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Differential cross section measurements for the production of a W boson in association with jets in proton–proton collisions at $\sqrt{s} = 7$ TeV

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A B S T R A C T

Measurements are reported of differential cross sections for the production of a W boson, which decays into a muon and a neutrino, in association with jets, as a function of several variables, including the transverse momenta (p_T) and pseudorapidities of the four leading jets, the scalar sum of jet transverse momenta (H_T), and the difference in azimuthal angle between the directions of each jet and the muon. The data sample of pp collisions at a centre-of-mass energy of 7 TeV was collected with the CMS detector at the LHC and corresponds to an integrated luminosity of 5.0 fb^{-1}. The measured cross sections are compared to predictions from Monte Carlo generators, MadGraph + pythia and sherpa, and to next-to-leading-order calculations from BlackHat + sherpa. The differential cross sections are found to be in agreement with the predictions, apart from the p_T distributions of the leading jets at high p_T values, the distributions of the H_T at high-H_T and low jet multiplicity, and the distribution of the difference in azimuthal angle between the leading jet and the muon at low values.

1. Introduction

This letter reports measurements of fiducial cross sections for W boson production in association with jets at the LHC. Measurements of the production of vector bosons in association with jets are fundamental tests of perturbative quantum chromodynamics (pQCD). The W + jets processes also provide the main background to other, much rarer, standard model (SM) processes, such as $t\bar{t}$ [1] and single top-quark production [2], and to Higgs boson production and a variety of physics processes beyond the SM. Searches for phenomena beyond the SM are often limited by the uncertainty in the theoretical cross sections for W (and Z) + jets processes at high momentum scales and large jet multiplicities. Therefore, it is crucial to perform precision measurements of W + jets production at the LHC.

Leptonic decay modes of the vector boson are often used in the measurement of SM processes and in searches for new physics, because they provide clean signatures with relatively low background. This letter focuses on the production of a W boson decaying into a muon and a neutrino, as part of a final-state topology characterised by one high-transverse-momentum (p_T) isolated muon, significant missing transverse energy (E_T^{miss}), and one or more jets. The cross sections are measured as a function of the inclusive and exclusive jet multiplicities for up to six jets. Differential cross sections are measured for different inclusive jet multiplicities as a function of the transverse momentum and the pseudorapidity (η) of the jets, where $\eta = -\ln[\tan(\theta/2)]$, and θ is the polar angle measured with respect to the anticlockwise beam direction. The cross sections are also measured as a function of the difference in azimuthal angle between the direction of each jet and that of the muon, and of H_T, which is defined as the scalar sum of the p_T of all jets with $p_T > 30$ GeV and $|\eta| < 2.4$. It is important to study the distribution of the jet p_T and the observable H_T because they are sensitive to higher order corrections, and are often used to discriminate against background in searches for signatures of physics beyond the SM. Additionally, H_T is often used to set the scale of the hard scattering process in theoretical calculations. Finally, the η distributions of jets and the azimuthal separations between the jets and the muon are also important, because they are sensitive to the modelling of parton emission.

The measurements presented in this letter use proton–proton (pp) collision data at a centre-of-mass energy of $\sqrt{s} = 7$ TeV recorded with the CMS detector at the LHC in 2011 and correspond to an integrated luminosity of 5.0 ± 0.1 fb^{-1} [3]. These measurements cover high jet multiplicities and higher jet p_T than earlier

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publications because the centre-of-mass energy and the integrated luminosity are higher. Previous studies of leptonic decay modes of the W boson in association with jets at the LHC have measured the cross sections and cross section ratios for W boson production in association with jets in pp collisions with an integrated luminosity of 36 pb^{-1} at $\sqrt{s} = 7$ TeV with the ATLAS [4] and CMS [5] detectors. Measurements have also been made with $\text{p}\bar{\text{p}}$ collisions with the D0 detector [6,7] at the Tevatron collider for integrated luminosities up to 4.2 fb^{-1}, as well as with the CDF detector [8] for an integrated luminosity of 320 pb^{-1}. Recent measurements have been made with the ATLAS detector with a centre-of-mass energy of 7 TeV and an integrated luminosity of 4.6 fb^{-1} [9].

In order to perform a differential measurement of the W + jets cross section, a high-purity sample of $\text{W} \to \mu\nu$ events is selected and the kinematic distributions are corrected to the particle level by means of regularised unfolding [10]. This procedure corrects a measured observable for the effects of detector response, finite experimental resolutions, acceptance, and efficiencies, and therefore allows for direct comparison with theoretical predictions. The measured differential cross sections are compared to the predictions of generators such as MadGraph 5.1.1 [11] interfaced with pythia 6.426 [12], sherpa 1.4.0 [13–16], and BlackHat [17,18], interfaced to sherpa. The BlackHat + sherpa samples [19] provide parton-level predictions of W + n ($n = 1$–5) jets at next-to-leading order (NLO), while the MadGraph + pythia and sherpa samples provide tree-level calculations followed by hadronisation to produce the final states.

The letter proceeds as follows: Section 2 presents the CMS detector. Section 3 describes the Monte Carlo (MC) event generators, as well as the data samples used for the analysis. The identification criteria for the final-state objects (leptons and jets) and the selection of the $\text{W} \to \mu\nu$ + jets events are presented in Section 4. Section 5 describes the modelling of instrumental backgrounds and irreducible physics backgrounds. The procedure used for unfolding is detailed in Section 6, and Section 7 describes the systematic uncertainties. Finally, the unfolded distributions are presented in Section 8 and compared to theoretical predictions, and Section 9 summarises the results.

2. The CMS detector

The CMS detector, presented in detail elsewhere [20], can be described with a cylindrical coordinate system with the $+z$ axis directed along the anticlockwise beam axis. The detector consists of an inner tracking system and calorimeters (electromagnetic, ECAL, and hadron, HCAL) surrounded by a 3.8 T solenoid. The inner tracking system consists of a silicon pixel and strip tracker, providing the required granularity and precision for the reconstruction of vertices of charged particles in the range $0 \le \phi < 2\pi$ in azimuth and $|\eta| < 2.5$. The crystal ECAL and the brass/scintillator sampling HCAL are used to measure the energies of photons, electrons, and hadrons within $|\eta| < 3.0$. The HCAL, when combined with the ECAL, measures jets with a resolution $\Delta E/E \approx 100\%/\sqrt{E\,[\text{GeV}]} \oplus 5\%$ [21]. The three muon systems surrounding the solenoid cover a region $|\eta| < 2.4$ and are composed of drift tubes in the barrel region ($|\eta| < 1.2$), cathode strip chambers in the endcaps ($0.9 < |\eta| < 2.4$), and resistive-plate chambers in both the barrel region and the endcaps ($|\eta| < 1.6$). Events are recorded based on a trigger decision using information from the CMS detector subsystems. The first level (L1) of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than 4 µs. The high-level trigger (HLT) processor further decreases the event rate from 100 kHz at L1 to roughly 300 Hz.

3. Data and simulation samples

Events are retained if they pass a trigger requiring one isolated muon with $p_\text{T} > 24$ GeV and $|\eta| < 2.1$. Signal and background simulated samples are produced and fully reconstructed using a simulation of the CMS detector based on Geant4 [22], and simulated events are required to pass an emulation of the trigger requirements applied to the data. These simulations include multiple collisions in a single bunch crossing (pileup). To model the effect of pileup, minimum bias events generated in pythia are added to the simulated events, with the number of pileup events selected to match the pileup multiplicity distribution observed in data.

A $\text{W} \to \ell\nu$ + jets signal sample is generated with MadGraph 5.1.1 and is used to determine the detector response in the unfolding procedure described in Section 6. Parton showering and hadronisation of the MadGraph samples are performed with pythia 6.424 using the Z2 tune [23]. The detector response is also determined using a different W + jets event sample generated with sherpa 1.3.0 [13–16], and is used in the evaluation of systematic uncertainties due to the unfolding of the data.

The main sources of background are the production of $\text{t}\bar{\text{t}}$, single top-quark, Z/γ^* + jets, dibosons (ZZ/WZ/WW) + jets, and multijet production. With the exception of multijet production, all backgrounds are estimated from simulation. The simulated samples of $\text{t}\bar{\text{t}}$ and Z/γ^* + jets are generated with MadGraph 5.1.1; single top-quark samples (s-, t-, and tW-channels) are generated with powheg version 1.0 [24–27]; VV samples, where V represents either a W boson or a Z boson, are generated with pythia version 6.424 using the Z2 tune [23]. Parton showering and hadronisation of the MadGraph and powheg samples are performed with pythia 6.424. The simulations with MadGraph and pythia use the CTEQ6L1 parton distribution functions (PDF) [28]. The simulation with sherpa uses the CTEQ6.6m PDF, and the simulations with powheg use the CTEQ6m PDF.

The W + jets and Z/γ^* + jets samples are normalised to next-to-next-to-leading order (NNLO) inclusive cross sections calculated with fewz [29]. Single top-quark and VV samples are normalised to NLO inclusive cross sections calculated with mcfm [30–33]. The $\text{t}\bar{\text{t}}$ contribution is normalised to the NNLO + next-to-next-to-leading logarithm (NNLL) predicted cross section from Ref. [34].

4. Object identification and event selection

Muon candidates are reconstructed as tracks in the muon system that are matched to tracks reconstructed in the inner tracking system [35]. Muon candidates are required to have $p_\text{T} > 25$ GeV, and to be reconstructed within the fiducial volume used for the high-level trigger muon selection, i.e. within $|\eta| < 2.1$. This ensures that the offline event selection requirements are as stringent as the trigger. In addition, an isolation requirement is applied to the muon candidates by demanding that the relative isolation is less than 0.15, where the relative isolation is defined as the sum of the transverse energy deposited in the calorimeters (ECAL and HCAL) and of the p_T of charged particles measured with the tracker in a cone of $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.3$ around the muon candidate track (excluding this track), divided by the muon candidate p_T. To ensure a precise measurement of the transverse impact parameter of the muon track relative to the interaction point, only muon candidates with tracks containing more than 10 hits in the silicon tracker and at least one hit in the pixel detector are considered. To reject muons from cosmic rays, the transverse impact parameter of the muon candidate with respect to the primary vertex is required to be less than 2 mm.

Jets are reconstructed using the CMS particle-flow algorithm [36,37], using the anti-k_T [38,39] algorithm with a distance param-