Selection:
\[ 5 < Q^2 < 100 \text{ GeV}^2 \]
\[ 0.1 < y < 0.7 \]

99/2000 data \( L = 64.3 \text{ pb}^{-1} \)
\( E_p=920, \ E_e=27.6 \)
\( \sqrt{s} \approx 318 \text{ GeV} \)

Dijet Selection:
Inclusive Kt-algorithm
\( E^*_{\perp \text{jet}} > 5 \text{ GeV} \)
\( -1 < \eta_{\text{lab}} < 2.5 \)

Two jets closest in \( \eta \) to the scattered electron chosen as the dijet system
Dijet Azimuthal Correlations

Infrared sensitivity, no NLO for $\Delta\phi^* \sim 180^\circ$

Normalise to visible cross section to reduce scale uncertainties (<20%)

NLO 2 jet ($\alpha_s^2$) fails
~ effectively LO

NLO 3 jet () better but still systematically below data for $\Delta\phi^* < 160^\circ$
Dijet Azimuthal Correlations

Similar story at higher $x_{bj}$!
Rapgap (direct) describes back-to-back ($\Delta \phi^* = 180^\circ$) jets

Rapgap (dir+res) and CDM give too many back-to-back jets and too few small $\Delta \phi$ dijets
Dijet Azimuthal Correlations

Sensitivity to unintegrated gluon density

Cascade J2003 much better than A0 (too hard)

Cascade + J2003 gives best description of any model
Summary

- $O(\alpha^3)$ huge improvement compared to $O(\alpha^2)$ predictions.
- Rapgap (direct fails) $\rightarrow$ ordered gluon radiation.
- Rapgap (direct + resolved) is better but it still fails $\rightarrow$ ordered gluon radiation.
- In general CDM gives best description of the data (even in normalisation) $\rightarrow$ unordered gluon radiation.
- Cascade expect improvements with new updf fits including new data.
- Non DGLAP dynamics clearly favoured by hadronic final state measurements at low $x$. 
Results in full


• See also: QCD Analysis of Dijet Production at Low $Q^2$ at HERA (J.Chýla et al., hep-ph/0501065).


• See also: Forward jet production in deep inelastic ep scattering and low-x parton dynamics at HERA (ZEUS Collaboration; S. Chekanov et al. Letters B 632 (2006) 13-26).

• 3-jet cross sections at low x and $Q^2$ (H1prelim-06-034). DIS06

• Azimuthal correlations in dijet events at low $Q^2$ DIS (H1prelim-06-032). DIS06
Implications for LHC?
• Use best models at HERA for LHC. But....

• Cascade only includes gluon processes. This limits present use for LHC. Can compare with like processes in Pythia ($fg \rightarrow fg, gg \rightarrow ff, gg \rightarrow gg$).

• Unintergrated pdfs need to be better constrained (useful results presented here).

• Ariadne missing splitting kernal $g \rightarrow qq$ (see contribution by Leif Lönnblad “ARIADNE at HERA and at the LHC” from HERA/LHC workshop proceedings for more details).

• Improvements expected, part of HERA/LHC program
Fig. 1: The transverse momenta of the Higgs boson, $p_T^{\text{Higgs}}$ for 3 different shower models for each production mechanism. The red solid line represents PYTHIA, the dashed green line ARIADNE and the dotted blue line HERWIG events. The vertical scale gives the number of events per bin, and a total of $10^5$ events have been generated with each program.
Fig. 7: $p_T^{Higgs}$ Higgs of PYTHIA, HERWIG + ME Corrections, MC@NLO and CASCADE, linear and logarithmic scale.
Low x Summary

Strong evidence of non DGLAP behaviour of the parton evolution at HERA ($x < 0.001$)

What does this mean for the LHC?
Backup
\[ S = \frac{\int_0^{2\pi/3} N_{Dijet}(\Delta \phi^*, x, Q^2) d\Delta \phi^*}{\int_0^{\pi} N_{Dijet}(\Delta \phi^*, x, Q^2) d\Delta \phi^*} \]

- Data show significant increase towards low x

- Study effect of higher orders:
  - LO predictions \([O(\alpha_s)]\)
    - at most 3 jets in final state
    - completely fails to describe data
  - NLO calculations \([up to O(\alpha_s^3)]\)
    - 3 or 4 jets in final state
    - reasonable description at large x, \(Q^2\)
    - but still too low at small x, \(Q^2\)

Luminosity: \(21\text{pb}^{-1}\)

\(5 < Q^2 < 100 \text{ GeV}^2\)

\(E_{T,1}^* > 7 \text{ GeV}\)

\(E_{T,2}^* > 5 \text{ GeV}\)

\(0.1 < y < 0.7\)

\(-1 < \eta < 2.5\)
- Estimate fraction of photon four momentum carried by parton in hard interaction:

\[ x_{\gamma}^{jets} = \frac{\sum (E_{j}^{*} - p_{z,j}^{*})}{\sum \frac{E^{*} - p_{z}^{*}}{hadrons}} \]

- direct part (\( x_{\gamma}^{jets} > 0.75 \)) well described
- resolved fraction (\( x_{\gamma}^{jets} < 0.75 \)) increases at smaller \( Q^{2} \)
  - data significantly above NLO calculations when using direct photon only
  - excess decreases with increasing \( Q^{2} \)

- JETVIP including \( \gamma^{*}_{T} \) improves description but excess for \( x_{\gamma}^{jets} < 0.75 \) remains
• NLOJET++ results in 3-jet mode significantly closer to data than those of 2-jet mode
  - have to cut out region $x_\gamma \sim 1$
  - no resolved photon
• largest corrections at small $x_\gamma$ and $Q^2$
• remaining gap between data and NLOJET++ 3-jet also most pronounced for small $x_\gamma$ and low $Q^2$
  - there is need for further higher order QCD corrections

- H1 data
- NLOJET for 2 jets
- Jetip full
- NLOJET for 3 jets

hep-ph/0501065
Forward $\pi^0$-meson production

- H1 data
- DIR + RES
- CCFM (CASCADE)
- DIR
- NLO (Aurenche et al.)
- mod. LO BFKL

$2 < Q^2 < 8 \text{ GeV}^2$

$8 < Q^2 < 20 \text{ GeV}^2$

$20 < Q^2 < 70 \text{ GeV}^2$

$p_{T,\pi}^* > 3.5 \text{ GeV}$
NLO predictions in good agreement with the H1 data
Large K factors and theoretical uncertainties
Need for NNLO analysis
H1 forward jets: triple differential cross section

Cross Section as fct. of $x_{bj}$ in 3x3 $p_T^2$-$Q^2$ bins (no $p_{T_{jet}}^2/Q^2$ cut)

d$^3\sigma/dx_{bj}dQ^2dp_T^2$:
best description: RG-DIR+RES
or CDM
RG-DIR below data, best at $r\sim1$
DISENT better at larger
$x_{bj}$, $Q^2$, $p_T^2$
CASCADE as single diff $\sigma$
too hard $x_{bj}$ spectra
H1 forward jets: triple differential cross section

Cross Section as fct. of $x_{bj}$ in 3x3 $p_T^2$-$Q^2$ bins (no $p_T^{2}/Q^2$ cut)

Comparison with RAPGAP and CDM

3 kinematic regions: