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Aad, G., Aakvaag, E., Abbott, B. et al. (2877 more authors) (2025) Search for Higgs boson decays into a pair of pseudoscalar particles in the γγτhadτhad final state using pp collisions at √s = 13 TeV with the ATLAS detector. Journal of High Energy Physics, 2025. 190. ISSN 1126-6708

https://doi.org/10.1007/jhep03(2025)190

Published for SISSA by Springer

Received: *December 19, 2024*
Accepted: *February 23, 2025*
Published: *March 25, 2025*

Search for Higgs boson decays into a pair of pseudoscalar particles in the $\gamma\gamma\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ final state using pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

JHEP03(2025)190

The ATLAS collaboration

E-mail: atlas.publications@cern.ch

Abstract: A search for exotic decays of the 125 GeV Higgs boson into a pair of new spin-0 particles, $H \to aa$, where one decays into a photon pair and the other into a τ-lepton pair, is presented. Hadronic decays of the τ-leptons are considered and reconstructed using a dedicated tagger for collimated τ-lepton pairs. The search uses 140 fb^{-1} of proton-proton collision data at a centre-of-mass energy of $\sqrt{s} = 13$ TeV recorded between 2015 and 2018 by the ATLAS experiment at the Large Hadron Collider. The search is performed in the mass range of the a boson between 10 GeV and 60 GeV. No significant excess of events is observed above the Standard Model background expectation. Model-independent upper limits at 95% confidence level are set on the branching ratio of the Higgs boson to the $\gamma\gamma\tau\tau$ final state, $\mathcal{B}(H \to aa \to \gamma\gamma\tau\tau)$, ranging from 0.2% to 2%, depending on the a-boson mass hypothesis.

Keywords: Hadron-Hadron Scattering

ArXiv ePrint: 2412.14046

https://doi.org/10.1007/JHEP03(2025)190

Contents

1 Introduction

The observation of a Standard Model (SM) like Higgs boson with a mass of 125 GeV [1, 2] marked the beginning of a new era in physics at the Large Hadron Collider (LHC). Currently, measurements of the properties of the Higgs boson have shown no significant deviations from the SM predictions, and the existing constraints on the couplings of the Higgs boson to SM particles limit the branching ratio into non-SM or *exotic* decays of the Higgs boson to less than approximately 10% [3, 4]. However, several beyond-the-SM scenarios predict a SM-like Higgs boson with a small intrinsic decay width ($\Gamma_H \sim 4\,\text{MeV}$) and non-SM decays with a branching ratio of ∼10% without modifying the couplings of the Higgs boson to SM particles beyond the existing bounds [5].

Light (pseudo)scalars, referred to here as a bosons, that couple to the 125 GeV Higgs boson (H) can enable new decay modes, and appear in many well-motivated extensions of the SM. Examples include theories with an extended Higgs sector [6–9], dark matter models [10–12], models with a first-order electroweak phase transition [13, 14], and theories with neutral naturalness [15, 16].

This paper presents a search for $H \to aa \to \gamma\gamma\tau_{\text{had}}\tau_{\text{had}}$, with the Higgs boson decaying into two a bosons, where one a decays into a photon pair and the other into a τ_{had} pair, considering only the hadronic decays of the τ-lepton. The dataset consists of the proton-proton (pp) collisions recorded at $\sqrt{s} = 13\,\text{TeV}$ with the ATLAS detector during the LHC Run 2

(2015–2018), corresponding to an integrated luminosity of 140 fb^{-1}. Searches targeting final states with either a photon pair or a τ-lepton pair, as decay products of such a (pseudo)scalar, have previously been conducted by both the ATLAS [17–19] and CMS [20–23] collaborations. However, this search presents the first result in the combined $\gamma\gamma\tau_{\text{had}}\tau_{\text{had}}$ final state. The two photons are used to provide a highly efficient trigger selection and an excellent mass resolution, while the two τ-leptons benefit from a large branching ratio in models where the coupling is proportional to the particle mass, such as two-Higgs-doublet models [24, 25].

This analysis uses the diphoton invariant mass, $m_{\gamma\gamma}$, as the main observable, further exploring the range below 60 GeV — reaching 10 GeV as the lowest mass probed, limited by the standard trigger and photon reconstruction techniques — studied for the first time in ref. [26] with pp collisions. A similar strategy is implemented, requiring a boosted photon pair with transverse momentum $p_{\text{T}}^{\gamma\gamma}$ larger than 50 GeV, which eases the description of the background shape with analytical functions. The requirement of an additional pair of hadronically decaying τ-leptons further increases the background rejection and new reconstruction techniques for boosted τ-lepton pairs are implemented to improve the sensitivity in the low-mass regime.

The paper is structured as follows. A brief discussion of the ATLAS detector and an overview of the Monte Carlo samples and data used in the analysis are presented in sections 2 and 3. The event reconstruction and selection are described in section 4, with special focus on the custom reconstruction of boosted di-τ signals. The signal modelling and background estimates are discussed in section 5, followed by a description of the dominant systematic uncertainties and the statistical method in section 6. Finally, the results are presented in section 7 and the conclusions are drawn in section 8.

2 ATLAS detector

The ATLAS experiment [27] 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

[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 $\Delta R \equiv \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.

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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 [28] detector, which is located close to the beampipe. A two-level trigger system is used to select events [29]. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz on average depending on the data-taking conditions. A software suite [30] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

3 Data and simulated event samples

The search is performed using the 13 TeV *pp* collision dataset collected from 2015 to 2018 by the ATLAS detector, referred to as the full Run 2 dataset in the following. Only events with stable beam conditions and all ATLAS subsystems operational are considered [31], corresponding to an integrated luminosity of 140 fb^{-1} with an uncertainty of 0.83% [32]. The data were recorded using a set of diphoton triggers [33] that required two electromagnetic energy clusters satisfying identification criteria based on their expected shower shapes and transverse energies (E_T) above a certain threshold that varied across the data-taking period to cope with the increase in instantaneous luminosity over the years. In 2015 and the first portion of 2016, the trigger required a E_T threshold of 20 GeV, while in the remainder of 2016 the threshold was set to 22 GeV. During 2017 and 2018, the E_T threshold was set to 20 GeV along with isolation requirements. An alternative dataset is used for background estimation, collected with a prescaled diphoton trigger with looser identification criteria for the EM shower shapes and a E_T threshold of 20 GeV, corresponding to an integrated luminosity of 6.3 fb^{-1}.

Monte Carlo (MC) simulated samples are used to model signal and background processes, as well as to derive related modelling uncertainties. The generated signal events are processed through a full simulation [34] of the ATLAS geometry and response based on GEANT4 [35], while the background events are processed through a faster simulation where the full simulation of the calorimeter is replaced with a parameterisation of the calorimeter response [36]. The effects of multiple *pp* interactions in the same bunch crossing as the hard scatter and in neighbouring ones (defined as pile-up) are included using simulated events generated with PYTHIA 8.186 [37] using the A3 set of tuned parameters [38] and the NNPDF2.3LO [39] parton distribution functions (PDF) set. Simulated events are weighted to reproduce the distribution of the average number of interactions per bunch crossing observed in data. All simulated events are reconstructed with the same reconstruction algorithms as those used for data.

Signal event samples are generated for the SM Higgs boson produced through gluon-gluon fusion (ggF), using the NNLOPS approach [40] with POWHEG BOX v2 [41–44] interfaced with PYTHIA 8.245 [45] using the AZNLO set of tuned parameters [46] to simulate parton showering, hadronisation and the full decay chain, $H \to aa \to \gamma\gamma\tau\tau$, where the τ-leptons are set to decay hadronically. The next-to-next-to-leading-order (NNLO) PDF4LHC15 [47] sets of PDFs were used. To study on-shell decays of the Higgs boson, the mass of the pseudoscalar resonance, m_a, is varied in 5 GeV steps within the range 10 GeV to 60 GeV. The decay width of the hypothetical resonance is set to 4 MeV, consistent with the narrow-width approximation, as this value is negligible compared to the experimental resolution. Only the ggF process

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— the dominant Higgs boson production mechanism, accounting for approximately 87% of the total cross-section — is considered in this study, ignoring the contributions from the other Higgs boson production modes.

The main background in this search originates from events with two prompt photons and associated jets, which are simulated using the SHERPA 2.2.4 [48] event generator. The matrix elements are calculated at next-to-leading-order (NLO) in QCD for up to one additional parton and at leading-order (LO) in QCD for two or three partons, and are merged with the SHERPA parton shower simulation using the MEPS@NLO prescription [49–52]. The NNPDF3.0NNLO [53] PDF set was used in conjunction with a dedicated parton-shower tune in the SHERPA generator [54]. Processes with two photons and two τ-leptons in the final state, originating at lowest order from SM Z-boson decays, are not considered in the analysis, as the cross-section is negligible compared with the dominant background.

Interference effects between the resonant signal and the background processes are expected to be small for narrow-width signals and are neglected.

4 Event reconstruction and selection

4.1 Event reconstruction

Events are required to contain at least one reconstructed pp collision vertex candidate with at least two associated ID tracks with transverse momenta (p_{T}) larger than 0.5 GeV [55]. The primary vertex (PV) for each event is chosen as the reconstructed vertex with the highest sum of the p_{T}^2 of its associated tracks.

Photon candidates are reconstructed from topological clusters of energy deposited in the EM calorimeter, as well as from charged particle vertex and vertices reconstructed in the inner detector originating from photon conversions, and they are calibrated as described in ref. [56]. The properties of the EM clusters associated with the two highest-E_{T} photons is used to correct the photon direction, resulting in improved diphoton mass resolution. To reduce the background from jets, photon candidates are required to satisfy *Tight* identification criteria based on the shape of EM showers in the LAr calorimeter and energy leakage into the hadronic calorimeter [56]. The criteria have an identification efficiency that increases with E_{T} from 70% at 22 GeV to 90% above 50 GeV. Events with one or both photon candidates satisfying a looser identification requirement from the prescaled data are kept for background estimations. To further improve the rejection of jets misidentified as photons, the candidates are required to be isolated using both calorimeter and tracking information. The calorimeter isolation transverse energy $E_{\mathrm{T}}^{\mathrm{iso,calo}}$ is required to be smaller than $0.065 \times E_{\mathrm{T}}^{\gamma}$, where $E_{\mathrm{T}}^{\mathrm{iso,calo}}$ is defined as the sum of the transverse energies of positive-energy topological clusters [57] within a cone of size $\Delta R = 0.2$ around the photon candidate, excluding the photon transverse energy E_{T}^{γ} and correcting for pile-up and underlying-event contributions [58–60]. The track isolation transverse energy $E_{\mathrm{T}}^{\mathrm{iso,trk}}$ is required to be less than $0.05 \times E_{\mathrm{T}}^{\gamma}$, where $E_{\mathrm{T}}^{\mathrm{iso,trk}}$ is defined as the scalar sum of the transverse momenta of tracks with $p_{\mathrm{T}} > 1$ GeV in a $\Delta R = 0.2$ cone around the photon candidate. The tracks considered must satisfy some loose track-quality criteria [56], should not be associated with the photon conversion vertex if it exists, and originate from the PV set as the diphoton production vertex. The combined isolation efficiency for pairs of photons fulfilling the identification criteria in simulated signal samples increases with $m_{\gamma\gamma}$ from 80% at 10 GeV to 90% at 90 GeV.

Electrons and muons are reconstructed to veto events with leptonic final states. Electrons are reconstructed from energy clusters in the EM calorimeter matched to tracks reconstructed in the ID, and are required to have $p_{\mathrm{T}} > 27$ GeV and $|\eta| < 2.47$. Electrons in the calorimeter barrel-endcap transition region ($1.37 < |\eta| < 1.52$) are excluded. Electrons must satisfy the *Tight* identification criteria [61], the longitudinal impact parameter must be smaller than 0.5 mm, and the transverse impact parameter significance smaller than 5, both defined with respect to the beam line. Isolation criteria are applied to the selected electrons using both tracking and calorimeter information with a p_{T}-dependent cone radius [56].

Muons are reconstructed using different methods depending on the availability of the tracks in the MS and the ID [62], and are required to have $p_{\mathrm{T}} > 27$ GeV and $|\eta| < 2.7$. Similarly to the electrons, muons are required to satisfy the *Medium* identification criteria [62], the longitudinal impact parameter smaller than 0.5 mm, and the transverse impact parameter significance smaller than 3. The isolation criteria are based on requirements from both the ID and calorimeters, also with a p_{T}-dependent cone radius [62].

Jets are reconstructed using the anti-k_t algorithm [63] as implemented in FastJet [64] with a radius parameter $R = 0.4$. The inputs to this algorithm are particle flow objects [65], which combine measurements from the ID and calorimeters [57] to improve the jet energy resolution and increase the jet reconstruction efficiency, especially at low jet p_{T}. The jet energy scale is calibrated to the particle level using simulation and further corrected with in-situ methods [66]. Jets are required to have $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.5$.

The reconstruction of the visible component of hadronically decaying τ-lepton candidates, $\tau_{\text{had-vis}}$, is seeded from jets reconstructed using the anti-k_t algorithm with a radius parameter $R = 0.4$ whose inputs are topoclusters, three-dimensional clusters of calorimeter cells [57], calibrated using a local hadronic calibration [67]. Reconstructed $\tau_{\text{had-vis}}$ candidates are required to have $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.5$ (excluding the transition region $1.37 < |\eta| < 1.52$) and either one or three associated tracks with a total charge of ± 1 [67]. The *Loose* identification criteria, applied for the $\tau_{\text{had-vis}}$ candidates, are based on a Recurrent Neural Network (RNN) algorithm, which uses tracks and calorimeter clusters associated to $\tau_{\text{had-vis}}$ candidates as well as high-level discriminating variables, to reject background from jets misidentified as $\tau_{\text{had-vis}}$ candidates [68]. In the following, a *resolved* di-τ object refers to two separated $\tau_{\text{had-vis}}$ candidates. The RNN identification is used for resolved $\tau_{\text{had-vis}}$ candidates, while a dedicated algorithm for *boosted* di-τ objects is described below.

The boosted di-τ object refers to two $\tau_{\text{had-vis}}$ that are within $\Delta R < 0.4$ from each other, such that the reconstruction is performed via a custom algorithm [69] using the substructure of a large-radius jet. The large-radius jet is reconstructed using the anti-k_t jet algorithm with a radius parameter $R = 1.0$ from particle-flow objects and required to have $p_{\mathrm{T}} > 50$ GeV, followed by the reclustering of its constituents into subjets with $p_{\mathrm{T}} > 10$ GeV, using the anti-k_t algorithm with $R = 0.2$. At least two subjets are required to define a boosted di-τ candidate, with each of the two containing either one or three associated tracks. The subjets are ordered in p_{T} and referred to as the *leading* and *sub-leading* subjets, respectively. The charge product of the two leading subjets is ± 1, where the charge of each subjet is defined as

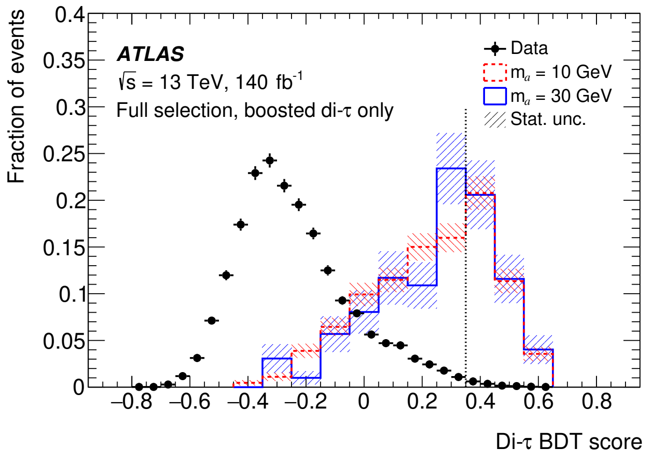

Figure 1. Di-τ BDT score distribution for data and two representative signal masspoints, for events that satisfy the selection criteria in section 4 and contain a boosted di-τ candidate. The BDT score > 0.35 selection (dotted line) is referred to as the *Medium* di-τ identification working point and is used in the analysis. Statistical uncertainties in the data are represented by the errors bars around the points and in the simulated signal by the hatched bands around the histograms.

the sum of the charges of the associated tracks. Then a dedicated identification algorithm is implemented to distinguish the boosted di-τ candidates from quark- or gluon-initiated jets, using a boosted decision tree (BDT) method, based on a set of kinematic variables. The discriminating variables are derived from track and calorimeter information of the subjets associated with the di-τ candidates. The performance of the reconstruction and identification algorithms is estimated in a calibration analysis, with the measurement of the di-τ identification efficiencies in data and simulation, the ratio of which is defined as the boosted di-τ *scale factor* (SF). The efficiency measurement is performed via the tag-and-probe technique using boosted di-τ objects from the SM $Z\,(\rightarrow \tau_{\text{had}}\tau_{\text{had}}) + \gamma$ process, recorded with a high-p_{T} photon trigger. A *Medium* di-τ BDT-based identification criterion is defined, corresponding to a BDT score > 0.35 selection. The estimated signal efficiency is approximately 70%, with a measured background rejection factor of about 240. The corresponding SF is $1.00 \pm 0.35\,(\text{stat.}) \pm 0.13\,(\text{syst.})$. The di-$\tau$ BDT score distributions for both data and simulated signal samples corresponding to m_a values of 10 GeV and 30 GeV are shown in figure 1.

The examination of the visible p_{T} of the di-τ decay products, $p_{\text{T,vis}}^{\tau\tau}$, in the boosted di-$\tau$ calibration analysis and in this search using simulated events, shows that the former exhibits values an order of magnitude higher. An extrapolation uncertainty is hence introduced to account for the different kinematic regimes probed in both studies. The boosted di-τ SF is extrapolated to the relevant $p_{\text{T,vis}}^{\tau\tau}$ range and is found to be consistent with unity within 50%, which is taken as a systematic uncertainty and added in quadrature to the boosted di-τ SF uncertainty.

4.2 Event selection

The event selection requires at least two photon candidates with transverse energies larger than 22 GeV and $|\eta| < 2.37$, excluding the transition regions of the calorimeter, $1.37 < |\eta| < 1.52$.

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The transverse energy requirement is chosen to mitigate the effects in the trigger efficiency near the trigger thresholds discussed in section 3. The diphoton invariant mass is computed using the transverse energies of the leading and sub-leading photon candidates and their angular separation in both azimuth ϕ and pseudorapidity η, determined from their positions in the calorimeter and the production vertex. An additional kinematic selection is placed on the transverse momentum of the diphoton system, $p_{\mathrm{T}}^{\gamma\gamma}$, requiring events to have a diphoton pair with $p_{\mathrm{T}}^{\gamma\gamma} > 50\,\mathrm{GeV}$. This requirement is motivated by the fact that the analysis targets diphoton pairs with low invariant masses, down to about half the trigger energy thresholds, and such pairs are typically highly boosted with respect to the ATLAS detector rest frame. Moreover, the $p_{\mathrm{T}}^{\gamma\gamma}$ requirement is chosen to reach the best compromise between the statistical uncertainty in the lowest part of the diphoton invariant mass spectrum and sculpting effects on the background shape from the trigger thresholds, whose mismodelling would result in large systematic uncertainties.

The selection additionally requires a boosted di-τ candidate or two resolved τ-leptons to provide coverage for the whole m_a mass spectrum. If the event contains a di-τ signature that is reconstructed by both the boosted and the resolved di-τ algorithms, the resolved τ-lepton pair is selected due to its corresponding di-τ-related identification uncertainties being significantly smaller. Considering both the resolved and boosted topologies, the di-τ tagger recovers sensitivity mostly in the $m_{\gamma\gamma} \lesssim 25\,\mathrm{GeV}$ domain, dominated by the presence of boosted di-τ objects, as shown in figure 2. As the di-τ signal is expected from a neutral particle, the τ-leptons are required to have opposite charges. As for the identification criteria, the two leading resolved τ-leptons must satisfy the *Loose* identification working point [68], whereas the boosted di-τ should fulfil the *Medium* working point [69]. Additionally, the events are required to contain no electrons or muons to reject backgrounds involving leptonic final states, which are not expected from the signal.

Additionally, events that fail the τ-lepton pair requirements, as well as the photon identification and isolation criteria, are kept for background composition studies. For boosted di-τ objects, the identification requirement is inverted using a BDT score < -0.2 selection, and the two leading subjets are required to have the same charge. In events with a resolved τ-lepton pair, either the two leading τ-leptons are required to have the same charge, or one of them has to fail the *Loose* identification requirement. In the following, these selections are referred to as the *inverted di-τ selections*.

5 Signal and background modelling

5.1 Signal parameterisation

The signal modelling strategy consists of fitting the diphoton invariant mass distribution of simulated signal samples with different masses to a double-sided Crystal Ball (DSCB) function, composed of a Gaussian core with power-law tails [70, 71]. The parameters of the DSCB function are extracted from these fits for each signal m_a hypothesis and parameterised linearly with respect to m_a. The width of the Gaussian core, driven entirely by the detector resolution, ranges from 0.2 to 1.0 GeV. The signal model agrees well with the simulated

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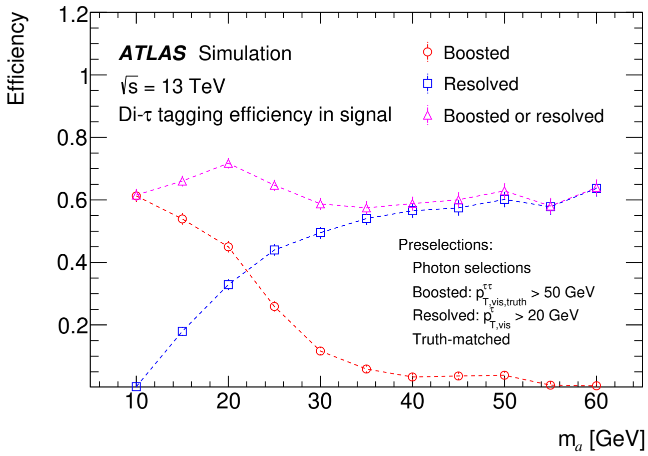

Figure 2. Di-τ reconstruction and identification combined efficiency in signal for the different di-τ categories: *boosted* (circles), *resolved* (squares) and *boosted or resolved* (triangles). The analysis uses the latter to maximize the signal efficiency across the whole mass range probed. The efficiency is defined using the *truth-matched* preselection that refers to both boosted di-τ objects and resolved τ-leptons, geometrically matching the reconstructed object or its constituents to the particle-level object within $\Delta R = 0.2$. Connecting dashed lines are only for visualization purposes. Only statistical uncertainties are represented.

signal samples, with differences below 2.5% of the fitted signal yield. This value is used as the signal modelling uncertainty.

5.2 Background estimation

Background decomposition

The dominant backgrounds generally consist of three components: the continuum diphoton production ($\gamma\gamma$), photon-jet (γj) and jet pair (jj) events, where one or more jets are misidentified as photons. In addition, these background processes contain a τ-lepton pair misidentified from one or more additional jets. The background consisting of events with genuine photons and hadronically decaying τ-lepton pairs — originating at lowest order from a Z boson decaying into a τ-lepton pair produced in association with a photon pair — is highly suppressed due to its small cross-section and the boosted selections, and is estimated to contribute only about 1% of the data. This leaves the background to be dominated by the photon processes.

The search makes use of a data-driven background estimate in which the continuum background shape is parameterised by an analytical function. Background templates are built to estimate the robustness of the background parameterisation and derive modelling systematic uncertainties. The nominal background template is composed of the irreducible and reducible sources: the former being the $\gamma\gamma$ component obtained from simulated diphoton samples; and the latter combining the γj and jj components obtained from control regions, inverting the photon identification criteria, in the alternative data samples. Those are recorded using the prescaled diphoton trigger that allows to relax the photon identification and isolation criteria. Due to the limited size of the data and simulated samples, both irreducible and reducible

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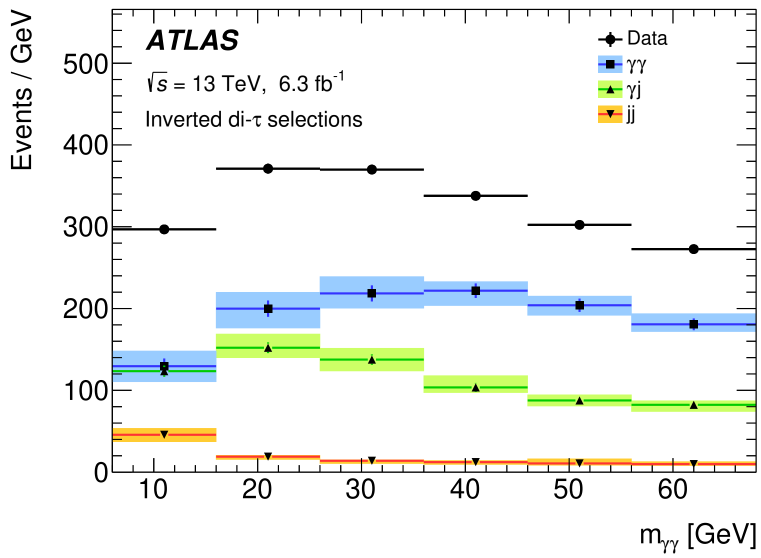

Figure 3. Diphoton invariant mass distribution in data after the inverted di-τ selections, and its decomposition into contributions from diphoton ($\gamma\gamma$), photon-jet (γj) and jet pair (jj) events as determined using the two-dimensional sideband method. The statistical uncertainties are shown as error bars, while the total uncertainties, including statistical and systematic components added in quadrature, are shown as shaded bands.

sources apply the inverted di-τ selections, defined in section 4. Comparing the diphoton invariant mass distributions obtained for different di-τ selections, their shapes are observed to agree within statistical uncertainties, allowing the use of such di-τ selections to describe the expected background in data. The two sources are then combined according to their relative fractions estimated by using the two-dimensional sideband method [72]. This method is used in analyses with final states containing two photons, alternately inverting their isolation and identification criteria to measure the contribution of the $\gamma\gamma$, γj and jj components, as shown in figure 3. The overall diphoton purity, defined within the $m_{\gamma\gamma}$ range 6–68 GeV as the fraction of the $\gamma\gamma$ component in the data, is 0.61 ± 0.01 (stat.) $\pm\, 0.04$ (syst.), in which the systematic uncertainty arises from the different choices of relaxed photon identification criteria.

Template shape description

The entire background template shape is described using an analytic functional form. The chosen function is a product of a sigmoid function that effectively describes the turn-on at low masses, and an exponential function that models the smoothly falling shape at high masses:

$$f\left(m_{\gamma\gamma}; N, \delta_{\text{sgmd}}, \tau_{\text{sgmd}}, \lambda_{\text{exp}}\right) = N \times \frac{1}{1 + e^{-(m_{\gamma\gamma} - \delta_{\text{sgmd}})/\tau_{\text{sgmd}}}} \times e^{-\lambda_{\text{exp}}\ m_{\gamma\gamma}},$$

where N is a normalisation constant, δ_{sgmd} and τ_{sgmd} are the parameters regulating the step of the sigmoid function, while λ_{exp} is the exponential function decay constant. The function parameters are fit to the background template in the $m_{\gamma\gamma}$ range 6–68 GeV.

Variations of the nominal background template are built to validate the flexibility of the function and to estimate systematic uncertainties. The variations are obtained by either

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modifying the photon identification criteria, varying the $\gamma\gamma$ purity by its uncertainty, or altering the di-τ identification criteria. The difference in the yield between the various template shape variations and the nominal ranges up to 10% for different di-τ selections and up to 4% when the photon identification criteria or the normalisation of the $\gamma\gamma$ component is varied.

Modelling bias evaluation

The uncertainty arising from the choice of background model is based on signal-plus-background fits to background-only template histograms [73]. Any fit signal yield is referred to as a *spurious signal* and is considered as a systematic uncertainty of the background model. The model described has a maximum bias of 13% of the statistical uncertainty of all the templates. Although the spurious signal is small, it is susceptible to statistical fluctuations in the data, as the template is built with limited statistics.

To reduce the statistical effects on the background modelling uncertainty, templates are smoothed using a Gaussian Processes regression [74]. This is a non-parametric regression technique used to estimate the underlying function of a dataset exploiting the correlation between points separated by a certain distance denominated the *length scale*, without modifying significantly the background shape nor introducing any bias in the yield [26]. The length scale encodes the minimum feature size expected in the background shape, corresponding in this analysis to the trigger turn-on of size between 1 and 2 GeV, which is also larger than the signal resolution. Background templates in the full $m_{\gamma\gamma}$ range 6–68 GeV are smoothed, removing the statistical fluctuations. Since the smoothing is based on the correlation between neighbouring data, the combined signal and background model fit is performed using the $m_{\gamma\gamma}$ range 10–60 GeV to mitigate any mismodelling introduced by the edge effect. With the statistical fluctuations mitigated, the estimated spurious signal is reduced to less than approximately 5% of the statistical uncertainty of the template.

The spurious signal is then estimated for all the background template variations described previously. This allows to estimate the bias from the choice of background modelling, which is always largest at the turn-on region and up to 8% of the expected statistical uncertainty. The systematic uncertainty results from the envelope of the maximum spurious signal obtained for all background template variations.

6 Statistical analysis

The presence of a $H \to aa \to \gamma\gamma\tau_{\text{had}}\tau_{\text{had}}$ signal is tested by means of a likelihood function built from the observed diphoton invariant mass distribution and the analytic functions discussed in sections 5.1 and 5.2, describing the signal and background components in the $m_{\gamma\gamma}$ range 6–68 GeV. The mass range is chosen to avoid bias in the background modelling due to the effects of the $p_{\text{T}}^{\gamma\gamma} > 50$ GeV selection. The search is then performed in the 10–60 GeV mass range to avoid edge effects. The parameter of interest to be extracted from the likelihood fit is the branching ratio $\mathcal{B}(H \to aa \to \gamma\gamma\tau\tau)$, which includes the Higgs boson production cross-section via the ggF process, 48.5 ± 2.4 pb [75], the dominant mechanism, and the total signal selection efficiency estimated from simulated signal samples. The efficiency accounts for the branching ratio for hadronically decaying τ-leptons, and it ranges from 2.2×10^{-4} to 1.0×10^{-4} for masses between 10 and 60 GeV. The mass dependence arises from the boosted

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<table>
<tr><th>Source</th><th colspan="2">Uncertainty</th></tr>
<tr><td colspan="3">In $\mathcal{B}(H \to aa \to \gamma\gamma\tau\tau)$ [%]</td></tr>
<tr><td></td><td>$m_a = 10\,\text{GeV}$</td><td>$m_a = 50\,\text{GeV}$</td></tr>
<tr><td>Boosted di-τ object</td><td>63</td><td>0.8</td></tr>
<tr><td>Theory</td><td>9.9</td><td>27</td></tr>
<tr><td>Pile-up reweighting</td><td colspan="2">4.5</td></tr>
<tr><td>Resolved τ reconstruction, identification and energy scale</td><td>0.3</td><td>4.0</td></tr>
<tr><td>Photon energy resolution</td><td colspan="2">3.0</td></tr>
<tr><td>Photon identification efficiency</td><td colspan="2">2.9</td></tr>
<tr><td>Signal shape modelling</td><td colspan="2">2.5</td></tr>
<tr><td>Photon isolation efficiency</td><td colspan="2">2.4</td></tr>
<tr><td>Photon trigger efficiency</td><td colspan="2">1.1</td></tr>
<tr><td>Photon energy scale</td><td colspan="2">< 1.0</td></tr>
<tr><td>Luminosity</td><td colspan="2">0.8</td></tr>
<tr><td>Trigger on closely spaced photons</td><td>0.8</td><td>< 0.1</td></tr>
<tr><td colspan="3">In background modelling</td></tr>
<tr><td>Spurious signal</td><td>$< 0.08\,\sigma_{\text{stat}}$
0.16 events</td><td>$< 0.01\,\sigma_{\text{stat}}$
0.06 events</td></tr>
</table>

Table 1. Summary of the main sources of systematic uncertainty. Their impact on the branching ratio is shown, except for the background modelling uncertainty, which is expressed both as a number of events and relative to the expected statistical uncertainty δS of a fitted signal. The m_a-dependent uncertainties are given for two m_a values, 10 GeV and 50 GeV.

and resolved selections — with the former being more efficient in the low-mass regime and the latter in the high-mass regime — as well as from the boosted topology required for the diphoton system via the $p_{\mathrm{T}}^{\gamma\gamma}$ selection.

The systematic uncertainties are implemented in the likelihood function as nuisance parameters constrained by Gaussian penalty terms, and are summarised in table 1. The theoretical uncertainties affecting the measurement of $\mathcal{B}(H \to aa \to \gamma\gamma\tau\tau)$ arise from variations of the renormalisation and factorisation scales, as well as the choice of the PDFs, modifying the total signal selection efficiency evaluated in simulated samples. The experimental uncertainties directly impacting the signal yield include those related to the integrated luminosity, the modelling of pile-up interactions in simulation, the trigger efficiency, the photon identification and isolation efficiencies, the photon energy scale and resolution, the boosted di-τ object, and the resolved τ-lepton reconstruction and identification efficiencies, as well as the τ-lepton energy scale. The boosted di-τ object uncertainty combines the di-τ scale factor uncertainty — accounting for the di-τ reconstruction, energy scale calibration, and the statistical uncertainty of the scale factor measurement — with the extrapolation uncertainty. An additional systematic uncertainty in the trigger is included to account for the capability of the trigger system to identify two closely spaced electromagnetic showers, as done in ref. [26]. Systematic uncertainties accounting for signal and background mismodelling are included, primarily arising from the signal shape parameterisation and the fit bias (discussed

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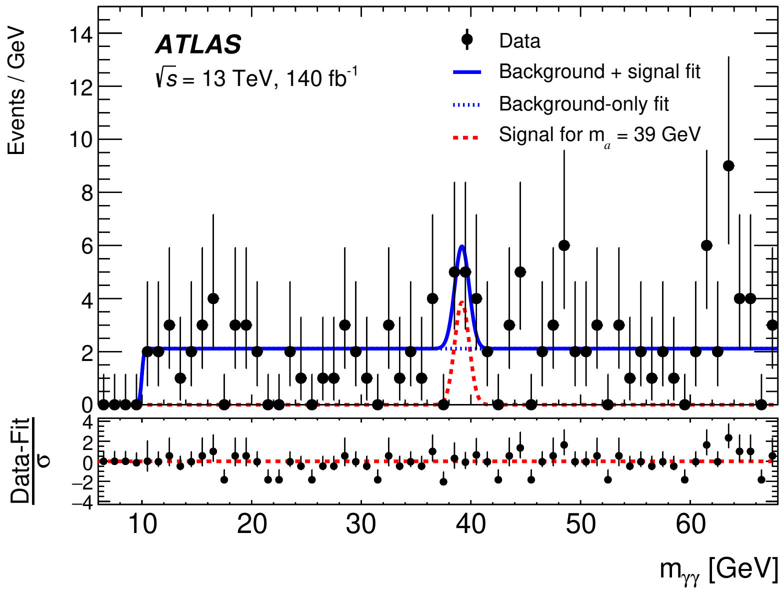

Figure 4. Distribution of the diphoton invariant mass for all events satisfying the analysis selections in the full Run 2 dataset with the background-only fit superimposed (dotted line). The background-plus-signal fit is given as an example for $m_a = 39\,\text{GeV}$ (solid line), and the corresponding signal hypothesis is shown (dashed line). The bottom panel shows the difference between the data points and the background-plus-signal fit, expressed in units of the statistical uncertainty in the data.

in section 5.2). All systematic uncertainties, except those specific to either the boosted or resolved τ-lepton reconstruction, are applied to both categories.

The best-fit branching ratio is obtained by performing an unbinned likelihood fit to the data under the signal-plus-background hypothesis. The compatibility of the observed data and the background-only hypothesis for a given signal hypothesis m_a is tested by estimating a local p-value based on a profile-likelihood-ratio test statistic [76].

In the absence of a signal, the expected and observed 95% confidence level (CL) exclusion limits on the branching ratio are evaluated using the modified frequentist approach CL_s [77] with the asymptotic approximation to the test-statistic distribution [76]. The asymptotic approximation was validated with pseudo-experiments and agrees within 10%.

7 Results

The diphoton invariant mass distribution of events satisfying the analysis selections is shown in figure 4, along with the background-only fit performed in the $m_{\gamma\gamma}$ range 6–68 GeV.

The result of the p-value scan as a function of the hypothesised resonance mass m_a is shown in figure 5(a). The most significant deviations from the background-only hypothesis are observed for masses of 39 GeV and 48 GeV, and correspond to significances of 2.2σ and 2.1σ, respectively.

The observed and expected 95% CL upper limits on $\mathcal{B}(H \to aa \to \gamma\gamma\tau\tau)$ as a function of m_a are shown in figure 5(b), ranging from 0.2% to 2% and 0.5% to 1%, respectively, where

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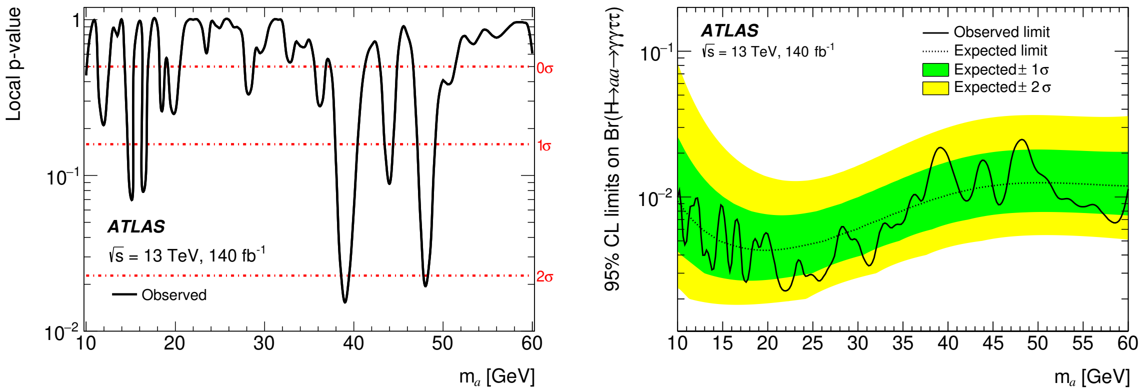

(a)

(b)

Figure 5. (a) Scan of the observed p-value as a function of m_a for the background-only hypothesis. (b) Observed (solid line) and expected (dashed line) upper limits at 95% CL on the branching ratio for $H \to aa \to \gamma\gamma\tau\tau$ as a function of m_a. The surrounding shaded bands correspond to ± 1 and ± 2 standard deviations around the expected limit.

the best sensitivity is achieved in m_a range 10–35 GeV. The dominant uncertainties arise from the limited number of pp collisions collected, partially accounted for in the boosted di-τ identification uncertainty, and from the di-τ extrapolation uncertainty addressing the difference in the kinematic regimes probed in this analysis and in the di-τ calibration study.

8 Conclusions

A search for SM Higgs boson decays into two pseudoscalars, a, with one decaying into a photon pair and the other into a hadronically decaying τ-lepton pair, $H \to aa \to \gamma\gamma\tau_{\text{had}}\tau_{\text{had}}$, is performed using 140 fb^{-1} of pp collision data at $\sqrt{s} = 13$ TeV collected with the ATLAS detector at the LHC. This analysis considers both resolved and boosted di-τ topologies, using for the first time a novel algorithm for reconstructing a collimated τ-lepton pair decaying hadronically, enhancing the search sensitivity at low values of the pseudoscalar mass. The diphoton invariant mass spectrum, ranging from 10 to 60 GeV, is analyzed to search for a narrow resonance on a smooth, quasi-flat background modelled by an analytic functional form. The data is consistent with the SM background expectation, and limits are set on the process branching ratio. The observed (expected) 95% confidence level upper limits on $\mathcal{B}(H \to aa \to \gamma\gamma\tau\tau)$ range from 0.2% (0.5%) to 2% (1%), with variations mainly due to statistical fluctuations of the data. As the first such search conducted at the LHC, it contributes to the broad program of searches for $H \to aa$ decays that is underway, probing different final states.

Acknowledgments

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.

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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 (U.K.) and BNL (U.S.A.), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in ref. [78].

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 DOCT); Chile: Agencia Nacional de Investigación y Desarrollo (FONDECYT 1230812, FONDECYT 1230987, FONDECYT 1240864); China: Chinese Ministry of Science and Technology (MOST-2023YFA1605700, MOST-2023YFA1609300), 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, ERC, BARD, 101116429), 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); 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); 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.

Data Availability Statement. The public release of data supporting the findings of this article will follow the CERN Open Data Policy [79]. Inquiries about plots and tables associated with this article can be addressed to atlas.publications@cern.ch.

Code Availability Statement. The ATLAS Collaboration's Athena software, including the configuration of the event generators, is open source (http://gitlab.cern.ch/atlas/athena).

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L.J. Beemster[16], M. Begalli[84d], M. Begel[30], J.K. Behr[49], J.F. Beirer[37], F. Beisiegel[25], M. Belfkir[119b], G. Bella[155], L. Bellagamba[24b], A. Bellerive[35], P. Bellos[21], K. Beloborodov[39], D. Benchekroun[36a], F. Bendebba[36a], Y. Benhammou[155], K.C. Benkendorfer[62], L. Beresford[49], M. Beretta[54], E. Bergeaas Kuutmann[166], N. Berger[4], B. Bergmann[135], J. Beringer[18a], G. Bernardi[5], C. Bernius[147], F.U. Bernlochner[25], F. Bernon[37], A. Berrocal Guardia[13], T. Berry[97], P. Berta[136], A. Berthold[51], S. Bethke[112], A. Betti[76a,76b], A.J. Bevan[96], N.K. Bhalla[55], S. Bharthuar[112], S. Bhatta[149], D.S. Bhattacharya[171], P. Bhattarai[147], Z.M. Bhatti[120], K.D. Bhide[55], V.S. Bhopatkar[124], R.M. Bianchi[132], G. Bianco[24b,24a], O. Biebel[111], M. Biglietti[78a], C.S. Billingsley[46], Y. Bimgdi[36f], M. Bindi[56], A. Bingham[176], A. Bingul[22b], C. Bini[76a,76b], G.A. Bird[33], M. Birman[174], M. Biros[136], S. Biryukov[150], T. Bisanz[50], E. Bisceglie[45b,45a], J.P. Biswal[137], D. Biswas[145], I. Bloch[49], A. Blue[60], U. Blumenschein[96], J. Blumenthal[102], V.S. Bobrovnikov[40], M. Boehler[55], B. Boehm[171], D. Bogavac[37], A.G. Bogdanchikov[39], L.S. Boggia[130], V. Boisvert[97], P. Bokan[37], T. Bold[87a], M. Bomben[5], M. Bona[96], M. Boonekamp[138], A.G. Borbély[60], I.S. Bordulev[39], G. Borissov[93], D. Bortoletto[129], D. Boscherini[24b], M. Bosman[13], K. Bouaouda[36a], N. Bouchhar[168], L. Boudet[4], J. Boudreau[132], E.V. Bouhova-Thacker[93], D. Boumediene[42], R. Bouquet[58b,58a], A. Boveia[122], J. Boyd[37], D. Boye[30], I.R. Boyko[40], L. Bozianu[57], J. Bracinik[21], N. Brahimi[4], G. Brandt[176], O. Brandt[33], B. Brau[105], J.E. Brau[126], R. Brener[174], L. Brenner[117], R. Brenner[166], S. Bressler[174], G. Brianti[79a,79b], D. Britton[60], D. Britzger[112], I. Brock[25], R. Brock[109], G. Brooijmans[43], A.J. Brooks[69], E.M. Brooks[160b], E. Brost[30], L.M. Brown[170], L.E. Bruce[62], T.L. Bruckler[129], P.A. Bruckman de Renstrom[88], B. Brüers[49], A. Bruni[24b], G. Bruni[24b], D. Brunner[48a,48b], M. Bruschi[24b], N. Bruscino[76a,76b], T. Buanes[17], Q. Buat[142], D. Buchin[112], A.G. Buckley[60], O. Bulekov[39], B.A. Bullard[147], S. Burdin[94], C.D. Burgard[50], A.M. Burger[37], B. Burghgrave[8], O. Burlayenko[55], J. Burleson[167], J.T.P. Burr[33], J.C. Burzynski[146], E.L. Busch[43], V. Büscher[102], P.J. Bussey[60], J.M. Butler[26], C.M. Buttar[60], J.M. Butterworth[98], W. Buttinger[137], C.J. Buxo Vazquez[109], A.R. Buzykaev[40], S. Cabrera Urbán[168], L. Cadamuro[67], D. Caforio[59], H. Cai[132], Y. Cai[24b,114c,24a], Y. Cai[114a], V.M.M. Cairo[37], O. Cakir[3a], N. Calace[37], P. Calafiura[18a], G. Calderini[130], P. Calfayan[35], G. Callea[60], L.P. Caloba[84b], D. Calvet[42], S. Calvet[42], R. Camacho Toro[130], S. Camarda[37], D. Camarero Munoz[27], P. Camarri[77a,77b], M.T. Camerlingo[73a,73b], D. Cameron[37], C. Camincher[170], M. Campanelli[98], A. Camplani[44], V. Canale[73a,73b], A.C. Canbay[3a], E. Canonero[97], J. Cantero[168], Y. Cao[167], F. Capocasa[27], M. Capua[45b,45a], A. Carbone[72a,72b], R. Cardarelli[77a], J.C.J. Cardenas[8], M.P. Cardiff[27], G. Carducci[45b,45a], T. Carli[37], G. Carlino[73a], J.I. Carlotto[13], B.T. Carlson[132,s], E.M. Carlson[170], J. Carmignani[94], L. Carminati[72a,72b], A. Carnelli[138], M. Carnesale[37], S. Caron[116], E. Carquin[140f], I.B. Carr[107], S. Carrá[72a], G. Carratta[24b,24a], A.M. Carroll[126], M.P. Casado[13,i], M. Caspar[49], F.L. Castillo[4], L. Castillo Garcia[13], V. Castillo Gimenez[168], N.F. Castro[133a,133e], A. Catinaccio[37], J.R. Catmore[128], T. Cavaliere[4], V. Cavaliere[30], L.J. Caviedes Betancourt[23b], Y.C. Cekmecelioglu[49], E. Celebi[83], S. Cella[37], V. Cepaitis[57], K. Cerny[125], A.S. Cerqueira[84a], A. Cerri[75a,75b], L. Cerrito[77a,77b], F. Cerutti[18a], B. Cervato[145], A. Cervelli[24b], G. Cesarini[54],

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S.A. Cetin[83], P.M. Chabrillat[130], J. Chan[18a], W.Y. Chan[157], J.D. Chapman[33], E. Chapon[138], B. Chargeishvili[153b], D.G. Charlton[21], C. Chauhan[136], Y. Che[114a], S. Chekanov[6], S.V. Chekulaev[160a], G.A. Chelkov[40,a], B. Chen[155], B. Chen[170], H. Chen[114a], H. Chen[30], J. Chen[63c], J. Chen[146], M. Chen[129], S. Chen[89], S.J. Chen[114a], X. Chen[63c], X. Chen[15,ag], C.L. Cheng[175], H.C. Cheng[65a], S. Cheong[147], A. Cheplakov[40], E. Cheremushkina[49], E. Cherepanova[117], R. Cherkaoui El Moursli[36e], E. Cheu[7], K. Cheung[66], L. Chevalier[138], V. Chiarella[54], G. Chiarelli[75a], N. Chiedde[104], G. Chiodini[71a], A.S. Chisholm[21], A. Chitan[28b], M. Chitishvili[168], M.V. Chizhov[40,t], K. Choi[11], Y. Chou[142], E.Y.S. Chow[116], K.L. Chu[174], M.C. Chu[65a], X. Chu[14,114c], Z. Chubinidze[54], J. Chudoba[134], J.J. Chwastowski[88], D. Cieri[112], K.M. Ciesla[87a], V. Cindro[95], A. Ciocio[18a], F. Cirotto[73a,73b], Z.H. Citron[174], M. Citterio[72a], D.A. Ciubotaru[28b], A. Clark[57], P.J. Clark[53], N. Clarke Hall[98], C. Clarry[159], S.E. Clawson[49], C. Clement[48a,48b], Y. Coadou[104], M. Cobal[70a,70c], A. Coccaro[58b], R.F. Coelho Barrue[133a], R. Coelho Lopes De Sa[105], S. Coelli[72a], L.S. Colangeli[159], B. Cole[43], P. Collado Soto[101], J. Collot[61], P. Conde Muiño[133a,133g], M.P. Connell[34c], S.H. Connell[34c], E.I. Conroy[129], F. Conventi[73a,ai], H.G. Cooke[21], A.M. Cooper-Sarkar[129], F.A. Corchia[24b,24a], A. Cordeiro Oudot Choi[130], L.D. Corpe[42], M. Corradi[76a,76b], F. Corriveau[106,ab], A. Cortes-Gonzalez[19], M.J. Costa[168], F. Costanza[4], D. Costanzo[143], B.M. Cote[122], J. Couthures[4], G. Cowan[97], K. Cranmer[175], L. Cremer[50], D. Cremonini[24b,24a], S. Crépé-Renaudin[61], F. Crescioli[130], M. Cristinziani[145], M. Cristoforetti[79a,79b], V. Croft[117], J.E. Crosby[124], G. Crosetti[45b,45a], A. Cueto[101], H. Cui[98], Z. Cui[7], W.R. Cunningham[60], F. Curcio[168], J.R. Curran[53], P. Czodrowski[37], M.J. Da Cunha Sargedas De Sousa[58b,58a], J.V. Da Fonseca Pinto[84b], C. Da Via[103], W. Dabrowski[87a], T. Dado[37], S. Dahbi[152], T. Dai[108], D. Dal Santo[20], C. Dallapiccola[105], M. Dam[44], G. D'amen[30], V. D'Amico[111], J. Damp[102], J.R. Dandoy[35], D. Dannheim[37], M. Danninger[146], V. Dao[149], G. Darbo[58b], S.J. Das[30], F. Dattola[49], S. D'Auria[72a,72b], A. D'Avanzo[73a,73b], T. Davidek[136], I. Dawson[96], H.A. Day-hall[135], K. De[8], C. De Almeida Rossi[159], R. De Asmundis[73a], N. De Biase[49], S. De Castro[24b,24a], N. De Groot[116], P. de Jong[117], H. De la Torre[118], A. De Maria[114a], A. De Salvo[76a], U. De Sanctis[77a,77b], F. De Santis[71a,71b], A. De Santo[150], J.B. De Vivie De Regie[61], J. Debevc[95], D.V. Dedovich[40], J. Degens[94], A.M. Deiana[46], J. Del Peso[101], L. Delagrange[130], F. Deliot[138], C.M. Delitzsch[50], M. Della Pietra[73a,73b], D. Della Volpe[57], A. Dell'Acqua[37], L. Dell'Asta[72a,72b], M. Delmastro[4], C.C. Delogu[102], P.A. Delsart[61], S. Demers[177], M. Demichev[40], S.P. Denisov[39], H. Denizli[22a,l], L. D'Eramo[42], D. Derendarz[88], F. Derue[130], P. Dervan[94], K. Desch[25], C. Deutsch[25], F.A. Di Bello[58b,58a], A. Di Ciaccio[77a,77b], L. Di Ciaccio[4], A. Di Domenico[76a,76b], C. Di Donato[73a,73b], A. Di Girolamo[37], G. Di Gregorio[37], A. Di Luca[79a,79b], B. Di Micco[78a,78b], R. Di Nardo[78a,78b], K.F. Di Petrillo[41], M. Diamantopoulou[35], F.A. Dias[117], T. Dias Do Vale[146], M.A. Diaz[140a,140b], A.R. Didenko[40], M. Didenko[168], E.B. Diehl[108], S. Díez Cornell[49], C. Diez Pardos[145], C. Dimitriadi[148], A. Dimitrievska[21], A. Dimri[149], J. Dingfelder[25], T. Dingley[129], I-M. Dinu[28b], S.J. Dittmeier[64b], F. Dittus[37], M. Divisek[136], B. Dixit[94], F. Djama[104], T. Djobava[153b], C. Doglioni[103,100], A. Dohnalova[29a], Z. Dolezal[136], K. Domijan[87a], K.M. Dona[41], M. Donadelli[84d],

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I. Sykora[29a], M. Sykora[136], T. Sykora[136], D. Ta[102], K. Tackmann[49,y], A. Taffard[163], R. Tafirout[160a], J.S. Tafoya Vargas[67], Y. Takubo[85], M. Talby[104], A.A. Talyshev[39], K.C. Tam[65b], N.M. Tamir[155], A. Tanaka[157], J. Tanaka[157], R. Tanaka[67], M. Tanasini[149], Z. Tao[169], S. Tapia Araya[140f], S. Tapprogge[102], A. Tarek Abouelfadl Mohamed[109], S. Tarem[154], K. Tariq[14], G. Tarna[28b], G.F. Tartarelli[72a], M.J. Tartarin[91], P. Tas[136], M. Tasevsky[134], E. Tassi[45b,45a], A.C. Tate[167], G. Tateno[157], Y. Tayalati[36e,aa], G.N. Taylor[107], W. Taylor[160b], A.S. Tegetmeier[91], P. Teixeira-Dias[97], J.J. Teoh[159], K. Terashi[157], J. Terron[101], S. Terzo[13], M. Testa[54], R.J. Teuscher[159,ab], A. Thaler[80], O. Theiner[57], T. Theveneaux-Pelzer[104], O. Thielmann[176], D.W. Thomas[97], J.P. Thomas[21], E.A. Thompson[18a], P.D. Thompson[21], E. Thomson[131], R.E. Thornberry[46], C. Tian[63a], Y. Tian[57], V. Tikhomirov[39,a], Yu.A. Tikhonov[39], S. Timoshenko[39], D. Timoshyn[136], E.X.L. Ting[1], P. Tipton[177], A. Tishelman-Charny[30], S.H. Tlou[34g], K. Todome[141], S. Todorova-Nova[136], S. Todt[51], L. Toffolin[70a,70c], M. Togawa[85], J. Tojo[90], S. Tokár[29a], O. Toldaiev[69], G. Tolkachev[104], M. Tomoto[85,113], L. Tompkins[147,o], E. Torrence[126], H. Torres[91], E. Torró Pastor[168], M. Toscani[31], C. Tosciri[41], M. Tost[11], D.R. Tovey[143], T. Trefzger[171], A. Tricoli[30], I.M. Trigger[160a], S. Trincaz-Duvoid[130], D.A. Trischuk[27], A. Tropina[40], L. Truong[34c], M. Trzebinski[88], A. Trzupek[88], F. Tsai[149], M. Tsai[108], A. Tsiamis[156], P.V. Tsiareshka[40], S. Tsigaridas[160a], A. Tsirigotis[156,u], V. Tsiskaridze[159], E.G. Tskhadadze[153a], M. Tsopoulou[156], Y. Tsujikawa[89], I.I. Tsukerman[39], V. Tsulaia[18a], S. Tsuno[85], K. Tsuri[121], D. Tsybychev[149], Y. Tu[65b], A. Tudorache[28b], V. Tudorache[28b], S. Turchikhin[58b,58a], I. Turk Cakir[3a], R. Turra[72a], T. Turtuvshin[40,ac], P.M. Tuts[43], S. Tzamarias[156,e], E. Tzovara[102], F. Ukegawa[161], P.A. Ulloa Poblete[140c,140b], E.N. Umaka[30], G. Unal[37], A. Undrus[30], G. Unel[163], J. Urban[29b], P. Urrejola[140a], G. Usai[8], R. Ushioda[158], M. Usman[110], F. Ustuner[53], Z. Uysal[83], V. Vacek[135], B. Vachon[106], T. Vafeiadis[37], A. Vaitkus[98], C. Valderanis[111], E. Valdes Santurio[48a,48b], M. Valente[160a], S. Valentinetti[24b,24a], A. Valero[168], E. Valiente Moreno[168], A. Vallier[91], J.A. Valls Ferrer[168], D.R. Van Arneman[117], T.R. Van Daalen[142], A. Van Der Graaf[50], H.Z. Van Der Schyf[34g], P. Van Gemmeren[6], M. Van Rijnbach[37], S. Van Stroud[98], I. Van Vulpen[117], P. Vana[136], M. Vanadia[77a,77b], U.M. Vande Voorde[148], W. Vandelli[37], E.R. Vandewall[124], D. Vannicola[155], L. Vannoli[54], R. Vari[76a], E.W. Varnes[7], C. Varni[18b], D. Varouchas[67], L. Varriale[168], K.E. Varvell[151], M.E. Vasile[28b], L. Vaslin[85], A. Vasyukov[40], L.M. Vaughan[124], R. Vavricka[136], T. Vazquez Schroeder[13], J. Veatch[32], V. Vecchio[103], M.J. Veen[105], I. Veliscek[30], L.M. Veloce[159], F. Veloso[133a,133c], S. Veneziano[76a], A. Ventura[71a,71b], S. Ventura Gonzalez[138], A. Verbytskyi[112], M. Verducci[75a,75b], C. Vergis[96], M. Verissimo De Araujo[84b], W. Verkerke[117], J.C. Vermeulen[117], C. Vernieri[147], M. Vessella[163], M.C. Vetterli[146,ah], A. Vgenopoulos[102], N. Viaux Maira[140f], T. Vickey[143], O.E. Vickey Boeriu[143], G.H.A. Viehhauser[129], L. Vigani[64b], M. Vigl[112], M. Villa[24b,24a], M. Villaplana Perez[168], E.M. Villhauer[53], E. Vilucchi[54], M.G. Vincter[35], A. Visibile[117], C. Vittori[37], I. Vivarelli[24b,24a], E. Voevodina[112], F. Vogel[111], J.C. Voigt[51], P. Vokac[135], Yu. Volkotrub[87b], E. Von Toerne[25], B. Vormwald[37], K. Vorobev[39], M. Vos[168], K. Voss[145], M. Vozak[37], L. Vozdecky[123], N. Vranjes[16], M. Vranjes Milosavljevic[16], M. Vreeswijk[117], N.K. Vu[63d,63c], R. Vuillermet[37], O. Vujinovic[102], I. Vukotic[41], I.K. Vyas[35], S. Wada[161], C. Wagner[147], J.M. Wagner[18a], W. Wagner[176], S. Wahdan[176], H. Wahlberg[92],

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C.H. Waits[123], J. Walder[137], R. Walker[111], W. Walkowiak[145], A. Wall[131], E.J. Wallin[100], T. Wamorkar[18a], A.Z. Wang[139], C. Wang[102], C. Wang[11], H. Wang[18a], J. Wang[65c], P. Wang[103], P. Wang[98], R. Wang[62], R. Wang[6], S.M. Wang[152], S. Wang[14], T. Wang[63a], W.T. Wang[81], W. Wang[14], X. Wang[167], X. Wang[63c], Y. Wang[114a], Y. Wang[63a], Z. Wang[108], Z. Wang[63d,52,63c], Z. Wang[108], C. Wanotayaroj[85], A. Warburton[106], R.J. Ward[21], A.L. Warnerbring[145], N. Warrack[60], S. Waterhouse[97], A.T. Watson[21], H. Watson[53], M.F. Watson[21], E. Watton[60], G. Watts[142], B.M. Waugh[98], J.M. Webb[55], C. Weber[30], H.A. Weber[19], M.S. Weber[20], S.M. Weber[64a], C. Wei[63a], Y. Wei[55], A.R. Weidberg[129], E.J. Weik[120], J. Weingarten[50], C. Weiser[55], C.J. Wells[49], T. Wenaus[30], B. Wendland[50], T. Wengler[37], N.S. Wenke[112], N. Wermes[25], M. Wessels[64a], A.M. Wharton[93], A.S. White[62], A. White[8], M.J. White[1], D. Whiteson[163], L. Wickremasinghe[127], W. Wiedenmann[175], M. Wielers[137], C. Wiglesworth[44], D.J. Wilbern[123], H.G. Wilkens[37], J.J.H. Wilkinson[33], D.M. Williams[43], H.H. Williams[131], S. Williams[33], S. Willocq[105], B.J. Wilson[103], D.J. Wilson[103], P.J. Windischhofer[41], F.I. Winkel[31], F. Winklmeier[126], B.T. Winter[55], M. Wittgen[147], M. Wobisch[99], T. Wojtkowski[61], Z. Wolffs[117], J. Wollrath[37], M.W. Wolter[88], H. Wolters[133a,133c], M.C. Wong[139], E.L. Woodward[43], S.D. Worm[49], B.K. Wosiek[88], K.W. Woźniak[88], S. Wozniewski[56], K. Wraight[60], C. Wu[21], M. Wu[114b], M. Wu[116], S.L. Wu[175], X. Wu[57], X. Wu[63a], Y. Wu[63a], Z. Wu[4], J. Wuerzinger[112,af], T.R. Wyatt[103], B.M. Wynne[53], S. Xella[44], L. Xia[114a], M. Xia[15], M. Xie[63a], A. Xiong[126], J. Xiong[18a], D. Xu[14], H. Xu[63a], L. Xu[63a], R. Xu[131], T. Xu[108], Y. Xu[142], Z. Xu[53], Z. Xu[114a], B. Yabsley[151], S. Yacoob[34a], Y. Yamaguchi[85], E. Yamashita[157], H. Yamauchi[161], T. Yamazaki[18a], Y. Yamazaki[86], S. Yan[60], Z. Yan[105], H.J. Yang[63c,63d], H.T. Yang[63a], S. Yang[63a], T. Yang[65c], X. Yang[37], X. Yang[14], Y. Yang[46], Y. Yang[63a], W-M. Yao[18a], H. Ye[56], J. Ye[14], S. Ye[30], X. Ye[63a], Y. Yeh[98], I. Yeletskikh[40], B. Yeo[18b], M.R. Yexley[98], T.P. Yildirim[129], P. Yin[43], K. Yorita[173], S. Younas[28b], C.J.S. Young[37], C. Young[147], N.D. Young[126], Y. Yu[63a], J. Yuan[14,114c], M. Yuan[108], R. Yuan[63d,63c], L. Yue[98], M. Zaazoua[63a], B. Zabinski[88], I. Zahir[36a], Z.K. Zak[88], T. Zakareishvili[168], S. Zambito[57], J.A. Zamora Saa[140d,140b], J. Zang[157], D. Zanzi[55], R. Zanzottera[72a,72b], O. Zaplatilek[135], C. Zeitnitz[176], H. Zeng[14], J.C. Zeng[167], D.T. Zenger Jr[27], O. Zenin[39], T. Ženiš[29a], S. Zenz[96], S. Zerradi[36a], D. Zerwas[67], M. Zhai[14,114c], D.F. Zhang[143], J. Zhang[63b], J. Zhang[6], K. Zhang[14,114c], L. Zhang[63a], L. Zhang[114a], P. Zhang[14,114c], R. Zhang[175], S. Zhang[91], T. Zhang[157], X. Zhang[63c], Y. Zhang[142], Y. Zhang[98], Y. Zhang[63a], Y. Zhang[114a], Z. Zhang[18a], Z. Zhang[63b], Z. Zhang[67], H. Zhao[142], T. Zhao[63b], Y. Zhao[35], Z. Zhao[63a], Z. Zhao[63a], A. Zhemchugov[40], J. Zheng[114a], K. Zheng[167], X. Zheng[63a], Z. Zheng[147], D. Zhong[167], B. Zhou[108], H. Zhou[7], N. Zhou[63c], Y. Zhou[15], Y. Zhou[114a], Y. Zhou[7], C.G. Zhu[63b], J. Zhu[108], X. Zhu[63d], Y. Zhu[63c], Y. Zhu[63a], X. Zhuang[14], K. Zhukov[69], N.I. Zimine[40], J. Zinsser[64b], M. Ziolkowski[145], L. Živković[16], A. Zoccoli[24b,24a], K. Zoch[62], T.G. Zorbas[143], O. Zormpa[47], W. Zou[43], L. Zwalinski[37]

[1] *Department of Physics, University of Adelaide, Adelaide, Australia*

[2] *Department of Physics, University of Alberta, Edmonton AB, Canada*

[3] [(a)] *Department of Physics, Ankara University, Ankara;* [(b)] *Division of Physics, TOBB University of Economics and Technology, Ankara, Türkiye*

[4] *LAPP, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France*

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[5] APC, Université Paris Cité, CNRS/IN2P3, Paris, France
[6] High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America
[7] Department of Physics, University of Arizona, Tucson AZ, United States of America
[8] Department of Physics, University of Texas at Arlington, Arlington TX, United States of America
[9] Physics Department, National and Kapodistrian University of Athens, Athens, Greece
[10] Physics Department, National Technical University of Athens, Zografou, Greece
[11] Department of Physics, University of Texas at Austin, Austin TX, United States of America
[12] Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[13] Institut de Física d'Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
[14] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
[15] Physics Department, Tsinghua University, Beijing, China
[16] Institute of Physics, University of Belgrade, Belgrade, Serbia
[17] Department for Physics and Technology, University of Bergen, Bergen, Norway
[18] [(a)] Physics Division, Lawrence Berkeley National Laboratory, Berkeley CA; [(b)] University of California, Berkeley CA, United States of America
[19] Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
[20] Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
[21] School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
[22] [(a)] Department of Physics, Bogazici University, Istanbul; [(b)] Department of Physics Engineering, Gaziantep University, Gaziantep; [(c)] Department of Physics, Istanbul University, Istanbul, Türkiye
[23] [(a)] Facultad de Ciencias y Centro de Investigaciónes, Universidad Antonio Nariño, Bogotá; [(b)] Departamento de Física, Universidad Nacional de Colombia, Bogotá, Colombia
[24] [(a)] Dipartimento di Fisica e Astronomia A. Righi, Università di Bologna, Bologna; [(b)] INFN Sezione di Bologna, Italy
[25] Physikalisches Institut, Universität Bonn, Bonn, Germany
[26] Department of Physics, Boston University, Boston MA, United States of America
[27] Department of Physics, Brandeis University, Waltham MA, United States of America
[28] [(a)] Transilvania University of Brasov, Brasov; [(b)] Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; [(c)] Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; [(d)] National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; [(e)] National University of Science and Technology Politechnica, Bucharest; [(f)] West University in Timisoara, Timisoara; [(g)] Faculty of Physics, University of Bucharest, Bucharest, Romania
[29] [(a)] Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; [(b)] Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
[30] Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
[31] Universidad de Buenos Aires, Facultad de Ciencias Exactas y Naturales, Departamento de Física, y CONICET, Instituto de Física de Buenos Aires (IFIBA), Buenos Aires, Argentina
[32] California State University, CA, United States of America
[33] Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
[34] [(a)] Department of Physics, University of Cape Town, Cape Town; [(b)] iThemba Labs, Western Cape; [(c)] Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; [(d)] National Institute of Physics, University of the Philippines Diliman (Philippines); [(e)] University of South Africa, Department of Physics, Pretoria; [(f)] University of Zululand, KwaDlangezwa; [(g)] School of Physics, University of the Witwatersrand, Johannesburg, South Africa
[35] Department of Physics, Carleton University, Ottawa ON, Canada
[36] [(a)] Faculté des Sciences Ain Chock, Université Hassan II de Casablanca; [(b)] Faculté des Sciences, Université Ibn-Tofail, Kénitra; [(c)] Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; [(d)] LPMR, Faculté des Sciences, Université Mohamed Premier, Oujda; [(e)] Faculté des sciences, Université Mohammed V, Rabat; [(f)] Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco

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[37] *CERN, Geneva, Switzerland*
[38] *Affiliated with an institute formerly covered by a cooperation agreement with CERN*
[39] *Affiliated with an institute covered by a cooperation agreement with CERN*
[40] *Affiliated with an international laboratory covered by a cooperation agreement with CERN*
[41] *Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America*
[42] *LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France*
[43] *Nevis Laboratory, Columbia University, Irvington NY, United States of America*
[44] *Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark*
[45] [(a)] *Dipartimento di Fisica, Università della Calabria, Rende;* [(b)] *INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy*
[46] *Physics Department, Southern Methodist University, Dallas TX, United States of America*
[47] *National Centre for Scientific Research "Demokritos", Agia Paraskevi, Greece*
[48] [(a)] *Department of Physics, Stockholm University;* [(b)] *Oskar Klein Centre, Stockholm, Sweden*
[49] *Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany*
[50] *Fakultät Physik, Technische Universität Dortmund, Dortmund, Germany*
[51] *Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
[52] *Department of Physics, Duke University, Durham NC, United States of America*
[53] *SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
[54] *INFN e Laboratori Nazionali di Frascati, Frascati, Italy*
[55] *Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany*
[56] *II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany*
[57] *Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland*
[58] [(a)] *Dipartimento di Fisica, Università di Genova, Genova;* [(b)] *INFN Sezione di Genova, Italy*
[59] *II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
[60] *SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
[61] *LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France*
[62] *Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America*
[63] [(a)] *Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei;* [(b)] *Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao;* [(c)] *School of Physics and Astronomy, Shanghai Jiao Tong University, Key Laboratory for Particle Astrophysics and Cosmology (MOE), SKLPPC, Shanghai;* [(d)] *Tsung-Dao Lee Institute, Shanghai;* [(e)] *School of Physics, Zhengzhou University, China*
[64] [(a)] *Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;* [(b)] *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany*
[65] [(a)] *Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong;* [(b)] *Department of Physics, University of Hong Kong, Hong Kong;* [(c)] *Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China*
[66] *Department of Physics, National Tsing Hua University, Hsinchu, Taiwan*
[67] *IJCLab, Université Paris-Saclay, CNRS/IN2P3, 91405, Orsay, France*
[68] *Centro Nacional de Microelectrónica (IMB-CNM-CSIC), Barcelona, Spain*
[69] *Department of Physics, Indiana University, Bloomington IN, United States of America*
[70] [(a)] *INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine;* [(b)] *ICTP, Trieste;* [(c)] *Dipartimento Politecnico di Ingegneria e Architettura, Università di Udine, Udine, Italy*
[71] [(a)] *INFN Sezione di Lecce;* [(b)] *Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
[72] [(a)] *INFN Sezione di Milano;* [(b)] *Dipartimento di Fisica, Università di Milano, Milano, Italy*
[73] [(a)] *INFN Sezione di Napoli;* [(b)] *Dipartimento di Fisica, Università di Napoli, Napoli, Italy*
[74] [(a)] *INFN Sezione di Pavia;* [(b)] *Dipartimento di Fisica, Università di Pavia, Pavia, Italy*
[75] [(a)] *INFN Sezione di Pisa;* [(b)] *Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy*
[76] [(a)] *INFN Sezione di Roma;* [(b)] *Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy*
[77] [(a)] *INFN Sezione di Roma Tor Vergata;* [(b)] *Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy*

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[78] [(a)] *INFN Sezione di Roma Tre;* [(b)] *Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy*
[79] [(a)] *INFN-TIFPA;* [(b)] *Università degli Studi di Trento, Trento, Italy*
[80] *Universität Innsbruck, Department of Astro and Particle Physics, Innsbruck, Austria*
[81] *University of Iowa, Iowa City IA, United States of America*
[82] *Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America*
[83] *Istinye University, Sariyer, Istanbul, Türkiye*
[84] [(a)] *Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora;* [(b)] *Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;* [(c)] *Instituto de Física, Universidade de São Paulo, São Paulo;* [(d)] *Rio de Janeiro State University, Rio de Janeiro;* [(e)] *Federal University of Bahia, Bahia, Brazil*
[85] *KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
[86] *Graduate School of Science, Kobe University, Kobe, Japan*
[87] [(a)] *AGH University of Krakow, Faculty of Physics and Applied Computer Science, Krakow;* [(b)] *Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
[88] *Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland*
[89] *Faculty of Science, Kyoto University, Kyoto, Japan*
[90] *Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka, Japan*
[91] *L2IT, Université de Toulouse, CNRS/IN2P3, UPS, Toulouse, France*
[92] *Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
[93] *Physics Department, Lancaster University, Lancaster, United Kingdom*
[94] *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
[95] *Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana, Slovenia*
[96] *School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
[97] *Department of Physics, Royal Holloway University of London, Egham, United Kingdom*
[98] *Department of Physics and Astronomy, University College London, London, United Kingdom*
[99] *Louisiana Tech University, Ruston LA, United States of America*
[100] *Fysiska institutionen, Lunds universitet, Lund, Sweden*
[101] *Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid, Spain*
[102] *Institut für Physik, Universität Mainz, Mainz, Germany*
[103] *School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*
[104] *CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France*
[105] *Department of Physics, University of Massachusetts, Amherst MA, United States of America*
[106] *Department of Physics, McGill University, Montreal QC, Canada*
[107] *School of Physics, University of Melbourne, Victoria, Australia*
[108] *Department of Physics, University of Michigan, Ann Arbor MI, United States of America*
[109] *Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America*
[110] *Group of Particle Physics, University of Montreal, Montreal QC, Canada*
[111] *Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany*
[112] *Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany*
[113] *Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan*
[114] [(a)] *Department of Physics, Nanjing University, Nanjing;* [(b)] *School of Science, Shenzhen Campus of Sun Yat-sen University;* [(c)] *University of Chinese Academy of Science (UCAS), Beijing, China*
[115] *Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America*
[116] *Institute for Mathematics, Astrophysics and Particle Physics, Radboud University/Nikhef, Nijmegen, Netherlands*
[117] *Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands*
[118] *Department of Physics, Northern Illinois University, DeKalb IL, United States of America*
[119] [(a)] *New York University Abu Dhabi, Abu Dhabi;* [(b)] *United Arab Emirates University, Al Ain, United Arab Emirates*

[120] *Department of Physics, New York University, New York NY, United States of America*
[121] *Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo, Japan*
[122] *Ohio State University, Columbus OH, United States of America*
[123] *Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America*
[124] *Department of Physics, Oklahoma State University, Stillwater OK, United States of America*
[125] *Palacký University, Joint Laboratory of Optics, Olomouc, Czech Republic*
[126] *Institute for Fundamental Science, University of Oregon, Eugene, OR, United States of America*
[127] *Graduate School of Science, Osaka University, Osaka, Japan*
[128] *Department of Physics, University of Oslo, Oslo, Norway*
[129] *Department of Physics, Oxford University, Oxford, United Kingdom*
[130] *LPNHE, Sorbonne Université, Université Paris Cité, CNRS/IN2P3, Paris, France*
[131] *Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America*
[132] *Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America*
[133] [(a)] *Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa;* [(b)] *Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa;* [(c)] *Departamento de Física, Universidade de Coimbra, Coimbra;* [(d)] *Centro de Física Nuclear da Universidade de Lisboa, Lisboa;* [(e)] *Departamento de Física, Escola de Ciências, Universidade do Minho, Braga;* [(f)] *Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain);* [(g)] *Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal*
[134] *Institute of Physics of the Czech Academy of Sciences, Prague, Czech Republic*
[135] *Czech Technical University in Prague, Prague, Czech Republic*
[136] *Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic*
[137] *Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom*
[138] *IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France*
[139] *Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America*
[140] [(a)] *Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;* [(b)] *Millennium Institute for Subatomic physics at high energy frontier (SAPHIR), Santiago;* [(c)] *Instituto de Investigación Multidisciplinario en Ciencia y Tecnología, y Departamento de Física, Universidad de La Serena;* [(d)] *Universidad Andres Bello, Department of Physics, Santiago;* [(e)] *Instituto de Alta Investigación, Universidad de Tarapacá, Arica;* [(f)] *Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
[141] *Department of Physics, Institute of Science, Tokyo, Japan*
[142] *Department of Physics, University of Washington, Seattle WA, United States of America*
[143] *Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom*
[144] *Department of Physics, Shinshu University, Nagano, Japan*
[145] *Department Physik, Universität Siegen, Siegen, Germany*
[146] *Department of Physics, Simon Fraser University, Burnaby BC, Canada*
[147] *SLAC National Accelerator Laboratory, Stanford CA, United States of America*
[148] *Department of Physics, Royal Institute of Technology, Stockholm, Sweden*
[149] *Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY, United States of America*
[150] *Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom*
[151] *School of Physics, University of Sydney, Sydney, Australia*
[152] *Institute of Physics, Academia Sinica, Taipei, Taiwan*
[153] [(a)] *E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;* [(b)] *High Energy Physics Institute, Tbilisi State University, Tbilisi;* [(c)] *University of Georgia, Tbilisi, Georgia*
[154] *Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel*
[155] *Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel*
[156] *Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece*
[157] *International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan*

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[158] Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
[159] Department of Physics, University of Toronto, Toronto ON, Canada
[160] [(a)] TRIUMF, Vancouver BC; [(b)] Department of Physics and Astronomy, York University, Toronto ON, Canada
[161] Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
[162] Department of Physics and Astronomy, Tufts University, Medford MA, United States of America
[163] Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America
[164] University of West Attica, Athens, Greece
[165] University of Sharjah, Sharjah, United Arab Emirates
[166] Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
[167] Department of Physics, University of Illinois, Urbana IL, United States of America
[168] Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain
[169] Department of Physics, University of British Columbia, Vancouver BC, Canada
[170] Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
[171] Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
[172] Department of Physics, University of Warwick, Coventry, United Kingdom
[173] Waseda University, Tokyo, Japan
[174] Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Rehovot, Israel
[175] Department of Physics, University of Wisconsin, Madison WI, United States of America
[176] Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
[177] Department of Physics, Yale University, New Haven CT, United States of America
[178] Yerevan Physics Institute, Yerevan, Armenia

[a] Also Affiliated with an institute covered by a cooperation agreement with CERN
[b] Also at An-Najah National University, Nablus, Palestine
[c] Also at Borough of Manhattan Community College, City University of New York, New York NY, United States of America
[d] Also at Center for High Energy Physics, Peking University, China
[e] Also at Center for Interdisciplinary Research and Innovation (CIRI-AUTH), Thessaloniki, Greece
[f] Also at CERN, Geneva, Switzerland
[g] Also at CMD-AC UNEC Research Center, Azerbaijan State University of Economics (UNEC), Azerbaijan
[h] Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève, Switzerland
[i] Also at Departament de Fisica de la Universitat Autonoma de Barcelona, Barcelona, Spain
[j] Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece
[k] Also at Department of Mathematical Sciences, University of South Africa, Johannesburg, South Africa
[l] Also at Department of Physics, Bolu Abant Izzet Baysal University, Bolu, Türkiye
[m] Also at Department of Physics, California State University, Sacramento, United States of America
[n] Also at Department of Physics, King's College London, London, United Kingdom
[o] Also at Department of Physics, Stanford University, Stanford CA, United States of America
[p] Also at Department of Physics, Stellenbosch University, South Africa
[q] Also at Department of Physics, University of Fribourg, Fribourg, Switzerland
[r] Also at Department of Physics, University of Thessaly, Greece
[s] Also at Department of Physics, Westmont College, Santa Barbara, United States of America
[t] Also at Faculty of Physics, Sofia University, 'St. Kliment Ohridski', Sofia, Bulgaria
[u] Also at Hellenic Open University, Patras, Greece
[v] Also at Henan University, China
[w] Also at Imam Mohammad Ibn Saud Islamic University, Saudi Arabia
[x] Also at Institucio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
[y] Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
[z] Also at Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences, Sofia, Bulgaria

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[aa] Also at Institute of Applied Physics, Mohammed VI Polytechnic University, Ben Guerir, Morocco
[ab] Also at Institute of Particle Physics (IPP), Canada
[ac] Also at Institute of Physics and Technology, Mongolian Academy of Sciences, Ulaanbaatar, Mongolia
[ad] Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[ae] Also at National Institute of Physics, University of the Philippines Diliman (Philippines), Philippines
[af] Also at Technical University of Munich, Munich, Germany
[ag] Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China
[ah] Also at TRIUMF, Vancouver BC, Canada
[ai] Also at Università di Napoli Parthenope, Napoli, Italy
[aj] Also at University of Colorado Boulder, Department of Physics, Colorado, United States of America
[ak] Also at University of the Western Cape, South Africa
[al] Also at Washington College, Chestertown, MD, United States of America
[am] Also at Yeditepe University, Physics Department, Istanbul, Türkiye
[*] Deceased

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