Results from the Tevatron

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- Detectors
- Total and Elastic Scattering
- Single Diffraction Processes
  - \(t\)-Distributions
- Double Diffraction Processes
- Double Pomeron Exchange Processes
  - Central Exclusive Production
- Energy scan

\(\checkmark\) new
Introduction

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

incident hadrons retain their quantum numbers remaining colorless

incident hadrons acquire color and break apart
Diffractive Signatures

Diffractive events could be identified by presence of:

- **intact leading particle**
- **large non exponentially suppressed rapidity gap**

Non-Diffractive (ND)  Single Diffraction (SD)  Double Diffraction (DD)  Double Pomeron Exchange (DPE)

![Diagram showing diffractive signatures](image-url)
**Diffraction: definitions**

**y** - rapidity  
\( y = \frac{1}{2} \ln \left( \frac{(E+p_z)}{E-p_z} \right) \)  
\( \eta \equiv y \bigg|_{m=0} = -\ln \tan(\frac{\phi}{2}) \)

**\( \eta \)** - pseudorapidity  
\( \eta \) - four-momentum transfer squared  
\( \xi \) - fractional momentum loss of pbar  
\( M_X \) - mass of diffractive system X

\( \xi = \frac{M_X^2}{s} \)  
\( \Delta \eta \approx \ln(s/M_X^2) \)
Tevatron $pp$ Collider

was shut down on September 30, 2011
CDF and D0 detectors

General purpose detectors

- Top performance (>85% data taking efficiency)
- ~10 fb⁻¹ per experiment
CDF II Detectors

- **Tracking** – Tracking Detectors
  \[ |\eta| < 2.0 \]

- **CCAL, PCAL** – Calorimeters
  \[ (15^\circ \text{in } \phi) \times 0.1 \text{in } \eta \]
  \[ |\eta| < 3.6 \]

- **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
  \[ 3.5 < |\eta| < 5.1 \]
Elastic Scattering

The particles after scattering are the same as the incident particles
\[ \xi = \Delta p / p = 0 \text{ for elastic events; } t = -(p_i - p_f)^2 \]

The cross section can be written as:
\[
\frac{d\sigma}{dt} \bigg|_{t=0} = e^{bt} \cong 1 - b(p\theta)^2
\]

<table>
<thead>
<tr>
<th>( \sqrt{s} )</th>
<th>Exp.</th>
<th>( t )-range [GeV^2]</th>
<th>( B [\text{GeV}^{-2}] ), ( \rho )</th>
</tr>
</thead>
<tbody>
<tr>
<td>546 GeV</td>
<td>CDF</td>
<td>0.025 \div 0.08</td>
<td>( B = 15.28 \pm 0.58 )</td>
</tr>
<tr>
<td>1.8 TeV</td>
<td>CDF</td>
<td>0.04 \div 0.29</td>
<td>( B = 16.98 \pm 0.25 )</td>
</tr>
<tr>
<td>E710</td>
<td>0.034 \div 0.65</td>
<td>( B = 16.3 \pm 0.3 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.001 \div 0.14</td>
<td>( B = 16.99 \pm 0.25 )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \rho = 0.140 \pm 0.069 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E811</td>
<td>0.002 \div 0.035</td>
<td>using ( \langle B \rangle_{CDF,E710} )</td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \rho = 0.132 \pm 0.056 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.96 TeV</td>
<td>DØ</td>
<td>0.9 \div 1.35</td>
<td>—</td>
</tr>
</tbody>
</table>

Fig. from TOTEM publications

Coulomb - nuclear interference
Pomeron exchange \( \sim e^{-B|t|} \)
Diffractive structure

pp at 14 TeV (BSW model)

\( \beta^e = 1540 \text{ m} \)
\( \beta^e = 18 \text{ m} \)
Elastic Scattering at $\sqrt{s}=1.96$ TeV

Forward Proton Spectrometer

- There are eight quadrupole spectrometers (Up, Down, In, Out) on the outgoing proton (P) and anti-proton (A) sides each comprised of two detectors (1, 2).

- Use Tevatron lattice and scintillating fiber hits to reconstruct $\xi$ and $|t|$ of scattered protons (anti-protons).

- The acceptance for $|t|>|t_{min}|$ where $t_{min}$ is a function of pot position: for standard operating conditions $|t| > 0.8 \text{ GeV}^2$. 

[Diagram of Forward Proton Spectrometer]
Elastic Scattering at $\sqrt{s}=1.96$ TeV

- In 2005 DØ proposed a store with special optics to maximize the $|t|$ acceptance of the FPD.

- In February 2006, the accelerator was run with the injection tune, $\beta^* =1.6m$ (instead of nominal 0.35 m).

- Only 1 proton and 1 anti-proton bunch were injected.

- Separators OFF (no worries about parasitic collisions with only one bunch).

- Integrated Luminosity ($30 \pm 4 \text{ nb}$) was determined by comparing the number of jets from Run IIA measurements with the number in the Large $\beta^*$ store.

- A total of 20 million events were recorded with a special FPD trigger list.
Elastic Scattering at $\sqrt{s}=1.96$ TeV

Elastic events have tracks in diagonally opposite spectrometers

Momentum dispersion in horizontal plane results in more halo (beam background) in the IN/OUT detectors, so concentrate on vertical plane AU-PD and AD-PU to maximize $|t|$ acceptance while minimizing background

AU-PD combination has the best $|t|$ acceptance
Systematic error dominated by trigger efficiency correction
Second biggest uncertainty- alignment = ±0.3 GeV²

14.3% error in the luminosity is not included
Elastic Scattering at $\sqrt{s}=1.96$ TeV

Comparison with CDF and E710
Elastic Scattering at $\sqrt{s}=1.96$ TeV

Comparison with UA4

DØ Run II Preliminary, $L=30$ nb$^{-1}$

- DØ (1.96 TeV)
- UA4 (0.546 TeV)

Slope steeper and slope change earlier for higher $\sqrt{s}$ (shrinkage)
Hard Single Diffraction

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

Can study diffractive production of high $p_T$ objects:
- jets, $W$, $J/\Psi$, $b$
- different insight into the nature of Pomeron

Method: measure ratio of diffractive to non-diffractive production
Hard Single Diffraction

Diffractive signature:
large rapidity gap –
slightly different
gap definitions

Fraction: R≡SD/ND ratio @ 1800 GeV

<table>
<thead>
<tr>
<th>Hard component</th>
<th>Fraction (R)%</th>
</tr>
</thead>
<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>
</tr>
</tbody>
</table>

All fractions ~ 1%
(differences due to kinematics)
➢ ~ uniform suppression
Diffractive Structure Function

Diffractive dijet cross section

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

Study the diffractive structure function

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

Experimentally determine diffractive structure function \( F_{jj}^D \)

at LO

\[ R_{\text{SD}}^{\text{ND}}(x, \xi) = \frac{\sigma(\text{SD}_{jj})}{\sigma(\text{ND}_{jj})} = \frac{F_{jj}^D(x, Q^2, \xi)}{F_{jj}(x, Q^2)} \]

- Data
- known PDF

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

\[ \beta \]

- CDF data
- H1 fit-2
- H1 fit-3
- \( E_{\text{T}}^{\text{jet}} > 7 \text{ GeV} \)
- \( Q^2 = 75 \text{ GeV}^2 \)
- \( 0.035 < \xi < 0.095 \)
- \( |t| < 1.0 \text{ GeV}^2 \)
The Diffractive Structure Function

\[ \sqrt{s} = 1.96 \text{ TeV} \]

same behavior for different \( \xi \) values

same behavior for different \( Q^2 \)
Kinematic Distributions for SD dijets

SD and ND dijets have similar $E_T$ distributions

SD dijets are shifted in $+ \eta$

The multiplicity distributions in MP

SD dijets are more back to back
Dynamic alignment of the RPS

Method: iteratively adjust the RPS X and Y offsets from the nominal beam axis until a maximum in the b-slope is obtained at t=0.
Fit to double exponential function:
\[
d\sigma/dt \propto 0.9 e^{b_1 t} + 0.1 e^{b_2 t}
\]

antiproton $|t|$ distribution

- no diffractive dips
- no $Q^2$ dependence
  in slope from inclusive to $Q^2 \sim 10^4 \text{ GeV}^2$
Background evaluation

schematic view of fiber tracker

- tracker’s upper edge: $|t| = 2.3$ (GeV/c)$^2$
- the lower edge is at $|t| = 6.5$ (GeV/c)$^2$ (not shown)
- background level: region of $Y_{\text{track}} > Y_0$ data for $|t| > 2.3$ (GeV/c)$^2$
$0.05 < \frac{z_{RPS}}{\sqrt{p}} < 0.08$

CDF Run II Preliminary

- RPS inclusive
- RPS.Jet20 ($Q^2 \sim 900$ GeV$^2$)
- DL model

Corrected number of events per 0.05

$|t|$ (GeV/c$^2$)
Diffractive W/Z production probes the quark content of the Pomeron

- to Leading Order, the W/Z are produced by a quark in the Pomeron
- production by gluons is suppressed by a factor of $\alpha_s$ and can be distinguished by an associated jet
Identify diffractive events using Roman Pots:
accurate event-by-event $\xi$ measurement
no gap acceptance correction needed
can still calculate $\xi_{cal}$

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

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

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

allows to determine:
neutrino and W kinematics
$x_{bj}$

reconstructed diffractive W mass

Phys. Rev. D 82, 112004, 2010
New Precise W Mass Measurement

New CDF measurement significantly exceeds precision of all previous measurements of $m_W$ combined!
Diffractive W Production

\[
\xi_{\text{cal}} < \xi_{\text{RP}} \quad \text{requirement removes most events with multiple pbar-p interactions}
\]

\[
50 < M_W < 120 \text{ GeV/c}^2 \quad \text{requirement on the reconstructed W mass cleans up possible mis-reconstructed events}
\]

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, extrapolated to all \( \xi \)
37 diffractive $Z \rightarrow ee/\mu\mu$ candidates (RP track, $\xi^{\text{cal}}<0.1$)

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

Fraction of diffractive $Z$

$R_Z (0.03 < \xi < 0.10, |t| < 1) = [0.85 \pm 0.20\,(\text{stat}) \pm 0.08\,(\text{syst})]\%$
W/Z Results

\[ R^W (0.03 < \xi < 0.10, \ |t|<1) = [0.97 \pm 0.05 \text{ (stat)} \pm 0.11 \text{ (syst)}] \% \]

Run I: \[ R^W (\xi<0.1) = [1.15 \pm 0.55] \% \rightarrow 0.97 \pm 0.47 \% \text{ in } 0.03 < \xi < 0.10 \ & \ |t|<1 \]

\[ R^Z (0.03 < x < 0.10, \ |t|<1) = [0.85 \pm 0.20 \text{ (stat)} \pm 0.11 \text{ (syst)}] \% \]

CDF/DØ Comparison – Run I (\( \xi < 0.1 \))

CDF PRL 78, 2698 (1997)
\[ R^w = [1.15 \pm 0.51 \text{ (stat)} \pm 0.20 \text{ (syst)}] \% \]
gap acceptance \( A^{\text{gap}} = 0.81 \)
Uncorrected for \( A^{\text{gap}} \)
\[ R^w = (0.93 \pm 0.44) \% \]

\[ R^w = [5.1 \pm 0.51 \text{ (stat)} \pm 0.20 \text{ (syst)}] \% \]
gap acceptance \( A^{\text{gap}} = (0.21 \pm 4) \% \)
Uncorrected for \( A^{\text{gap}} \)
\[ R^w = [0.89 + 0.19 - 0.17 \] \%
\[ R^z = [1.44 + 0.61 - 0.52 \] \%

This analysis is a good example of agreement between RPS and large rapidity gap identification methods.
Exclusive Production

At the Tevatron we use similar processes with larger cross sections to test and calibrate theoretical predictions. Dijets, $\gamma\gamma$, $\chi_c$

LHC

 suppression at LO of the background sub-processes ($J_z=0$ selection rule)

“exclusive channel” → clean signal (no underlying event)

• At the Tevatron we use similar processes with larger cross sections to test and calibrate theoretical predictions.

CDF
Observation of Excl. Dijet Production

Reconstruct $R_{jj} = \frac{M_{jj}}{M_X}$, 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 $gg \rightarrow ggg, qqg$ contributions
Calculation by KMR is consistent within its factor of 3 uncertainty.

\( d\sigma_{jj}^{\text{excl}} \) vs Dijet Mass

derived from CDF excl. dijet x-sections using ExHuME

- Stat. and syst. errors are propagated from measured cross section uncertainties using \( M_{jj} \) distribution shapes of ExHuME generated data.
Goal: Search for exclusive events in the dijet channel at high dijet mass using the *rapidity gap* method

- **Data** requirements:
  - two jets (only)
  - $|y_{1,2}| < 0.8,$
  - $p_{T1} > 60$ GeV, $p_{T2} > 40$ GeV,
  - $M_{jj} > 100$ GeV
  - $\Delta \phi > 3.1$

**Method:**
- use new separation variable:

\[
\Delta = \frac{1}{2} \exp(-\sum_{2.0<|\eta|<3.0} E_T) + \frac{1}{2} \exp(-\sum_{3.0<|\eta|<4.2} E_T)
\]
Exclusive Events at High $M_{jj}$

A clear excess of data with respect to ND, SD, IDP

**events with $\Delta > 0.85$**
Exclusive Dimuon Production

\[ \bar{p} + p \rightarrow \bar{p} + \mu^+ \mu^- + p \]

Many Physics Processes in this data:

- \(3 \text{ GeV/c}^2 < M_{\mu\mu} < 4 \text{ GeV/c}^2\)

exclusive \(\chi_c\) in DPE

- Observation of exclusive \(\chi_c\) PRL 102 242001 (2009)
Exclusive dimuon production

\[ p + \bar{p} \rightarrow p + \mu^+ \mu^- + \bar{p} \]

3 GeV/c^2 < \text{M}_{\mu\mu} < 4 \text{ GeV/c}^2

Trigger:

muon + track + forward rapidity gaps in BSCs

2 oppositely charged muon tracks with \( p_T > 1.4 \text{ GeV/c, } |\eta| < 0.6 \)

\( \varepsilon_{\text{excl}} \sim 0.093 \Rightarrow L = 1.48 \text{ fb}^{-1} \) but \( L_{\text{eff}} \sim 140 \text{ pb}^{-1} \)
Exclusive J/ψ and ψ(2s)

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

Theoretical Predictions
- 2.8 nb [Szczurek07,]
- 2.7 nb [Klein&Nystrand04]
- 3.0 nb [Conclaves&Machado05], and
- 3.4 nb [Motkya&Watt08].

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

Fit:
2 Gaussians + QED continuum
Exclusive $\chi_c \rightarrow J/\psi (\rightarrow \mu^+ \mu^-) + \gamma$

- Allowing EM towers ($E_T > 80$ MeV)
- Large increase in the $J/\psi$ peak
- Minor change in the $\psi(2s)$ peak

Evidence for $\chi_c \rightarrow J/\psi + \gamma$ production

$\sigma / d\gamma \big|_{\gamma=0} = 75 \pm 14$ nb, compatible with theoretical predictions
- 160 nb (Yuan 01)
- 90 nb (KMR01)
Exclusive $\gamma\gamma$ Production

3 candidates observed, limit set

Requirements: no other particles in the detectors up to $|\eta| < 7.4$

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


more data!
adjusted triggers
Exclusive $\gamma\gamma$ Production

Use control sample to understand

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

$$\sigma_{|\eta| < 1, E_T > 2.5\text{GeV}} = 2.88 \pm 0.59(\text{stat}) \pm 0.62(\text{sys}) \text{ pb}$$

$$\sigma_{\text{LPair}} = 3.25 \pm 0.07 \text{ pb}$$

$$\sigma_{|\eta| < 1, E_T > 5.0\text{GeV}} = 0.60 \pm 0.28(\text{stat}) \pm 0.14(\text{sys}) \text{ pb}$$

$$\sigma_{\text{DPair}} = 0.58 \pm 0.003 \text{ pb}$$

Kinematic distributions of photon pair
Exclusive $\gamma\gamma$ Production

Just published! *PRL 108, 081801 (2012)*

Observed 43 events $>> 5\,\sigma$

$$\sigma_{\gamma\gamma_{\text{excl}}} = 2.48 \pm 0.42 (\text{stat}) \pm 0.41 (\text{sys}) \text{ pb}$$

Good agreement with the theoretical predictions
Study s-dependence of high cross-sections physics
...mostly non-pQCD

1. Study of MB events:
2. Study of UE events
3. Gap-X Gap events
Tevatron energy scan - data

September 8 – 16, 2011
• 3x3 bunches
• Special trigger
• 1 interaction per crossing (no pile-up)

Total data taking time:
10 h at 300 GeV and 39 h at 900 GeV

<table>
<thead>
<tr>
<th>$\sqrt{s}$</th>
<th>0-bias</th>
<th>Minbias</th>
<th>Gap-X-Gap</th>
<th>Jets</th>
<th>$e,\mu,\nu$</th>
<th>Total # events</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>1.89 M</td>
<td>12.1 M</td>
<td>9.2 M</td>
<td>8.3 K</td>
<td>352</td>
<td>23.2 M</td>
</tr>
<tr>
<td>900</td>
<td>8.0 M</td>
<td>54.3 M</td>
<td>21.8 M</td>
<td>550 K</td>
<td>16 K</td>
<td>84.7 M</td>
</tr>
</tbody>
</table>
Conclusions

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

- Working on datasets collected at √s=300 and 900 GeV – plan to have some results by summer conferences

- So what is in the future for diffractive studies at the LHC and beyond?
  
  ✓ need reliable MC simulations!
  ✓ new types of measurements
  ✓ new methods for identification of diffractive events
Ref: Papers on diffraction at CDF

**Soft Diffraction**

**Double Pomeron Exc.**
PRL 93, 141603 (2004)

**Multi-Gap Diffraction**

**Single Diffraction**
PRD 50, 5355 (1994)

**Double Diffraction**
PRL 87, 141802 (2001)

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**Hard Diffraction**

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

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

**Charmonium**
- 1.96 TeV PRL 102, 242001 (2009)

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

**Roman Pot Tag**

**Dijets:**
- 1.8 TeV PRL 84, 5043 (2000)

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

**Jet-Gap-Jet**
- 1.8 TeV PRL 74, 855 (1995)
- 1.8 TeV PRL 80, 1156 (1998)
- 630 GeV PRL 81, 5278 (1998)
Forward Detectors are crucial for diffractive studies.

- Use Roman Pots for antiproton tagging.
- Use Miniplugs and BSCs for rapidity gaps.
Forward Detectors at CDFII: Roman Pot Spectrometers (RPS)

Fiber Tracker

• 3 stations
• 57 meters from IP
• 3 trigger counters
• 240 channels

Position resolution $\pm 80 \mu m$

Typical resolutions

in $\xi$ $\delta \xi = \pm 0.001$; in $t$ $\delta t = \pm 0.07 GeV^2$

MIPs (>1000 counts)
BSCs are located along beam pipe used for **triggering events with forward rapidity gaps**
Forward Detectors at CDFII: MiniPlug Calorimeters (MPs)


Designed to measure the energy and lateral position of both electromagnetic and hadronic showers “towerless” geometry – no dead regions
Methodologies were developed to get around the challenges:

Results are mostly MC free

\( \xi \) variable can be determined two ways

- Determine \( \xi \) using Roman Pots tracking
- Also can determine \( \xi \) from \( E_T \) in calorimeters

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

Important to have MiniPlugs

Main challenge: multiple interactions spoiling diffractive signatures

use \( \xi^{\text{cal}} < 0.1 \) to reject overlap events \( \rightarrow \) non-diffractive contributions
Challenges and Methods:

ξ distributions

Flat part at ξ < 0.1

$$\frac{d\sigma}{d\xi} \propto \frac{1}{\xi} \rightarrow \frac{d\sigma}{d(\log \xi)} = \text{const}$$

Peak at ξ = 1

-overlap events from multiple interactions

MP calorimeters allow to separate diffractive and non-diffractive parts

CDF Run II Preliminary

Events (J5 norm to 0.2 < ξ^x_p < 3)

- J5 (E_T^tower > 5 GeV)
- RP + J5

SD
BG

w/o MP
Methods and Challenges:

\( \xi \) with RPS and calorimeter info

- pile-up events
- calibration of \( \xi \) from calorimeter with \( \xi \) from RPS

CDF Run II Preliminary

February 27, 2012

Christina Mesropian Trento Workshop
LO exclusive gg → q̅q̅ suppressed (J_\pi = 0 rule)

Look for heavy flavor jet suppression relative to inclusive dijets at high R_jj

Suppression of heavy flavor for R_jj > 0.4 is consistent in shape and magnitude with the results based on MC based extraction of exclusive dijet signal.