

# Search for displaced photons produced in exotic decays of the Higgs boson using 13 TeV $pp$ collisions with the ATLAS detector

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A search is performed for delayed and nonpointing photons originating from the displaced decay of a neutral long-lived particle (LLP). The analysis uses the full run 2 dataset of proton-proton collisions delivered by the LHC at a center-of-mass energy of  $\sqrt{s} = 13$  TeV between 2015 and 2018 and recorded by the ATLAS detector, corresponding to an integrated luminosity of  $139 \text{ fb}^{-1}$ . The capabilities of the ATLAS electromagnetic calorimeter are exploited to precisely measure the arrival times and trajectories of photons. The results are interpreted in a scenario where the LLPs are pair produced in exotic decays of the 125 GeV Higgs boson, and each LLP subsequently decays into a photon and a particle that escapes direct detection, giving rise to missing transverse momentum. No significant excess is observed above the expectation due to Standard Model background processes. The results are used to set upper limits on the branching ratio of the exotic decay of the Higgs boson. A model-independent limit is also set on the production of photons with large values of displacement and time delay.

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## I. INTRODUCTION

The Standard Model (SM) provides an accurate description of the fundamental particles and interactions at energy scales up to a few hundred GeV. However, the SM fails to explain several key phenomena, such as gravity, dark matter, and the matter-antimatter asymmetry in the Universe. Such shortcomings suggest the presence of new physics, motivating the search for beyond-the-SM (BSM) physics.

Supersymmetry (SUSY) [1–7] is a theoretically well-motivated extension of the SM that proposes the existence of new SUSY partners (sparticles) of the SM particles. The sparticle has identical quantum numbers to its SM partner, differing only by half a unit of spin. A new quantum number, dubbed R parity, distinguishes between supersymmetric and SM particles. In R-parity-conserving SUSY models [8–12], the lightest SUSY particle (LSP) is stable, and SUSY production in proton-proton ( $pp$ ) collisions at the LHC would produce sparticles in pairs. The sparticles would then decay in cascades involving other sparticles and SM particles until the LSP is produced. A neutral, weakly interacting LSP would usually escape the detector without interacting, so LHC searches for SUSY often require a large amount of missing transverse momentum ( $E_T^{\text{miss}}$ ) in the event.

In gauge-mediated SUSY breaking (GMSB) models [13–18], the gravitino ( $\tilde{G}$ ) is the LSP for typical model parameter values. GMSB phenomenology is largely determined by the properties of the next-to-lightest supersymmetric particle (NLSP), since the decay chains of the sparticles with higher mass would typically lead to the NLSP, which would subsequently decay to produce the LSP. The weak coupling of the NLSP to the gravitino LSP could generate a non-negligible lifetime of the NLSP, leading to displaced NLSP decays [17].

An electrically neutral long-lived NLSP would avoid direct detection as it traveled partway (or entirely) through the ATLAS detector before decaying, with a prominent decay mode being to a photon plus the LSP. The photons resulting from displaced NLSP decays would be produced with some delay compared to prompt photons, due mostly to the time of flight of the massive NLSP before its decay. In addition, due to the opening angle between the photon and LSP produced in the NLSP decay, the photons would tend to be “nonpointing,” meaning that their flight path would not be consistent with originating from the primary vertex (PV) of the hard scatter of the event. The capabilities of the ATLAS liquid-argon (LAr) electromagnetic (EM) calorimeter to make precise “pointing” measurements of the flight direction and the arrival time of photons ( $t_\gamma$ ) can be exploited to search for such photons. Given the size of the ATLAS detector, requiring LAr calorimeter measurements of the delayed photons restricts the sensitivity of the analysis to NLSP lifetimes of  $\mathcal{O}(\text{ns})$ .

Previous ATLAS analyses searched for nonpointing and delayed photons produced in long-lived NLSP decays in

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the datasets of  $pp$  collisions collected at center-of-mass energies of 7 [19] and 8 TeV [20] during run 1 of the LHC. Neither search found an excess above the SM background expectation and set limits in the context of a particular set of GMSB SUSY models. A recent run 2 CMS search for long-lived particles in such models also found that their data agreed with the SM prediction [21].

The discovery in 2012 of a particle with a mass near 125 GeV that is consistent with expectations for the SM Higgs boson opens new avenues for searches with BSM sensitivity. Specifically, the coupling of the Higgs boson to mass leads to search prospects for pairs of sparticles produced in Higgs boson decays, provided the sparticles are sufficiently light. Additional motivation for this production mechanism arises from current uncertainties in the branching ratios of the Higgs boson. Current experimental constraints from the Higgs boson property measurements allow the branching ratio for Higgs boson decays into invisible BSM states to be as large as 13% at 95% C.L. [22].

This analysis utilizes the full run 2 ATLAS dataset of 13 TeV  $pp$  collisions and searches for evidence of Higgs boson decays into a pair of long-lived electrically neutral NLSP particles, each of which subsequently decays into an LSP, which escapes the detector, and a photon. Given the value of the Higgs boson mass, the energies of the final-state photons, as well as the value of  $E_T^{\text{miss}}$ , are not sufficiently high to provide a trigger for the events. Instead, the analysis considers SM Higgs boson production in association with either a  $Z$  boson,  $W$  boson or  $t\bar{t}$  system. Leptonic decays of the associated  $W/Z$  boson or  $t\bar{t}$  system are exploited to provide a single-lepton (electron or muon) trigger. An example leading-order Feynman diagram, for the case of  $H + Z$  production, is shown in Fig. 1. To reduce the model dependence of the results, the analysis considers a simplified model where the masses of the NLSP and LSP and the lifetime of the NLSP are treated as independent parameters.

In addition to the requirement of the lepton trigger, selected events must have at least one photon candidate. Events are divided into two orthogonal final states, with the  $1\gamma$  final state requiring exactly one photon and the  $\geq 2\gamma$  final state requiring two or more photons. As detailed in Sec. V, the analysis strategy exploits measures of photon pointing and timing. The pointing information is used to divide the selected events into five nonoverlapping categories with different signal-to-background ratios, while the timing information provides the distribution for a likelihood fit used to search for the possible presence of signal events.

The analysis exploits the expectation of significant  $E_T^{\text{miss}}$  in signal events, due to the escaping LSPs, as well as any neutrinos produced in the leptonic decays of the associated system. In addition, the signal would produce delayed photons, which would have a positive value for their time of

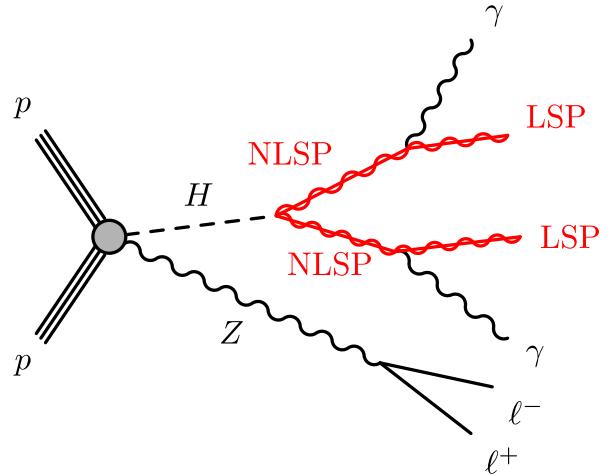


FIG. 1. Example Feynman diagram of the signal model, with a Higgs boson produced in association with a  $Z$  boson. The Higgs boson decays into a pair of electrically neutral NLSP particles which are long-lived, each of which then decays into a photon and an LSP. The  $Z$  boson decays into a charged-lepton pair (electrons or muons).

arrival at the EM calorimeter, whereas prompt backgrounds have time distributions centered at zero. The analysis therefore performs the signal search utilizing a signal region (SR) defined by requiring high  $E_T^{\text{miss}}$  and  $t_\gamma > 0$ . The data-driven background estimate is determined using a control region (CR) with low values of  $E_T^{\text{miss}}$ . The background estimate is validated using two different validation regions (VRs): the first requires intermediate values of  $E_T^{\text{miss}}$  and is denoted by  $\text{VR}(E_T^{\text{miss}})$ , while the second, denoted by  $\text{VR}(t)$ , imposes the same  $E_T^{\text{miss}}$  requirement as the SR but reverses the timing requirement by requiring  $t_\gamma < 0$ . By construction, the various regions are mutually exclusive, and any signal contamination of the CR,  $\text{VR}(E_T^{\text{miss}})$  and  $\text{VR}(t)$  data samples can be safely neglected. The development of the background modeling using the CR, and its validation using the VRs, were finalized before the data in the SR were unblinded and the final results obtained.

## II. ATLAS DETECTOR

The ATLAS detector [23] at the LHC covers nearly the entire solid angle around the collision point.<sup>1</sup> It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadron

<sup>1</sup>ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the center of the detector and the  $z$  axis along the beam pipe. The  $x$  axis points from the IP to the center of the LHC ring, and the  $y$  axis points upward. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the  $z$  axis. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ . Angular distance is measured in units of  $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ .

calorimeters, and a muon spectrometer incorporating three large superconducting air-core toroidal magnets.

The inner-detector system (ID) is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range  $|\eta| < 2.5$ . The high-granularity silicon pixel detector covers the vertex region and typically provides four measurements per track, the first hit normally being in the insertable B layer installed before run 2 [24,25]. It is followed by the silicon microstrip tracker, which usually provides eight measurements per track. These silicon detectors are complemented by the transition radiation tracker (TRT), which enables radially extended track reconstruction up to  $|\eta| = 2.0$ . The TRT also provides electron identification information based on the fraction of hits (typically 30 in total) above a higher energy-deposit threshold corresponding to transition radiation.

The calorimeter system covers the pseudorapidity range  $|\eta| < 4.9$ . Within the region  $|\eta| < 3.2$ , electromagnetic (EM) calorimetry is provided by barrel (EMB) and end cap (EMEC) high-granularity lead/liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering  $|\eta| < 1.8$  to correct for energy loss in material upstream of the calorimeters. Hadron calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures within  $|\eta| < 1.7$ , and two copper/LAr hadron end cap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules, optimized for electromagnetic and hadronic energy measurements, respectively. The abilities of the LAr EM calorimeter to measure the flight direction and the arrival time of photons, which are key to this analysis, are described in detail in Sec. IV.

The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in a magnetic field generated by the superconducting air-core toroidal magnets. The field integral of the toroids ranges between 2.0 and 6.0 T m across most of the detector. Three layers of precision chambers, each consisting of layers of monitored drift tubes, covers the region  $|\eta| < 2.7$ , complemented by cathode-strip chambers in the forward region, where the background is highest. The muon trigger system covers the range  $|\eta| < 2.4$  with resistive-plate chambers in the barrel and thin-gap chambers in the end cap regions.

Events of interest are selected by the first-level trigger system implemented in custom hardware, followed by selections made by algorithms implemented in software in the high-level trigger [26]. The first-level trigger accepts events from the 40 MHz bunch crossings at a rate below 100 kHz, which the high-level trigger further reduces in order to record events to disk at about 1 kHz.

An extensive software suite [27] is used in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

### III. DATA AND MONTE CARLO SAMPLES

This analysis uses a dataset of  $\sqrt{s} = 13$  TeV  $pp$  collisions recorded by the ATLAS detector from 2015 to 2018, corresponding to the full run 2 period of the LHC. Signal events with a Higgs boson produced in association with a Z boson were collected using the unprescaled single-electron and single-muon triggers [28,29] with the lowest transverse momentum threshold for the electron or muon. After data quality requirements [30] are applied to ensure that all detector components were in good working condition, the dataset corresponds to an integrated luminosity of  $139.0 \pm 2.4$  fb $^{-1}$  [31,32]. The mean number of interactions per bunch crossing (“pileup”) during run 2 was  $\langle \mu \rangle = 33.7$ .

No SM background Monte Carlo (MC) simulation samples are needed, since the analysis uses a fully data-driven background estimation procedure. To study the signal, MC samples for the  $ZH$  production process were generated at leading order (LO) using MadGraph5\_aMC@NLO2.6.2 [33], with a Higgs boson mass of 125 GeV, and normalized to the cross sections reported in Ref. [34]. The generated events were interfaced to PYTHIA 8 [35] to simulate subsequent decays of the Higgs boson and supersymmetric particles in the signal model and also the parton showering. The A14 set of tuned parameters [36] and the NNPDF2.3LO PDF set [37] were used in the event generation. The signal model MC events were passed through a Geant4 [38] simulation of the ATLAS detector [39] and reconstructed with the same software [27] as used for the data. The generation of the simulated event samples includes the effect of pileup, both within the same bunch crossing as well as in bunch crossings before or after the one containing the hard interaction. Events in the simulation are weighted in order to reproduce the amount of pileup observed in the run 2 data-taking period.

The final state and kinematics of the Higgs boson decay depend on the masses of the NLSP and LSP, in addition to the lifetime of the NLSP. The signal generation was implemented with the  $\tilde{\chi}_1^0$  as the NLSP and the  $\tilde{\chi}_2^0$  as the LSP, but the NLSP and LSP masses and NLSP lifetime were treated as free parameters. Therefore, GMSB signal models were generated in a three-dimensional grid. The grid of MC signal models was constructed with NLSP masses from 30 up to 60 GeV, near the kinematic limit enforced by the Higgs boson mass. For each value of NLSP mass, LSP masses from 0.5 GeV up to a value of  $m_{\text{NLSP}} - 10$  GeV were considered. Given the typical step size of 10 GeV used for both the NLSP and LSP masses, a total of 18 different ( $m_{\text{NLSP}}, m_{\text{LSP}}$ ) pairs were simulated for a given value of NLSP lifetime. For each set of NLSP and LSP mass values, at least two different NLSP lifetimes, typically 2 and 10 ns, were simulated. Results can be generalized to other lifetime values by appropriately reweighting the samples of simulated events.

Some cross-checks of detector performance utilize MC samples of  $Z \rightarrow ee$  events and events with radiative

$Z \rightarrow \ell\ell\gamma$  decays, with  $\ell\ell$  designating an opposite-sign same-flavor lepton (electron or muon) pair. The photon time resolution is not modeled accurately in the MC simulation, which underestimates the time resolution observed in data. Therefore, additional smearing is applied to the photon times as simulated in the MC signal events. In addition to a contribution applied independently to each photon, the additional smearing includes a correlated event-level contribution to account for the impact of the spread of the actual  $pp$  collision times, which results from the longitudinal profiles of the colliding proton bunches along the LHC beam line. The combined smearing contributions are tuned to match the timing performance observed for electrons in data because, due to their similar EM shower development, electrons and photons have similar timing performance. The correlated and uncorrelated contributions to the time measurement are deconvolved by studying the times of electron-positron pairs in  $Z \rightarrow ee$  events.

#### IV. PHOTON POINTING AND TIMING MEASUREMENTS

Photons produced in the decays of long-lived NLSPs can be nonpointing, delayed, or both. This analysis is made possible by the capability of the LAr EM calorimeters to perform precise measurements of the pointing and timing of EM objects, and in particular photons, as discussed in more detail below. The measurements of pointing and timing are almost completely uncorrelated for prompt backgrounds. The lack of correlation results from the fact that, as described below, the pointing measurement uses the spread of the EM shower to precisely measure its centroids in the first two layers in the EM calorimeter, while the timing measurement uses the time reconstructed from the pulse shape of only the second-layer cell with the maximum energy deposit. In contrast, these measurements would be correlated for a photon that is produced in the decay of a heavy NLSP. Using both variables therefore provides a powerful way to separate signal from background.

##### A. Pointing measurements

For  $|\eta| < 2.5$ , the LAr EM calorimeter is segmented into three layers in depth that can be used to measure the longitudinal profile of the shower. The first layer uses highly granular “strips” segmented in the  $\eta$  direction, with a typical transverse segmentation of  $\Delta\eta \times \Delta\phi = 0.003 \times 0.1$ , designed to allow efficient discrimination between single-photon showers and two overlapping showers from the decay of a  $\pi^0$  meson. The second layer has a typical transverse segmentation of  $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$  and collects most of the energy deposited in the calorimeter by EM showers initiated by electrons or photons. Very high-energy EM showers can leave significant energy deposits in the third layer, which serves as a

“tail catcher” and which can also be used to correct for energy leakage beyond the EM calorimeter.

By precisely measuring the centroids of the EM shower in the first and second EM calorimeter layers, the flight direction of photons can be determined, from which one can calculate the value of  $z_\gamma$ , defined as the  $z$  coordinate of the extrapolation of the line through these centroids in the  $z$ - $r$  plane back to the beam line ( $x = y = 0$ ). The angular resolution of the EM calorimeter’s measurement of the flight direction of prompt photons is about  $60 \text{ mrad}/\sqrt{E}$ , where  $E$  is the photon energy in GeV. This angular resolution corresponds to a resolution in  $z_\gamma$  of about 15 mm for prompt photons with energies in the range of 50–100 GeV in the EM barrel calorimeter. Given the geometry, the  $z_\gamma$  resolution is worse for photons reconstructed in the end cap calorimeters.

This analysis uses the measurement of the photon flight direction to search for photons that do not point back to the PV. The pointing variable used in the analysis is  $\Delta z_\gamma = z_\gamma - z_{\text{PV}}$ , with  $z_{\text{PV}}$  being the  $z$  coordinate of the PV of the event, selected as described in Sec. V B. Given that  $z_{\text{PV}}$  is measured with high precision using the tracker, the  $\Delta z_\gamma$  resolution is essentially equivalent to the resolution in  $z_\gamma$ .

While the geometry of the EM calorimeter is optimized for detecting particles that point back to near the nominal interaction point at the center of the detector (i.e.  $x = y = z = 0$ ), the fine segmentation allows good pointing performance to be achieved over a wide range of photon impact angles. Using a sample of electrons from  $Z \rightarrow ee$  events, the calorimeter pointing performance is validated in data by using the finite spread of the  $pp$  collision region along the  $z$  axis. The pointing resolution degrades gradually with increasing  $|\Delta z_\gamma|$  (see Fig. 1 in Ref. [20]). The Geant4-based simulation of the ATLAS detector shows good agreement with the resolution observed in data over the range of  $|\Delta z_\gamma|$  values (up to about 200 mm) that can be accessed in data. This gives confidence in the ability of the MC simulation to estimate the resolution at the larger  $|\Delta z_\gamma|$  values characteristic of signal photons. The resolution remains much smaller than  $|\Delta z_\gamma|$  in the full region where the signal is expected. The studies also show similar pointing performance for photons and electrons, as expected given their similar EM shower development.

##### B. Timing measurements

Photons from long-lived NLSP decays would reach the LAr calorimeter with a slight delay compared to prompt photons produced directly in the hard scattering. This delay results mostly from the flight time of the heavy NLSP, which would have a distribution of relativistic speed ( $\beta = v/c$ ) that typically peaks near 0.9 and has a tail to much lower values. In addition, the opening angle in the NLSP decay, which causes the photon to be nonpointing,

results in the geometrical path to the calorimeter being longer than that for a prompt photon from the PV.

The EM calorimeter, with its novel “accordion” design, and its readout, which incorporates fast shaping, has excellent time resolution. Test-beam measurements [40] of individual EMB calorimeter modules demonstrated a time resolution of  $\approx 100$  ps in response to high-energy electrons. *In situ* calibration tests in the ATLAS cavern show a time resolution of  $\approx 70$  ps [41], limited not by the calorimeter but by the jitter of the calibration pulse injection system. To avoid that the electronic readout significantly degrades the intrinsic timing performance of the calorimeter, quality-control tests during production of the electronics required the clock jitter on the LAr readout boards to be less than 20 ps, with typical values of 10 ps [42].

During the run 2 period from 2015 to 2018, the hardware configuration of the readout of the various LAr channels was adjusted such that the channels were synchronized online within a uniformity of order 1 ns. While this level of precision is sufficient for the trigger system to correctly identify the bunch crossing corresponding to a particular event of interest, a dedicated calibration for each channel is applied offline to improve the time resolution significantly for EM clusters. The time calibration is based on a large sample of  $W \rightarrow e\nu$  events and is performed with zero defined as the expected value for a prompt electron from the PV of the hard collision. The time calibration includes corrections for the dependence of the time measurement on energy, crosstalk, flight path from the PV, collision conditions, and the behavior of individual channels.

The LAr energy and time for each calorimeter cell are reconstructed by applying the optimal filtering algorithm [43] to the set of four samples of the signal shape read out for each calorimeter channel, with successive samples of the waveform separated by 25 ns. More specifically, the deposited energy per cell and the time of the deposition are calculated using appropriately weighted linear combinations of the set of samples of the waveform:

$$E = \sum_{i=0}^3 a_i S_i \quad \text{and} \quad t = \frac{1}{E} \sum_{i=0}^3 b_i S_i,$$

where  $S_i$  denotes the four samples of the signal waveform. The parameters  $a_i$  and  $b_i$  are the optimal filter coefficients, the values of which are calculated, knowing the pulse shape and noise autocorrelation matrix, to deliver the best energy and time resolutions.

For this analysis, the arrival time of an EM object is measured using the second-layer EM calorimeter cell with the largest energy deposit among cells in the associated EM cluster ( $E_{\text{cell}}$ ). For the EM shower of an electron or photon with an energy in the range of interest, this cell typically contains about 20%–50% of the total energy deposited in the EM shower.

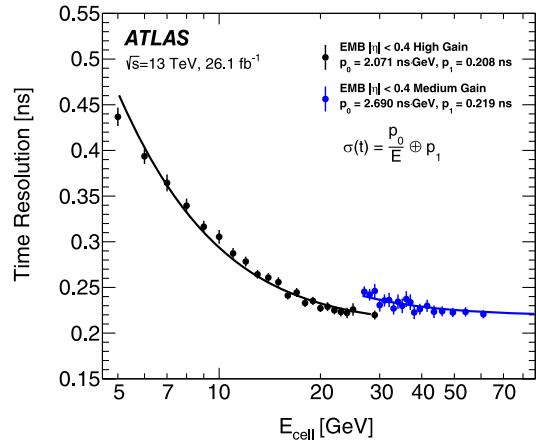


FIG. 2. Time resolution obtained with the LAr EM calorimeter as a function of  $E_{\text{cell}}$ , the energy in the second-layer cell with the largest energy deposit. The solid lines show the results of fitting the expected form, namely  $\sigma(t) = p_0/E_{\text{cell}} + p_1$ , to the data points. The results shown are obtained using  $Z \rightarrow ee$  events recorded in 2018, for electrons in the EMB calorimeter with  $|\eta| < 0.4$ , and for both the high and medium gain readout scales. Similar results are obtained over the full run 2 dataset and for the full coverage of the EM calorimeter.

To cover the full dynamic range of physics signals of interest, the ATLAS LAr calorimeter readout boards [42] employ three overlapping linear gain scales, dubbed high, medium and low, where the relative gain is reduced by a factor of about 10 for each successive scale. For a given event, any individual LAr readout channel is digitized using the gain scale that provides optimal energy resolution, given the energy deposited in that calorimeter cell. The calibration of the time is determined separately for high and medium gain for each channel. The number of electron candidates from the  $W \rightarrow e\nu$  sample digitized using low gain, typically those with energies above about 200 GeV, is insufficient to obtain statistically precise results for the calibration constants. Therefore, the analysis requires that selected photons be digitized using either high or medium gain, which has a negligible impact on the signal efficiency for this analysis.

An independent sample of  $Z \rightarrow ee$  events is used to validate the time calibration and determine the resolution that is obtained by performing Gaussian fits to the time distributions in bins of cell energy. Figure 2 shows the time resolution for high and medium gain cells with  $|\eta| < 0.4$ , as a function of  $E_{\text{cell}}$ , the energy in the second-layer calorimeter cell used to calculate the time for the sample of  $Z \rightarrow ee$  events. Similar results are obtained over the full coverage of the EM calorimeter.

The time resolution  $\sigma(t)$  is expected to follow the form  $\sigma(t) = p_0/E_{\text{cell}} + p_1$ , where  $E_{\text{cell}}$  is the cell energy,  $\oplus$  denotes addition in quadrature, and the fit parameters  $p_0$  and  $p_1$  are the coefficients of the so-called noise term and constant term, respectively. Superimposed on Fig. 2 are the

TABLE I. Optimized requirements defining the low- $\Delta m$  and high- $\Delta m$  SR selections, as well as the corresponding CRs and VRs. Also included are the optimized binnings for photon pointing and timing for both the  $1\gamma$  and  $\geq 2\gamma$  channels.

Parameter	Low- $\Delta m$ selection				High- $\Delta m$ selection			
	$(\Delta m = 10 \text{ GeV})$				$(\Delta m > 10 \text{ GeV})$			
CR	VR( $E_{\text{T}}^{\text{miss}}$ )	VR( $t$ )	SR	CR	VR( $E_{\text{T}}^{\text{miss}}$ )	VR( $t$ )	SR	
$E_{\text{cell}}$			$>7$					
$E_{\text{T}}^{\text{miss}}$	$<30$	30–50	$>80$	$>80$	$<30$	30–50	$>50$	$>50$
$t_{\gamma}$	$>0$	$>0$	$<0$	$>0$	$>0$	$>0$	$<0$	$>0$
$ \Delta z_{\gamma} $ bins [mm]				[0, 50, 100, 200, 300, 2000]				
$ t_{\gamma} $ bins [ns]				[0, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5, 12.0]				
$1\gamma$ channel				[0, 0.2, 0.4, 0.6, 0.8, 1.0, 12.0]				
$\geq 2\gamma$ channel				[0, 0.2, 0.4, 0.6, 0.8, 1.0, 12.0]				

results of fits to this expected form of the time resolution function. The fits yield values of  $p_1$ , which gives the time resolution in the limit of large energy deposits, of 208 (217) ps for high (medium) gain. The slightly poorer resolution for medium gain is due to limited event yields in the  $W \rightarrow e\nu$  sample used to determine the time calibration constants. By examining the timing distributions of the two electrons in  $Z \rightarrow ee$  candidate events, the time measurements are observed to include a correlated contribution of  $\approx 190$  ps, which, for a given PV position, agrees well with the expected distribution of collision times due to the longitudinal spread of the proton bunches along the LHC beam line. Assuming this contribution to the time resolution to be uncorrelated with the LAr contributions implies the LAr contributions are  $\sim 50$ –150 ps, depending on  $|\eta|$ , demonstrating that the offline calibration achieves an *in situ* time resolution comparable to that achieved in the more constrained test beam measurements [40]. There is only a modest variation in time resolution over the ranges of photon energies considered since, as described in Sec. V C (see Table I), selected photons in the analysis are required to have  $E_{\text{cell}} > 7$  GeV.

The signal timing templates are constructed using the timing variable of the simulated signal samples. Additional resolution uncertainties are assigned to cover the observed discrepancy between radiative  $Z \rightarrow \ell\ell\gamma$  events in data and those from MC simulation. The photon timing resolution uncertainty is implemented in the likelihood function (see Sec. VII for details) such that the effects in the timing distribution are correlated between pointing categories. Uncertainties accounting for fluctuations in the statistically limited signal MC samples are also included in the likelihood function.

## V. EVENT SELECTION

The requirements applied in the selection of various physics objects in the event are described below, followed by the selection of events and the optimization of these selections.

### A. Object selection

The reconstruction and identification of electrons and photons are described in Ref. [44]. Shape variables computed from the lateral and longitudinal energy profiles of the EM showers in the calorimeter are used to identify photons and electrons and to distinguish them from backgrounds.

Photons are required to satisfy  $p_{\text{T}} > 10$  GeV and  $|\eta| < 2.37$ , excluding the region  $1.37 < |\eta| < 1.52$ , which corresponds to the transition region between the EMB and EMEC calorimeters. In addition, to reduce the probability of jets being misidentified as photons, photons must satisfy both calorimeter-based and track-based isolation requirements. The calorimeter isolation variable is defined as the energy of EM calorimeter-cell clusters in a cone of size  $\Delta R = 0.2$  around the photon candidate, excluding a fixed window containing most of the photon shower. Corrections accounting for photon energy leakage from this window into the surrounding cone, for pileup, and for the underlying event are applied [44]. The calorimeter isolation is required to be less than 6.5% of the photon's transverse energy. The track-based isolation variable is defined as the scalar sum of the  $p_{\text{T}}$  of all tracks with  $p_{\text{T}} > 1$  GeV within  $\Delta R = 0.2$  of the photon candidate. The track isolation variable is required to be less than 5% of the photon's transverse energy.

A set of photon selection criteria, designed for high efficiency and modest background rejection, defines the so-called loose photon identification used in this analysis. The loose photon identification does not impose requirements on the EM shower shape in the first (strips) layer of the EM calorimeter and uses only variables that describe the shower shape in the second layer of the EM calorimeter and leakage into the hadronic calorimeter. The loose photon identification thereby minimizes the bias against identification of nonpointing photons. Figure 3 shows the loose photon identification efficiency as a function of  $|\Delta z_{\gamma}|$ , with the simulated results for the signal photons from this analysis superimposed on data and MC results for SM

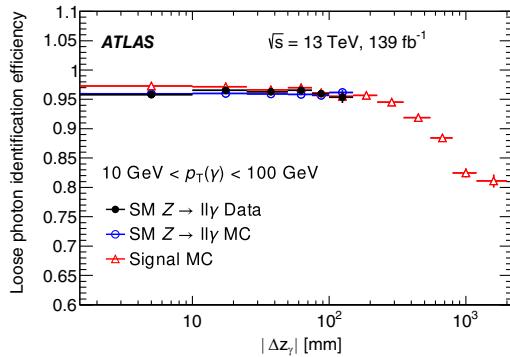


FIG. 3. The loose photon identification efficiency, shown as a function of  $|\Delta z_\gamma|$ , for photons with transverse momentum in the range 10–100 GeV and with  $E_{\text{cell}} > 7$  GeV. The simulated results for signal photons from long-lived particle decays in this analysis are overlaid with data and MC results for SM  $Z \rightarrow \ell\ell\gamma$  events. For the  $Z \rightarrow \ell\ell\gamma$  events,  $|\Delta z_\gamma|$  is measured from the center of the detector ( $z = 0$ ), exploiting the spread of  $pp$  collisions along the beam line.

$Z \rightarrow \ell\ell\gamma$  events. For the  $Z \rightarrow \ell\ell\gamma$  events,  $|\Delta z_\gamma|$  is measured from the center of the detector ( $z = 0$ ), exploiting the spread of  $pp$  collisions along the beam line. The radiative  $Z \rightarrow \ell\ell\gamma$  sample is selected by requiring events to have a photon plus two same-flavor opposite-sign leptons (electrons or muons), with  $m(\ell\ell\gamma)$  being within 10 GeV of the known  $Z$  boson mass, and the dilepton invariant mass being less than 83 GeV. To reduce the impact of electrons being misidentified as photons, candidate events in the  $Z \rightarrow ee\gamma$  sample are vetoed if the invariant mass of either  $e\gamma$  pair is consistent with the  $Z$  boson mass. The  $Z \rightarrow \ell\ell\gamma$  selection results in a very pure sample of photons, from which the efficiency of applying the loose photon identification requirement is measured after removing the remaining background component using a template fit to the  $\ell\ell\gamma$  invariant mass distribution [45]. As seen in Fig. 3, the loose photon identification efficiency is very high and quite constant within the beam spot ( $|\Delta z_\gamma|$  less than about 200 mm), and the results for the various samples are in good agreement, providing confidence in the use of MC simulation to estimate the identification efficiency for signal photons at higher  $|\Delta z_\gamma|$  values. As shown, the efficiency decreases gradually for photons produced further from the center of the detector. To cover potential mismodeling of the efficiency drop in the high pointing region, photon identification uncertainty is introduced and discussed in Sec. VII B.

Some studies in this analysis use the medium photon working point, which adds a requirement on one shower shape variable in the strips layer in order to increase the photon purity at the cost of some decrease in efficiency. Detailed descriptions of both the loose and medium photon identification criteria can be found in Ref. [44].

Electrons are reconstructed by matching tracks in the ID to topological clusters of calorimeter cells formed using the

same dynamical, topological cell-clustering algorithm as in the photon reconstruction [44]. Electron candidates are required to have  $p_T > 10$  GeV and  $|\eta| < 2.47$  and must satisfy a medium electron identification selection based on a likelihood discriminant using calorimeter shower shapes and track parameters [44]. Isolation criteria using calorimeter- and track-based information are applied to electrons. The reconstructed track matched to the electron candidate must be consistent with the PV position: its longitudinal impact parameter  $z_0$  relative to the PV is required to satisfy  $|z_0 \sin \theta| < 0.5$  mm. In addition, the electron track's transverse impact parameter with respect to the beam axis divided by its uncertainty,  $|d_0|/\sigma(d_0)$ , must be less than 5.

Muons are reconstructed by matching tracks from the MS and ID subsystems. Muons in the range  $2.5 < |\eta| < 2.7$  without an ID track but whose MS track is compatible with the interaction point are also considered. Muon candidates are required to have  $p_T > 10$  GeV and  $|\eta| < 2.7$  and must satisfy the medium muon identification requirements [46]. Muons are required to satisfy calorimeter- and track-based isolation requirements [46] that are 95%–97% efficient for muons with  $p_T \in [10, 60]$  GeV and 99% efficient for  $p_T > 60$  GeV. Muon tracks must satisfy  $|z_0 \sin \theta| < 0.5$  mm and  $|d_0|/\sigma(d_0) < 3$ . Finally,  $\tau$  leptons are required to have at least 20 GeV of  $p_T$  and to lie within  $|\eta| < 1.37$  or  $1.52 < |\eta| < 2.5$ .

Jets are used only indirectly in the analysis, through an overlap removal procedure and corrections to the calculation of  $E_T^{\text{miss}}$ . Jets are reconstructed by applying a particle-flow algorithm [47] to noise-suppressed positive-energy topological clusters [48] of calorimeter cells from the anti- $k_t$  algorithm [49,50] with radius parameter  $R = 0.4$ . Jets must have  $p_T > 25$  GeV and  $|y| < 4.4$ . A jet-vertex-tagger multivariate discriminant [51] is applied to jets with  $p_T < 60$  GeV and  $|\eta| < 2.4$  to suppress jets from pileup.

An overlap removal procedure is performed in order to avoid double counting of objects. First, electrons overlapping with photons within  $\Delta R < 0.4$  are removed. Jets overlapping with photons ( $\Delta R < 0.4$ ) and electrons ( $\Delta R < 0.2$ ) are removed. Electrons overlapping with the remaining jets ( $\Delta R < 0.4$ ) are removed, to match the requirements imposed when measuring isolated electron efficiencies. Finally, muons overlapping with photons or jets ( $\Delta R < 0.4$ ) are removed.

The value of  $E_T^{\text{miss}}$  is defined as the magnitude of the negative vector sum of the transverse momenta of the selected photons, electrons, muons and jets, as well as the transverse momenta of remaining low- $p_T$  particles, estimated using tracks matched to the PV but not to any of the selected objects [52].

## B. Event selection

Selected events are required to have a candidate PV for the hard scatter, reconstructed from at least two charged tracks, each with  $p_T > 500$  MeV. If multiple vertices are

reconstructed, the PV is selected as the one with the largest sum of the  $p_T^2$  values of the associated tracks.

Events are required to pass the lowest unprescaled single-lepton (electron or muon) trigger. For data taken in 2015, the electron (muon) trigger required the lepton to satisfy  $p_T > 24(20)$  GeV. For 2016–2018, these kinematic requirements on the trigger leptons were both increased to  $p_T > 26$  GeV. The offline event selection required at least one electron or muon, with  $p_T > 27$  GeV, satisfying medium identification, and matching the trigger lepton.

Triggered events are subject to a common set of preselection requirements. In addition to the lepton requirement above, selected events are required to have at least one photon candidate with  $p_T > 10$  GeV and satisfying loose photon identification.

To reject events with an electron misreconstructed as a photon, events with an electron are rejected if the invariant mass of the electron-photon pair satisfies  $|m_{e\gamma} - m_Z| < 15$  GeV.

To suppress photons from earlier or later bunch crossings, photons are required to have measured arrival times at the LAr calorimeter of  $|t_\gamma| < 12$  ns.

### C. Analysis strategy and optimization

Due to their different signal-to-background ratios, the  $1\gamma$  and  $\geq 2\gamma$  final states are treated separately in the analysis. The  $\geq 2\gamma$  final state has lower background, and higher sensitivity for smaller values of the NLSP lifetime, for which there is a significant probability for both NLSPs to decay before reaching the EM calorimeter. The use of the  $1\gamma$  final state recovers sensitivity for events where one photon is missed or where one NLSP decays beyond the boundaries of the ID.

For all selected events, the final statistical analysis uses the pointing and timing measurements of only one photon. Since the  $\Delta z_\gamma$  distribution should be symmetric for both signal and background, the pointing distribution is folded by taking  $|\Delta z_\gamma|$  as the variable of interest instead of  $\Delta z_\gamma$  itself. The inputs to the statistical analysis are therefore the values of  $|\Delta z_\gamma|$  and  $t_\gamma$  measured for the photon selected in each event. Given the fact that, due to geometry, the pointing resolution along the  $z$  axis is better for EMB photons than for EMEC photons, the photon selected for the statistical analysis must be detected in the EMB. Thus,  $1\gamma$  events must have their single photon in the EMB. For  $\geq 2\gamma$  events, at least one photon must be in the EMB; for events with more than one EMB photon, the highest- $E_T$  EMB photon is selected for the statistical analysis.

A study was performed in order to optimize the SR definition across the two-dimensional signal grid of NLSP and LSP masses. The kinematic distributions of the signal have a significant dependence on the value of the mass splitting,  $\Delta m = m_{\text{NLSP}} - m_{\text{LSP}}$ . Higher values of  $\Delta m$  typically lead to production of higher-energy photons and to more modest values of  $E_T^{\text{miss}}$ . In contrast, lower

$\Delta m$  leads to lower photon energies and higher values of  $E_T^{\text{miss}}$ . The optimization study revealed that close-to-optimal results can be achieved across the entire signal grid by the definition of two different SR selections: the low- $\Delta m$  SR selection is applied to signal models with  $\Delta m = 10$  GeV and the high- $\Delta m$  SR selection is applied to signal models with  $\Delta m > 10$  GeV. The definitions of the two SR selections, which include different requirements on  $E_{\text{cell}}$  and  $E_T^{\text{miss}}$ , are summarized in Table I, along with definitions of the corresponding CRs and VRs.

While exploring the optimal SR selections, the optimization procedure also examined how to best choose the number of bins and locations of the corresponding bin edges for both the photon pointing and timing variables. Considerations included maximizing the sensitivity while avoiding any empty bins in the required background templates constructed from CR data. The binning optimization was performed separately for the  $1\gamma$  and  $\geq 2\gamma$  final states. The results led to the choice of a common pointing binning, with a total of five pointing categories. Optimization of the timing binning led to seven (six) bins for the  $1\gamma$  ( $\geq 2\gamma$ ) final state, the difference being mostly due to the lower CR event yields for the  $\geq 2\gamma$  channel. The bin definitions are included in Table I.

The signal acceptance is about 22% (10%) for signal models with an NLSP lifetime of 2 (10) ns, where the acceptance is defined as the fraction of simulated signal events passing the trigger and having at least one lepton and at least one photon reconstructed in the final state. The lower acceptance for higher NLSP lifetimes is expected, as more NLSP decays occur outside the ATLAS ID and their decay photons are not captured by the EM calorimeter. The signal efficiency is around 40% for all the signal models, defined as the fraction of simulated signal events within the signal acceptance that pass the SR selection requirements.

## VI. BACKGROUND ESTIMATION

The background is expected to be completely dominated by  $pp$  collision events, with possible backgrounds due to cosmic rays, beam-halo events, or other noncollision processes being negligible. The source of the loose photons in background events contributing to the selected sample is expected to be either a prompt photon, an electron misidentified as a photon, or a jet misidentified as a photon. In each case, the object providing the loose photon signature is prompt and originates from the PV.

The pointing and timing distributions expected for the background sources are determined entirely using control samples in data. This avoids a reliance on the precise MC simulation of the pointing and timing performance for the backgrounds and especially of the tails of their  $|\Delta z_\gamma|$  and  $t_\gamma$  distributions. Additionally, using data samples naturally accounts for the influence of pileup, the possibility of selecting the wrong PV, and any instrumental or other effects that might influence the background measurements.

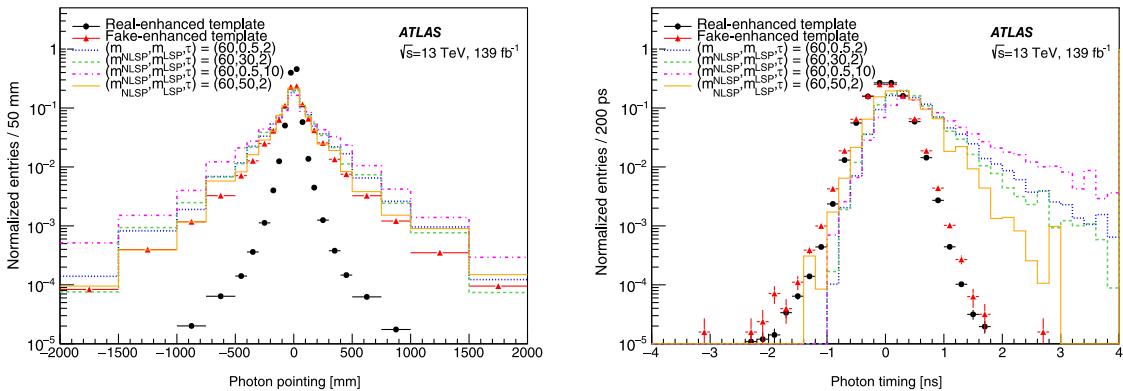


FIG. 4. Photon pointing ( $\Delta z_\gamma$ ) and timing ( $t_\gamma$ ) distributions for the genuine-photon enriched and fake-photon enriched samples. Superimposed are the expected distributions for selected signal models. The signal models are labeled by the values of their NLSP and LSP masses ( $m_{\text{NLSP}}$  and  $m_{\text{LSP}}$  in GeV) and NLSP lifetime ( $\tau$  in nanoseconds).

It is known [20] that the measured  $|\Delta z_\gamma|$  and  $t_\gamma$  distributions of genuine photons are narrower than those of other physics objects (particularly jets) that are misreconstructed as photons. The  $|\Delta z_\gamma|$  distribution is particularly sensitive to the background composition, since it depends on details of the EM shower development. Consequently, the statistical analysis (see Sec. VIII) uses the  $|\Delta z_\gamma|$  value only to separate the events into mutually independent pointing categories and implements the normalization of the background in each pointing category as an independent, unconstrained nuisance parameter. Therefore, the fitting procedure eliminates the need to model the pointing distribution of the background and reduces the background modeling issue to one of determining the shape of the background timing template.

Variations of the shape of the background  $t_\gamma$  distribution are explored by dividing the CR data into a genuine-photon enriched sample and a fake-photon enriched sample. The actual purities of the individual samples do not need to be known; they just need to be different from each other, so that the total background timing template can then be constructed as a linear combination of the timing templates from these two samples.

The sample of events from the CR is divided into mutually exclusive subsamples according to whether or not the photon passes an identification requirement (typically either the medium or tight definitions given in Ref. [44]) that is more stringent than the loose identification used to define the overall CR. The photons that fail the more stringent identification are used to form the fake-photon enriched sample, while those that pass it are put in the genuine-photon enriched sample. To increase the event yield, the genuine-photon enriched control sample also includes photons from the radiative  $Z \rightarrow \ell\ell\gamma$  decay sample.

As discussed earlier, the time resolution depends on  $E_{\text{cell}}$ , the energy deposited in the second-layer cell of the EM calorimeter that is used to measure the arrival time of the

photon. To mitigate any potential discrepancy between the CR and SR timing shapes that arises from kinematic differences, a reweighting procedure is applied to the control samples so that the photon  $E_{\text{cell}}$  distribution in the CR after reweighting is the same as that in the SR.

Due to imperfections in calibrations, limited event yields, or other effects, the photon timing distributions in the data can have small nonzero mean values, at the level of up to a few tens of picoseconds. Before constructing the final background timing templates, the means are determined by fitting the timing distributions, which are then shifted to eliminate any small residual nonzero mean values. To avoid any bias being introduced by possible signal contributions, the fits are restricted to the core of the timing distributions.

Figure 4 shows the unit-normalized shapes of the pointing and timing distributions for the inclusive genuine-photon enriched and fake-photon enriched samples. Superimposed are the distributions for selected signal models.

The timing templates are derived separately in each of the pointing categories. In general, the fraction of the genuine-photon enriched template in the linear combination is a free nuisance parameter in the likelihood function and can be determined when fitting to data. In two of the pointing categories, the shapes of the timing distributions for the genuine-photon enriched and fake-photon enriched samples are found to be statistically consistent according to a Kolmogorov-Smirnov test, so the fit cannot obtain a well-determined value for the nuisance parameter. For these two pointing categories, the genuine-photon enriched and fake-photon enriched template fractions are each set to a constant value of 0.5, to exploit the statistical power obtained by combining the two samples.

## VII. SYSTEMATIC UNCERTAINTIES

Systematic uncertainties affecting the search are primarily experimental. Theoretical uncertainties are also

relevant, when the search result is interpreted to yield a constraint on the decay of the Higgs boson into long-lived particles.

In the statistical analysis, the background normalization for each  $|\Delta z_\gamma|$  category is determined using an independent nuisance parameter. Therefore, it is not necessary to include systematic uncertainties for the background's normalization or its shape in the variable  $|\Delta z_\gamma|$ . The various systematic uncertainties relevant for this analysis can be divided into two categories: so-called “flat” uncertainties are not a function of  $|\Delta z_\gamma|$  or  $t_\gamma$  and affect only the overall signal yield, while “shape” uncertainties are those that are related to the shapes of the unit-normalized  $|\Delta z_\gamma|$  and  $t_\gamma$  distributions for signal or to the shape of the background  $t_\gamma$  template.

The various systematic uncertainties are outlined below. However, their impact on the limits is very minor, and the results of the analysis are dominated by the statistical uncertainties. Implementing the full set of systematic uncertainties degrades the sensitivity, as measured by the expected 95% C.L. limits on the branching ratio  $\mathcal{B}(H \rightarrow \text{NLSP NLSP})$ , by only about 5% compared to the results obtained with only statistical uncertainties considered.

### A. Signal normalization uncertainties

Theoretical uncertainties of the signal model arise from the fact that the Higgs boson production processes are calculated at LO in QCD, from uncertainties in the value of the strong coupling constant  $\alpha_s$ , and from the choice of parton distribution functions. While the cross sections of the Higgs boson production processes are normalized to the best available theoretical calculations [34], the missing higher-order QCD calculations in the event generation may lead to a potential mismodeling of signal efficiency. Such uncertainties are estimated by varying the factorization and renormalization scales used in the event generation separately by factors of 0.5 and 2.0 relative to their nominal values, and the uncertainty is taken as the maximum difference between the yields obtained with the nominal scales and the different variations. In addition, the variation in signal selection efficiency due to the choice of PDF sets in the event generation is also estimated. The total combined theoretical uncertainty in the signal yield reaches about 17% and is included as a single nuisance parameter in the fit.

Examples of instrumental systematic uncertainties which affect the overall signal yield include uncertainties in photon and lepton reconstruction and identification efficiencies, reconstruction of  $E_T^{\text{miss}}$ , and the integrated luminosity measurement. The uncertainty in the integrated luminosity is 1.7%, evaluated using the methodology described in Ref. [31]. The photon identification efficiency is studied using a sample of photons from radiative  $Z \rightarrow \ell\ell\gamma$  decays, selected as described in Sec. VI. The efficiency

of the loose identification is around 95% for  $p_T(\gamma) \approx 20$  GeV, increasing gradually to about 99% for  $p_T(\gamma) > 60$  GeV. The measured efficiency in data is well reproduced in MC simulations.

Summing the instrumental uncertainties in quadrature yields a small total uncertainty in the signal yield, up to a few percent. These uncertainties are incorporated into the likelihood model as a single nuisance parameter scaling the signal yields uniformly across the ten pointing categories, where the magnitude of the uncertainty is calculated separately for the  $1\gamma$  and  $\geq 2\gamma$  channels.

### B. Signal shape systematic uncertainties

Uncertainties in photon timing and pointing measurements, the identification efficiency for photons with large pointing values, as well as the timing templates, affect the distribution of relative event yields between timing bins in different pointing categories. These uncertainties therefore affect the shapes of the signal distributions and are incorporated into the likelihood model such that varying their corresponding nuisance parameters introduces correlated shape effects in the timing and pointing distributions. For example, as shown in Fig. 3, the loose photon identification requirements provide very high efficiency for identifying photons, but that efficiency has a modest dependence on  $|\Delta z_\gamma|$ , dropping by about 15% (5%) for the highest  $|\Delta z_\gamma|$  bin for low (high)  $p_T(\gamma)$  values. To obtain a conservative estimate of the uncertainty in identifying nonprompt photons, the ratio of efficiency in each  $|\Delta z_\gamma|$  category above 150 mm to the efficiency measured in data for  $|\Delta z_\gamma| = 100\text{--}150$  mm is calculated. The deviation of these ratio values from unity provides a binned relative uncertainty in the photon identification efficiency that increases as  $|\Delta z_\gamma|$  increases.

### C. Background shape systematic uncertainties

Several types of systematic uncertainties are considered for the shapes of the background timing distributions. These include the bin-by-bin statistical uncertainties for both the genuine-photon enriched and fake-photon enriched templates to account for fluctuations in data control samples.

In addition, a shape uncertainty correlated between timing bins within the same pointing category is introduced to account for uncertainties arising from the choice of CR samples for determining the genuine-photon enriched and fake-photon enriched timing distributions. The uncertainties are derived by comparing different choices for the division of events into those two subsamples, namely by requiring photons to pass the medium or the tight identification requirements in order to be included in the genuine-photon enriched sample.

Finally, a background-only fit of the likelihood function to the  $\text{VR}(t)$  data is performed. The  $\text{VR}(t)$  data have the same requirements as the SR but with  $t_\gamma < 0$ . This selection

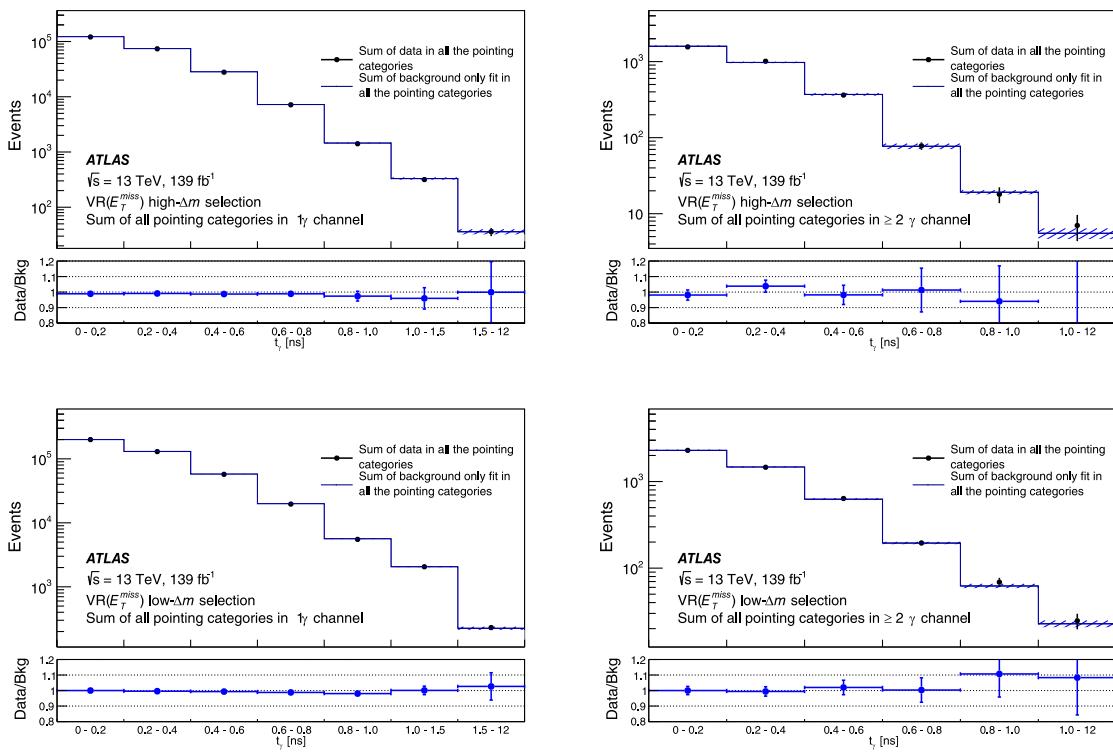


FIG. 5. Timing distributions for  $\text{VR}(E_T^{\text{miss}})$  data and the estimated background, as determined by a background-only fit. The upper (lower) row shows the results for the high- $\Delta m$  (low- $\Delta m$ ) selection. The fit for each selection is performed simultaneously across ten timing distributions, namely the five pointing categories for each of the two final states ( $1\gamma$  and  $\geq 2\gamma$ ). For conciseness, the figures show the sum of the data across all five pointing categories, compared with the sum of the background-only fits, with the left (right) figure displaying the results for the  $1\gamma$  ( $\geq 2\gamma$ ) final state.

ensures negligible signal contamination and can therefore be used to test the robustness of the background model. The residual difference between data in the  $\text{VR}(t)$  region and the fitted background is considered as a nonclosure uncertainty for the background templates. While the nonclosure uncertainties are zero for most of the time bins, a few have values up to about 40% of the background uncertainty in that bin.

### VIII. STATISTICAL ANALYSIS

Binned likelihood fits to data in the SR are performed to test the background-only and signal-plus-background hypotheses. The likelihood function is constructed by simultaneously fitting the ten timing distributions to their PDFs. The systematic uncertainties described in Sec. VII are incorporated into the likelihood function as nuisance parameters with Gaussian constraint PDFs. The background normalization and the background template admixture in each pointing category are floating nuisance parameters constrained by data.

A profile likelihood ratio is used to perform frequentist hypothesis tests [53]. The  $p_0$  value, defined as the probability of statistical fluctuations making the background distributions appear to contain at least as much signal

as the data distributions, is calculated for different signal models.

Before applying the statistical analysis to the SR data, the method and background model were validated by fitting to the  $\text{VR}(E_T^{\text{miss}})$  data. Since the background estimation method essentially models the photon object property of timing and does not depend on the event selection, the fits to the  $\text{VR}(E_T^{\text{miss}})$  photon sample, which is statistically independent from the SR, provide a validation of the method. As shown in Fig. 5, the  $\text{VR}(E_T^{\text{miss}})$  data are well described by a background-only fit, for both the high- $\Delta m$  and low- $\Delta m$  selections. Further validation of the statistical analysis included signal injection tests, in which varying signal models and strengths were injected into the  $\text{VR}(E_T^{\text{miss}})$  data; in all cases, the fit correctly extracted the strength of the injected signal.

### IX. RESULTS

The postfit plots comparing the timing distributions of the SR data and the estimated background in each pointing category are shown in Figs. 6 and 7 for the high- $\Delta m$  and low- $\Delta m$  selections, respectively. Superimposed on the figures are the expected signal distributions for a few example signal models. The data are in good agreement

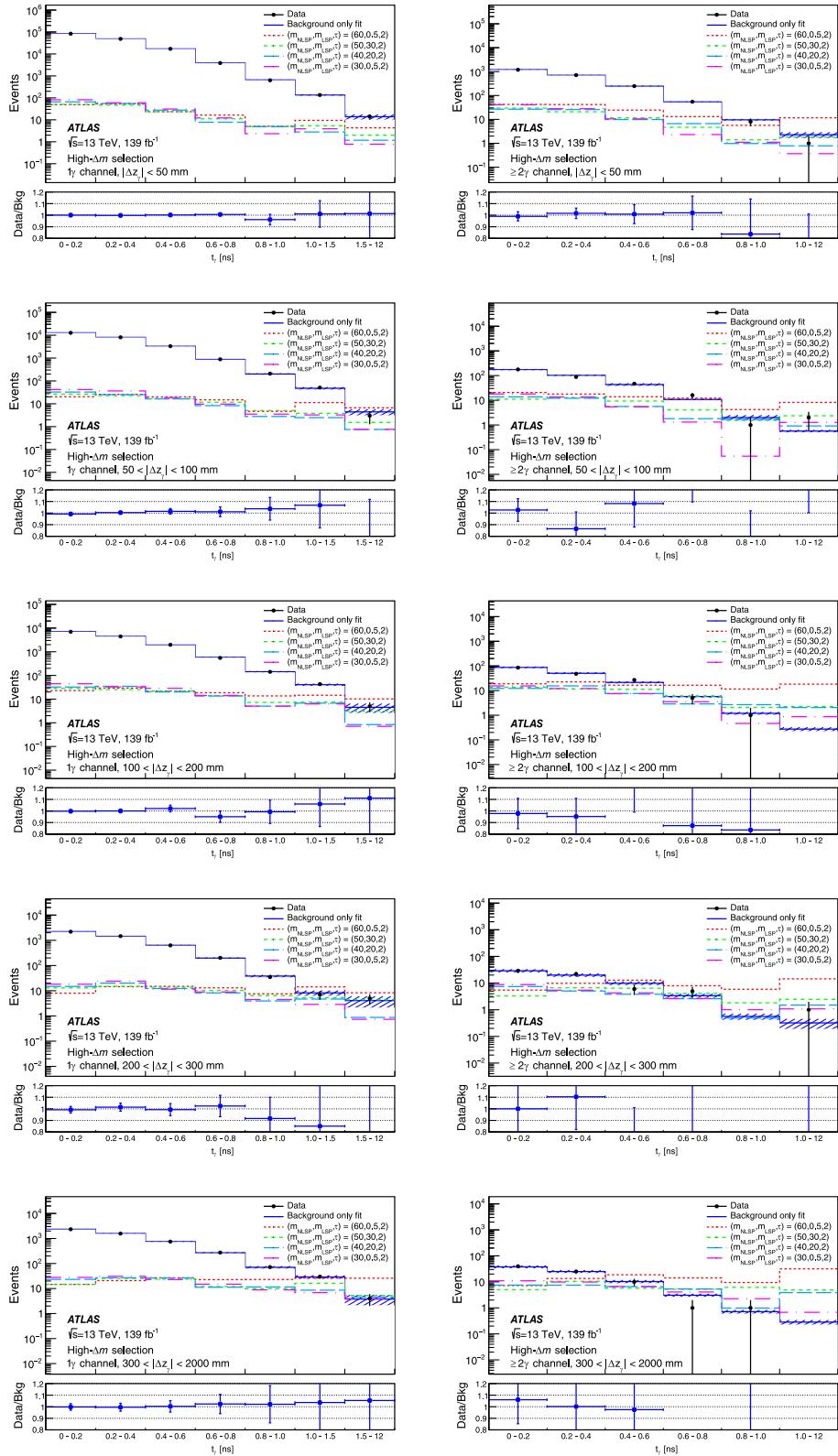


FIG. 6. Timing distributions for SR data and the estimated background, as determined by the background-only fit, for the high- $\Delta m$  selection. The plots on the left (right) show the time distributions for each of the five pointing categories for the  $1\gamma$  ( $\geq 2\gamma$ ) final state. For comparison, the expected timing shapes for a few different signal points are shown superimposed, with a signal normalization corresponding to a value of  $\mathcal{B}(H \rightarrow \text{NLSP NLSP}) = 20\%$ . The signal models are labeled by their values of the NLSP and LSP masses (in GeV) and NLSP lifetime (in nanoseconds).

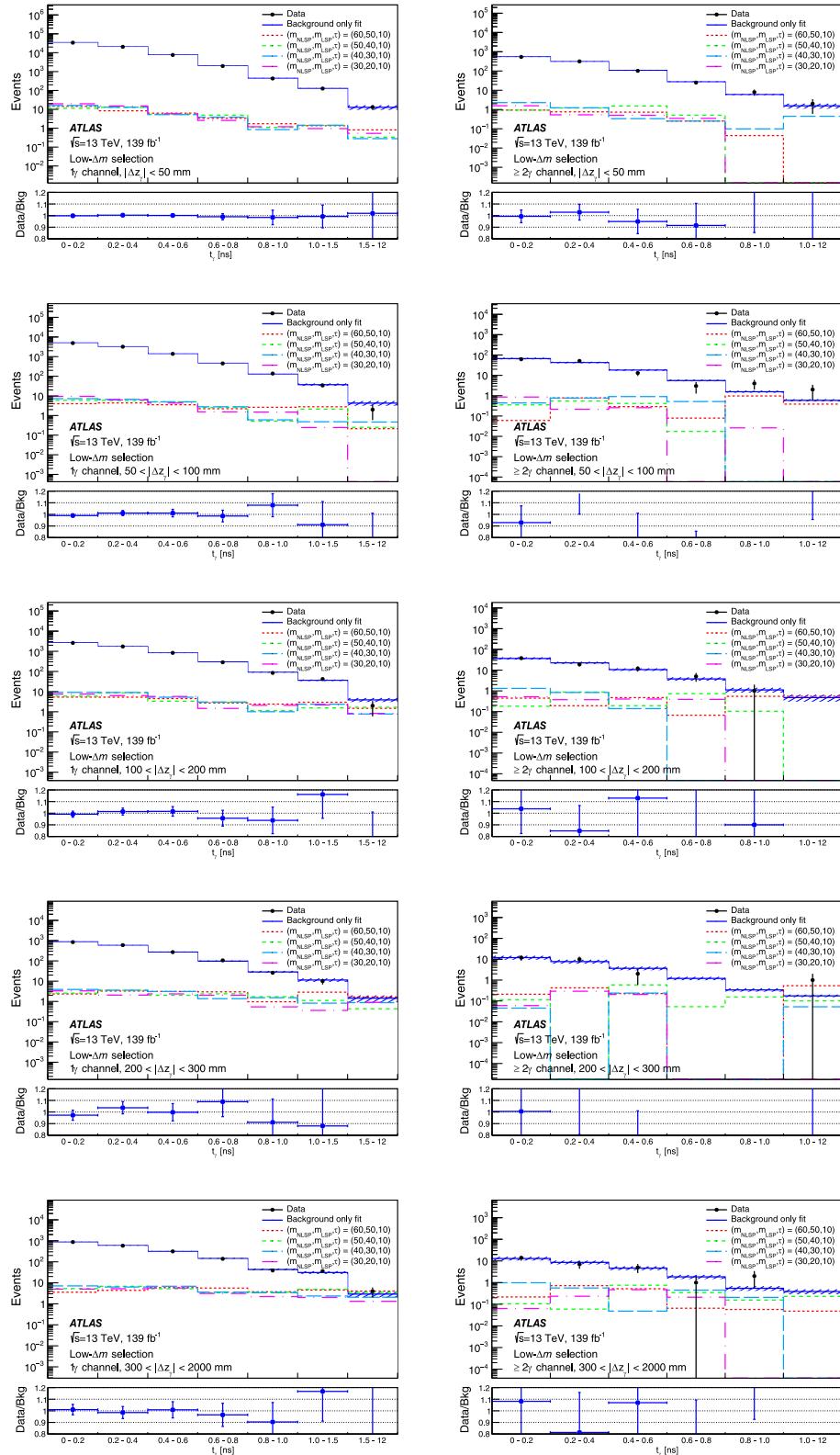


FIG. 7. Timing distributions for SR data and the estimated background, as determined by the background-only fit, for the low- $\Delta m$  selection. The plots on the left (right) show the time distributions for each of the five pointing categories for the  $1\gamma$  ( $\geq 2\gamma$ ) final state. For comparison, the expected timing shapes for a few different signal points are shown superimposed, with a signal normalization corresponding to a value of  $\mathcal{B}(H \rightarrow \text{NLSP NLSP}) = 20\%$ . The signal models are labeled by their values of the NLSP and LSP masses (in GeV) and NLSP lifetime (in nanoseconds).

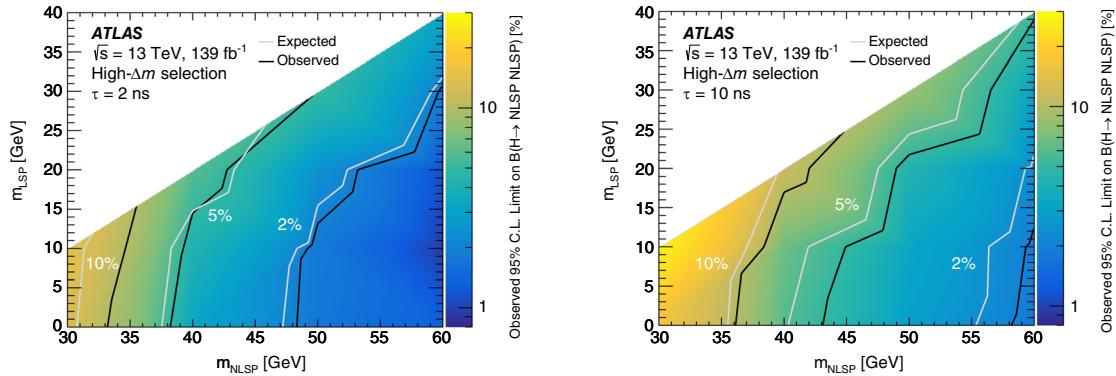


FIG. 8. Interpolated 95% C.L. limits on  $\mathcal{B}(H \rightarrow \text{NLSP NLSP})$  in the plane of LSP mass versus NLSP mass for the high- $\Delta m$  selection. The plot on the left (right) corresponds to the results with the NLSP lifetime equal to 2 (10) ns. A smoothing function is used to continuously fill the plane, interpolating between the results for the discrete signal models which were simulated on a grid with 10 GeV spacing, and with a minimum value of  $\Delta m = 20$  GeV for the signal models covered by the high- $\Delta m$  selection. For visualization purposes, contours are superimposed indicating where the expected and observed 95% C.L. limits on  $\mathcal{B}(H \rightarrow \text{NLSP NLSP})$  reach values of 2%, 5%, and 10%.

with the fitted background-only hypothesis in all categories for both the high- $\Delta m$  and low- $\Delta m$  selections. No significant excesses are observed, with the largest excess for any signal model considered having a significance of about 1.2 standard deviations. Therefore, a modified frequentist C.L.s method [54] is used to set 95% C.L. upper limits on  $\mathcal{B}(H \rightarrow \text{NLSP NLSP})$ , assuming that  $\mathcal{B}(\text{NLSP} \rightarrow \text{LSP} + \gamma)$  is equal to unity.

For a fixed NLSP lifetime, the limits are directly obtained for the 18 simulated signal models, covering a two-dimensional grid of NLSP masses ranging from 30 to 60 GeV and LSP masses from 0.5 GeV to  $m_{\text{NLSP}} - 10$  GeV. For visualization purposes, a bilinear interpolation between the discrete signal points simulated for each fixed lifetime is performed in order to obtain the 95% C.L. limits across the full available range of NLSP and LSP masses. In the high- $\Delta m$  case, the interpolation is performed on a two-dimensional grid of  $m_{\text{LSP}}$  versus  $m_{\text{NLSP}}$ . The results for fixed NLSP lifetimes of 2 and 10 ns are shown in Fig. 8. A selection

of contours corresponding to fixed values of the expected and observed 95% C.L. upper limits on  $\mathcal{B}(H \rightarrow \text{NLSP NLSP})$  is superimposed on the  $(m_{\text{NLSP}}, m_{\text{LSP}})$  plane.

In the low- $\Delta m$  case, the interpolation can only be performed in one dimension, providing the 95% C.L. limit versus the NLSP mass, since the LSP mass is fixed according to the relation  $m_{\text{NLSP}} - m_{\text{LSP}} = 10$  GeV. The observed and expected 95% C.L.  $\mathcal{B}(H \rightarrow \text{NLSP NLSP})$  upper limit curves for the low- $\Delta m$  selection are shown in Fig. 9 for NLSP lifetimes of 2 and 10 ns.

Examining the results in Figs. 8 and 9, there is a clear dependence of the achieved limit on the signal mass splitting,  $\Delta m$ . The most stringent constraints are achieved toward the bottom right corner of Fig. 8, where 95% C.L. upper limits on  $\mathcal{B}(H \rightarrow \text{NLSP NLSP})$  of order 1% are obtained. In that region of the signal mass grid, the mass splitting between the NLSP and LSP is large, giving rise to higher-energy photons and, therefore, higher photon acceptance and lower backgrounds. Moving from the bottom

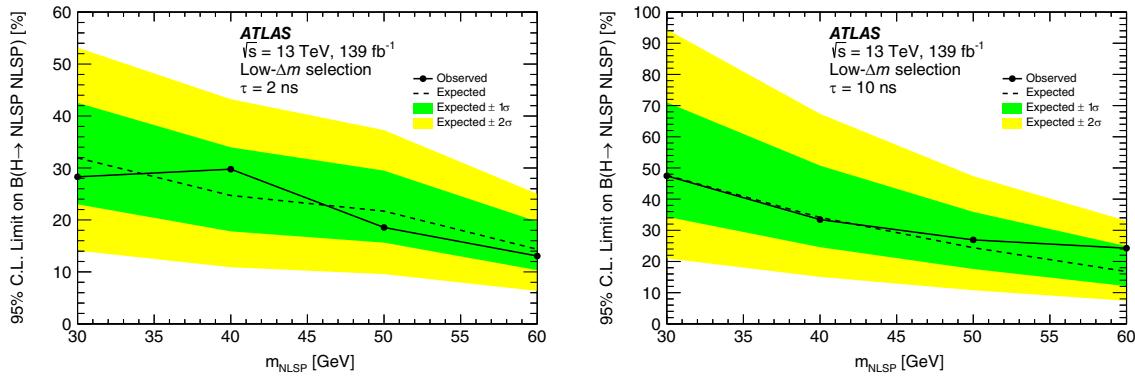


FIG. 9. Interpolated 95% C.L. limits on  $\mathcal{B}(H \rightarrow \text{NLSP NLSP})$  as a function of NLSP mass for signal points in the low- $\Delta m$  selection. Straight lines are drawn between the results for the discrete signal models considered by the low- $\Delta m$  selection, which were simulated with  $\Delta m = 10$  GeV. The plot on the left (right) corresponds to the results with the NLSP lifetime equal to 2 (10) ns.

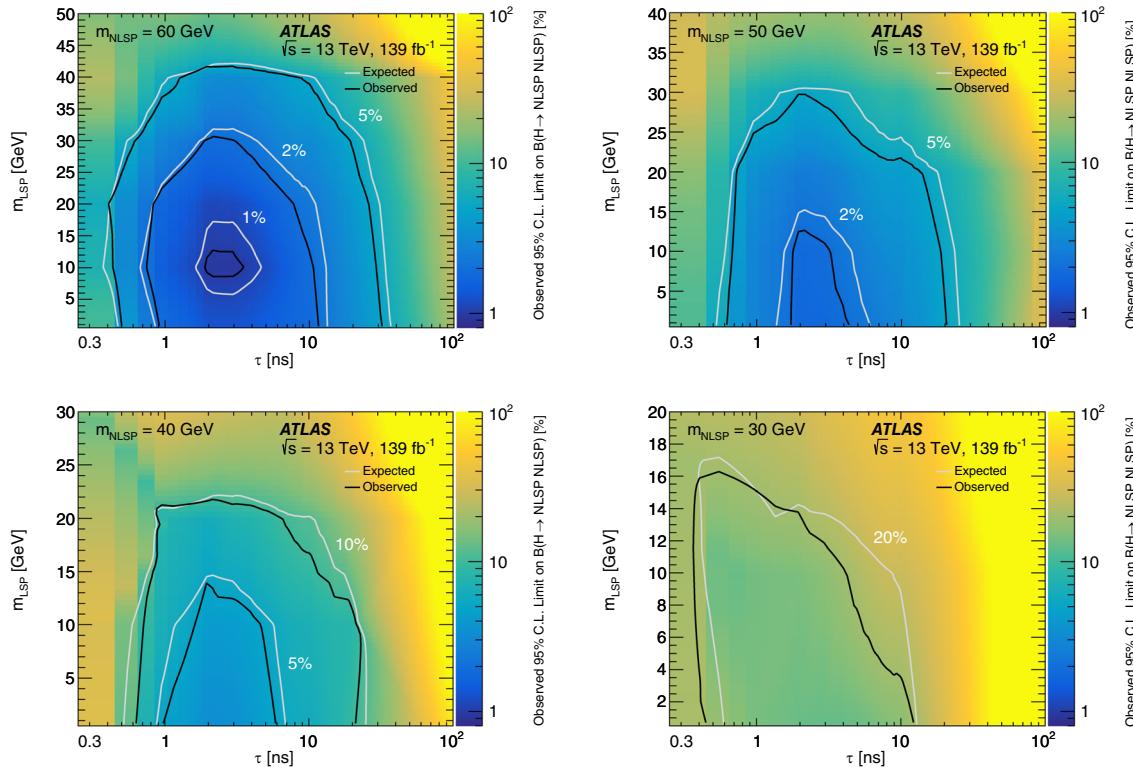


FIG. 10. Interpolated 95% C.L. limits on  $\mathcal{B}(H \rightarrow \text{NLSP NLSP})$  in the plane of LSP mass versus NLSP lifetime. Within each plot, the NLSP mass is held fixed, with values of 60 (top left), 50 (top right), 40 (bottom left), and 30 GeV (bottom right). A smoothing function is used to continuously fill the plane, interpolating between the results for the discrete signal models, which were simulated on a grid with 10 GeV spacing. For visualization purposes, contours are superimposed to indicate where the expected and observed 95% C.L. limits on  $\mathcal{B}(H \rightarrow \text{NLSP NLSP})$  reach values of 1%, 2%, 5%, 10% or 20%, depending on the plot.

right to upper left in Fig. 8, the limits smoothly become less stringent as the mass splitting decreases, a trend which continues into the low- $\Delta m$  results in Fig. 9. However, it should be noted that the 95% C.L. upper limit on  $\mathcal{B}(H \rightarrow \text{NLSP NLSP})$  is below 10% over most of the two-dimensional mass plane for the high- $\Delta m$  case shown in Fig. 8.

The observed BSM limits also depend on the NLSP lifetime. Comparing the left and right plots of Figs. 8 and 9 shows that, for a given set of NLSP and LSP mass values, the upper limits on  $\mathcal{B}(H \rightarrow \text{NLSP NLSP})$  for an NLSP lifetime of 2 ns are tighter than those for a 10 ns NLSP lifetime. This reflects the fact that the probability of at least one NLSP decaying before reaching the EM calorimeter is higher for low-lifetime signal points, resulting in higher photon (and therefore signal) acceptance. The lifetime dependence of the results is further explored by appropriately reweighting the simulated MC samples, typically generated with fixed NLSP lifetimes of either 2 or 10 ns, in order to produce reweighted samples corresponding to other lifetime values, ranging from 250 ps to 100 ns.

Using this lifetime reweighting method, Fig. 10 presents the 95% C.L. limits on  $\mathcal{B}(H \rightarrow \text{NLSP NLSP})$  in the two-dimensional plane of LSP mass versus NLSP lifetime. An interpolation is again used to provide smooth results

throughout the plane, connecting the discrete mass values that were simulated. The results are shown separately in four plots, with the NLSP mass fixed within a given plot, and with the four fixed NLSP mass values considered being 30, 40, 50, and 60 GeV.

The results in Fig. 10 demonstrate that the limits are most stringent for NLSP lifetimes of the order of a few nanoseconds, as expected given the size of the ID. The limits become weaker for both shorter and longer lifetimes. The sensitivity decreases for longer lifetimes because more NLSP decays occur outside the ID volume and therefore fewer decay photons are reconstructed in the EM calorimeter, with a resultant loss of signal acceptance. For very short lifetimes, the signal pointing and timing distributions become more difficult to separate from the prompt background, reducing the sensitivity of the analysis. These trends can be illustrated more clearly by examining the evolution of the limits as a function of NLSP lifetime for fixed NLSP and LSP masses, as shown in Fig. 11.

In addition to the results reported above for LLPs produced in Higgs boson decays, a more model-independent test is performed to provide a limit on the production of displaced photons with large values of both pointing and timing, using the selection requirements of the high- $\Delta m$

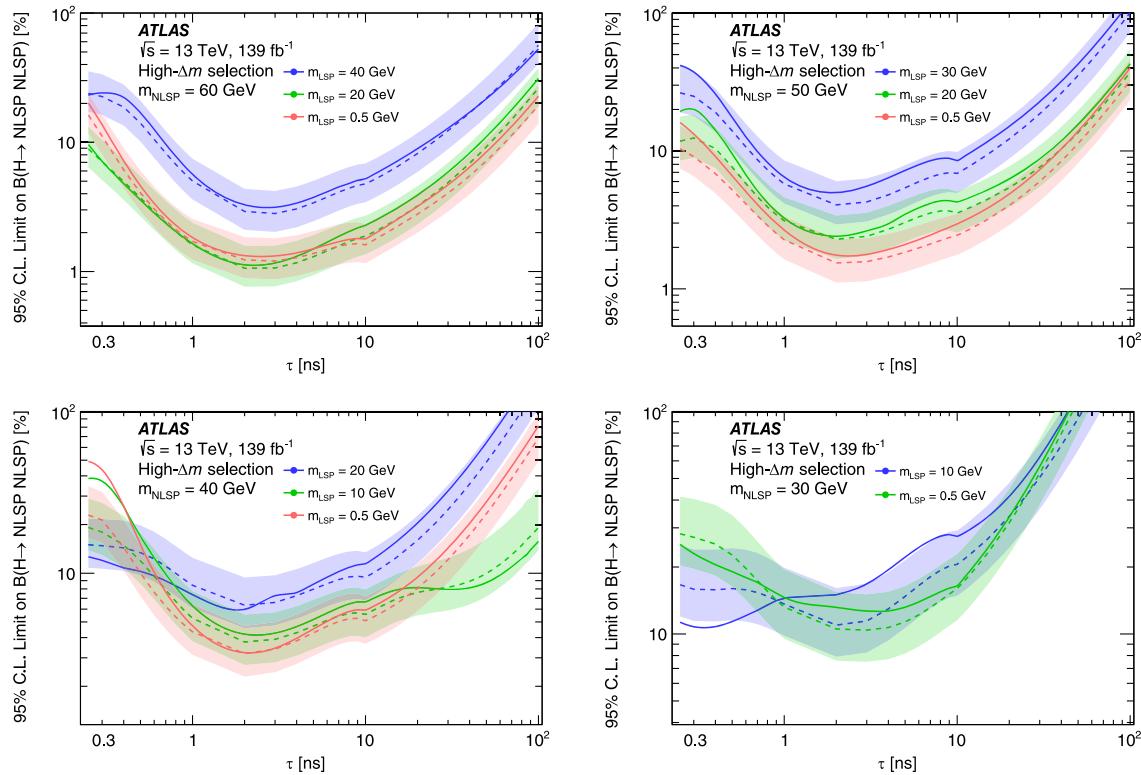


FIG. 11. The 95% C.L. limits on  $\mathcal{B}(H \rightarrow \text{NLSP NLSP})$  from the high- $\Delta m$  selection as a function of NLSP lifetime for fixed values of the NLSP and LSP masses. Within each plot, the NLSP mass is held fixed, with values of 60 (top left), 50 (top right), 40 (bottom left), and 30 GeV (bottom right). Each plot includes multiple curves, each with the LSP mass fixed, as shown in the legend. The 95% C.L. observed limits are shown as solid lines, while the 95% C.L. expected limits and their  $\pm 1\sigma$  uncertainties are shown as the dotted lines and shaded bands, respectively. The crossings of the observed and expected limits are a result of changing relative importance of the  $1\gamma$  and  $\geq 2\gamma$  channels as a function of signal lifetimes.

analysis. The test is performed separately for the  $1\gamma$  and  $\geq 2\gamma$  channels, as well as their combination. The model-independent test region is defined for each channel by the lower bound for the single bin with the highest pointing and timing values. The pointing requirement is thus  $|\Delta z_\gamma| > 300$  mm for both channels, while the timing requirement is  $t_\gamma > 1.5$  (1) ns for the  $1\gamma$  ( $\geq 2\gamma$ ) channel. The same likelihood fit procedure described in Sec. VIII is applied but eliminating the model-independent test regions from the fit. The background prediction and uncertainty in the model-independent test regions are then determined by extrapolating the results of this background-only fit

to the model-independent region with higher pointing and timing values.

The model-independent limits are summarized in Table II. For the two channels combined, four events are observed in the data, whereas the background prediction is  $4.1 \pm 1.7$  events. Since the observed numbers of events are consistent with the background expectation in all regions, the results are used to set 95% C.L. upper limits on the visible cross sections of BSM signals in the model-independent test regions. The reconstruction efficiency for signal events, after taking into account the acceptance of the selection, is typically around 5% for signal samples considered in this analysis.

TABLE II. Expected background event yield and observed event yield in the model-independent test regions, as defined for the  $1\gamma$  and  $\geq 2\gamma$  channels by the listed requirements, as well as for the combination of the two channels. Also shown are the values of  $\sigma_{\text{vis}}^{95}$ , the corresponding 95% C.L. limit on the visible cross section of BSM signals.

Channel	Test region requirements	Expected	Observed	$\sigma_{\text{vis}}^{95}$ [fb]
$1\gamma$	$1.5 < t_\gamma < 12$ ns, $ \Delta z_\gamma  > 300$ mm	$3.8 \pm 1.6$	4	0.042
$\geq 2\gamma$	$1.0 < t_\gamma < 12$ ns, $ \Delta z_\gamma  > 300$ mm	$0.28 \pm 0.04$	0	0.022
$\geq 1\gamma$		$4.1 \pm 1.7$	4	0.041

## X. CONCLUSION

A search is performed for delayed and nonpointing photons produced from exotic decays of the 125 GeV Higgs boson into a pair of BSM LLPs, such as the NLSP present in GMSB models. The dataset used was recorded by the ATLAS detector at the LHC and corresponds to an integrated luminosity of  $139 \text{ fb}^{-1}$  of  $pp$  collisions at a center-of-mass energy of  $\sqrt{s} = 13 \text{ TeV}$ .

Using measurements of the trajectories and arrival times of photons in the ATLAS LAr EM calorimeter to search for possible displaced photons, no excess is observed above the expectation from prompt backgrounds, which are modeled entirely using data control samples. The results are used to set limits on  $\mathcal{B}(H \rightarrow \text{NLSP NLSP})$  for NLSP lifetimes ranging from 0.25 to 100 ns, assuming that  $\mathcal{B}(\text{NLSP} \rightarrow \text{LSP} + \gamma) = 100\%$ . The limits are determined in a two-dimensional grid of NLSP mass values from 30 to 60 GeV and LSP masses from 0.5 GeV up to  $m_{\text{NLSP}} - 10 \text{ GeV}$ . The most stringent constraints limit  $\mathcal{B}(H \rightarrow \text{NLSP NLSP})$  to less than about 1% for intermediate NLSP lifetime values and for the largest NLSP mass and mass splitting between the NLSP and LSP. A model-independent limit is also set on the production of photons with large values of displacement and time delay.

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Baker<sup>170</sup>, P. J. Bakker<sup>113</sup>, E. Bakos<sup>15</sup>, D. Bakshi Gupta<sup>8</sup>, S. Balaji<sup>146</sup>, R. Balasubramanian<sup>113</sup>, E. M. Baldin<sup>37</sup>, P. Balek<sup>132</sup>, E. Ballabene<sup>70a,70b</sup>, F. Balli<sup>134</sup>, L. M. Baltes<sup>63a</sup>, W. K. Balunas<sup>32</sup>, J. Balz<sup>99</sup>, E. Banas<sup>85</sup>, M. Bandieramonte<sup>128</sup>, A. Bandyopadhyay<sup>24</sup>, S. Bansal<sup>24</sup>, L. Barak<sup>150</sup>, E. L. Barberio<sup>104</sup>, D. Barberis<sup>57b,57a</sup>, M. Barbero<sup>101</sup>, G. Barbour,<sup>95</sup>, K. N. Barends<sup>33a</sup>, T. Barillari<sup>109</sup>, M.-S. Barisits<sup>36</sup>, J. Barkeloo<sup>122</sup>, T. Barklow<sup>142</sup>, R. M. Barnett<sup>17a</sup>, P. Baron<sup>121</sup>, D. A. Baron Moreno<sup>100</sup>, A. Baroncelli<sup>62a</sup>, G. Barone<sup>29</sup>, A. J. Barr<sup>125</sup>, L. Barranco Navarro<sup>47a,47b</sup>, F. Barreiro<sup>98</sup>, J. 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 S. Biondi<sup>ID</sup>,<sup>23b,23a</sup> A. Biondini<sup>ID</sup>,<sup>91</sup> C. J. Birch-sykes<sup>ID</sup>,<sup>100</sup> G. A. Bird<sup>ID</sup>,<sup>20,133</sup> M. Birman<sup>ID</sup>,<sup>167</sup> T. Bisanz<sup>ID</sup>,<sup>36</sup> D. Biswas<sup>ID</sup>,<sup>168,i</sup>  
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 M. Bosman<sup>ID</sup>,<sup>13</sup> J. D. Bossio Sola<sup>ID</sup>,<sup>36</sup> K. Bouaouda<sup>ID</sup>,<sup>35a</sup> J. Boudreau<sup>ID</sup>,<sup>128</sup> E. V. Bouhova-Thacker<sup>ID</sup>,<sup>90</sup> D. Boumediene<sup>ID</sup>,<sup>40</sup>  
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