Constraints on non-Standard Model Higgs boson interactions in an effective Lagrangian using differential cross sections measured in the $H \rightarrow \gamma\gamma$ decay channel at $\sqrt{s} = 8$ TeV with the ATLAS detector

ATLAS Collaboration *

1. Introduction

The discovery of a Higgs boson at the ATLAS and CMS experiments [1,2] offers a new opportunity to search for physics beyond the Standard Model (SM) by examining the strength and structure of the Higgs boson’s interactions with other particles. Thus far, the interactions of the Higgs boson have been probed using the $k$-framework [3], in which the strength of a given coupling is allowed to vary from the SM prediction by a constant value. In this approach, the total rate of a given production and decay channel can differ from the SM prediction, but the kinematic properties of the Higgs boson in each decay channel are unchanged.

An alternative framework for probing physics beyond the SM is the effective field theory (EFT) approach [3–8], whereby the SM Lagrangian is augmented by additional operators of dimension six or higher. Some of these operators produce new tensor structures for the interactions between the Higgs boson and the SM particles, which can modify the shapes of the Higgs boson kinematic distributions as well as the associated jet spectra. The new interactions arise as the low-energy manifestation of new physics that exists at energy scales much larger than the partonic centre-of-mass energies being probed.

In this Letter, the effects of operators that produce anomalous CP-even and CP-odd interactions between the Higgs boson and photons, gluons, W bosons and Z bosons are studied using an EFT-inspired effective Lagrangian. The analysis is performed using a simultaneous fit to five detector-corrected differential cross sections in the $H \rightarrow \gamma\gamma$ decay channel, which were previously published by the ATLAS Collaboration [9]. These are the differential cross sections as functions of the diphoton transverse momentum ($p_T^{\gamma\gamma}$), the number of jets produced in association with the diphoton system ($N_{jets}$), the leading-jet transverse momentum ($p_T^{\text{jet}_{\text{leading}}}$), and the invariant mass ($m_{jj}$) and difference in azimuth angle ($\Delta\phi_{jj}$) of the leading and sub-leading jets in events containing two or more jets. The inclusion of differential information significantly improves the sensitivity to operators that modify the Higgs boson’s interactions with W and Z bosons. To perform a simultaneous analysis of these distributions, the statistical correlations between bins of different distributions need to be included in the fit procedure. These correlations are evaluated by analysing the $H \rightarrow \gamma\gamma$ candidate events in the data, and are published as part of this Letter to allow future studies of new physics that produces non-SM kinematic distributions for $H \rightarrow \gamma\gamma$.

2. Higgs effective Lagrangian

The effective Lagrangian used in this analysis is presented in Ref. [8]. In this model, the SM Lagrangian is augmented with the dimension six CP-even operators of the Strongly Interacting Light Higgs formulation [6] and corresponding CP-odd operators. The $H \rightarrow \gamma\gamma$ differential cross sections are mainly sensitive to the
operators that affect the Higgs boson’s interactions with gauge bosons and the relevant terms in the effective Lagrangian can be specified by

\[ \mathcal{L}_{\text{eff}} = \bar{c}_1 \mathcal{O}_1 + \bar{c}_2 \mathcal{O}_2 + \bar{c}_{\text{HW}} \mathcal{O}_{\text{HW}} + \bar{c}_{\text{HB}} \mathcal{O}_{\text{HB}} + \bar{c}_{\tilde{\gamma}} \mathcal{\tilde{\gamma}} + \bar{c}_{\tilde{g}} \mathcal{\tilde{g}} + \bar{c}_{\text{HW}} \mathcal{O}_{\text{HW}} + \bar{c}_{\text{HB}} \mathcal{O}_{\text{HB}}, \]

where \( \bar{c}_1 \) and \( \bar{c}_2 \) are ‘Wilson coefficients’ specifying the strength of the new CP-even and CP-odd interactions, respectively, and the dimension-six operators \( \mathcal{O}_i \) are those described in Refs. [8,10]. In the SM, all of the Wilson coefficients are equal to zero. The \( \mathcal{O}_1 \) and \( \mathcal{O}_2 \) operators introduce new interactions between the Higgs boson and two photons. The \( \mathcal{O}_{\text{HW}} \) and \( \mathcal{O}_{\text{HB}} \) operators introduce new interactions between the Higgs boson and two gluons and the analysis presented in this Letter is sensitive to these operators through the gluon fusion production mechanism. The \( \mathcal{O}_{\text{HW}} \) and \( \mathcal{O}_{\text{HB}} \) operators introduce new \( \text{HHW}, \text{HZZ} \) and \( \text{HZ}\gamma \) interactions. The \( \text{HHW} \) and \( \text{HZZ} \) interactions are also impacted by \( \mathcal{O}_{\text{HB}} \) and, to a lesser extent, \( \mathcal{O}_1 \) and \( \mathcal{\tilde{\gamma}} \). The analysis presented in this Letter is sensitive to the \( \mathcal{O}_{\text{HW}}, \mathcal{O}_{\text{HW}}, \mathcal{O}_{\text{HB}} \) and \( \mathcal{O}_{\text{HB}} \) operators through vector-boson fusion and associated production.

Other operators in the full effective Lagrangian of Ref. [8] can also modify Higgs boson interactions. Combinations of some of the CP-even operators have been constrained using global fits to experimental data from LEP and the LHC [8,11,12].

3. Statistical correlations between differential distributions

ATLAS [13] is a multipurpose particle physics detector with cylindrical geometry and nearly 4π coverage in solid angle. The analysis is performed using proton–proton collision data at a centre-of-mass energy \( \sqrt{s} = 8 \text{ TeV} \) and an integrated luminosity of 20.3 fb\(^{-1}\).1

The object and event selections used to define the differential distributions are described in detail in Ref. [9]. The statistical correlations between the measured cross sections as a function of different distributions are obtained using a random sampling with replacement method on the detector-level data. This procedure is often referred to as ‘bootstrapping’ [14]. Bootstrapped event samples are constructed from the data by assigning each event a weight pulled from a Poisson distribution with unit mean. The five differential distributions are then reconstructed using the weighted events, and the signal yields in each bin of a differential distribution are determined using an unbiased maximum-likelihood fit of the diphoton invariant mass spectrum (full details of the fit can be found in Ref. [9]). The procedure is repeated 10 000 times with statistically independent weights and the correlation between two bins of different distributions is determined from the scatter graph of the corresponding extracted cross sections. The observed correlations between bins of the measured \( p_T^{\gamma\gamma} \) and \( N_{\text{jets}} \) cross sections are shown in Fig. 1.

The statistical uncertainties on the correlation due to the finite number of bootstrap samples ranges from 0.5% to 1%. The statistical uncertainty on the correlations due to the finite number of events in data is determined to be less than 2% using the statistical overlap and variance of signal and background events in a mass window around the Higgs boson mass. In order to validate this approach, a set of pseudo-experiments was created from input conditions (with known correlations) chosen to be similar to those in data in terms of purity, kinematics and sample size. For each pseudo-experiment, a value for the correlation is determined using 10 000 bootstrapped samples and compared to the input correlations. No bias due to the bootstrapping is observed in the central value obtained from 500 pseudo-experiments.

As part of this Letter, the correlations computed above are made publicly available in HEPDATA [15], allowing the analysis to be repeated using alternative effective Lagrangians, complete EFT frameworks, or other models with non-SM Higgs boson interactions.

4. Theoretical predictions

The effective Lagrangian has been implemented in FeynRules [10].2 Parton-level event samples are produced for specific values of Wilson coefficients by interfacing the universal file output from FeynRules to the MADGRAPH5 [17] event generator. Higgs boson production via gluon fusion is produced with up to two additional partons in the final state using leading-order matrix elements. The 0-, 1- and 2-parton events are merged using the MLM matching scheme [18] and passed through the \PYTHIA6 generator [19] to create the fully hadronic final state. Event samples containing a Higgs boson produced either in association with a vector boson or via vector-boson fusion are produced using leading-order matrix elements and passed through the \PYTHIA6 generator. For each production mode, the Higgs boson mass is set to 125 GeV [20] and events are generated using the CTEQ6L1 parton distribution function and the AUET2 parameter set [21]. All other Higgs boson production modes are assumed to occur as predicted by the SM.

Event samples are produced for different values of a given Wilson coefficient. The particle-level differential cross sections are produced using \RIVET [22]. The \PROFESSOR method [23] is used to interpolate between these samples, for each bin of each distribution, and provides a parameterisation of the effective Lagrangian prediction. The parameterisation function is determined using 11 samples when studying a single Wilson coefficient, whereas

---

1. ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) at the centre of the detector and the z-axis along the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates \((r, \phi)\) are used in the transverse plane, \(\phi\) being the azimuthal angle around the beam pipe.

2. The implementation in Ref. [10] involves a redefinition of the gauge boson propagators that results in unphysical amplitudes unless certain physical constants are also redefined. The original implementation did not include the redefinition of these physical constants. However, the impact of redefining the physical constants is found to be less than 1% on the predicted cross sections across the range of Wilson coefficients studied. The relative change in the predicted Higgs boson cross sections as functions of the different Wilson coefficients is also found to agree with that predicted by the Higgs characterisation framework [16], with less than 2% variation across the parameter ranges studied.
25 samples are used when studying two Wilson coefficients simultaneously. As the Wilson coefficients enter the effective Lagrangian in a linear fashion, second-order polynomials are used to predict the cross sections in each bin. The method was validated by comparing the differential cross sections obtained with the parameterisation function to the predictions obtained with dedicated event samples generated at the specified point in parameter space.

The model implemented in FeynRules fixes the Higgs boson width to be that of the SM, \( \Gamma_H = 4.07 \text{ MeV} \) [3]. The cross sections are scaled by \( \Gamma_H/(\Gamma_H + \Delta \Gamma) \), where \( \Delta \Gamma \) is the change in partial width due to a specific choice of Wilson coefficient. The change in partial width is determined for each Higgs coupling using the partial-width calculator in MadGraph5 and normalised to reproduce the SM prediction from HDECAY [24].

The leading-order predictions obtained from MadGraph5 are reweighted to account for higher-order QCD and electroweak corrections to the SM process, assuming that these corrections factorise from the new physics effects. The differential cross section as a function of variable \( X \) for a specific choice of Wilson coefficient, \( c_i \), is given by

\[
\frac{d\sigma}{dX} = \sum_j \left( \frac{d\sigma}{dX} \right)_{\text{ref}} \left( \frac{d\sigma}{dX} \right)_{\text{MG5}}^{c_i} / \left( \frac{d\sigma}{dX} \right)_{c_i=0}^{\text{MG5}},
\]

where the summation \( j \) is over the different Higgs boson production mechanisms, ‘MG5’ labels the MadGraph5 prediction and ‘ref’ labels a reference sample for SM Higgs boson production.

The reference sample for Higgs boson production via gluon fusion is simulated using MG5_aMC@NLO [25] with the CT10 parton distribution function [26]. The \( H + n \)-jets topologies are generated using next-to-leading-order (NLO) matrix elements for each parton multiplicity \( (n = 0, 1 \text{ or } 2) \) and combined using the FFx merging scheme [27]. The parton-level events are passed through PYTHIA8 [28] to produce the hadronic final state using the AU2 parameter set [29]. The sample is normalised to the total cross section predicted by a next-to-next-to-leading-order plus next-to-next-to-leading-logarithm (NNLO+NNLL) QCD calculation with NLO electroweak corrections applied [3]. The reference sample for Higgs boson production via vector-boson fusion (VBF) is generated at NLO accuracy in QCD using the POWHEG Box [30]. The events are generated using the CT10 parton distribution function (PDF) and PYTHIA8 with the AU2 parameter set. The VBF sample is normalised to an approximate-NNLO QCD cross section with NLO electroweak corrections applied [3]. The reference samples for Higgs boson production in association with a vector boson (\( VH, V = W, Z \)) or a top–antitop pair (\( t\bar{t}H \)) are produced at leading-order accuracy using PYTHIA8 with the CTEQ6L1 PDF and the 4C parameter set [21]. The \( ZH \) and \( WH \) samples are normalised to cross sections calculated at NNLO in QCD with NLO electroweak corrections, whereas the \( t\bar{t}H \) sample is normalised to a cross section calculated to NLO in QCD [3].

The ratio of the differential cross sections to the SM predictions for some representative values of the Wilson coefficients are shown in Fig. 2. The impact of the \( \xi_g \) and \( \xi_{gg} \) coefficients are presented for the gluon fusion production channel and show a large change in the overall cross section normalisation. The \( \xi_g \) coefficient also changes the shape of the \( \Delta\phi_{jj} \) distribution, which is expected from consideration of the tensor structure of CP-even and CP-odd interactions [31,32]. The impact of the \( \xi_{tH} \) and \( \xi_{t\bar{t}H} \) coefficients are presented for the VBF + VH production channel and show large shape changes in all of the studied distributions. The \( \Delta\phi_{jj} \) distribution is known to discriminate between CP-odd and CP-even interactions in the VBF production channel [34].

### 5. Limit-setting procedure

Limits on the Wilson coefficients are set by constructing a \( \chi^2 \) function

\[
\chi^2 = (\hat{\sigma}_{\text{data}} - \hat{\sigma}_{\text{pred}})^T C^{-1} (\hat{\sigma}_{\text{data}} - \hat{\sigma}_{\text{pred}}),
\]

where \( \hat{\sigma}_{\text{data}} \) and \( \hat{\sigma}_{\text{pred}} \) are vectors from the measured and predicted cross sections of the five analysed observables, and \( C = C_{\text{stat}} + C_{\text{exp}} + C_{\text{pred}} \) is the total covariance matrix defined by the sum of the statistical, experimental and theoretical covariances. The predicted cross section \( \hat{\sigma}_{\text{pred}} \) and its associated covariance \( C_{\text{pred}} \) are continuous functions of Wilson coefficients. Scans of one or two Wilson coefficients are carried out and the minimum \( \chi^2 \) value, \( \chi^2_{\text{min}} \), is determined. The confidence level (CL) of each scan point can be calculated as

\[
1 - \text{CL} = n \int dx f(x; m),
\]

with \( \chi^2(c_i) \) being the \( \chi^2 \) value evaluated for a given Wilson coefficient \( c_i \), and \( f(x; m) \) being the \( \chi^2 \) distribution for \( m \) degrees of freedom and \( n = 1 \) or \( \frac{1}{2} \) for two-sided or one-sided limits. The coverage of CL and the effective number of degrees of freedom are determined using ensembles of pseudo-experiments.\(^4\)

The input data vector is compared in Fig. 3 to the SM hypothesis as well as two non-SM hypotheses specified by \( \xi_g = 1 \times 10^{-4} \) and \( \xi_{tH} = 0.05 \), respectively.

The covariance matrix for experimental systematic uncertainties is constructed from all uncertainty sources provided by Ref. [9], which include the jet energy scale and resolution uncertainties, photon energy and resolution uncertainties, and model uncertainties. Identical sources are assumed to be fully correlated across samples using form-factor predictions from VBFNLO [33]. The impact on the \( \xi_{tH} \) and \( \xi_{t\bar{t}H} \) limits are negligible for \( \Delta \phi > 1 \text{ TeV} \).

\(^4\) For one-dimensional limits on the CP-even (odd) Wilson coefficients, good agreement is found between the asymptotic formula and the pseudo-experiment test statistic with \( m = 1 \) and \( n = 1 \left(\frac{1}{2}\right) \). For the two-dimensional limits on \( \xi_g \) versus \( \xi_{gg} \), and \( \xi_{tH} \) versus \( \xi_{t\bar{t}H} \), good agreement between pseudo-experiments and asymptotic formula is found for \( m = 1 \) and \( n = 1 \). For the two-dimensional limit on \( \xi_g \) versus \( \xi_{\gamma} \), good agreement between pseudo-experiments and asymptotic formula is found for \( m = 2 \) and \( n = 1 \).
bins and variables and the sign of an error amplitude is taken into account when computing the covariance matrix. The statistical uncertainties on the cross correlation have a negligible impact on the results reported here.

The covariance matrix for the theoretical uncertainties is constructed to account for missing higher-order corrections and PDF uncertainties in the SM reference predictions. The uncertainties in the gluon fusion reference samples are: (i) a shape uncertainty, estimated by simultaneously varying the factorisation and renormalisation scales in MCG@NLO by a factor of 0.5 or 2.0, and (ii) uncertainties on the NNLO+NNLL QCD plus NLO electroweak total cross-section prediction [3], arising from missing higher-order corrections and PDF uncertainties; these uncertainties are assumed to be fully correlated among bins and observables. For VBF, ZH and WH, shape uncertainties are neglected because their impact is expected to be negligible with respect to all other theory uncertainties. Normalisation uncertainties for these processes are taken from Ref. [3].

The benefit of using more than one differential distribution in the analysis is quantified using an ‘Asimov dataset’, which is a representative dataset of the median expected cross-section measurement assuming the SM. For $\tilde{c}_g$ and $\tilde{c}_y$, the use of a single inclusive distribution ($p_T^{\gamma\gamma}$ or $N_{\text{jets}}$) results in the same expected limits as the full five-dimensional fit. For $\tilde{c}_y$ and $\tilde{c}_y$, the most sensitive variable is found to be $p_T^{\gamma\gamma}$, with a 5% improvement in the expected limits obtained from using the five-dimensional information. For $\tilde{c}_{HW}$ and $\tilde{c}_{HW}$, the most sensitive variable is $\Delta\phi_{jj}$ and an 18% improvement in the expected limits is obtained from using the five-dimensional fit. In summary, the expected sensitivity for $\tilde{c}_g$, $\tilde{c}_y$, $\tilde{c}_y$ and $\tilde{c}_y$ arises mainly from the normalisation of the different production mechanisms, and can be probed using the inclusive distributions that distinguish between the different processes, whereas the $\tilde{c}_{HW}$ and $\tilde{c}_{HW}$ coefficients benefit more from the full five-dimensional information due to the induced shape changes in the kinematics of the VBF + VH process.

6. Results

The 68% and 95% confidence regions for a two-dimensional scan of $\tilde{c}_y$ and $\tilde{c}_y$ are shown in Fig. 4, after setting all other Wilson coefficients to zero. These additional interactions can interfere with the corresponding SM interactions. Destructive interference, for example, causes the $H \rightarrow \gamma\gamma$ branching ratio to be zero at $\tilde{c}_y \sim -2 \times 10^{-3}$ and the gluon fusion production cross section to be zero at $\tilde{c}_y \sim -2.2 \times 10^{-4}$. The impact of these effects is evident in the structure of the obtained limits in the two-dimensional parameter plane.

The 68% and 95% confidence regions for a two-dimensional scan of $\tilde{c}_g$ and $\tilde{c}_g$ are shown in Fig. 5, after setting all other Wilson coefficients to zero. The $\Delta\phi_{jj}$ distribution is sensitive to the $\tilde{c}_g$ parameter through the gluon fusion production mechanism (Figs. 2 and 3) and the limit on $\tilde{c}_g$ is improved with the inclusion of this data in the fit. This is evident in Fig. 5 where the limit band is constricted at the largest values of $\tilde{c}_g$.

The 68% and 95% confidence regions obtained from scanning $\tilde{c}_{HW}$ and $\tilde{c}_{HW}$ are shown in Fig. 6, after setting $\tilde{c}_{HW} = \tilde{c}_{HW}$ and $\tilde{c}_{HW} = \tilde{c}_{HW}$ to ensure that the partial width for $H \rightarrow Z\gamma$ is unchanged from the SM prediction. As discussed in Section 5, these Wilson coefficients produce large shape changes in all distributions and the obtained limits are strongest when fitting all five distributions simultaneously.

The 95% confidence regions for $\tilde{c}_{HW}$ and $\tilde{c}_{HW}$ can be translated into the Higgs Characterisation framework [16] and compared to the ATLAS results for non-SM CP-even and CP-odd $H\gamma$ interactions, which were obtained using an angular analysis of the decay

---

5 Values of $|\tilde{c}_{HW} - \tilde{c}_{HW}| > 0.033$ lead to a very large decay rate for the $H \rightarrow Z\gamma$ process that is contradicted by the experimental constraints reported by ATLAS [35].
products in the WW* and ZZ* decay channels [36]. The translated limits are $-0.08 < \kappa_{WW}/\kappa_{SM} < 0.09$ and $-0.22 < \tan(\alpha) \cdot \kappa_{WW}/\kappa_{SM} < 0.22$, where the variables $\kappa_{WW}$, $\kappa_{WW}$, $\kappa_{SM}$ and $\alpha$ are defined in Refs. [16,36]. The limits obtained in this analysis are a factor of approximately seven stronger than those in Ref. [36], due to increased sensitivity to the different Higgs boson production channels arising from the inclusion of rate and jet kinematic information in the signal hypothesis.

The observed limits on $\tilde{c}_{HW}$ and $\tilde{c}_{HW}$ are also not excluded by current signal strength measurements. For example, the signal strength in the $H \to ZZ^*$ and $H \to WW^*$ channels is predicted to be approximately 1.3 for $\tilde{c}_{HW} = 0.1$, which is consistent with the dedicated measurements [37,38].

The 95% confidence regions for a one-dimensional scan of the Wilson coefficients are given in Table 1.

Table 1

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>95% CL limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tilde{c}_y$</td>
<td>$[-7.4, 5.7] \times 10^{-4}$</td>
</tr>
<tr>
<td>$\tilde{c}_y^*$</td>
<td>$[-1.8, 1.8] \times 10^{-3}$</td>
</tr>
<tr>
<td>$\tilde{c}_g$</td>
<td>$[-0.7, 1.3] \times 10^{-4}$</td>
</tr>
<tr>
<td>$\tilde{c}_g^*$</td>
<td>$[-2.4, 2.4] \times 10^{-4}$</td>
</tr>
<tr>
<td>$\tilde{c}_\ell$</td>
<td>$[-8.6, 9.2] \times 10^{-2}$</td>
</tr>
<tr>
<td>$\tilde{c}_{HW}$</td>
<td>$[-0.23, 0.23]$</td>
</tr>
</tbody>
</table>

7. Summary

The strength and structure of the Higgs boson's interactions with other particles have been investigated using an effective Lagrangian. Limits are placed on anomalous CP-even and CP-odd interactions between the Higgs boson and photons, gluons, W-bosons and Z-bosons, using a fit to five differential cross sections previously measured by ATLAS in the $H \to \gamma \gamma$ decay channel at $\sqrt{s} = 8$ TeV [9]. No significant deviations from the SM predictions are observed. To allow a simultaneous fit to all distributions, the statistical correlations between these distributions have been determined by re-analysing the candidate $H \to \gamma \gamma$ events in the proton–proton collision data. These correlations are made publicly [15] available to allow for future analysis of theories with non-SM Higgs boson interactions.

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 also thank B. Fuks and V. Sanz for clarifications and calculations regarding the effective Lagrangian implementation used in this article.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFV and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MPO CR and VSC CR, Czech Republic; DLR, DFG and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNISW and NCN, Poland; FCT, Portugal; MNE/IA, Romania; MES of Russia and NRC KI, Russian Federation; JINR, MESTD, Serbia; MSSR, Slovakia; ARRS, 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, the Canada Council, Canarie, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, Region Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSF; BMBF, GIF and Minerva, Israel; NRF, Norway; the Royal Society and Leverhulme Trust, United Kingdom.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and 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) and in the Tier-2 facilities worldwide.

References


1 Department of Physics, University of Adelaide, Adelaide, Australia
2 Physics Department, SUNY-Albany, Albany, NY, United States
3 Department of Physics, University of Alberta, Edmonton, AB, Canada
4 (a) Department of Physics, Ankara University, Ankara, Turkey; (b) Istanbul Aydin University, Istanbul, Turkey; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey
5 LAPP, CNRS/IN2P3 and Université Savoie Mont Blanc, Annecy-le-Vieux, France
6 High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States
7 Department of Physics, University of Arizona, Tucson, AZ, United States
8 Department of Physics, The University of Texas at Arlington, Arlington, TX, United States
9 Physics Department, University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12 Institut de Física d’Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain
13 Institute of Physics, University of Belgrade, Belgrade, Serbia
14 Department for Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19 (a) Department of Physics, Bogazici University, Istanbul, Turkey; (b) Department of Physics Engineering, Gaziantep University, Gaziantep; (c) Department of Physics, Dogus University, Istanbul, Turkey
20 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston, MA, United States
23 Department of Physics, Brandeis University, Waltham, MA, United States
24 (a) Universidade Federal do Rio de Janeiro COPPE/UFRJ, Rio de Janeiro; (b) Electrical Circuits Department, Federal University ofJuiz de Fora (UFJF), Juiz de Fora; (c) Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; (d) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton, NY, United States
26 (a) Transylvania University of Brasov, Brasov; (b) National Institute of Physics and Nuclear Engineering, Bucharest; (c) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; (d) University Politehnica Bucharest, Bucharest; (e) West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa, ON, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
32 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
33 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) School of Physics, Shandong University, Shandong; (e) Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai; (f) Physics Department, Tsinghua University, Beijing 100084, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington, NY, United States
36 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
37 (a) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; (b) Dipartimento di Fisica, Università della Calabria, Rende, Italy
38 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
39 Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas, TX, United States
41 Physics Department, University of Texas at Dallas, Richardson, TX, United States
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham, NC, United States
46 SUPA – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 (a) INFN Sezione di Genova; (b) Dipartimento di Fisica, Università di Genova, Genova, Italy
51 (a) E. Andreiashivili Institute of Physics, Tbilisi, Georgia; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
53 SUPA – School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom
54 II Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany
55 Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France
56 Department of Physics, Hampton University, Hampton, VA, United States
57 Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, United States
58 (a) Kurchatov-Institut für Physik, Hamburger Hochschule, Hambourg; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany
59 Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
60 (a) Department of Physics, The Chinese University of Hong Kong, Shatin, N.T., Hong Kong; (b) Department of Physics, The University of Hong Kong, Hong Kong; (c) Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China
61 Department of Physics, Indiana University, Bloomington, IN, United States
62 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität Innsbruck, Austria
63 University of Iowa, Iowa City, IA, United States
64 Department of Physics and Astronomy, Iowa State University, Ames, IA, United States
65 Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
66 KER, High Energy Accelerator Research Organization, Tsukuba, Japan
67 Graduate School of Science, Kobe University, Kobe, Japan
68 Faculty of Science, Kyoto University, Kyoto, Japan
69 Kyoto University, Education, Kyoto, Japan
70 Department of Physics, Kyushu University, Fukuoka, Japan
71 Instituto de Fisica de Estructural, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
72 Physics Department, Lancaster University, Lancaster, United Kingdom
73 (a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
74 Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom
75 Department of Physics, Jozef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
76 School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom
77 Department of Physics, Royal Holloway University of London, Surrey, United Kingdom
78 Department of Physics and Astronomy, University College London, London, United Kingdom
79 Louisiana Tech University, Ruston, LA, United States
80 Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
81 Fysiska institutionen, Lunds universitet, Lund, Sweden
82 Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
83 Institut für Physik, Universität Mainz, Mainz, Germany
84 School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
85 CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
86 Department of Physics, University of Massachusetts, Amherst, MA, United States
87 Department of Physics, McGill University, Montreal, QC, Canada
88 School of Physics, University of Melbourne, Victoria, Australia
89 Department of Physics, The University of Michigan, Ann Arbor, MI, United States
90 Department of Physics and Astronomy, Michigan State University, East Lansing, MI, United States
91 (a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano, Italy
92 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Belarus
93 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Belarus
94 Department of Physics, Massachusetts Institute of Technology, Cambridge, MA, United States
95 Group of Particle Physics, University of Montreal, Montreal, QC, Canada
96 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
97 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
98 National Research Nuclear University MEPhI, Moscow, Russia
99 D.V. Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
100 fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
101 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
102 Nagaoka Institute of Applied Science, Nagaoka, Japan
103 Graduate School of Science and Kobayashi–Maskawa Institute, Nagoya University, Nagoya, Japan
104 (a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli, Italy
105 Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, United States
106 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
107 Nikhef National Institute for Subatomic Physics and University Institute for Amsterdam, Amsterdam, Netherlands
108 Department of Physics, Northern Illinois University, DeKalb, IL, United States
109 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
110 Department of Physics, New York University, New York, NY, United States
111 Ohio State University, Columbus, OH, United States
112 Faculty of Science, Okayama University, Okayama, Japan
113 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, United States
114 Department of Physics, Oklahoma State University, Stillwater, OK, United States
115 Palacký University, RCP, Olomouc, Czech Republic
116 Center for High Energy Physics, University of Oregon, Eugene, OR, United States
117 LAT, Université Paris-Sud and CNRS/IN2P3, Orsay, France
118 Graduate School of Science, Osaka University, Osaka, Japan
119 Department of Physics, University of Oslo, Oslo, Norway
120 Department of Physics, Oxford University, Oxford, United Kingdom
121 (a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia, Italy
122 Department of Physics, University of Pennsylvania, Philadelphia, PA, United States
123 National Research Center “Kurchatov Institute”, B.P. Konstantinov Petersburg Nuclear Physics Institute, St. Petersburg, Russia
124 (a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
125 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, United States
126 (a) Laboratório de Instrumentação e Física Experimental de Partículas – LIP, Lisboa; (b) Faculdade de Ciências, Universidade de Lisboa, Lisboa; (c) Department of Physics, University of Coimbra, Coimbra; (d) Centro de Física Nuclear da Universidade de Lisboa, Lisboa; (e) Departamento de Fisica, Universidade do Minho, Braga; (f) Departamento de Física Teórica y del Cosmos and CAFFE, Universidade de Granada, Granada (Spain); (g) Dep Fisica y CEITIF de Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
127 Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
128 Czech Technical University in Prague, Prague, Czech Republic
129 Faculty of Mathematics and Physics, Charles University in Prague, Prague, Czech Republic
130 State Research Center Institute for High Energy Physics, Protvino, Russia
131 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
132 (a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
133 (a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica di Roma Tor Vergata, Roma, Italy
134 (a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy
135 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies – Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucléaires, Rabat; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPIE-Marrakech; (d) Faculté des Sciences, Université Mohamed Premier et LPTPM, Oujda; (e) Faculté des Sciences, Université Mohammed V, Rabat, Morocco
136 DSMR/P3 (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France
137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, United States
138 Department of Physics, University of Washington, Seattle, WA, United States
139 Department of Physics and Astronomy, University of Shef feld, Sheffield, United Kingdom
140 Department of Physics, Shinshu University, Nagano, Japan
141 Fachbereich Physik, Universität Siegen, Siegen, Germany
142 Department of Physics, Simon Fraser University, Burnaby, BC, Canada
143 SLAC National Accelerator Laboratory, Stanford, CA, United States