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Observation of hard diffraction at the LHC

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Abstract

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Observation of Hard Diffraction at the LHC

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The feasibility is discussed of rediscovering hard diffraction in pp collisions at the LHC with the first 10-100 pb^{-1} collected by the CMS detector. Studies are presented of single-diffractive dijet production, single-diffractive W boson production and Y photoproduction at $\sqrt{s} = 14$ TeV. The prospects of assessing the rapidity gap survival probability and the low- x structure of the proton are discussed.

1 Introduction

A substantial fraction of pp interactions consists of diffractive reactions, $pp \rightarrow pX$ or $pp \rightarrow pXp$, in which the incoming proton(s) emerge from the interaction intact, or excited into a low mass state, with an energy loss within a few per cent. Diffractive events are characterised by the exchange of a colour singlet object with vacuum quantum numbers, the so-called pomeron, now also understood in terms of partons from the proton. The absence of colour flow between the proton(s) and the system X results in the topological signature of these events, i.e. large gap(s) in the rapidity distribution of the final state (large rapidity gap, LRG).

Diffractive reactions are predominantly soft but can also occur in the presence of a hard scale, as observed at UA8, HERA and Tevatron. The hard scale may be provided by jets, heavy quarks or the W or Z boson mass and allows perturbative QCD (pQCD) to be used. Cross sections can then be factorized into a partonic cross section, which describes the hard scattering and is calculable in pQCD, times a diffractive parton distribution function (dPDF), which can be interpreted as the proton PDF under the condition that the proton remains intact. However, in hadron-hadron collisions this factorization is broken by rescattering between spectator partons, which fill the large rapidity gap. The resulting suppression of the diffractive cross section is quantified by the rapidity gap survival probability, S^2 , which is an important ingredient to be measured at the beginning of the LHC data-taking.

Three preliminary studies have been performed by the CMS Collaboration to demonstrate the feasibility of rediscovering hard-diffraction with the early LHC data by means of single diffractive (SD) dijet and W production and Y photoproduction. A center of mass energy of 14 TeV and a zero pile-up scenario, which allows a rapidity gap based selection, have been assumed. For more details on the analyses presented here, the reader is referred to [2, 3, 4].

2 The CMS detector

The CMS apparatus is described in detail in [5]. A crucial role in the analyses presented here is played by calorimeters installed in the forward region: HF and CASTOR.

The forward part of the hadron calorimeter, HF, is located 11.2 m from the interaction point and covers the regions $3 \leq |\eta| \leq 5$. It consists of steel absorbers and embedded radiation hard quartz fibers, which provide a fast collection of Cherenkov light, and has ϕ and η segmentation. CASTOR is a sampling calorimeter located at 14.3 m from the interaction point, with

tungsten plates as absorbers and fused silica quartz plates as active medium. The read-out has azimuthal and longitudinal segmentation (16 and 14 segments, respectively) while there is no segmentation in η . It is currently installed only on one side of the interaction point and extends the CMS forward hermeticity to $-6.6 < \eta < -5.2$.

3 SD W and dijet production

The feasibility of observing single diffractive W and dijet events by means of a rapidity gap based selection was investigated by the CMS Collaboration. The two processes were already studied at the Tevatron [6, 7, 8], and are important because they are sensitive to the diffractive structure function of the proton and to the rapidity gap survival probability. Two experimental scenarios were considered. In the first, no forward detectors beyond the forward calorimeter HF were assumed. In this case the pseudo-rapidity coverage is limited to $|\eta| < 5$. In the second, additional coverage at $-6.6 < \eta < -5.2$ was assumed by means of the CASTOR calorimeter.

The single diffractive signals were simulated with the POMWIG Monte Carlo generator [9], assuming $S^2 = 5\%$. Non-diffractive events were simulated with PYTHIA [10] or MADGRAPH [11]. Unless otherwise stated, all Monte Carlo samples were processed through the full detector simulation, trigger emulation and reconstruction.

3.1 Event selection

3.1.1 $W \rightarrow \mu\nu$ production

The W was selected in the $\mu\nu$ decay channel with the analysis cuts used for inclusive $W \rightarrow \mu\nu$ production [12]. Events with a candidate muon of transverse momentum $p_T < 25$ GeV in the pseudo-rapidity range $|\eta| > 2.0$ were rejected, as were events with at least two muons with $p_T > 20$ GeV. Muon isolation was imposed by requiring $\sum p_T < 3$ GeV in a cone with $\Delta R < 0.3$. The transverse mass was required to be $M_T > 50$ GeV. The contribution from top events containing muons was reduced by rejecting events with more than 3 jets with $E_T > 40$ GeV (selected with a cone algorithm with radius of 0.5) and events with acoplanarity greater than 1 rad between the muon and the direction associated to the missing transverse energy.

3.1.2 Dijet production

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 [13] algorithm and jet-energy scale (JES) corrections were applied. At least two jets with $E_T > 55$ GeV were required.

3.1.3 Diffractive selection

Diffractive events have on average lower multiplicity with respect to the non-diffractive ones both in the central region and in the hemisphere which contains the scattered proton, the so-called *gap side*. Signal event candidates were therefore selected on the basis of the

multiplicity distribution in the central tracker and in the forward calorimeters (HF and CASTOR).

The gap side was identified as that with lower energy sum in the HF. This selection was made for all events, though the concept is relevant only for the diffractive ones. In addition, for the dijet analysis the two leading jets were required to be in $-4 < \eta < 1$ for events with the gap side at positive rapidities and $-1 < \eta < 4$ for events with the gap side at negative rapidities. The η separation between the two leading jets was required to be $\Delta\eta < 3$. Finally, a cut was applied on the track multiplicity in the central tracker, $N_{\text{track}} \leq 5$. For the events passing this selection, the multiplicity distributions in the HF and CASTOR calorimeters were studied.

3.2 Observation of the single diffractive signal

In the following we will describe how a diffractive sample can be extracted from forward detector multiplicity plots, focussing on the dijet channel [2]; an analogous procedure was also applied in the SD W analysis, as described in [3]. The dijet study was performed assuming an integrated luminosity for single interactions of 10 pb^{-1} ; the number of events in the plots shown in this section is normalized to this luminosity.

Figure 1 shows the HF tower multiplicity for the low- η (“low- η slice”, $2.9 < \eta < 4.0$) and high- η HF (“forward slice”, $4.0 < \eta < 5.2$) regions for events with central tracker multiplicity $N_{\text{track}} \leq 5$. Plots are shown for the gap side only. In the figure, the left and central panels display the distributions expected for the diffractive and background events, respectively. Signal events exhibit a clear peak at zero multiplicity. Conversely, the non-diffractive events have on average higher multiplicities; this distribution is interesting by itself as it is sensitive to the underlying event in non-diffractive interactions. Finally, the right panel shows the sum of the POMWIG and PYTHIA events – this is the type of distribution expected from the data. The diffractive signal at low multiplicities is visible.

Figure 1: Two dimensional HF tower multiplicity distributions for the gap side. Left: POMWIG events. Central: PYTHIA events. Right: Sum of the PYTHIA and POMWIG events.

The HF tower multiplicity vs CASTOR ϕ sector multiplicity was also studied for the gap side. Since CASTOR will be installed at the LHC start-up on the negative side of the interaction point, only events with the gap on that side were considered. The CMS software chain available for this study did not include the simulation/reconstruction code for CASTOR; therefore, the multiplicity of generated hadrons with energy above a 10 GeV threshold in each of the CASTOR azimuthal sectors was used. Figure 2-left panel shows the PYTHIA plus

POMWIG distribution, analogous to that of Fig. 1-right panel, for the combination of HF and CASTOR. The signal to background ratio improves greatly with respect to the HF only case since a wider η coverage suppresses non-diffractive events, where the gap is due to statistical fluctuations in the rapidity distribution of the hadronic final state. A simple way to isolate a

Figure 2: Two dimensional multiplicity distribution (HF vs CASTOR), for SD dijet (left panel) and W (right panel) channel.

sample of signal events from these plots is to use the zero-multiplicity bins, where diffractive events cluster and the non-diffractive background is small. Our study shows that when an effective integrated luminosity for single interactions of 10 pb^{-1} becomes available, single diffractive dijet production can be observed with $\mathcal{O}(300)$ signal events. Moreover, since the cross section for this process is directly proportional to the rapidity gap survival probability, the measurement of the event yield may also give early information on S^2 .

The HF and CASTOR multiplicity plot for the W production is shown in Fig. 2-right panel. In this case the number of events is normalized to an integrated luminosity for single interactions of 100 pb^{-1} . Here again a sample of diffractive events can be obtained by using the zero-multiplicity bins. The plot shows that with the assumed integrated luminosity the SD W production can then be observed with $\mathcal{O}(100)$ signal events.

4 Exclusive Υ photoproduction

The Υ mesons can be exclusively produced through the reaction $pp \rightarrow p\Upsilon p \rightarrow pl^+l^-p$, in which one of the protons radiates a quasi-real photon that interacts, via colour-singlet exchange, with the other proton. This reaction has been studied at HERA, and can be investigated at CMS with the Υ decaying in the $\mu^+\mu^-$ channel [4]. Assuming the STARLIGHT Monte Carlo [14] cross section prediction, the 1S, 2S and 3S resonances will be clearly visible in the $\mu^+\mu^-$ invariant mass spectrum with 100 pb^{-1} of single interaction data (see Fig. 3). The LHC measurements would extend the accessible range in $W_{\gamma p}$ (γp center-of-mass energy) for $\sigma(\gamma p \rightarrow \Upsilon(1S)p)$ by approximately a factor three with respect to HERA. A study of the t dependence of the cross-section in these events is also possible using the p_T^2 distribution of the Υ as an estimator of the true t distribution. This dependence is sensitive to the two-dimensional gluon distribution of the proton and would give access to its generalized parton distribution functions (GPDs). Finally, the rapidity gap survival probability for this process is expected to be close to unity [15]. The yield of exclusive

Figure 3: Dimuon invariant mass. The lines show the results of the fit: the dashed line is the Υ component, the dotted line is the $\gamma\gamma$ continuum, and the solid line is the sum of the two.

Υ photoproduction should thus be essentially unsuppressed – and can be used to further constrain the understanding of the rapidity gap survival probability.

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