A search for pairs of highly collimated photon-jets in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector


Published in:
Physical Review D. Particles, Fields, Gravitation, and Cosmology

DOI:
10.1103/PhysRevD.99.012008

Link to publication

License
CC BY

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: https://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

UvA-DARE is a service provided by the library of the University of Amsterdam (http://dare.uva.nl)

Download date: 08 Feb 2021
Search for pairs of highly collimated photon-jets in $pp$ collisions at $\sqrt{s}=13$ TeV with the ATLAS detector

M. Aaboud et al.*, (ATLAS Collaboration)

(Received 3 September 2018; published 18 January 2019)

Results of a search for the pair production of photon-jets—collimated groupings of photons—in the ATLAS detector at the Large Hadron Collider are reported. Highly collimated photon-jets can arise from the decay of new, highly boosted particles that can decay to multiple photons collimated enough to be identified in the electromagnetic calorimeter as a single, photonlike energy cluster. Data from proton-proton collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 36.7 fb$^{-1}$, were collected in 2015 and 2016. Candidate photon-jet pair production events are selected from those containing two reconstructed photons using a set of identification criteria much less stringent than that typically used for the selection of photons, with additional criteria applied to provide improved sensitivity to photon-jets. Narrow excesses in the reconstructed diphoton mass spectra are searched for. The observed mass spectra are consistent with the Standard Model background expectation. The results are interpreted in the context of a model containing a new, high-mass scalar particle with narrow width, $X$, that decays into pairs of photon-jets via new, light particles, $a$. Upper limits are placed on the cross section times branching ratios $\sigma \times B(X \to aa) \times B(a \to \gamma\gamma)$ for 200 GeV $< m_X < 2$ TeV and for ranges of $m_a$ from a lower mass of 100 MeV up to between 2 and 10 GeV, depending upon $m_X$. Upper limits are also placed on $\sigma \times B(X \to aa) \times B(a \to 3\gamma)$ for the same range of $m_X$ and for ranges of $m_a$ from a lower mass of 500 MeV up to between 2 and 10 GeV.

DOI: 10.1103/PhysRevD.99.012008

I. INTRODUCTION

The quest for new particles at the Large Hadron Collider (LHC) at CERN has been greatly rewarded by closely examining collision events that contain photons in the final state. Despite the relatively small branching ratio predicted for the process in the Standard Model (SM), the decay of the Higgs boson into two photons is readily identifiable due to the good energy resolution of the electromagnetic (EM) calorimeters of the ATLAS [1] and CMS [2] detectors and the relatively small backgrounds in final states with only photons. The search for this process was one of the main methods by which the Higgs boson was observed [3,4]. Moreover, the establishment of a wide range of results that so far are consistent with the SM at the LHC at a center-of-mass energy of 13 TeV motivates a renewed focus on searches for new physics that target general experimental signatures, including nonstandard photon signatures, rather than specific signal models. In many beyond the Standard Model (BSM) theories [5–13], new scalar, pseudoscalar, or vector gauge bosons can decay into photon-only final states that lead to collimated groupings of photons (“photon-jets” [14,15]). In some cases, the Lorentz boost of the new particles is large enough to lead to an opening angle between the trajectories of the final-state photons that is smaller than or comparable to the angular size of an energy cluster in the EM calorimeter corresponding to a single photon, resulting in highly collimated photon-jets. Such boosted particles arise, for example, when a high-mass particle produced in the proton-proton collision decays into intermediate particles, with much lower masses, that subsequently decay into photons. Thus, events selected to contain two, well-separated, reconstructed photons can be used to search for pairs of highly collimated photon-jets resulting from BSM particle decays.

A search for highly collimated photon-jets using 36.7 fb$^{-1}$ of LHC proton-proton collision data collected by the ATLAS detector in 2015 and 2016 at a center-of-mass energy of 13 TeV is presented. Candidate photon-jet pair production events are selected from those containing two reconstructed photons (denoted “$\gamma R$”), using a set of identification criteria much less stringent than that typically...
used for the selection of photons, and with additional criteria applied to provide improved sensitivity to photon-jets. Narrow excesses are searched for in the spectra of the reconstructed diphoton mass $m_{\gamma\gamma}^\text{peak}$.

The results of the search are interpreted in the context of a benchmark BSM scenario involving a high-mass, narrow-width scalar particle, $X$, with mass $m_X > 200$ GeV, originating from the gluon-gluon fusion process and that can decay into a pair of intermediate particles with spin $0$, $a$, as shown in Fig. 1. The $a$ particle can in general decay to several final states, but here is restricted to decay either into a pair of photons, via $X \rightarrow aa \rightarrow 4\gamma$, or into three neutral pions, via $X \rightarrow aa \rightarrow 6\pi^0 \rightarrow 12\gamma$, yielding events containing a pair of photon-jets of either low or high multiplicity; the result is interpreted for both cases. Because the search is performed using events that contain two calorimeter deposits that are initially loosely identified as individual photons, the search is sensitive to the parameter region in which the $a$ particle is highly boosted, $m_a < 0.01 \times m_X$.

II. ATLAS DETECTOR

The ATLAS detector [1] is a multipurpose detector with a forward-backward symmetric cylindrical geometry. The detector covers nearly the entire solid angle around the collision point. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, EM and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting toroid magnets.

The inner-detector system is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range $|\eta| < 2.5$. The high-granularity silicon pixel detector covers the vertex region. The innermost layer of the pixel detector, the insertable B-layer [16], was installed between Run 1 and Run 2 of the LHC. The pixel detector typically provides four measurements per track. It is followed by the silicon microstrip tracker that normally provides four two-dimensional measurement points per track. These silicon detectors are complemented by the transition radiation tracker, which enables radially extended track reconstruction up to $|\eta| = 2.0$. The transition radiation tracker 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 a high-granularity lead/liquid-argon (LAr) EM calorimeter. The EM calorimeter is divided into a barrel section covering $|\eta| < 1.475$ and two end cap sections covering $1.375 < |\eta| < 3.2$. For $|\eta| < 2.5$, the EM calorimeter is composed of three sampling layers in the longitudinal direction of shower depth. The first layer is segmented into high-granularity strips in the $\eta$ direction, with a typical cell size of $\Delta\eta \times \Delta\phi = 0.003 \times 0.1$ for the ranges $|\eta| < 1.4$ and $1.5 < |\eta| < 2.4$, and a coarser cell size of $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ for other regions. This fine granularity in the $\eta$ direction allows identification of events with two overlapping showers originating from the decays of neutral hadrons in hadronic jets, mostly $\pi^0 \rightarrow \gamma\gamma$ decays. The second layer has a cell size of $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$. This layer collects most of the energy deposited in the calorimeter by photon and electron showers. The third layer is used to correct for energy leakage beyond the EM calorimeter from high-energy showers. The thicknesses of the first, second, and third layers at $\eta = 0$ are 4.3 radiation lengths ($X_0$), $16X_0$, and $2X_0$, respectively, and they vary with the pseudorapidity range [1]. Placed in front of these layers, an additional thin LAr presampler layer covering $|\eta| < 1.8$ is used to correct for energy loss in material upstream of the calorimeters. Hadronic calorimetry is provided by the steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$, and two copper/LAr hadronic endcap calorimeters. The solid angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules optimized for EM and hadronic measurements respectively.

A two-level trigger system, the first level implemented in custom hardware followed by a software-based level, is used to reduce the event rate to about 1 kHz for offline storage.
III. PHOTON-JET SIGNAL CHARACTERISTICS

Photon-jets, defined as collimated groupings of photons, can arise from decays of particles that are highly boosted as a result of themselves being the decay products of higher-mass particles. For the benchmark BSM scenario considered here, the extent to which photons from decays of a particle are collimated depends on the ratio of the masses of the X and a, particularly in the case where the X particle is produced with a momentum significantly less than its mass.

For large values of the ratio $m_a/m_X$, the boost of the a is small enough to yield more than two individual photons, well separated and isolated, that can be identified in the detector. In this regime, a general search for new phenomena in events with at least three isolated photons, using a three-photon trigger, was performed by ATLAS at 8 TeV [17]. This search was sensitive to cases where the angular separation between photons was large, for $\Delta R_{\gamma\gamma} \gtrsim 0.3$, which corresponds to $m_a/m_X \gtrsim 0.08$ for the benchmark signal scenario. For slightly smaller values of the ratio $m_a/m_X$, the individual final-state photons appear too close together in the detector and fail isolation criteria, limiting the sensitivity of the 8 TeV ATLAS search in this regime.

For very small values of the ratio $m_a/m_X$, the boost of the a is large enough to lead to angular separations between the final-state photons of $\Delta R_{\gamma\gamma} \lesssim 0.04$, which is approximately the same size as a standard single-photon energy cluster in the ATLAS EM calorimeter. In this case, existing triggers cannot distinguish a calorimeter energy deposit resulting from highly collimated photons from that of a single photon. Thus, diphotonlike events can be used as a starting point for a search for highly collimated photon-jets, and the sensitivity to this region of the photon-jet parameter space can be increased by placing criteria on the shape of the shower in the EM calorimeter in addition to those applied in the trigger. This analysis presents a search for highly collimated photon-jets that is sensitive to a wide mass range for the parent X particle, $m_X > 200$ GeV, and for $m_a/m_X < 0.01$ in the benchmark signal scenario.

For this benchmark scenario, for the process $X \to \gamma\gamma$ (after applying data-quality requirements), collected under normal data-taking conditions for $pp$ collisions during 2015 and 2016 at a center-of-mass energy of $\sqrt{s} = 13$ TeV. The data were selected using an unscaled trigger that filters events with two energy deposits in the EM calorimeter that satisfy trigger-level loose identification criteria with transverse energy values of $E_{T,1} > 35$ GeV and $E_{T,2} > 25$ GeV.

Samples of the benchmark signal scenario with two different final states, $X \to \gamma\gamma \to 4\gamma$ and $X \to \gamma\gamma \to 6\gamma$, were simulated. For the production of the X via gluon-gluon fusion, MadGraph5_AMC@NLO [18] Version 2.3.3, at next-to-leading order (NLO) in quantum chromodynamics (QCD) with the NNPDF30NLO parton distribution function (PDF) set [19], was used. For the subsequent decay of the X into $\gamma\gamma$ and into the photon-jet final states, Pythia 8 [20] Version 8.210, with the A14 set of tuned parameters [21], was used, as well as for the parton-shower

\[ \delta \gamma\gamma \Rightarrow \gamma\gamma \cdots \to \sum_{\gamma\gamma} \]

\[ \Delta R_{\gamma\gamma} \Rightarrow \gamma\gamma \gtrsim 0.04, \]

\[ m_a/m_X \gtrsim 0.08 \]

\[ m_a/m_X \lesssim 0.04 \]

\[ m_a/m_X \lesssim 0.01 \]

\[ m_X > 200 \text{ GeV} \]

\[ m_a/m_X < 0.01 \]

\[ E_{T,1} > 35 \text{ GeV} \]

\[ E_{T,2} > 25 \text{ GeV} \]

\[ m_a \gtrsim 4 \times m_X \]

\[ m_a \lesssim m_X \]

\[ m_a \lesssim 6 \gamma \]

\[ \delta \gamma\gamma \Rightarrow \gamma\gamma \cdots \to \sum_{\gamma\gamma} \]

\[ \Delta R_{\gamma\gamma} \Rightarrow \gamma\gamma \gtrsim 0.04, \]

\[ m_a/m_X \gtrsim 0.08 \]

\[ m_a/m_X \lesssim 0.04 \]

\[ m_a/m_X \lesssim 0.01 \]

\[ m_X > 200 \text{ GeV} \]

\[ m_a/m_X < 0.01 \]

\[ E_{T,1} > 35 \text{ GeV} \]

\[ E_{T,2} > 25 \text{ GeV} \]

\[ m_a \gtrsim 4 \times m_X \]

\[ m_a \lesssim m_X \]

\[ m_a \lesssim 6 \gamma \]

\[ \delta \gamma\gamma \Rightarrow \gamma\gamma \cdots \to \sum_{\gamma\gamma} \]

\[ \Delta R_{\gamma\gamma} \Rightarrow \gamma\gamma \gtrsim 0.04, \]

\[ m_a/m_X \gtrsim 0.08 \]

\[ m_a/m_X \lesssim 0.04 \]

\[ m_a/m_X \lesssim 0.01 \]

\[ m_X > 200 \text{ GeV} \]

\[ m_a/m_X < 0.01 \]

\[ E_{T,1} > 35 \text{ GeV} \]

\[ E_{T,2} > 25 \text{ GeV} \]

\[ m_a \gtrsim 4 \times m_X \]

\[ m_a \lesssim m_X \]

\[ m_a \lesssim 6 \gamma \]
and hadronization simulation of initial state radiation jets. The samples were produced using a narrow-width approximation (NWA) approach with the resonance widths of the $X$ and $a$ set to 4 and 1 MeV, respectively. Samples were simulated for mass ranges of $200 \text{ GeV} < m_X < 2000 \text{ GeV}$ and $0.1 \text{ GeV} < m_a < 0.01 \times m_X$.

The nonresonant production of diphoton events in the SM is the dominant background source for this analysis, and these events were simulated with Sherpa 2.1.1 [22]. Matrix elements were calculated with up to two additional partons at leading order (LO) in QCD and merged with the Sherpa parton-shower simulation [23] using the ME+PS@LO prescription [24]. The CT10 PDF set [25] was used in conjunction with a dedicated parton-shower tune of Sherpa. These samples are used to validate the background modeling based on analytic functions (described in Sec. VI B). Simulated samples of the reducible SM background consisting of one photon and one hadronic jet from the hard process were also generated with Sherpa 2.1.1 using the same PDF set, parton-shower tune, and merging prescription as for the diphoton sample—with matrix elements calculated at LO with up to four additional partons. These samples are used for optimizing the search strategy described in Sec. V.

Additional interactions in the same or nearby bunch crossings (pileup) were simulated using Pythia 8.1.86 [20] using the A2 set of tuned parameters [26] and the MSTW2008LO PDF [27] set and overlayed on the simulated signal and SM background events. All simulated event samples were produced using the ATLAS simulation infrastructure [28], using the full Geant 4 [29] simulation of the ATLAS detector. Simulated events were then reconstructed with the same software as used for the data.

V. OBJECT AND EVENT SELECTION

This analysis selects events containing at least two reconstructed photons, obtained from a diphoton trigger, and then searches for pair-produced photon-jets. This is accomplished by applying additional selection criteria and scanning for deviations from the expected background in the $m_{\gamma\gamma}$ spectrum, defined as the distribution of the mass values of the two reconstructed photons, which would correspond to the mass of the high-mass particle $m_X$ in the case of a signal event. No attempt is made to reconstruct the mass of the $a$ in the process $X \rightarrow aa \rightarrow \gamma\gamma$-jets (although specifics of the $a$ are taken into account in several parameters of the signal modeling, which is detailed in Sec. VI A).

A. Initial event selection with two loose photons

Reconstructed photons are obtained from clusters of energy deposited in the EM calorimeter [30]. In the barrel section a cluster size of $3 \times 7$ cells in the middle layer is used (equivalent to an area of size $\Delta \eta \times \Delta \phi = 0.075 \times 0.175$), while a cluster of $5 \times 5$ cells in the middle layer is used in the end cap sections (equivalent to an area of $\Delta \eta \times \Delta \phi = 0.125 \times 0.125$). Reconstructed photons are required to match photon objects calculated at the trigger level, within the separation of $\Delta R < 0.07$, and may have associated tracks and conversion vertices reconstructed in the inner detector.

The two leading reconstructed photons are required to be within the fiducial calorimeter region of $|\eta| < 2.37$, excluding the transition region at $1.37 < |\eta| < 1.52$ between the barrel and end cap calorimeters. The criterion $E_{T,1} > 0.4 \times m_{\gamma\gamma}$ is applied to the leading reconstructed photon, and $E_{T,2} > 0.3 \times m_{\gamma\gamma}$ to the subleading reconstructed photon. These criteria increase the sensitivity to photon-jet pairs from a scalar resonance, since such candidate signal events tend to contain photons with larger $E_{T}/m_{\gamma\gamma}$ ratios compared with those from background events dominated by $t$-channel processes [31]. Only events with $m_{\gamma\gamma} > 175 \text{ GeV}$ are selected for further analysis.

The two leading reconstructed photons are required to be isolated from other calorimeter energy deposits and from nearby tracks not associated with the photon. The calorimeter isolation variable $E_{T}^{iso}$ is defined as the sum of energy deposits in the calorimeter in a cone of size $\Delta R = 0.4$ around the barycenter of the photon cluster (excluding the energy associated with the photon cluster) minus $0.022 \times E_{T}$. This cone energy is corrected for the leakage of the photon energy from the photon cluster and for the effects of pileup [32]. The calorimeter isolation variable is required to satisfy $E_{T}^{iso} < 2.45 \text{ GeV}$. The track isolation variable $p_{T}^{iso}$ is defined as the scalar sum of the transverse momenta of tracks not associated with the photon in a cone of size $\Delta R = 0.2$ around the barycenter of the photon cluster. It is required to satisfy $p_{T}^{iso} < 0.05 \times E_{T}$.

B. Optimized photon selection for photon-jet signatures

Photon identification in ATLAS [30] is based on a set of requirements placed on several discriminating variables that characterize the shower development in the calorimeter (“shower shapes”), defined to reject the background from hadronic jets misidentified as photons. Nine discriminating variables are defined, and they are described in detail in Table 1 of Ref. [30]. One variable quantifies the shower leakage fraction in the hadronic calorimeter, and three variables quantify the lateral shower development in the EM calorimeter second layer. The other five variables quantify the lateral shower development in the finely segmented strips of the first layer, and two of them are utilized to identify photon candidates with two separate local energy maxima in the fine strips, which are characteristic of neutral hadron decays in hadronic jets, primarily from $a \rightarrow \gamma\gamma$.

Several reference selections are defined, including those referred to as “loose” and “tight.” The loose selection is based only on shower shapes in the second layer of the EM calorimeter and on the leakage in the hadronic calorimeter,
and is used by the photon triggers, including the diphoton trigger used for the collection of the data sample for this search. The tight selection is based on all nine variables and is used for the standard photon identification in ATLAS, but is not used in this search. The criteria for the tight selection change as a function of the $\eta$ values of the reconstructed photons, to account for the calorimeter geometry and effects from the material upstream of the calorimeter, and are separately optimized for reconstructed photons with and without an associated conversion vertex to increase the photon identification efficiency.

In this search, both reconstructed photons are required to fulfill the “loose” selection. This selection is defined by removing requirements on all five variables quantifying the shower development in the finely segmented strip layer of the calorimeter ($w_{\text{13}}$, $w_{\text{rot}}$, $F_{\text{side}}$, $\Delta E$, and $E_{\text{ratio}}$), defined in Table 1 of Ref. [30], with respect to the standard tight selection. The requirements on the other four variables ($R_{\text{had}}$, $R_{\eta}$, $w_{\gamma 2}$, and $R_{\phi}$) remain the same as for the standard tight selection. By definition, the loose selection between loose and tight. Based on simulated samples of signal and SM background processes, this loose selection provides good sensitivity to photon-jet signals. This is explained by the fact that energy clusters of photon-jets exhibit multiple local energy maxima in the fine strip layer, since the angular separation of photons constituting the photon-jet can be larger than the segmentation of the strips, depending on the mass parameters $m_X$ and $m_{\gamma}$ of the benchmark signal scenario, as seen in Fig. 2. For signal mass values $0.003 < m_{\gamma}/m_X < 0.006$ and $m_X > 200$ GeV, the total selection efficiency is less than 5% when the standard tight selection is applied, in addition to the selection criteria described in Sec. V A, and this increases to 20%-50% with the loose selection. Comparing the two selection criteria, an increase in the overall event yield of roughly 30% is observed with the loose selection. Thus, the analysis sensitivity to photon-jet signals is increased by the use of the loose selection, rather than the standard tight selection.

Additionally, the choice of loose selection allows the definition of a set of “not loose” criteria (i.e., where at least one of the two reconstructed photons fails the loose selection) that is used to define the control regions for the evaluation of the background composition, as described in Sec. VIB.

### C. Categorization of events by the shower shape variable $\Delta E$

After the preselection of events with two leading reconstructed photons satisfying the isolation and loose identification criteria described in the previous sections, the final signal region is defined by dividing the events into two orthogonal categories based on the value of the calorimeter variable $\Delta E$ for the reconstructed photons. The quantity $\Delta E$ corresponds to a shower shape variable based on information in the first layer of the EM calorimeter, and quantifies the relative size of multiple, individual energy deposits that may be contained within a single energy cluster.

It is defined as

$$\Delta E = E_{\text{2nd max}} - E_{\text{min}}$$

where $E_{\text{2nd max}}$ is the energy of the strip cell with the second-largest energy, and $E_{\text{min}}$ is the energy in the strip cell with the lowest energy located between the strips with the largest and the second-largest energy. If the strip cells with the largest and the second-largest energy are located next to each other, or if there is no second-largest energy strip, then $\Delta E = 0$. This variable is useful for identifying the $\pi^0 \rightarrow \gamma\gamma$ process, prevalent in hadronic jets, which leaves a characteristic signature in the first layer of the EM calorimeter that often yields two peaks in the $\eta$ direction, resulting in large $\Delta E$ values. When the photon-jet signals from decays such as $a \rightarrow \gamma\gamma$ and $a \rightarrow 3\pi^0 \rightarrow 6\gamma$ have angular separation of photons larger than the segmentation of the first layer of the EM calorimeter, they leave signatures in the calorimeter similar to $\pi^0 \rightarrow \gamma\gamma$ events. Thus, the variable $\Delta E$ is used to effectively select photon-jet signals.

The categorization by $\Delta E$ is as follows:

1. **Low-$\Delta E$ category**: both reconstructed photons are required to have values of $\Delta E$ below given thresholds. This requirement corresponds to reconstructed photons with a signature in the fine strip layer similar to that of single photons.
2. **High-$\Delta E$ category**: at least one of the two leading reconstructed photons is required to have a value of $\Delta E$ above a given threshold. This requirement corresponds to events containing reconstructed photons which have a $\pi^0$-like signature.

The thresholds for the value of $\Delta E$ used to determine whether an event appears in either the low- or high-$\Delta E$ category are the same as those used in the standard tight photon selection. These thresholds range from 100 to 500 MeV, depending on the photon $\eta$ and whether there are associated tracks or conversion vertices.

<table>
<thead>
<tr>
<th>$m_{\gamma\gamma}$ range</th>
<th>175–400 GeV</th>
<th>400–600 GeV</th>
<th>600–800 GeV</th>
<th>&gt;800 GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Low-$\Delta E$ category</strong></td>
<td>$5.3 \times 10^4$</td>
<td>$2.5 \times 10^3$</td>
<td>$5.2 \times 10^2$</td>
<td>$2.3 \times 10^2$</td>
</tr>
<tr>
<td><strong>High-$\Delta E$ category</strong></td>
<td>$9.8 \times 10^3$</td>
<td>$3.5 \times 10^2$</td>
<td>$5.2 \times 10^1$</td>
<td>$2.1 \times 10^1$</td>
</tr>
</tbody>
</table>

012008-5
The high-ΔE category is found to have a significantly better signal-to-background ratio compared with the low-ΔE category, since reconstructed photons with large ΔE values typically correspond to photon-jets with a larger angular spread among the constituent photons. The high-ΔE criterion also effectively reduces the contribution of single photons, which tend to have small ΔE values. Hadronic jets from SM processes containing $\pi^0 \rightarrow \gamma\gamma$ decays are likely to fall into the high-ΔE category, but the contribution of these events is small due to the isolation requirements. This leads to lower expected background event yields in the high-ΔE category, resulting in better signal-to-background ratios compared with the low-ΔE category. The number of events observed in each category for different ranges of $m_{\gamma\gamma}$ is shown in Table I. Although overall the ratio of signal-to-background is lower for the low-ΔE category, it still provides increased sensitivity to photon-jet signals with smaller angular separation, and so both categories are used in this search.

D. Summary of the selection

The overall efficiency, $e$, of selecting signal events after applying all criteria, including kinematic acceptance and excluding the categorization by ΔE, is shown in Fig. 3(a), and the fraction, $f$, of signal events that appear in the low-ΔE category is shown in Fig. 3(b), both as a function of $m_\gamma$ and $m_X$ for the decay $X \rightarrow aa \rightarrow 4\gamma$. The selection efficiency is low for small values of $m_X$ and large values of $m_\gamma$, and almost all events are in the low-ΔE category for large values of $m_X$ and small values of $m_\gamma$. For smaller $m_\gamma$ and larger $m_X$, $f$ increases because of the small angular spread of photons inside the photon-jet, which leads to a calorimeter signature similar to that of a single photon. Additionally, for larger $m_\gamma$ and smaller $m_X$, $f$ also increases because individual photons are reconstructed separately due to the large angular separation, resulting in events containing more than two reconstructed photons, each of which more resembles a single photon. The results for the decay $X \rightarrow aa \rightarrow 6\pi^0$ are similar to those of the decay $X \rightarrow aa \rightarrow 4\gamma$.

Table II displays the number of events in data that satisfy each selection criterion. The fraction of events with both of the two leading reconstructed photons found in $|\eta| < 1.37$ (i.e. the barrel section) is 59% (63%) for the low-ΔE (high-ΔE) category.

VI. SIGNAL AND BACKGROUND MODELING

The reconstructed signal mass shape is modeled with a double-sided Crystal Ball (DSCB) function. The backgrounds are determined by fitting functions to the observed mass spectra of two reconstructed photons, $m_{\gamma\gamma}$. 

![Graphs showing selection efficiency and fraction of events in the low-ΔE category for different $m_{\gamma\gamma}$ values.](image-url)
A. Signal modeling

The DSCB function has been shown to be effective in modeling new-particle resonances expected to have a Gaussian core surrounded by asymmetric and non-Gaussian low- and high-mass tails, and is described in detail elsewhere [31]. In this analysis the DSCB is a function of the mass of two reconstructed photons (photon-jets in simulated signal samples), with parameters to account for the peak position and width of the Gaussian part, as well as for the upper and lower tails where the resonance shape meets the smoothly falling two-photon mass background. For the benchmark signal scenario investigated here, since the reconstructed photons are photon-jets (e.g., $a \rightarrow \gamma\gamma$ and $a \rightarrow 3\pi^{0} \rightarrow 6\gamma$), the reconstructed $m_{\text{jet}^{a}}$ corresponds to the mass of two $a$ particles, i.e., the mass of the parent particle, $X$.

For the benchmark signal scenario, for very small values of $m_{a}/m_{X}$, the behavior of the DSCB as a function of the mass of two photon-jets is nearly identical to that of the BSM process $X \rightarrow 2\gamma$. The position of the fitted peak of the DSCB is slightly lower than the mass input to the generator. With the NWA approach, the width of the Gaussian core $\sigma_{\text{CB}}$ is dominated by detector resolution, and it increases linearly with $m_{X}$, from 2 GeV for $m_{X} = 200$ GeV to 14 GeV for $m_{X} = 2$ TeV. For larger values of $m_{a}/m_{X}$, the wider opening angle between the photons inside a photon-jet leads to a greater fraction of the energy of the shower leaking out of the window defined by the cells of the EM calorimeter to collect energy for the reconstruction of photons, leading to a further increase in the mass shift and width of the DSCB. For instance, for $m_{X} = 600$ GeV and $m_{a} = 5$ GeV, the width is $\sigma_{\text{CB}} = 8$ GeV for the process $X \rightarrow aa \rightarrow 4\gamma$, and $\sigma_{\text{CB}} = 9$ GeV for the process $X \rightarrow aa \rightarrow 6\pi^{0}$. For a given $m_{X}$ and $m_{a}$, the same signal mass shape modeling results are used for the analysis of the two orthogonal event categories (the low-$\Delta E$ category and the high-$\Delta E$ category), since only a small dependence of the signal mass distributions on $\Delta E$ is observed.

To validate the mass shape modeling results, injection tests are performed, where a fixed number of signal events are inserted into a pseudo-dataset reproducing a background-only $m_{\text{jet}^{a}}$ spectrum of one of the two event categories, and the number of events inserted is then compared with the number determined by fitting the DSCB. The pseudo-datasets are generated from background probability density functions [represented by Eq. (1), described in Sec. VI B] with the parameters determined from a fit to the observed $m_{\text{jet}^{a}}$ spectra in collision data. For each simulated sample of the benchmark scenario, with different values of $m_{a}$ and $m_{X}$, separate tests are performed for an increasing number of injected signal events. The average of the number of events determined from the fit to multiple pseudo-datasets and the number inserted should be identical in an ideal case, and the difference between these two numbers is taken as a systematic uncertainty in the signal mass shape modeling.

The fraction, $f$, of signal events that appear in the low-$\Delta E$ category is parametrized as a function of the mass parameters $m_{X}$ and $m_{a}$ of the benchmark signal scenario, to have a continuous model for all the masses considered in the results. The values of $f$ are taken from simulation and a third-order spline interpolation is performed as a function of $m_{a}/m_{X}$.

Similarly, the total signal selection efficiency, $\epsilon$, is calculated from the individual signal mass points generated, and is parameterized as a function of $m_{X}$ and $m_{a}$. This serves as an input to the calculation of the cross-section times branching ratios for the benchmark signal scenario.

The modeling of signal mass shape, for $\epsilon$ and $f$ as functions of $(m_{X}, m_{a})$ is performed separately for the two different final states of the benchmark signal scenario, $X \rightarrow aa \rightarrow 4\gamma$ and $X \rightarrow aa \rightarrow 6\pi^{0}$. In general, the results are similar for the two decay scenarios. The main distinction is in the different trend in $f$ with respect to $m_{X}$ and $m_{a}$, especially the threshold in $m_{a}/m_{X}$ at which the values of $f$ transition from $f > 0.5$ to $f < 0.5$. This threshold is found to be at $m_{a}/m_{X} \approx 0.0015$ for $X \rightarrow aa \rightarrow 4\gamma$, and at $m_{a}/m_{X} \approx 0.0020$ for $X \rightarrow aa \rightarrow 6\pi^{0}$.

B. Background modeling

The backgrounds in this search mainly consist of the SM production of events containing either two prompt photons; one prompt photon and one hadronic jet; or two hadronic jets. Prompt photons are defined as photons not originating from hadron decays. Hadronic jets can be misreconstructed as a photon. The three background components are denoted $\gamma\gamma$, $\gamma j$, and $jj$, respectively, with the first symbol indicating the one with a higher value of $E_{T}$. The $m_{\text{jet}^{a}}$ distribution of the sum of these background components is described by an analytic function, separately for each of the two $\Delta E$ categories. The parameters of the two analytic functions are determined from fits to the $m_{\text{jet}^{a}}$ distributions in the analysis signal region of collision data from a lower edge of $m_{\text{jet}^{a}} = 175$ GeV.

Based on simulated samples, the contribution from Drell–Yan processes, where the two isolated electrons are misreconstructed as photons, is expected to be at the sub-percent level in the analysis signal region. The shape of the $m_{\text{jet}^{a}}$ distribution of the Drell–Yan contribution in the mass range $m_{\text{jet}^{a}} > 175$ GeV is expected to be similar to that of the $\gamma\gamma$ component, and it is therefore absorbed into the analytic function fit for the continuum background components.

The choice of the functional form describing the background distribution is based on studies of background templates. A variety of functional forms are considered for the background parameterization to achieve a good compromise between limiting the size of a potential bias toward
the identification of a signal when none is present (the *spurious signal*) and retaining good statistical power. The size of the spurious signal for a given functional form is estimated by performing a maximum-likelihood fit to the background templates using the sum of signal and background parameterizations.

To determine the overall shape of the background mass spectra, background templates are determined using both the simulation and collision data, separately for each of the two $\Delta E$ categories. A simulated sample of prompt diphoton events is used to model the shape of the contribution from $\gamma\gamma$ events. Subsets of collision data that are similar but orthogonal to the signal region are used to determine the shapes of the $\gamma j$, $jj$ and $jj$ components, where the subleading reconstructed photon, leading reconstructed photon, or both reconstructed photons, respectively, are required to fail the default isolation criterion but satisfy a looser one. This looser criterion is defined by loosening the requirement for the calorimeter isolation variable to $E_{T}^{\mathrm{iso}} < 7$ GeV. The resulting samples of $\gamma\gamma$, $\gamma j$, $jj$, and $jj$ are summed to derive the background templates, scaled with the background composition fractions determined from the method described below.

The background composition of a given mass spectrum of two reconstructed photons is estimated using a matrix method [33], where events are categorized into four subsets by whether both, only the leading, only the subleading, or neither of the two leading reconstructed photons satisfy the calorimeter isolation requirement. The method relies on external estimates of the efficiency for prompt photons satisfying calorimeter isolation and the rate at which hadronic jets can mimic a photon satisfying calorimeter isolation (the “fake rate”). Photon isolation efficiency is estimated with simulated samples of prompt photons. The isolation variables of photons in simulated samples are adjusted by applying correction factors obtained from small differences observed between photon-enriched control samples of collision data and simulation. An uncertainty is assessed for the photon isolation efficiency by comparing the nominal efficiencies with those derived without applying the corrections to the isolation variable in simulated samples. Fake rates are determined using subsets of collision data with selection criteria imposed so that they are similar but orthogonal to the analysis signal region (“control regions”). These control regions are defined by requiring reconstructed photons to fail the baseline loose photon selection but satisfy another, looser photon selection. This looser photon selection, with respect to the loose selection, is defined by removing requirements on two additional shower shape variables that quantify the lateral shower development in the EM calorimeter second layer ($w_{g2}$ and $R_{g}$, described in Table 1 of Ref. [30]). A difference of approximately 1 GeV is found between the isolation energy spectra in the signal and control regions. This is accounted for by shifting the threshold of the isolation selection criteria by ±1 GeV, determining the resulting change in the calculated fake rates, and assigning the difference as a systematic uncertainty in these values.

An additional uncertainty is assessed by altering the definition of the control regions. To accomplish this, a looser photon selection, with respect to the loose’ selection, is defined by removing the requirement on one shower shape variable ($w_{g2}$) instead of two and comparing the difference between the resulting fake rates.

The resulting background compositions are shown in Table III. Good agreement is seen between the observed isolation spectrum and the expected spectrum based on the matrix method results, within uncertainties, as shown in Fig. 4.

The background templates are derived with the summation of the $\gamma\gamma$, $\gamma j$, $jj$ and $jj$ components scaled by the background composition fractions, separately for each of the two $\Delta E$ categories, as described above. The resulting background templates are presented in Fig. 5.

To evaluate the size of the spurious signal, a test is performed using these background templates and the signal modeling described in Sec. VI A. The background templates are normalized to the integrated luminosity for this search, 36.7 fb$^{-1}$. A family of functions, adapted from those used by searches for new physics signatures in dijet final states [34], is chosen to describe the shape of the $m_{\gamma\gamma R}$ distribution:

$$g(x; a, b) = N(1 - x^2)^a \sum_{j=0}^{k} b_j \log(x)^j.$$  

The variable $x$ is defined as $x = m_{\gamma\gamma R}/\sqrt{s}$. The parameters $a$ and $b_j$ are free parameters and $N$ is the normalization factor. The spurious signal tests are then performed using a maximum-likelihood fit of the sum of the signal and background parameterizations to each of the two background templates. The spurious signal is allowed to be negative as well as positive. The final functional form used to model the background when performing the search for resonances is one where the estimated spurious signal is required to be smaller than 30% of the statistical uncertainty in the fitted signal yield across the full mass spectrum. The cutoff of 30% is chosen to ensure that the contribution of this systematic uncertainty to the total

<table>
<thead>
<tr>
<th>TABLE III. Summary of the measured background compositions for the two categories.</th>
<th>Low-(\Delta E) category</th>
<th>High-(\Delta E) category</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\gamma\gamma$</td>
<td>0.930 - 0.027</td>
<td>0.48 ± 0.16</td>
</tr>
<tr>
<td>$\gamma j$</td>
<td>0.051 - 0.018</td>
<td>0.32 ± 0.09</td>
</tr>
<tr>
<td>$jj$</td>
<td>0.014 - 0.005</td>
<td>0.108 ± 0.001</td>
</tr>
<tr>
<td>$jj$</td>
<td>0.005 - 0.003</td>
<td>0.09 ± 0.05</td>
</tr>
</tbody>
</table>
FIG. 4. Comparison of the observed $E_{T}^{\mathrm{iso}}$ spectra and the expected spectra based on the background composition measurement results. The modeled spectra of $\gamma\gamma$ (dashed), $\gamma j$ (dotted), $j\gamma$ (dot-dashed), and $jj$ (long-dashed) components are added using the background composition measured with the matrix method. The results are compared for each of the two $\Delta E$ categories where (a) shows the leading reconstructed photon in the low-$\Delta E$ category, (b) the subleading reconstructed photon in the low-$\Delta E$ category, (c) the leading reconstructed photon in the high-$\Delta E$ category, and (d) the subleading reconstructed photon in the high-$\Delta E$ category.

FIG. 5. Background templates used for the spurious signal test. The sum of the background components for each of the two $\Delta E$ categories, and the breakdown into components ($\gamma\gamma$, $\gamma j$, $j\gamma$, and $jj$) are shown. The unbinned likelihood fit with the chosen functional form [shown in Eq. (1) with $k = 1$] is superimposed. The expected background compositions, which are measured inclusively for events in $m_{\gamma j}\gamma > 175$ GeV, are shown on the figures.
uncertainty, including all statistical and systematic uncertainties, is subdominant and smaller than 5%.

The method is validated by checking that similar results are obtained when the test is performed using variations of the background templates, for which the background compositions are shifted within the uncertainties presented in Table III. When the fraction of the $\gamma\gamma$ component is shifted up and those for $\gamma j$, $jj$, and $jj$ are shifted down, or vice versa, the size of the resulting spurious signals are consistent within the statistical uncertainty of the background templates.

The resulting functional form used for the background mass spectrum evaluation of the two categories is shown in Eq. (1) with $k = 1$. Figure 5 shows the level of agreement between this functional form and the background templates. The resulting background model and its associated systematic uncertainties are used when searching for resonances in the mass spectra of the signal region.

VII. SYSTEMATIC UNCERTAINTIES

Several sources of systematic uncertainties that affect the determination of the signal yield are taken into account. In most cases, systematic uncertainties are smaller than statistical errors.

The uncertainty in the combined 2015 + 2016 integrated luminosity is 2.1%. It is derived, following a methodology similar to that detailed in Ref. [35], from a calibration of the luminosity scale using $x$-$y$ beam-separation scans performed in August 2015 and May 2016.

The impact of the photon energy resolution on signal modeling is evaluated. It mainly affects the mass shape width, $\sigma_{CB}$, of the Crystal Ball function used to model the signal mass shape. The photon energy resolution is adjusted by one standard deviation from the nominal value in both positive and negative directions, and the resulting change in the fitted signal width is determined. The relative difference in the fitted value of $\sigma_{CB}$ ranges from as small as a few percent to as large as 37%, increasing with larger $m_X$ and dependent slightly on $m_t$, and is taken as a systematic uncertainty.

Systematic uncertainties in the extracted signal yield due to signal mass shape modeling are evaluated via injection tests, described in Sec. VI A. The final fitted values of the number of signal events deviate from the injected values by less than 1% almost everywhere, rising to a maximum of 5% for some signal mass values at the edge of the analysis search region of $m_\gamma = 0.1$ GeV for the high-$\Delta E$ category and $m_\gamma = 0.01 \times m_X$ for the low-$\Delta E$ category. This is taken as the estimate of the systematic uncertainty in the signal yield.

Uncertainties in the modeling of the category fraction, $f$, are evaluated by an envelope to cover the deviations of the values of $f$ from simulation and the parameterization. The absolute value of the change in $f$ varies as a function of $m_\gamma/m_X$, from 3% at $m_\gamma/m_X = 0$, increasing to 12%–14% at around $m_\gamma/m_X = 0.002$, and decreasing to 6%–10% at $0.002 < m_\gamma/m_X < 0.01$. This is taken as the estimate of the systematic uncertainty in $f$.

Other systematic uncertainties in the extracted signal yield and the migration of signal events between the two orthogonal $\Delta E$ categories are evaluated by comparisons between nominal and systematically varied versions of various experimental uncertainty sources, such as the photon energy scale and resolution, isolation selection efficiency, shower shape modeling, and pileup. The systematic uncertainties due to the photon energy scale and resolution are adapted from results determined during LHC Run 1 [32], with minor updates derived from data-driven corrections determined using Run 2 data. Uncertainties related to the loose photon identification scheme are evaluated with the systematic variations for the shower shape modeling, without the correction factors applied to simulation derived from small differences observed between photon-enriched control samples of collision data and simulation [36]. The uncertainty in the photon calorimeter isolation efficiency is calculated from changes due to applying and not applying corrections derived from small differences observed between photon-enriched control samples of collision data and simulation. The uncertainties of the efficiency correction factors using photon-enriched control samples of collision data are used to derive the uncertainty in the photon track isolation efficiency. The pileup uncertainty is taken into account by propagating it through the event selection. The uncertainties in $\epsilon$ and $f$ due to these sources for the mass regions considered for the benchmark signal scenario are calculated. The uncertainties are less than 1% in almost all cases, rising to $\sim$4% for some isolation and shower shape uncertainties for larger values of $m_\gamma/m_X$ at the edge of the analysis sensitivity.

Additional systematic uncertainties in the loose diphoton trigger efficiency are not assessed. The $E_T$ requirements for reconstructed photons are much larger than the value at which the diphoton trigger utilized becomes nearly 100% efficient, and any additional uncertainties in signal efficiency due to mismodeling of the trigger-level shower shape variables are accounted for when calculating uncertainties in offline loose identification, because the loose photon identification definitions at the trigger and offline levels are strongly correlated.

The uncertainty in the signal kinematic acceptance, which is included in the definition of the total signal selection efficiency, is evaluated for the choice of PDF set used for the simulation of the signal samples. It is less than 1% in most cases, rising to $\sim$4% for large $m_X$ around $m_X \sim 2$ TeV.

The systematic uncertainties related to the evaluation of the background mass spectrum are determined from the spurious signal method, described in Sec. VI B. The spurious signal as a function of $m_X$ and $m_\gamma$ is parametrized so that the modeling between mass points is continuous.
This parametrization is performed in such a way that it can slightly overestimate the size of spurious signals, especially at the lower end of the \( m_X \) range, \( m_X = 200 \) GeV. The size of the parametrized spurious signal decreases for larger \( m_X \) and depends slightly on the \( m_a \) value, ranging from 85 to \( 6 \times 10^{-3} \) events for the low-\( \Delta E \) category, and from 32 to \( 1 \times 10^{-2} \) events for the high-\( \Delta E \) category.

The systematic uncertainties are generally smaller than the statistical errors, with the systematic uncertainty in the background evaluated from the spurious signal being the largest contribution. This is because the parametrization of the size of spurious signals slightly overestimates the values at the lower end of the \( m_X \) range, as described above. The impact of the systematic uncertainties on the expected limit decreases with the resonance mass \( m_X \) from 51% at most for \( m_X = 200 \) GeV to 5% at most for \( m_X > 800 \) GeV. The impact of the systematic uncertainties on the signal yield obtained from the fit is summarized in Table IV.

<table>
<thead>
<tr>
<th>( m_X ) [GeV], ( m_a ) [GeV]</th>
<th>( (200, 0.1) )</th>
<th>( (200, 0.3) )</th>
<th>( (200, 2) )</th>
<th>( (600, 0.1) )</th>
<th>( (600, 0.9) )</th>
<th>( (600, 5) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Statistical</td>
<td>66%</td>
<td>72%</td>
<td>86%</td>
<td>99%</td>
<td>94%</td>
<td>98%</td>
</tr>
<tr>
<td>Spurious signal (low-( \Delta E ))</td>
<td>74%</td>
<td>37%</td>
<td>9%</td>
<td>13%</td>
<td>5%</td>
<td>3%</td>
</tr>
<tr>
<td>Spurious signal (high-( \Delta E ))</td>
<td>6%</td>
<td>67%</td>
<td>55%</td>
<td>2%</td>
<td>24%</td>
<td>22%</td>
</tr>
<tr>
<td>Category fraction ( f )</td>
<td>7%</td>
<td>19%</td>
<td>9%</td>
<td>3%</td>
<td>25%</td>
<td>7%</td>
</tr>
<tr>
<td>Signal mass resolution</td>
<td>7%</td>
<td>2%</td>
<td>5%</td>
<td>13%</td>
<td>12%</td>
<td>1%</td>
</tr>
<tr>
<td>Signal mass shape (low-( \Delta E ))</td>
<td>3%</td>
<td>1%</td>
<td>( \cdots )</td>
<td>5%</td>
<td>4%</td>
<td>3%</td>
</tr>
<tr>
<td>Signal mass shape (high-( \Delta E ))</td>
<td>( \cdots )</td>
<td>( \cdots )</td>
<td>1%</td>
<td>3%</td>
<td>3%</td>
<td>2%</td>
</tr>
</tbody>
</table>

**TABLE IV.** Breakdown of the relative contributions to the total uncertainty in the signal yield obtained from the fit. For each source of uncertainty \( \sigma_{\text{source}} \), the fraction \( \sigma_{\text{source}}/\sigma_{\text{total}} \) is presented, where \( \sigma_{\text{total}} \) is the total uncertainty that includes the statistical uncertainty. The sum in quadrature of the individual components differs from 100% due to small correlations between the components. The values here are for the signal process \( X \rightarrow aa \rightarrow 4\gamma \). The mass points \((m_X, m_a) = (200 \text{ GeV}, 0.3 \text{ GeV}), (600 \text{ GeV}, 0.9 \text{ GeV})\) correspond to those values for which the systematic uncertainty of the category fraction \( f \) is the highest. Similar results are found for the decay \( X \rightarrow aa \rightarrow 6\pi^0 \).

Gaussian function (for spurious signal and uncertainties related to the migration of events between the \( \Delta E \) categories) or a log-normal function (for all other uncertainties). Two nuisance parameters are introduced for the extracted signal yield due to signal mass shape modeling uncertainties, one for each \( \Delta E \) category, and they are multiplied by the signal normalizations of each category. One nuisance parameter is introduced for the impact of the photon energy resolution on the mass shape width, and it is multiplied by the signal mass shape width \( \sigma_{\text{CB}} \). One nuisance parameter is introduced for the modeling of the category fraction, \( f \), which is added to \( f \) to shift its value. Several nuisance parameters are introduced for experimental uncertainty sources and PDF uncertainty that affect the extracted signal yield, total signal selection efficiency, \( \epsilon \), and category fraction, \( f \). Two nuisance parameters are introduced for the spurious signals, one for each \( \Delta E \) category. For a given signal mass \((m_X, m_a)\) hypothesis, the spurious signals are given the same \( m_{\text{tau}} \) shape as the signal component, and normalized by the size of the spurious signals.

The calculation of \( p \)-values for the background-only hypothesis \((p_0)\) is performed for a narrow resonance from \( m_X = 200 \) GeV to \( m_X = 2.7 \) TeV, with a scan step of 1 GeV. Since the samples for the benchmark signal scenario were simulated for the \( m_X \) values in the range \( 200 \) GeV \(< m_X < 2 \) TeV, the results of signal mass shape modeling, modeling of category fraction \( f \), and systematic uncertainties are extrapolated for the \( m_X \) values in the range \( 2 \) TeV \(< m_X < 2.7 \) TeV.

Expected and observed upper limits, at the 95% confidence level (C.L.), on the production cross section times the product of branching ratios are calculated as a function of the mass parameters of the benchmark signal scenario, \( m_X \) and \( m_a \), following the CLs modified frequentist prescription [38]. Upper limits are determined separately for the two final states of the benchmark signal scenario where the \( a \) particle decays into either a pair of photons or three neutral pions.

---

**VIII. STATISTICAL PROCEDURE**

For a given fixed signal mass hypothesis, a mass spectrum fit including both the background and signal components is performed to the full mass spectrum of \( m_{\text{tautau}} > 175 \) GeV, using an unbinned maximum-likelihood approach, simultaneously for the two categories (low-\( \Delta E \) and high-\( \Delta E \) categories). A constraint is placed on the ratio of the two separate normalization factors of the signal component for the two categories, evaluated from the category fraction \( f \), which depends on the signal masses \( m_X \) and \( m_a \). Deviations from the background-only hypothesis are searched for starting from \( m_X = 200 \) GeV, and the entire \( m_{\text{tautau}} \) range is used for the background component for each hypothesis test. The \( p \)-values are calculated with the profile likelihood ratio as the basis for the test statistic and utilizing an asymptotic approximation [37].

Systematic uncertainties (described in Sec. VII) are treated as nuisance parameters in the likelihood function, where each is a floating parameter constrained by either a

---

012008-11
The assumptions inherent in the use of the asymptotic approximation are validated by sampling distributions of the test statistic using pseudoexperiments, for a few signal mass points. The asymptotic approximation yields median values of the expected upper limits within 5% of those calculated with a large number of pseudoexperiments for most of the values of $m_X$ and $m_a$ tested. Due to the small number of events in data in the region $m_{\gamma \gamma a} > 1$ TeV in the high-$\Delta E$ category, larger deviations are observed for $m_X > 1$ TeV and large $m_a$. The deviation is smaller than 5% at $(m_X, m_a) = (1$ TeV, $10$ GeV), but the expected upper limits obtained from the asymptotic approximation are smaller than those from pseudoexperiments by 20% for $(m_X, m_a) = (1.5$ TeV, $10$ GeV), and 30% for $(m_X, m_a) = (2$ TeV, $10$ GeV).

**IX. RESULTS**

The observed $m_{\gamma \gamma a}$ spectra in the signal region are shown in Fig. 6. The results of the two-dimensional scan of $p_0$, equivalently expressed in terms of the local significance—the number of standard deviations away from the mean of a normal distribution—are shown in Fig. 7. Two different regimes can be seen in this plot, above and below the threshold at $m_a \sim 0.0015 \times m_X$. These are a result of the categorization of events based on the $\Delta E$ variable. For $m_a \lesssim 0.0015 \times m_X$, a larger fraction of signal events is expected in the low-$\Delta E$ category, and for $m_a \gtrsim 0.0015 \times m_X$, a larger fraction of signal events is expected in the high-$\Delta E$ category. The largest local deviation from the background-only hypothesis is found to be 2.7$\sigma$, corresponding to $m_X = 729$ GeV and $m_a = 0.1$ GeV for the decay $X \rightarrow aa \rightarrow 4\gamma$. The width of the signal mass shape for $m_X = 729$ GeV and $m_a = 0.1$ GeV is 6 GeV, and thus this deviation appears as a small area in Fig. 7. A small excess of events is also observed centered around $m_X = 1.1$ TeV and $m_a = 7$ GeV, which corresponds to a local deviation of 2.2$\sigma$. The observed maximum local deviation is less significant than the median of the largest deviation obtained in background-only pseudoexperiments, calculated in the search region defined by $m_X$ values from 200 GeV to 2.7 TeV and $m_a$ values from 0.1 GeV to $0.01 \times m_X$. The $m_{\gamma \gamma a}$ mass distribution is found to be consistent with the background-only hypothesis.

The 95% C.L. observed and expected upper limits on the cross section for the production via gluon-gluon fusion of a high-mass scalar particle, $X$, with narrow width times the branching ratios into a pair of $a$ particles and the subsequent decay of each $a$ into a pair of photons, $\sigma_X \times B(X \rightarrow aa) \times B(a \rightarrow \gamma \gamma)^2$, are shown in Fig. 8, separately for different values of $m_a$. The same result is presented in Fig. 9, with the ratio $m_a / m_X$ shown on the horizontal axis. This plot illustrates the two features of this search. First, when the ratio $m_a / m_X$ is larger than a threshold of roughly 0.0015, more signal events are expected in the high-$\Delta E$ category, which has a significantly better signal-to-background ratio compared with the low-$\Delta E$ category, thus leading to stronger upper limits.

![FIG. 6. Observed distributions of the mass of two reconstructed photons passing all analysis selections, $m_{\gamma \gamma a}$, for the two signal region categories. The background-only fit result is superimposed. The $\pm 1\sigma$ uncertainty originating from the uncertainties in the fit function parameter values is shown as a shaded band around the fit. The lower panel of each plot displays the significance associated with the observed event yield in each bin, calculated before considering systematic uncertainties. The calculation assumes that the event yield in each bin is Poisson-distributed with a mean given by the background-only fit. The computation is performed with a one-sided test based on the positive or negative tail of the Poisson distribution, depending on the sign of the difference between the event yield and the fit estimate, with negative significance values quoted for negative differences [39].](image-url)
shown in Fig. 8, with slight differences arising mainly from the different trend of the category fraction, to the mass values especially for approximation. This leads to an underestimate of the limits, expressed in significance. They are presented as a function of $m_a$ and $m_X$ for the benchmark signal scenario involving a scalar particle $X$ with narrow width decaying via $X \rightarrow aa \rightarrow 4\gamma$.

The 95% C.L. observed and expected upper limits on the production cross section times the product of branching ratios for the benchmark signal scenario involving a scalar particle $X$ with narrow width decaying via $X \rightarrow aa \rightarrow 4\gamma$, $\sigma_X \times B(X \rightarrow aa) \times B(a \rightarrow \gamma\gamma)^2$. They are evaluated as a function of $m_a$/$m_X$ for fixed values of $m_X$. The limits are calculated using the asymptotic approximation. This leads to an underestimate of the limits, especially for $m_X > 1$ TeV and large $m_a$. The results for the $X \rightarrow aa \rightarrow 6\pi^0$ case are qualitatively similar.

FIG. 9. The observed and expected upper limits on the production cross section times the product of branching ratios for the benchmark signal scenario involving a scalar particle $X$ with narrow width decaying via $X \rightarrow aa \rightarrow 6\pi^0$, $\sigma_X \times B(X \rightarrow aa) \times B(a \rightarrow 3\pi^0)^2$. The limits are calculated using the asymptotic approximation. This leads to an underestimate of the limits, especially for $m_X > 1$ TeV and large $m_a$. The limits for $m_a = 5$ and 10 GeV do not cover as large a range as the other mass points, since the region of interest is limited to $m_a < 0.01 \times m_X$.

X. CONCLUSION

A search for pairs of highly collimated groupings of photons—photon-jets—that are identified as single, pho-

nlike energy clusters in the EM calorimeter of the ATLAS detector at the LHC is presented. Data from proton-proton
collisions at a center-of-mass energy of 13 TeV collected in 2015 and 2016, corresponding to an integrated luminosity of 36.7 fb$^{-1}$, are used. Pairs of photon-jets can arise, for example, as the final-state decay products of a new high-mass resonance decaying via new light resonances into highly collimated groupings of photons. Candidate photon-jet events are initially selected with a loose diphoton trigger and then potential photon-jets are selected using a combination of variables that model EM shower development. Sensitivity to photon-jets is then increased by categorizing reconstructed photons by one of those shower shape variables and narrow resonances are searched for in the resulting mass distributions of two reconstructed photons. The observed mass spectra are consistent with the SM background expectation.

The results are interpreted in the context of a BSM scenario containing a high-mass scalar particle with narrow width, $X$, that decays into photon-jets via low-mass intermediate particles with spin 0, $a$. For the range of $m_X$ investigated, from 200 GeV to 2 TeV, upper limits on $\sigma \times B(a \rightarrow \gamma \gamma) \times B(a \rightarrow \gamma \gamma)^2$ are found to range from 0.2 to 1 fb over most of the range of $m_X$, for $100\text{ MeV} < m_a < 2\text{ GeV}$, rising to $10\text{ to }100\text{ fb}$ for values of $m_X$ at the low end of the range, depending upon $m_a$. Similarly, upper limits on $\sigma \times B(X \rightarrow aa) \times B(a \rightarrow \pi^0 \pi^0)^2$ are found to range from 0.2 fb to 1 fb over most of the range of $m_X$, for $500\text{ MeV} < m_a < 2\text{ GeV}$, rising to $10\text{ to }100\text{ fb}$ for values of $m_X$ at the low end of the range. These limits are calculated using an asymptotic approximation. In addition to the calculated upper limits for this benchmark signal scenario, the results, including the evaluation of the observed upper limits, are provided in HepData [40] in a largely model-independent way, to enable reinterpretation in the context of other signal models containing highly collimated photon-jets of low or high photon multiplicity.

ACKNOWLEDGMENTS

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; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG, Georgia; BMBF, HGF, and MPG, Germany; GSRT, Greece; RGC, Hong Kong SAR, China; ISF, I-CORE and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, the Canada Council, CANARIE, CRC, Compute Canada, FQRNT, and the Ontario Innovation Trust, Canada; EPLANET, ERC, ERDF, FP7, Horizon 2020 and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, Région Auvergne and Fondation Partager le Savoir, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSRF; BSF, GIF and Minerva, Israel; BRF, Norway; CERCA Programme Generalitat de Catalunya, Generalitat Valenciana, Spain; the Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, 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), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [41].

SEARCH FOR PAIRS OF HIGHLY COLLIMATED PHOTON ...

PHYS. REV. D 99, 012008 (2019)

SEARCH FOR PAIRS OF HIGHLY COLLIMATED PHOTON …

PHYS. REV. D 99, 012008 (2019)
(ATLAS Collaboration)

1Department of Physics, University of Adelaide, Adelaide, Australia
2Department of Physics, SUNY Albany, Albany, New York, USA
3Department of Physics, University of Alberta, Edmonton, Alberta, Canada
4aDepartment of Physics, Ankara University, Ankara, Turkey
4bIstanbul Aydin University, Istanbul, Turkey
4cDivision of Physics, TOBB University of Economics and Technology, Ankara, Turkey
5LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy, France
6High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois, USA
7Department of Physics, University of Arizona, Tucson, Arizona, USA
8Department of Physics, University of Texas at Arlington, Arlington, Texas, USA
9Physics Department, National and Kapodistrian University of Athens, Athens, Greece
10Physics Department, National Technical University of Athens, Zografou, Greece
11Department of Physics, University of Texas at Austin, Austin, Texas, USA
12Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
12aIstanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul, Turkey
12bDepartment of Physics, Bogazici University, Istanbul, Turkey
12cDepartment of Physics Engineering, Gaziantep University, Gaziantep, Turkey
13Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
14Institut de Fisica d’Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona, Spain
15aInstitute of High Energy Physics, Chinese Academy of Sciences, Beijing, China
15bDepartment of Physics, Tsinghua University, Beijing, China
15cDepartment of Physics, Nanjing University, Nanjing, China
15dUniversity of Chinese Academy of Science (UCAS), Beijing, China
15eInstitute of Physics, University of Belgrade, Belgrade, Serbia
15fDepartment for Physics and Technology, University of Bergen, Bergen, Norway
15gPhysics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley, California, USA
16Institut für Physik, Humboldt Universität zu Berlin, Berlin, Germany
17Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19Centre de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia
20Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21Physikalisches Institut, Universität Bonn, Bonn, Germany
22Department of Physics, Boston University, Boston, Massachusetts, USA
23Transilvania University of Brasov, Brasov, Romania
24National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca, Romania
25Institut de Fisica d’Altes Energies, Barcelona Institute of Science and Technology, Barcelona, Spain
26Department of Physics, Carleton University, Ottawa, Ontario, Canada
27Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovak Republic
28Institut de Fisica d’Altes Energies, Barcelona Institute of Science and Technology, Barcelona, Spain
29Physics Department, Brookhaven National Laboratory, Upton, New York, USA
30Departamento de Fisica, Universidad de Buenos Aires, Buenos Aires, Argentina
31Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
32Department of Physics, University of Cape Town, Cape Town, South Africa
33Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa
34School of Physics, University of the Witwatersrand, Johannesburg, South Africa
35Physics Department, Carleton University, Ottawa, Ontario, Canada
36Faculté des Sciences Ain Chock, Région Universitaire de Physique des Hautes Énergies - Université Hassan II, Casablanca, Morocco
SEARCH FOR PAIRS OF HIGHLY COLLIMATED PHOTON ... PHYS. REV. D 99, 012008 (2019)
SEARCH FOR PAIRS OF HIGHLY COLLIMATED PHOTON …

PHYS. REV. D 99, 012008 (2019)

117 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands

118 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands

119 Department of Physics, Northern Illinois University, DeKalb, Illinois, USA

120a Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk, Russia

120b Novosibirsk State University Novosibirsk, Russia

121 Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia

122 Department of Physics, New York University, New York, New York, USA

123 The Ohio State University, Columbus, Ohio, USA

124 Faculty of Science, Okayama University, Okayama, Japan

125 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma, USA

126 Department of Physics, Oklahoma State University, Stillwater, Oklahoma, USA

127 Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic

128 Center for High Energy Physics, University of Oregon, Eugene, Oregon, USA

129 LAL, Universitâ© Paris-Sud, CNRS/IN2P3, Universitâ© Paris-Saclay, Orsay, France

130 Graduate School of Science, Osaka University, Osaka, Japan

131 Department of Physics, University of Oslo, Oslo, Norway

132 Department of Physics, Oxford University, Oxford, United Kingdom

133 LPNHE, Sorbonne Universitâ©, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France

134 Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania, USA

135 Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia

136 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, Pennsylvania, USA

137a Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Portugal

137b Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa, Portugal

137c Departamento de Física, Universidade de Coimbra, Coimbra, Portugal

137d Centro de Física Nuclear da Universidade de Lisboa, Lisboa, Portugal

137e Departamento de Física, Universidade do Minho, Braga, Portugal

137f Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain), Spain

137g Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal

138 Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic

139 Czech Technical University in Prague, Prague, Czech Republic

140 Charles University, Faculty of Mathematics and Physics, Prague, Czech Republic

141 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

142 IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

143 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, California, USA

144a Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile

144b Departamento de Física, Universidad Técnica Federico Santa María, Valparaiso, Chile

145 Department of Physics, University of Washington, Seattle, Washington, USA

146 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

147 Department of Physics, Shinshu University, Nagano, Japan

148 Department Physik, Universität Siegen, Siegen, Germany

149 Department of Physics, Simon Fraser University, Burnaby, British Columbia, Canada

150 SLAC National Accelerator Laboratory, Stanford, California, USA

151 Physics Department, Royal Institute of Technology, Stockholm, Sweden

152 Department of Physics and Astronomy, Stony Brook University, Stony Brook, New York, USA

153 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

154 School of Physics, University of Sydney, Sydney, Australia

155 Institute of Physics, Academia Sinica, Taipei, Taiwan

156a E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia

156b High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia

157 Department of Physics, Technion, Israel Institute of Technology, Haifa, Israel

158 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

159 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

160 International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo, Japan

161 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
Tomsk State University, Tomsk, Russia
Department of Physics, University of Toronto, Toronto, Ontario, Canada
TRIUMF, Vancouver, British Columbia, Canada
Department of Physics and Astronomy, York University, Toronto, Ontario, Canada
Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan
Department of Physics and Astronomy, Tufts University, Medford, Massachusetts, USA
Department of Physics and Astronomy, University of California Irvine, Irvine, California, USA
Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
Department of Physics, University of Illinois, Urbana, Illinois, USA
Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia, Spain
Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada
Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, Canada
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg, Germany
Department of Physics, University of Warwick, Coventry, United Kingdom
Waseda University, Tokyo, Japan
Department of Particle Physics, Weizmann Institute of Science, Rehovot, Israel
Department of Physics, University of Wisconsin, Madison, Wisconsin, USA
Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, Yale University, New Haven, Connecticut, USA
Yerevan Physics Institute, Yerevan, Armenia

Deceased.
Also at Department of Physics, King’s College London, London, United Kingdom.
Also at Istanbul University, Department of Physics, Istanbul, Turkey.
Also at Instituto de Física Teórica de la Universidad Autónoma de Madrid, Spain.
Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.
Also at TRIUMF, Vancouver, British Columbia, Canada.
Also at Department of Physics and Astronomy, University of Louisville, Louisville, Kentucky, USA.
Also at Department of Physics, California State University, Fresno, California, USA.
Also at Department of Physics, University of Fribourg, Fribourg, Switzerland.
Also at Department de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain.
Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia.
Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China.
Also at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa, Portugal.
Also at Università di Napoli Parthenope, Napoli, Italy.
Also at Institute of Particle Physics (IPP), Canada.
Also at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany.
Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy.
Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania.
Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France.
Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia.
Also at Borough of Manhattan Community College, City University of New York, New York, USA.
Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece.
Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa.
Also at Louisiana Tech University, Ruston, Louisiana, USA.
Also at California State University, East Bay, Hayward, California, USA.
Also at Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain.
Also at Department of Physics, University of Michigan, Ann Arbor, Michigan, USA.
Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France.
Also at Graduate School of Science, Osaka University, Osaka, Japan.
Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany.
Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands.
Also at Near East University, Nicosia, North Cyprus, Mersin, Turkey.
Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia.
Also at CERN, Geneva, Switzerland.
Also at Department of Physics, Stanford University, Stanford, California, USA.