The PADME experiment at INFN LNF

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Abstract. At the end of 2015 INFN has formally approved a new experiment, PADME, to search for invisible decays of the A' dark photon at the DAFNE Linac in Frascati. The experiment is designed to detect the A' produced in positron-on-fixed target annihilation, by measuring the final state missing mass. The collaboration aims to complete the design and construction of the experiment by the end of 2017 and to collect $\sim 10^{13}$ positrons on target by the end of 2018, thus allowing to reach a sensitivity on the ε coupling constant of $\sim 10^{-3}$ and on the dark photon mass up to ~ 23.7 MeV/c^2

1. Introduction

The long standing problem of reconciling the cosmological evidence of the existence of dark matter with the lack of any clear experimental observation of it has recently revived the idea that these new particles are not directly connected with the Standard Model (SM) gauge fields, but only through mediator fields or portals, connecting our world with new secluded or hidden sectors. One of the simplest models just adds an additional U(1) symmetry, with its corresponding vector boson A'. All SM particles will be neutral under this symmetry, while the new field will couple to the charged particles of the SM with an effective charge εe. For this reason the A' is also called Dark Photon (DP)[1, 2]. Additional interest arises from the observation that A' in the mass range 1 MeV/c^2 to 100 MeV/c^2 and coupling $\varepsilon \sim 10^{-3}$, would justify the discrepancy between theory and observation for the muon anomalous magnetic moment, $(g-2)_\mu$ [3].

If there are no particles in the hidden sector with mass smaller than one half of A' boson, the dark photon can only have SM decays (visible decays). Currently, the region of the ε, $m_{A'}$ plane favored by $(g-2)_\mu$ discrepancy is excluded for an A' boson decaying into SM particles (see Fig.1 left). In the most general case the A' can decay into Dark Matter (DM) invisible decays. In this scenario, there are still unexplored regions in the $(g-2)_\mu$ favored band, as shown in Fig.1 right.

A comprehensive overview of the experimental programs on this field is presented in [6].

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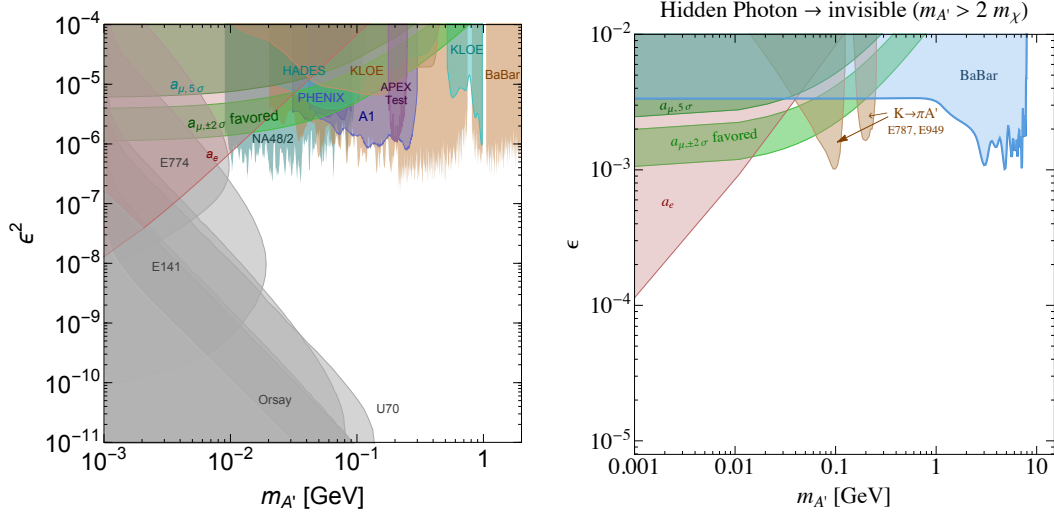
Figure 1. Current DP search status: on the left for visible decays (adapted from [4]), on the right for the invisible ones (adapted from [5]). Typical DP exclusion plot have the A' mass on the x-axis and the coupling constant (squared) on the y-axis. In both cases the 2σ anomalous muon magnetic moment favored band is indicated.

2. The PADME experiment

At the end of 2015, INFN has formally approved a new experiment, PADME, to search for invisible decays of the A' at the DAΦNE Linac of the Laboratori Nazionali di Frascati (LNF). PADME (Positron Annihilation into Dark Mediator Experiment) is designed to detect invisible decaying DPs produced in the process $e^+ e^- \to A' \gamma$, where the e^+ are accelerated by the DAΦNE LINAC to 550 MeV and interact with e^- in a fixed target [7, 8].

3. The Frascati Beam Test Facility

PADME will be built in the Beam Test Facility (BTF) experimental hall, hosting a transfer-line from the DAΦNE LINAC [9]. The BTF is able to provide up to 50 bunches/s with a maximum energy of 550 and 800 MeV, for positrons and electrons respectively, and with duration (at constant intensity) ranging from 1.5 to 40 ns. The energy spread is 0.5%, while the beam spot size can vary by orders of magnitude: $[0.5, 25]$ mm (vertical) × $[0.6, 55]$ mm (horizontal). The number of particles that can be provided per bunch ranges from 1 to 10^{10}. The BTF hall will be rearranged in order to host the PADME experiment.

4. The detector

The detector will identify events with a single photon generated in the e^+/e^- annhilation, measuring also the missing squared invariant mass of the final state. This will be evaluated by exploiting energy-momentum conservation and the fully constrained initial state of an e^+ beam, with known momentum and position, on an active fixed target. The A' boson squared invariant mass M_{miss}^2 can be estimated as:

$$M_{miss}^2 = \left(\vec{P}_{e^-} + \vec{P}_{beam} - \vec{P}_\gamma \right)^2,$$

where $\vec{P}_{e^-} = \vec{0}$ and $P_{beam} = 550$ MeV along the initial beam direction are the e^- and the e^+ momentum respectively and $\vec{P}_\gamma$ is the photon final state.

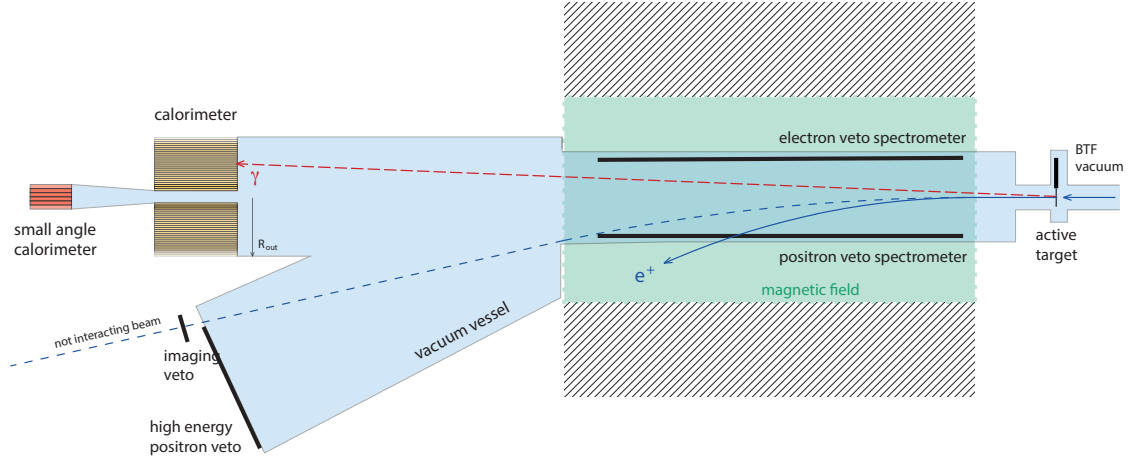The detector, which is shown in Fig.2, consists of [7]:

Figure 2. PADME detector layout. From right to left: the active target, the e^+e^- vetoes inside the magnetic dipole, the high energy e^+ veto near the non-interacting beam exit, the ECAL and the SAC. The distance between the ECAL and the target is $3\,\mathrm{m}$.

- a diamond active target, which allows to measure the beam intensity and position (precision of $\approx 5\,\mathrm{mm}$) by means of graphite perpendicular strips. The diamond low Z helps to reduce the occurrence of bremsstrahlung processes. The area is $2 \times 2\,\mathrm{cm}^2$ and the small thickness ($50\,\mu\mathrm{m}$ or $100\,\mu\mathrm{m}$) reduces the probability of e^+ multiple interactions.

- a dipole magnet, located $20\,\mathrm{cm}$ after the target, designed to deflect non-interacting beam particles out of the detector and to direct the positrons that lost part of their energy (mainly through bremsstrahlung) towards the vetoes. The field is $0.5\,\mathrm{T}$ over a gap of $23\,\mathrm{cm}$ for $1\,\mathrm{m}$ length.

- positrons/electrons veto, divided in two parts: one located inside the dipole for positrons and electrons, and another one, near the beam exit, for high energy positrons that lost only a small part of their energy, mainly through bremsstrahlung processes. It is composed of $1 \times 1 \times 16\,\mathrm{cm}^3$ bars of plastic scintillators. The arrays inside the magnet are $\approx 1\,\mathrm{m}$ long, while the high energy positron one is $\approx 0.5\,\mathrm{m}$ long.

- an electromagnetic calorimeter (ECAL), made of 616 BGO crystals $2 \times 2 \times 22\,\mathrm{cm}^3$, placed at $3\,\mathrm{m}$ from the target. Energy resolution is expected to be $\sim \frac{(1-2)\%}{\sqrt{E}}$. The ECAL has cylindrical shape ($30\,\mathrm{cm}$ radius) with a central square hole, of $10\,\mathrm{cm}$ side, to allow the bremsstrahlung radiation to pass through and reach the Small Angle Calorimeter. This is necessary because of the long BGO decay time of $300\,\mathrm{ns}$: the ECAL would be continuously "blinded" by the bremsstrahlung photons rate. The angular coverage is $(20, 93)\,\mathrm{mrad}$.

- a small Angle Calorimeter (SAC), made of 49 $2 \times 2 \times 20\,\mathrm{cm}^3$ lead glass (SF57) crystals, located along the line of flight of the low-energy photons coming from the target and passing through the ECAL central hole. Its main task is to veto 3γ events. The lead glass Cerenkov response time makes it a good candidate for this task, being fast enough for the expected photon rate. The angular coverage is $(0, 20)\,\mathrm{mrad}$.

The DP signature is a single γ in the ECAL with no other particles detected in the vetoes. Being $E_{beam} = 550\,\mathrm{MeV}$, the largest A' boson mass produced in annihilation processes is $23.7\,\mathrm{MeV}$.
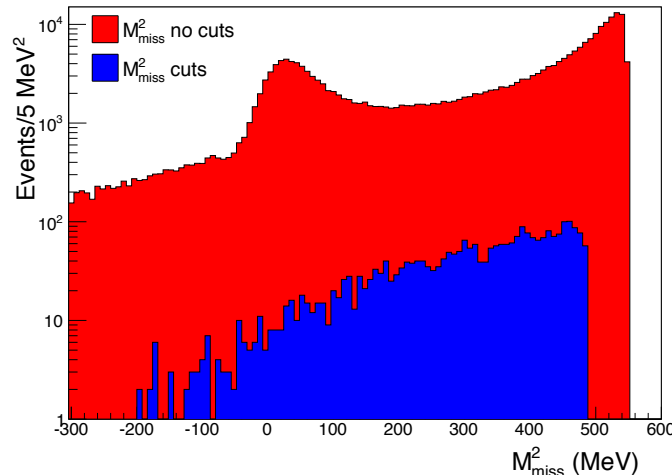
Figure 3. Background before (red) and after (blue) events selection [7].

5. Backgrounds and sensitivity

The SM physical processes expected to take place in the e^+ beam interaction with the target are bremsstrahlung and $e^+ e^- \to \gamma\gamma(\gamma)$ [7]. The probability that their kinematics will mimic a DP production event in our detector can be reduced through an optimization of the ECAL geometry and granularity and of the veto system. The beam intensity plays a crucial role for the pileup probability: clusters cannot be resolved in time by the calorimeter if they are temporally too close to each other [7]. Fig.3 shows the background reduction obtained requiring only one cluster in the ECAL, with no hits in the vetoes, no photons with energy $> 50\,\mathrm{MeV}$ in the SAC, and cluster energy in a range optimized depending on $m_{A'}$.

The DP sensitivity evaluation is based on $2.5 \cdot 10^{10}$ GEANT4 simulated $550\,\mathrm{MeV}$ positrons on target extrapolated to 10^{13} e^+. This number of particles can be obtained by running PADME for 2 years at 60% efficiency with 5000 e^+ per bunch (40 ns) at a repetition rate of 50 Hz. The obtained result for a DP decaying to invisible particles is shown in Fig.4 for different bunch durations: favored $(g-2)_\mu$ region can be explored in a model independent way (the only hypothesis on the DP is the coupling to leptons) up to masses of $23.7\,\mathrm{MeV}$ [7]. Single Event Sensitivity (SES) refers to the sensitivity in absence of background.

6. Conclusions

Theoretical models with a DP can provide a solution to the DM puzzle. Additionally, a DP with mass in the $[1, 100]\mathrm{MeV}$ range and coupling constant $\varepsilon \sim 10^{-3}$ would explain the muon anomalous magnetic moment discrepancy.

PADME will perform a model independent search for an invisible decaying DP, using the accelerator complex at the INFN LNF. The collaboration aims at reaching a sensitivity on ε of $\sim 10^{-3}$ for DP with masses up to $23.7\,\mathrm{MeV}$.

References

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[4] B. Echenard, R. Essig and Y. M. Zhong, JHEP **1501**, 113 (2015).
[5] R. Essig *et al.*, JHEP **1311**, 167 (2013).
[6] M. Raggi and V. Kozhuharov, Riv. Nuovo Cim. **38**, 449 (2015).

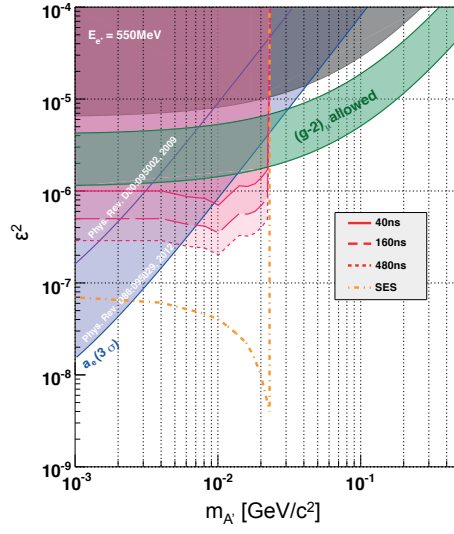**Figure 4.** PADME sensitivity to $A' \rightarrow invisible$. Increasing bunch length it is possible to explore smaller ε. SES refers to single event sensitivity.

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