

High mass exclusive diffractive dijet production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

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We present evidence for diffractive exclusive dijet production with an invariant dijet mass greater than 100 GeV in data collected with the D0 experiment at the Fermilab Tevatron Collider. A discriminant based on calorimeter information is used to measure a significant number of events with little energy (typically less than 10 GeV) outside the dijet system, consistent with the diffractive exclusive dijet production topology. The probability for these events to be explained by other dijet production processes is 2×10^{-5} , corresponding to a 4.1 standard deviation significance.

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Hard diffraction was first observed about twenty years ago in the UA8 experiment at the CERN $p\bar{p}$ collider SPS [1] and has been studied extensively in several experiments: H1 and ZEUS at the DESY ep Collider HERA [2] and D0 and CDF at the Fermilab Tevatron [3]. At hadron colliders, hard diffractive events are identified by the signature of a hard scatter in the presence of a region devoid

of any activity in the forward region of the detector or by tagging beam hadrons in the final state. Hard diffractive events can be described by the exchange of a colorless object (Pomeron) [4]. Diffractively produced objects such as dijets, diphotons and χ_c charmonium can be observed in the detector together with Pomeron remnants. A subset of hard diffractive events in which both incoming hadrons remain intact is defined in such a way that all the energy not carried away by the outgoing beam particles is used to produce the diffractive system [5, 6]. This mechanism is defined as hard exclusive diffractive production. We search for this production mechanism in the sample of dijet events with large dijet invariant mass, corresponding to large values of the reduced center-of-mass energy of the Pomeron's system.

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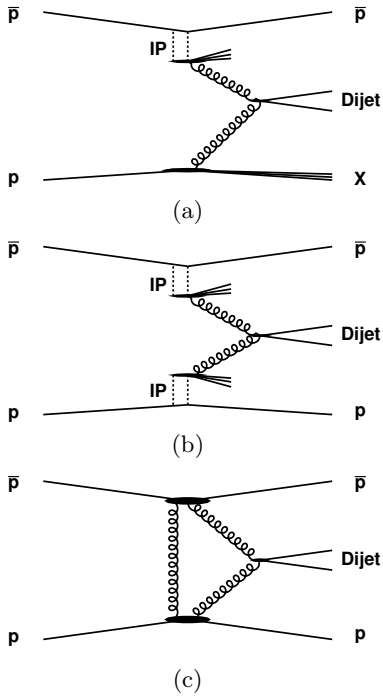


FIG. 1: Production of central dijet events in hard diffraction: (a) single diffraction, in which only either the proton or the antiproton is diffracted by a Pomeron (P) exchange, while the other breaks up; (b) inclusive double Pomeron production, where proton and antiproton remain intact, and additional QCD radiation can be observed from Pomeron remnants; and (c) exclusive diffractive production where both protons remain intact and only the dijet system is produced in the central region.

Exclusive diffractive production (EDP) of a final state X , $p\bar{p} \rightarrow p + X + \bar{p}$, has been proposed as a future search channel for new physics, as well as for the Higgs boson, at the Large Hadron Collider (LHC) [7]. In this process, the kinematic properties such as the mass of the object X can be computed with high precision by measuring only the momentum loss of the outgoing protons in the final state. The CDF Collaboration reported the observation of exclusive diffractive events in the dijet, dielectron, diphoton and charmonium channels [8]. These results support the existence of EDP, but are restricted to low mass objects (typically less than 100 GeV), while at the LHC, searches for new physics are expected to extend to higher masses. In this article, we report evidence for exclusive diffractive dijet production with invariant masses greater than 100 GeV in data collected by the D0 experiment.

We consider three different classes of hard diffractive production in addition to non-diffractive production: single diffractive (SD) dijet production (Fig. 1 (a)), inclusive diffractive production through double Pomeron exchange (IDP) (Fig. 1 (b)), and exclusive diffractive dijet production (Fig. 1 (c)). In SD, one of the beam hadrons remains

intact while the other breaks up. In IDP, both beam hadrons are intact after the collision. The IDP and EDP processes with proton dissociations are expected to be suppressed by about a factor ten relative to the channel where the beam hadrons remain intact [9]. The parton distributions of the Pomeron are taken from recent H1 measurements [10] and used to compute the diffractive jet production cross section at the Tevatron. An additional multiplicative factor (gap survival probability) [11] of 0.1 is introduced to account for soft production of particles from the underlying $p\bar{p}$ events that populate the rapidity gaps [4].

The background to EDP in the dijet mass region considered here originates from SD, IDP and non diffractive (NDF) events which have either low multiplicity or small energy deposits in the forward calorimeters. Due to the steeply falling nature of these distributions, these backgrounds are expected to be small. NDF background events are simulated using the PYTHIA v6.202 [12] Monte Carlo (MC) generator with default settings and the diffractive (SD and IDP) backgrounds are determined using the POMWIG v2.0 [13] and FPMC v1.0 [9] generators respectively. An EDP of dijet events at the lowest order of QCD [6] is simulated using FPMC through the exchange of two gluons.

The data used in this analysis were collected with the D0 detector in the period between August 2002 and April 2006 at the Tevatron Collider at a center-of-mass energy $\sqrt{s} = 1.96$ TeV. The D0 detector is described in detail elsewhere [14]. For this analysis, the most relevant components are the central and forward calorimeters used for jet reconstruction and the identification of a rapidity gap devoid of any energy (above noise) in the calorimeter, respectively. The D0 liquid argon and uranium calorimeter is divided in three parts housed in independent cryostats covering the following regions in pseudorapidity: $|\eta| < 1.1$ (central calorimeter), and $1.6 < |\eta| < 4.2$ (two forward calorimeters) where $\eta = -\ln[\tan(\theta/2)]$ and θ is the polar angle with respect to the beam axis. Jets in EDP events are expected to be more central than in the other jet production processes, therefore both jets are required to be central with a rapidity $|y| < 0.8$, where the rapidity is defined as $y = 0.5 \ln(E + p_z)/(E - p_z)$ where E is the jet energy and p_z is the momentum component of the jet along the beam axis. The forward region of the calorimeter is used to check for the presence of a rapidity gap on each side of the dijet system.

The instantaneous luminosity used in this analysis is required to be in the range $[5 - 100] \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$, where the contribution from two or more $p\bar{p}$ interactions in a single event is in general much less than 20%. This reduces the contamination of multiple interactions in the same bunch crossing to the rapidity gap selection. Data were collected using a inclusive jet trigger requiring at least one jet in an event to be above a p_T threshold of 45 GeV on the uncorrected energy, in order to select

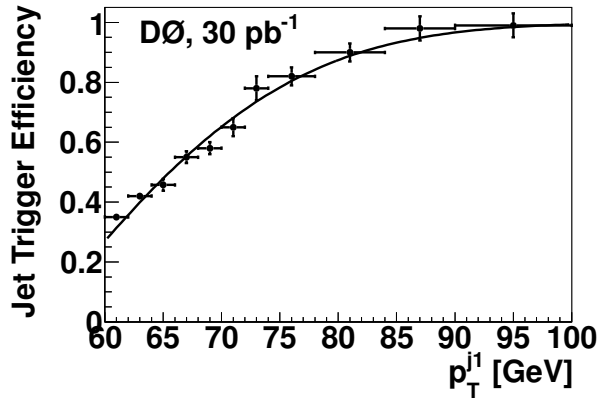


FIG. 2: Jet trigger efficiency as a function of the leading jet p_T (p_T^{j1}). For events with $p_T^{j1} > 100$ GeV, the efficiency is close to 100% and no correction is needed.

exclusive diffractive events in the region of dijet invariant mass above 100 GeV. Due to prescales imposed to avoid saturating the data acquisition system rate capabilities, the equivalent integrated luminosity of the sample is about 30 pb^{-1} . By comparing the highest- p_T jet spectrum with data collected with a trigger with a lower p_T threshold of 15 GeV, the trigger was found not to be fully efficient for jet p_T between 60 GeV and 100 GeV and the Monte Carlo events were reweighted with the trigger efficiency in this jet p_T range. The trigger efficiency as a function of jet p_T is shown in Fig. 2.

Jets are reconstructed using an iterative midpoint cone algorithm [15] with a cone size $\mathcal{R} = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2} = 0.7$, where φ is the azimuthal angle. The highest- p_T and second-highest p_T jets are required to have p_T greater than 60 GeV and 40 GeV, respectively, and only dijet events with an invariant mass greater than 100 GeV are selected. To enhance the number of events without additional QCD radiation [6], the two jets are required to be back-to-back in azimuthal angle φ , with a separation $\Delta\varphi > 3.1$. A possible contribution of fake dijet events due to cosmic rays is suppressed by the requirement that the missing transverse momentum is less than 70% of the leading jet transverse momentum.

The MC events are required to satisfy the same selection criteria as the data. They are processed through a GEANT-based [16] simulation of the D0 detector response and the same reconstruction code as data. To simulate calorimeter noise and the effects of additional $p\bar{p}$ interactions, data events from random $p\bar{p}$ crossings are overlaid on the MC events, using data from the same time period as considered in the analysis. The MC events are weighted to obtain the same instantaneous luminosity profile as the data to have the same additional energy deposits in the forward region of the calorimeter as in data. The sum of the number of NDF, SD and IDP events is normalized to data and their fractions are determined by

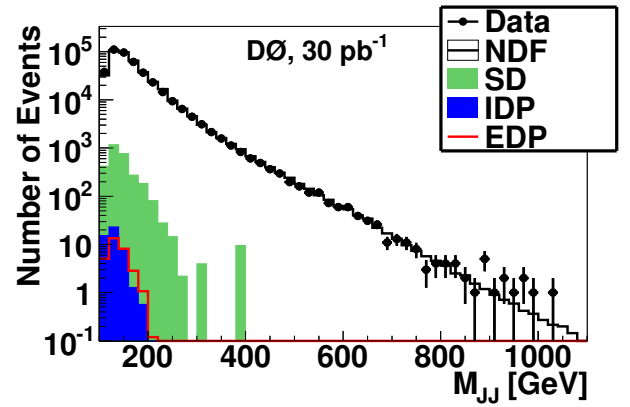


FIG. 3: Dijet invariant mass distribution for MC and data. Good agreement between the MC simulation and data is found after applying jet energy scale corrections and scale factors corresponding to the trigger efficiencies, the luminosity profiles, and the MC normalization.

the theoretical cross sections. The EDP contribution is expected to be negligible at this stage. Good agreement between the MC simulation and data is seen in the dijet invariant mass distributions in Fig. 3. By varying the requirement on the leading jet p_T , the uncertainty on the normalization was estimated to be 5%.

To discriminate between exclusive events and background (NDF, SD and IDP) we exploit the large rapidity gap that is expected between the central jets and the proton and antiproton beams. Two separate regions of pseudorapidity η are defined in the calorimeter far from the two central jets. The very forward region ($3.0 < |\eta| < 4.2$) allows discrimination of diffractive events (SD and IDP) from NDF events, which are accompanied by beam remnants in this region of the calorimeter. The intermediate forward region ($2.0 < |\eta| < 3.0$) is used to identify EDP events, since they show larger rapidity gaps than SD and IDP. To prevent noise contamination in the calorimeter region under consideration, noisy cells in the forward region of the calorimeters, which present an occupancy that differed by more than five standard deviations from the average, are removed. The cell response in MC was also adjusted to data by applying a MC-to-data correction factor for each cell. This correction factor was obtained using data collected requiring either minimal activity in the D0 luminosity counters or the presence of low p_T jets. After performing these corrections, the calorimeter cell information was used to form the following variable in order to discriminate between the different classes of events

$$\Delta = \frac{1}{2} \exp\left(-\sum_{2 < |\eta| < 3} E_T\right) + \frac{1}{2} \exp\left(-\sum_{3 < |\eta| < 4.2} E_T\right). \quad (1)$$

Here E_T is the transverse energy in a given cell, and the sum is performed over all cells in the indicated rapidity

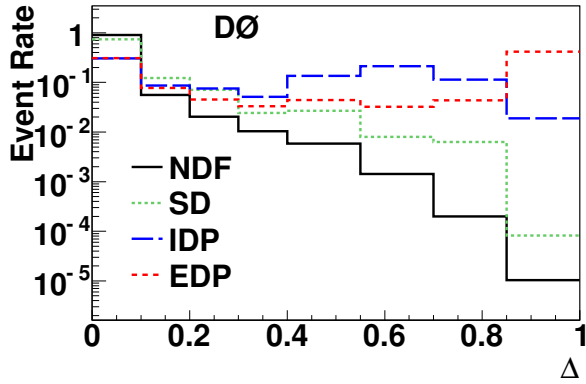
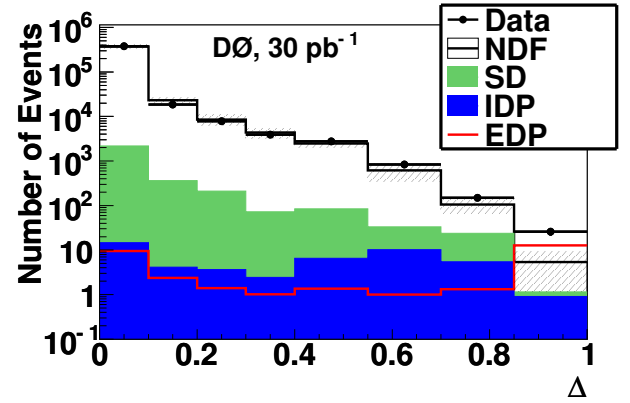


FIG. 4: Distribution of Δ normalized to unity for all MC samples. EDP peaks at $\Delta > 0.85$. The EDP contribution at low Δ values is due to pile-up events, where a second proton-antiproton inelastic scattering occurs in the same bunch crossing.

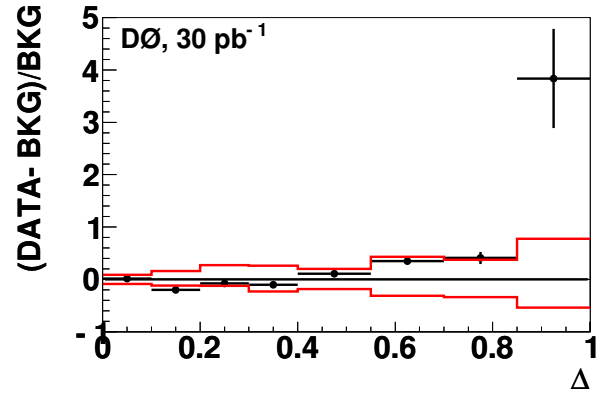
range. Figure 4 displays the Δ distribution normalized to unity for all MC samples. Also shown is the expected distribution from EDP events, showing a characteristic peak at $\Delta > 0.85$, corresponding to energy deposits in the forward calorimeter which are typically smaller than 10 GeV.

Systematic uncertainties are assessed on the MC background prediction of the differential distribution for Δ . The leading systematic uncertainty is due to the calorimeter cells calibration factors. They are varied simultaneously by three standard deviations from their central value leading to a change of 25% of the background for $\Delta > 0.85$. The effect of the jet energy scale uncertainties modifies the background by 12%. The jet energy resolution in simulation has been varied to match the data, yielding a small change of the normalization of 0.5% which is assigned as an uncertainty. To estimate the uncertainties of the trigger efficiency correction and the instantaneous luminosity reweighting, the analysis was repeated using a 15 GeV jet p_T trigger threshold resulting in a 3% systematic shift. An additional systematic uncertainty due to the MC to data normalization is estimated to be 5%. An uncertainty of 50% on the SD and IDP MC cross sections accounts for the uncertainty on the partonic structure of the Pomeron and survival probability gap factor. The non-diffractive parton distribution function uncertainties were considered and found to be negligible with respect to the other uncertainties. The total background prediction is $5.4^{+4.2}_{-2.9}$ events and 26 signal candidate events are observed in data.

Figure 5 shows the comparison of the Δ distributions in data and MC (NDF, SD and IDP) normalized to their leading order cross sections. Good agreement is observed between data and MC except at high values of Δ where EDP dominates. The significance of the excess with respect to the NDF, SD and IDP backgrounds



(a)



(b)

FIG. 5: (a) Distribution of Δ for data and contributions from NDF, SD and IDP. The hatched band indicates the total uncertainty on the background. (b) Normalized difference between data and NDF, SD and IDP processes. The red solid lines are ± 1 standard deviation systematic uncertainties on the background.

is determined using a modified frequentist method [17]. It is obtained via fits of the signal+background and background-only hypotheses to pseudo-data samples containing only background. The effect of systematic uncertainties is constrained by maximizing a likelihood function for background and signal+background hypotheses over all systematic uncertainties. Pseudo experiments used to determine the significance of the EDP signal include variations over each systematic uncertainty. The observed significance corresponds to the fraction of outcomes that yield an EDP cross section at least as large as that measured in data. Seven bins are used as input for the significance calculation: six bins for Δ between 0.1 and 0.85, where the predominant region used in the MC normalization is removed, and the $\Delta \geq 0.85$ bin. The probability for the observed excess to be explained by an upward fluctuation of the background is 2×10^{-5} , corresponding to an excess of 4.1 standard deviations. Table I gives the observed number of events compared

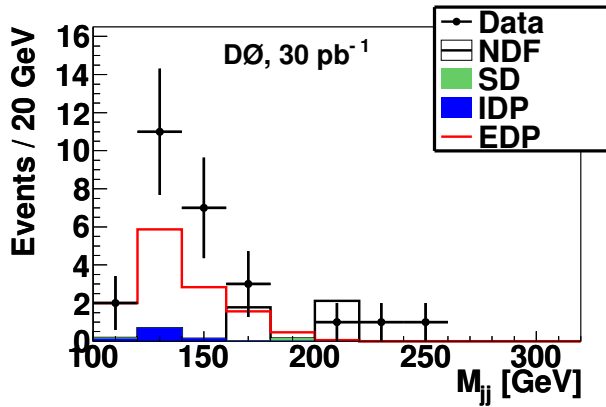


FIG. 6: Dijet invariant mass distribution for stacked MC (NDF, SD and IDP) and data after applying the requirement on $\Delta \geq 0.85$. The EDP distribution is shown without adding the stacked background.

to background and EDP expectations. Figure 6 displays the dijet invariant mass distribution for $\Delta > 0.85$. To illustrate the differences between the diffractive dijet exclusive events with $\Delta > 0.85$, where the calorimeter has little energy deposition outside the central region, and the non-diffractive events, two event displays are shown in Fig. 7. The excess in data can contain events where the proton is dissociated into low-mass states that escape detection. The contribution of such events is estimated to be up to 10% of the EDP cross section [9].

To summarize, we have presented evidence at the 4.1 standard deviation level for events consistent with the exclusive dijet production event topology in $p\bar{p}$ collisions at a center-of-mass energy $\sqrt{s} = 1.96$ TeV at high dijet invariant mass ($M_{JJ} > 100$ GeV). These are the highest mass states studied for exclusive production in hadron colliders. Such event signatures are expected to play an important role in future studies at the Tevatron and LHC.

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Sample	NDF	IDP	SD	EDP	BKG	DATA
All Δ	409527	48.3	2930	30.9	412505	412505
$\Delta \geq 0.85$	$4.2^{+4.0}_{-2.9}$	$0.9^{+0.4}_{-0.5}$	$0.2^{+0.1}_{-0.1}$	$12.9^{+1.0}_{-1.2}$	$5.4^{+4.2}_{-2.9}$	26

TABLE I: Number of predicted events for each MC sample for all Δ and for $\Delta \geq 0.85$. The total uncertainties are quoted.

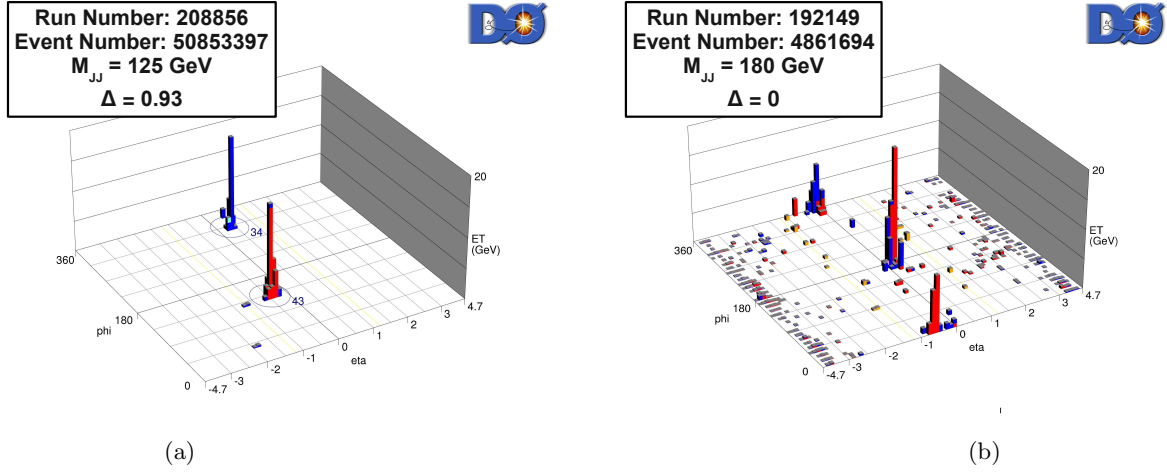


FIG. 7: Event displays showing E_T in the $\eta - \phi$ plane: (a) Exclusive diffractive event candidate: No energy deposition is present in the forward regions, only two central jets are observed in the detector. (b) Background event: In addition to the two jets present in the detector, energy deposition is present in the forward regions. The different colors correspond to energy deposits in different layers of the calorimeter.