

The PADME experiment at LNF

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Abstract. The PADME experiment, approved by INFN at the end of 2015, aims to search for missing mass signals in the annihilation of positrons on a thin fixed target produced by invisible decays of the dark photon. The detector construction will be completed by the end of 2017 to be ready to run in spring of 2018. The collaboration aims at collecting about 10^{13} positron on target by the end of 2018 to reach a sensitivity down to 1×10^{-3} on the coupling of A' up to 23.7 MeV mass.

1 Introduction

The existence, the nature, and the interactions on the dark matter with Standard Model (SM) particles are among the most important open questions in modern particle physics. Despite an intense experimental activity, no direct evidence of dark matter interaction with ordinary matter through the known SM forces, except the gravity, has been reported. This experimental evidence suggests that a new force might be the solution to the dark matter puzzle. The idea of a new force and a new "dark sector" of particles, originally proposed in the '80[1], has been recently revitalised by the possibility of explaining the long standing discrepancy between theory predictions and experimental measurements of muon anomalous magnetic moment $(g-2)_\mu$ [2]. The simplest "dark sector" model introduces a single new force with a gauge structure similar to the SM electromagnetic interaction, $U(1)_D$, and the corresponding mediator the so called "dark photon" (A'). The dark photon (DP) has the quantum numbers of both the SM electromagnetic interaction and the dark sector force. For this reason the DP can then mix with the ordinary photon and be produced in collisions of electrons, positrons, and protons on a target or in meson decays[4]. In this case the charges of SM fermions with respect to the $U(1)_D$ interaction will be proportional to the electric charge and the associated mixing term in the QED Lagrangian will be:

$$\mathcal{L}_{mix} = -\frac{\epsilon}{2} F_{\mu\nu}^{QED} F_{dark}^{\mu\nu}. \quad (1)$$

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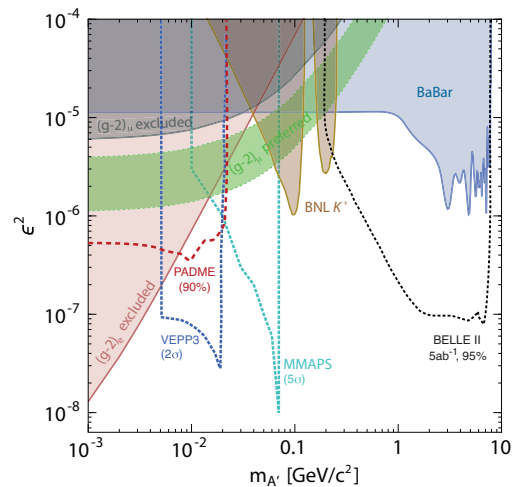


Figure 1. Status of the dark photon invisible decays searches.

The associated mixing coupling constant, ϵ , can be so small ($< 10^{-3}$) to hide the dark sector particle to experimental searches so far. An intense experimental activity in the last 5 years allowed to exclude a large fraction of the parameter space, including the $(g-2)_\mu$ favorite region, in the hypothesis that the dark photon decays to SM final states[3]. An exciting possibility is that dark matter states χ with mass smaller than $M_{A'}/2$ exist, thus allowing dark photon's invisible decays, $A' \rightarrow \chi\chi$. In this scenario almost all of the current constraints do not hold. Current limits on invisible dark photon's decays are summarised in fig.1 together with the expected reach of future missing mass proposals. The green band represents the region of the parameter space preferred by the $(g-2)_\mu$ explanation.

2 The PADME technique

The main goal of the PADME experiment is to search for dark photons produced by the annihilation of a positron beam with the electrons at rest in a thin active diamond target[5]. The resulting final state of the process $e^+e^- \rightarrow A'\gamma$ with $A' \rightarrow \chi\chi$, will be a single photon and nothing else. Measuring the incoming positron (P_{beam}) and recoil photon (P_γ) 4-momenta, the mass of the missing state (A') can be measured as:

$$M_{miss}^2 = (P_{e^-} + P_{beam} - P_\gamma)^2. \quad (2)$$

being the electron in the target at rest. Once the number of A' candidates in each of the missing mass regions has been measured a natural choice for the A' production rate normalisation is the $e^+e^- \rightarrow \gamma\gamma$ process. The A' coupling constant ϵ can be determined using the formula

$$\frac{\sigma(e^+e^- \rightarrow A'\gamma)}{\sigma(e^+e^- \rightarrow \gamma\gamma)} = \frac{N(A'\gamma)}{N(\gamma\gamma)} * \frac{Acc(\gamma\gamma)}{Acc(A'\gamma)} = \epsilon^2 * \delta, \quad (3)$$

where $N(A'\gamma) = N(A'\gamma)_{obs} - N(A'\gamma)_{bkg}$ is the number of the signal candidates after the background subtraction, $N(\gamma\gamma)$ is the number of observed annihilation events, δ is the $e^+e^- \rightarrow A'\gamma$ cross section enhancement factor. The measurement of the ratio reduces the theoretical uncertainties just to the determination of the enhancement factor δ [4].

The PADME experiment setup uses the 550 MeV/c positron beam of the DAΦNE Beam Test Facility[7] impinging on a thin diamond target and is composed of the following parts:

- **Thin (100 μ m) active diamond target**, to measure the average position of the beam during a single BTF spill
- **Dipole magnet**, to deflect the primary positron beam out of the calorimeter acceptance and to convey any charged particle from interactions in the target toward the charged particle veto detectors
- **Charged particles veto**, to reject bremsstrahlung background.
- **Vacuum chamber**, to minimise the unwanted interactions of primary and secondary particles.
- **BGO Electromagnetic calorimeter**, to measure and/or veto final state photons.
- **Small angle fast photon veto**, to veto photons emitted at small angle with respect to the primary positron beam.

A schematic view of the experimental apparatus is shown in Figure 2.

A beam of 5000 positrons with very precise energy and angular distribution will cross the active diamond target 50 times per second. The target will measure the beam position and total charge providing information on the interaction point and luminosity of the experiment. In case a dark photon event occurs the 4-momentum of the recoil photon produced in the $e^+e^- \rightarrow A'\gamma$ annihilation will be measured by an electromagnetic calorimeter, placed at a distance of 3 m from the production target. The PADME

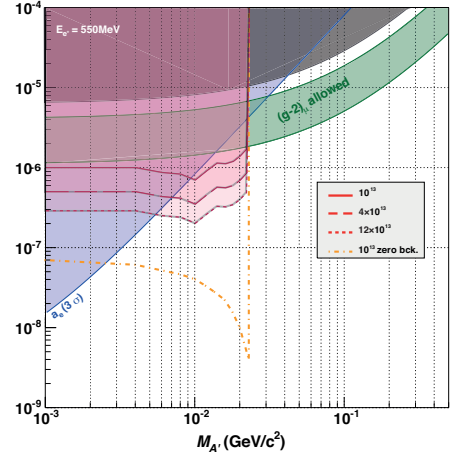


Figure 3. The PADME experiment projected sensitivity.

calorimeter will be realised as a 600 mm diameter cylinder made up of 616 BGO crystals $21 \times 21 \times 230$ mm³, read-out by 19mm diameter photo-multiplier tubes. The small size of the crystals, which are reshaped blocks of the end-cap electromagnetic calorimeter of the L3 experiment, will allow the PADME calorimeter to reach ~ 5 mm position resolution for electromagnetic clusters allowing a precise measurement of the direction of the impinging photon. A 100×100 mm² central hole will allow the most part of Bremsstrahlung photons to reach a smaller and faster Cherenkov based veto detector, featuring a much better time resolution and smaller dead time. Thanks to CERN (TE-MSC-MNC) a dipole magnet from the SPS transfer line, modified to provide 0.55 T over a gap of 23 cm will be used to sweep away the non-interacting positrons.

The rejection of events with a radiating positrons will mainly rely on charged particle veto detectors made of scintillating bars read out by silicon photomultipliers, placed inside the magnetic field of the dipole: a set of scintillators will be placed along each of the deflection sides vetoing lower momentum positrons/electrons, while another set will be placed outside the magnet, close to the nominal beam trajectory to detect higher momentum positrons. The entire volume from the target to the veto detectors and to the front face of the BGO calorimeter will be in vacuum, in order to minimize interactions of photons and charged particles, so that a relatively large and asymmetrically shaped vacuum vessel is realised. The PADME detector is under construction at the Laboratori Nazionali di Frascati of INFN and is expected to be operational by the end of 2017.

3 PADME sensitivity study

The PADME physics potential is extended beyond dark photon searches: presently a sensitivity estimate based on Monte Carlo simulations is available only for the invisible dark photon decays produced by annihilation process.

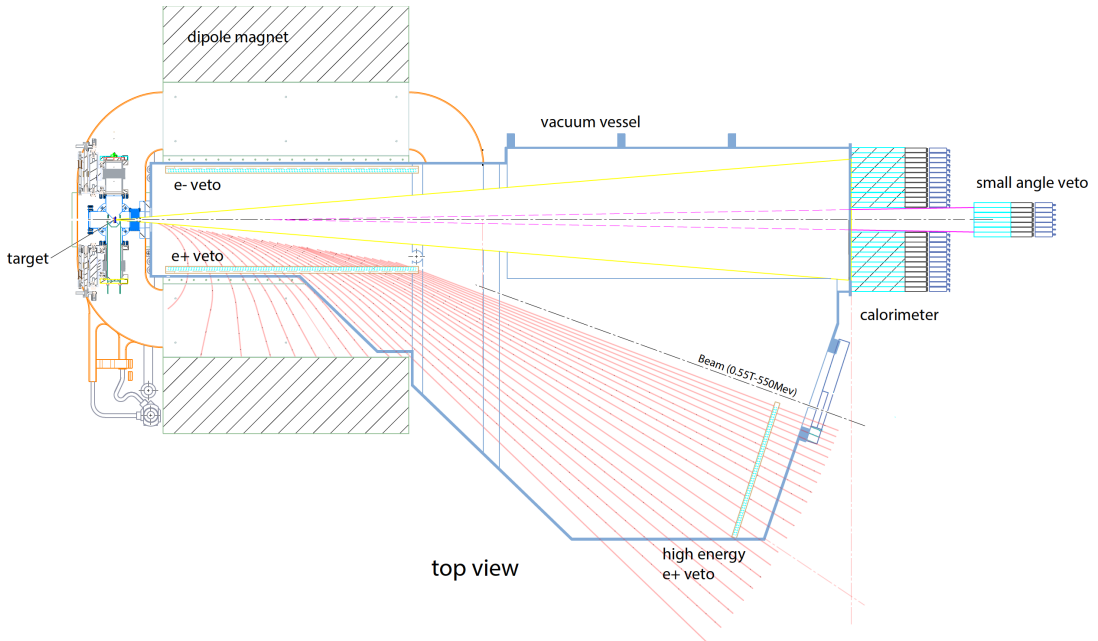


Figure 2. Top view of the PADME experiment.

The sensitivity of the PADME experiment has been estimated using a detailed Monte Carlo simulation, based on GEANT4, assuming 40 ns long beam bunches, each containing 5,000 positrons of 550 MeV/c momentum, with a momentum spread of 1%, an angular divergence of ~ 1 mrad, and a Gaussian beam spot with $\sigma_{x,y}$ 1 mm. This beam configuration allows to integrate a total luminosity of 1×10^{13} positrons in 3.15×10^7 s corresponding to two years data taking at 50% efficiency. Recent development in the BTF extraction line allowed to reach bunch lengths up to 200 ns. Profiting of this possibility the PADME experiment running time can be significantly reduced.

To emulate the bunch structure, a simultaneous multi positron gun has been implemented, taking into account beam spot size, beam divergence, and energy spread in each single burst. The simulation includes backgrounds simulated by GEANT4 low-energy electromagnetic libraries, two photon annihilation, ionization processes, Bhabha and Moller scattering, and the production of δ -rays. A custom generator for the three photon annihilation background and to simulate the A' production and its decays into e^+e^- or invisible have been developed. Realistic performance of the detectors have been simulated: in particular for the reconstruction of the calorimeter clusters, the energy resolution obtained with the calorimeter prototype during test beams ($2\% / \sqrt{E(\text{GeV})}$ [8]), a minimum detectable energy of 1 MeV, and 1 ns timing resolution have been used.

The sensitivity of the PADME experiment to the invisible decays of the dark photon is shown in fig. 3 for various scenarios of recorded luminosity. The effect of the

residual background is evident by comparing the sensitivity curve for 10^{13} positrons on target and the corresponding single event sensitivity (orange dashed curve). A margin of improvement of one order of magnitude in the full mass range still exist.

4 Conclusions

Searches for dark photons are well motivated within several new physics scenarios. The PADME experiment will be able to search for invisible decays of the dark photon using the present Beam Test Facility of the DAΦNE LINAC in just one-two years of data taking with a sensitivity on the A' mass up to $23.7 \text{ MeV}/c^2$ in a complete model independent way. The experiment's construction will be completed by the end of 2017 and the first beam for physics is expected in spring of 2018. An upgrade of the BTF positron beam energy will also allow to extend the sensitivity of PADME to higher mass values. Additional physics goals including APLs, are under investigation.

Acknowledgments

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