Measurement of forward jet production at low x in DIS

on behalf of the
H1 collaboration

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Outline

• Why is the forward region important?
• Forward jet selection
• Theoretical Calculations / MC Models
• Results
• Conclusions
Why Forward?

$F_2$ - very inclusive - very well described by DGLAP.

Dijet cross-section, Jet Rates - measure hard subsystem.

Energetic jet/particle in forward region - information on full evolution ladder.
Test QCD at small $x$.
Signals of parton dynamics beyond DGLAP?

Events with energetic jet in the forward region.

Target phase space for evolution in $x$
(BFKL)
\[ x_{jet} \gg x_{Bj}. \]

Suppress phase space for evolution in $Q^2$.
(Suppress DGLAP)
\[ p_t^{2, \text{forward jet}} \sim Q^2. \]
Jet algorithm: Inclusive $k_t$-algorithm

Events with energetic jet in the forward region.
Target phase space for evolution in $x$.
Suppress phase space for evolution in $Q^2$.

Forward jet

$1.74 < \eta_{jet} < 2.79$

$p_t > 3.5$ GeV

Suppress QPM

$x_{JET} = \frac{E_{JET}}{E_p} > 0.035$

Suppress DGLAP

$0.5 < \frac{p_t^2}{Q^2} < 5$

If $N_{\text{forward jet}} > 1 \rightarrow$ Most forward jet is selected
Kinematic range and Measurements

Kinematic range

\[ 5 < Q^2 < 85 \text{ GeV}^2 \]
\[ 0.1 < y < 0.7 \]
\[ 0.0001 < x_{Bj} < 0.004 \]
\[ 10 \text{ GeV} < E'_e \]

Measurements

Forward jet cross-sections

\[ \frac{d\sigma}{dx_{Bj}} \]
\[ d^3\sigma \]
\[ \frac{d\sigma}{dx_{Bj} dp_t^2 dQ^2} \]

2+Forward jet cross-sections, \( \frac{d\sigma}{d\Delta\eta_2} \)

As a function of the rapidity

between the forward jet and the most forward di-jet.
**QCD Models**

**RAPGAP**: LO ME+PS: **DGLAP** evolution where the parton ladder is strongly ordered in $Q^2$ and $k_t^2$.

**RAPGAP RES $\gamma$**: RAPGAP with an additional DGLAP evolution parton ladder from the hard subsystem to the photon.

**PDF**: CTEQ6L, $\gamma$PDF: SaS1D  

Scales: $\mu_r^2 = \mu_f^2 = Q^2 + p_t^2$
QCD Models continue...

**CDM (ARIADNE):** LO ME (QPM, BGF). Color Dipole Model (QCDC and higher orders). Random walk in $k_t$.

![Diagram of QCD processes](image)

**PDF: CTEQ6L**

**CASCADE:** LO ME. Initial state CCFM partons showers with emissions ordered in angle.
**Fixed Order Calculations**

**DISENT**: NLO di-jet ($\alpha_s^2$).

(Forward jet cross-sections.)

**NLOJET++**: NLO 3-jet ($\alpha_s^2$).

(2+forward jet cross-sections.)

(Need to correct for hadronization effects.)
\[
\frac{d\sigma}{dx_{Bj}}
\]

Comparison to Exact Calculations (DISENT)

H1 forward jet data

- $H1$ prelim.
- $E$ scale uncert.
- NLO di-jet $1+\delta_{HAD}$
- $0.5 \mu_{r,f} < \mu_{r,f} < 2 \mu_{r,f}$
- PDF uncert.
- LO di-jet $1+\delta_{HAD}$

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

PDF: CTEQ6M

- NLO di-jet ok for larger $x_{Bj}$.
- LO contribution ($\alpha_s$) $\ll$ NLO contribution ($\alpha_s^2$)
\[ \frac{d\sigma}{dx_{Bj}} \]

Comparison to QCD Models

- **PS with DGLAP** evolution similar to NLO.
- **RG DIR+RES** best.
- **CDM and RG DIR+RES** too low for lower \( x_{Bj} \).
- **CASCADE** to low at lower \( x_{Bj} \), to high at higher \( x_{Bj} \).
- **All models** to low in lowest \( x_{Bj} \)-bin.
Cross-section as a function of $x_{Bj}$ in $3 \times 3$ $p_t^2 - Q^2$ bins. No $\frac{p_t^2}{Q^2}$-cut.

(Different regions in $\frac{p_t^2}{Q^2} = r$.)

Large $x_{Bj}$, $Q^2$ and $p_t^2 \Rightarrow$ NLO describes data
Smaller $x_{Bj}$, $Q^2$ and $p_t^2 \Rightarrow$ NLO insufficient

Note different ranges in $x_{Bj}$!

$$\frac{d^3\sigma}{dx_{Bj}dp_t^2dQ^2}$$

\[ \mu_r^2 = p_t^2, \quad \mu_f^2 = <p_{t,fwdjet}^2> = 24, 55 \text{ resp. } 183 \text{ GeV}^2 \]
Comparison to QCD models.

\[ p_T^2 < Q^2 \ (r < 1) - \text{DGLAP-like dynamics} \]

\[ p_T^2 \sim Q^2 \ (r \sim 1) - \text{BFKL-like dynamics} \]

\[ p_T^2 > Q^2 \ (r > 1) - \text{resolved } \gamma \text{-like dynamics} \]

- **RAPGAP DIR** - fails, but is closest to the data in the most DGLAP like region
- **RAPGAP DIR+ RES \( \gamma \)** - Good
- **CDM** - Alright, but problems in res. \( \gamma \) region.
- **CASCADE** - Goes in the right direction.
2+forward jet cross-section, $\frac{d\sigma}{d\Delta\eta_2}$

Select two hardest jets ($p_t > 6$ GeV) JET1 and JET2 - in addition to the forward jet ($p_t > 6$ GeV) 2+Forward Jet Event. (No $\frac{p_t^2}{Q^2}$-cut.)

$$\eta_e < \eta_{JET1} < \eta_{JET2} < \eta_{FWDJET}$$

$$\Delta\eta_1 = \eta_{JET2} - \eta_{JET1}$$
$$\Delta\eta_2 = \eta_{FWDJET} - \eta_{JET2}$$

$\Delta\eta_1 < 1$: small $\eta$ separation between the two hard jets - small $x_g$ - room for many emissions - long ladder favoured

$\Delta\eta_1 > 1$: large $\eta$ separation between the two hard jets - Shorter parton ladder
2+forward jet cross-section

NLO 3-jet $1 + \delta_{\text{had}}$ calculations

(NLOJET++)

\[ \mu_r^2 = \mu_f^2 = \frac{p_{i,\text{JET}1}^2 + p_{i,\text{JET}2}^2 + p_{i,\text{FWDJET}}^2}{3} \]

\[ 0.25 \mu_{r,f}^2 < \mu_{r,f}^2 < 4 \mu_{r,f}^2 \]

Data within scale uncertainty for $\Delta\eta_1 > 1$ ("short ladder"-region)
2+forward jet cross-section, \( \frac{d\sigma}{d\Delta\eta_2} \)

**QCD Generators**

- **CDM close** to describe the data.

- **CASCADE** closer to data than RG-DIR

- **ME+PS** fails, except for at high \( \Delta\eta_2 \) where \( \Delta\eta_1 > 1 \) (the ”non-BFKLish”-region), as is the case for the resolved photon model.
Conclusions - Forward Jet Measurement

- Large $x_{Bj}$, $Q^2$ and $p_t^2$ → NLO dijet describes forward jet cross section. Small $x_{Bj}$, $Q^2$ and $p_t^2$ → NLO dijet fails.

- DGLAP LO ME+PS (RAPGAP) and NLO di-jet fail for fwd jet cross-sections
  - CDM and LO ME+PS DIR+RESolved $\gamma$ OK (except 2+fwdjet)
  - CASCADE is in improvement compared to simple DGLAP evolution.

- 2+fwd cross-section -
  Models not ordering the transverse momenta still predict a higher cross-section. CDM good.

- Data suggests that more hard radiation (CDM, RES-$\gamma$, CASCADE) is needed compared to NLO and simple DGLAP evolution.

- Models that break the ordering of transverse momenta give better agreement with data (CDM, RES-$\gamma$, CASCADE), while simple DGLAP evolution restricts the phase space too much.