Parton Dynamics at Low Bjorken $x$
in Deep Inelastic Scattering at HERA

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- HERA and ZEUS
- Parton Evolution: DGLAP, BFKL
- Forward Jet Measurement
- Summary
- HERA II
HERA Accelerator

HERA: an electron-proton collider at DESY in Hamburg, Germany

- 820/920 GeV protons
- 27.5 GeV e±
- 300/318 GeV c.o.m. energy
- 220 bunches, 96ns. crossing time
- 90 mA protons, 40 mA positrons
- Instantaneous luminosity: \( L^{\text{inst}} = 1.8 \times 10^{31} \text{ cm}^{-2} \text{ s}^{-1} \)

2 collider experiments
--> H1 and ZEUS
2 fixed target experiments
--> HERA-B and HERMES

HERA I: 1992-2000
~130 pb-1 taken by ZEUS, H1

2000-2002 Luminosity Upgrade

HERA II: 2003-2007
Projected Luminosity: \( L^{\text{sum}} \ldots 500 \text{ pb}^{-1} \)
ZEUS Detector

- Uranium-scintillator calorimeter sandwich design, compensating longitudinal segmentation: electron/hadron separation
- Transverse segmentation: position detection
- Argon-ethane central tracking drift chamber operates in 1.4T magnetic field

- 27.5 GeV positrons
- 820/920 GeV protons
- 99.7% solid angle coverage
ZEUS Central Tracker and Calorimeter

CTD
Drift chamber inside 1.4T solenoid
Vertex Resolution: 4mm in z

CAL:
Cell geometries:
EMC: 10x20cm. (RCAL), 5x20cm (B/FCAL)
HAC: 20x20cm.

Energy Resolution:
35% / ÖE for HAC
18% / ÖE for EMC

Cell geometries:
EMC: 10x20cm. (RCAL), 5x20cm (B/FCAL)

ZEUS Coordinate System

$^x$ $^y$ $^z$

$\eta = \frac{1}{2} \ln \frac{1 + \tan(\phi/2)}{1 - \tan(\phi/2)}$

27.5 GeV positrons
820 GeV protons
Deep Inelastic Scattering

\[ Q^2 = q^2 = (k - k')^2 \]
Momentum transfer
Resolution variable \( q = 1/l \)

\[ x_{Bj} = \frac{Q^2}{2pÂq} \]
fraction of proton's momentum carried by the struck parton

\[ y_{Bj} = \frac{pÂq}{pÂk} \]
fraction of electron's energy transferred to the proton in the proton's rest frame

E-p scattering mediated by a g, Z0 (Neutral Current), W± (Charged Current)

\( \sqrt{s} \) = center-of-mass energy

\[ Q^2 = sÂxÂy \]
HERA extends kinematic reach well beyond fixed-target experiments

\[ 0.45 \, GeV^2 \quad Q^2 \quad 20000 \, GeV^2 \]

\[ 10^{-6} \quad x \quad 0.9 \]

At \( \bar{\sum} = 320 \, GeV \),
HERA equivalent to 50TeV fixed-target experiment
Deep Inelastic Scattering Cross Section

NC DIS Cross section made up of:
- matrix element calculation
- propagator
- parton density function (PDF)

\[
\frac{d^2 \hat{E} (e^+ p \gamma E e^\pm X)}{dxdQ^2} = \frac{2 \alpha}{xQ^4} \left[ Y_f F_2(x, Q^2) \ Y \ xF_3(x, Q^2) \ y^2 F_L(x, Q^2) \right]
\]

\[
Y_\pm = 1 \pm (1 - y^2)
\]

F2 parameterizes interaction between photon and spin \( \frac{1}{2} \) partons;
can be written in terms of the quark densities:

\[
F_2(x, Q^2) = A(Q^2) [ xq(x, Q^2) + xq(x, Q^2) ]
\]

\[\text{quarks}\]
Quantum Chromodynamics

Quark-parton model:
valence quarks are free
$F_2$ independent of $Q^2$ -> scaling

Quarks account for only half the momentum in the proton

$P_{ij}$ – QCD Splitting Functions – probability for a mother parton $i$ to emit a daughter parton $j$

low $x$ =>
increasing gluon

Gluons impart transverse energy to quarks ® scaling violation
DIS Processes and Orders of as

Quark-parton model (QPM) events:

Dominant contributor to inclusive cross section

zeroth-order as process in QCD (no gluons)

2-parton final states:
Boson-Gluon Fusion & QCD Compton

first-order as processes in QCD (1 gluon vertex)
Factorization of DIS cross section: \( \hat{E}_{DIS} = \sum_i q_i(x, \hat{A}_F^2) \hat{E}_{part}^{i}(x, \hat{A}_F^2) \)

- \( i = \text{gluons, all quark flavors} \)
- \( kT_{\text{parton}} > m_F: \) parton is included in partonic cross section
- \( kT_{\text{parton}} < m_F: \) parton is “absorbed” into parton distribution

\[ \frac{dE_{DIS}}{d \ln \hat{A}_F} = 0 \quad \rightarrow \quad \frac{d q_i}{d \ln \hat{A}_F} = \frac{s}{2 \hat{\Lambda}^2} + \frac{d}{d \ln \hat{A}_F} \sum_{\text{splitting functions}} P_{ij}(x, \hat{A}_F^2) q_j(x, \hat{A}_F^2) \]

The splitting functions can be expanded in a perturbation series in \( a_s \), yielding terms \((a_s \ln Q^2)_n\), \((a_s \ln(1/x))_n\) and \((a_s \ln Q^2 \ln(1/x))_n\)
Quark and gluon parton distribution functions (PDF's) are predicted at a certain x and Q2, given an initial distribution at x0 and Q02.

Quark and gluon parton distribution functions (PDF's) are predicted at a certain x and Q2, given an initial distribution at x0 and Q02.

\[
\frac{dq_i(x, Q^2)}{d \ln Q^2} = \frac{s(Q^2)}{2 x} \int \frac{dz}{z} \left[ q_i(y, Q^2) P_{qq}(\frac{x}{z}) f g(y, Q^2) P_{gq}(\frac{x}{z}) \right]
\]

splitting functions -calculable by QCD

\[
\frac{dg(x, Q^2)}{d \ln Q^2} = \frac{s(Q^2)}{2 x} \int \frac{dz}{z} \left[ q_i(y, Q^2) P_{gq}(\frac{x}{z}) f g(y, Q^2) P_{gg}(\frac{x}{z}) \right]
\]

In the perturbation series calculation of the evolution of the PDF's with x and Q2, there are terms proportional to (aslnQ2)n, (asln(1/x))n and (aslnQ2ln(1/x))n. DGLAP Approximation:

sums terms aslnQ2, ignores asln(1/x)

has limited applicability ---\( \cdot s \ln(Q^2) \sim 1 \cdot \frac{1}{x} \)

DGLAP = Dokshitzer, Gribov, Lipatov, Altarelli, Parisi
An alternate resummation scheme for determining the parton densities

At small $x$, $\ln(1/x)$ terms in perturbation series not negligible.

BFKL approximation: 
sums terms as $\ln(1/x)$, ignores $\ln Q^2$ has limited applicability --->

\[
\cdot s \ln \frac{1}{x} \sim 1 \quad \cdot s \ln (Q^2) \quad 1
\]

BFKL = Balitzki, Fadin, Kuraev, Lipatov
DGLAP: $x = x_n < x_{n-1} < ... < x_1$, $Q^2 = k_{T,n}^2 >> ... >> k_{T,1}^2$

BFKL: $x = x_n << x_{n-1} << ... << x_1$, no ordering in $k_T$

- **DGLAP kT ordering**
- **BFKL** produces additional hadrons from high transverse momentum forward partons, above the DGLAP prediction.
- **Gluon Ladder**
- **HERA forward region**
- **forward fadeout h democracy**
Parton Showering Models:
- Color-Dipole (CDM): Ariadne (BFKL-like)
- MEPS: Lepto (DGLAP-like)

MC used for:
- detector acceptance
- hadronization corrections
- ISR/FSR corrections

Monte Carlo
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.
NLO calculations give partonic level cross sections for one higher order in as
--no attempt at modeling higher order contribution

Programs for DIS:
DISENT (Seymour and Catani)
DISASTER++ (Graudenz)
MEPjet (Mirkes, Zeppenfeld)

For comparison with data, NLO cross sections need to be corrected from parton to hadron level – Ariadne.

2 implementations of NLO calculation by DISENT

**Inclusive Jet (QPM) Phase Space**

\[
d\hat{\mathcal{E}}_{\text{LO}} = A_0 \\
d\hat{\mathcal{E}}_{\text{NLO}} = A_1 f B_1 \cdot \frac{1}{s} 
\]

**QPM Suppressed (Dijet) Phase Space**

\[
d\hat{\mathcal{E}}_{\text{LO}} = C_1 \cdot \frac{1}{s} \\
d\hat{\mathcal{E}}_{\text{NLO}} = C_2 \cdot \frac{1}{s} f D_2 \cdot \frac{2}{s} 
\]

Renormalization Scale \( \mu_R \): Scale at which the strong coupling constant is evaluated.

Renormalization scale uncertainty determined by effect on cross section by scale variation:

\[
\frac{Q}{2}, \ \hat{A}_R, \ 2Q \\
\]

-- dominant theoretical uncertainty
Jets are selected in the lab frame using the longitudinally invariant kT-cluster algorithm: Catani et al.; Ellis & Soper

Combine particles $i$ and $j$ into a jet if $d_{i,j}$ is smaller of $\{d_i, d_{i,j}\}$.

Can be applied to partons, hadrons and detector quantities in the same way.
Data Selection: Inclusive Jets

Data Set: ZEUS 96/97 (~38.6 pb⁻¹)

Phase space selection

\[ Q_2 > 25 \text{ GeV} \quad y > 0.04 \quad E_{\text{el}} > 10 \text{ GeV} \quad E_{T,\text{jet}} > 6 \text{ GeV} \quad -1 < h_{\text{jet}} < 3 \]

--- region of high trigger and detector acceptance
--- good reconstruction of hadronic system
--- high purity DIS sample
--- ensures a hard jet is measured
--- detector acceptance

\[ \frac{1}{2} = \ln \left( \tan \frac{3\theta}{4} \right) \]

DIS selection made by requesting high-energy positron in the final state with additional cuts applied to reject background.
Inclusive Jet Cross Section vs. $h_{jet}$

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

- Significant discrepancy with NLO at high $h$,
  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 $O(\alpha_s)$

BFKL?
Parton shower missing from NLO?
Inclusive Jet Cross Section vs. Q2, x

Discrepancy between data and NLO localized in lowest xBj and Q2 bins, regions where BFKL may be important
Inclusive Jet Cross Sections vs. total Inclusive Cross Sections using DISENT

<table>
<thead>
<tr>
<th>Inclusive jet phase space</th>
<th>Fully inclusive DIS phase space</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q2 &gt; 25 GeV²</td>
<td>Q2 &gt; 25 GeV²</td>
</tr>
<tr>
<td>ET_{jet} &gt; 6 GeV</td>
<td></td>
</tr>
<tr>
<td>y &gt; 0.04</td>
<td>y &gt; 0.04</td>
</tr>
<tr>
<td>-1 &lt; h_{jet} &lt; 3</td>
<td>no jet</td>
</tr>
<tr>
<td></td>
<td>selected!</td>
</tr>
</tbody>
</table>

A hard lower cut-off in the jet ET significantly limits the phase space included in the inclusive jet cross section does not dominate the inclusive DIS cross section at low xBj and Q2.
Remember that our signal events are Boson-Gluon Fusion and QCDC events with high-ET forward going jets!

To enhance our “signal-to-background” ratio (reject QPM), we restrict our phase space:
- events must have hadronic angle $> 90^\circ$
- jet h must be in forward half of detector

In QPM events, only 1 jet =>
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 h must be in forward half of detector

$$\cos^h = \frac{(p_x)^2 f (p_y)^2 f (E/p_z)^2}{(p_x)^2 f (p_y)^2 f (E/p_z)^2}$$
Reselection of Phase Space

Inclusive Jet Phase Space

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

Disent Calculations:
- \( \text{LO} = O(\alpha_S^0) = \text{QPM} \)
- \( \text{NLO} = \text{QPM} + \text{corrections} \)

“QPM Suppressed” Phase Space

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

Disent Calculations:
- \( \text{LO} = O(\alpha_S^1) = \text{BGF} + \text{QCDC} \)
- \( \text{NLO} = O(\alpha_S^2) = \text{BGF} + \text{QCDC} \)
- Just 1 order in the series of \( \alpha_S \)
- 2 orders in the series of \( \alpha_S \)
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.
Further restrictive phase space suggested by Mueller, Navalet

limitation on $Q^2/E_{T,\text{jet}}$ suppresses events exhibiting DGLAP evolution

$$Q^2 \sim E_{T,\text{jet}}^2$$

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

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

BFKL Jets Sample:
- $Q^2 > 25$ GeV
- $y > 0.04$
- $E_{\text{el}} > 10$ GeV
- $E_{T,\text{jet}} > 6$ GeV
- $0 < h_{\text{jet}} < 3$
- $\cos(gh) < 0$
- $0.5 < Q^2/E_{T,\text{jet}}^2 < 2$
Inclusive Jet Cross Section vs hjet 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>
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-xBj and high-hjet region.

Experimental improvements:

A forward jet analysis is in progress that measures farther forward using an additional forward plug calorimeter. New forward tracking detectors have been installed, and should improve reconstruction in the forward region for HERA II. With improved jet reconstruction, measure at lower jet transverse energy.
HERA II goals and accomplishments:
Increase instantaneous luminosity over $1.8 \times 10^{-31} \text{ cm}^{-2} \text{s}^{-1}$ by factor 3-5
specific luminosity reached, beam currents gradually ramped
1 fb-1 total integrated luminosity – factor 5-10 over HERA I
HERA delivers stable lumi, with each experiment taking 5-10 pb-1
70% longitudinal polarization of e± beams → achieved 50% with e+

Detector upgrades:
tracking chambers:
  silicon vertex (ZEUS) and forward/backward tracking (both)
forward proton spectrometer (H1)
luminosity detectors (both)
triggers (both)
Neutral Current DIS
\[ e^\pm p \rightarrow e^\pm X \text{ (g,Z0 exchange)} \]
\[ Q_2 = 2325 \text{ GeV}^2 \]
\[ x = 0.08 \]

Charged Current DIS
\[ e^\pm p \rightarrow n X \text{ (W\pm exchange)} \]
\[ Q_2 = 2800 \text{ GeV}^2 \]
\[ p_T = 38 \]
HERA II Analyses

Structure Function Measurements:

more accurate CC, NC ! \( xF_3, FL \) polarized cross section

charm, bottom contributions

parton density functions

Polarized CC

with 50 pb\(^{-1} \)

Ratio to central CTEQ6

Uncertainty estimates

by CTEQ at \( Q^2 = 10 \text{ GeV}^2 \)

\( u \) density most constrained

gluon density poorly constrained at high \( x \)

extrapolation

sensitivity to new physics

Zeus

Polarized CC

with 50 pb\(^{-1} \)
New Physics Searches:
- Quark Substructure
- Leptoquarks
- Contact Interactions
- SUSY
- Large Extra Dimensions
- Isolated Leptons and missing pT

H1 observe an excess in HERA I of events with a high pT isolated lepton and missing pT

\[ (d\sigma/dQ^2)_{\text{FORM}} = (d\sigma/dQ^2)_{\text{SM}} \left(1 - R^2 Q^2 / 6\right)^2 \]

Example:
\[ e^+ e^- \rightarrow q(X) \rightarrow \gamma Z^0 \rightarrow e^+ e^- q(X) \]

Excessive W production? Supersymmetry? Excited quarks?

ZEUS does not observe excess

Look for new results from HERA II in this year's spring and summer conferences.
HERA densities extrapolate into LHC region

DGLAP parton densities, QCD knowledge from HERA

LHC measurements

HERA measurements crucial for understanding signal + background at LHC!
End of Talk
Steady increase of luminosity accumulation during HERAI, with ZEUS taking 130 pb⁻¹.

- 17 pb⁻¹ of e⁻
- 115 pb⁻¹ of e⁺
- 820 GeV protons through 1997
- 920 GeV protons 1998-present

Post-upgrade:

Several sources of background delayed delivery of lumi, most problems solved, now stable running

Projected Total HERAII Luminosity:

\[ L^{\text{sum}} = 500 \, \text{pb}^{-1} \]
Central Tracking Detector

CTD: drift chamber inside 1.4T solenoid
Vertex Resolution: 4mm in z
1mm transverse views down the beampipe in x-y
Deep Inelastic Scattering Event

820/920 GeV $e^+$ p on 27.5 GeV $e^+$ p
large forward boost
Q2 correlated to scattered positron angle

This event:
Q2~3600 GeV$^2$
$x \sim 0.15$
$y \sim 0.2$
Gluon density can be extracted from fits to $F_2$ along lines of constant $x$

$$g(x, Q^2) \sim \frac{dF_2(x, Q^2)}{d\ln Q^2}$$

$F_2$ increasing at lower $x$ implies increasing gluon density.
Looking for presence of strong forward jets accompanied by hadronic activity in central and/or rear parts of the detector
Previous ZEUS Measurement

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 h jet finding with kT-algorithm
Jet and event reconstruction

Experimental challenges:
need good description of data by MC
need high jet finding purity and efficiency

- Data
  - Ariadne

Data is well described by Ariadne

Purities and efficiencies ~60%, except at high h and low ET.
### Systematic Uncertainties

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

#### Systematic Checks

<table>
<thead>
<tr>
<th>Check Description</th>
<th>Variation</th>
</tr>
</thead>
<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 h 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. Q2 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>