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# Measurements of $W$ and $Z$ boson production in association with jets in ATLAS

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The production of $W$ and $Z$ bosons in association with light or heavy flavour jets at the LHC is sensitive to the flavour content of the proton and provides an important test of perturbative QCD. In this contribution, measurements by the ATLAS experiment probing the charm and beauty content of the proton are presented. Inclusive and differential cross-sections of $Z$-boson production with at least one $c$-jet, or one or two $b$-jets are measured for events in which the $Z$-boson decays into a pair of electrons or muons. Predictions from several Monte Carlo generators based on next-to-leading-order matrix elements interfaced with a parton-shower simulation, with different choices of flavour schemes for initial-state partons, are compared with the measured cross-sections. Moreover, measurements of inclusive, differential cross-sections for the production of missing transverse momentum plus jets are presented. The measurements are designed both to allow comparison to Standard Model predictions, and to be sensitive to potential extensions to the Standard Model, particularly those involving the production of Dark Matter particles.

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## 1. Introduction

In the Run-2, the Large Hadron Collider (LHC) [1] collided protons at the centre-of-mass energy $\sqrt{s}$ = 13 TeV. The dataset from $pp$ collisions by the LHC Run-2 is the largest available for physics, corresponding to an integrate luminosity $\mathcal{L}$ = 140 fb$^{-1}$, as recorded by the ATLAS Experiment [2].

The large dataset allows not only to increase the sensitivity to rare events and explore extreme corners of the phase-space, but also to perform high precision measurements of the Standard Model (SM) processes, necessary to test theoretical predictions and indirectly probe the sensitivity to new physics. Among the SM, the vector boson $V$ ($V$= $W$, $Z$) production in association with jets ($V$+jets) stands out for the clear signature and the abundant statistics. The $V$+jets events represent perfect candidates for studying perturbative quantum chromodynamics (QCD) and the internal structure of the proton. In particular, $V$+jets measurements allow the testing of the state-of-the-art theoretical predictions, by comparing the measurements with several models and different accuracies in perturbative QCD. Moreover, $V$+jets production provides valuable information for the determination of parton distribution functions (PDFs), which describes the momentum distribution of quarks and gluons in the protons. Finally, $V$+jets processes are significant background to many searches for new physics and measurements of rare processes. A precise modelling of the background is essential to correctly isolate the processes under study.

This contribution presents recent ATLAS results on $V$+jets production, based on full Run-2 dataset: the measurement of events with missing transverse momentum and jets is described in Section 2; the associated production of the $Z$-boson with $b$- and $c$-jets is presented in Section 3. Conclusions are drawn in Section 4.

## 2. Differential cross-sections of events with missing transverse momentum and jets

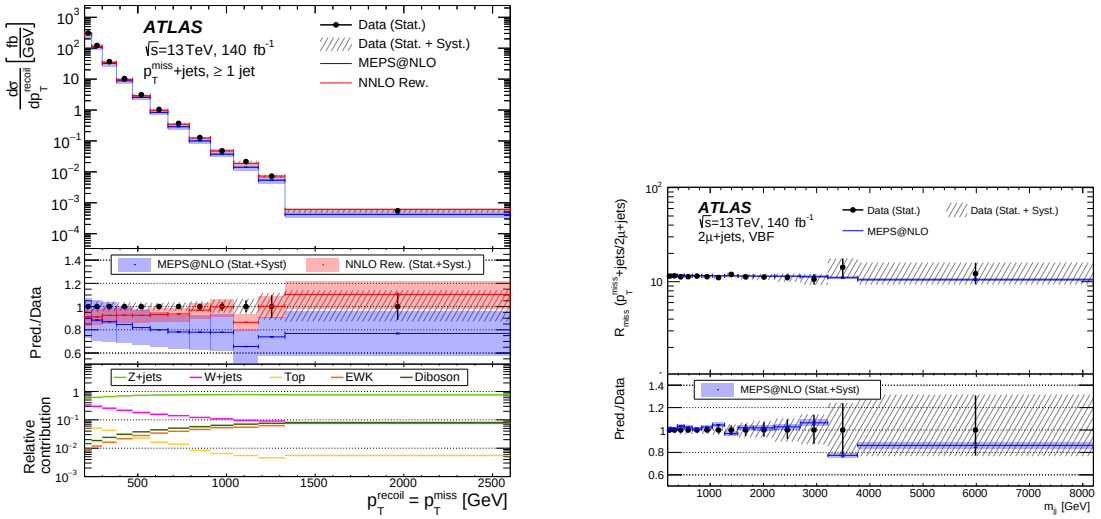
Many Beyond Standard Model (BSM) theories predict a non-interacting Dark Matter (DM) particle which gives rise to large missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$) and jets in the final state. The measurement of events with $p_{\mathrm{T}}^{\mathrm{miss}}$ and jets is designed to have minimal model dependence in the final result. The analysis is final-state-driven, being defined in a way that all SM processes contributing to the final state are considered as signal and measured simultaneously. The study is performed in the inclusive jet and in the di-jets signal regions, where the vector-boson fusion processes are enhanced (VBF-like).

The differential cross-section as a function of $p_{\mathrm{T}}^{\mathrm{miss}}$ in the inclusive jet signal region is shown in Fig.1. The SM contributions to the $p_{\mathrm{T}}^{\mathrm{miss}}$+jets final state are shown. The dominant process comes from $Z$+jets with the $Z$-boson decaying into neutrinos.

In the same phase-space, the measurement of the SM $Z$+jets production with $Z(\rightarrow \nu\nu)$ is performed [3]. In this analysis, all background processes are subtracted from data before correcting to particle level with the iterative Bayesian unfolding. Several auxiliary measurements of the hadronic system recoiling against leptons and photons are also made. The ratios between cross-sections of $p_{\mathrm{T}}^{\mathrm{miss}}$+jets final state and auxiliary measurements are derived. Fig.1 presents the ratio of the $p_{\mathrm{T}}^{\mathrm{miss}}$+jets and the $Z(\rightarrow \mu\mu)$+2 jets cross-sections in the VBF-like signal region as a function of the invariant mass of the two most energetic jets ($m_{\mathrm{jj}}$). It is quite noticeable the reduction of

the dominant experimental uncertainties in this ratio; in addition, the poor modelling of the $m_{\mathrm{jj}}$ measured distribution is reduced [3].

The results are reasonably described by the SM predictions, as confirmed by the quantitative $\chi^2$-study presented in Ref. [3]. The $p_{\mathrm{T}}^{\mathrm{miss}}$+jets measurements are reinterpreted in BSM scenarios with DM candidates, which could enhance the $p_{\mathrm{T}}^{\mathrm{miss}}$ spectrum. The limits obtained on a simplified DM model are consistent with a previously published ATLAS search analysis [4]. This demonstrates that particle level measurements can be used for future interpretations, compensating a small loss in sensitivity with respect to direct searches, with the advantage of avoiding repeating complex detector simulations.




**(a)** **(b)**

**Figure 1:** (a) The differential cross-section measurement of $p_{\mathrm{T}}^{\mathrm{miss}}$+jets production in the inclusive jet signal region. The middle pannel shows the ratio of predictions to data and the lower panel summarises the relative contributions from different SM processes. (b) The ratio of $p_{\mathrm{T}}^{\mathrm{miss}}$+jets and $Z(\rightarrow \mu\mu)$+2 jets cross-sections as a function of the invariant mass of the two most energetic jets ($m_{\mathrm{jj}}$) in the VBF-like signal region. [3]

## 3. Differential cross-sections measurements of $Z$-boson production in association with $b$ and $c$-jets

The measurements of the $Z$-boson production in association with heavy flavour jets ($Z$+HF), namely jets originating from the hadronisation of $b$- and $c$-quarks, provide a fundamental test of perturbative QCD, probing the effect of missing higher-order terms in the theoretical predictions. The $Z$+HF processes are sensitive to the different theoretical approximations ("Flavour-Schemes" (FS)) used in the matrix-element (ME) of the calculations, which are related to the treatment of the $b$- and $c$-quark masses and thresholds. For example, the $Z$+$b$-jets measurement is sensitive to the difference between 4FS and 5FS: in the former, $b$-quarks do not contribute to the proton wave function and do not enter in the PDF evolution, while in the latter, $b$-quark density is allowed in the initial state by a $b$-quark PDF. Furthermore, $Z$+HF production provides unique assess to $b$-

and $c$-quark PDFs: in particular $Z$+$c$-jets processes allow the exploration of the sensitivity to the intrinsic charm (IC) component in the proton. The hypothesis under which $c$-quark pairs contribute to the proton structure ("intrinsic") was postulated nearly 40 years ago and has never been confirmed experimentally [5].

While $Z$+$b$-jets production has already been measured by ATLAS [6], this is the first ATLAS measurement of $Z$+$c$-jets processes. The measurement is designed to extract simultaneously $Z$+$b$-jets and $Z$+$c$-jets differential cross-sections. For this purpose, $Z$+jets events, with the $Z$-boson decaying into electron or muon pairs, are selected only if the jets pass a flavour tagging algorithm with 85% efficiency on $b$-jets, retaining ~35% of $c$-jets. The large background contamination from $t\bar{t}$ events is determined with a data-driven method in a $e\mu$ control region. The dominant background is given by $Z$+jets events where the jet has a flavour different from the one the analysis aims to measure. To correctly determine the fraction of $b$-, $c$- and light-jets, a likelihood fit of the flavour-tagging algorithm score ("flavour-fit") is performed [7]. Since the flavour-fit is applied in each bin of every measured observable, the modelling of the $Z$+jets flavour composition is also corrected.

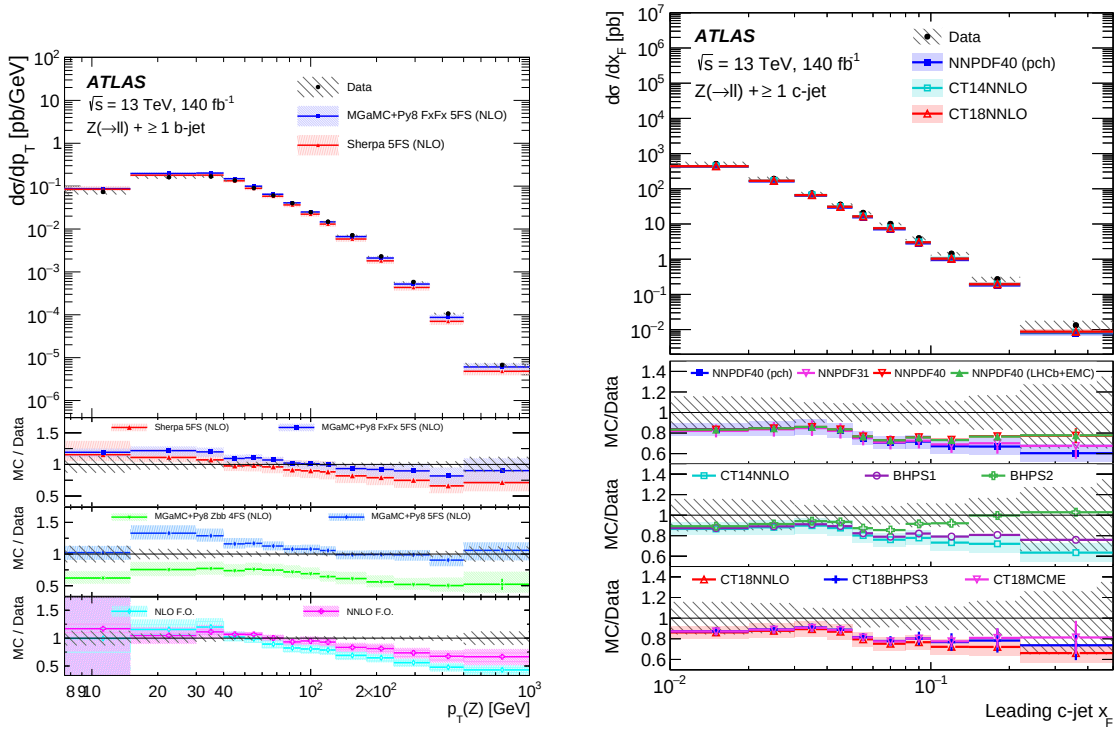



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**Figure 2:** (a) Differential cross-section for $Z$+≥1 b-jet production as a function of the $Z$-boson $p_{\mathrm{T}}$. The data are compared with several Monte Carlo generators with different FS and to fixed-order calculations. (b) Differential cross-section for $Z$+≥1 c-jet production as a function of the leading c-jet $x_{\mathrm{F}}$. The data are compared with the nominal MGaMC+Py8 FxFxprediction and with those obtained by reweighting to PDFs testing several IC models. [7].

The background-subtracted data are corrected to particle level with the iterative Bayesian unfolding and compared with several theoretical predictions. The $Z$+≥1 b-jet and $Z$+≥2 b-jets

inclusive cross-section measurements are in agreement with the previous ATLAS results based on the 36 fb$^{-1}$ dataset [6], with an improved precision of 5.6% and 9.4%, respectively. The $Z$+≥1 c-jet inclusive cross-section has a total systematic uncertainty of 13.2%.

Fig.2a presents the differential cross-section for $Z$+≥1 b-jet events as a function of the $Z$-boson $p_{\mathrm{T}}$. The state-of-the-art MGaMC+Py8 FxFx and Sherpa 2.2.11 5FS NLO Monte Carlo (MC) calculations provide the best agreement with the data. The MGaMC+Py8 4FS NLO prediction underestimates the measured cross-section in the entire spectrum, due to the lack of resummation of the logarithmic terms. The effect of missing higher-order terms in the QCD expansion arises when comparing the data to the fixed-order predictions: the NNLO calculation gives a better description of the measurement than the NLO prediction, but still it cannot describe the whole $p_{\mathrm{T}}$ spectrum. The large uncertainty on the fixed-order predictions is dominated by the uncertainty on a correction applied to compensate for the different jet flavour definitions used in the measurement and in the calculations. Since the QCD scale uncertainty is small, this indicates the importance of using infrared- and collinear-safe jet flavour definitions in future precision measurements.

Differential cross-section results for $Z$+≥1 c-jet processes are compared with various IC models, obtained by reweighting the nominal MGaMC+Py8 FxFx MC generator to different PDF sets [7]. Fig.2b presents the $Z$+≥1 c-jet measured cross-section as a function of the Feynman variable $x_{\mathrm{F}}$ ($x_{\mathrm{F}}$= 2 | $p_z^{c-\mathrm{jet}}$ | /$\sqrt{s}$) of the leading $c$-jet. The BHPS2 model, which predicts that a large fraction of proton momentum is carried by IC (2.6%), provides the best description of the data. However, for more realistic scenarios, such as the IC PDFs from the NNPDF and CT18 families, the improvement of adding the IC component is still marginal and no significant difference in the modelling among various PDF was found.

## 4. Conclusions

In this contribution, the most recent ATLAS results on $V$+jets from $pp$ collision at $\sqrt{s}$ = 13 TeV are presented. The measurement of events with missing transverse momentum and jets, designed to be sensitive to BSM phenomena, provides results highly reinterpretable in many BSM searches. The measurements of $Z$+≥1 b-jet, $Z$+≥2 b-jets and $Z$+≥1 c-jet production cross-sections provide essential inputs for the improvements of theoretical predictions and Monte Carlo modelling, allowing a better quantitative understanding of perturbative QCD and the proton structure. The first $Z$+≥1 c-jet ATLAS result is provided and compared with several models of the IC component in the proton.

## References

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