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Probing MeV to 90 GeV axion-like particles with LEP and LHC

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ABSTRACT

Axion-like particles (ALPs), relatively light (pseudo-)scalars coupled to two gauge bosons, are a common feature of many extensions of the Standard Model. Up to now there has been a gap in the sensitivity to such particles in the MeV to 10 GeV range. In this note we show that LEP data on $Z \to \gamma\gamma$ decays provides significant constraints in this range (and indeed up to the Z-mass). We also discuss the sensitivities of LHC and future colliders. Particularly the LHC shows promising sensitivity in searching for a pseudo-scalar with $4 \lesssim m_a \lesssim 60$ GeV in the channel $pp \to 3\gamma$ with $m_{3\gamma} \approx m_Z$.

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1. Introduction

Over the last few years there has been a rising interest in searching for particles with low mass but also weak coupling to the Standard Model. In part this is motivated by the simple fact that "the new particles have weak couplings to the Standard Model" provides an equally good answer to the question "why haven't we found the new physics" as "the new particles are very heavy". Accordingly we should search in both of these directions. Additional motivation comes from theoretical studies demonstrating that relatively light and weakly coupled particles arise quite naturally in a wide range of extensions of the Standard Model, also in connection with dark matter. See, e.g. [1–3] for some reviews/overviews.

In this note we will be concerned with lightish (pseudo-)scalar particles, called axion-like particles or ALPs [4–7]. ALPs are loosely defined as relatively light scalar or pseudoscalar particles coupled to two gauge bosons and/or two Standard Model fermions.[1] They are one of the prime test-models in the search for light weakly coupled new physics. In field theory models (pseudo-)scalars with such interactions naturally arise as pseudo-Nambu–Goldstone bosons of spontaneously broken approximate symmetries [4] and or by mixing with the Higgs boson [12–14]. In string models moduli and string axions provide natural candidates [15–20]. Last but not least, ALPs could also provide nice messengers to dark matter (sectors) [21,22] and in some cases could even be the dark matter particles themselves [6,23].

In this note we want to focus in particular on axion-like particles whose dominant interaction with the Standard Model is via two gauge bosons (i.e. where interactions with the Standard Model fermions can be neglected). This can be viewed as a simple test example,[2] but such a situation also arises quite naturally in string models [20]. Practically we consider interactions with two photons and with two hypercharge bosons,

$$\mathcal{L}_{\rm int} \supset -\frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu}\tilde{F}_{\mu\nu} \quad \text{or} \quad -\frac{1}{4} g_{aBB} a B^{\mu\nu}\tilde{B}_{\mu\nu}. \tag{1.1}$$

This interaction is for the specific case of a pseudo-scalar, but the analyses of this paper can be straightforwardly generalized to scalar, and we expect quantitatively similar results.

This note is motivated by two very simple observations:

- The striking gap in the limits on the ALP coupling to two photons shown in Fig. 1 in the MeV to roughly 10 GeV region.[3] While reactor experiments have explored this mass region [32–40] the corresponding limits depend on a coupling to

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[1] Their name, of course, originates from the similarity to the famous axion introduced to solve the strong CP problem [8–11]. The axion crucially features a low mass and couplings to two gauge bosons as well as optional couplings to the Standard Model fermions. As a consequence of solving the strong CP problem, the axion couplings are proportional to the axion mass with an essentially known and fixed proportionality constant. In any plot of mass vs coupling strength axion models therefore populate a relatively narrow band. From the phenomenological point of view we can simply take axion-like particles as a straightforward generalization of axions where we relax the strict relation between mass and coupling and allow them to populate the whole mass vs coupling plane.

[2] Therefore we also happily continue the coupling to relatively large values that may be difficult to generate in a perturbative embedding.

[3] Although future fixed target experiments such as, e.g. SHiP [31], will nicely extend [3] the "beam dump" region in Fig. 1, they are limited to weaker couplings because they require a sizeable decay length for the ALPs.

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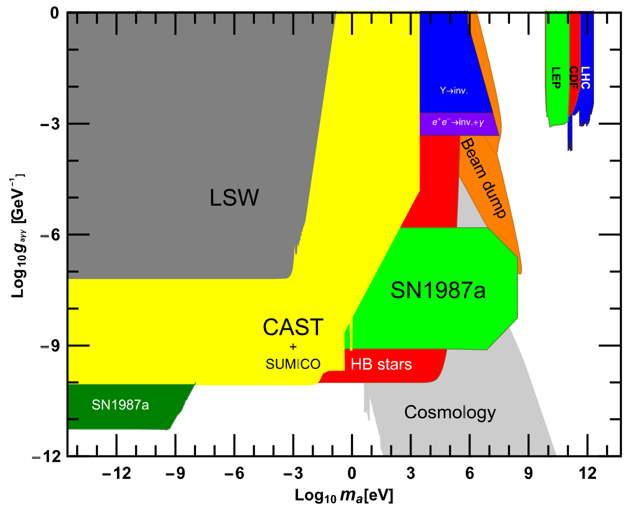

Fig. 1. Limits on the axion-like particle to two photon coupling. Figure slightly adapted from [3] which is a compilation adapted from [1,24] updated with [25–30]. Note the gap in the MeV to 10 GeV region.

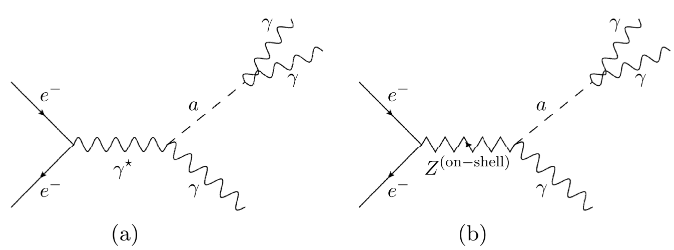

Fig. 2. Production of ALPs with subsequent decay into two photons. *Left panel:* $a+\gamma$ production via a virtual photon and subsequent decay to 3γ. *Right panel:* production of an on-shell Z and subsequent decays into $a+\gamma$ and then 3γ.

fermions (typically nucleons) and are not directly applicable if there only is a coupling to gauge bosons.

- The interaction with hypercharge bosons can to some degree be viewed as the more fundamental one. However, this coupling allows a decay of a Z-boson via $Z \to a\gamma$. It is therefore natural to look for unusual decays of the Z which promises sensitivity to ALPs with mass $\lesssim m_Z \approx 90$ GeV.

Indeed LEP data [41,42] on the decay $Z \to 3\gamma$ has already been used to constrain ALP couplings to two photons [28] via the process $e^+e^- \to a+\gamma$, $a \to 2\gamma$ as shown in Fig. 2(a). Our analysis differs in two essential points. First we also consider the coupling to the hypercharge bosons. This allows for the decay of an on-shell Z into an ALP and a photon in contrast to the production of an ALP and a photon via a (highly) virtual photon (cf. Fig. 2(b)). This on-shell production significantly enhances the sensitivity. Second and more importantly we also use data on $Z \to 2\gamma$ decays. The search for a 3γ signature is only sensitive for sufficiently high ALP masses such that the two photons arising from the decay of a fast moving ALP can be separated. In practice this limits the sensitivity to masses $m_a \gtrsim 10$ GeV. However two tightly collimated photons essentially produce the same detector response as one photon with the combined energy. One can therefore use the $Z \to 2\gamma$ search in this regime. This allows us to fill in the sensitivity gap in the MeV to 10 GeV region as shown in our result plots Figs. 4(a) and 4(b). Finally, we note that we only use data from the Z-pole measurement [41,43–47], while [28] also uses higher energy data [42].

The remainder of this note is structured as follows. In the next Section 2 we describe our analysis of the two and three photon LEP searches and present the corresponding new limits. Following this we have a look at the prospects at LHC and at future colliders in Section 3. We briefly summarize and conclude in Section 4.

2. Searching ALPs at LEP with $Z \to 2\gamma$ and $Z \to 3\gamma$

2.1. ALPs from Z decays

For some time of its operation LEP has run with an energy on or close to the Z mass. During this time a huge number of Z were produced ($\sim$ few $\times 10^6$). This opportunity has been used to constrain the branching ratios for unusual Z decays, in particular decays to two and three photons [41,43–47].

In presence of a coupling of ALPs to two hypercharge bosons, the Z boson can decay to an ALP and a photon with a rate,

$$\Gamma_{Z\to a+\gamma} = \frac{g^2_{aBB}\sin^2(\theta_W)\cos^2(\theta_W)}{96\pi} m_Z^3, \tag{2.1}$$

where θ_W is the Weinberg angle.

The ALP subsequently decays into two photons with a rate,

$$\Gamma_{a\to 2\gamma} = \frac{g^2_{aBB}\cos^4(\theta_W)}{64\pi} m_a^3. \tag{2.2}$$

For detection purposes two factors are important. First the decay length in the laboratory frame has to be within the detector, more precisely before the electromagnetic calorimeter. It is given by

$$\begin{aligned}\ell_{\rm decay} &= \frac{\gamma_a}{\Gamma_{a\to 2\gamma}} \approx \frac{m_Z}{2m_a}\frac{1}{\Gamma_{a\to 2\gamma}} \\ &\sim 2\text{ cm}\left(\frac{10^{-3}\text{ GeV}^{-1}}{g_{aBB}}\right)^2\left(\frac{100\text{ MeV}}{m_a}\right)^4,\end{aligned} \tag{2.3}$$

where γ_a is the relativistic factor for the ALP. On the left hand side we have used that in the LEP Z peak measurement Z bosons are produced at rest and consequently for ALP masses much smaller than the Z mass, half the energy goes into the ALP. For small masses and couplings the decay length limits the sensitivity of the measurement. In the low mass regime we therefore only take the fraction of events that decays within the first 10 cm into account. In practice for the couplings accessible with LEP data this only has an effect for masses $\lesssim$100 MeV. For larger masses essentially all ALPs decay within the detector.

The second important factor is whether the two photons of the $a \to 2\gamma$ decay can be separated in the experiment. This decides whether the constraints of the $Z \to 3\gamma$ measurements are applicable or one has to consider those from $Z \to 2\gamma$. For central production, the separation is roughly given by

$$\Delta R \sim \frac{2m_a}{p_T} \sim \frac{4m_a}{m_Z}, \tag{2.4}$$

see Fig. 3. We generate the distributions of Fig. 3 using Madgraph [56] and impose no cuts at generator level.

For example requiring a separation of 20 degrees as in [41] $\Delta R \sim \sin(20^\circ) \sim 0.34$ one finds that this limits the mass reach of the $Z \to 3\gamma$ to ALP masses $m_a \gtrsim$ few GeV (cf. also [28]).

However, if the separation is very small the two photons from the ALP decay appear essentially as one photon of the combined energy. Indeed already the LEP collaborations themselves used the $Z \to 2\gamma$ measurements to constrain the branching ratios of Z into photon and mesons which subsequently decay into two photons, e.g. $Z \to \gamma + \pi^0$ or $Z \to \gamma + \eta$.

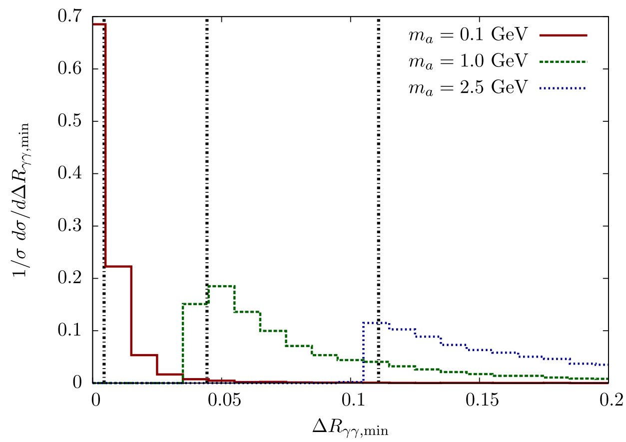

Fig. 3. ΔR separation of the two closest photons for different values of m_a in the process $e^+e^- \to Z \to a\gamma \to 3\gamma$. The black vertical lines correspond to $\Delta R = 4m_a/m_Z$.

Let us now apply this to the case of our ALPs. In practice we consider three regions.

1) $m_a \leq m_{\pi^0} = 135$ MeV. Here we use the limit from on the branching ratio $BR(Z \to \gamma + \pi^0) \leq 5.2 \times 10^{-5}$ [46] simply as $BR(Z \to \gamma + a) = \Gamma_{Z\to a\gamma}/\Gamma_Z \leq 5.2 \times 10^{-5}$.
2) $m_{\pi^0} \leq m_a \leq 10$ GeV. In this region we have simulated angular distribution for the production and decay $e^+ + e^- \to Z \to a + \gamma \to 3\gamma$. This we compared bin by bin to the distribution given in [46]. For those bins where there was a (non-significant) excess in a bin we have added this excess to the statistical uncertainty to obtain a conservative bound.
3) $10\ \text{GeV} \leq m_a \leq m_Z = 91.2$ GeV most of the decays result in clearly separable 3γ events. Accordingly we have used the limit $BR(Z \to \gamma + a \to 3\gamma) \leq BR(Z \to 3\gamma) \leq 10^{-5}$ from [41].

The resulting limits are shown in green in Fig. 4(a). The solid line indicates the limit from $Z \to 3\gamma$ and the dashed one that from the $Z \to 2\gamma$ measurements. The latter one is sensitive to relatively low ALP masses and indeed most of the "hole" mentioned in the introduction is covered by this measurement.

We note that the stronger limit at large masses from the $Z \to 3\gamma$ measurement as compared to Ref. [28] arises from the on-shell production of the Z boson. Using the production via a virtual photon, as done in the next subsection, produces results roughly compatible with Ref. [28].

2.2. ALPs from production via virtual photons

While a pure coupling to two hypercharge bosons will always lead to a decay $Z \to a + \gamma$ it is possible to have a combination of couplings to two hypercharge bosons and to two $SU(2)_{\text{weak}}$ bosons such that the corresponding ALP-photon-Z coupling does not exist and one is effectively dominated by a two photon coupling. Although we think that the presence of an ALP-photon-Z coupling is rather generic it is nevertheless worthwhile to also consider the latter case.

If ALPs are coupled only to two photons, production has to occur via a virtual photon as shown in Fig. 2(a). In general an ALP photon pair produced in this manner has an invariant mass given by the centre of mass energy of the two colliding particles producing the virtual photons and therefore not necessarily m_Z. However, this is still the case for the LEP measurement at the Z peak, because at a lepton collider such as LEP the two colliding particles have a definite energy given by the collider energy and for the measurements we consider this was (nearly) m_Z.

Aside from the difference in production the analysis follows along similar lines as in the previous subsection. To obtain the limits in this case we have simply rescaled the limits with the appropriate lower ALP production cross section.

The resulting limits are shown in light green Fig. 4(b). Again the solid line indicates the $Z \to 3\gamma$ measurement and the dashed one the $Z \to 2\gamma$ limit. As above we see that the two photon measurement extends the reach to low masses. In the overlapping region our limits are slightly weaker than those of [28] which also used data based on more integrated luminosity at energies off the Z-peak (since the production via photons is always off-shell there is no special benefit in Z-peak data).

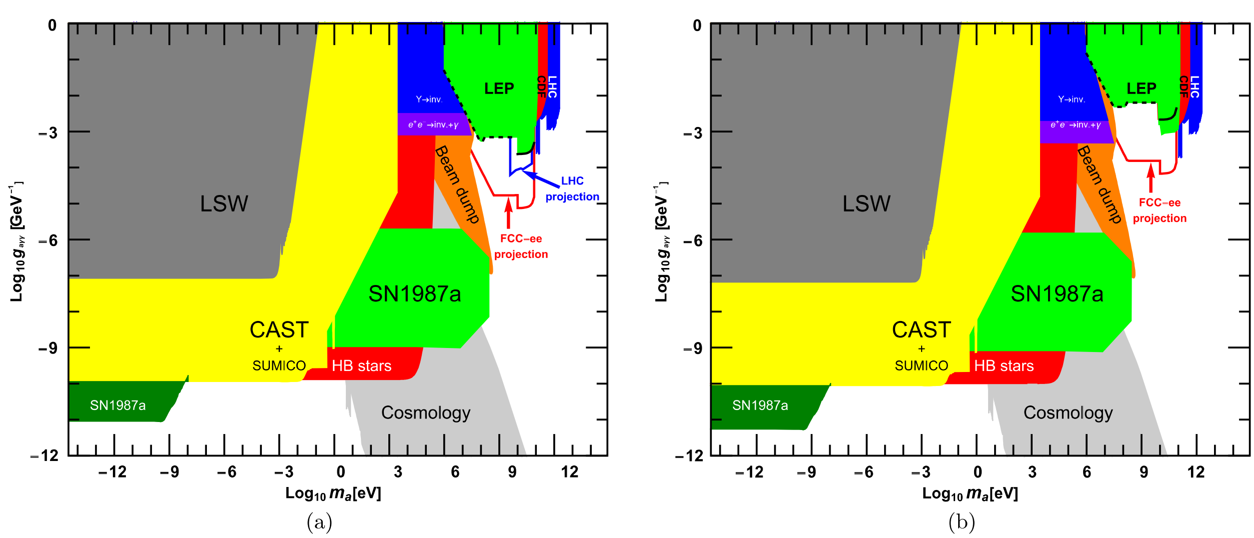

Fig. 4. *Left panel:* Limits on a coupling to two hypercharge bosons. *Right panel:* Limits on a coupling only to photons. The new LEP limits from 2 and 3 photon signatures are shaded in green and enclosed by dashed and solid black lines, respectively. The future FCC-ee limit is indicated by the red solid line. Our projected LHC sensitivity for 13 TeV and 100 fb^{-1} by the blue line (only applicable to the coupling to hypercharge bosons). The rest of the figure is adapted from [1,3,24–30]. The FCC-ee limits are based on the assumption that the collider is running with a center-of-mass energy of m_Z. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

3. ALPs at LHC and future colliders

3.1. Future electron–positron machines

Let us first consider the sensitivity of future lepton colliders such as ILC [48,49], CEPC [50], and FCC-ee [51,52]. For these the analysis that one can perform is exactly as in the previous section and limits can be obtained for both the pure photon and the hyperacharge coupling in Eq. (1.1).

Indeed with at FCC-ee running at the Z-peak we can hope for about 10^7 times as many Z-bosons as were produced with LEP-I running at the Z-peak. Naively, we can scale the improvement in the branching ratio as $\sqrt{N_Z}$. We therefore expect that the branching ratios could be improved by a factor 10^3–10^5. Accordingly the limits on the couplings are improved by a factor of 30–100.[4] This is shown by the red lines labeled FCC-ee indicated in Fig. 4. Expecting improvements also in the detectors and a dedicated analysis one can hope that the actual sensitivity will actually be significantly better.

3.2. Testing the hypercharge coupling with LHC

However, while the FCC-ee or any similar machine is still in the distant future the LHC is running right now. Searches for ALPs coupled to two gauge bosons at LHC have already been considered in [27]. However, in that paper the opportunity to look for relatively low mass ALPs from the decay of Z bosons via a coupling of the ALP to hypercharge bosons was not considered. This is what we will do here.[5] As we will see this allows significant improvements of the LHC sensitivity for ALPs coupled to hypercharge bosons[6] (second coupling in Eq. (1.1)).

If one has the option of an on-shell Z-boson decaying into $a+\gamma$ one has an additional clean search channel: one can look for two or three photons reconstructing to the Z-mass. With a total cross section for Z production in the range of

$$\sigma(pp \to Z + X) \sim 3 \times 10^4\,\text{pb} \quad 7\,\text{TeV} \tag{3.1}$$

LHC has already produced a very large number,

$$N_Z^{\text{LHC}} \sim 7 \times 10^8, \tag{3.2}$$

of Z bosons.

At LHC experiments, isolated photons are reconstructed by studying the shower profile in the electromagnetic calorimeter. Highly collimated photon-pairs are likely to violate the reconstruction requirements for isolated photons. For a first sensitivity study of this channel we will limit ourselves to the scenario where three isolated photons can be reconstructed. We parametrize the photon reconstruction efficiency and jet-fake-photon rate according to [55], i.e. we smear the momenta of all reconstructed final state objects with Gaussians and parametrize the photon reconstruction efficiency with

$$\mathcal{E}_\gamma = 0.76 - 1.98 e^{-p_{T,\gamma}/16.1\,\text{GeV}} \tag{3.3}$$

and the jet-photon fake rate with

$$\mathcal{P}_{j\to\gamma} = 0.0093 e^{-0.036 p_{T,j}/\text{GeV}}. \tag{3.4}$$

[4] We note that due to the smaller couplings that are tested, the region affected by a too long decay length can now extend up to a few × 100 MeV. Yet, with a suitable analysis for displaced vertices this effect may be ameliorated.

[5] During finalization of this article, a search by ATLAS in the channel $pp \to Z' \to 3\gamma$ was published [54].

[6] For a study of relatively light pseudo-scalars coupled to fermions at LHC see [53].

Two of the photons in the signal tend to be highly collimated. Hence, we define photons to be isolated if $p_{T,\gamma} \geq 20$ GeV and if the amount of hadronic energy in a cone of $R = 0.1$ around the photon is less than 10% of the photon's transverse energy. With three fairly hard photons the final state is likely to satisfy trigger requirements.

We generate signal samples with Madgraph [56] and background samples with Sherpa [57]. As dominant backgrounds we consider the processes 3γ, $2\gamma + j$ and $\gamma + 2j$, where the first background is irreducible while the other two require one or two of the photons to be mis-identified.

While the angular separation for two of the photons strongly depends on the mass of a, the transverse momentum distribution does not. Hence, to reduce background without biasing our selection towards a specific mass of the axion-like particle, we require for the photons staggered p_T cuts, i.e.

$$p_{T,\gamma_1} \geq 30\,\text{GeV}, \quad p_{T,\gamma_2} \geq 20\,\text{GeV}, \quad p_{T,\gamma_3} \geq 20\,\text{GeV}, \tag{3.5}$$

and their invariant mass to be in a window around the Z boson mass,

$$80\,\text{GeV} \leq m_{3\gamma} \leq 100\,\text{GeV}. \tag{3.6}$$

Eventually we reconstruct the axion-like particle by requiring that at least one of the three di-photon combinations satisfies

$$m_a - 3\,\text{GeV} \leq m_{\gamma_i\gamma_j} \leq m_a + 3\,\text{GeV}. \tag{3.7}$$

In Fig. 5 we show the transverse momentum distributions and ΔR-separations of the three signal photons for $m_a = 4$, 20 and 60 GeV after the reconstruction steps Eqs. (3.5)–(3.7). For the backgrounds we find generically $\sigma(\gamma jj) \simeq 4\sigma(\gamma\gamma j) \simeq 9\sigma(3\gamma)$, i.e. the much larger inclusive production cross section of γjj is almost, but as a result of the large fake rate for $p_{T,\gamma} \simeq 20$ GeV not quite, reduced to the irreducible 3γ background.

We show in Table 1 signal and background rates after reconstructing the Z boson and the axion-like resonance. We find that a large range of masses can be excluded with 100 fb^{-1} assuming $\sqrt{s} = 13$ TeV, outperforming existing limits from LEP (see Fig. 4(a)). However, while we apply a crude fast-detector simulation to take into account reconstruction efficiencies and fake rates relevant for this process, the signal and background rates have only been calculated at leading-order accuracy. Hence, the statistical significance we quote is plagued by large theory uncertainties. In the steps of Eqs. (3.5)–(3.7) we focused on a reconstruction of the final state that is not biased towards a specific m_a. If a specific m_a is envisioned, the cuts can be optimized towards a stronger separation of signal and background. The simple counting experiment we use to evaluate the statistical significance can also be severely affected by normalization uncertainties and pileup contributions. However, as long as the axion-like particle is a narrow resonance, a side-band analysis, similar to the prominent Standard Model search of a Higgs boson decaying into photons [58,59], can retain sensitivity irrespective of these problems.

For $m_a < 4$ GeV existing photon reconstruction strategies start to fail since $\Delta R_{\gamma_2\gamma_3} \lesssim 0.15$. Photons will not be considered isolated anymore and there will be a mistag rate where the two photons induce a shower similar to a single photon. To improve the sensitivity for small masses dedicated reconstruction strategies, e.g. di-/multi-photon taggers [60], would need to be developed.

4. Conclusions

Relatively light (pseudo-)scalars coupled to two gauge bosons often dubbed axion-like particles (ALPs), are a feature of many extensions of the Standard Model. They are also attractive because of possible connections to dark matter. Z decays provide a unique

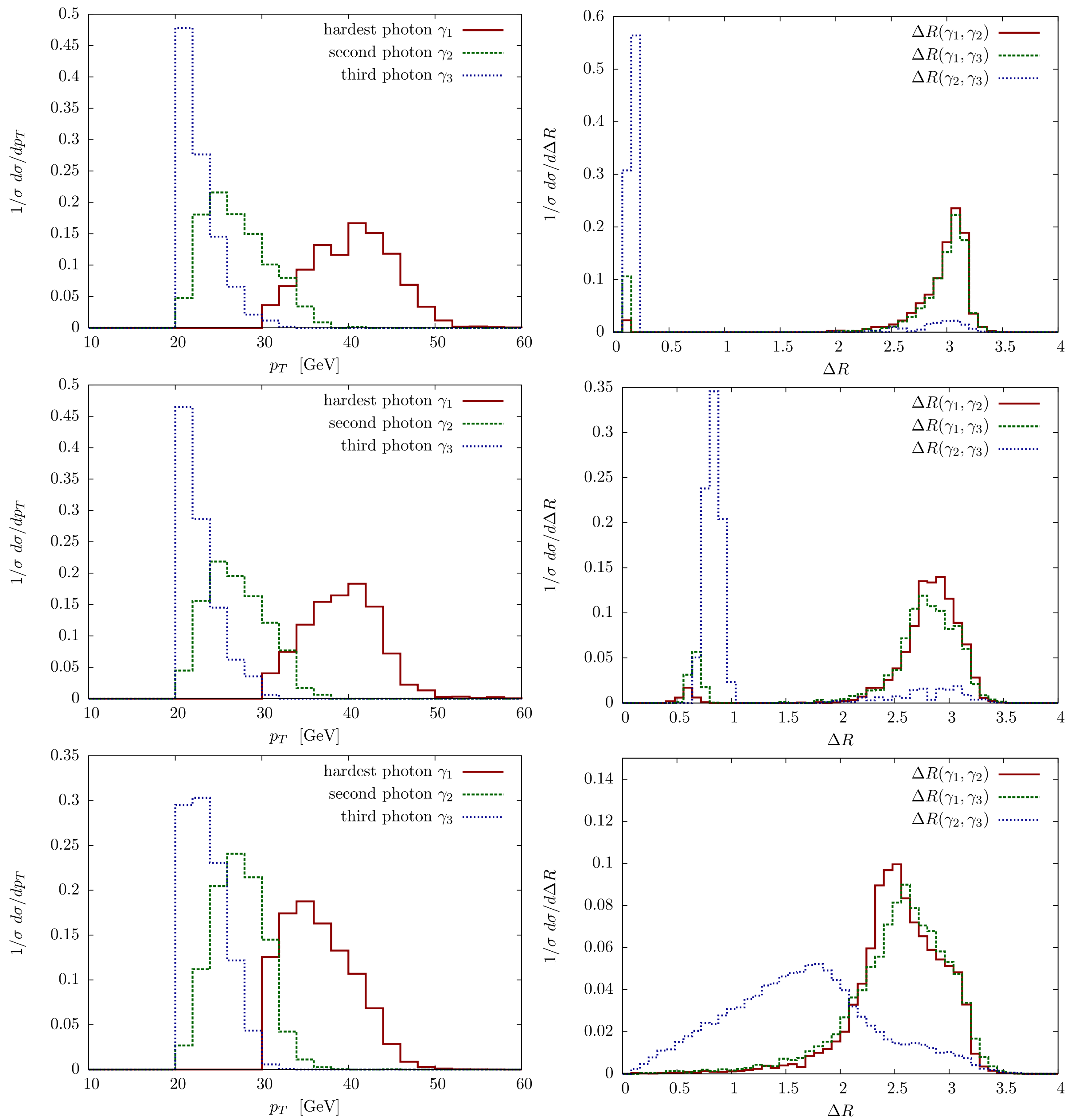

Fig. 5. Transverse momentum distributions for the hardest, second and third hardest photons (left). ΔR separations of the three photons (right). We choose $m_a = 4$ GeV (upper panels), $m_a = 20$ GeV (middle panels) and $m_a = 60$ GeV (lower panels).

Table 1
Signal and background cross sections for $pp \to Z \to a\gamma$ analysis. We assume $g = 10^{-4}$ GeV^{-1} and calculate the final significance for 100 fb^{-1}. The cross sections are shown after applying the cuts of Eqs. (3.5)–(3.7). ϵ_S and ϵ_B denote the signal and background survival rate after all cuts.

m_a [GeV]	σ_S [fb]	ϵ_S	$\sigma_{3\gamma}$ [fb]	$\sigma_{2\gamma j}$ [fb]	$\sigma_{\gamma 2j}$ [fb]	ϵ_B	S/B	$S/\sqrt{B}_{100}$
4	0.0948	$1.6 \cdot 10^{-3}$	0.0028	0.0042	0.0274	$2.6 \cdot 10^{-10}$	2.76	5.1
8	0.0971	$1.7 \cdot 10^{-3}$	0.0059	0.0170	0.0935	$8.7 \cdot 10^{-10}$	0.83	2.8
15	0.0788	$1.7 \cdot 10^{-3}$	0.0110	0.0266	0.0984	$8.7 \cdot 10^{-10}$	0.62	2.2
20	0.0910	$2.0 \cdot 10^{-3}$	0.0150	0.0260	0.0889	$1.0 \cdot 10^{-9}$	0.70	2.5
45	0.1031	$4.6 \cdot 10^{-3}$	0.0350	0.0692	0.1745	$2.1 \cdot 10^{-9}$	0.37	2.0
60	0.0979	$9.9 \cdot 10^{-3}$	0.0771	0.1429	0.3986	$4.6 \cdot 10^{-9}$	0.16	1.2

opportunity to search for ALPs in the MeV to multi-GeV range. Using data from LEP-I we have excluded a previously allowed range of masses for ALPs coupled to two photons. Future precision measurements of Z decays at electron–positron colliders such as FCC-ee promise improvements in the sensitivity by about two orders of magnitude over the current limits.

We also performed a first analysis on the LHC discovery prospects of light resonances in 3γ final states with an invariant mass close to the Z mass, i.e. for unusual and rare Z-decays. We find that ATLAS and CMS have a significant discovery potential for ALPs, possibly outperforming LEP. Hence, a dedicated experimental analysis of this channel would be highly desirable.

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