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A LIGHT DARK MATTER PORTAL: THE AXION-LIKE PARTICLE

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Abstract

This article presents the Axion-like Particle (ALP) as a possible candidate for a portal to a light dark sector, with a special focus on the ALP research and phenomenology at accelerators such as PADME (Positron Annihilation into Dark Matter Experiment) at the Laboratori Nazionali di Frascati (LNF) of INFN.

1 Introduction

Cosmological and astrophysical evidence provides proofs of Dark Matter (DM) in a wide range of distance scales. If we assume that DM is a particle, we can affirm that none of the Standard Model (SM) particles is a good candidate. It is believed that Dark Matter is a manifestation of an entire Dark Sector (DS). The DS would be comprised of new particles not charged under SM gauge groups, and possibly new forces, linked with visible sector by a mediator known as *portal*. The simplified models are representative of a broader class of more complex UV-models considering few and relevant parameters, especially the portal, where the new terms in the Lagrangian should be renormalisable, and respect the Lorentz invariance, SM gauge invariance as well as the DM stability. This approach points out the importance of the portal as a door towards the dark sector because it opens the possibility to directly produce the mediator.

As alternative to the most famous candidate, the WIMP[1], the exploration of the hidden sector is well-motivated. Here the DM is lighter and/or much more weakly interacting (*feebly*) than usually

[1] The Weakly Interactive Massive Particle (WIMP) is a particle thermally produced in the early universe, with mass in the range GeV-TeV and annihilation cross-section at electroweak scale in order to produce the observed relic density [1], $\Omega_{DM} h^2 = 0.1198 \pm 0.0015$.

assumed. These models could be an harbinger of new physics sector at a scales which would be experimentally inaccessible in WIMP searches. Therefore we need a high intensity source to produce light DM particle at a detectable rate. The search for new physics in low mass and coupling range is known as the *low-energy high-precision frontier*.

There are different candidates of portals for sub-GeV dark sectors, according to the nature of the particle [2]. This paper will consider a spin-0 mediator called Axion-like Particle and in particular the ALP production with e^+e^- annihilation at accelerators.

2 The Axion-like Particle

The axion-like particle is a light pseudoscalar particle, singlet under the SM gauge group, with a derivative coupling to the Standard Model. In essence, it is a pseudo Nambu-Goldstone boson of a general new spontaneously broken global symmetry. It is mainly motivated by string theories [3], or proposed in many extensions to the SM to address open problem as Strong-CP Problem [4] or Hierarchy Problem [5], as well as a possible solution for the muon magnetic moment anomaly [6]. It is not necessarily the QCD axion particle, so mass and couplings are independent parameters. For this reason ALPs scan a wide mass range: at masses below MeV scale they can have implications for cosmology and astrophysics [7], at masses larger than MeV scales they have interesting implications for particle physics. Consequently ALPs can have a different role in dark sector: a dark matter as weakly interactive *slim* particle (WISPy) [8] or as portal, respectively. This work will consider the latter hypothesis.

The effective Lagrangian that describes the simplified model considered is

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}M_a^2 a^2 - \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu} - g_{a\psi\bar{\psi}}\partial_\mu a \bar{\psi}\gamma_\mu\gamma_5\psi + \mathcal{L}_{DM} \tag{1}$$

where the fourth term describes the interaction between the axion-like particle and the photons; $\tilde{F}_{\mu\nu}$ is the dual of electromagnetic strength $F_{\mu\nu}$; and the fifth term, assuming a leptophilic ALP, provides the interaction with the electrons, so $\psi \equiv e$ where e is the electron field[2]. The couplings $g_{a\gamma\gamma}$ and g_{aee}, which are real and dimensionful, and the ALP mass M_a are the free parameters to constraint with accelerators. The DM interaction will not be considered here.

3 ALP Production at accelerators

Over the past few years an increasing interest for experimental searches at accelerators has been given to ALPs in this mass range. In this work an ALP phenomenology in PADME [9] experiment will be described. The PADME setup (for more details about the experimental setup see [10]) is shown in fig.1.

Basically PADME searches the light dark particle (ALP as well as dark photon [9] [11]) using a positron beam on a thin diamond target, detecting the SM photon produced in the annihilation reaction: $e^+e^- \to \gamma + X$ where X is the light dark particle. The experiment aims to measure a peak in the missing mass spectrum for the invisible decay: $M^2_{miss} = (P_{e^+} + P_{e^-} - P_\gamma)^2$ where P_i are the 4-impulse of positron, electron and final photon respectively. The four momenta are reconstructed by knowing initial positron beam energy and position thanks to the active target, and measuring final photon energy and angle of recoiling thanks to 616 BGO crystals of the Electromagnetic Calorimeter (ECAL) and 25 PbF_2 crystals of Small Angle Calorimeter (SAC). The electron and positron coming from background processes,

[2]Developing the partial derivative, the fifth term can be written as $m_e g_{aee} a \bar{e}\gamma_5 e$.

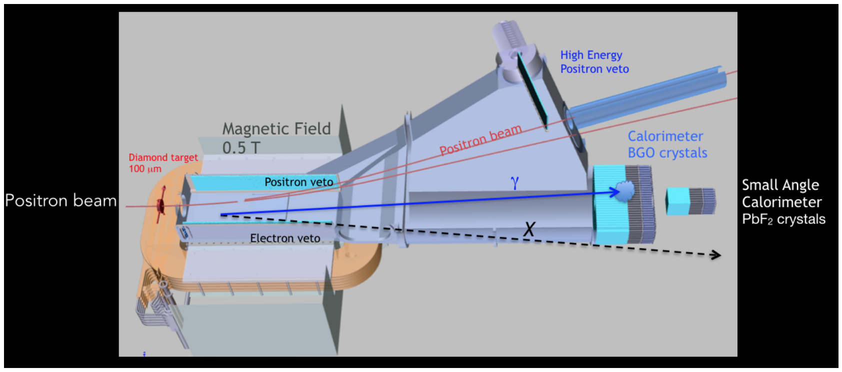

Figure 1: *Schematic view of the PADME setup.*

Bremsstrahlung or Bhabha scattering, or decaying particle, are bended from a dipole magnet of 0.49 T in which is integrated a P/E veto system.

At accelerators, after having produced the ALP from e^+e^- annihilation, two techniques of detection exist based on its mass range: for $M_a < 2M_{DM}$, the ALP decays to 2γ or e^+e^- pair, the so-called *visible* decay. The experimental signature is given by 3γ or a pair of e^+e^- plus an in-time photon; for $M_a > 2M_{DM}$ the ALP decays to DM-DM or for long-lived ALP, the so-called *invisible* decay. The observable of this process is a photon plus missing energy/momentum/mass according to the technique of the experiment.

The strategy for the dark particle identification is model-independent, unless the leptophilic assumption: only one cluster in ECAL, energy between $E_\gamma < 400\,\text{MeV}$ for pile-up and $E_\gamma > 30\,\text{MeV}$ for Bremsstrahlung, no signal in veto system (within $\pm 2\,\text{ns}$), no cluster in SAC with energy above 50 MeV for residual 3γ events.

3.1 Cross-Section of positron-electron annihilation into ALP-photon at PADME

Taking into account the Lagrangian in eq.1, the production of ALP plus one photon from e^+e^- annihilation comes through two different Feynman diagrams: *s-channel* with photon mediator, and *t-* and *u-channel* with electron mediator, see fig.2.

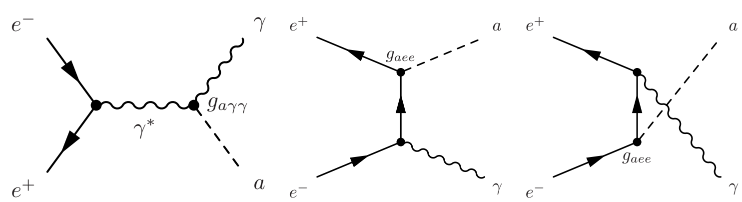

Figure 2: *Feynman diagrams of* $e^+e^- \to a + \gamma$*: (a) s-channel photon mediator; (b) t-channel and (c) u-channel electron mediator.*

The different contributions of the diagrams at the total cross-section are reported in the following plot (fig.3): in the left side the couplings are set to one, in right side the cross-sections are weighting the single contribution with opportune couplings according to the current limits [12] [13]. In these plots the

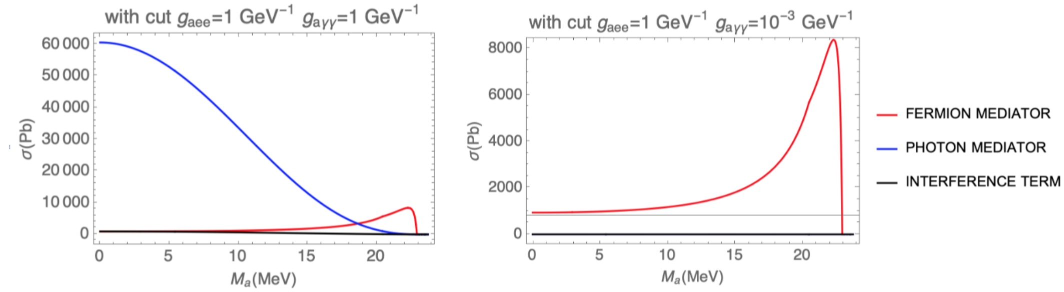

Figure 3: *Cross-sections as a function of the ALP mass setting the energy of the incident positron at* 550 MeV*, angular acceptance* $0.026 < \theta(\text{rad}) < 0.083$ *and photon energy threshold* $E_\gamma > 30\,\text{MeV}$*. "Fermion mediator", "Photon mediator" and "Interference term" corresponds to: left)* $g_{aee} = 1\, g_{a\gamma\gamma} = 0$*,* $g_{aee} = 0\, g_{a\gamma\gamma} = 1$ *and* $g_{aee} = 1\, g_{a\gamma\gamma} = 1$ *respectively, right)* $g_{aee} = 1\, g_{a\gamma\gamma} = 0$*,* $g_{aee} = 0\, g_{a\gamma\gamma} = 10^{-3}$ *and* $g_{aee} = 1\, g_{a\gamma\gamma} = 10^{-3}$ *respectively. All the couplings have dimension* GeV^{-1}.

positron beam energy at 550 MeV, the angular acceptance of ECAL ($0.026 < \theta(rad) < 0.083$) and the threshold gamma energy $> 30\,\text{MeV}$ are set.

The s-channel diagram would be the dominant contribution at the cross-section at small masses, while the fermion mediator increases more approaching to kinematical limit of $M_a = 23.7\,\text{MeV}$. But taking into account the current limit on couplings, the fermion mediator is apparently the only relevant channel in all mass range. However $g_{a\gamma\gamma}$ constrians found in literature [12)] are a naive recast of previous dark photon data. So a detailed study of detector acceptances and efficiencies is required before closing the parameter space area. The PADME analysis aims to fix direct limits on these couplings.

The probability that a single positron annihilate in the following process $e^+e^- \to \gamma + a$ in PADME is given by $N_e\sigma_{e^+e^-\to a+\gamma} = 6 d_t N_A \frac{\rho}{A}\sigma$, with N_e the total number of electrons in a unit surface area of target. These is found considering $d_t = 100\mu\text{m}$ target thickness, N_A Avogadro number, $\rho = 3.5\,\text{g/cm}^3$ diamond density, $A = 12\,\text{g/mol}$ atomic mass. Assuming 2-years of data taking at 60% efficiency with bunch length of 200 ns, at 49 Hz and 20k e^+/bunch, we will collect around 10^{13} Positron-on-Target (POT). As is showed in fig.4 for $g_{aee} = 1$ and $M_a = 22\,\text{MeV}$ we expect around 1000 events.

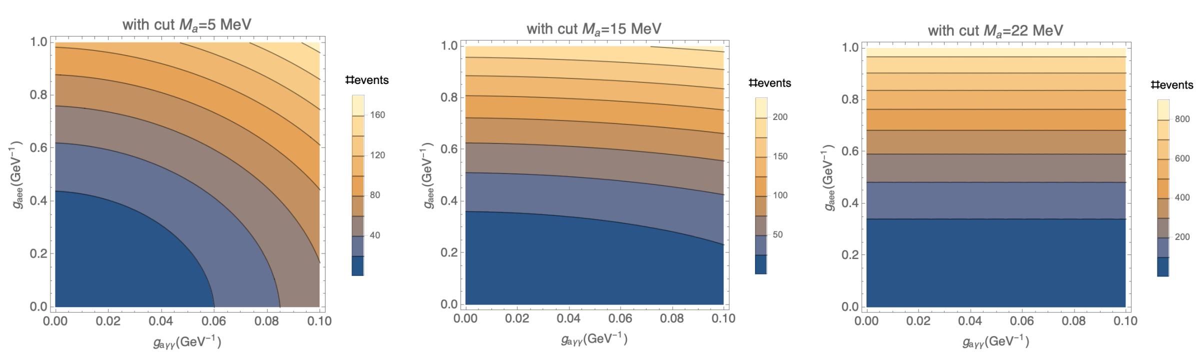

Figure 4: *Values of* g_{aee} *and* $g_{a\gamma\gamma}$ *couplings needed to get the number of events showed in the gradient color for three different ALP masses,* $M_a = 5, 15, 22\,\text{MeV}$.

3.2 ALP decays

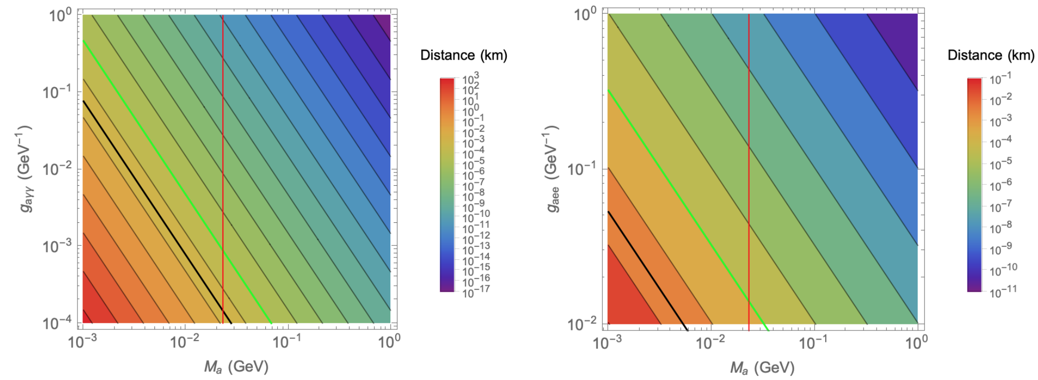

Figure 5: *Parameter Space analysis from ALP decays. Left: the grandient color is the values of decay length from $a \to \gamma\gamma$ for photon-ALP coupling $g_{a\gamma\gamma}$ in function of M_a; Right: the grandient color is the values of decay length from $a \to e^+e^-$ for fermion-ALP coupling g_{aee} in function of M_a. The red line represents the center-of-mass of experiment. The green line is the limit,* 10 cm*, for having the visible decay mode. The black line is the size of experiment,* 3.7 m.

In order to study the phenomenology of ALP in PADME, an analysis of the decay width of ALP in $\gamma\gamma$ and e^+e^- is needed:

$$\Gamma_{a\to\gamma\gamma} = \frac{g_{a\gamma\gamma}^2 M_a^3}{64\pi}, \quad \Gamma_{a\to e^+e^-} \simeq \tfrac{g_{aee}^2 M_a m_e^2}{8\pi} \tag{2}$$

Considering the boost $\gamma_a \simeq E_a/M_a$ with E_a the ALP mass, the decay length is $L_{a\to ij} = \gamma_a \hbar c/\Gamma_{a\to ij}$. In fig.5 a parameter scan (couplings vs ALP mass) is showed where the gradient color is the decay length of ALP in km. Only the regions to the left of the red line, the kinematical limit $M_a < 23.7\,\text{MeV}$, are accessible to PADME. For a detector size $L_D = 3.7\,\text{m}$ (black line), in the bottom left corner the ALP leaves the detector before decaying and the invisible decay mode can be explored. Conversely, above the green line (set at 10 cm), the particle decays close to the point of annihilation and the final decay products, such as 2γ or e^+e^- pair, can be easily detected. Unfortunately the PADME veto measures only the absolute value of the momentum and not the direction, consequently the peak in the $M^2_{e^+e^-}$ distribution cannot be reconstructed, but installing a good spectrometer could be a future upgrade of PADME. In the middle region it is difficult to discriminate the signature and a tricky analysis is required.

4 Conclusions

After many years of high-energy accelerators, high-luminosity and ultra-sensitive detectors are investigating new and low energy scales of Dark Sector. A good candidate as pseudoscalar mediator is the axion-like particle. ALP is a generalisation of QCD axion with free mass and couplings. The PADME experiment is testing new physics at MeV-scales and it could produce a light portal, as the ALP, searching a peak in missing mass distribution. The analysis is new because both interactions, with photons and fermions, have been considering. The cross-section of $e^+e^- \to \gamma + a$ suggests that the fermionic mediator gives the dominant contribution since g_{aee} is not strong constrained by current limits. However, even if the photon coupling window is opened only around 10^{-3}, the constraints are only an approximation since they are a recast of dark photon analysis. PADME are exploring directly these regions. PADME is able to produce a relevant number of event. A direct analysis of acceptances is planning through computational tools such as MADGRAPH, and then later, to evaluate the experiment sensitivity for the invisible ALP decays, Monte Carlo simulations with GEANT4 will be performed. Data taking is started at the beginning of October 2018 for four months and we have collected $\sim 10^{12}$ POT. A run II is planned at the end on 2019 in order to reach $\sim 10^{13}$ POT.

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