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Evidence for Longitudinally Polarized W Bosons in the Electroweak Production of Same-Sign W Boson Pairs in Association with Two Jets in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

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This Letter reports the first evidence of electroweak production of same-sign W boson pairs where at least one of the W bosons is longitudinally polarized and the most stringent constraint to date for the production of two longitudinally polarized same-sign W bosons. 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, collected with the ATLAS detector during run 2 of the Large Hadron Collider. The study is performed in final states including two same-sign leptons (electrons or muons), missing transverse momentum, and at least two jets with a large invariant mass and a large rapidity difference. Two independent fits are performed targeting the production of same-sign W bosons with at least one, or two longitudinally polarized W bosons. The observed (expected) significance of the production with at least one longitudinally polarized W boson is 3.3 (4.0) standard deviations. An observed (expected) 95% confidence level upper limit of 0.45 (0.70) fb is reported on the fiducial production cross section of two longitudinally polarized same-sign W bosons.

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The longitudinal polarization states of the W and Z bosons are generated by the Goldstone bosons from spontaneous electroweak (EW) symmetry breaking via the Higgs mechanism [1–5] within the standard model (SM) of particle physics. The characterization of the Higgs boson discovered in 2012 [6–9] at the Large Hadron Collider [10] (LHC) is an important avenue of research for physics beyond the SM. Polarized production of W and Z boson pairs via vector-boson-scattering (VBS) processes provides a sensitive test of the EW symmetry breaking mechanism. In particular, couplings of longitudinally polarized W and Z bosons to the Higgs boson prevent the divergence of tree-level VBS amplitudes at high energies when the two outgoing bosons are longitudinally polarized, restoring the unitarity at the TeV scale [11–13]. This Letter reports studies of the EW production of polarized same-sign W boson pairs ($W^\pm W^\pm$). The first evidence of production with at least one of the W bosons longitudinally polarized is reported along with the most stringent constraint to date on the production of two longitudinally polarized same-sign W bosons. The $W^\pm W^\pm$ candidates are selected using the leptonic decay modes of the W bosons into electrons or muons, $W^\pm W^\pm \to \ell^\pm \nu \ell'^\pm \nu$, where the combination of ℓ and ℓ' can be $e^\pm e^\pm$, $e^\pm \mu^\pm$ or $\mu^\pm \mu^\pm$. The dataset corresponds to an integrated luminosity of 140.1 ± 1.2 fb^{-1} [14,15] of 13 TeV proton-proton (pp) collisions, collected with the ATLAS detector [16] during Run 2 of the LHC (2015–2018).

In pp collisions, the VBS processes at leading-order (LO) involve two initial quarks each of which radiates a gauge boson. The process is characterized by the subsequent interaction and decay of the two gauge bosons and by the presence of two jets (j), typically close to the beam direction. In the VBS production of same sign W boson pairs, the final state consists of two leptons with the same electric charge, two neutrinos, and two jets with a large rapidity separation. The EW production of $W^\pm W^\pm$ (EW $W^\pm W^\pm jj$) involves only EW interaction vertices, of which the VBS processes constitute an important component. The production of $W^\pm W^\pm jj$ involving strong interaction vertices at LO (QCD $W^\pm W^\pm jj$) is relatively small as quark-gluon and gluon-gluon initiated diagrams are not present at LO. Representative Feynman diagrams for EW $W^\pm W^\pm jj$ and QCD $W^\pm W^\pm jj$ processes are shown in Fig. 1. The ratio of the EW $W^\pm W^\pm jj$ to the QCD $W^\pm W^\pm jj$ production cross sections is of the order of five in the fiducial region of this analysis.

The first experimental observation of the unpolarized EW $W^\pm W^\pm jj$ production were reported by the CMS and ATLAS Collaborations at $\sqrt{s} = 13$ TeV using a partial LHC Run 2 data corresponding to an integrated luminosity of approximately 36 fb^{-1} [17,18]. Measurements of cross sections for the production of unpolarized EW $W^\pm W^\pm jj$

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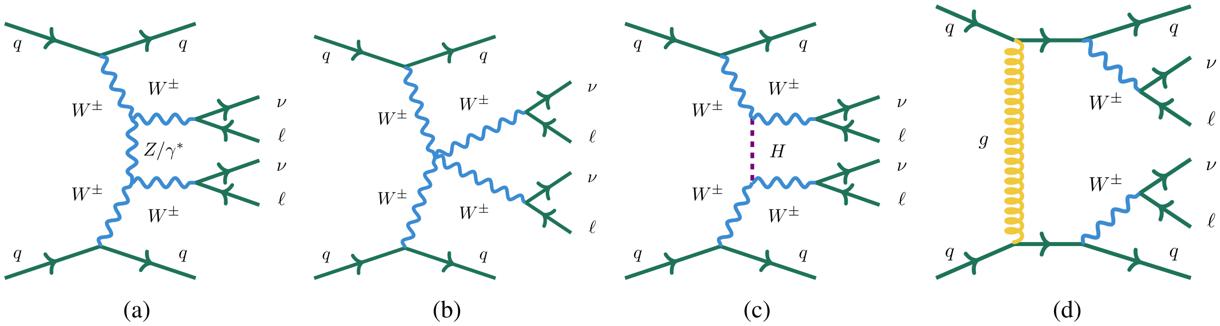

FIG. 1. Representative Feynman diagrams for a VBS EW $W^\pm W^\pm jj$ production that either include (a) triple-gauge-boson vertices, (b) a quartic gauge boson vertex, or (c) the exchange of a Higgs boson, and (d) for a QCD $W^\pm W^\pm jj$ production.

process were recently reported by the ATLAS and CMS Collaborations using the full Run 2 dataset, corresponding to an integrated luminosity of approximately 140 fb^{-1} [19,20]. The CMS Collaboration published first studies of the polarized EW $W^\pm W^\pm jj$ production, reporting an observed (expected) significance of 2.3 (3.1) standard deviations for the production with at least one longitudinally polarized W boson [21].

The polarized EW $W^\pm W^\pm jj$ production is classified into three contributions, $W^\pm_\mathrm{L} W^\pm_\mathrm{L} jj$, $W^\pm_\mathrm{L} W^\pm_\mathrm{T} jj$, and $W^\pm_\mathrm{T} W^\pm_\mathrm{T} jj$, where $W^\pm_\mathrm{L}$ and $W^\pm_\mathrm{T}$ denote longitudinally and transversely polarized W bosons, respectively. The differences in the emission process from the initial-state quarks, scattering, and decay of the $W^\pm_\mathrm{L}$ and $W^\pm_\mathrm{T}$ bosons result in kinematic differences for the final state leptons and jets [22]. The limited data sample size does not allow for a precise simultaneous measurement of the three contributions. In addition, there are nontrivial correlations between event kinematic variables, and a single kinematic distribution is not sufficient to optimally separate the different polarization contributions. Consequently, dedicated deep neural networks (DNN) are trained independently using kinematic variables to separate the $W^\pm_\mathrm{L} W^\pm_\mathrm{L} jj$ contribution from the $W^\pm_\mathrm{L} W^\pm_\mathrm{T} jj$ and $W^\pm_\mathrm{T} W^\pm_\mathrm{T} jj$ contributions ($W^\pm_\mathrm{T} W^\pm jj$) and to separate the $W^\pm_\mathrm{L} W^\pm_\mathrm{L} jj$ and $W^\pm_\mathrm{L} W^\pm_\mathrm{T} jj$ contributions ($W^\pm_\mathrm{L} W^\pm jj$) from the $W^\pm_\mathrm{T} W^\pm_\mathrm{T} jj$ contribution.

The polarization vectors are defined in the $W^\pm W^\pm$ center-of-mass reference frame. The studies are also performed using the center-of-mass reference frame of the initial-state partons to define the polarization vectors. The choice of the $W^\pm W^\pm$ center-of-mass reference frame leads to a larger contribution of the $W^\pm_\mathrm{L} W^\pm_\mathrm{L} jj$ process compared to the center-of-mass reference frame of the initial-state partons or protons [23,24]. The expected contributions of the $W^\pm_\mathrm{L} W^\pm_\mathrm{L} jj$ and $W^\pm_\mathrm{L} W^\pm_\mathrm{T} jj$ processes, defined using the $W^\pm W^\pm$ center-of-mass reference frame, are about 10% and 30% of the overall expected EW $W^\pm W^\pm jj$ production cross section, respectively. The fractions of the $W^\pm_\mathrm{L} W^\pm_\mathrm{L} jj$ ($W^\pm_\mathrm{L} W^\pm_\mathrm{T} jj$) and $W^\pm_\mathrm{L} W^\pm_\mathrm{T} jj$ ($W^\pm_\mathrm{T} W^\pm_\mathrm{T} jj$) processes in the $W^\pm_\mathrm{L} W^\pm jj$ ($W^\pm_\mathrm{T} W^\pm jj$) signal sample are fixed to the SM prediction.

The ATLAS detector [16] is a multipurpose particle physics detector with cylindrical geometry [25]. 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 (HCAL) calorimeters, and a muon spectrometer (MS) based on three air-core toroidal superconducting magnets with eight coils each. The ATLAS trigger system consists of a hardware-based level-1 trigger followed by a software-based high-level trigger [26]. An extensive software suite [27] 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.

Detailed information about the reconstruction, identification, and calibration of physics objects, as well as the simulation, triggers, and event selection used in this analysis, can be found in Ref. [20] which reports the measurements of fiducial and differential cross sections of the unpolarized $W^\pm W^\pm jj$ production. A brief description is given here. The final state probed by this analysis consists in the leptonic decays (electrons or muons) of two W bosons produced in association with two jets. Candidate events used for this analysis are selected with single-lepton (e or μ) triggers [26,28,29].

Electron candidates are reconstructed from ECAL energy clusters and matched to a track reconstructed in the ID [30]. Electrons are identified using a likelihood function based on shower shape variables in the ECAL, ID track variables, and the quality of the track-cluster matching. Electrons are required to satisfy the "Tight" likelihood-based identification criteria [31] and have to have $p_T > 27$ GeV and $|\eta| < 2.47$ excluding the calorimeter transition region $1.37 < |\eta| < 1.52$. A charge selector tool based on boosted decision trees uses shower shape and track-to-cluster matching variables [30] to reject electron candidates where the charge is likely misidentified. Muons are reconstructed from tracks in the MS, matched to a corresponding track in the ID [32]. Muons are identified by a set of requirements on the number of hits in the different

ID subdetectors and different MS stations, on the track fit properties, and on variables that test the compatibility of the individual measurements in the two detector systems. Muons are required to satisfy the "medium" identification selection [32] and have $p_T > 27$ GeV and $|\eta| < 2.5$. Electrons and muons must be compatible with the hypothesis that they originate from the primary vertex and are required to satisfy the "Gradient" [30] and "PflowTight" [32] isolation criteria, respectively.

Jets are reconstructed using the anti-k_t algorithm [33,34], with a radius parameter of $R = 0.4$, using particle-flow objects [35] as input. Contamination from jets originating in additional pp interactions per bunch crossing (pile-up) is reduced by using the jet-vertex-tagger algorithm [36]. At least two jets with $|\eta| < 4.5$ are required to be present in each event, with $p_{\mathrm{T}} > 65$ GeV for the leading jet and $p_{\mathrm{T}} > 35$ GeV for the subleading jet.

The event selection in the signal region (SR) requires a same-sign lepton pair with an invariant mass $m_{\ell\ell}$ greater than 20 GeV. The missing transverse momentum, with magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$, must be larger than 30 GeV in the SR to exploit the presence of neutrinos in the final state. The $E_{\mathrm{T}}^{\mathrm{miss}}$ is calculated from the negative vector sum of the transverse momenta of all of the selected and calibrated objects in the event including a track-based soft term [37]. The VBS topology is characterized by at least two jets with a large invariant mass, m_{jj}, and a large absolute rapidity difference, $|\Delta y_{jj}|$. The m_{jj} of the two highest-p_{T} jets must satisfy $m_{\mathrm{jj}} > 500$ GeV with $|\Delta y_{jj}| > 2.0$. Additional requirements to suppress background contributions from the Drell-Yan background in the dielectron final state, from top quark processes, and from processes with more than two leptons in the final state are described in Ref. [20]. The data yield in the SR is 475 events. The expected purities in the SR of the EW and QCD $W^{\pm}W^{\pm}jj$ processes and of their interference are approximately 58%, 5.2%, and, 1.6%, respectively. The interference effects among the different $W^{\pm}W^{\pm}jj$ polarization states in the SR are found to be negligible.

The SM production of WZ/γ^* boson pairs in association with two jets, denoted as $W^{\pm}Zjj$, constitutes a large background, contributing to approximately 16% of the overall expected event yield in the SR. It contributes when one of the leptons is not selected, typically because it is outside of the geometrical acceptance of the detector. The production of $W^{\pm}Zjj$ at LO has contributions both from processes that involve only electroweak (EW) interaction vertices (EW $W^{\pm}Zjj$) and from processes that involve strong interaction vertices (QCD $W^{\pm}Zjj$). The contributions of the EW and QCD $W^{\pm}Zjj$ processes are estimated with Monte Carlo (MC) simulated events. The modeling of the QCD $W^{\pm}Zjj$ process is constrained in a dedicated signal-depleted control region (CR) defined by requiring three charged leptons in the final state, $m_{\mathrm{jj}} > 200$ GeV, and a trilepton invariant mass greater than 106 GeV.

Leptons from hadron decays and jets misidentified as leptons are referred to as nonprompt leptons. The nonprompt lepton background arises mainly from $W +$ jets and semileptonic $t\bar{t}$ processes. The nonprompt lepton, electron charge misidentification and photon conversion backgrounds are estimated using data-driven methods as described in Ref. [20], and contribute to approximately 18% of the overall expected event yield. Events with the same selection criteria as in the SR but requiring $200 < m_{\mathrm{jj}} < 500$ GeV are used to define the "low-m_{jj}" CR. This CR has a similar background composition as in the SR and is used to control the uncertainties of the major background contributions. Finally, small background contributions from triboson VVV ($V = W/Z/\gamma$), $t\bar{t}V$, and tZq processes are estimated using MC simulations and together contribute to less than 2% of the expected event yield in the SR.

MC simulated event samples are used to model the signal $W^{\pm}W^{\pm}jj$ process with different polarization states, as well as other background processes. Simulated events are processed through the ATLAS simulation infrastructure [38] using GEANT4 [39]. The effect of pile-up is simulated by overlaying the hard-scattering process with minimum-bias events generated with PYTHIA8.186 [40] using the A3 set of tuned parameters [41]. Different pile-up conditions between data and simulation are taken into account by reweighting the mean number of interactions per bunch crossing in simulation to the number observed in data. Detailed descriptions of the simulated MC samples used for modeling the various background events can be found in Ref. [20]. The large QCD $W^{\pm}Zjj$ background is simulated with the SHERPA2.2.12 event generator [42] using matrix elements that contain all diagrams with four EW vertices. This process is calculated for up to one additional parton at next-to-LO (NLO) and up to three additional partons at LO using COMIX [43] and OPENLOOPS [44], and merged with the SHERPA parton shower based on the Catani-Seymour dipole factorization [45].

This analysis uses state-of-the-art calculations and simulations to incorporate the NLO EW and QCD effects in modeling the polarized EW $W^{\pm}W^{\pm}jj$ production. The polarized on-shell $W_{\mathrm{L}}^{\pm}W_{\mathrm{L}}^{\pm}jj$, $W_{\mathrm{L}}^{\pm}W_{\mathrm{T}}^{\pm}jj$, and $W_{\mathrm{T}}^{\pm}W_{\mathrm{T}}^{\pm}jj$ signal processes are simulated in narrow-width approximation using SHERPA3 [46,47] with up to one additional parton at LO in QCD and EW and merged with the SHERPA parton shower. The NNPDF3.0NLO [48] set of parton distribution function (PDF) is used. This multijet merging approach has been shown to capture the bulk of NLO QCD corrections to polarization fractions, as they typically stem from real emission rather than virtual diagrams [47,49], thus providing the most accurate hadron-level prediction available for these signal processes. Diagrams involving the s-channel and triboson contributions are omitted in this simulation by the use of the VBS approximation [50] to avoid possible divergences. The contributions of these missing diagrams and further missing off-shell production effects are estimated using unpolarized $\ell^{\pm}\nu\ell^{\pm}\nu jj$ SHERPA3 simulated samples at the same perturbative accuracy. These effects are taken into account by applying corrections to the signal predictions using all kinematic information in the full phase space via neural networks at particle level following the approach of Ref. [51]. The size of the corrections in the SR is approximately 10%. In an alternative approach, the corrections are applied via particle level m_{jj} reweighting and the resulting differences in the shapes of the signal distributions are considered as an uncertainty. This uncertainty is treated as uncorrelated among the $W_{\mathrm{L}}^{\pm}W_{\mathrm{L}}^{\pm}jj$, $W_{\mathrm{L}}^{\pm}W_{\mathrm{T}}^{\pm}jj$, and $W_{\mathrm{T}}^{\pm}W_{\mathrm{T}}^{\pm}jj$ signal processes to account for any residual differences in the size of the corrections.

The first calculations of the fixed-order next-to-LO (NLO) EW corrections for the production of polarized EW $W^{\pm}W^{\pm}jj$ production have been recently performed [24]. The pure EW corrections are dominant and reduce the LO cross section of the EW $W^{\pm}W^{\pm}jj$ process by approximately 15% in the SR and have even larger impact in high-energy tails of distributions. The NLO EW corrections have different impacts for the $W_{\mathrm{L}}^{\pm}W_{\mathrm{L}}^{\pm}jj$, $W_{\mathrm{L}}^{\pm}W_{\mathrm{T}}^{\pm}jj$, and $W_{\mathrm{T}}^{\pm}W_{\mathrm{T}}^{\pm}jj$ processes with smaller in magnitude corrections for the longitudinal modes. Their effect is taken into account by applying m_{jj} dependent factors to the signal samples. In an alternative approach, the corrections are applied as leading jet p_{T} dependent factors and the difference is considered as a systematic uncertainty.

Systematic uncertainties in this measurement arise from experimental and theory sources. The results are driven by the statistical uncertainty of the data in the SR and none of the considered systematic uncertainties have a significant impact on the sensitivity of this result. Experimental systematic uncertainties are related to the trigger, lepton reconstruction, identification and isolation efficiencies [31,32], lepton energy (momentum) scale and resolution [30,32], jet energy scale and resolution [52], b-jet identification [53], modeling of $E_{\mathrm{T}}^{\mathrm{miss}}$ [37], pile-up, and integrated luminosity [14,15]. The uncertainties related to the nonprompt lepton, electron charge misidentification, and photon conversion backgrounds are described in Ref. [20]. Theoretical uncertainties associated with the signal and other background processes are evaluated using simulation. The theory uncertainties in the physics modeling of the polarized $W^{\pm}W^{\pm}jj$ processes are estimated by varying the factorization, renormalization, resummation, and merging scales [47], the strong coupling constant α_S, and the choice of the PDF [54]. Additional uncertainties related to the propagation of the NLO EW corrections and the corrections due to the off-shell production and missing diagrams are considered as described above. The systematic uncertainties with the largest impact on the result are related to the finite number of data events used for data-driven background estimates, the theory uncertainties in the physics modeling of the polarized $W^{\pm}W^{\pm}jj$ production, and uncertainties in the jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ scale and resolution.

To measure the production of the $W_{\mathrm{L}}^{\pm}W_{\mathrm{L}}^{\pm}jj$ and $W_{\mathrm{L}}^{\pm}W^{\pm}jj$ processes, a first DNN (inclusive DNN) is trained to separate the unpolarized EW $W^{\pm}W^{\pm}jj$ production from the background processes. Two independent DNNs (signal DNNs) are then trained to extract the polarization information by separating the production of $W_{\mathrm{L}}^{\pm}W_{\mathrm{L}}^{\pm}jj$ from $W_{\mathrm{T}}^{\pm}W^{\pm}jj$ and $W_{\mathrm{L}}^{\pm}W^{\pm}jj$ from $W_{\mathrm{T}}^{\pm}W_{\mathrm{T}}^{\pm}jj$. Dedicated optimizations of the model structures and hyperparameters are performed for each DNN with the open source framework OPTUNA [55]. The number of hidden layers are 9 and 10 for the inclusive and signal DNNs, respectively, with up to 204 neurons per layer used for the $W_{\mathrm{L}}^{\pm}W^{\pm}jj$ signal DNN. The kinematic variables showing the best discrimination, evaluated by removing each variable and retraining the network, are retained. Up to 20 such variables are retained for each DNN from a larger set. The variable importance is also evaluated with the SHAP framework [56]. The m_{jj} variable provides a strong discrimination for the inclusive DNN as background processes tend to have smaller m_{jj} values than those from the EW $W^{\pm}W^{\pm}jj$ production. Similarly, angular variables such as the differences in the azimuthal angle, pseudorapidity, and distance ΔR between the leading and subleading leptons and jets provide an important separation for the signal DNNs. Kinematic variables related to the transverse mass and p_{T} of the systems constructed from the leptons, jets, and $E_{\mathrm{T}}^{\mathrm{miss}}$ are also considered. The distributions of selected kinematic variables showing a strong discrimination for the $W_{\mathrm{L}}^{\pm}W^{\pm}jj$ signal DNN are shown in Fig. 2. Events from $W_{\mathrm{L}}^{\pm}W_{\mathrm{L}}^{\pm}jj$ generally exhibit larger $|\Delta\eta_{\ell\ell}|$ and $\Delta\phi_{jj}$, and smaller m_{T}, than those from $W_{\mathrm{T}}^{\pm}W_{\mathrm{T}}^{\pm}jj$. A complete list of variables used for the DNNs, along with the distributions of additional discriminating variables, is discussed in the Appendix. The modeling of these DNN scores for the background processes is validated in the low-m_{jj} CR.

Binned maximum-likelihood fits are performed separately for the $W_{\mathrm{L}}^{\pm}W_{\mathrm{L}}^{\pm}jj$ and $W_{\mathrm{L}}^{\pm}W^{\pm}jj$ processes using the inclusive and the corresponding signal DNN score distributions. The signal DNN score distributions in three regions of the inclusive DNN score, with boundaries at (0, 0.2, 0.6, 1.0) and (0, 0.3, 0.7, 1.0), are fitted for the $W_{\mathrm{L}}^{\pm}W_{\mathrm{L}}^{\pm}jj$ and $W_{\mathrm{L}}^{\pm}W^{\pm}jj$ processes, respectively. The region boundaries are chosen independently to maximize the significances of the $W_{\mathrm{L}}^{\pm}W_{\mathrm{L}}^{\pm}jj$ and $W_{\mathrm{L}}^{\pm}W^{\pm}jj$ processes while ensuring that each bin contains at least 10 events originating from the other processes. For each fit, the three regions of the inclusive DNN score in the SR, the low-m_{jj} and QCD

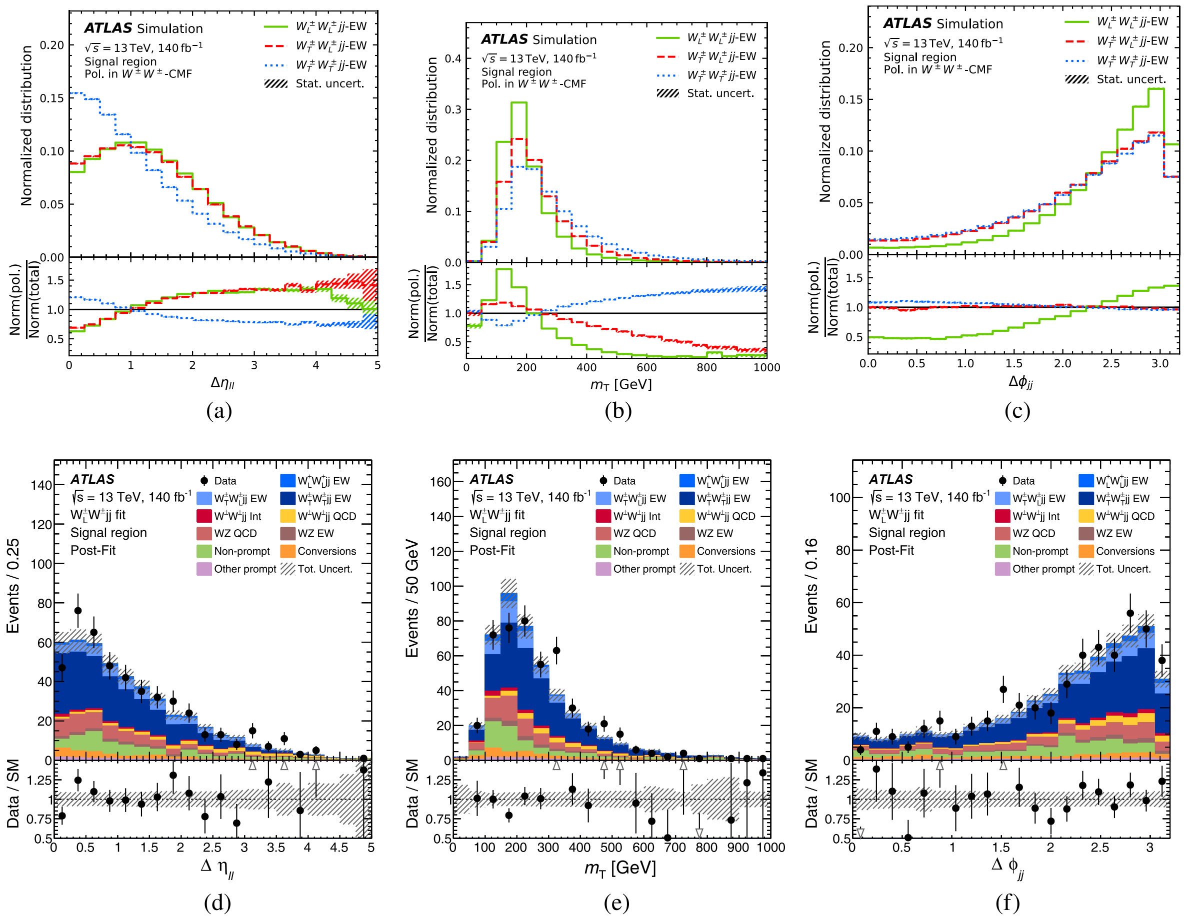

FIG. 2. Distributions in the SR for the [(a) and (d)] difference in pseudorapidity between the leading and subleading leptons, $|\Delta\eta_{\ell\ell}|$, [(b) and (e)] transverse mass of the dilepton system and $E_{\mathrm{T}}^{\mathrm{miss}}$ [20], m_{T}, and [(c) and (f)] difference in azimuthal angle between the leading and subleading jets, $\Delta\phi_{jj}$. The ratios of the contributions of each process to the total contribution are shown in the bottom panels in (a)–(c). The predicted yields are shown with their best-fit normalization and shape in (d)–(f). The shaded area surrounding the expectation represents the total uncertainties in the predicted yields. The ratios of the observed yields to the total SM predictions are shown by the points in the bottom panels. The "other prompt" category combines ZZ, VVV, $t\bar{t}V$, and tZq background processes. The polarization vectors are defined in the $W^\pm W^\pm$ center-of-mass reference frame.

$W^\pm Zjj$ CRs are fitted simultaneously with the $W_{\mathrm{L}}^\pm W_{\mathrm{L}}^\pm jj$ ($W_{\mathrm{L}}^\pm W^\pm jj$), $W_{\mathrm{T}}^\pm W^\pm jj$ ($W_{\mathrm{T}}^\pm W_{\mathrm{T}}^\pm jj$), and QCD $W^\pm Zjj$ normalizations kept as floating parameters. The relatively small contributions of the EW $W^\pm Zjj$ and QCD $W^\pm W^\pm jj$ processes are normalized to the SM predictions and allowed to vary within their uncertainties. The systematic uncertainties are included as nuisance parameters [57] with Gaussian priors. The nuisance parameters are adjusted in the fit with the shape and normalization of each distribution varying within the specified constraints.

The signal DNN score distributions in each region of the inclusive DNN are shown in Fig. 3 with the normalizations and nuisance parameters adjusted by the fit. A good separation between the different polarization states is achieved. The post-fit yields are shown in the Appendix. The normalization factors for the QCD $W^\pm Zjj$ process are 0.74 ± 0.08 and 0.75 ± 0.08 for the $W_{\mathrm{L}}^\pm W_{\mathrm{L}}^\pm jj$ and $W_{\mathrm{L}}^\pm W^\pm jj$ fits, respectively, consistent with the value reported in Ref. [20]. No uncertainties are significantly constrained or pulled in the simultaneous fit.

The fiducial cross sections times branching fraction for the $W_{\mathrm{L}}^\pm W_{\mathrm{L}}^\pm jj$ [$\sigma\mathcal{B}(W_{\mathrm{L}}^\pm W_{\mathrm{L}}^\pm jj)$] and $W_{\mathrm{L}}^\pm W^\pm jj$ [$\sigma\mathcal{B}(W_{\mathrm{L}}^\pm W^\pm jj)$] processes are extracted in the fiducial region defined to be as close as possible to the detector region as described in Ref. [20]. The fiducial phase space definition requires two prompt leptons at particle level (e or μ) with $p_{\mathrm{T}} > 27$ GeV and $|\eta| < 2.5$, dressed by adding the four-momenta of nearby prompt photons within a small cone of $\Delta R < 0.1$, with $m_{\ell\ell} > 20$ GeV. Contributions of events with τ-leptons from at least one of the W boson decays, with the τ-lepton decaying leptonically to an electron or a muon, are excluded from the fiducial region definition. At least two jets are required at particle level with $|\eta| < 4.5$ and $p_{\mathrm{T}} > 65$ GeV (35 GeV)

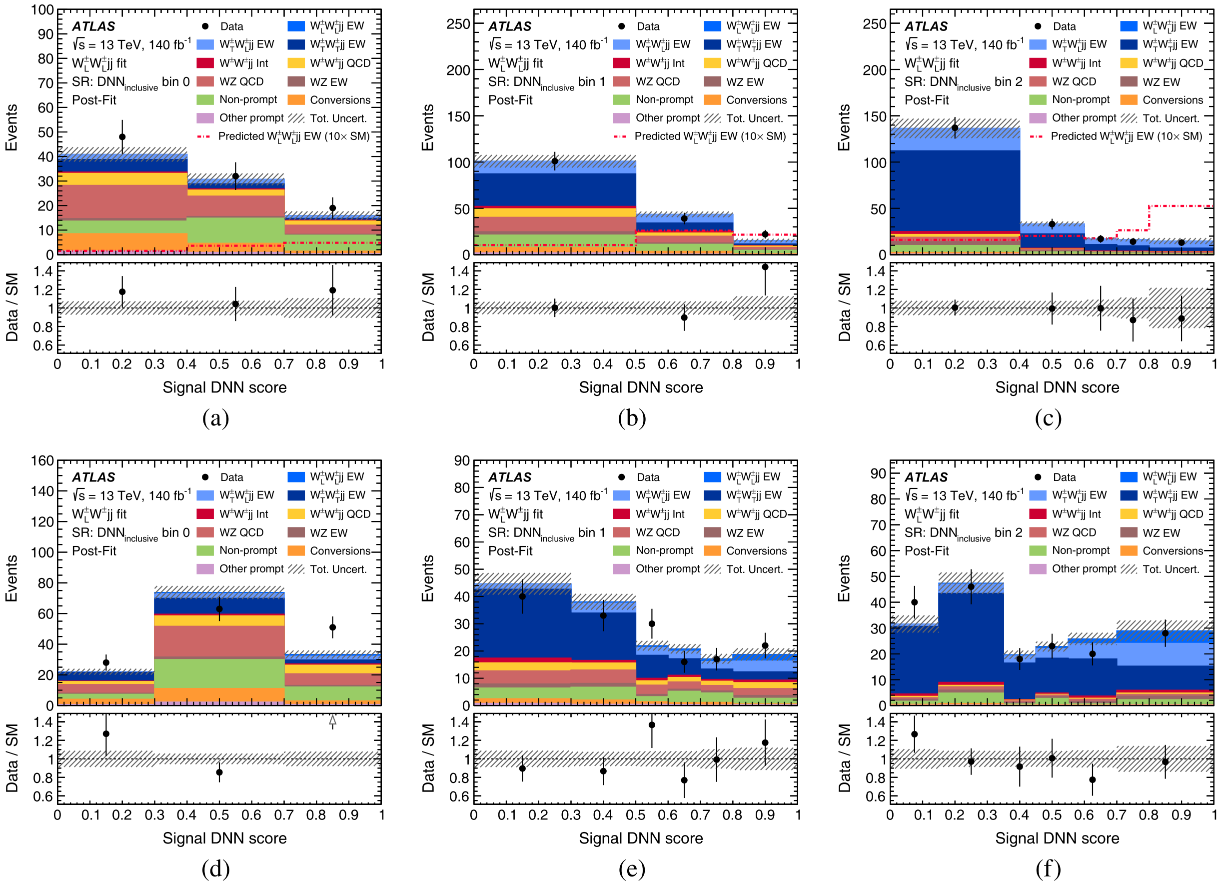

FIG. 3. Distributions of the signal DNN score in the SR for the $W^{\pm}_{\mathrm{L}}W^{\pm}_{\mathrm{L}}jj$ measurement in regions of the inclusive DNN with score values of (a) 0 to 0.2, (b) 0.2 to 0.6, and (c) 0.6 to 1, and for the $W^{\pm}_{\mathrm{L}}W^{\pm}jj$ measurement in regions of the inclusive DNN with score values of (d) 0 to 0.3, (e) 0.3 to 0.7, and (f) 0.7 to 1. The polarization vectors are defined in the $W^{\pm}W^{\pm}$ center-of-mass reference frame. The predicted yields are shown with their best-fit normalization and shape. The shaded area surrounding the expectation represents the total uncertainties in the predicted yields. The ratios of the observed yields to the total SM predictions are shown by the points in the bottom panels. The other prompt category combines ZZ, VVV, $t\bar{t}V$, and tZq background processes. The dashed lines in (a)–(c) show the SM predictions of the $W^{\pm}_{\mathrm{L}}W^{\pm}_{\mathrm{L}}jj$ contributions multiplied by a factor of 10.

for the leading (subleading) jet, with the m_{jj} of the two highest-p_{T} jets greater than 500 GeV and $|\Delta y_{jj}| > 2$.

No significant excess of events consistent with the $W^{\pm}_{\mathrm{L}}W^{\pm}_{\mathrm{L}}jj$ production is observed. The observed (expected) 95% confidence level (C.L.) upper limit on $\sigma\mathcal{B}(W^{\pm}_{\mathrm{L}}W^{\pm}_{\mathrm{L}}jj)$ is 0.45 (0.70) fb. The 95% C.L. limits are derived using the $\mathrm{CL_s}$ method [58,59]. The expected limit is evaluated using an Asimov dataset [60] assuming the SM contributions of the $W^{\pm}_{\mathrm{L}}W^{\pm}_{\mathrm{L}}jj$ and $W^{\pm}_{\mathrm{T}}W^{\pm}jj$ processes. Assuming the null hypothesis of no contribution from the $W^{\pm}_{\mathrm{L}}W^{\pm}_{\mathrm{L}}jj$ process, an expected 95% C.L. upper limit of 0.43 fb on $\sigma\mathcal{B}(W^{\pm}_{\mathrm{L}}W^{\pm}_{\mathrm{L}}jj)$ is obtained using an Asimov dataset. The significance of a nonzero $W^{\pm}_{\mathrm{L}}W^{\pm}jj$ event yield is quantified assuming contributions only from the $W^{\pm}_{\mathrm{T}}W^{\pm}_{\mathrm{T}}jj$ process. The observed significance for the $W^{\pm}_{\mathrm{L}}W^{\pm}jj$ process is 3.3σ with an expected significance, evaluated with an Asimov dataset, of 4.0σ. The asymptotic approximation [60], whose validity was confirmed through studies with pseudoexperiments, is used to calculate the limits and significances.

The measured $\sigma\mathcal{B}(W^{\pm}_{\mathrm{L}}W^{\pm}_{\mathrm{L}}jj)$ and $\sigma\mathcal{B}(W^{\pm}_{\mathrm{T}}W^{\pm}jj)$, and $\sigma\mathcal{B}(W^{\pm}_{\mathrm{L}}W^{\pm}jj)$ and $\sigma\mathcal{B}(W^{\pm}_{\mathrm{T}}W^{\pm}_{\mathrm{T}}jj)$, and the corresponding theoretical predictions from SHERPA3 are summarized in Table I. The NLO EW corrections and the corrections to take into account the off-shell production and missing contributions as described earlier are included in the predictions. The uncertainties in the predictions are dominated by the scale variations, with an uncertainty of about 24%. The measured cross sections are in agreement with the SM predictions. The results of the studies performed using the initial-state parton-parton reference frame to define the polarization vectors are shown in the Appendix.

In summary, this Letter reports the first evidence of EW production of polarized same-sign W boson pairs where at least one of the W bosons is longitudinally polarized and the most stringent limits to date on the fiducial cross section

TABLE I. Measured and predicted fiducial cross sections for the $W^\pm_{\mathrm{L}}W^\pm_{\mathrm{L}}jj$ and the $W^\pm_{\mathrm{T}}W^\pm jj$, and the $W^\pm_{\mathrm{L}}W^\pm jj$ and the $W^\pm_{\mathrm{T}}W^\pm_{\mathrm{T}}jj$ processes. The polarization vectors are defined in the $W^\pm W^\pm$ center-of-mass reference frame. The total measurement uncertainty is shown along with the statistical, modeling systematic and experimental systematic uncertainties. The modeling uncertainties include the theory uncertainties affecting the signal and background processes as well as the effect of a finite number of MC events and of data events used for data-driven background estimates. The predicted cross sections from SHERPA3 include the NLO EW corrections and the corrections to take into account the off-shell production and missing contributions. The predicted cross section uncertainties include the PDF, α_S, parton shower, and scale variations.

Process	Predicted $\sigma\mathcal{B}$ (fb)	Measured $\sigma\mathcal{B}$ (fb)	Uncertainty breakdown (fb)
$W^\pm_{\mathrm{L}}W^\pm_{\mathrm{L}}jj$	0.29 ± 0.07	0.01 ± 0.21(tot)	± 0.20(stat) $\pm$ 0.02(mod syst) $\pm$ 0.05(exp syst)
$W^\pm_{\mathrm{T}}W^\pm jj$	2.56 ± 0.64	3.39 ± 0.35(tot)	± 0.30(stat) $\pm$ 0.08(mod syst) $\pm$ 0.16(exp syst)
$W^\pm_{\mathrm{L}}W^\pm jj$	1.18 ± 0.29	0.88 ± 0.30(tot)	± 0.28(stat) $\pm$ 0.05(mod syst) $\pm$ 0.08(exp syst)
$W^\pm_{\mathrm{T}}W^\pm_{\mathrm{T}}jj$	1.67 ± 0.40	2.49 ± 0.32(tot)	± 0.30(stat) $\pm$ 0.05(mod syst) $\pm$ 0.12(exp syst)

of two longitudinally polarized same-sign W bosons. 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, collected with the ATLAS detector at the LHC. The study is performed in final states including two same-sign leptons (electrons or muons), missing transverse momentum, and at least two jets with large invariant mass and a large rapidity difference. An observed (expected) 95% C.L. upper limit of 0.45 (0.70) fb is reported on the EW production of two longitudinally polarized same-sign W bosons. The observed significance of the production with at least one longitudinally polarized W boson is 3.3 standard deviations with a measured fiducial cross section of 0.88 ± 0.30 fb, in agreement with the SM prediction.

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Data availability—The data that support the findings of this Letter are not publicly available. The data are available from the authors upon reasonable request.

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End Matter

Appendix—The variables used in the training and optimization of the DNNs are summarized in Table II. The distributions of selected variables showing a significant separation between the $W_L^\pm W_L^\pm jj$, $W_L^\pm W_T^\pm jj$, and $W_T^\pm W_T^\pm jj$ processes are shown in Fig. 4. The expected signal and background yields in the SR for different regions of the inclusive DNN score are shown in Table III. A summary of the fractional uncertainties on $\sigma\mathcal{B}(W_L^\pm W^\pm jj)$ measurement is shown in Table IV.

The results of the studies performed using the initial-state parton-parton reference frame to define the polarization vectors are reported. The measured $\sigma\mathcal{B}(W_L^\pm W_L^\pm jj)$ and $\sigma\mathcal{B}(W_T^\pm W^\pm jj)$, and $\sigma\mathcal{B}(W_L^\pm W^\pm jj)$ and $\sigma\mathcal{B}(W_T^\pm W_T^\pm jj)$, and the corresponding theoretical predictions from

TABLE II. Variables used in the training and optimization of the DNNs. The variables are scaled with different scaling functions for the training and application.

Kinematics	Descriptions	Scaling
	Object-level variables	
$p_T^{\ell_1}$	p_T of the leading lepton	$\log_{10}(x)$
$\eta^{\ell 1}$	η of the leading lepton	x
ℓ_1 type	Flavor of the leading lepton	x
$p_T^{\ell_2}$	p_T of the subleading lepton	$\log_{10}(x)$
η^{ℓ_2}	η of the subleading lepton	x
$\phi^{\ell_2}-\phi^{\ell_1}$	Difference in azimuthal angle between the leading and subleading leptons	x
ℓ_2 type	Flavor of the subleading lepton	x
$p_T^{j_1}$	p_T of the leading jet	$\log_{10}(x)$
η^{j_1}	η of the leading jet	x
$\phi^{j_1}-\phi^{\ell_1}$	Difference in azimuthal angle between the leading jet and leading lepton	x
$p_T^{j_2}$	p_T of the subleading jet	$\log_{10}(x)$
η^{j_2}	η of the subleading jet	x
$\phi^{j_2}-\phi^{\ell_1}$	Difference in azimuthal angle between the subleading jet and leading lepton	x
E_T^{miss}	Missing transverse momentum	$\log_{10}(x)$
$\phi(E_T^{\text{miss}})-\phi^{\ell_1}$	Difference in azimuthal angle between the missing transverse momentum and leading lepton	x
	Event-level variables	
$Z^\star_{\ell_1}$	Zeppenfeld variable of the leading lepton [62]	$\sqrt{x}$
$Z^\star_{\ell_2}$	Zeppenfeld variable of the subleading lepton [62]	$\sqrt{x}$
$m_T^{\ell_1}$	Transverse mass of the leading lepton and E_T^{miss}	$\sqrt{x}$
$m_T^{\ell_2}$	Transverse mass of the subleading lepton and E_T^{miss}	$\sqrt{x}$
$\Delta R_{\ell\ell}$	Distance ΔR between the leading and subleading leptons	x
$\Delta\eta_{\ell\ell}$	Difference in pseudorapidity between the leading and subleading leptons	$\sqrt{x}$
$m_{\ell\ell}$	Invariant mass of the two leptons	$\log_{10}(x)$
$p_T^{\ell\ell}$	p_T of the dilepton system	$\sqrt{x}$
m_T	Transverse mass of the dilepton system and E_T^{miss} [20]	$\sqrt{x}$
m_T^o	Projected transverse mass $\sqrt{(p_T^{\ell_1}+p_T^{\ell_2}+E_T^{\text{miss}})^2-(\vec{p}_T^{\,\ell_1}+\vec{p}_T^{\,\ell_2}+\vec{E}_T^{\text{miss}})^2}$ [63]	$\sqrt{x}$
ΔR_{jj}	Distance ΔR between the leading and subleading jets	x
Δy_{jj}	Rapidiy difference between the leading and subleading jets	x
m_{jj}	Invariant mass of the two jets	$\log_{10}(x)$
$\Delta\phi_{jj}$	Difference in azimuthal angle between the leading and subleading jets	x
$(p_T^{\ell_1}\cdot p_T^{\ell_2})/(p_T^{j_1}\cdot p_T^{j_2})$	p_T ratio of the leptons and jets [22]	$\log_{10}(x+0.02)$
$\min(\Delta R_{\ell,j})$	Minimal distance ΔR between the leptons and jets	x

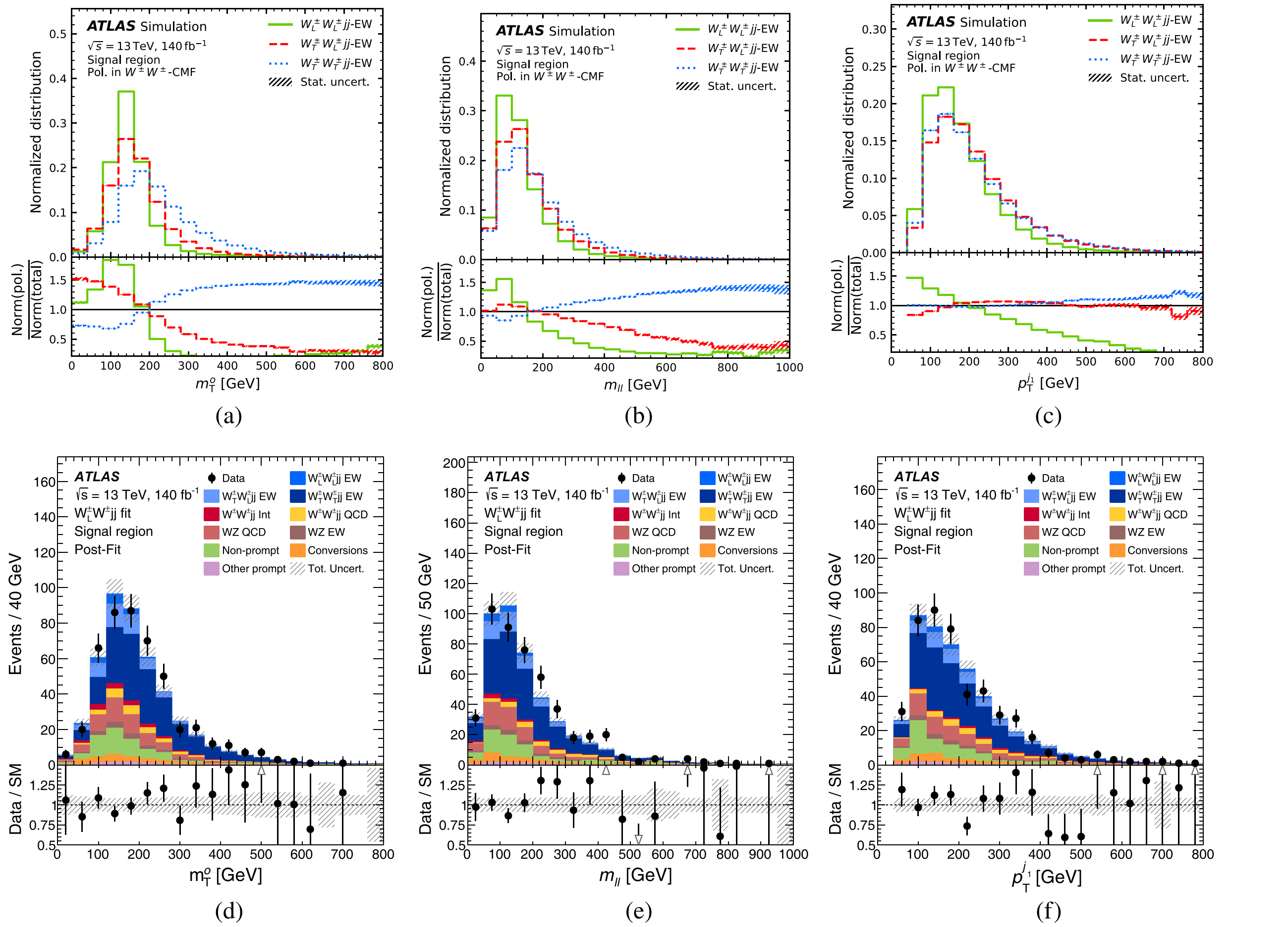

FIG. 4. Distributions in the SR for the [(a) and (d)] m_T^o, [(b) and (e)] $m_{\ell\ell}$, and [(c) and (f)] $p_T^{j_1}$. The ratios of the contributions of each process to the total contribution are shown in the bottom panels in (a)–(c). The predicted yields are shown with their best-fit normalization and shape in (d)–(f). The shaded area surrounding the expectation represents the total uncertainties in the predicted yields. The ratios of the observed yields to the total SM predictions are shown by the points in the bottom panels. The other prompt category combines ZZ, VVV, $t\bar{t}V$, and tZq background processes. The polarization vectors are defined in the $W^{\pm}W^{\pm}$ center-of-mass reference frame.

SHERPA3 are shown in Table V. The observed significance for the $W_L^{\pm}W^{\pm}jj$ process is 2.5σ with an expected significance of 3.5σ. The observed (expected) 95% C.L. upper limit on $\sigma\mathcal{B}(W_L^{\pm}W_L^{\pm}jj)$ is 0.60 (0.63) fb. The expected limit is evaluated using an Asimov data set assuming the SM contributions of the $W_L^{\pm}W_L^{\pm}jj$ and $W_T^{\pm}W^{\pm}jj$ processes. An expected limit of 0.46 fb is obtained using an Asimov dataset assuming the null hypothesis of no contribution from the $W_L^{\pm}W_L^{\pm}jj$ process.

TABLE III. Post-fit expected signal and background yields and observed data events in the SR. The yields are shown for the fit for the $W_L^\pm W^\pm jj$ measurement in regions of the inclusive DNN score. The total uncertainties in the predicted yields are shown. The conversions category combines $V\gamma$ and charge misidentifcation background processes. The other prompt category combines ZZ, VVV, $t\bar{t}V$, and tZq background processes. The polarization vectors are defined in the $W^\pm W^\pm$ center-of-mass reference frame.

Process	Region 0 to 0.3	Region 0.3 to 0.7	Region 0.7 to 1
$W_L^\pm W_L^\pm jj$	1.8 ± 0.7	5.6 ± 1.9	8.3 ± 2.8
$W_L^\pm W_T^\pm jj$	6.0 ± 2.5	17.8 ± 6.2	25.7 ± 8.5
$W_T^\pm W_T^\pm jj$	18.4 ± 4.4	64.0 ± 10.0	111.9 ± 14.7
QCD $W^\pm W^\pm jj$	14.4 ± 4.1	12.5 ± 3.5	2.6 ± 0.8
Int $W^\pm W^\pm jj$	2.3 ± 0.1	6.0 ± 0.2	4.8 ± 0.1
QCD $W^\pm Zjj$	33.3 ± 2.6	20.3 ± 1.6	4.5 ± 0.4
EW $W^\pm Zjj$	3.3 ± 0.1	6.2 ± 0.2	5.5 ± 0.2
Nonprompt	31.2 ± 4.3	20.2 ± 2.9	10.4 ± 3.1
Conversions	14.6 ± 3.7	6.2 ± 1.8	1.6 ± 0.5
Other prompt	3.7 ± 0.7	2.6 ± 0.6	0.8 ± 0.2
Total SM	129 ± 7	161 ± 10	176 ± 13
Data	142	158	175

TABLE IV. The fractional uncertainty of different components on the $\sigma\mathcal{B}(W_L^\pm W^\pm jj)$ measurement. The contribution of a systematic uncertainty (uncertainty group) to the total uncertainty is evaluated by fixing the respective NP (NPs) to its (their) best-fit value(s), redoing the fit, and subtracting the uncertainties in the cross-section in quadrature. The procedure is implemented incrementally such that the sum in quadrature of the grouped systematic and statistical uncertainties corresponds to the total cross-section uncertainty by construction. Lepton calibration uncertainties encompass the effects of the calibration of lepton energy or momentum scale and resolution, as well as the lepton trigger, reconstruction, identification, and isolation efficiencies. The background modeling statistical category is related to the effect of a finite number of data events used for data-driven background estimates and of MC events. The polarization vectors are defined in the $W^\pm W^\pm$ center-of-mass reference frame.

Source of uncertainty	$\Delta\sigma/\sigma$ (%)
Experimental	
Lepton calibration	0.2
Jet energy and E_T^{miss} scale and resolution	3.9
Pileup modeling	1.2
Background, charge misidentification and photon conversion	0.5
Background, nonprompt	4.2
Background modeling statistical	7.2
Luminosity	1.1
Modeling	
$W^\pm W^\pm jj$ EW + QCD uncertainties	4.7
Background, WZ scale, PDFs, and α_s	0.4
Background, WZ reweighting	0.3
Small background normalizations	1.1
Normalization factors	2.5
Experimental and modeling	11.1
Data statistical	32.2
Total	34.1

TABLE V. Measured and predicted fiducial cross sections for the $W^{\pm}_{\mathrm{L}}W^{\pm}_{\mathrm{L}}jj$ and the $W^{\pm}_{\mathrm{T}}W^{\pm}jj$, and the $W^{\pm}_{\mathrm{L}}W^{\pm}jj$ and the $W^{\pm}_{\mathrm{T}}W^{\pm}_{\mathrm{T}}jj$ processes. The polarization vectors are defined in the initial-state parton-parton reference frame. The total measurement uncertainty is shown along with the statistical, modeling systematic and experimental systematic uncertainties. The modeling uncertainties include the theory uncertainties affecting the signal and background processes as well as the effect of a finite number of MC events and of data events used for data-driven background estimates. The predicted cross sections from SHERPA3 include the NLO EW corrections and the corrections to take into account the off-shell production and missing contributions. The predicted cross section uncertainties include the PDF, α_S, and scale variations.

Description	Predicted $\sigma\mathcal{B}$ (fb)	Measured $\sigma\mathcal{B}$ (fb)	Uncertainty breakdown (fb)
$W^{\pm}_{\mathrm{L}}W^{\pm}_{\mathrm{L}}jj$	0.19 ± 0.05	0.16 ± 0.22(tot)	± 0.21(stat) $\pm$ 0.02(mod syst) $\pm$ 0.06(expt syst)
$W^{\pm}_{\mathrm{T}}W^{\pm}jj$	2.67 ± 0.66	3.40 ± 0.35(tot)	± 0.31(stat) $\pm$ 0.08(mod syst) $\pm$ 0.16(expt syst)
$W^{\pm}_{\mathrm{L}}W^{\pm}jj$	1.24 ± 0.31	0.84 ± 0.37(tot)	± 0.35(stat) $\pm$ 0.05(mod syst) $\pm$ 0.11(expt syst)
$W^{\pm}_{\mathrm{T}}W^{\pm}_{\mathrm{T}}jj$	1.62 ± 0.39	2.46 ± 0.37(tot)	± 0.34(stat) $\pm$ 0.06(mod syst) $\pm$ 0.14(expt syst)

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