Observation of Diffractively Produced W Bosons in pp Collision with the CMS Experiment

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A study of forward energy flow in leptonically decaying W bosons using data of an integrated luminosity corresponding to 36 pb^{-1} of pp collisions at a center-of-mass energy of 7 TeV is presented. This data was recorded with the CMS detector during the 2010 running of the LHC. In this sample of W events, about 300 events with no significant energy deposits in one of the forward calorimeters are observed. This corresponds to a large pseudorapidity gap of at least 1.9 units. The majority of the charged leptons from these W decays are found in the hemisphere opposite to the gap. This gives a strong indication of a diffractive component in the W production, which can be explained in terms of diffractive PDFs which have, on average, a smaller x than the conventional parton PDFs.

1 Introduction

In proton-proton (pp) collisions a significant fraction of the interactions is expected to arise from single-diffractive (SD) reactions, where one of the colliding protons emerges intact from the interaction, having lost only a few percent of its energy. Such SD events may be ascribed to the exchange of vacuum quantum numbers (often called Pomeron exchange), interrupting the color flow and, as a consequence leads to the absence of hadron production over a wide range of rapidity adjacent to the outgoing proton direction. Experimentally, these large rapidity gaps will appear as regions of pseudorapidity, devoid of detectable particles (further called Large Rapidity Gap: LRG). See Figure 1 for an illustration of diffractive W production.

Besides soft-diffractive interactions, hard-diffractive events, where the LRG signature is found in association with jets, heavy flavors or W/Z bosons, have been observed at previous colliders like SPS, HERA and the Tevatron [1,2,3,4,5,6]. The diffractive parton distribution functions (PDF) have been introduced and measured in electron-proton collisions. In hadron-hadron diffractive interactions, soft multi-parton interactions occur between the proton remnants, filling the large rapidity gap and reduce the observed yields of hard-diffractive events by some factor; the so-called gap survival probability. A recent study by CDF [7] indicates that the fractions of diffractively produced W and Z bosons are (1.00±0.11)% and (0.88±0.22)% respectively.

This paper, which focuses on the observation of diffractively produced W bosons, follows closely the more extensive analysis presented in Ref. [8], where the forward energy flow and central charged-particle multiplicity and their correlations in leptonically decaying W and Z boson events are studied in details. It is found that the currently available Monte Carlo simulations of the

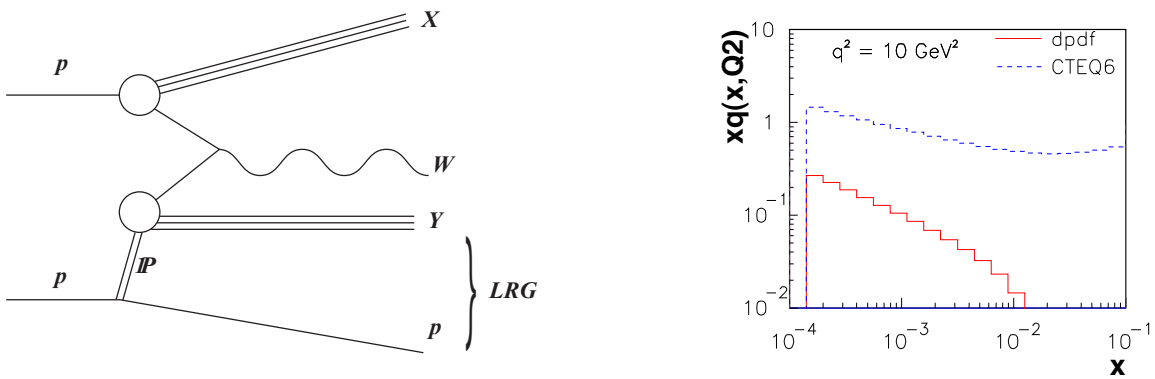

Figure 1: (left): Diffractive W production with the exchange of vacuum quantum numbers ($\mathbb{P}$). LRG denotes the large pseudorapidity gap. (right): Diffractive (solid red line) and conventional (dashed blue line) parton distribution functions. The cut off for very low x is artificial.

underlying event structure, using non-diffractive soft-hadron production models, do not describe simultaneously these different observables.

2 Event Selection

A detailed description of the CMS detector can be found elsewhere [9]. The selection of W events is based on the presence of exactly one central (i.e. $|\eta| < 1.4$) and isolated lepton (electron or muon) with high transverse momentum, $p_T > 25$ GeV. In addition a large missing transverse momentum of more than 30 GeV, from the escaping neutrino, and a transverse mass of more than 60 GeV are required. This selection results in an essentially background free (less than 1%) W sample.

At the LHC, several simultaneous pp interactions can happen in the same bunch crossing in addition to the selected W event; the so called pileup. As the LHC instantaneous luminosity was increasing during 2010 operation, the number of such pileup events per bunch crossing was increasing with time. While the selection efficiency of W events is independent of the instantaneous luminosity, the charged-particle multiplicity and the forward energy flow are not, and thus the LRG signature is strongly affected by pileup; i.e. the gap is "filled". In order to limit effects from pileup, events with more than one vertex are rejected.
Pileup can be categorized as hard and soft events. Hard pileup, producing detectable central charged particles and thus a vertex, are rejected by the multi vertex veto. The soft component, presumably from diffractive proton dissociation, has no detectable transverse activity in the central region, especially no reconstructed vertices.
This selection results in about 32 000 single vertex W events.

3 Forward Energy Flow in W Events

Figure 2 (left) shows the minimum of the forward energy deposits in the two hadronic forward calorimeters (HF+ and HF-, depending on the z-coordinate), which have a pseudorapidity coverage of approximately $3 < |\eta| < 5$. As already mentioned in the introduction, the simulation of the forward energy flow in W events is not describing the data very well. More details can be found in Ref. [8].

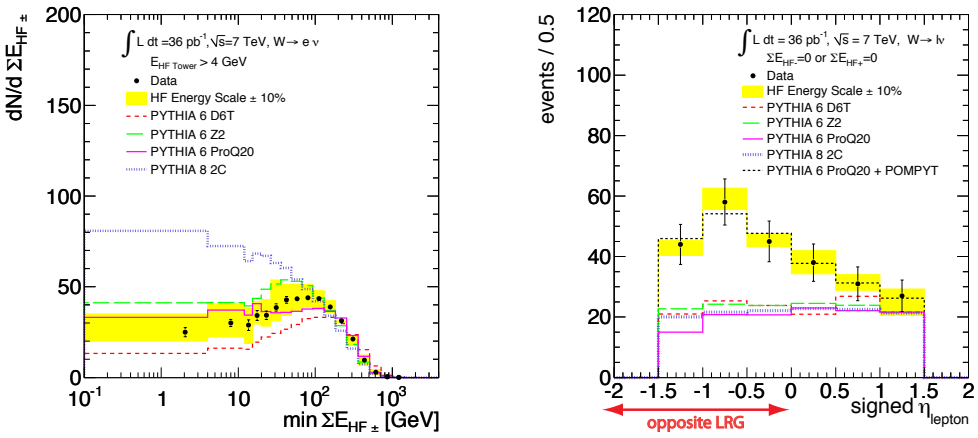

Figure 2: (left): minimum of the forward energy deposits in the two hadronic forward calorimeters in $W \to e\nu_e$ events. LRG events, having no measurable energy in one side of the detector, cluster in the first bin. (right): signed lepton pseudorapidity η. A negative signed η_{lepton} means that the lepton is in the opposite hemisphere as the gap. The yellow band corresponds to the main systematic uncertainty coming from the jet energy scale, which is assumed to be 10%.

A LRG event is defined by the requirement that none of the calorimeter towers, in at least one side of the HF, has a measurable energy deposit, giving no total energy deposit in one side of the detector. This results in LRG events with a minimal gap size of 1.9 units in η. This subset is expected to be enhanced by a diffractive component of W production.

Table 1 summarizes the observed LRG event yields and their fractions to all selected single vertex W events. The dataset has been split into three periods with different instantaneous luminosities, and thus different average numbers of pileup events. The fraction of LRG events decreases with increasing luminosity. As already mentioned, this can be explained by HF energy deposits from soft pileup events, filling the gap.

The inefficiency to detect a vertex in events with forward energy from soft pileup depends on the instantaneous luminosity and is estimated from zero-bias events. After correcting the observed numbers from Table 1 for these pileup effects, a constant fraction of LRG events of $(1.46 \pm 0.09(\text{stat.}) \pm 0.38(\text{syst.}))\%$, for electrons and muons combined, is found.

4 Hemisphere Correlation between LRGs and W bosons

Figure 2 (right) shows the distribution of the signed charged lepton pseudorapidity η_{lepton} in W events with a LRG (electrons and muons combined). The sign is defined to be positive when the

Table 1: Number of LRG events with a single vertex and their relative fraction to all selected single vertex W events (in brackets), for the total dataset and divided into three different periods of different instantaneous luminosities, resulting in a different number of average pileup (PU) events.

avg. number PU events	$W \to e\nu_e$	$W \to \mu\nu_\mu$
total dataset	100 (0.71%)	145 (0.81%)
< 1	17 (1.13%)	31 (1.61%)
$1 - 2$	57 (0.72%)	91 (0.86%)
> 2	26 (0.57%)	23 (0.42%)

gap and the lepton are in the same hemisphere and negative otherwise. The data shows that the charged leptons from the W decays are found more often in the hemisphere opposite to the gap. Defining an asymmetry as the ratio of the difference between the number of events in each hemisphere and the sum, the corresponding asymmetry is $(-21.0 \pm 6.4\%)$.
In comparison, the various non-diffractive MC simulations (i.e. PYTHIA with different tunes) predict a flat signed η_{lepton}. On the other hand, events generated with a purely diffractive production model (i.e. POMPYT), exhibit a strong asymmetry. This can be explained in terms of diffractive PDFs, which have on average a smaller momentum fraction x than the conventional proton PDFs; see Figure 1 (right) for an illustration of this fact. The produced W boson is thus boosted in the direction of the parton with the larger x, which is typically the direction of the dissociated proton, i.e. opposite to the gap.

The signed η_{lepton} from non-diffractive and purely diffractive Monte Carlo is fitted to the distribution from data, resulting in a fraction of diffractive events of $(50.0 \pm 9.3(\text{stat.}) \pm 5.2(\text{syst.}))\%$, assuming the PYTHIA6 Pro-Q20 tune as the non-diffractive component. The other tunes yield similar results. Figure 2 (right) shows this combined simulation and the purely non-diffractive components for the other tunes.

The asymmetry in the signed η_{lepton} distribution for non-LRG events decreases with increasing forward energy deposits; e.g. for HF energy deposits of $20 - 100$ GeV, $200 - 400$ GeV and > 500 GeV, the asymmetries are $(-3.5 \pm 1.1)\%$, $(-2.7 \pm 1.0)\%$, and $(0.9 \pm 2.3)\%$ respectively. The small residual asymmetry in low HF energy events is insignificant in comparison to the one for LRG events. However it could be explained by the presence of a diffractive component in which the LRG signature is destroyed by multi-parton interactions or undetected pileup events. For higher HF energy deposits, the asymmetry vanishes completely.

5 Summary

Out of approximately 32 000 W events ca. 300 are found with a LRG. The fraction of events with LRG, as predicted by the non-diffractive Monte Carlo simulation (PYTHIA) is strongly tune dependent. An asymmetry between the number of events with the charged lepton in the opposite and the same hemisphere as the gap is observed. Such an asymmetry is predicted by the purely diffractive simulation (POMPYT). Using an admixture of diffractive and non-diffractive Monte Carlo, describes the data. The fraction of the diffractive component is determined from a binned maximum likelihood fit and is of about $(50.0 \pm 9.3(\text{stat.}) \pm 5.2(\text{syst.}))\%$, thus providing strong evidence for diffractive W production at the LHC.

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