PROCEEDINGS OF SCIENCE

Searching for the Dark Photon with PADME

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The PADME Experiment at Laboratori Nationali di Frascati is designed to search for the Dark Photon, a hypothetical gauge boson responsible for the interaction between the visible and the hidden sector. PADME explores the process of annihilation of beam positrons with the electrons in a fixed target, employing the missing mass technique: in case the annihilation results in the associate production of one visible and one Dark photon, the first can be registered by the experiment's electromagnetic calorimeter and the Dark Photon mass can be reconstructed knowing the beam energy. This paper presents the analysis techniques that are being employed for the PADME data, as well as the background composition and rejection procedure.

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1. Introduction

Since the early XX-th century the observation of different anomalous astrophysical and cosmological effects has led to the introduction of the Dark Matter hypothesis. Among the possible explanations is the existence of yet unobserved massive particles, neutral under electromagnetic interactions. Depending on their mass, they are classified as WIMPs (Weakly Interacting Massive Particles) with masses above 1 GeV/c^2 [1] or WISPs (Weakly Interacting Slim Particles) with sub-GeV masses [2]. These "hidden sector" particles might interact with ordinary matter through a new interaction. Experimental searches are therefore directed not only to the observation of Dark Matter particles but also towards the force-carrier of the proposed new interaction. The models for a vector portal introduce a new U(1) gauge symmetry with its corresponding gauge boson - the Dark Photon A' [3]. The interaction with the Standard Model fermions may arise effectively through the kinetic mixing term

$$L_{int} = \frac{\epsilon}{2} F^{\mu\nu}_{QED} F^{Dark}_{\mu\nu}, \tag{1}$$

where ϵ is the $A - A'$ mixing parameter.

The initial setup of PADME (Positron Annihilation into Dark Matter Experiment) [4] is designed to probe this hypothesis by searching for the associate production of a Dark Photon together with a visible Standard Model photon in an electron-positron annihilation process:

$$e^+e^- \to \gamma A' \tag{2}$$

If the visible photon is registered by the experiment's calorimeter, the A' mass can be reconstructed by using the missing mass technique. This requires good knowledge of the main background processes and developing a precise procedure for their rejection by employing several other subdetectors. This work presents the Dark Photon search strategy for the PADME Run II data as well as a description of the background composition and the steps for its suppression.

2. The PADME Run II setup and data taking

The PADME experiment uses the pulsed positron beam from the Beam Test Facility (BTF) [5] at the DAΦNE accelerator at Laboratori Nationali di Frascati, capable of reaching energies up to 550 MeV. A schematic view of the experiment with the different subdetectors is shown on Figure 1. The first detector on the beam line is the active target [6] serving as the medium for the interaction. It is capable of providing estimation of the beam position and spread, as well as its multiplicity. A dipole magnet provides a 0.5 T magnetic field, bending the non-interacted beam to the exit window where it is monitored by a TimePix3 silicon pixel detector [7]. Three sets of charged particle vetoes [8] detect any electrons and positrons which may be part of background events. They provide momentum measurement with down to $\sim$ 5 MeV resolution and $<$ 1 ns offline time resolution. The calorimetric system is placed at the far end of the apparatus, 3.45 m away from the target. The Electromagnetic calorimeter (ECal) [9] is made of 616 BGO crystals and has a $\sim$ 500 ps time resolution and $\sim$ 2.6% energy resolution at the energy of interest. The Small Angle Calorimeter (SAC) [10] is placed behind a hole in the middle of the ECal. It provides a $<$ 100 ps time resolution, important for registering the high amount of Bremsstrahlung photons entering this region.

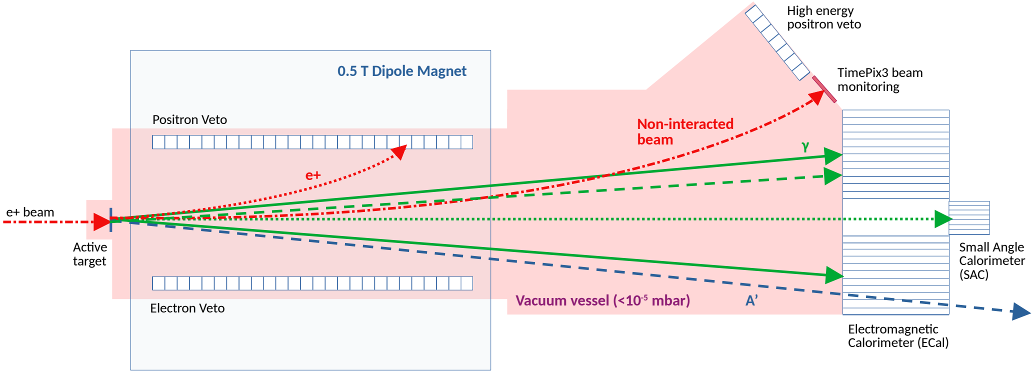

Figure 1: PADME Run II setup with several different particles and processes, observed in the experiment. Photons are shown in green, positrons in red and the hypothetical Dark Photon in blue. The continiuous arrows represent two photons, originating from an $e^+e^- \to \gamma\gamma$ annihilation event; the dashed lines - a photon and a Dark Photon, produced in an $e^+e^- \to \gamma A'$ event and the dotted lines - a positron and a photon, coming from a Bremsstrahlung event.

The PADME Run II data taking was realized in the second half of 2020. A primary positron beam with 430 MeV energy was used, with bunch length of 280 ns at a 50 Hz rate and $\sim 27 \times 10^3$ positrons per bunch multiplicity. A total of $\sim 5.5 \times 10^{12}$ positrons were collected during the running period.

3. Dark Photon search in PADME

The A' production cross-section $\sigma(e^+e^- \to \gamma A')$ can be obtained by comparing the detected A' events to the estimated number of positrons on target

$$\sigma(e^+e^- \to \gamma A') = \frac{N_{A'}}{N_{POT}\ \epsilon_{sig}\ N_{e/S}}, \tag{3}$$

where $N_{A'}$ is the number of registered A' events, N_{POT} is the number of positrons-on-target, ϵ_{sig} is the acceptance and $N_{e/S} = 0.0106\ b^{-1}$ is the number of electrons per unit of area in the target. Then the effective coupling ϵ is obtained as

$$\epsilon^2 = \frac{1}{\delta}\frac{\sigma(e^+e^- \to \gamma A')}{\sigma(e^+e^- \to \gamma\gamma)}, \tag{4}$$

where δ is a kinematics factor depending on $M_{A'}$, with $\delta \to 2$ for $M_{A'} \to 0$ MeV.

To search for candidate A' events, the missing mass for single photons detected by the experiment's calorimeter is calculated:

$$M^2_{miss} = (P_{e^+} + P_{e^-} - P_\gamma)^2, \tag{5}$$

where P_{e^+}, P_{e^-} and P_γ are the four-momenta of the beam positron, target electron and registered photon respectively. Figure 2 shows the distribution of the missing mass squared for different A' masses for events, generated using the PADME Monte Carlo simulation for a single 430 MeV positron hitting the target and producing an A' event.

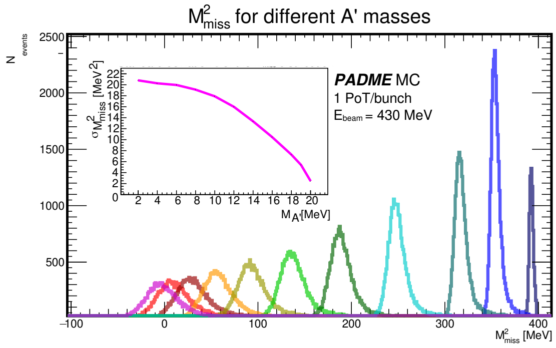

Figure 2: Squared missing mass for photons in simulated $e^+e^- \rightarrow \gamma A'$ events where a single 430 MeV positron hits the target. The $\sigma_{M^2_{miss}}$ decreases with $M_{A'}$ approaching 22 MeV.

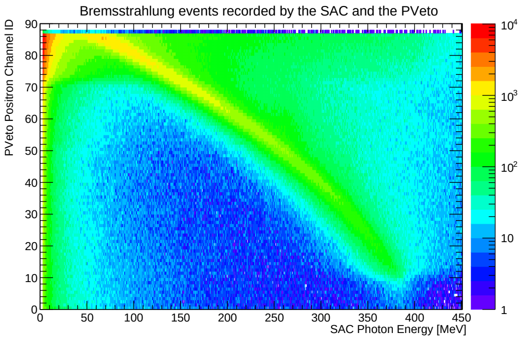

Figure 3: Photon energy in the SAC versus the positron position in the PVeto for in-time γ e^+ pairs obtained for MC simulation with E_{beam} = 432 MeV and 2.5×10^4 positrons per bunch.

The main background process is Bremsstrahlung

$$e^+N \longrightarrow e^+N\gamma \tag{6}$$

which also results in a single-photon final state. To isolate and suppress these events, photons registered by the calorimeters are matched to positrons, registered by the positron and the high energy positron veto. If a photon coincides in time ($\Delta t \leq 5\ ns$) with a positron in the veto, its energy and the positron position in the veto are checked if they match the Bremsstrahlung distribution (Figure 3), in which case the photon is rejected.

Another background process is two- and three photon annihilation

$$e^+e^- \longrightarrow \gamma\gamma(\gamma) \tag{7}$$

If all the photons are registered in the ECal, these events are rejected by ensuring a time isolation for the selected photon from other photons in the calorimeters. In some cases only one of the photons is registered, resulting in a single-photon event. It can be rejected based on its energy and position.

4. Conclusions

The 2020 run of the PADME Experiment was dedicated to the search for associate production of a Dark Photon in e^+e^- annihilation events. The data analysis exploits the missing mass technique, probing the region 2 MeV $\leq M_{A'} \leq$ 20 MeV. To cope with the high background levels, Bremsstrahlung events are suppressed by rejecting photons matched to close-in-time hits in the positron veto, and two- and three photon annihilation events are rejected by isolating photons in the calorimeters in time. Recently, the analysis was boosted forward by the implementation of novel machine-learning based methods for pulse and cluster reconstruction [11], allowing to cope with the high instantaneous rate. In the case of an excess, the number of observed events will allow the estimation of ϵ, while in case of no excess, the limit on ϵ will provide ground for further development of the background reduction procedure or for exploring different search techniques.

In 2022 the PADME setup was modified for the search of resonant production of a hypothetical new particle with 17 MeV mass [12].

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