Measurement of fiducial and differential $W^+W^-$ production cross-sections at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS Collaboration

CERN, 1211 Geneva 23, Switzerland

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Abstract A measurement of fiducial and differential cross-sections for $W^+W^-$ production in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS experiment at the Large Hadron Collider using data corresponding to an integrated luminosity of 36.1 fb$^{-1}$ is presented. Events with one electron and one muon are selected, corresponding to the decay of the diboson system as $WW \rightarrow e^{\pm}\nu_{\mu}\bar{\nu}_{\mu}$. To suppress top-quark background, events containing jets with a transverse momentum exceeding 35 GeV are not included in the measurement phase space. The fiducial cross-section, six differential distributions and the cross-section as a function of the jet-veto transverse momentum threshold are measured and compared with several theoretical predictions. Constraints on anomalous electroweak gauge boson self-interactions are also presented in the framework of a dimension-six effective field theory.

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1 Introduction

The measurement of the production of $W$-boson pairs through interactions of quarks and gluons probes the electroweak (EW) gauge structure of the Standard Model (SM) and allows further tests of the strong interaction between quarks and gluons. The $WW$ production process is also important as it constitutes large irreducible backgrounds in searches for physics beyond the SM and to $H \rightarrow WW^*$ production. Its large production cross-section combined with the large sample of proton–proton ($pp$) collision data delivered by the Large Hadron Collider (LHC), enables this process to be studied differentially with a better statistical precision than was possible in previous measurements.

The first measurements of $WW$ production were carried out at the LEP electron–positron collider [1]. At the Tevatron this process was measured in proton–antiproton collisions by the CDF [2,3] and DØ [4] Collaborations. In $pp$ collisions at the LHC, $WW$ production cross-sections were determined for centre-of-mass energies of $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV by the ATLAS [5,6] and CMS [7,8] Collaborations. In addition, a dedicated measurement of the $WW + 1$-jet final state was carried out by the ATLAS Collaboration [9] at $\sqrt{s} = 8$ TeV. At $\sqrt{s} = 13$ TeV, the total cross-section for $WW$ production was measured by the ATLAS Collaboration [10], albeit only for the small 2015 data sample, which did not allow any differential studies.

The cross-section measurements at $\sqrt{s} = 7$ and $\sqrt{s} = 8$ TeV revealed discrepancies between data and theory that have since been addressed through the inclusion of higher-
order corrections in perturbative quantum chromodynamics (QCD) [11–16]. This has remedied the mismatch between the total measured and predicted cross-sections, but some discrepancies in the differential distributions persist. The high-energy behaviour of the \( WW \) cross-section and the angular distributions of the \( WW \) decay products could be affected by new physical phenomena at higher partonic centre-of-mass energies, such as EW doublet or triplet scalars [17,18] or degenerate and non-degenerate top-quark superpartners (stops) in supersymmetry (SUSY) scenarios [19,20]. These specific models can be constrained by their contribution to dimension-six operators in an effective Lagrangian at tree level [17]. At lower partonic centre-of-mass energies, \( WW \) production can also be used to provide complementary constraints on compressed EW SUSY scenarios with low stop masses [21].

The \( WW \) signal is composed of two leading sub-processes: \( q\bar{q} \rightarrow WW \) production\(^1\) (in the \( t- \) and \( s\)-channels) and gluon–gluon fusion production (both non-resonant \( gg \rightarrow WW \) and resonant \( gg \rightarrow H \rightarrow WW \)). Figure 1 shows representative sub-processes. To allow for a proper treatment and inclusion of the interference, which is especially relevant in the tails of kinematic distributions, the resonant production is kept as part of the signal. The fiducial phase space is defined to be orthogonal to the \( H \rightarrow WW \) measurements by the ATLAS Collaboration [22,23] using a requirement on the dilepton invariant mass. Therefore the Higgs boson contribution included in the signal definition is dominated by off-shell production and interference effects. The production of two \( W \) bosons from the decay of top–antitop quark pairs is not considered part of the signal.

The different sub-processes for \( WW \) production are known theoretically at different orders in the strong coupling constant \( \alpha_s \). The \( q\bar{q} \rightarrow WW \) production cross-section is known to \( O(\alpha_s^3) \), next-to-next-to-leading order (NNLO) [11,15]. Recently, also a NNLO prediction matched to a parton shower has become available [15,24,25]. The non-resonant \( gg \rightarrow WW \) production cross-section is known to \( O(\alpha_s^3) \), next-to-leading order (NLO) [26], and its interference with the resonant \( gg \rightarrow WW \) production cross-section is known to \( O(\alpha_s^2) \).

This paper presents a measurement of the fiducial cross-section for \( WW \) production at \( \sqrt{s} = 13 \text{ TeV} \) using \( pp \) collision data recorded in 2015 and 2016 by the ATLAS experiment, corresponding to an integrated luminosity of 36.1 \( \text{fb}^{-1} \). The \( WW \rightarrow e^+\nu\mu^-\bar{\nu} \) decay channel is studied (denoted in the following by \( WW \rightarrow e\mu \)). The measurement is performed in a phase space close to the geometric and kinematic acceptance of the experimental analysis. This includes a veto on the presence of jets with transverse momenta (\( p_T \)) above a series of thresholds, with a \( p_T = 35 \text{ GeV} \) threshold used as a baseline. Measuring the fiducial cross-section as a function of the jet veto \( p_T \) threshold provides an indirect measure of the jet \( p_T \) spectrum in \( WW \) events, without removing the jet veto that is necessary for background suppression.

Six differential distributions involving kinematic variables of the final-state charged leptons are measured in the baseline phase space. Three of them characterize the energy of the process: the transverse momentum of the leading lepton \( p_T^{\text{lead} \ell} \), the invariant mass of the dilepton system \( m_{e\mu} \) and the transverse momentum of the dilepton system \( p_T^{e\mu} \). Three further distributions probe angular correlations and the spin state of the \( WW \) system. These are the rapidity of the dilepton system \( |y_{e\mu}| \), the difference in azimuthal angle between the decay leptons \( \Delta\phi_{e\mu} \), and \( |\cos \theta^*| \) defined as:

\[
|\cos \theta^*| = \left| \tanh \left( \frac{\Delta\eta_{e\mu}}{2} \right) \right|,
\]

where \( \Delta\eta_{e\mu} \) is the difference between the pseudorapidities of the leptons.\(^2\) This variable is longitudinally boost-invariant and sensitive to the spin structure of the produced diparticle pairs as discussed in Ref. [27]. The unfolded \( p_T^{\text{lead} \ell} \) distribution is used to set limits on anomalous triple-gauge-boson couplings, since this distribution was identified as the most sensitive to the effect of these couplings.

2 ATLAS detector

The ATLAS detector [28] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and nearly 4\( \pi \) coverage in solid angle. It consists of inner tracking devices surrounded by a superconducting solenoid, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer. The inner detector (ID) provides charged-particle tracking in the pseudorapidity region \( |\eta| < 2.5 \) and vertex reconstruction. It comprises a silicon pixel detector, a silicon microstrip tracker, and a straw-tube transition radiation tracker. The ID is placed inside a solenoid that produces a 2 T axial magnetic field. Lead/liquid-argon (LAr) sampling calorimeters provide EM energy measurements with high granularity. 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 both the EM and hadronic energy measurement.

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\(^1\) The notation \( q\bar{q} \rightarrow WW \) is used to include both the \( q\bar{q} \) and \( gg \) initial states for \( WW \) production.

\(^2\) ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the \( z \)-axis coinciding with the axis of the beam pipe. The \( x \)-axis points from the interaction point to the centre of the LHC ring, and the \( y \)-axis points upward. The pseudorapidity is defined in terms of the polar angle \( \theta \) as \( \eta = -\ln \tan(\theta/2) \), and \( \phi \) is the azimuthal angle around the beam pipe relative to the \( x \)-axis. The angular distance is defined as \( \Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \). Transverse energy is computed as \( E_T = E \cdot \sin \theta \).
measurements up to $|\eta| = 4.9$. The muon spectrometer (MS) is operated in a magnetic field provided by air-core superconducting toroids and includes tracking chambers for precise muon momentum measurements up to $|\eta| = 2.7$ and trigger chambers covering the range $|\eta| < 2.4$.

A two-level trigger system [29] selects the events used in the analysis. The first level is implemented in custom electronics, while the second trigger level is a flexible software-based system.

3 Data and simulated event samples

The data were collected at a centre-of-mass energy of 13 TeV during 2015 and 2016, and correspond to an integrated luminosity of 36.1 fb$^{-1}$. Only high-quality data with all detectors in normal operating conditions are analysed. The average number of interactions per bunch crossing was estimated to be $\langle \mu \rangle = 24$.

Simulated event samples are used for most of the background estimates, for the correction of the signal yield due to detector effects, and for comparison with the measured cross-sections.

The $WW$ signal was modelled using the NLO perturbative QCD POWHEG-BOX v2 event generator [30–34] for $q\bar{q}$ initial states. The $gg \rightarrow WW$ contribution was generated using the SHERPA 2.1.1+OPENLOOPS framework [35,36] at leading order (LO) with up to one additional parton and includes non-resonant and resonant Higgs boson production and interference terms. The SHERPA 2.1.1+OPENLOOPS framework also allows these contributions to be generated and studied separately. In both cases, the CT10 [37] parton distribution functions (PDF) were used. POWHEG-BOX was interfaced to PYTHIA 8.210 [38] for the modelling of parton showering and hadronization as well as underlying-event simulation, using the AZNLO [39] set of tuned parameters (‘tune’) and the CTEQ6L1 [40] PDF set. SHERPA used its own parton shower, fragmentation and underlying-event model. Alternative signal samples for the quark-induced production were generated using POWHEG-BOX interfaced to HERWIG++ 2.7.1 [41] with the UEE5.2 tune [42], and using the SHERPA 2.2.2 generator with its own model for parton showering, hadronization and the underlying event. The SHERPA 2.2.2 prediction was obtained at NLO with up to one additional parton emission and up to three at LO and employs the NNPDF3.0 [43] PDF set. The $WW$ signal predictions were normalized to the NNLO cross-section [11]; the $gg \rightarrow WW$ process was normalized to its inclusive NLO cross-section [26].

The background processes considered are: top-quark pair production ($t\bar{t}$), associated production of a top quark with a $W$ boson ($Wt$), single vector-boson production ($W$ or $Z$, in association with jets), multijet production, other diboson production ($WZ$, $ZZ$, $W\gamma$ and $Z\gamma$) and triboson production ($WWW$, $WWZ$, $WZZ$ and $ZZZ$), where $Z$ stands for $Z/\gamma^*$. For the generation of $t\bar{t}$ and $Wt$ processes at NLO, POWHEG-BOX v2 [44] and POWHEG-BOX v1 [30] respectively were used with the CT10 PDF set. For the parton shower, hadronization and underlying event, simulated events were interfaced to PYTHIA 8.186 for $t\bar{t}$ and PYTHIA 6.425 [45] for single-top production, using the A14 tune [46] and the Perugia 2012 [47] tune, respectively. The top-quark mass was set to 172.5 GeV. In the $t\bar{t}$ sample, the $h_{\text{damp}}$ parameter that regulates the high-$p_T$ emission, against which the $t\bar{t}$ system recoils, was set to 1.5 times the top-quark mass following studies reported in Ref. [48]. Alternative samples were generated with different settings to assess the uncertainty in modelling top-quark events. To estimate uncertainties in additional QCD radiation in top-quark processes, a pair of samples was produced with the alternative sets of A14 ($t\bar{t}$) or Perugia 2012 ($Wt$) parameters for higher and lower radiation, as well as with different renormalization and factorization scales which were both varied either by a factor of 2 or 0.5. For the higher-radiation samples, the value of the $h_{\text{damp}}$ parameter was doubled. Two alternative Monte Carlo (MC) programs were used to estimate the impact of the choice of hard-scatter generator and hadronization algorithm in top-quark events; for each of these samples one of the two components was replaced by an alternative choice. The alter-
native choices are MadGraph5_aMC@NLO 2.3 [49] for
the hard-scatter generator and HERWIG 7 [50] (HERWIG++
2.7.1) for the hadronization algorithm in $t\bar{t}$ ($Wt$) events. In
addition, the modelling of the overlap at NLO between $Wt$
and $t\bar{t}$ diagrams [51] was studied. The effect was assessed
by generating $Wt$ events with different schemes for over-
lap removal using the POWHEG-BOX event generator inter-
faced to PYTHIA 6.425 for the simulation of parton showering
and non-perturbative effects. The top-quark events were nor-
amalized using the NNLO+next-to-next-to-leading-logarithm
(NNLL) QCD cross-section [52] for $t\bar{t}$, and the NLO+NNLL
cross-section [53] for $Wt$ production.

The $Z+\text{jets}$ process (with $Z \to e\mu/\mu\mu/\tau\tau$) was modelled
using SHERPA 2.2.1 [54] with the NNPDF3.0 PDF set. This
process was calculated with up to two additional partons at
NLO and up to four additional partons at LO. The $W+\text{jets}$ and
alternative $Z+\text{jets}$ events were produced with the POWHEG-
BOX generator at NLO accuracy using the CT10 PDF set,
interfaced to PYTHIA 8.186 for parton showering, hadroni-
zation and the underlying event. As in the $WW$ samples, the
AZNLO tune was used for the underlying event together with the
CTEQ6L1 PDF set. The $Z+\text{jets}$ and $W+\text{jets}$ events were
normalized using their respective NNLO cross-section cal-
culations [55].

The background from diboson production processes ($WZ$,
$ZZ$, $W\gamma$ and $Z\gamma$) was simulated using the SHERPA 2.2.2
generator with the NNPDF 3.0 PDF set. The samples include up
to one additional parton emission at NLO and up to three
at LO. Alternative samples for $WZ$ and $ZZ$ processes were produced
using the same POWHEG-BOX+PYTHIA 8 set-up as the
$q\bar{q}$-initiated $WW$ signal samples discussed above. The
background from triboson production was modelled using the
SHERPA+OPENLOOPS generator with the CT10 PDF set,
calculated at NLO for inclusive production and including up
to two hard parton emissions at LO. The $WZ$, $ZZ$
and triboson samples produced with SHERPA were nor-
malized to the cross-section calculated by SHERPA, with hard
parton emissions at NLO or LO as discussed, and thus already
capturing some of the NNLO effects. The $WZ$ and $ZZ$
backgrounds simulated with POWHEG-BOX were normalized
to their NNLO cross-sections [56–60].

EVTGEN 1.2.0 [61] was used for the properties of the
bottom and charm hadron decays after hadronization in all samples generated with POWHEG-BOX and Mad-
Graph5_aMC@NLO.

Additional interactions in the same or nearby bunch cross-
ings (pile-up) were simulated using PYTHIA 8.186 using the
A2 tune [62] and the MSTW2008LO PDF [63] set and were overlaid on the simulated signal and background events.

All simulated event samples were produced using the
ATLAS simulation infrastructure [64], using the full GEANT
4 [65] simulation of the ATLAS detector. Simulated events
were then reconstructed with the same software as used for

4 Event reconstruction and selection

The $WW$ event candidates are selected by requiring each
event to contain exactly one electron and exactly one muon of
opposite charge, each passing the selections described below.
Events with a same-flavour lepton pair are not used because
they have a larger background from the Drell–Yan process.

Candidate events are required to have at least one vertex
with at least two associated tracks with $p_T > 400$ MeV.
The vertex with the highest $\sum p_T^2$ of the associated tracks is
considered to be the primary vertex.

4.1 Trigger

Candidate events were recorded by either a single-muon
or a single-electron trigger that imposed a minimum lep-
ton transverse momentum threshold that varied during data-
taking. The $p_T$ threshold of the leptons required by triggers in
2015 was 24 GeV for electrons and 20 GeV for muons, both
satisfying loose isolation requirements. Due to the higher
instantaneous luminosity in 2016 the trigger threshold was
increased to 26 GeV for both the electrons and the muons, and
more restrictive isolation for both the leptons as well as
more restrictive identification requirements for electrons
were applied. Additionally, single-lepton triggers with higher
$p_T$ thresholds but with no isolation or with loosened iden-
tification criteria were used to increase the efficiency. The
trigger efficiency for events satisfying the full selection cri-
tera described below is about 99% and is determined using a
simulated signal sample that is corrected to reflect the data
efficiencies with corrections measured using $Z \to ee$ [66]
and $Z \to \mu\mu$ [67] events. These data-driven corrections are
of the order of 2% with permille level uncertainties.

4.2 Leptons

Electron candidates are reconstructed from the combina-
tion of a cluster of energy deposits in the EM calorimeter and
a track in the ID [66]. Candidate electrons must satisfy the
TightLH quality definition described in Ref. [66]. Signal elec-
trons are required to have $E_T > 27$ GeV and the pseudora-
pidity of electrons is required to be $|\eta| < 2.47$, excluding
the transition region between the barrel and endcaps in the
LAr calorimeter ($1.37 < |\eta| < 1.52$). In addition, a require-
ment is added to reject electrons that potentially stem from
photon conversions to reduce the $W\gamma$ background [66]. This
uses a simple classification based on the candidate electron’s
\( E/p \) and \( p_T \), the presence of a hit in the pixel detector, and the secondary-vertex information, to determine whether the electron could also be considered as a photon candidate and rejected.

Muon candidates are reconstructed by combining a track in the ID with a track in the MS [67]. The Medium quality criterion, as defined in Ref. [67], is applied to the combined tracks. Signal muons are required to have \( p_T > 27 \) GeV and \( |\eta| < 2.5 \).

Leptons are required to originate from the primary vertex. The longitudinal impact parameter of each lepton track, calculated relative to the primary vertex and multiplied by \( \sin \theta \) of the track, is required to be smaller than 0.5 mm. Furthermore, the significance of the transverse impact parameter, defined by the transverse impact parameter \( (d_0) \) of a lepton track relative to the beam line, divided by its estimated uncertainty \( (\sigma_{d_0}) \), is required to satisfy \( |d_0/\sigma_{d_0}| < 3.0 \) (5.0) for muons (electrons). Leptons are also required to be isolated using information from ID tracks and energy clusters in the calorimeters in a cone around the lepton. The expected isolation efficiency is at least 90% (99%) at a \( p_T \) of 25 (60) GeV using the Gradient working point defined in Refs. [66,67].

4.3 Jets

Jet candidates are reconstructed within the calorimeter acceptance using the anti-\( k_t \) jet clustering algorithm [68] using the FastJet code [69] with a radius parameter of \( R = 0.4 \), which combines clusters of topologically connected calorimeter cells [70,71]. The jet energy is calibrated by applying a \( p_T \)- and \( \eta \)-dependent correction derived from MC simulation with additional corrections based on data [72]. As part of the jet energy calibration a pile-up correction based on the concept of jet area is applied to the jet candidates [73]. Jets are required to have a pseudorapidity \( |\eta| < 4.5 \).

The jet-vertex-tagger (JVT) technique [74] is used to separate hard-scatter jets from pile-up jets within the acceptance of the tracking detector by requiring a significant fraction of the jets’ summed track \( p_T \) to come from tracks associated with the primary vertex. For jets with \( 2.5 < |\eta| < 4.5 \), a forward-JVT selection is applied to suppress pile-up jets [75].

Candidate jets are discarded if they are within a cone of size \( \Delta R = 0.2 \) around an electron candidate, or if they have fewer than three associated tracks and are within a cone of size \( \Delta R = 0.2 \) around a muon candidate. However, if a jet with three or more associated tracks is within a cone of size \( \Delta R = 0.4 \) around a muon candidate, or any jet is within a region \( 0.2 < \Delta R < 0.4 \) around an electron candidate, the corresponding electron or muon candidate is discarded.

Within the ID acceptance, jets originating from the fragmentation of \( b \)-hadrons (\( b \)-jets) are identified using a multivariate algorithm (MV2c10 BDT) [76,77]. The chosen operating point has an efficiency of 85% for selecting jets containing \( b \)-hadrons, as estimated from a sample of simulated \( tt \) events and validated with data [77].

4.4 Missing transverse momentum

The missing transverse momentum is computed as the negative of the vectorial sum of the transverse momenta of tracks associated with jets and muons, as well as tracks in the ID that are not associated with any other component. The \( p_T \) of the electron track is replaced by the calibrated transverse momentum of the reconstructed electron [78]. This definition has been updated for Run 2 data-taking conditions [79], and denoted by \( E_{T}^{\text{miss,track}} \) with its absolute value denoted by \( E_{T}^{\text{miss,track}} \). The tracks are required to be associated with the primary vertex and to satisfy the selection criteria described in Ref. [79].

The \( E_{T}^{\text{miss,track}} \) takes advantage of the excellent vertex resolution of the ATLAS detector and gives a missing transverse momentum estimate that is robust in the presence of pile-up, but it neglects the contribution of neutral particles, which do not form tracks in the ID. The pseudorapidity coverage of \( E_{T}^{\text{miss,track}} \) is also limited to the tracking volume of \( |\eta| < 2.5 \), which is smaller than the calorimeter coverage of \( |\eta| < 4.9 \). For events without any reconstructed jets, the \( E_{T}^{\text{miss,track}} \) provides a small improvement of the \( E_T^{\text{miss}} \) resolution compared with the standard reconstruction algorithms [79].

4.5 Signal region definition

The signal region (SR), in which the measurement is performed, is defined as follows. To reduce the background from other diboson processes, events are required to have no additional electrons or muons with \( p_T > 10 \) GeV fulfilling loosened selection criteria. For this looser selection, the GradientLoose isolation requirement [66,67] is used for both the electrons and the muons, which has an expected isolation efficiency of at least 95% (99%) at a \( p_T \) of 25 (60) GeV. Moreover, a less stringent MediumLH requirement [66] is applied for electron identification.

To suppress the background contribution from top-quark production, events are required to have no jets with \( p_T > 35 \) GeV and \( |\eta| < 4.5 \), and no \( b \)-jets with \( p_T > 20 \) GeV and \( |\eta| < 2.5 \). The jet \( p_T \) requirement is optimized to minimize the total systematic uncertainty in the measurement. The additional \( b \)-jet veto requirement allows the background from top-quark production to be suppressed by a factor of three, while keeping 97% of the \( WW \) signal events. For the remaining top-quark background events that pass all selection criteria, the \( b \)-jets are mainly produced outside the accep-
Table 1 Summary of lepton, jet, and event selection criteria for WW candidate events. In the table $\ell$ stands for $e$ or $\mu$. The definitions of lepton identification and isolation are detailed in Refs. [66] and [67].

<table>
<thead>
<tr>
<th>Selection requirement</th>
<th>Selection value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T^{\ell}$</td>
<td>$&gt; 27$ GeV</td>
</tr>
<tr>
<td>$\eta^{\ell}$</td>
<td>$</td>
</tr>
<tr>
<td>Lepton identification</td>
<td>Tight/LH (electron), Medium (muon)</td>
</tr>
<tr>
<td>Lepton isolation</td>
<td>Gradient working point</td>
</tr>
<tr>
<td>Number of additional leptons ($p_T &gt; 10$ GeV)</td>
<td>0</td>
</tr>
<tr>
<td>Number of jets ($p_T &gt; 35$ GeV, $</td>
<td>\eta</td>
</tr>
<tr>
<td>Number of $b$-tagged jets ($p_T &gt; 20$ GeV, $</td>
<td>\eta</td>
</tr>
<tr>
<td>$E_{\text{miss, track}}^T$</td>
<td>$&gt; 20$ GeV</td>
</tr>
<tr>
<td>$p_T^{\mu}$</td>
<td>$&gt; 30$ GeV</td>
</tr>
<tr>
<td>$m_{\mu\mu}$</td>
<td>$&gt; 55$ GeV</td>
</tr>
</tbody>
</table>

In addition, the requirements of $E_{\text{miss, track}}^T > 20$ GeV and $p_T^{\mu} > 30$ GeV suppress the Drell–Yan background contributions. A further requirement on the invariant mass of the lepton pair ($m_{\mu\mu} > 55$ GeV) reduces the $H \to WW^*$ contribution to a level below 1% of the expected signal. This last requirement is inverted compared with the one used in the recent measurement of $H \to WW^*$ production at 13 TeV by ATLAS [23], making the two measurements statistically independent. Otherwise, both measurements use similar selections for events in the 0-jet category, although with lower $p_T$ requirements in the $H \to WW^*$ analysis.

The lepton, jet, and event selection criteria are summarized in Table 1.

5 Background estimation

After applying all selection requirements described in Sect. 4, the dominant background is from top-quark production. This includes $t\bar{t}$ and $W$-associated single-top production, which both yield two real leptons in the final state.

The non-prompt lepton background originates from leptonic decays of heavy quarks, hadrons misidentified as leptons, and electrons from photon conversions. Such lepton-like objects are collectively referred to as fake leptons. Events with fake leptons are mainly due to the production of $W+jets$, $s$- and $t$-channel single-top production, both with leptonic $W$-boson decay and a jet misidentified as a lepton, or from multijet production with two jets misidentified as leptons.

Other processes can contribute as well, but are negligible in the signal region. Since most of these events – more than 98% – correspond to $W+jets$ production, this background is referred to as $W+jets$ background in the following.

Drell–Yan production of $\tau$-leptons ($Z \to \tau\tau$) can also give rise to the $e\mu$ final state. Other diboson ($WZ$, $ZZ$, $W\gamma$ and $Z\gamma$) and triboson ($VVV$, where $V=W$, $Z$) production processes constitute a smaller background contribution. A summary table comparing the number of observed candidate events in data to the respective numbers of predicted signal and background events in the signal region can be found in Sect. 5.5.

5.1 Background from top-quark production

Background from top-quark production is estimated using a partly data-driven method [6,80], in which the top-quark contribution is extrapolated from a control region (top CR) to the signal region. The top CR is selected by applying the $WW$ signal selection except for the b-jet and jet-veto requirements. To reduce the $WW$ signal contamination in this control region, an additional requirement on the scalar sum of the transverse momenta of leptons and jets, $H_T > 200$ GeV, is applied. The remaining non-top-quark contribution estimated by MC simulation is subtracted and the resulting number of top-quark events, $N_{\text{top}}^{\text{MC}}$, is corrected for the $H_T$ cut efficiency, $\epsilon_{H_T}$, using top-quark MC samples. With the efficiency for top-quark events to satisfy the jet-veto requirement, $\epsilon_{\text{jet-veto}}$, the top-quark background contribution in the signal region can be calculated as:

$$N_{\text{SR}}^{\text{top}} = \frac{N_{\text{CR}}^{\text{top}}}{\epsilon_{H_T}} \times \epsilon_{\text{jet-veto}}.$$ 

The jet-veto efficiency, which mainly quantifies the fraction of top events with jets below the jet-veto and b-jet veto $p_T$ thresholds, is calculated from simulation, with an extra correction factor [6,80]:

$$\epsilon_{\text{jet-veto}} = \frac{\epsilon_{\text{MC}}}{\epsilon_{\text{MC}}} \times \left( \frac{\text{Data single-jet-veto}}{\text{MC single-jet-veto}} \right)^{(n_{\text{jets}})}$$

where $\epsilon_{\text{single-jet-veto}}$ is defined as the fraction of top-quark events that contain no jets other than the b-tagged jet, and $\epsilon_{\text{MC}}$ extrapolates the top-quark MC prediction from the top CR (without $H_T$ requirement) to the signal region. The $\epsilon_{\text{single-jet-veto}}$ is determined both in data and simulation using events with two leptons, the same requirements on $E_{\text{miss, track}}^T$, $p_T^{\mu}$ and $m_{\mu\mu}$ as for the signal selection, and at least one b-tagged jet. The small contributions to this region of the signal and other background contributions, mainly $W+jets$ production, are subtracted before the calculation of $\epsilon_{\text{Data single-jet-veto}}$. The ratio $\epsilon_{\text{Data single-jet-veto}} / \epsilon_{\text{MC single-jet-veto}}$ then corrects for differences in the veto efficiency for a single jet between data and
simulation. It is found to be consistent with one. The exponent \((n_{\text{jets}})\) represents the average number of jets in the top CR and is measured to be approximately 2.5 in both data and top-quark background simulation. It is varied by ±1.0 as part of the uncertainty in the method to conservatively cover \((n_{\text{jets}})\) variations in different control regions as well as variations due to detector uncertainties and modelling, with a small impact (1.8%) on the total uncertainty in the top-quark background estimate.

The top-quark background estimate includes detector uncertainties in addition to the uncertainties in the method. Modelling uncertainties are determined using alternative MC samples and include the modelling of the parton shower, extra QCD radiation and the effect of the choice of generators. Interference effects between \(Wt\) and \(t\bar{t}\) are also considered. These modelling uncertainties are estimated by comparing the results from different MC samples described in Sect. 3. The cross-section uncertainty is taken to be 6% for \(t\bar{t}\) [52, 81–86] and 10% for \(Wt\) production [53, 87]. The top-quark background estimate includes detector uncertainties in the signal region is about 12% using this partly data-driven approach, making use of cancellations of systematic uncertainties in the ratio \(e_{\text{MC}}^\text{MC}/e_{\text{data}}^\text{data}(n_{\text{jets}})\) in Eq. (1). It is dominated by the \(b\)-tagging and modelling uncertainties. The contribution of the \(t\bar{t}\) and \(Wt\) background to the total expected yield in the signal region is about 25% (17% \(t\bar{t}\) and 8% \(Wt\)).

The differential top-quark background contribution and its uncertainties are evaluated by applying the same procedure in each bin of the measured observables. As an example, Fig. 2 shows the relevant quantities used in this partly data-driven method, as a function of the transverse momentum of the leading (highest \(p_T\)) lepton. The systematic uncertainties in \(\Delta L_{\text{SR}}\) are significantly reduced due to the systematics cancellations compared with the uncertainty bands from Fig. 2. The decrease of \(e_{\text{MC}}^\text{MC}\) at high leading lepton \(p_T\) is due to an increase in the typical \(p_T\) of extra jets which recoil against the leptons, near the jet-veto \(p_T\) threshold, and hence reducing the probability to still pass the jet veto. Since the efficiency ratio, \(e_{\text{single-jet-veto}}^\text{data}/e_{\text{single-jet-veto}}^\text{MC}\), is found to be independent of any kinematic variable, the single value of 0.98 ± 0.05 is used for all differential distributions. This is shown as a dashed line in the lower right panel of Fig. 2.

5.2 Background from Drell–Yan production

The estimate of the Drell–Yan background process is based on MC simulation, with a 5% theoretical cross-section uncertainty [88]. A validation region dominated by Drell–Yan events is defined with the same selections as for the signal region, but with the \(e\mu\) invariant mass required to be 45 GeV < \(m_{e\mu}\) < 80 GeV and with the events failing either the \(p_T^{\text{miss}}\) or the \(E_T^{\text{miss,track}}\)-requirement to make the sample orthogonal to that in the signal region. Good agreement between the data and the simulation is observed in this region. The shape uncertainty is evaluated by using an alternative MC event generator, as detailed in Sect. 3, and includes uncertainties due to the modelling of the acceptance. The total uncertainty in the Drell–Yan background is 11% and the contribution of this background in the signal region is found to be 4%.

5.3 Background from \(W+jets\) production

The yield of \(W+jets\) is estimated by comparing in data the number of events with leptons satisfying either of two alternative sets of selection requirements, together with the \(WW\) signal selection criteria, following the same procedure as that described in Ref. [6]. The loose lepton selection criteria are defined such that the signal sample is a subset of the loose lepton sample. For electrons, the loose selection corresponds to the Medium\(LH\) quality definition [66] and no isolation requirements are imposed. For muons, the loose selection is the same as for signal muons, except that the isolation requirement is omitted. The tight selection criteria are the same as those used for the signal selection. With the introduction of real-lepton and fake-lepton efficiencies, a system of four equations can be solved to estimate the number of \(W+jets\) events. Here, the number of events that have exactly one loose muon (electron) and one tight electron (muon), two loose leptons or two tight leptons, are used. The real-lepton (fake-lepton) efficiency used in these equations is defined as the probability for prompt (fake) leptons selected with the loose criteria to satisfy the tight selection criteria.

The efficiencies for real electrons (muons) are determined using MC simulation, with data-to-MC correction factors [66, 67] applied. The efficiencies for fake electrons (muons) are measured using a multijet data sample, in a control region with exactly one loose electron (muon) and between one and three jets.

Events in this control region are also required to have low \(E_T^{\text{miss,track}}\) and low transverse mass\(^3\) \(m_T\), to fulfill angular requirements between \(E_T^{\text{miss,track}}\) and the jets in the event, and to have no \(b\)-tagged jets. Real-lepton contributions to the control region are estimated using MC simulation and are subtracted.

Both the real- and fake-lepton efficiencies are derived as functions of \(p_T\) and \(\eta\) of the lepton. This is sufficient to describe the most important correlations with the differential distributions studied. Moreover, as the loose lepton selection in the \(W+jets\) background estimate at low lepton-\(p_T\) (\(p_T < 50\) GeV for muons or \(p_T < 60\) GeV for electrons)

\(^3\) The transverse mass is defined as: \(m_T = \sqrt{2p_T^tE_T^{\text{miss,track}}(1 - \cos(\Delta\phi(t, E_T^{\text{miss,track}})))}\).
Inputs to the partly data-driven method for the top background estimate as a function of the $p_T$ of the leading lepton: (upper left) events selected in data and in simulation in the top CR, with a requirement of $H_T > 200$ GeV applied, (upper right) the $H_T$ cut efficiency $\epsilon_{H_T}$, (lower left) the MC-based jet-veto efficiency $\epsilon_{MC\text{-jet-veto}}$, and (lower right) the efficiency ratio $\epsilon_{Data\text{-single-jet-veto}}/\epsilon_{MC\text{-single-jet-veto}}$. The latter is constant within uncertainties, and therefore replaced by the inclusive efficiency ratio (dashed line). In all figures, statistical and systematic uncertainties are displayed as hatched bands.

is typically looser than in the trigger selection, the efficiencies are provided separately for low-$p_T$ electrons or muons that satisfy or fail to satisfy the trigger selection requirements. The fake-lepton efficiency for the non-triggered leptons is estimated using events recorded with triggers that have lower muon-$p_T$, only MediumLH electron quality and no lepton isolation requirements, but only record a fraction of the events satisfying these criteria.

The uncertainty in the $W$+jets background is directly related to the uncertainties in the real- and fake-lepton efficiencies. For real-lepton efficiencies, these take into account uncertainties in electron and muon reconstruction and isolation correction factors. Uncertainties in the fake lepton efficiencies include variations in the control region definition, as well as normalization and shape uncertainties in the subtracted contributions from other processes in the control region. The control region variations are designed to cover the uncertainty in the flavour composition of the jets faking leptons, and include variations of the $m_T$ requirement and the number of $b$-tagged jets.

The total uncertainty in the $W$+jets yield is 90% and is dominated by the uncertainty in the fake and real electron efficiencies, because of the greater contribution of electron fakes to the $W$+jets background. The $W$+jets background amounts to 3% of the expected yield in the signal region.

The differential $W$+jets distributions necessary for the differential cross-section measurements are also determined in a fully data-driven way, by evaluating the same system of linear equations [6] in each bin of the differential distributions.

The predicted contributions to the backgrounds from $W$+jets are validated using a data control sample in which the two selected leptons are required to have the same electric charge (same-sign) and satisfy all the other selection requirements. Figure 3 shows the pseudorapidity difference between the leptons and the transverse momentum of the sub-leading
lepton for this same-sign control sample. The predictions and the data agree well.

5.4 Background from multi-boson production

The estimate of the diboson background from \(WZ\), \(ZZ\), \(W\gamma\) and \(Z\gamma\) processes is based on MC simulation. These processes contribute about 3\% to the total number of events. The uncertainty in the cross-section for these diboson processes is taken as 10\% \([89,90]\) and variations in the shape and the acceptance are considered for \(WZ\) and \(ZZ\) production by using alternative MC generators, as detailed in Sect. 3.

The \(V\gamma\) background simulation is validated in data using the events passing the same selection as for the signal region, except inverting the electron identification criteria and requiring the reconstructed electron track to have no hit in the innermost layer of the pixel detector. The \(WZ\) background simulation is validated in data using events that allow for the presence of a third loosely isolated lepton with \(p_T > 10\) GeV and require the same-flavour lepton pair to be of opposite sign and with invariant mass of 80 GeV < \(m_{ee/\mu\mu}\) < 100 GeV, while otherwise passing the signal region selection. Good agreement between the data and the simulation is found in both regions.

The background from triboson production (\(WWW\), \(WWZ\), \(WZZ\) and \(ZZZ\)) is less than 0.1\% and is evaluated using MC simulation. The cross-section uncertainty is taken as 30\% \([89]\).

5.5 \(WW\) candidate events and estimated background yields

After applying all the selection requirements, 12 659 events are observed in data, with a contribution of 65\% from \(WW\) production, which is estimated using simulation (see Sect. 3).

A summary of the data, signal, and background yields is shown in Table 2. Kinematic distributions comparing the selected data with the signal and backgrounds in the signal region are shown in Fig. 4. Fair agreement between data and expectations is observed for the overall normalization and the shapes of various kinematic distributions. Small under-predictions in the peak region of the leading lepton \(p_T\) distribution, the low \(m_{ee/\mu\mu}\) region and a small downward trend in the ratio of the data to expectations in the \(\Delta\phi_{ee/\mu\mu}\) distribution have also been observed in the previous ATLAS measurement at

<table>
<thead>
<tr>
<th>Number of events</th>
<th>Statistical uncertainty</th>
<th>Systematic uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top-quark</td>
<td>3120 ± 50</td>
<td>± 370</td>
</tr>
<tr>
<td>Drell–Yan</td>
<td>431 ± 13</td>
<td>± 44</td>
</tr>
<tr>
<td>(W+)jets</td>
<td>310 ± 60</td>
<td>± 280</td>
</tr>
<tr>
<td>(WZ)</td>
<td>290 ± 11</td>
<td>± 33</td>
</tr>
<tr>
<td>(ZZ)</td>
<td>16 ± 1</td>
<td>± 2</td>
</tr>
<tr>
<td>(V\gamma)</td>
<td>66 ± 11</td>
<td>± 10</td>
</tr>
<tr>
<td>Triboson</td>
<td>8 ± 1</td>
<td>± 3</td>
</tr>
<tr>
<td>Total background</td>
<td>4240 ± 80</td>
<td>± 470</td>
</tr>
<tr>
<td>Signal ((WW))</td>
<td>7690 ± 30</td>
<td>± 220</td>
</tr>
<tr>
<td>Total signal+background</td>
<td>11,930 ± 90</td>
<td>± 520</td>
</tr>
<tr>
<td>Data</td>
<td>12,659 –</td>
<td>–</td>
</tr>
</tbody>
</table>
\( \sqrt{s} = 8 \text{ TeV} \) [6]. The trend in the \( \Delta \phi_{\ell \mu} \) distribution was also observed at \( \sqrt{s} = 8 \text{ TeV} \) by CMS Collaboration [8]. For the \( \Delta \phi_{\ell \mu} \) distribution, the largest discrepancy between data and expectations (of about three standard deviations) is observed in the range \( 1.3 < \Delta \phi_{\ell \mu} < 1.6 \).

6 Fiducial cross-section determination

The \( WW \) cross-section is evaluated in the fiducial phase space of the \( e\mu \) decay channel, as defined in Table 3. In simulated events, electrons and muons are required to originate from one of the \( W \) bosons produced in the hard scatter, and the momenta of photons emitted in a cone \( \Delta R = 0.1 \) around the lepton direction are added to the lepton momentum after QED final-state radiation to form ‘dressed’ leptons [91]. Final-state particles with lifetimes greater than 30 ps are clustered into jets (referred to as particle-level jets) using the same algorithm as for detector-level jets, i.e. the anti-\( k_t \) algorithm with radius parameter \( R = 0.4 \). The selected charged leptons and any neutrino in the event are not included in the jet clustering. The fiducial phase space at particle level does not make any requirement on jets containing \( b \)-quarks. The missing transverse momentum is defined at particle level as the transverse component of the vectorial sum of the neutrino momenta. Its magnitude is denoted in Table 3 by \( E_{\text{miss}}^T \).

The fiducial cross-section is obtained as follows:

\[
\sigma_{\text{fid}}^{WW \rightarrow e\mu} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{C \times L},
\]

where \( L \) is the integrated luminosity, \( N_{\text{obs}} \) is the observed number of events, \( N_{\text{bkg}} \) is the estimated number of background events and \( C \) is a factor that accounts for detector inefficiencies, resolution effects and contributions from \( \tau \)-lepton decays. The \( C \) factor is defined as the ratio of the number of reconstructed \( WW \) events after the final selection with electrons or muons in the final state (including electrons or muons from \( \tau \)-lepton decays) to the number of \( WW \) events generated in the fiducial region where only direct decays of \( W \) bosons to electrons and muons are allowed. The \( C \) factor takes into account the contribution to the \( WW \) signal originating outside of the fiducial phase space. This contribution is estimated from MC simulation to be about 21\% of the expected reconstructed signal, about 40\% of which originates from \( \tau \)-lepton decays. The \( C \) factor has a value of 0.613 with an uncertainty of 3\%, including experimental and unfolding method sources, as detailed in Sect. 7.

The fiducial cross-section as a function of the jet-veto \( p_T \) threshold is determined using the same method, but modifying the selection requirements to exclude events with jets above a transverse momentum of 30 GeV, 35 GeV, 40 GeV, 45 GeV, 50 GeV, 55 GeV, and 60 GeV, respectively. The values for \( C \) are determined for each threshold and increase from 0.598 to 0.625.

The differential cross-sections are determined using an iterative Bayesian unfolding method [92, 93] with one iteration for \( m_{\ell\ell}, p_T^{\text{lead \ell}}, |y_{\ell\ell}|, \Delta \phi_{\ell\mu} \) and \( |\cos \delta^*| \), and two iterations for \( p_T^{e\mu} \). The number of iterations is optimized to find a balance between too many iterations, causing high statistical uncertainties in the unfolded distributions, and too few iterations, which can bias the measurement towards the MC prediction. The unfolding procedure corrects for migrations between bins in the distributions during the reconstruction of the events, and applies fiducial as well as reconstruction efficiency corrections. The fiducial corrections take into account events that are reconstructed in the signal region, but originate from outside the fiducial region; the reconstruction efficiency corrects for events inside the fiducial region that are not reconstructed in the signal region due to detector inefficiencies. Tests with MC simulation demonstrate that the method is successful in retrieving the true distribution in the fiducial region from the reconstructed distribution in the signal region.

7 Systematic uncertainties

Systematic uncertainties in the \( WW \) cross-section measurements arise from the reconstruction of leptons and jets, the background determination, pile-up and integrated luminosity uncertainties, as well as the procedures used to correct for detector effects, and theoretical uncertainties in the signal modelling.

For leptons and jets, uncertainties in the momentum or energy scale and resolution are considered [67, 72, 94]. Uncertainties in the lepton reconstruction and identification efficiencies [66, 67] as well as the efficiency of the jet vertex tagging requirements [74, 75] in the simulation are taken into account. Uncertainties in the \( b \)-tagging, which mainly stem from the top-quark background contributions, are also taken into account based on the studies in Refs. [95, 96]. The impact of uncertainties in the scale and resolution of \( E_{\text{miss,track}}^T \) are estimated as discussed in Ref. [79]. The pile-up modelling uncertainty is evaluated by varying the number of simulated
Fig. 4 Kinematic distributions of the selected data events after the full event selection (from left to right and top to bottom): $p_T^{\text{lead } \ell}$, $m_{\ell\nu}$, $p_T^{\text{lep}}$, $|y_{\ell\nu}|$, $\Delta\phi_{\ell\nu}$ and $|\cos\theta^*|$. Data are shown together with the predictions of the signal and background production processes. Statistical and systematic uncertainties in the predictions are shown as hatched bands. The lower panels show the ratio of the data to the total prediction. An arrow indicates that the point is off-scale. The last bin includes the overflow.
pile-up interactions by its uncertainty of 10% of the nominal value. The variations are designed to cover the uncertainty in the ratio of the predicted to the measured cross-section of non-diffractive inelastic events producing a hadronic system of mass $m_X > 13$ GeV\cite{97}, where the nominal value of $\sigma_{inel} = 74$ mb is used in the simulation.

Uncertainties in MC-based background processes include variations of the shapes of predicted distributions, the normalization, and the statistical uncertainties in the simulation, in addition to the full set of detector-related uncertainties. The first two are estimated as discussed in Sects. 3 and 5. The uncertainties in the background from top-quark and W+jets production are mitigated by the use of the data-driven methods described in Sect. 5.

Uncertainties due to the unfolding procedure and the modelling of the signal process are considered by repeating the cross-section extraction with modified inputs. The uncertainty due to the choice of generator for the hard interaction, the parton shower model and the underlying-event modelling for the MC-based unfolding inputs, is estimated by using SHERPA 2.2.2 instead of POWHEG-BOX+PYTHIA 8 for $q\bar{q}$-initiated $WW$ production, with the samples detailed in Sect. 3. The impact of mismodelling of the data by POWHEG-BOX+PYTHIA 8 for each observable is estimated by reweighting the distribution at generator level to improve the agreement between data and simulation after event reconstruction. The obtained prediction at detector level, which is then very similar to data, is unfolded with the normal inputs and the difference from the reweighted prediction at generator level is considered as an uncertainty. The impact of statistical uncertainties in the nominal signal simulation is estimated using pseudo-data. The theory uncertainties cover PDF and scale variations of the unfolding inputs. The PDF uncertainty is estimated as the 68% confidence level (CL) envelope of the CT10\cite{37} prediction. The uncertainty associated with higher-order QCD corrections is evaluated by varying the renormalization ($\mu_R$) and factorization ($\mu_F$) scales independently by factors of 2 and 0.5 with the constraint $0.5 \leq \mu_R/\mu_F \leq 2$.

The uncertainty in the combined 2015+2016 integrated luminosity is 2.1%. It is derived from the calibration of the luminosity scale using $x$-$y$ beam-separation scans, following a methodology similar to that detailed in Ref. [98], and using the LUCID-2 detector for the baseline luminosity measurements [99]. The LHC beam energy uncertainty is estimated to be 0.1% [100]. It affects the signal cross-section by less than 0.2% and is not considered in the total uncertainty.

A summary of the systematic uncertainties in the fiducial cross-section measurement is shown in Table 4. The total uncertainty is dominated by the $b$-tagging uncertainty (3.4%), the jet energy scale uncertainty (3%), and the modelling of the $W$+jets (3.1%) and top-quark (2.6%) backgrounds.

<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>0.7</td>
</tr>
<tr>
<td>Muon</td>
<td>0.9</td>
</tr>
<tr>
<td>Jets</td>
<td>3.0</td>
</tr>
<tr>
<td>$b$-tagging</td>
<td>3.4</td>
</tr>
<tr>
<td>$E_T^{miss,tack}$</td>
<td>0.4</td>
</tr>
<tr>
<td>Pile-up</td>
<td>1.6</td>
</tr>
<tr>
<td>$W$+jets background modelling</td>
<td>3.1</td>
</tr>
<tr>
<td>Top-quark background modelling</td>
<td>2.6</td>
</tr>
<tr>
<td>Other background modelling</td>
<td>1.3</td>
</tr>
<tr>
<td>Unfolding, incl. signal MC stat. uncertainty</td>
<td>1.4</td>
</tr>
<tr>
<td>PDF+scale</td>
<td>0.1</td>
</tr>
<tr>
<td>Systematic uncertainty</td>
<td>6.7</td>
</tr>
<tr>
<td>Statistical uncertainty</td>
<td>1.3</td>
</tr>
<tr>
<td>Luminosity uncertainty</td>
<td>2.1</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>7.1</td>
</tr>
</tbody>
</table>

### 8 Theoretical predictions

Theoretical predictions are calculated for the fiducial and the differential cross-sections and include the $q\bar{q} \rightarrow WW$ and $gg \rightarrow WW$ sub-processes. The $q\bar{q}$-initiated production makes up 95% of the total cross-section, while the non-resonant and resonant $gg$-initiated sub-processes account for 5%.

NNLO predictions for the $q\bar{q} \rightarrow WW$ production cross-sections are determined using the MATRIX program \cite{101–103}, including off-shell effects and the non-resonant and resonant gluon-initiated contributions at LO. For improved precision, the MATRIX prediction for $q\bar{q}$-initiated production is also complemented with NLO corrections to gluon-induced $W$ production \cite{104} and with extra NLO EW corrections that also include the photon-induced ($\gamma\gamma \rightarrow WW$) contribution \cite{105}. For all these predictions, the NNPDF 3.1 LUXqed PDF set is used \cite{106,107}, the renormalization and factorization scales are set to $m_{WW}/2$, and the scale uncertainties are evaluated according to Ref. \cite{108}. The PDF uncertainty corresponds to the 68% CL variations of the NNPDF set. The MATRIX prediction itself does not include EW radiative effects from leptons in contrast to the MC simulation used to define leptons in the fiducial region, where photons from the parton shower outside a cone of $\Delta R = 0.1$ can be present. The application of NLO EW corrections compensates, at least partially, for this difference. It is observed that the NLO corrections to the $gg \rightarrow WW$ sub-process increase the fiducial cross-section by 3%, whereas the NLO EW corrections, applied to the sum of $q\bar{q}$- and $gg$-initiated production, decrease it by 6%.
Table 5 Predictions of the $WW$ fiducial cross-section. Predictions matched to parton showers are normalized to inclusive fixed-order calculations

<table>
<thead>
<tr>
<th>Prediction</th>
<th>Reference</th>
<th>Normalization</th>
<th>$\sigma_{\text{fiducial}}$ (fb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MATRIX NNLO $q\bar{q} \to WW$ and $gg \to WW$ at LO</td>
<td>[101–103]</td>
<td>–</td>
<td>357 ± 20</td>
</tr>
<tr>
<td>MATRIX NNLO $q\bar{q} \to WW$ and $gg \to WW$ at NLO</td>
<td>[104]</td>
<td>–</td>
<td>368 ± 21</td>
</tr>
<tr>
<td>(MATRIX NNLO $q\bar{q}$ and $gg$ at NLO) $\times$ NLO EW</td>
<td>[105]</td>
<td>–</td>
<td>347 ± 20</td>
</tr>
<tr>
<td>SHERPA 2.1.1 + OPENLOOPS $gg \to WW$</td>
<td>[36]</td>
<td>NLO [104]</td>
<td>19.0 ± 1.9</td>
</tr>
<tr>
<td>POWHEG-BOX + PYTHIA 8 $q\bar{q} \to WW$ (+ SH+OL $gg \to WW$)</td>
<td>[30–34,38]</td>
<td>NNLO [101–103]</td>
<td>350 ± 7</td>
</tr>
<tr>
<td>POWHEG-BOX + HERWIG++ $q\bar{q} \to WW$ (+ SH+OL $gg \to WW$)</td>
<td>[30–34,41]</td>
<td>NNLO [101–103]</td>
<td>357 ± 11</td>
</tr>
<tr>
<td>SHERPA 2.2.2 $q\bar{q} \to WW$ (+ SH+OL $gg \to WW$)</td>
<td>[54]</td>
<td></td>
<td>341 ± 20</td>
</tr>
</tbody>
</table>

NLO predictions for $q\bar{q} \to WW$ production, which are matched to a parton shower ($q\bar{q}$ NLO+PS), are determined using either POWHEG-BOX interfaced to PYTHIA 8 or HERWIG++, or SHERPA 2.2.2. They are combined with the SHERPA+OPENLOOPS calculation for the gluon-induced nonresonant and resonant $WW$ production ($gg$ LO+PS). These predictions are described in detail in Sect. 3. The NLO+PS predictions also include photon final-state radiation and thus already part of the EW effects. Therefore no additional EW correction is applied.

A summary of fiducial cross-section predictions for $WW$ production is given in Table 5. Predictions from the different generators matched to parton showers agree well among each other and with the fixed-order predictions. For the SHERPA 2.2.2 prediction, scale uncertainties are larger than for the POWHEG-BOX predictions because the SHERPA calculation includes matrix elements with higher jet multiplicities, which results in a larger uncertainty estimate when varying the renormalization and factorization scales in the matrix element calculation. For fixed-order predictions, scale uncertainties are large because they are evaluated according to Ref. [108].

9 Results

9.1 Cross-section measurements and comparisons with theoretical predictions

The measured fiducial cross-section for $WW \to e\mu$ production at $\sqrt{s} = 13$ TeV is:

$$\sigma_{\text{fid}} = (379.1 \pm 5.0 \text{ (stat)} \pm 25.4 \text{ (syst)} \pm 8.0 \text{ (lumi)}) \text{ fb}.$$  

The combined statistical and systematic uncertainty of the measurement, including the uncertainty in the luminosity, is 7.1%.

A comparison between the fiducial cross-section measurement and fixed-order theoretical calculations is shown in Fig. 5. The measurement is compared with the NNLO QCD MATRIX predictions including the full set of QCD and EW corrections, discussed in detail in Sect. 8. The predictions agree well with the measurement.

The measured fiducial cross-sections as a function of the jet-veto $p_T$ thresholds are shown in Fig. 6. The fiducial cross-section rises by about 30% when accepting events containing jets with a transverse momentum of up to 60 GeV, as compared with 30 GeV. The measurement is compared to NNLO predictions from MATRIX (Fig. 6, left), and to NLO+PS predictions from POWHEG-BOX+PYTHIA 8, POWHEG-BOX+HERWIG++ and SHERPA 2.2.2 for $q\bar{q}$-initiated states, combined with SHERPA+OPENLOOPS (LO+PS) for the $gg$ initial states (Fig. 6, right). All three $q\bar{q}$ NLO+PS predictions are normalized to the NNLO theoretical prediction for the total cross-section, with the $gg$ LO+PS contribution normalized to NLO. With increasing jet-veto $p_T$ threshold, the fiducial cross-section rises as it becomes more inclusive. All predictions agree within uncertainties with the data, but are consistently at the lower bound of these.
Fig. 6 Comparison of the measured fiducial cross-section as a function of the jet-veto $p_T$ threshold with various theoretical predictions. The measurement is compared with NNLO predictions from MATRIX on the left. This calculation does not include the NLO EW correction and is Born-level, whilst the measurement is conducted using dressed leptons, which might account for some of the differences seen. On the right a comparison with NLO+PS predictions from Powheg-Box, Sherpa 2.2.2 for $q\bar{q}$ initial states, combined with Sherpa+OpenLoops (LO+PS) for the $gg$ initial states is shown. All three $q\bar{q}$ NLO+PS predictions are normalized to the NNLO theoretical prediction for the total cross-section, with the $gg$ LO+PS contribution normalized to NLO. The measured cross-section values are shown as points with error bars giving the statistical uncertainty and solid bands indicating the size of the total uncertainty. Theoretical predictions are indicated as markers with hatched bands denoting PDF+scale uncertainties.

The measured fiducial cross-sections as a function of $p_T^{\text{lead }\ell}$, $m_{\ell\ell}$, $p_T^{\ell\mu}$, $|\gamma_{\ell\mu}|$, $\Delta\phi_{\ell\mu}$ and $|\cos \theta^*|$ are shown in Figs. 7 and 8. They are compared with the NNLO QCD predictions from MATRIX, including NLO corrections for $gg \rightarrow WW$ production and extra NLO EW corrections, as well as with the same $q\bar{q}$ NLO+PS predictions as stated above (combined with $gg$ LO+PS) normalized to the NNLO (NLO) theoretical prediction for the total cross-section. All of these predictions provide a fair description of the data, except for low values of the $p_T$ of the leading lepton as well as low values of invariant mass $m_{\ell\ell}$ and $\Delta\phi_{\ell\mu} < 1.8$. For the $p_T^{\text{lead }\ell}$ distribution, Powheg-Box+Pythia 8 and Sherpa 2.2.2 underpredict the cross-section by up to 15–20%. For the other two distributions, all predictions display similar underestimates of the measured differential cross-section but to slightly varying degrees, depending on the size of their uncertainties. The most consistent difference is observed at around $\Delta\phi_{\ell\mu} \approx 1.5$. A similar underprediction of the data, shifted slightly to lower $\Delta\phi_{\ell\mu}$ values (around $0.5–1.0$) was seen in both the ATLAS and CMS measurements at 8 TeV [6,8] when compared with the predictions from a variety of MC generators. Global $\chi^2$ comparisons are carried out for all the predictions. They do not display any significant differences between predictions and data with the largest $\chi^2$ per degree of freedom being 18.5/14 when comparing the Sherpa 2.2.2 +Sherpa+OpenLoops prediction with the measured $p_T^{\text{lead }\ell}$ distribution.

9.2 Limits on anomalous gauge couplings

The self-couplings of the electroweak gauge bosons can be probed via the $WWZ$ and $WW\gamma^*$ vertices, present when the $W$ bosons are produced via s-channel $Z/\gamma^*$ exchange, as shown in Fig. 1. New physics processes at a high energy scale ($\Lambda$) that alter $WW$ production can be described by operators with mass dimensions larger than four in an effective field theory (EFT) framework [109]. The higher-dimensional operators of the lowest order from purely EW processes have dimension six, and can generate anomalous triple-gauge-boson couplings (aTGC). A deviation from the SM in measured $WW$ production rates or in certain kinematic distributions, as predicted by these theories, could provide evidence for physics beyond the SM. In the EFT framework employed, there are five dimension-six operators ($O_i$) and the relevant EFT coefficients (coupling constants) are: $c_{WWW}$, $c_W$, $c_B$, $c_{WWW}$ and $c_{WW}$ [109]. The dimensionless coefficients...
Fig. 7 Measured fiducial cross-sections of $WW \rightarrow e\mu$ production for four of the six observables (from left to right and top to bottom): $p_{T}^{lead\ell}$, $m_{ll}$, $p_{T}^{\ell}$, and $|y_{ll}|$. The measured cross-section values are shown as points with error bars giving the statistical uncertainty and solid bands indicating the size of the total uncertainty. The results are compared with the NNLO prediction with extra NLO EW corrections and NLO corrections for $gg \rightarrow WW$ production, and with NLO+PS predictions from \textsc{Powheg-Box}+\textsc{Pythia} 8, \textsc{Powheg-Box}+\textsc{Herwig++} and \textsc{Sherpa} 2.2.2 for $q\bar{q}$ initial states, combined with \textsc{Sherpa}+\textsc{OpenLoops} (LO+PS) for the $gg$ initial states. All three $q\bar{q}$ NLO+PS predictions are normalized to the NNLO theoretical prediction for the total cross-section, with the $gg$ LO+PS contribution normalized to NLO. Theoretical predictions are indicated as markers with hatched bands denoting PDF+scale uncertainties.

Theoretical predictions are parameterized by the Lagrangian:

$$L = L_{SM} + \sum_{i} \frac{c_{i}}{\Lambda^2} O_{i}.$$
Fig. 8 Measured fiducial cross-sections of $WW \rightarrow e\mu$ production for two of the six observables: $\Delta\phi_{e\mu}$ and $|\cos\theta^*|$. The measured cross-section values are shown as points with error bars giving the statistical uncertainty and solid bands indicating the size of the total uncertainty. The results are compared with the NNLO prediction with extra NLO EW corrections and NLO corrections for $gg \rightarrow WW$ production, and with NLO+PS predictions from Powheg-Box+Pythia 8, Powheg-Box+Herwig++, and Sherpa 2.2.2 for $q\bar{q}$ initial states, combined with Sherpa+OpenLoops (LO+PS) for the $gg$ initial states. All three $q\bar{q}$ NLO+PS predictions are normalized to the NNLO theoretical prediction for the total cross-section, with the $gg$ LO+PS contribution normalized to NLO. The theoretical predictions are indicated as markers with hatched bands denoting PDF+scale uncertainties.

Templates of the $p_{T}^{\text{lead}}\ell$ distribution representing the pure SM contribution, the aTGC contribution, and the interference between the SM and aTGC contributions at LO are prepared at generator level using MadGraph5_aMC@NLO version 2.6.3.2 [110], interfaced to Pythia 8.212 with the A14 tune for parton showering and hadronization. The relative size of the SM cross-section modification increases with $p_{T}^{\text{lead}}\ell$ so that the last measured bin is most sensitive to the aTGC effects. To ensure a good agreement of the MadGraph5_aMC@NLO prediction with the baseline SM prediction, a bin-wise correction, determined as the ratio of the pure SM contributions from Powheg-Box+Pythia 8 (normalized to the NNLO cross-section) and MadGraph5_aMC@NLO, is applied.

It is verified that the pure SM assumption used in the unfolding procedure introduces no bias to the extraction of limits from the unfolded cross-section. A reweighting procedure implemented in the MadGraph5_aMC@NLO [111] generator is used to obtain multiple signal predictions that include aTGCs of a magnitude corresponding to the upper limits set by the Run 1 analysis [6]. The simulation is interfaced to Herwig 6.5 [112] and passed through the ATLAS detector simulation. Neither the reconstruction efficiency and the fiducial corrections nor the bin-to-bin migrations are significantly different.

The measured $p_{T}^{\text{lead}}\ell$ cross-section and the MadGraph5_aMC@NLO prediction, interfaced to Pythia 8, as described above, are used to construct a likelihood function, in which statistical and systematic measurement uncertainties are modelled by a multivariate Gaussian distribution. Systematic uncertainties in the theory prediction are considered as nuisance parameters, each constrained with a Gaussian distribution. Since electroweak radiative effects are already partially taken into account in the parton shower of the MadGraph5_aMC@NLO prediction, the effect of applying NLO EW corrections to the $p_{T}^{\text{lead}}\ell$ distribution in addition is considered as a further systematic uncertainty.

Frequentist confidence intervals for the EFT coefficients are computed from values of a profile likelihood ratio test statistic [113]. Observed and expected 95% CL intervals for the EFT coefficients are summarized in Table 6. Due to the higher centre-of-mass energy, the limits reported here are more restrictive than those previously published by the ATLAS and CMS Collaborations in the $WW$ final state [6,8]. Compared to results from inclusive $WZ$ production [114] and electroweak $W$ and $Z$ boson production in association with two jets [115], both at $\sqrt{s} = 13$ TeV, the limits on $c_B/\Lambda^2$...
from this analysis are the most stringent (by about a factor 2), while those on \( c_{WWW}/\Lambda^2 \) and \( c_{W}/\Lambda^2 \) are weaker by factors of about 1.6 – 4. Limits on the CP-odd operators \( O_{WWW} \) and \( O_W \) are not provided by the other two measurements.

The sensitivity to dimension-six operators mostly stems from their direct effect on the \( WW \) cross-section as a function of \( p_T^{\text{lead } \ell} \), except for the \( c_W \) coefficient where both the direct contribution and the interference between the SM and terms containing EFT operators contribute equally.

### 10 Conclusion

The cross-section for the production of \( W^+W^- \) pairs in \( pp \) collisions at \( \sqrt{s} = 13 \) TeV (with subsequent decays into \( WW \to e\nu\mu\nu_\mu \)) is measured in a fiducial phase space that excludes the presence of jets with transverse momentum above 35 GeV. The measurement is performed with data recorded by the ATLAS experiment at the LHC in 2015 and 2016, which correspond to an integrated luminosity of 36.1 fb\(^{-1}\). The measured fiducial cross-section is \( \sigma_{\text{fid}} = (379.1 \pm 5.0 \text{ (stat)} \pm 25.4 \text{ (syst)} \pm 8.0 \text{ (lumi)}) \) fb, and is found to be consistent with theoretical predictions, including NNLO QCD and NLO EW corrections. The fiducial cross-section is also measured as a function of the transverse momentum threshold for the jet veto. Differential cross-sections are measured as a function of kinematic and angular variables of the final-state charged leptons and are compared with several predictions from perturbative QCD calculations. Data and theory show fair agreement for all differential distributions. The distribution of the transverse momentum of the leading lepton is used to investigate anomalous triple-gauge-boson coupling parameters. No evidence for anomalous \( WWZ \) and \( WW\gamma \) couplings is found, hence limits on their magnitudes are set. These limits are more restrictive than those derived at \( \sqrt{s} = 8 \) TeV.

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## Data Availability Statement

This manuscript has no associated data or the data will not be deposited. [Authors’ comment: All ATLAS scientific output is published in journals, and preliminary results are made available in Conference Notes. All are openly available, without restriction on use by external parties beyond copyright law and the standard conditions agreed by CERN. Data associated with journal publications are also made available: tables and data from plots (e.g. cross section values, likelihood profiles, selection efficiencies, cross section limits, ...) are stored in appropriate repositories such as HEPDATA (http://hepdata.cedar.ac.uk/). ATLAS also strives to make additional material related to the paper available that allows a reinterpretation of the data in the context of new theoretical models. For example, an extended encapsulation of the analysis is often provided for measurements in the framework of RIVET (http://rivet.hepforge.org/).]

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13 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
14 Institut de Física d’Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
15 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China; (b) Physics Department, Tsinghua University, Beijing, China; (c) Department of Physics, Nanjing University, Nanjing, China; (d) University of Chinese Academy of Science (UCAS), Beijing, China
16 Institute of Physics, University of Belgrade, Belgrade, Serbia
17 Department for Physics and Technology, University of Bergen, Bergen, Norway
18 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, USA
19 Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
20 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
21 School of Physics and Astronomy, University of Birmingham, Birmingham, UK
22 Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia
23 (a) Dipartimento di Fisica, INFN Bologna and Universita’ di Bologna, Bologna, Italy; (b) INFN Sezione di Bologna, Bologna, Italy
24 Physikalisches Institut, Universität Bonn, Bonn, Germany
25 Department of Physics, Boston University, Boston, MA, USA
26 Department of Physics, Brandeis University, Waltham, MA, USA
27 (a) Transilvania University of Brasov, Brasov, Romania; (b) Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania; (c) Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi, Romania; (d) Physics Department, National Institute for Research and Development of Isotopic and Molecular Technologies, Cluj-Napoca, Romania; (e) University Politehnica Bucharest, Bucharest, Romania; (f) West University in Timisoara, Timisoara, Romania
28 (a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
29 Physics Department, Brookhaven National Laboratory, Upton, NY, USA
30 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
31 California State University, Long Beach, CA, USA
32 Cavendish Laboratory, University of Cambridge, Cambridge, UK
33 (a) Department of Physics, University of Cape Town, Cape Town, South Africa; (b) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa; (c) School of Physics, University of the Witwatersrand, Johannesburg, South Africa
34 Department of Physics, Carleton University, Ottawa, ON, Canada
35 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies, Université Hassan II, Casablanca, Morocco; (b) Faculté des Sciences, Université Ibn-Tofail, Kenitra, Morocco; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA, Marrakech, Morocco; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco; (e) Faculté des sciences, Université Mohammed V, Rabat, Morocco
36 CERN, Geneva, Switzerland
37 Enrico Fermi Institute, University of Chicago, Chicago, IL, USA
38 LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France
39 Nevis Laboratory, Columbia University, Irvington, NY, USA
40 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
41 (a) Dipartimento di Fisica, Università della Calabria, Rende, Italy; (b) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Frascati, Italy
42 Physics Department, Southern Methodist University, Dallas, TX, USA
43 Physics Department, University of Texas at Dallas, Richardson, TX, USA
44 National Centre for Scientific Research “Demokritos”, Agia Paraskevi, Greece
45 (a) Department of Physics, Stockholm University, Sweden; (b) Oskar Klein Centre, Stockholm, Sweden
46 Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany
47 Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
48 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
49 Department of Physics, Duke University, Durham, NC, USA
50 SUPA-School of Physics and Astronomy, University of Edinburgh, Edinburgh, UK
Laboratório de Instrumentação e Física Experimental de Partículas-LIP, Lisbon, Portugal; Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal; Departamento de Física, Universidade de Coimbra, Coimbra, Portugal; Centro de Física Nuclear da Universidade de Lisboa, Lisbon, Portugal; Departamento de Física, Universidade do Minho, Braga, Portugal; Universidad de Granada, Granada, Spain; Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal; Av. Rovisco Pais, 1, 1049-001 Lisbon, Portugal

Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic

Czech Technical University in Prague, Prague, Czech Republic

Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic

Particle Physics Department, Rutherford Appleton Laboratory, Didcot, UK

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, USA

Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile; Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

Department of Physics, University of Washington, Seattle, WA, USA

Department of Physics and Astronomy, University of Sheffield, Sheffield, UK

Department of Physics, Shinshu University, Nagano, Japan

Department Physik, Universität Siegen, Siegen, Germany

Department of Physics, Simon Fraser University, Burnaby, BC, Canada

SLAC National Accelerator Laboratory, Stanford, CA, USA

Physics Department, Royal Institute of Technology, Stockholm, Sweden

Departments of Physics and Astronomy, Stony Brook University, Stony Brook, NY, USA

Department of Physics and Astronomy, University of Sussex, Brighton, UK

School of Physics, University of Sydney, Sydney, Australia

Institute of Physics, Academia Sinica, Taipei, Taiwan

E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia; High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel

Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan

Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

Tomsk State University, Tomsk, Russia

Department of Physics, University of Toronto, Toronto, ON, Canada

TRIUMF, Vancouver, BC, Canada; Department of Physics and Astronomy, York University, Toronto, ON, Canada

Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

Department of Physics and Astronomy, Tufts University, Medford, MA, USA

Department of Physics and Astronomy, University of California Irvine, Irvine, CA, USA

Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

Department of Physics, University of Illinois, Urbana, IL, USA

Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain

Department of Physics, University of British Columbia, Vancouver, BC, Canada

Department of Physics and Astronomy, University of Victoria, Victoria, BC, Canada

Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany

Department of Physics, University of Warwick, Coventry, UK

Waseda University, Tokyo, Japan

Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel

Department of Physics, University of Wisconsin, Madison, WI, USA

Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany

Department of Physics, Yale University, New Haven, CT, USA
Yerevan Physics Institute, Yerevan, Armenia

Also at Borough of Manhattan Community College, City University of New York, New York, NY, USA
Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa
Also at CERN, Geneva, Switzerland
Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland
Also at Departamento de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
Also at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates
Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece
Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY, USA
Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, UK
Also at Department of Physics, California State University, East Bay, USA
Also at Department of Physics, California State University, Fresno, USA
Also at Department of Physics, California State University, Sacramento, USA
Also at Department of Physics, King’s College London, London, UK
Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia
Also at Department of Physics, Stanford University, Stanford, CA, USA
Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
Also at Department of Physics, University of Michigan, Ann Arbor, MI, USA
Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia
Also at Giresun University, Faculty of Engineering, Giresu, Turkey
Also at Graduate School of Science, Osaka University, Osaka, Japan
Also at Hellenic Open University, Patras, Greece
Also at Instiucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, The Netherlands
Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria
Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
Also at Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
Also at Institute of Particle Physics (IPP), Vancouver, Canada
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
Also at Instituto de Fisica Teorica, IFT-UAM/CSIC, Madrid, Spain
Also at Istanbul University, Dept. of Physics, Istanbul, Turkey
Also at Joint Institute for Nuclear Research, Dubna, Russia
Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
Also at Louisiana Tech University, Ruston, LA, USA
Also at LPNHE, Sorbonne Université, Université de Paris, CNRS/IN2P3, Paris, France
Also at Manhattan College, New York, NY, USA
Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
Also at National Research Nuclear University MEPhI, Moscow, Russia
Also at Physics Department, An-Najah National University, Nablus, Palestine
Also at Physics Department, University of South Africa, Pretoria, South Africa
Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
Also at School of Physics, Sun Yat-sen University, Guangzhou, China
Also at The City College of New York, New York, NY, USA
Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China
aw Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia

ax Also at TRIUMF, Vancouver, BC, Canada

ay Also at Universita di Napoli Parthenope, Naples, Italy

∗ Deceased