The PADME experiment

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1 Introduction

Direct observations of dark matter signals are necessary to shed light on the cosmological and astrophysical evidences, in order to understand the nature of such unknown matter that at present has manifested itself only via gravitational interactions.

There are models attempting to solve the problem, as well as the muon $(g-2)$ anomaly, that have postulated the existence of a low-mass spin-1 particle, referred to as A', that would possess a gauge coupling of electroweak strength to dark matter, and a much smaller coupling to the Standard Model (SM) hypercharge.

PADME aims to search for signals of this light dark photon using the beam of the LNF LINAC. The experiment, approved by INFN at the end of 2015, will study the reaction:

$$e^+e^- \to \gamma A'$$

and foresees to detect A' by searching for missing mass signals.

2 The PADME experiment

The goal of the PADME experiment is to search for dark photons produced in the annihilation process of the positron beam of the DAΦNE LINAC with a thin carbon target and then identified using a missing mass technique [1]. The basic elements of the PADME experiment are:

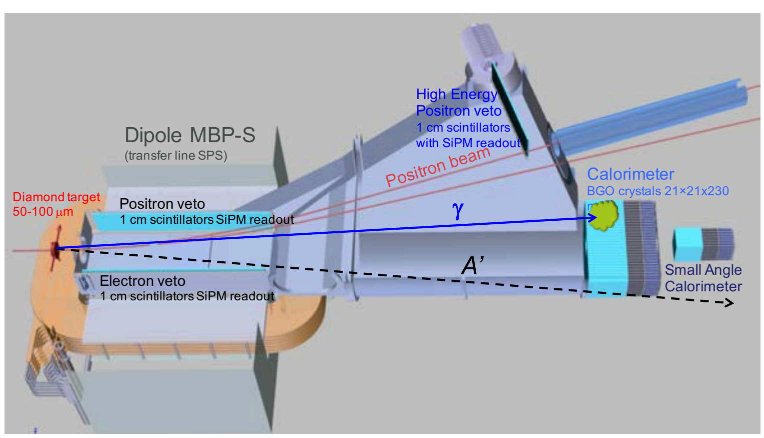

Figure 1: *PADME detector layout. From left to right: the active target, the positron/electron vetoes inside the magnetic dipole, the high energy e*$^+$ *veto near the non-interacting beam exit, the e.m. calorimeters. The distance from the target to the first calorimeter is roughly 3 m.*

- a high intensity and low divergence positron beam, impinging on a thin, active target, capable of monitoring the beam spot;
- a vacuum chamber to avoid spurious positron interactions;
- a magnet to deflect the beam of positrons emerging from the target, with the additional task of measuring the momentum of the interacting positrons, thus improving the rejection of the Bremsstrahlung background;
- a finely-segmented, high-resolution e.m. calorimeter, to measure the momentum of the single SM photons.

A schematic view of the PADME layout can be seen in fig. 1.

The processes that will mainly take place in the beam-target interaction are Bremsstrahlung and $e^+e^- \rightarrow \gamma\gamma(\gamma)$. In order to cut out these background events, two extra components are crucial: a fast Small Angle Calorimeter (SAC) and a charged particle veto system. Fig. 2 shows the results of Montecarlo simulations performed to check background rejection capability requiring only one cluster in the main calorimeter (with energy in a range optimized depending on $m_{A'}$), no hits in the vetoes, and no photons with energy > 50 MeV in the SAC.

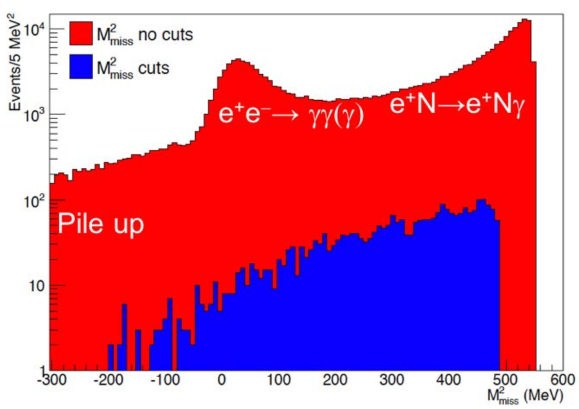

Figure 2: *Montecarlo simulated squared missing mass for background events. In red with no selection cuts, in blue after all cuts are applied (see text for more details).*

3 Activity of the PADME LNF group

During 2016 the PADME collaboration has worked on one side to optimize and freeze all the subdetector elements, and to start the procurement of the needed components, on the other on the modification of the LINAC operation mode to increase the bunch length of the positron beam. The LNF group has involvements on general items such as the experimental hall, the beam-line, the magnet, the vacuum chamber and the overall mechanics, but also contributes to specific items like the e.m. calorimeters, the charged particle veto system, and the beam monitoring systems. In the following a brief description of the work done is given.

3.1 Detector activity

The first work done in between the end of 2015 and the first half of 2016 regards the dipole.

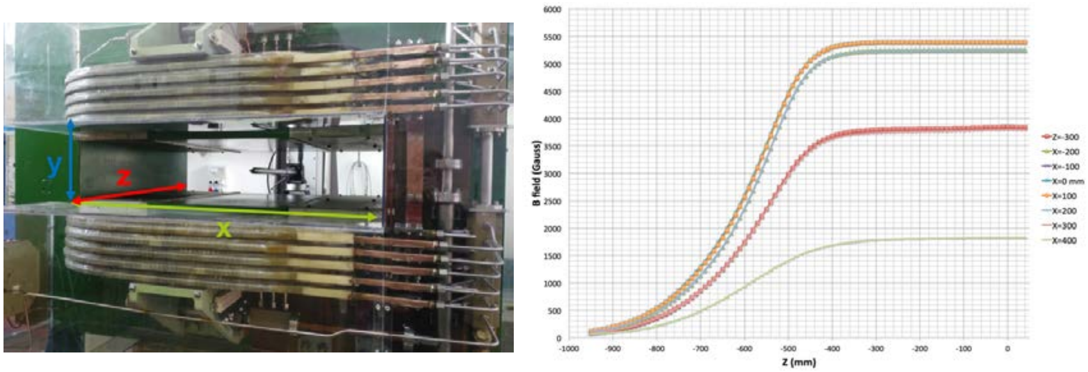

Figure 3: **left** *the PADME magnet.* **right** *Longitudinal scan of magnetic field at different transverse positions.*

A magnet with the characteristics necessary for the experiment has been found at CERN within the spare dipoles of the SPS transport line (MBP-S), and it has been shipped to Frascati at the end of 2015. During 2016, the dipole vertical gap has been increased to 230 mm, to better suit the experiment needs, and the field map has been measured in different conditions (see fig. 3).

For the e.m. calorimeters, during 2016 the final design has been worked out. The key point of the PADME experiment is to detect with high efficiency the energy, direction and time of the single photons emitted from the target. Therefore, to avoid pile-up due to the high number of primary positrons, the main calorimeter (ECAL) will have a central hole to cut out most of the Bremsstrahlung photons produced in the interaction with the target. In the shadow of this hole, a second, small size and faster calorimeter (SAC), will be placed.

The final design of the ECAL foresees a tight matrix of 616 crystals arranged in a cylinder of external radius 30 cm, with a central squared hole of 10 cm. Fig. 4 shows two basic elements of this array; each one consists of a BGO crystal, $20\times20\times230$ mm^3, painted with an optical reflecting paint, and glued to the corresponding photosensor.

Figure 4: *Two elements of the PADME main e.m. calorimeter. The dimensions of the BGO crystals are $20\times20\times230$ mm^3.*

The choice of the scintillating material has been driven by different aspects: high density, small radiation length and Moliére radius (due to the calorimeter small dimensions), high light output (due to the low energy range), cost. The BGO crystals that were used by the L3 experiment at LEP, that are property of INFN, meet all the requirements at the only cost of cutting them at the proper size. Therefore, after having checked that these crystals could be reconditioned and re-shaped, they have been adopted.

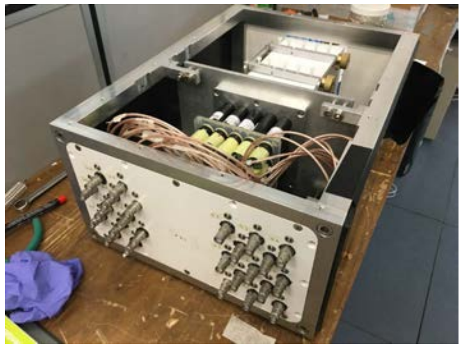

Figure 5: *Layout of the PADME main e.m. calorimeter prototype. It consists of a matrix of 25 BGO crystals on which different photosensors can be mounted for tests.*

For the light collection, tests aimed at evaluating the best readout technology have been performed at the beginning of 2016. They showed that avalanche photodiodes (APDs), even with a relatively large area of $10{\times}10$ mm^2, have a gain that is insufficient to perform a high resolution energy measurement in the PADME energy rage (from a few to a few hundred MeV). The readout system will therefore be based on 19 mm diameter photomultipliers. On July 2016, XP1911 HZC Photonics tubes [2] have been tested at the BTF, on a calorimeter prototype made of 25 BGO crystals obtained by machining the L3 recovered ones. The 25 channels of the prototype were fed into a CAEN V1742 high-speed digitizer [3], based on the DRS4 chip, set to a sampling speed of 1 GS/s (1 ns/sample).

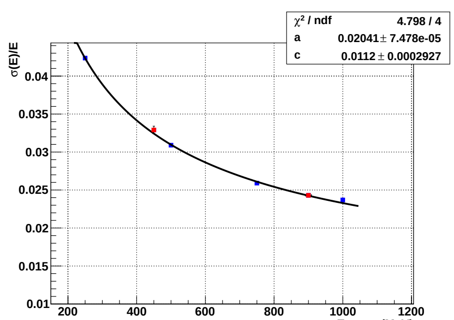

Figure 6: *Energy resolution measured with a prototype of the PADME ECAL at the LNF BTF. Red and blue points refer to two different beam energies of 450 and 250 MeV, respectively. The line is the best fit curve whose parameters are quoted in the inset.*

The test beam has demonstrated that the technical solutions chosen for this detector meet all the requirements. Fig. 6 shows the energy resolution obtained as a function of the photon energy.

Placed 50 cm downstream the ECAL, the SAC will be an array of fast detectors able to veto photons at small angles. Lead glass SF57 crystals have been tested at the BTF in December 2016. For the readout, fast photomultipliers are mandatory, while for the signal digitization the same electronics chain of the ECAL can be used, since the used board can reach a sampling frequency of 5 GS/s. The tests have showed that the combination of a $20{\times}20{\times}200$ mm^3 SF57 crystal with a Hamamatsu R9880U-110 [4] photomultiplier give encouraging results. Other lead glass materials, such as PbF_2, having an higher density, a better transparency down to 250 nm, and a high radiation hardness, could be a better choice in order to have a more compact and robust calorimeter. Tests with this crystal are foreseen for next year.

Concerning the charged particle vetos, necessary to detect electron and positrons inside the dipole and the high energy positron exiting the setup, the full sample of 400 scintillator bars has been acquired from Uniplast, Russia. They have a length of 20 cm and a square cross section of 1 cm^2. A rectangular groove with cross section of 1.3×1.3 mm^2 has been machined along the bars providing a placement for a WLS fiber with 1.2 mm diameter.

A two layer prototype has been assembled, with 8 bars in each layer, as shown in figure 7. The light from the fiber ends has been sent to a H9500 multianode PMT (MAPMT), exploiting a pattern allowing to study the cross talk and the gain uniformity.

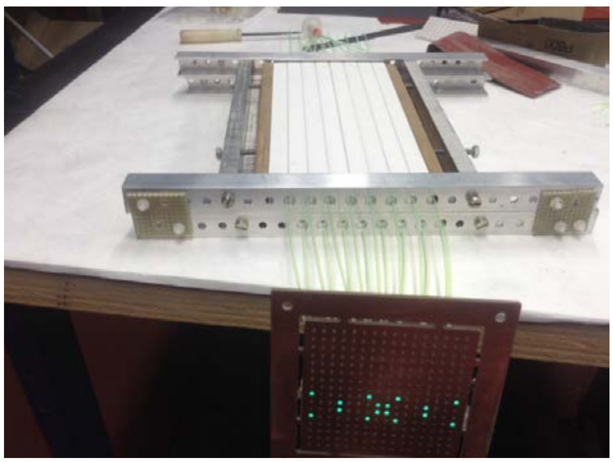

Figure 7: *A picture of the double layer prototype of the charged particle veto before coupling it to the multianode PMT.*

The prototype has been tested at the BTF in a single particle per bunch regime. The signals from the MAPMT have been digitized with the usual CAEN V1742 module sets to a sampling frequency of 5 GS/s. The efficiency of the scintillator bars have been determined at about 99%, for a noise below 1% in the readout window. Different methods for time reconstruction have also been studied. The best time resolution has been achieved by taking the weighed sum of the absolute values of the individual samples. A value of the order of 1 ns and better has been obtained, as shown in figure 8 (black points).

3.2 Beam line activity

The PADME luminosity scales linearly with the beam pulse length, since this allows a larger number of positrons on target, keeping constant the pile-up probability on the calorimeters. At present, the BTF beam, extracted from the DAΦNE LINAC, is set up to provide pulses at 510 MeV with a maximum length of 40 ns, a repetition rate up to 50 Hz and an energy spread of about 1 %. This is not ideal for the experiment and in order to have the possibility to stretch the positron bunches, during 2016, a new LINAC pulsing system has been installed. A dedicated machine development run has been performed and pulses of electrons up to 250 ns have been produced. The energy spread measured during the test period was around 2-3 %. Other dedicated tests are foreseen for 2017 to tune the LINAC and bring the energy spread at the level of 1 %.

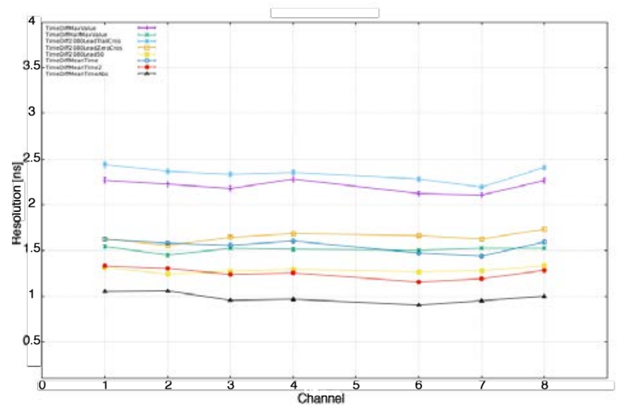

Figure 8: *Estimated time resolution (in ns) for the different scintillator slabs. The different lines represent different evaluation methods (see test for more details).*

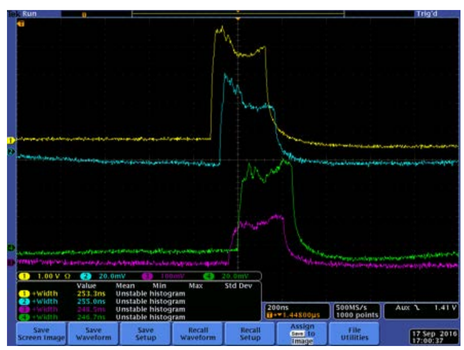

Figure 9: *Bunch length measured at different points of the DAΦNE LINAC during the tests to extend bunch duration. A length of 250 ns has been reached (yellow curve) at the end of the line.*

4 List of Conference Talks presented by LNF group members in Year 2016

1. G. Piperno, “The PADME experiment”, poster presented at the 15th Incontri di Fisica delle Alte Energie (IFAE 2016), Genova, Italy, 30 March - 1 April 2016.

2. M. Raggi, “The PADME experiment at LNF”, invited talk at the Workshop on Dark Sector 2016, SLAC Menlo Park, California, USA, 28-30 April, 2016.

3. G. Piperno, “The PADME experiment at Laboratori Nazionali di Frascati”, talk at the 5th Young Researchers Workshop on Physics Challenges in the LHC Era within the 18th Frascati Spring School “Bruno Touschek” in Nuclear, Subnuclear and Astroparticle Physics, Frascati, Italy, 9-13 May 2016.

4. V. Kozhuharov, M. Raggi, P. Valente, “New projects on dark photon search”, invited talk at the XVI Vulcano Workshop, Vulcano Island (Sicily, Italy), 22-28 May, 2016.

5. G. Piperno, “The PADME experiment”, talk at the 11th International Conference on Identification of Dark Matter (IDM 2016), Sheffield, UK, 9-13 July 2016.

6. V. Kozhuharov, "Background to the search for dark photon", talk at the Advances in Dark Matter and Particle Physics 2016, Messina, Italy, 23-27 October 2016.
7. P. Gianotti,"Status and prospects for the PADME experiment at LNF", invited talk at the KLOE-2 Workshop on e^+e^- collision physics at 1 GeV, Frascati, Italy, 26-28 October 2016.

5 Publications

1. J.Alexander *et al.*, "Dark Sectors 2016 Workshop: Community Report", arXiv:1608.08632 [hep-ph] in press
2. V. Kozhuharov, M. Raggi, P. Valente, arXiv:1610.04389 [hep-ex], to be published in Frascati Physics Series Vol. 64 (2016) *Frontier Objects in Astrophysics and Particle Physics*.
3. M. Raggi *et al.*, arXiv:1611.05649[physics.ins-det], submitted to Nucl. Instrum. Meth. **A**.

References

1. `http://www.lnf.infn.it/acceleratori/padme/`.
2. `http://hzcphotonics.com`.
3. CAEN Mod. 1742, Technical Information Manual, rev6 06 February 2016.
4. `https://www.hamamatsu.com/jp/en/R9880U-110.html`