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 for only 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 living independently of those in the Standard Model (SM). The connection within these two worlds can be theoretically realized by a low-mass spin-1 particle, indicated with the symbol A', that would manifest as 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 the ordinary world and the dark world.

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 DAΦNE complex LINAC and identifying the A' as a missing mass signal.

PADME (Positron Annihilation into Dark Matter Experiment) is an international collaboration that in 2023 counted about 25 scientists from LNF, the INFN section of Roma1, the Sapienza University of Rome (IT), the Sofia University (BG), the Princeton University (USA).

The apparatus was built, installed and commissioned with the beam from October 2018 to February 2019 (Run-I). In 2020 a second data acquisition period (from July to December 2020) took place. The first part was dedicated to beam tuning and detector calibration, while from September $\sim 5 \times 10^{12}$ positrons-on-target (POT) were recorded to start addressing the main physics goal (Run-II).

The range of physics subjects that the PADME experiment can explore is wider and comprises other topics than the DP search. Simulations have been performed to determine the experiment sensitivity to the production of Axion-Like Particles (ALPs) or a Dark Higgs (DH). The PADME detector can actually study the production of new particles X through the in-flight annihilation of positrons with the electrons of the target, either in association with an ordinary photon $e^+e^- \to \gamma X$, or resonantly $e^+e^- \to X$. This feature, combined with the possibility to change easily and precisely the beam energy, turned out ideal for Run-III that was conceived to study the existence of a new particle named X_{17} via the reaction $e^+e^- \to X_{17} \to e^+e^-$ 2). This state was introduced to explain an anomalous behaviour observed by a nuclear physics experiment performed at the ATOMKI institute of Debrecen in Hungary. The experiment studied the de-excitation of certain high energy nuclear states (^{8}Be, ^{4}He, ^{12}C) via Internal Pair Creation. In the angular distribution of the measured e^+e^- pairs, a bump appeared and the most plausible explanation for such behaviour is to acknowledge that the decay of the excited state proceeds through the creation of an unstable particle of mass ~ 17 MeV [3, 4, 5]. If the existence of this state is confirmed, it would represent the first evidence of dark matter produced in accelerator experiments.

2 The PADME experiment

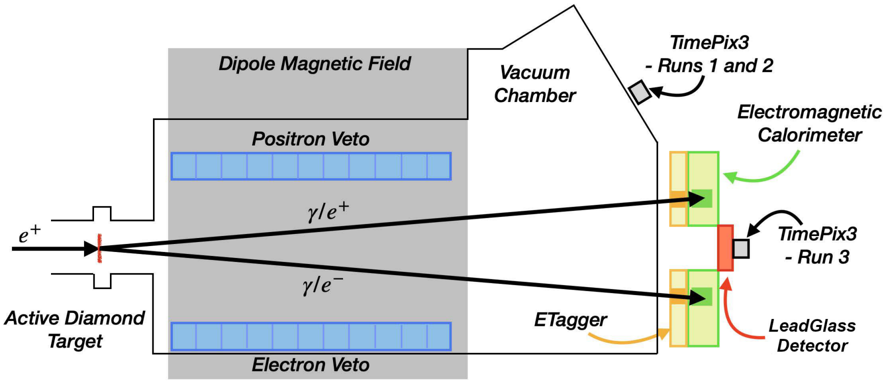

Figure 1: *The layout of the PADME experiment. During Run-III, dedicated to the X_{17} study, some changes were implemented to the experimental setup: the magnetic field was switched off and the veto detectors were not used; to allow lepton/photon separation an array of plastic scintillators was mounted in front of the main electromagnetic calorimeter (ETagger); a LeadGlass crystal was installed in place of the SAC behind the main calorimeter's hole, to be used as an online beam monitor; the solid state beam monitor (TimePix3) was moved behind the LeadGlass.*

The main 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 [6].

Figure 1 shows a scheme of the apparatus that for 2022 data taking was partially modified in order to fit the requirements of the new measurement. The new setup consists of:

- a low divergence positron beam, impinging on a diamond, thin active target, capable of monitoring the beam spot dimensions and intensity;
- a vacuum chamber to avoid particle's spurious interactions;
- a dipole magnet, instrumented on both sides with 2 arrays of plastic scintillator sticks, meant to deflect and measure charged particles, during Run-III it was switched off;
- 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; During 2022 data taking, it had also to detect e^+e^- pairs from X_{17} decay. To disentangle them from photons, a new detector (ETagger) was installed. It consists of an array of plastic scintillator slabs placed in front each row of ECal crystals. Lepton/photon separation is performed combining the signals of the 2 detectors in coincidence/anticoincidence;

Another change implemented to the experimental setup regards the Small Angle Calorimeter (SAC) whose original purpose was to detect Bremsstrahlung photons in coincidence with the veto detectors. Since these last were off in 2022, the SAC was replaced by a LeadGlass crystal aimed at monitoring online beam energy. A more precise evaluation of beam energy was obtained offline processing the signals of the solid state beam monitor detector. It consists in an array (6×2) of Timepix3 chips [7] able to record either the time-of-arrival (ToA) and the energy of the incident particles providing excellent energy and time resolutions.

3 Activity of the PADME Group in 2023

The year 2023 was dedicated to the analysis of the data collected in Run-III for the X_{17} campaign. Taking advantage of the unique opportunity to have positrons in the energy range 250-450 MeV, PADME is in an ideal position to produce the X_{17} state in a resonant mode and subsequently detect it via its decay to an e^+e^- pair [2]. The PADME Run-III (from October to December 2022) consisted in an energy scan of the X_{17} mass region. In the unique situation of knowing the mass of the particle to the level of few hundreds keV, this can be identified looking for an excess of the number of e^+e^- pairs produced at different beam energies with respect to what is expected from the SM. Figure 2 shows the projected 90% C.L. sensitivity of PADME Run-III on the coupling of a X_{17} vector boson. The estimate is based on the collected statistics and a measured beam energy spread of $\sigma_E = 0.3\%$.

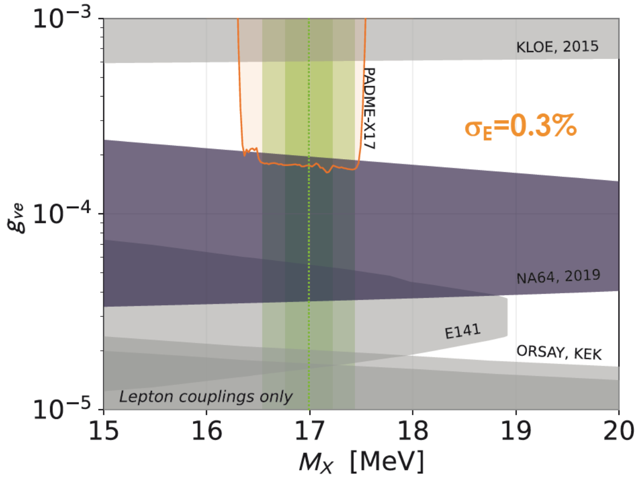

Figure 2: *PADME expected sensitivity to a vector X_{17}. Different grey areas represent the excluded regions for the coupling coming from other experiments. The green bands indicate the expected 1 and 2 σ mass regions for the X_{17}.*

The main background to the $X_{17} \to e^+e^-$ signal is the elastic (Bhabha) electron-positron scattering. While the $t-$channel is peaked at high energies for the scattered positron, the $s-$channel has the same signal kinematics. In addition, two clusters from $\gamma\gamma$ events have to be rejected. Since the PADME veto spectrometer cannot be used to constrain e^+e^- vertices not originating from the target, it has been decided to identify the decays of the X_{17} using the ECal. Thus, to allow low-momentum charged particles to reach the calorimeter, the magnetic field was switched off. In order to disentangle e^+e^- from photons the ETagger information is used.

PADME Run-III collected data can be divided in 3 samples (see Fig. 3):

- *on resonance*, 47 points collected in the energy range 263-299 MeV. For each energy value $\sim 10^{10}$ POT were recorded;
- *below resonance*, 5 points collected in the energy range 205-211 MeV with the same statistics, for each energy value, of on resonance points. They are necessary to define the analysis method;
- *above resonance*, 5 different runs of $\sim 0.4 \times 10^{10}$ POT collected all at the same energy, 402 MeV, but at different times to check stability and reproducibility of the apparatus response.

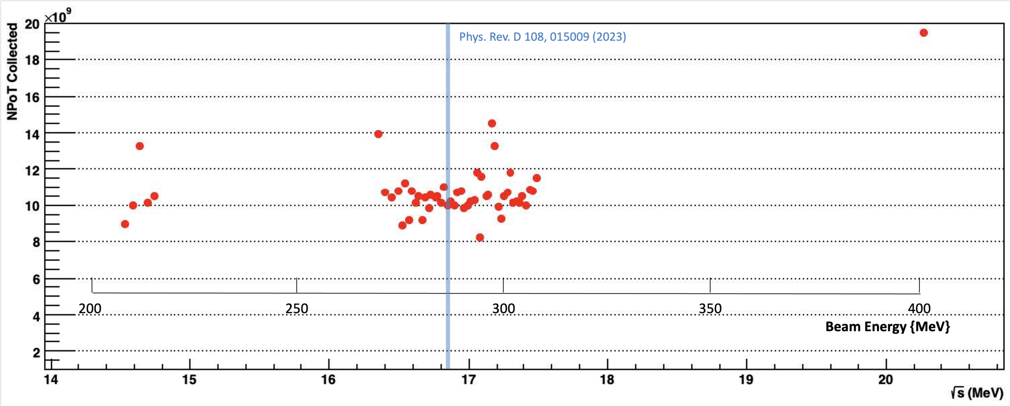

Figure 3: *Summary of the PADME data collected during Run-III as a function of the value of the* $\sqrt{s}$ *at which they have been recorded. The pale-blue line represents the most probable value for the mass of the* X_{17} *evaluated by the authors of* $^{9)}$.

The overall analysis strategy relies on the determination of several independent observables with the advantage of allowing a precise evaluation of the systematic errors. The first measured observable is the ratio between the number of events with 2 clusters in the ECal and the number of POT ($N(2cl)/N_{POT}$). Since the $e^+e^- \rightarrow \gamma\gamma$ process counts only for a 20% of the total cross section, at a first look to check if the X_{17} is produced, it has been decided to evaluate this quantity. The measurement will give a high statistical significance and will not require the evaluation of the systematics induced by the ETagger detector. On a parallel line, by using the information of the ETagger, it is evaluated the ratio $N(ee)/N(\gamma\gamma)$. This observable will be dominated by the tagging efficiency and will have a lower statistical significance, due to the smaller $\gamma\gamma$ cross section. On the other hand, it will be independent from a precise knowledge of the beam integrated luminosity (N_{POT}). Finally evaluating $N(ee)/N_{POT}$ and $N(\gamma\gamma)/N_{POT}$ it would be possible to understand the nature of the X_{17}: vector or pseudo-scalar. At the time of this this report writing, we are determining the above-mentioned quantities for the signal sidebands energy regions. This operation will allow us to determine the trend of the background whose functional form will then be extrapolated to the signal region to be subtracted from the data.

Figure 4 gives an idea of the data quality and stability. The 2 plots show both the $N(2cl)/N_{POT}$ ratio for the 5 different runs (236–240) collected *above resonance* (*Left*) and *below resonance* (*Right*). The RMS of all measurements are $< 1\%$ indicating that systematics uncertainties are almost negligible. The fits to the data show also a good χ^2. The trend, visible in the data collected *below* *resonance*, is due to the apparatus acceptance and is well reproduced by the MonteCarlo simulation.

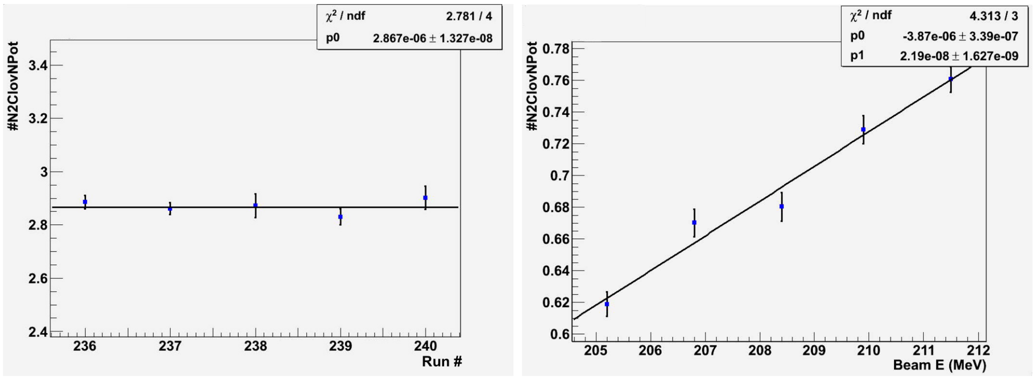

Figure 4: *Two cluster events normalized to the number of POT for the 5 runs collected at 402 MeV (Left) and for the 5 runs collected at different energies below resonance (Right). The RMS of both plots are $< 1\%$ compatible with pure statistical uncertainties. The fits to the data show good χ^2. The observed trend in the right plot is reproduced by the MonteCarlo simulation (Vertical scales are arbitrary).*

4 List of Conference Talks presented by LNF Speakers in Year 2023

Below is the list of conference presentations given by LNF PADME members in 2023:

1. M. Mancini,"Study of the X17 anomaly with the PADME experiment", talk at the *ALpine Particle physics Symposium (ALPS2023)*, Obergurgl, 26 - 31 Mar. 2023.
2. P. Gianotti, "Investigating the dark sector with the PADME experiment", talk at the *20th International Conference on Hadron Spectroscopy and Structure (HADRON 2023)*, Genova, 5 - 9 Jun. 2023.
3. I. Sarra,"Search for a Dark Photon with the PADME experiment", invited talk at the *17th International Workshop on Meson Physics (MESON 2023)*, Krakow, 22 - 27 Jun. 2023.
4. C. Taruggi, "Dark Matter searches with the PADME experiment", talk at the *2023 European Physical Society Conference on High Energy Physics (EPS-HEP2023)*, DESY Hamburg, 20 - 25 Aug. 2023.
5. C. Taruggi, "Il bosone X17 nella ricerca italiana: Il caso di PADME e oltre", invited talk at the *109º Congresso Nazionale Società Italiana di Fisica*, Fisciano (Salerno), 11 - 15 Sep. 2023.
6. M. Mancini, "Studio della produzione risonante del bosone X17 presso l'esperimento PADME", talk at the *109º Congresso Nazionale Società Italiana di Fisica*, Fisciano (Salerno), 11 - 15 Sep. 2023.
7. E. Di Meco, "Nuovo setup dell'apparato sperimentale PADME per la rivelazione dell'X17", talk at the *109º Congresso Nazionale Società Italiana di Fisica*, Fisciano (Salerno), 11 - 15 Sep. 2023.

8. D. Domenici, “Study of the X17 anomaly with the PADME experiment”, talk at the *16th International Conference on Meson-Nucleon Physics and the Structure of the Nucleon (MENU2023)*, Mainz, 16 - 20 Oct. 2023.
9. P. Gianotti,“Dark matter search via positron’s interactions”, invited talk at the *15th European Research Conference on Electromagnetic Interactions with Nucleons and Nuclei*, Paphos, 31 Oct. - 4 Nov. 2023.

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

5 List of Publications by LNF Authors in Year 2023

Below is the list of papers published by LNF PADME members in 2023:

1. F. Bossi *et al.*, “Cross-section measurement of two-photon in-flight annihilation of positrons at $\sqrt{s} = 20$ MeV with the PADME detector”, Phys. Rev. D 107 (2023) 012008.
2. P. Gianotti, “The study of the X17 anomaly with the PADME experiment”, J.Phys.Conf.Ser. 2586 (2023) 01214.
3. V. Kozhuharov, “The PADME experiment at LNF-INFN”, PoS BPU11 (2023) 078.
4. S. Bertelli *et al.*, “Beam diagnostics with silicon pixel detector array at PADME experiment”, JINST 19 (2024) 01, C01016.
5. S. Bertelli *et al.*, “Design and performance of the front-end electronics of the charged particle detectors of PADME experiment”, JINST 19 (2024) 01, C01051.

The complete list of papers published by the PADME collaboration in 2023 can be find here `http://padme.lnf.infn.it/papers/`.

References

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   M. Pospelov, Phys. Rev. D 80, 095002 (2009).
2. L. Darmé, M. Mancini, E. Nardi and M. Raggi, Phys. Rev. D 106 no. 11 (2022) 115036.
3. A. J. Krasznahorkay *et al.*, Phys. Rev. Lett. 116 (2016) 042501.
4. A. J. Krasznahorkay *et al.*, Phys. Rev. C 104 (2021) 044003.
5. A. J. Krasznahorkay *et al.*, Phys.Rev.C 106 (2022) L061601.
6. M. Raggi and V. Kozhuharov, Rivista del Nuovo Cimento 38 no. 10 (2015).
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9. P. B. Denton and J. Gehrlein, Phys. Rev. D 108, (2023) 015009.