Forward Jets with the CAL

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- Motivation
- Event Selection
- Monte Carlo Programs
- Forward Jet Measurements
- Summary and Plans
Parton Evolution Schemes

Perturbative expansion of parton evolution equations:

\[ \sim A_{mn} \left( \ln Q^2 \right)^m \left( \ln \frac{1}{x} \right)^n \]

(can't be calculated explicitly to all orders)

DGLAP resummation: \[ \sum (\alpha_s \ln Q^2)^n \]

BFKL resummation: \[ \sum (\alpha_s \ln \frac{1}{x})^n \]

As terms small in x contribute strongly to BFKL resummation scheme, BFKL evolution may become important at the lowest x values HERA can measure.
Gluon Ladder

DGLAP and BFKL formalism based on ordering of partons emitted along the parton ladder:

DGLAP:
\[ x = x_n < x_{n-1} < \ldots < x_1 \]
\[ Q^2 = k_{T,n}^2 \gg \ldots \gg k_{T,1}^2 \]
⇒ forward fadeout

BFKL:
\[ x = x_n << x_{n-1} << \ldots << x_1 \]
no \( k_T \) ordering
⇒ eta democracy
\[ \eta = -\ln \left( \tan \frac{\theta}{2} \right) \]

BFKL ⇒ additional hadrons from high transverse momentum forward partons, above the DGLAP prediction.

A requirement on the hadronic angle (current jet) allows the exploration of lower \( x_Bj \).
Event Selection

Data Set: ZEUS 96/97 (~38.6 pb⁻¹)
Monte Carlo: Detector acceptance estimated with LO Color Dipole Model (CDM) implemented with Ariadne, using CTEQ4M PDFs
Trigger Chain: FLT40,41,42,43,44; SLT DIS6; TLT DIS03,04; DST11,12,14

Inclusive Sample:
- $Q^2 > 25 \text{ GeV}^2$
- $y > 0.04$
- $E_{T,jet} > 6 \text{ GeV}$
- $-1 < \eta_{jet} < 3$
- $E_{el} > 10 \text{ GeV}$

QPM Suppressed Sample:
- $Q^2 > 25 \text{ GeV}^2$
- $y > 0.04$
- $E_{T,jet} > 6 \text{ GeV}$
- $0 < \eta_{jet} < 3$
- $\cos(\gamma_h) < 0$
- $E_{el} > 10 \text{ GeV}$

BFKL Forward Jets Sample:
- $Q^2 > 25 \text{ GeV}^2$
- $y > 0.04$
- $E_{T,jet} > 6 \text{ GeV}$
- $0 < \eta_{jet} < 3$
- $\cos(\gamma_h) < 0$
- $E_{el} > 10 \text{ GeV}$
- $0.5 < Q^2/E_{T,jet}^2 < 2$ (effective $Q^2 > 18 \text{ GeV}$)

Detector Cuts:

$|Z_{vtx}| < 50$
$y_{el} < 0.95; y_{jb} > 0.04$
$38 < E-p_z < 65$
$p_T^{CAL}/\sqrt{E_T^{CAL}} < 3$

Phase Space Selections

Sinistra $E_{el} > 10 \text{ GeV}$
14x14 boxcut
electron isolation 0.1

jets are selected using $k_T$-inclusive algorithm in the laboratory frame
→ better reach to low $x$
→ better resolution in the forward
2 implementations of NLO calculation by DISENT

Inclusive Jet (QPM) Phase Space (1)

\[ d \sigma_{LO} = A_0 \]
\[ d \sigma_{NLO} = A_1 + B_1 \alpha_s^1 \]

OPM Suppressed Phase Spaces (2&3)

\[ d \sigma_{LO} = C_1 \alpha_s^1 \]
\[ d \sigma_{NLO} = C_2 \alpha_s^1 + D_2 \alpha_s^2 \]

• employs subtraction method
• \( \mu_r = \mu_f = Q \)
• estimated renormalisation scale uncertainty: \( \frac{Q}{2} < \mu_r < 2Q \)
• PDF : CTEQ6
• corrected from partons to hadrons using Ariadne (CDM MC)
Inclusive Jet Cross Section vs. $\eta_{\text{jet}}$

Cross section drops in forward region due to $y$-cut

- Significant discrepancy with NLO at high $\eta$,
- Ariadne (BFKL-like LO MC) can describe the data
- Lepto (DGLAP-like LO MC) gives fairly good description

Cross section dominated by QPM events - should be well understood! NLO is $O(\alpha_s^2)$

BFKL?
Parton shower missing from NLO?
Discrepancy between data and NLO localized in lowest $x_B$ and $Q^2$ bins, regions where BFKL may be important.
Event Topology: Isolating the Signal

Remember that our signal events are Boson-Gluon Fusion and QCDC events with high-$E_T$ forward going jets!

In QPM events, only 1 jet $\Rightarrow$ hadronic angle $=$ jet angle

To enhance our “signal-to-background” ratio (reject QPM), we restrict our phase space:

- events must have hadronic angle $> 90^\circ$  
- jet $\eta$ must be in forward half of detector
Reselection of Phase Space

Inclusive Jet Phase Space

- $Q^2 > 25 \text{ GeV}^2$
- $y > 0.04$
- $E_{el} > 10 \text{ GeV}$
- $E_{T,jet} > 6 \text{ GeV}$
- $-1 < \eta_{jet} < 3$

“QPM Suppressed” Phase Space

- $Q^2 > 25 \text{ GeV}^2$
- $y > 0.04$
- $E_{el} > 10 \text{ GeV}$
- $E_{T,jet} > 6 \text{ GeV}$
- $0 < \eta_{jet} < 3$
- $\cos(\gamma_{had}) < 0$

Disent Calculations:

LO = $O(\alpha_s^0) = \text{QPM}$

NLO = QPM + corrections

Just 1 order in the series of $\alpha_s$

2 orders in the series of $\alpha_s$
Inclusive Jet Cross Section vs. $\eta_{\text{jet}}$ for “QPM Suppressed” Phase Space

For our signal events, agreement with NLO within errors. NLO now includes terms $O(\alpha_s^2)$.

Ariadne gives good description of data

Lepto gives fair description of data

Renormalization scale uncertainty grows in the forward region.
Inclusive Jet Cross Section vs. $Q^2, x$ for QPM Suppressed Phase Space

NLO based on DGLAP agrees with data within errors.
BFKL Phase Space

Further restrictive phase space suggested by Mueller, Navalet

Inclusive Sample:
- $Q^2 > 25$ GeV
- $y > 0.04$
- $E_{el} > 10$ GeV
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QPM Suppressed Sample:
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BFKL Jets Sample:
- $Q^2 > 25$ GeV
- $y > 0.04$
- $E_{el} > 10$ GeV
- $E_{T, jet} > 6$ GeV
- $0 < \eta_{jet} < 3$
- $\cos(\gamma_h) < 0$
- $0.5 < Q^2/E_{T, jet}^2 < 2$
BFKL Phase Space – Data/MC Comparison

CDM (Ariadne) describes data well.

plots are area normalized
Efficiencies, purities reasonable. Low purity in highest eta bin. Can improve with eta correction.
Inclusive Jet Cross Section vs $\eta_{\text{jet}}$ for BFKL Phase Space

Data shows excess over NLO

Large renormalization scale uncertainty persists

Ariadne (BFKL-like MC) gives excellent description of data over entire region

Lepto (DGLAP-like MC) cannot describe data
NLO Calculation can describe the data.
Inclusive jet cross sections at $Q^2 > 25 \text{ GeV}^2$, $y > 0.04$ have been measured over the full rapidity acceptance region in three phase space regions.

<table>
<thead>
<tr>
<th></th>
<th>NLO Calculation</th>
<th>Ariadne (BFKL-like MC)</th>
<th>Lepto (DGLAP-like MC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive PS</td>
<td>cannot describe data in forward</td>
<td>good description</td>
<td>good description</td>
</tr>
<tr>
<td>QPM Suppressed PS</td>
<td>data above NLO; agreement w/in errors</td>
<td>good description</td>
<td>fair description</td>
</tr>
<tr>
<td>BFKL PS</td>
<td>data above NLO</td>
<td>excellent description</td>
<td>data above Lepto</td>
</tr>
</tbody>
</table>
Conclusions and Plans

- Large renormalization scale uncertainty indicates higher order contributions are important for obtaining an accurate prediction from the theory.

  A resummed NLO calculation, perhaps using the BFKL implementation, would be interesting to compare to the data, both for its cross section predictions and as a measure of the renormalization scale uncertainty in the low-$x_{Bj}$ and high-$\eta_{jet}$ region.

Paper Publication:  
- writing has begun
- SL leaves at end of April
- action items
  - cross sections in most forward region $2 < \eta < 3$
  - CASCADE prediction
  - fine tuning of systematics
End of Talk
HERA densities extrapolate into LHC region

DGLAP parton densities, QCD knowledge from HERA

LHC measurements

HERA measurements crucial for understanding signal + background at LHC!
Looking for presence of strong forward jets accompanied by hadronic activity in central and/or rear parts of the detector
Quark and gluon parton distribution functions (PDF's) are predicted at a certain $x$ and $Q^2$, given an initial distribution at $x_0$ and $Q_0^2$.

\[
\frac{dq_i(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dz}{z} \left[ q_i(y,Q^2) P_{qq} \left( \frac{x}{z} \right) + g(y,Q^2) P_{qg} \left( \frac{x}{z} \right) \right]
\]

splitting functions
- calculable by QCD

\[
\frac{dg(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s(Q^2)}{2\pi} \int_x^1 \frac{dz}{z} \left[ \sum q_i(y,Q^2) P_{gq} \left( \frac{x}{z} \right) + g(y,Q^2) P_{gg} \left( \frac{x}{z} \right) \right]
\]

In the perturbation series calculation of the evolution of the PDF's with $x$ and $Q^2$, there are terms proportional to $(\alpha_s \ln Q^2)^n$, $(\alpha_s \ln(1/x))^n$ and $(\alpha_s \ln Q^2 \ln(1/x))^n$.

DGLAP Approximation:
- sums terms $\alpha_s \ln Q^2$, ignores $\alpha_s \ln(1/x)$
- has limited applicability $\Rightarrow \alpha_s \ln(Q^2) \sim 1$, $\alpha_s \ln \frac{1}{x} \ll 1$

DGLAP = Dokshitzer, Gribov, Lipatov, Altarelli, Parisi
Previous ZEUS Measurement

ZEUS 1995

![Graph showing data and Monte Carlo models]

Issues:
- all Monte Carlo models underestimate the data at low $x$
- LO Monte Carlo models are not consistent with each other

Improvements:
- new data set: 6x more statistics
- new calculation: NLO
- higher reach in $\eta$
- jet finding with $k_T$-algorithm
LEPTO:
- $k_T$-ordered parton shower - DGLAP
- Hadronization: Lund String Model

ARIADNE:
- Parton showering with CDM (Color Dipole Model: BFKL-like)
- Hadronization: Lund String Model

Lund String Model: Color string stretched across pairs of final state partons. Energy stored in the string gives rise to hadrons.

Detector acceptance estimated with LO Color Dipole Model (CDM) implemented with Ariadne, which has the best description of data
A hard lower cut-off in the jet $E_T$ significantly limits the phase space

$\Rightarrow$ inclusive jet cross section does not dominate

inclusive DIS cross section at low $x_{Bj}$ and $Q^2$
Systematic Uncertainties

Systematic uncertainties arise from
• data measurement resolution
• poor description of data by MC at cut boundary
• model dependencies in MC

<table>
<thead>
<tr>
<th>Systematic Checks</th>
<th>Typical/Maximal (in a bin) Variation</th>
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<tbody>
<tr>
<td>1. Lepto instead of Ariadne</td>
<td>6% / 15%</td>
</tr>
<tr>
<td>2. Calorimeter Energy Scale ±3%</td>
<td>5% / 23%</td>
</tr>
<tr>
<td>3. Jet Et cut variation ± 1 GeV</td>
<td>2% / 13%</td>
</tr>
<tr>
<td>4. Jet $\eta$ cut (forward) variation ± 0.2</td>
<td>1% / 5%</td>
</tr>
<tr>
<td>5. Electron energy cut variation ± 1 GeV</td>
<td>2% / 5%</td>
</tr>
<tr>
<td>6. $Q^2$ cut variation ± 2 GeV</td>
<td>1% / 3%</td>
</tr>
<tr>
<td>7. Vtx cut variation ± 10 cm.</td>
<td>1% / 2%</td>
</tr>
<tr>
<td>8. High E-pz cut variation ± 3 GeV</td>
<td>1% / 1%</td>
</tr>
<tr>
<td>9. Low E-pz cut variation ± 3 GeV</td>
<td>1% / 1%</td>
</tr>
<tr>
<td>10. Hadronic angle cut variation ± 0.1</td>
<td>3% / 12%</td>
</tr>
</tbody>
</table>