Recent forward physics and diffraction results from CMS

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Abstract. Recent CMS results on forward physics and diffraction are reviewed. The differential diffractive cross section is measured as a function of \( \xi = M_X^2/s \) in the region dominated by single dissociation (SD) and double dissociation (DD), where \( M_X \) is the mass of one of the two final-state hadronic systems separated by the largest rapidity gap in the event. The total SD and DD cross sections are extracted. The observation of a hard color-singlet exchange process in events with a large rapidity gap between two leading jets (jet-gap-jet) is reported. The fraction of jet-gap-jet to all dijet events is measured as a function of the second leading jet transverse momentum and the size of the pseudorapidity gap. The measured fractions are compared with predictions as well as Tevatron data.

1 Introduction

Diffractive interactions account for about a quarter of the total inelastic proton-proton cross section at high energies. These interactions are characterized by at least one large rapidity gap (LRG) that is not suppressed exponentially. Depending on the topology of the event, one can differentiate between single and double dissociation (SD and DD), and central diffraction (CD). An LRG is presumed to be mediated by a color-singlet exchange (CSE). Measurements of diffractive processes at the LHC provide valuable input to phenomenological models, as these cross sections cannot be calculated within perturbative QCD, and extrapolations in \( \sqrt{s} \) from lower energies vary depending on model parameters.

Another interesting and related area of research is the study of events with a LRG between two jets at high transverse momentum \( p_T \). Normally dijet production is the consequence of an exchange of a colored object, and the color field associated with the exchanged parton calls for additional soft parton emissions, populating the \( \eta \) interval between the jets. For dijet events with central LRG, the BFKL approach is expected to describe the data [1]. The LRG is a signature of CSE, this time involving a hard scale, with a much higher momentum transfer compared to soft diffractive events. Thus, studies of CSE events as a function of the rapidity gap width helps disentangle the BFKL dynamics from the DGLAP evolution. The results are also sensitive to rescattering processes, as those can destroy the LRG.

The detailed description of the CMS detector can be found in [2]. For measurements of diffraction, the extensive forward instrumentation is relevant: the forward component of the hadron calorimeter, HF (2.9 < |\( \eta \) | < 5.2), the CASTOR calorimeter [3] (−6.6 < \( \eta \) < −5.2), the Zero Degree Calorimeter (ZDC) and the Forward Shower Counters (FSC). The TOTEM experiment, including Roman Pots and

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Figure 1. Detector-level distributions of the reconstructed and calibrated $\xi_X$ for (left) the entire FG2 sample, and the FG2 subsamples with (middle) no CASTOR tag, and (right) a CASTOR tag (statistical errors only). The data are compared to the predictions of the PYTHIA 8 MBR simulations, which are normalized to the integrated luminosity of the data sample. The contribution of each of the generated processes is shown separately.

2 Diffractive dissociation cross sections

In the experimental analysis presented here, the SD and DD events are separated using the CASTOR calorimeter [3], covering the $-6.6 < \eta < -5.2$ region. A special data set of 16.2 $\mu$b$^{-1}$ at $\sqrt{s} = 7$ TeV was used, where the probability of more than one $pp$ collisions occurring coincidentally was only 7%, collected in 2010. Monte Carlo (MC) simulations are used to correct the measured distributions for the geometrical acceptance and efficiency of the detector [4].

The $pp$ collisions are selected with a very inclusive minimum bias trigger. No reconstructed collision vertex or charged particle tracks are required, but at least two reconstructed particle-flow (PF) objects above 4 GeV total energy in the forward region. The acceptance of this selection is 90% for events where any of the diffractive $M_X$ and $M_Y$ masses exceed 12.6 GeV.

Various event topologies are defined: FG1 (FG2) events contain an $\eta$-gap on the positive (negative) $\eta$-side. In case of FG1 (FG2) topologies, the $\eta$-gap extends to $\eta_{\text{max}}$ and $\eta_{\text{min}}$ which are the highest (lowest) $\eta$ of the PF objects in the central detector. In order to select samples of FG1 and FG2 events with the forward LRG signature in the detector, the requirements $\eta_{\text{max}} < 1$ and $\eta_{\text{min}} > -1$ are imposed, respectively. The detection of the low-mass dissociated system, $Y$, and thereby the separation of DD and SD events, is performed by using a CASTOR tag, defined as the presence of a signal above the energy threshold (1.48 GeV) in the CASTOR calorimeter.

The forward rapidity gap cross section is expressed as a function of $\xi_X = M_X^2 / s$. Since $\xi_X$ is not directly measurable, it is approximated experimentally by $\xi_X = \Sigma (E' \mp p'_{\xi}) / \sqrt{s}$, where $E'$ and $p'_{\xi}$ refer to PF objects, where the dissociated system is on the positive (negative) side. Good correlation between $\xi_X$ and $\xi_X^+$ was found using single diffractive events simulated by the PYTHIA 8 Minimum Bias Rockefeller (MBR) tune. Based on this correlation, the measured $\xi_X^+$ values can be calibrated (translated into $\xi_X$). Figure 1 shows the distribution of this calibrated $\log_{10} \xi_X^{\text{cal}}$ for the FG2 sample, compared to model predictions, including the SD, DD and ND components separately. The separation of SD and DD processes by the CASTOR tag is clearly seen in these figures.

The PYTHIA 8 MBR tune describes the data well (using a Pomeron trajectory with $\epsilon = 0.08$), and is subsequently used to extract the diffractive cross sections. The differential cross sections are mea-
especially when both of the
an extrapolation from (obtained from the PYTHIA 8 MBR model (with
tance and migration e
are corrected for the small fraction of simultaneous
−processes to obtain the visible SD cross section (generator level interval) and for events with CASTOR tag (0
and log
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< 0.5 was performed. Similarly, the DD cross section in the CASTOR-tagged sample
−
< 0.5, favor ϵ = 0.08, especially when both of the M_Y and M_X masses are low. The PYTHIA 6 Z2∗ tune, using the Schuler-
forecast of the Pomeron trajectory ϵ = 0.104) is found to be
2.99 ± 0.02(stat) +0.32(stat) -0.29(syst) mb and σ_{CASTOR} = 1.18 ± 0.02(stat) ± 0.13(syst) mb.

The σ_{no–CASTOR} cross section is dominated by SD events, with background mainly originating from DD processes. The latter is well understood via the CASTOR-tagged events. The PYTHIA 8 MBR simulation was used to correct for the small non-diffractive (ND) fraction and other diffractive processes to obtain the visible SD cross section (−5.5 < log_{10} ξ_X < −2.5), which is found to be
4.06 ± 0.04(stat) +0.69(stat) -0.63(syst) mb. The main contributors to σ_{CASTOR} are DD events, with a dominant background from ND events. The corrected visible DD cross section in the CASTOR-tagged sample (−5.5 < log_{10} ξ_X < −2.5 and 0.5 < log_{10} M_Y < 1.1) is
1.06 ± 0.02(stat) ± 0.12(syst) mb.

In order to compare the SD measurement with results of other experiments and theoretical models, an extrapolation from (−5.5 < log_{10} ξ_X < −2.5) to ξ < 0.05 was performed. Similarly, the DD cross section was extrapolated to Δη > 3. This was performed using extrapolation factors determined with PYTHIA 8 MBR, which describes all aspects of our data well. The multiplicative factor of

![Figure 2](image-url)

**Figure 2.** Cross sections \(d\sigma/d\log_{10} ξ_X\) for \(\log_{10} M_Y < 0.5\) (dominated by single diffraction, left panel) and \(0.5 < \log_{10} M_Y < 1.1\) (dominated by double diffraction, right panel) compared to MC predictions: (top) PYTHIA 8 MBR, PYTHIA 8 4C, PYTHIA Z2∗, and (bottom) PHOJET, QGSJET-II 03, QGSJET-II 04, EPOS. Error bars are dominated by systematic uncertainties.
3 Dijet events with a rapidity gap

The fraction of jet-gap-jet events in $p\bar{p}$ collisions was measured to be around 1% at the Tevatron. Here we present the first observation of such events at the LHC, along with the CSE fraction at $\sqrt{s} = 7$ TeV, using two jets with $p_T > 40$ GeV and $1.5 < |\eta| < 4.5$. The CSE signal is extracted from the charged particle multiplicity distribution in the central region $|\eta| < 1$ between the jets, using tracks with $p_T > 0.2$ GeV. For this analysis it is essential that the probability of overlapping $pp$ collisions is low. The amount of data used correspond to $8\,pb^{-1}$ integrated luminosity collected in 2010 [8].

Jets are clustered with the anti-$k_T$ algorithm, with a radius parameter $R=0.5$. The jet energy corrections are derived from simulation and confirmed with measurements of dijet and $\gamma$+jet energy balance. Jet-gap-jet events are simulated with the HERWIG 6 generator, which takes into account the reactions involving hard CSE via elastic parton-parton scattering according to the Mueller-Tang model, which is based on BFKL evolution [9]. Multi-parton interactions (MPI) in the underlying event is provided by the JIMMY package [10].

The data are divided into three bins of the $p_T$ of the lower-energy jet in the dijet system; $p_T^{jet2}$: 40–60 GeV, 60–100 GeV and 100–200 GeV. At most one primary collision vertex is allowed in each event, and the jets have to satisfy the conditions $|\eta^{jet1}| > 1.5$, $|\eta^{jet2}| > 1.5$ and $\eta^{jet1} \cdot \eta^{jet2} < 0$, in order to ensure the necessary separation between the jets and the region (gap) where the charged particle multiplicity is measured.

The left panel of Figure 4 shows the measured track multiplicity distribution for the $60 < p_T^{jet2} < 100$ GeV bin. The data are well described by the PYTHIA 6 simulation (LO DGLAP), except the lowest multiplicity bins, where a large excess is observed, indicating CSE events. This excess is however well described by the HERWIG 6 model (LL BFKL). It was verified that the kinematical
distributions of jets in the zero-track bin agree well with MC predictions. It was also found that the CSE dijets are more balanced, both in azimuthal angle and transverse momentum, compared to non-CSE dijets.

In order to quantify the contribution of CSE events in inclusive the dijet sample and measure the CSE fraction, $f_{\text{CSE}}$, one has to subtract the background events first, estimated to have a non-CSE origin. The $f_{\text{CSE}}$ fraction is not sensitive to trigger inefficiencies and jet reconstruction uncertainties, as they cancel in the ratio.

Two methods are used to estimate the number of background events. First, the shape of the charged particle multiplicity distribution is obtained from a sample with the two leading jets being on the same side of the CMS detector (SS sample, $|\eta^{\text{jet1}}| > 1.5$, $|\eta^{\text{jet2}}| > 1.5$ and $\eta^{\text{jet1}} \cdot \eta^{\text{jet2}} > 0$). The region in which the multiplicity was measured was widened to be $|\eta| < 1.2$ (for details, see [8]) and normalized to the nominal opposite-sign (OS) sample. The number of events in the first multiplicity bins is taken as the estimate of the background. An example of the SS and OS multiplicity distributions is shown in the right panel of Fig. 4 for the $100 < p_{T}\text{jet} < 200$ GeV bin. The second method involves a negative binomial fit to the charged particle multiplicity distribution restricted to the multiplicity region 3–35. The number of background events with these two methods agree within statistical uncertainties. The non-CSE background amounts to about half of the events in the first three bins of the multiplicity distribution.

The left panel of Figure 5 presents the CSE fraction in the three $p_{T}\text{jet}^2$ regions, compared to results from the Tevatron ($\sqrt{s} = 1.8$ TeV). The CSE fraction shows a slight increase with $p_{T}\text{jet}^2$, while a suppression of the gap fraction is observed as $\sqrt{s}$ increases. This trend is in agreement with that observed at different Tevatron energies ($\sqrt{s} = 0.63$ and 1.8 TeV), and can be explained by a changing rescattering contribution, in which the interactions between spectator partons destroy the rapidity gap. The measurement is also presented on the right panel of Fig. 5, which shows the dependence of $f_{\text{CSE}}$ on the $\eta$-separation of the two jets, $\Delta\eta_{jj}$, for each $p_{T}\text{jet}^2$ bin. The gap fraction increases with $\Delta\eta_{jj}$, not reproduced by the Mueller-Tang model.
In Summary, we have presented various measurements concerning color-singlet exchange processes, in particular, inclusive single- and double-diffraction cross sections (those visible by our apparatus as well as extrapolations to a larger phase space), and dijet events with a large rapidity gap between them, that need to invoke CSE to explain their presence in the data. Comparisons to earlier measurements and phenomenological models contribute to the further scrutiny of these important processes in hadron-hadron interactions.

References

[8] V. Khachatryan et al. (CMS) (2015), CMS-PAS-FSQ-12–001