THE PADME EXPERIMENT

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1 Introduction

One of the most intriguing mysteries in physics today, is that the matter seen in the universe accounts only for about 5% of the observed gravity. This has triggered the idea that enormous amounts of invisible dark matter should be present.

Among the different theoretical models that try to define what dark matter could be, there are those postulating the existence of a "Hidden Sector" populated by new particles that do not couple with those of the Standard Model (SM). The connection within these two worlds is theoretically realized by a low-mass spin-1 particle, indicated with the symbol A', that would manifest a gauge coupling of electroweak strength to dark matter, and a much smaller coupling to the SM hypercharge 1). This Dark Photon (DP) could be the portal connecting ordinary and dark worlds.

The PADME experiment aims to search for signals of such a DP studying the reaction:

$$e^+e^- \to \gamma A' \tag{1}$$

using the positron beam of the LNF LINAC and identifying the A' as a missing mass signal.

PADME (Positron Annihilation into Dark Matter Experiment) is an international collaboration of about 50 people that involves, in addition to LNF researchers, scientists from the INFN sections of Roma1, Roma2 and Lecce, the Sapienza University of Rome (IT), the Salento University (IT), the Sofia University (BG), the Cornell University (USA), and the Atomki Institute of Debrecem (H).

The apparatus was built, installed and commissioned with the beam from October 2018 to February 2019 (Run-I). In 2020 a new data acquisition period (from July to December 2020) took place. The first part was dedicated to beam tuning and detector calibration, while from September $\sim 5\times10^{12}$ positrons-on-target (POT) were recorded to start addressing the main physics goal (Run-II). During 2021 the main activity of the collaboration has been the data analysis of the collected data.

2 The PADME experiment

The goal of the PADME experiment is to search for DPs produced in the annihilation process of the positron beam of the LNF LINAC with the electrons of a thin, low Z target and then identified using a missing mass technique 2).

Figure 1 shows a scheme of the apparatus whose basic elements are:

- a low divergence positron beam, impinging on a thin, diamond active target, capable of monitoring the beam size and intensity;

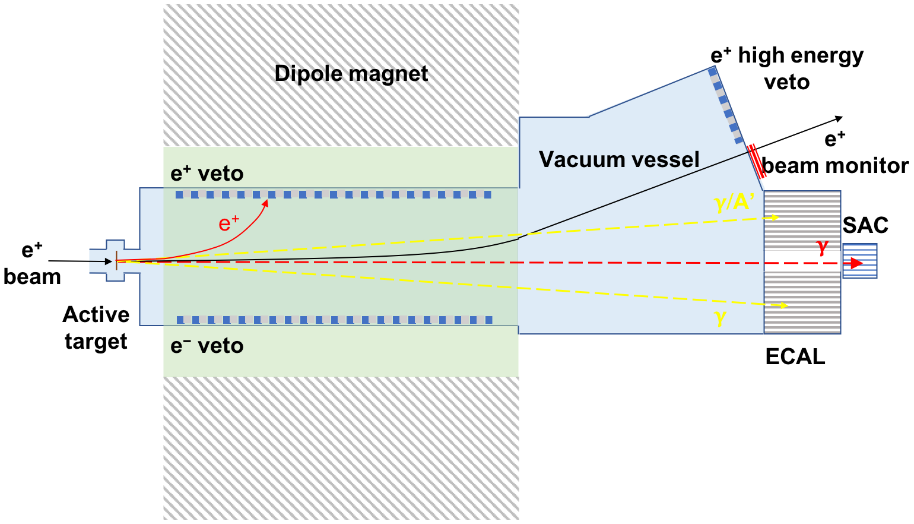

Figure 1: *The layout of the PADME experiment From left to right: the active target, the positron/electron vetoes inside the magnetic field, the high energy* e^+ *veto near the non-interacting beam exit, the e.m. calorimeters (ECal, SAC), the solid state beam monitor detector.*

- a vacuum chamber to avoid spurious particle interactions;
- a magnet to deflect the non-interacting positrons, and with the additional task of allowing the measurement of the momentum of the interacting positrons, thus contributing to the rejection of the Bremsstrahlung background;
- a finely-segmented, high-resolution e.m. calorimeter (ECal), with the main purpose to detect the single SM photon of reaction 1. ECal has in the center, a square hole to allow high frequency Bremsstrahlung photons to pass through;

Since the processes that mainly take place in the beam-target interaction are Bremsstrahlung and $e^+e^- \to \gamma\gamma(\gamma)$, to cut out these background events, two extra components are crucial:

- a fast Small Angle Calorimeter (SAC), placed behind the central hole of ECal. This is used to detect and veto background photons (mainly from Bremsstrahlung);
- three stations of plastic scintillator sticks located inside the vacuum chamber, two within the dipole magnet gap (Pveto and Eveto), and the third one on the beam exit (HEPveto). Their purpose is to veto charged particles produced in the interaction.

To allow a more accurate monitoring of the beam, in the target region are installed two planes of silicon pixel detectors placed up and down stream the active diamond target. Each plane consists of two MIMOSA 28 Ultimate chips, developed for the upgrade of the STAR vertex detector [3]. These devices integrate a Monolithic Active Pixel Sensor (MAPS) with a fast binary readout. Each sensor consists of a matrix of 928×960 pixels of 20.7 μm side with a thickness of 50 μm. For the STAR experiment the chips, that dissipate 150 mW/cm^2, operate in air without cooling. For PADME, the detectors have been placed in vacuum and a modified PCB, providing cooling, has been developed by the LNF electronic service.

The MIMOSA detector cannot stay on the beam line during the data taking, therefore an extra monitoring device is placed out of the vacuum on the positron beam exit trajectory. This is an array (6×2) of Timepix3 chips [4] able to record either the time-of-arrival (ToA) and the energy of the incident particles providing excellent energy and time resolutions. Each silicon chip (designed in 130 nm CMOS technology) contains 256×256 pixels (55×55 μm^2). The complete detector has been build ad installed at LNF by the ADVACAM company [5].

The physics potential of the PADME experiment extends beyond DP search. The present detector is also sensitive to any Feebly Interacting Particle (FIP) that can be produced in the positron-on-target interaction. Furthermore, minor modifications of the present setup, will allow to enlarge the scientific reach of the experiment. A detailed study of all possible extensions of the PADME scientific program has been one of the subjects of a workshop that took place at LNF on January the 13^{th} 2021: **Fisica Fondamentale a Frascati** [6]. The aim of this meeting was to brainstorm on the opportunities to continue to carry out at LNF experimental activities that could contribute to the scientific exploration of fundamental open questions in particle physics.

For what concerns PADME, an analysis has been performed together with the colleagues of the theory division to establish the reach for Dark Photons ad Axion Like Particles searches with the present or an improved e^+ beam. From this work emerged that the PADME experiment is probably the best suited to confute or validate the particle explanation of the so called $X17$ anomaly. This is a “bump” in the angular distribution of e^+e^- pairs observed by the Atomki collaboration in nuclear decays of ^{8}Be [7] and ^{4}He [8] excited states. By lowering the BTF beam energy to ~ 282 MeV, it would be possible to produce resonantly the above mentioned particle in the annihilation with the electrons of the target.

The document issued after the workshop [9] has been submitted in May to the evaluation of the LNF Scientific Committee in order to get advice on the future scientific programs of the laboratory. For what concerns PADME, the Committee endorsed in the November report a dedicated data taking, for 2022, devoted to the $X17$ search.

3 Activity of the PADME LNF Group

As already mentioned in the previous section, at LNF year 2021 started with a one-day workshop organized to identify the major future activities the laboratory could address within a time horizon of several years before the entering in operation of the EuPRAXIA facility. The topics that have been identified are: (i) the quest for dark matter candidates in terms of FIPs; (ii) probing the axion solution to the strong CP puzzle by searching for dark matter axions with superconducting cavities and with large volume haloscopes; (iii) the study of the low energy QCD problems related to the role of strangeness in nuclear matter. Thus, following the recommendations of the LNF Scientific Committee that evaluated the final document produced after the workshop, the PADME collaboration has started investigating the possibility to extend the scientific program of the experiment to other topics related to the dark matter problem.

Side of this activity, the collaboration continued to analyze the data collected in Run-I and Run-II with the final goal to determine the sensitivity to the DP coupling. In order to arrive to this reach, many preliminary steps are necessary. In particular the study of all sources of backgrounds, and the complete understanding of the detector's response.

PADME took data in two runs: in RUN-I, from September 2018 to February 2019, data have been collected with a secondary positron beam of energy 545 MeV. Only in the last few days, a primary positron beam of energy of 490 MeV was used. RUN-II took place in Fall 2020 with a primary positron beam of 430 MeV; in each run were collected $\sim 5 \times 10^{12}$ positrons-on-target. In between the two data taking campaigns, the beam line was improved to mitigate the beam background with the addition of collimators, a widening of the beam pipe, and a change in the material and location of the window separating the LINAC tight vacuum from the PADME beam line where a less stringent vacuum is realized. In particular, the original beryllium window, 250 μm thick, was replaced with a mylar window, 125 μm thick, located more upstream from the PADME target. The improved beam quality is clearly shown by the total energy per bunch measured by ECal which goes form 9 GeV with the secondary beam down to 1 GeV with the same beam line but a primary positron beam and finally reaches a few hundred of MeV in RUN-II after the optimization of the beam line (see fig. 2).

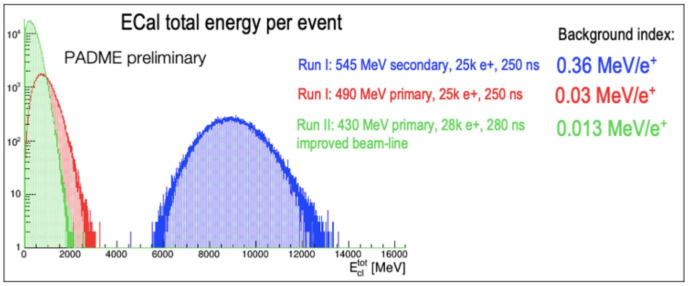

Figure 2: *Total energy per bunch measured by ECal in different run conditions, removing the target. Blue: Run-I secondary beam; Red: Run-I primary beam; Green: Run-II primary beam.*

Once the beam background was understood and properly reduced, the collaboration started to study the physics induced background. This is represented by Bremsstrahlung and annihilations in 2 or 3 γs. In particular, the study of $e^+ + e^- \to \gamma\gamma$ allows also to performe an absolute calibration of the ECal energy scale and to monitor the detector stability. Figure 3 shows the histogram of the sum of the energy of events with two clusters detected in the ECal.

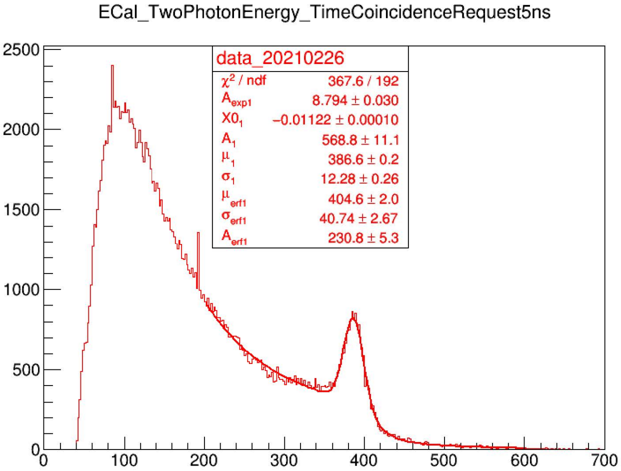

Figure 3: *Total energy of events with two clusters in the ECal. The superimposed curve shows the best fit to the two photons final state. The position of the mean value of the gaussian distribution should correspond to the beam energy.*

By monitoring this quantity on a run by run basis, it is possible control the ECal performance.

Actually, it was observed that the ECal response was, as expected, temperature dependent since BGO crystals light yield is strongly related to their temperature. By calibrating the crystal signals taking into account the temperature measured by the sensors installed on ECal itself, it was possible to keep almost constant the calorimeter behaviour (seefig. 4).

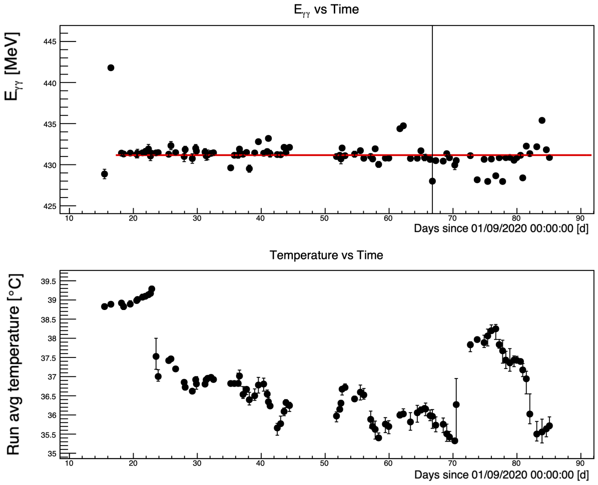

Figure 4: *Top) Beam energy value extracted analysing 2-photons events as a function of time (obtained with the fitting procedure shown in fig. 3). Bottom) ECal temperature measurements as a function of time.*

Two photons events are also important to asses single-photon reconstruction efficiency in PADME that is crucial for the DP analysis. In fact, once a photon is identified, it is possible to probe the efficiency for the detection of the second. Finally, to test completely the behaviour of the PADME detector, the measurement of the absolute cross-section of the process $e^+ + e^- \to \gamma\gamma$ will be performed with an estimated precision of 5% to be compared with the expectation of SM calculation. At present, this result is almost achieved and the corresponding paper will be submitted soon.

4 List of Conference Talks presented by LNF Speakers in Year 2021

Here below, it is the list of conference presentations given by LNF PADME members:

1. V. Kozhuharov,"Searching X17 with positrons at PADME", invited talk at the *Workshop Shedding light on X17*, Rome, 6 – 8 Sep. 2021.

2. P. Gianotti, "The PADME Scientific Program", talk at the *22nd Particles and Nuclei International Conference (PANIC2021)*, hosted by LIP, Faculty of Sciences of the University of Lisbon and held online, 5 – 10 Sep. 2021.

3. D. Domenici, "Search for feebly interactive particles: the PADME experiment", talk at the *10th International Conference on New Frontiers in Physics (ICNFP 2021)*, Crete, Greece, 23 Aug. – 7 Oct. 2021.

4. C. Taruggi, "The Padme calorimeter", poster at the *5th Technology and Instrumentation in Particle Physics Conference (TIPP2021)*, TRIUMF, Canada, 24 – 28 May 2021.

For the complete list of presentations to conferences given by the PADME collaborators, refer to `http://padme.lnf.infn.it/talks/`.

5 List of Publications by LNF Authors in Year 2021

Here below, it is the list of papers published by PADME LNF members in 2021:

1. J. Alexander *et al.*, “The PADME detectorr”, Phys. Scripta **96** (2021) no.12, 124026 doi:10.1088/1402-4896/ac2542
2. P. Gianotti, “The Physics Program of the PADME Experiment”, Acta Phys. Polon. Supp. **14** (2021), 35.
   doi:10.5506/APhysPolBSupp.14.35.

The complete list of papers published by the PADME collaboration in 2019 can be find here `http://padme.lnf.infn.it/papers/`.

References

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   M. Pospelov, Phys. Rev. D 80, 095002 (2009).
2. M. Raggi and V. Kozhuharov, Rivista del Nuovo Cimento 38 no. 10 (2015).
   DOI 10.1393/ncr/i2015-10117-9
3. I. Valin *et al.*, JINST 7, C01102 (2012).
4. T. Poikela *et al.*, JINST 9, C05013 (2014).
5. ADVACAM s.r.o., U Pergamenky 12, 17000 Praha 7, Czech Republic, (`https://advacam.com`).
6. Workshop “Fisica Fondamentale a Frascati”, 13 Jan 2021, (`https://agenda.infn.it/event/25299/`).
7. A. J. Krasznahorkay *et al.*, Phys. Rev. Lett. 116 042501 (2016).
8. A. J. Krasznahorkay *et al.*, Phys. Rev. C 104, 4, 044003 (2021).
9. F. Bossi *et al.*, INFN-21-04/LNF.