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# Observation of electroweak production of $W^+W^-$ in association with jets in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

## The ATLAS collaboration

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Abstract: A measurement of the production of $W$ bosons with opposite electric charges in association with two jets is presented based on $140\,\mathrm{fb}^{-1}$ of data collected by the ATLAS detector in proton-proton collisions at $\sqrt{s} = 13$ TeV. The analysis is sensitive to the scattering of $W$ bosons, which is of particular interest in the ATLAS physics programme as it can be used to probe the electroweak symmetry breaking mechanism of the Standard Model. This signal is observed with a significance of 7.1 standard deviations above the background expectation, while 6.2 standard deviations were expected. The measured cross-section is determined in a signal-enriched fiducial volume and is found to be $2.7 \pm 0.5$ fb, which is consistent with the theoretical prediction of $2.20^{+0.14}_{-0.13}$ fb.

Keywords: Hadron-Hadron Scattering

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## 1 Introduction

The scattering of $W$ bosons can be used to probe the electroweak (EWK) symmetry breaking mechanism of the Standard Model (SM). Without a SM Higgs boson, the scattering of longitudinally polarised $W$ bosons yields a cross-section that violates unitarity at high centre-of-mass energy [1]. Should either the triple or quartic gauge couplings for these processes prove to be inconsistent with the SM prediction, it will point towards the necessity for a new description of the EWK sector of the SM [2].

This paper presents the observation by the ATLAS Collaboration of the EWK production of $W^+W^-$ in association with two jets (EWK $W^+W^-jj$), which includes the scattering of $W$ bosons with opposite electric charges. This analysis is carried out with 140 $\text{fb}^{-1}$ of proton-proton collision data at $\sqrt{s} = 13$ TeV from LHC Run 2. The CMS Collaboration previously observed this process using 138 $\text{fb}^{-1}$ of data [3]. The signal is characterised by one $W$ boson decaying into an electron and an electron neutrino, and the other decaying into a muon and a muon neutrino. This decay channel is chosen for its enhanced detection sensitivity over a final state with leptons of the same flavour. In this vector boson scattering (VBS) scenario, the scattered $W$ bosons are radiated from the quarks that initiate the hard interaction, so that the final state particles of the process at leading order (LO) in the strong coupling constant consist of two quarks that hadronise into jets, an electron, a muon, and two neutrinos that manifest as missing transverse energy ($E_{\text{T}}^{\text{miss}}$) in the ATLAS detector. Tree-level Feynman diagrams for the processes included in the signal are shown in figure 1.



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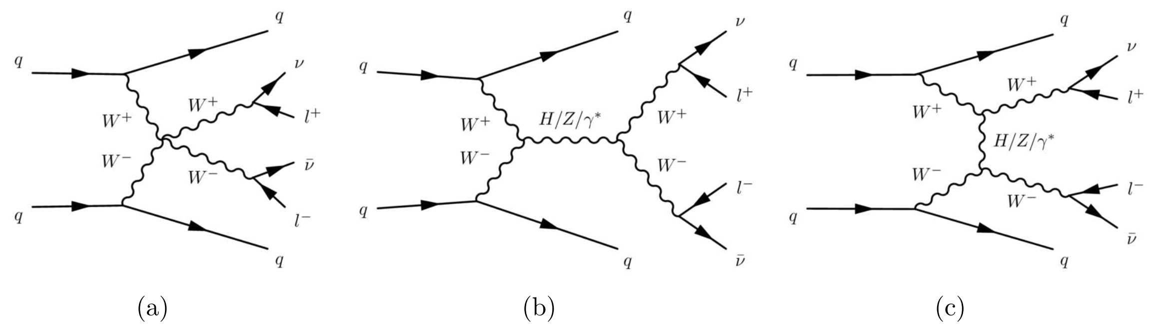


**Figure 1.** Examples of tree-level Feynman diagrams for the electroweak production of $W^+W^-jj$ events via the vector boson scattering of two $W$ bosons radiated from the initial partons. The (a) quartic coupling of the $W$ bosons, (b) $s$-channel and (c) $t$-channel diagrams are illustrated.

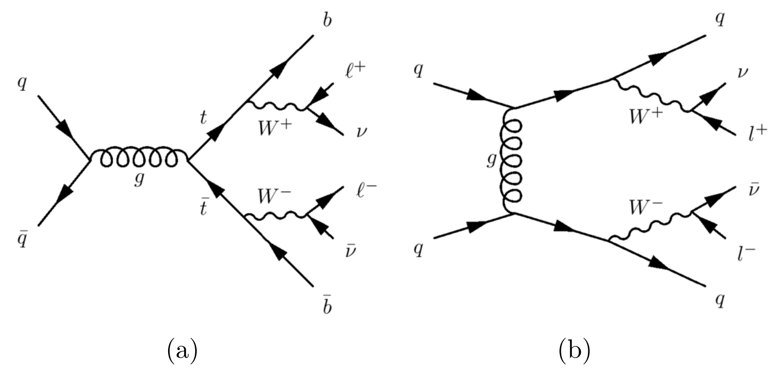


**Figure 2.** Examples of tree-level Feynman diagrams for the two main backgrounds: (a) $t\bar{t}$ and (b) strong $W^+W^-jj$.

Figure 1(a) illustrates the quartic coupling of the $W$ bosons, while figures 1(b) and 1(c) represent the $s$-channel and $t$-channel VBS diagrams, respectively.

A discriminant based on a neural network (NN) is employed to distinguish the VBS signal from a large background dominated by the production of top quarks (in pairs or singly). This measurement is well suited to this approach due to the distinct kinematic correlations between the physics objects in the final state. In the VBS process, the radiation of the $W$ bosons from the quarks provides them with a boost that results in jets with high transverse momentum ($p_{\mathrm{T}}$) entering the forward regions of the detector. The colourless exchange between the $W$ bosons leads to a deficit of hadronic activity in the central region of the detector compared to the background processes. Figure 2 displays the diagrams for the two leading backgrounds, namely the production of top quark pairs ($t\bar{t}$) and $W^+W^-jj$ production by the strong interaction (strong $W^+W^-jj$).



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## 2 ATLAS detector

The ATLAS experiment [4] at the LHC is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and a near $4\pi$ coverage in solid angle.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity within the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers up to $|\eta| = 2.7$ and fast detectors for triggering up to $|\eta| = 2.4$. The luminosity is measured mainly by the LUCID-2 [5] detector, which is located close to the beampipe. A two-level trigger system is used to select events [6]. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz on average depending on the data-taking conditions. A software suite [7] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

## 3 Data and simulated event samples

The analysis is based on data collected by the ATLAS detector in proton-proton collisions at a centre-of-mass energy of 13 TeV during Run 2 of the LHC, between 2015 and 2018. After requiring the data to fulfil data quality criteria [8], the total luminosity of Run 2 amounts to 140 fb$^{-1}$, with an uncertainty of 0.83% [9].

Monte Carlo (MC) predictions of SM processes were produced using the ATLAS simulation infrastructure [10] that incorporates the complete Geant4 [11] simulation of the ATLAS detector. The effect of multiple interactions in the same or nearby bunch crossing (pile-up) was simulated by generating a set of inelastic proton-proton collision events using Pythia 8.186 [12] with the A3 set of tuned parameters (tune) [13] and the NNPDF2.3 LO set of parton distribution functions (PDF) [14]. These events are then overlaid on top of the original hard-scatter signal and background events.

Signal $W^+W^-jj$ events were modelled via a pure EWK prediction that incorporates diagrams of order $\mathcal{O}(\alpha_{\text{EWK}}^6)$ in perturbation theory. The Higgs boson contribution is

[1]ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$-axis points upwards. Polar coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the $z$-axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln\tan(\theta/2)$ and is equal to the rapidity $y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right)$ in the relativistic limit. Angular distance is measured in units of $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.



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suppressed by a generator-level cut on the invariant mass of the decay leptons and neutrinos, while $s$-channel contributions are neglected. All the leptonic decays of the $W$ boson are considered, with 11% of the signal events selected by the analysis involving at least one $W$ boson decaying into a $\tau$-lepton and a neutrino. Events were simulated with POWHEG BOX v2 [15–18] at next-to-leading order (NLO) in quantum chromodynamics (QCD) with the NNPDF3.0 NLO PDF set [19]. The sample was interfaced to PYTHIA 8.244 [20] for the parton shower using CTEQ6L1 PDF set [21] with the AZNLO tune [22] and the dipole recoil shower scheme, preventing the generation of excess central jet radiation [23].

The top-quark pair and single-top quark $Wt$ production were modelled using the POWHEG BOX v2 [24] generator at NLO in QCD with the NNPDF3.0 PDF set. The events were interfaced to PYTHIA 8.230 for the parton shower, hadronisation, and underlying event, with parameters set according to the A14 tune [25] and using the NNPDF2.3 LO PDF set. The mass of the top quark was set to $m_{\text{top}} = 172.5$ GeV. The $h_{\text{damp}}$ parameter[2] was set to 1.5 $m_{\text{top}}$ for $t\bar{t}$ events. For $Wt$ events, the four-flavour and five-flavour schemes were used to model the $t$-channel and the $s$-channel, respectively. The decays of bottom and charm hadrons were performed by EVTGEN 1.6.0 [26]. The $t\bar{t}$ sample was normalised to the cross-section predicted at next-to-next-to-leading order (NNLO) in QCD including the resummation of next-to-next-to-leading-logarithmic (NNLL) soft-gluon terms calculated using TOP++ 2.0 [27–33], while the $Wt$ cross-section was corrected to the theory prediction calculated at NLO in QCD with NNLL soft-gluon corrections [34, 35].

The $W^+W^-$ production in association with two jets, originating from the strong interaction $q\bar{q} \to W^+W^-$ and $gg \to W^+W^-$ processes (strong $W^+W^-jj$), was simulated with SHERPA 2.2.2 [36]. The former relies on matrix elements with up to one additional parton emission at NLO accuracy in QCD and up to three additional partons at LO, while the latter allows up to one additional parton at LO and includes off-shell effects and Higgs boson contributions. The virtual QCD correction was provided by the OPENLOOPS library [37, 38]. The process initiated by gluon-gluon fusion ($gg$) was normalised to a cross-section at NLO accuracy in QCD [39].

The strong production of $Z/\gamma^*$+jets events was simulated with SHERPA 2.2.1 using NLO matrix elements for up to two partons, and LO matrix elements for up to four partons, as calculated with the COMIX [40] and OPENLOOPS libraries.

The strong production of $W$+jets was simulated with MADGRAPH5_AMC@NLO [41] with up to four partons at LO in QCD. The sample was showered with PYTHIA 8.210 using the A14 tune and the NNPDF2.3 LO PDF set and the cross-section was normalised to the NNLO prediction from FEWZ [42].

The $WZ$ and $ZZ$ processes were simulated with POWHEG BOX v2 at NLO in QCD. The samples were showered with PYTHIA 8.210 using the CTEQ6L1 PDF set with the AZNLO tune. Only the strong production was considered, the weak production was found to be negligible. Leptonic decays of WWW, WWZ and ZZZ productions were modelled with SHERPA 2.2.2 using factorised gauge boson decays. Matrix elements were accurate at NLO in QCD for the

[2]The resummation damping factor that partly controls the matching of POWHEG matrix elements to the parton shower and thus effectively regulates the high-transverse-momentum radiation against which the $t\bar{t}$ system recoils.

inclusive process and at LO for up to two additional parton emissions. The virtual QCD correction for matrix elements was computed at NLO accuracy via the OpenLoops library. The $WZ$, $ZZ$, and triboson simulations are collectively referred to as ‘multiboson’ production.

Higgs boson production from gluon-gluon fusion was simulated with Powheg NNLOPS [43, 44]. The prediction was normalised to the N$^3$LO order cross-section in QCD and the NLO cross-section in EWK [45–55]. The sample was showered with Pythia 8.212 using PDF4LHC15 PDF set [56] with the AZNLO tune. Higgs boson production from vector boson scattering was simulated with Powheg Box v2 at NLO in QCD and interfaced to Pythia 8.230 for parton showering. Both samples described above are only used to tune the selection cuts, so that such events have a negligible contribution to the events selected in the analysis.

The matrix element calculations from all the samples generated with Sherpa were matched and merged with the parton shower from Sherpa [57] based on Catani-Seymour dipole factorisation using the MEPS@NLO prescription [58–60]. The NNPDF3.0 NNLO PDF set was used along with a dedicated set of tuned parton shower parameters developed by the authors of Sherpa.

## 4 Event selection

The candidate signal events are composed of $W$ pairs produced in association with two or three jets, and decaying into an electron and a muon with opposite electric charges plus neutrinos. The analysis of this final state requires a proper reconstruction, calibration and selection of these physics objects.

The events considered in the analysis were recorded by requiring a combination of single electron and single muon triggers [61, 62]. The primary online electrons and muons considered are required to have a low $p_{\mathrm{T}}$ threshold ranging from 24 GeV to 26 GeV and from 20 GeV to 26 GeV, respectively. Furthermore, these leptons must satisfy a loose to tight lepton quality requirement, depending on the data taking period. Additional triggers with looser lepton identification criteria, and with $p_{\mathrm{T}}$ thresholds from 60 GeV to 140 GeV for electrons and from 50 GeV for muons, were used to increase the efficiency of the event selection. This exceeds 99% for candidate events fulfilling the selection criteria described in table 1.

Electrons are reconstructed from energy deposits in the calorimeter that are matched to tracks [63]. They are calibrated and required to have $|\eta| = 2.47$, excluding the transition region between the barrel and the endcaps of the EM calorimeter, namely $1.37 < |\eta| < 1.52$. Muons are reconstructed by combining the tracking information from the inner detector and the muon spectrometer [64]. They are calibrated and required to have $|\eta| = 2.5$. Selected electrons and muons must fulfil their respective `Tight` identification criteria, which relies on a likelihood in the case of electrons.

The primary vertex is selected from event candidates with the highest $\sum p_{\mathrm{T}}^2$ of the associated tracks recorded in the inner detector with $p_{\mathrm{T}} > 500$ MeV, and both leptons are required to originate from it. This requires the longitudinal impact parameter $z_0$ of the tracks associated with the leptons to satisfy $|z_0 \sin\theta| < 0.5$ mm and their transverse impact parameter significance $d_0/\sigma_{d_0}$ to fulfil $|d_0/\sigma_{d_0}| < 5$ and $< 3$, for electrons and muons, respectively. Leptons are further required to be isolated using information from the tracks in the inner detector and from the energy clusters in the calorimeters in a cone around the lepton. The `Gradient` [65] criteria is used for electrons, while muons are isolated according to the `Tight_FixedRad` criteria, which is close to the `Tight` working point described in Reference [66], yet with improved background rejection for muon $p_{\mathrm{T}} > 50\,\mathrm{GeV}$.

Jets are reconstructed using the anti-$k_t$ clustering algorithm [67, 68] with a radius parameter of $R = 0.4$, and by using the particle flow reconstruction [69], which combines calorimeter deposits and tracks to determine jet properties. They are calibrated to account for the detector response, including a correction to their energy resolution [70]. Only jets within $|\eta| < 4.5$ are kept, and to suppress jets originating from additional proton-proton interactions, those with $p_{\mathrm{T}} < 60\,\mathrm{GeV}$ and $|\eta| < 2.4$ are required to satisfy a `tight` jet-vertex tagger working point [71]. Jets with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.5$ originating from the decay of a $b$-hadron are identified ($b$-tagged) using the `DL1r` $b$-tagging algorithm [72, 73] at the 85% efficiency working point.

The $p_{\mathrm{T}}$ of the final state neutrinos can be inferred from the missing transverse momentum $\vec{p}_T^{\,\mathrm{miss}}$ (with magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$), which is reconstructed from the calibrated leptons and jets. The tracks from the inner detector that are not associated with a physics object are also considered in the determination of $E_{\mathrm{T}}^{\mathrm{miss}}$ [74].

Candidate events are required to have a primary vertex associated with at least two tracks, to ensure a proton-proton collision occurred. Selected events are also required to contain at least one electron and one muon with $p_{\mathrm{T}} > 27\,\mathrm{GeV}$ and opposite electric charges. Events with any additional electron satisfying the `Loose` [65] isolation working point and likelihood-based `Tight` (if $10\,\mathrm{GeV} < p_{\mathrm{T}} < 25\,\mathrm{GeV}$) or `Medium` [63] (if $p_{\mathrm{T}} > 25\,\mathrm{GeV}$) criteria, are rejected. Events containing an additional `Loose` muon with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ satisfying the `Loose` [64] isolation working point are also rejected.

Only events containing either two or three jets with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ are considered, as signal rates for higher multiplicities are significantly smaller. The centrality of the leptons relative to the two leading jets in $p_{\mathrm{T}}$ is defined as

$$\zeta = \text{centrality} = \min\left\{\left[\min(\eta_{\ell_1}, \eta_{\ell_2}) - \min(\eta_{j_1}, \eta_{j_2})\right], \left[\max(\eta_{j_1}, \eta_{j_2}) - \max(\eta_{\ell_1}, \eta_{\ell_2})\right]\right\}, \quad (4.1)$$

where $\eta_{j_{1(2)}}$ and $\eta_{\ell_{1(2)}}$ are the leading (subleading) jet and lepton pseudorapidities, respectively. To enhance the signal to background ratio the centrality is required to exceed 0.5. Due to the relative arrangement of the leptons and jets in an EWK $W^+W^-jj$ event, the signal process tends to produce events with a positive lepton centrality.

Events surviving all these requirements constitute an inclusive sample in which the final state objects are well measured and the kinematic features that distinguish the signal from background processes are exploited to improve the purity of the selected sample. The production of Higgs boson mediated $W$ boson pairs via vector boson fusion is suppressed by discarding events with an invariant mass of the two leptons ($m_{e\mu}$) below 80 GeV, and Drell-Yan events are reduced by requiring the $E_{\mathrm{T}}^{\mathrm{miss}}$ to be above 15 GeV and by focusing on the $e\mu$ decay channel for the decay of the $W$ boson pair. The contribution of $W$ boson pairs with the same electric charge is negligible given all the requirements above.

The definition of the signal region (SR) is completed by discarding events containing at least one $b$-jet, which suppresses the contribution from background processes involving

| Category | Requirements |
|---|---|
| Leptons | $p_{\mathrm{T}} > 27\,\mathrm{GeV}$ |
| | $\lvert\eta\rvert < 2.47$ excluding $1.37 < \lvert\eta\rvert < 1.52$ (electrons) |
| | $\lvert\eta\rvert < 2.5$ (muons) |
| | Identification: `Tight` |
| | Isolation: `Gradient` (electrons), `Tight_FixedRad` (muons) |
| | $\lvert d_0/\sigma_{d_0}\rvert < 5$ (electrons), $\lvert d_0/\sigma_{d_0}\rvert < 3$ (muons) |
| | $\lvert z_0 \sin\theta\rvert < 0.5\,\mathrm{mm}$ |
| $b$-jets | $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.5$ (`DL1r` $b$-tagging with 85% efficiency) |
| Jets | $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $\lvert\eta\rvert < 4.5$ |
| Events | One electron and one muon with opposite electric charges |
| | No additional lepton with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$, `Loose` isolation, |
| | `Tight`/`Medium` (electrons) and `Loose` (muons) identification |
| | $m_{e\mu} > 80\,\mathrm{GeV}$ |
| | $E_{\mathrm{T}}^{\mathrm{miss}} > 15\,\mathrm{GeV}$ |
| | No $b$-jet |
| | Two or three jets |
| | $\zeta > 0.5$ |

**Table 1.** Selection cuts on physics objects and events that define the signal region.

top quark decays. Although the SR is designed to specifically suppress certain backgrounds, a small fraction of the EWK $W^+W^-jj$ events survive the event selection. The kinematic requirements on the different objects considered are summarised in table 1, and the event yields for the different processes in the signal region, after the fit described in section 8, are provided in table 2, distinguishing between the two- and three-jet categories.

Finally, the discrimination between signal and background in the SR is performed by a NN, defined in section 5, which is used to extract the signal via a likelihood fit.

## 5 Neural network discriminant

A neural network is used to separate between the signal and the main remaining backgrounds from the SM, which constitute a large fraction of the SR. The discrimination power of the NN is improved by training it separately for SR events including exactly two or three jets, which differ by the radiation of an additional gluon in the case of signal. The training and evaluation of the NN are achieved with the Keras [75] library interfaced within TMVA [76], by only considering the dominant top quark and strong $W^+W^-jj$ processes as backgrounds. The signal and the background samples are each split into a training and a testing components of equal sizes. Two hidden layers with 108 nodes on the first hidden layer and 60 on the second

| | Event yields | |
|---|---|---|
| Process | $n_{\text{jets}} = 2$ | $n_{\text{jets}} = 3$ |
| EWK $W^+W^-jj$ | $158 \pm 27$ | $54 \pm 13$ |
| $t\bar{t}$ | $2394 \pm 194$ | $1625 \pm 125$ |
| Single top | $491 \pm 34$ | $225 \pm 21$ |
| Strong $W^+W^-jj$ | $1214 \pm 256$ | $514 \pm 121$ |
| $W$+jets | $37 \pm 97$ | $19 \pm 48$ |
| $Z+$jets | $216 \pm 62$ | $65 \pm 25$ |
| Multiboson | $101 \pm 5$ | $42 \pm 3$ |
| SM prediction | $4610 \pm 77$ | $2546 \pm 48$ |
| Data | 4610 | 2533 |

**Table 2.** The composition of the events in the signal region predicted by the SM and the total predicted yield compared with the data. The events are split into two categories, depending on the number of jets. The uncertainties include both statistical and systematic contributions, and correspond to the values after the likelihood fit described in section 8. The uncertainties in the total predictions are smaller than the individual component uncertainties due to correlations induced by the fit.

one are implemented. The output layer incorporates two neurons and the final output of the network takes values between 0 and 1. The optimisation of the hyperparameters, including the number of neurons and layers, is accomplished by maximizing the resulting area under the ROC curve,[3] via a grid search. This figure of merit also influences the choice of the input variables to the NN, which are mostly weakly correlated between each other.

The set of input variables used in the two-jet category consists of the leading and subleading jet $p_{\text{T}}$, $m_{\ell\ell}$, $\zeta$, the $E_{\text{T}}^{\text{miss}}$ significance,[4] the difference $\Delta\eta_{jj}$ between the pseudorapidities of the two leading jets, the azimuthal angle separation $\Delta\phi_{jj}$ between the two leading jets, and the invariant mass $m_{e\mu jj}$ constructed from the four-vectors of the two leading leptons and the two leading jets. In the case of the three-jet category, the same input variables are used with the addition of the $p_{\text{T}}$ and the centrality of the third-leading jet, the latter being defined as

$$\zeta_3 = \text{third-leading jet centrality} = \left| y_{j_3} - \frac{1}{2} \cdot \frac{y_{j_1} + y_{j_2}}{y_{j_1} - y_{j_2}} \right|, \tag{5.1}$$

where $y_{j1}$, $y_{j2}$ and $y_{j3}$ are the rapidities of the leading, subleading and third-leading jets in $p_{\text{T}}$, respectively. For both jet categories, the most sensitive variables in the NN are the $p_{\text{T}}$ of the two leading jets, as they tend to have larger values in VBS processes. Furthermore, in the three-jet category, the third-leading jet has a centrality ($\zeta_3$) that peaks at high values in signal events, as it is frequently emitted from one of the two leading forward jets, thus

[3] Receiver Operating Characteristic curve.

[4] $E_{\text{T}}^{\text{miss}}$ significance is computed as $\frac{|\vec{p}_T^{\,\text{miss}}|}{\sqrt{\sigma_{\text{L}}^2(1-\rho_{\text{LT}}^2)}}$, where $\sigma_{\text{L}}$ is the total variance in the direction longitudinal to $E_{\text{T}}^{\text{miss}}$, and $\rho_{\text{LT}}$ is the correlation coefficient of the longitudinal (L) and transverse (T) $E_{\text{T}}^{\text{miss}}$ measurements.



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providing an additional gain in sensitivity. The invariant mass $m_{jj}$, constructed from the two leading jets in $p_{\mathrm{T}}$, although usually considered to enhance a VBS phase space, is not used in the input to the NN because it can largely be derived from the observables already used.

To avoid overtraining the NN and to increase its robustness, a dropout regularisation with a rate of 0.1 is applied to both hidden layers. This procedure randomly drops some neurons from the NN at each step of the training, which can be interpreted as considering the average of different layer set-ups. The evaluation of the NN using either the training or an independent test sample produces compatible responses. The NN is further validated in the SR by comparing data and simulation for the correlations of the input variables between each other and against the NN output. Finally, the binning of the NN output is optimised to increase the sensitivity to the signal at high NN output values.

## 6 Background determination

The main background to the EWK production of $W^+W^-jj$ events consists of top quarks produced either individually or in pairs, and in total represents 66% of the SR. The second most important background is the strong production of pairs of $W$ bosons in association with jets, which amounts to 24% of the SR. The remaining backgrounds are the production of a $Z$ boson in association with jets (4%), other multiboson events (2%), and a $W$ boson in association with jets where one jet is misidentified as a lepton (below 1%).

The background originating from the production of top quarks is modelled by simulation, and further constrained with data in a dedicated control region (CR). The latter is defined with the same cuts as the SR except for requiring one of the two leading jets to be a $b$-jet. This region is thus dominated by events including a top quark, as highlighted in figure 3, which shows the NN discriminant evaluated from events in the CR, using the same model as in the SR for the two- and three-jet categories. In the NN distribution, signal-like and background-like events tend to have NN output values closer to 1 and 0, respectively. The normalisation of the predicted top quark production is constrained by a binned likelihood fit that includes both the CR and the SR, as described in section 8. The top quark CR proves to be necessary to constrain the normalisation of top quark events, since the low bins of the NN output in the SR, although enriched in top quarks, are found not to have a sufficient constraining power due to the substantial number of strong $W^+W^-jj$ events with similar NN shape in the SR.

It is challenging to define a dedicated CR to enhance the strong production of $W^+W^-jj$ events, given the significant contribution of events originating from the production of top quarks. Nevertheless, the normalisation of simulated $W^+W^-jj$ events is left as a free parameter in the likelihood fit in order to constrain it with data together with the top quark background, using events from the top quark CR and SR.

The less relevant background consisting of $W$ boson production in association with jets is modelled by simulation. To better account for this fraction of events where jets are misreconstructed as leptons, the prediction is scaled up by 15% to 60% across the NN distribution using a constraint from a data region enriched in fake leptons. The latter is defined by selecting leptons with a looser identification, and by requiring that at least one of the two leptons fails to satisfy the isolation and the tight identification requirements, the



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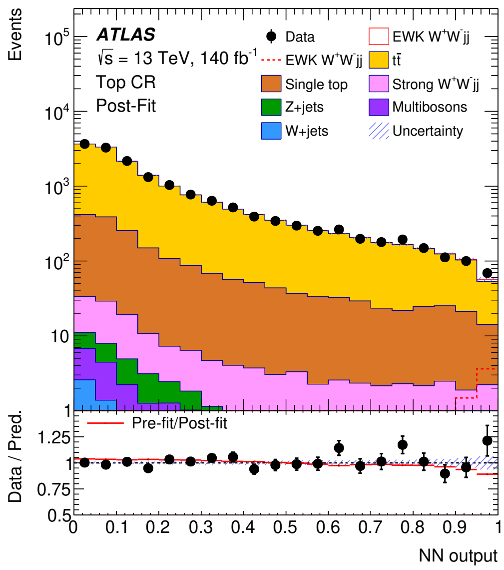


**Figure 3.** Distribution of the NN output in the top quark CR, with the top quark, strong $W^+W^-jj$, and signal processes constrained by the likelihood fit described in section 8. The two- and three-jet categories are merged. Data corresponds to the black dots, the signal normalised to its simulated cross-section is represented by the unstacked dashed histogram, and the post-fit predictions of the SM together with the signal are depicted by the stacked filled histograms. The lower panel shows the ratio of the data to the post-fit predictions of the SM, and the ratio of the pre-fit to the post-fit SM yields. The uncertainty in the total contribution from the SM is illustrated by a hashed band.

other selection cuts being the same as in the SR. The semileptonic decays of top quarks is accounted for in the fake region as it includes fake leptons coming from $b$-jets.

Since only a few events arising from the $Z$ boson and multiboson predictions survive the SR selection, these backgrounds are modelled by simulation with no additional constraints from data.

Figure 4 shows the distributions of the leading and subleading jet $p_{\mathrm{T}}$, the centrality, and the invariant mass $m_{e\mu jj}$ constructed from the four-vectors of the selected leptons and jets in the two-jet signal region. Figure 5 shows the distributions of the leading and subleading jet $p_{\mathrm{T}}$, the centrality, and the third-leading jet centrality in the three-jet signal region. All figures are shown after the binned likelihood fit described in section 8, and demonstrate a good overall modelling of these observables, which are used as input to the NN. However, some variables like the leading jet $p_{\mathrm{T}}$ are sensitive to the mismodelling of the top quark $p_{\mathrm{T}}$, which is not corrected for. The potential subsequent tensions in the agreement between data and the SM prediction are however mostly covered at the edge of the uncertainty bands.

## 7 Uncertainties

Systematic uncertainties in the measurement of the signal cross-section originate from experimental and theoretical sources due to the signal and background modelling.

The dominant experimental uncertainties are related to the calibration of the jets, namely the jet energy scale and resolution [70], the $b$-tagging efficiency and the jet flavour composition. Other sources of experimental uncertainties are due to the calibration of the leptons, which

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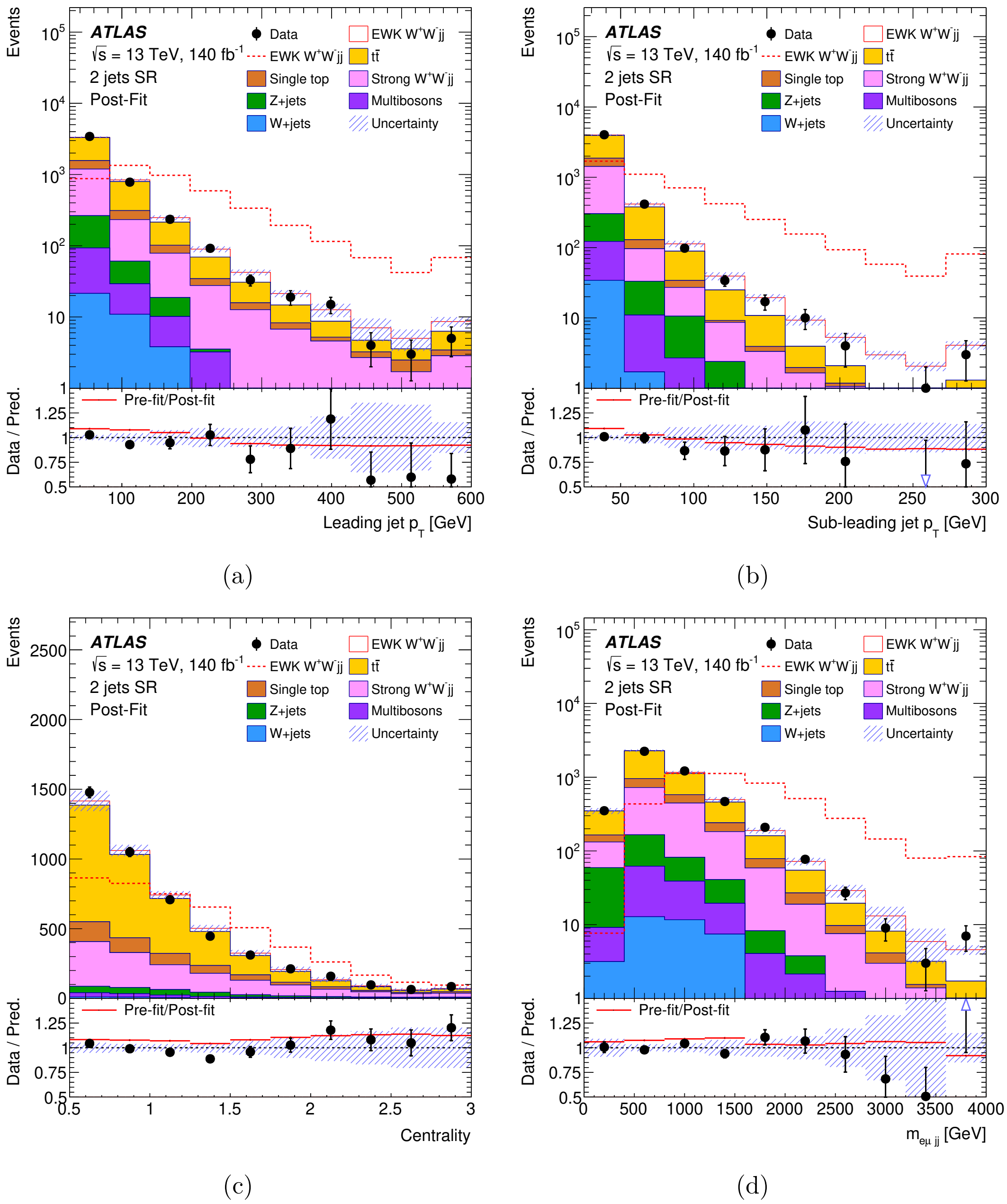


**Figure 4.** Distributions of (a) the leading and (b) subleading jet $p_{\mathrm{T}}$, (c) the centrality and (d) the invariant mass $m_{e\mu jj}$ constructed from the four-vectors of the two leading leptons and jets. The observables are presented in the SR in the two jet case, with the top quark, strong $W^+W^-jj$, and signal processes constrained by the likelihood fit described in section 8. Data corresponds to the filled dots, the signal normalised to the total SM background is represented by the unstacked dashed histogram, and the post-fit predictions of the SM together with the signal are depicted by the stacked filled histograms. The lower panels show the ratios of the data to the post-fit predictions of the SM, and the ratio of the pre-fit to the post-fit SM yields. The uncertainty in the total contribution from the SM is illustrated by a hashed band.

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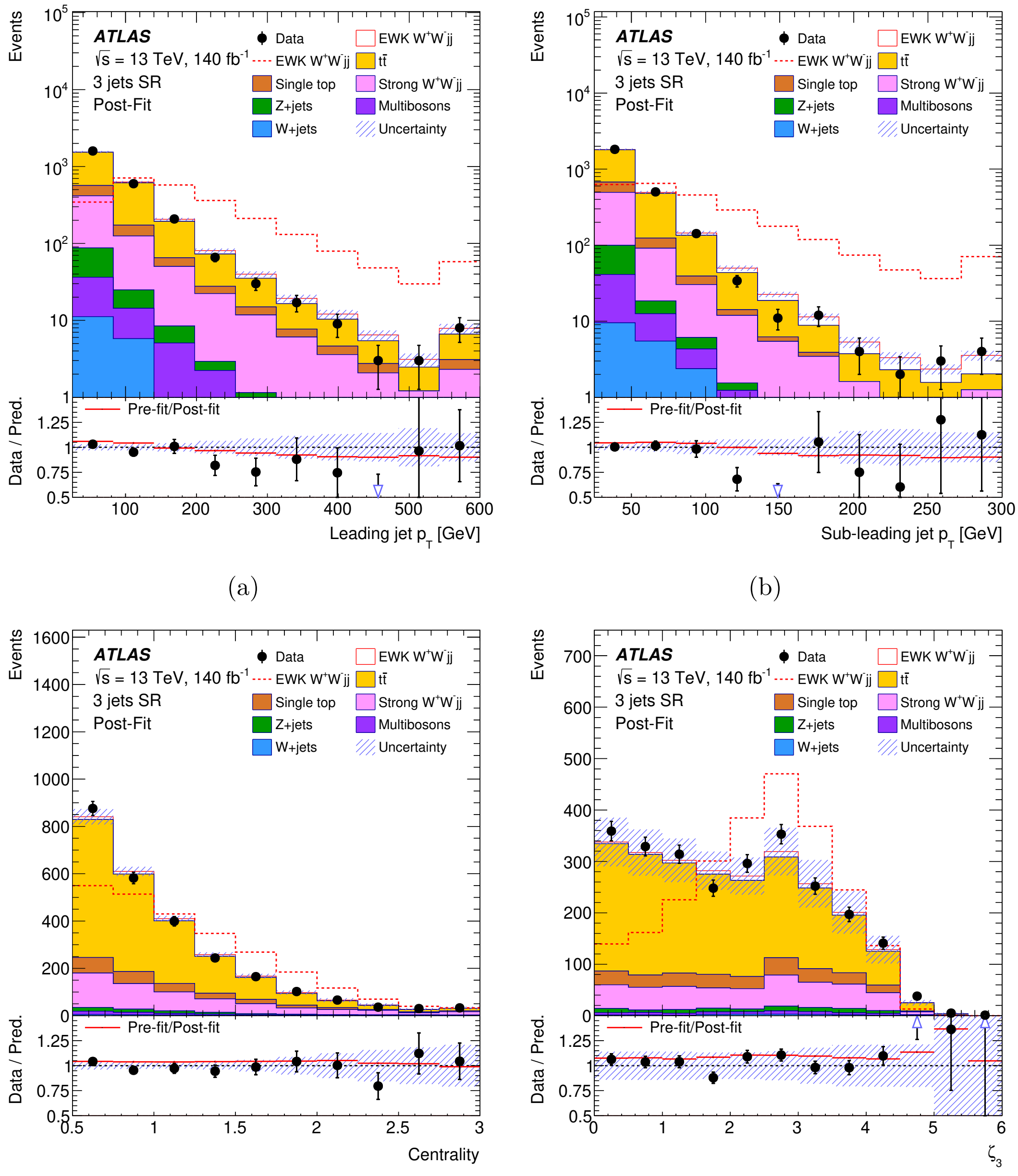


**Figure 5.** Distributions of (a) the leading and (b) subleading jet $p_{\mathrm{T}}$, (c) the centrality and (d) the third-leading jet centrality $\zeta_3$. The observables are presented in the SR in the three jet case, with the top quark, strong $W^+W^-jj$, and signal processes constrained by the likelihood fit described in section 8. Data corresponds to the filled dots, the signal normalised to the total SM background is represented by the unstacked dashed histogram, and the post-fit predictions of the SM together with the signal are depicted by the stacked filled histograms. The lower panels show the ratios of the data to the post-fit predictions of the SM, and the ratio of the pre-fit to the post-fit SM yields. The uncertainty in the total contribution from the SM is illustrated by a hashed band.



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affects their identification and isolation efficiencies, their energy resolution and momentum scale [63, 77], and the lepton trigger efficiencies and pile-up modelling. To account for the mismodelling of the simulated $W$+jets background where one jet is misidentified as a lepton, a conservative uncertainty of 100% is assigned to its normalisation, with a negligible impact on the signal extraction. As this uncertainty is modelled by a gaussian in the likelihood fit, the corresponding postfit errors provided in table 2 overlaps with negative estimates. All experimental uncertainties are propagated through the analysis and the final impact on the signal strength is evaluated when performing the likelihood fit.

The uncertainties in the modelling of the signal includes variations of the renormalisation and factorisation scales, the PDF, the parton shower and the initial- and final-state radiation. To estimate the uncertainty due to missing higher-order QCD corrections, the renormalisation and factorisation scales are varied up and down by factors of two, avoiding opposite variations. The parton shower uncertainty is estimated by comparing the nominal simulation, described in section 3, with an alternative prediction performed using POWHEG BOX v2 interfaced to HERWIG 7.2.1 [78, 79] with the dipole shower model and the H7.1-Default hadronisation and underlying-event tune. The interference between EWK and strong production of $W^+W^-jj$ was evaluated using MADGRAPH5_aMC@NLO, and the resulting value was taken as an uncertainty in the signal, amounting to 1%.

Theoretical uncertainties in the prediction of the background are mostly due to the simulation of top quark events. The parton shower and hadronisation modelling is evaluated by comparing the nominal POWHEG+PYTHIA 8 prediction with an alternative one performed using POWHEG BOX v2 interfaced to HERWIG 7.04 with the H7UE set of tuned parameters and the MMHT2014 LO PDF set [80]. Similarly, the uncertainty in the matching of NLO matrix elements to the parton shower is evaluated by comparing the nominal simulation with events generated by MADGRAPH5_aMC@NLO 2.6.2 at NLO in QCD with the five-flavour scheme and the NNPDF2.3 NLO PDF set and interfaced to PYTHIA 8.230. The uncertainty due to higher-order QCD effects and initial-state radiation for the top quark background is evaluated by varying the renormalisation and factorisation scales, the $h_{\rm damp}$ parameter, and the VAR3c up and down variants of the A14 tune [81]. The final-state radiation uncertainty is evaluated by scaling up and down by a factor of two the renormalisation scale used for final-state parton shower emissions. The uncertainty associated with the $Wt$ interference with $t\bar{t}$ is estimated by comparing the nominal $Wt$ simulation, where $t\bar{t}$ contributions are removed at the amplitude level using the diagram-removal scheme [82], with an alternative $Wt$ simulation, where $t\bar{t}$ contributions are removed at the cross-section level using the diagram-subtraction scheme [82].

Theoretical uncertainties in the strong $qq \to WW$ and $Z$ + jets backgrounds originate from the renormalisation and factorisation scales, and are estimated by using the same method as for the signal. The theoretical uncertainty on the $gg \to WW$ production is neglected as this background represents less than 7% of the $qq \to WW$ process, and has no impact on the final result.

Finally, PDF uncertainties are estimated by using a reweighting procedure at the matrix element level for 100 variations of the NNPDF3.0 NLO PDF set for the signal and for the top quark, strong $W^+W^-jj$, and $Z$ + jets backgrounds. For each bin of the NN, the standard deviation of these variations is taken as the uncertainty.

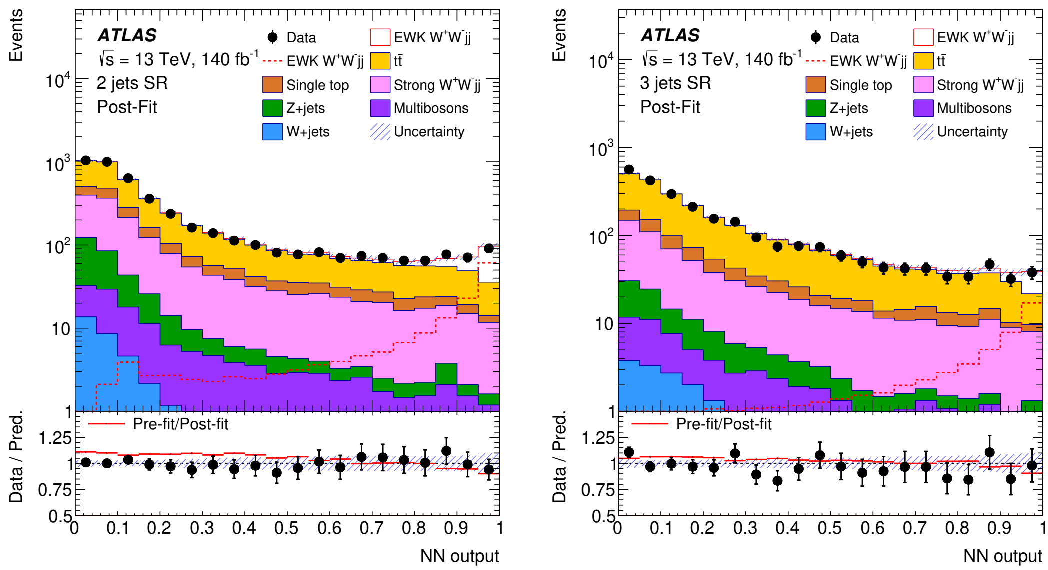
## 8 Signal extraction and cross-section measurement

A profile likelihood fit [83, 84] is performed on the NN output observable, simultaneously in the SR and CR, with the normalisations of the signal ($\mu$), top quark and strong $W^+W^-jj$ processes set as floating parameters. These normalisations consist of multiplicative factors to the nominal process simulation to match the observation in data. The NN is trained separately for events with two or three jets in the SR, with distinct distributions being fitted for the two categories. However, events with both jet multiplicities from the CR are merged together. Figures 3 and 6 show the neural network distribution after the fit in the CR and SR, respectively. A good description of the data by the predicted signal and background events can be observed in both figures.

As illustrated in figure 7, the normalisation of the top quark background is well constrained by the fit, contrary to the normalisation of the strong $W^+W^-jj$ production, which does not benefit from a dedicated CR, as it is challenging to isolate. The impact of the uncertainty due to the normalisation of the strong $W^+W^-jj$ background on the total uncertainty is however limited, as this process represents only about 10 to 15% of the events at large NN output values. The split of the SR into a component with two jets and another one with three jets was found to improve the expected signal significance by about one standard deviation. The observed and expected signal significance obtained from the fit are 7.1 and 6.2 standard deviations, respectively.

The uncertainty in the signal strength $\mu$ derived from the likelihood fit is referred to as $\Delta\mu$. For each source of systematic uncertainty, a new fit is performed with the other nuisance parameters left constant at their best fit values from the nominal fit, providing a variation of the uncertainty in the signal strength $\Delta\mu^{'}$. The impact of each category of uncertainty is defined as $\sqrt{(\Delta\mu)^2 - (\Delta\mu')^2}/\mu$ and is reported in table 3. The uncertainty in the luminosity and the experimental uncertainties specific to a given physics object are treated as fully correlated across the different predictions and regions in the fit. The theoretical uncertainties in the prediction of the top quark background are considered as correlated between the CR and the SR. The dominant uncertainty in the fit is due to the limited number of events in the data and amounts to 12.3%, while the total uncertainty is 18.5%. The nuisance parameters with an impact smaller than 0.5% are pruned, with negligible effect on the results.

The cross-section for VBS $W^+W^-jj$ production is measured at particle level in a fiducial region designed to be close to the most sensitive subset of the SR. Its event selection is detailed in table 4, and combines the two- and three-jet categories. In the fiducial volume, particle-level electrons and muons are required to originate from the hard scatter. The impact of photons emitted in a cone of radius $\Delta R = 0.1$ around each lepton direction is considered by adding their momenta to the lepton momentum. At particle level, jets are defined by clustering stable final-state particles using the anti-$k_t$ algorithm with a distance parameter of $R = 0.4$, and the missing transverse momentum is evaluated as the transverse component of the vectorial sum of the neutrino momenta. Events where the two leading jets have an invariant mass $m_{jj}$ smaller than 500 GeV are excluded from the fiducial region, while this is not required in the reconstruction-level SR. Events with $m_{jj}$ above 500 GeV in the fiducial region are primarily reconstructed with NN output values larger than 0.6, which constitutes a region where the fraction of reconstructed signal events in the SR exceeds 5%




(a) (b)

**Figure 6.** Distributions of the neural network output in the SR for (a) two jets and (b) three jets, with the top quark, strong $W^+W^-jj$, and signal processes constrained by the likelihood fit described in section 8. Data corresponds to the filled dots, the signal normalised to its simulated cross-section is represented by the unstacked dashed histogram, and the post-fit predictions of the SM together with the signal are depicted by the stacked filled histograms. The lower panels show the ratios of the data to the post-fit predictions of the SM, and the ratio of the pre-fit to the post-fit SM yields. The uncertainty in the total contribution from the SM is illustrated by a hashed band.

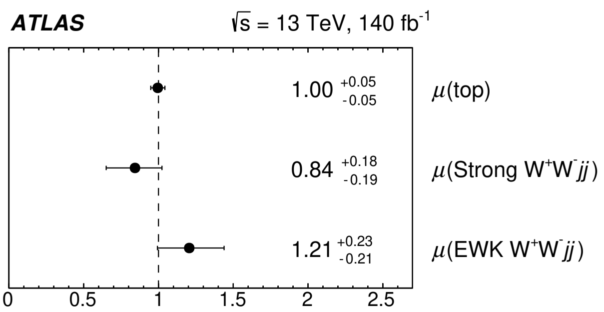



**Figure 7.** Measurement of the signal strength $\mu = \mu(\mathrm{EWK}\ W^+W^-jj)$ from the likelihood fit described in section 8 together with the normalisations of the backgrounds originating from the top quark and strong $W^+W^-jj$ events.

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| Sources | $\frac{\sqrt{(\Delta\mu)^2-(\Delta\mu')^2}}{\mu}$ [%] |
|---|---|
| MC statistical uncertainty | 7.7 |
| Top quark theoretical uncertainties | 6.3 |
| Signal theoretical uncertainties | 5.8 |
| Jet experimental uncertainties | 4.9 |
| Strong $W^+W^-jj$ theoretical uncertainties | 1.3 |
| Luminosity | 0.8 |
| Misidentified lepton uncertainty | 0.5 |
| $b$-tagging | 0.4 |
| Lepton experimental uncertainties | 0.1 |
| Others | 0.3 |
| Data statistical uncertainty | 12.3 |
| Top quark normalisation uncertainty | 4.9 |
| Strong $W^+W^-jj$ normalisation uncertainty | 2.2 |
| Total uncertainty | 18.5 |

**Table 3.** Impact of systematic uncertainties on the signal strength $\mu$ after the fit. The different nuisance parameters are merged into various categories. The statistical and total uncertainties are also provided.

in each NN bin and therefore drives the determination of the signal strength $\mu$. The cut on $m_{jj}$ in the fiducial volume allows the production of triboson events to be suppressed, thus providing a fiducial cross-section purely related to the $W^+W^-jj$ production. The fiducial cross-section for VBS $W^+W^-jj$ production is obtained by multiplying $\mu$ by the theoretical fiducial cross-section. Therefore, the cut on $m_{jj}$ also avoids $\mu$ being applied to regions of the phase space where the signal is negligible.

Using Powheg Box v2, the theoretical cross-section for the VBS $W^+W^-$ production is $2.20^{+0.14}_{-0.13}$ fb, while the observed fiducial cross-sections is $2.65^{+0.49}_{-0.46}$ fb.



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| Category | Requirements |
|---|---|
| Leptons | $p_{\mathrm{T}} > 27\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.5$ |
| $b$-jets | $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $\lvert\eta\rvert < 2.5$ |
| Jets | $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ and $\lvert\eta\rvert < 4.5$ |
| Events | One electron and one muon with opposite electric charges |
| | No additional lepton |
| | $m_{e\mu} > 80\,\mathrm{GeV}$ |
| | $E_{\mathrm{T}}^{\mathrm{miss}} > 15\,\mathrm{GeV}$ |
| | No $b$-jet |
| | Two or three jets |
| | $\zeta > 0.5$ |
| | $m_{jj} > 500\,\mathrm{GeV}$ |

**Table 4.** Definition of the fiducial region at particle level.

## 9 Conclusion

The cross-section of the electroweak production of pairs of scattering $W$ bosons with opposite electric charges is measured using a dataset amounting to $140\,\mathrm{fb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$.

The analysis focuses on the final state consisting of an electron and a muon with opposite electric charges, missing transverse energy, and two or three jets. A NN is used to discriminate between the signal and the dominant processes from the SM, namely top quark and strong $W^+W^-jj$ production, and to extract the signal yield. The signal is observed with a significance of 7.1 standard deviations, while 6.2 standard deviations were expected. The observed cross-section is determined in a signal-enriched fiducial volume, and amounts to $2.7 \pm 0.5\,\mathrm{fb}$, which is consistent with the theoretical prediction of $2.20^{+0.14}_{-0.13}\,\mathrm{fb}$. The dominant source of uncertainty is due to the limited number of events in the data.


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