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Submitted to: Phys. Lett. B.

CERN-EP-2024-261
26th November 2024

Search for Higgs boson decays into a Z boson and a light hadronically decaying resonance in 140 fb^{-1} of 13 TeV pp collisions with the ATLAS detector

The ATLAS Collaboration

A search for decays of the Higgs boson into a Z boson and a light resonance, with a mass of 0.5–3.5 GeV, is performed using the full 140 fb^{-1} dataset of 13 TeV proton–proton collisions recorded by the ATLAS detector during Run 2 of the LHC. Leptonic decays of the Z boson and hadronic decays of the light resonance are considered. The resonance can be interpreted as a J/ψ or η_c meson, an axion-like particle, or a light pseudoscalar in two-Higgs-doublet models. Due to its low mass, it would be produced with high boost and reconstructed as a single small-radius jet of hadrons. A neural network is used to correct the Monte Carlo simulation of the background in a data-driven way. Two additional neural networks are used to distinguish signal from background. A binned profile-likelihood fit is performed on the final-state invariant mass distribution. No significant excess of events relative to the expected background is observed, and upper limits at 95% confidence level are set on the Higgs boson's branching fraction to a Z boson and a light resonance. The exclusion limit is ~10% for the lower masses, and increases for higher masses. Upper limits on the effective coupling $C^{\text{eff}}_{ZH}/\Lambda$ of an axion-like particle to a Higgs boson and Z boson are also set at 95% confidence level, and range from 0.9 to 2 TeV^{-1}.

Contents

1 Introduction

Since its discovery in 2012 [1, 2], the Higgs boson has been studied intensively by the ATLAS and CMS experiments at the CERN Large Hadron Collider (LHC) [3]. So far, all of its measured properties have been found to be consistent with the predictions of the Standard Model (SM) [4, 5]. The expected value in the SM for the total decay-width of the Higgs boson is 4.1 MeV [6]. However, the limited precision of the measurement ($4.5^{+3.0}_{-2.5}$ MeV [7], $3.2^{+2.4}_{-1.7}$ MeV [8]) still allows significant contributions from 'beyond the SM' (BSM) decays. Because the decay width is so small, even a small coupling to a non-SM particle could result in new decay modes with large branching fractions. These decays are very interesting because several models predict additional particles that address limitations of the SM, for example the nature of dark matter or the strong CP problem. The most restrictive upper limits at 95% confidence level (CL) on the Higgs branching fractions to invisible or undetected decays are 13% [4] and 11% [9], respectively.

One of the simplest extensions of the SM is the two-Higgs-doublet model (2HDM) [10, 11], which introduces a second Higgs doublet, allowing the presence of additional lighter Higgs bosons. For some parameter values in both the 2HDM and the 2HDM with an additional singlet (2HDM+S) [12, 13], the additional particles can have large couplings to the observed Higgs boson. The two Higgs doublets in these models are also needed to generate the fermion and boson masses in the Minimal Supersymmetric Standard Model (MSSM) [14] and next-to-MSSM (NMSSM) [15]. The extension of the MSSM to the NMSSM with this additional scalar field can solve the μ-problem of the MSSM [16], and greatly reduces the fine-tuning and little-hierarchy problems.

Axions and axion-like particles (ALPs) are other well-known light resonances predicted by theoretical models [17, 18]. Axions were initially introduced to address the strong CP problem [19], but ALPs are of much wider interest. They are one of the leading dark-matter candidates [20] and could also explain the observed tension between the theoretical prediction and the measured magnetic moment of the muon [21].

There has recently been increasing interest in light-resonance (a) decays of the Higgs boson. Both ATLAS and CMS have published several results, most of them focusing on masses of O(1-10 GeV), pairs of a-resonances ($H \to aa$), and leptonic/photonic decays of the a-resonance [22–24].

However, in both the 2HDM(+S) and axion models certain assumptions can lead to dominant decay modes that are hadronic. For instance, in the type-II 2HDM+S, assuming $\tan\beta = 1$, the branching fraction $\mathcal{B}(a \to gg)$ exceeds 85% for masses up to 3 GeV [25]. Similarly, for an ALP with Wilson coefficients equal to 1, the branching fraction for decays into gluons is almost 100% for masses greater than 3 GeV, and decays into pions are significant for masses up to 1 GeV [18].

A light scalar resonance, with a mass of up to a few GeV, originating from a Higgs boson decay can be also interpreted within the SM. For example, $c\bar{c}$ mesons such as η_c and J/ψ (Q) have masses ~3 GeV and decay mostly into hadrons, with $\mathcal{B} \sim 85\%$. However, their production through $H \to ZQ$ is suppressed and the expected branching fractions are of the order of 10^{-5} and 10^{-6} for η_c and J/ψ respectively [26].

This analysis focuses on the $H \to Za$ decay, utilizing leptonic decays of the Z boson for event triggering [27]. It specifically targets a low-mass (≤4 GeV) hadronically decaying a-resonance from the $H \to Za$ process. It supersedes the initial version of the analysis published in 2020 [28], and aims to address the primary limitation of that study: the background modelling uncertainty. The present analysis incorporates a novel neural-network approach to improve the background modelling, leading to significantly stronger exclusion limits, and includes several additional methodological upgrades. Moreover, an axion interpretation is included, resulting in the exclusion of a range of Higgs-Z-a effective coupling values.

2 ATLAS detector

The ATLAS experiment [29] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer. The inner tracking detector covers the pseudorapidity range $|\eta| < 2.5$. It consists of silicon pixel, silicon microstrip, and transition radiation tracking detectors. Lead/liquid-argon (LAr) sampling calorimeters provide electromagnetic (EM) energy measurements with high granularity within the region $|\eta| < 3.2$. A steel/scintillator-tile hadronic calorimeter covers the central pseudorapidity range ($|\eta| < 1.7$). The endcap and forward regions are instrumented with LAr calorimeters for EM and hadronic energy measurements up to $|\eta| = 4.9$. The muon spectrometer surrounds the calorimeters and is based on three large superconducting air-core toroidal magnets with eight coils each. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. The muon spectrometer includes a system of precision tracking chambers up to $|\eta| = 2.7$ and fast detectors for triggering up to $|\eta| = 2.4$. The luminosity is measured mainly by the LUCID–2 [30] detector, which is located close to the beampipe. A two-level trigger system is used to select events [31]. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz

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

on average depending on the data-taking conditions. A software suite [32] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3 Data and simulated event samples

This search uses the entire Run 2 proton–proton (pp) collision dataset recorded by the ATLAS detector at the LHC between 2015 and 2018. The dataset corresponds to an integrated luminosity of 140 fb^{-1} [33] at a pp centre-of-mass energy of $\sqrt{s}$ = 13 TeV. The data are required to satisfy criteria that ensure that the detector was in good operating condition [34].

Samples of Monte Carlo (MC) simulated signal events ($gg \to H \to Za \to \ell\ell gg$ or $\ell\ell q\bar{q}$) are generated via the gluon–gluon fusion (ggF) process using Powheg Box v2 [35–37] and the PDF4LHC15nnlo next-to-next-to-leading-order (NNLO) parton distribution function (PDF) set [38]. The simulation achieves NNLO accuracy for arbitrary inclusive $gg \to H$ observables by reweighting the Higgs boson rapidity spectrum in H_J−MiNLO [39–41] to that in HNNLO [42]. The samples are normalized to match the total Higgs boson production cross-section of 55.6 pb (for a mass of 125.09 GeV) at $\sqrt{s}$ = 13 TeV [42] because the event acceptance for ggF production is similar to that for other Higgs boson production processes.

Particle decays, hadronization, parton showers and the underlying event in the signal samples are modelled with Pythia 8.212 [43] and EvtGen 1.6.0 [44], using a set of tuned parameters called the A14 tune [45] and the NNPDF23lo PDF set [46]. The branching fractions of the a resonance are determined using the Pythia 8 MSSM scenario with two Higgs doublets, which predicts $a \to gg$ to be the dominant decay mode until $a \to c\bar{c}$ becomes kinematically accessible. The signal MC samples used in this analysis have a-resonance masses covering the range 0.5–4 GeV. The Z boson is required to decay into a pair of electrons, muons, or τ-leptons. Two dedicated samples with η_c or J/ψ decays ($H \to Z\eta_c$ or ZJ/ψ) are also simulated using Pythia 8. An alternative set of signal samples where Herwig 7.1 [47] is used to model the parton shower and hadronization is produced to estimate the uncertainties associated with the modelling of the $a \to$hadrons decay.

The background in this analysis is dominated by Z + jets events. It is modelled in the same way as the signal samples, using Powheg and Pythia+EvtGen for event generation and showering. The CTEQ6L1 PDF set [48] and the AZNLO tune of Pythia 8 are used. The Z + jets events can also be modelled with Sherpa 2.2.1 [49], using the NNPDF3.0nnlo PDF set [50] for the modelling of the hard interaction and parton shower. In this case, the inclusive production cross-sections are known to NNLO in QCD [51]. The Powheg sample is chosen because it is larger than the Sherpa sample. Only samples with $Z \to ee$ or $Z \to \mu\mu$ decays are considered. An additional ~5% contribution from $Z \to \tau\tau$ decays is effectively taken into account by including the Z boson's transverse momentum among the background reweighting variables, as described in Section 5.

The ZZ and ZW processes constitute small (<1%) backgrounds in this analysis. They are modelled with Sherpa 2.2.1, using the NNPDF3.0nnlo PDF set. The $t\bar{t}$ process also produces a small (<1%) background in this analysis. For the $t\bar{t}$ background, the hard interaction is modelled using Powheg, while the decay, hadronization, parton shower and underlying event are modelled using Pythia 8 and EvtGen. The above-mentioned processes constitute the total background in this analysis.

The simulated event samples also include a GEANT4-based simulation of the ATLAS detector and its response [52, 53], and the effect of other pp interactions in either the bunch crossing containing the hard interaction or neighbouring ones.

4 Event selection

The low-mass signal resonance is highly boosted due to the relatively large kinetic energy imparted to it because of the sizeable mass difference between the Higgs boson and Z boson. It is therefore reconstructed as a single small-radius ($R = 0.4$) jet using particle flow objects [54] as input to the anti-k_t algorithm [55, 56].

Jets are calibrated such that the average detector-level jet energy scale (JES) matches that of the corresponding particle-level jets, using a combination of simulation-based and in situ techniques [57]. They are required to have $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.5$, and satisfy a jet cleaning requirement [58]. To reject jets from pile-up interactions, jets with $p_{\mathrm{T}} < 60$ GeV and $|\eta| < 2.4$ are required to pass a *Tight* 'jet vertex tagger' [59] requirement.

Jet substructure variables are built using tracks matched to the calorimeter jet by ghost association [60]. In this method the tracks are included in the jet clustering process with negligible energy so that they do not influence the jet's kinematic properties. These tracks must have $p_{\mathrm{T}} > 500$ MeV and $|\eta| < 2.5$, and satisfy loose quality criteria and track-to-vertex matching requirements [61] to reject fake tracks from the reconstruction and tracks from pile-up, respectively.

Electron candidates are reconstructed by matching tracks in the inner detector to topological energy clusters in the electromagnetic calorimeter [62]. Muons are reconstructed using tracks in the muon spectrometer, matched to tracks in the inner detector if available [63]. Electrons and muons are required to satisfy *Loose* identification and *Loose* isolation criteria, to have transverse momentum $p_{\mathrm{T}} > 18$ GeV, and at least one must have $p_{\mathrm{T}} > 27$ GeV and be reconstructed within $|\eta| < 2.47$ (e) or $|\eta| < 2.7$ (μ) (but electrons within $1.37 < |\eta| < 1.52$ are excluded). An inner-detector track associated with an electron (muon) must have a transverse impact parameter significance $d_0/\sigma_{d_0} < 5\,(3)$ relative to the beamline, and a longitudinal impact parameter z_0 satisfying $|z_0 \sin(\theta)| < 0.5$ mm. An overlap removal procedure resolves cases in which multiple electrons, muons or jets are reconstructed from the same detector signature.

Events are selected by a combination of single-electron or single-muon triggers for each data-taking period [64–66], and the lepton reconstructed online by the trigger is required to be within $\Delta R = 0.1$ of an offline reconstructed lepton. Events are required to have at least one reconstructed primary interaction vertex [67]. At least two same-flavour opposite-charge electrons or muons are required to pass this selection, and have an invariant mass compatible with the mass of the Z boson: $81 < m_{\ell\ell} < 101$ GeV. If multiple same-flavour opposite-sign lepton pairs fulfil this requirement, the pairing with an invariant mass closest to that of the Z boson is chosen. A small fraction of the $Z \to \tau^+\tau^-$ decays can pass the selection if the two τ-leptons decay to leptons of the same flavour. Higgs boson candidates are reconstructed from the lepton pair and jet system ($\ell\ell j$), which is required to have an invariant mass passing a loose preselection requirement: $m_{\ell\ell j} < 250$ GeV. If multiple jets satisfy these requirements, the jet with the highest p_{T} is selected. The jet is required to have at least two ghost-associated tracks.

5 Background reweighting

Neither Powheg nor Sherpa model the main $Z +$jets accurately enough. A classifier ($C(x)$) is known to be able to approximate the density ratio of two datasets when trained to distinguish between them, $p_1(x)/p_2(x) \approx C(x)/(1 - C(x))$ [68]. In line with this approach, a neural network (NN) is trained to estimate the multidimensional density ratio of the total-background to data, with the goal of simultaneously improving the modelling of jet substructure and event kinematic variables. Its output is transformed into an additional weight for each MC event in order to equalize the two density functions. Events falling in the region $120 < m_{\ell\ell j} < 140$ GeV, where the most of the signal is expected, are excluded from the training. Any signal contamination outside this region is negligible. The NN is able to reweight events in the excluded region effectively.

The training variables consist of event kinematic variables (final-state invariant mass and transverse momentum, and dilepton and jet transverse momenta) and jet substructure variables. Seven dimensionless variables, constructed from the jet's ghost-associated tracks, are chosen to capitalize on the presence of a narrow jet or two-pronged substructure in the jet's track system: the number of tracks; the ratio of the p_{T} of the highest-p_{T} track to the p_{T} of the track system; the angular separation ΔR between the highest-p_{T} track and the jet axis; N-subjettiness τ_N [69] (with $N = 2$, exclusive-k_t-subjet axes with radius parameters of 0.2, and a jet-axis radius parameter of 0.4), which is an effective discriminating variable for tagging boosted objects; angularity ($\tilde{\tau}_{-2}$) [70], which quantifies how the energy of the jet is distributed relative to the jet axis; and U_1 (with $\beta = 0.7$) and M_2 (with $\beta = 0.3$), which are modified energy correlation functions [71] designed for quark–gluon discrimination and to target two-pronged substructure, respectively.

The reweighting NN is a simple feed-forward network designed and trained using Keras [72]. The hyperparameter optimization uses a mixture of various methods. First, an exponential loss function for log-likelihood-ratio estimation [73] is used along with a hyperbolic tangent function ($8 \tanh x$) which limits the maximum output of the last neuron. Second, the ReLU neuron activation function, typically suggested for feed-forward NNs, is used. For the loss minimizer, stochastic gradient descent was chosen over adaptive moment estimation (Adam) because it provides more flexibility to tune its internal parameters. The number of layers (3), the number of neurons per layer (100), the learning rate (0.11), the decay rate (0.001), the momentum (0.975) and the batch size (200) are chosen via probabilistic Bayesian optimization. The goal of Bayesian optimization is to minimize the error function $f(x)$, which is a measure of the algorithm's mismodelling as a function of the hyperparameters. The set of hyperparameters is chosen with the use of Bayesian statistics for the prior and the observations. The optimization is implemented with the *Hyperopt* library and the Tree-structured Parzen Estimator algorithm [74]. This strategy reaches optimal performance significantly more quickly than other approaches such as random or grid searches. The training ends when the validation loss stops improving (with 10-epoch patience) and the epoch with the best value is chosen (epoch 50). Finally, the events are reweighted with an appropriate factor arising from the NN output. The final-state invariant mass and three other variables used in the reweighting are shown in Figure 1.

6 Signal–to–background discrimination

After the initial event selection, two NNs are used to further suppress the background. First, a *regression* NN is used to estimate the mass of the a-resonance, and second, a *classification* NN is used to discriminate between signal and background. The reconstructed jet mass has quite poor resolution for such low-energy jets and it cannot inform the classifier where a specific event lies in the hadronic resonance mass spectrum.

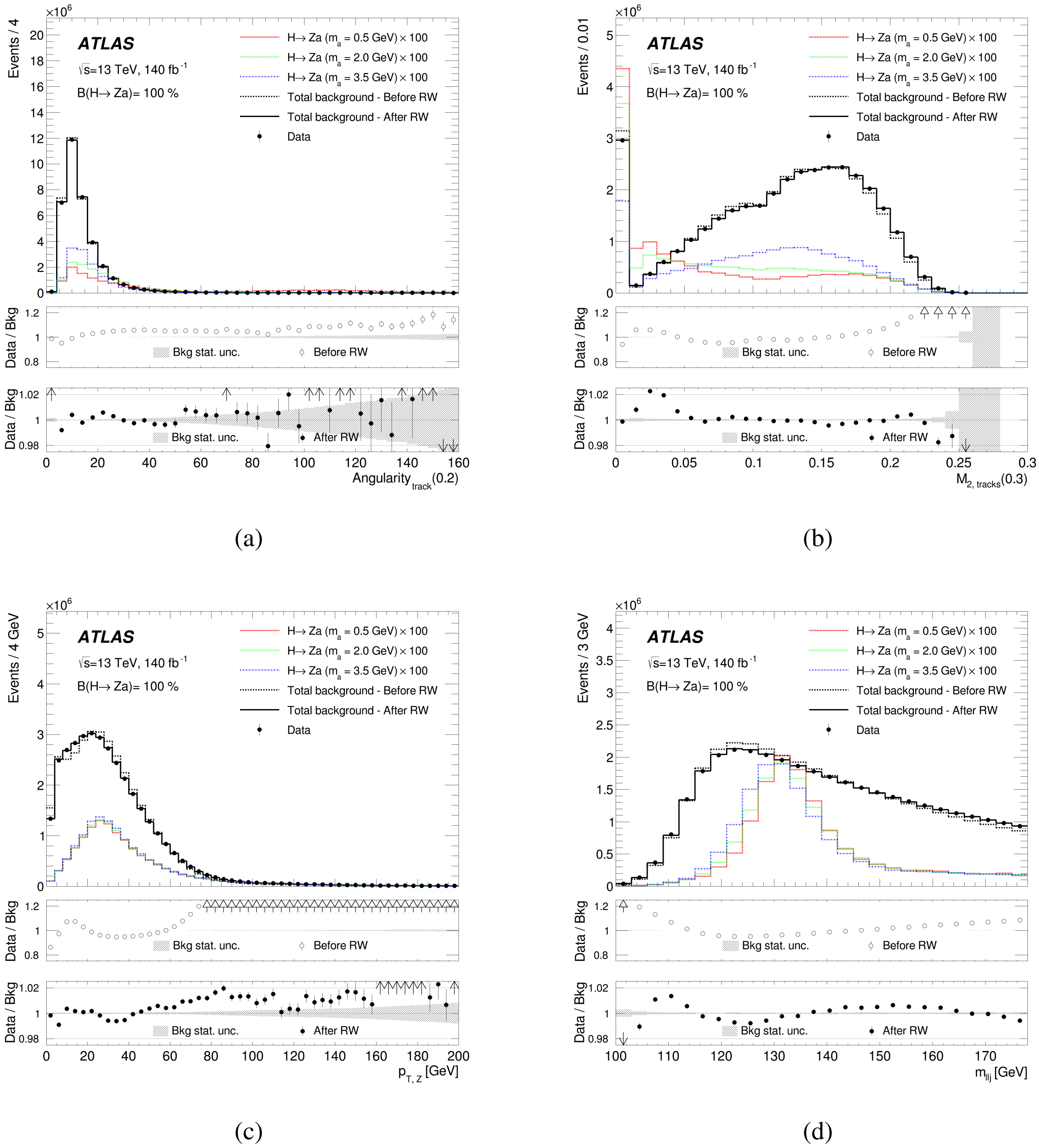


Figure 1: The (a) angularity, (b) modified energy correlation function, (c) Z boson transverse momentum, and (d) invariant mass of the lepton pair plus jet system, for data, background (pre- and post-reweighting) and three $H \to Za$ signal hypotheses (for $a \to q\bar{q}/gg$ inclusively). Events are required to pass the complete event selection but not the classification NN requirement. The background normalization is set equal to that of the data for events passing the preselection and being in the $m_{\ell\ell j}$ 100–180 GeV region. The signal normalization assumes the SM Higgs boson inclusive production cross-section, $\mathcal{B}(H \to Za) = 100\%$, and it is scaled up by a factor of 100. The error bars (hatched regions) represent the data (MC) sample's statistical uncertainty in the histograms and the ratio plots. Vertical arrows indicate data points that fall outside the displayed y-axis range.

Therefore, the regression NN is trained with the seven jet substructure variables to estimate the mass of the resonance (two of the variables are shown in Figures 1(a) and 1(b)). Its output in Figure 2(a) differentiates between the various signal hypotheses significantly better than the jet mass. It is then provided along with the values of the same seven variables to the classification NN. The regression-NN strategy is preferable to other commonly used approaches (e.g. a parameterized NN using the generator-level resonance mass) as it allows the analysis to be conducted with a single classification NN and a single background model, without a significant decrease in performance.

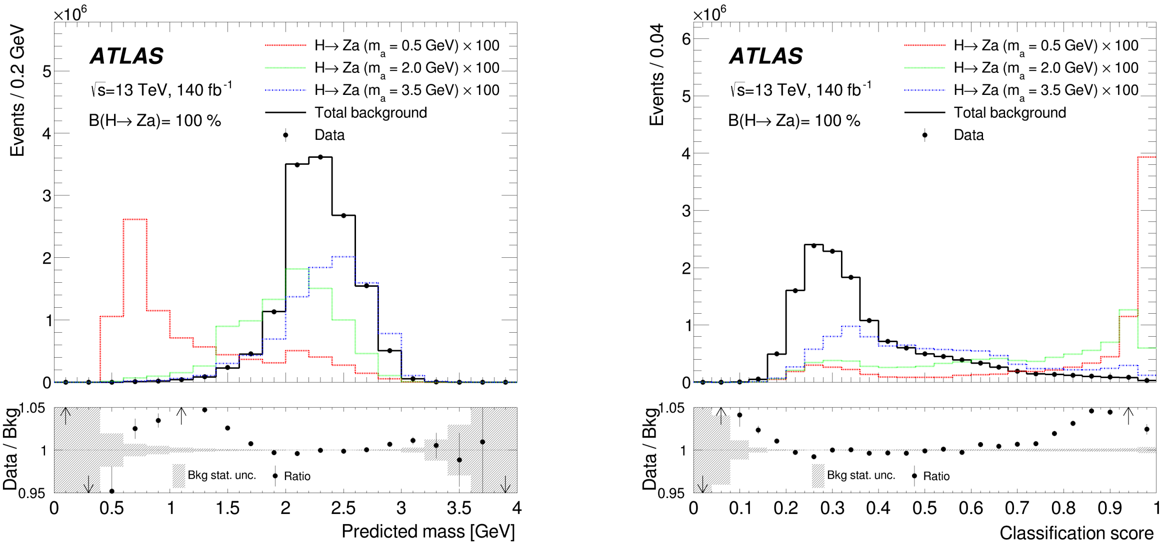
The regression NN is trained on nine different signal-hypothesis samples ranging from 0.5 to 4 GeV in steps of 0.5 GeV. The classification NN is trained with all the signal hypotheses against the total background. Both the quark and gluon decay modes are included and their relative contributions come from the MSSM scenario mentioned in Section 3. The fraction of gg decays varies from 97% to 6% for masses of 0.5 to 4 GeV and the $q\bar{q}$ decay fraction varies correspondingly from 0% to 56%. The hyperparameter optimization follows the same methodology as used for the reweighting, encompassing typically suggested functions, self-optimizing algorithms and Bayesian optimization. Both the NN performance and the level of MC–data agreement (χ^2 test) for the output distributions are taken into account to select the best set. The optimized hyperparameter values for the regression / classification NN are as follows: number of layers (4 / 3), number of neurons per layer (35 / 10), neuron activation function (ReLU / ReLU), output function (linear / sigmoid), loss function (Huber / binary cross-entropy), loss minimizer (Adam / Adam), batch size (160 / 100), regularization (R2, 10^{-11} / R2, 10^{-10}) and epochs (50 / 29). Figure 2 shows the regression and classification NN output variables for the reweighted background, the data and three signal hypotheses.

Although the NNs are trained with a mixture of $a \to gg$ and $a \to q\bar{q}$ decays (with different branching fractions), their performance is generally similar for the two cases. Their performance is poorer for the higher masses, where a-resonance decays tend to have higher track multiplicity, making the hadronic decay appear similar to background jets. This is reflected in the distributions of jet substructure training variables, which are indeed very similar for higher-mass signals and background in Figures 1(a) and 1(b). The $a \to c\bar{c}$ decay mode becomes dominant in the 4 GeV sample, leading to quite different kinematics and much poorer NN performance. Consequently, the 4 GeV $a \to q\bar{q}$ case is omitted from the final results.

A single threshold requirement is placed on the classification NN's output variable to reject background events for all signal hypotheses. The threshold value is chosen to be 0.93, which rejects 99.3% of the background for a signal efficiency of more than 30% for $m_a = 0.5$ GeV, ~10% for $m_a = 2$ GeV, and ~3% for $m_a = 3.5$ GeV. Although this threshold value is not optimal for the higher masses, it allows a single background model to be used. Events passing the classification NN selection populate the signal region (SR). The MC expected yields for the reweighted background, three signal hypotheses and the data in the SR are shown in Figure 3(a).

7 Statistical model

A measure of the signal strength is extracted for each given signal hypothesis using a binned maximum-likelihood fit [75] to the distribution of the final-state invariant mass $m_{\ell\ell j}$ in the range 100–178 GeV, as shown in Figure 3(b). The signal strength is translated to $\mathcal{B}(H \to Za)$ assuming $\mathcal{B}(a \to gg) = 100\%$ or $\mathcal{B}(a \to q\bar{q}) = 100\%$. Systematic uncertainties are included in the fit as nuisance parameters which modify the signal and background model and they are implemented as Gaussian constraints on the nominal values.

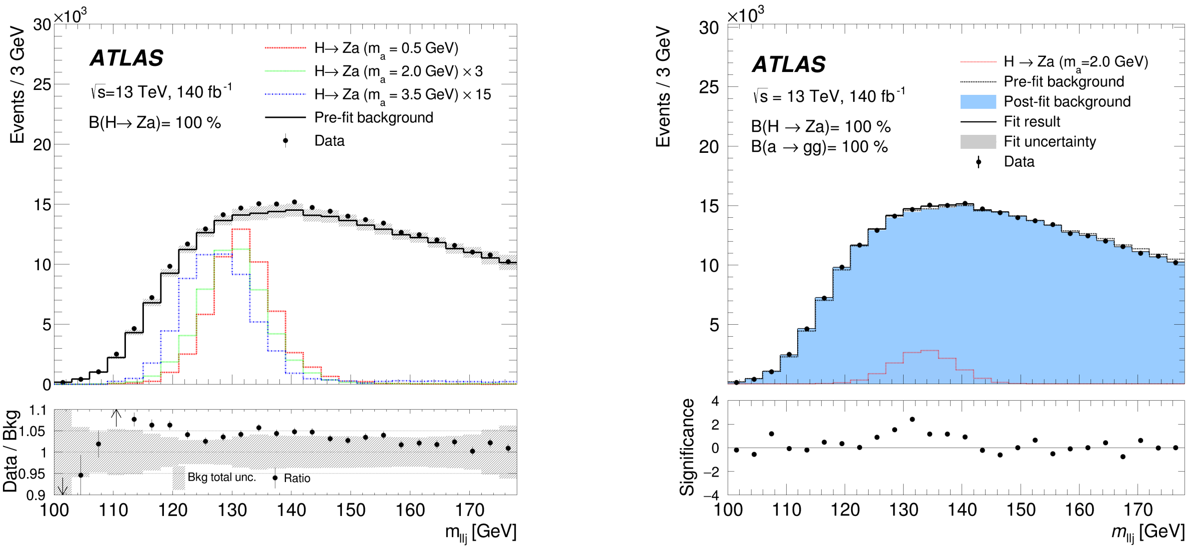


(a) (b)

Figure 2: The (a) regression and (b) classification NN output variables for data, reweighted background, and three $H \to Za$ signal hypotheses ($a \to q\bar{q}/gg$ inclusively). Events are required to pass the complete event selection, including a $120 < m_{\ell\ell j} < 140$ GeV requirement, but not the classification NN output variable requirement. The background normalization is set equal to that of the data for events passing the preselection and being in the $m_{\ell\ell j}$ 100–180 GeV region. The signal normalization assumes the SM Higgs boson inclusive production cross-section, $\mathcal{B}(H \to Za) = 100\%$, and it is scaled up by a factor of 100. The error bars (hatched regions) represent the data (MC) sample's statistical uncertainty in the histograms and the ratio plots. Vertical arrows indicate data points that fall outside the displayed y-axis range.

The signal model is produced from a simple Gaussian fit with mean μ and width σ of the MC-simulated $m_{\ell\ell j}$ distribution. Different (μ, σ) values are obtained for each mass point and decay mode ($a \to gg/q\bar{q}$). The signal's mean (μ) shifts from 125 GeV for $m_a = 4$ GeV to 131.5 GeV for $m_a = 0.5$ GeV. This mass dependence is expected, as higher masses result in less collimated jets, causing some energy to fall outside the jet cone. Additionally, the jet calibration is not optimized for such low energies, contributing to the shift in the mean. A mean value around 1 GeV higher is observed for $a \to gg$ decays. The signal's width (σ) of 5.0–5.5 GeV varies little with the decay mode or m_a value. For the background the reweighted MC shape is used.

Systematic uncertainties are the dominant source of uncertainty for this analysis. For the signal, both the theory and experimental uncertainties are considered. The experimental uncertainties come from the jet reconstruction, and the lepton reconstruction, identification, isolation and track-to-vertex matching, as well as from the pile-up distribution and the triggering. The jet uncertainties (energy scale and resolution) are found to have the largest effect. The experimental uncertainties are expected to mostly affect the signal distribution (Gaussian μ and σ) and they result in a combined uncertainty of about 1.0 GeV for both μ and σ ($\Delta\mu = 1.1$ GeV and $\Delta\sigma = 0.7$ GeV). Theory uncertainties in parton showering and hadronization are estimated by comparing the nominal Pythia MC signal samples with alternative Herwig samples. The Herwig samples are produced separately for $a \to gg$ and $a \to q\bar{q}$, but only for masses greater than 2 GeV due to Herwig technical specifications. The uncertainties are extrapolated to the lower masses. They affect the Gaussian mean (μ), resulting in $\Delta\mu = 0.5$–2.5 GeV, but their effect on the Gaussian width is minor. In



(a) (b)

Figure 3: Invariant mass of the lepton pair plus jet system for data, reweighted background, and various signal hypotheses. Events are required to pass the complete event selection (preselection and classification NN requirement). In (a) the pre-fit background distribution is shown along with three $H \rightarrow Za$ signal hypotheses coming from the pure MC sample ($a \rightarrow q\bar{q}/gg$ inclusively). The background normalization is set equal to that of the data for events passing the preselection and being in the region 100–180 GeV. In (b) the background shape and normalization come from the fit to the data. The signal includes only gg decays, its shape comes from the fit, and it is normalized to $\mathcal{B}(H \rightarrow Za) = 100\%$. The error bars represent the data sample's statistical uncertainty and the grey bands represent the full background model uncertainty, (a) before the fit (assuming all the uncertainties are uncorrelated) and (b) after the fit. The lower panels show (a) the ratio of the data to the pre-fit background prediction and (b) the per-bin signal significance with respect to the post-fit background, $(N_{\text{data}} - N_{\text{bkg}}) \big/ \sqrt{\sigma^2_{\text{data}} + \sigma^2_{\text{bkg}}}$. The post-fit background uncertainty is calculated from a fit under the background-only hypothesis. Vertical arrows indicate data points that fall outside the displayed y-axis range.

general, the effect on μ tends to decrease for higher masses and it is ~1 GeV larger for gg decays than for $q\bar{q}$ decays. More importantly, the theory uncertainties affect the classification NN's efficiency, which leads to a quite large uncertainty in the expected number of events, about 60% for $a \rightarrow gg$ and about 25% for $a \rightarrow q\bar{q}$. This is the most significant uncertainty for this analysis, and it is due to Pythia generally decaying the a-resonance with lower multiplicity than Herwig. The NN is particularly effective in identifying two-track jets, and these are more common in the Pythia samples. For η_c and J/ψ uncertainties from the $m_a = 3.0$ GeV model are used. In addition, a total Higgs boson production cross-section uncertainty of $^{+5.6\%}_{-7.4\%}$ is included [6].

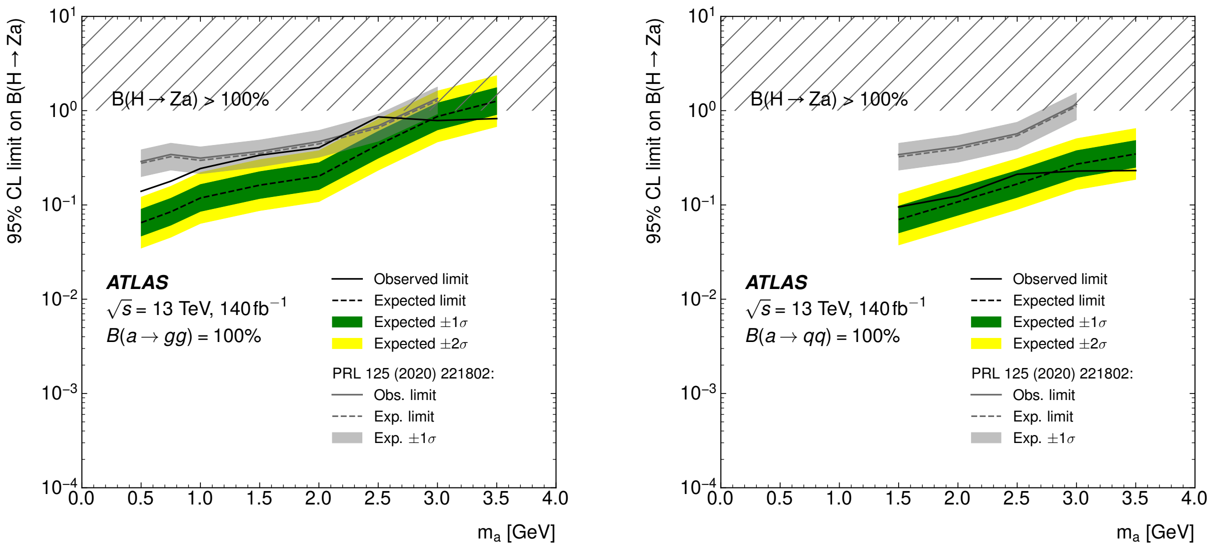
Five kinds of uncertainties incorporate all the possible reweighting performance, experimental and theory uncertainties in the background modelling. All of them are included in the fit as alternative shapes for the background distribution. For the NN performance, two uncertainties are considered. The first is estimated from a control region (CR) that includes the same number of background events as the SR. It is defined by changing the classification NN requirement from >0.93 (SR) to 0.883–0.93. For any reasonable $H \rightarrow Za$ branching fraction (<20%), the resulting signal contamination has a negligible effect in the shape of the systematic distribution produced in the CR. The ratio of data events to MC events in this region is used to derive a shape systematic uncertainty. The second is estimated using a bootstrapping method. Ten replicas of the original MC and data event samples are created by weighting each event with a random Poisson($\mu = 1$) number. For each replica a reweighting NN is trained, and a systematic uncertainty distribution is built from the bin-by-bin standard deviations in the SR. The main sources of experimental uncertainty are the jet energy scale and resolution. MC samples are produced with corresponding scale and resolution variations, their predictions are reweighted using the nominal model, and the resulting shape differences are used. Other experimental uncertainties, such as tracking uncertainties, are found to be insignificant. The effect of theory uncertainties in the parton showering and hadronization are estimated by using the alternative SHERPA Z + jets sample. A second reweighting NN is trained using this sample, with the same input variables and training procedure as for the nominal POWHEG sample. The ratio of the distributions in the SR is used as an additional systematic uncertainty. The MC statistical uncertainty is also taken into account.

Finally, a luminosity uncertainty is included. The uncertainty in the combined 2015–2018 integrated luminosity is 0.83% [33], obtained using the LUCID-2 detector [30] for the primary luminosity measurements, complemented by measurements using the inner detector and calorimeters.

8 Results and interpretations

Hypotheses with signal mean greater than ~130 GeV (corresponding to $m_a = 0.5-2.5$ GeV and $a \rightarrow gg$) accommodate the slight excess of events observed in data for $m_{\ell\ell j}$ around 135 GeV and create a potential small signal as shown in Figure 3(b). Conversely, if the signal mean is lower, the data are more compatible with the background only hypothesis. The largest local significance is $\sim 1.5\sigma$ and it is observed for $m_a = 0.5$ GeV in the $a \rightarrow gg$ scenario. Upper limits at 95% CL are set on $\mathcal{B}(H \rightarrow Za)$ for the various signal hypotheses, using the profile-likelihood test statistic [75] and the CL_S technique [76]. The observed and expected upper limits for $a \rightarrow gg$ and $a \rightarrow q\bar{q}$ are shown in Figure 4, in comparison to the limits from Ref. [28]. For $a \rightarrow q\bar{q}$, only decays to the heaviest possible quarks are considered. The slight excess around 135 GeV mentioned above, causes the observed limits to be higher than the expected limits for cases where the signal mean is greater than ~130 GeV. The expected limits are generally more restrictive for $a \rightarrow q\bar{q}$ because of the lower signal theory uncertainty.

Limits are also set on $H \rightarrow Z\eta_c$ and $H \rightarrow ZJ/\psi$ decays; however, the analysis has limited sensitivity for these cases and cannot exclude any physical branching fraction (it excludes $\mathcal{B}(H \rightarrow Z\eta_c) > 1.2$ and $\mathcal{B}(H \rightarrow ZJ/\psi) > 1.4$). Finally, ALP decay rates can be obtained by assuming the effective Wilson coefficients (determining the coupling strength to various particles) are equal to 1 [18]. For ALP masses of 0.5–1 GeV the 3π decay mode is one of the leading ones. However, the analysis is not sensitive to the $3\pi^0$ decay mode, due to the lack of inner-detector tracks. For $\mathcal{B}(a \rightarrow \pi^+\pi^-\pi^0) = 0.10$ (0.20) and $m_a = 0.5$ GeV (1 GeV), the upper limit on $\mathcal{B}(H \rightarrow Za)$ is 0.45 (0.81). This can be used to exclude values of the effective coupling $C_{ZH}^{\text{eff}}/\Lambda$ of the candidate axion to the Higgs and Z bosons. At 95% CL, $C_{ZH}^{\text{eff}}/\Lambda < 2.0$ TeV^{-1} for $m_a = 0.5$ GeV and $C_{ZH}^{\text{eff}}/\Lambda < 0.89$ TeV^{-1} for $m_a = 1$ GeV.



(a) (b)

Figure 4: Observed 95% CL upper limits on $\mathcal{B}(H \to Za)$ for (a) $\mathcal{B}(a \to gg) = 100\%$ and (b) $\mathcal{B}(a \to q\bar{q}) = 100\%$, and the expectation under the background-only hypothesis together with its $\pm 1\sigma$ and $\pm 2\sigma$ intervals. The weaker limits from the previous version of the analysis [28] are also shown. Linear interpolation is used to set limits between the mass points for which MC signal samples were generated.

9 Conclusions

A search for Higgs boson decays into a Z boson and a light resonance of mass 0.5–3.5 GeV is performed using 140 fb^{-1} of proton—proton collisions at $\sqrt{s} = 13$ TeV recorded by the ATLAS detector at the LHC. The search considers leptonic decays of the Z boson and hadronic decays of the light resonance that are collimated into a single small-radius jet. Separate neural networks are used to improve the modelling of the simulated background, and to discriminate signal from background. A binned profile-likelihood fit is performed on the invariant mass of the dilepton-plus-jet system. No significant excess above the Standard Model background prediction is found and upper limits at 95% confidence level are set on the branching fraction for $H \to Za$, where a is a light pseudoscalar, as a function of its mass m_a, separately for the $a \to gg$ and $a \to q\bar{q}$ scenarios. Compared to a previous ATLAS search using the same dataset, the innovative techniques used in this analysis allow to improve the branching fraction limits by a factor of up to two (three) in the case of $a \to gg$ ($a \to q\bar{q}$). Upper limits are also set on the branching fractions for $H \to Z\eta_c$ and $H \to ZJ/\psi$, and on the effective coupling of an axion-like particle to the Higgs boson and Z boson ($C^{\text{eff}}_{ZH}/\Lambda$).

Acknowledgements

We thank CERN for the very successful operation of the LHC and its injectors, as well as the support staff at CERN and at our institutions worldwide without whom ATLAS could not be operated efficiently.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF/SFU (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), 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. [77].

We gratefully acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; ANID, Chile; CAS, MOST and NSFC, China; Minciencias, Colombia; MEYS CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS and CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF and MPG, Germany; GSRI, Greece; RGC and Hong Kong SAR, China; ICHEP and Academy of Sciences and Humanities, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW, Poland; FCT, Portugal; MNE/IFA, Romania; MSTDI, Serbia; MSSR, Slovakia; ARIS and MVZI, Slovenia; DSI/NRF, South Africa; MICIU/AEI, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; NSTC, Taipei; TENMAK, Türkiye; STFC/UKRI, United Kingdom; DOE and NSF, United States of America.

Individual groups and members have received support from BCKDF, CANARIE, CRC and DRAC, Canada; CERN-CZ, FORTE and PRIMUS, Czech Republic; COST, ERC, ERDF, Horizon 2020, ICSC-NextGenerationEU and Marie Skłodowska-Curie Actions, European Union; Investissements d'Avenir Labex, Investissements d'Avenir Idex and 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 MINERVA, Israel; NCN and NAWA, Poland; La Caixa Banking Foundation, CERCA Programme Generalitat de Catalunya and PROMETEO and GenT Programmes Generalitat Valenciana, Spain; Göran Gustafssons Stiftelse, Sweden; The Royal Society and Leverhulme Trust, United Kingdom.

In addition, individual members wish to acknowledge support from Armenia: Yerevan Physics Institute (FAPERJ); CERN: European Organization for Nuclear Research (CERN PJAS); Chile: Agencia Nacional de Investigación y Desarrollo (FONDECYT 1230812, FONDECYT 1230987, FONDECYT 1240864); China: Chinese Ministry of Science and Technology (MOST-2023YFA1605700), National Natural Science Foundation of China (NSFC - 12175119, NSFC 12275265, NSFC-12075060); Czech Republic: Czech Science Foundation (GACR - 24-11373S), Ministry of Education Youth and Sports (FORTE CZ.02.01.01/00/22_008/0004632), PRIMUS Research Programme (PRIMUS/21/SCI/017); EU: H2020 European Research Council (ERC - 101002463); European Union: European Research Council (ERC - 948254, ERC 101089007), European Union, Future Artificial Intelligence Research (FAIR-NextGenerationEU PE00000013), Italian Center for High Performance Computing, Big Data and Quantum Computing (ICSC, NextGenerationEU); France: Agence Nationale de la Recherche (ANR-20-CE31-0013, ANR-21-CE31-0013, ANR-21-CE31-0022, ANR-22-EDIR-0002); Germany: Baden-Württemberg Stiftung (BW Stiftung-Postdoc Eliteprogramme), Deutsche Forschungsgemeinschaft (DFG - 469666862, DFG - CR 312/5-2); Italy: Istituto Nazionale di Fisica Nucleare (ICSC, NextGenerationEU), Ministero dell'Università e della Ricerca (PRIN - 20223N7F8K - PNRR M4.C2.1.1); Japan: Japan Society for the Promotion of Science (JSPS KAKENHI JP22H01227, JSPS KAKENHI JP22H04944, JSPS KAKENHI JP22KK0227, JSPS KAKENHI JP23KK0245); Netherlands: Netherlands Organisation for Scientific Research (NWO Veni 2020 - VI.Veni.202.179); Norway: Research Council of Norway (RCN-314472); Poland: Ministry of Science and Higher Education (IDUB AGH, POB8, D4 no 9722), Polish National Agency for Academic Exchange (PPN/PPO/2020/1/00002/U/00001), Polish National Science Centre (NCN 2021/42/E/ST2/00350, NCN OPUS 2023/51/B/ST2/02507, NCN OPUS nr 2022/47/B/ST2/03059, NCN UMO-2019/34/E/ST2/00393, NCN & H2020 MSCA 945339, UMO-2020/37/B/ST2/01043, UMO-2021/40/C/ST2/00187, UMO-2022/47/O/ST2/00148, UMO-2023/49/B/ST2/04085, UMO-2023/51/B/ST2/00920); Slovenia: Slovenian Research Agency (ARIS grant J1-3010); Spain: Generalitat Valenciana (Artemisa, FEDER, IDIFEDER/2018/048), Ministry of Science and Innovation (MCIN & NextGenEU PCI2022-135018-2, MICIN & FEDER PID2021-125273NB, RYC2019-028510-I, RYC2020-030254-I, RYC2021-031273-I, RYC2022-038164-I); Sweden: Carl Trygger Foundation (Carl Trygger Foundation CTS 22:2312), Swedish Research Council (Swedish Research Council 2023-04654, VR 2018-00482, VR 2022-03845, VR 2022-04683, VR 2023-03403, VR grant 2021-03651), Knut and Alice Wallenberg Foundation (KAW 2018.0458, KAW 2019.0447, KAW 2022.0358); Switzerland: Swiss National Science Foundation (SNSF - PCEFP2_194658); United Kingdom: Leverhulme Trust (Leverhulme Trust RPG-2020-004), Royal Society (NIF-R1-231091); United States of America: U.S. Department of Energy (ECA DE-AC02-76SF00515), Neubauer Family Foundation.

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