Search for new resonances in $W\gamma$ and $Z\gamma$ final states in $pp$ collisions at $\sqrt{s}=8$ TeV with the ATLAS detector

ATLAS Collaboration*

Abstract

This Letter presents a search for new resonances decaying to final states with a vector boson produced in association with a high transverse momentum photon, $V\gamma$, with $V=W\rightarrow \ell\nu$ or $Z\rightarrow \ell^+\ell^-$, where $\ell=e$ or $\mu$. The measurements use 20.3 fb$^{-1}$ of proton-proton collision data at a center-of-mass energy of $\sqrt{s}=8$ TeV recorded with the ATLAS detector. No deviations from the Standard Model expectations are found, and production cross section limits are set at 95% confidence level. Masses of the hypothetical $\alpha_t$ and $\omega_t$ states of a benchmark Low Scale Technicolor model are excluded in the ranges $[275, 360]\text{ GeV}$ and $[200, 700]\cup[750, 890]\text{ GeV}$, respectively. Limits at 95% confidence level on the production cross section of a singlet scalar resonance decaying to $Z\gamma$ final states have also been obtained for masses below 1180 GeV.

Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/3.0/). Funded by SCOAP3.

1. Introduction

The search for diboson resonances is an essential step in exploring the source of Electroweak Symmetry Breaking (EWSB). The observation of a Higgs boson decaying to $\gamma\gamma$, $ZZ$ and $W^{+}W^{-}$ final states, reported by the ATLAS and CMS Collaborations [2,3], represents a milestone in particle physics history. However, the precise nature of the observed Higgs boson is not well known, and a dynamical mechanism of EWSB and fermion mass generation may yet involve a variety of heavy bosons of spin-0 or spin-1.

This Letter presents a search for narrow scalar and vector heavy resonances decaying to $W\gamma$ or $Z\gamma$ final states, where the $W$ and $Z$ bosons decay to leptons ($e$ or $\mu$). The existence of a new vector or scalar resonance coupling to a boson pair $W\gamma$ or $Z\gamma$ is predicted by many physics scenarios, including various new physics models with scalar particles [3,4] and vector particles [5].

The Low Scale Technicolor (LSTC) [5] model is used as a benchmark model for the search for spin-1 resonances decaying to $W\gamma$ and $Z\gamma$ final states explored in this paper. The discovery of a Higgs boson, with its parameters in agreement with the Standard Model (SM) predictions, does not exclude the full phase space of the LSTC model, and the basic phenomenology would remain valid for a Technicolor model with a light composite Higgs boson. To minimize the model dependence of the search results, the signal cross section is measured within a well defined fiducial region. The predicted new bound states of the lightest doublet of technifermions, the technisinos $\alpha_t$, $\alpha_T$, $\rho_t$ and $\pi_t$, generate a new phenomenology. The mass splittings between the technisinos are set to be as follows: $\alpha_t = m_{\alpha_t}$, $\alpha_T \approx 1.1 \times m_{\rho_t}$ and $m_{\rho_t} - m_{\pi_t} = m_W$ [6]. The decays of technisinos to technipions are therefore kinematically forbidden. The technisinos mostly decay to pairs of electroweak gauge bosons, the most abundant decay channels being $\alpha_t \rightarrow Z\gamma$, $\alpha_t \rightarrow W\gamma$ and $\rho_t \rightarrow WZ, W\gamma$. These technisinos resonances are expected to be narrow, with typical values $\Gamma(\rho_t, \alpha_t, \pi_t) \approx 1\text{ GeV}$.

A phenomenological model describing a singlet scalar particle $\phi$ [7,8] is chosen as another benchmark in the search for spin-0 resonances decaying to $Z\gamma$. The neutral scalar could be composite, produced by a hypothetical new strong interaction. It could be the pseudo-Goldstone boson playing an important role in the dynamical EWSB. This low energy effective model is independent of the underlying dynamical details and Lagrangian can be written as follows:

$$L_{\text{eff}} = \frac{4\pi\alpha_s}{\Lambda} \phi G_{\mu\nu}^a G^{a\mu\nu} + \frac{c_W}{\Lambda \sin^2 \theta_W} \phi W_{\mu\nu} W^{\mu\nu}$$

$$+ \frac{4\pi\alpha_{em}}{\Lambda \cos^2 \theta_W} \phi B_{\mu\nu} B^{\mu\nu}. \quad (1)$$

Here $\alpha_s$ and $\alpha_{em}$ are, respectively, the couplings of the strong and electromagnetic interactions, $\Lambda$ is the cutoff scale and $\theta_W$ is the Weinberg angle. Moreover, $c_W$, $c_{\theta W}$ and $c_B$ are the coupling coefficients between the scalar field $\phi$ and the gluon field strength $G_{\mu\nu}^a$, the SU(2) field strength $W_{\mu\nu}^a$ and the U(1) field strength $B_{\mu\nu}$, respectively. The scalar field $\phi$ interacts directly with the...
gauge boson pairs via the dimension-5 operators rather than via the loop-induced processes, and could lead to enhanced production and branching ratio to $Z\gamma$ if $\Lambda$ is in the TeV scale. No SM Yukawa interaction of $\phi$ with fermions is allowed so that there is no decay to $b\bar{b}$ or $t\bar{t}$ final states. The WW and ZZ decays of $\phi$ are suppressed compared with the SM Higgs boson.

Previous limits on new resonances decaying to $W\gamma$ and $Z\gamma$ final states from $pp$ and $pp$ production have been obtained at the Tevatron by the DØ Collaboration [9] and at the Large Hadron Collider (LHC) by the ATLAS Collaboration [10]. At ATLAS, the production of $\tau\ell$ and $\omega\tau\ell$ for masses below 703 GeV and 494 GeV, respectively, was excluded within the LSTC benchmark parameters. The most stringent limits on LSTC have been set by the CMS [11] Collaboration, excluding the production of $\rho_{1}$ for masses below $m_{\rho_{1}} < 1.14$ TeV, but using a slightly different choice of parameters.

2. ATLAS detector and data sample

The ATLAS detector [12] is composed of an inner tracker detector (ID) surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic (EM) and hadronic calorimeters (HC), and a muon spectrometer (MS) immersed in the magnetic field produced by a system of superconducting toroids. The ID consists of three subsystems: the pixel and silicon microstrip detectors cover the pseudorapidity range $|\eta| < 2.5$, while the transition radiation tracker, made of straw tubes, has an acceptance range of $|\eta| < 2.0$. The calorimeter system covers the range $|\eta| < 4.9$. The highly segmented electromagnetic calorimeter plays a crucial role in electron and photon identification. It is composed of lead absorbers with Liquid Argon (LAr) as the active material and spars $|\eta| < 3.2$. In the region $|\eta| < 1.8$, a pre-sampler detector using a thin layer of LAr is used to correct for the energy lost by electrons and photons upstream of the calorimeter. The hadronic tile calorimeter ($|\eta| < 1.7$) is a steel/scintillating-tile detector and is located directly outside the envelope of the barrel electromagnetic calorimeter. The end-caps and forward calorimeters use LAr as the active material, with copper (EM) and tungsten (HC) as absorber materials. The MS is composed of three large superconducting air-core toroid magnets of eight coils each, a system of three stations of high precision tracking chambers in the range $|\eta| < 2.7$, and a muon trigger system which covers $|\eta| < 2.4$. The precision measurement is ensured by monitored drift tubes and, at large pseudorapidities ($|\eta| > 2$), for the innermost layer, by cathode strip chambers. The muon trigger system is composed of resistive plate chambers in the barrel region ($|\eta| < 1.05$), and thin gap chambers in the end-cap ($1.05 < |\eta| < 2.4$).

The ATLAS trigger system has three distinct levels, L1, L2 and the event filter, where each trigger level refines the decisions made at the previous level. The data used for the present analysis were collected in 2012 from $pp$ collisions at a center-of-mass energy of 8 TeV at the LHC. The total integrated luminosity is 20.3 fb$^{-1}$ with an uncertainty of 2.8% [13]. Events are selected by triggers requiring at least one identified electron or muon. The transverse energy ($E_T$) threshold for the single-lepton trigger is 24 GeV. The lepton trigger efficiencies are measured using Z boson candidates as a function of the transverse momentum $p_T$ and $\eta$. The trigger efficiencies for the leptons are approximately 70% for muons with $|\eta| < 1.05$, 90% for muons in the range $1.05 < |\eta| < 2.4$ [14], and 95% for electrons in the range $|\eta| < 2.4$.

3. Signal and background simulated samples

Monte Carlo (MC) event samples, including a full simulation [15] of the ATLAS detector with GEANT4 [16], are used to compare the data to the signal and background expectations. All MC samples are simulated with additional $pp$ interactions (pile-up) in the same and neighboring bunch crossings.

The production and decay of neutral ($\omega\tau\ell \rightarrow Z\gamma$) and charged technimesons ($\omega\rightarrow W\gamma$) in the LSTC model are handled by the Pythia6.426 generator [17]. The following parameters are used in the event generation: number of technicolors $N_{TC}=4$; techniquark charges $Q_{U} = 1$ and $Q_{D} = 0$ for the $Z\gamma$ final state and $Q_{U} = 1/2$ and $Q_{D} = -1/2$ for the $W\gamma$ final state. With this parameterization of the techniquark charges, the dominant contribution to the $W\gamma$ final state is from $\tau\ell$ decay. By removing the $\rho_{1}$ contribution, the model dependence that could result from having two nearby peaks in the benchmark signal is further reduced. The sine of the mixing angle between the technipions and the electroweak gauge boson longitudinal component is set to 1/3. As stated in the introduction, the mass splittings between the technimesons are set to: $m_{\omega_{2}} = m_{\omega_{3}} = m_{\omega_{1}}/1.1$, and $m_{\omega_{1}} = m_{\omega_{2}} = m_{\omega_{3}}$.

Simulations of the signals for singlet scalar particles are generated using MadGraph5 [18] interfaced to Pythia8 [19] for parton shower and fragmentation processes. The generation uses the leading-order (LO) parton distribution function (PDF) set MSTW2008LO [20]. Since the kinematic distribution of the $Z\gamma$ decay into a scalar boson is determined by its spin and CP properties in the narrow-width approximation, the gluon–gluon fusion production and the decay are simulated using the SM Higgs process in MadGraph5, fixing the resonance width to 5.75 MeV.

The cross section of the singlet scalar process $gg \rightarrow \phi \rightarrow Z\gamma$ is calculated by choosing two sets of coupling parameters in Eq. (1). In the parameter set (a), the coupling coefficients are set to $c_{Z} = c_{W} = c_{\varphi} = -1/4\pi$, as suggested by Naive Dimensional Analysis (NDA) [21]. Here, the relative phases are chosen to enhance the $Z\gamma$ coupling. If a large new color number $N_{C} = 4$ of the underlying strong dynamics is considered in NDA [22,23], and larger couplings with the electroweak gauge bosons are assumed (8), then larger values of the coefficients can also be possible, depending on the underlying theory. Thus another parameter set (b) is selected as follows: $c_{Z} = 1/2\pi$, $c_{W} = -c_{\varphi} = c_{\varphi} = 1/\pi$. In both parameterizations, the $Z\gamma$ decay rate is dominant over the $\gamma\gamma$ decay rate. The underlying dynamics scale is set to be $\Lambda = 6$ TeV, motivated by the Higgs boson couplings measurements [24,25]. The width of the singlet scalar for each of set (a) and (b) is well below the experimental resolution over the full mass range studied.

The main background processes, SM $pp \rightarrow \tau^{+}\tau^{-}\gamma$ and $pp \rightarrow \tau^{+}\tau^{-}$ production, are modeled using the Sherpa (1.4.1) generator [26]. An invariant mass cut of $m(\ell^{+}\ell^{-}) > 40$ GeV is applied at the generator level when simulating the $pp \rightarrow \tau^{+}\tau^{-}\gamma$ process. The CTEQ [27] PDF is used for samples generated with Sherpa. In the $W\gamma$ analysis, the $Z(\ell^{+}\ell^{-})$ and $Z(\tau^{+}\tau^{-})$ backgrounds are modelled with Pythia8. The final state radiation of photons from charged leptons is treated in Pythia8 using Photos. Tauola (1.20) [28] is used to model $\tau$ lepton decays. Events with one or more hard photons at the generator level ($p_T > 10$ GeV) in $Z(\ell^{+}\ell^{-})$ and $Z(\tau^{+}\tau^{-})$ MC simulations are removed, in order to avoid overlaps with $Z\gamma$ MC samples. In the $Z\gamma$ analysis, $Z(\ell^{+}\ell^{-})$ and $Z(\tau^{+}\tau^{-})$ MC samples are used to cross check the data-driven $Z +$ jet background estimation.

---

1. 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 $(\rho, \phi)$ are used in the transverse ($\rho, \phi$) plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = \ln \cosh \theta$. The distance $\Delta R$ in the $\eta$-$\phi$ space is defined as $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$. The distance $\Delta R$ in the $\eta$-$\phi$ space is defined as $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$.
The Powheg [29] generator is used to simulate tt̄ production, and is interfaced to PYTHIA8 for parton showering and fragmentation. The single top quark, WW, WZ and ZZ processes are modelled by MC@NLO (4.02) [30,31], interfaced to Herwig (6.520) [32] for parton showering and fragmentation processes and to JIMMY (4.30) [33] for underlying event simulation. The LO MRST2007 [34] PDF set is used to simulate the $Z(\ell^+\ell^-)$ backgrounds, and the CT10 PDF set is used in simulating tt̄, single top quark, WW, WZ and ZZ production.

4. Physics object reconstruction and selection

The W and Z bosons are reconstructed from their leptonic decays and are required to be in an isolated high $E_T$ photon. Furthermore, collision events are selected by requiring a reconstructed vertex with at least three charged particle tracks with $p_T > 0.4$ GeV. In events with more than one candidate vertex, the one with the highest sum of the $p_T$ of associated tracks is chosen.

An electron candidate is obtained from an energy cluster in the EM calorimeter associated with a reconstructed track in the ID. The transverse energy of electrons is required to be greater than 25 GeV. The electron cluster must lie within the overall fiducial acceptance of the EM calorimeters and the ID. In the Wγ final states, the electrons found in the transition region between the barrel and end-cap EM calorimeters are removed in order to improve the $E_T^{\text{miss}}$ resolution. The acceptance requirements are $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$ for Wγ events and $|\eta| < 2.47$ for Zγ events. At the electron track’s closest approach to the primary vertex, the ratio of the transverse impact parameter $d_0$ to its uncertainty (the $d_0$ significance) must be smaller than 6.5, and the longitudinal impact parameter $z_0$ must be less than 10 mm. Tight electron identification, as defined in Ref. [35], is used in the $W(e\nu)$ analysis, whereas loose isolation [35] is used to select electrons in the Z(\ell^+\ell^-)γ analysis. In order to reduce the background due to a jet misidentified as an electron, a calorimeter-based isolation requirement is applied to the electron candidate. The normalized calorimeter isolation ($R_{\text{iso}}$) for electrons must satisfy $R_{\text{iso}} < 0.20$. It is computed as the sum of the positive-energy topological clusters with a reconstructed barycenter falling in a cone of $\Delta R < 0.2$ around the candidate electron cluster divided by the electron $E_T$.

The energy deposited by the electron is subtracted.

In both Wγ and Zγ analyses, muon candidates are identified by associating complete tracks or track segments in the MS to tracks in the ID [36]. Each of these muon candidates corresponds to a combined ID and MS track originating from the primary vertex with transverse momentum $p_T > 25$ GeV and $|\eta| < 2.4$. In the Zγ analysis, muon candidates can also be formed from tracks reconstructed either in the ID or in the MS. This allows one to increase the signal efficiency by extending the muon $|\eta|$ acceptance up to 2.7. In the central barrel region $|\eta| < 0.1$, which lacks MS coverage, ID tracks are identified as muons based on the associated energy deposits in the calorimeter. These muons are required to have a calorimeter energy deposit consistent with that of a minimum ionizing particle. Muons are required to be isolated by imposing $R_{\text{iso}} < 0.3$ (0.15 for muons without an ID track), where $R_{\text{iso}}$ is the sum of the $p_T$ of the tracks in a $\Delta R = 0.2$ cone around the muon direction, excluding the track of the muon, divided by the muon $p_T$. The $d_0$ significance must be smaller than 3.5, and $z_0$ must be less than 10 mm.

Overlap removal is applied to electrons and muons that satisfy all selection criteria and share the same ID track, in order to avoid double counting. In particular, if the muon is identified by the MS, then the electron candidate is discarded, otherwise the muon candidate is rejected.

Photon candidate reconstruction relies on clustered energy deposits in the EM calorimeter with $E_T > 40$ GeV in the range $|\eta| < 2.37$ (excluding the calorimeter transition region 1.37 < $|\eta| < 1.52$). Clusters without matching tracks are directly classified as unconverted photon candidates. Clusters that are matched to tracks which originate from reconstructed conversion vertices in the ID or to tracks consistent with coming from a conversion are considered as converted photon candidates. Both unconverted and converted candidates are used in the present analysis. Tight requirements on the shower shapes [35] are applied to suppress the background from multiple showers produced in meson (e.g. $\pi^0, \eta$) decays. To further reduce this background, a photon isolation requirement $E_T^{\text{iso}} < 4$ GeV is applied. The isolation variable $E_T^{\text{iso}}$ is the total transverse energy recorded in the calorimeters within a cone of $\Delta R = 0.4$ around the photon position excluding the energy deposit of the photon itself. The value of $E_T^{\text{iso}}$ is corrected for leakage from the photon energy cluster core into the isolation cone and for contributions from the underlying event and pile-up [35,37].

Jets are reconstructed from calibrated topological clusters built from energy deposits [12] in the calorimeter using the anti-kt jet clustering algorithm [38] with radius parameter $R = 0.4$. The selected jets are required to have $p_T > 25$ GeV with $|\eta| < 4.5$, and to be well separated from the lepton and photon candidates ($\Delta R(\ell)/\eta, \gamma, \text{jet}) > 0.3$).

The Wγ final state has missing transverse momentum, $E_T^{\text{miss}}$ [39], due to the undetected neutrino from the W boson decay. Its magnitude and direction are measured from the vector sum of the transverse momentum vectors associated with clusters of energy reconstructed in the calorimeters with $|\eta| < 4.9$. A correction is applied to the energy of those clusters that are associated with a reconstructed physical object (jet, electron, τ-lepton, photon). Reconstructed muons are also included in the sum, and any calorimeter energy deposits associated with them are excluded to avoid double counting.

5. Wγ and Zγ event selection

The $W\nu\gamma$ candidate events are selected by requiring exactly one lepton with $p_T > 25$ GeV, at least one photon with $E_T^\gamma > 40$ GeV and $E_T^{\text{miss}} > 35$ GeV. In addition, the transverse mass $m_T$ of the lepton-$E_T^{\text{miss}}$ system is required to be greater than 40 GeV. A Z-veto requirement is applied in the electron channel of the Wγ analysis by requiring that the electron–photon invariant mass be not within 15 GeV of the Z boson mass. This is used to suppress the background where one of the electrons from the Z boson decay is mis-identified as a photon.

The $\ell^+\ell^-\gamma$ candidates are selected by requiring two oppositely charged same-flavor leptons with an invariant mass between 65 and 115 GeV, and at least one photon with $E_T^\gamma > 40$ GeV. For $\mu^+\mu^-\gamma$, at least one of the two muons must be reconstructed both in the ID and the MS. If more than one Z candidate is found in the same event, the one with mass closest to the Z mass is retained.

In both the Wγ and Zγ analyses, a selection requirement $\Delta R(\ell, \gamma) > 0.7$ is applied to suppress the contributions from photons radiated from the selected leptons. If more than one photon passes all of the selection criteria, the one with the highest $p_T$ is selected.

2 The transverse mass is defined as $m_T = \sqrt{2p_T^{}(\ell) E_T^{\text{miss}} (1 - \cos \Delta \phi)}$, where $\Delta \phi$ is the azimuthal separation between the directions of the lepton and the missing transverse momentum vector.
Table 1

Total number of events passing the W/Zγ selection requirements in the data, and expected number of SM background events in the \( e\gamma, \mu\gamma, e^+e^-\gamma \) and \( \mu^+\mu^-\gamma \) final states. The first uncertainty is statistical and, when present, the second uncertainty shows an estimate of the systematic effects. The systematic uncertainty is only presented for W + jets and \( \gamma + \text{jets} \) background in W\( \gamma \) analysis, and for \( Z + \text{jets} \) background in Z\( \gamma \) analysis, since the uncertainty on these background estimates dominates the uncertainty of the total background estimate. The “other backgrounds” include contributions from single top, WW and WZ production.

<table>
<thead>
<tr>
<th>Background</th>
<th>( e\gamma )</th>
<th>( \mu\gamma )</th>
<th>( e^+e^-\gamma )</th>
<th>( \mu^+\mu^-\gamma )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( W(\ell\gamma) )</td>
<td>6100 ± 50</td>
<td>8710 ± 150</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( Z(\ell\gamma) )</td>
<td>1160 ± 40</td>
<td>1160 ± 40</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( Z(\ell\ell \text{ + jets}) )</td>
<td>570 ± 20</td>
<td>310 ± 11</td>
<td>4 ± 1</td>
<td>5 ± 1</td>
</tr>
<tr>
<td>( W(\ell\ell \text{ + jets}) )</td>
<td>790 ± 50 ± 320</td>
<td>1110 ± 70 ± 310</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \gamma + \text{jets} )</td>
<td>870 ± 60 ± 300</td>
<td>1460 ± 110 ± 510</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>( \ell\ell )</td>
<td>700 ± 20</td>
<td>1310 ± 20</td>
<td>6100 ± 150</td>
<td>-</td>
</tr>
<tr>
<td>Other backgrounds</td>
<td>160 ± 10</td>
<td>110 ± 10</td>
<td>24 ± 0.3</td>
<td>1.7 ± 0.2</td>
</tr>
<tr>
<td>Total expected</td>
<td>9780 ± 80 ± 450</td>
<td>14000 ± 120 ± 620</td>
<td>1960 ± 59 ± 80</td>
<td>2340 ± 90 ± 50</td>
</tr>
<tr>
<td>Total observed</td>
<td>10437</td>
<td>14082</td>
<td>2086</td>
<td>2429</td>
</tr>
</tbody>
</table>

Fig. 1. Three-body transverse mass distribution for the \( e\gamma \) (a) and \( \mu\gamma \) (b) final states. The background-only fit to the data and the one standard deviation uncertainty band are shown. The significance (see text for details) as a function of \( m_t^3 \) in the lower panel includes only statistical uncertainties. The expected signal for a resonance mass of 600 GeV is superimposed.

6. Analysis strategy

A search for a signal is performed with an unbinned maximum likelihood fit of the mass spectra of the \( e\gamma \) and \( \ell^+\ell^-\gamma \) systems. In order to select and validate the probability density function used to model the background shape, a study of the background composition is also performed. In the final results, the background normalization and shape are extracted by performing a signal-plus-background maximum likelihood fit directly to the data spectrum.

7. Study of the background composition

The composition of the backgrounds affecting the \( e\gamma \) and \( \ell^+\ell^-\gamma \) searches are studied by using a combination of simulation and data-driven methods. The dominant contribution is the SM \( V\gamma \) production, then come other processes, like \( V + \text{jets} \), \( \gamma + \text{jets} \), \( \ell\ell \) and other diboson final states, such as WW and WZ. The SM \( V\gamma \) backgrounds are estimated using SHERPA MC samples. A control region is defined to validate the MC modeling. The events in the control regions are selected by imposing the nominal event selection criteria, except that the photon \( E_T^\gamma \) is required to be between 15 and 40 GeV. The comparison of the relevant kinematic distributions, such as the transverse momenta of the leptons and photons and the transverse missing energy corresponding to the undetected neutrino, in the control regions shows that the \( V\gamma \) background is well modeled by the MC simulation.

The backgrounds estimated from data are Z/W + jets and \( \gamma + \text{jets} \) in the \( e\gamma \) final state, and Z + jets in the \( \ell^+\ell^-\gamma \) final state. The data-driven backgrounds are estimated by using a two-dimensional sideband method, as described in Ref. [40]. The remaining backgrounds, i.e. \( \ell\ell \), single top, WW, WZ, and ZZ are estimated with MC simulations.

The background prediction obtained in all four final states is shown in Table 1. The distribution of the W\( \gamma \) system three-body transverse mass for the selected W\( \gamma \) events is shown in Fig. 1, while Fig. 2 presents the Z\( \gamma \) invariant mass distribution. Here, data are compared to the sum of the SM expected backgrounds and show fair agreement. The significance, shown as a function of the mass in the lower panels, only includes statistical uncertainties and is defined as the \( z \)-value between the data points and the fit expectation, which is the deviation at the right of the mean of a Gaussian distribution, expressed in units of standard deviations, as described in Ref. [41]. The event rate in the high mass region has a significance below three standard deviations, and is attributed to a statistical fluctuation.

The W\( \gamma \) system three-body transverse mass is defined as:

\[
(m_{t}^{3\gamma})^2 = \left(\sqrt{m_{t}^2 + E_{t}^\gamma + E_{t}^\ell} + E_{t}^{miss}\right)^2 - \left(E_{t}^\gamma + E_{t}^\ell + E_{t}^{miss}\right)^2. \tag{2}
\]
8. Fit model and statistical methods

The signal and background parameterizations have been chosen to best describe the mass distribution shapes of, respectively, fully simulated MC samples and a mixture of MC samples and data-driven estimates. The fit to data takes into account all systematic uncertainties, discussed in Section 8.4.

8.1. Background modeling

All the mass distributions, shown in Figs. 1 and 2, have a broad maximum in the low mass region due to the kinematic cuts used. The shape of the SM background is thus parameterized only for masses larger than 180 GeV.

A probability density function is chosen to describe the expected SM background mass distribution for the range, between 180 GeV and 1.6 TeV. The variation of the background composition, within systematic uncertainties, presented in Section 7 is also taken into account in evaluating the background parametrization systematics. For both the $W\gamma$ and $Z\gamma$ final states, the probability density function best describing the SM background distribution, in the chosen range, is found to be the sum of two exponentials. The impact of the choice of the background model on the final result has been studied, as discussed in Section 8.4.

The results of the unbinned fit to the data can be seen as the solid curve on each of the mass spectra in Figs. 1 and 2. A good description of data is found, and the Pearson’s $\chi^2$ per degree of freedom obtained for the background-only fit is close to unity for all distributions.

8.2. Signal modeling

The parameterizations of the signal shapes have been obtained from the benchmark signal MC samples. For all $W/\gamma$ spin-1 and $Z\gamma$ spin-0 resonances considered, the signal mass distribution is described by the sum of a Crystal-Ball function (CB) [42–44], which reproduces the core mass resolution plus a non-Gaussian tail for low mass values, and a small wider Gaussian component that takes into account outliers in the mass distribution. The mean value of the CB and the Gaussian are chosen to be the same.

For simulated events, the mean fitted mass is found to be within 2 GeV of the generated resonance mass for the $Z\gamma$ final state. At the reconstruction level, the full width at half maximum of the $Z\gamma$ signal grows approximately linearly from 7 GeV to 38 GeV in the electron channel, and from 7 GeV to 100 GeV in the muon channel, for masses generated between 200 GeV and 1.6 TeV. The full width at half maximum of the $W\gamma$ transverse mass also grows approximately linearly, and goes from 50 GeV to 100 GeV in the electron channel, and from 45 GeV to 190 GeV in the muon channel, for masses generated between 200 GeV and 1.6 TeV. These widths are completely dominated by reconstruction effects, since we assume the hypothetical signals to be narrow.

8.3. Statistical method

The search is conducted by performing a scan of the $m_{Z\gamma}$ and $m_{W\gamma}$ distributions using a probability density function describing both the background shape and a signal peak at a given mass. The step size used in the scan is 20 GeV for the $W\gamma$ channel and 10 GeV for the $Z\gamma$ channel. The difference in the scan step takes into account the different resolutions of a hypothetical peak in the two channels. The scan starts at a signal mass of 227 GeV for the $W\gamma$ final state, and of 200 GeV for the $Z\gamma$ final state, and goes up to 1600 GeV. Each fit is performed in a mass range of [180, 1600] GeV for both $Z\gamma$ and $W\gamma$ final states, in order to ensure that there are enough events in the sidebands of a hypothetical signal peak.

The background normalization and the two exponential coefficients of the SM background probability density function are free to vary in the fit. The parameters of the signal probability density functions are fixed to their nominal values from fits to the MC signal model, except for the normalization of the signal and for the nuisance parameters that account for the systematic uncertainties on the signal event rate and resolution, described below. The systematic uncertainty related to the choice of parameterization for the background, on the other hand, has been estimated by testing different parameterizations and verifying that the extracted background and signal yields do not vary significantly, and was found to be negligible with respect to the other systematic and statistical uncertainties considered.

The signal yield, $N_S$, depends on the parameter of interest of the fit, i.e. the signal fiducial cross section $\sigma_{\text{fid}}$ at a given signal mass, as follows:

$$N_S = \sigma_{\text{fid}} \cdot \epsilon_{\text{Reco}} \cdot \int L \, dt,$$

where the factor $\epsilon_{\text{Reco}}$ is the signal reconstruction efficiency, defined as the number of reconstructed signal events passing the full
event selection divided by the number of events generated in the fiducial region defined in Table 2. The signal reconstruction efficiency has been estimated by using signal MC simulated samples, and accounts for effects due to the detector resolution on the lepton and photon transverse momentum and energies, and on the missing transverse energy. The parameter $\epsilon^p_{\ell}$ in the table is defined at particle level as the sum of the energy carried by final state particles in a $\Delta R = 0.4$ cone around the photon direction (not including the photon) divided by the energy carried by the photon. To account for the effect of final state QED radiation, the energy of the generated lepton at particle level is defined as the energy of the lepton after radiation plus the energy of all radiated photons within a $\Delta R = 0.1$ cone around the lepton direction. The $\sigma_{\text{bkg}}$ parameter is the same for both muon and electron channels in each final state, and is thus determined by simultaneously performing the fit in the two channels, so that the results obtained are less sensitive to statistical fluctuations.

In order to test different hypothetical values of the parameter of interest, the test statistic based on the Profile Likelihood Ratio $\lambda(\theta)\mid \text{data}$ is used, where $\theta$ is the vector of nuisance parameters, defined in Ref. [45]. It is defined from the likelihood describing the probability density function of $m_{\ell\gamma}^{\text{obs}}$ and $m_{\ell\gamma}^{\text{exp}}$ under a signal-plus-background hypothesis and is a function of the parameter of interest and of the nuisance parameters related to the systematic uncertainties. The statistical tests are then performed on the $m_{\ell\gamma}^{\text{obs}}$ and $m_{\ell\gamma}^{\text{exp}}$ distributions combining the muon and electron channels in each final state.

The probability of the background-only hypothesis, or local $p_0$-value, is obtained by using a frequentist approach. The latter gives the probability that the background fluctuates to the observation or above. If no hint for a new physics signal is found, the data is interpreted by using a modified frequentist approach (CL$_S$ [46]) for setting limits. A fiducial cross section is claimed to be excluded at 95% CL when CL$_S$ is less than 0.05.

### 9. Results

The two largest deviations from the background-only configuration are observed, in the spin-1 search, at 1350 GeV for the $W\gamma$ final state, and at 350 GeV and 700 GeV for the $Z\gamma$ final state. Similarly, in the spin-0 search, the largest deviation is close to 350 GeV. The $p_0$-values are estimated to be greater than 0.01 in all cases, corresponding in all cases to a local significance below approximately 2.5$\sigma$. These small excesses, also visible in the mass spectra in Figs. 1 and 2, are at the level expected due to statistical fluctuations. No evidence of a new physics signal is found in the $W\gamma$ and $Z\gamma$ final states when analyzing the totality of the 8 TeV data collected by ATLAS in the mass ranges considered.

Therefore, 95% CL limits are set on the production of LSTWinos and composite scalars decaying to $W\gamma$ and $Z\gamma$ final states.

---

4 An Asimov dataset is defined as being a single representative dataset replacing the ensemble of simulated datasets.
states. Fig. 3 shows the observed and expected limits in the fiducial region obtained for an LSTC $\sigma_{l} \rightarrow W\gamma$ (a), $\sigma_{l} \rightarrow Z\gamma$ (b), and for a composite scalar $\phi \rightarrow Z\gamma$ (c). Using 20.3 fb$^{-1}$ of 8 TeV data, the LSTC benchmark model is excluded at 95% CL in the range [275, 960] GeV for $W\gamma$, and [200, 700] $\cup$ [750, 890] GeV for $Z\gamma$. In the spin-0 searches, no sensitivity is reached for the composite scalar model with the parameter set (a), whereas composite scalar models with the parameter set (b) are excluded at 95% CL in most of the mass range [200, 1180] GeV.

10. Conclusions

This paper describes the results of searches with the ATLAS detector for LSTC technimesons and composite scalar particles decaying to $W\gamma$ final states. The observed data prove to be consistent with the SM background expectations. Using the LSTC benchmark model, the production of $\sigma_{l}$ is excluded up to $m_{\sigma_{l}} = 960$ GeV in the $W\gamma$ mode and the production of $\sigma_{l}$ is excluded in most of the mass range below 890 GeV in the $Z\gamma$ channel. Using the benchmark composite scalar model, the production of $\phi$ is excluded in most of the mass range below 1180 GeV for coupling scenario (b) described in text. The limits on the LSTC benchmark are more stringent than the previous results obtained at ATLAS and documented in Ref. [40].

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNNRF, DNSRC and Lundbeck Foundation, Denmark; EPLANET, ERC and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMFB, DFG, HGF, MPG and AvH Foundation, Germany; GSRT and NSRF, Greece; ISF, MINERVA, GIF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRS, Morocco; FOM and NWO, Netherlands; BRF and RCN, Norway; MNISW and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZS, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the
Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

References


1 Department of Physics, University of Adelaide, Adelaide, Australia
2 Physics Department, SUUNY Albany, Albany, NY, United States
3 Department of Physics, University of Alberta, Edmonton, AB, Canada
4 (a) Department of Physics, Ankara University, Ankara, Turkey; (b) Department of Physics, Gazi University, Ankara, Turkey; (c) Division of Physics, TOBB University of Economics and Technology, Ankara, Turkey; (d) Turkish Atomic Energy Authority, Ankara, Turkey
5 LAP, CERN/SPS and Université de Savoie, Annecy-le-Vieux, France
6 High Energy Physics Division, Argonne National Laboratory, Argonne, IL, United States
7 Department of Physics, University of Arizona, Tucson, AZ, United States
8 Department of Physics, The University of Texas at Arlington, Arlington, TX, United States
9 Physics Department, University of Athens, Athens, Greece
10 Physics Department, National Technical University of Athens, Zografou, Greece
11 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
12 Instituto de Física de Altas Energías and Departamento de Física de la Universidad Autónoma de Barcelona, Barcelona, Spain
13 (a) Institute of Physics, University of Belgrade, Belgrade, Serbia; (b) Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
14 Department of Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, CA, United States
16 Department of Physics, Humboldt-Universität, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19 Department of Physics, Bogazici University, Istanbul, Turkey; (a) Department of Physics, Dogus University, Istanbul, Turkey; (b) Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey
20 INFN Sezione di Bologna, Italy; (a) Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, Universität Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston, MA, United States
23 (a) Department of Physics, Brandeis University, Waltham, MA, United States
24 (a) Universidad Federal do Rio de Janeiro COPPE/UFRJ, Rio de Janeiro, Brazil; (b) Federal University of Juiz de Fora (UFJF), Juiz de Fora, Brazil; (c) Federal University of Sao Joao del Rei (UFJF), Juiz de Fora, Brazil; (d) Instituto de Física, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton, NY, United States
26 (a) National Institute of Physics and Nuclear Engineering, Bucharest, Romania; (b) National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Chig Narovca, Romania; (c) University Politehnica Bucharest, Bucharest, Romania; (d) West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavour National Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa, ON, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago, IL, United States
32 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
33 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing, China; (b) Department of Modern Physics, University of Science and Technology of China, Hefei, China; (c) Department of Physics, Nanjing University, Nanjing, China; (d) School of Physics, Shandong University, Shandong, China; (e) Physics Department, Shanghai Jiao Tong University, Shanghai, China
34 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
35 Nevis Laboratory, Columbia University, Irvington, NY, United States
36 Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark
37 INFN-Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati, Italy; (a) Dipartimento di Fisica, Università della Calabria, Rende, Italy
38 (a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland; (b) Marian Smoluchowski Institute of Physics, Jagellonian University, Krakow, Poland
39 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas, TX, United States
41 Physics Department, University of Texas at Dallas, Richardson, TX, United States
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik II, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham, NC, United States
46 SLAC – School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
Also at Institut Catalana de Recerca i Estudis Avançats, ICREA, Barcelona, Spain.

Also at Department of Physics, The University of Texas at Austin, Austin, TX, United States of America.

Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

Also at CERN, Geneva, Switzerland.

Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan.

Also at Manhattan College, New York, NY, United States of America.

Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.

Also at CERN, Geneva, Switzerland.

Also at Ochanomizu University, Tokyo, Japan.

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at Manhattan College, New York, NY, United States of America.

Also at Novosibirsk State University, Novosibirsk, Russia.

Also at Department of Physics, The University of Texas at Austin, Austin, TX, United States of America.

Also at Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France.

Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.

Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India.

Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy.

Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.

Also at Section de Physique, Université de Genève, Geneva, Switzerland.

Also at International School for Advanced Studies (SISSA), Trieste, Italy.

Also at Department of Physics and Astronomy, University of South Carolina, Columbia, SC, United States of America.

Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.

Also at Faculty of Physics, M.V. Lomonosov Moscow State University, Moscow, Russia.

Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia.

Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary.

Also at Department of Physics, Oxford University, Oxford, United Kingdom.

Also at Department of Physics, Nanjing University, Jiangsu, China.

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

Also at Department of Physics, The University of Michigan, Ann Arbor, MI, United States of America.

Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa.

Also at University of Malaya, Department of Physics, Kuala Lumpur, Malaysia.

Deceased.