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W boson production in association with jets at CMS

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Summary. — The production of a W boson in association with jets provides a stringent test of perturbative QCD and is a background process in searches for new physics. Differential cross section measurements of W bosons produced in association with jets and heavy flavor quarks in proton-proton collisions at center-of-mass energies of 8 TeV and 13 TeV in the CMS experiment at the LHC are presented. The measurements are compared to higher-order calculations and event simulations that devise matrix element calculations interfaced with parton showers.

1. – Introduction

Precision measurements of standard model (SM) processes are crucial for probing the fundamental structure of the electroweak (EW) and the strong interactions. W boson production in association with jets (W + jets) is an important SM benchmark and measurements of this process provide tests for perturbative quantum chromodynamics (pQCD) predictions to high precision. Small theoretical uncertainty on the production and small experimental uncertainty on the selection of W + jets processes enable to study higher-order perturbative effects and parton distribution functions (PDFs). Measurements of the W + jets processes are important for tuning Monte Carlo (MC) based event generators and theoretical calculations. Their measurements are also important for modeling backgrounds to rare SM productions such as Higgs boson and single top quark and to beyond the SM signatures such as supersymmetry and dark matter.

In the W + jets measurements, the W boson is reconstructed through its leptonic decays into a lepton and a neutrino ($W(l\nu), l = e, \mu$) and its production in association with jets is characterised with the measured differential cross sections as functions of numerous observables consisting mainly of jet kinematics and angular correlations. Measured W + jets distributions are unfolded to particle-level for detector effects and compared to the predictions from MC-based event generators and theoretical calculations.

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The predictions include leading-order (LO) and next-to-leading-order (NLO) matrix element (ME) calculations interfaced with parton showers, and NLO and next-to-next-to-leading-order (NNLO) fixed-order calculations, where available. In this report, the latest results of the W + jets measurements are reviewed based on 8 TeV and 13 TeV proton-proton (pp) collision data collected by the Compact Muon Solenoid (CMS) experiment [1] at the CERN Large Hadron Collider (LHC).

2. – W + jets at 8 TeV

The measurement of the differential cross sections for a $W(\mu\nu)$ boson in association with jets is presented based on a data sample corresponding to an integrated luminosity of 19.6 fb^{-1} recorded by the CMS detector at $\sqrt{s} = 8$ TeV [2]. The W + jets events are selected by the transverse momentum and pseudorapidity requirements of $p_T(\mu) > 25$ GeV and $|\eta(\mu)| < 2.1$ for the muon and of $p_T(\text{jets}) > 30$ GeV and $|\eta(\text{jets})| < 2.4$ for the jets. The W boson transverse mass selection of $m_T(W) > 50$ GeV is applied to discriminate against non-W final states such as QCD multijet events with a relatively low value of the $m_T(W)$ variable. The differential cross sections are measured as functions of several observables including the jet multiplicity and kinematics and the angular correlations between the jets and the muon. The measured differential cross sections are compared to the predictions from the event generators of tree-level MADGRAPH5_aMC@NLO [3] (+ PYTHIA 6 [4]) at LO accuracy, MADGRAPH5_aMC@NLO [5] (+ PYTHIA 8 [6]) at

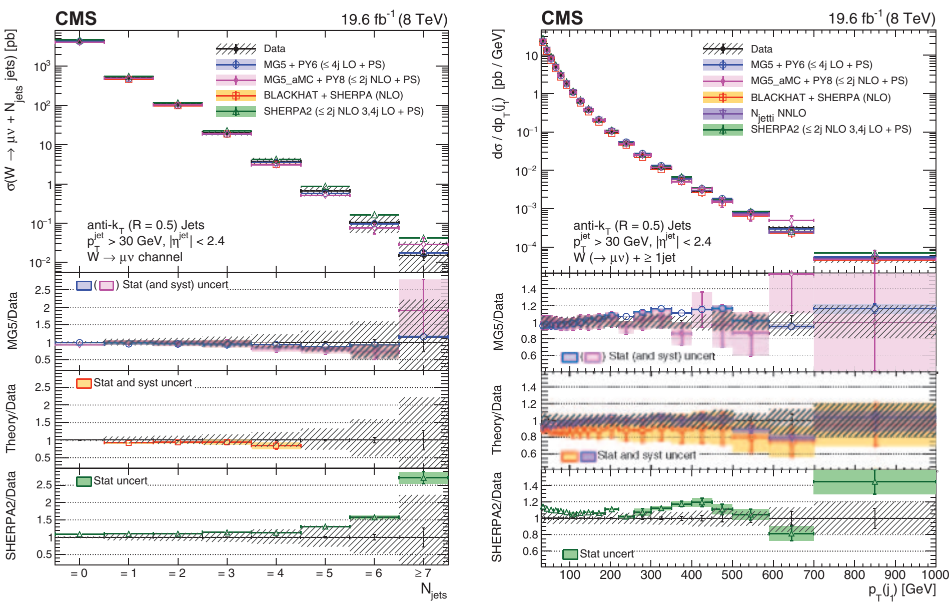

Fig. 1. – The W + jets differential cross sections measurement as functions of the jet multiplicity (left) and the leading jet p_T (right) [2]. The measured distributions are compared to several predictions including N_{jetti} NNLO for W boson and one jet production in the leading jet p_T distribution. Black circular markers with the grey hatched band represent the data measurement and its total experimental uncertainty. The colored filled bands around the predictions show either their statistical uncertainties or their statistical and systematic uncertainties added in quadrature.

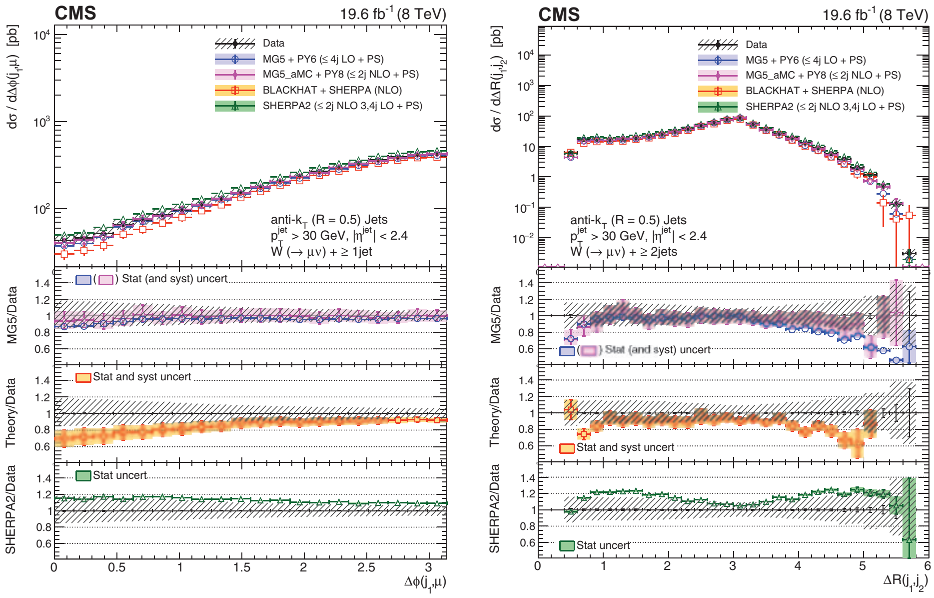

Fig. 2. – The W + jets differential cross sections measurement as functions of the $\Delta\phi(j_1, \mu)$ (left) and the $\Delta R(j_1, j_2)$ (right) [2]. Black circular markers with the grey hatched band represent the data measurement and its total experimental uncertainty. The colored filled bands around the predictions show either their statistical uncertainties or their statistical and systematic uncertainties added in quadrature.

NLO accuracy up to 2 additional partons merged using FxFx scheme [7], and SHERPA 2 [8] NLO (+ BLACKHAT [9,10]). The total cross section for MADGRAPH5_aMC@NLO LO is normalized to the inclusive NNLO cross section calculated with FEWZ 3.1 [11]. The measured cross sections are also compared to the fixed-order theoretical predictions provided by BLACKHAT + SHERPA [12] at NLO and by an NNLO calculation in pQCD using the N-jettiness subtraction scheme ($\mathrm{N_{jetti}}$) [13,14] for W boson and at least one jet production. Non-perturbative effects such as hadronization and multiple-parton interactions are accounted for the fixed-order calculations.

The measured differential cross sections as functions of the jet multiplicity up to seven jets and the leading jet p_{T} for at least one jet are compared to the predictions as shown in fig. 1. The MADGRAPH5_aMC@NLO LO and NLO FxFx predictions show good agreement with data within the experimental uncertainties over the entire ranges of the jet multiplicity and the leading jet p_{T}. The SHERPA 2 shows higher trend in describing data at higher jet multiplicities and in the leading jet p_{T} distribution. The $\mathrm{N_{jetti}}$ NNLO prediction is in good agreement with data in the leading jet p_{T} distribution. The differential cross sections are also measured as functions of the angular correlation variables that are sensitive to the modeling of higher order corrections and parton emissions. The best description of the W + jets data are provided by the MADGRAPH5_aMC@NLO FxFx prediction for the azimuthal separation between the leading jet and the muon ($\Delta\phi(j_1, \mu)$) and for the angular distance between the first leading jet and the second leading jet ($\Delta R(j_1, j_2)$) as shown in fig. 2. The BLACKHAT + SHERPA fixed-order NLO shows some deviations from data at low-$\Delta\phi(j_1, \mu)$ values. Sherpa 2 shows higher trend over almost the entire ranges of the $\Delta\phi(j_1, \mu)$ and $\Delta R(j_1, j_2)$ distributions.

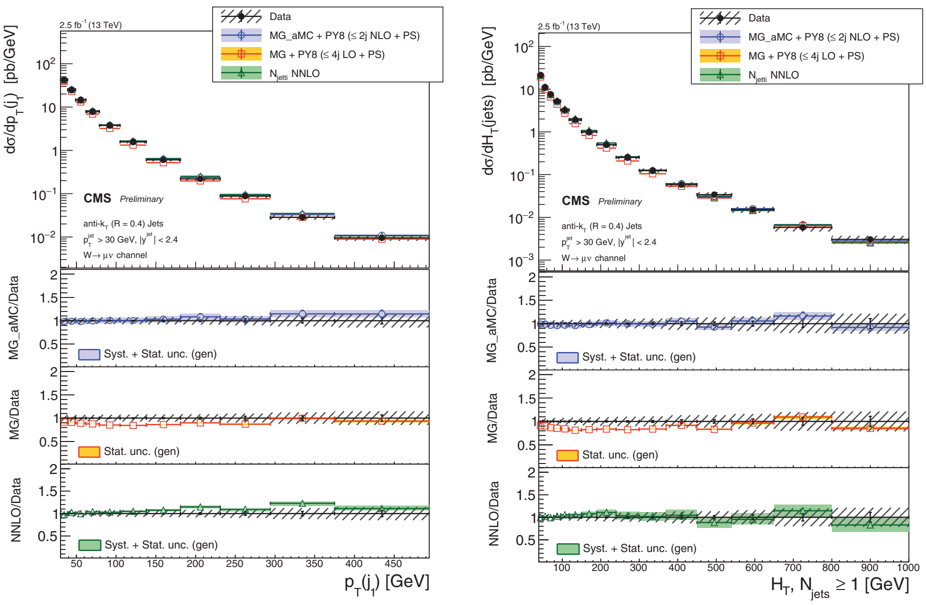

Fig. 3. – The W + jets differential cross sections measurement at 13 TeV as functions of the leading jet p_T (left) and the H_T variable (right) for one jet inclusive production [15]. Black circular markers with the grey hatched band represent the data measurement and its total experimental uncertainty. The colored filled bands around the predictions show either the statistical uncertainties or the statistical and the systematic uncertainties added in quadrature.

3. – W + jets at 13 TeV

The differential cross sections for a W ($\mu\nu$) boson in association with jets are measured from a data sample corresponding to an integrated luminosity of 2.5 fb^{-1} recorded by the CMS detector at $\sqrt{s} = 13$ TeV [15]. The analysed W + jets events are required to have a muon with $p_T(\mu) > 25$ GeV within $|\eta(\mu)| < 2.4$ and jets with $p_T(\text{jets}) > 30$ GeV inside the rapidity acceptance of $|y(\text{jets})| < 2.4$. The events are further required to be in the W boson transverse mass peak region, defined by $m_T(\text{W}) > 50$ GeV. The measured differential distributions are compared to predictions by the LO MADGRAPH5_aMC@NLO (+ PYTHIA 8), the merged NLO MADGRAPH5_aMC@NLO (+ PYTHIA 8) using the FxFx merging scheme, and the N_{jetti} NNLO calculation for W boson and one jet inclusive production. Total cross section for MADGRAPH5_aMC@NLO LO is normalized to the NNLO cross section computed with FEWZ 3.1. The first differential cross section results of the measurement based on 13 TeV data are given as functions of the leading jet p_T and the H_T variable, defined as the scalar sum of the jets p_T, for one jet inclusive production in fig. 3. The MADGRAPH5_aMC@NLO FxFx and the N_{jetti} NNLO predictions show remarkable agreement with data over the entire ranges of the leading jet p_T and the H_T distributions. The MADGRAPH5_aMC@NLO prediction at LO slightly underestimates data, generally at lower-p_T and -H_T regions. The tested event generators at 13 TeV with the W + jets data build confidence in their use for the simulation of W + jets background processes in searches for physics beyond the SM at the LHC.

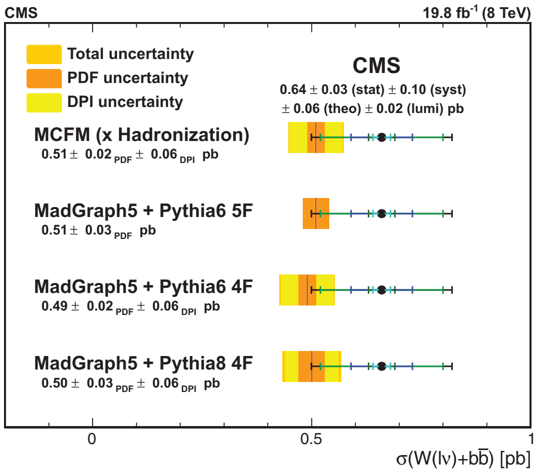

Fig. 4. – The comparison between the measured $W(l\nu)+b\bar{b}$ production cross section and the SM predictions [16]. The orange band indicates the uncertainty in the given prediction associated with PDF choice and the yellow band represents the uncertainty associated with douple-parton interaction (DPI). The effects of DPI are already included in MADGRAPH5 + PYTHIA 6 using 5FS approach, so the DPI correction is not needed for this prediction. The measured cross section is also shown with the total uncertainty in black and the luminosity, statistical, theoretical, and systematic uncertainties as indicated.

4. – W + 2 b jets at 8 TeV

The production cross section of the W boson in association with exactly two b jets ($W(l\nu) + b\bar{b}, l = e, \mu$) is measured using a data sample with an integrated luminosity of 19.8 fb^{-1}, collected by the CMS experiment at $\sqrt{s} = 8$ TeV [16]. The W $+ b\bar{b}$ process is a background for the SM Higgs boson production in association with a vector boson, where the Higgs boson decays into two b jets. The $W+b\bar{b}$ events in this measurement are required to have leptons with $p_T(l) > 30$ GeV and $|\eta(l)| < 2.1$ and exactly two b-tagged jets with $p_T(b) > 25$ GeV and $|\eta(b)| < 2.4$ in the signal region. The $W+b\bar{b}$ signal yields are extracted using a likelihood fit to the $m_T(W)$ distribution. The measured production cross section for this process in the combined lepton channel, $\sigma(pp \rightarrow W(l\nu) + b\bar{b}) = 0.64 \pm 0.03(\text{stat.}) \pm 0.10(\text{syst.}) \pm 0.06(\text{theo.}) \pm 0.02(\text{lumi.})$ pb, is compared to theoretical predictions of MADGRAPH5_aMC@NLO at LO (+ PYTHIA 6) using both 4 and 5 flavor number schemes (FSs), MADGRAPH5_aMC@NLO at LO (+ PYTHIA 8) using 4FS, and MCFM [17, 18] NLO. The SM predictions agree with each other and are in agreement with the measured cross section within their uncertainties as shown in fig. 4. The measurement provides an important test of pQCD with heavy flavors and its results are sensitive to the b quark content of the PDFs based on the comparison between 4FS and 5FS approaches.

5. – EW production of W + 2 jets at 8 TeV

The EW production of a W boson in association with two jets plays an important role in testing the gauge sector of the SM, particularly the aspects of gauge boson self-interactions. These processes can be used as a probe of triple-gauge-boson couplings

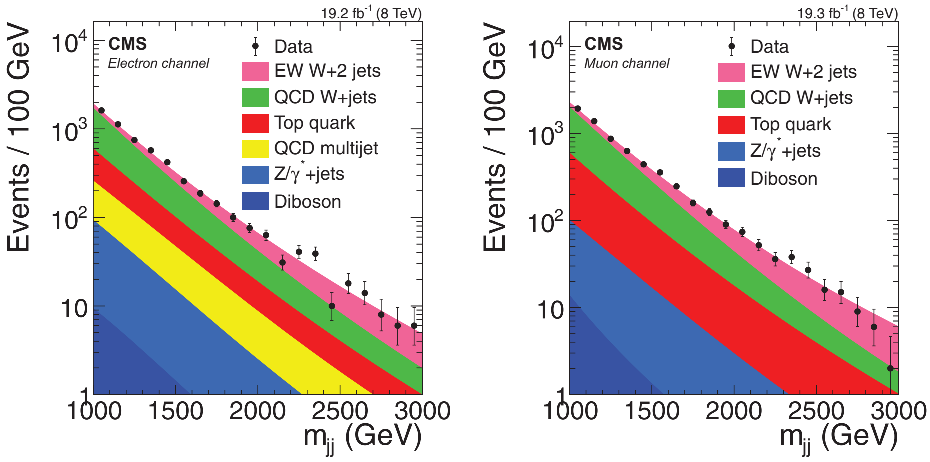

Fig. 5. – The observed m_{jj} distributions for the fitted projections of the contribution of the EW W + 2 jets signal events and background processes in electron (left) and muon (right) decay channels [19].

and constitute a background to Higgs boson measurements in the vector boson fusion (VBF) channel. The cross section for the EW production of a W boson in association with two forward jets is measured by the CMS experiment at a center-of-mass energy of $\sqrt{s} = 8\,\mathrm{TeV}$ [19]. The data set used corresponds to an integrated luminosity of 19.3 fb^{-1}. The fiducial cross section is measured for W bosons decaying into electrons (muons) with p_{T} greater than 30 (25) GeV and $|\eta| < 2.5$ (2.1). Events are required to have at least two jets with $p_{\mathrm{T}}(\mathrm{j}_1) > 60\,\mathrm{GeV}$ and $p_{\mathrm{T}}(\mathrm{j}_2) > 50\,\mathrm{GeV}$ that are well-separated in $|y| < 4.7$ with the large invariant mass of the jet pair of $m_{\mathrm{jj}} > 1\,\mathrm{TeV}$. A boosted decision tree (BDT) method is used to separate between signal events and background events with largest contribution from QCD W + jets processes. An unbinned maximum-likelihood fit to the m_{jj} distributions as shown in fig. 5 is used to extract the number of signal events. The measured cross section for the EW W + 2 jets production, $\sigma = 0.42 \pm 0.04(\mathrm{stat.}) \pm 0.09(\mathrm{syst.}) \pm 0.01(\mathrm{lumi.})\,\mathrm{pb}$, is consistent with the SM LO prediction of $\sigma_{\mathrm{SMLO}} = 0.50 \pm 0.02(\mathrm{scale}) \pm 0.02(\mathrm{PDF})\,\mathrm{pb}$ obtained for the same process with MADGRAPH5_aMC@NLO interfaced to PYTHIA 6.

6. – Conclusion

The CMS Collaboration has explored W boson production in association with jets including heavy flavor jets in the most relevant areas and provided unique precision tests for pQCD effects using 8 TeV and 13 TeV pp collision data at the LHC. The W + jets differential cross sections are measured over several orders of magnitude as functions of several observables probing wider kinematic regimes. The measured cross sections are compared to the predictions from LO and NLO ME event generators interfaced to parton showers, and NLO and NNLO fixed-order theoretical calculations. The measured W + jets differential cross sections as functions of the observables including the jet multiplicity, the jet kinematics, and the angular correlation variables are generally well modeled by the predictions. The predictions from the MADGRAPH5_aMC@NLO at NLO accuracy using the FxFx merging scheme and the $\mathrm{N_{jetti}}$ NNLO calculation provide the best descriptions of the W + jets data in the measured distributions, where the NNLO calculation is available for W boson and one jet inclusive production. The W + $b\bar{b}$ production is sensitive to the b quark structure of the proton and the measured production cross section for this process is in agreement with the SM predictions using two different FS approaches. The study of the EW W + 2 forward jets is important for investigating more into the SM VBF processes. The measured fiducial cross section for the EW W + 2 jets processes are in agreement with the SM LO prediction. Finally, the CMS experiment aims for many more new results on the production of W boson and jets including heavy flavor jets to provide more accurate description of data and to probe unprecedented kinematic regimes.

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