PROCEEDINGS OF SCIENCE

Dark Matter searches with the PADME experiment

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The parameters space for Weakly-Interacting-Massive-Particles as possible explanation for Dark Matter, is shrinking more and more. This triggered new attempts to create dark matter at accelerators. This alternative approach represents an innovative and open-minded way to broaden this research field in a wider range of energies with high-sensitivity detectors.
In this panorama is inserted the Positron Annihilation into Dark Matter Experiment (PADME) ongoing at the Laboratori Nazionali di Frascati of INFN. PADME was conceived to search a Dark Photon signal by studying the missing-mass spectrum of single photon final states resulting from positrons annihilations with the electrons of a fixed target. Actually, the PADME approach allows to look for any new particle produced in e^+e^- collisions through a virtual off-shell photon such as long lived Axion-Like-Particles (ALPs), proto-phobic X bosons, Dark Higgs...
After the detector commissioning and the beam-line optimization, PADME collaboration collected in 2020 about 5×10^{12} positrons on target at 430 MeV. A fraction of these data have been used to evaluate the cross-section of the process $e^+e^- \rightarrow \gamma\gamma(\gamma)$ at $\sqrt{s} = 20$ MeV with a precision of 5%. This is the first measurement ever done at this energy, that detected the two final state photons, making it the first measurement allowing to define stringent limits to processes beyond Standard Model.
PADME has also the unique opportunity to confirm/disprove the particle nature of the X17 anomaly observed in the ATOMKI nuclear physics experiments studying de-excitation of some light nuclei. The PADME 2022 data taking was conducted with this scope. About 10^{10} positrons have been stopped on the target for each of the 47 beam energy values in the range $262 - 298$ MeV. This precise energy scan is intended to study the reaction $e^+e^- \rightarrow X17 \rightarrow e^+e^-$.

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1. Introduction

The Standard Model (SM) of particle physics is one of the most astounding scientific achievement of the last century. However, many physics observations cannot find a proper fit inside it. One of the most interesting problems of modern physics is the behaviour of some cosmological phenomena that could not take place if one only takes into account gravitational laws and the amount of matter that we observe. The galaxy rotation velocity, the Bullet Cluster structure and some gravitational lensing phenomena are only some of these observation: if we keep gravitational law as it is, we could explain these phenomena introducing a new kind of invisible matter, that interacts at least gravitationally with SM particles. We call this kind of matter *dark matter* (DM). During last decades, many experiments tried to find some direct evidence of the existence of DM. Nevertheless, at present day no shared proof by multiple experiments has been found. One possible interpretation of this issue could be that DM lives in a separate world with respect to the one where SM particles live . These two worlds could be connected by a new interaction, whose mediator acts like a portal. We can call this separate world dark sector (DS), and the mediator dark photon (DP). If the new interaction has a small coupling constant, one could explain why DM detection is so difficult.

2. The PADME experiment

PADME was originally designed to search for DP, through the annihilation of a positron beam on a fixed target[1] [2]. If we define the DP as A', the production process of DP can be written as:

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

with known beam energy and target at rest. The only assumption here is that DP couples to leptons. The quadri-momentum of photon γ in the final state must be detected to close the kinematics of the reaction. The existence of A' can be observed as a peak in the squared missing mass distribution:

$$M^2_{miss} = (P_{e^+} + P_{e^-} - P_\gamma)$$

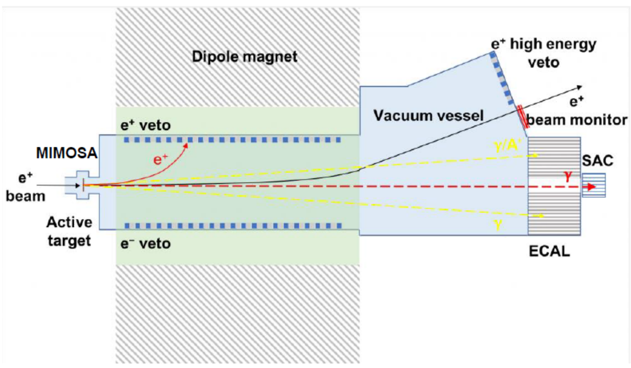

Figure 1: The layout of the experiment.

The detector (fig. 1) can be summarized as follows: the positron beam (maximum energy 550 MeV, bunch multiplicity ~ 25k particles), provided by the Beam Test Facility of the Laboratori

Nazionali di Frascati [3] [4], hits an active diamond target (100 μm thickness), that provides the interaction point and the beam multiplicity. Another subdetector, the MIMOSA pixel beam tracker, can be moved remotely on beam in place of the target in order to measure its divergence. A magnetic field (~0.5 T) deflects the charged particles in a vacuum chamber, towards the charged particles veto detectors, made of plastic scintillators bars. The photons, produced after the annihilation, reach the electromagnetic calorimeter, which is made of BGO crystals and has a cylindrical shape, with a hole in the center. The hole allows Bremsstrahlung radiation, which is one of the main background of the experiment, to reach the small angle calorimeter, placed behind the electromagnetic calorimeter, which is made of PbF_2 crystals. The non-interacting beam particles are deflected to the high energy veto detector and the TimePix3 beam monitor. A beam of 550 MeV, 200 ns bunch duration, 49 Hz repetition rate, allows exploring DP masses up to 23.7 MeV.

3. First runs physics results

Two data taking were performed between 2018 and 2020. One of the main issues the collaboration had to address was a much larger beam-induced background than expected. A detailed simulation of the beamline was necessary in order to understand it and find a way to reduce it. For this reason, different configurations of the beamline were used during the two data taking.

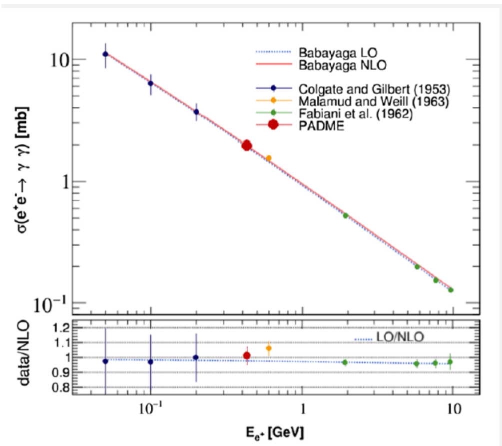

Figure 2: Comparison between PADME experimental result and theory predictions, at the leading order and next to leading order approximation, for the positron annihilation cross section in flight as a function of the positron energy.

The first measured physics process was the multi-photon annihilation $e^+e^- \to \gamma\gamma(\gamma)$ [5]. The most recent measurement of this process under 500 MeV with a 20% precision was carried out in 1963. The PADME result (fig. 2) is in good agreement with SM predictions:

$$\sigma(e^+e^- \to \gamma\gamma(\gamma)) = 1.977 \pm 0.018(stat) \pm 0.045(stat) \pm 0.110(n.collisions)mb$$
$$QED@NLO\sigma(e^+e^- \to \gamma\gamma(\gamma)) = 1.9478 \pm 0.0005(stat) \pm 0.0020(syst)mb$$

4. The beryllium anomaly

During a nuclear experiment studying the internal pair creation in the decay of excited ^{8}Be, the ATOMKI collaboration (Hungary) discovered an anomaly in the angular emission of e^+e^- couples [6]. The same anomaly was observed in the decay of ^{4}He [7] and ^{12}C [8]. The anomaly is compatible with the emission of a 17 MeV particle, called the X17 boson (most probably a vector particle). Many experiments, already existing or specifically built for the purpose, are trying to validate the ATOMKI observation. PADME has the unique chance to use a complementary technique to produce X17, since BTF is the only facility in the world that is able to deliver a positron beam with the precise characteristics to allow the resonant production of the X17 boson. If the X17 is resonantly produced, the cross section of the annihilation process shows a sharp increase with respect to the background.

5. The X17 search at PADME

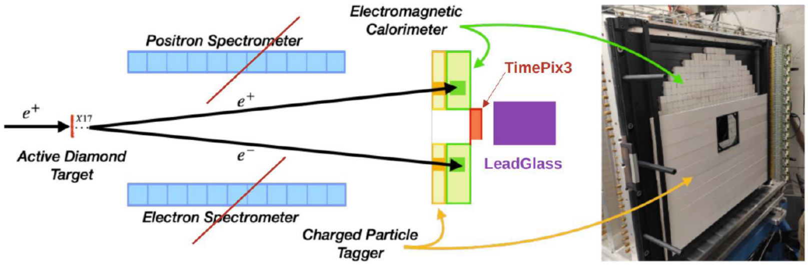

Figure 3: The layout of the detector after the upgrade for the X17 data taking.

In order to perform the X17 measurement, PADME underwent a detector update (fig. 3). In this case, the searched signal is $e^+e^- \to X17 \to e^+e^-$. For this reason, since we need to detect the charged particles in the final state of the process, and the charged particles veto detector do not allow a precise measurement of the quadrimomentum, the magnetic field of the experiment was turned off. In order to discriminate between charged and neutral particles, a plastic scintillator charged particle tagger (ETagger) was developed, and placed in front of the electromagnetic calorimeter. The small angle calorimeter was removed, in its place the TimePix3 beam monitor and a leadglass calorimeter were placed, used as luminosity monitor.

6. The resonant strategy

As already mentioned, the X17 boson could be produced at resonance in PADME/BTF [9]. In this way, e^+e^- annihilation cross-section has a very sharp increase wrt to the background (mainly Bhabha scattering $e^+e^- \to e^+e^-$). A beam energy of 282 MeV corresponds to an available center of mass energy of $\sqrt{s} \approx 17$ MeV. For this reason, an energy scan with step of 0.7 MeV was performed between 260 MeV and 300 MeV (10^{10} positrons on target per point, equal to 25 h of data taking per point). Two energy scans option can be seen in fig. 4. The beam energy spread σ_E is a crucial parameter for the signal-to-background optimization, as one can see from the formula for the number of X17 N_{X17} that could be produced in PADME:

$$N_{X17} \simeq 1.8 \times 10^{-7} \times \left(\frac{g_{Ve}}{2 \times 10^{-4}}\right)^2 \left(\frac{1MeV}{\sigma_E}\right)$$

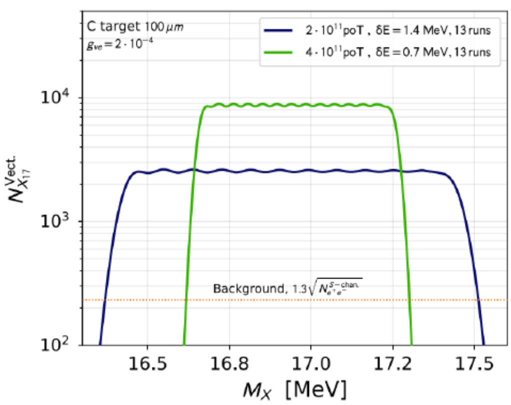

Figure 4: Number of expected vector X17 as function of M_X, in case of energy resolution 1.4 MeV (blue curve) and 0.7 MeV (green curve) for $g_{Ve} = 2 \times 10^{-4}$. T he dotted orange line corresponds to the square root of the number of Bhabha events.

where g_{Ve} is the coupling constant between X17 and leptons. The main backgrounds for this measurement are Bhabha scattering and $\gamma\gamma$ production.

7. Preliminary results

PADME took different sets of data. For each energy point, 10^{10} positrons on target were collected:

- 47 points around the X17 resonance;
- 6 points out of resonance (5 below, 1 above), to compare data with the Montecarlo simulation, and check the systematics;
- 3 points without target (for background studies).

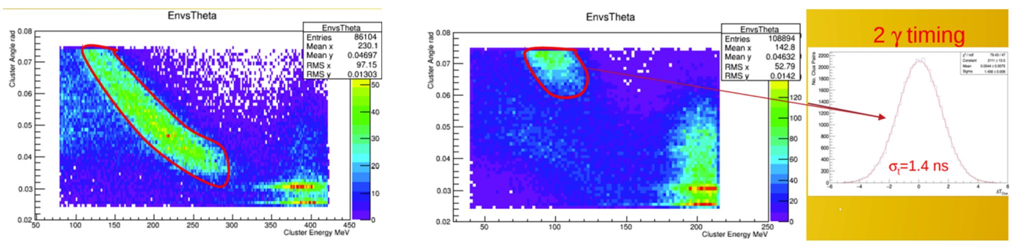

Figure 5: Cluster angle vs cluster energy above resonance (left) and below (center); the Δt between cluster (right).

One of the first studies the collaboration performed on these data regards the ratio between the number of two-clusters events detected by the electromagnetic calorimeter ($N(e^+e^- + \gamma\gamma)$) and the number of positrons on target (N_{POT}). A good signal/background separation can be obtained simply using the kinematic relation between the energy of the photons E_γ and their angular emission θ_γ, and selecting 2 clusters in time in ECal with Δt < 5 ns (fig. 5).

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8. Conclusions

The PADME experiment studies the annihilation process e^+e^- using a positron beam (max energy 550 MeV) on a fixed target to produce new physics particles. PADME first two data taking (2018 – 2020) were crucial to optimize the beam and to finalize the detector calibrations and data reconstruction. A reliable Montecarlo simulation of the experiment, including the beam line, has been developed. The first physics result, regarding the multi-photon annihilation $e^+e^- \to \gamma\gamma(\gamma)$, was published in [5].
PADME third data taking (2022) was carried out to search for the X17 boson, a particle that could be involved in the anomaly decay of ^{8}Be, ^{4}He and ^{12}C observed by the ATOMKI collaboration. The preliminary studies on data are promising, and backgrounds looks under control. The analysis strategy for the X17 search can be found in [9].

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