Search for pairs of highly collimated groupings of photons at 13 TeV with the ATLAS detector

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A search for a new scalar particle decaying to a pair of photon-jets—collimated groupings of photons—is performed with the ATLAS detector at the Large Hadron Collider. The dataset of pp collisions at a centre-of-mass energy of 13 TeV was collected in 2015 and 2016, corresponding to an integrated luminosity of 36.7 fb^{-1}. Photon-jets arise when a high-mass scalar particle decays into a pair of light particles, which consecutively decay to photons. When these light particles are highly boosted, their decay to photons lead to photon-jets. Candidate events with a pair of photon-jets are searched for in events containing two reconstructed photons with high transverse energy. No statistically significant excess of events from the background expectation is observed. The results are interpreted in the scenario of a scalar particle with a narrow width (X) decaying into a pair of spin-0 particles (a). Upper limits are placed on the product of the cross-section and branching ratios $\sigma \times \mathscr{B}(X \to aa) \times \mathscr{B}(a \to \gamma\gamma)^2$ and $\sigma \times \mathscr{B}(X \to aa) \times \mathscr{B}(a \to 3\pi^0)^2$ for the ranges $200\,\text{GeV} < m_X < 2\,\text{TeV}$ and $m_a < 0.01 \times m_X$.

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1. Introduction

Several possible extensions of the Standard Model (SM) predict new resonances decaying to final states with only photons. In certain scenarios, the decay of a high-mass scalar particle leads to groupings of highly collimated photons ("photon-jets" [1, 2]) , which appear as single energy clusters in the electromagnetic (EM) calorimeter. When a high-mass scalar particle decays to a pair of light particles, these light particles are highly boosted. When the pair of these boosted light particles consecutively decay to photons, they lead to a pair of photon-jets.

A search for a new resonance decaying to a pair of photon-jets is performed using the *pp* collision data collected by the ATLAS detector [3] at the Large Hadron Collider (LHC). The dataset collected under normal data-taking conditions during 2015 and 2016 at a centre-of-mass energy of 13 TeV and corresponds to an integrated luminosity of 36.7 fb^{-1} (after applying data-quality requirements), is used.

The results are interpreted in the benchmark signal scenario of a scalar particle (X) with a narrow width and the mass $m_X > 200$ GeV decaying into a pair of light particles with spin-0 (a), as shown in Figure 1. The particle X is considered to be produced by the gluon-gluon fusion process. Two decay modes of the particle a are considered: $a \to \gamma\gamma$, which leads to $X \to aa \to 4\gamma$, and $a \to 3\pi^0 \to 6\gamma$, which leads to $X \to aa \to 6\pi^0 \to 12\gamma$. Both of these decays lead to a pair of photon-jets if the mass difference between X and a is large. In general, several decay modes of a leading to photons can be considered, but here the discussion is restricted to the two decay modes above, which yield a pair of photon-jets with either low or high multiplicity of photons.

Figure 1: Diagrams of the benchmark signal scenario which results in a pair of photon-jets.

For the decay $X \to aa \to 4\gamma$, the angular separation of the two photons consisting a photon-jet, $\Delta R_{\gamma\gamma} = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, is inversely proportional to the Lorentz factor of the particle a, $\gamma_a = E_a/m_a$ (where E_a is the energy of the a). When the particle X is produced nearly at rest, because the distribution of E_a has a central value of $E_a \sim m_X/2$, the value of $\Delta R_{\gamma\gamma}$ can be approximated as $\Delta R_{\gamma\gamma} \sim 4 \times m_a/m_X$. Similarly for the decay $X \to aa \to 6\pi^0$, the angular spread of photons consisting a photon-jet is roughly proportional to the ratio m_a/m_X. A larger value of $\Delta R_{\gamma\gamma}$ leads to a wider energy cluster in the EM calorimeter, which does not fulfill the analysis selection requirements described in Section 2. Thus, this search has limited sensitivity to such signal events. Based on the evaluation of the sensitivity using the simulated samples of signal events, the search is found to be sensitive to the region $m_a < 0.01 \times m_X$, in which the particle a is highly boosted.

2. Analysis procedure

The analysis is based on events containing two reconstructed photons (denoted "γ_R") with high transverse energy E_T. In the case of a signal event, a pair of reconstructed photons corresponds to

a pair of photon-jets. Therefore, signal events will form a resonance in the spectra of the mass of two leading reconstructed photons $m_{\gamma_R \gamma_R}$. The collision data were collected using an unprescaled trigger which filters events with two energy deposits in the EM calorimeter that satisfy trigger-level loose photon selection requirements. The leading and the subleading reconstructed photons are required to fulfill $E_{T,1}/m_{\gamma_R \gamma_R} > 0.4$ and $E_{T,2}/m_{\gamma_R \gamma_R} > 0.3$, respectively. The reconstructed photons are required to be isolated from other calorimeter energy deposits and nearby tracks which are not associated with the reconstructed photon. The two leading reconstructed photons are required to fulfill a photon selection criterion based on the shower shape in the EM calorimeter. This criterion (denoted "Loose$'$") is defined to be looser than the standard criterion used for the photon selection in ATLAS, and it is optimized to increase sensitivity to photon-jet signals.

The signal region is divided into two orthogonal event categories, defined using the shower shape in the EM calorimeter. The first layer of the EM calorimeter is finely segmented in the η direction, with a typical strip cell width of 0.003 in η for $|\eta| < 1.4$ and $1.5 < |\eta| < 2.4$, and a wider width in the other η regions. The shower shape variable ΔE utilizes this fine segmentation of the strip cells, and it is defined as the relative size of the energy deposit in the strip cell with the second largest energy, as shown in Figure 2. Because a photon-jet consists of two or more photons, it leads to a reconstructed photon with a large value of ΔE. On the other hand, the non-resonant $\gamma\gamma$ events, which are the largest background source in the signal region, result in pairs of reconstructed photons with small values of ΔE. Thus, this categorization increases the sensitivity to photon-jet signal events. The events containing two leading reconstructed photons with small values of ΔE are categorized in the low-ΔE category, and other events are categorized in the high-ΔE category. The threshold of ΔE used for the categorization ranges between 100 and 500 MeV, depending on the $|\eta|$ of the reconstructed photon and whether it has an associated conversion vertex or not.
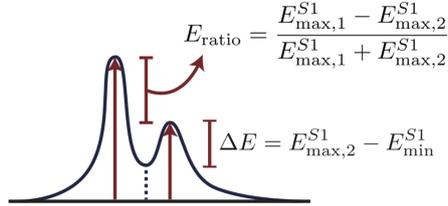
$$E_{\text{ratio}} = \frac{E^{S1}_{\text{max},1} - E^{S1}_{\text{max},2}}{E^{S1}_{\text{max},1} + E^{S1}_{\text{max},2}}$$

$$\Delta E = E^{S1}_{\text{max},2} - E^{S1}_{\text{min}}$$

Figure 2: A schematic diagram illustrating the definition of the EM calorimeter shower shape variable ΔE. The energy deposit of the shower in the first layer of the EM calorimeter is displayed, with the horizontal direction representing the position of the strip cell in the η direction, and the vertical direction representing the energy deposit in each strip cell.

To evaluate the compatibility of the observed $m_{\gamma_R \gamma_R}$ spectra with the background expectation, an unbinned maximum likelihood fit considering both the signal and background components is performed for the two event categories simultaneously. For the probability density function (PDF) of the signal component, the double-sided Crystal Ball (DSCB) function is used, which is defined as a Gaussian function with both the lower and higher end of the function connected to power-law tails. The shape of the DSCB functions are taken from the simulated samples of the signal events. The ratio of the normalizations of the two DSCBs, one for each of the two event categories, is fixed based on the value evaluated using simulated samples of signal events. This ratio depends strongly

on the value of m_a/m_X.

The main sources of the background in the signal region are non-resonant $\gamma\gamma$, γj, and jj events, where j denotes a hadronic jet. The background component is evaluated in a fully data-driven way, inclusively for all the background sources, by using a PDF with free parameters. This PDF is defined as the following:

$$g_i(x; a_i, b_i, c_i) = N_i \left(1 - x^{\frac{1}{2}} \right)^{a_i} x^{b_i + c_i \log x} \tag{2.1}$$

The variable x is defined as $x = m_{\gamma_R \gamma_R}/\sqrt{s}$. The parameters a_i, b_i, and c_i are free parameters, N_i is the normalization factor, and $i = 1, 2$ denotes each of the two event categories. The validation of this PDF is performed by evaluating the agreement between Eq. 2.1 and the background expectation, which is derived by combining simulated samples for $\gamma\gamma$ events and control samples of the collision data for γj and jj events. The small deviation observed in this closure test is taken as the systematic uncertainty of this background modeling method.

3. Results

The observed spectra of $m_{\gamma_R \gamma_R}$ in the two event categories are shown in Figure 3. No statistically significant excess of events from the background expectation is observed. The 95% confidence level observed and expected upper limits on the product of the production cross-section of the particle X via gluon-gluon fusion process and the branching ratios are shown in Figure 4 as a function of m_X and for different values of m_a. These upper limits are calculated using the CL_s method and the asymptotic approximation. The asymptotic approximation leads to an underestimate of the limits for mass regions with a small number of observed events, especially for $m_X > 1$ TeV and $m_a/m_X > 0.002$.

4. Conclusion

A search for a new scalar resonance with narrow width decaying to a pair of photon-jets is performed with the ATLAS detector at the LHC, using a dataset of pp collision at a centre-of-mass energy of 13 TeV corresponding to an integrated luminosity of 36.7 fb^{-1}. No statistically significant excess of events from the background expectation is observed, and upper limits are placed on the product of cross-section and the branching ratios of the benchmark signal scenario.

Acknowledgments

References

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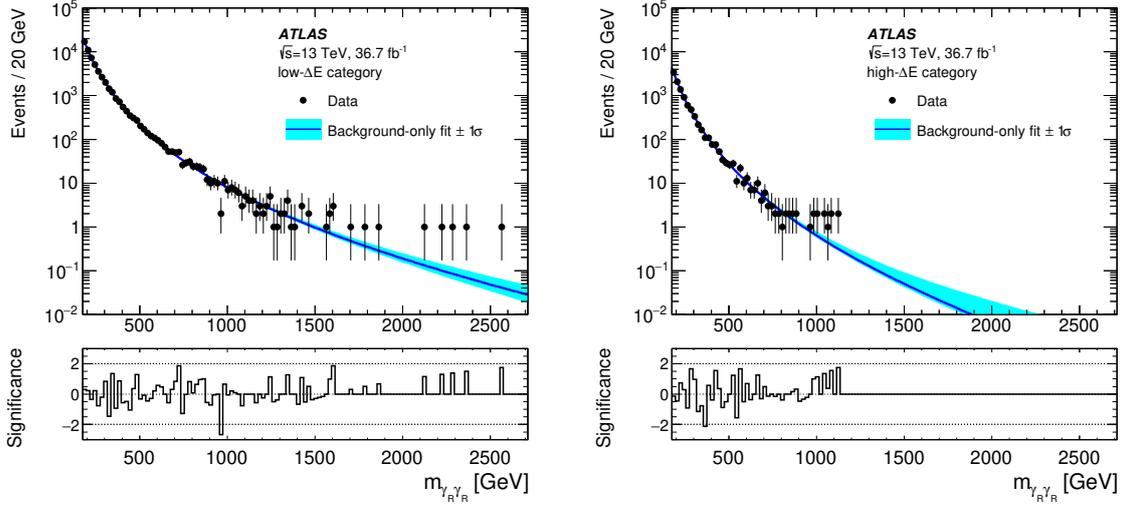
Figure 3: The observed distributions of the mass of the two reconstructed photons $m_{\gamma_R \gamma_R}$ in the two events categories of the signal region. The shaded bands around the fit result show the $\pm 1\sigma$ uncertainty originating from the uncertainties in the values of the fit function parameters. The lower panels show the significance associated with the observed event yield in each bin, calculated without the consideration of the systematic uncertainties. This calculation assumes that the event yield in each bin is Poisson-distributed with a mean given by the background-only fit [4].
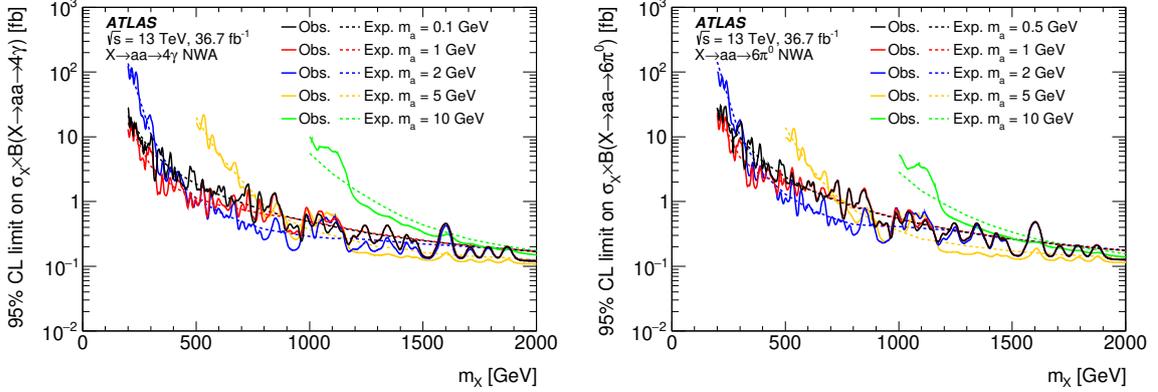

Figure 4: The observed and expected upper limits on the production times the branching ratios, $\sigma \times \mathscr{B}(X \to aa) \times \mathscr{B}(a \to \gamma\gamma)^2$ and $\sigma \times \mathscr{B}(X \to aa) \times \mathscr{B}(a \to 3\pi^0)^2$. The limits for $m_a = 5$ GeV and 10 GeV do not cover the m_X range as large as the other m_a values, because the region of interest of this analysis is limited to $m_a < 0.01 \times m_X$ [4].

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

[4] ATLAS Collaboration, *A search for pairs of highly collimated photon-jets in pp collisions at* $\sqrt{s} = 13$ TeV *with the ATLAS detector*, submitted to Phys. Rev. D, [hep-ex/1808.10515].