ALP searches at the LHC: FASER as a light-shining-through-walls experiment

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We propose the use of FASER as a light-shining-through-walls experiment to search for axions and axionlike particles (ALPs). LHC collisions generate a high intensity and high energy photon flux in the forward direction which can oscillate into ALPs in the magnetic fields that are used to confine the beam. These ALPs then pass through about 100 m of rock before reaching the magnetic fields of FASER, where they can convert back into photons and be detected by an electromagnetic calorimeter. In the next years, FASER and its successor FASER2 at the Forward Physics Facility will be able to explore regions of the ALP parameter space inaccessible by other laboratory-based experiments.

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I. INTRODUCTION

Axions are among the best motivated scenarios of new physics beyond the Standard Model (BSM). Most famously, the QCD axion arises as a low-energy consequence of the elegant Peccei-Quinn solution to the strong *CP* problem of the SM [1–6]. But the interest in axionlike particles (ALPs) goes well beyond the QCD axion. Indeed these pseudo-Nambu-Goldstone bosons arise in a plethora of BSM constructions such as theories with extra dimensions [7], Majoron models [8], theories of flavor [9,10] and are ubiquitous within string theory [11]. They all share the basic properties that stem from its pseudo-Nambu-Goldstone nature: axions are light and present feeble derivative or anomalous interactions suppressed by the axion decay constant f_a. Moreover, they are excellent dark matter candidates [12–14].

As a consequence, a strong experimental program has been developed and in the next decades we will explore large regions of the ALP parameter space. Most of the experiments only take advantage of the ALP coupling to photons. In this case the relevant Lagrangian reads

$$\mathcal{L} \supset -\frac{1}{2} m_a^2 a^2 - \frac{1}{4} g_{a\gamma\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu}, \qquad (1)$$

where $F_{\mu\nu}$ is the electromagnetic field strength and $\tilde{F}^{\mu\nu}$ its dual. The resulting parameter space is therefore spanned by the ALP mass m_a and the ALP coupling $g_{a\gamma\gamma}$. ALP search experiments utilize a variety of experimental techniques that range from laboratory-based light-shining-through walls (LSW) experiments such as ALPS II [15], helioscopes looking for solar ALPs such as CAST [16,17] and the future IAXO [18,19], haloscopes looking for dark matter ALPs [20–25] but also colliders [26,27], flavor probes [28–31], as well as beam dump [32] and neutrino [33,34] experiments for larger masses. There are also a number of astrophysical constraints (typically through energy-loss arguments) and cosmological bounds which provide a nice complementarity with respect to proposed experiments. However, these considerations vary in their robustness. For example, the supernova bound from the SN1987 neutrino signal [35] has been recently put in question [36] although not everyone in the community agrees with this criticism and it has been argued that the SN1987 also constrains the ALP through the γ-ray signal and the diffuse cosmic γ-ray background [37]. Similarly some cosmological bounds can be significantly relaxed in nonstandard cosmological scenarios [38,39]. This is why there is a growing community interest in purely laboratory based ALP experiments, which has been advocated for (e.g. in Ref. [40]).

In this paper we contribute to this effort by noting that the LHC accelerator in combination with the recently installed FASER experiment [41–43] can be used as a LSW experiment without requiring any modification of the current experimental setup. The LSW detection principle is based on the coherent ALP-photon oscillation in the presence of an external magnetic field. A strong photon beam is directed at a thick wall with a photon detector placed behind it. In the absence of ALPs, no signal is expected in the detector. However, if ALPs exist the strong magnetic fields perpendicular to the beam located at both

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sides of the wall may induce the photons to convert to ALPs which can freely pass through the wall. These ALPs can then oscillate back to photons and be detected on the other side of the wall. Effectively, this double conversion mechanism allows a small fraction of the photon beam to pass through the wall where it can be detected. LSW experiments use this mechanism to search for ALPs.

In this study we explore the sensitivity of both FASER and future forward detectors proposed in the context of the Forward Physics Facility (FPF) [44,45] for light ALP searches. The main advantage of this proposal with respect to existing LSW experiments lies on the high energies of LHC photons which allows us to explore higher ALP masses. With respect to other accelerator searches, this proposal enjoys a better sensitivity at lower masses since it relies on coherent conversion in an external macroscopic magnetic field instead of production/detection through scattering or perturbative decay. In the following, we will discuss the production of ALPs at the LHC in Sec. II, their detection in Sec. III, and the resulting sensitivity in Sec. IV.

II. ALP PRODUCTION AT THE LHC

For more than half a century, hadron colliders have been the primary tools to probe the fundamental laws of nature at the highest energies. The currently most energetic realization of these hadron collider experiments is the LHC at CERN, which started to collect data in 2010 and is expected to run until 2040. With a collision energy of 14 TeV, it is able to produce heavy particles with masses at the weak scale and beyond, and large detectors like ATLAS and CMS have been built around the LHC collision point to detect their decay products. Their biggest achievement thus far is the discovery of the Higgs boson in 2012 [46,47] and the main objectives for their remaining operation are to study the properties of the Higgs and to search for new heavy particles at the TeV scale. In addition, the LHC also produces an enormous number of energetic light particles, which are mainly produced in the forward direction. As first pointed out by the authors of Ref. [41], this provides an additional opportunity to search for light and weakly coupled particles. In the following, we will apply this idea in the context of ALPs.

As a by-product of proton-proton collisions, the ATLAS experiment also produces an intense and strongly collimated beam of photons with energy $E_\gamma \sim$ TeV in the far forward direction. These photons mainly result from the decay of neutral pions, which were for example formed in the hadronization of the beam remnants. In this study, we use the double differential photon spectrum $d^2\sigma/dEd\theta$ (with respect to the photon energy and angle with respect to the beam axis) provided by the FORESEE [48] tool, which were obtained by the EPOS-LHC [49] event generator as implemented in the CRMC [50] package. The photon distribution is shown in Fig. 2. Roughly speaking, we expect about 10^{14} photons per fb^{-1} of integrated luminosity to be produced within 1 mrad of the beam axis.

These photons travel down the beam pipe, where they pass through a variety of magnets before being absorbed in the LHC infrastructure. An overview of the magnetic fields that are relevant for our study is presented in Fig. 1. This includes the so-called inner triplet, which is a set of quadrupole magnets to focus the proton beam before the collision, and the D1 dipole magnet, which separates the incoming and outgoing proton beams before they enter their separate beam pipes. Note that the exact dimensions and strength of these magnets will undergo some changes in the future. The LHC in its current configuration will operate until about 2025. Afterwards, it will be upgraded in preparation of the following high-luminosity LHC (HL-LHC) era. When modeling the magnetic fields, we assume that the dipole magnets have a constant field strength B, while quadrupole magnets are specified by a field gradient B' and their field strength is given by $B = B' \cdot r$ where r denotes the distance from the center [51]. We further model the beam pipe as a cylinder with diameter of 5.3 cm and

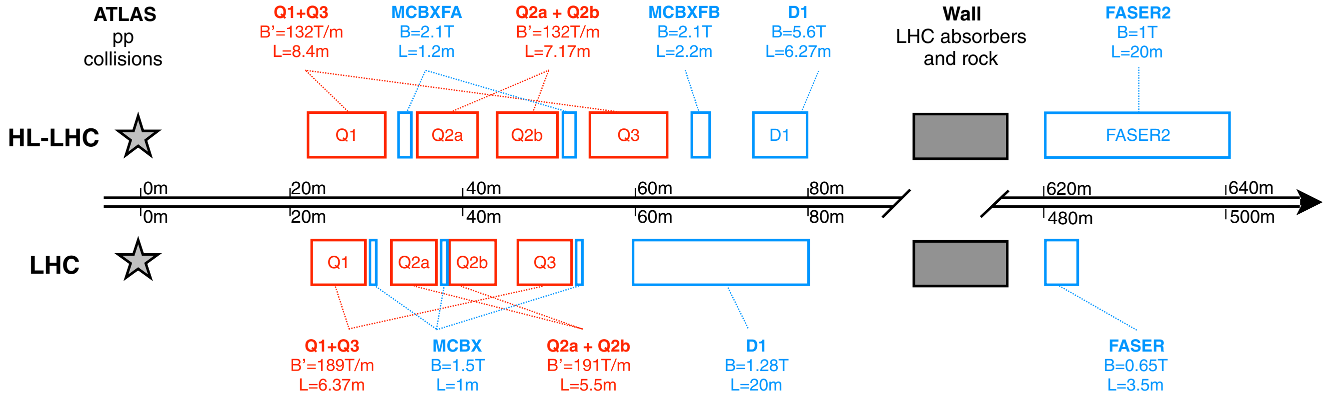

FIG. 1. Considered magnetic fields at the high-luminosity LHC (HL-LHC) (top) and LHC run 3 (bottom) downstream from the ATLAS collisions point. We show dipoles in blue and quadruples in red, and indicate their corresponding length L, magnetic field B and field gradient B'. Here we have used the magnetic fields as presented in Refs. [52,53].

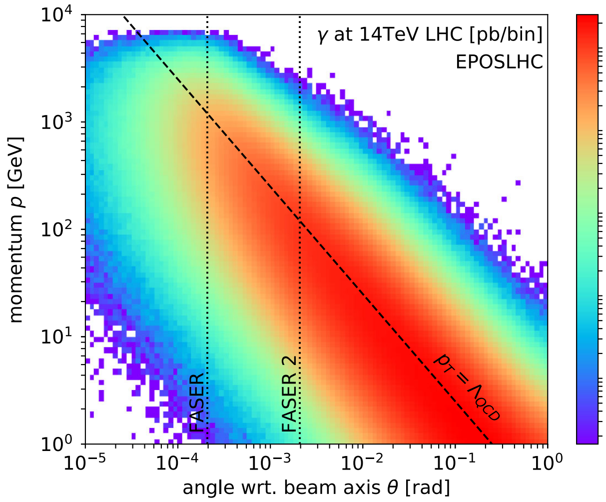

FIG. 2. Differential production rate of photons at 14 TeV LHC predicted by EPOS-LHC in the (θ, p) plane, where θ and p are the proton's angle with respect to the beam axis and momentum, respectively. The angular coverage for FASER and FASER 2 are indicated by the vertical dotted lines.

assume that photons are quickly absorbed once they leave the vacuum.

When passing these strong magnetic fields, the photons could oscillate into ALPs. The corresponding conversion probability can be written as [54]

$$P_{\gamma\to a} \simeq \frac{1}{2} \times \frac{g_{a\gamma\gamma}^2}{4} \left| \int dz \vec{B}(z) e^{iqz} \right|^2, \tag{2}$$

where we integrate the magnetic field coherently along the trajectory of the photon. The additional factor $1/2$ in front accounts for the fact that the photon beam is unpolarized and only the photons with a polarization parallel to the magnetic field can convert into ALPs since $F\tilde{F} \sim \vec{E} \cdot \vec{B}$. Here $q = E_\gamma - (E_\gamma^2 - m_a^2)^{1/2} \simeq m_a^2/(2E_\gamma)$ is the momentum transfer. In our case, the magnetic fields along a single photon's trajectory are piecewise constant which allows us to write

$$P_{\gamma\to a} \simeq \frac{g_{a\gamma\gamma}^2}{8} \left| \sum\nolimits_i \vec{B}_i L_i e^{iqz_i} \frac{\sin(qL_i/2)}{qL_i/2} \right|^2, \tag{3}$$

where $\vec{B}_i$ is the field strength of the dipole and quadrupole magnets seen by the photon, L_i is the length and z_i is the central position of each magnet. Using that the typical length of the magnets is $L \sim 100$ m and the typical energy of the photons is $E_\gamma \sim 1$ TeV, we can distinguish two relevant kinematic regimes. For small masses $m_a \ll \mathcal{O}(100)$ eV and hence $qL \ll 1$, the conversion takes place coherently along the full length of the magnetic field. This can be understood from the fact that the phase velocity of both the ALP and the photon are approximately the same and thus the probability amplitude of the conversion at any point interferes constructively with that in the rest of the conversion region. As a consequence of the probability being enhanced, scaling with the square of the length $\propto L^2$ and becomes mass independent. However, for large masses $m_a \gg \mathcal{O}(100)$ eV and hence $qL \gg 1$ the ALP and photon states do not remain in phase along all the conversion length. Hence, the probability becomes suppressed $P_{\gamma\to a} \sim 1/m_a^4$ and other production mechanisms become more dominant.

Eventually, the photons produced at the LHC will collide with elements of the LHC infrastructure and be absorbed. For very forward going photons, this occurs in the TAN neutral particle absorber, which is located at about 140 m downstream from the ATLAS interaction point. This provides a further opportunity for ALP production via the Primakoff process, in which the photon converts into an axion when interacting with nuclei in the target material. In the limit of small ALP masses m_a and small momentum transfer q, the corresponding cross section can be written as [55–57]

$$\sigma_{\mathrm{Prim}} \simeq \frac{g_{a\gamma\gamma}^2}{2} \alpha Z^2 \int F^2(q^2) d \log q = 9.8 \times g_{a\gamma\gamma}^2. \tag{4}$$

Here we have assumed that the target material is made of iron with atomic number $Z = 26$ and integrated the form factor $F(q^2)$ as is used in Refs. [56,57]. The photon to ALP conversion probability is given by

$$P_{\gamma\to a} = \frac{\sigma_{\mathrm{Prim}}}{\sigma_{\mathrm{conv}}} = 7.4 \times 10^{-4} \times (g_{a\gamma\gamma} \times \mathrm{GeV})^2, \tag{5}$$

where $\sigma_{\mathrm{conv}} \simeq 5$ barn is the conventional cross section for the photon interaction with the target material (dominated by pair production). At the LHC, this production mechanism dominates for high ALP masses $m_a > 1$ keV.

After the TAN neutral particle absorber, essentially all photons originating from the primary collision have been absorbed. The produced ALPs will then continue to propagate along the beam collision axis. Roughly 270 m downstream from the ATLAS interaction point, the LHC magnets start to deflect the beam to bring it on its roughly circular orbit and LHC tunnels curve away from the beam collision axis.

III. AXION DETECTION

To detect the produced beam of ultrarelativistic ALPs an additional magnetic field is needed to convert them back into photons. As we will see, the recently installed FASER experiment is already placed directly in the beam of LHC ALPs and equipped with a strong magnetic field to perform that task.

About 480 m downstream from ATLAS, the beam collision axis intersects with the service tunnel TI12.

This location provides a unique opportunity to access the beam of light and weakly interacting particles that are produced in the forward direction of the LHC [41]. The FASER experiment has recently been installed there to exploit this opportunity [41–43,58–60]. The main goal of FASER is to search for light long-lived particles at the LHC [41,61–64]. In addition, the experiment also contains the FASERν neutrino detector which will for the first time detect and study of TeV energy neutrinos produced at the LHC [65–67]. The FASER experiment will operate during LHC run 3, from 2022 to 2025, with an expected integrated luminosity of 150 fb^{-1}.

The experiment consists of a decay volume and tracking spectrometer which are placed inside an otherwise empty magnetized area of length of 3.5 m, diameter of 20 cm and field strength of 0.6 T. Located behind the spectrometer is a preshower detector [68] for photon identification and an electromagnetic calorimeter to measure the photon energy. FASER therefore already provides an ideal setup for ALP detection. The corresponding probability of ALP to photon conversion can be written as

$$P_{a\to\gamma} \simeq \frac{g_{a\gamma\gamma}^2}{4}\left|\int dz B(z) e^{iqz}\right|^2 = \frac{g_{a\gamma\gamma}^2}{4} B^2 L^2 \frac{\sin^2(qL/2)}{(qL/2)^2}. \quad (6)$$

Similarly to the production, the conversion probability is mass independent for small ALP masses and decreases for $m_a \gg 100$ eV. The expected signal then would be a single high energy photon in the preshower detector and electromagnetic calorimeter.[1]

A continuation of FASER's physics program during the HL-LHC era has been proposed in the context of the FPF [44,45]. The FPF would be a new cavern located about 620 m downstream from ATLAS where it will provide space for a variety of experiments and collect 3 ab^{-1} of data. In particular, this would include a larger version of the FASER detector, called FASER2. This detector is envision to be roughly 20 m long with an aperture of 2 m and a magnetic field of 1 T which would increase the ALP to photon conversion probability by roughly two orders of magnitude in comparison to FASER.

In addition to FASER2, the FPF contains three neutrino detectors: the emulsion based neutrino detector FASERν2, the electronic neutrino detector AdvSND and the noble gas neutrino detector FLArE. These could provide an additional opportunity for ALP detection, as these could also undergo the inverse Primakoff scattering process and convert into photons via collisions with the detector material. The signal would be a single highly energetic photon that emerges inside the detector. Perhaps the best suited detector for this purpose is FLArE as it provides timing capabilities, a high spatial resolution, particle identification capabilities as well as a good energy estimate. In particular, the particle identification would allow to distinguish photons and electrons, and hence suppress a possible background from neutrino electron scattering that would also provide an isolated electromagnetic shower. The FLArE detector is envisioned to have a 1 m × 1 m × 7 m target volume filled with liquid argon. The corresponding ALP conversion probability is given by

$$P_{a\to\gamma} = \sigma_{\mathrm{Prim}} n_{Ar} L = 0.028 \times (g_{a\gamma\gamma} \times \mathrm{GeV})^2, \quad (7)$$

where n is the number density of liquid argon nuclei and σ_{Prim} is the cross section for the Primakoff process defined in Eq. (4), which has now been evaluated for $Z = 18$.

IV. RESULTS AND DISCUSSION

We can now combine our previous results to estimate the sensitivity of the LSW setup at the LHC to probe ALPs.[2] For this, we compute the expected number of events as

$$N = \mathcal{L} \int dE \int d\theta \frac{d^2\sigma}{dE d\theta} \cdot P_{\gamma\to a}(E) \cdot P_{a\to\gamma}(E), \quad (8)$$

where $\mathcal{L}$ is the LHC's integrated luminosity, $d^2\sigma/(dEd\theta)$ is the double differential photon production cross section with respect to the photon energy and angle with respect to the beam axis, $P_{\gamma\to a}$ is the probability of photon to ALP conversion in the LHC infrastructure and $P_{a\to\gamma}$ is the probability of ALP to photon conversion in the detector. The angular integral is performed within the detector's angular acceptance. In order to obtain the sensitivity contours we require the number of events to be larger than 3 over the full run-time of the experiment for a point in the parameter space to be excluded at 95% confidence level. Here we use that the converted photons can be identified by FASER's electromagnetic calorimeter and preshower detector and assume that backgrounds can be reduced to a negligible level by the experiment's veto system. A more detailed discussion of possible background sources for the monophoton signature and how they can be rejected can be found in Ref. [69] in the context of sterile neutrino decays $N \to \nu\gamma$ arising in neutrino dipole portal models.

We present our obtained sensitivity on the ALP parameter space in Fig. 3 alongside existing constraints. In the left panel, we show the broad picture including all existing constraints on ALPs arising from helioscopes [70–73], haloscopes [74–98] and LSW experiments [99–104] (red);

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[1] An interesting characteristic of the photons produced via $a \to \gamma$ conversion in FASER is that they are linearly polarized in the direction of the magnetic field since $F\tilde{F} \sim \vec{E}\cdot\vec{B}$. However, this feature is not experimentally accessible at FASER and thus FASER cannot distinguish between a scalar and a pseudoscalar.

[2] A notebook containing this analysis has been added to the FORESEE package.

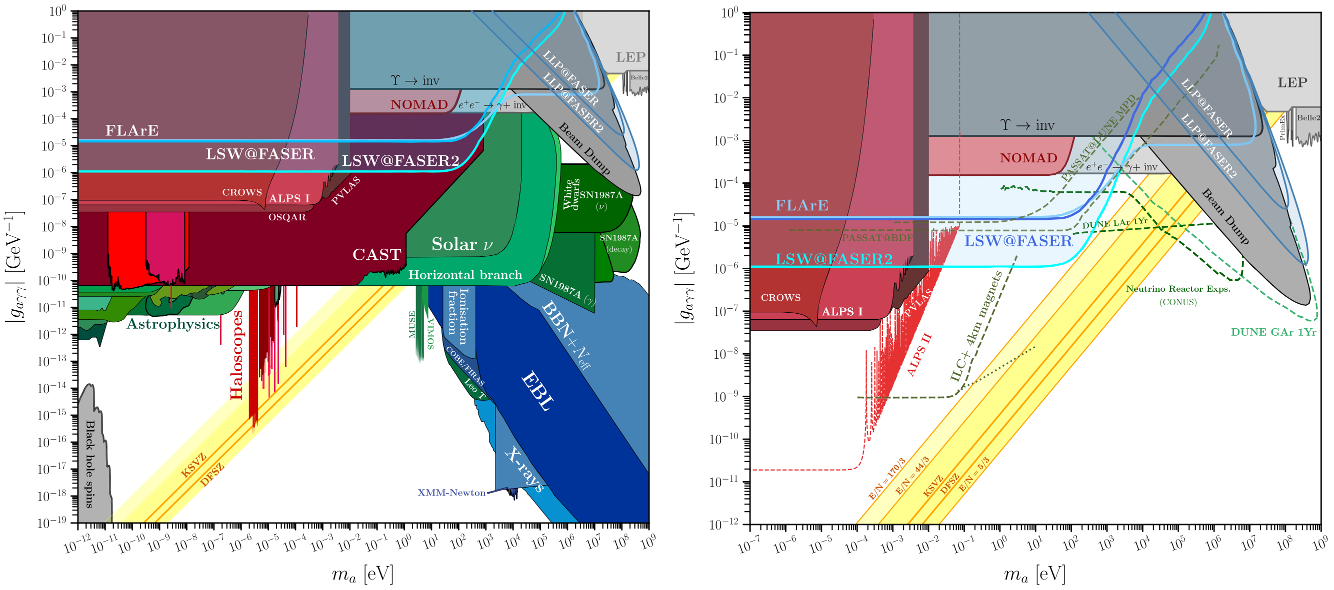

FIG. 3. Sensitivity projections of FASER, FASER2 and FLArE as a LSW experiment for ALP searches (shown as blue solid lines) as compared with all current ALP bounds (left) and only purely laboratory based bounds and projections (right). The theoretical predictions for different QCD axion models are shown in orange where $g_{a\gamma\gamma} = \alpha/(2\pi f_a)(E/N - 1.92)$ [159]. See text for details. We provide the data of the sensitivity projections of this work as arXiv ancillary files [160]. Existing experimental bounds adapted from AXIONLIMITS [161].

astrophysics[3] [37,107–141] (green); cosmology [38,142] (blue); and accelerator experiments [32,143–157] (gray). The projected sensitivity for searches at FASER and future experiments at the FPF is indicated by the blue solid lines. Even though the regions that can be explored by LSW searches at FASER and FASER2 are excluded by helioscopes, astrophysical or cosmological arguments, these searches will be able to probe regions of the parameter space that have not been explored by any purely laboratory based experiment. This is shown in the right panel, where we show the bounds from current ground-based experiments together with the projections of future experiments and proposals. Note that these experiments are based on different ALP detection strategies which do not rely on extra astrophysical or cosmological assumptions and thus can be considered especially robust. Classical LSW experiments such as ALPS [99], PVLAS [102], CROWS [100] and OSQAR [101] as well as a search at NOMAD [143] utilize the coherent conversion of ALPs into photons in an external magnetic field and are shown in reddish tones. In contrast, many high energy physics experiments look for the ALP decay into photons and thus are sensitive to heavier ALPs with larger couplings, as shown in gray tones. This includes both searches for long-lived ALPs at beam dump experiments such as CHARM [149], E141 [150,151], E137 [152,153], NuCal [32,154,158] and NA64 [155] as well as resonance searches for promptly decaying ALPs at Belle 2 [156], PrimEx [157] and LEP [144–148].

As explained in the previous section, our LSW proposal at the LHC benefits from both the coherent conversion in the external magnetic fields and the Primakoff conversion via scattering with nuclei in the target material. The LSW@FASER line corresponds to the reach of the currently installed FASER detector, while LSW@FASER2 represents the reach that will be achieved by the future FASER2 detector at the FPF. Similarly to other LWS experiments it is easy to understand the shape of the bound. For small ALP masses, $m_a \ll \mathcal{O}(100)$ eV the factor $qL \ll 1$ and the conversion probability in Eq. (3) becomes independent on the ALP mass giving rise to a flat bound on $g_{a\gamma\gamma}$. For higher ALP masses, $qL \gg 1$, the coherence is lost and the probability is suppressed by $1/m_a^8$ (the suppression factor $1/q^2 \sim E_\gamma^2/m_a^4$ arises both at production and detection). The bound on $g_{a\gamma\gamma}$ thus grows as $\propto m_a^2$. For even larger masses, the Primakoff conversion in nuclei becomes the dominant ALP production channel; therefore one of the suppression factors disappears and the bound on $g_{a\gamma\gamma}$ grows only as $\propto m_a$. Furthermore, we also show the projections for the neutrino detector FLArE that will be installed as part of the FPF and could detect the ALPs via Primakoff conversion in nuclei and becomes dominant for larger masses. At large masses $m_a \gtrsim 10$ keV, both the production and detection proceeds through the Primakoff process and the sensitivity in $g_{a\gamma\gamma}$ becomes independent of the ALP mass. At high masses and large couplings the ALP lifetime becomes so small that the majority of ALPs decay before

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[3] The supernova bounds are taken from Refs. [37,105,106] and should be considered conservative regarding the upper end of the bound that corresponds to the trapping limit [37].

reaching the detector, hence limiting the reach at FLArE. ALP decays within the detector volume also provide an additional search channel that has been investigated in Refs. [63,64]. The corresponding reach of these long-lived particle searches is shown by the LLP@FASER and LLP@FASER2 lines.

For comparison, we also show the projected sensitivity of other proposed searches and experiments for ALPs as dashed lines in Fig. 3. Using a high intensity LASER beam and optical resonant cavities, the ALPS II experiment [104] plans to probe ALP masses smaller than $\sim 10^{-4}$ eV with exceptional sensitivity down to couplings of $\sim 2 \times 10^{-11}$ GeV^{-1}. A proposal to probe higher masses has been recently put forward in Ref. [162] for the International Linear Collider (ILC) [163] using the photon beam that would be required for positron production followed by 4 km of 1 T magnets (adding up conversion and reconversion lengths). As for the configuration of the magnetic field, on top of the uniform case they also consider nonhomogeneous (or *wiggled*) magnetic field profiles which improve the sensitivity for higher ALP masses $m_a \gtrsim 0.1$ eV (shown with a dotted line). In addition, the authors of Refs. [164,165] have proposed a class of experiments dubbed PASSAT which use helioscope magnets as detectors for ALPs produced via Primakoff effect at the target of beam dump experiments. In Fig. 3, we show two realizations of this idea, one using the CAST magnets placed at the proposed beam dump facility (BDF) and one using the multipurpose detector (MPD) of the proposed DUNE experiment. To probe ALPs with even higher masses, several searches for their interactions via inverse Primakoff scattering as well as their decays at neutrino experiments have been proposed. We show the corresponding sensitivity both for CONUS as an example of coherent elastic neutrino scattering experiments at nuclear reactors [166] as well as DUNE as an example of high energy accelerator experiments [33]. Further searches for the decay of long-lived ALPs have also been proposed for other beam dump type experiments, see Ref. [32] or Ref. [167] for recent reviews.

Regarding the possible UV complete models that FASER as a LSW experiment will be able to explore, we find that the projections are not able to reach the KSVZ and DFSZ axion benchmarks and they barely touch the preferred QCD axion window [168–170], which is illustrated by the diagonal yellow shaded region. Therefore this proposal mainly probes other axionlike particles. Nonetheless, FASER could still probe QCD axions that solve the strong *CP* problem in the context of photophilic axion models where the axion coupling to photon is enhanced [171–173] or the $Z_{\mathcal{N}}$ axion model [174–176] where the axion mass is suppressed.

Another interesting feature of our proposal is the ability of measuring the ALP mass given a positive signal. Both helioscopes and LSW experiments provide the best bounds in the maximum coherence limit $qL \ll 1$ and when that condition is fulfilled they are not sensitive to the ALP mass. However, for ALP masses such that $qL \sim 1$ the conversion probability depends on the energy of the photon [as one can see by substituting $q \simeq m_a^2/(2E_\gamma)$ in Eq. (6)]. This oscillatory behavior as a function of the photon energy depends on the axion mass and thus may allow to extract it [177,178]. Our proposal is most competitive in the region where the ALP-photon conversion is suppressed due to the loss of coherence $qL \gtrsim \mathcal{O}(1)$ and therefore in the hypothetical scenario of a positive detection we could benefit from the excellent energy resolution of the FASER calorimeter [43] of about 1% to extract the ALP mass.

It is also worth emphasizing that the coherent ALP-photon oscillation in a magnetic field could be relevant for other ALP searches where the ALP couples not only to photons but also to other particles such as electrons or heavy electroweak gauge bosons. For example, some searches could use coherent conversion for ALP production and ALP decay or scattering via the coupling to electrons for detection. Alternatively, ALPs could be produced through another mechanism (e.g. rare meson decay via the ALP coupling to electroweak gauge bosons or quarks) and be detected via coherent conversion [30,179,180].

Regarding the outlook and possible improvements of this idea, there exist several techniques that could enhance the reach of this proposal and have already been proposed in the past for helioscopes or LSW [181,182]. One option is the use of a buffer gas in the conversion cavity that generates an effective photon mass that maintains the coherence of the oscillation for larger masses. Another option is the use of nonhomogeneous magnetic field [162,181] or the use of resonant cavities in the conversion chambers [54,99,183]. Although it does not seem trivial to implement the buffer gas and the resonant cavity improvements for such energetic photons, the use of nonhomogeneous magnetic field profiles might be a viable option at the FPF.

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