Rapidity Gaps in Photoproduction at HERA

Preliminary Examination

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Outline of Talk

• Introduction
• HERA and ZEUS
• Photoproduction and Diffraction
• Rapidity Gaps
• Comparisons between Data and MC
• Event Sample and Cuts
• Summary
• **Particle Scattering**
  - Particles interact via probe exchange
  - Wavelength of probe: $\lambda = \frac{h}{Q}$
    - $h$: Planck’s Constant
    - $Q$: related to Photon Momentum
    - Smaller wavelength means greater resolution

• **Lepton-Proton Collisions**
  - HERA: $ep$ CMS Energy $\sim 300$ GeV
    - Deep Inelastic Scattering: $Q^2 \sim 40,000$ GeV$^2$
  - Currently possible to probe to 0.001fm (Proton is 1fm)
Quark Parton Model and QCD

• Quarks and Gluons are colored objects called partons

• QCD describes “Strong” Interaction
  • Interactions between partons with strong coupling $\alpha_s$

• Interaction mediated by exchange of gluons
  • Process called “Color Flow”
  • Multiple gluons can be exchanged

• Individual quarks have color, but only exist in colorless combinations (hadrons)
  • “Color Confinement”
Jets

What is Produced

“Hadron Level”

- Colored Partons produced in hard scatter
- Partons undergo hadronization to form colorless hadrons (Fragmentation)
- Colorless collimated “spray” of hadrons called a “Jet”
- Hadronization in calorimeter → observe deposited energy

What is Observed in Detector

“Detector Level”

Particle Shower

Calorimeter

Hadrons
Photoproduction

- Photon carries very little 4-momentum ($Q^2 \sim 0$)
- Photon is almost real
- Most ep events are photoproduction
  - Cross section has $1/Q^4$ dependence
- Direct: $\gamma$ couples directly to a parton in proton
- Resolved:
  - Fluctuation of $\gamma$ into partonic state
  - Parton from $\gamma$ couples to parton in proton
Color Non-Singlet and Singlet Exchange in Photoproduction

**Color Non-Singlet Exchange:**
- Jets are color connected to each other
- Gap between jets filled with final state particles

**Color Singlet Exchange:**
- Jets are not color connected to each other
- No final state particles between jets (Empty Gap)
• Final state particles preserve quantum numbers of associated initial state particles

• Characteristics of Diffraction
  • Small momentum transfer \( (t) \) at \( P \) vertex
  • Exchange object (Pomeron) has quantum numbers of vacuum
  • Absence of particles between \( P \) and \( \gamma \) remnants (next slide)

\[ t = (P-P') \]
QCD Scale

Leading Order (LO)  \[ A = A_0 + A_1 \alpha_S + A_2 \alpha_S^2 + \ldots \]

Next to Leading Order (NLO)

• Running of \( \alpha_S \)
  - As scale \( \mu \) increases, \( \alpha_S(\mu) \) decreases \( (\mu = E_T \text{ or } Q) \)

• Perturbative QCD
  - Small \( \alpha_S(\mu) \) (hard scale)
  - Series expansion used to calculate observables

• Nonperturbative QCD
  - Large \( \alpha_S(\mu) \) (soft scale)
  - Series not convergent

HERA DIS Data: Running of \( \alpha_S(\mu) \)

\[ \begin{align*}
\alpha_S(\mu) & \approx 0.1 + 0.15 \mu + 0.2 \mu^2 + \ldots \\
& \mu \text{ (GeV)}
\end{align*} \]

\[ \begin{align*}
\alpha_S(\mu) & \approx 0.1184 \pm 0.0031 \\
& \mu = \text{ET}_{\text{jet}}
\end{align*} \]
Hard Diffractive Scattering in Photoproduction

- Photoproduction: $Q^2 \sim 0$
- Diffraction: Absence of particles between jets, low $t$
- Hard process
  - High jet $E_T \rightarrow$ hard scale
  - Hard QCD inside soft QCD process
  - pQCD applicable to a hard QCD process

Sample contains more events with high $E_T$ jets than predicted by diffraction without hard processes
HERA Description

- 820/920 GeV Protons
- 27.5 GeV e⁻ or e⁺
- CMS Energy 300/318 GeV
  - Equivalent to 50 TeV fixed target
- 220 bunches
  - Not all filled
- 96 ns crossing time
- Currents:
  - ~90mA protons
  - ~40mA positrons
- Instantaneous Luminosity:
  - $1.8 \times 10^{31} \text{cm}^{-2}\text{s}^{-1}$

$$L = \frac{R_{tot} - \left( I_{tot} / I_{unp} \right) R_{unp}}{\sigma_{BH}}$$

DESY
Hamburg, Germany
**HERA Luminosity**

- **Total Integrated Luminosity since 1992:**
  - $e^{-}$: $\sim 27$ pb$^{-1}$
  - $e^{+}$: $\sim 165$ pb$^{-1}$

- Luminosity upgrade recently completed
  - 5x increase in Luminosity
  - Longitudinal polarization of $e$

- Starting up now
  - Goal: 1 fb$^{-1}$ by end of 2006
ZEUS Calorimeter

- Depleted Uranium and Scintillator
- 99.8% Solid Angle Coverage
- Energy Resolution (single particle test beam)
  - Electromagnetic: $0.18 / \sqrt{E(\text{GeV})}$
  - Hadronic: $0.35 / \sqrt{E(\text{GeV})}$
- Measures energy and position of final state particles

\[ \eta = -\ln[\tan(\theta/2)] \]
Central Tracking Detector

- Cylindrical Drift Chamber inside 1.43 T Solenoid
- Measures event vertex
- Vertex Resolution
  - Transverse (x-y): 1mm
  - Longitudinal (z): 4mm
• First Level
  • Dedicated custom hardware
  • Pipelined without deadtime
  • Global and regional energy sums
  • Isolated $\mu$ and $e^+$ recognition
  • Track quality information

• Second Level
  • Commodity Transputers
  • Calorimeter timing cuts (next slide)
  • $E - p_z$ cuts
  • Vertex information
  • Simple physics filters

• Third Level
  • Commodity processor farm
  • Full event info available
  • Refined jet and electron finding
  • Advanced physics filters
Background Rejection: Timing

"Distance" between FCAL and RCAL is \( \sim 10 \text{ns} \)

On Time Event

- \( T_F = 0 \text{ns} \)
- \( T_R = 0 \text{ns} \)

Beam Gas Event

- \( T_F = 0 \text{ns} \)
- \( T_R = -10 \text{ns} \)

Calorimeter timing at Level 2

- ZEUS Calorimeter timing resolution < 1 ns

\( T_{RCAL} \)
Kinematic Variables

- Center of Mass Energy of $ep$ system squared
  - $s^2 = (p+k)^2 \sim 4E_p E_e$
- Center of Mass Energy of $\gamma p$ system squared
  - $W^2 = (q+p)^2$
- Photon Virtuality (4-momentum transfer squared at electron vertex)
  - $q^2 = -Q^2 = (k-k')^2$
- Fraction of Proton’s Momentum carried by struck quark
  - $x = Q^2/(2p \cdot q)$
- Fraction of e’s energy transferred to Proton in Proton’s rest frame
  - $y = (p \cdot q)/(p \cdot k)$
- Variables are related
  - $Q^2 = sxy$
Kinematic Reconstruction

Measured Quantities: $E_h$, $p_z$, $p_T^2$

<table>
<thead>
<tr>
<th>Variable</th>
<th>Jacquet-Blondel Method ($E_h$, $p_z$, $p_T^2$)</th>
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<tbody>
<tr>
<td>$y$</td>
<td>$\frac{E_h - p_{z,h}}{2E_e}$</td>
</tr>
<tr>
<td>$Q^2$</td>
<td>$\frac{p_{T,h}^2}{1 - y_{JB}}$</td>
</tr>
<tr>
<td>$x$</td>
<td>$\frac{Q_{JB}^2}{s \cdot y_{JB}}$</td>
</tr>
</tbody>
</table>
Jet Finding: Cone Algorithm

Particles close to each other in phase space used to retrace hadronization and fragmentation processes to original parton

\[ R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \]

- Maximize total $E_T$ of hadrons in cone of $R=1$
- Procedure
  - Construct seeds (starting positions for cone)
  - Move cone around until a stable position is found
  - Decide whether or not to merge overlapping cones
- Advantages:
  - Lorentz invariant along z axis
  - Conceptually simple
Jet Finding: Longitudinally Invariant K\textsubscript{T} Algorithm

- In ep: \( k_T \) is transverse momentum with respect to beamline
- For every object \( i \) and every pair of objects \( i, j \) compute
  - \( d_{i}^{2} = E_{T,i}^{2} \) (distance to beamline in momentum space)
  - \( d_{ij}^{2} = \min\{E_{T,i}^{2},E_{T,j}^{2}\}[(\Delta \eta)^{2} + (\Delta \phi)^{2}]^{1/2} \) (distance between objects)
- Calculate \( \min\{d_{i}^{2},d_{ij}^{2}\} \) for all objects
  - If \( d_{ij}^{2} \) is the smallest, combine objects \( i \) and \( j \) into a new object
  - If \( d_{i}^{2} \) is the smallest, the object \( i \) is a jet
- Advantages:
  - No ambiguities (no seed required and no overlapping jets)
  - \( k_T \) distributions can be predicted by QCD
• $x_\gamma$: Fraction of $\gamma$ momentum involved in collision
  - Direct Photoproduction: $x_\gamma \sim 1$
  - Resolved Photoproduction: $x_\gamma < 1$

• $x_P$: Fraction of $P$ momentum involved in hard interaction

$$x_\gamma^{OBS} = \frac{\sum E_T e^{-\eta}}{2 y E_e^{jets}}$$

$$x_P^{OBS} = \frac{\sum E_T e^{\eta}}{2 E_P^{jets}}$$
Direct Photoproduction Event
Resolved Photoproduction Event


**Model Events: PYTHIA Generator**

- **Parton Level**
  - LO Matrix Element + Parton Shower

- **Hadron Level**
  - Hadronization Model

- **Detector Level**
  - Detector simulation based on GEANT

Factorization: Long range interactions below certain scale absorbed into proton’s structure
Topography of Rapidity Gaps

- 2 jets represented as circles in ($\eta, \phi$) phase space
  - Distance between jet centers: $\Delta \eta$
  - Radius of jet cone: $R \sim 1$

- Gap indicates color singlet exchange
- No final state particles between jets (Rapidity Gap)
The Gap Fraction

Dijet events with Rapidity Gap

\[ f(\Delta \eta) = \frac{d \sigma_{\text{gap}} / d \Delta \eta}{d \sigma / d \Delta \eta} \]

\[ \sigma_{\text{gap}} = \sigma_{\text{gap}}^{\text{singlet}} + \sigma_{\text{gap}}^{\text{non-singlet}} \]

• **Singlet:**
  • \( f(\Delta \eta) \) constant in \( \Delta \eta \)

• **Non-Singlet:**
  • Particle production fluctuations \( \rightarrow \) gap
  • Non-diffractive exchange
  • \( f(\Delta \eta) \) decreases exponentially with \( \Delta \eta \)

Expectation for Behavior of Gap Fraction (J. D. Bjorken, V. Del Duca, W.-K. Tang)
1994 ZEUS Results

**Gap Fraction**

![Graph showing f(Δη) versus Δη for data and PYTHIA predictions.](image)

**Gap Fraction Fit**

![Graph showing fit of f(Δη) versus Δη for data and PYTHIA predictions.](image)

- **Suggests Color Singlet (Diffractive) Exchange**

- **Color singlet exchange not in ZEUS 1994 PYTHIA**

- **f(Δη) excess at high Δη suggests singlet contribution**
  - Excess of Gap Fraction ~ 0.07
  - P and γ remnants limit size of measurable gap

**Data:**

<table>
<thead>
<tr>
<th>Δη</th>
<th>Data</th>
<th>PYTHIA</th>
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</thead>
<tbody>
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<td>2</td>
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<td>![PYTHIA Point]</td>
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</tr>
<tr>
<td>3</td>
<td>![Data Point]</td>
<td>![PYTHIA Point]</td>
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<td>3.5</td>
<td>![Data Point]</td>
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<tr>
<td>4</td>
<td>![Data Point]</td>
<td>![PYTHIA Point]</td>
</tr>
</tbody>
</table>

- **2 Jets With:**
  - $E_T > 6\text{GeV}$,
  - $\eta < 2.5$,
  - $\Delta \eta > 2$,
  - $|\eta_{\text{avg}}| < 0.75$,
  - $0.15 \leq y \leq 0.7$
2002 H1 (ep) Results

• Color Singlet exchange added in PYTHIA and HERWIG
  - PYTHIA: $\gamma$ exchange
  - HERWIG: IP exchange
  - Now agrees with data at high $\Delta \eta$

• Low Statistics for large $\Delta \eta$

Jet Cuts:

- $E_T^{\text{Jet } 1} > 6.0$ GeV
- $E_T^{\text{Jet } 2} > 5.0$ GeV
- $\eta^{1,2} < 2.65$
- $2.5 < |\Delta \eta| < 4.0$
- $165 < W_{\gamma p} < 233$ GeV
Event Selection – 1996 ZEUS Data

Trigger Cuts

- FLT
  - Total CAL energy > 14 GeV
  - Good Track

- SLT
  - E-p_z > 8.0 GeV
    - Eliminates beam gas events
  - E_T^{Box} > 8.0 GeV
    - Sum of E_T in all CAL cells excluding 1st ring around FCAL beam pipe
    - Ensure energy is not from proton remnant
  - At least one CAL SLT EMC cluster
  - Vert. Tracks/Tot. Tracks > 0.15

- TLT
  - >2 jets with E_T ≥ 4 GeV, |η| < 2.5
  - p_z/E < 1.0

Offline Cuts

- |z_{vtx}| < 40cm
  - Region of best acceptance and prediction by MC

- No Scattered Electron
  - Select photoproduction events

- 0.2 < y_{JB} < 0.85
  - Lower: Remove beam gas
  - Upper: Remove DIS events
Jet Finding

- Jets built using calorimeter cells
- $k_T$ Algorithm
- Jets ordered in decreasing $E_T$
- Cuts on Jets:
  - $E_T^{Jet 1} > 6$ GeV
  - $E_T^{Jet 2} > 5$ GeV
  - $|\eta^{Jet 1,2}| < 2.4$
  - $|\Delta \eta| > 2.0$

Jets Separated by a large rapidity gap
Position of interaction vertex well simulated.
Important as anchor of tracking reconstruction.
Simulation of $y_{JB}$

$y_{JB} = (E-p_z)/55$ GeV

Reweighting PYTHIA in $y_{JB}$ may be necessary

Upper $y_{JB}$ cut

Lower $y_{JB}$ cut

PYTHIA Total

PYTHIA Direct
Jet Distributions: Highest $E_T$ Jet

**ZEUS Data vs. PYTHIA**

Direction and energy of produced partons understood

Jet kinematics and detector effects well understood and simulated

![Graphs showing distributions of $E_T$, $\eta$, and $\phi$ for first jet ordered in $E_T$.](image)

ZEUS 1996

PYTHIA 6.1

PYTHIA 6.1 dir
Jet Distributions: 2nd Highest $E_T$

Zeus Data vs. PYTHIA

2nd Jet allows test of jet finding algorithms

Jet kinematics and detector effects well understood and simulated
Simulation of $\Delta \eta$

- Validates
  - Jet finding
  - Hadron models
  - Detector simulation

- Distance in $\eta$ between jets well simulated
  - Important for study of Rapidity Gaps
$x_{\gamma}^{\text{OBS}}$ used to distinguish direct and resolved
Below 0.75 is resolved enhanced

Fit of MC to Data yields:
43% Direct
57% Resolved
Summary

• Conclusions
  • Compare diffractive photoproduction events to pQCD predictions
  • First look at rapidity gaps in ZEUS 1996 Data
  • Jet kinematics are well understood and simulated and detector effects accounted for
  • Hard Scale in Soft Process \(\Rightarrow\) pQCD applicable for a soft process

• Plans
  • First add 1997 Data and then 1999-2000 Data
  • Measure jet cross-sections and gap fraction
  • Understand systematic uncertainties
    • Cuts on kinematic variables
    • Mixing of direct and resolved PYTHIA contributions
    • Calorimeter energy scale
    • Use of HERWIG instead of PYTHIA for acceptance corrections