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Dark sector studies with the PADME experiment

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The investigation of dark matter nature, its origin, and the way it interacts with ordinary matter plays a crucial role in fundamental science. Several particle physics experiments at accelerators are searching for hidden particles signals to contribute setting more stringent limits on the characteristics of dark matter. The Positron Annihilation into Dark Matter Experiment (PADME), ongoing at the Laboratori Nazionali di Frascati of INFN, is looking for hidden particle signals by studying the missing-mass spectrum of single photon final states resulting from positrons annihilation on the electrons of a fixed target. PADME is expected to reach a sensitivity of up to 10^{-6} on ϵ^2 (the kinetic mixing coefficient) representing the coupling of a low-mass dark photon ($m < 23.7$ MeV$/c^2$) with ordinary photons. By measuring the cross-section of the $e^+ e^- \to \gamma\gamma$ process at $\sqrt{s} = 21$ MeV$/c^2$ and comparing it with Standard Model expectation, it is also possible to set limits on hidden particles decays to photon pairs. In this contribution details on the PADME measurement of two-photon annihilation cross-section are illustrated with its implication to the dark matter studies.

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1. Dark sector and the PADME experiment

Several extensions of the Standard Model (SM) of particle physics have been proposed in order to account for the required amount of dark matter in our Universe: given the restricted parameter space available for the favoured option of weakly interacting massive particles due to the extensive searches at LHC, attention has been recently turned to alternative models, proposing various possibilities for light, feebly interacting particles. A number of those model introduce a new dark sector, in which a "portal" particle couples both to dark matter heavy particles and to the SM. These models are classified in terms of the mediator, which can be a vector (a "dark photon", A'), a pseudo-scalar (an axion-like particle), a scalar (a "dark Higgs") or a fermion. In particular, dark photon models are characterized by just two parameters: its mass, m'_A, and coupling to SM particles, ϵ.

The PADME experiment has been originally designed [1] for searching "invisible" decays of A', i.e. in case it is heavy enough to decay to dark matter particles, $A' \rightarrow \chi\overline{\chi}$, thus escaping detection. It profits of the positron beam accelerated by the Frascati National Laboratories LINAC, extracted to one of the two beam-lines of the BTF (Beam-Test Facility), BTF-1. The experiment aims at detecting the production of dark particles in the in-fligth annihilations of the positrons of the beam onto the atomic electrons of a thin target, either in associated production with a photon, or in resonant production e^+e^-. The maximum nominal energy of the LINAC in positron mode is 550 MeV, thus limiting the search in fixed-target annihilations to masses $m_X < 23.7$ MeV$/c^2$. The production of a massive particle, like a dark photon, in $e^+e^- \rightarrow \gamma A'$ is signaled by a non-vanishing missing mass closing the kinematics, since the beam energy is known, by measuring the momentum of the photon (electrons are assumed to be practically at rest).

The position and energy of photons are measured by a finely segmented BGO electromagnetic calorimeter (ECal) [2], made by 616 crystals arranged in a cylindrical shape. Other detectors are used to reject the two main backgrounds, i.e. the Bremsstrahlung emission of a photon on the active, diamond target (0.1 mm thick, with graphite strips) [3], and the annihilation in two or three photons. Being the angular distribution of the Bremsstrahlung radiation sharply peaked in the forward direction, the ECal has been realized with a central hole, behind which is placed a faster, Cherenkov detector, made of a square matrix of 25 PbF_2 crystals [4]. This small angle calorimeter (SAC) is used in conjunction with plastic scintillator bars read out by means of green-shifting fibers and SiPM [5], placed in a vertical magnetic field, which allows tagging the positrons having irradiated a photon. The magnetic field (of about 0.5 T), provided by a wide gap (23 cm) dipole, also sweeps the non-interacting positron beam away from the calorimeters. At the exit from the vacuum vessel and before being dumped onto the concrete of the BTF hall, the beam can be imaged by a hybrid Silicon pixel detector, consisting of TimePix sensors, each made of a 256×256 square pixels of 0.055 mm side, arranged in a 6×2 matrix.

This setup has been optimized for the search of dark photons decaying invisibly in associated production, i.e. by looking for a bump in the missing mass distribution of single photon events. However, the scintillating bar detectors have been placed on both sides of the dipole magnet axis, so to allow reconstructing events with a pair of charged particles, coming from the $A' \rightarrow e^+e^-$ visible decays or from the SM processes, in particular the Bhabha scattering.

The flight path up to a polar angle of $\sim$ 100 mrad, including the scintillating bar detectors

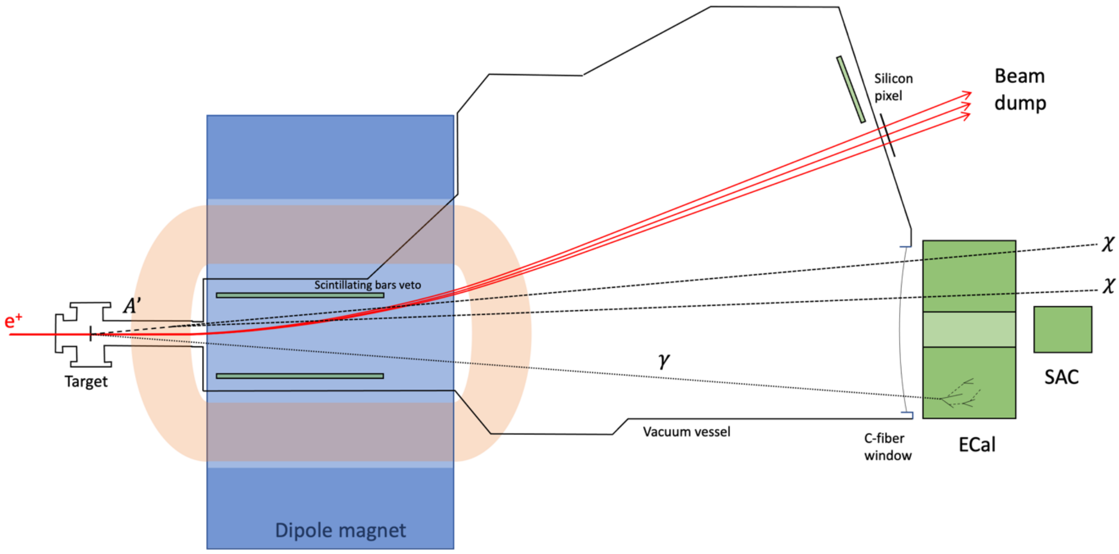

Figure 1: Schematic view of the PADME experiment (not to scale).

between the dipole magnet poles, is inside a vacuum vessel connected to the BTF-1 beam-line on the upstream side and separated from the ECal by a large, 3 mm thick, carbon fiber window. A schematic view of the experiment is shown in Fig. 1.

2. PADME experiment status

PADME has taken data in two periods, in fall 2019 (Run I) and fall 2020 (Run II), collecting a similar statistics of $\approx 5 \times 10^{12}$ positrons on target (pot), but with different beam configurations: with a secondary beam of 490 MeV positrons, produced onto the attenuating target of the BTF yielding a high beam-induced background, in Run I, and by using the "primary" beam produced at the positron converter of the Frascati LINAC and accelerated to 430 MeV, in Run II. In order to reduce the pile-up, the density of positrons in a single beam pulse was limited to $\sim 10^2$ particles/ns, trying to produce the maximum lenght of the macro-bunches, up to $\sim$ 300 ns [6].

Between Run I and Run II the thin window separating the machine and experiment vacuum systems was also replaced and moved upstream, thus greatly reducing the amount of off-momentum beam particles entering the final dipole of the BTF beam-line and hitting the ECal. Further details on the beam, on the experiment commissioning and on the background studies can be found in [7, 8].

A small fraction of Run II data, about 10%, was used to measure the inclusive in-flight cross section $\sigma(e^+e^- \rightarrow \gamma\gamma(\gamma)$ with a precision of $\sim$ 5% [9], with two different analysis methods: a tag-and-probe two clusters selection, and a single photon selection exploiting the energy-angle correlation in two photons events. The result for the cross-section measurement

$$\sigma(e^+e^- \rightarrow \gamma\gamma(\gamma)) = 1.930 \pm 0.01073 \text{ mb},$$

not only is the best determination in the sub-GeV regime, as shown in Fig. 2, but also opens the possibility of setting limits to dark sector models, for instance for a pseudo-scalar decaying

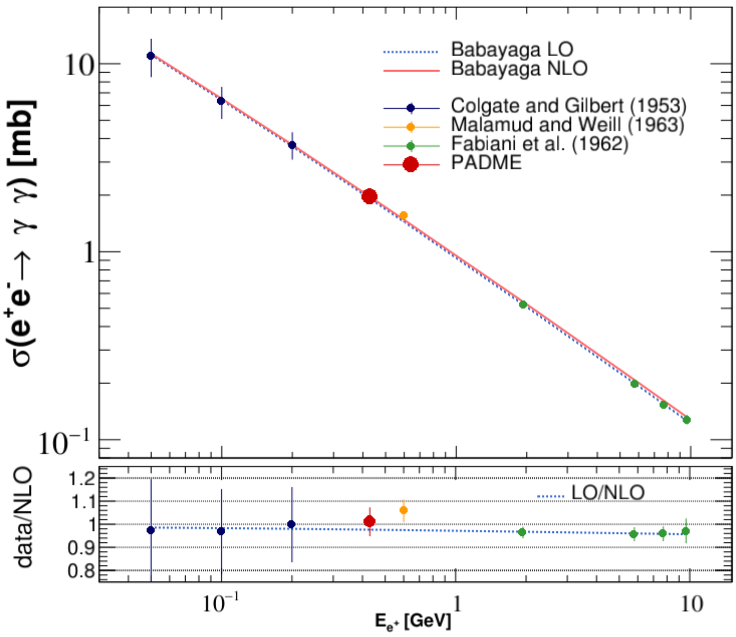

Figure 2: Theory predictions, at the leading order and next-to-leading order approximation, for the positron annihilation cross-section in flight as a function of the positron energy. The PADME measurement is compared to earlier measurements. Data to theory ratios are shown in the bottom pad.

into photons. Moreover, such a measurement allowed to assess the performance of the PADME calorimeter and is an important intermediate step towards the single photon analysis looking for the associated production of a dark photon.

3. PADME perspectives

Since 2016 the observation of an anomaly in a nuclear physics experiment, known as "Beryllium anomaly", has gained stronger and stronger evidence: a unexpected bump in the angular distribution of the e^+e^- produced by internal pair conversion in the decay of excited ^{8}Be nuclei [10] , has been also seen, by the same collaboration, also in the de-excitation of ^{4}He [11] and ^{12}C nuclei [12]. In all three cases, with large significances of more than 5σ, the production of a neutral boson with mass of around 17 MeV$/c^2$ has been advocated (the so-called X17 particle).

The PADME experiment, with a slightly modified setup, can address this anomaly by looking for the production of such a boson in e^+e^- annihilations into X17, by exploiting the increase of several orders of magnitude of the production cross-section expected when the positron beam energy is such that $\sqrt{s} \simeq m_{X17}$ [13].

The main background to the $X17 \to e^+e^-$ 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 an identical kinematics with respect to the signal. 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 which do not come from the production target, the basic idea is to identify decays of a massive particle

Figure 3: The scintillating bar electron tag detector (ETag) being assembled and mounted in front of the PADME crystal calorimeter (ECal).

into electron-positron pairs using the ECal, as for the $\gamma\gamma$ events. In order to allow low-momentum charged particles to reach the calorimeter the magnetic field has to be switched off. Provided that the beam intensity is kept low enough to have a negligible pile-up probability, the ECal can reconstruct precisely the e^+e^- invariant mass from the energy and angle of the clusters. This technique requires however to disentangle charged particles and photon clusters. For this purpose an additional detector (the electron tagger, ETag) has been realized and installed in front of ECal (in Fig. 3 shown during the assembly). The ETag is made of 5 mm thick scintillating bars, each read out by 4 SiPM: the vertical segmentation of 4 cm allows to have a sustainable rate while covering the fiducial region of the calorimeter with a reasonable number of channels.

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