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DOI
10.1103/PhysRevLett.113.171801

Publication date
2014

Document Version
Final published version

Published in
Physical Review Letters

Citation for published version (APA):
https://doi.org/10.1103/PhysRevLett.113.171801

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Search for Scalar Diphoton Resonances in the Mass Range 65–600 GeV with the ATLAS Detector in pp Collision Data at $\sqrt{s} = 8$ TeV

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(Received 25 July 2014; published 20 October 2014)

A search for scalar particles decaying via narrow resonances into two photons in the mass range 65–600 GeV is performed using 20.3 fb$^{-1}$ of $\sqrt{s} = 8$ TeV pp collision data collected with the ATLAS detector at the Large Hadron Collider. The recently discovered Higgs boson is treated as a background. No significant evidence for an additional signal is observed. The results are presented as limits at the 95% confidence level on the production cross section times branching ratio into two photons, in a fiducial volume where the reconstruction efficiency is approximately independent of the event topology. The upper limits set extend over a considerably wider mass range than previous searches.

In July 2012, the ATLAS and CMS collaborations reported the discovery of a new particle [1,2] whose measured couplings and properties are compatible with the standard model Higgs boson (H) [3–6]. However, several extensions to the standard model—in particular, models featuring an extended Higgs sector [7–13]—predict new scalar resonances below or above the H mass which may be narrow when their branching ratio to two photons is non-negligible.

This Letter presents a search for a scalar particle X of mass $m_X$ decaying via narrow resonances into two photons. It extends the method developed for the measurement of the H couplings in the $H \to \gamma\gamma$ channel [3] to the range 65 $< m_X < 600$ GeV. Analytical descriptions of the signal and background distributions are fitted to the measured diphoton invariant mass spectrum $m_{\gamma\gamma}$ to determine the signal and background yields. The result is presented as a limit on the production cross section times the branching ratio $BR(X \to \gamma\gamma)$, restricted to a fiducial volume where the reconstruction efficiency is approximately independent of the event topology. The resonance with mass $m_X$ is considered narrow when its intrinsic width is smaller than 0.09 GeV + 0.01$m_X$. This upper limit is defined such that the bias in the number of fitted signal events is kept below 10%. This ensures that the diphoton invariant mass width is dominated by the experimental resolution in the ATLAS detector. Model-dependent interference effects between the resonance and the continuum diphoton background are not considered.

The ATLAS detector [14] at the LHC [15] covers the pseudorapidity [16] range $|\eta| < 4.9$ and the full azimuthal angle $\phi$. It consists of an inner tracking detector covering the pseudorapidity range $|\eta| < 2.5$, surrounded by electromagnetic and hadronic calorimeters and an external muon spectrometer.

The search is carried out using the $\sqrt{s} = 8$ TeV pp collision data set collected in 2012, with stable beam conditions and all ATLAS subsystems operational, which corresponds to an integrated luminosity of $L = 20.3 \pm 0.6$ fb$^{-1}$ [17]. The data were recorded using a diphoton trigger that required two electromagnetic clusters with transverse energies $E_T$ above 20 GeV, both fulfilling identification criteria based on shower shapes in the electromagnetic calorimeter. The efficiency of the diphoton trigger [18] is (98.7 ± 0.5)% for signal events passing the analysis selection.

The event selection requires at least one reconstructed primary vertex with two or more tracks with transverse momenta $p_T > 0.4$ GeV, and at least two photon candidates with $E_T > 22$ GeV and $|\eta| < 2.37$, excluding the barrel and end cap transition region of the calorimeter, $1.37 < |\eta| < 1.56$.

Photon reconstruction is seeded by clusters of electromagnetic calorimeter cells. Clusters without matching tracks are classified as unconverted photons. Clusters with matched tracks are considered as electron candidates but are classified as converted photons if they are associated with two tracks consistent with a $\gamma \to e^+e^-$ conversion process, or a single track leaving no hit in the innermost layer of the inner tracking detector. The photon energy calibration procedure is the same as in Ref. [3].

Photon candidates are required to fulfill identification criteria based on shower shapes in the electromagnetic calorimeter, and on energy leakage into the hadronic calorimeter [19]. Identification efficiencies, averaged over $\eta$, range from 70% to above 99% for the $E_T$ range under consideration. To further reduce the background from jets, the calorimeter isolation transverse energy $E_T^{iso}$ is required.
to be smaller than 6 GeV, where $E_T^{\text{iso}}$ is defined as the sum of transverse energies of the positive-energy topological clusters [20] within a cone of size $\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2} = 0.4$ around the photon candidate. The core of the photon shower is excluded, and $E_T^{\text{iso}}$ is corrected for the leakage of the photon shower into the isolation cone. The contributions from the underlying event and pileup are subtracted using the technique proposed in Ref. [21] and implemented as described in Ref. [22]. In addition, the background with dominantly photon (primary vertex tracks with track isolation subtracted using the technique proposed in Ref. [21] and the contributions from the underlying event and pileup are for the leakage of the photon shower into the isolation cone. The contributions from the underlying event and pileup are subtracted using the technique proposed in Ref. [21] and implemented as described in Ref. [22]. In addition, the track isolation—defined as the scalar sum of the $p_T$ of the primary vertex tracks with $p_T > 1 \text{ GeV}$ in a $\Delta R = 0.2$ cone around the photon candidate, excluding the conversion tracks—is required to be smaller than 2.6 GeV.

The $m_{\gamma\gamma}$ invariant mass is evaluated using the leading photon ($\gamma_1$) and subleading photon ($\gamma_2$) energies measured in the calorimeter, the azimuthal angle $\Delta \phi$ and the pseudorapidity $\Delta \eta$ separations between the photons determined from their positions in the calorimeter, and the position of the reconstructed diphoton vertex [3].

After selection, the data sample consists of a continuum background with dominantly $\gamma\gamma$, $\gamma\gamma$-jet, and jet-jet events and Drell–Yan (DY) production of electron pairs where both electrons are misidentified as photons. Two peaking backgrounds arise from the Z boson component of the DY and from $H \rightarrow \gamma\gamma$.

To increase the sensitivity, the search is split into two analyses: a categorized low-mass analysis covering the range $65 < m_X < 110 \text{ GeV}$ and an inclusive high-mass analysis covering $110 < m_X < 600 \text{ GeV}$. To provide sidebands on both sides of the tested mass point $m_X$, the $m_{\gamma\gamma}$ ranges are wider than the $m_X$ ranges probed and overlap at the transition between the two analyses.

The low-mass analysis requires a precise modeling of the DY background, dominated by the Z boson resonance, where both electrons are misidentified as photons, mostly classified as converted photons. The loss of signal sensitivity is mitigated by separating the events into three categories with different signal-to-background ratios, according to the conversion status of the photon pair: two unconverted (UU), one converted and one unconverted (CU), or two converted (CC) photons. Table I shows the fractions of signal and DY events expected in each category.

<table>
<thead>
<tr>
<th>$\gamma\gamma$ category</th>
<th>UU</th>
<th>CU</th>
<th>CC</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{data}}$</td>
<td>272184</td>
<td>253804</td>
<td>63224</td>
</tr>
<tr>
<td>$N_{\text{DY}}$</td>
<td>$1080 \pm 260$</td>
<td>$3400 \pm 600$</td>
<td>$2700 \pm 250$</td>
</tr>
<tr>
<td>$f_{\text{DY}}$</td>
<td>15.0%</td>
<td>47.3%</td>
<td>37.7%</td>
</tr>
<tr>
<td>$f_X$</td>
<td>48.7%</td>
<td>42.5%</td>
<td>8.8%</td>
</tr>
</tbody>
</table>

In each category, the Z resonance shape is described by a double-sided Crystal Ball function [23]. Because of the limited size of the fully simulated $Z \rightarrow ee$ sample [25,26] where both electrons are misidentified as photons, the shape parameters are determined by a fit to a dielectron data sample, where both electrons are required to fulfill shower shape identification criteria and the same $E_T$ thresholds as the photons.

Since most of the electrons misidentified as photons underwent large bremsstrahlung, the invariant mass distribution of the Z boson reconstructed as a photon pair is wider and shifted to lower masses by up to 2 GeV with respect to the Z boson mass reconstructed as an electron pair. The $Z \rightarrow ee$ invariant mass distributions extracted from data in each category are transformed by applying $E_T$-dependent shifts and smearing factors to the electron $E_T$ and $\phi$, to match the kinematics of the electrons misidentified as photons. Two sets of transformations are derived for $\gamma_1$ and $\gamma_2$ depending on their conversion status, using a $Z \rightarrow ee$ sample generated with POWHEG [27,28], interfaced with PYTHIA8 [29] for showering and hadronization. Figure 1 illustrates the effect of the electrons’ transformations on the invariant mass shapes in the fully simulated $Z \rightarrow ee$ sample. Systematic uncertainties on the template shapes and the Z peak position are evaluated by varying the parameters of the electrons’ transformations by $\pm 1\sigma$.

The DY normalization is computed from the $e \rightarrow \gamma$ fake rates, defined as the ratios of $e\gamma$ to $ee$ pairs measured in $Z \rightarrow ee$ data, separately for $\gamma_1$ and $\gamma_2$ and each conversion status. A correction factor obtained from fully simulated $Z \rightarrow ee$ events is applied to account for additional effects, mainly the differences in isolation efficiencies and vertex reconstruction efficiency between $\gamma\gamma$ and $ee$ events. The associated uncertainties (9% to 25%) are dominated by the uncertainties on the isolation efficiencies.
The determination of the analytical form of the continuum background and the corresponding uncertainties follow the method detailed in Ref. [1]. The sum of a Landau distribution and an exponential distribution is used over the full $m_{\gamma\gamma}$ range. The bias on the signal yield induced by the analytical shape function is required to be lower than 20% of the statistical uncertainty on the fitted signal yield for the background-only spectrum. This bias is measured from a large sample generated from a parametrized detector material description.

The systematic uncertainty on the background is accounted for by a mass-dependent conversion uncertainty. Figure 2 shows background-only fits to the response and is accounted for by a mass-dependent bias on the signal yield induced by the choice of ggF samples [3]. The systematic uncertainty on the signal yield due to the photon energy resolution uncertainty ranges from 10% to 40% as a function of $m_{\gamma\gamma}$.

The systematic uncertainty on the signal shape parameters as a function of $m_{\gamma\gamma}$ is also modeled with a double-sided Crystal Ball function and normalized for the signal-to-background ratio.
where \( N_{\text{data}} \) is the number of fitted signal events in data, \( N_{\text{MC}}^{\text{reco}} \) the number of simulated signal events passing the selection criteria and \( N_{\text{MC}}^{\text{fid}} \) the number of simulated signal events generated within the fiducial volume. The fiducial volume, defined from geometrical and kinematical constraints at the generated particle level, is optimized to reduce the model dependence of \( C_X \) using fully simulated samples of the five \( X \) production modes to cover a large variety of topologies. The photon selection at generation level is similar to the selection applied to the data: two photons with \( E_T > 22 \) GeV and \( |\eta| < 2 \) are required; for \( m_X \) greater than 110 GeV, the relative cuts \( E_T^{\gamma_1}/m_{\gamma\gamma} > 0.4 \) and \( E_T^{\gamma_2}/m_{\gamma\gamma} > 0.3 \) are imposed. The particle isolation, defined as the scalar sum of \( p_T \) of all the stable particles (except neutrinos) found within a \( \Delta R = 0.4 \) cone around the photon direction, is required to be less than 12 GeV. The \( C_X \) factor is parametrized from the ggF(\( X \)) samples and ranges from 0.56 to 0.71 as a function of \( m_X \). Systematic uncertainties include the maximum difference between the

\[ C_X \]

de the five production modes, the effect of the underlying event (U.E.) and pileup.

The statistical analysis of the data uses unbinned maximum likelihood fits. The DY and \( H \) shapes and normalizations are allowed to float within the uncertainties. In the low-mass analysis, a simultaneous fit to the three conversion categories is performed. Only two excesses with 2.1 \( \sigma \) and 2.2 \( \sigma \) local significances above the background are observed over the full mass range 65–600 GeV, for \( m_X = 201 \) GeV and \( m_X = 530 \) GeV, respectively. This corresponds to a deviation of less than 0.5 \( \sigma \) from the background-only hypothesis. Consequently, a 95% limit on \( \sigma_{\text{fid}} \cdot \text{BR}(X \rightarrow \gamma\gamma) \) is computed using the procedure of Ref. [1]. The systematic uncertainties listed in Table II are accounted for by nuisance parameters in the likelihood function. In the low-mass analysis, the dominant uncertainties are the DY normalization and the residual topology dependence of \( C_X \). In the high-mass analysis, the largest uncertainties arise from the energy resolution and the

\[ \text{TABLE II. Summary of the systematic uncertainties.} \]

<table>
<thead>
<tr>
<th>Signal and Higgs boson yield</th>
<th>Z component of Drell–Yan</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Luminosity</strong></td>
<td>2.8%</td>
</tr>
<tr>
<td><strong>Trigger</strong></td>
<td>0.5%</td>
</tr>
<tr>
<td>( \gamma ) identification(^a)</td>
<td>1.6%–2.7%</td>
</tr>
<tr>
<td>( \gamma ) isolation(^a)</td>
<td>1%–6%</td>
</tr>
<tr>
<td>Energy resolution(^a)</td>
<td>10%–40%</td>
</tr>
<tr>
<td><strong>Signal and Higgs boson peak position</strong></td>
<td>0.6%</td>
</tr>
<tr>
<td><strong>Energy scale</strong></td>
<td></td>
</tr>
<tr>
<td>Continuum ( \gamma\gamma, \gamma j, jj, DY )</td>
<td>1–67 events</td>
</tr>
<tr>
<td><strong>Signal bias(^a)</strong></td>
<td></td>
</tr>
</tbody>
</table>

\(^a\)Mass dependent.

\(^b\)Category dependent.

\(^c\)Factorization scale plus parton density function uncertainties [34].

![Figure 4](image-url) FIG. 4 (color online). Observed and expected 95% C.L. limit on the fiducial cross section times branching ratio \( \text{BR}(X \rightarrow \gamma\gamma) \) as a function of \( m_X \) in the range 65 < \( m_X \) < 600 GeV. The discontinuity in the limit at \( m_X = 110 \) GeV (vertical dashed line) is due to the transition between the low-mass and high-mass analyses. The green and yellow bands show the \( \pm 1\sigma \) and \( \pm 2\sigma \) uncertainties on the expected limit. The inset shows a zoom around the transition point.
theoretical uncertainty on the production rate of the standard model Higgs boson around 126 GeV.

The observed and expected limits, shown in Fig. 4, are in good agreement, consistent with the absence of a signal. The limits on $\sigma_{\text{fid}} BR(X \rightarrow \gamma\gamma)$ for an additional scalar resonance range from 90 fb for $m_X = 65$ GeV to 1 fb for $m_X = 600$ GeV. These results extend over a considerably wider mass range than the previous searches by the ATLAS and CMS collaborations [1,35], are complementary to spin-2 particles searches [36,37], and are the first such limits independent of the event topology.

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; BMWF 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; DNRF, DNSRC, and Lundbeck Foundation, Denmark; EPLANET, ERC, and NSRF, European Union; IN2P3-CNRS and CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, 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; CNRST, 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; AARS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SES, SNSF, and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society, and Leverhulme Trust, United Kingdom; DOE and NSF, U.S. 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, and Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (United Kingdom) and BNL (U.S.), and in the Tier-2 facilities worldwide.

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[16] 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 line. The x axis points from the IP to the center of the LHC ring, and the y axis points upward. Cylindrical coordinates (r, $\phi$) are used in the transverse plane, with $\phi$ being the azimuthal angle around the beam line. Observables labeled transverse are projected into the x-y plane. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln\tan(\theta/2)$.
[23] A double-sided Crystal Ball function is composed of a Gaussian distribution at the core, connected with two power-law distributions describing the lower and upper tails [24].
[31] Differences between this choice of reference mass and the new mass measurements [32,33] are covered by the energy scale uncertainties listed in Table II.
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