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Probing the dark sector with PADME

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Summary. — Among the theoretical models addressing the dark matter problem, the category based on a secluded sector is attracting increasing interest. The PADME experiment, at the Laboratori Nazionali di Frascati (LNF) of INFN, is designed to be sensitive to the production of a low mass gauge boson A' of a new $U(1)$ symmetry holding for dark particles. The "dark photon" is weakly coupled to the photon of the Standard Model, and it provides an experimental signature for one of the simplest implementation of the dark sector paradigm. The DAΦNE Beam-Test Facility of LNF will provide a high intensity, mono-energetic positron beam impacting on a low Z target. The PADME detector will measure with high precision the momentum of the photon, produced along with A' boson in e^+e^- annihilation in the target, thus allowing to measure the A' mass as the missing mass in the final state. This technique, particularly useful in case of invisible decays of the A' boson, will be exploited for the first time in a fixed target experiment. Simulation studies predict a sensitivity on the interaction strength (ϵ^2 parameter) down to 10^{-6}, in the mass region $1\,\text{MeV} < M_{A'} < 23.7\,\text{MeV}$, for one year of data taking with a 550 MeV beam. In 2018 the first run will take place, and early data will give the opportunity to compare the detector performance with the design requirements.

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1. – Introduction

Understanding the composition of the universe is one of the most important challenges in modern physics. Astrophysical observations demonstrate that baryonic matter is a small constituent of the universe total mass, and that we know nothing about the dominant constituent that we call "dark matter" (DM). The nature of dark matter is actually unknown, and there are several different candidates and interactions able to explain observations ranging many orders of magnitude in mass, from many solar masses to a tiny fraction of an eV, and coupling strengths, from the electromagnetic constant down to 10^{-16} or lower. One of the most considered possibilities is that DM is made of non Standard Model (SM) massive, several GeV, particles weakly coupled to ordinary matter, the so-called "Weakly Interacting Massive Particle" (WIMP). A strong effort has been put in the last two decades into probing this hypothesis, using both underground scattering experiment and high energy accelerators. Unfortunately, no convincing evidence of the existence of WIMPs has been found so far. The possibility that dark matter is lighter than the weak scale, is recently reviving as a compelling solution to the dark matter puzzle.

2. – The dark sectors and the dark photon

One class of models addressing the possibility that dark matter mass is below the weak scale ($M_{DM} < 1$–10 GeV) are the so called "dark sector" (DS) or "secluded sectors" models. In this paradigm the dark matter is decoupled from the SM matter, and just one or few new particles having SM and dark sector charges, called "mediators", are able to connect the dark sectors to the ordinary matter through a new interaction called "portal interaction". Assuming that this new interaction needs to respect SM symmetries, few possibilities have been identified for the mediator particle: it can be a scalar, a pseudoscalar, a fermion, or a vector.

A particularly rich phenomenology attracted the experimental and theoretical attention in the last few years on the vector portal interaction [1]. The most general interaction of an electrically neutral vector particle A with the Standard Model fermions can be written in the form of a $U(1)$ interaction. Its mediator will be a massive "photon like" particle which couples to SM with a strength ϵe called Dark Photon (DP) or A'.

The origin of the coupling of A' to the fermion fields could arise in various models. Since almost any extension of the Standard Model introduces new symmetries and gauge groups, the wide range of possibilities go from maximally universal models to the ones including a single type of fermions or even a single lepton generation [2].

The experiments searching for A' at accelerators rely on its coupling to SM particles, primarily electrons and quarks, to produce them at colliders or in fixed target collisions. In a well motivated and general scenario, the coupling arise from the "kinetic mixing" interaction, which mixes the A' boson of the non-SM "dark" gauge group $U(1)_D$ with the SM photon,

$$\mathcal{L} = \frac{1}{2}\epsilon F^{\mu\nu}F'_{\mu\nu}, \tag{1}$$

where ϵ is a dimensionless parameter while $F^{\mu\nu}$ is the tensor of the SM $U(1)_{em}$ and $F'_{\mu\nu}$ of the dark $U(1)_D$ respectively. Due to the mixing with the standard model photon, the DP can be produced in electromagnetic processes similar to those in the SM. The most

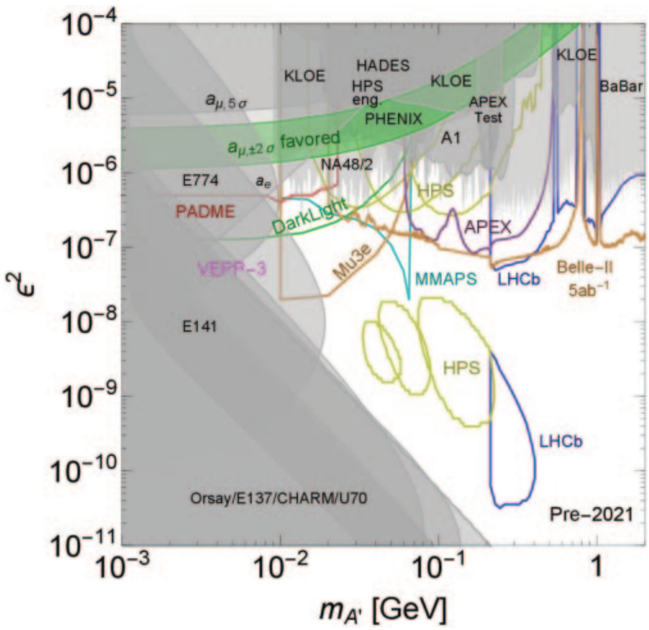

Fig. 1. – Status of DP visible decay searches $A' \to \ell^+\ell^-$ [2]. Filled area are already excluded while lines represent projections for future dedicated searches.

considered are: emission of A' in electron bremsstrahlung (A'-strahlung), $e^+e^- \to \gamma A'$ annihilation, and mesons decays with photons in the final state ($\pi^0 \to \gamma A', \eta \to \gamma A'$).

Due to its coupling to SM fermions, if no dark sector decay channels exist, A' will decay to any SM lepton (mostly electrons and μ) or meson (dominantly pions). In this case the A' will be long lived and can be detected by searching for electron or muon pairs in accelerators and beam dump experiments. A significant combined effort of colliders, fixed target, and dump experiments led to the conclusion that the coupling strength to fermion ϵ^2 is lower than 1×10^{-6} for A' masses below 1GeV as shown in fig. 1.

A more exciting hypothesis postulates the existence of dark fermions χ with masses lower than half of the A' mass, thus allowing decays to dark matter, the so called "invisible decays". In this scenario, being the coupling of A' to dark matter $\alpha_D \gg \epsilon$, all the constraints coming from lepton decay searches can be evaded and the parameter space looks much less constrained as shown in fig. 2.

3. – The PADME experiment at LNF

The PADME experiment [3,4] at the DAΦNE LINAC of the INFN Laboratori Nazionali di Frascati (LNF), has been designed to search for the A' invisible decays by using a positron beam hitting a thin diamond target. The A' can be detected by searching for a narrow unexpected peak in the spectrum of the missing mass measured in single photon final states. The measurement requires the precise determination of the 4-momentum of the recoil photon and of the impinging positron. In order to precisely measure the primary positron momentum, a dedicated beam monitor based on silicon pixel technology has been designed for the Beam Test Facility of the DAΦNE linac. The experiment is currently taking data at the DAΦNE Beam Test Facility and aims to col-

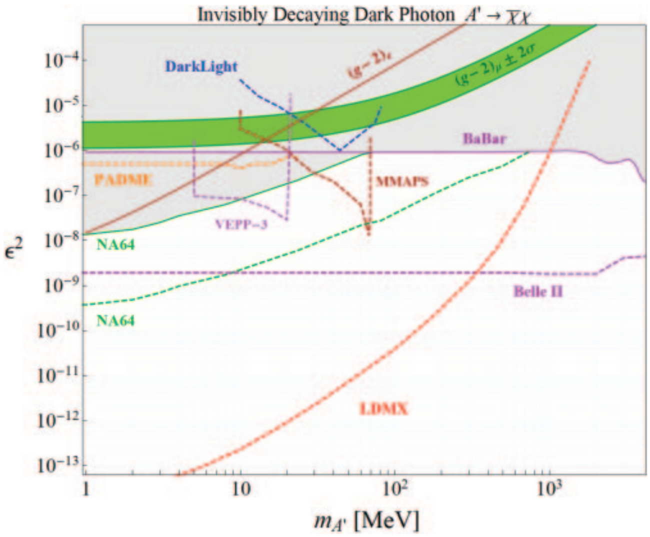

Fig. 2. – Status of DP invisible decay searches $A' \to \chi\bar{\chi}$ [2]. Filled area are already excluded while dashed lines represent projections for future dedicated searches.

lect $\sim 10^{13}$ positrons on target by the end of 2019. The PADME experiment shown in fig. 3 will use a 550 MeV positron beam impinging on a 100 μm thick active target made of polycrystalline diamond [5]. The recoil photons from $e^+e^- \to \gamma A'$ annihilation process will be detected by a quasi-cylindrical electromagnetic calorimeter (ECal) made of 616 $21 \times 21 \times 230$ mm^3 BGO crystals, located 3.3 m downstream the target, providing very precise energy and position measurements. The ECal also serves as multi-photon final states veto, to reject positron annihilation into two and three gamma events. The non-interacted beam positrons, will be deflected outside the acceptance of the calorimeter by a 1 m long dipole magnet with a 26 cm vertical gap. Three different sets of plastic scintillator bars, two of which located inside the magnet, will serve to detect the charged

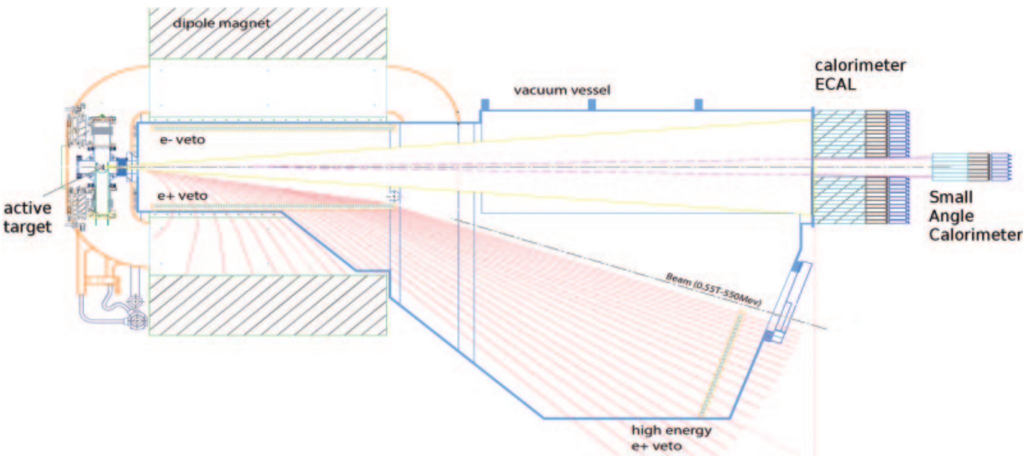

Fig. 3. – Schematics of the PADME detector.

particles, thus providing an efficient veto for the positron bremsstrahlung background. The veto detectors are located on both sides with respect to the beam axis, as shown in fig. 3, and thanks to the magnetic field allow to distinguish electrons from positrons originated from the target. In addition, a very fast small angle calorimeter will be placed along the beam axis, in order to suppress the residual three photon annihilation background with a forward energetic photon. The entire setup, except the two calorimeters, will be located in vacuum to minimise the possible beam-residual ga interactions.

4. – The PADME experiment sensitivity

The PADME experiment sensitivity estimate is based on a GEANT4 simulation extrapolated to 10^{13} positrons on target (POT) [4]. This number of particles can be obtained by running PADME for 2 years at 50% efficiency with 5000 e^+ per 40 ns bunch at a repetition rate of 49 Hz. A recent upgrade of the DAΦNE LINAC gun allows to extend the bunch length duration up to 200 ns, when the LINAC is operated in dedicated mode. In this conditions a data sample of 1×10^{13} POT can be obtained in 6 months while in 2 years a sample of 4×10^{13} POT is within reach. The bounds obtained for A' decaying into invisible particles, shown in fig. 4, are obtained after a detailed background evaluation including positron bremsstrahlung, two and three gamma annihilation. Signal events for different values of the A' mass, obtained using the CalcHep simulation tool, have been used to evaluate signal acceptance. The red line shows the expected bound for 1×10^{13} POT while the red dashed line shows the one for 4×10^{13} POT. The favoured $(g\text{-}2)_\mu$ region can be explored in a model independent way (the only hypothesis is that A' couples to leptons) up to masses of 23.7 MeV [4].

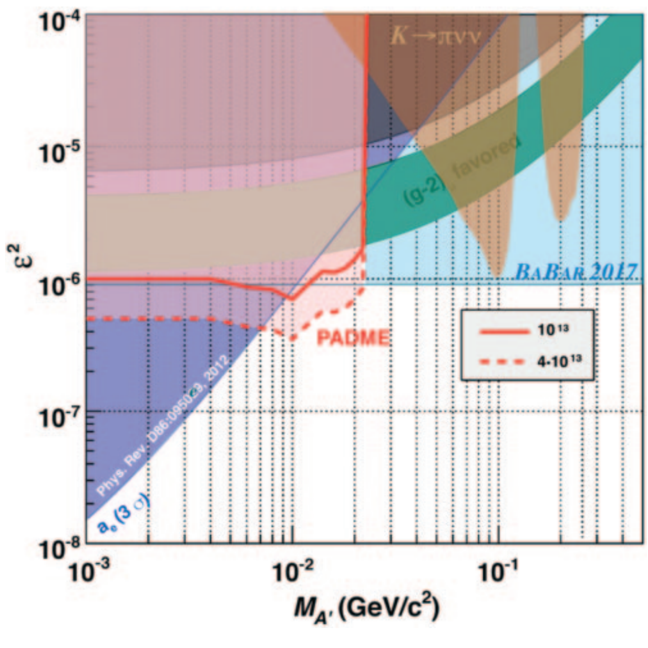

Fig. 4. – PADME estimated sensitivity for A' decaying into invisible particles for different values of the integrated luminosity.

5. – The ^{8}Be anomaly at PADME

In 2016 an anomaly on the angular distribution of e^+e^- pair produced in the decays of an excited state of ^{8}Be has been observed at the Atomiki Laboratory in Hungary [6]. Among the possible interpretations of the origin of the anomaly it has been pointed out by Feng *et al.* that the existence of a slightly modified dark photon, called X-boson, could reconcile the anomaly evading existing experimental constraints [7]. The mass of such a new particle, $\sim$17 MeV, is within reach for the PADME experiment, that will be able to detect its decay into electron-positron pair using the plastic scintillators based charged particle veto detectors. The capability of PADME to explore the still unconstrained parameter space could be boosted by exploiting the unique capability of the DAΦNE Beam Test Facility to provide positrons at the energy $\sim$ 282.7 MeV necessary to produce the 17 MeV mass X-boson through resonant annihilation [8]. Modifications of the PADME apparatus to optimise the sensitivity to the X-boson are currently under study.

6. – Conclusions

The PADME experiment started its data taking in October 2018 at the DAΦNE Beam Test Facility. The main goal of the experiment is to search for the invisible decays of A' in the mass region below 24 MeV. Exploiting the capability of detecting photon and charged particles, the PADME experiment will be also able to explore different types of dark sector scenario such as axion-like particles, proto-phobic X-boson, and Dark Higgs.

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