TEVATRON RESULTS

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• Diffractive reactions at hadron colliders are defined as reactions in which no quantum numbers are exchanged between colliding particles.

Identified by presence of:
- intact leading particle
- or
- large rapidity gap

Non- Diffractive (ND)

Single Diffraction (SD)

Double Diffraction (DD)

Double Pomeron Exchange (DPE)

Higgs, dijets, $\gamma\gamma$, $\chi_c$
**Diffraction: definitions**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
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<tbody>
<tr>
<td>$y$</td>
<td>rapidity</td>
</tr>
<tr>
<td>$\eta$</td>
<td>pseudorapidity</td>
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<tr>
<td>$y = \frac{1}{2} \ln \left( \frac{E+p_z}{E-p_z} \right)$</td>
<td></td>
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<tr>
<td>$\eta = y \bigg</td>
<td>_{m=0} = -\ln \tan(\theta/2)$</td>
</tr>
<tr>
<td>$t$</td>
<td>four-momentum transfer squared</td>
</tr>
<tr>
<td>$\xi$</td>
<td>fractional momentum loss of $p/p\bar{p}$</td>
</tr>
<tr>
<td>$M_X$</td>
<td>mass of diffractive system $X$</td>
</tr>
<tr>
<td>$\xi = \frac{M_X^2}{s}$</td>
<td></td>
</tr>
<tr>
<td>$\Delta \eta \approx \ln(s/M_X^2)$</td>
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Diffractive Processes

Hadronic processes can be characterized by an energy scale:

**soft processes** - energy scale of the order of the hadron size (~ 1 fm)
   pQCD is inadequate to describe these processes

**hard processes** – “hard” energy scale (> 1 GeV²)
   can use pQCD,
   “factorization theorems” - can separate perturbative part from non-perturbative

Discovery of **hard diffraction** - jet production in ppbar collisions with a leading proton in the final state (1988 UA8)

**Hard diffractive processes allow to study diffraction in the pQCD framework.**

**At the Tevatron we study both soft and hard diffractive processes.**
Experimental Techniques

### CDF II

- **Tracking**
  - Tracking Detectors $|\eta| < 2.0$

- **CCAL, PCAL**
  - Calorimeters $(15^\circ \text{in } \varphi) \times 0.1 \text{ (in } \eta))$ $|\eta| < 3.6$

- **RPS**
  - Roman Pot Spectrometers $0.02 < \xi < 0.1$
  - $0 < |t| < 2 \text{ GeV}^2$

- **BSC**
  - Beam Shower Counters $5.4 < |\eta| < 7.4$

- **MPCAL**
  - MiniPlug Calorimeters $3.5 < |\eta| < 5.1$
Forward Detectors are crucial for diffractive studies
Forward Detectors are crucial for diffractive studies use Roman Pots for antiproton tagging
Forward Detectors are crucial for diffractive studies. They use Miniplugs and BSCs for rapidity gaps.
Fordward Detectors at CDFII: Roman Pot Spectrometers (RPS)

Fiber Tracker
- 3 stations
- 57 meters from IP

- 3 trigger counters
- 240 channels

Position resolution ±80µm
Typical resolutions
in ξ: δξ=± 0.001; in t: δt=±0.07GeV²

Acceptance: 0 < |t| < 2, 0.03 < ξ < 0.1

Scintillator fiber xy-tracker
270µ pitch, 2 m lever arm

MIPs ( >1000 counts)
Forward Detectors at CDFII: Beam Shower Counters (BSCs)

BSCs are scintillator counters located along beam pipe used for **triggering events with forward rapidity gaps**
designed to **measure the energy and lateral position** of both electromagnetic and hadronic showers “towerless” geometry – no dead regions
Study s-dependence of high cross-sections physics

...mostly non-pQCD

1. Study of MinBias events:
2. Study of Underlying Events
3. Gap-X Gap events
Hard Single Diffraction

Diffractive signature:
- large rapidity gap
- intact $p/p\bar{p}$ detected in RomanPots

Can study diffractive production of high $p_T$ objects: jets, $W$, $J/\Psi$, $b$

different insight into the nature of Pomeron

Diffractive dijet cross section

$$\sigma(\bar{p}p \rightarrow \bar{p}X) \approx F_{jj} \otimes F_{jj}^D \otimes \hat{O}(ab \rightarrow jj)$$

Study the diffractive structure function

$$F_{jj}^D = F_{jj}^D(x, Q^2, t, \xi)$$

at LO

Data

Experimentally determine diffractive structure function

$$F_{jj}^D$$

$$R_{SD}^{ND}(x, \xi) = \frac{\sigma(SD_{jj})}{\sigma(ND_{jj})} = \frac{F_{jj}^D(x, Q^2, \xi)}{F_{jj}(x, Q^2)}$$

known PDF
Factorization breakdown between HERA and Tevatron

\[ \sqrt{s} = 1.8 \text{ TeV} \]

\[ \langle \xi \rangle = 0.04, 0.05, 0.06, 0.07, 0.08, 0.09 \]
\[ \Delta \xi = 0.01 \]

\[ E_T^{\text{jet}1,2} \geq 7 \text{ GeV} \]
\[ |t| \leq 1.0 \text{ GeV}^2 \]

stat errors only
\[ x = 0.5 \times \xi_{\text{min}} \]

no \( \xi \) dependence

\( \beta \) - momentum fraction of parton in pomeron

H1 fit-2
H1 fit-3
CDF data

\[ E_T^{\text{jet}1,2} > 7 \text{ GeV} \]
\[ Q^2 = 75 \text{ GeV}^2 \]

\[ 0.035 < \xi < 0.095 \]
\[ |t| < 1.0 \text{ GeV}^2 \]
Looking at Fraction for various single hard diffractive productions:

\[ R \equiv \frac{SD}{ND} \text{ ratio} \]

@ 1800 GeV  

All fractions ~ 1%  

(differences due to kinematics)  

\( \sim \) uniform suppression

<table>
<thead>
<tr>
<th>Hard component</th>
<th>Fraction (R) %</th>
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<tbody>
<tr>
<td>Dijet</td>
<td>0.75 ± 0.10</td>
</tr>
<tr>
<td>W</td>
<td>1.15 ± 0.55</td>
</tr>
<tr>
<td>b</td>
<td>0.62 ± 0.25</td>
</tr>
<tr>
<td>J/ψ</td>
<td>1.45 ± 0.25</td>
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CDF Diff. Dijets at \( \sqrt{s} = 1.96 \) TeV triggered by intact p\(\bar{p}\) in RPS

\[ Q^2 \text{ varies from } 100-10,000 \text{ GeV}^2 \]

In good agreement with 1.8 TeV results

\[ 0.03 \leq \xi \leq 0.09 \]

\[ Q^2 = \langle E_T^{\text{jett}} \rangle^2, \quad \langle E_T \rangle = \langle E_T^{\text{jett}} + E_T^{\text{jet}} \rangle / 2 \]

overall syst. uncertainty: ± 20% (norm), ± 6% (slope)
antiproton $|t|$ distribution

- no diffractive dips
- no $Q^2$ dependence

in slope from inclusive to $Q^2 \sim 10^4 \text{ GeV}^2$

Fit to double exponential function:

$$d\sigma/dt \propto 0.9 \ e^{b_1 \times t} + 0.1 \ e^{b_2 \times t}$$

PRD 86, 032009 (2012)

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Search for diffraction minimum around $t$ of 2.5 GeV$^2$?

PRD 86, 032009 (2012)

Fitted with electromagnetic form factor squared $F_1(t)^2$

$$F_1(t) = \frac{4m_p^2 - 2.8t}{4m_p^2 - t} \cdot \left( \frac{1}{1 - t/0.71} \right)^2$$

from

$$\frac{d\sigma^{SD}}{dt} = N_{\text{norm}} \cdot F_1(t)^2 \cdot \exp \left[ 2\alpha' \cdot \ln \frac{1}{\xi} \cdot t \right]$$

where $\alpha' \approx 0.25 \text{ (GeV/c)}^{-2}$ is the slope of the the $IP$-trajectory.
Diffractive W/Z production probes the quark content of the Pomeron

**Identify diffractive events using RP:**
- accurate event-by-event $\xi$ measurement
- no gap acceptance correction needed
- can still calculate $\xi_{\text{cal}}$

\[
\xi_{\text{cal}} = \sum_{\text{towers}} \frac{E_T}{\sqrt{s}} e^{-\eta}
\]

In W production, the difference between $\xi_{\text{cal}}$ and $\xi_{\text{RP}}$ is related to missing $E_T$ and $\eta_\nu$

\[
\xi_{\text{RP}} - \xi_{\text{cal}} = \frac{E_T}{\sqrt{s}} e^{-\eta_\nu}
\]

allows to determine:
- neutrino and W kinematics

**Fraction of diffractive W**

\[
R_W (0.03<\xi<0.10, |t|<1) = [0.97 \pm 0.05(\text{stat}) \pm 0.10(\text{syst})]\% 
\]

consistent with Run I result (with Large Rapidity Gap method), extrapolated to all $\xi$
Diffractive Z Production

estimate 11 overlap ND+SD background events based on ND $\xi_{\text{cal}}$ distribution

Fraction of diffractive Z

$R_Z (0.03 < \xi < 0.10, |t|<1) = [0.85\pm0.20(\text{stat})\pm0.08(\text{syst})]\%$

CDF Run II

$\sqrt{s} = 1.96$ TeV

PRD 82, 112004, 2010

37 diffractive $Z \rightarrow \text{ee/}\mu\mu$ candidates

(RP track, $\xi_{\text{cal}}<0.1$)
Double Diffraction

Jets separated by a large rapidity gap - Color Singlet Exchange (CSE)

Diffractive signature:
large central rapidity gap – slightly different gap definitions

Bjorken’s estimate of gap “survival” probability
\( \langle S \rangle \sim 0.1 \)

**PRL 72, 2332, 1994 (D0)**

**PRL 74, 855, 1995 (CDF)**

**PRL 80, 1156, 1998 (CDF)**

**PRD 47, 101, 1993**
Jet-Gap-Jet at the Tevatron

CDF

R=[1.13±0.12(stat) ±0.11(syst)]% @ 1800 GeV
R=[2.7±0.7(stat) ±0.6(syst)]% @ 630 GeV

PRL 80, 1156, 1998

R is estimated using OS jets as signal and SS jets as a control sample

D0 data compared to Enberg, Ingelman model (NLL BFKL + MPI+SCI)
 Fraction of events with gaps:

~10% in soft DD events and ~1% in jet events

The distributions are similar in shape within the uncertainties
Multi Gap Events

Diffractive signature: recoil $p\bar{p}$ AND large rapidity gap on proton side

would be interesting to study at LHC

second gap production is not suppressed
Central Exclusive Production

Interactions of the form

\[ pp \rightarrow p [\text{exclusive}X] p \]

**QED background:** 2 $\gamma$ exchange
- QED process with small proton form-factor corrections

**Pomeron exchange:**
- **Photoproduction:** Photon-pomeron fusion
  - Probes gluon density at small values of proton's momentum fraction, $x$
  - Perturbative calculations accessible for higher mass of [exclusive]
- **Double pomeron exchange:** Pomeron-pomeron fusion
  - [exclusive $X$] must be neutral PC = ++, no net flavor: $f_{0;2}; \chi_{c;b}; \gamma\gamma; JJ;H$

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Extensive program of CEP measurements at CDF, continued by many interesting results from LHC
Observation of Exclusive Dijets

Reconstruct $R_{jj} = M_{jj}/M_X$, where $M_{jj}$ mass of dijet system, $M_X$ – mass of system X

Observe excess over inclusive DPE dijet MC’s at high dijet mass fraction

Signal at $R_{jj}=1$ is smeared due to shower/hadronization effects, NLO $gg\rightarrow gg,qg,qg$ contributions
Requirements: no other particles in the detectors up to $|\eta| < 7.4$

Study noise level by looking at “zero-bias” events:
“no interaction” or “interaction” class of events

\[ p + \bar{p} \rightarrow p + e^+e^- + \bar{p} \text{ via } \gamma + \gamma \ (QED) \]

\[
\begin{align*}
\sigma |\eta| < 1, E_T > 2.5 \text{GeV} & = 2.88 \pm 0.59 (\text{stat}) \pm 0.62 (\text{sys}) \text{ pb} \\
\sigma_{\text{LPair}} |\eta| < 1, E_T > 2.5 \text{GeV} & = 3.25 \pm 0.07 \text{ pb} \\
\sigma |\eta| < 1, E_T > 5.0 \text{GeV} & = 0.60 \pm 0.28 (\text{stat}) \pm 0.14 (\text{sys}) \text{ pb} \\
\sigma_{\text{Dpair}} |\eta| < 1, E_T > 5.0 \text{GeV} & = 0.58 \pm 0.003 \text{ pb}
\end{align*}
\]
Observed 43 events >> 5 \sigma

\sigma_{\gamma\gamma}^{exc} = 2.48 \pm 0.42 \text{(stat)} \pm 0.41 \text{(sys)} \text{ pb}

Good agreement with the theoretical predictions
Exclusive J/ψ, ψ(2s) and χ_c → J/ψ

J/ψ production
243 ± 21 events
\[ \frac{d\sigma}{dy}|_{y=0} = 3.92 \pm 0.62 \text{ nb} \]
In agreement with theor. pred.

ψ(2s) production
34±7 events
\[ \frac{d\sigma}{dy}|_{y=0} = 0.54 \pm 0.15 \text{ nb} \]
R = ψ(2s)/J/ψ = 0.14 ± 0.05
In agreement with HERA:
R = 0.166 ± 0.012 in a similar kinematic region

Trigger:
muon + track + frwd rapidity gaps in BSCs (5.1<|η|<7.1)
2 oppositely charged muon tracks with \( p_T > 1.4 \text{ GeV/c}, \ |\eta| < 0.6 \)
3 GeV/c² < \( M_{\mu\mu} < 4 \text{ GeV/c}^2 \)

Allowing EM towers (\( E_T > 80 \text{ MeV} \))
large increase in the J/ψ peak
minor change in the ψ(2s) peak

Evidence for χ_c → J/ψ + γ production
\[ \frac{d\sigma}{dy}|_{y=0} = 75 \pm 14 \text{ nb}, \]
compatible with theoretical predictions

Fit:
2 Gaussians + QED continuum

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Central exclusive production studies with energy scan data - 300 GeV, 900 GeV and 1960 GeV

- 3x3 bunches
- Special trigger
- 1 interaction per crossing (no pile-up)

Selection:
\( \pi^+\pi^- \) and no other activity in \(|\eta|>5.9\)

The cross section ratio
\[ R(0.9:1.96) = 1.28 \]
for \( 1<M(\pi\pi)<2 \) GeV

consistent with
Regge phenomenology (~1/ln(s))

- \( f_2(1270) \), shoulder from \( f_0(1370) \) interference
- some structure around 1.4-2.4 GeV
- data falls monotonically above 2.4 GeV
Conclusions

Very extensive program of diffractive studies at the Tevatron – new forward detectors R&D, new methodologies developed, many pioneering measurements performed.

Diffractive cross sections measured - important input for phenomenological models, MC tuning, and cosmic ray physics

Hard diffraction - many interesting results from Tevatron, still little studied at the LHC, proton tagging is crucial for expanding number of channels e.g. diffractive dijets, W, Z, J/Ψ

Rich program for exclusive processes:
Many observations from Tevatron:
✓ expect more results on central exclusive production!
✓ more diffractive measurements from the Tevatron energy scan data –
✓ soft DD production(?)
✓ new types of measurements - MPI in Diffractive events?
✓ new MC tools became available – can apply to existing data…
Ref: Papers on diffraction at CDF

Double Pomeron Exc.
PRL 93, 141603 (2004)

Multi-Gap Diffraction

Soft Diffraction

Single Diffraction
PRD 50, 5355 (1994)

Double Diffraction
PRL 87, 141802 (2001)

Hard Diffraction

Dijets:
1.8 TeV PRL 85, 4217 (2000)
1.96 TeV PRD 77, 052004 (2008)

Di-photons
1.96 TeV PRL 108, 081801 (2012)
1.96 TeV PRL 99, 242002 (2007)

Charmonium
1.96 TeV PRL 102, 242001 (2009)
π⁺π⁻ 1.96(0.9) TeV PRD91, 091101(2015)

Rapidity Gap Tag
W PRL 78, 2698 (1997)
Dijets PRL 79, 2636 (1997)
J/Ψ PRL 87, 241802 (2001)

Jet-Gap-Jet
1.8 TeV PRL 74, 855 (1995)
1.8 TeV PRL 80, 1156 (1998)
630 GeV PRL 81, 5278 (1998)

Roman Pot Tag
Dijets:
1.96 TeV PRD 86, 032009 (2012)
1.8 TeV PRL 84, 5043 (2000)

W/Z:
1.96 TeV PRD 82, 112004 (2010)