PROCEEDINGS OF SCIENCE

Electroweak boson measurements in p+Pb and Pb+Pb collisions with ATLAS

Jakub Kremer[*†] **on behalf of the ATLAS Collaboration**
AGH University of Science and Technology
Faculty of Physics and Applied Computer Science
al. Mickiewicza 30, 30-059 Kraków, Poland
E-mail: jakub.kremer@cern.ch

Electroweak bosons produced in nucleus–nucleus collisions at LHC energies are excellent probes of the collision geometry and centrality. In proton–nucleus collisions, they provide insight into cold nuclear matter effects such as nuclear modifications of parton distribution functions or initial-state parton energy loss. This report presents the latest ATLAS results on massive electroweak boson production in Pb+Pb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV using data collected by the ATLAS experiment in 2015, as well as a measurement of prompt photon production in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV.

7th Annual Conference on Large Hadron Collider Physics - LHCP2019
20-25 May, 2019
Puebla, Mexico

[*] Speaker.

[†] This work was partly supported by the National Science Centre of Poland under grants UMO-2016/23/B/ST2/01409 and UMO-2018/28/T/ST2/00048, by a joint project of the Polish National Agency for Academic Exchange and AGH UST (PPI/PRO/2018/1/00026/U/00), and by PL-Grid infrastructure.

PoS(LHCP2019)166

1. Introduction

Measurements of electroweak boson production in proton–proton (pp) collisions provide precise tests of Standard Model predictions, including both the electroweak theory and quantum chromodynamics (QCD). In particular, measurements differential in rapidity can be used to constrain parton distribution functions (PDFs). Electroweak boson measurements in pp collisions are also important references for measurements in proton–lead (p+Pb) and lead–lead (Pb+Pb) collisions. In p+Pb collisions, electroweak boson production is sensitive to cold nuclear matter effects such as nuclear modifications of PDFs (nPDFs) or initial-state parton energy loss. In Pb+Pb collisions, a strongly interacting quark–gluon plasma is created, but electroweak bosons and leptons produced in W or Z boson decays are not expected to interact substantially with the plasma. This feature makes electroweak bosons excellent probes of the initial-state geometry of the collision.

Modifications of electroweak boson production in p+Pb collisions relative to pp collisions can be quantified using the nuclear modification factor, $R_{p\mathrm{Pb}}$:

$$R_{p\mathrm{Pb}} = \frac{1}{A_{\mathrm{Pb}}} \frac{\sigma_{p+\mathrm{Pb}}}{\sigma_{pp}}, \tag{1.1}$$

where $A_{\mathrm{Pb}} = 208$ is the lead nucleus mass number, while $\sigma_{p+\mathrm{Pb}}$ and σ_{pp} are cross-sections for electroweak boson production in p+Pb and pp collisions at the same centre-of-mass energy, respectively.

In the case of Pb+Pb collisions, the definition of the nuclear modification factor, R_{AA}, incorporates also the collision geometry:

$$R_{\mathrm{AA}} = \frac{N_{\mathrm{AA}}/N_{\mathrm{evt}}}{\langle T_{\mathrm{AA}} \rangle \cdot \sigma_{pp}}. \tag{1.2}$$

Here, $N_{\mathrm{AA}}/N_{\mathrm{evt}}$ is the electroweak boson yield measured per minimum-bias Pb+Pb collision, and σ_{pp} is the cross-section for the corresponding process measured in pp collisions at the same centre-of-mass energy. The geometry of the collision is represented by the average nuclear thickness function, $\langle T_{\mathrm{AA}} \rangle$. The quantity $\frac{N_{\mathrm{AA}}/N_{\mathrm{evt}}}{\langle T_{\mathrm{AA}} \rangle}$ is also referred to as the normalised production yield.

This report presents measurements of W and Z boson production based on data from 25 pb^{-1} of pp collisions at $\sqrt{s} = 5.02$ TeV [1] and 0.49 nb^{-1} of Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [2,3] delivered by the Large Hadron Collider (LHC). In addition, a measurement of prompt photon production in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV [4] is presented, which uses 165 nb^{-1} of data. The datasets used in these measurements were collected by the ATLAS experiment [5] in 2015 (pp, Pb+Pb collisions) and 2016 (p+Pb collisions).

2. Measurements of W and Z boson production in pp collisions

The measurements of W and Z boson production in pp collisions at $\sqrt{s} = 5.02$ TeV are done in the electron and muon decay channels. Candidate events are selected using single-lepton triggers with p_{T} thresholds of 15 GeV and 14 GeV for electrons and muons, respectively. Reconstructed leptons are required to pass selections related to their kinematics, reconstruction quality and isolation. Candidate events for W boson production are required to contain exactly one good lepton matched to the trigger, while for Z bosons oppositely charged lepton pairs with an invariant mass in the range $66 < m_{\ell\ell} < 116$ GeV are considered. Background contributions to the W boson selection are reduced by applying requirements on the missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV, and the transverse mass, $m_{\mathrm{T}} > 40$ GeV, of the candidate events. These quantities are evaluated from the hadronic recoil reconstructed using particle flow objects [6]. Remaining background contributions of 3–6% (0.3%) for W (Z) boson selections are subtracted.

Differential fiducial cross-sections for W^+ and Z boson production are presented in Figure 1. The presented cross-sections are calculated from a combination of results obtained separately in the electron and muon channels. The measured cross-sections are compared to theoretical predictions calculated at next-to-next-to-leading order (NNLO) in QCD with an optimised version of the DYNNLO 1.5 code [7, 8]. The calculations use various modern PDF sets: CT14 NNLO [9], NNPDF3.1 [10], MMHT2014 [11], HERAPDF2.0 [12] and ABMP16 [13]. For both the W and Z bosons, the data are best described by predictions using the NNPDF3.1 set, which was derived from previous high-precision measurements of W and Z boson production from the ATLAS and CMS Collaborations. Predictions calculated with most of the PDF sets tend to underestimate the data by a few percent, in particular for Z bosons with dilepton rapidities of $|y_{\ell\ell}| < 1$.

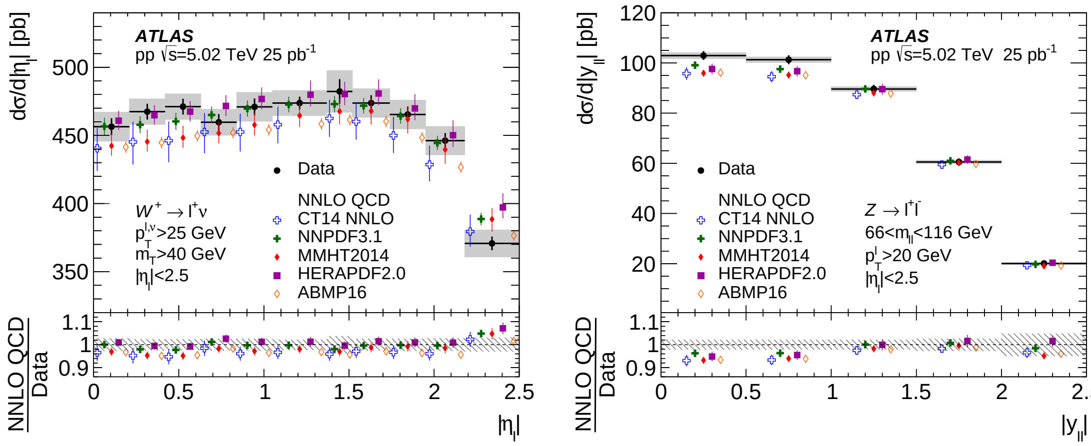

Figure 1: Differential cross-sections for W^+ (left) and Z boson (right) production as a function of absolute decay lepton pseudorapidity and dilepton rapidity, respectively, compared with theoretical predictions [1]. Statistical and systematic errors are shown as corresponding bars and shaded bands on the data points. The luminosity uncertainty is not included. Only the dominant uncertainty (PDF) is displayed for the theory. The lower panel shows the ratio of predictions to the measured differential cross-section in each bin, and the shaded band shows the sum in quadrature of statistical and systematic uncertainties of the data.

3. Measurement of prompt photon production in *p*+Pb collisions

The production of prompt photons in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV is measured in events collected using several single-photon triggers with transverse-energy (E_{T}^{γ}) thresholds ranging from 15 GeV to 35 GeV. Reconstructed photons are required to pass a kinematic selection, as well as requirements related to their reconstruction quality and isolation. Background contributions to the selected event sample are estimated in a data-driven way using a sideband method, which yields purities varying between 45% and 99% with E_{T}^{γ}.

Figure 2 shows the nuclear modification factor for prompt photon production measured as a function of E_{T}^{γ}. Since no direct measurement of prompt photon production in *pp* collisions at $\sqrt{s} = 8.16$ TeV is available, the cross-sections used to calculate $R_{p\mathrm{Pb}}$ values are extracted by extrapolating cross-sections measured in *pp* collisions at $\sqrt{s} = 8$ TeV [14]. The measured $R_{p\mathrm{Pb}}$ factor is compared to predictions incorporating energy loss of initial-state partons [15]. These predictions are calculated with two different sets of energy-loss parameters and, for comparison, without energy loss. The data are best described by the calculation excluding energy loss, which suggests that initial-state partons lose little to no energy in soft interactions occurring prior to the hard scattering.

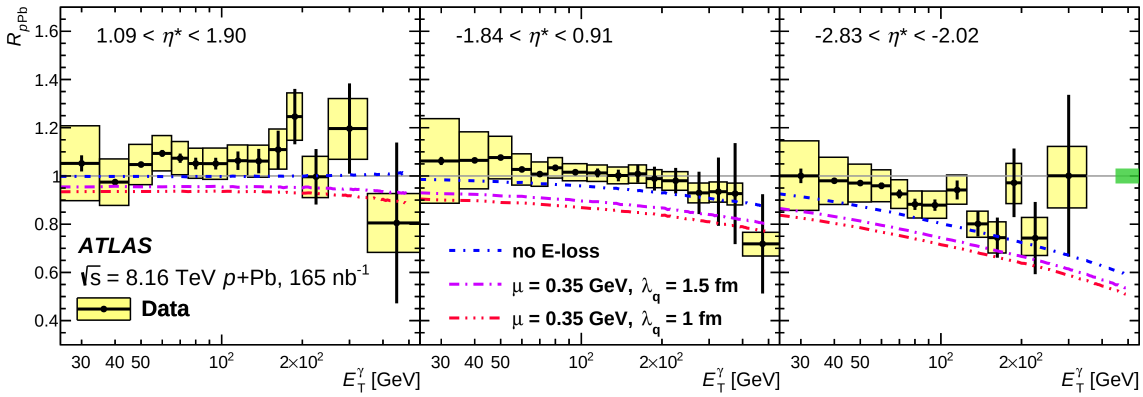

Figure 2: Nuclear modification factor $R_{p\mathrm{Pb}}$ for isolated, prompt photons as a function of photon transverse energy E_{T}^{γ}, shown for different centre-of-mass pseudorapidity, η^*, regions in each panel [4]. The data are compared with an initial-state energy-loss calculation. The yellow bands and vertical bars correspond to total systematic and statistical uncertainties in the data, respectively. The green box (at the far right) represents the combined 2.4% *p*+Pb and 1.9% *pp* luminosity uncertainties.

The sensitivity of the data to cold nuclear matter effects is further enhanced with the ratio of $R_{p\mathrm{Pb}}$ factors measured at forward and backward pseudorapidities, since systematic uncertainties are largely reduced in the ratio. The measured ratio is presented as a function of E_{T}^{γ} in Figure 3, with systematic uncertainties of about 3% in most of the considered E_{T}^{γ} range. The data are compared to theoretical predictions calculated with the JETPHOX code [16] at next-to-leading order (NLO) in QCD. The calculations use either the free-nucleon CT14 PDF set or one of two nPDF sets: EPPS16 [17] or nCTEQ15 [18]. Both calculations assuming nPDFs are compatible with the data over a broad E_{T}^{γ} range, but the best agreement is provided by the free-nucleon PDF prediction.

4. Measurements of W and Z boson production in Pb+Pb collisions

The measurements of W and Z boson production in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV follow a similar strategy to the measurements in *pp* collisions. In the case of the W boson analysis, the missing transverse momentum calculation uses only charged-particle tracks, since energy measurements in the calorimeters are distorted by a significantly larger underlying-event contribution than in *pp* collisions. This additional activity results in an increased contribution of multi-jet background events, which varies with the collision centrality. The event selection in the Z boson analysis does not require leptons to be isolated, which increases the multi-jet background contribution to 0.5–2%.

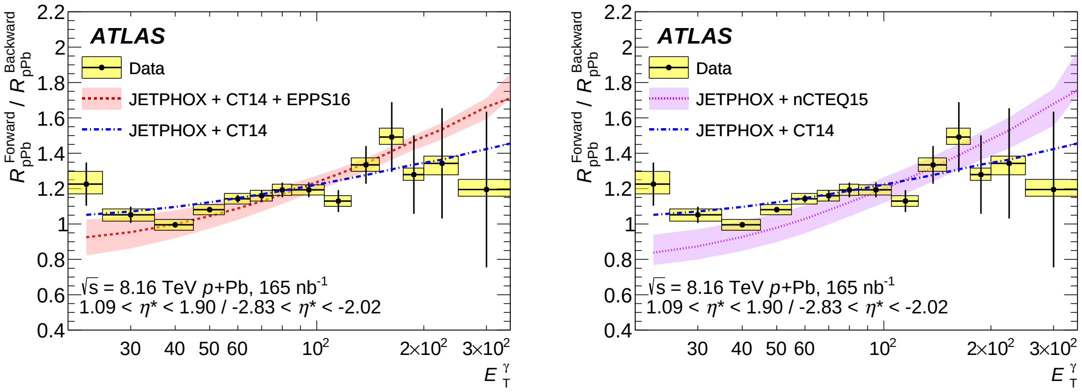

Figure 3: Ratio of the nuclear modification factor $R_{p\mathrm{Pb}}$ between forward and backward pseudorapidity for isolated, prompt photons as a function of photon transverse energy E_{T}^{γ} [4]. The data are compared with the expectations based on JETPHOX with the EPPS16 nuclear PDF set (left) or with the nCTEQ15 nuclear PDF set (right). The yellow bands and vertical bars correspond to total systematic and statistical uncertainties in the data, respectively. The red and purple bands correspond to the systematic uncertainties in the calculations.

Figures 4 and 5 present differential normalised production yields for W and Z bosons, respectively. These measurements are performed in the same fiducial phase-space as in pp collisions and are also obtained from a combination of results from individual channels. The data are compared to theoretical predictions calculated at NLO in QCD with the MCFM code [19], using the CT14 PDF set (including isospin effect [20]) as well as the EPPS16 and nCTEQ15 nPDF sets. All calculations predict the shape of the distributions well, but they differ in the overall normalisation. The yields calculated using the free-nucleon CT14 PDF set are lower than the data by a few percent, while predictions based on nPDF sets underestimate the measured yields by 10–20%.

Nuclear modification factors for W and Z boson production are shown in Figure 6 as a function of the average number of nucleons participating in the collision, $\langle N_{\mathrm{part}}\rangle$, which is closely related to the collision centrality. The R_{AA} values are calculated using the cross-sections measured in pp collisions from Ref. [1] and are compared to theoretical predictions calculated with the MCFM code using the CT14 PDF set. Due to the isospin effect, the R_{AA} factor for W^+ (W^-) bosons is expected to be constant at about 0.8 (1.2), while for Z bosons it is expected to be about 1.02. For mid-central and central collisions, the measured R_{AA} factors do not depend on $\langle N_{\mathrm{part}}\rangle$ and agree with predictions. However, in peripheral collisions, a slight excess over the predicted R_{AA} values appears. The difference amounts to at most 1.2 standard deviations for W^- bosons.

In Refs. [2, 3], the measurements of W and Z boson production yields are repeated with geometrical parameters obtained from a recent implementation of the Glauber model. This model update includes e.g. the neutron skin effect and an updated value of the inelastic nucleon–nucleon cross-section, but the impact of these improvements on the measured yields is much smaller than the measurement uncertainties. The updated yield measurements are compared to theoretical predictions accounting for the neutron skin effect, which leads to a centrality-dependent modification of the predicted yields. However, the modification is at most 1.4% for W^+ bosons in peripheral collisions, and does not improve significantly the description of the data.

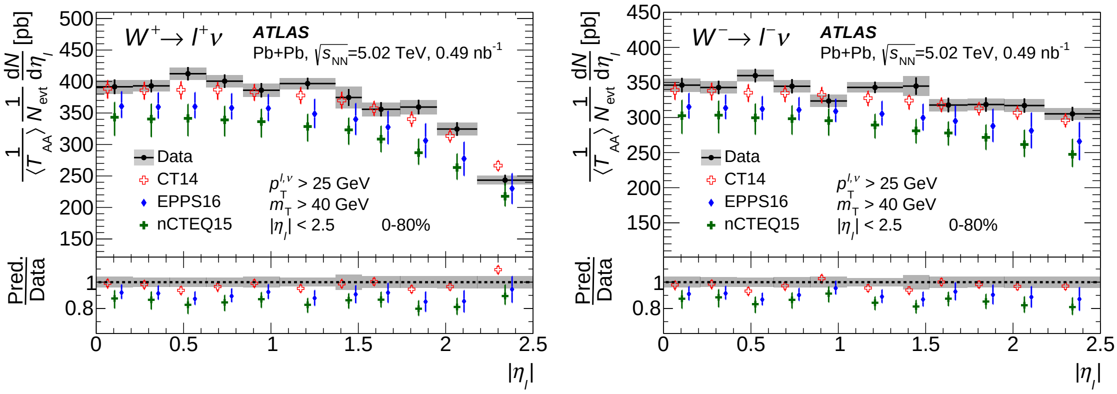

Figure 4: Differential normalised production yields for W^+ (left) and W^- (right) bosons as a function of absolute pseudorapidity of the charged lepton for the combined electron and muon channels [2]. Error bars show statistical uncertainties, whereas systematic uncertainties are shown as shaded boxes. Systematic uncertainties related to $\langle T_{AA} \rangle$ are not included. The measured distributions are compared with theory predictions calculated with the CT14 NLO PDF set as well as with EPPS16 and nCTEQ15 nPDF sets. For the theory predictions, the error bars represent total uncertainties due to PDF uncertainties, scale variations and α_S variations. The lower panels show the ratios of predicted yields to the measured ones, and the shaded band shows the sum in quadrature of statistical and systematic uncertainties of the data. The points for theory predictions are shifted horizontally for better visibility.

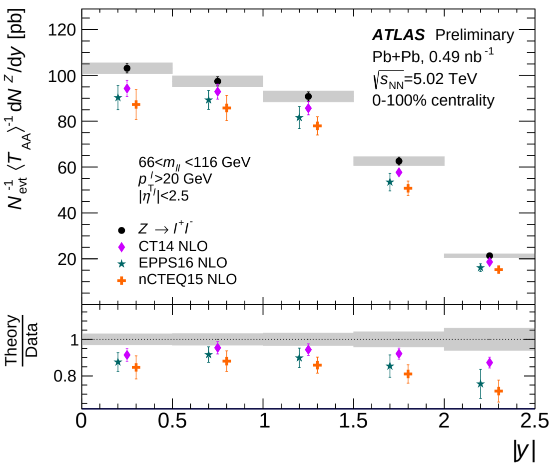

Figure 5: The upper panel shows the rapidity dependence of the normalised production yields for Z bosons compared with theoretical predictions [3]. The lower panel shows the ratio of the theoretical predictions to the data. The error bars on the data points indicate the statistical uncertainties and the shaded boxes show the systematic uncertainties. The error bars on predictions show the theoretical uncertainty. The points corresponding to nPDF predictions are shifted horizontally from the bin centre for clarity.

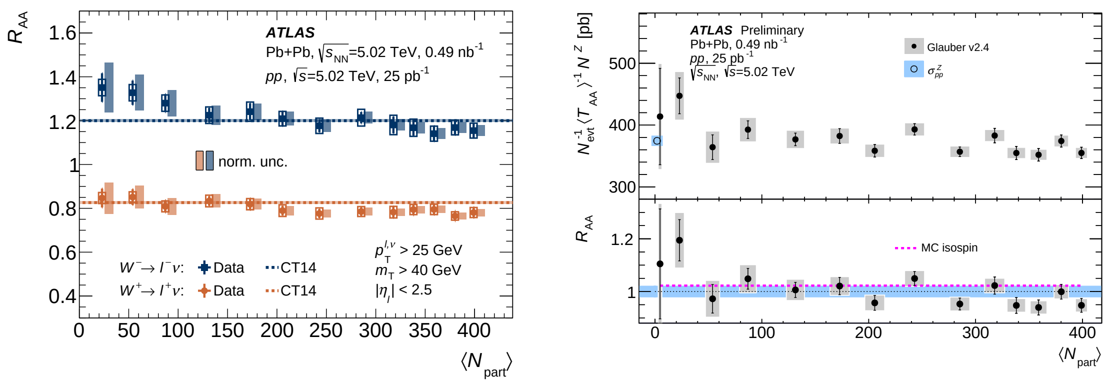

Figure 6: Nuclear modification factor R_{AA} obtained from the fiducial W^+, W^- (left) and Z boson (right, bottom panel) production yields as a function of $\langle N_{\mathrm{part}}\rangle$ [2,3]. Error bars show statistical uncertainties, whereas systematic uncertainties are shown as the boxes around the data points. In the left plot, the systematic uncertainties due to $\langle T_{\mathrm{AA}}\rangle$ and luminosity of the *pp* dataset are not included in those boxes and are shown as separate shaded boxes plotted to the right of the data points for better visibility.

5. Summary

Measurements of W and Z boson production in *pp* collisions at $\sqrt{s} = 5.02$ TeV with the ATLAS detector at the LHC provide a precise reference for heavy-ion measurements of electroweak boson production. The total uncertainty in integrated fiducial cross-sections is at the level of 2.3–2.4%. In addition, the measured integrated and differential cross-sections are in good agreement with NNLO QCD predictions obtained using the NNPDF3.1 PDF set, while predictions calculated with other modern PDF sets tend to underestimate the data by a few percent.

The measurement of prompt photon production in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV provides insight into cold nuclear matter effects. The measured nuclear modification factors are found to be compatible with the modest effects of nPDFs, but disfavour a significant energy loss of partons in the initial state.

In Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV, W and Z bosons serve as probes of the initial state of the collision, including its geometry and nPDFs. The rapidity dependence of normalised production yields for W and Z bosons shows a slight underestimate of data by NLO QCD predictions calculated using the CT14 PDF set, while predictions obtained with the EPPS16 and nCTEQ15 nPDF sets deviate further from the data. Nuclear modification factors for W and Z boson production do not change with $\langle N_{\mathrm{part}}\rangle$ in mid-central and central collisions, which is in agreement with predictions, while in peripheral collisions a slight excess over predictions is observed.

References

[1] ATLAS Collaboration, Eur. Phys. J. C **79** (2019) 128, Erratum: Eur. Phys. J. C **79** (2019) 374.

[2] ATLAS Collaboration, arXiv:1907.10414 [nucl-ex].

[3] ATLAS Collaboration, ATLAS-CONF-2019-024, https://cds.cern.ch/record/2681562.

[4] ATLAS Collaboration, arXiv:1903.02209 [nucl-ex].

[5] ATLAS Collaboration, JINST **3** (2008) S08003.

[6] ATLAS Collaboration, Eur. Phys. J. C **77** (2017) 466.

[7] S. Catani and M. Grazzini, Phys. Rev. Lett. **98** (2007) 222002.

[8] S. Catani, L. Cieri, G. Ferrera, D. de Florian and M. Grazzini, Phys. Rev. Lett. **103** (2009) 082001.

[9] S. Dulat et al., Phys. Rev. D **93** (2016) 033006.

[10] R. D. Ball et al., Eur. Phys. J. C **77** (2017) 663.

[11] L. A. Harland-Lang, A. D. Martin, P. Motylinski and R. S. Thorne, Eur. Phys. J. C **75** (2015) 204.

[12] H1 and ZEUS Collaborations, Eur. Phys. J. C **75** (2015) 580.

[13] S. Alekhin, J. Blümlein, S. Moch and R. Plačakytė, Phys. Rev. D **96** (2017) 014011.

[14] ATLAS Collaboration, JHEP **08** (2016) 005.

[15] Z.-B. Kang, I. Vitev and H. Xing, Phys. Rev. C **92** (2015) 054911.

[16] P. Aurenche, J. Ph. Guillet, E. Pilon, M. Werlen and M. Fontannaz, Phys. Rev. D **73** (2006) 094007.

[17] K. J. Eskola, P. Paakkinen, H. Paukkunen and C. A. Salgado, Eur. Phys. J. C **77** (2017) 163.

[18] K. Kovařík et al., Phys. Rev. D **93** (2016) 085037.

[19] J. M. Campbell, R. K. Ellis and W. T. Giele, Eur. Phys. J. C **75** (2015) 246.

[20] P. Paakkinen, K. J. Eskola and H. Paukkunen, Phys. Lett. B **768** (2017) 7.

PoS(LHCP2019)166