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

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SMU Seminar
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Rapidity Gaps Between Jets in Photoproduction

Photoproduction

Diffraction

Hard Diffractive Photoproduction

HERA and ZEUS

Simulation of photoproduction events

Reconstruction

Event Selection

Comparisons between Data and MC

Results
Direct & Resolved Photoproduction

Direct Photoproduction

\[ e \rightarrow e' \]

\[ \gamma \rightarrow q \]

\[ P \rightarrow \text{Proton Remnant} \]

Boson-Gluon Fusion

- Direct: \( \gamma \) couples directly to parton in proton
- Resolved: parton from \( \gamma \) couples to parton in proton

Resolved Photoproduction

\[ e \rightarrow e' \]

\[ \gamma \rightarrow g \]

\[ P \rightarrow \text{Proton Remnant} \]

\[ gg \rightarrow qq \]
Diffraction in ep Collisions

- Two “definitions” of diffraction
  - Final state particles preserve quantum numbers of associated initial state particles
  - Presence of rapidity gap (next slide)
- Exchange object: Pomeron
  - 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 IP and quark
    - Perturbative QCD (pQCD) is applicable
Hard Diffractive Photoproduction

Rapidity Gap Between Hadron & Proton Remnant

\[ e(k) \rightarrow \gamma(q) \rightarrow e'(k') \]

Subject of this analysis

Study the nature of the Pomeron
- Observe Color-Singlet (CS) exchange

Hard Scale allows application of pQCD to diffractive process
Rapidity Gaps between Final State Hadrons

- 2 Sources of Rapidity Gaps between Final State Hadrons
  - Diffraction
    - Color-Singlet Exchange: Pomeron
    - Lack of color radiation produces gap
  - Particle Fluctuations
    - Color-Octet Exchange (non-diffractive)
    - Fluctuations in particle multiplicity produces gap
The Gap Fraction $f(\Delta \eta)$

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

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

### Expectation for Behavior of Gap Fraction

(J. D. Bjorken, V. Del Duca, W.-K. Tang)

$$f_{\text{gap}}$$

### All Dijet Events with large Rapidity separation between jets

$$\sigma_{\text{gap}} = \sigma_{\text{gap singlet}} + \sigma_{\text{gap non-singlet}}$$

- **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 $\Delta \eta$
HERA

- Beam Energy
  - 820 GeV Protons (1992-97)
  - 920 GeV Protons (since 1998)
  - 27.5 GeV e+ or e-
  - CMS: ~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
  - ~$4 \times 10^{31}$ cm$^{-2}$s$^{-1}$

DESY
Hamburg, Germany

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- **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$^{-1}$
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
    - $\sigma/\rho_T = [(0.005\rho_T)^2 + (0.0016)^2]^{1/2}$
  - Vertex Position
    - x and y: accurate to 1 mm
    - z: accurate to 4 mm

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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 (smallest geometrical unit)
  - Hadronic and Electromagnetic Cells
- Resolution (from test beam)
  - Electromagnetic: $\sigma = 0.18/\sqrt{E(\text{GeV})}$
  - Hadronic: $\sigma = 0.35/\sqrt{E(\text{GeV})}$
**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** (300 ms)
  - Commodity processor farm
  - Full event info available
  - Refined jet and lepton finding
  - Advanced physics filters

Crossing: $10^7$ Hz
After FLT: $\sim$1000 Hz
After SLT: $\sim$100 Hz
After TLT: $\sim$1 Hz
Simulation of $\gamma p$ Events

**PYTHIA**

- Most accurate hadronization model possible
  - Many input parameters
- Adjustable $p_T^{\text{min}1}$ and $p_T^{\text{min}2}$
  - $p_T^{\text{min}1}$: $p_T^{\text{min}}$ of hardest interaction
  - $p_T^{\text{min}2}$: $p_T^{\text{min}}$ 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
  - 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 $\gamma p$
• Simplest universal hadronization model
  • Few input parameters
• Adjustable $p_T^{\text{min}1}$ (but not $p_T^{\text{min}2}$)
• 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
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 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>$\gamma$</td>
<td>$1 - \frac{E'_e}{2E_e} (1 - \cos \theta_e)$</td>
<td>$\frac{\sum_i (E_i - p_{z,i})}{2E_e}$</td>
</tr>
<tr>
<td>$Q^2$</td>
<td>$2E_eE'_e (1 + \cos \theta_e)$</td>
<td>$\frac{(\sum_i p_{z,i})^2 + (\sum_i p_{y,i})^2}{1 - y_{JB}}$</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 $\gamma p$: $x_\gamma \sim 1$
  - Resolved $\gamma p$: $x_\gamma < 1$
Rapidity Gap Topology

- Distance between leading and trailing jet centers of: $\Delta \eta$
- $E_T^{\text{Gap}}$: 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

- Modified Default ZEUS MC parameters
  - Tuning based on JetWeb parameters (Global fit to collider data)
  - Tuned $p_T^{\text{Min}}$ to ZEUS $E_T^{\text{GAP}}$ distributions

- Tuned PYTHIA 6.1
  - Proton PDF: CTEQ 5L (Set 46)
  - Photon PDF: SaS-G 2D
  - $p_T^{\text{Min} 1} = 1.9$, $p_T^{\text{Min} 2} = 1.7$ (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: $x^{\text{OBS}}$ 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: \( E_{\text{TOT}} \) for \( E_T^{\text{GAP}} < 1.5 \text{ GeV} \)

- For Inclusive Sample
  - PYTHIA – Detector Level
    - 96% NCS
    - 4% CS
  - HERWIG – Detector Level
    - 94% NCS
    - 6% CS

- Compare to other methods
  - Fit to Num Jets for \( E_T^{\text{GAP}} < 1.5 \text{ GeV} \)
  - Hadron level \( E_T^{\text{GAP}} \)
  - Similar results

![Graph showing fit of HERWIG to \( E_{\text{TOT}} \) for \( E_T^{\text{GAP}} < 1.5 \text{ GeV} \)]
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 good Electron with \(E_e > 5\) GeV AND \(y_e < 0.85\)
- \(\sum p_T / \sqrt{\sum E_T} < 2\) GeV\(^{1/2}\)
- \(|z_{vtx}| < 40\) cm
- \(0.2 < y_{JB} < 0.85\)

#### Dijets with Large Rapidity Separation:
- \(E_{T1,2} > 5.1, 4.25\) GeV (corresponds to \(E_{T1,2} > 6.0, 5.0\) GeV at hadron level)
- \(|\eta^{1,2}| < 2.4\)
- \(\frac{1}{2}|\eta^1 + \eta^2| < 0.75\)
- \(2.5 < |\eta^1 - \eta^2| < 4.0\) (Gap Definition)

#### 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)

\(~70,000\) Events in Inclusive Sample
• PYTHIA describes the inclusive variables
• Addition of CS makes small improvement for inclusive variables
**Gap Kinematic Variables**

**Data vs. PYTHIA \( E_T^{\text{CUT}} = 1 \text{GeV} \)**

- PYTHIA describes the gap variables (\( E_T^{\text{CUT}} = 1 \ \text{GeV} \))
- Addition of CS makes substantial improvements

- **Detector Level**

```
- PYTHIA describes the gap variables (\( E_T^{\text{CUT}} = 1 \ \text{GeV} \))
- Addition of CS makes substantial improvements
```
Inclusive Kinematic Variables
Data vs. HERWIG

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

- HERWIG describes the gap variables ($E_T^{CUT} = 1\text{ GeV}$)
- Addition of CS makes substantial improvements
Systematics

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

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<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
Cross Section Systematics
Unfolded with HERWIG

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Order of Systematics (left to right in each bin)


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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

~3% CS for PYT and HER
Acceptance Corrected Data vs MC
$E_T^{\text{Gap}}$ and $\Delta \eta$ Cross Sections

- Data acceptance corrected with average of PYT & HER
- MCs fit to average of corrected data yield Scale Factors
  - HER: $1.01\times NCS + 1.32\times CS$   PYT: $1.25\times NCS + 404\times CS$
  - High CS scale factor in PYTHIA because High-t $\gamma$ not a real physical model
  - Addition of CS maximizes agreement with Data for PYT and HER
Adding \( \Delta \eta \) for Different Gap Fractions
Unfolded with AVG of PYT & HER

- Adding \( \sim 3\% \) CS maximizes agreement with data for entire \( x_\gamma^{\text{OBS}} \) region
- Adding 1-2\% CS maximizes agreement with data for resolved region
  - Resolved region should allow comparisons with Tevatron (1-1.5\% CS)
W for Different Gap Fractions
Unfolded with AVG of PYT & HER

For All $x^\text{OBS}_\gamma$

- $E_T^{\text{GAP}} < 0.5 \text{ GeV}$
- $E_T^{\text{GAP}} < 1.0 \text{ GeV}$
- $E_T^{\text{GAP}} < 1.5 \text{ GeV}$

For $x^\text{OBS}_\gamma < 0.75$

- $E_T^{\text{GAP}} < 0.5 \text{ GeV}$
- $E_T^{\text{GAP}} < 1.0 \text{ GeV}$
- $E_T^{\text{GAP}} < 1.5 \text{ GeV}$

For Resolved

- $E_T^{\text{GAP}} < 0.5 \text{ GeV}$
- $E_T^{\text{GAP}} < 1.0 \text{ GeV}$
- $E_T^{\text{GAP}} < 1.5 \text{ GeV}$

- $3\%$ CS maximizes agreement with Data for PYT & HER total $x^\text{OBS}_\gamma$
- $1-2\%$ CS maximizes agreement with Data for resolved region
- Disagreement at low $W$ for All $x^\text{OBS}_\gamma$ sample
\[ x_{\gamma}^{\text{OBS}} = \sum_{\text{jets}} E_T e^{-\eta} \]

\[ x_{\gamma} = \frac{\sum E_T e^{-\eta}}{2 y E_e} \]

- Adding \~3% CS maximizes agreement with data for PYT & HER
- HERWIG agreement remains better than PYTHIA agreement
- PYTHIA agreement in resolved region improved compared to $\Delta \eta$

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

ZEUS 1995

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 $\Delta \eta$

Data consistent

$E_T^{GAP} < 1.5$ GeV closest to previous results

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Comparison to H1 Measurement

- **Gap Fraction for** $E_T^{Gap} < 1.0$ GeV
  - Excess of data when compared to NCS MC
  - Data described by NCS+CS MC
  - Consistent with ZEUS within errors
  - 6.6 pb$^{-1}$ of Lumi

![Graph showing comparison to H1 Measurement](image)
Rapidity Gap Between Jets

Summary

• Conclusions
  • Evidence of ~3% Color-Singlet Exchange
  • 1-2% Color-Singlet Exchange in resolved region
  • PYTHIA and HERWIG without CS MC is below data
  • Addition of CS MC gives agreement with data
  • $E_T^{\text{Gap}}, \Delta \eta, W,$ and $x_\gamma^{\text{OBS}}$ cross sections and gap fractions well described
  • ZEUS and H1 Data agree within errors

• In Progress
  • Examine $W$ dependence
  • Explore comparisons with Tevatron
- 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: \((\text{Detector} \&\& \text{Generator})_i / \text{Reconstructed in any bin}\)
Purities and Efficiencies

\[ \Delta \eta \]

PYTHIA

\begin{align*}
\text{Purity} & \quad 0.4 \quad 0.3 \quad 0.2 \quad 0.1 \quad 0.05 \quad 0.01 \\
\Delta \eta & \quad 2.5 \quad 3 \quad 3.5 \quad 4
\end{align*}

\begin{align*}
\text{Efficiency} & \quad 0.35 \quad 0.3 \quad 0.25 \quad 0.2 \quad 0.15 \quad 0.1 \quad 0.05 \quad 0.01 \\
\Delta \eta & \quad 2.5 \quad 3 \quad 3.5 \quad 4
\end{align*}

\begin{align*}
\text{Stability} & \quad 1.2 \quad 1 \quad 0.8 \quad 0.6 \quad 0.4 \quad 0.2 \quad 0.1 \quad 0.05 \quad 0.01 \\
\Delta \eta & \quad 2.5 \quad 3 \quad 3.5 \quad 4
\end{align*}

\begin{align*}
\text{Corr Factor} & \quad 4 \quad 3 \quad 2 \quad 1
\end{align*}

HERWIG

\begin{align*}
\text{Purity} & \quad 0.4 \quad 0.3 \quad 0.2 \quad 0.1 \quad 0.05 \quad 0.01 \\
\Delta \eta & \quad 2.5 \quad 3 \quad 3.5 \quad 4
\end{align*}

\begin{align*}
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\end{align*}

- 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: Bin i**