IL NUOVO CIMENTO **48 C** (2025) 79
DOI 10.1393/ncc/i2025-25079-0

Colloquia: IFAE 2024

Measurement of the production cross-section of a Z boson in association with b- and c-jets(*)

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received 2 December 2024

Summary. — The recently published measurement of the production cross-section of a Z boson in association with heavy flavor jets, *i.e.*, b- or c-jets, at the ATLAS experiment is presented using 140 fb^{-1} of proton-proton collision data from the Run 2 of the Large Hadron Collider. This proceeding discusses inclusive and differential cross-section measurements in two signal regions, $Z + 1$ b- or c-jet and $Z + 2$ b-jets. The measurements are compared with predictions from different Monte Carlo generators based on next-to-leading-order matrix element calculations. Selected observables are compared with various models containing different fractions of intrinsic charm (IC).

1. – Introduction

The recently published [1] measurement of the production cross-section of a Z boson in association with heavy-flavor jets, namely b- and c-jets, using 140 fb^{-1} of proton-proton collisions data at the center-of-mass energy $\sqrt{s} = 13$ TeV at the ATLAS experiment [2] is presented here. This measurement provides an excellent test of perturbative QCD and is crucial in the understanding of Parton Density Functions (PDFs), especially of heavy flavor quarks and gluons. The accuracy of these measurements is crucial for background modeling in analyses such as those involving Higgs-boson decays to $b-$ or $c-$quarks and Beyond Standard Model physics. The paper also touches on theoretical approaches for modeling $Z+$ heavy-flavor-jets production, including the difference between three-flavour scheme (3FS) or four-/five-flavour schemes (4/5FS). The latter includes the resummation of $\alpha \ln\left(\frac{Q^2}{m^2}\right)$ terms where m is the mass of a heavy quark. This resummation intervenes when the scale of the process Q is much larger than the quark mass, allowing the treatment of quarks as massless. Furthermore, $Z + c$-jets measurements for a selection of variables are compared to benchmark theoretical models which include different fractions of intrinsic charm, since it was shown in previous papers [3] that the forward rapidity region might have sensitivity to this phenomenon.

(*) IFAE 2024 - "Energy Frontier" session

2. – Event selection

Signal is selected identifying the Z boson from its decay in two charged leptons and identifying two signal regions based on the number of tagged b- and c-jets: 1-TAG for $Z+ \geq 1$ b-jets or $Z+ \geq 1$ c-jets and 2-TAG for $Z+ \geq 2$ b-jets. Jets are reconstructed with the anti-k_T algorithm (radius parameter $R = 0.4$). They are selected according to the criteria in table I. The flavor of the jet is identified with the DL1r tagger, which uses information on tracks and secondary vertices to identify heavy-flavored jets. A specific working point is chosen to ensure 30% efficiency for c-jets and 85% for b-jets.

3. – Background modeling and flavor fit

The most interesting challenge in background modeling comes from the fact that, in the 1-TAG signal region, b- and c-jets are alternatively selected as signal, each time considering the other process as background. It is of the utmost importance, then, to have a precise modeling of the shapes of the Z+jets distributions, extracting the relative contribution of $Z + b$-jets, $Z + c$-jets and Z+light-jets in the regions of interest for the analysis. This is obtained through a flavor fit, which is a maximum likelihood fit on flavor-sensitive variables. As seen in fig. 1, background normalization scaling factors are extracted from a fit on the flavor tagging algorithm discriminant, which is defined in Eq. 1, and used for bin-by-bin corrections. The observable is binned in four intervals corresponding to different ranges of $b-$tagging efficiency ($85-77\%$, $77-70\%$, $70-60\%$ and $< 60\%$).

$$D_{DL1r} = \ln\left(\frac{p_b}{f_c \cdot p_c + (1-f_c) \cdot p_{light}}\right) \tag{1}$$

The second most notable source of background is $t\bar{t}$. This contribution is estimated via a data-driven approach: instead of relying solely on theoretical predictions, a control region is defined and enriched with the $t\bar{t}$ process until the control region purity is above 90%. A transfer factor is then used to extrapolate from the control region to the signal region. This approach reduces the theoretical uncertainties related to the event simulation. The other, secondary, sources of background are multijet (estimated with a similar data-driven technique based on a template fit) and single-top and diboson processes, which are both evaluated with Monte Carlo samples.

Table I. – *Selection parameters.*

Z selection	
Leptons	exactly 2 of the same flavour and opposite charge
Di-lepton mass	76 GeV $< m_{\ell\ell} <$ 106 GeV
Missing transverse energy	$E_T^{miss} <$ 60 GeV if $p_T <$ 150 GeV
Jet selection	
Kinematic constraints	$p_T >$ 20 GeV, $\lvert\eta\rvert < 2.5$
Tagging requirements	≥ 1 or ≥ 2 flavor-tagged jets

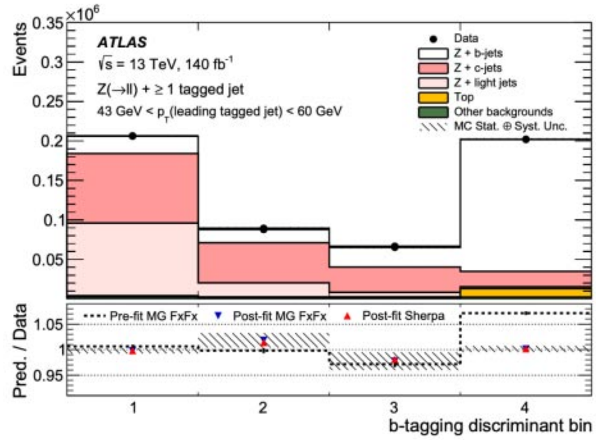


Fig. 1. – Flavour-sensitive distribution of the discriminant of the DL1r algorithm for the 1-TAG region fit in the interval [43,60] GeV of $p_{T,b}$. The main panel compares data and post-fit distributions to data when using the MG_aMC@NLO+Pythia8 FxFx and Sherpa generators for Z+jets simulated samples. The total uncertainty of the MG_aMC@NLO+Pythia8 FxFx post-fit distribution is shown as a hatched band [1].

4. – Uncertainties

The main sources of uncertainties are related to b-tagging, jet modeling and identification, and unfolding, which is the procedure that allows to compare data at detector level to the cross-sections as presented by theoretical predictions. An example of systematic uncertainties breakdown can be seen in fig. 2.

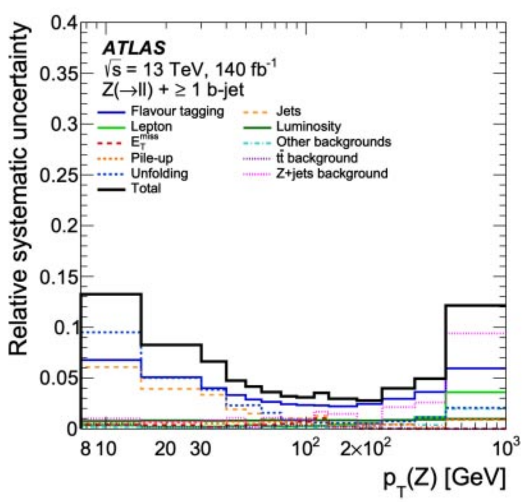
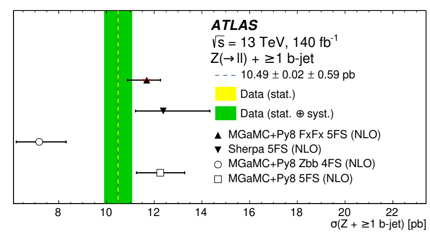
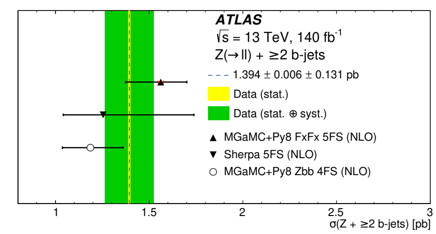


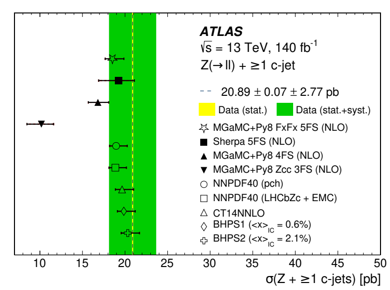
Fig. 2. – Relative systematic uncertainties in the fiducial cross-section as a function of p_T of the Z boson in events with at least one b-jet. The total uncertainty is shown with solid black line, while the different components are shown in different line styles and colours [1].



(a) – $Z+\geq 1$ b-jet



(b) – $Z+\geq 2$ b-jet



(c) – $Z+\geq 1$ c-jet

Fig. 3. – Measured fiducial cross-sections for all three signal regions. The data are compared with the predictions from the 5FS multi-leg generators MG_aMC@NLO+Pythia8 FxFx and Sherpa 2.2.11, with MG_aMC@NLO+Pythia8 4FS (NLO), and with MG_aMC@NLO+Pythia8 5FS (NLO). [1]

5. – Results

Inclusive cross-sections results are shown in figure 3. The measured cross-sections are:

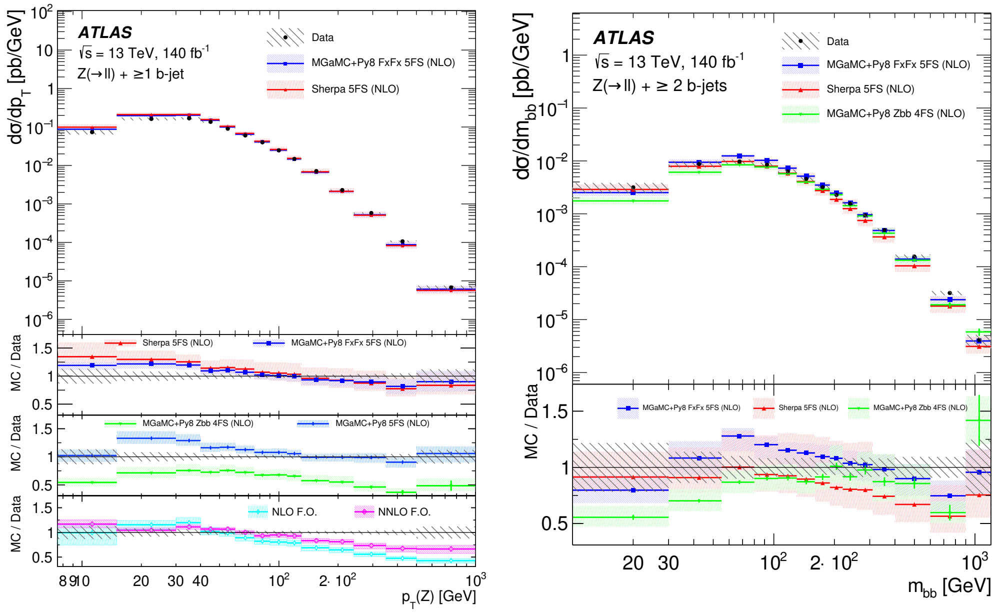
- $\sigma\,(Z+\geq 1\ b\text{−jets}) = 10.49 \pm 0.02\ (\text{stat.}) \pm 0.59\ (\text{syst})$ pb;
- $\sigma\,(Z+\geq 2\ b\text{−jets}) = 1.394 \pm 0.006\ (\text{stat.}) \pm 0.131\ (\text{syst})$ pb;
- $\sigma\,(Z+\geq 1\ c\text{−jets}) = 20.89 \pm 0.07\ (\text{stat.}) \pm 2.77\ (\text{syst})$ pb.

For what concerns differential cross-sections, some of them are shown in fig.s 4a and 4b. In the 5FS both Madgraph and Sherpa generators model data in a satisfying way (across the whole spectrum in the $Z+\geq 1$ b-jets case, in the lower part of the m_{bb} spectrum in $Z+\geq 2$ b-jets), whereas the 4FS underestimates data. Furthermore, NNLO QCD fixed-order predictions are a better estimate than NLO ones.

A similar situation can be observed for $Z+\geq 1$ c-jets (fig. 5), where the 5FS slightly underestimates data at higher momenta, the 4FS gives a reasonable estimate, and the 3FS wildly underestimates data.

6. – Focus on intrinsic charm

To perform the studies on intrinsic charm sensitivity, the ratio between the Forward and Central region was observed, to cancel out several systematic uncertainties. The



(a) – $Z+\geq 1$ b-jet: p_T of the Z boson

(b) – $Z+\geq 2$ b-jet: di-mass of the b-jets

Fig. 4. – Measured fiducial cross-section for $Z+\geq 1$ b-jet production as a function of $p_T(Z)$ and $Z+\geq 2$ b-jets production as a function of m_{bb}. The data are compared with the predictions from the 5FS multi-leg generators MG_aMC@NLO+Pythia8 FxFx and Sherpa 2.2.11, with MG_aMC@NLO+Pythia8 4FS (NLO) and MG_aMC@NLO+Pythia8 5FS (NLO), and with NLO and NNLO fixed-order (F.O.) predictions.

two regions were defined by a cut on pseudorapidity $\eta = 1.2$ identified by optimizing on reweighted events with PDFs with different fractions of intrinsic charm [4]. Almost all IC models show a similar trend with respect to data, and there is no appreciable difference with models without IC. However, the BHPS2 model with a fraction of intrinsic charm around 2% seems to perform a little bit better, despite being considered rather unrealistic. The comparisons are shown in fig. 6.

7. – Conclusions

The measurement of the production cross-section of a Z-boson in association with b- and c-quarks was presented, based on 140 fb^{-1} of $p-p$ data collected by the ATLAS experiment at $\sqrt{s} = 13$ TeV. For the first time, $Z+\geq 1$ c-jet was performed in ATLAS. With respect to previous publications [5], the accuracy of the measurement has improved by a factor of 1.5 and, in certain instances, even by a factor of 2. The measurements were compared with several theoretical predictions. The 5FS provides the best description of data, but no model is accurate enough for $Z+\geq 1$ c-jets. The other flavor schemes, 4FS and 3FS, underestimate the respective data. Fixed-order QCD NNLO predictions perform better than their NLO counterparts, although not on the entire phase space.

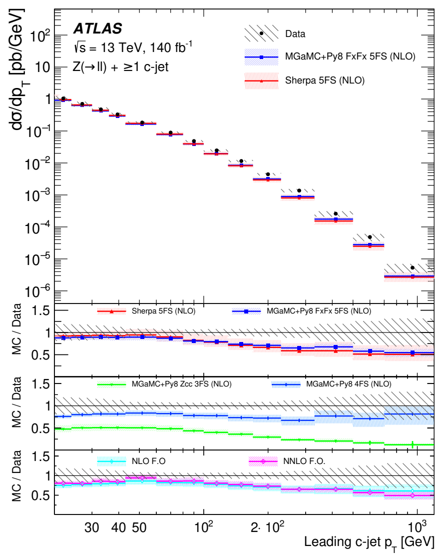


Fig. 5. – Measured fiducial cross-section for $Z+\geq 1$ c-jet production as a function of leading c-jet p_T. The data are compared with the predictions from the 5FS multi-leg generators MG_aMC@NLO+Pythia8 FxFx and Sherpa 2.2.11, with MG_aMC@NLO+Pythia8 3FS (NLO) and MG_aMC@NLO+Pythia8 4FS (NLO), and with NLO and NNLO fixed-order (F.O.) predictions.

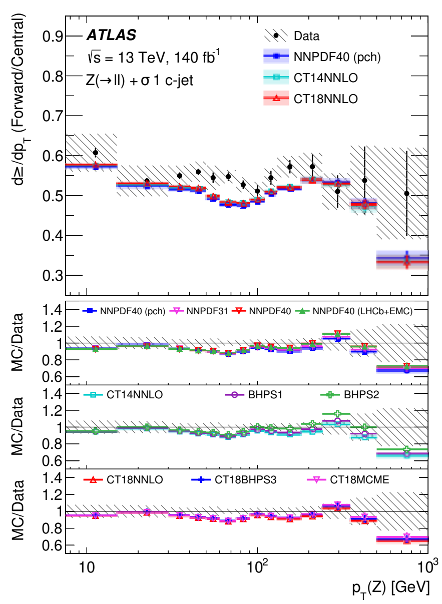


Fig. 6. – Measured fiducial cross-section for $Z+\geq 1$ c-jet production as a function of R($p_T(Z)$). The data are compared with the nominal MG_aMC@NLO+Pythia8 FxFx predictions and with those using the PDFs testing several IC models.

REFERENCES

[1] ATLAS Collaboration, *Measurements of the production cross-section for a Z boson in association with b- or c-jets in proton-proton collisions at* $\sqrt{(s)} = 13$ *TeV with the ATLAS detector*,https://arxiv.org/abs/2403.15093.
[2] ATLAS Collaboration, *JINST*, **3** (2008) S08003.
[3] LHCb Collaboration, *Phys. Rev. Lett.*, **128** (2022) 082001.
[4] Boccardo L., *Search for intrinsic charm in the proton at the ATLAS experiment*, https://cds.cern.ch/record/2892687.
[5] ATLAS Collaboration, *J. High Energy Phys.*, **2020** (2020) 44.