VECTOR-BOSON PRODUCTION IN ASSOCIATION WITH JETS AT ATLAS AND CMS (INCLUDING HEAVY FLAVOUR JETS)*

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Vector-boson production in association with jets is among the Standard Model processes leaving the clearest signatures in high-energy physics experiments. The latest results on $W/Z+$jets measurements from the ATLAS and CMS experiments at the LHC are presented. Particular attention is given to how these measurements can be used to extract relevant electroweak and QCD parameters, and also be re-interpreted to set limits on exotic models.

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1. Introduction

Vector-boson production is one of the most fundamental processes in particle physics and plays a crucial role in the Standard Model. These processes constitute relevant backgrounds in many particle physics analyses, covering both searches for exotic phenomena, Higgs boson physics measurements and Standard Model measurements, motivating the need for a high-precision estimate of their cross sections. They also enable us to determine QCD parameters and to probe the quark structure of the proton. The high-precision study of these processes additionally allows us to test the accuracy of Monte Carlo event generators, including matrix element, parton shower, and parton distribution functions (PDFs) setups. These proceedings present the latest $W/Z+$jets production cross-sections measurements, performed by the

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ATLAS and CMS experiments [1, 2] at the LHC [3]. The measurements are obtained using the respective experimental pp collisions datasets of 140 fb^{-1} (ATLAS) and 138 fb^{-1} (CMS), recorded with a centre-of-mass energy of $\sqrt{s} = 13$ TeV.

2. Measurement of $W + c$ production cross sections

The associated production of a W boson with a charm quark ($W + c$) in proton–proton (pp) collisions at the LHC can effectively be used as a probe to study the s-quark content of the proton. This sensitivity originates from the dominance of the $s + g \to W + c$ leading diagram over the Cabibbo-suppressed $d + g \to W + c$ process.

2.1. CMS experiment measurements

The CMS Collaboration has measured the integral and differential cross sections of the W boson production in association with a c-quark [4]. Events have been selected requiring one electron or one muon, originating from the W boson decay and a c-jet. Charm jets have been tagged via the presence of a muon or a secondary vertex inside the jet.

The combined measured fiducial cross section is

$$\sigma(W + c) = 148.7 \pm 0.4(\text{stat.}) \pm 5.6(\text{syst.})\ \text{pb} \tag{1}$$

as also shown in Fig. 1. The measurement is optimally described by the MadGraph5_aMC@NLO+Pythia8 prediction with the choice of the NLO NNPDF3.0 PDFs and the CUETP8M1 tune. Additionally, a measurement of the cross-section ratio

$$R_c^{\pm} = \frac{\sigma(pp \to W^+ + \bar{c})}{\sigma(pp \to W^- + c)} \tag{2}$$

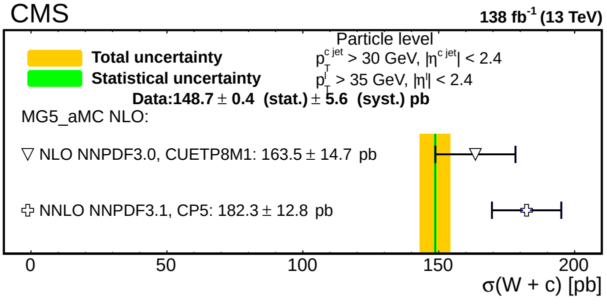


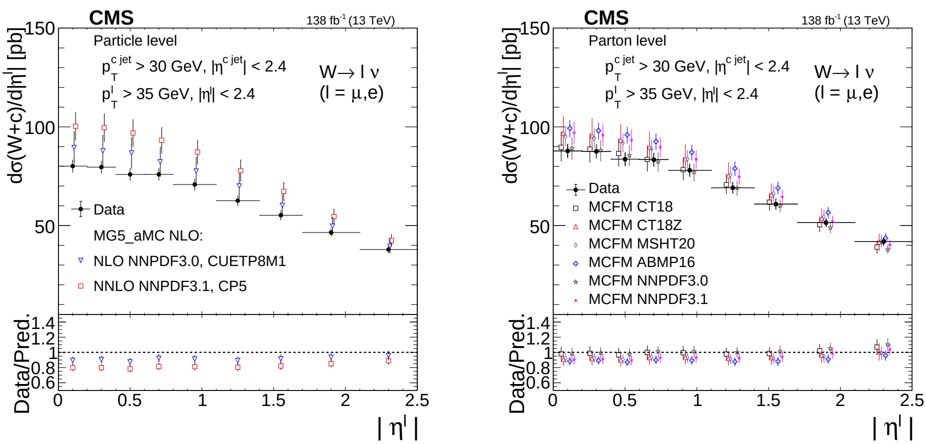
Fig. 1. Measurement of the $W + c$ integral fiducial cross section, compared with the MadGraph5_aMC@NLO prediction using different PDFs sets [4].

has been provided, resulting in

$$R_c^{\pm} = 0.950 \pm 0.005(\text{stat.}) \pm 0.010(\text{syst.}), \tag{3}$$

and has been compared with several predictions obtained assuming different models for the $s\bar{s}$ quark content of the proton.

The integral cross-section measurement has been complemented with differential cross-section measurements, as functions of the transverse momentum and the pseudo-rapidity of the lepton originating from the W-boson decay (see Fig. 2). Both the particle-level and the parton-level unfolding procedures have been exploited, the latter consisting in an additional correction accounting for the c-quark fragmentation and hadronisation process, and yielding better agreement with data.



(a) (b)

Fig. 2. Differential cross sections for the $W+c$ production in bins of pseudo-rapidity of the light lepton originating from the W boson: (a) unfolded to the particle level and (b) unfolded to the parton level [4].

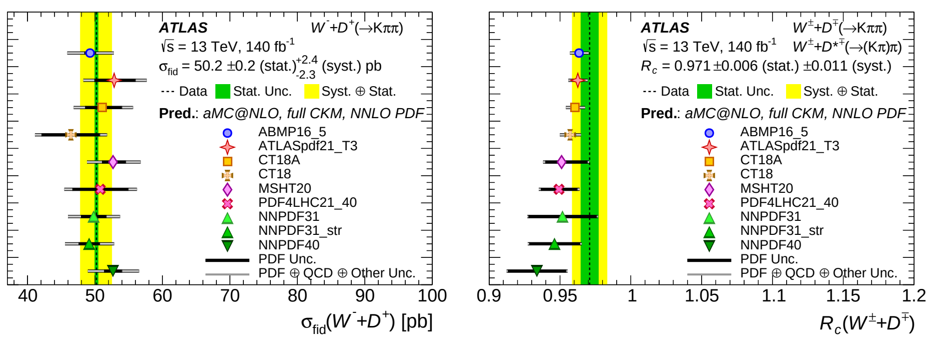
2.2. *ATLAS experiment measurements*

A similar study of the $W + c$ process has been published by the ATLAS Collaboration [5]. In this case, the charm quark has been tagged via the direct detection of a charmed hadron, through a secondary vertex fit. The W boson, instead, has similarly been reconstructed via the presence of an electron or a muon, and missing transverse momentum in the final state. Four reconstructed charmed mesons are considered, specifically: $D^+ \to K^-\pi^+\pi^+$, $D^{*+} \to D^0\pi^+ \to (K^-\pi^+)\pi^+$, and their charge conjugate decays.

Figure 3 (a) shows the measured fiducial cross section for final states involving $W^- + D^+$, which resulted

$$\sigma_{\text{fid}}(W^- + D^+) = 50.2 \pm 0.2(\text{stat.})^{+2.4}_{-2.3}(\text{syst.})\ \text{pb}\,, \tag{4}$$

and has been compared with aMC@NLO+Pythia8 predictions with several PDF choices, all showing agreement within their uncertainty. Similar measurements and predictions have been obtained for the cross sections of the other decay modes: $\sigma_{\text{fid}}(W^+ + D^-)$, $\sigma_{\text{fid}}(W^- + D^{*+})$, $\sigma_{\text{fid}}(W^+ + D^{*-})$. Additionally, the ratio of charm-to-anti-charm production cross sections $R_c^{\pm}$ has been studied, as shown in Fig. 3 (b). In this case, the predictions using PDFs allowing $s\bar{s}$ asymmetry (MSHT20, PDF4LHC21, NNPDF) are showing tension with respect to the measured value, meaning that the $s\bar{s}$ symmetric scenario is preferred.



(a) (b)

Fig. 3. Observables measured in final states involving W boson in association with a c-hadron: (a) fiducial cross section for the $W^- + D^+$ final state, (b) fiducial cross-section ratio $R_c^{\pm}$ [5].

3. Measurements of $Z + b, c$ production cross sections

The production of a Z boson associated with heavy-flavour quarks — namely b-quarks and c-quarks — in pp collisions is among the processes most commonly involved in the background events of many Higgs boson measurements or searches for new physics. The cross-section measurement for these processes constitutes therefore an important benchmark to test the accuracy of the Monte Carlo generators to be used in such analyses, and also provides tests of perturbative quantum chromodynamics (pQCD) and of the proton internal structure.

3.1. ATLAS experiment measurements

The ATLAS Collaboration has measured integral and differential production cross sections of events containing a Z boson decaying into electrons or muons and produced in association with b- or c-jets [6].

Events have been categorised according to the associated jets multiplicity as $Z+ \geq 1\,b$-jets, $Z+ \geq 2\,b$-jets, $Z+ \geq 1\,c$-jets, and separate measurements have been performed corresponding to these categories (see Fig. 4). The $Z+ \geq 1\,b$-jets and $Z+ \geq 2\,b$-jets fiducial cross sections resulted optimally described by MadGraph5_aMC@NLO+Pythia8 with the choice of the 5-flavour scheme (FS). Instead, the $Z+ \geq 1\,c$-jets cross section resulted optimally described by MadGraph5_aMC@NLO+Pythia8 with the 4-FS.

Some of the presented differential cross-section measurements have been optimised in bins of variables sensible to the possible presence of a valence-like charm quark in the proton (*intrinsic charm*). Data have been compared to predictions with PDFs choices testing different intrinsic charm hypotheses, without observing a significant evidence for its presence.

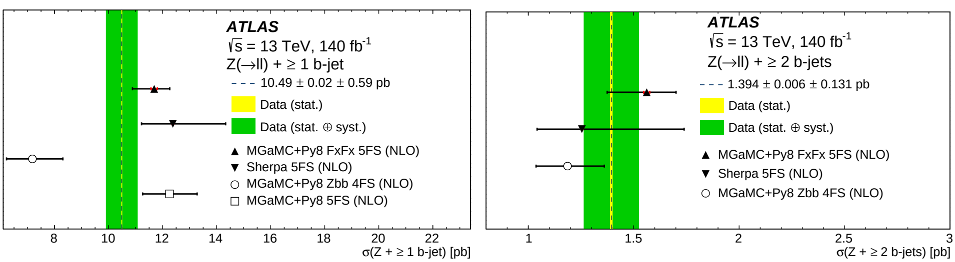


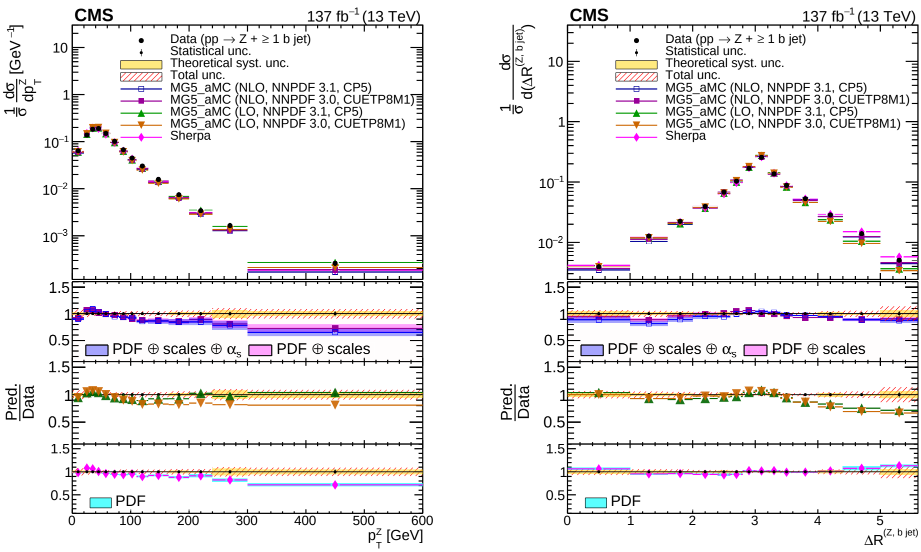
Fig. 4. Measured fiducial cross sections for (a) $Z+ \geq 1\,b$-jets, (b) $Z+ \geq 2\,b$-jets, compared to Monte Carlo predictions with the relative flavour schemes [6].

3.2. CMS experiment measurements

The integral and differential cross sections of the $Z + b$-jets production have been measured also by the CMS experiment and reported in Ref. [7]. Similarly to the ATLAS Collaboration measurement, events are categorised according to the multiplicity of b-jets associated with the Z-boson productions: $Z+ \geq 1\,b$-jets, $Z+ \geq 2\,b$-jets and considering decays of the Z into electrons and muons. The measured fiducial integral cross sections are:

$$\begin{aligned}\sigma(Z \geq 1b\text{-jets}) &= 6.52 \pm 0.04(\text{stat.}) \pm 0.40(\text{syst.}) \pm 0.14(\text{theo.})\ \text{pb}\,,\\ \sigma(Z \geq 2b\text{-jets}) &= 0.65 \pm 0.03(\text{stat.}) \pm 0.07(\text{syst.}) \pm 0.02(\text{theo.})\ \text{pb}\,. \quad (5)\end{aligned}$$

Normalised cross sections are measured in bins of several kinematic variables and are used to test the accuracy of the corresponding Monte Carlo predictions. Two exemplary variables are reported in Fig. 5 where the cross sections are differentiated in bins of vector-boson transverse momentum p_{T}^{Z}, and angular separation between the vector boson and the leading b-jet $\Delta R^{(Z,b-\mathrm{jet})}$. The differential spectrum in p_{T}^{Z} is best described by the MadGraph5_aMC@LO generator, which however is yielding slight mismodelling at high values of $\Delta R^{(Z,b-\mathrm{jet})}$, thus showing the complexity of the modelling of angular variables.



(a) (b)

Fig. 5. Normalised differential cross-sections measurements for the $Z+\geq 1\,b$-jets production in bins of (a) vector boson transverse momentum, (b) angular separation between the vector boson and the leading b-jet [7].

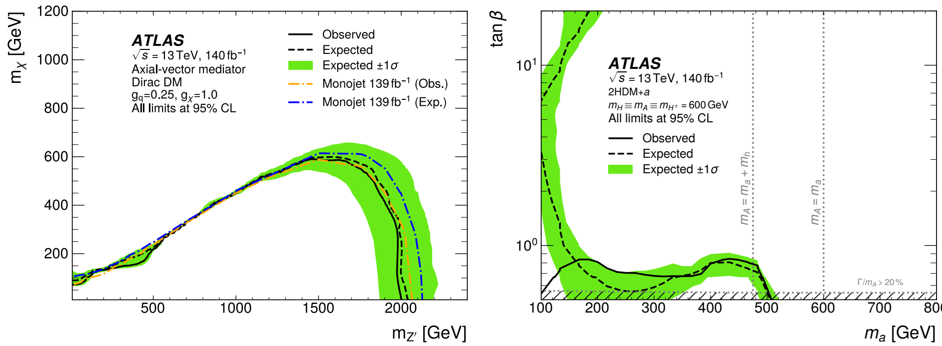
4. Other vector bosons in association with jets measurements

4.1. Measurement of p_T^{miss} + jets production cross sections with the ATLAS experiment

The ATLAS Collaboration has also published a measurement of inclusive and differential cross sections for the production of events with missing transverse momentum in association with jets [8]. The measurement includes the determination of di-jet distributions in a region in which vector boson fusion processes are enhanced. Additionally, measurements of the $Z \to \nu\nu$ process are provided.

Ratios between the measured $p_{\mathrm{T}}^{\mathrm{miss}}$+jets cross-section distributions are derived, to take advantage of the cancellations in modelling effects and some major systematic uncertainties, and are used to constraint new physics phenomenological models involving dark matter particles.

One common benchmark for dark matter involves extending the Standard Model with an additional U(1) symmetry group, associated with a Z' vector boson, and involving dark matter Dirac fermions χ [9]. Figure 6 (a) shows a recasted contour in the $m_{Z'}$–m_{χ} plane, yielding an exclusion competitive with the previous dedicated detector-level ATLAS search [10]. Additionally, the 2HDM+a model [11] has been studied, involving two Higgs doublets along with a pseudoscalar a which couples to dark matter. Figure 6 (b) shows the exclusion obtained for this model, in the plane (m_a, $\tan\beta$), where m_a is the mass of the pseudoscalar and $\tan\beta = v_2/v_1$ is the ratio of the vacuum expectation values of the two Higgs fields.



(a) (b)

Fig. 6. Exclusion limits at 95%, obtained recasting the $p_{\mathrm{T}}^{\mathrm{miss}}$+jets cross-sections measurements for: (a) a simplified model involving a dark matter Dirac fermion χ, (b) the 2HDM+a model [8].

4.2. Measurement of the $W \to cq/W \to q\bar{q}'$ branching fraction ratio with the CMS experiment

Vector-boson production can also be exploited to perform flavour physics measurements. The CMS Collaboration has recently published a measurement of the W-boson hadronic decay branching fraction ratio $R_c^W = \mathcal{B}(W \to cq)/\mathcal{B}(W \to q\bar{q}')$ [12]. The measurement enabled to derive the sum of squared elements in the second row of the Cabibbo–Kobayashi–Maskawa matrix, 0.970 ± 0.041, and the element $|V_{cs}| = 0.959 \pm 0.021$.

5. Conclusions

These proceedings summarised the most recent measurements of vector-boson production in association with jets, obtained by the ATLAS and CMS collaborations at the Large Hadron Collider. Several analysis strategies have been described, evidencing how these measurements can be used to extract electroweak and QCD parameters, and can also be exploited to draw exclusion limits on exotic new physics models.

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