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Studies of the Energy Dependence of Diboson Polarization Fractions and the Radiation-Amplitude-Zero Effect in *WZ* Production with the ATLAS Detector

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This Letter presents the first study of the energy dependence of diboson polarization fractions in $WZ \to \ell\nu\ell'\ell'(\ell,\ell' = e,\mu)$ production. The dataset used corresponds to an integrated luminosity of 140 fb^{-1} of proton-proton collisions at a center-of-mass energy of 13 TeV recorded by the ATLAS detector. Two fiducial regions with an enhanced presence of events featuring two longitudinally polarized bosons are defined. A nonzero fraction of events with two longitudinally polarized bosons is measured with an observed significance of 5.3 standard deviations in the region with $100 < p_T^Z \leq 200$ GeV and 1.6 standard deviations in the region with $p_T^Z > 200$ GeV, where p_T^Z is the transverse momentum of the Z boson. This Letter also reports the first study of the radiation-amplitude-zero effect. Events with two transversely polarized bosons are analyzed for the $\Delta Y(\ell_W Z)$ and $\Delta Y(WZ)$ distributions defined respectively as the rapidity difference between the lepton from the W boson decay and the Z boson and the rapidity difference between the W boson and the Z boson. Significant suppression of events near zero is observed in both distributions. Unfolded $\Delta Y(\ell_W Z)$ and $\Delta Y(WZ)$ distributions are also measured and compared to theoretical predictions.

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In the Standard Model (SM) of particle physics, the longitudinal polarization components of the W and Z bosons are generated by the Goldstone bosons from electroweak symmetry breaking via the Higgs mechanism. Physics beyond the SM could cause different effects on the polarization of W (or Z) bosons in diboson processes [1,2]. A sensitive test of the mechanism of electroweak symmetry breaking and gauge symmetry can thus be obtained by studying different polarization states in diboson processes. This Letter presents the first study of the energy dependence of WZ diboson polarization fractions in two fiducial regions with an enhanced presence of events featuring two longitudinally polarized bosons. In addition, it reports the first study of the radiation-amplitude-zero (RAZ) effect in WZ production with two transversely polarized bosons [3,4]. The WZ candidates are reconstructed using leptonic decay modes of the gauge bosons into electrons and muons, $WZ \to \ell\nu\ell'\ell'$ ($\ell,\ell' = e,\mu$). The dataset used corresponds to an integrated luminosity of 140 fb^{-1} of proton-proton collisions at a center-of-mass energy of 13 TeV recorded by the ATLAS detector from 2015 to 2018.

At leading-order (LO) in quantum chromodynamics (QCD), WZ production occurs through quark-antiquark interactions in the s, t, and u channels. The dominant helicity amplitude with two transversely polarized bosons is exactly zero when the scattering angle of the W boson in the WZ rest frame with respect to the incoming antiquark direction approaches 90° [3,4]. This is a direct consequence of the gauge structure in the SM. This RAZ effect leads to a dip around 0 in the $\Delta Y(WZ)$ and $\Delta Y(\ell_W Z)$ distributions, with $\Delta Y(WZ)$ defined as the rapidity difference between the W and Z bosons, and $\Delta Y(\ell_W Z)$ defined as the rapidity difference between the lepton from the W decay and the Z boson. The RAZ effect has been observed for $W\gamma$ [5–7] for which it is found that the sensitivity for $W\gamma$ resonances is enhanced in this radiation valley [8]. However, the RAZ effect has not yet been observed for WZ due to the W boson polarizations in WZ production [9]. In addition, the next-to-leading order (NLO) QCD corrections dilute the RAZ effect and make it hard to observe experimentally [10,11]. To reduce jet activity and to increase the significance of the dips, a selection criterion on the transverse momentum of the WZ system (p_T^{WZ}) is applied.

The diboson polarization fractions f_{00}, f_{TT}, f_{0T}, and f_{T0} as defined in Ref. [12] are interpreted as probabilities of correlated polarization states of the W and Z bosons. Here, 00 (TT) indicates that both bosons are longitudinally (transversely) polarized, and $0T$ ($T0$) indicates that the W (Z) boson is longitudinally polarized and the Z (W) boson is transversely polarized. The ATLAS Collaboration

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has measured both single and diboson polarization fractions using inclusive WZ events [12], which are dominated by TT events with low momentum W and Z bosons [1,2,13]. This analysis focuses on WZ events with Z bosons required to have high transverse momenta (p_T^Z). The combination of high p_T^Z and low p_T^{WZ} significantly reduces the TT contribution and increases f_{00}. As a result, f_{00} increases from 5%–7% in the inclusive region to 20%–30% in the region with high p_T^Z and low p_T^{WZ} [14].

The ATLAS detector [15] is a multipurpose particle physics detector with cylindrical geometry [16]. It consists of an inner tracking detector (ID) surrounded by a superconducting solenoid providing a 2 T axial magnetic field, sampling electromagnetic (ECAL) and hadronic calorimeters using liquid argon as active material and lead, copper or tungsten as absorber material, and a muon spectrometer (MS) based on three air-core toroidal superconducting magnets. The ATLAS trigger system consists of a hardware-based level-1 trigger followed by a software-based high-level trigger [17]. Events used for this analysis are selected with single-lepton (e or μ) triggers [17–19]. An extensive software suite [20] is used in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

Electron candidates are reconstructed from energy clusters in the ECAL matched to ID tracks. Electrons are identified using a likelihood function based on shower shape variables in the ECAL, track variables, and the quality of the track-cluster matching. Electrons are required to satisfy a "medium" likelihood requirement [21] and have $p_T > 15$ GeV and $|\eta| < 2.47$ excluding the crack region $1.37 < |\eta| < 1.52$. Muons are reconstructed by matching the tracks in the MS with tracks in the ID. Muons are required to pass a "medium" identification selection [22] and have $p_T > 15$ GeV and $|\eta| < 2.7$. Electrons and muons must be compatible with the hypothesis that they originate from the primary vertex [21,22]. They are also required to be isolated from other particles using both calorimeter-cluster and ID-track information [23].

Jets are reconstructed with the anti-k_t algorithm with a radius parameter of 0.4, using a particle-flow procedure [24] with clusters of energy deposited in the calorimeter and tracks reconstructed in the ID as inputs. Jets are required to have $p_T > 30$ GeV and $|\eta| < 4.5$. To suppress pile-up jets, jets with $p_T < 60$ GeV and $|\eta| < 2.4$ have to pass a requirement on the jet vertex tagger [25]. The missing transverse momentum vector with magnitude denoted by E_T^{miss}, is calculated as the negative vector sum of the transverse momentum of all identified "hard" physics objects (electrons, muons, jets), with a contribution from an additional soft term based on ID tracks matched to the primary vertex but not assigned to any of the "hard" objects [26]. Ambiguities in the identity of reconstructed leptons, jets, and photons are resolved with an overlap-removal procedure described in Ref. [27].

Candidate WZ events are selected using triggers that require at least one electron or muon. To ensure the trigger efficiency is well determined, at least one of the candidate leptons in the event must be trigger matched and have $p_T > 25$ GeV for data taken in 2015 or $p_T > 27$ GeV for data taken from 2016 to 2018. Events are required to contain exactly three lepton candidates satisfying the selection criteria described above. To reduce contributions from the $ZZ^{(*)} \to \ell\ell\ell'\ell'$ process, events with a fourth lepton candidate satisfying looser selection criteria are rejected. For this looser selection, the lepton p_T requirement is reduced to $p_T > 5$ GeV. Electrons are allowed to be reconstructed in the region $1.37 < |\eta| < 1.52$, and "loose" identification requirements [21,22] are used for both the electrons and muons. A less stringent requirement is also applied for electron isolation [12]. Candidate events are required to have at least one pair of leptons with the same flavor and opposite charge, with an invariant mass that is consistent with the Z boson pole mass (91.188 GeV [28]) to within 10 GeV. This pair is considered to be the Z boson candidate. If more than one pair can be formed, the pair whose invariant mass is closest to the Z boson pole mass is taken as the Z boson candidate. The remaining third lepton is assigned to the W boson decay. To suppress backgrounds with nonprompt leptons from hadron (including b-flavored and c-flavored hadrons) decays and jets misidentified as leptons, the W lepton is required to pass tighter isolation requirements and have $p_T > 20$ GeV. The transverse mass of the W candidate, defined as $m_{\mathrm{T}}^W = \sqrt{2p_T^{\ell}E_T^{\text{miss}}[1-\cos\Delta\phi]}$, is required to be greater than 30 GeV, where $\Delta\phi$ is the angle between the third lepton and the E_T^{miss} in the transverse plane, and p_T^{ℓ} the transverse momentum of the third lepton. These selection criteria are used to select inclusive WZ events. The overall acceptance times efficiency after these selections ranges from 40% to 60% depending on the channel.

The W-mass constraint method is used to calculate the longitudinal component of the neutrino momentum ($p_z(\nu)$). The E_T^{miss} of the event is assumed to come from the neutrino, and $p_z(\nu)$ is estimated by constraining the invariant mass of the third lepton and the neutrino to be the pole mass of the W boson (80.385 GeV [28]). A quadratic equation leads to two solutions. If they are real, the one with the smaller magnitude of $|p_z(\nu)|$ is chosen; otherwise, the real part is chosen [29]. The effect of these choices is consistent between the data and Monte Carlo (MC) and does not bias our measurements.

For RAZ studies, an additional criterion of $p_T^{WZ} < 20, 40$, or 70 GeV is applied to define three regions with reduced jet activity in each event. Diboson polarization fractions are measured in two regions enhanced in events with 00 polarization (00-enhanced), defined with two additional criteria applied on the inclusive region: $p_T^{WZ} < 70$ GeV, and either $100 < p_T^Z \leq 200$ GeV or $p_T^Z > 200$ GeV.

MC simulated samples are used to model the signal WZ process with different polarization states, as well as other physics processes with at least three prompt leptons. Simulated events are processed through the full ATLAS detector simulation based on GEANT4 [30,31], and reconstructed with the same algorithms as those used for the data. To simulate pileup effects, additional pp interactions are added to the MC samples in proportion to the mean interactions per bunch crossing occurring in the various data periods.

For inclusive WZ production, NLO QCD [3,32] and NLO electroweak corrections [33–35] have been calculated. Next-to-next-to-leading-order QCD corrections are also known in the on shell case, including off shell effects [36,37] and combined with electroweak corrections [38]. Diboson polarizations in WZ production have been studied at NLO QCD [39,40] and NLO QCD + electroweak accuracy [41,42]. However, the automated MC simulation with two polarized vector bosons and full spin correlations is only available at LO in the narrow-width approximation. In this analysis, polarized WZ events are generated at LO using MADGRAPH_AMC@NLO2.7.3 [43]. The boson polarizations are defined in the WZ center-of-mass frame. To account for the real part of NLO QCD corrections, events are simulated with no jets and with one jet at LO, and the two samples are merged with PYTHIA8 [44] using the CKKW-L scheme [45]. Jets are defined to have $p_T > 25$ GeV and $|\eta| < 2.5$ at the parton level. In addition, PYTHIA8 is used for the simulation of parton showering, hadronization, and the underlying event. The NNPDF3.0nlo parton distribution functions set [46] is used for the parton process generation. Separate MC samples are generated corresponding to the four states 00, $0T$, $T0$, and TT, respectively. For each polarization state, different samples are generated for $p_T^Z > 150$ GeV and $p_T^Z \leq 150$ GeV in order to increase statistics for events with high p_T^Z. Separate samples are also generated for events with at least one boson decay to τ lepton, and the τ lepton decays leptonically to an electron or a muon. An inclusive MC sample is created by adding the four polarized samples. These MC sets are referred to as MADGRAPH0,1j@LO, and the inclusive cross section is scaled to the NLO QCD prediction [47–49]. Scale factors are also derived to reweight simulated MADGRAPH0,1j@LO events to agree with data for three jet multiplicity bins (0 jets, 1 jet, and ≥ 2 jets) in the inclusive region to account for missing higher-order QCD effects.

To cross check the modeling of polarized WZ events, an inclusive $WZ \to \ell\nu\ell'\ell'$ sample is generated at NLO in QCD with SHERPA2.2.2 [50]. PYTHIA8 is used for the modeling of the parton shower, hadronization, and underlying event. The inclusive MADGRAPH0,1j@LO sample is compared to this SHERPA sample. In addition, the MADGRAPH0,1j@LO sample is also compared to the NLO QCD and NLO QCD + electroweak calculations [40–42] for each polarization state. In general good agreement is observed for polarization fractions and kinematic distributions in both inclusive and 00-enhanced signal regions.

Owing to the requirement of three isolated charged leptons in the final state, only about 10% of events come from background processes. To estimate background processes with three prompt leptons in the final state, $q\bar{q}$-initiated and gg-initiated $ZZ^{(*)}$ processes are simulated using SHERPA2.2.2. It provides a matrix element calculation accurate to NLO in QCD for zero- and one-jet final states, and LO accuracy for two- and three-jet final states. Both $t\bar{t}Z$ and $t\bar{t}W$ processes are generated at NLO in QCD using the MADGRAPH_AMC@NLO2.6.5 generator and interfaced with PYTHIA8 for the modeling of the parton shower. Triboson (VVV with $V = W$, Z) events are simulated using the SHERPA generator at NLO in QCD with 0 partons and at LO accuracy with one and two additional partons. These background samples are normalized to cross sections with higher-order corrections applied [51–54]. Backgrounds with at least one misidentified lepton (labeled as "nonprompt background") are evaluated using a data-driven technique described in Refs. [12,55].

Instrumental systematic uncertainties are related to the lepton trigger, reconstruction and identification efficiencies [22,56], lepton isolation criteria [23], lepton energy (momentum) scale and resolution [22,57], jet energy scale and resolution [58], jet vertex tagging [59,60], b-jet identification [61], modeling of E_T^{miss} [26] and pileup, and integrated luminosity [62,63].

Theoretical uncertainties associated with the signal and other background processes are evaluated using simulation. Shape and acceptance uncertainties on the WZ process due to renormalization and factorization scales [64], PDFs [65], and parton shower, are also considered. The normalization uncertainties on the processes included in the "Prompt" background category are between 10% and 20% [66–68]. Systematic uncertainties due to the potential mismodeling of NLO QCD and electroweak corrections are estimated by applying reweighting corrections estimated from Ref. [42] as a function of different sets of variables: the cosine of the scattering angle of the W boson in the WZ rest frame with respect to the z axis ($\cos\theta_V$) and $\Delta Y(\ell_W Z)$ for NLO QCD corrections, and average p_T of the three charged leptons and $\Delta Y(\ell_W Z)$ for NLO electroweak corrections. Additionally, uncertainties from the implementation of the NLO electroweak corrections are estimated by taking the difference between the additive and the multiplicative prescription as described in [38]. The interference effects among different polarization states are found to be negligible. The methods used are similar to the ones described in Ref. [69].

For the RAZ measurement, good agreement is observed between data and SM predictions for the $\Delta Y(WZ)$ and $\Delta Y(\ell_W Z)$ distributions in the three regions with $p_T^{WZ} < 20$, 40, or 70 GeV. Since a dip is expected only for the TT

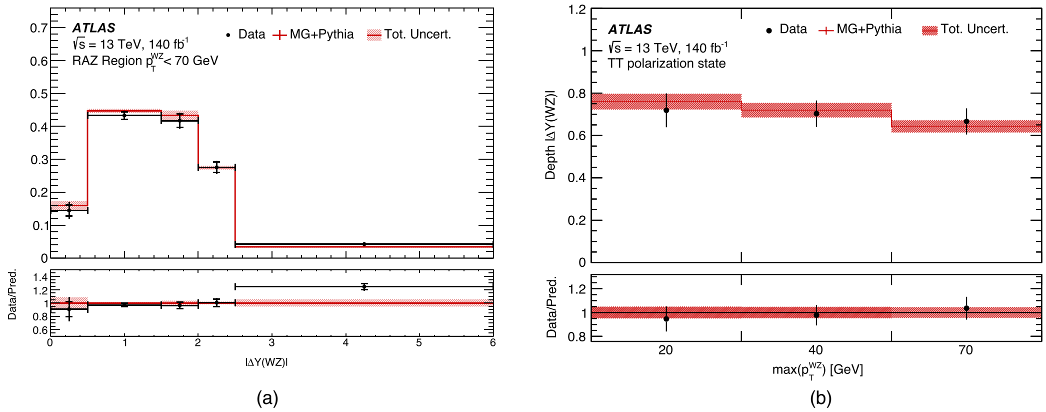

FIG. 1. (a) Comparison between the $00 + 0T + T0$-subtracted normalized unfolded $|\Delta Y(WZ)|$ data distribution and the SM prediction for TT events with $p_T^{WZ} < 70$ GeV; (b) The depth of the RAZ dip for the unfolded $|\Delta Y(WZ)|$ distribution of the TT polarization as a function of the p_T^{WZ} cut value used. The measured data are shown as black points, and the vertical error bars show the size of the total uncertainty, with tick marks used to reflect the size of the statistical uncertainty only. The MADGRAPH0,1j@LO prediction for the TT polarization state is shown in red.

component, the estimated contributions from all background processes (∼10%) and WZ 00, $0T$, and $T0$ polarization states (∼27%) are subtracted from data. The WZ 00, $0T$, and $T0$ contributions are normalized to the SM predicted cross sections. The measured $|\Delta Y(\ell_W Z)|$ and $|\Delta Y(WZ)|$ distributions for the TT polarization state are corrected for detector effects using an iterative Bayesian unfolding method [70,71] to estimate the actual particle level normalized differential cross sections in these three p_T^{WZ} regions. The unfolding procedure corrects for migrations between bins in the rapidity-difference distributions during the reconstruction of the events and applies fiducial as well as reconstruction efficiency corrections. Corrections are derived using the polarized MADGRAPH0,1j@LO samples. To reduce bias due to the assumed true distribution, the method is applied iteratively, at the cost of an increased statistical uncertainty. Three iterations are used in the final unfolding procedure. Figure 1(a) shows the comparison between the unfolded $|\Delta Y(WZ)|$ distribution and the TT-only prediction for events with $p_T^{WZ} < 70$ GeV. Good agreement is observed between these two distributions except the last bin where the discrepancy is 3.1 standard deviations. In addition, the unfolding procedure is applied to inclusive events (no subtraction of contributions from 00, $0T$, and $T0$ polarization states) in all three RAZ regions. Good agreement is also found in this case between unfolded $|\Delta Y(\ell_W Z)|$ and $|\Delta Y(WZ)|$ distributions and the SM predictions.

The depth of the RAZ dip, represented by the variable $\mathcal{D}$, is defined as $\mathcal{D} = 1–2 \times N_{\rm central}^{\rm unf}/N_{\rm sides}^{\rm unf}$, where $N_{\rm central}^{\rm unf}$ ($N_{\rm sides}^{\rm unf}$) indicates the number of events with $|\Delta Y(WZ)| < 0.5$ ($0.5 < |\Delta Y(\ell_W Z)| < 1.5$) after the unfolding. A positive value of $\mathcal{D}$ indicates the existence of a dip. A comparison between the measured and predicted $\mathcal{D}$ values using the $|\Delta Y(WZ)|$ distribution as a function of the p_T^{WZ} cut value used is shown in Fig. 1(b). The same procedure is also applied for the $\Delta Y(\ell_W Z)$ distribution, and again good agreement is observed between data and predictions for the depth of the dip observed.

Table I shows the expected signal and background event yields as well as the observed data in the two 00-enhanced regions. To measure the polarization fractions, a dedicated boosted decision tree (BDT) is trained independently to separate the 00 polarization state from the other polarization states ($0T$, $T0$, and TT) in each of the two signal regions defined by p_T^Z. The BDTs are implemented using the TMVA package [72], and the simulated MADGRAPH0,1j@LO samples are used for training. Seven variables are used for both signal regions: $\Delta Y(\ell_W Z)$, $p_T(WZ)$, the subleading lepton transverse momentum from the Z boson decay, the transverse momentum of the lepton from the W boson decay, $E_T^{\rm miss}$, the cosine of the angle

TABLE I. Number of events for the expected signal, background, and data observed in the two signal regions with $p_T^{WZ} <$ 70 GeV and either $100 < p_T^Z \leq 200$ GeV or $p_T^Z > 200$ GeV. Contributions from W_0Z_0, W_0Z_T, W_TZ_0, and W_TZ_T processes are estimated from the MC simulation before the fit is performed. The uncertainties include both statistical and systematic contributions.

Process	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
W_0Z_0	222 ± 5	47.6 ± 1.5
$W_0Z_T + W_TZ_0$	323 ± 12	23.7 ± 0.8
W_TZ_T	856 ± 31	124 ± 4
Prompt background	169 ± 18	24.1 ± 2.7
Nonprompt background	68 ± 29	2.8 ± 1.1
Total expected	1640 ± 60	222 ± 8
Data	1740	236

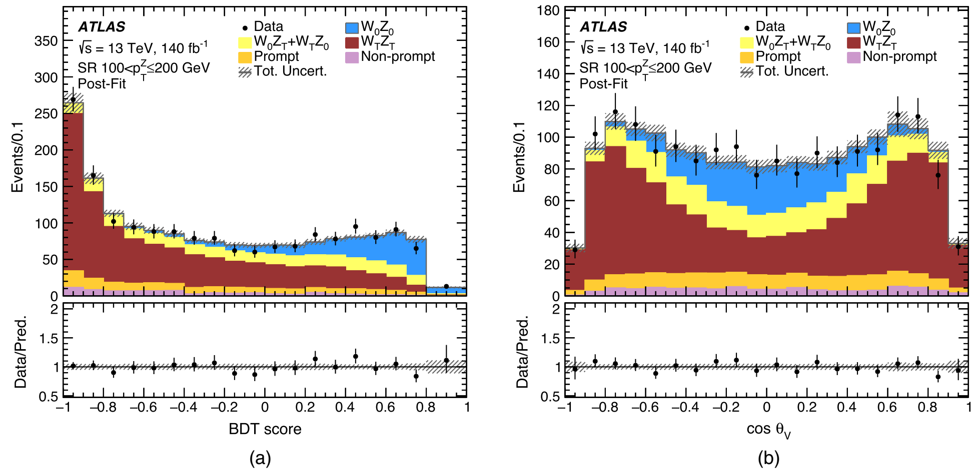

FIG. 2. The comparison between the data and the postfit SM predictions for (a) the BDT distribution and (b) the vector boson scattering angle $\cos\theta_V$ for the fiducial region with $100 < p_T^Z \leq 200$ GeV. The bottom panels show the ratios of the data to the postfit SM predictions. The uncertainty bands include both the MC statistical and systematic uncertainties.

between the direction of the lepton from the W decay in the W rest frame and the direction of the W boson in the WZ rest frame, and the cosine of the angle between the direction of the negatively charged lepton from the Z decay in the Z rest frame and the direction of the Z boson in the WZ rest frame.

Binned maximum-likelihood fits [73] are performed using the BDT score distributions in the two signal regions. Each source of systematic uncertainty is implemented in the likelihood function as a nuisance parameter with a Gaussian constraint. Three unconstrained parameters, f_{00}, f_{0T+T0}, and a signal strength modifier common to all three polarization templates, are used in the fit. The f_{0T} and f_{T0} contributions are merged into a single contribution f_{0T+T0} with the relative ratio according to the SM predictions, because they cannot be separated by our BDT. The fit includes the corrections for detector efficiency and acceptance effects, obtained from a comparison of particle-level and reconstruction-level Monte Carlo simulations. The BDT score distributions with background normalizations, signal normalization, and nuisance parameters adjusted by the profile-likelihood fit are shown in Fig. 2(a) for the fiducial region with $100 < p_T^Z \leq 200$ GeV. The comparison between the data and the postfit predictions is also shown for $\cos\theta_V$ in Fig. 2(b).

The postfit f_{00} and f_{0T+T0} parameters together with the expected and observed significances for f_{00} are detailed in Table II. For the region with $100 < p_T^Z \leq 200$ GeV, the observed (expected) significance is found to be $5.2(4.3)\sigma$. In addition, the implicit f_{TT} parameter is shown as determined by $f_{TT} = 1 - f_{00} - f_{0T+T0}$ alongside its uncertainty as determined by Gaussian error propagation. The values of the observed correlations between f_{00} and f_{0T+T0} as determined by the fits are -0.84 for the region with $100 < p_T^Z \leq 200$ GeV and -0.82 for the region with $p_T^Z > 200$ GeV.

The predicted fiducial polarization fractions listed in Table II are calculated at the particle level in a fiducial phase space chosen to closely follow the event selection criteria using the MADGRAPH0,1j@LO samples reweighted to include higher-order QCD effects and NLO electroweak corrections [42]. Prompt leptons are dressed by adding the four-momenta of nearby prompt photons within a small cone of $\Delta R < 0.1$. The distance between the two leptons from the Z boson decay is required to have $\Delta R(\ell_Z^-, \ell_Z^+) > 0.2$, and the distance between the negatively charged lepton from the Z boson decay and the charged lepton from the W boson decay is required to have $\Delta R(\ell_Z^-, \ell_W) > 0.3$. The dressed charged leptons are

TABLE II. Measured diboson polarization fractions in the two signal regions with $p_T^{WZ} < 70$ GeV and $100 < p_T^Z \leq 200$ GeV or $p_T^Z > 200$ GeV using three unconstrained parameters. The SM predicted fractions for all four polarization states are also shown.

	Measurement			Prediction	
	$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV		$100 < p_T^Z \leq 200$ GeV	$p_T^Z > 200$ GeV
f_{00}	$0.19 \pm {}^{0.03}_{0.03}(\text{stat}) \pm {}^{0.02}_{0.02}(\text{syst})$	$0.13 \pm {}^{0.09}_{0.08}(\text{stat}) \pm {}^{0.02}_{0.02}(\text{syst})$	f_{00}	0.152 ± 0.006	0.234 ± 0.007
f_{0T+T0}	$0.18 \pm {}^{0.07}_{0.08}(\text{stat}) \pm {}^{0.05}_{0.06}(\text{syst})$	$0.23 \pm {}^{0.17}_{0.18}(\text{stat}) \pm {}^{0.06}_{0.10}(\text{syst})$	f_{0T}	0.120 ± 0.002	0.062 ± 0.002
f_{TT}	$0.63 \pm {}^{0.05}_{0.05}(\text{stat}) \pm {}^{0.04}_{0.04}(\text{syst})$	$0.64 \pm {}^{0.12}_{0.12}(\text{stat}) \pm {}^{0.06}_{0.06}(\text{syst})$	f_{T0}	0.109 ± 0.001	0.058 ± 0.001
f_{00} obs (exp) sig.	$5.2(4.3)\sigma$	$1.6(2.5)\sigma$	f_{TT}	0.619 ± 0.007	0.646 ± 0.008

required to have $|\eta| < 2.5$. Leptons from the $Z(W)$ boson decay are required to have $p_T > 15(20)$ GeV. The invariant mass of the two leptons from the Z decay is required to be within $|m_{\ell\ell} - m_Z| < 10$ GeV, and the transverse mass of the W boson is required to be $m_T^W > 30$ GeV. The WZ system is required to have $p_T^{WZ} < 70$ GeV, and either $100 < p_T^Z \leq 200$ GeV or $p_T^Z > 200$ GeV.

Another fit is performed using two unconstrained parameters, f_{00} and the total number of WZ events. The mixed f_{0T+T0} and doubly transversal f_{TT} contributions are combined into a single contribution (f_{XX}) defined as $f_{XX} = 1 - f_{00}$. The 00 fraction is found to be $f_{00} = 0.17 \pm {}^{0.02}_{0.02}(\text{stat}) \pm {}^{0.01}_{0.02}(\text{syst})$ for the region with $100 < p_T^Z \leq 200$ GeV and $0.16 \pm {}^{0.05}_{0.05}(\text{stat}) \pm {}^{0.02}_{0.03}(\text{syst})$ for the region with $p_T^Z > 200$ GeV. The corresponding observed (expected) significance for a nonzero f_{00} value is $7.7(6.9)\sigma$ for the first region and $3.2(4.2)\sigma$ for the second region. This fit results in better sensitivities for f_{00}; however, it may be less conservative as the ratio of f_{0T+T0} and f_{TT} is assumed to have the value predicted by the SM.

In summary, studies of the RAZ effect and the energy dependence of diboson polarization fractions in WZ production are presented in this Letter. The measurements use leptonic decay modes of the gauge bosons to electrons or muons. Significant dips are observed in the $\Delta Y(\ell_W Z)$ and $\Delta Y(WZ)$ distributions for inclusive TT events with different p_T^{WZ} cuts applied, indicating the presence of the RAZ effect in WZ production at the LHC. Unfolded $|\Delta Y(\ell_W Z)|$ and $|\Delta Y(WZ)|$ distributions are also measured and compared to theoretical predictions. Diboson polarization fractions are measured in two signal regions with enhanced longitudinal polarization for both bosons. The measured fractions are found to be consistent with the SM predictions. A nonzero fraction of events where both bosons are longitudinally polarized is measured with an observed significance of 5.2σ (1.6σ) in the phase space with $100 < p_T^Z \leq 200$ GeV ($p_T^Z > 200$ GeV).

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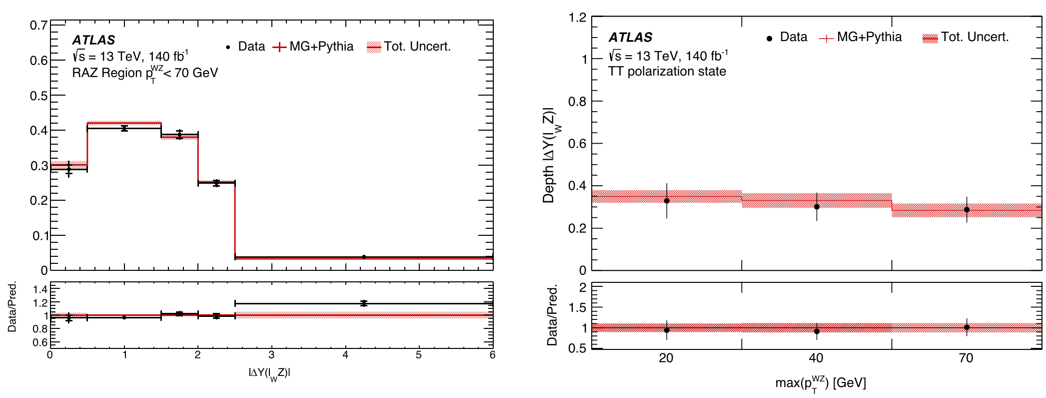
End Matter

Appendix—The unfolded distribution of the $\Delta Y(\ell_W Z)$ considering as signal the TT component for events with $p_T^{WZ} < 70$ GeV is shown in Fig. 3(a). A comparison between the measured and predicted $\mathcal{D}$ values using the $|\Delta Y(\ell_W Z)|$ distribution as a function of the p_T^{WZ} cut value used is shown in Fig. 3(b). Good agreement is observed between data and predictions for the unfolded distributions and the depth of the dip.

Unfolded $|\Delta Y(WZ)|$ and $|\Delta Y(\ell_W Z)|$ distributions for inclusive WZ events with $p_T^{WZ} < 20, 40$, or 70 GeV are also measured and compared to theoretical predictions. This alternative signal definition considers all polarization states together and avoids assumptions on the 00, $0T$, and $T0$ cross



(a) (b)

FIG. 3. (a) Comparison between the $00 + 0T + T0$-subtracted normalized unfolded $|\Delta Y(\ell_W Z)|$ data distribution and the SM prediction for TT events with $p_T^{WZ} < 70$ GeV; (b) The depth of the RAZ dip for the unfolded $|\Delta Y(\ell_W Z)|$ distribution of the TT polarization as a function of the p_T^{WZ} cut value used. The measured data are shown as black points, and the vertical error bars show the size of the total uncertainty, with tick marks used to reflect the size of the statistical uncertainty only. The MADGRAPH0,1j@LO prediction for the TT polarization state is shown in red.

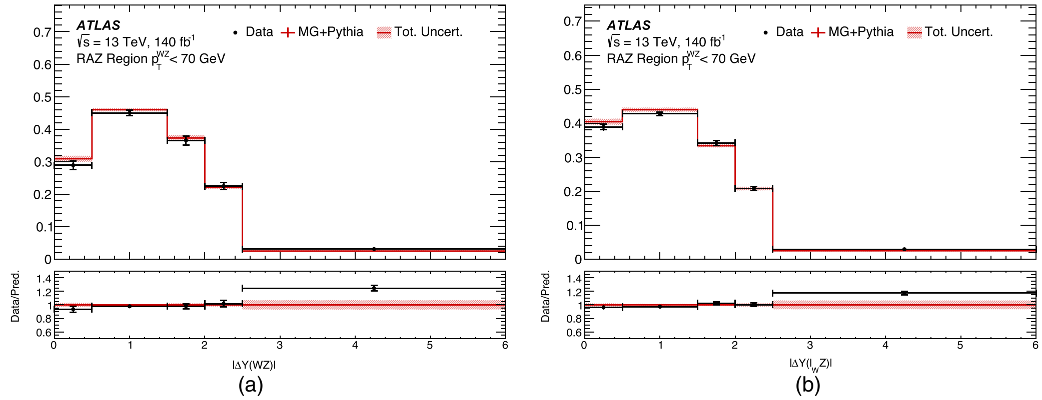


FIG. 4. Comparison between the unfolded (a) $|\Delta Y(WZ)|$ and (b) $|\Delta Y(\ell_W Z)|$ distributions and the SM prediction for inclusive WZ events with $p_T^{WZ} < 70$ GeV. The measured data are shown as black points with horizontal bars indicating the bin range and the vertical inner (outer) error bars representing the statistical (total) uncertainty. The MADGRAPH0,1j@LO prediction for the sum of all polarization states is shown in red.

sections. Figure 4 shows the comparison plots for events with $p_T^{WZ} < 70$ GeV. The uncertainties on the unfolded distributions are dominated by the data statistical uncertainty in all bins. In general, the SM predictions agree well with the measured normalized differential cross sections within the quoted uncertainties. The largest difference is observed in the last bin of the $|\Delta Y(WZ)|$ distribution reaching a local significance of 2.6 standard deviations.

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