PHYSICAL REVIEW C **104**, 044905 (2021)

Centrality dependence of electroweak boson production in PbPb collisions at the CERN Large Hadron Collider

Florian Jonas
Westfälische Wilhelms-Universität, Institut für Kernphysik, 48149 Münster, Germany and
ORNL, Physics Division, 37830 Oak Ridge, Tennessee, USA

Constantin Loizides
ORNL, Physics Division, 37830 Oak Ridge, Tennessee, USA

(Received 17 May 2021; accepted 6 October 2021; published 19 October 2021)

Recent data on the nuclear modification of W and Z boson production measured by the ATLAS collaboration in PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV show an enhancement in peripheral collisions, seemingly contradicting predictions of the Glauber model. The data were previously explained by arguing that the nucleon-nucleon cross section may be shadowed in nucleus-nucleus collisions and hence suppressed compared with the proton-proton cross section at the same collision energy. This interpretation has quite significant consequences for the understanding of heavy-ion data, in particular in the context of the Glauber model. Instead, we provide an alternative explanation of the data by assuming that there is a mild bias present in the centrality determination of the measurement; on the size of the related systematic uncertainty. Using this assumption, we show that the data is in agreement with theoretical calculations using nuclear parton distribution functions. Finally, we speculate that the centrality dependence of the W^-/W^+ ratio may point to the relevance of a larger skin thickness of the Pb nucleus, which, if present, would result in a few percent larger PbPb cross section than currently accounted for in the Glauber model and may hence be the root of the centrality bias.

DOI: 10.1103/PhysRevC.104.044905

I. INTRODUCTION

Recent data by the ATLAS collaboration on W [1] and Z [2] boson production in PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV are significantly more precise than earlier measurements at lower center-of-mass energy [3–7]. As commonly done, possible modifications of yields in PbPb collisions from nuclear effects were quantified with the nuclear modification factor

$$R_{AA}^{i,\rm cent} = \frac{Y_{AA}^{i,\rm cent}}{N_{\rm coll}^{\rm cent}\, Y_{pp}^{i}} = \frac{Y_{AA}^{i,\rm cent}}{T_{AA}^{\rm cent}\, \sigma_{pp}^{i}} \qquad (1)$$

by comparing the measured yields of bosons of type $i = W^+$, W^-, or Z in PbPb collisions to the yields measured in inelastic pp collisions scaled by the number of incoherent nucleon–nucleon (NN) collisions for a given collision centrality. The determination of collision centrality as well as the calculation of the number of collisions $N_{\rm coll}$ and the nuclear overlap T_{AA} relies on the Glauber model [8,9]. In the Glauber model a nucleus-nucleus (AA) collision is approximated in the eikonal formalism, where nucleons in the projectile travel along straight lines and undergo multiple independent collisions with nucleons in the target using the inelastic NN cross section σ_{NN} as internucleon interaction strength, so that $N_{\rm coll} = T_{AA}\sigma_{NN}$. The centrality, which is usually given as a percentage of the total nuclear interaction cross section, is commonly determined by fitting the expectations from the Glauber model coupled with simple mechanisms for particle production to measured multiplicity or transverse energy distributions. The absolute scale of the centrality is determined by an anchor point (AP), which relates, e.g., a measured multiplicity to a specific centrality.

The data on the modification factors for W and Z bosons were found [1,2] to exceed state-of-the-art perturbative calculations at next-to-leading (NLO) order using nuclear-modified parton distribution functions (PDFs) by 1–3 standard deviations, in particular for peripheral collisions. Eskola *et al.* argued [10] that the data can be explained by using a fitted value for σ_{NN} that is significantly smaller than the reference value used at $\sqrt{s_{\rm NN}} = 5.02$ TeV. Since the extracted value was found to be consistent with the expectations from an eikonal minijet model incorporating nuclear shadowing, their findings question the standard approach of using the measured inelastic pp cross section as input to Glauber calculations.

In this paper we provide an alternative explanation for the data by assuming a bias of the anchor point used for the centrality determination, where the size of the bias is compatible with the related systematic uncertainties of the measurement. We furthermore explore the influence of the neutron skin on the centrality dependence of W^+ and W^- bosons, as well as potential consequences for the overall PbPb cross section used in the Glauber model. The paper is structured as follows: In Sec. II we first discuss in more detail the nuclear shadowing explanation offered by Eskola *et al.* [10] and its potential shortcomings. In Sec. III, we introduce the assumed

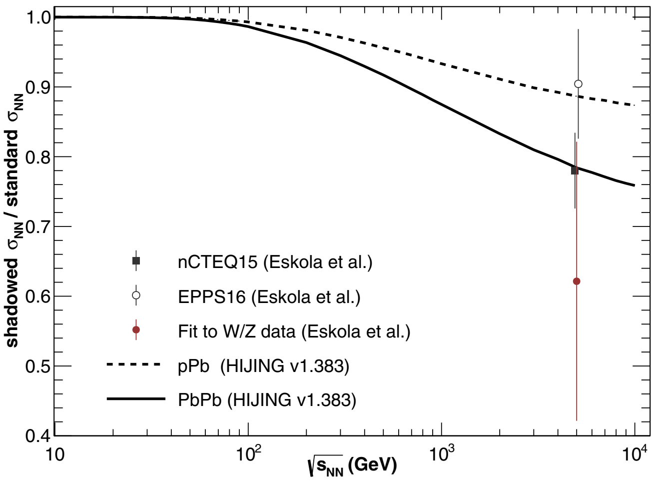

FIG. 1. Ratio of shadowed over standard inelastic cross section in pPb and PbPb collisions as function of $\sqrt{s_{\rm NN}}$ calculated with HIJING [11]. The results from Eskola *et al.* [10], i.e., the fit to the boson data as well as the computed cross sections at 5.02 TeV with their minijet model, normalized by 70 mb, are also shown. The reported central values were slightly shifted to assign symmetric uncertainties. For the calculations, the results for different factorization scales were combined assuming they were independent of each other.

AP bias and show that it counteracts the multiplicity bias usually present for high-$p_{\rm T}$ probes. In Sec. IV, we construct a reference model for the R_{AA} that includes no nuclear effects by incorporating the centrality dependence of the isospin and the deduced residual bias and compare the reference model with the data. In Sec. V, we discuss the influence of the neutron skin on the measurement. Finally, we summarize our findings in Sec. VI.

II. SHADOWING OF THE INELASTIC NUCLEON-NUCLEON CROSS SECTION?

As mentioned above, Eskola *et al.* showed [10] that data and calculations on the boson R_{AA} can be brought to agreement, when using a fitted value of $\sigma_{NN} = 41.5^{+16.2}_{-12.0}$ mb instead of 70 ± 5 mb (or instead of the more precise value of 67.6 ± 0.6 mb [12]). The extracted cross section turned out to be consistent with the expectations from an eikonal minijet model incorporating nuclear shadowing using the EPPS16 [13] or nCTEQ15 [14] nuclear PDFs (see Fig. 1). Using a different value for σ_{NN} than the measured inelastic pp cross section as input to Glauber calculations would break binary-collision scaling and hence question the common approach to construct a reference for the number of hard collisions obtained in AA collisions using the Glauber model. Furthermore, the potential shadowing of the inelastic cross section is collision energy and system dependent. As demonstrated in Fig. 1, which also shows the ratio of shadowed over standard inelastic cross section in pPb and PbPb collisions as function of $\sqrt{s_{\rm NN}}$ calculated with the HIJING [11] minijet model, the effect increases with increasing collision energy, and is roughly twice as strong for PbPb than for pPb collisions. For PbPb collisions at 5.02 TeV, HIJING predicts a similar suppressed cross section as the nCTEQ15 calculation, while the EPPS16 calculation expects a smaller suppression, both consistent with the suppressed results but with no suppression. At the highest RHIC energy of $\sqrt{s_{\rm NN}} = 0.2$ TeV, the expected suppression is already below 5%.

The central value of about 41.5 mb for the reduced cross section is rather small, only about 60% of the typical σ_{NN} used at 5.02 TeV and of similar magnitude as the unshadowed cross section at the highest RHIC energy. Using $\sigma_{NN} = 41.5$ mb essentially squeezes AA collisions into a smaller range of impact parameters, and the relative change of T_{AA} to the T_{AA} computed at 67.3 mb increases with decreasing centrality reaching factor ≈1.5 for most-peripheral collisions. This would result in an observable change for the nuclear modification factors measured previously at 5.02 TeV, which primarily have been measured for hadrons and jets, would be smaller, by up to 35% in most-peripheral collisions.

For nominal σ_{NN} derived from inelastic pp collision data [12], Glauber MC calculations give $\sigma^{\rm MC}_{\rm PbPb} = 7.55 \pm 0.15$ b at $\sqrt{s_{\rm NN}} = 2.76$ TeV and $\sigma^{\rm MC}_{p\rm Pb} = 2.08 \pm 0.03$ b at $\sqrt{s_{\rm NN}} = 5.02$ TeV, in good agreement with the measured values of $\sigma_{\rm PbPb} = 7.7 \pm 0.6$ b [15], and $\sigma_{p\rm Pb} = 2.08 \pm 0.08$ b [16,17], respectively. Reducing the input σ_{NN} by 40% for PbPb and 20% for pPb collisions reduces the respective total cross sections computed by Glauber MC by about 5%, which is about the relative size of the respective systematic uncertainties. At high collisions energies (and with large nuclei) the measurement of the total AA cross section is complicated by the huge background generated by the electromagnetic fields of the incoming nuclei, making a direct measurement of this effect difficult.

III. MULTIPLICITY AND ANCHOR POINT BIAS

As discussed above, an explanation of the data through the assumption of significant shadowing the inelastic NN cross section σ_{NN} implies rather strong consequences for interpreting the data using the Glauber model and would affect earlier measurements in PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV, in particular precise measurements of charged particle R_{AA} in peripheral collisions [18–20]. It is therefore important to explore alternative explanations of the data, focusing on the measurement itself and possible biases rather than to conclude immediately assuming physical effects. Before discussing the possible biases and their effect on the data, we mention a few details of the measurement and the associated systematic uncertainties. We focus on the Z-boson measurement [2], which is reported for minimum-bias collisions, i.e., integrated over the 0%–100% centrality range. Even though many arguments are also valid for the W-boson measurement [1], we choose the Z-boson measurement as a starting point due to the fact that isospin effects are small (see Table I).

Even a centrality-integrated measurement depends on the estimate of the total hadronic sample and hence implicitly on the centrality determination (unless a cross section is directly measured in PbPb collisions). The Z-boson yield $Y = \frac{N\varepsilon}{n_{\rm evts}c}$ was obtained from the measured raw Z-boson candidate yield N, corrected for signal impurity and inefficiency ε, divided by

TABLE I. Calculated fiducial cross sections $\sigma_{pp}^{\rm fid}$ for W and Z bosons using the MCFM [26] program at NLO with the NNPDF3.1 [27] for pp, pn, and nn collisions at $\sqrt{s} = 5.02$ TeV, as described in the text. The average value of R_{AA} due to the isospin dependence $R_{\rm iso}$ was obtained from these cross sections using the fractions $Z^2/A^2 = 0.155$, $(A-Z)^2/A^2 = 0.478$, and $2Z(A-Z)/A^2 = 0.367$ as weights. The systematic uncertainties on the cross sections are about 1% or lower and cancel in $R_{\rm iso}$. The average value of R_{AA} including nuclear effects, $R_{AA}^{\rm th}$, was obtained by taking the ratio of the cross section calculated with nuclear PDFs, nNNPDF2.0 [28], and EPPS16 [13] relative to the respective proton PDFs, NNPDF3.1 [27], and CT14 [29]. The uncertainties of $R_{AA}^{\rm th}$ are obtained from the respective PDF uncertainties propagated as uncorrelated to the ratio.

	$\sigma_{pp}^{\rm fid}$ (pb)	$\sigma_{pn}^{\rm fid}$ (pb)	$\sigma_{nn}^{\rm fid}$ (pb)	$R_{\rm iso}$	$R_{AA}^{\rm th,nNNPDF2.0}$	$R_{AA}^{\rm th,EPPS16}$
W^+	2233	1889	1554	0.81	0.725 ± 0.022	0.753 ± 0.012
W^-	1382	1614	1855	1.20	1.085 ± 0.035	1.110 ± 0.017
Z	357.7	361.9	364.5	1.01	0.933 ± 0.030	0.960 ± 0.012

the number of hadronic PbPb events $n_{\rm evts}$, corrected for trigger and event selection inefficiencies c.

The centrality classes of a measurement are usually obtained by fitting a measured quantity such as the transverse energy $E_{\rm T}$ with a Glauber model and then mapping this quantity to percentiles of the total inelastic cross section (see, e.g., Fig. 1 of Ref. [21]). However, since a measured quantity is used, various effects enter the measurement and the fully integrated $E_{\rm T}$ distribution does not correspond to the total inelastic cross section. In particular, for more-peripheral collisions, various effects influence the measured yield, such as the determination of the total event sample, contributions from (out-of-time) pileup collisions, as well as contributions from electromagnetic background sources. A so-called anchor point (AP) is determined, i.e., a value of the measured quantity above which one is certain that X percent of the total event sample are contained, that sets the absolute scale of the distribution. In case of the ATLAS measurement, the determination of the total event sample was done by anchoring the 0%–80% centrality class with a precision about 1.4% and then extrapolated to the 80%–100% class by using the Glauber model. Except for the contribution from pileup, which was quantified to be less than 2% in the most-peripheral (80%–100%) class, the background effects were accounted for, and uncertainties reaching up 7% (stat.) and 8% (sys.) were assigned. The uncertainty of the trigger and event selection were quantified to reach values of up to 5%.

From the above discussion, it is clear that the overall normalization of the PbPb collision data is crucial. An effective precision of better than a few percent in the total number of hadronic collisions needs to be achieved. Underestimating the number of hadronic collisions, will reduce the effective total cross section $\sigma_{\rm PbPb}$ (and T_{AA}) by a similar amount and may be mistakenly argued to result from a shadowed cross section. Since the total event sample is determined by using an anchor point in multiplicity or transverse energy distributions (at 80% in the transverse energy distribution measured at $3.1 < |\eta| < 4.9$ for the ATLAS measurements), we refer to a bias in the determination of the total event sample as *anchor point* (AP) bias in the following. In addition to a potential bias on the estimated total sample, a bias due to the ordering of events in multiplicity classes can arise. This bias is known as *multiplicity bias* and is discussed in detail in Ref. [22]. We now explain the effects of the two biases and their interplay, first briefly outlining the multiplicity bias and its effect on the Z-boson yield and then moving on to the effects of the assumed AP bias.

As previously explained, events are typically ordered according to multiplicity or transverse energy measured in certain rapidity intervals (see, e.g., Ref. [9]). The centrality classification, which relies on measurements dominated by soft particle production, biases the average multiplicity of individual NN collisions and hence can affect the normalization of yields of collisions dominated by hard processes due to a correlation between soft-and-hard particle production [22]. Hard scatterings are more probable in central NN collisions with large partonic overlap thereby leading a large-underlying event activity, so that a peripheral PbPb event with a hard scattering often has a hadronic activity much larger than the average in its centrality class. Peripheral nuclear events with a hard scattering can thereby be wrongly assigned to a more-central class, leading to a seemingly suppressed quantity in peripheral-centrality classes. The correlation between hard scatterings and the underlying event, which first was observed for jet production in $p\bar{p}$ collisions at $\sqrt{s} = 540$ GeV [23] is similarly present for Z-boson production (e.g., see Fig. 24 of Ref. [24]) and hence should appear also in peripheral PbPb collisions (in the form of a decreasing R_{AA} with decreasing centrality). The magnitude of the multiplicity bias on Z yield is shown in Fig. 2 resulting in a reduced yield by up to 20% in the most-peripheral centrality class. It was computed using the bias factor from the HG-PYTHIA model (Fig. 3 of Ref. [22]) taking into account that $N_{\rm coll}$ determined from so-called Glauber fits of the data already corrected for part of the bias (relevant only for the most-peripheral class, see Fig. 1 of Ref. [20]). The HG-PYTHIA model, which uses the HIJING [11] multiparton model to determine the number of hard NN collisions in a nuclear collision and the PYTHIA [25] event generator to generate the corresponding NN events, was previously used to explain the apparent suppression of the nuclear modification factor of high-$p_{\rm T}$ particle production in peripheral collisions [20].

To study the sensitivity of the measurement to the precision of the AP determination, we perform a Glauber simulation for PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV (using TGLAUBERMC [12] with $\sigma_{NN} = 67.6$ mb). The events are categorized into centrality classes obtained from ordering according to the impact parameter in the calculation. In determining a biased value for $T_{AA} = N_{\rm coll}/\sigma_{NN}$, it is assumed that the AP, nominally at 100% in our calculation, is shifted by a few

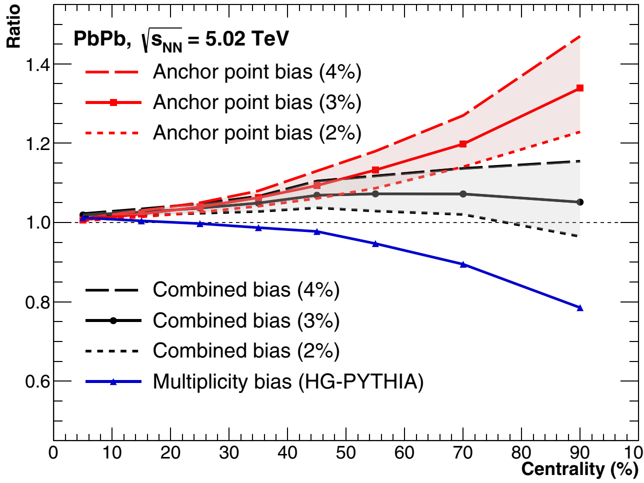

FIG. 2. Illustration of the combined bias (black) resulting from an AP bias of 2%–4% and the multiplicity bias. The effect of the AP bias (red) is expressed as the ratio of T_{AA} computed with and without the bias for PbPb collisions at 5.02 TeV using TGLAUBERMC [12] with $\sigma_{NN} = 67.6$ mb. The multiplicity bias (blue) from the centrality determination is estimated from HG-PYTHIA [22].

percent with respect to the true value, i.e., pretending that a few percent of the most-peripheral events are missed without correcting for it. The ratio of T_{AA} obtained by missing 2%–4% of the most-peripheral events to the nominal T_{AA} in intervals of centrality is shown in Fig. 2. The effect on T_{AA} (or rather N_{coll}) is quite large: Already in the 50%–60% class a 10% bias on the yield can be expected, which enlarges to 30% for the most-peripheral (80%–100%) class.

The combined bias (c_{bias}) on the expected Z-boson nuclear modification factor, which can be estimated as the product of the anchor and multiplicity biases, is shown in Fig. 2 for an assumed AP bias of 2%–4%. Already an AP bias of 2% can essentially counteract the multiplicity bias, while a 3% or 4% bias on the anchor point leads to a small, gradually increasing enhancement of up to about 5% and 10% for peripheral collisions. Hence, an alternative explanation of the enhancement seen in the data that does not rely on the shadowing of the inelastic cross section may simply be that about 3% of the hadronic events were not accounted for in the ATLAS measurement. In the rapidity-dependent centrality-integrated results, these missing events would reflect as a normalization issue, while in the centrality-dependent measurements, they would lead to an approximate constant, depending on the actual size of the AP bias also slightly rising, enhancement with decreasing centrality.

During the writing of this paper, a new Z-boson measurement of the CMS collaboration [30], which uses about three times more PbPb collision data than Ref. [1], was published, which exhibits a slightly falling R_{AA} with decreasing centrality, as expected by HG-PYTHIA and in contrast to the findings by ATLAS. To quantitatively check the consistency between the ATLAS and CMS measurements, we account for the fiducial acceptance imposed by the lepton daughter selection of $|\eta^l| < 2.5$ for the ATLAS measurement, which in PYTHIA amounts to 72%. Integrating the data from Fig. 4 of Ref. [1] and comparing with the integrated data from Fig. 2 (or the 90% point from Fig. 4) of Ref. [30] converted into yields per minimum-bias PbPb collision, we find an approximately 5% higher Z-boson yield measured by ATLAS compared with that measured by the CMS collaboration, corroborating our point.

While we focused on explaining the effects of the two biases on the Z-boson measurement, they similarly affect the W-boson measurement, in addition to the contribution of the isospin and its centrality dependence, which is stronger for $W^{\pm}$, as discussed below.

IV. REFERENCE MODEL FOR R_{AA} IN ABSENCE OF NUCLEAR EFFECTS

Using the bias factor c_{bias}, we can compute the reference of the nuclear modification factor in absence of nuclear effects for bosons of type $i = W^+, W^-$, or Z as

$$R_{AA}^{i,\mathrm{ref}}(C) = R_{AA}^{i,\mathrm{iso}}(C)c_{\mathrm{bias}}(C), \tag{2}$$

where

$$R_{AA}^{i,\mathrm{iso}}(C) = \left[f_{pp}(C)\sigma_{pp}^{i,\mathrm{fid}} + f_{pn}(C)\sigma_{pn}^{i,\mathrm{fid}} + f_{nn}(C)\sigma_{nn}^{i,\mathrm{fid}}\right]\big/\sigma_{pp}^{i,\mathrm{fid}} \tag{3}$$

describes the isospin dependence of R_{AA} versus centrality C in the absence of nuclear effects. The boson production cross sections $\sigma_{pp}^{i,\mathrm{fid}}$, $\sigma_{\mathrm{pn}}^{i,\mathrm{fid}}$, and $\sigma_{\mathrm{nn}}^{i,\mathrm{fid}}$ in pp, pn, and nn collisions at 5.02 TeV, given in Table I, were calculated at next-to-leading order (NLO) using the MCFM [26] program and NNPDF3.1 [27] parton distribution functions. The same fiducial selections as for the data were applied: $p_{\mathrm{T}}^{l,\nu} > 25$ GeV/c, $\eta^l < 2.5$, and $m_{\mathrm{T}} > 40$ GeV/c^2 for the W, and $p_{\mathrm{T}}^{l} > 20$ GeV/c, $\eta^l < 2.5$, and $66 < m_{\mathrm{inv}} < 116$ GeV/c^2 for the Z bosons. The $\sigma_{pp}^{i,\mathrm{fid}}$ were found to describe the data in pp collisions to within their respective systematic uncertainties about 1% and lower [31]. To calculate the cross sections for pn and nn collisions, a neutron PDF is needed, which is obtained from the proton PDF by exploiting isospin symmetry, i.e., switching the contributions from up and down flavors. The differences of $\sigma^{i,\mathrm{fid}}$ seen for W^+ and W^- are caused by their differing weak isospin $T_3^{W^{\pm}} = \pm 1$, where, e.g., the production of a W^+ is favored in the case of an incoming proton ($T_3^{uud} = +1/2$). The fraction of pp, pn, and nn collisions relative to all NN collisions at a given centrality was calculated using TGLAUBERMC [12] with standard settings for PbPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV (i.e., $\sigma_{NN} = 67.6$ mb), as can be seen in Fig. 14 of Ref. [12]. In central collisions, the fractions are about $f_{pp} = 0.16$, $f_{pn} = 0.48$, and $f_{nn} = 0.36$, very close to the average values of $Z^2/A^2 = 0.155$, $(A - Z)^2/A^2 = 0.478$, and $2Z(A - Z)/A^2 = 0.367$. Due to the so-called neutron skin of Pb, i.e., the fact neutrons dominantly populate the outer regions of the Pb nucleus, the number of collisions involving neutrons rise with decreasing centrality, resulting in fractions of about 0.05, 0.45, and 0.50, respectively, in most-peripheral collisions. Compared with the W bosons, Z bosons are expected to have a negligible isospin dependence on centrality, because the respective pp, pn, and nn cross sections are numerically very similar (see Table I). A more detailed

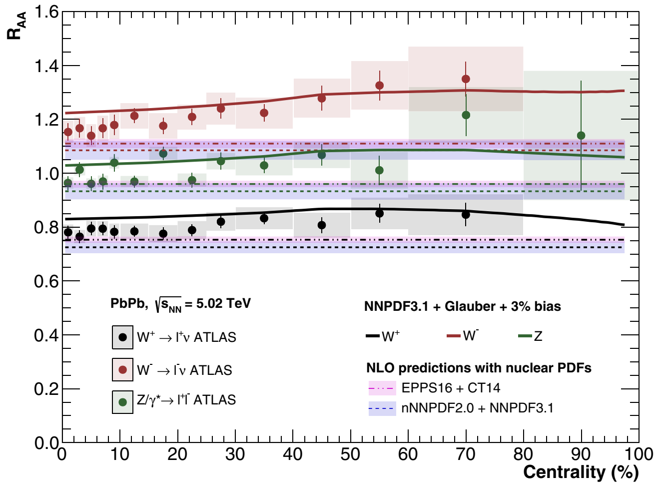

FIG. 3. Measured W^+, W^-, or Z boson R_{AA} [1,2] as a function of centrality compared with various calculations. The solid lines show the expected value for R_{AA} without nuclear modification, R_{AA}^{ref} from Eq. (2), using the NNPDF3.1 [27], a NLO cross-section calculations with the centrality-dependent weights from Glauber to describe the isospin dependence and an anchor bias of 3%, as explained in the text. The dashed lines with the shaded band denote the R_{AA}^{th} obtained from NLO calculations incorporating nuclear effects via the use of the nNNPDF2.0 [28] and EPPS16 [13] PDFs given in Table I.

discussion of the neutron skin and the sensitivity of the data to its thickness is deferred to Sec. V. In central collisions, where there is no effect from the multiplicity and AP biases (see Fig. 2), the value of R_{AA}^{ref} is close to that of the average value of R_{AA}^{iso}, which was computed using the fractions for the different collision types and the respective cross sections in Table I.

Figure 3 shows the data of the W^+, W^-, and Z boson R_{AA} measured by the ATLAS collaboration [1,2] as a function of centrality. The data are compared with our model of the expected value for R_{AA} without nuclear modification, $R_{AA}^{i,\mathrm{ref}}$ from Eq. (2), assuming the presence of a common AP bias of 3% in the data. As demonstrated in the figure, the reference calculation well describes the observed upward trend of the data and is consistent with the data in peripheral collisions. In central collisions, the data exhibit a trend to be a 3%–4% below the reference values. However, when comparing with theoretical predictions $R_{AA}^{i,\mathrm{th}}$ that do incorporate nuclear effects (dotted lines), one finds that data and predictions are consistent within uncertainties, even though the central values of the data tend to be 3%–6% above the predictions. The theoretical predictions of $R_{AA}^{i,\mathrm{th}}$ are given in Table I and were obtained by taking the ratio of the cross section calculated with the nNNPDF2.0 [28] and EPPS16 [13] nuclear PDFs relative to the respective proton PDFs, NNPDF3.1 [27], and CT14 [29]. The shown uncertainties are the 1σ uncertainties of the respective proton and nuclear PDFs, which were treated as uncorrelated in the ratio, while the scale uncertainties of the NLO calculations were canceled in the ratio.

A more precise comparison of the consistency of the data with the reference calculation is provided in Fig. 4, which shows the data divided by $R_{AA}^{i,\mathrm{ref}}$ as a function of centrality, again with the AP bias of 3%. The band around unity illustrates the change of the ratio if instead 2% or 4% had been assumed for the AP bias, confirming that the data and reference are consistent over full range of centrality. The ratio can be well described assuming a constant dependence with centrality, with about 5% suppression relative to the reference, in agreement with the predicted $R_{AA}^{i,\mathrm{th}}$, in particular when using the EPPS16 [13] nuclear PDFs. An alternative way to interpret the ratio shown in the figure is to quantify the nuclear modifications of all three bosons adjusted for isospin effects and biases, where agreement with unity would correspond to “no nuclear modification.” The differing assumptions for an underlying AP bias can then be viewed as a normalization uncertainty increasing with centrality.

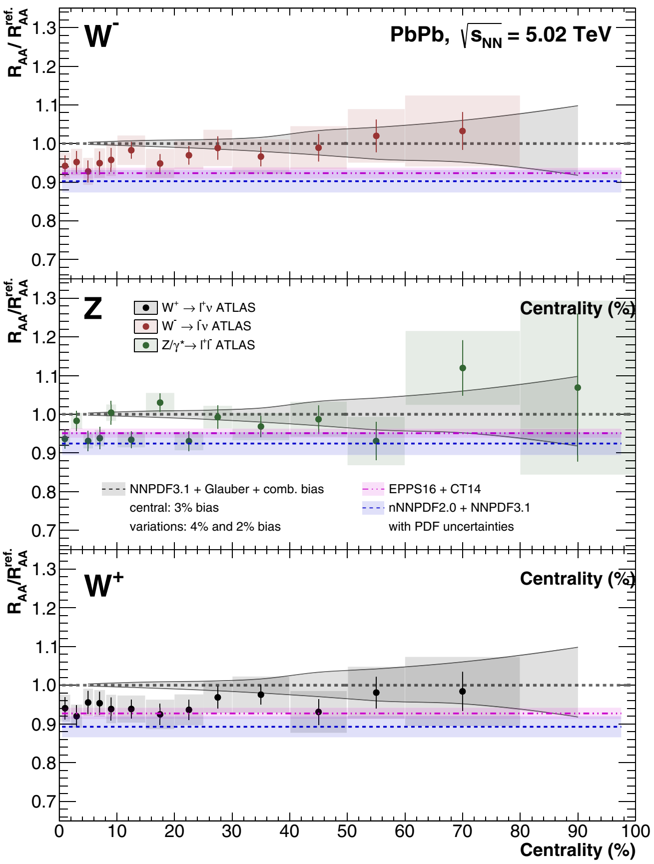

FIG. 4. Measured W^+, W^-, or Z boson R_{AA} [1,2] normalized by $R_{AA}^{i,\mathrm{ref}}$, from Eq. (2), as a function of centrality. The central value was obtained assuming an AP bias of 3% The band around unity denotes the change of the ratio if 2% (upper value) or 4% (lower value) had been assumed instead. The dashed lines with the shaded band denote the $R_{AA}^{i,\mathrm{th}}$ using the nNNPDF2.0 [28] and EPPS16 [13] PDFs normalized by $R_{AA}^{i,\mathrm{iso}}$, given in Table I.

V. INFLUENCE OF NEUTRON SKIN

To investigate the centrality dependence of the isospin, we study the $R_{AA}^{W^-}/R_{AA}^{W^+}$ ratio using the ATLAS data [1] as a function of centrality, similarly to an earlier study using an optical

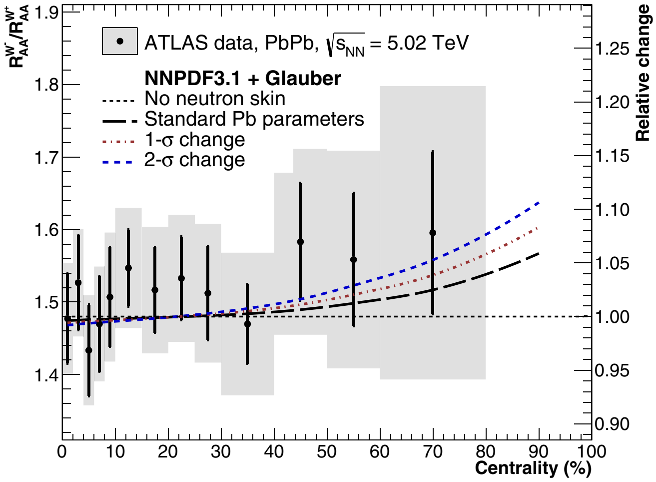

FIG. 5. $R_{AA}^{W^-}/R_{AA}^{W^+}$ ratio using the ATLAS data [1] as a function of centrality compared with the same W^-/W^- ratio computed with R_{AA}^{ref}. The y scale on the right denotes the relative change of the model relative to the baseline (no neutron skin) given by the respective R_{AA}^{iso} ratio, shown as a constant line. In the Glauber model the parameters for the proton and neutron distributions of Pb were modified by one and two standard deviations of their respective uncertainties, as described in the text.

Glauber model [32]. In this ratio, the overall normalization as well as the effects from the possible biases do not play a role, since they fully cancel. The systematic uncertainties of the data, which are also expected to cancel to some degree, in particular in peripheral collisions, were taken as independent. In Fig. 5, the data are compared with the same ratio computed with R_{AA}^{ref}, where essentially everything cancels except the dependence on the isospin resulting from the description of the Pb nucleus from protons and neutrons in the Glauber model. In TGLAUBERMC [12], the standard parameters for the radius r and the diffusivity a of the two-parameter Fermi distribution of Pb are $r_{\text{p}} = 6.68 \pm 0.02$ fm, $a_{\text{p}} = 0.447 \pm 0.01$ fm for protons and $r_{\text{n}} = 6.69 \pm 0.03$ fm, $a_{\text{n}} = 0.560 \pm 0.03$ fm for neutrons. With this default parametrization of the Pb nucleus the computed $R_{AA}^{W^-}/R_{AA}^{W^+}$ ratio exhibits a rather moderate increase of up to 5%, consistent with the data. To study the sensitivity of the isospin effect, the parameters for the proton and neutron distributions of Pb were modified by one and two standard deviations of their respective uncertainties in opposite direction, i.e., the proton parameters were reduced and the neutron parameters were enhanced, effectively probing different neutron skin thicknesses. In this way, protons get pushed more to the inside and neutrons more to the outside of the Pb nucleus, which is reflected in the changing difference of the neutron and proton root-mean-square radius ΔR from 0.15 to 0.24 and 0.33 fm, respectively, consistent with $\Delta R = 0.283 \pm 0.071$ fm [33] derived from recent measurements of parity violation in electron scattering. The investigated variations lead to a relative change of up to 10% in the expected $R_{AA}^{W^-}/R_{AA}^{W^+}$ ratio for peripheral collisions compared with the absence of a neutron skin, in good agreement with the data within the uncertainties. Currently, the large uncertainties of the data do not allow us to discriminate the Pb nucleus parameters. However, with a factor ten or more increase of integrated luminosity in Run-3/4 at the Large Hadron Collider (LHC) one certainly will be able to make a more definitive statement. This is of particular importance as the investigated changes in the Pb parameters also lead to an increase of the PbPb cross section by about 2%–4% (since neutrons were pushed outwards slightly increasing the overall Pb area). The resulting differences on the total cross section would be significantly larger than 0.6% obtained by the ATLAS collaboration when changing the TGLAUBERMC from v2.4 to v3.2 in the centrality determination [1]. The visible cross section of the forward plastic scintillating arrays of ALICE at about 50% centrality was determined [34], with about 2% precision to 3.9 b, naively extrapolated leading to $\sigma_{\text{PbPb}} = 7.8$ b consistent with a few percent increase (albeit with an uncertainty of similar size) relative to the expected cross section. In other words, the source of the AP bias may originate from a smaller neutron skin thickness implemented in the Glauber model than recently extracted from the electron parity experiments. Since all collaborations at the LHC use the same parametrization of the Pb nucleus in the Glauber calculations, it is not clear why the new CMS data [30] do not exhibit a similar problem if the underlying source of the problem stems from the skin thickness. It is imaginable (but not possible to quantitatively investigate within the scope of this paper) that the AP bias gets enhanced when relying on the anchor point at 80% (ATLAS) instead of 90% (CMS), making the ATLAS measurements more sensitive to the correction for missing events than the CMS measurement.

VI. SUMMARY

Data on the nuclear modification of W and Z bosons measured by the ATLAS collaboration in PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV show an enhancement in peripheral collisions for all three bosons that was recently explained by arguing that the nucleon-nucleon cross section may be shadowed in nucleus-nucleus collisions. This interpretation has significant consequences for the understanding of heavy-ion data, in particular in the context of the Glauber model, since the ratio of shadowed over standard inelastic cross section in pPb and PbPb collisions changes as function of collision energy (Fig. 1), and so one no longer could use the measured σ_{pp} cross section as input to the Glauber model. Instead, we provide an alternative explanation of the data by assuming that there is a mild centrality bias of about 3% present in the measurement, i.e., in the determination of the anchor point. Such an anchor-point bias would cancel the multiplicity bias present for hard probes and effectively result in a slightly rising bias with centrality on the measured boson yield (Fig. 2). We construct a reference model for the data in absence of nuclear effects by computing the isospin dependence of R_{AA} using NLO calculations and the Glauber model [Eq. (2)] together with the bias factor. The data of the W^+, W^-, or Z boson R_{AA} measured by the ATLAS collaboration are in agreement with our reference model (Fig. 3); in particular, the rising trend in the data can be well explained with our reference model. Dividing the data by the reference model we extract a rather centrality-independent suppression relative to the unmodified baseline of about 5%, consistent with NLO calculations using nuclear PDFs, in particular with the EPPS16 PDFs (Fig. 4). The centrality dependence of the $R_{AA}^{W^-}/R_{AA}^{W^+}$ ratio potentially hints at the relevance of a larger skin thickness of the Pb nucleus than presently included in the Glauber model, although the present precision of the data does not allow for a firm conclusion (Fig. 5). Higher-precision data from Run-3/4 and the LHC will be needed to investigate this possibility; these data may also be used as experimental proxy for the nuclear overlap function. Furthermore, in order to allow a centrality-determination independent measurement the boson cross section in essentially zero-bias PbPb collisions should be measured.

ACKNOWLEDGMENTS

The authors acknowledge financial support by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract number DE-AC05-00OR22725. One author was furthermore financially supported by the Federal Ministry of Education and Research (BMBF) in the ErUM Framework under contract number 05P19PMCA1.

[1] G. Aad *et al.* (ATLAS Collaboration), Measurement of $W^\pm$ boson production in PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with the ATLAS detector, Eur. Phys. J. C **79**, 935 (2019).

[2] G. Aad *et al.* (ATLAS Collaboration), Z boson production in PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV measured by the ATLAS experiment, Phys. Lett. B **802**, 135262 (2020).

[3] S. Chatrchyan *et al.* (CMS Collaboration), Study of Z Boson Production in PbPb Collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV, Phys. Rev. Lett. **106**, 212301 (2011).

[4] S. Chatrchyan *et al.* (CMS Collaboration), Study of W boson production in PbPb and pp collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV, Phys. Lett. B **715**, 66 (2012).

[5] G. Aad *et al.* (ATLAS Collaboration), Measurement of Z Boson Production in PbPb Collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV with the ATLAS Detector, Phys. Rev. Lett. **110**, 022301 (2013).

[6] S. Chatrchyan *et al.* (CMS Collaboration), Study of Z production in PbPb and pp collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV in the dimuon and dielectron decay channels, J. High Energy Phys. 03 (2015) 022.

[7] G. Aad *et al.* (ATLAS Collaboration), Measurement of the production and lepton charge asymmetry of W bosons in PbPb collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV with the ATLAS detector, Eur. Phys. J. C **75**, 23 (2015).

[8] M. L. Miller, K. Reygers, S. J. Sanders, and P. Steinberg, Glauber modeling in high energy nuclear collisions, Annu. Rev. Nucl. Part. Sci. **57**, 205 (2007).

[9] D. d'Enterria and C. Loizides, Progress in the Glauber model at collider energies, Annu. Rev. Nucl. Part. Sci. **71**, 315 (2021).

[10] K. J. Eskola, I. Helenius, M. Kuha, and H. Paukkunen, Shadowing in Inelastic Nucleon-Nucleon Cross Section? Phys. Rev. Lett. **125**, 212301 (2020).

[11] M. Gyulassy and X.-N. Wang, HIJING 1.0: A Monte Carlo program for parton and particle production in high-energy hadronic and nuclear collisions, Comput. Phys. Commun. **83**, 307 (1994).

[12] C. Loizides, J. Kamin, and D. d'Enterria, Improved Monte Carlo Glauber predictions at present and future nuclear colliders, Phys. Rev. C **97**, 054910 (2018); **99**, 019901(E) (2019).

[13] K. J. Eskola, P. Paakkinen, H. Paukkunen, and C. A. Salgado, EPPS16: Nuclear parton distributions with LHC data, Eur. Phys. J. C **77**, 163 (2017).

[14] K. Kovarik *et al.*, nCTEQ15 - Global analysis of nuclear parton distributions with uncertainties in the CTEQ framework, Phys. Rev. D **93**, 085037 (2016).

[15] B. Abelev *et al.* (ALICE Collaboration), Measurement of the Cross Section for Electromagnetic Dissociation with Neutron Emission in PbPb Collisions at $\sqrt{s_{\rm NN}} = 2.76$ TeV, Phys. Rev. Lett. **109**, 252302 (2012).

[16] B. B. Abelev *et al.* (ALICE Collaboration), Measurement of visible cross sections in proton-lead collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV in van der Meer scans with the ALICE detector, J. Instrum. **9**, P11003 (2014).

[17] V. Khachatryan *et al.* (CMS Collaboration), Measurement of the inelastic cross section in proton-lead collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV, Phys. Lett. B **759**, 641 (2016).

[18] V. Khachatryan *et al.* (CMS Collaboration), Charged-particle nuclear modification factors in PbPb and pPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV, J. High Energy Phys. 04 (2017) 039.

[19] ATLAS Collaboration, Measurement of nuclear modification factor R_{AA} in PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with the ATLAS detector at the LHC, Report number ATLAS-CONF-2017-012.

[20] S. Acharya *et al.* (ALICE Collaboration), Analysis of the apparent nuclear modification in peripheral PbPb collisions at 5.02 TeV, Phys. Lett. B **793**, 420 (2019).

[21] G. Aad *et al.* (ATLAS Collaboration), Measurement of the pseudorapidity and transverse momentum dependence of the elliptic flow of charged particles in lead-lead collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS detector, Phys. Lett. B **707**, 330 (2012).

[22] C. Loizides and A. Morsch, Absence of jet quenching in peripheral nucleus-nucleus collisions, Phys. Lett. B **773**, 408 (2017).

[23] G. Arnison *et al.* (UA1 Collaboration), Hadronic jet production at the CERN proton-antiproton collider, Phys. Lett. B **132**, 214 (1983).

[24] G. Aad *et al.* (ATLAS Collaboration), Measurement of distributions sensitive to the underlying event in inclusive Z-boson production in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector, Eur. Phys. J. C **74**, 3195 (2014).

[25] T. Sjöstrand, S. Mrenna, and P. Z. Skands, PYTHIA 6.4 physics and manual, J. High Energy Phys. 05 (2006) 026.

[26] J. Campbell and T. Neumann, Precision Phenomenology with MCFM, J. High Energy Phys. 12 (2019) 034.

[27] R. D. Ball *et al.* (NNPDF Collaboration), Parton distributions from high-precision collider data, Eur. Phys. J. C **77**, 663 (2017).

[28] R. Abdul Khalek, J. J. Ethier, J. Rojo, and G. van Weelden, nNNPDF2.0: quark flavor separation in nuclei from LHC data, J. High Energy Phys. 09 (2020) 183.

[29] S. Dulat, T.-J. Hou, J. Gao, M. Guzzi, J. Huston, P. Nadolsky, J. Pumplin, C. Schmidt, D. Stump, and C. P. Yuan, New parton distribution functions from a global analysis of quantum chromodynamics, Phys. Rev. D **93**, 033006 (2016).

[30] A. M. Sirunyan *et al.* (CMS Collaboration), High Precision Measurements of Z Boson Production in PbPb Collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV, Phys. Rev. Lett. **127**, 102002 (2021).

[31] M. Aaboud *et al.* (ATLAS Collaboration), Measurements of W and Z boson production in pp collisions at $\sqrt{s} = 5.02$ TeV with the ATLAS detector, Eur. Phys. J. C **79**, 128 (2019); **79**, 374(E) (2019).

[32] H. Paukkunen, Neutron skin and centrality classification in high-energy heavy-ion collisions at the LHC, Phys. Lett. B **745**, 73 (2015).

[33] D. Adhikari *et al.*, An Accurate Determination of the Neutron Skin Thickness of ^{208}Pb Through Parity-Violation in Electron Scattering, Phys. Rev. Lett. **126**, 172502 (2021).

[34] ALICE Collaboration, ALICE luminosity determination for PbPb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV; https://cds.cern.ch/record/2749127