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Observation of WWW Production in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector

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This Letter reports the observation of WWW production and a measurement of its cross section using 139 fb^{-1} of proton-proton collision data recorded at a center-of-mass energy of 13 TeV by the ATLAS detector at the Large Hadron Collider. Events with two same-sign leptons (electrons or muons) and at least two jets, as well as events with three charged leptons, are selected. A multivariate technique is then used to discriminate between signal and background events. Events from WWW production are observed with a significance of 8.0 standard deviations, where the expectation is 5.4 standard deviations. The inclusive WWW production cross section is measured to be $820 \pm 100\,(\mathrm{stat}) \pm 80\,(\mathrm{syst})$ fb, approximately 2.6 standard deviations from the predicted cross section of 511 ± 18 fb calculated at next-to-leading-order QCD and leading-order electroweak accuracy.

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Measurements of triboson production at colliders directly probe the strength of gauge boson self-interactions within the standard model (SM) via triple gauge couplings and quartic gauge couplings [1,2]. Any significant deviations from the SM predictions would provide evidence of new physics at a higher energy scale than is presently accessible [3–8]. Triboson final states are among the least-understood SM processes due to their small production cross sections. In particular, searches for the production of three W bosons (WWW) have been performed by both the ATLAS [9,10] and CMS [11,12] Collaborations. Using proton-proton (pp) collisions at a center-of-mass energy ($\sqrt{s}$) of 13 TeV delivered by the Large Hadron Collider (LHC) [13], the ATLAS Collaboration analyzed 80 fb^{-1} of data and provided evidence for both WWW and WWZ/WZZ production [10], and the CMS Collaboration analyzed 137 fb^{-1} of data and observed the combined production of three massive vector bosons (WWW, WWZ, WZZ, and ZZZ) [12].

This Letter reports the observation of WWW production and a measurement of its cross section using 139 fb^{-1} of data at $\sqrt{s} = 13$ TeV [14] taken with the ATLAS detector. At leading order (LO) in QCD, WWW production can proceed via the radiation of each W boson from a fermion, via a W boson produced in association with an intermediate Z/γ^* or Higgs boson that decays via the WW^* intermediate state, or via a quartic gauge coupling vertex. Representative Feynman diagrams are shown in Fig. 1. The analysis selection is sensitive to processes with both on-shell and off-shell W boson decays. For simplicity all these processes (including $WH \to WWW^*$) are generically referred to as WWW throughout this Letter. Two decay channels, $WWW \to \ell^\pm \nu \ell^\pm \nu qq$ and $WWW \to \ell^\pm \nu \ell^\pm \nu \ell^\mp \nu$ with $\ell = e$ or μ, are considered and are hereafter referred to as 2ℓ and 3ℓ, respectively. Events with electrons and muons produced through τ leptons are also included. The experimental signature of the 2ℓ channel consists of two same-sign charged leptons, missing transverse momentum, and two jets, while the signature of the 3ℓ channel consists of three charged leptons and missing transverse momentum.

The ATLAS detector [15] is a multipurpose particle physics detector with cylindrical geometry [16]. It consists of an inner tracker (ID) surrounded by a superconducting solenoid, sampling electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer (MS) with three toroidal superconducting magnets. A two-level trigger system is used to select events for storage. Events used in this analysis were selected online by single-electron or single-muon 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.

The proton interaction vertex with the highest p_T^2 sum of associated ID tracks is selected as the primary vertex. Electrons are reconstructed from energy deposits in the EM calorimeter associated with tracks found in the ID. Muons are reconstructed by combining tracks reconstructed in the ID with tracks or track segments found in the MS. Electrons (muons) must have $p_T > 20$ GeV and be reconstructed within $|\eta| < 2.47$ ($|\eta| < 2.5$), excluding electrons within

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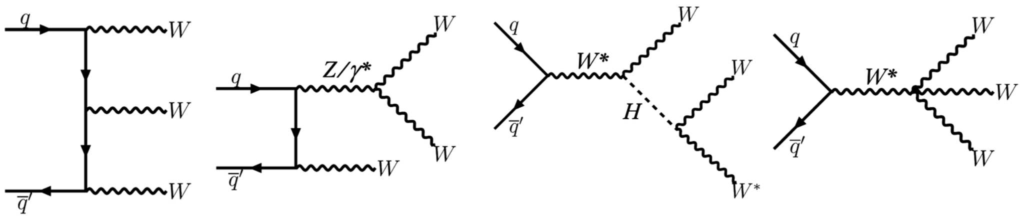

FIG. 1. Representative Feynman diagrams at LO for the production of three massive W bosons, including diagrams sensitive to triple and quartic gauge couplings.

$1.37 < |\eta| < 1.52$. To ensure that selected leptons originate from the primary vertex, their tracks are required to have $|d_0/\sigma_{d_0}| < 5(3)$ for electrons (muons) and $|z_0 \sin\theta| < 0.5$ mm for both lepton flavors, where d_0 and σ_{d_0} are the transverse impact parameter and its uncertainty, and z_0 is the longitudinal impact parameter. Electrons are required to satisfy the "tight" likelihood-based identification criterion defined in Ref. [21], and muons must satisfy the "medium" cut-based identification criterion defined in Ref. [22]. To reject leptons that likely originate from light-hadron decays or heavy-flavor decays, leptons are required to pass a tight isolation requirement ("PLVTight") [23], which takes into account the energy deposits and charged-particle tracks (including the lepton track) in a cone around the lepton direction. Electrons must also satisfy a charge identification criterion based on a boosted decision tree (BDT) discriminant [24] to reduce the contamination from electrons with misidentified electric charge.

Particle-flow jets are reconstructed from tracks in the ID and topological energy clusters in the calorimeter [25]. Jet candidates are required to have $p_T > 30$ GeV in the forward region ($2.5 < |\eta| < 4.5$) and $p_T > 20$ GeV in the central region ($|\eta| < 2.5$). To reduce the effect from additional pp collisions in the same or a nearby bunch crossing (pileup), jets with 20 GeV $< p_T <$ 60 GeV and $|\eta| < 2.5$ are required to pass a "jet vertex tagger" requirement [26]. Jets containing b-flavored hadrons ("b jets") are identified by a multivariate discriminant [27,28] combining track impact parameter values with information from secondary vertices reconstructed within the jet. A working point corresponding to an 85% efficiency for identifying b jets in $t\bar{t}$ events is used. Procedures described in Ref. [10] that ensure the selected electron, muon, and jet candidates do not overlap are applied before the lepton "PLVTight" and $|d_0/\sigma_{d_0}|$ requirements.

The missing transverse momentum, whose magnitude is denoted by E_T^{miss}, is calculated as the negative of the vector sum of the transverse momenta of all reconstructed objects associated with the primary vertex. To account for soft hadronic activity, a term including tracks associated with the primary vertex but not with any of the reconstructed objects is included in the calculation of E_T^{miss} [29].

To select candidates in the 2ℓ signal regions (SRs), events are required to have exactly two leptons with the same electric charge, at least two central jets, and no identified b jets. Three final states based on the lepton flavors are considered, namely $e^\pm e^\pm$, $e^\pm\mu^\pm$, and $\mu^\pm\mu^\pm$. The highest-p_T lepton must have $p_T > 27$ GeV and the dilepton invariant mass $m_{\ell\ell}$ is required to be between 40 and 400 GeV. The two highest-p_T central jets are required to have $m_{jj} < 160$ GeV and $|\Delta\eta_{jj}| < 1.5$, where m_{jj} is the dijet invariant mass and $\Delta\eta_{jj}$ is the pseudorapidity separation between the two jets. The m_{jj} and $\Delta\eta_{jj}$ selection suppresses contributions from the $W^\pm W^\pm$ vector-boson scattering process. In the case of the $e^\pm e^\pm$ final state, the dilepton system is required to have $m_{\ell\ell} < 80$ GeV or $m_{\ell\ell} > 100$ GeV and an E_T^{miss} significance [30] requirement, $\mathcal{S}(E_T^{\text{miss}}) > 3$, is applied to suppress contributions from the $Z+$jets process where the charge of one electron is misidentified. To select candidates in the 3ℓ SR, events are required to have exactly three leptons including at least one with $p_T > 27$ GeV, no identified b jets, and no same-flavor opposite-sign (SFOS) lepton pairs. Events with $e^\pm e^\pm \mu^\mp$ and $\mu^\pm\mu^\pm e^\mp$ final states are considered. To suppress contributions from $WZ+$jets production in the 2ℓ SRs and $ZZ+$jets production in the 3ℓ SR, events are removed if they contain additional electrons (muons) reconstructed with $p_T > 7(4.5)$ GeV and $|\eta| < 2.47(2.7)$ passing the loose [21] ([22]) identification requirement.

Monte Carlo (MC) simulated samples are used to model the signal WWW process, as well as contributions from other physics processes with prompt leptons. Simulated events were processed through the full ATLAS detector simulation [31] based on GEANT4 [32]. The effects of pileup are included in the simulation.

Events with three on-shell W bosons were generated by SHERPA2.2.2 [33,34] with the NNPDF3.0NNLO parton distribution function (PDF) [35]. Events with an off-shell W boson through $WH \to WWW^*$ were generated using POWHEG BOXv2 [36] interfaced to PYTHIA8.235 [37] for parton showering [38] with the NNPDF2.3LO PDF and the AZNLO set of tuned parameters [39]. Both processes are included in the signal definition and were generated at next-to-leading-order (NLO) QCD accuracy and LO electroweak accuracy with all spin correlations taken into account in the vector-boson decays. The cross section for the process with on-shell (off-shell $WH \to WWW^*$) W bosons is 209 ± 17 fb (302 ± 8 fb). The inclusive cross section is

$\sigma^{\rm pred}(pp \to WWW) = 511 \pm 18$ fb. The cross sections and uncertainties used in this analysis are consistent with the latest calculations with NLO QCD and NLO electroweak corrections applied for the on-shell WWW process [40] and with next-to-next-to-next-to-leading-order (NNNLO) QCD and NLO electroweak corrections applied for the $WH \to WWW^*$ process [41].

The dominant background originates from the $\ell\nu\ell\ell +$ jets($WZ +$ jets) process, and its contribution is estimated using simulated events generated with SHERPA2.2.2 using the NNPDF3.0NNLO PDF and a threshold of 4 GeV on the Z boson mass. The matrix element calculations for the WZ process were performed with up to one additional parton at NLO QCD accuracy and up to three additional partons at LO QCD accuracy. To ensure proper modeling of the WZ background, the MC predictions for $WZ + 0$ jets, $WZ + 1$ jet, and $WZ + \geq 2$ jets are multiplied by scale factors obtained during the fit to the data to be described later, which includes three WZ control regions (CR). These CRs are obtained by requiring exactly three leptons with one SFOS lepton pair, $E_T^{\rm miss}$ significance $\mathcal{S}(E_T^{\rm miss}) > 3$, no b jets identified, and a trilepton invariant mass 110 GeV $< m_{\ell\ell\ell} <$ 500 GeV.

The contribution from backgrounds with nonprompt leptons from hadron (including b-flavored and c-flavored hadrons) decays and jets misidentified as leptons is estimated using a data-driven method described in Ref. [42]. Lepton-like jets are defined by requiring the leptons to meet a looser selection criterion but fail the signal-lepton requirements. Compared to signal leptons, muonlike jets have $|d_0/\sigma_{d_0}| < 10$, and electronlike jets have the likelihood-based identification criterion loosened to "medium" [21]. The PLVTight tight isolation criterion is dropped for both lepton flavors. Since the nonprompt-lepton background in the SRs comes mainly from the $t\bar{t}$ process where one of the b jets is misidentified as an isolated lepton, a lepton "fake factor" is determined from $t\bar{t}$-enriched samples selected using the same signal region criteria, except requiring one b jet and, in the 3ℓ case, including events with a SFOS lepton pair with $m_{\ell\ell} <$ 80 GeV or $m_{\ell\ell} >$ 100 GeV. To estimate the nonprompt-lepton background, this fake factor is applied as a weight to events selected with the same set of criteria as the signal region but with a leptonlike jet. The nonprompt-lepton background estimate is validated by checking that the estimate agrees with the data in the $t\bar{t}$-enriched samples where the fake factors are measured.

The $W\gamma/Z\gamma$ background mostly contributes to the event selection when the photon is being misidentified as an electron. This contribution (referred to as "γ conversions") is evaluated using a data-driven method similar to the nonprompt-lepton background estimation by introducing electronlike photons. An electronlike photon is a reconstructed object that is like an electron except that its associated track has no hits in the innermost layer of the pixel detector. The photon fake factor is determined using $Z\gamma \to \mu\mu\gamma$ events selected with two muons, no b jets, and one electron or one electronlike photon. The trilepton invariant mass must satisfy 80 GeV $< m_{e\mu\mu} <$ 100 GeV.

The charge-flip background originates from processes in which the charge of at least one prompt electron is misidentified. The muon charge misidentification rate is found to be negligible. The electron charge misidentification rate is measured using a tag-and-probe method applied to $Z \to e^+e^-$ events, where the two electrons have the same reconstructed charge [42]. The charge-flip background is estimated by applying the measured electron charge misidentification rates to $e^\pm e^\pm$, $e^\pm \mu^\pm$, and $e^\pm e^\pm \mu^\mp$ data events that meet all signal region requirements except for the SFOS lepton pair veto requirement. This method is validated with events selected using the same set of signal region criteria as used in the $e^\pm e^\pm$ final state, except the dilepton mass must satisfy 80 GeV $< m_{\ell\ell} <$ 100 GeV and the $E_T^{\rm miss}$ significance requirement $\mathcal{S}(E_T^{\rm miss}) > 3$ is removed.

Other SM processes with prompt leptons include $t\bar{t}W$, $t\bar{t}Z$, tZq, $t\bar{t}H$, WWZ, WZZ, ZZZ, and $W^\pm W^\pm jj$ production. Their contributions are estimated using simulated events normalized to the integrated luminosity of the data sample and the cross sections provided by the event generators. The $t\bar{t}W$, $t\bar{t}Z$, and tZq processes were modeled using MADGRAPH5_AMC@NLO2.3.3 [43] together with PYTHIA8.210, with up to two additional partons in the matrix-element calculations. The $t\bar{t}H$ process was modeled using POWHEG BOX V2 interfaced with PYTHIA8.230. Other triboson processes (WWZ, WZZ, ZZZ) and the strong production of $W^\pm W^\pm jj$ were modeled using SHERPA2.2.2. The calculations for triboson processes were performed with no extra partons at NLO QCD accuracy and up to two additional partons at LO QCD accuracy. The electroweak production of $W^\pm W^\pm jj$ was modeled using SHERPA2.2.11, and the calculations were performed with up to one additional parton at LO QCD accuracy. Contributions from the on-shell WWW and $WH \to WWW^*$ processes were removed from $W^\pm W^\pm jj$ production. Contributions from double parton scattering processes are found to be negligible.

To improve the separation between signal and background, two BDTs are trained using the XGBoost [44] package and are applied separately to the 2ℓ and 3ℓ SRs. All backgrounds are included in the BDT training. Each BDT is trained with 11 variables, some of which differ between the two sets. The three variables with the highest discriminating power are $|m_{jj} - m_W|$, where m_W is the pole mass of the W boson, forward jet p_T, and $\mathcal{S}(E_T^{\rm miss})$ for the 2ℓ channnel, and the ratio $\mathcal{S}(E_T^{\rm miss})/E_T^{\rm miss}$, p_T of the second highest-p_T lepton, and number of jets for the 3ℓ channel. A k-fold cross-validation procedure is used to produce the final discriminant. Fivefold (fourfold) cross-validation BDTs are trained in the 2ℓ SRs (3ℓ SR) and each BDT is trained on 80% (75%) of the expected signal and

TABLE I. Number of events for postfit signal, background, and data observed in the 2ℓ and 3ℓ SRs. The uncertainties shown include both the statistical and systematic contributions.

	$e^{\pm}e^{\pm}$	$e^{\pm}\mu^{\pm}$	$\mu^{\pm}\mu^{\pm}$	3ℓ
WWW signal	28.4 ± 4.3	124 ± 19	82 ± 12	34.8 ± 5.2
WZ	81.1 ± 5.7	346 ± 22	170 ± 10	16.4 ± 1.5
Charge-flip	31.1 ± 7.3	19 ± 5	…	1.7 ± 0.4
γ conversions	60.8 ± 8.5	139 ± 15	…	1.5 ± 0.1
Nonprompt	17.0 ± 4.0	145 ± 23	104 ± 21	26.6 ± 2.9
Other	22.3 ± 2.4	100 ± 10	58 ± 6	8.0 ± 0.9
Total predicted	241 ± 11	873 ± 22	415 ± 17	89.0 ± 5.4
Data	242	885	418	79

background events. To produce the BDT distribution used in the fit, each of the five (four) trained BDTs is applied to the 20% (25%) of the events not used to train the BDTs.

To extract the WWW inclusive cross section, a binned maximum likelihood fit [45] is performed using the BDT distributions in the 2ℓ SRs ($e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$, and $\mu^{\pm}\mu^{\pm}$) and the 3ℓ SR as well as the $m_{\ell\ell\ell}$ distributions in the three WZ CRs, amounting to seven distributions with 50 bins in total. The fit includes four unconstrained parameters that scale the number of events for a particular process predicted by MC simulation: the signal strength $\mu(WWW)$ for WWW production and three scale factors for $WZ + 0$ jets, $WZ + 1$ jet, and $WZ + \geq 2$ jets. The ratio of on-shell WWW production to $WH \rightarrow WWW^{*}$ production is determined from MC simulation and is allowed to vary within the theoretical uncertainties of the two processes.

Systematic uncertainties are included in the fit as nuisance parameters constrained by Gaussian probability density functions. Correlations between systematic uncertainties arising from common sources are maintained across processes and channels. Instrumental systematic uncertainties are related to the lepton trigger, reconstruction and

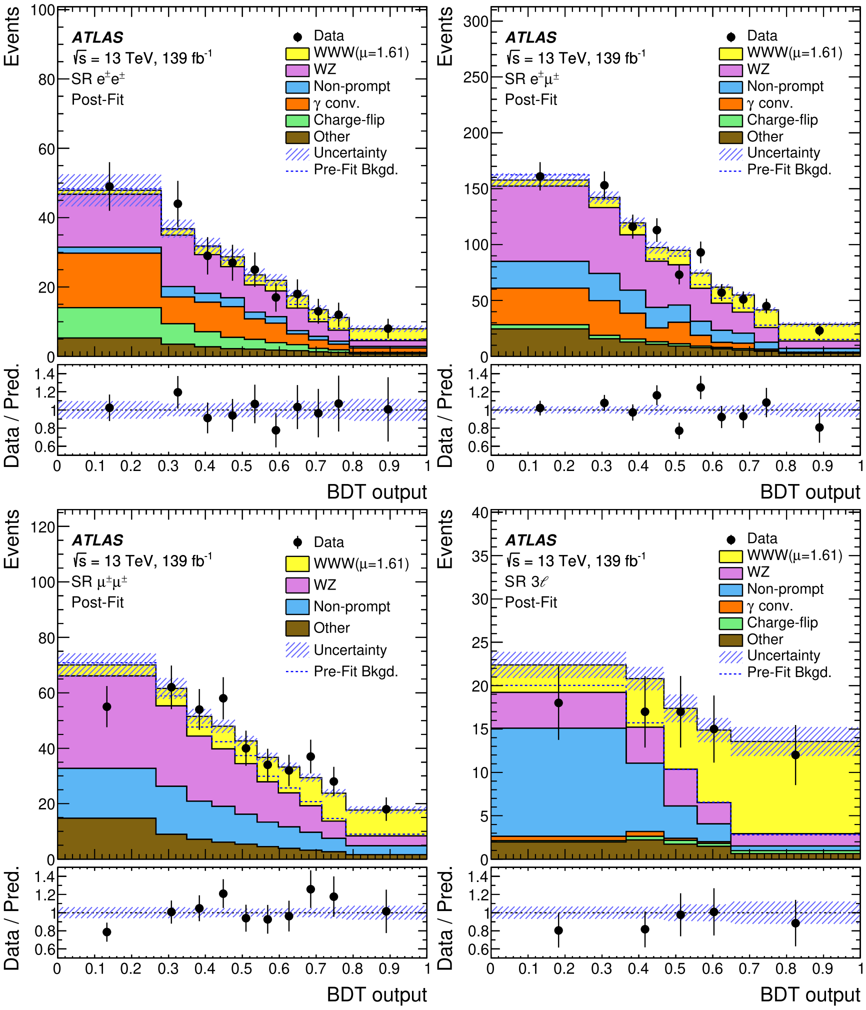

FIG. 2. Postfit BDT output distribution in the $e^{\pm}e^{\pm}$ (top left), $e^{\pm}\mu^{\pm}$ (top right), $\mu^{\pm}\mu^{\pm}$ (bottom left), and 3ℓ (bottom right) channels. The bottom panel of each plot shows the ratio of the data to the total prediction. The uncertainty bands include both the statistical and systematic uncertainties as obtained by the fit. The signal is scaled to the fitted signal strength of 1.61.

identification efficiencies [22,24], lepton isolation criteria [23], lepton energy scale and resolution [22,46], jet energy scale and resolution [47], jet vertex tagging [48,49], b-jet identification [27], modeling of E_T^{miss} [50] and pileup, and integrated luminosity [14,51]. Theoretical uncertainties associated with the signal processes and the background processes with prompt leptons are evaluated using simulation. For the signal and WZ background, acceptance and distribution shape uncertainties due to the renormalization and factorization scales [52], PDFs [53], and parton showering, are also included in the simultaneous fit. The normalization uncertainties for the processes included in the "Other" background category in Table I and Fig. 2 are between 10% and 20% [54–57]. The fit includes the systematic uncertainties of each of the data-driven background estimates, and also the systematic uncertainties due to limited MC sample size.

The signal strength is measured to be $\mu(WWW) = 1.61 \pm 0.25$, where the uncertainty also includes the signal cross-section uncertainty (3.6%) affecting the predicted inclusive cross section from the signal MC samples. The three WZ scale factors are found to be 1.12 ± 0.11, 0.98 ± 0.04, and 0.88 ± 0.18 for the 0-jet, 1-jet, and ≥ 2-jet bins. Table I shows the postfit signal and background event yields as well as the observed yield in each SR. The contribution of the WH process to the WWW yield ranges between 40% and 44% in the four SRs. All nuisance parameters remain within their one standard deviation uncertainty after the fit. Figure 2 shows a comparison between data and postfit predictions for the BDT output score distribution in all SRs. For various postfit kinematic distributions in the SRs, data and predictions are found to have a p value greater than 0.05 from a χ^2 test that takes into account the systematic uncertainties and correlations used in the fit to data.

The background-only hypothesis is rejected with an observed (expected) significance of 6.6 (4.0) standard deviations for the 2ℓ SRs and 4.8 (3.8) standard deviations for the 3ℓ SR calculated using the asymptotic approximation [58]. The combined observed (expected) significance is found to be 8.0 (5.4) standard deviations, constituting the first observation of WWW production. The signal strength is also measured separately by fitting the BDT distribution in each SR with the three WZ CRs. The values are found to be consistent: 1.54 ± 0.76 for $e^{\pm}e^{\pm}$, 1.44 ± 0.39 for $e^{\pm}\mu^{\pm}$, 2.23 ± 0.46 for $\mu^{\pm}\mu^{\pm}$, and 1.32 ± 0.39 for 3ℓ.

The measured inclusive $pp \to$ WWW production cross section is calculated as the product of the measured signal strength and the cross section from MC simulation, and is found to be $\sigma^{\text{meas}}(pp \to WWW) = 820 \pm 100\,(\text{stat}) \pm 80\,(\text{syst})$ fb. The largest systematic uncertainty contribution is 6% from data-driven estimates (mainly nonprompt background), followed by 3% from prompt-lepton-background modeling uncertainties (primarily WZ theory uncertainties).

In conclusion, the first observation of the $pp \to WWW$ process is reported by the ATLAS experiment at the LHC. Events with two same-sign charged leptons in association with at least two jets, as well as events with three charged leptons and no same-flavor opposite-sign lepton pairs, were selected from 139 fb^{-1} of 13 TeV pp collisions. Two BDTs were trained to improve the separation between signal and background. The SM background-only hypothesis is rejected with an observed (expected) significance of 8.0 (5.4) standard deviations. The inclusive $pp \to WWW$ production cross section is measured to be $820 \pm 100\,(\text{stat}) \pm 80\,(\text{syst})$ fb, approximately 2.6 standard deviations from the predicted cross section of 511 ± 18 fb calculated at NLO QCD and LO electroweak accuracy.

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