Search for Higgs boson pair production in the $\gamma\gamma WW^*$ channel using pp collision data recorded at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS Collaboration

DOI
10.1140/epjc/s10052-018-6457-x

Publication date
2018

Document Version
Final published version

Published in
European Physical Journal C

License
CC BY

Citation for published version (APA):
ATLAS Collaboration (2018). Search for Higgs boson pair production in the $\gamma\gamma WW^*$ channel using pp collision data recorded at $\sqrt{s} = 13$ TeV with the ATLAS detector. European Physical Journal C, 78(12), Article 1007. https://doi.org/10.1140/epjc/s10052-018-6457-x

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

UvA-DARE is a service provided by the library of the University of Amsterdam (https://dare.uva.nl)
Search for Higgs boson pair production in the $\gamma\gamma WW^*$ channel using $pp$ collision data recorded at $\sqrt{s} = 13$ TeV with the ATLAS detector

ATLAS Collaboration

CERN, 1211 Geneva 23, Switzerland

Received: 24 July 2018 / Accepted: 14 November 2018 / Published online: 11 December 2018
© CERN for the benefit of the ATLAS collaboration 2018

Abstract

Searches for non-resonant and resonant Higgs boson pair production are performed in the $\gamma\gamma WW^*$ channel with the final state of $\gamma\gamma\ell\nu jj$ using 36.1 fb$^{-1}$ of proton–proton collision data recorded at a centre-of-mass energy of $\sqrt{s} = 13$ TeV by the ATLAS detector at the Large Hadron Collider. No significant deviation from the Standard Model prediction is observed. A 95% confidence-level observed upper limit of 7.7 pb is set on the cross section for non-resonant production, while the expected limit is 5.4 pb. A search for a narrow-width resonance $X$ decaying to a pair of Standard Model Higgs bosons $HH$ is performed with the same set of data, and the observed upper limits on $\sigma(pp \rightarrow X) \times B(X \rightarrow HH)$ range between 40.0 and 6.1 pb for masses of the resonance between 260 and 500 GeV, while the expected limits range between 17.6 and 4.4 pb. When deriving the limits above, the Standard Model branching ratios of the $H \rightarrow \gamma\gamma$ and $H \rightarrow WW^*$ are assumed.

1 Introduction

A particle consistent with the Standard Model (SM) Higgs boson ($H$) was discovered by both the ATLAS and CMS experiments at the Large Hadron Collider (LHC) in 2012 [1, 2]. Various studies of its properties have been performed [3–7], and no significant deviation from the SM predictions has been found. The SM Higgs boson is a strong probe of physics beyond the SM. This paper documents searches for both non-resonant and resonant production of Higgs boson pairs ($HH$) in the semileptonic $\gamma\gamma WW^*$ final state using 36.1 fb$^{-1}$ of proton–proton ($pp$) collision data recorded by the ATLAS detector at a centre-of-mass energy of $\sqrt{s} = 13$ TeV. Previous searches for Higgs boson pair production have been performed by both the ATLAS and CMS experiments with data recorded at $\sqrt{s} = 8$ TeV in the final states $bb\gamma\gamma$ [8], $bb\gamma\gamma [9, 10]$, $b\tau^+\tau^-$ [11–13] and $\gamma\gamma WW^*$ [11], as well as multi-lepton and multi-photon [14]. The $pp$ collision data at $\sqrt{s} = 13$ TeV have been analysed in order to search for Higgs boson pairs in the final states $bb\gamma\gamma$ [15] and $bbWW^*$ [16]. No significant excess was observed compared to the SM prediction. However, it is important to explore the 13 TeV data in the channels that are not covered yet, such as the $\gamma\gamma WW^*$ channel presented in this paper. Although this decay channel is not the most sensitive amongst all possible Higgs boson decays, it relies on the Higgs boson couplings to vector bosons, which are already relatively well measured. Furthermore, this channel will contribute to the final combination of all measurable $HH$ decays.

The SM prediction of the Higgs boson pair production cross section is several orders of magnitude smaller than the single-Higgs-boson production rate [17], due to additional $ttH$ or $HHH$ vertices, an additional on-shell Higgs boson that reduces the kinematic phase space, and the fact that the two leading-order (LO) Feynman diagrams have strong destructive interference [18]. In Fig. 1a, the so-called box diagram represents Higgs boson pair production via a heavy-quark loop, where the cross section scales with the squared value of the $ttH$ or $bbH$ coupling constants. In Fig. 1b, the so-called triangle diagram contributes to Higgs boson pair production via the exchange of a virtual Higgs boson and is the only tree-level diagram sensitive to the Higgs boson self-coupling constant ($\lambda_{HHH}$), the squared value of which scales the cross section.

In many beyond-the-SM (BSM) scenarios, Higgs boson pair production can be enhanced by modifying the $ttH$, $bbH$ or $\lambda_{HHH}$ coupling constants from their SM values, reducing the effect of the destructive interference [19] between Fig. 1a and Fig. 1b, or by replacing the virtual Higgs boson with an intermediate scalar resonance, cf. Fig. 1c. Various BSM models with extended Higgs sectors predict a heavy Higgs boson decaying into a pair of Higgs bosons similar to the one in the SM. Such models include the two-Higgs-doublet models (2HDM) [20], the minimal supersymmetric extension of the SM [21], twin Higgs models [22] and composite
Higgs models [23,24]. Heavy resonances, other than heavy Higgs bosons, that can decay into a pair of SM Higgs bosons, are predicted in different models, and could for instance be gravitons [25], radions [26] or stoponium [27].

This paper reports searches for non-resonant and resonant production of pairs of Higgs bosons in the semileptonic $\gamma\gamma WW^*$ final state ($\gamma\gamma \ell\nu jj$), i.e. with two photons, two jets, one charged lepton and a neutrino. This final state benefits from the large branching fraction of $H \rightarrow WW^*$ [17], a characteristic signature from two photons and one lepton, as well as the excellent resolution of the diphoton invariant mass $m_{\gamma\gamma}$, which provides good discrimination from a smooth continuum background composed of multi-photon and multi-jet SM processes. Given the expected sensitivity in 13 TeV data, the di-Higgs-boson mass range between 260 and 500 GeV is explored in the search for a scalar resonant Higgs boson pair production.

2 The ATLAS detector

The ATLAS experiment [28] is a multipurpose particle detector with a forward-backward symmetric cylindrical geometry and nearly 4$\pi$ coverage in solid angle. It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic (EM) and hadronic calorimeters, and a muon spectrometer (MS). The ID covers the pseudorapidity range $|\eta| < 2.5$ and consists of silicon pixel, silicon microstrip, and transition-radiation tracking systems. The innermost pixel layer, the insertable B-layer [29], was installed at a mean radius of 3.3 cm after Run 1, and has been operational since the beginning of Run 2. Lead/liquid-argon (LAr) EM sampling calorimeters with high granularity provide energy measurements of EM showers. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range $(|\eta| < 1.7)$. The endcap and forward regions are covered by LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The MS surrounds the calorimeters and is based on three large air-core toroid superconducting magnets with eight coils each and with bending power in the range 2.0–7.5 T m. It includes a system of fast detectors for triggering purposes and precision tracking chambers. A dedicated two-level trigger system is used to select events [30]. The first-level trigger is implemented in hardware and uses a subset of the detector information to reduce the accepted event rate to at most 100 kHz. This is followed by a software-based trigger level that reduces the accepted event rate to an average of 1 kHz.

3 Data and simulated samples

3.1 Data samples

The full set of $pp$ collision data collected during 2015 and 2016 are used in this analysis. The two datasets were recorded at the same centre-of-mass energy $\sqrt{s} = 13$ TeV, albeit with different beam conditions. Beam intensities in 2016 were typically higher than in 2015, resulting in a higher instantaneous luminosity and a larger number of $pp$ collisions in each bunch crossing. The integrated luminosity of the combined 2015+2016 dataset used in this analysis is $36.1 \pm 0.8 \text{ fb}^{-1}$. This dataset were collected in run periods during which all subsystems were operational. The events are collected with a trigger requiring the presence of at least two photons, one with a transverse energy $E_T > 35$ GeV and the second with $E_T > 25$ GeV, and the longitudinal and transverse profiles of the EM shower were required to be consistent with those expected for a photon. The corresponding trigger efficiency reaches about 99% for the events that pass the event selection of the analysis.
3.2 Simulated event samples

Simulated Monte Carlo (MC) samples are used to estimate the signal acceptance and study the modelling for both non-resonant SM Higgs boson pair production and resonant BSM Higgs boson pair production. MC samples are also used to estimate the acceptance and study the modelling for SM single-Higgs-boson production processes, and to study the modelling of the SM continuum background from events with multiple photons and jets (Sect. 5), which is the dominant background in the analysis. Eventually, it is estimated by a data-driven method for both its normalisation and shape.

The simulated samples for signals are listed in Table 1. The event generator MadGraph5\_aMC@NLO 2.2.3 [31] was used for the production of non-resonant [32] and resonant [33] signal MC samples at next-to-leading order (NLO) in QCD, where four values of the resonance mass ($m_X = 260, 300, 400$ and $500 \text{ GeV}$) are considered. The events were generated by a Higgs Effective Field Theory (HEFT) using the MC@NLO method [34] and were reweighted in order to take into account the effects of the finite top-quark mass. The parton shower was implemented using Herwig++ 2.7.1 [35] with a set of tuned underlying-event parameters called the UEEE5 tune$^2$ [36], and the parton distribution function (PDF) set CTEQ6L1 [37] was used.

- For non-resonant Higgs boson pair production, the inclusive cross sections are normalised to the SM prediction of $33.41 \text{ fb}$ [17,38], calculated at NNLO in QCD, including resummation of soft-gluon emission at next-to-next-to-leading-logarithmic (NNLL) accuracy, as prescribed by the LHC Higgs Cross Section Working Group [17]. The effect of the finite top-quark mass is also taken into account at NLO [39].

- For resonant Higgs boson pair production, a narrow decay width, which is negligible compared to the experimental mass resolution, is assumed. The interference between non-resonant and resonant Higgs boson pair production is implemented in the generator. The interference is minimal and remains negligible when a narrow decay width is assumed.

Table 2 lists the simulated samples for the dominant SM single-Higgs-boson production modes: gluon–gluon fusion (ggF), vector-boson fusion (VBF), associated production with a $W$ or $Z$ boson ($VH$), and associated production with a pair of top quarks ($t\bar{t}H$). For all these processes, the PYTHIA 8.186 parton shower is used for the modelling of non-perturbative effects. The AZNLO tune [40] is used in ggF, VBF and $VH$ simulations, while the A14 tune is used in $t\bar{t}H$ simulations.

- **gluon–gluon fusion**: The ggF production is accurate to NNLO in QCD, using the POWHEG method [41] for matching the matrix element with the parton shower, and the MiNLO method [42,43] to simultaneously achieve NLO accuracy for inclusive Higgs boson production. Furthermore, a reweighting procedure was performed using the HNNLO program [44–46] to achieve full NNLO accuracy [47]. This sample is referred to as NNLOPS. The PDF4LHC15 NLO PDF set [48] was used. The inclusive cross section of the ggF production is normalised to the calculation at next-to-next-to-next-to-leading-order ($N^3\text{LO}$) QCD and NLO electroweak (EW) accuracies [49].

- **VBF and $VH$**: VBF and $VH$ production was simulated at NLO in QCD with POWHEG- Box v2 [41,50,51] using the PDF4LHC15 NLO PDF set. The inclusive VBF contribution is normalised to the cross section calculated with NLO QCD and NLO EW corrections [52–54] with an approximate NNLO QCD correction applied [55]. The contributions are normalised to cross sections calculated with NNLO QCD [56] and NLO EW corrections [57] for $WH$ and $q\bar{q} \rightarrow ZH$ and at NLO and next-to-leading-logarithm (NLL) accuracy in QCD for $gg \rightarrow ZH$ [58].

- **$t\bar{t}H$**: The $t\bar{t}H$ production is simulated using MadGraph5\_aMC@NLO 2.2.3 and its inclusive cross section is normalised to a calculation with NLO QCD and NLO EW corrections [59–62].
ring in the data used in this analysis. The particles in the final states of the generated processes were passed through either a GEANT4 [65] simulation of the ATLAS detector, or through the ATLAS fast simulation framework [66], which has been extensively validated against the GEANT4 simulation model. The output from the detector simulation is then analysed using the same reconstruction software as the data. The MC samples for single-Higgs-boson production were simulated with the GEANT4 framework, while the other samples used in this analysis were produced with the ATLAS fast simulation framework.

4 Object and event selection

The event selection is based on the properties of the visible objects in the final state, which includes one charged lepton (electron or muon), two jets, and two photons. These objects are reconstructed from detector-level objects, such as energy clusters in the EM calorimeter and tracks in the ID, as well as in the MS.

4.1 Object reconstruction

Photon candidates are reconstructed from clusters of energy deposited in the EM calorimeter [67]. If the candidates are matched with a reconstructed conversion vertex or tracks consistent with the hypothesis of a $\gamma \rightarrow e^+e^-$ conversion, they are classified as converted photon candidates. If the matched track is consistent with the hypothesis of an electron produced in the beam interaction region, they are classified as electron candidates. If the candidates are not matched with a reconstructed conversion vertex or tracks satisfying the conversion requirement, they are classified as unconverted photon candidates. The energy is determined by summing the energies of all cells that belong to the associated cluster [68] and is corrected using a combination of simulation-based and data-driven calibration factors [69] determined from $Z \rightarrow e^+e^-$ events collected in 2015 and 2016. The photon energy resolution in simulation is corrected to match the resolution in data [67]. The reconstructed photon candidates are required to meet “tight” photon identification criteria [68], which are based on the lateral and longitudinal energy profiles of EM showers in the calorimeter. The identification efficiency is measured as a function of the transverse energy of photons ($E_T^\gamma$). It ranges from 90 to 98% for converted photons and from 85 to 95% for unconverted photons, in the $E_T^\gamma$ interval between 25 and 200 GeV. To suppress the background from jets misidentified as photons, all reconstructed photon candidates are required to meet a set of calorimeter- and track-based isolation criteria [70]. A calorimeter-based isolation variable $E_T^{iso}$ is defined as the sum of the transverse energies ($E_T$) of all positive-energy topological clusters of calorimeter cells [71] within $\Delta R = 0.2$ of the photon candidate, excluding the energy of the photon candidate itself. The selection applied to the calorimeter-based isolation variable is $E_T^{iso} < 0.065 E_T$. A track-based isolation variable $p_T^{iso}$ is defined as the scalar sum of the transverse momenta ($p_T$) of tracks with $p_T > 1$ GeV within $\Delta R = 0.2$ of the photon candidate, excluding tracks from photon conversions. The selection on the track-based isolation variable is $p_T^{iso} < 0.05 E_T$. Only photon candidates with $|\eta| < 2.37$ are considered, excluding the transition region between the barrel and endcap calorimeters ($1.37 < |\eta| < 1.52$).

Electron candidates are reconstructed from clusters of energy deposited in the EM calorimeter matched to a track in the inner detector, as described above. A likelihood-based (LH) algorithm is used [72] to perform the electron identification against the background from jets or non-prompt electrons. Electron candidates are identified according to the “medium LH” criteria. Muon candidates are identified by matching a reconstructed ID track with a reconstructed MS track [73]. The identification classifies muon candidates as either “loose” or “medium”, based on the number of hits in the different ID and MS subsystems, and on the significance of the difference $|q/p_{MS} - q/p_{ID}|$, where $q$ is the

---

### Table 2 Simulated SM single-Higgs-boson background samples with $m_H = 125$ GeV

<table>
<thead>
<tr>
<th>Processes</th>
<th>Generators</th>
<th>QCD order</th>
<th>EW order</th>
<th>PDF</th>
<th>Parton shower</th>
<th>Normalisation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ggF</td>
<td>POWHEG</td>
<td>NNLO</td>
<td>NLO</td>
<td>PDF4LHC15</td>
<td>PYTHIA 8.186</td>
<td>N3LO (QCD) + NLO (EW)</td>
</tr>
<tr>
<td>VBF</td>
<td>POWHEG</td>
<td>NLO</td>
<td>NLO</td>
<td>PDF4LHC15</td>
<td>PYTHIA 8.186</td>
<td>NNLO (QCD) + NLO (EW)</td>
</tr>
<tr>
<td>W⁺H</td>
<td>POWHEG</td>
<td>NLO</td>
<td>NLO</td>
<td>PDF4LHC15</td>
<td>PYTHIA 8.186</td>
<td>NNLO (QCD) + NLO (EW)</td>
</tr>
<tr>
<td>W⁻H</td>
<td>POWHEG</td>
<td>NLO</td>
<td>NLO</td>
<td>PDF4LHC15</td>
<td>PYTHIA 8.186</td>
<td>NNLO (QCD) + NLO (EW)</td>
</tr>
<tr>
<td>$q\bar{q} \rightarrow ZH$</td>
<td>POWHEG</td>
<td>NLO</td>
<td>NLO</td>
<td>PDF4LHC15</td>
<td>PYTHIA 8.186</td>
<td>NNLO (QCD) + NLO (EW)</td>
</tr>
<tr>
<td>ggZH</td>
<td>POWHEG</td>
<td>NLO</td>
<td>NLO</td>
<td>PDF4LHC15</td>
<td>PYTHIA 8.186</td>
<td>NLO NLL (QCD)</td>
</tr>
<tr>
<td>ttH</td>
<td>MADGRAPH</td>
<td>AMC@NLO</td>
<td>NLO</td>
<td>NLO</td>
<td>NNPDF3.0</td>
<td>PYTHIA 8.186</td>
</tr>
</tbody>
</table>
charge and $p$ is the momentum of the muon candidate, as well as on the energy deposit in the tile hadronic calorimeters. The “medium” candidates are used in the analysis. An efficiency ranging from 84 to 93% as a function of $E_T$ or $p_T$ is achieved in the combined identification and reconstruction of electrons, and 96% (above 98%) in muon identification (reconstruction), in the range where the objects are selected. The electron (muon) is required to pass the “Loose” (“GradientLoose”) isolation criterion based on the sum of $p_T$ of tracks lying within a cone of $\Delta R = \min (10 \text{ GeV}/p_T^{\text{e}/\mu}, 0.3)$ and the sum of $E_T$ of topological clusters of calorimeter cells within a cone of $\Delta R = 0.2$ (0.2) around the electron (muon) candidate, excluding the contributions from the electron (muon) candidate. With these requirements the isolation efficiencies for electrons (muons) are above 99% (0.057 $p_T^{\gamma}/95.57\%$) [72,73]. Finally, the electron candidates are required to have $E_T > 10 \text{ GeV}$ and $|\eta| < 2.47$, excluding the transition region between the barrel and endcap calorimeters (1.37 < $|\eta|$ < 1.52), whereas the muon candidates are required to have $p_T > 10 \text{ GeV}$ and $|\eta| < 2.7$.

Jets are reconstructed via the FastJet package [74] using the anti-$k_t$ clustering algorithm [75] with a radius parameter $R = 0.4$. The jet energies are determined at the EM scale and calibrated using particle-level correction factors based on a combination of simulation and data [76–80]. Jets are required to have $|\eta| < 2.5$ and $p_T > 25 \text{ GeV}$. In addition, a jet-vertex tagging algorithm (JVT) [81] is applied to jets with $|\eta| < 2.4$ and $p_T < 60 \text{ GeV}$ in order to suppress jets originating from pile-up interactions. In this algorithm, a multivariate discriminant based on two track-based variables is constructed to reject pile-up jets while maintaining a high efficiency for the hard-scatter jet independent of the number of primary vertices in the event. The selected jets are classified as $b$-jets using a multivariate technique [82,83], which takes advantage of the information about secondary vertices, the impact parameters of the associated tracks and the topologies of decays of heavy-flavour hadrons. The $b$-tagging working point is selected to have an efficiency of 70% for a $b$-jet from $t\bar{t}$ decays, with a rejection factor of 12 for jets originating from $c$-quarks ($c$-jets), and of close to 400 for jets initiated by light-flavour quarks or gluons (light-flavour jets).

An overlap removal procedure is performed in the following order to avoid double counting of detector-level objects when reconstructing physics objects. Electrons with $\Delta R(e, \gamma) < 0.4$ are removed. Jets with $\Delta R(\text{jet}, \gamma) < 0.4$ or $\Delta R(\text{jet}, e) < 0.2$ are removed. Electrons with $\Delta R(e, \text{jet}) < 0.4$ are removed. Muons with $\Delta R(\mu, \gamma) < 0.4$ or $\Delta R(\mu, \text{jet}) < 0.4$ are removed.

### 4.2 Event selection

The events passing the diphoton trigger are required to contain at least two jets, no $b$-jet, and at least one charged lepton ($e$ or $\mu$, but including contributions from fully leptonic $\tau$-lepton decays) in the final state. The two photon candidates with the leading (sub-leading) $E_T$ are required to satisfy $E_T^{\gamma}/m_{\gamma\gamma} > 0.35$ (0.25). The $b$-jet veto suppresses the $t\bar{t}H$ process. Furthermore, the transverse momentum of the diphoton system ($p_T^{\gamma\gamma}$) is required to be larger than 100 GeV for maximising the sensitivity and keeping at least 70% of signal events. This requirement suppresses continuum background events when searching for non-resonant Higgs boson pair production, or resonant production with resonance masses of 400 GeV or higher. However, the $p_T^{\gamma\gamma}$ selection is omitted in the search for resonance masses below 400 GeV due to a limited separation between signal and continuum background in this kinematical region, as can be seen in Fig. 2. These final selection criteria, together with a requirement on the invariant diphoton mass of 105 GeV < $m_{\gamma\gamma}$ < 160 GeV, define the event sample on which the signal search is performed for the various assumed signal models. A data “sideband” sample is selected applying the same criteria, but excluding the Higgs mass region $m_{\gamma\gamma}$ 121.7–128.5 GeV, and can be used together with other samples to study the continuum background.

If there were an observable signal, one of the Higgs bosons would be directly visible in the $m_{\gamma\gamma}$ distribution. The combination of two jets and at least one charged lepton would be consistent with $H \rightarrow WW^*$ for the other Higgs boson. Its signature would in principle be enhanced by a missing transverse energy ($E_T^{\text{miss}}$) requirement to indicate a neutrino, but a selection on $E_T^{\text{miss}}$ was found not to produce any significant improvement in sensitivity, and so was not applied. The magnitude of $E_T^{\text{miss}}$ [84,85] is measured from the negative vectorial sum of the transverse momenta of all photon, electron and muon candidates and of all hadronic jets after accounting for overlaps between jets, photons, electrons, and muons, as well as an estimate of soft contributions based on tracks.

After all selections described above, the combined acceptance and selection efficiency for non-resonant production is 8.5%, while it ranges from 6.1 to 10% as a function of the mass of the resonance ($m_X$) from 260 to 500 GeV, as shown in Table 3. The efficiency for the non-resonant Higgs boson pair production is at the same level as the efficiency for the high-mass resonant production, as the Higgs bosons and their decay products tend to exhibit large transverse momenta due to the box diagram shown in Fig. 1a.
5 Signal and background estimation

A fit to the $m_{\gamma\gamma}$ distribution is performed to extract the signal yield as described in Sect. 7. The shapes of both the signal and background distributions are modelled with analytical functions. For both Higgs boson pair production and single-Higgs-boson processes, the $m_{\gamma\gamma}$ distributions are modelled with double-sided Crystal Ball functions [86]. Their shape parameters are determined by a fit to simulated samples. The single-Higgs-boson contribution is normalised to the SM cross-sections as described in Sect. 3.2. Higgs boson pair production is regarded as a background to the resonant search. Its contribution is also set to the SM prediction of Sect. 3.2.

The continuum background is modelled with an exponential function of a second-order polynomial. Several functional forms were evaluated by fitting the sidebands in data and MC samples under different conditions of photon purity and lepton multiplicity. Photon purity was lowered, compared to the final data selection, by reversing the requirements on photon isolation or identification. For higher photon purity, MC samples with prompt photons were used. The lepton multiplicity was varied to be zero or at least one. For all combinations of conditions, the exponential function with a second-order polynomial gave the best fits, with satisfactory $\chi^2$, and was chosen to model the continuum background.

The expected numbers of signal and background events are shown in Table 4 together with the number of events observed in data. Only events within a mass window of $m_H \pm 2 \sigma_{m_{\gamma\gamma}}$ are reported, where the Higgs boson mass ($m_H$) is taken to be 125.09 GeV [87] and the diphoton mass resolution ($\sigma_{m_{\gamma\gamma}}$) is 1.7 GeV and is obtained from simulation. The dominant background is from continuum processes with multiple photons and jets. A small background arises from SM single-Higgs-boson production processes, among which $t\bar{t}H$ and $WH$ productions give the leading contributions with, respectively, a fraction of 41.5% (39.2%) and 23.3% (22.5%) of the whole single-Higgs-boson contribution with (without) the $p_T^{\gamma\gamma} > 100$ GeV selection.

### Table 3

<table>
<thead>
<tr>
<th>$m_X$ (GeV)</th>
<th>No $p_T^{\gamma\gamma}$ selection</th>
<th>$p_T^{\gamma\gamma} &gt; 100$ GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>260</td>
<td>6.1</td>
<td>7.8</td>
</tr>
<tr>
<td>300</td>
<td>7.1</td>
<td>10</td>
</tr>
<tr>
<td>400</td>
<td>9.7</td>
<td>8.5</td>
</tr>
</tbody>
</table>

The shape parameters and normalisation are free to float in the fit to the data. Since any functional form might introduce spurious signals, this effect is estimated with a sample mixing irreducible prompt-photon background from simulation and reducible backgrounds from data, as described in Sect. 6.

### Table 4

<table>
<thead>
<tr>
<th>Process</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>No $p_T^{\gamma\gamma}$ selection</td>
<td>$p_T^{\gamma\gamma} &gt; 100$ GeV</td>
</tr>
<tr>
<td>Continuum background</td>
<td>22 ± 5</td>
</tr>
<tr>
<td>SM single-Higgs</td>
<td>1.92 ± 0.15</td>
</tr>
<tr>
<td>SM di-Higgs</td>
<td>0.046 ± 0.004</td>
</tr>
<tr>
<td>Sum of expected background</td>
<td>24 ± 5</td>
</tr>
<tr>
<td>Data</td>
<td>33</td>
</tr>
</tbody>
</table>

6 Systematic uncertainties

6.1 Theoretical uncertainties

Theoretical uncertainties in the prediction of the cross section of single Higgs bosons are estimated from variations of the normalisation and factorisation scales, PDF, and the running QCD coupling constant ($\alpha_S$) [17]. Among the dominant production modes $t\bar{t}H$ and $VH$, the cross section of $t\bar{t}H$ has the largest uncertainty: up to 9.2% in the scale variations, up to 3.0% in the PDF variations, and 2.0% in the $\alpha_S$ variations, as prescribed by the LHC Higgs Cross Section Working Group [17].

The theoretical uncertainties in the efficiency times acceptance ($\epsilon \times A$) are estimated from scale, PDF and parton shower variations. The scale uncertainty ranges from 2.1 to
4.1% for resonant production and is 3.4% for non-resonant production. The PDF uncertainty is around 2.5 and 3.0% for the resonant and non-resonant production, respectively. The parton shower uncertainty is estimated by comparing \textsc{Pythia} 8 and \textsc{Herwig++} as two different shower models, and ranges from 6.0% at $m_X = 500 \text{ GeV}$ to 29.6% at $m_X = 260 \text{ GeV}$ for resonant production, and is 7.8% for non-resonant production. This uncertainty is large in low-mass resonant production because the jet spectrum at low-$p_T$ is more susceptible to variations in the parton shower model. Non-resonant Higgs boson pair production is considered as a background in the search for resonant Higgs boson pair production. The scale, PDF, $\alpha_S$ and HEFT uncertainties in the calculation of the cross section for SM Higgs boson pair production are also taken into account. These values are 6.0%, 2.1%, 2.3%, and 5.0%, respectively, following the recommendations in Ref. [17]. Further uncertainties arising from the $H \rightarrow \gamma\gamma$ and $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$ branching ratios ($B$) are considered as well. They are 2.1% and 1.5% [17], respectively.

6.2 Modelling uncertainties in the continuum background

The exponential function of a second-order polynomial is determined to provide the simplest and most robust functional form for modelling the continuum background as described in Sect. 5. The uncertainties in the modelling are estimated by fitting a signal-plus-background model to a simulated background-only sample that has such a large number of events that its own statistical uncertainty does not affect the test results. The fitted number of signal events ($n_{\text{sig}}$) quantifies spurious signal events. The fits are performed with the assumed $m_H$ ranging from 120 to 130 GeV in steps of 0.5 GeV. The maximum value of the fitted signal yields $\ln n_{\text{sig}}$ is regarded as a bias in the yields due to the background modelling (the spurious signal), and is, conservatively, taken into account in the fit as the modelling uncertainty. The fitted $\ln n_{\text{sig}}$ value reaches as large as 0.46 when not applying the $p_T^{\gamma\gamma}$ selection, and 0.26 when applying the selection. The simulated background-only samples include the irreducible process of $\gamma\gamma\ell\nu jj$ and the reducible processes represented by events where one or two hadronic jets are misidentified as photons. The reducible processes are modelled by the data events with reversed photon identification or isolation requirements. The two components are combined according to the measured diphoton purity, which is about 88% (90% with $p_T^{\gamma\gamma}$ selection) and normalised according to the number of selected data events.

6.3 Experimental uncertainties

The uncertainty in the measurement of the combined 2015+2016 integrated luminosity is 2.1%. It is derived, following a methodology similar to that detailed in Ref. [88], from a calibration of the luminosity scale using $x-y$ beam-separation scans performed in August 2015 and May 2016. All processes that are estimated using simulation are affected by the uncertainty in the luminosity measurement.

The efficiency of the diphoton trigger is estimated using bootstrap methods [89] with a systematic uncertainty of 0.4%. The photon identification uncertainty is obtained by varying the data-to-simulation efficiency corrections within their uncertainties, derived from control samples of photons from radiative $Z$ boson decays and from inclusive $\gamma$ events, and of electrons from $Z \rightarrow e^+e^-$ decays. A maximal uncertainty of 1.7% in the yields is evaluated in all of the SM single-Higgs-boson, SM di-Higgs-boson and BSM Higgs boson production processes. The photon–track isolation uncertainty is derived from measurements of the uncertainty in the data-to-simulation efficiency corrections using inclusive-photon control samples, while the uncertainty from the calorimeter isolation requirement is evaluated from the difference between applying and not applying corrections derived from inclusive-photon events to the calorimeter isolation variable in the simulation. In general, the overall isolation uncertainty is less than 1%. The uncertainties from the photon energy resolution and scale affect the yields by less than 0.2%. The relevant impact on the shape of the diphoton invariant mass is also considered by introducing variations of the resolution and mean values of the fit function and is estimated using simulation. The photon energy resolution varies the resolution of the $m_{\gamma\gamma}$ shape by 5.2–11.4%, while the photon energy scale affects the mean value by about 0.5%. The jet energy scale (JES) and the corresponding uncertainties are derived from both simulation and in situ calibration using data [77,90]. This affects the event selection efficiency by 2.4–9.9%, depending on the process. The jet energy resolution (JER) uncertainty is evaluated by smearing jet energies according to the systematic uncertainties of the resolution measurement [80,91], and its impact on the event selection efficiency ranges from 0.1 to 1.6%. The $b$-tagging uncertainties is derived separately for $b$-jets, $c$-jets and light-flavour jets [82]. Overall, their impact on the yields is not more than 4%. Uncertainties arising from the reconstruction, identification and isolation of both the electron and muon candidates [72,73], are propagated to the event yield variations, and they are found to have an impact of less than 1%. Finally, the pile-up reweighting procedure, which matches the distribution of the number of interactions per bunch crossing between simulation and data, has associated systematic uncertainties of less than 1%. All experimental uncertainties are correlated among all processes that use simulation to model the yields and the kinematics. A summary of the systematic uncertainties in the expected yields of the di-Higgs-boson and single-Higgs-boson production is presented in Table 5. In the search for non-resonant Higgs boson pair production, SM Higgs boson pair production is
Table 5  Summary of relative systematic uncertainties, in percent, propagated to the yields for the MC-estimated processes. Entries marked by ‘-‘ indicate that the systematic uncertainty is not applicable for the corresponding process. The extrapolation uncertainties in b-tagging include two components: one is from the extrapolation to high-$p_T$ ($p_T > 300$ GeV) jets and the other one is from extrapolating c-jets to $\tau$-jets. The values for resonant production shown here assume $m_X = 260$ GeV.

<table>
<thead>
<tr>
<th>Source of uncertainties</th>
<th>Non-resonant $HH \to HH$</th>
<th>$X \to HH$</th>
<th>Single-$H$ bkg $p_T^{\gamma\gamma} &gt; 100$ GeV</th>
<th>Single-$H$ bkg No $p_T^{\gamma\gamma}$ selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luminosity 2015 + 2016</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Event sample size</td>
<td>1.7</td>
<td>2.2</td>
<td>1.6</td>
<td>1.3</td>
</tr>
<tr>
<td>Pile-up reweighting</td>
<td>0.5</td>
<td>0.9</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Photon</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Identification</td>
<td>1.7</td>
<td>1.4</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Isolation</td>
<td>0.8</td>
<td>0.7</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Energy scale</td>
<td>0.2</td>
<td>&lt; 0.1</td>
<td>0.2</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Jet</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy scale</td>
<td>4.0</td>
<td>9.9</td>
<td>2.4</td>
<td>2.6</td>
</tr>
<tr>
<td>Energy resolution</td>
<td>0.1</td>
<td>1.6</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>b-tagging</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$b$-hadron jets</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>3.8</td>
<td>3.6</td>
</tr>
<tr>
<td>c-hadron jets</td>
<td>1.5</td>
<td>1.0</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Light-flavour jets</td>
<td>0.3</td>
<td>0.3</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Extrapolation</td>
<td>&lt; 0.1</td>
<td>&lt; 0.1</td>
<td>0.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>Lepton</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron</td>
<td>0.5</td>
<td>0.7</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Muon</td>
<td>0.5</td>
<td>0.7</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Theory</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PDF on $\sigma$</td>
<td>2.1</td>
<td>–</td>
<td>3.4</td>
<td>3.4</td>
</tr>
<tr>
<td>$\alpha_S$ on $\sigma$</td>
<td>2.3</td>
<td>–</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Scale on $\sigma$</td>
<td>6.0</td>
<td>–</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>HEFT on $\sigma$</td>
<td>5.0</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Scale on $\epsilon \times A$</td>
<td>2.8</td>
<td>2.5</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>PDF on $\epsilon \times A$</td>
<td>3.0</td>
<td>2.4</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Parton shower on $\epsilon \times A$</td>
<td>7.8</td>
<td>29.6</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>$B(H \to \gamma\gamma)$</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>$B(H \to WW^*)$</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Total</td>
<td>13.6</td>
<td>31.8</td>
<td>7.1</td>
<td>6.8</td>
</tr>
</tbody>
</table>

considered to be the signal process, while single Higgs boson production is considered to be a background. In the search for the resonant Higgs boson pair production, both SM single Higgs boson production and non-resonant Higgs boson pair productions are considered to be background processes.

7 Results

A fit to $m_{\gamma\gamma}$ is performed in the signal region to extract the signal yield. The statistical model is constructed with a likelihood function:

$$\mathcal{L}(\mu, \theta) = \prod_i \left( n_{\text{Signal}}(\mu, \theta) + n_{\text{ex}} \times f_{\text{DSCB}} \left( m_{\gamma\gamma}^i, \theta \right) \\
+ n_{\text{Cont}} \times f_{\text{Cont}} \left( m_{\gamma\gamma}^i, \theta \right) + n_{\text{SM-one-Higgs}}(\theta) \times f_{\text{DSCB}} \left( m_{\gamma\gamma}^i, \theta \right) + n_{\text{SM-di-Higgs}} \times f_{\text{DSCB}} \left( m_{\gamma\gamma}^i, \theta \right) \right) \prod G(0|\theta, 1)$$

(1)

- $i$ stands for the event index,
- $n_{\text{Signal}}$ is the expected number of signal events,
- $\mu$ is the cross section (times the branching fraction of $X \to HH$) of non-resonant (resonant) production,
Fig. 3 Invariant mass spectrum of the diphoton system in the searches for both resonant and non-resonant Higgs boson pair production, with the corresponding backgrounds for (a) \( m_X = 260 \text{ GeV} \) without any \( p_T^{\gamma\gamma} \) selection and (b) the non-resonant case with a \( p_T^{\gamma\gamma} > 100 \text{ GeV} \) selection. Fits to \( m_{\gamma\gamma} \) are performed using the full signal-plus-background model. In each plot, only the background component is present. The shape parameters and normalisation of the continuum background model are determined in the fits. The “SM Higgs boson” in (a) contains the single-Higgs-boson background and SM di-Higgs-boson background. The band shows the uncertainty of the “Total background” in the upper panel and is calculated by a sampling method. The bottom panel shows the difference between the number of events in data and the estimated number of background events, as determined by the fits.

- \( n_{sp} \) is the estimated spurious signal yield due to our choice of continuum background modelling,
- \( f_{2\text{SCB}} \) is the probability density function (pdf) of a double-sided Crystal Ball distribution for signal,
- \( n_{\text{Cont}} \) is the expected number of continuum background events,
- \( f_{\text{Cont}} \) is the pdf of the continuum background, i.e. an exponential function of a second-order polynomial,
- \( n_{\text{SM-one-Higgs}} \) is the expected number of single-Higgs-boson events, which is set to the SM prediction and can vary with uncertainties,
- \( f_{2\text{SCB}} \) is the pdf of a double-sided Crystal Ball distribution for the SM single-Higgs-boson background,
- \( n_{\text{SM-di-Higgs}} \) is the expected number of the SM di-Higgs-boson events,
- \( f_{3\text{SCB}} \) is the pdf of a double-sided Crystal Ball distribution for SM di-Higgs-boson background,
- \( G(0|\theta, 1) \) is the pdf of a Gaussian distribution used to constrain the nuisance parameters \( \theta \) that model systematic uncertainties as introduced in Sect. 6.

Equation (1) is used directly for the BSM resonant signal searches. For the non-resonant SM Higgs boson pair search, the SM Higgs boson pair term is removed.

The distributions in the final signal-plus-background fit using the likelihood function above are shown for two sets of selections separately: in Fig. 3a without requiring the \( p_T^{\gamma\gamma} \) selection for masses below 400 GeV, and in Fig. 3b requiring \( p_T^{\gamma\gamma} > 100 \text{ GeV} \) for masses above 400 GeV, as well as for the search for non-resonant Higgs boson pair production. The fits are performed separately on the two distributions to search for resonant signals in both the low-mass and high-mass ranges. The observed data are found to be compatible with the sum of the expected SM backgrounds by performing a likelihood-ratio test [92]. The largest data excess has a local significance of 2.0 standard deviations at 400 GeV without the \( p_T^{\gamma\gamma} \) selection. A modified frequentist method CLs [93] is used to calculate the 95% confidence-level (CL) exclusion limits with the asymptotic approximation [92]. Unfolding the SM Higgs boson branching fractions to \( WW^* \) and \( \gamma\gamma^* \) for the signal, the expected upper limit on the cross section for non-resonant Higgs boson pair production is 5.4 pb, while the observed limit is 7.7 pb, as shown in Table 6. The difference between the expected and observed limits is due to a slight excess of events in data. The expected upper limit on the cross section times the branching fraction of \( X \rightarrow HH \) ranges from 17.6 to 4.4 pb, while the observed limit ranges from 40 to 6.1 pb, as a function of \( m_X \) between 260 and 500 GeV, as shown in Fig. 4a.

Assuming the SM Higgs branching fractions of \( B(H \rightarrow WW^*) = (21.52 \pm 0.32)\% \) and \( B(H \rightarrow \gamma\gamma) = (0.227 \pm 0.005)\% \) [17], the expected upper limit on the cross section for non-resonant production of \( HH \rightarrow \gamma\gamma WW^* \) is 5.3 pb, while the observed limit is 7.5 pb, as shown in Table 6. The expected upper limit on the cross section for resonant production of \( X \rightarrow HH \rightarrow \gamma\gamma WW^* \) ranges from 17.2 to 4.3 fb, while the observed limit ranges from 39.1 to 6.0 fb, as a function of \( m_X \) between 260 and 500 GeV, as shown in Fig. 4b. The statistical uncertainty dominates in the final
Table 6  The 95% CL upper limits for the non-resonant production and the ratios of the limits to the SM cross-section value of $\sigma(pp \rightarrow HH) = 33.4^{+2.4}_{-2.8}$ pb [17]. The $\pm 1\sigma$ and $\pm 2\sigma$ intervals around the median limit are also presented

<table>
<thead>
<tr>
<th></th>
<th>+2$\sigma$</th>
<th>+1$\sigma$</th>
<th>Median</th>
<th>−1$\sigma$</th>
<th>−2$\sigma$</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper limits on $\sigma(HH)$ (pb)</td>
<td>12</td>
<td>8.0</td>
<td>5.4</td>
<td>3.9</td>
<td>2.9</td>
<td>7.7</td>
</tr>
<tr>
<td>Upper limits on $\sigma(HH) \times B(\gamma\gamma WW^*)$ (fb)</td>
<td>12</td>
<td>7.8</td>
<td>5.3</td>
<td>3.8</td>
<td>2.8</td>
<td>7.5</td>
</tr>
<tr>
<td>Ratios of limits over the SM $\sigma(HH)$</td>
<td>360</td>
<td>240</td>
<td>160</td>
<td>120</td>
<td>87</td>
<td>230</td>
</tr>
</tbody>
</table>

Fig. 4 95% CL expected (dashed line) and observed (solid line) limits on the resonant Higgs boson pair production cross section times the branching fraction of $X \rightarrow HH$ as a function of $m_X$ (a) with and b without assuming the SM branching fractions of $H \rightarrow WW^*$ and $H \rightarrow \gamma\gamma$.

The CLs method and the asymptotic approximation are used. The $\pm 1\sigma$ and $\pm 2\sigma$ bands on the expected limit are also presented. To the right of the vertical dashed line at $m_X = 400$ GeV, the $p_{T\gamma\gamma} > 100$ GeV selection is applied in both plots, but not to the left.

8 Conclusion

This paper presents searches for non-resonant and resonant Higgs boson pair production with a semileptonic $\gamma\gamma WW^*$ final state using 36.1 fb$^{-1}$ of $pp$ collision data collected at 13 TeV with the ATLAS detector at the LHC. No significant excess above the expected SM background is observed. A 95% confidence-level upper limit of 7.7 pb is set on the cross section for non-resonant production, while the expected limit is 5.4 pb, compared to the SM Higgs boson pair production cross section of 33.4 fb. The observed upper limit on the resonant production cross section times the branching fraction of $X \rightarrow HH$ ranges between 40 pb and 6.1 pb, while the expected limit ranges between 17.6 and 4.4 pb, for a hypothetical resonance with a mass in the range of 260–500 GeV. When deriving the limits above, the SM branching ratios of $H \rightarrow WW^*$ and $H \rightarrow \gamma\gamma$ are assumed.

Acknowledgements We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; STSC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DLR and DMSRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MINE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZS, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, CRC and Compute Canada, Canada; COST, ERC, ERDF, Horizon 2020, and Marie Sklodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF, Greece; BSF-NSF and GIF, Israel; CERCA Programme Generalitat de Catalunya, Spain; The Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [94].
Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. Funded by SCOAP3.

References

Graduate School of Science, Kobe University, Kobe, Japan

Graduate School of Science, Kobe University, Kobe, Japan

Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, Kraków, Poland; Marian Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland

Institute of Nuclear Physics Polish Academy of Sciences, Kraków, Poland

Faculty of Science, Kyoto University, Kyoto, Japan

Kyoto University of Education, Kyoto, Japan

Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan

Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina

Physics Department, Lancaster University, Lancaster, UK

Oliver Lodge Laboratory, University of Liverpool, Liverpool, UK

Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia

School of Physics and Astronomy, Queen Mary University of London, London, UK

Department of Physics, Royal Holloway University of London, Egham, UK

Department of Physics and Astronomy, University College London, London, UK

Louisiana Tech University, Ruston, LA, USA

Institut für Physik, Universität Mainz, Mainz, Germany

School of Physics, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

Physik Department, University of Massachusetts, Amherst, MA, USA

Department of Physics, McGill University, Montreal, QC, Canada

School of Physics, University of Melbourne, Melbourne, VIC, Australia

Department of Physics, University of Michigan, Ann Arbor, MI, USA

Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA

B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus

Research Institute for Nuclear Problems of Byelorussian State University, Minsk, Belarus

Group of Particle Physics, University of Montreal, Montreal, QC, Canada

P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia

Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia

National Research Nuclear University MEPhI, Moscow, Russia

D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia

Fakultät für Physik, Ludwig-Maximilians-Universität München, Munich, Germany

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Munich, Germany

Nagasaki Institute of Applied Science, Nagasaki, Japan

Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan

Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA

Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, The Netherlands

Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, The Netherlands

Department of Physics, Northern Illinois University, DeKalb, IL, USA

Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia; Novosibirsk State University, Novosibirsk, Russia

Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia

Department of Physics, New York University, New York, NY, USA

Ohio State University, Columbus, OH, USA

Faculty of Science, Okayama University, Okayama, Japan

Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, USA

Department of Physics, Oklahoma State University, Stillwater, OK, USA

Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic
Center for High Energy Physics, University of Oregon, Eugene, OR, USA
LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
Graduate School of Science, Osaka University, Osaka, Japan
Department of Physics, University of Oslo, Oslo, Norway
Department of Physics, Oxford University, Oxford, UK
LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
Department of Physics, University of Pennsylvania, Philadelphia, PA, USA
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;
Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada, Spain;
Departamento and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
Institute of Physics, Academy of Sciences of the Czech Republic, 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
Department of 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
Also at National Research Nuclear University MEPhI, Moscow, Russia
Also at Near East University, Nicosia, North Cyprus, Mersin, Turkey
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, United States of America
Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China
Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
Also at TRIUMF, Vancouver BC, Canada
Also at Universita di Napoli Parthenope, Napoli, Italy
*Deceased