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Search for signatures of electroweakinos with photons, jets, and large missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector

The ATLAS Collaboration

A search for final states characterised by at least one isolated high transverse-momentum photon, jets and large missing transverse momentum is presented. Such a final state might occur in gauge-mediated supersymmetric models where a pair of binos and higgsinos mix to form neutralinos, one of which decays into a photon plus a gravitino while the other decays into a Higgs boson, a Z boson or a photon, plus a gravitino. The search is performed using the full Run-2 data sample of 140 fb^{-1} of $\sqrt{s} = 13$ TeV proton–proton collisions collected by the ATLAS detector at the Large Hadron Collider. No significant excess of events is observed above the Standard Model prediction and model-dependent exclusion limits at the 95% confidence level are set. These limits are interpreted in terms of the masses of gauginos, which are excluded up to 1.2 TeV depending on their branching ratios, and on their branching ratios as a function of their mass.

Contents

1 Introduction

This paper describes a search for an excess of events with isolated high transverse-momentum (high-p_{T}) photons, jets and large missing transverse momentum ($\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$, with magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$) over the Standard Model (SM) prediction that may constitute a striking signature of physics beyond the SM.

The results are interpreted in the context of supersymmetry (SUSY) [1–7], a theoretical extension of the SM that solves the hierarchy problem [8, 9] through the addition of a new fermionic/bosonic supersymmetric partner to each boson/fermion in the SM together with an extended Higgs sector with two Higgs doublets. Theories of gauge-mediated SUSY breaking (GMSB) [10–12] presume a hidden sector in which supersymmetry is broken by a vacuum expectation value, and the symmetry breaking is communicated to the visible sector through SM gauge boson interactions. In SUSY models with low-energy SUSY breaking scales, such as GMSB or general gauge mediation (GGM) [13, 14], the ultra-light gravitino ($\tilde{G}$) is the lightest supersymmetric particle (LSP) and stable under R-parity conservation. Therefore, the gravitino is a candidate for dark matter [15, 16]. In this paper, GGM models are considered, which are extensions of the GMSB idea, allowing decoupled mass scales for strongly interacting supersymmetric partners.

A general feature of SUSY models is the mixing of binos, winos and higgsinos (the superpartners of the electroweak gauge bosons and the Higgs bosons, respectively). These electroweakinos mix to form neutralino ($\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$) and chargino ($\tilde{\chi}_2^{\pm}, \tilde{\chi}_1^{\pm}$) mass eigenstates, where the states are ordered by increasing values of their mass.

The phenomenology of the models is driven by the nature of the next-to-lightest SUSY particle (NLSP). In this study, the NLSP is assumed to be the lightest neutralino $\tilde{\chi}_1^0$, as occurs in a large fraction of the GGM parameter space. The $\tilde{\chi}_1^0$ decays into a $\tilde{G}$ and either a γ, a Z boson, or the lightest neutral Higgs boson h, assumed to be the 125 GeV Higgs boson observed by ATLAS [17] and CMS [18].

If the $\tilde{\chi}_1^0$ is predominantly bino, the main decay channel is $\tilde{\chi}_1^0 \to \gamma\tilde{G}$, while a state with a dominant higgsino component decays as $\tilde{\chi}_1^0 \to h\tilde{G}$. In addition, since the longitudinal polarisation component of the Z boson is also a Goldstone mode of the Higgs field, a higgsino admixture neutralino can also decay as $\tilde{\chi}_1^0 \to Z\tilde{G}$.

Consequently, a pair of $\tilde{\chi}_1^0$ produced in a hadron collider can give rise to a signature containing two final-state bosons (hh, $h\gamma$, hZ, $Z\gamma$, ZZ or $\gamma\gamma$) plus $E_{\mathrm{T}}^{\mathrm{miss}}$ from the stable, undetectable LSP particles ($\tilde{G}$). Several analyses using these signatures have been conducted in the search for SUSY particles produced via strong interactions at the LHC [19–30]. A previous search by ATLAS for the case of electroweak production was performed using data from pp collisions at $\sqrt{s}$ = 8 TeV corresponding to an integrated luminosity of 20.3 fb^{-1} [26]. In Run 2 of the Large Hadron Collider (LHC) [31], previous ATLAS searches for electroweakinos have focused on exclusive diphoton signatures, initially using partial data [29], and later with the full data sample, targeting Higgs boson decays into two photons [32, 33]. More recently, CMS has reported their corresponding Run-2 results using a similar signature and targeting related models [34].

The present result is based on the full Run-2 ATLAS data sample and complements earlier searches focused on strong production channels. This analysis enhances the sensitivity to electroweak production by probing new regions of the parameter space, employing a more inclusive selection of final states, and extending the reach to higher masses than previous ATLAS electroweakinos searches, investigating neutralino masses up to 1.2 TeV. Another key innovation in this study is the scanning over different combinations of branching ratios to derive exclusion limits, significantly broadening the scope compared to previous analyses.

The analysis presented in this paper targets the production of $\tilde{\chi}_1^0$ considered as a bino–higgsino admixture resulting in final states with at least one γ plus two $\tilde{G}$. Example diagrams of the processes in the R-parity conservation GGM model are shown in Figure 1. The phenomenology of bino–higgsino models and their implications for LHC searches are also discussed in the context of extended Higgs sector scenarios in Ref. [35].

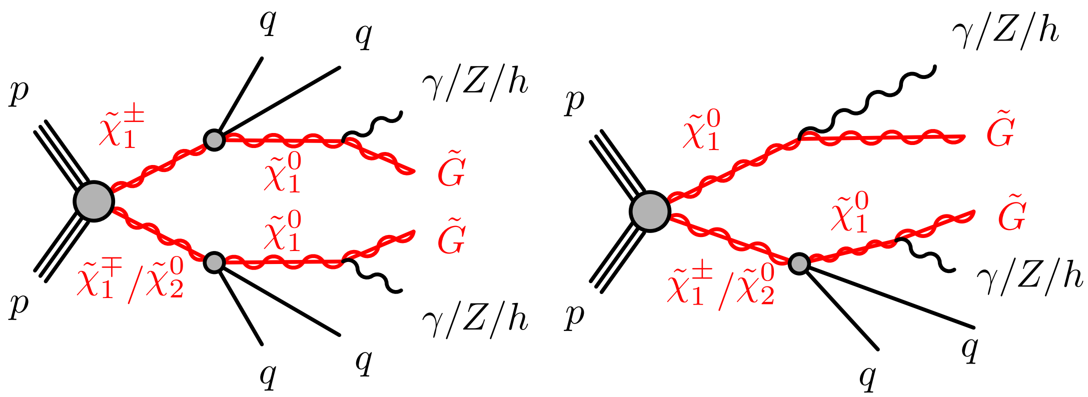


Figure 1: Example production diagrams of neutralinos and their subsequent decay into a final state with a photon, jets and missing transverse momentum.

2 ATLAS detector

The ATLAS detector [36] at the LHC covers nearly the entire solid angle around the collision point.[1] It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic (EM) and hadron 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 of $|\eta| < 2.5$. 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 (IBL) installed before Run 2 [37, 38]. It is followed by the silicon microstrip tracker (SCT), 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 $|\eta| < 3.2$, EM calorimetry is provided by barrel and endcap 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 a steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadron endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimised for EM and hadronic energy measurements respectively.

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, cover 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 endcap regions.

Interesting events 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 [39]. The first-level trigger accepts events from the 40 MHz bunch crossings at a rate close to 100 kHz, which the high-level trigger further reduces in order to record complete events to disk at about 1.25 kHz.

A software suite [40] 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.

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

3 Simulation samples

Samples of the targeted GGM SUSY signals and SM backgrounds were simulated at $\sqrt{s} = 13$ TeV using dedicated Monte Carlo (MC) generators. For the design of the signal regions (SR) and the interpretation of the results a collection of signal samples was generated selecting a set of benchmark points. The bino component of the lightest neutralino couples to both the photon and the Z boson, while the higgsino component couples to the Z or Higgs boson. To generate the signal samples a simplified approach was implemented, where the masses of the particles, the decay branching fractions and the mixing matrices were the only input parameters. The four most relevant electroweakino production channels were considered: $\tilde{\chi}_1^0\,\tilde{\chi}_2^0$, $\tilde{\chi}_1^0\,\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0\,\tilde{\chi}_1^\pm$ and $\tilde{\chi}_1^+\,\tilde{\chi}_1^-$. Production modes including $\tilde{\chi}_3^0$ are highly suppressed and are not considered for this search. The samples corresponding to the signal points were produced as a function of the $\tilde{\chi}_1^0$ mass, $m_{\tilde{\chi}_1^0}$, from 150 to 1450 GeV in steps of 100 GeV. The $\tilde{\chi}_2^0$ ($\tilde{\chi}_1^\pm$) mass was chosen to be equal to $m_{\tilde{\chi}_1^0} + 11(10)$GeV, while the $\tilde{G}$ mass was set to 1 eV. The rest of the sparticle masses were set in the decoupled regime at 4.5 TeV. The $\tilde{\chi}_2^0$ ($\tilde{\chi}_1^\pm$) were set to always decay into $\tilde{\chi}_1^0$ via an off-shell Z ($W^\pm$), with the latter having SM decays. The $\tilde{\chi}_1^0$ branching fractions were set to be equal between $\tilde{G} + \gamma$, $\tilde{G} + Z$ and $\tilde{G} + h$ decays. This choice allows for a re-weighting of the events in order to reproduce different models, characterised by the $\tilde{\chi}_1^0$ branching ratio, and also offers the possibility to set exclusion limits as a function of the branching ratio using only one set of signal samples. All signal events contain a pair of $\tilde{\chi}_1^0$ in the decay chain, so each event can be classified by the decay product of the pair, i.e. $\gamma\gamma, \gamma h, \gamma Z, ZZ, Zh$ or hh. Two benchmark scenarios are studied as the most representative for the final state with photons and jets: the $\tilde{\chi}_1^0$ decaying 50% into $\gamma + \tilde{G}$ and 50% into $Z + \tilde{G}$, and the $\tilde{\chi}_1^0$ decaying 50% into $\gamma + \tilde{G}$ and 50% into $h + \tilde{G}$ (referred to as the '$\gamma + Z$' and '$\gamma + h$' benchmark models respectively). All signal samples were generated at leading order (LO) in quantum chromodynamics (QCD) with up to two additional partons with MadGraph 5 [41] interfaced to Pythia 8.2 [42] using the A14 tune and the NNPDF2.3lo PDF set[43].

The cross-section of each process was calculated using resummino-3.0.0 [44–48] at next-to-leading plus next-to-leading-logarithmic (NLO+NLL) precision, using CTEQ6.6 and the MSTW2008 parton distribution functions (PDFs), with their corresponding variations in PDF sets and in scales as described in Ref. [49].

Samples of $t\bar{t}\gamma$ events were generated with MadGraph5_aMC@NLO [41] at NLO (with $m_{\text{top}} = 172.5$ GeV), interfaced to the Pythia 8.2 parton shower model [42] with the A14 set of tuned parameters (tune) [50]. The NNPDF3.0nlo [51] set of PDFs was used. The production of Higgs boson events, $t\bar{t}h(\rightarrow \gamma\gamma)$, was modelled using the Powheg Box v2 [52–56] generator at NLO with the NNPDF3.0nlo PDF set. The events were interfaced to Pythia 8.2 using the A14 tune and the NNPDF2.3lo PDF set.

The rest of the SM backgrounds were simulated with the Sherpa 2.2 [57] generator. Matrix elements at LO or NLO accuracy in QCD were calculated with the Comix [58] and OpenLoops 1 [59–61] libraries. The matrix element calculations were matched and merged with the Sherpa parton shower based on Catani–Seymour dipole factorisation [58, 62] using the MEPS@NLO prescription [63–66]. These background samples were simulated using the NNPDF3.0nnlo PDF set, along with the dedicated set of tuned parton-shower parameters developed for Sherpa.

For the production of $V\gamma$ ($W\gamma$ and $Z\gamma$) and prompt single-photon (γ + jets) final states, Sherpa 2.2.2 was used (without NLO electroweak corrections). Matrix elements at NLO for up to one (two) additional parton emission(s) and at LO accuracy for up to three (four) additional parton emissions were calculated for the $V\gamma$ (γ + jets) samples. Diphoton and $V\gamma\gamma$ ($W\gamma\gamma$ and $Z\gamma\gamma$) events were simulated with Sherpa 2.2.4. In this set-up, matrix elements at LO accuracy in QCD for up to three additional parton emissions were matched and merged with the Sherpa parton shower. To avoid any double counting of events when considering both the $V\gamma$ and $V\gamma\gamma$ samples, duplicated processes were removed, focusing on $V\gamma$ events with a photon from QED final-state radiation.

The contribution from other backgrounds including diboson $VV\gamma$ SM processes are found to be negligible. Backgrounds due to jets or electrons misidentified as photons are estimated via data-driven techniques and are discussed in Section 6.

The SM background samples were processed with a full ATLAS detector simulation [67] based on Geant4 [68]. The SUSY signal samples were passed through ATLFAST-II, a fast simulation of the ATLAS detector response based on a parameterisation of the performance of the ATLAS EM and hadronic calorimeters and on Geant4 elsewhere. MC events were reconstructed with the same algorithms used for data. An event-by-event reweighting was applied to all MC samples to realistically model the LHC conditions during data collection. This reweighting matches the simulated distribution of the number of inelastic pp collisions per bunch crossing (pile-up) to the one observed in data. The effect of pile-up was modelled by overlaying each hard-scattering event with simulated inelastic pp collisions generated by Pythia 8.186 [69] using the NNPDF2.3lo set of PDFs and the A3 tune [70]. SM background samples, except the ones that use the Sherpa event generator, were processed with EvtGen 1.7.0 [71] for the b- and c-hadron decays. The simulations were further corrected with efficiency scale factors and a smearing of the energy scale of photons, leptons and jets, to better describe the data. Table 1 presents a summary of the signal and background samples used in the analysis.

Table 1: Details of the SUSY signal and SM background MC samples considered in the analysis.

Process	Generators	PDF sets	Order
Signal	MadGraph 5 / Pythia 8.2	NNPDF2.3lo	0,1,2j@LO
$t\bar{t}\gamma$	MadGraph5_aMC@NLO / Pythia 8.2	NNPDF3.0nlo / NNPDF2.3lo	NLO
$t\bar{t}h(\rightarrow\gamma\gamma)$	Powheg / Pythia 8.2	NNPDF3.0nlo / NNPDF2.3lo	NLO
$W\gamma/Z\gamma$	Sherpa 2.2.2	NNPDF3.0nnlo	0,1j@NLO + 2,3j@LO
γ + jets	Sherpa 2.2.2	NNPDF3.0nnlo	1,2j@NLO + 3,4j@LO
$\gamma\gamma/W\gamma\gamma/Z\gamma\gamma$	Sherpa 2.2.4	NNPDF3.0nnlo	0,1,2,3j@LO

4 Event reconstruction

Primary vertices are formed from sets of two or more charged-particle tracks, each with transverse momentum $p_{\mathrm{T}} > 0.5$ GeV that are consistent with having originated at the same three-dimensional space point within the luminous region of the colliding proton beam [72]. When more than one such primary vertex is found the vertex with the largest scalar sum of the squared transverse momenta of the associated tracks is chosen.

The offline electron and photon reconstruction uses dynamic, variable-size clusters of energy deposits measured in topologically connected EM and hadronic calorimeter cells [73], called ‘topo-clusters’. These are matched to reconstructed charged-particles tracks from the ID. Topo-clusters that are not matched to a track or a conversion vertex are classified as unconverted photons. On the other hand, if a topo-cluster is matched to a conversion vertex, it is classified as a converted photon. Finally, when a topo-cluster is matched to a track, it is classified as an electron [74].

Photon candidates are required to satisfy the 'tight' identification criteria for the lateral and longitudinal shower shape [74], have $p_{\mathrm{T}} > 50$ GeV and $|\eta| < 2.37$, and are removed if they are within the EM calorimeter (ECAL) barrel–endcap transition region defined by $1.37 < |\eta| < 1.52$. To reduce the background from jets that could be misidentified as photons, both track and calorimetric isolation requirements are applied to signal-region photon candidates. The calorimetric isolation energy, $E_{\mathrm{T}}^{\mathrm{iso}}$, is computed as the sum of the topo-clusters' transverse energies [73] calibrated at the EM scale within a cone of size $\Delta R = 0.4$ around the cluster barycentre. This $E_{\mathrm{T}}^{\mathrm{iso}}$ is required to be less than $2.45\ \mathrm{GeV} + 0.022 p_{\mathrm{T}}$, where p_{T} is that of the photon. The track isolation variable, $p_{\mathrm{T}}^{\mathrm{iso}}$, is obtained as the scalar sum of the transverse momenta of good-quality tracks inside a cone of size $\Delta R = 0.2$ around the candidate, and is required to be less than $0.05 p_{\mathrm{T}}$.

Although electron and muon candidates are not used as part of the signal-region event selection they are included in the definition of some of the control and validation region selections.

Electron candidates are required to have $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.47$, and to originate from the primary vertex in both the r–z and r–ϕ planes. Longitudinal and transverse impact parameters (z_0 and d_0) relative to the primary vertex are required to satisfy $|z_0 \sin\theta| < 0.5$ mm and $|d_0|/\sigma_{d_0} < 5$, where σ_{d_0} is the uncertainty in d_0. A 'tight' set of identification criteria is imposed [74] that is based on the characteristics of the EM shower development, the quality of the associated reconstructed track, and the angular proximity of the track to the calorimeter energy deposition. Electrons are required to satisfy a 'loose' isolation criterion [74], and not be within the ECAL barrel–endcap transition region.

Muons are reconstructed by combining compatible track information from the MS and the ID. Muon candidates are required to have $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.7$, to satisfy the 'medium' quality criteria [75], to originate from the primary vertex in both the r–z and r–ϕ planes (with impact parameters satisfying $|z_0 \sin\theta| < 0.5$ mm and $|d_0|/\sigma_{d_0} < 3$) and to satisfy a 'loose' isolation requirement [75].

Jets are reconstructed using the anti-k_t algorithm [76, 77] with a radius parameter $R = 0.4$, using the information collected in both calorimeters and track detectors [78]. The expected average energy contribution from pile-up interactions is subtracted according to the jet area.

Track-based selection requirements are applied to reject jets with $p_{\mathrm{T}} < 60$ GeV and $|\eta| < 2.4$ that originate from pile-up interactions [79]. Jets are kept if they are in the central, $|\eta| < 2.8$, region of the detector and have $p_{\mathrm{T}} > 20$ GeV. For the $E_{\mathrm{T}}^{\mathrm{miss}}$ computation only (defined in the following) a broader selection including up to $|\eta| < 4.5$ is considered. Although jets containing b-hadrons (b-jets) are not explicitly used in the signal-region selections, they are used in the definition of control regions from which the $W\gamma$ and $t\bar{t}\gamma$ MC normalisation factors are extracted, as described in Section 5. The b-jets are selected from the selected jets within the ID acceptance using the same p_{T} requirement, and identified by the DL1r algorithm [80]. This algorithm uses the long lifetime, high decay multiplicity, hard fragmentation and large mass of b-hadrons to distinguish them from light-flavour jets (jets originated from light quarks and gluons). The b-tagging algorithm working point is chosen so that it has a nominal efficiency of 77% for b-jets in simulated $t\bar{t}$ events and a corresponding probability of misidentifying light-flavour jets below 1% [80–82].

The missing transverse momentum is computed with an object-based algorithm considering objects satisfying baseline requirements [30]. Calorimeter energy deposits are matched to high-p_{T} objects in the following order: electrons, photons, jets and muons. Primary-vertex tracks not associated with any such objects are included in the 'soft term' [83] contribution to $E_{\mathrm{T}}^{\mathrm{miss}}$. The $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ is computed from the negative vector sum of the transverse momenta of calibrated reconstructed physical objects and the soft term.

Due to possible final-state object misidentification, a single object can be reconstructed in more than one way and thus effectively counted multiple times. A procedure to remove these overlaps is applied to preselected objects before the corresponding isolation requirements are imposed. The basic strategy and the order of removal is described in Refs. [84, 85].

5 Event selection

This analysis is performed using the full Run-2 data sample of LHC proton–proton collisions at $\sqrt{s} = 13$ TeV collected by the ATLAS detector between 2015 and 2018, corresponding to an integrated luminosity of 140 fb^{-1} after the application of beam, detector and data quality requirements [86].

Events were selected using the single-photon trigger [87],and are required to have at least one offline photon with $p_{\text{T}} > 145$ GeV. The trigger was fully efficient for the signal selection requirements, as described in [74].TRIG-2018-05,

A set of signal regions sensitive to the targeted SUSY signatures are defined for the analysis, discriminating against SM processes contributing to the same final state. Given the relatively high mass of the electroweakinos targeted by this search the p_{T} of the final-state photon is expected to be large.

Three discovery signal regions (SRL, SRM and SRH) are defined to target the phase space of the model with low, medium and high $\tilde{\chi}_1^0$ mass. At higher masses, a more energetic gravitino is produced and consequently $E_{\text{T}}^{\text{miss}}$ is expected to be larger. The main distinction between the signal regions is therefore the requirement on this variable.

The contribution of $E_{\text{T}}^{\text{miss}}$ relative to the total energy contribution of all objects present in the event is quantified using the ratio of $E_{\text{T}}^{\text{miss}}$ and the effective mass, $m_{\text{eff}} = E_{\text{T}}^{\text{miss}} + p_{\text{T}}^{\text{leading}\,\gamma} + \sum_i^{\text{jets}} p_{\text{T}}^i$, where the leading photon is the one with the highest p_{T}. The $\frac{E_{\text{T}}^{\text{miss}}}{m_{\text{eff}}}$ ratio is expected to be larger for the SUSY signal than for the backgrounds, hence the requirement on this variable in the signal region.

In events characterised by a large reconstructed $E_{\text{T}}^{\text{miss}}$ without a significant contribution from non-interacting particles but arising from instrumental sources and poorly reconstructed objects, the $E_{\text{T}}^{\text{miss}}$ vector tends to be aligned with either the photon or one of the two leading jets. A selection based on the transverse angular separations between these objects, $\Delta\phi(\gamma, E_{\text{T}}^{\text{miss}})$ between the leading photon and the $E_{\text{T}}^{\text{miss}}$ vector and $\Delta\phi(\text{jet}, E_{\text{T}}^{\text{miss}})$ the minimum separation between the leading or sub-leading jet and the $E_{\text{T}}^{\text{miss}}$ vector, allows the contributions from these background processes to be reduced. The significance of $E_{\text{T}}^{\text{miss}}$ [83] is another discriminant between both sources of $E_{\text{T}}^{\text{miss}}$, thus a requirement is applied on it to further increase sensitivity. Additional jets are expected to be produced frequently in the signal decay chain, thus at least one jet is required in each signal region. In order to be orthogonal to the analysis focusing on similar final states but with the lightest Higgs boson decaying into photons [33], events with two photons with their invariant mass within the Higgs boson mass window ($120 < m_{\gamma\gamma} < 130$ GeV) are excluded. This selection has a negligible impact on the overall sensitivity of the search.

The event selection criteria for the full set of signal regions are summarised in Table 2, including both the inclusive selections for discovery (SRL, SRM, and SRH) and the orthogonal selections for exclusion (SRLe and SRMe). The additional signal subregions SRLe and SRMe are designed to improve the exclusion limits in the absence of an excess of events in the inclusive signal regions. Compared to the discovery signal regions, the requirements on $E_{\text{T}}^{\text{miss}}$ and $E_{\text{T}}^{\text{miss}}$ significance are tightened in order to make the three signal regions orthogonal (SRLe, SRMe and SRH), allowing a simultaneous exclusion fit. The signal region SRH is used both for discovery and limit setting without any modifications as shown schematically in Figure 2.

Table 2: Selections for the discovery signal regions SRL, SRM, SRH, and the exclusion signal regions SRLe and SRMe.

Signal regions	SRL	SRM	SRH	SRLe	SRMe
N_{photons}			> 0		
$p_{\text{T}}^{\text{leading }\gamma}$ [GeV]			> 145		
N_{jet}			> 0		
$\Delta\phi(\text{jet}, E_{\text{T}}^{\text{miss}})$			> 0.4		
$\Delta\phi(\gamma, E_{\text{T}}^{\text{miss}})$			> 0.4		
$E_{\text{T}}^{\text{miss}}/m_{\text{eff}}$			> 0.5		
$m_{\gamma\gamma}$ [GeV]			$\notin [120, 130]$		
$E_{\text{T}}^{\text{miss}}$ [GeV]	> 200	> 300	> 400	> 200 ($\notin$ SRM)	> 300 ($\notin$ SRH)
$E_{\text{T}}^{\text{miss}}$ significance	> 20	> 30	> 35	> 20 ($\notin$ SRM)	> 30 ($\notin$ SRH)

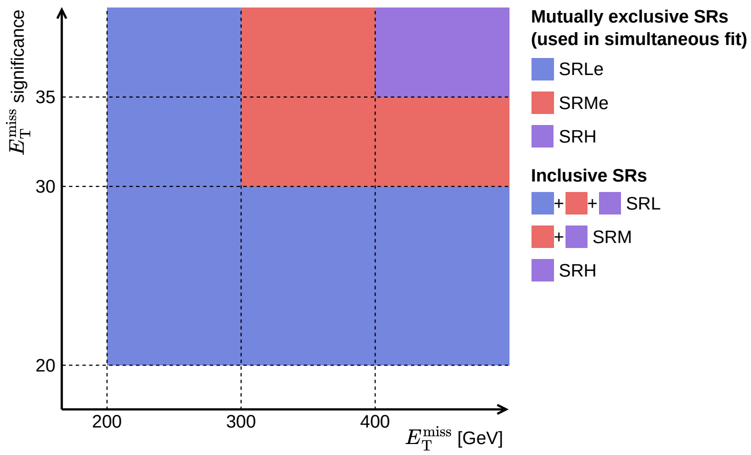


Figure 2: Schematic view of the three signal regions, defined in the $E_{\text{T}}^{\text{miss}}$ and $E_{\text{T}}^{\text{miss}}$ significance plane, used in the simultaneous fit for exclusion limits (SRLe, SRMe and SRH). The other inclusive SRs can be defined from these as SRL = SRLe ∪ SRMe ∪ SRH and SRM = SRMe ∪ SRH. The dotted lines represent the requirements on the corresponding variables.

6 Background estimation

The background for this search is composed of all SM processes that produce photons, jets and $E_{\text{T}}^{\text{miss}}$ in the final state. Both the production of neutrinos or a misreconstruction of the energy of one or more objects can generate $E_{\text{T}}^{\text{miss}}$ in the final state. Processes with jets or electrons can emulate the targeted topologies if any of these is misreconstructed as a photon.

The dominant SM background contribution to the SRs is expected to be from $Z(\to \nu\nu)\gamma$, with a lesser contribution from $W\gamma$ and $t\bar{t}\gamma$ in most regions of the analysis. The simulated predictions for these contributions are normalised using dedicated control regions where the simulations are constrained by the number of data events observed. Other minor processes, such as $t\bar{t}h(\to \gamma\gamma)$, $\gamma + \text{jets}$, $\gamma\gamma$ and $W\gamma\gamma/Z\gamma\gamma$, are estimated directly using the MC simulation. An estimate of the background contribution due to misidentified jets or electrons is determined via data-driven techniques.

Three control regions labelled CRZ, CRW, and CRT are used to obtain the MC normalisation for the $Z(\to \nu\nu)\gamma$, $W\gamma$ and $t\bar{t}\gamma$ events, respectively. These CRs are designed to be orthogonal but still kinematically similar to SRs, and enhanced in the background process of interest, with negligible signal contamination (less than 5%). Since $Z(\to \nu\nu)\gamma$ has the same final state as the SUSY signal, the design of a CR is not possible without having a high signal contamination. Therefore, a single CRZ with two electrons or two muons, focusing on the leptonic decays of the Z boson, $Z(\to ee)\gamma$ and $Z(\to \mu\mu)\gamma$, is used to normalise the three corresponding backgrounds simultaneously in each of the CRs. Since these processes have no $E_{\mathrm{T}}^{\mathrm{miss}}$ in the final state, an alternative reconstruction of $E_{\mathrm{T}}^{\mathrm{miss}}$, removing the leptons present in the event, is used to construct the CRs kinematically closer to the SRs. The CRT region is defined by requiring a photon, a lepton, jets and at least two b-tagged jets, with a looser $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement to increase the yields. The CRW region is defined by requiring a photon, a lepton and a b-jet veto to mitigate the contamination from $t\bar{t}\gamma$, and a requirement on the transverse mass of the lepton and $E_{\mathrm{T}}^{\mathrm{miss}}$, $m_{\mathrm{T}}(l, E_{\mathrm{T}}^{\mathrm{miss}})$[2], to increase the background purity. All CRs invert the requirement on $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$ to ensure orthogonality with the SRs.

A further set of event selections define validation regions (VRs) used to verify the results of the background estimation procedure. They are designed to lie kinematically between the signal regions and the control regions, with one or more criteria inverted or modified to reduce possible signal contamination. In general the requirement on $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$ is in accordance with the SRs, and the $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement increased to be closer to them. The VRZ, VRW and VRT are designed to validate the correct estimate of the $Z(\to \nu\nu)\gamma$, $W\gamma$ and $t\bar{t}\gamma$ backgrounds.

Jets can be misidentified as photons (called 'fake photons') if they contain a neutral hadron that carries most of the jet energy and that decays into a pair of collimated photons, resulting in an EM object resembling a single, highly energetic photon. This background arises primarily from QCD multijets, W + jets and semileptonic $t\bar{t}$ events, and it is reduced by applying the 'tight' identification criteria to photon candidates. After this requirement, the data sample is expected to be dominated by real photons with moderate jet contamination. This misidentification rate is not modelled accurately in MC simulation, thus a data-driven sideband counting method [85] is used. The method makes use of the different isolation profiles expected for real photons and misidentified jets [88]. Both tracking and calorimetric isolation variables of the photon candidate, as defined in Section 4, are considered simultaneously. The photon trigger used to collect the data required a looser photon identification than the 'tight' offline version. Some photon candidates from misidentified jets fail to satisfy the offline requirement but satisfy an intermediate selection. These jets, called 'non-tight photons', are defined as those candidates satisfying the 'loose' identification and the 'tight' selection requirements, except for at least one of four criteria associated with energy deposits in the EM calorimeter [85], chosen to be largely uncorrelated with the isolation variables. Hence the use of non-tight photons enhances the contribution of jets misidentified as photons (called 'jets faking photons'), as required for this method. In the identification–isolation plane, the method defines a signal region A consisting of isolated photon candidates that satisfy the 'tight' identification, and three control regions, namely B, C and D, with photon candidates being non-isolated and 'tight', isolated and non-tight, and non-isolated and non-tight, respectively. A small contribution of real photons still contaminates the three defined control regions; these are additionally referred to as 'leaked-photons'.

To accurately count the number of real, leaked and fake photons in the different regions, a series of template fits to the isolation profiles in data are performed using templates obtained from MC [74]. These

[2] $m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{l} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos[\Delta\phi(p_{\mathrm{T}}^{l}, p_{\mathrm{T}}^{\mathrm{miss}})])}$

templates are fitted using double sided asymmetric Crystal Ball (DSACB) functions (a Gaussian core with asymmetric non-Gaussian power-law tails) [89] to the tight and non-tight photon distributions in data. DSACB functions are also used to model the contribution of jets faking photons. The procedure to count the events is as follows. Firstly, using the leaked-photons template obtained from MC, the fake photons template is obtained by doing a composite fit to the non-tight photons isolation distribution in data. In this way, both the leaked and fake photons components are obtained in the non-tight regions C and D. Secondly, using the fake photon template and the real photon template obtained from MC, a fit to the tight data profile distribution is performed, resulting in the real and fake photons components in regions A and B. Finally, real, leaked and fake photons components can be extracted from the distributions by integrating the shapes in the isolated and non-isolated ranges.

For this method to be applicable, the correlation between identification and isolation for jets misidentified as photons must be small. Deviations from this expected behaviour are corrected by computing a factor that takes the residual correlation into account [85]. It is computed in auxiliary ABCD regions (defined in a similar way as before but where the calorimetric isolation requirement fails) as the ratio $N_{\mathrm{A}}N_{\mathrm{D}}/N_{\mathrm{B}}N_{\mathrm{C}}$, where N_{X} is the number of jets faking photons in the auxiliary ABCD regions. The residual correlation is found to be less than 20%. Furthermore, corrections to the method using the number of leaked-photons are applied. The systematic uncertainties in the method are evaluated by varying the definition of the non-tight objects, and considering the differences introduced by the residual correlation between the regions.

Electrons and positrons can also be misidentified as photons, and when they have high-p_{T} there can be significant contamination from SM processes such as $W/Z+$jets and $t\bar{t}$ in the signal regions. This background is estimated by weighting the number of electron events observed in electron control samples by the electron-to-photon fake rate. Electron control samples are taken from the same control, validation and signal regions as used in the analysis, but the photon kinematic selections are applied to electrons, and then a high-p_{T} isolated electron is required and signal photons are vetoed. To estimate the electron-to-photon fake rate, a method based on a sample of $Z(\rightarrow ee)$ data events is used [84, 85]. Since the Z boson cannot decay directly into an electron and a photon, the electron–photon events appearing under the Z peak most likely correspond to misidentified electrons. However, the same applies to other particles decaying into pairs of electrons that could contribute to the background around the Z mass values. Therefore, these background contributions are subtracted by also taking into account the contamination from random combinatorics background. Also, only events with $E_{\mathrm{T}}^{\mathrm{miss}} < 40$ GeV are selected, to avoid electrons from the W decays. The electron-to-photon fake factor is then estimated as the ratio of the number of electron–photon pairs to the number of electron–electron pairs found under the Z peak when fitting the invariant mass distribution. This fit uses a double sided Crystal Ball (DSCB) function to model the Z peak, and a Gaussian distribution to model the small non-resonant backgrounds to $Z(\rightarrow ee)$ production. Only the pairs within a defined invariant mass window are selected to compute the electron-to-photon fake factor. This window is defined as $\pm 3\sigma$ around the centre of the peak in the DSCB function, where σ is the width of the peak. Systematic uncertainties are evaluated by varying the Z-mass integration range, the energy calibration, and recalculating the fake factor without background subtraction. The background estimation is then performed by applying the electron-to-photon misidentification rate to an electron-control sample. This control sample mirrors the original control, validation, and signal regions of the analysis but replaces photon selections with analogous electron criteria. Specifically, events are required to contain a high-p_{T}, isolated electron (while vetoing genuine photons), and all other kinematic selections used for photons are applied to electrons. The prediction of the background due to electrons misidentified as photons is validated in a dedicated validation region (VRE) based on the calculated fake factors. It mostly targets $W(e\nu)+$jets events (by requiring low $m_{\mathrm{T}}(\gamma, E_{\mathrm{T}}^{\mathrm{miss}})$), where a boosted W boson (including those coming from top quarks) decays into a neutrino (giving high $E_{\mathrm{T}}^{\mathrm{miss}}$) and an almost collinear high-p_{T} electron (misidentified as a photon).

The selection criteria for the CRs and VRs are presented in Table 3.

Table 3: Selection criteria for the control regions and the validation regions used for the W, top, Z, and fakes background estimation. All CRs and VRs also include the following common cuts: $N_{\mathrm{photons}} > 0$, $p_{\mathrm{T}}^{\mathrm{leading}\,\gamma} > 145$ GeV and $N_{\mathrm{jet}} > 0$. The asterisk * means that $E_{\mathrm{T}}^{\mathrm{miss}}$ in this case is reconstructed without considering the leptons. Additionally in regions CRZ and VRZ an $E_{\mathrm{T}}^{\mathrm{miss}} < 50$ selection is applied in the variable including leptons.

Variable	CRW	CRT	CRZ	VRW	VRT	VRZ	VRE
N_{leptons}	1	≥ 1	2	1	≥ 1	2	–
N_{bjets}	0	≥ 2	–	–	≥ 1	–	–
$\Delta\phi(\mathrm{jet}, E_{\mathrm{T}}^{\mathrm{miss}})$	> 0.4	> 0.4	$> 0.4^*$	> 0.4	> 0.4	$> 0.4^*$	> 0.4
$\Delta\phi(\gamma, E_{\mathrm{T}}^{\mathrm{miss}})$	> 0.4	> 0.4	$> 0.4^*$	> 0.4	> 0.4	$> 0.4^*$	< 0.4
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 200	> 150	$> 100^*$	> 200	> 200	$> 200^*$	> 200
$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$	< 0.35	< 0.35	$< 0.35^*$	> 0.35	> 0.35	$> 0.35^*$	> 0.25
$E_{\mathrm{T}}^{\mathrm{miss}}$ significance	–	–	–	< 20	< 20	–	> 10
$m_{\mathrm{T}}(l, E_{\mathrm{T}}^{\mathrm{miss}})$ [GeV]	< 100	–	–	–	–	–	–
$m_{\mathrm{T}}(\gamma, E_{\mathrm{T}}^{\mathrm{miss}})$ [GeV]	–	–	–	–	–	–	< 80

Likelihood fits [90] are performed assuming (i) a background-only hypothesis on all CRs to estimate the total background in the SRs and VRs; (ii) a model-dependent signal plus background hypothesis where the fit is performed in the CRs and independent SRs simultaneously; and (iii) a model-independent signal plus background hypothesis, where both the CRs and individual SRs are used in the same manner as for the model-dependent signal fit with the number of signal events in the SRs added as a parameter to the fit. This approach constrains the expected background to the yields observed in the data using the CRs and reduces the systematic uncertainties.

Figure 3 shows the data event yields and the SM expectation in the different control and validation regions obtained with a background-only maximum-likelihood fit, constraining the normalisation of the dominant backgrounds and including those estimated by using data-driven techniques. The lower panel shows the statistical significance, in standard deviations, between the observed and expected yields in the VRs [91] and the normalisation factors for each CRs. The normalisation factors are close to unity, except for the CRT region (1.34 ± 0.12), in agreement with previous results [30]. Good agreement is found between data and SM background predictions in all validation regions.

7 Systematic uncertainties

All background processes estimated either by making use of MC simulations or by data-driven methods, as well as MC signal predictions, are affected by systematic uncertainties that mainly originate from two kinds of sources: experimental and theoretical ones. These uncertainties can impact the expected yields in the analysis regions and are introduced in the fits as nuisance parameters.

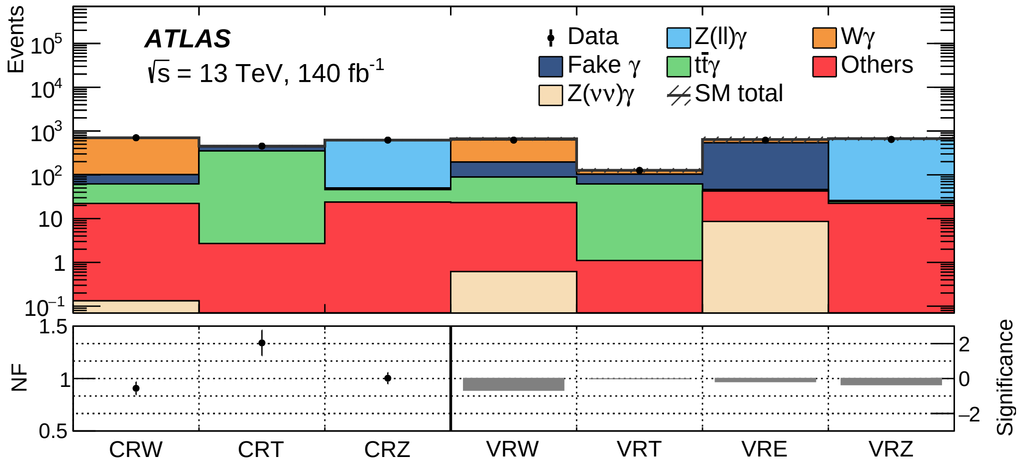


Figure 3: The observed and expected yields after the background-only fit in the control and validation regions. The lower panel shows the background normalisation factors (NF) estimated in each control region, and the significance, in standard deviations, between the observed and expected yields in the validation regions, considering both the systematic and statistical uncertainties in the background expectation. The significance shown is calculated with the profile likelihood method from [92], adding a minus sign if the yield is below the prediction. Minor background processes, such as γ + jets, $\gamma\gamma$ and $W\gamma\gamma/Z\gamma\gamma$, are included under 'Others'.

The uncertainty in the combined 2015–2018 integrated luminosity is 0.83% [93], obtained using the LUCID-2 detector [94] for the primary luminosity measurements. The uncertainty in the pile-up reweighting is also considered.

The systematic uncertainties due to the photon identification and isolation efficiencies are estimated following the prescriptions in Ref. [74]. They are evaluated by varying the correction factors for the photon selection efficiencies in MC simulation by the corresponding uncertainties. The photon energy scale is determined using samples of $Z \to ee$ events, varying the scale corrections and resolutions upwards and downwards by one standard deviation [74]. For electrons [74] and muons [95], similarly to photons, the uncertainties from the identification efficiencies, energy scales and resolutions are determined from $Z \to ll$ and $J/\psi \to ll$ control samples, where l denotes electrons or muons.

For jets, the energy scale and resolution uncertainties are derived following the procedure described in Ref. [96], using a simplified scheme with 38 parameters. A set of b-tagging uncertainties is also considered, taking an envelope around the nominal jet weight for the selection of different flavour jets [80–82].

For $E_{\mathrm{T}}^{\mathrm{miss}}$, the uncertainties of the constituent objects are propagated through the calculation, and additional uncertainties accounting for the scale and resolution of the soft term [83] are considered.

There are two different kinds of uncertainties affecting the estimate of the background due to jets/$e^{\pm}$ misidentified as photons: the systematic uncertainty from the method used to estimate the fake factors and the statistical uncertainty in the control sample (see Section 6).

For each of the main simulation background samples ($Z(\nu\nu)\gamma$, $W\gamma$, $Z(ll)\gamma$ and $t\bar{t}\gamma$) and signals, different sources of theory uncertainties are assessed. For renormalisation and factorisation scales μ_{r} and μ_{f} three independent nuisance parameters are used: two varying each of the scales independently by a factor of two, and one as a coherent variation of both scales. The PDF uncertainty is taken from an envelope of the nominal PDF (NNPDF3.0) and its variations [97]. Finally, uncertainties associated with the α_s determination are considered.

The relative impact of each systematic uncertainty in the SM background expectation after the background-only fit is presented in Table 4.

Table 4: Summary of the different systematic uncertainties in the SM background expectation (in %) for the different SRs after the background-only fit. The individual uncertainties can be correlated and do not necessarily add in quadrature to equal the total (stat. + syst.) uncertainty.

	SRL [%]	SRM [%]	SRH [%]	SRLe [%]	SRMe [%]
Total (stat. + syst.) uncertainty	8.8	10.0	13.3	8.9	10.9
MC statistical uncertainty	1.7	5.0	7.5	1.9	6.9
MC theory	6.0	6.0	5.9	6.0	6.1
Jet energy resolution, scale, and pile-up rejection	4.1	3.8	7.7	4.2	1.9
Photon identification and isolation	1.7	1.3	1.7	1.8	1.1
Pile-up reweighting	1.7	< 1	1.3	1.8	< 1
Muon reconstruction and identification	1.6	1.3	1.6	1.8	< 1
Jet b-tagging calibration	1.6	1.2	1.6	1.8	< 1
Fake photons from jets	1.6	< 1	1.7	1.7	1.6
Electron reconstruction, identification, and isolation	1.6	1.2	1.6	1.7	1.0
Fake photons from electrons	1.6	1.7	2.1	1.5	1.6
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft-term resolution and scale	1.3	1.3	1.7	1.3	1.1
Electron/photon energy resolution and scale	< 1	2.1	< 1	1.3	3.1
Luminosity	< 1	< 1	< 1	< 1	< 1

8 Results

A background-only fit is performed, as discussed in Section 6, to evaluate the SM background expectations in all regions of the analysis. The observed event yield in each CR is used as a constraint in the fit to adjust the corresponding background normalisation, assuming that no signal contributes to this yield. The systematic uncertainties in the expected values are included in the fit as nuisance parameters, constrained by Gaussian or log-normal distributions with widths corresponding to the sizes of the uncertainties. They are treated as correlated, when appropriate, between the various regions. The results of the fit are validated in the VRs as shown previously in Figure 3.

The observed and expected yields in the SRs are presented in Table 5, discriminating the different background contributions (minor backgrounds like γ + jets, $\gamma\gamma$ and $W\gamma\gamma/Z\gamma\gamma$, are grouped into a single label 'Others'). No excess is found above the predicted SM background. The comparisons are also shown in Figure 4.

The predictions slightly exceed the observed data, though the difference is not statistically significant, remaining below two standard deviations. After obtaining these results, further studies were carried out to assess possible mismodelling of the diboson or fake-photon backgrounds, but no evidence of any anomalies was observed. A similar trend was observed in an ATLAS Z cross-section study [98] and in the equivalent CMS GGM SUSY search [34].

Table 5: Observed events, background estimates after the background-only fit, and model-independent limits in all the signal regions. The background uncertainties are both systematic and statistical. Minor backgrounds like γ + jets, $\gamma\gamma$ and $W\gamma\gamma/Z\gamma\gamma$ are grouped into 'Others'. The model-independent fit results include the 95% confidence level (CL) upper limits on the visible cross-section ($\langle\epsilon\sigma\rangle^{95}_{\text{obs}}$), the number of signal events (S^{95}_{obs}), and the number of signal events given the expected number (and $\pm1\sigma$ excursions on the expectation) of background events (S^{95}_{exp}). The discovery p-value is in all cases $p_0 = 0.50$ and its associated significance $Z = 0$.

Signal region	SRL	SRM	SRH	SRLe	SRMe
Observed events	173	21	8	152	13
Expected SM events	214 ± 19	32.5 ± 3.3	14.6 ± 2.0	182 ± 16	17.9 ± 2.0
$Z(\nu\nu)\gamma$	116 ± 14	16.4 ± 2.2	7.2 ± 1.1	100 ± 12	9.2 ± 1.4
$W\gamma$	57 ± 8	10.0 ± 1.6	4.6 ± 1.1	47 ± 7	5.5 ± 0.9
Fake γ	28 ± 5	3.9 ± 0.9	2.0 ± 0.5	24 ± 5	1.9 ± 0.5
$Z(ll)\gamma$	1.60 ± 0.21	0.38 ± 0.10	0.20 ± 0.07	1.22 ± 0.23	0.18 ± 0.10
$t\bar{t}\gamma$	1.27 ± 0.29	0.15 ± 0.04	0.02 ± 0.02	1.12 ± 0.26	0.13 ± 0.04
Others	10.7 ± 0.8	1.64 ± 0.23	0.64 ± 0.07	9.0 ± 0.9	1.00 ± 0.21
$\langle A\epsilon\sigma\rangle^{95}_{\text{obs}}$ [fb]	0.15	0.05	0.04	0.15	0.05
S^{95}_{obs}	20.6	7.2	5.4	21.3	7.0
S^{95}_{exp}	44^{+17}_{-12}	15^{+7}_{-4}	$10.1^{+5.0}_{-3.1}$	40^{+16}_{-11}	$11.1^{+5.4}_{-3.4}$

Figure 5 shows the observed distributions of $E_{\text{T}}^{\text{miss}}$ and its significance in the discovery signal region (SRL), compared with the expected background.

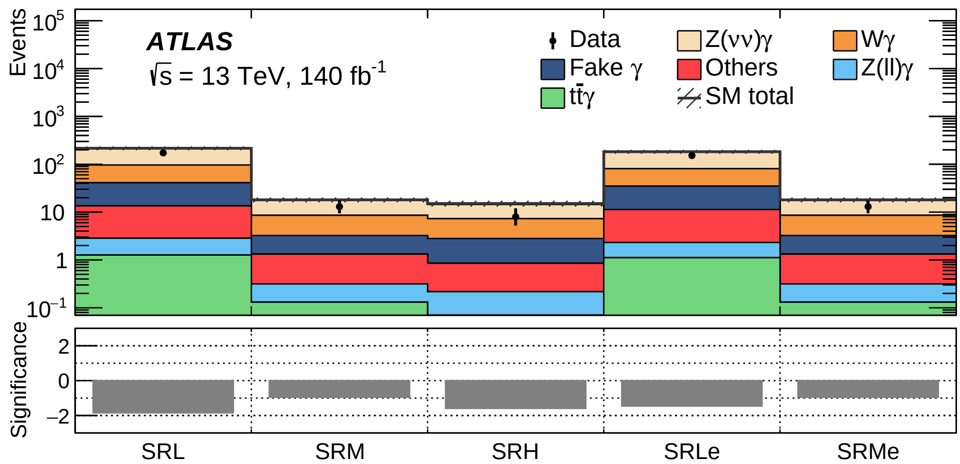
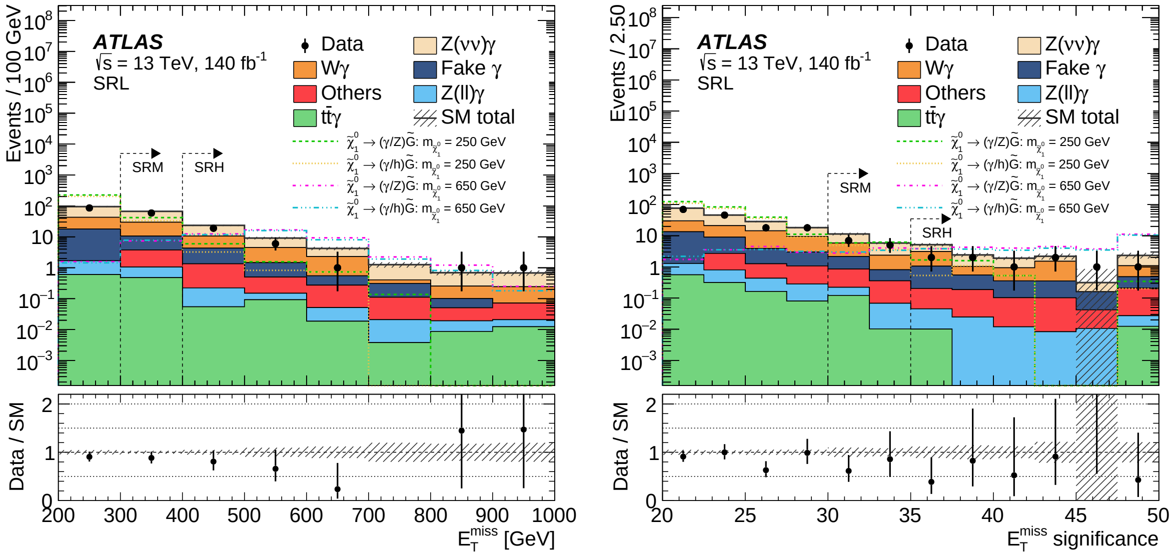


Figure 4: The observed and expected yields in all the signal regions. The lower panel shows the difference, in standard deviations, between the observed and expected yields considering both the systematic and statistical uncertainties in the background expectation.

For each SR, model-independent upper limits at 95% confidence level (CL) are set on the number of observed (S^{95}_{obs}) and expected (S^{95}_{exp}) events, from any scenario of physics beyond the SM that could produce an excess in the final state considered. The limits are obtained using the CL$_{\text{s}}$ prescription in the asymptotic approximation [92, 99]. In Table 5 the upper limits on the number of events are presented together with the 95% CL upper limit on the visible cross-section $\sigma \times A \times \epsilon$ (denoted $\langle A\epsilon\sigma\rangle^{95}_{\text{obs}}$), obtained by normalising the upper limit on the number of signal events to the integrated luminosity, where σ is the production

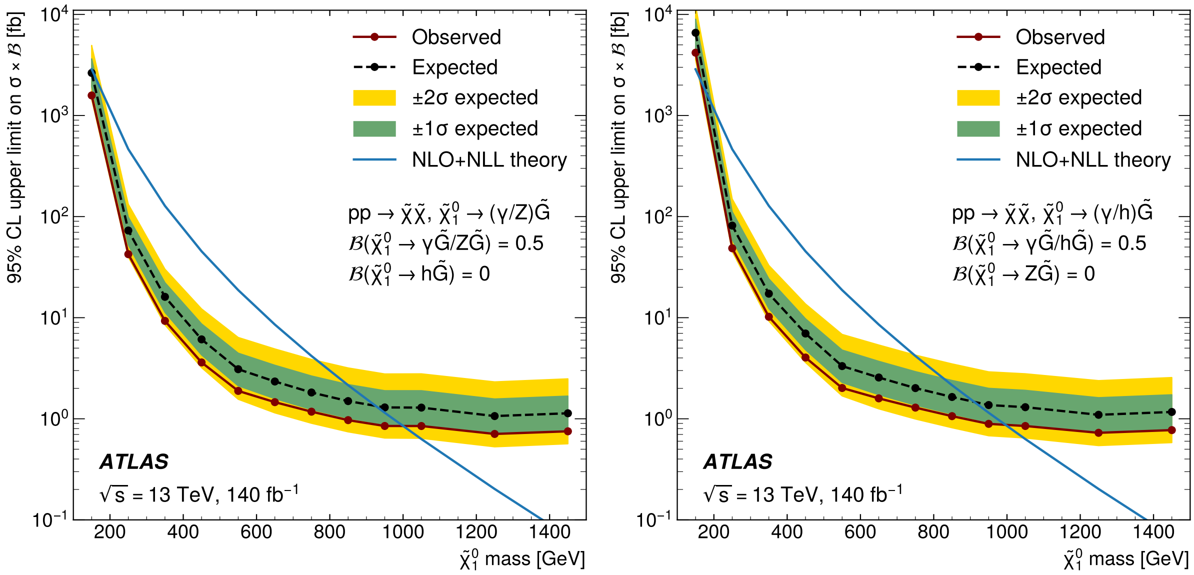


(a) (b)

Figure 5: Observed distributions in the signal region SRL after the background-only fit for (a) E_T^{miss} and (b) E_T^{miss} significance variables. The E_T^{miss} and E_T^{miss} significance requirements (that simultaneously define the other signal regions, SRM and SRH), are indicated in the distributions. The uncertainties in the SM background are statistical only. The last bin includes overflow. The figure shows predictions for different models and masses of neutralinos.

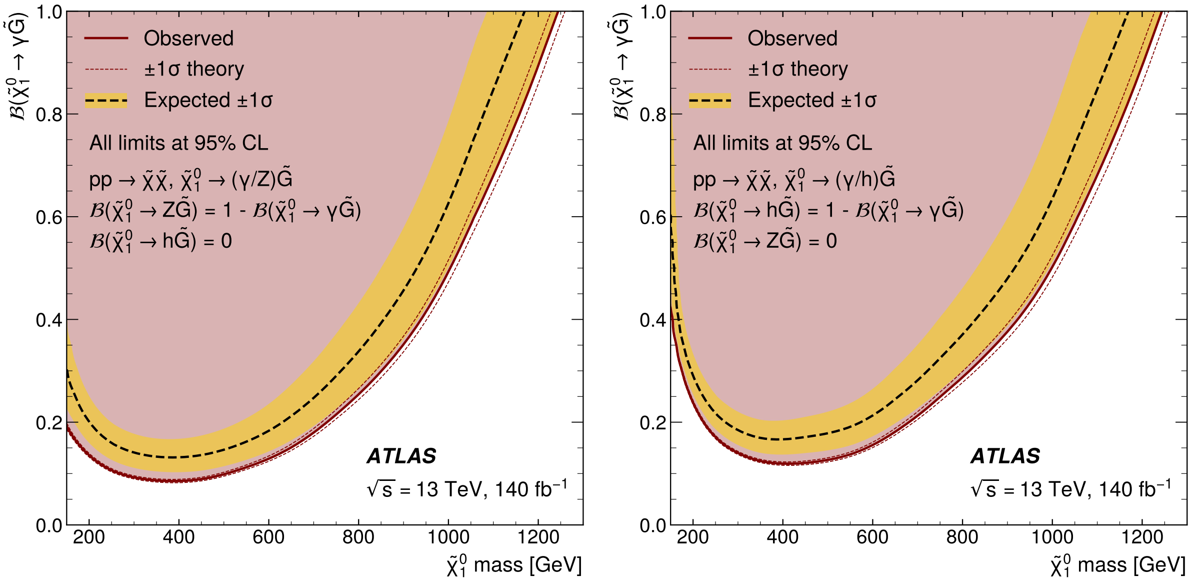
cross-section for a beyond-the-SM signal, A is the acceptance (fraction of events with objects satisfying all the kinematic selections at particle level) and ϵ is the efficiency (fraction of observed events after detector reconstruction). For all the SRs, the discovery p-value (p_0) is capped at 0.5 because the predictions exceed the observation.

In view of the absence of an excess in the observed data relative to predictions the results are also used to establish exclusion limits in the various signal models. The signal contamination in the CRs and the experimental systematic uncertainties in the signal are taken into account for this calculation. All the independent SRs (SRLe, SRMe and SRH) are statistically combined to set model-dependent upper limits on the cross-sections times branching ratios (Figure 6), masses and variable branching ratios (Figures 7 and 8). The exclusion reach is highest in the pure photon branching ratio space, with a maximum around 1.2 TeV, gradually decreasing to 450 GeV for $\mathcal{B}(\tilde{\chi}_1^0 \rightarrow \gamma\tilde{G}) = 10\%$ where the decays to Z or h bosons dominate. For those regions where the sensitivity is lower the low mass region can not be excluded, as can be seen in Figure 7, and the lowest mass that can be excluded lies between 250 GeV and 170 GeV. The observed limits are stronger than the expected limits in accordance with the observed deficit in the data.



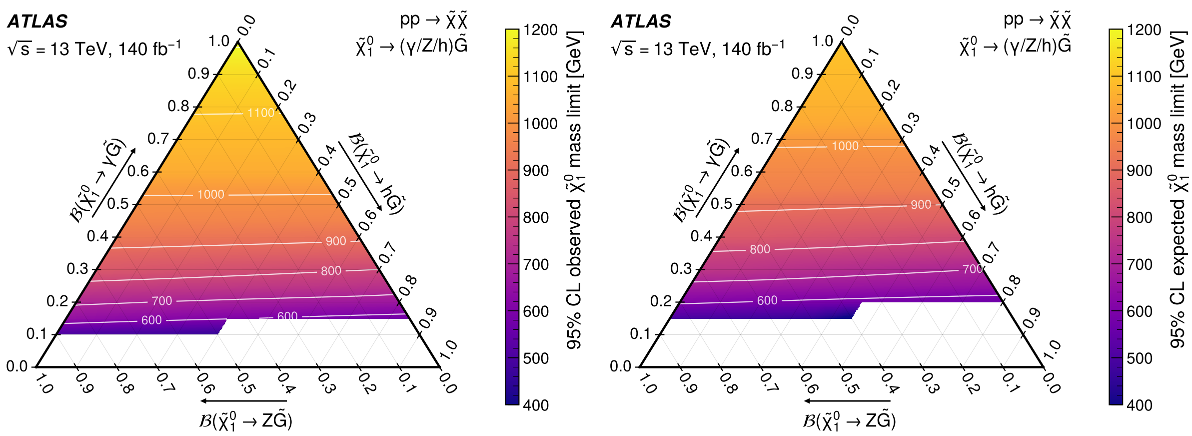
(a) (b)

Figure 6: Observed and expected exclusion limits in the cross-section as a function of the $\tilde{\chi}_1^0$ mass, at 95% CL combining the three exclusion signal regions, for the full Run 2 data sample corresponding to an integrated luminosity of 140 fb^{-1}, for (a) the $\gamma + Z$ and (b) the $\gamma + h$ benchmark models.



(a) (b)

Figure 7: Observed and expected exclusion limits in the branching ratio to photons of the $\tilde{\chi}_1^0$ as a function of its mass, at 95% CL. In (a) the branching ratio to the Higgs boson is fixed to zero, while in (b) the branching ratio to the Z boson is fixed to zero. The shaded area indicates excluded values.



(a) (b)

Figure 8: (a) Observed and (b) expected exclusion limits on the $\tilde{\chi}_1^0$ mass at 95% CL in the plane of branching ratios $\mathcal{B}(\tilde{\chi}_1^0 \to \gamma\tilde{G})$, $\mathcal{B}(\tilde{\chi}_1^0 \to Z\tilde{G})$, and $\mathcal{B}(\tilde{\chi}_1^0 \to h\tilde{G})$ that satisfy $\mathcal{B}(\tilde{\chi}_1^0 \to \gamma\tilde{G}) + \mathcal{B}(\tilde{\chi}_1^0 \to Z\tilde{G}) + \mathcal{B}(\tilde{\chi}_1^0 \to h\tilde{G}) = 1$. Only models with $\mathcal{B}(\tilde{\chi}_1^0 \to \gamma\tilde{G}) \geq 0.15$ are considered. The colour scale indicates the excluded neutralino mass in GeV, while the contour lines mark regions of constant excluded mass values.

9 Conclusion

A search is presented for an excess of events featuring at least one photon, at least a jet and missing transverse momentum, as anticipated in scenarios where the lightest neutralino $\tilde{\chi}_1^0$ is a mixture of bino and higgsino states. LHC proton–proton collisions at a centre-of-mass energy of $\sqrt{s} = 13$ TeV are analysed using data collected by the ATLAS detector during the complete 2015–2018 data-taking period, corresponding to a total integrated luminosity of 140 fb^{-1}.

Two strategies are employed: one optimised for discovery and another combining several non-overlapping signal regions in a simultaneous fit to achieve optimal exclusion limits for benchmark signals.

No excess is found above the predicted background in any of the signal regions. Model-independent limits are set on the visible cross-section for new physics processes. Exclusion limits are set on GGM models with LSP masses up to 1000 GeV in two reference final-state scenarios containing a Z or a Higgs boson in addition to the photon. The results are also interpreted in a model with variable branching ratios setting limits that range from 400 GeV to 1200 GeV.

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References

[1] Y. A. Gol'fand and E. P. Likhtman, *Extension of the Algebra of Poincare Group Generators and Violation of p Invariance*, JETP Lett. **13** (1971) 323, [Pisma Zh.Eksp.Teor.Fiz. 13:452-455,1971].

[2] D. V. Volkov and V. P. Akulov, *Is the Neutrino a Goldstone Particle?*, Phys. Lett. B **46** (1973) 109.

[3] J. Wess and B. Zumino, *Supergauge transformations in four dimensions*, Nucl. Phys. B **70** (1974) 39.

[4] J. Wess and B. Zumino, *Supergauge Invariant Extension of Quantum Electrodynamics*, Nucl. Phys. B **78** (1974) 1.

[5] S. Ferrara and B. Zumino, *Supergauge Invariant Yang-Mills Theories*, Nucl. Phys. B **79** (1974) 413.

[6] A. Salam and J. Strathdee, *Super-symmetry and non-Abelian gauges*, Phys. Lett. B **51** (1974) 353.

[7] S. P. Martin, *A Supersymmetry primer*, (1997), [Adv. Ser. Direct. High Energy Phys.18,1(1998)], arXiv: `hep-ph/9709356 [hep-ph]`.

[8] R. Barbieri and G. F. Giudice, *Upper bounds on supersymmetric particle masses*, Nucl. Phys. B **306** (1988) 63.

[9] B. de Carlos and J. A. Casas, *One-loop analysis of the electroweak breaking in supersymmetric models and the fine-tuning problem*, Phys. Lett. B **309** (1993) 320, arXiv: `hep-ph/9303291`.

[10] M. Dine and W. Fischler, *A Phenomenological Model of Particle Physics Based on Supersymmetry*, Phys. Lett. B **110** (1982) 227.

[11] L. Alvarez-Gaumé, M. Claudson and M. B. Wise, *Low-energy supersymmetry*, Nucl. Phys. B **207** (1982) 96.

[12] C. R. Nappi and B. A. Ovrut, *Supersymmetric Extension of the SU(3) x SU(2) x U(1) Model*, Phys. Lett. B **113** (1982) 175.

[13] C. Cheung, A. L. Fitzpatrick and D. Shih, *(Extra)ordinary gauge mediation*, JHEP **07** (2008) 054, arXiv: `0710.3585 [hep-ph]`.

[14] P. Meade, N. Seiberg and D. Shih, *General Gauge Mediation*, Prog. Theor. Phys. Suppl. **177** (2009) 143, arXiv: `0801.3278 [hep-ph]`.

[15] H. Goldberg, *Constraint on the photino mass from cosmology*, Phys. Rev. Lett. **50** (1983) 1419.

[16] J. Ellis, J. Hagelin, D. V. Nanopoulos, K. Olive and M. Srednicki, *Supersymmetric relics from the big bang*, Nucl. Phys. B **238** (1984) 453.

[17] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. B **716** (2012) 1, arXiv: `1207.7214 [hep-ex]`.

[18] CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys. Lett. B **716** (2012) 30, arXiv: `1207.7235 [hep-ex]`.

[19] ATLAS Collaboration, *Search for diphoton events with large missing transverse momentum in* $1\,fb^{-1}$ *of 7 TeV proton–proton collision data with the ATLAS detector*, Phys. Lett. B **710** (2012) 519, arXiv: `1111.4116 [hep-ex]`.

[20] ATLAS Collaboration, *Search for supersymmetry in events with photons, bottom quarks, and missing transverse momentum in proton–proton collisions at a centre-of-mass energy of 7 TeV with the ATLAS detector*, Phys. Lett. B **719** (2013) 261, arXiv: `1211.1167 [hep-ex]`.

[21] ATLAS Collaboration, *Search for Diphoton Events with Large Missing Transverse Energy in 7 TeV Proton–Proton Collisions with the ATLAS Detector*, Phys. Rev. Lett. **106** (2011) 121803, arXiv: `1012.4272 [hep-ex]`.

[22] ATLAS Collaboration, *Search for diphoton events with large missing transverse energy with* $36\,pb^{-1}$ *of 7 TeV proton–proton collision data with the ATLAS detector*, Eur. Phys. J. C **71** (2011) 1744, arXiv: `1107.0561 [hep-ex]`.

[23] CMS Collaboration, *Search for Supersymmetry in* pp *Collisions at* $\sqrt{s} = 7$ *TeV in Events with Two Photons and Missing Transverse Energy*, Phys. Rev. Lett. **106** (2011) 211802, arXiv: `1103.0953 [hep-ex]`.

[24] CMS Collaboration, *Search for supersymmetry in events with a lepton, a photon, and large missing transverse energy in* pp *collisions at* $\sqrt{s} = 7$ *TeV*, JHEP **06** (2011) 093, arXiv: `1105.3152 [hep-ex]`.

[25] CMS Collaboration, *Search for stealth supersymmetry in events with jets, either photons or leptons, and low missing transverse momentum in* pp *collisions at* 8 *TeV*, Phys. Lett. B **743** (2015) 503, arXiv: `1411.7255 [hep-ex]`.

[26] ATLAS Collaboration, *Search for photonic signatures of gauge-mediated supersymmetry in* 8 *TeV* pp *collisions with the ATLAS detector*, Phys. Rev. D **92** (2015) 072001, arXiv: `1507.05493 [hep-ex]`.

[27] CMS Collaboration, *Search for supersymmetry with photons in* pp *collisions at* $\sqrt{s} = 8$ *TeV*, Phys. Rev. D **92** (2015) 072006, arXiv: `1507.02898 [hep-ex]`.

[28] ATLAS Collaboration, *Summary of the ATLAS experiment's sensitivity to supersymmetry after LHC Run 1 — interpreted in the phenomenological MSSM*, JHEP **10** (2015) 134, arXiv: 1508.06608 [hep-ex].

[29] ATLAS Collaboration, *Search for photonic signatures of gauge-mediated supersymmetry in* 13 *TeV* pp *collisions with the ATLAS detector*, Phys. Rev. D **97** (2018) 092006, arXiv: 1802.03158 [hep-ex].

[30] ATLAS Collaboration, *Search for new phenomena in final states with photons, jets and missing transverse momentum in* pp *collisions at* $\sqrt{s}$ = 13 *TeV with the ATLAS detector*, JHEP **07** (2023) 021, arXiv: 2206.06012 [hep-ex].

[31] L. Evans and P. Bryant, *LHC Machine*, JINST **3** (2008) S08001.

[32] ATLAS Collaboration, *Search for direct production of electroweakinos in final states with missing transverse momentum and a Higgs boson decaying into photons in* pp *collisions at* $\sqrt{s}$ = 13 *TeV with the ATLAS detector*, JHEP **10** (2020) 005, arXiv: 2004.10894 [hep-ex].

[33] ATLAS Collaboration, *Search for pair-produced higgsinos decaying via Higgs or Z bosons to final states containing a pair of photons and a pair of* b*-jets with the ATLAS detector*, Phys. Lett. B **856** (2024) 138938, arXiv: 2404.01996 [hep-ex].

[34] CMS Collaboration, *Search for new physics in multijet events with at least one photon and large missing transverse momentum in proton–proton collisions at* 13 *TeV*, JHEP **10** (2023) 046, arXiv: 2307.16216 [hep-ex].

[35] J. Liu, N. McGinnis, C. E. M. Wagner and X.-P. Wang, *Searching for the Higgsino-Bino Sector at the LHC*, JHEP **09** (2020) 073, arXiv: 2006.07389 [hep-ph].

[36] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3** (2008) S08003.

[37] ATLAS Collaboration, *ATLAS Insertable B-Layer: Technical Design Report*, ATLAS-TDR-19; CERN-LHCC-2010-013, 2010, URL: https://cds.cern.ch/record/1291633, Addendum: ATLAS-TDR-19-ADD-1; CERN-LHCC-2012-009, 2012, URL: https://cds.cern.ch/record/1451888.

[38] B. Abbott et al., *Production and integration of the ATLAS Insertable B-Layer*, JINST **13** (2018) T05008, arXiv: 1803.00844 [physics.ins-det].

[39] ATLAS Collaboration, *Performance of the ATLAS trigger system in 2015*, Eur. Phys. J. C **77** (2017) 317, arXiv: 1611.09661 [hep-ex].

[40] ATLAS Collaboration, *Software and computing for Run 3 of the ATLAS experiment at the LHC*, Eur. Phys. J. C **85** (2025) 234, arXiv: 2404.06335 [hep-ex].

[41] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, JHEP **07** (2014) 079, arXiv: 1405.0301 [hep-ph].

[42] T. Sjöstrand et al., *An Introduction to PYTHIA 8.2*, Comput. Phys. Commun. **191** (2015) 159, arXiv: 1410.3012 [hep-ph].

[43] NNPDF Collaboration, R. D. Ball et al., *Parton distributions with LHC data*, Nucl. Phys. B **867** (2013) 244, arXiv: 1207.1303 [hep-ph].

[44] W. Beenakker et al., *The Production of charginos/neutralinos and sleptons at hadron colliders*, Phys. Rev. Lett. **83** (1999) 3780, arXiv: hep-ph/9906298 [hep-ph].

[45] J. Debove, B. Fuks and M. Klasen, *Threshold resummation for gaugino pair production at hadron colliders*, Nucl. Phys. B **842** (2011) 51, arXiv: 1005.2909 [hep-ph].

[46] B. Fuks, M. Klasen, D. R. Lamprea and M. Rothering, *Gaugino production in proton-proton collisions at a center-of-mass energy of* 8 *TeV*, JHEP **10** (2012) 081, arXiv: 1207.2159 [hep-ph].

[47] B. Fuks, M. Klasen, D. R. Lamprea and M. Rothering, *Precision predictions for electroweak superpartner production at hadron colliders with* RESUMMINO, Eur. Phys. J. C **73** (2013) 2480, arXiv: 1304.0790 [hep-ph].

[48] J. Fiaschi and M. Klasen, *Neutralino-chargino pair production at NLO+NLL with resummation-improved parton density functions for LHC Run II*, Phys. Rev. D **98** (2018) 055014, arXiv: 1805.11322 [hep-ph].

[49] C. Borschensky et al., *Squark and gluino production cross sections in pp collisions at* $\sqrt{s}$ *= 13, 14, 33 and 100 TeV*, Eur. Phys. J. C **74** (2014) 3174, arXiv: 1407.5066 [hep-ph].

[50] ATLAS Collaboration, *ATLAS Pythia 8 tunes to* 7 *TeV data*, ATL-PHYS-PUB-2014-021, 2014, URL: https://cds.cern.ch/record/1966419.

[51] NNPDF Collaboration, R. D. Ball et al., *Parton distributions for the LHC Run II*, JHEP **04** (2015) 040, arXiv: 1410.8849 [hep-ph].

[52] P. Bärnreuther, M. Czakon and A. Mitov, *Percent-Level-Precision Physics at the Tevatron: Next-to-Next-to-Leading Order QCD Corrections to* $q\bar{q} \rightarrow t\bar{t} + X$, Phys. Rev. Lett. **109** (2012) 132001, arXiv: 1204.5201 [hep-ph].

[53] P. Nason, *A New method for combining NLO QCD with shower Monte Carlo algorithms*, JHEP **11** (2004) 040, arXiv: hep-ph/0409146 [hep-ph].

[54] S. Frixione, P. Nason and C. Oleari, *Matching NLO QCD computations with parton shower simulations: the POWHEG method*, JHEP **11** (2007) 070, arXiv: 0709.2092 [hep-ph].

[55] S. Alioli, P. Nason, C. Oleari and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, JHEP **06** (2010) 043, arXiv: 1002.2581 [hep-ph].

[56] H. B. Hartanto, B. Jäger, L. Reina and D. Wackeroth, *Higgs boson production in association with top quarks in the POWHEG BOX*, Phys. Rev. D **91** (2015) 094003, arXiv: 1501.04498 [hep-ph].

[57] E. Bothmann et al., *Event generation with Sherpa 2.2*, SciPost Phys. **7** (2019) 034, arXiv: 1905.09127 [hep-ph].

[58] T. Gleisberg and S. Höche, *Comix, a new matrix element generator*, JHEP **12** (2008) 039, arXiv: 0808.3674 [hep-ph].

[59] F. Buccioni et al., *OpenLoops 2*, Eur. Phys. J. C **79** (2019) 866, arXiv: 1907.13071 [hep-ph].

[60] F. Cascioli, P. Maierhöfer and S. Pozzorini, *Scattering Amplitudes with Open Loops*, Phys. Rev. Lett. **108** (2012) 111601, arXiv: 1111.5206 [hep-ph].

[61] A. Denner, S. Dittmaier and L. Hofer, *Collier: A fortran-based complex one-loop library in extended regularizations*, Comput. Phys. Commun. **212** (2017) 220, arXiv: 1604.06792 [hep-ph].

[62] S. Schumann and F. Krauss, *A Parton shower algorithm based on Catani-Seymour dipole factorisation*, JHEP **03** (2008) 038, arXiv: 0709.1027 [hep-ph].

[63] S. Höche, F. Krauss, M. Schönherr and F. Siegert, *A critical appraisal of NLO+PS matching methods*, JHEP **09** (2012) 049, arXiv: 1111.1220 [hep-ph].

[64] S. Höche, F. Krauss, M. Schönherr and F. Siegert, *QCD matrix elements + parton showers. The NLO case*, JHEP **04** (2013) 027, arXiv: 1207.5030 [hep-ph].

[65] S. Catani, F. Krauss, B. R. Webber and R. Kuhn, *QCD matrix elements + parton showers*, JHEP **11** (2001) 063, arXiv: hep-ph/0109231 [hep-ph].

[66] S. Höche, F. Krauss, S. Schumann and F. Siegert, *QCD matrix elements and truncated showers*, JHEP **05** (2009) 053, arXiv: 0903.1219 [hep-ph].

[67] ATLAS Collaboration, *The ATLAS Simulation Infrastructure*, Eur. Phys. J. C **70** (2010) 823, arXiv: 1005.4568 [physics.ins-det].

[68] S. Agostinelli et al., *Geant4 – a simulation toolkit*, Nucl. Instrum. Meth. A **506** (2003) 250.

[69] T. Sjöstrand, S. Mrenna and P. Skands, *A brief introduction to PYTHIA 8.1*, Comput. Phys. Commun. **178** (2008) 852, arXiv: 0710.3820 [hep-ph].

[70] ATLAS Collaboration, *The Pythia 8 A3 tune description of ATLAS minimum bias and inelastic measurements incorporating the Donnachie–Landshoff diffractive model*, ATL-PHYS-PUB-2016-017, 2016, url: https://cds.cern.ch/record/2206965.

[71] D. J. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Meth. A **462** (2001) 152.

[72] ATLAS Collaboration, *Vertex Reconstruction Performance of the ATLAS Detector at $\sqrt{s} = 13$ TeV*, ATL-PHYS-PUB-2015-026, 2015, url: https://cds.cern.ch/record/2037717.

[73] ATLAS Collaboration, *Topological cell clustering in the ATLAS calorimeters and its performance in LHC Run 1*, Eur. Phys. J. C **77** (2017) 490, arXiv: 1603.02934 [hep-ex].

[74] ATLAS Collaboration, *Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton–proton collision data*, JINST **14** (2019) P12006, arXiv: 1908.00005 [hep-ex].

[75] ATLAS Collaboration, *Muon reconstruction and identification efficiency in ATLAS using the full Run 2 pp collision data set at $\sqrt{s} = 13$ TeV*, Eur. Phys. J. C **81** (2021) 578, arXiv: 2012.00578 [hep-ex].

[76] M. Cacciari, G. P. Salam and G. Soyez, *The anti-k_t jet clustering algorithm*, JHEP **04** (2008) 063, arXiv: 0802.1189 [hep-ph].

[77] M. Cacciari, G. P. Salam and G. Soyez, *FastJet user manual*, Eur. Phys. J. C **72** (2012) 1896, arXiv: 1111.6097 [hep-ph].

[78] ATLAS Collaboration, *Jet reconstruction and performance using particle flow with the ATLAS Detector*, Eur. Phys. J. C **77** (2017) 466, arXiv: 1703.10485 [hep-ex].

[79] ATLAS Collaboration, *Performance of pile-up mitigation techniques for jets in pp collisions at $\sqrt{s}$ = 8 TeV using the ATLAS detector*, Eur. Phys. J. C **76** (2016) 581, arXiv: 1510.03823 [hep-ex].

[80] ATLAS Collaboration, *ATLAS b-jet identification performance and efficiency measurement with $t\bar{t}$ events in pp collisions at $\sqrt{s}$ = 13 TeV*, Eur. Phys. J. C **79** (2019) 970, arXiv: 1907.05120 [hep-ex].

[81] ATLAS Collaboration, *Measurement of the c-jet mistagging efficiency in $t\bar{t}$ events using pp collision data at $\sqrt{s}$ = 13 TeV collected with the ATLAS detector*, Eur. Phys. J. C **82** (2022) 95, arXiv: 2109.10627 [hep-ex].

[82] ATLAS Collaboration, *Calibration of the light-flavour jet mistagging efficiency of the b-tagging algorithms with Z+jets events using 139 fb^{-1} of ATLAS proton–proton collision data at $\sqrt{s}$ = 13 TeV*, Eur. Phys. J. C **83** (2023) 728, arXiv: 2301.06319 [hep-ex].

[83] ATLAS Collaboration, *The performance of missing transverse momentum reconstruction and its significance with the ATLAS detector using 140 fb^{-1} of $\sqrt{s}$ = 13 TeV pp collisions*, Eur. Phys. J. C **85** (2025) 606, arXiv: 2402.05858 [hep-ex].

[84] ATLAS Collaboration, *Search for supersymmetry in a final state containing two photons and missing transverse momentum in $\sqrt{s}$ = 13 TeV pp collisions at the LHC using the ATLAS detector*, Eur. Phys. J. C **76** (2016) 517, arXiv: 1606.09150 [hep-ex].

[85] ATLAS Collaboration, *Search for dark matter in association with an energetic photon in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector*, JHEP **02** (2021) 226, arXiv: 2011.05259 [hep-ex].

[86] ATLAS Collaboration, *ATLAS data quality operations and performance for 2015–2018 data-taking*, JINST **15** (2020) P04003, arXiv: 1911.04632 [physics.ins-det].

[87] ATLAS Collaboration, *Performance of electron and photon triggers in ATLAS during LHC Run 2*, Eur. Phys. J. C **80** (2020) 47, arXiv: 1909.00761 [hep-ex].

[88] ATLAS Collaboration, *Measurement of the inclusive isolated prompt photon cross section in pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector*, Phys. Rev. D **83** (2011) 052005, arXiv: 1012.4389 [hep-ex].

[89] J. E. Gaiser, *Charmonium Spectroscopy From Radiative Decays of the J/ψ and ψ'*, SLAC-0255, Ph.D. Thesis, 1982.

[90] M. Baak et al., *HistFitter software framework for statistical data analysis*, Eur. Phys. J. C **75** (2015) 153, arXiv: 1410.1280 [hep-ex].

[91] G. Choudalakis and D. Casadei, *Plotting the differences between data and expectation*, Eur. Phys. J. Plus **127** (2012) 25, arXiv: 1111.2062 [physics.data-an].

[92] G. Cowan, K. Cranmer, E. Gross and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, Eur. Phys. J. C **71** (2011) 1554, arXiv: 1007.1727 [physics.data-an], Erratum: Eur. Phys. J. C **73** (2013) 2501.

[93] ATLAS Collaboration,
Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC, Eur. Phys. J. C **83** (2023) 982, arXiv: 2212.09379 [hep-ex].

[94] G. Avoni et al., *The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS*, JINST **13** (2018) P07017.

[95] ATLAS Collaboration, *Muon reconstruction performance of the ATLAS detector in proton–proton collision data at $\sqrt{s} = 13$ TeV*, Eur. Phys. J. C **76** (2016) 292, arXiv: 1603.05598 [hep-ex].

[96] ATLAS Collaboration, *Jet energy scale measurements and their systematic uncertainties in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Phys. Rev. D **96** (2017) 072002, arXiv: 1703.09665 [hep-ex].

[97] J. Butterworth et al., *PDF4LHC recommendations for LHC Run II*, J. Phys. G **43** (2016) 023001, arXiv: 1510.03865 [hep-ph].

[98] ATLAS Collaboration, *Measurement of the $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ production cross section in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector and limits on anomalous triple gauge-boson couplings*, JHEP **12** (2018) 010, arXiv: 1810.04995 [hep-ex].

[99] A. L. Read, *Presentation of search results: The CL_s technique*, J. Phys. G **28** (2002) 2693.

[100] ATLAS Collaboration, *ATLAS Computing Acknowledgements*, ATL-SOFT-PUB-2025-001, 2025, URL: https://cds.cern.ch/record/2922210.

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Reznicek[136], H. Riani[36d], N. Ribaric[51], B. Ricci[69a,69c], E. Ricci[78a,78b], R. Richter[112], S. Richter[47a,47b], E. Richter-Was[87b], M. Ridel[130], S. Ridouani[36d], P. Rieck[120], P. Riedler[37], E.M. Riefel[47a,47b], J.O. Rieger[117], M. Rijssenbeek[151], M. Rimoldi[37], L. Rinaldi[24b,24a], P. Rincke[167,55], G. Ripellino[167], I. Riu[13], J.C. Rivera Vergara[171], F. Rizatdinova[124], E. Rizvi[96], B.R. Roberts[18a], S.S. Roberts[139], D. Robinson[33], M. Robles Manzano[102], A. Robson[59], A. Rocchi[76a,76b], C. Roda[74a,74b], S. Rodriguez Bosca[37], Y. Rodriguez Garcia[23a], A.M. Rodríguez Vera[118], S. Roe[37], J.T. Roemer[37], O. Røhne[128], R.A. Rojas[37], C.P.A. Roland[130], A. Romaniouk[79], E. Romano[73a,73b], M. Romano[24b], A.C. Romero Hernandez[168], N. Rompotis[94], L. Roos[130], S. Rosati[75a], B.J. Rosser[40], E. Rossi[129], E. Rossi[72a,72b], L.P. Rossi[61], L. Rossini[54], R. Rosten[122], M. Rotaru[28b], B. Rottler[54], D. Rousseau[66], D. Rousso[48], S. 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Santana Queiroz[18b], L. Santi[37], C. Santoni[41], H. Santos[133a,133b], A. Santra[175], E. Sanzani[24b,24a], K.A. Saoucha[85b], J.G. Saraiva[133a,133d], J. Sardain[7], O. Sasaki[84], K. Sato[163], C. Sauer[37], E. Sauvan[4], P. Savard[161,ai], R. Sawada[159], C. Sawyer[137], L. Sawyer[99], C. Sbarra[24b], A. Sbrizzi[24b,24a], T. Scanlon[98], J. Schaarschmidt[142], U. Schäfer[102], A.C. Schaffer[66,45], D. Schaile[111], R.D. Schamberger[151], C. Scharf[19], M.M. Schefer [20], V.A. Schegelsky [38], D. Scheirich [136], M. Schernau [140f], C. Scheulen [56], C. Schiavi [57b,57a], M. Schioppa [44b,44a], B. Schlag [149], S. Schlenker [37], J. Schmeing [177], E. Schmidt [112], M.A. Schmidt [177], K. Schmieden [102], C. Schmitt [102], N. Schmitt [102], S. Schmitt [48], N.A. Schneider [111], L. Schoeffel [138], A. Schoening [63b], P.G. Scholer [35], E. Schopf [147], M. Schott [25], S. Schramm [56], T. Schroer [56], H-C. Schultz-Coulon [63a], M. Schumacher [54], B.A. Schumm [139], Ph. Schune [138], H.R. Schwartz [7], A. Schwartzman [149], T.A. Schwarz [108], Ph. Schwemling [138], R. Schwienhorst [109], F.G. Sciacca [20], A. Sciandra [30], G. Sciolla [27], F. Scuri [74a], C.D. Sebastiani [37], K. Sedlaczek [118], S.C. Seidel [115], A. Seiden [139], B.D. Seidlitz [42], C. Seitz [48], J.M. Seixas [83b], G. Sekhniaidze [72a], L. Selem [60], N. Semprini-Cesari [24b,24a], A. Semushin [179], D. Sengupta [56], V. Senthilkumar [169], L. Serin [66], M. Sessa [72a,72b], H. Severini [123], F. Sforza [57b,57a], A. Sfyrla [56], Q. Sha [14], E. Shabalina [55], H. Shaddix [118], A.H. Shah [33], R. Shaheen [150], J.D. Shahinian [131], M. Shamim [37], L.Y. Shan [14], M. Shapiro [18a], A. Sharma [37], A.S. Sharma [170], P. Sharma [30], P.B. Shatalov [38], K. Shaw [152], S.M. Shaw [103], Q. Shen [14], D.J. Sheppard [148], P. Sherwood [98], L. Shi [98], X. Shi [14], S. Shimizu [84], C.O. Shimmin [178], I.P.J. Shipsey [129,*], S. Shirabe [90], M. Shiyakova [39,z], M.J. 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Smolek [135], P. Smolyanskiy [135], A.A. Snesarev [39], H.L. Snoek [117], S. Snyder [30], R. Sobie [171,ab], A. Soffer [157], C.A. Solans Sanchez [37], E.Yu. Soldatov [39], U. Soldevila [169], A.A. Solodkov [34h], S. Solomon [27], A. Soloshenko [39], K. Solovieva [54], O.V. Solovyanov [41], P. Sommer [50], A. Sonay [13], A. Sopczak [135], A.L. Sopio [52], F. Sopkova [29b], J.D. Sorenson [115], I.R. Sotarriva Alvarez [141], V. Sothilingam[63a], O.J. Soto Sandoval [140c,140b], S. Sottocornola [68], R. Soualah [85a], Z. Soumaimi [36e], D. South [48], N. Soybelman [175], S. Spagnolo [70a,70b], M. Spalla [112], D. Sperlich [54], B. Spisso [72a,72b], D.P. Spiteri [59], L. Splendori [104], M. Spousta [136], E.J. Staats [35], R. Stamen [63a], E. Stanecka [88], W. Stanek-Maslouska [48], M.V. Stange [50], B. Stanislaus [18a], M.M. Stanitzki [48], B. Stapf [48], E.A. Starchenko [38], G.H. Stark [139], J. Stark [91], P. Staroba [134], P. Starovoitov [85b], R. Staszewski [88], C. Stauch [111], G. 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Toscani[31], C. Tosciri[40], M. Tost[11], D.R. Tovey[145], T. Trefzger[172], P.M. Tricarico[13], A. Tricoli[30], I.M. Trigger[162a], S. Trincaz-Duvoid[130], D.A. Trischuk[27], A. Tropina[39], L. Truong[34c], M. Trzebinski[88], A. Trzupek[88], F. Tsai[151], M. Tsai[108], A. Tsiamis[158], P.V. Tsiareshka[39], S. Tsigaridas[162a], A. Tsirigotis[158,u], V. Tsiskaridze[155a], E.G. Tskhadadze[155a], Y. Tsujikawa[89], I.I. Tsukerman[38], V. Tsulaia[18a], S. Tsuno[84], K. Tsuri[121], D. Tsybychev[151], Y. Tu[64b], A. Tudorache[28b], V. Tudorache[28b], S.B. Tuncay[129], S. Turchikhin[57b,57a], I. Turk Cakir[3a], R. Turra[71a], T. Turtuvshin[39,ac], P.M. Tuts[42], S. Tzamarias[158,d], Y. Uematsu[84], F. Ukegawa[163], P.A. Ulloa Poblete[140c,140b], E.N. Umaka[30], G. Unal[37], A. Undrus[30], G. Unel[165], J. Urban[29b], P. Urrejola[140a], G. Usai[8], R. Ushioda[160], M. Usman[110], F. Ustuner[52], Z. Uysal[82], V. Vacek[135], B. Vachon[106], T. Vafeiadis[37], A. Vaitkus[98], C. Valderanis[111], E. Valdes Santurio[47a,47b], M. Valente[37], S. Valentinetti[24b,24a], A. Valero[169], E. Valiente Moreno[169], A. Vallier[91], J.A. Valls Ferrer[169], D.R. Van Arneman[117], A. Van Der Graaf[49], H.Z. Van Der Schyf[34h], P. Van Gemmeren[6], M. Van Rijnbach[37], S. Van Stroud[98], I. Van Vulpen[117], P. Vana[136], M. Vanadia[76a,76b], U.M. Vande Voorde[150], W. Vandelli[37], E.R. Vandewall[124], D. Vannicola[157], L. Vannoli[53], R. Vari[75a], M. Varma[178], E.W. Varnes[7], C. Varni[118], D. Varouchas[66], L. Varriale[169], K.E. Varvell[153], M.E. Vasile[28b], L. Vaslin[84], M.D. Vassilev[149], A. Vasyukov[39], L.M. Vaughan[124], R. Vavricka[136], T. Vazquez Schroeder[13], J. Veatch[32], V. Vecchio[103], M.J. Veen[105], I. Veliscek[30], I. Velkovska[95], L.M. Veloce[161], F. Veloso[133a,133c], S. Veneziano[75a], A. Ventura[70a,70b], A. Verbytskyi[112], M. Verducci[74a,74b], C. Vergis[96], M. Verissimo De Araujo[83b], W. Verkerke[117], J.C. Vermeulen[117], C. 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Wall[131], E.J. Wallin[100], T. Wamorkar[18a], K. Wandall-Christensen[169], A. Wang[62], A.Z. Wang[139], C. Wang[102], C. Wang[11], H. Wang[18a], J. Wang[64c], P. Wang[103], P. Wang[98], R. Wang[61], R. Wang[6], S.M. Wang[154], S. Wang[14], T. Wang[116], T. Wang[62], W.T. Wang[129], W. Wang[14], X. Wang[168], X. Wang[144a], X. Wang[48], Y. Wang[114a], Y. Wang[62], Z. Wang[108], Z. Wang[144b], Z. Wang[108], C. Wanotayaroj[84], A. Warburton[106], A.L. Warnerbring[147], S. Waterhouse[97], A.T. Watson[21], H. Watson[52], M.F. Watson[21], E. Watton[59], G. Watts[142], B.M. Waugh[98], J.M. Webb[54], C. Weber[30], H.A. Weber[19], M.S. Weber[20], S.M. Weber[63a], C. Wei[62], Y. Wei[54], A.R. Weidberg[129], E.J. Weik[120], J. Weingarten[49], C. Weiser[54], C.J. Wells[48], T. Wenaus[30], T. Wengler[37], N.S. Wenke[112], N. Wermes[25], M. Wessels[63a], A.M. Wharton[93], A.S. White[61], A. White[8], M.J. White[1], D. Whiteson[165], L. Wickremasinghe[127], W. Wiedenmann[176], M. Wielers[137], R. Wierda[150], C. Wiglesworth[43], H.G. Wilkens[37], J.J.H. Wilkinson[33], D.M. Williams[42], H.H. Williams[131], S. Williams[33], S. Willocq[105], B.J. Wilson[103], D.J. Wilson[103], P.J. Windischhofer[40], F.I. Winkel[31], F. Winklmeier[126], B.T. Winter[54], M. Wittgen[149], M. Wobisch[99], T. Wojtkowski[60], Z. Wolffs[117], J. Wollrath[37], M.W. Wolter[88], H. Wolters[133a,133c], M.C. Wong[139], E.L. Woodward[42], S.D. Worm[48], B.K. Wosiek[88], K.W. Woźniak[88], S. Wozniewski[55], K. Wraight[59], C. Wu[161], C. Wu[21], J. Wu[159], M. Wu[114b], M. Wu[116], S.L. Wu[176], S. Wu[14,ak], X. Wu[62], Y. Wu[62], Z. Wu[4], Z. Wu[114a], J. Wuerzinger[112], T.R. Wyatt[103], B.M. Wynne[52], S. Xella[43], L. Xia[114a], M. Xia[15], M. Xie[62], A. Xiong[126], J. Xiong[18a], D. Xu[14], H. Xu[62], L. Xu[62], R. Xu[131], T. Xu[108], Y. Xu[142], Z. Xu[52], R. Xue[132], B. Yabsley[153], S. Yacoob[34a], Y. Yamaguchi[84], E. Yamashita[159], H. Yamauchi[163], T. Yamazaki[18a], Y. Yamazaki[86], S. Yan[59], Z. Yan[105], H.J. Yang[144a,144b], H.T. Yang[62], S. Yang[62], T. Yang[64c], X. Yang[37], X. Yang[14], Y. Yang[159], Y. Yang[62], W-M. Yao[18a], C.L. Yardley[152], J. Ye[14], S. Ye[30], X. Ye[62], Y. Yeh[98], I. Yeletskikh[39], B. Yeo[18b], M.R. Yexley[98], T.P. Yildirim[129], K. Yorita[174], C.J.S. Young[37], C. Young[149], N.D. Young[126], Y. Yu[62], J. Yuan[14,114c], M. Yuan[108], R. Yuan[144b,144a], L. Yue[98], M. Zaazoua[62], B. Zabinski[88], I. Zahir[36a], A. Zaio[57b,57a], Z.K. Zak[88], T. Zakareishvili[169], S. Zambito[56], J.A. Zamora Saa[140d], J. Zang[159], R. Zanzottera[71a,71b], O. Zaplatilek[135], C. Zeitnitz[177], H. Zeng[14], J.C. Zeng[168], D.T. Zenger Jr[27], O. Zenin[38], T. Ženiš[29a], S. Zenz[96], D. Zerwas[66], M. Zhai[14,114c], D.F. Zhang[145], G. Zhang[14,ak], J. Zhang[143a], J. Zhang[6], K. Zhang[14,114c], L. Zhang[62], L. Zhang[114a], P. Zhang[14,114c], R. Zhang[114a], S. Zhang[91], T. Zhang[159], Y. Zhang[142], Y. Zhang[98], Y. Zhang[62], Y. Zhang[114a], Z. Zhang[143a], Z. Zhang[66], H. Zhao[142], T. Zhao[143a], Y. Zhao[35], Z. Zhao[62], Z. Zhao[62], A. Zhemchugov[39], J. Zheng[114a], K. Zheng[168], X. Zheng[62], Z. Zheng[149], D. Zhong[168], B. Zhou[108], H. Zhou[7], N. Zhou[144a], Y. Zhou[15], Y. Zhou[114a], Y. Zhou[7], C.G. Zhu[143a], J. Zhu[108], X. Zhu[144b], Y. Zhu[144a], Y. Zhu[62], X. Zhuang[14], K. Zhukov[68], N.I. Zimine[39], J. Zinsser[63b], M. Ziolkowski[147], L. Živković[16], A. Zoccoli[24b,24a], K. Zoch[61], A. Zografos[37], T.G. Zorbas[145], O. Zormpa[46], L. Zwalinski[37].

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