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Measurements of the production of a Z boson in association with 2 b-jets with the ATLAS experiment at LHC

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Summary. —
This contribution presents new differential cross-section measurements on the production of a Z boson in association with at least two b-jets as a function of variables not previously reported, using the full Run 2 dataset of proton-proton collisions at a center-of-mass energy of 13 TeV recorded with the ATLAS experiment at LHC. These measurements are relevant for perturbative QCD and Higgs boson studies. This contribution also presents detector level measurements in the kinematical region of high transverse momenta of the jets, where they appear as a unique large jet, using the same dataset.

1. – Introduction

The measurement of the production of a Z boson is association with jets originating from b-quark hadronisation (b-jets) contributes improving the knowledge in perturbative QCD (pQCD) and it is crucial in the understanding of Parton Distribution Functions (PDFs). Furthermore, this kind of measurements provide an essential input to improve the Monte Carlo (MC) simulations used to estimate the Z + b-jets backgrounds in the Higgs boson measurements and searches for New Physics. In particular, the Z + b-jets process is crucial for background modeling in analyses of Higgs boson production in association with a Z boson, where the Higgs boson decays in 2 b-quarks [1].

This contribution is built upon previous measurements [2, 3] of the production of a Z boson in association with two b-jets that used 140 fb^{-1} of proton-proton collision data at center-of-mass energy $\sqrt{s} = 13$ TeV at the ATLAS experiment [4] at LHC, providing differential cross-sections as a function of new observables not included in these last publications.

Two kinematic regions are explored: the resolved, where the two b-jets are well separated and reconstructed as distinct jets, and the boosted region, where the jets are at high transverse momentum (p_T) and are reconstructed as a single jet with large radius. This last region is crucial to study the radiation pattern around the b-quarks, that is largely unknown, to develop taggers and to study gluon splitting.

2. – Analysis Strategy

Events are selected if they are recorded during stable beam conditions and if they satisfy detector and data-quality requirements. Candidate events were selected using either a single-electron or single-muon trigger, which were subject to minimum p_T thresholds as well as quality and isolation requirements.

Signal events are selected by identifying Z boson decays in two charged leptons of opposite charges (e^+e^- or $\mu^+\mu^-$) in association with at least two b-jets that are reconstructed using the anti-k_T algorithm [5]. Jet flavour is identified with the DL1r tagger [6], that uses information of tracks and secondary vertices to identify heavy-flavour jets.

The data distributions are background subtracted and corrected for experimental effects, enabling the extraction of cross-section measurements to be compared with predictions from signal MC generators.

In the resolved region, jets are reconstructed with a radius parameter R = 0.4 and the flavour-tagging working point corresponds to a b-tagging efficiency of 85 %. In the boosted region, the two b-quarks are reconstructed as subjets within a single large jet (fat jet) with radius R = 1.0, using a b-tagging working point with 70 % efficiency. All selection criteria are summarised in Table I.

TABLE I. – *Selection parameters for Z + 2 b-jets analysis.*

Z selection	
Leptons	Exactly 2 leptons with opposite charge and same flavour
Muon selection	$p_T > 27$ GeV, $\|\eta\| < 2.5$
Electron selection	$p_T > 27$ GeV, $\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.5$
Z mass window	76 GeV $< m_{\ell\ell} <$ 106 GeV
Missing E_T	$E_T^{miss} < 60$ GeV if $p_T^Z < 150$ GeV
Resolved analysis	
b-jets	≥ 2 b-tagged jets (85% WP), anti-k_t with $R = 0.4$, $p_T > 20$ GeV, $\|y\| < 2.5$, $\Delta R(jet, \ell) > 0.4$
Boosted analysis	
Fat jets	≥ 1 large-R jet ($R = 1.0$), $p_T > 200$ GeV, $\|y\| < 1.5$
b-subjets	≥ 2 b-tagged (70% WP), matched to a fat jet

3. – Modeling for resolved and boosted region

The Monte Carlo predictions for signal (Z + 2 b-jets) are calculated at next-to-leading order (NLO) in pQCD and interfaced with parton shower models. Two different generators are used: `MadGraph5_aMC@NLO v2.6.5` [7] combined with `Pythia v8.245` [8] parton shower using the FxFx [9] merging procedure (`MGaMC+PY8 FxFx`) and SHERPA2.2.11 [10]. Both generators employ the five-flavour scheme (5FS), where the b and c quarks are treated as massless and included in the proton's initial state. An alternative version of `MGaMC+PY8 FxFx` uses the four-flavour scheme (4FS) where only the c quark is massless and included in the proton's initial state.

The dominant background is composed by events with a Z boson produced in association with jets where jet flavour is different from the targeted in the measurement, i.e. light jets, c-jets and Z + 1 b-jet. It is determined using a set of maximum likelihood fits to data of a flavour-sensitive observable. The top quark pair background is estimated using data-driven techniques, while minor backgrounds are estimated via simulations. The contributions of the signal and of the different backgrounds for the resolved region are displayed in Table II, while those for the boosted region are shown in Table III.

TABLE II. – *Resolved region*

Signal $Z+ \geq 2\,b$-jets	
$Z + bb$	46%
Backgrounds	
$Z + b$	11%
$Z + c$	23%
$Z + l$	7%
Top	12%
Others	2%
Total predicted	$325\,300 \pm 600$
Data	309 199

TABLE III. – *Boosted region*

Signal $Z+ \geq 2\,b$-jets	
$Z + bb$	80%
Backgrounds	
$Z + b$	4%
$Z + c$	2%
Diboson	9%
Top	5%
Others	$< 1\%$
Total predicted	$1\,218 \pm 410$
Data	1 483

The data are compared to the MC predictions after the selection at detector level, as shown in Fig. 1 for the resolved region as a function of the transverse momentum of the leading b-jet, the b-jet with higher p_T. The uncertainty bands account for statistical uncertainties in the simulated samples, systematic uncertainties related to event selection and background estimation. The distributions are shown for a combination of the muon and electron channel. In this figure, MGAMC+PY8 FxFx is compatible within the uncertainties with the data, while Sherpa largely underestimates the data at high p_T region.

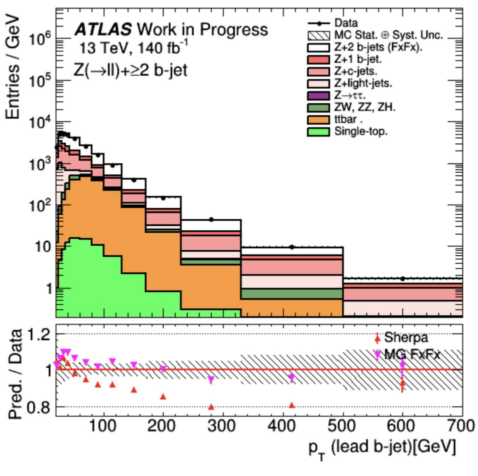

Fig. 1. – Detector level plot of the transverse momentum of the leading b-jet in the resolved region in the combined channel.

For the boosted region, the detector level comparison is shown in Fig. 2 for the transverse momentum of the fat jet, for the mass of the fat jet and for the angular separation between the two b-jets in the fat jet. The predictions are made with MGAMC+PY8 FxFx at NLO. These preliminary results show that the NLO MC predictions underestimate the data.

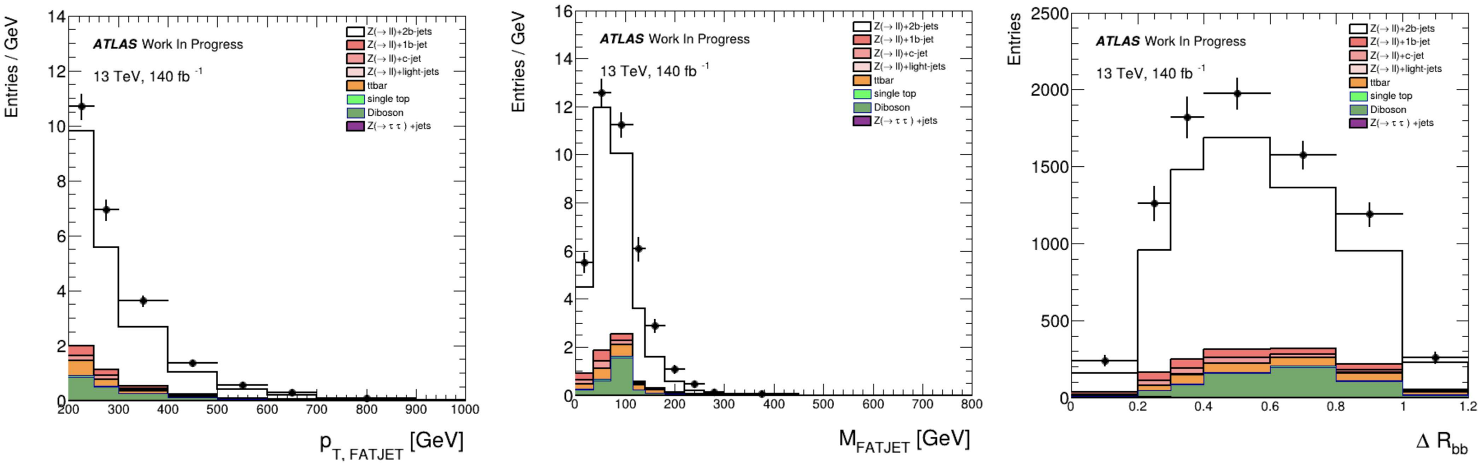

Fig. 2. – Detector level plots of the p_T of the fat jet, the mass of the fat jet and the ΔR_{bb}

4. – Cross-section measurements in the resolved region

The background-subtracted data are corrected for selection efficiency, resolution effects through the unfolding, which transforms measured distributions at detector-level into particle-level ones in a fiducial volume, making them detector-independent. This is done using the Iterative Bayesian method implemented via the RooUnfold package [11].

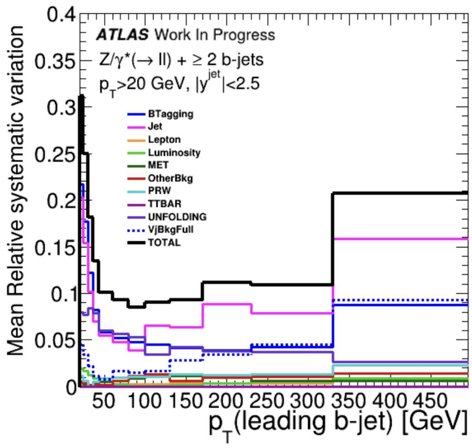

Fig. 3. – Systematic uncertanties as a function of the transverse momentum of the leading b-jet in the resolved region.

In this analysis the fiducial phase space is very close to the detector-level one, so the unfolding procedure relies at minimum on MC-based acceptance corrections, resulting in small associated modeling uncertainties.

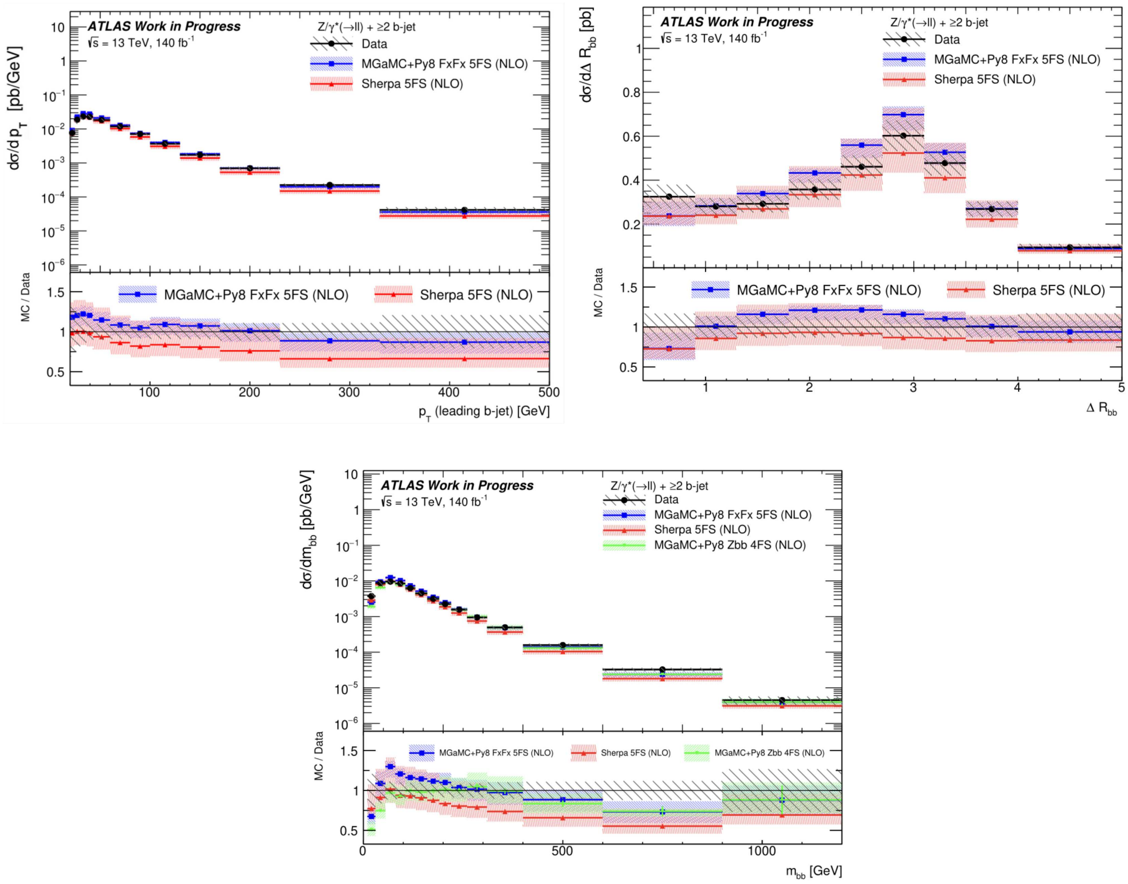

Fig. 4. – Differential cross section measurements as a function of the p_T of the leading b-jet, the ΔR_{bb} and the invariant mass of the two b-jets.

The experimental uncertainties (leptons, jets, b-tagging, etc.) on signal and background are propagated through the unfolding process. Additionally, uncertainties inherent to the unfolding procedure itself are taken into account. Fig. 3 shows the systematic uncertainties as a function of the p_T of the leading b-jet. The dominant contributions arise from jet energy scale and b-tagging uncertainties. The uncertainty on the leading b-jet p_T ranges from 10 % to 30 %, while is smaller for the other variables.

In Fig. 4 the differential cross section measurements are shown as a function of the p_T of the leading b-jet, the angular separation of the 2 b-jets and the invariant mass of the 2 b-jets. In the first two distributions, predictions from both `MGaMC+PY8 FxFx` and Sherpa generators in the 5FS are compared to the data, while for the invariant mass of the two b-jets the `MGaMC+PY8 FxFx` generator in the 4FS is also included. The differential cross section as a function of the p_T of the leading b-jet is important for the study of the pQCD and the MC modeling. Among the predictions, `MGaMC+PY8 FxFx` (5FS) shows the best agreement with data. Both Sherpa 2.2.11 and MGAMC+PY8 FxFx show a good agreement with data within uncertainties in the differential cross section as a function of the angular separation of the 2 b-jets, crucial for the study of the gluon splitting. The differential cross section as a function of the mass of the 2 b-jets is fundamental for the study of the Higgs boson produced in association with a Z boson, where the Higgs boson decays in 2 b-jets. While all MC predictions are consistent with data within the uncertainties, no generator fully reproduces the shape of the distriburion.

5. – Conclusion

The measurements of the Z boson in association with two b-jets production cross section in both resolved and boosted topologies using 140 fb^{-1} of data has been presented.

In the resolved region, no MC prediction (NLO+PS), that have a matrix element at NLO supplemented by parton shower, provides a perfect description of all observables. MGAMC+PY8 FxFx (5FS) better describes the p_T observables, while Sherpa 2.2.11 (5FS) describes better the angular observables in the Z + 2b topology.

In the boosted region, preliminary results reveal larger discrepancies between data and predictions than in the resolved region at detector level. In particular, the MGAMC+PY8 FxFx (5FS) predictions underestimate the data by up to 20 % at detector level.

REFERENCES

[1] ATLAS Collaboration, *Combined measurements of Higgs boson production and decay using up to 139 fb*$^{-1}$ *of proton–proton collision data at* $\sqrt{s} = 13$ *TeV collected with the ATLAS experiment*, *Eur. Phys. J. C 81*, **(2021)** (178) , CERN-EP-2020-087

[2] 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*, *Eur. Phys. J. C 84*, **(2024)** (984) , CERN-EP-2024-081

[3] Santoro G., *Measurements of the production of a Z boson in association with two b-jets in proton–proton collisions at* $\sqrt{s} = 13$ *TeV with the ATLAS experiment*, Master Thesis, CERN-THESIS-2024-256, CDS 2919195. Available at: https://repository.cern/records/tk77d-4es51/files/CERN-THESIS-2024-256.pdf

[4] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, *JINST*, **3** (2008) S08003

[5] Cacciari M., Salam G.P. and Soyez G., *The anti-*k_t *jet clustering algorithm*, *JHEP*, **04** (2008) 063, LPTHE-07-03

[6] ATLAS Collaboration, *ATLAS flavour-tagging algorithms for the LHC Run 2 collision dataset*, *Eur. Phys. J. C 83*, **(2023)** (681) , CERN-EP-2022-226

[7] Alwall J. *et al.*, *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, *JHEP*, **07** (2014) 079

[8] Sjöstrand T. *et al.*, *An introduction to PYTHIA 8.2*, *Comput. Phys. Commun.*, **191** (2015) 159

[9] Frederix R. and Frixione S., *Merging meets matching in MC@NLO*, *JHEP*, **12** (2012) 061

[10] ATLAS Collaboration, *Modelling and computational improvements to the simulation of single vector-boson plus jet processes for the ATLAS experiment*, *JHEP*, **08** (2022) 089, CERN-EP-2021-231

[11] Adye T., *ROOT Unfolding Framework*, Available at: https://hepunx.rl.ac.uk/ adye/software/unfold/RooUnfold.html