Observation of Single-Diffractive Production of Di-jets at the LHC

The CMS Collaboration

Abstract

We present a study of single-diffractive di-jet production in $pp$ collisions at $\sqrt{s} = 14 \text{ TeV}$, $pp \rightarrow Xp$ with $X$ including a di-jet system, with the CMS detector. We discuss the feasibility of observing this process with an integrated effective luminosity for single interactions of $10 \text{ pb}^{-1}$. 
1 Introduction

A substantial fraction of the total proton-proton cross section is due to diffractive reactions of the type $pp \rightarrow XY$, where $X, Y$ are either protons or low-mass systems which emerge from the interaction with energy approximately equal to that of the incoming beam particles, to within a few per cent. The two (groups of) final-state particles are well separated in phase space and have a large gap in rapidity between them (“large rapidity gap”, LRG). Diffractive events can be described in terms of a colourless exchange with the vacuum quantum numbers (the “Pomeron”) and notably no colour (hence the LRG).

In this paper, the single-diffractive (SD) reaction $pp \rightarrow Xp$ is studied, in which $X$ includes a di-jet system (Fig. 1). This reaction is sensitive to the diffractive structure function (dPDF) of the proton, specifically its gluon component (see e.g. [1]). It is also sensitive to the “rapidity gap survival probability” $\langle |S^2| \rangle$, which quantifies the effects of the rescattering between spectator partons; to first approximation, the cross section is directly proportional to $\langle |S^2| \rangle$, independent of kinematics. This process has been studied at the Tevatron, where the ratio of the yields for SD and inclusive di-jet production has been measured to be approximately 1% [3, 4]. Theoretical expectations for LHC are at the level of a fraction of a per cent [5, 6]. There are, however, significant uncertainties in the predictions, notably due to the uncertainty of $\langle |S^2| \rangle$. While there is some consensus that $\langle |S^2| \rangle \simeq 0.05$ [7, 8] for hard diffractive processes at LHC energies, values of $\langle |S^2| \rangle$ as low as 0.004 and as high as 0.23 have been proposed [9].

Figure 1: Sketch of the single-diffractive reaction $pp \rightarrow Xp$ in which $X$ includes a di-jet system. The symbol $P$ indicates the exchange with the vacuum quantum numbers (Pomeron). The large rapidity gap (LRG) is also indicated.

The aim of this paper is to quantify the yield of SD di-jet production at CMS given an integrated effective luminosity for single interactions of $10 \text{ pb}^{-1}$; an instantaneous luminosity of $2 \times 10^{30} \text{ cm}^{-2}\text{s}^{-1}$ is assumed. The present analysis follows closely and complements that of SD $W$ production described in [10]. We also discuss the feasibility of observing this process for different values of $\langle |S^2| \rangle$ and argue that a simple measurement of the event yield may be sufficient to exclude extreme values of $\langle |S^2| \rangle$.

The CMS apparatus is described in detail elsewhere [11]. Two experimental scenarios are considered here. In the first, no forward detectors beyond the CMS forward calorimeter HF are assumed. In this case the pseudo-rapidity coverage is limited to $|\eta| < 5$. In the second, additional coverage at $-6.6 < \eta < -5.2$ is assumed by means of the CASTOR calorimeter. HF and CASTOR are briefly discussed in the next section.
2 The HF and CASTOR calorimeters

The forward part of the hadron calorimeter, HF, is located 11.2 m from the interaction point. It consists of steel absorbers and embedded radiation hard quartz fibers, which provide a fast collection of Cherenkov light. Each HF module is constructed of 18 wedges in a nonprojective geometry with the quartz fibers running parallel to the beam axis along the length of the iron absorbers. Long (1.65 m) and short (1.43 m) quartz fibers are placed alternately with a separation of 5 mm. These fibers are bundled at the back of the detector and are read out separately with phototubes.

CASTOR is a sampling calorimeter located at $\sim 14$ m from the interaction point, with tungsten plates as absorbers and fused silica quartz plates as active medium. The plates are inclined by $45^\circ$ with respect to the beam axis. The calorimeter has the shape of an octagonal cylinder. Particles passing through the quartz emit Cherenkov photons which are transmitted to photomultiplier tubes through air-core light-guides. The electromagnetic section is 22 radiation length deep with 2 tungsten-quartz sandwiches, and the hadronic section consists of 12 tungsten-quartz sandwiches. The total depth is 10.3 interaction lengths. The calorimeter read-out has azimuthal and longitudinal segmentation (16 and 14 segments, respectively). There is no segmentation in $\eta$.

3 Monte Carlo Simulation

Single-diffractive di-jet production was simulated by using the POMWIG generator [5], version v2.0 beta. POMWIG is a modified version of HERWIG [12] which can generate diffractive interactions. All standard HERWIG hard subprocesses are available for Pomeron-proton, photon-Pomeron and Pomeron-Pomeron collisions. For the diffractive PDFs and the Pomeron flux, the result of the NLO H1 2006 fit B [13] was used. A rapidity gap survival probability of 0.05 was assumed. For the inclusive proton PDF, the CTEQ61 [14] parameterisation was used. Events were generated over the kinematic range $10^{-6} < \xi < 0.2$ and $10^{-6} < |t| < 4 \text{ GeV}^2$ and for values of the hard-scattering transverse momentum $\hat{p}_T > 40$ GeV. Here $\xi$ is the fractional momentum loss of the scattered proton and $t$ is the four-momentum transfer squared at the proton vertex. The corresponding cross section is 168 nb, leading to about 1.7 million events per $10 \text{ pb}^{-1}$.

For non-diffractive (ND) di-jet production, the MADGRAPH [15] generator was used. The cross section is of order $25 \mu b$ for values of the hard-scattering transverse momentum $\hat{p}_T > 50$ GeV. With the given numbers for the cross sections, the ratio of diffractive to inclusive yields is of order 0.5%.

Unless otherwise noted, all samples were processed through the CMS fast detector simulation, as well as the trigger emulation and reconstruction packages.

4 Event Selection

4.1 Di-jet Selection

At the trigger level, events were selected by requiring at least 2 jets with average uncorrected transverse energy greater than 30 GeV. Offline, jets were reconstructed with the SiSCone5 [16] algorithm and jet-energy scale (JES) corrections were applied. At least two jets with $E_T > 55$ GeV were required. All plots shown in this paper are for energy-corrected jets.
4.2 Diffractive Selection

The left panel of Fig. 2 shows the generated energy-weighted $\eta$ distribution for stable particles in diffractive and non-diffractive events; only diffractive events with the scattered proton at positive rapidities (the peak at $\eta \gtrsim 10$) are included in the plot. Diffractive events have, on average, lower multiplicity both in the central region and in the hemisphere that contains the scattered proton, the so-called “gap side”, than non-diffractive events. The right panel of Fig. 2 shows the multiplicity distribution in the central tracker for $|\eta| < 2$ after the di-jet selection cuts. Diffractive events have a multiplicity distribution that peaks at low values, unlike that of non-diffractive events. Diffractive event candidates were therefore selected on the basis of the multiplicity distribution in the central tracker, in the HF as well as in CASTOR.

Figure 2: Left: Generated energy-weighted $\eta$ distribution for stable particles (excluding neutrinos) per event in diffractive (POMWIG, continuous line) and non-diffractive (MADGRAPH, dashed line) events. The HF and CASTOR coverage is shown. The areas of the two distributions are normalised to unity. Right: Track multiplicity distribution in the central tracker ($|\eta| < 2$) after the di-jet selection cuts for diffractive (POMWIG, continuous histogram) and non-diffractive (MADGRAPH, dashed histogram) events. The tracks associated to the jets were excluded.

The gap side was selected as that with lower energy sum in the HF. This selection was made for all events though the concept is relevant only for diffractive events. In addition, the two leading jets were required to be between $-4 < \eta < 1$ for events with the gap side at positive rapidities and $-1 < \eta < 4$ for events with the gap side at negative rapidities (cf. Fig. 9 in the Appendix). When CASTOR is used, only events with the gap on the negative side are considered, since CASTOR will be installed on that side first. The rapidity separation between the two leading jets was required to be $\Delta \eta < 3$ (cf. Fig. 9 in the Appendix). For the SD events passing this selection, the probability of selecting the gap side incorrectly is about 10%.

In addition, a cut was applied on the track multiplicity in the central tracker. The plots shown in this paper were obtained with maximum multiplicity for $|\eta| < 2$, $N_{\text{track}}^{\max}$ of 1, 5 and no cut at all. For the events passing this cut, multiplicity distributions in the HF and CASTOR calorimeters were studied, from which a diffractive sample can be extracted.
5 HF and CASTOR Multiplicity Distributions

5.1 HF

Figure 3 shows the multiplicity of HF towers above threshold for the low-\(\eta\) region in HF ("central slice", \(2.9 < \eta < 4.0\)) vs that in the high-\(\eta\) region ("forward slice", \(4.0 < \eta < 5.2\)) for events with a cut on the central tracker multiplicity \(N_{\text{max}}^{\text{track}} = 5\). The top left plot shows the POMWIG distribution; it exhibits a clear peak at zero multiplicity. Conversely, the non-diffractive events from MADGRAPH have on average higher multiplicities, as shown in the top right plot. Finally, the bottom plot shows the sum of the POMWIG and MADGRAPH distributions – the type of histogram expected from the data. The diffractive signal appears as an enhancement at low multiplicities. Table 1 gives the number of signal and background events in the zero-multiplicity bins for various \(N_{\text{max}}^{\text{track}}\) cuts.

![Figure 3: Low-\(\eta\) ("central slice") vs high-\(\eta\) ("forward slice") HF tower multiplicity for events with maximum track multiplicity in the central tracker \(N_{\text{max}}^{\text{track}} = 5\). Top left: POMWIG events. Top right: MADGRAPH events. Bottom: Sum of the POMWIG and MADGRAPH distributions.](image)

The accepted events with zero multiplicity in both HF slices, i.e. the events with a candidate rapidity gap extending over the whole HF, typically have \(\xi < 0.01\), and thus populate the region where Pomeron exchange is expected to dominate over sub-leading exchanges.

5.2 HF vs CASTOR

The HF tower multiplicity vs CASTOR \(\phi\) sector multiplicity for the gap side is presented in Fig. 4 for \(N_{\text{max}}^{\text{track}} = 5\). The CMS software chain available for this study did not include simulation/reconstruction code for CASTOR; therefore, the multiplicity of generated hadrons with...
Table 1: Diffractive and non-diffractive di-jet event yields expected with (1) zero HF multiplicity, (2) zero HF and CASTOR multiplicity, as a function of $N_{\text{max, track}}$. The signal yields are given for $\langle |S|^{2} \rangle = 0.05$ (nominal) as well as $\langle |S|^{2} \rangle = 0.004$ and $\langle |S|^{2} \rangle = 0.23$. The uncertainties are computed as $\sqrt{N}$.

<table>
<thead>
<tr>
<th>$N_{HF} = 0$</th>
<th>$N_{\text{max, track}}$</th>
<th>$N_{\text{diff}}$ (0.05)</th>
<th>$N_{\text{diff}}$ (0.004)</th>
<th>$N_{\text{diff}}$ (0.23)</th>
<th>$N_{\text{non-diff}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>no cut</td>
<td>1047 ± 32</td>
<td>84 ± 9</td>
<td>4816 ± 69</td>
<td>1719 ± 41</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>803 ± 28</td>
<td>64 ± 8</td>
<td>3694 ± 61</td>
<td>943 ± 31</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>362 ± 19</td>
<td>29 ± 5</td>
<td>1665 ± 41</td>
<td>276 ± 16</td>
<td></td>
</tr>
<tr>
<td>$N_{HF} = 0$, $N_{\text{CASTOR}} = 0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>no cut</td>
<td>504 ± 22</td>
<td>40 ± 6</td>
<td>2318 ± 48</td>
<td>67 ± 8</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>409 ± 20</td>
<td>33 ± 4</td>
<td>1881 ± 43</td>
<td>31 ± 6</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>236 ± 15</td>
<td>19 ± 4</td>
<td>1086 ± 33</td>
<td>8 ± 3</td>
<td></td>
</tr>
</tbody>
</table>

energy above a 10 GeV threshold in each of the CASTOR azimuthal sectors was used. Particle energies and momenta were not smeared. The CASTOR-based studies presented here should be taken as order-of-magnitude, indicative results.

The diffractive signal at low multiplicities is much more visible than in the HF-only case. The number of signal events at zero multiplicities is approximately 50% of that in the HF-only case, a consequence of CASTOR being assumed only on one side. The plots suggest that if only the CASTOR multiplicity is used, the diffractive signal is further enhanced. Table 1 gives the number of signal and background events in the zero-multiplicity bins. Here as well, the accepted events with zero multiplicity typically have $\xi \approx 0.01$.

6 Data-Driven Evidence of Diffractive Di-jet Production

The plots discussed in the previous section can be used to demonstrate the presence of diffractive di-jet production in the data without relying on the MC. This is done by showing that the size of the diffractive signal can be controlled in a predictable way by modifying the diffractive selection procedure, notably the $N_{\text{max, track}}$ cut, the $\eta$ coverage and the gap-side selection criteria.

Figure 5 shows the HF-only and HF vs CASTOR gap-side multiplicity distributions for different cuts on the central tracker (see also Table 1). The size of the enhancement in the zero-multiplicity bins relative to the rest of the distribution increases monotonically when the $N_{\text{max, track}}$ cut is tightened – the opposite of what would happen if the enhancement were a statistical fluctuation. The relative size of the enhancement also increases when going from the HF-only coverage to the HF plus CASTOR coverage: a wider $\eta$ coverage suppresses non-diffractive events, where the gap is due to statistical fluctuations in the rapidity distribution of the hadronic final-state.

For the side opposite to the gap, no low-multiplicity enhancement is visible, independent of the $N_{\text{max, track}}$ cut. If the gap side is chosen randomly for each event, the signal is reduced, but its dependence on the $N_{\text{max, track}}$ cut is unchanged. Figure 6 shows how the signal evolves when going from the side opposite to the gap, to a random gap selection, to the gap side selected as discussed in Sect. 4.2 for the HF-only case and $N_{\text{max, track}} = 5$; similar results hold for other $N_{\text{max, track}}$ values and for the HF plus CASTOR case.

Finally, the shape of the background multiplicity distribution in the gap side is similar for the
events with a randomly selected gap side and with proper gap-side selection. The multiplicity distributions for the events with the random gap selection can then be subtracted from those of Fig. 5, thereby suppressing the background contribution. The result is shown in Fig. 7 for $N_{\text{track}}^{\text{max}} = 5$. The signal size is about 30-50\% of that in Fig. 5, but the background is suppressed.

In summary, while a single set of selection criteria for studying multiplicity may not be enough to demonstrate the existence of a SD di-jet signal, a set of selections like those presented indicate that there is a signal whose size can be controlled in a systematic way. Once the existence of the signal is established, a sample of diffractive events can be obtained by using the zero-multiplicity bins, where the diffractive events cluster and the non-diffractive background is small. When an integrated effective luminosity for single interactions of $10 \text{ pb}^{-1}$ becomes available, SD di-jet production can then be observed with $O(300)$ signal events. Observation of a signal at this level would exclude very low values of the rapidity gap survival probability, see Sect. 6.1.

### 6.1 Sensitivity to the Value of the Rapidity Gap Survival Probability

Table 1 gives the expected signal and background yields in the zero-multiplicity bins also for values of the rapidity gap survival probability $\langle |S|^2 \rangle = 0.004$ and $\langle |S|^2 \rangle = 0.23$. In the former case, the observable signal becomes marginal, even with the widest possible $\eta$ coverage (HF+CASTOR). Conversely, $\langle |S|^2 \rangle = 0.23$ gives rise to a very prominent signal, also in the HF-only case.
6.1 Sensitivity to the Value of the Rapidity Gap Survival Probability

Figure 5: HF-only (top row) and HF vs CASTOR (bottom row) multiplicity distributions for signal plus background events with no cut on the track multiplicity in the central tracker (left column), \( N_{\text{track}}^\text{max} = 5 \) (central column) and \( N_{\text{track}}^\text{max} = 1 \) (right column).

Figure 6: HF-only multiplicity distributions (signal plus background) for the side opposite to the gap (left), for a random selection of the gap (centre) and for standard gap selection (right), all with \( N_{\text{track}}^\text{max} = 5 \).

In order to assess the significance of these yields, a preliminary, conservative estimate of the systematic uncertainties was obtained by summing in quadrature the contributions due to the sensitivity to the HF threshold (±15%), the JES (±30%), the use of different jet algorithms (±20%) and a +30% contribution due to proton dissociation (see Sect. 7), yielding a ±50/−40% systematic uncertainty.

Observation of an event yield of 236 ± 15(stat.) ±120(syst.) (cf. Table 1, \( N_{\text{track}}^\text{max} = 1 \) and HF+CASTOR) or 409 ± 20(stat.) ±120(syst.) (cf. Table 1, \( N_{\text{track}}^\text{max} = 5 \) and HF+CASTOR) would exclude \(|S|^2\) = 0.004, for which no signal is visible.
7 Proton-Dissociative Contribution

An important contribution to the observed yields is due to SD di-jet production with proton-dissociation, $pp \rightarrow XY$, where $X$ contains a di-jet system and $Y$ is a low-mass state into which the proton has diffractively dissociated. Dissociative events in which $Y$ escapes undetected in the forward region cannot be distinguished from the signal events.

A study of proton-dissociation has been carried out in [17]: about 50% of the proton-dissociative background can be rejected by vetoing events with activity in the Zero Degree Calorimeter (ZDC). The study also concluded that only about 10% of the dissociative events have activity in CASTOR and not in the ZDC; since the dissociative cross section is of the same order as the non-dissociative, this result indicates that the CASTOR multiplicity distributions are not affected significantly by the dissociative contribution. Requiring no activity in the ZDC, CASTOR and HF rejects about 70% of the dissociative events. Since the dissociative process is also diffractive, the effect of the dissociative events that cannot be tagged is thus to enhance the diffractive signal by about 30%.

8 Summary and Outlook

Observation of single-diffractive di-jet production is an important ingredient in establishing hard diffraction at the LHC. Once the signal is observed, the ratio of the single-diffractive to inclusive di-jet yields can be measured. This ratio is experimentally robust and gives access to the rapidity gap survival probability as well as to the gluon component of the diffractive PDFs of the proton in a region where they have not yet been measured.

A procedure has been discussed to arrive at the observation of single diffractive di-jet production with an integrated effective luminosity for single interactions of $10 \text{ pb}^{-1}$. The procedure is based on the detection of large rapidity gaps in the final state of the event using HF and CASTOR, complemented by the multiplicity information from the central tracker. A set of plots has been shown that can be used to demonstrate the presence of diffractive di-jet production in the data without relying on the simulation.

Assuming a rapidity gap survival probability of 0.05, $O(300)$ reconstructed signal events are expected if CASTOR is available. Observation of a signal at this level would exclude very low values of the rapidity gap survival probability. The measurement would also allow the tuning
of the underlying event simulation in non-diffractive Monte Carlos, which drives the shape of the multiplicity distributions for non-diffractive events. If CASTOR is not available, the HF information alone may be sufficient.

References


A Additional Material

A.1 Di-jet Selection

Figures 8 and 9 show the \( E_T \) and \( \eta \) distributions of the two leading jets, for both the POMWIG and MADGRAPH samples after the high-level trigger (HLT) selection. The \( E_T \) distributions for the diffractive and non-diffractive samples are similar, but those as a function of \( \eta \) are not – a reflection of the different topology of diffractive and non-diffractive events.
Figure 8: Jet transverse energy distributions after the HLT selection for the reconstructed POMWIG (continuous lines) and MADGRAPH (dashed lines) samples before offline cuts. For ease of comparison the area under the curves is normalised to unity. Left: most energetic jet. Right: second most energetic jet.
Figure 9: Jet pseudorapidity distributions after the HLT selection for the reconstructed POMWIG (continuous lines) and MADGRAPH (dashed lines). For this plot, diffractive events were generated with the gap side in the positive $\eta$ hemisphere. The area under the curves is normalised to unity. Top left: Most energetic jet. Top right: Second most energetic jet. Bottom: Pseudorapidity difference between the two leading jets.