Photoproduction of Events with Rapidity Gaps Between Jets with ZEUS at HERA

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Outline

- Introduction to Rapidity Gaps
  - Photoproduction
  - Diffraction
  - Hard Diffractive Photoproduction
- HERA and ZEUS
- Simulation of photoproduction events
- Reconstruction
- Event Selection
- Comparisons between Data and MC
- Results
Photoproduction in ep Collisions

- **Q^2 \sim 0 in Photoproduction**
  - ep cross section has 1/Q^4 dependence
  - Majority of ep events are photoproduction
- **Time γ has to fluctuate into hadronic object: t \sim E_γ/Q^2**
  - Vector Dominance Model (VDM)
    - Long time: γ forms bound states of mesons
  - **Anomalous**
    - Medium time: γ fluctuates into unbound qq pair
  - **Direct**
    - Short time: γ acts as a point-like object
- **Resolved = VDM + Anomalous**
**Direct & Resolved Photoproduction**

- **Direct Photoproduction**
  - $\gamma$ couples directly to parton in proton

- **Resolved Photoproduction**
  - Parton from $\gamma$ couples to parton in proton

- **Boson-Gluon Fusion**
  - $gg \rightarrow qq$
Diffraction in $ep$ Collisions

- **Two “definitions” of diffraction**
  - Final state particles preserve quantum numbers of associated initial state particles
  - Presence of rapidity gap

- **Exchange object: Pomeron (IP)**
  - Quantum numbers of vacuum
  - Does not radiate color charge

- **Small momentum transfer at $p$ vertex**
  - Soft diffraction: No hard scale exists
  - Hard diffraction: A hard scale exists
    - Example: Large momentum transfer between Pomeron and quark
    - Perturbative QCD ($pQCD$) is applicable
Hard Diffractive Photoproduction

Rapidity Gap Between Hadron & Proton Remnants

Rapidity Gap Between 2 Final State Hadrons

Subject of this analysis

- Study the nature of the Pomeron exchange
  - Observe Color-Singlet (CS) exchange
- Hard Scale allows application of pQCD to diffractive process
Rapidity Gaps between Jets

2 Sources of Rapidity Gaps between Jets

- **Color-singlet Exchange**
  - Lack of color radiation produces gap
  - Example: Pomeron exchange

- **Color-Non-Singlet Exchange**
  - Fluctuations in particle multiplicity produces gap
  - Non-diffractive
The Gap Fraction $f(\Delta \eta)$

**Color Singlet**
- Gap created by lack of color flow
- $f(\Delta \eta)$ constant in $\Delta \eta$

**Color Non-Singlet**
- Gap created by multiplicity fluctuations
- $f(\Delta \eta)$ decreases exponentially with $\Delta \eta$

**Expectation for Behavior of Gap Fraction** (J. D. Bjorken, V. Del Duca, W.-K. Tung)

\[
d f_{\text{gap}} = \frac{d \sigma_{\text{gap}}}{d \Delta \eta} \frac{d \sigma}{d \Delta \eta}
\]

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

Dijet Events with large Rapidity separation between jets & $E_T^{\text{Gap}} < E_T^{\text{Cut}}$

All Dijet Events with large Rapidity separation between jets
HERA

DESY
Hamburg, Germany

• Beam Energy
  • 820 GeV Protons (1992-97)
  • 920 GeV Protons (since 1998)
  • 27.5 GeV e+ or e-
  • CM Energy: ~300/320 GeV
    • Equivalent to 50 TeV Fixed Target experiment

• 96 ns crossing time
• 220 bunches
  • Not all filled
• Currents:
  • ~90 mA Protons
  • ~40 mA Leptons
• Instantaneous Lumi
  • ~4x10^{31} cm^{-2} s^{-1}
• HERA I: 1992 – 2000
  • $e^-$: 27 pb$^{-1}$
  • $e^+$: 166 pb$^{-1}$

• HERA II: 2002 – 2007
  • 5x lumi and polarization
  • $e^-$: 205 pb$^{-1}$
  • $e^+$: 90 pb$^{-1}$
ZEUS Detector

Calorimeter

“Forward”

e

“Barrel”

Central Tracking Detector

p

“Rear”
Central Tracking Detector

- **Cylindrical Drift Chamber in 1.43 T magnetic field**
- **Covers** $15^\circ < \theta < 164^\circ$ (-1.96 < $\eta$ < 2.04)
- **Organization**
  - 16 azimuthal sectors
  - 9 concentric superlayers
  - 8 radial layers in a superlayer
  - Between 32-96 cells in a superlayer
- **Resolutions**
  - **Track transverse momentum**
    - $\sigma/p_T = [(0.005p_T)^2 + (0.0016)^2]^{1/2}$
  - **Vertex Position**
    - x and y: accurate to 1 mm
    - z: accurate to 4 mm
Uranium Calorimeter

- Composed of plastic scintillator and depleted uranium
- Compensating
  - Equal response to electrons and hadrons of same energy
- Sampling
  - Most energy absorbed by U
- Segmented
  - 3 Regions: FCAL, BCAL, RCAL
  - Regions → Modules → Towers → Cells
  - Hadronic and Electromagnetic Cells
- Resolution (from test beam)
  - Electromagnetic: $\sigma = 0.18/\sqrt{E}\text{(GeV)}$
  - Hadronic: $\sigma = 0.35/\sqrt{E}\text{(GeV)}$

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Rapidity Gaps Between Jets in PHP

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ZEUS Trigger

- **First Level (4.4 $\mu$s)**
  - Dedicated custom hardware
  - Pipelined without deadtime
  - Global & regional energy sums
  - Isolated $e$ and $\mu$ recognition
  - Track quality information

- **Second Level (6 ms)**
  - Commodity transputers
  - Calorimeter timing cuts
  - Cuts on $E-p_z$ and $E_T$
  - Vertex and tracking information
  - Simple physics filters

- **Third Level (0.3 s)**
  - Commodity processor farm
  - Full event info available
  - Refined jet and lepton finding
  - Advanced physics filters

Crossing: $10^7$ Hz

After FLT: ~1000 Hz

After SLT: ~100 Hz

After TLT: ~1 Hz
Simulation of $\gamma p$ Events
PYTHIA

- Accurate hadronization model
  - Many input parameters

- Adjustable $p_T^{\text{Min1}}$ and $p_T^{\text{Min2}}$
  - $p_T^{\text{Min1}}$: $p_T^{\text{Min}}$ of hardest interaction
  - $p_T^{\text{Min2}}$: $p_T^{\text{Min}}$ of soft secondary interactions (Multi-Parton Interactions)

- QCD Radiation: Matrix Element+Parton Shower (MEPS)

- Hadronization: String Model

- Multi-Parton Interactions in resolved MC

- Color-singlet exchange in PYTHIA
  - No Pomeron exchange model in PYTHIA
  - Use high-$t$ $\gamma$ exchange for $qq$ scattering in LO resolved process
  - Reproduce topology of rapidity gap events
  - Not a source of events with rapidity gaps in hard diffractive $\gamma p$
Simulation of γp Events
HERWIG

• Simple universal hadronization model
  • Few input parameters
• Adjustable $p_T^{\text{Min1}}$ (but not $p_T^{\text{Min2}}$)
• QCD Radiation: MEPS
• Hadronization: Cluster Model
• JIMMY package used to simulate MPIs
  • Multi-Parton Interactions in resolved & CS MC
• Color-singlet exchange in HERWIG
  • BFKL pomeron as exchange object
    • Resummation of leading log diagrams in $1/x$
Reconstruction

- Tracks: Use only information from CTD
- Vertex: Use CTD tracks fit to 5-parameter Helix model
- Calorimeter
  - Use cell position, magnitude of PMT pulse, time of PMT pulse
  - Island formation: Cells merged based on location and size of energy deposits
- $e^-/e^+$: SINISTRA95 Neural Network electron finder
- Energy Flow Objects (EFOs)
  - Combine track and calorimeter information for hadrons
    - CTD has better angular resolution than CAL
    - CTD has better energy resolution at low energy than CAL
**k_T Cluster Jet Algorithm**

- Historically used in e^+e^- experiments

**Procedure**

- For every object \(i\) and pair of objects \(i,j\) compute
  - \(d_{i}^2 = E_{T,i}^2\) (distance to beamline in momentum space)
  - \(d_{i,j}^2 = \min\{E_{T,i}^2, E_{T,j}^2\}[(\Delta \eta)^2 + (\Delta \phi)^2]^{1/2}\) (distance between objects)
- Calculate \(\min\{d_{i}^2, d_{i,j}^2\}\) for all objects
  - If \(d_{i,j}^2\) is the smallest, combine objects \(i\) and \(j\) into a new object
  - If \(d_{i}^2\) is the smallest, object \(i\) is a jet

**Advantages**

- Collinear and infrared safe
- No problems with overlapping jets
- Distributions can be predicted by QCD
Kinematic Variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Electron Method</th>
<th>Jacquet-Blondel Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \eta )</td>
<td>( 1 - \frac{E'_e}{2E_e} (1 - \cos \theta_e) )</td>
<td>( \sum_i (E_i - p_{z,i}) ) ( \frac{2E_e}{2E_e} )</td>
</tr>
<tr>
<td>( Q^2 )</td>
<td>( 2E_eE'_e (1 + \cos \theta_e) )</td>
<td>( \frac{(\sum_i p_{z,i})^2 + (\sum_i p_{y,i})^2}{1 - \eta_{JB}} )</td>
</tr>
</tbody>
</table>

- Jet \( E_T = [p_x^2 + p_y^2]^{1/2} \)
- Jet \( \eta = -\ln (\tan \theta/2) \) where \( \theta = \tan^{-1}(E_T/p_z) \)
- \( x_\gamma \): Fraction of \( \gamma \) momentum involved in collision
  - Direct \( \gamma p \): \( x_\gamma \approx 1 \)
  - Resolved \( \gamma p \): \( x_\gamma < 1 \)

\[
x_\gamma^{OBS} = \frac{\sum_{jets} E_T e^{-\eta}}{2 \gamma E_e}
\]
Rapidity Gap Topology

- Distance between leading and trailing jet centers: $\Delta \eta$
- $E_T^{\text{Gap}}$: Total $E_T$ of jets between leading and trailing jet centers
- Gap Event has small energy in Gap: $E_T^{\text{Gap}} < E_T^{\text{Cut}}$
- Gap definition based on $E_T$ better than that based on multiplicity
  - Collinear and infrared safe
  - Gap spans between centers of leading & trailing jets (increased statistics)
Monte Carlo Tuning

• PYTHIA and HERWIG parameters modified
  • Tuning based on JetWeb parameters (Global fit to collider data)
  • Tuned $p_T^{\text{Min}}$ to ZEUS $E_T^{GAP}$ distributions

• Tuned PYTHIA 6.1
  • Proton PDF: CTEQ 5L (Set 46)
  • Photon PDF: SaS-G 2D
  • $p_T^{\text{Min}1} = 1.9$ GeV $p_T^{\text{Min}2} = 1.7$ GeV (default 2.0 GeV, 1.5 GeV)

• Tuned HERWIG 6.1
  • Proton PDF: CTEQ 5L (Set 46)
  • Photon PDF SaS-G 2D
  • Square of factor to reduce proton radius: 3.0 (default 1.0)
  • Probability of Soft Underlying Event: 0.03 (default 1.0)
  • $p_T^{\text{Min}1} = 2.7$ GeV (default 1.8 GeV)
Acceptance Correction
Direct + Resolved MC

- Correct data for acceptance: Detector $\rightarrow$ Hadron level
- Dir & Res relative amounts fit to Data
  - $x_\gamma^{\text{OBS}}$ distribution
- PYTHIA – Detector Level
  - 28% Direct
  - 72% Resolved
- HERWIG – Detector Level
  - 44% Direct
  - 56% Resolved
- Non-Color-Singlet (NCS)
  - Direct and Resolved only
Acceptance Correction
Direct + Resolved + Color Singlet

- Correct data for acceptance: Detector → Hadron level
- NCS & CS relative amounts fit to Data
  - Dir and Res fractions fixed from $x_{\gamma}^{\text{OBS}}$ fit
  - $E_{\text{TOT}}$ for $E_T^{\text{GAP}} < 1.5$ GeV
- For Inclusive Sample
  - PYTHIA – Detector Level
    - 96% NCS (Direct + Resolved)
    - 4% CS (Direct + Resolved)
  - HERWIG – Detector Level
    - 94% NCS
    - 6% CS
- Compare to other methods
  - Fit to Num Jets for $E_T^{\text{GAP}} < 1.5$ GeV
  - Hadron level $E_T^{\text{GAP}}$
  - Similar results
# Rapidity Gap Event Selection

## ZEUS 1996-97 Data (38 pb$^{-1}$)

### Trigger Selection:
- FLT, SLT, and TLT requirements to select dijet photoproduction events

### Clean Photoproduction Sample:
- Reject events having Electron with $E_e > 5$ GeV AND $y_e < 0.85$
- $\Sigma p_T / \Sigma \sqrt{E_T} < 2$ GeV$^{1/2}$
- $|z_{vtx}| < 40$ cm
- $0.2 < y_{JB} < 0.85$

### Dijets with Large Rapidity Separation:
- $E_T^{1,2} > 5.1, 4.25$ GeV (corresponds to $E_T^{1,2} > 6.0, 5.0$ GeV at hadron level)
- $|\eta^{1,2}| < 2.4$
- $1/2|\eta^1 + \eta^2| < 0.75$
- $2.5 < |\eta^1 - \eta^2| < 4.0$ (Gap Definition)

### ~ 70,000 Events in Inclusive Sample

### 4 Samples of Gap Events:
- $E_T^{\text{CUT}} = 0.6, 1.2, 1.8, 2.4$ GeV (corr. to $E_T^{\text{CUT}} = 0.5, 1.0, 1.5, 2.0$ at hadron level)
Inclusive Kinematic Variables
Data vs. PYTHIA

- PYTHIA describes the inclusive variables
- Addition of CS makes small improvement for inclusive sample
• PYTHIA describes the gap variables ($E_T^{\text{Cut}} = 1 \text{ GeV}$)
• Addition of CS makes substantial improvement for gap sample
Inclusive Kinematic Variables
Data vs. HERWIG

- HERWIG describes the inclusive variables
- Addition of CS makes small improvement for inclusive sample
Gap Kinematic Variables
Data vs. HERWIG ($E_T^{\text{Cut}} = 1$ GeV)

- HERWIG describes the gap variables ($E_T^{\text{Cut}} = 1$ GeV)
- Addition of CS makes substantial improvement for gap sample

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Systematics

- Kinematic Cuts: +/- HERWIG Resolutions
- Amount of CS in unfolding varied by 25%
- CAL Energy Scale varied by 3%
- Difference between PYT and HER acceptance correction

<table>
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<tr>
<th>Variable</th>
<th>+/- Change</th>
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</tr>
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<tbody>
<tr>
<td>$E_T^{1,2}$</td>
<td>13%</td>
<td>$\eta^{1,2}$</td>
<td>2%</td>
</tr>
<tr>
<td>$\frac{1}{2}</td>
<td>\eta^1+\eta^2</td>
<td>$</td>
<td>9%</td>
</tr>
<tr>
<td>$y_{JB}$</td>
<td>5%</td>
<td>$p_T^{\text{Miss}}/\sqrt{E_T}$</td>
<td>10%</td>
</tr>
<tr>
<td>$y_e$</td>
<td>6%</td>
<td>$Z_{vtx}$</td>
<td>25%</td>
</tr>
<tr>
<td>$E_T^{\text{Cut}}$</td>
<td>36%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Same systematics used for all bins
- Systematic variation in cross section dependent on $E_T^{\text{Gap}}$, $\Delta\eta$, $W$, and $x_\gamma^{\text{OBS}}$ bins
Acceptance Corrected Data vs MC

$E_T^{\text{Gap}}$ Cross Section

- Acceptance Correction
  - Average of PYT & HER
- Systematic Errors from HER
  - Difference between HER & PYT values added to systematic
- MCs fit to Data
  - $\chi^2$ Minimization
  - Yield Scale Factors
    - HER: $1.01^{\text{NCS}} + 1.32^{\text{CS}}$
    - PYT: $1.25^{\text{NCS}} + 404^{\text{CS}}$
  - High CS Scale Factor in PYTHIA due to High-\(t\) $\gamma$ exchange
  - Same scale factors used in all following plots

Fit to $E_T^{\text{Gap}}$ Cross Section results in ~3%
CS contribution for both PYTHIA & HERWIG
Acceptance Corrected Data vs MC $\Delta \eta$ Cross Sections

- **Inclusive Cross Section**
  - MC with and without CS added describes data

- **Gap Cross Section**
  - MC without CS disagrees with data
  - MC with CS added describes data

- **Gap Fraction**
  - MC without CS disagrees with data
  - MC with CS added describes data
$\Delta \eta$ for Different Gap Fractions
Unfolded with AVG of PYT & HER

All $x_\gamma^{\text{OBS}}$

- MC with CS added describes data for entire $x_\gamma^{\text{OBS}}$ region
- CS contribution in resolved region is 1-2% from Gap Fraction
  - Resolved region should allow comparison to Tevatron (1-1.5% CS)
W for Different Gap Fractions
Unfolded with AVG of PYT & HER

- Disagreement at low W for All $x_\gamma^{\text{OBS}}$ sample
- CS contribution in resolved region is 1-2% from Gap Fraction
  - Resolved region should allow comparisons to Tevatron
$x_\gamma^{\text{OBS}}$ for Different Gap Fractions
Unfolded with AVG of PYT & HER

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

- PYTHIA and HERWIG with CS describes the data well
- HERWIG agreement remains better than PYTHIA agreement
- PYTHIA agreement in resolved region improved compared to $\Delta \eta$

Resolved region: $x_\gamma^{\text{OBS}} < 0.75$
Should allow comparison to Tevatron
Comparisons to Previous ZEUS Measurement

**ZEUS 1995**

- Data •
- PYTHIA ○

**Gap defined by multiplicity (not $E_T$)**

$f(\Delta \eta) = 0.11$ for $3.5 < \Delta \eta < 4.0$

1-4% CS from 2-4 in $\Delta \eta$

Measurements consistent

**ZEUS (this analysis)**

$E_T^{\text{GAP}} < 0.5$ GeV

$E_T^{\text{GAP}} < 1.0$ GeV

$E_T^{\text{GAP}} < 1.5$ GeV

$E_T^{\text{GAP}} < 2.0$ GeV

$E_T^{\text{GAP}}$ < 1.5 GeV closest to previous results
Comparison to H1 Measurement

- **Gap Fraction for** $E_T^{\text{Gap}} < 1.0$ GeV
  - 6.6 pb$^{-1}$ of Lumi
  - Excess of data when compared to NCS MC
  - Data described by NCS+CS MC
  - Consistent with ZEUS within errors
- **Reference**
  - C. Aldoff et al.
Rapidity Gap Between Jets
Summary

• Conclusions
  • Data demonstrate evidence of ~3% Color-Singlet contribution estimated at the cross section level for entire phase space
    • Observe ~1-2% Color-Singlet in resolved region
  • Data consistent with published ZEUS and H1 results
  • PYTHIA and HERWIG describe data well after the Color-Singlet contribution is added

• In Progress
  • Examine W dependence
  • Explore comparisons with Tevatron
### Purities and Efficiencies

**$E_T$ Gap**

#### PYTHIA

<table>
<thead>
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<th>Efficiency</th>
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<tbody>
<tr>
<td>$E_{\text{GAP}}$ (GeV)</td>
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<tr>
<td>0</td>
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</tr>
<tr>
<td>5</td>
<td>0.2</td>
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<td>10</td>
<td>0.3</td>
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#### HERWIG

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#### Stability

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#### Correction Factor

$$\text{Correction Factor}_i = \frac{\text{Purity}_i}{\text{Efficiency}_i}$$

#### Stability

$$\text{Stability}_i = \frac{\text{Detector}_i \text{ && Generator}_i}{\text{Reconstructed in any bin}_i}$$

- **Purity**: $(\text{Detector} \&\& \text{Generator})_i / (\text{Detector})_i$
- **Efficiency**: $(\text{Detector} \&\& \text{Generator})_i / (\text{Generator})_i$
- **Correction Factor**: $(\text{Generator} / \text{Detector})_i = (\text{Purity} / \text{Efficiency})_i$
- **Stability**: $(\text{Detector} \&\& \text{Generator})_i / \text{Reconstructed in any bin}_i$
Purities and Efficiencies $\Delta \eta$

**PYTHIA**

- **Purity:** \( \frac{\text{Detector} \&\& \text{Generator}}{\text{Detector}} \) \_i
- **Efficiency:** \( \frac{\text{Detector} \&\& \text{Generator}}{\text{Generator}} \) \_i
- **Correction Factor:** \( \frac{\text{Generator}}{\text{Detector}} \) \_i = \( \frac{\text{Purity}}{\text{Efficiency}} \) \_i
- **Stability:** \( \frac{\text{Detector} \&\& \text{Generator}}{\text{Reconstructed in any bin}} \) \_i

**HERWIG**

- **Purity:** \( \text{Inclusive} \) \_i
- **Efficiency:** \( E_T^{\text{Cut}} = 1.0 \text{ GeV} \) \_i
- **Stability:** \( \text{Inclusive} \) \_i
- **Correction Factor:** \( E_T^{\text{Cut}} = 1.0 \text{ GeV} \) \_i

\_i: Bin i
Cross Section Systematics Unfolded with HERWIG

Order of Systematics (left to right in each bin)


Cross Sections
Unfolded with PYT & HER

• Data unfolded separately with PYT & HER
• NCS MC fit to data in $E_T^{\text{GAP}}$ cross section
• CS MC added by fitting NCS+CS to $E_T^{\text{Gap}}$
  • Addition of CS maximizes agreement with Data for PYT and HER