Observation of electroweak production of a same-sign $W$ boson pair in association with two jets in $pp$ collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

The ATLAS Collaboration

This Letter presents the observation and measurement of electroweak production of a same-sign $W$ boson pair in association with two jets using 36.1 fb$^{-1}$ of proton–proton collision data recorded at a center-of-mass energy of $\sqrt{s} = 13$ TeV by the ATLAS detector at the Large Hadron Collider. The analysis is performed in the detector fiducial phase-space region, defined by the presence of two same-sign leptons, electron or muon, and at least two jets with a large invariant mass and rapidity difference. A total of 122 candidate events are observed for a background expectation of 69 $\pm$ 7 events, corresponding to an observed signal significance of 6.5 standard deviations. The measured fiducial signal cross section is $\sigma_{\text{fid.}} = 2.89^{+0.51}_{-0.48}$ (stat.) $^{+0.29}_{-0.28}$ (syst.) fb.
The scattering of two massive vector bosons (VBS), $VV \rightarrow VV$ with $V = W$ or $Z$, is an important process for studying the mechanism of electroweak symmetry breaking [1–3]. VBS processes involve quartic gauge-boson self interactions, and the $s$- and $t$-channel exchanges of a gauge or Higgs boson. In the Standard Model, the Higgs boson regularizes the VBS amplitude by canceling out the divergencies arising from longitudinally polarized vector bosons at high energy [4–7].

At the LHC, the VBS final state of two gauge bosons and two jets ($VVjj$) can be produced via two classes of mechanisms. The first class, referred to as strong production, involves both strong and electroweak interactions at Born level. The second class, referred to as electroweak production, involves only weak interactions at Born level [8] and includes VBS diagrams where the two jets have a large invariant mass and large rapidity difference. The ratio of electroweak to strong production cross sections for the $W^+W^-jj$ channel is of order five in the fiducial VBS phase-space region of this analysis, which is the largest such ratio when compared to other VBS diboson processes. Tree-level diagrams not involving self-interactions are suppressed in the $W^+W^-jj$ final state [9]. Diagrams with self-interactions in the $s$-channel, however, are absent. Previously, an observation of $W^+W^-jj$ electroweak production was reported by the CMS Collaboration [10] and evidence was reported by the ATLAS Collaboration using a smaller dataset [11, 12].

This Letter presents an observation and measurement of the electroweak production of $W^±W^±jj$ events in which both $W$ bosons decay into an electron or muon and a neutrino. This study uses 36.1 fb$^{-1}$ of proton–proton ($pp$) collision data collected by the ATLAS detector at √s = 13 TeV. The ATLAS detector [13] is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and almost 4π coverage in solid angle.1 The inner tracking detector (ID) covers $|\eta| < 2.5$ in pseudorapidity and consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. The ID is surrounded by a superconducting solenoid and an almost hermetic calorimeter system, which provides three-dimensional reconstruction of particle showers up to $|\eta| = 4.9$. The muon spectrometer has three air-core toroidal magnets: a barrel toroid and two endcap toroids. Three layers of precision tracking stations with drift tubes and cathode strip chambers allow precise muon momentum measurement up to $|\eta| = 2.7$. Resistive-plate and thin-gap chambers provide muon triggering capability up to $|\eta| = 2.4$.

Monte Carlo (MC) simulation is used to generate signal and background predictions. The generated events are processed through a detector simulation [14] based on Geant4 [15] and are reconstructed using the same algorithms as used for data. The simulation includes the effect of multiple $pp$ interactions per bunch crossing as detailed in Ref. [16].

Processes producing four leptons were simulated using Sherpa v2.2.2 [17–20] with the NNPDF3.0NNLO [21] set of parton distribution functions (PDF). Electroweak diboson production in association with two jets was simulated with diagrams including exactly six orders of the EW coupling [22]. The simulation of the strong production processes includes diagrams with exactly four electroweak (EW) vertices [23]. The simulation of both the $W^±W^±jj$ electroweak signal and $W^±W^±jj$ strong background processes includes up to one additional parton at LO accuracy in QCD. For $\ell\ell\ell\nu$ and $4\ell$ final states, matrix elements include up to one parton at next-to-leading-order (NLO) and three partons at leading-order (LO) accuracy in

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1 ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the z-axis along the beam direction. The x-axis points from the IP to the center of the LHC ring, and the y-axis points upward. Cylindrical coordinates $(r, \phi)$ are used in the $(x, y)$ plane, $\phi$ being the azimuthal angle around the beam direction. The rapidity is defined as $y = \frac{1}{2} \ln \left( \frac{E+p_z}{E-p_z} \right)$ where $E$ is the energy of the particle and $p_z$ is the projection of the momentum along the z-axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = - \ln \tan(\theta/2)$. The distance $\Delta R$ is defined as $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. 

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p perturbative quantum chromodynamics (QCD). All multileg processes were simulated combining the various final-state topologies with the MEPS merging algorithm [20, 24] and matched to the Sherpa v2.2.2 internal parton shower, hadronization and underlying-event modeling [19, 25]. The renormalization and factorization scales were set to the invariant mass of the four-lepton system at the matrix-element level. An alternative signal sample was simulated with Powheg-Box [26–29] and PYTHIA8.230 [30] at NLO QCD accuracy and employing the VBS approximation [31], the NNPDF3.0NLO PDF set, and renormalization and factorization scales set to the W boson mass. The $V\gamma jj$ processes were simulated with exactly three EW vertices using Sherpa v2.1.1 at NLO (up to one parton) or LO accuracy (up to three partons) using the CT10NLO PDF set [32]. Electroweak $V\gamma jj$ processes were simulated using Sherpa v2.2.4 with NNPDF3.0NNLO, with exactly five orders of the EW coupling, and at LO QCD accuracy. The triboson production processes were simulated with Sherpa v2.1.1 and the CT10NLO PDF set. Madgraph5_aMC@NLO [33] with NNPDF3.0NLO and PYTHIA8.210 were used to simulate $t\bar{t}V$ processes at NLO QCD accuracy.

The $W^*W^* jj$ electroweak production cross section is measured in a fiducial region defined at particle level in MC simulation by requiring exactly two same-sign leptons with a transverse momentum, $p_T$, greater than 27 GeV and $|\eta| < 2.5$; leptons are defined as electrons and muons produced in W boson decays and that do not originate from $\tau$ decays. The lepton four-momentum includes the four-momenta of photons inside a cone of size $\Delta R = 0.1$ around the lepton. The two leptons must be separated by a distance of $\Delta R_{\ell\ell} > 0.3$ and have an invariant mass, $m_{\ell\ell}$, greater than 20 GeV. The magnitude of the vector sum of the transverse momenta of the two final-state neutrinos with highest $p_T$ must be greater than 30 GeV. Jets are reconstructed using the anti-$k_t$ algorithm [34] with radius parameter $R = 0.4$ and using all final-state particles, except for neutrinos and charged leptons from W boson decays. Jets are required to have $p_T > 35$ GeV and $|\eta| < 4.5$. Events with a charged lepton that is within a cone of radius $\Delta R_{\ell j} = 0.3$ around a jet are vetoed. The fiducial region requires at least two jets, including one with $p_T > 65$ GeV and another with $p_T > 35$ GeV. The two highest-$p_T$ jets must have an invariant mass $m_{jj} > 500$ GeV and a rapidity difference $|\Delta y_{jj}| > 2$.

The fiducial cross section predicted by Sherpa for $W^*W^* jj$ electroweak production is $2.01^{+0.33}_{-0.23}$ fb. The uncertainty includes independent variations of the renormalization and factorization scales by factors of 0.5 and 2 with the constraint $0.5 \leq \mu_F/\mu_R \leq 2$ which contribute $^{+14\%}_{-11\%}$; it also includes uncertainties from the NNPDF3.0 ensemble, as well as differences between the CT14 [35] and MMHT2014 [36] PDF sets ($^{+22.5\%}_{-1.5\%}$) [37]. Uncertainties in the parton shower, hadronization, and underlying-event modeling are evaluated by varying the MEPS matching and resummation scales and amount to $^{+58\%}_{-18\%}$. Powheg+PYTHIA8 predicts a signal fiducial cross section of $3.08^{+0.45}_{-0.46}$ fb, with the uncertainties derived using the same procedures as for the Sherpa prediction, except for the uncertainty in the parton shower modeling, which is estimated as the difference relative to Powheg+Herwig7 [38, 39]. The Sherpa electroweak samples suffer from a non-optimal setting of the color flow for the parton shower, which leads to an excess of central emissions. The resulting effect on differential distributions is alleviated since up to one additional parton is included in the matrix element, although this leads to the lower predicted cross section [22].

Events are required to contain at least one reconstructed proton interaction vertex. The vertex with the highest $p_T^2$ sum of associated ID tracks is selected as the primary vertex. Electrons are reconstructed from energy clusters in the electromagnetic calorimeter that are matched to tracks reconstructed in the ID with the requirement of a hit in the innermost pixel layer [40]. Electron and muon candidates must satisfy loose identification criteria [40, 41], have $p_T > 6$ GeV, and $|\eta| < 2.47$ and $|\eta| < 2.7$, respectively. ID tracks matched to electron and muon candidates are required to originate from the primary vertex. The transverse impact parameter significance of the electron (muon) candidate must satisfy $|d_0/\sigma_{d_0}| < 5$ (10);
the longitudinal impact parameter multiplied by the sine of the polar angle of the lepton candidates must satisfy $|z_0 \sin \theta| < 0.5$ mm. Electrons and muons passing these selections are further referred to as baseline leptons.

Jets are reconstructed from calorimeter energy clusters [42, 43] using the anti-$k_t$ algorithm with radius parameter $R = 0.4$. Jets are required to have $p_T > 30$ GeV in the forward region ($2.4 < |\eta| < 4.5$) and $p_T > 25$ GeV in the central region ($|\eta| < 2.4$). Central jets with $p_T < 60$ GeV must be matched to the primary vertex [44]. Jets containing $b$-hadrons ($b$-jets) are identified in the range of $|\eta| < 2.5$ with an efficiency of 85% using techniques described in Ref. [45]. Selected electron, muon and jet candidates are required to be non-overlapping using the procedures described in Ref. [16]. The missing transverse momentum, $E_T^{\text{miss}}$, is computed using selected electrons, muons and jets, and the track-based soft term defined in Ref. [46].

Events are selected online by single-electron or single-muon triggers [47]. Candidate events are selected by requiring exactly two same-sign baseline leptons, electron or muon, with $m_{\ell\ell} > 20$ GeV and by requiring $E_T^{\text{miss}} > 30$ GeV. They are required to contain at least two jets, including one with $p_T > 65$ GeV and another with $p_T > 35$ GeV. Events with at least one identified $b$-jet are rejected in order to reduce background contributions from top-quark pair production ($t\bar{t}$). The two highest-$p_T$ jets are required to have $m_{jj} > 200$ GeV and $|\Delta y_{jj}| > 2$. These jet selection criteria were optimized to separate the $W^+W^- j j$ electroweak process from the strong production and other background processes.

After these selections, the dominant source of background events is due to leptons originating from decays of heavy-flavor hadrons and jets misidentified as electrons, collectively referred to as non-prompt leptons. Additional selection criteria are applied to reduce their contributions. Signal electrons are required to satisfy tight identification criteria [40], to have $p_T > 27$ GeV, and to be outside the calorimeter transition region ($1.37 < |\eta| < 1.52$). Signal muons are required to satisfy medium identification criteria [41], and to have $p_T > 27$ GeV. Signal electrons and muons are further required to be isolated from nearby particles, with isolation criteria defined using calorimeter clusters and ID tracks. These isolation criteria are optimized to have an efficiency of at least 90% for $p_T > 25$ GeV and at least 99% for $p_T > 60$ GeV [40, 41]. For di-electron events, the electron pseudorapidity is restricted to $|\eta| < 1.37$ and events with $|m_{ee} - 91.2$ GeV$| < 15$ GeV are discarded. These criteria reduce the background from electron charge misreconstruction described later. Candidate events with exactly two signal leptons are said to pass the full event selection.

The contributions from the $WZ$, $V\gamma$, $ZZ$, $t\bar{t}V$ and triboson production are estimated using simulation. The predicted event yields of the $WZ$ and $V\gamma$ processes are normalized to data in dedicated control regions. The normalization of the $WZ$ background is determined using events with exactly three leptons, two of which are required to pass the signal lepton selection, and that satisfy the dijet and $E_T^{\text{miss}}$ selection criteria. Events from $V\gamma$ production enter the signal region when a photon is misidentified as an electron. The modeling of this misidentification process in simulation is corrected using $Z \rightarrow \mu^+\mu^-\gamma$ events where a photon is emitted by a muon and then misidentified as an electron. These events are selected by requiring exactly two opposite-sign signal muons, one signal electron, $E_T^{\text{miss}} < 30$ GeV and a trilepton invariant mass satisfying $75$ GeV $< m_{\mu\mu\mu} < 100$ GeV. A normalization factor of 1.8 is derived from this control region and used to correct the simulated $V\gamma$ events. To account for the differences between the $Z\gamma$ and $W\gamma$ processes, the full effect of this correction factor is assigned as a systematic uncertainty, corresponding to 44% of the estimated $V\gamma$ yield. The relative contributions from electroweak and strong production of $WZ$ and $V\gamma$ processes are estimated from simulation since this analysis is not sensitive to their different admixtures. Theoretical uncertainties in the predictions of the $ZZ$, $V\gamma$, triboson, and $t\bar{t}V$ backgrounds vary from 20% to 30% [23, 48, 49].
Background contributions with non-prompt leptons are estimated by weighting data events from dedicated control regions by scale factors. These scale factors are measured in dijet events containing exactly one lepton that is $p_T$-balanced by a $b$-jet. The $b$-jet requirement enhances non-prompt lepton contributions and suppresses contributions from $W/Z$ bosons, which are subtracted from data using simulation. The scale factor is defined as the ratio of the number of signal leptons to the number of leptons passing a dedicated background selection. The background leptons are required to pass the baseline lepton selection and fail the signal lepton selection, where background electrons are in addition required to satisfy medium identification criteria [40]. Moreover, the background electron (muon) $p_T$ is required to be greater than 20 (15) GeV. Separate scale factors are computed for muons and for central and forward electrons. The scale factors are measured as a function of the scalar sum of the background lepton $p_T$ and the additional activity around the lepton. This activity, $p_T^{iso30}$, is quantified by the sum of the $p_T$ of ID tracks that are within a cone of size $\Delta R = 0.3$ around the lepton and originate from the primary vertex.

Data events, that are weighted by the scale factors, are taken from control regions defined using the full event selection criteria except that one lepton is required to pass the background lepton selection and its $p_T$ is replaced with $p_T + p_T^{iso30}$, with this sum required to be greater than 27 GeV. A statistically independent control region is defined for each bin of the $m_{jj}$ distribution. The uncertainty of the estimated non-prompt background yields is approximately 50% in $\mu^+\mu^\pm$ final states and varies between 40% and 90% for $e^+e^\pm$ and $e^\pm\mu^\pm$ final states. It includes the systematic uncertainty of the scale factors and the statistical uncertainty of the control regions. The former uncertainty is derived from variations in the composition of the dijet control regions where these factors are measured, obtained by varying the selection criteria. The entire method is validated in regions enriched with non-prompt leptons from $t\bar{t}$ ($W$+jet) events selected by requiring exactly two same-sign leptons and exactly one (zero) $b$-jet among a total of at least (less than) two jets. In these regions, the number of observed data events and the number of predicted background events agree within their uncertainties.

Opposite-sign lepton pairs pass the full event selection when an electron undergoes an interaction with the detector material resulting in incorrect charge reconstruction. The probability of this charge misreconstruction, $\epsilon_{\text{misrec.}}$, is measured in $Z \rightarrow e^+e^-$ events [40] and it increases from about 0.1% in the central region to a few percent in the forward region for $|\eta| > 2$. The background contributions from electron charge misreconstruction are estimated from data using opposite-sign lepton pairs that satisfy the full event selection criteria, except for the same-sign requirement; these events are weighted by $\epsilon_{\text{misrec.}}$, and the electron energy loss due to the material interaction is corrected with $\eta$-dependent factors derived from simulation [40]. The overall method is validated by comparing the number of observed same-sign electron pairs having $|m_{ee} - 91.2$ GeV$| < 15$ GeV with the predicted background yield, with the two numbers agreeing within the systematic uncertainty of 15%. This uncertainty is dominated by the statistical uncertainty in the measurement of $\epsilon_{\text{misrec.}}$, which is less than 10% in the forward region and up to 20% in the central region. The charge misreconstruction of muons is found to be negligible.

The systematic uncertainties arising from the mismodeling of the reconstructed objects are estimated primarily from data and their impact on the analysis is assessed using simulated events. The dominant source is the uncertainty of the jet energy scale, which amounts to 2% for the signal and 10% for the $WZ$ background. The uncertainty in the measurement of the integrated luminosity is 2.1% [50].

The theory modeling uncertainties of the $m_{jj}$ distributions predicted by Sherpa for $W^\pm W^\pm jj$ and $WZ$ processes are evaluated using the procedures described above. Only the modeling of the event selection efficiency and the shape of the $m_{jj}$ distribution affect the measured fiducial cross section of the $W^\pm W^\pm jj$ signal, since absolute normalization uncertainties cancel in this measurement. Effects of the NLO electroweak corrections [51] and of the interference between electroweak and strong $W^\pm W^\pm jj$
production [52] are assigned as an uncertainty in the \( m_{jj} \) shape of the \( W^\pm W^\pm jj \) signal, amounting to 6% and 4%, respectively. This approach is used because of the lack of event generators that implement the complete NLO calculation and because the interference contribution is defined only at the leading order [8]. The overlap of the QED radiation in the SHERPA parton shower model with the NLO EW corrections is found to be negligible.

Signal events are categorized by their lepton flavor and charge into six mutually exclusive channels: \( e^+/e^- \), \( e^\pm/\mu^\pm \), and \( \mu^+/\mu^- \), in order to exploit their different signal and background compositions. The signal region is defined as \( m_{jj} > 500 \) GeV and further split into four \( m_{jj} \) bins, optimized to increase the expected signal sensitivity. Events with \( 200 \) GeV < \( m_{jj} < 500 \) GeV serve as additional control regions, dominated by contributions from non-prompt lepton and WZ backgrounds. The resulting 30 bins of the \( m_{jj} \) distributions in the signal and control regions are combined in a profile likelihood fit [53] to extract the fiducial cross section.

The signal strength, a free parameter in the fit, multiplies the expected fiducial \( W^\pm W^\pm jj \) electroweak production cross section used to produce the signal template. The signal template of reconstructed \( W^\pm W^\pm jj \) electroweak events also includes candidate events with electrons and muons produced in \( W \) decays into \( \tau \) lepton. Since the fiducial cross section prediction does not include such events, their fractional contribution predicted by the simulation is removed from the fiducial cross section measurement. Systematic uncertainties are included in the fit as nuisance parameters constrained by Gaussian functions. The WZ control region is also included in the fit as a single bin and the normalization of the WZ background is included as a free parameter. The analysis choices maximize the expected significance for the \( W^\pm W^\pm jj \) electroweak signal predicted by SHERPA at 4.4\( \sigma \). A significance of 6.5\( \sigma \) is expected for the signal predicted by POWHEG-Box.

Figure 1: Event yields for data, signal and background in the WZ and 200 < \( m_{jj} < 500 \) GeV control regions (left) and the \( m_{jj} \) distribution for events meeting all selection criteria for the signal region (right). Signal and background distributions are shown as predicted after the fit. The hatched band represents the statistical and systematic uncertainties of the background predictions added in quadrature. The backgrounds from \( VV \) production and electron charge misreconstruction are combined into the “e/\( \gamma \) conversions” category. The “Other prompt” category combines ZZ, VVV and t\( \bar{t} \)V background contributions. The last bin on the right figure includes the overflow.

Table 1 compares the numbers of data events in the signal region with the background and signal event yields after the fit; the signal region contains 122 data events, compared with a best-fit yield of 69 ± 7 background events. By fitting the data and background events in the signal and control regions, the background-only
The measured fiducial cross section includes contributions from both the $W^\pm W^\pm jj$ electroweak production and its interference with the $W^\pm W^\pm jj$ strong production, estimated to be approximately 6% of the predicted fiducial cross section for $W^\pm W^\pm jj$ electroweak production. The fiducial cross section for the $W^\pm W^\pm jj$ electroweak production, without the interference effect, is predicted by SHERPA and POWHEG+PYTHIA8 to be $2.01^{+0.33}_{-0.23}$ fb and $3.08^{+0.45}_{-0.46}$ fb, respectively. The impact on the measured fiducial cross section of using POWHEG+PYTHIA8 instead of SHERPA to generate the $m_{jj}$ signal template was tested and found to be smaller than the 3.6% signal modeling uncertainty.
Figure 2: The $m_{\ell\ell}$ distribution for events meeting all selection criteria for the signal region is shown as predicted after the fit. The hatched band represents the statistical and systematic uncertainties of the background prediction added in quadrature. The fitted signal strength and nuisance parameters have been propagated, with the exception of the uncertainties due to the interference and electroweak corrections for which a flat uncertainty is assigned. The backgrounds from $V\gamma$ production and electron charge misreconstruction are combined in the “$e/\gamma$ conversions” category. The “Other prompt” category combines $ZZ$, $VVV$ and $t\bar{t}V$ background contributions. The last bin of the distribution includes the overflow.
Table 2: Impact of different components of systematic uncertainty on the measured fiducial cross section, without taking into account correlations. The impact of one source of systematic uncertainty is computed by first performing the fit with the corresponding nuisance parameter fixed to one standard deviation up or down from the value obtained in the nominal fit, then these up and down variations are symmetrized. The impacts of several sources of systematic uncertainty are added in quadrature for each component. The categorization of sources of systematic uncertainties into experimental and theory modeling correspond to those used for the measured fiducial cross section.

<table>
<thead>
<tr>
<th>Source</th>
<th>Impact [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experimental</strong></td>
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</tr>
<tr>
<td>Electrons</td>
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</tr>
<tr>
<td>Muons</td>
<td>1.3</td>
</tr>
<tr>
<td>Jets and $E_T^{miss}$</td>
<td>3.2</td>
</tr>
<tr>
<td>$b$-tagging</td>
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</tr>
<tr>
<td>Pileup</td>
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<tr>
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<tr>
<td>Background, misid. leptons</td>
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</tr>
<tr>
<td>Background, charge misrec.</td>
<td>0.3</td>
</tr>
<tr>
<td>Background, other</td>
<td>1.8</td>
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<tr>
<td><strong>Theory modeling</strong></td>
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<td>$W^+W^-jj$ electroweak-strong interference</td>
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<td>$W^+W^-jj$ electroweak, EW corrections</td>
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<td>$W^+W^-jj$ electroweak, shower, scale, PDF &amp; $\alpha_s$</td>
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<td><strong>Luminosity</strong></td>
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</table>
In summary, $W^+W^-jj$ electroweak production is observed with a significance of 6.5$\sigma$ in 36.1 fb$^{-1}$ of $pp$ collision data recorded at $\sqrt{s} = 13$ TeV by the ATLAS detector at the LHC. The corresponding fiducial cross section is measured to be $\sigma_{\text{fid.}} = 2.89^{+0.51}_{-0.48}$ (stat.) $^{+0.24}_{-0.22}$ (exp. syst.) $^{+0.14}_{-0.16}$ (mod. syst.) $^{+0.08}_{-0.06}$ (lumi.) fb.

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