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Search for a Dark Photon with the PADME experiment

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Despite the variety of attempts to produce dark matter at accelerators, none of the experiments so far produced any evidence. The elusiveness of dark matter has triggered innovative and open-minded approaches with high-sensitivity detectors spanning a wide range of energies. The Positron Annihilation into Dark Matter Experiment (PADME) ongoing at the Laboratori Nazionali di Frascati of INFN is one of the initiatives born within this scenario. PADME is searching for a Dark Photon signal by studying the missing-mass spectrum of single-photon final states resulting from the annihilation of a positron from the beam with an atomic electron in a fixed target. In 2020, after detector commissioning and beam-line optimisation, the PADME collaboration collected about 5×10^{12} positrons accelerated at the energy of 430 MeV on target. These data are now under study in order to tune all analysis procedures. This contribution gives an overview of the scientific program of the experiment, reporting on the detector performance achieved so far, and presents a preview of the ongoing studies of Standard Model processes ($\gamma\gamma$ events and Bremsstrahlung).

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1. Introduction

Dark matter is one of the most intriguing mysteries in physics since many decades. All of the astrophysical and cosmological evidences (galaxy rotation velocities, hot gas in galaxy clusters, distributions of gas, star and gravitationally interacting matter in colliding galaxy clusters, fluctuations in the cosmic microwave background, large structure formation) must be contrasted with the lack of observation of any candidate in direct detection experiments [1]. Still non baryonic cold dark matter is an essential component of successful and widely accepted cosmological models. Among the best motivated candidates, weakly interactive particles with mass and coupling values at the electroweak scale would nicely match the relic density of thermal dark matter. However, the search for direct production of such particles at the high energy frontier of the Large Hadron Collider has shrunk the allowed phase space of the most appealing models to "un-natural" corners [2]. Therefore, the experimental and theoretical investigation is moving toward an approach less model driven and generally wide-open. In this context the hypothesis of DARK matter living in a hidden sector has become popular as a sort of extension of the WIMP paradigm, with particles or mediators down to the MeV scale, still accessible at accelerators and generally compatible with the relic abundance from the thermal freeze-out hypothesis [3]. Interestingly enough, this range of scales is also motivated by a few experimental anomalies, like the mismatch between theory prediction and measurement of the muon anomalous magnetic moment and the ^{8}Be anomaly. That is the physics context where the PADME project was born [4].

2. The PADME concept

The goal of PADME is to investigate a minimal vector-portal scenario for the hidden sector hypothesis, by searching for a massive dark photon, A'. This particle would correspond to the gauge field of a $U(1)$ symmetry in the hidden sector responsible for interactions between dark matter particles. The mass and a universal effective coupling to the Standard Model (SM) particles, dominated by the kinetic mixing between the Standard Model photon and the dark photon, would be

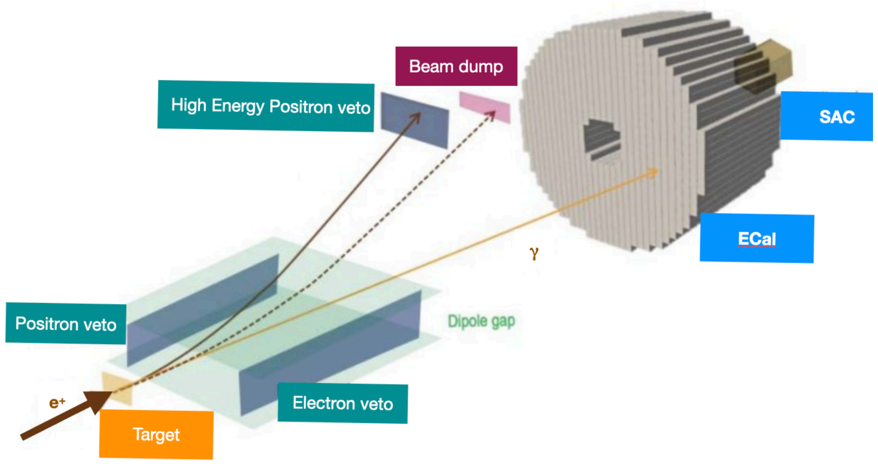

Figure 1: Sketch of the PADME detectors.

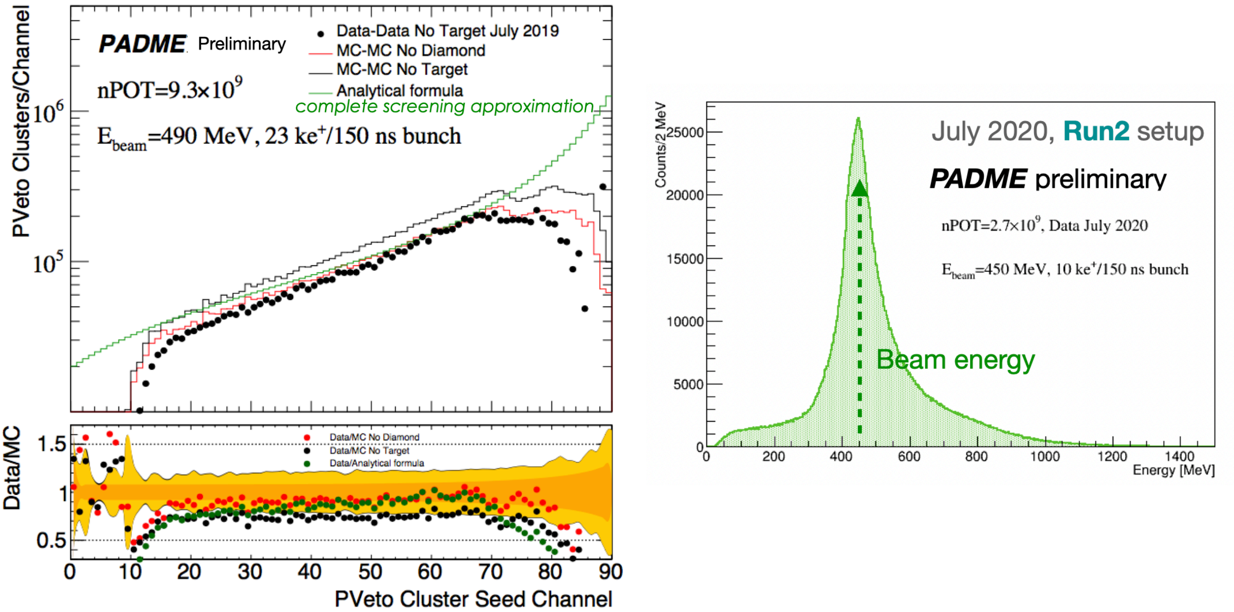

Figure 2: Left: number of clusters in the positron veto detector as a function of the channel number (increasing with the positron kinetic energy.) of the hit used as seed for the cluster. The distribution is dominated by Bremsstrahlung positrons. Right: sum of the kinetic energy of a positron hitting the PVeto and a photon in the SAC calorimeter in time coincidence; data are from RUN-2 with a beam energy of 430 MeV.

the only two parameters necessary to describe the phenomenology. The A' boson can be produced in meson decays, in Bremsstrahlung processes from electrons or positrons, and in e^+e^- annihilation. Its dominant decay modes can lead, depending on the mass hierarchy, to final states with pairs of Standard Model fermions (namely e^+e^-, $\mu^+\mu^-$ or light hadrons) or dark matter. The latter case corresponds to an invisible final state, due to the negligible interaction between hidden sector particles and ordinary matter. PADME is designed to investigate the production in e^+e^- annihilation of an A' boson decaying to invisible particles. The experiment is located at the INFN LNF and exploits the LINAC of the DAΦNE accelerator complex. Frascati has seen the birth of high energy physics at colliders, in 1961 with AdA, the first e^+e^- collider, followed by ADONE and, more recently, DAΦNE. The beam line reaching PADME can be feed with two kinds of positron beams: a secondary beam produced by 750 MeV electrons from the LINAC in interactions within a copper target, or a primary positron beam, obtained by 220 MeV electrons converted in a tungsten target near the electron gun. In both cases the maximum energy reached is about 550 MeV and the beam is pulsed with a repetition rate of 50 Hz. The current is limited to 100 e^+/ns to avoid high pileup of events in the PADME detectors. The experiment exploits the annihilation of a positron from the beam with an atomic electron in a 100 μm thick fixed target of synthetic diamond, potentially leading to the production of a dark photon with mass below 23.7 MeV in association with a Standard Model photon representing the only visible object in the final state of a signal event. Energy and direction of the photon allow to compute the missing mass, given the fully constrained initial state and this provides a clear signal for the production of an invisible dark photon with the possibility to measure both mass and effective coupling. The only assumption is a coupling to the electron, while no specific hypothesis is needed for the dark matter mass and coupling to A'. The design sensitivity to the coupling is 10^{-3} for about 10^{13} positrons hitting the target. The main challenge to be faced to reach such result is the control and modelling of the beam induced background. The detector, schematically shown in Figure 1, consists of the following components: a precision electromagnetic calorimeter (ECal) made of 616 BGO crystals arranged in a cylindrical matrix for the detection of the photon produced along with the dark photon; a fast PbF_2 calorimeter (SAC) behind the central hole of the BGO calorimeter, for the detection of forward Bremsstrahlung photons with a time resolution of less than 90 ps; three scintillating detectors, each consisting of bars arranged with a pitch of about 1 cm individually readout by silicon photomultipliers. A dipole magnet located between the target and the calorimeters is responsible for swiping the beam out of the calorimeter acceptance. Moreover, in combination with the scintillator arrays it acts as a spectrometer for the measurement of the momentum of positrons or electrons emerging from the target after an inelastic interaction. The components of the veto system are: two positron detectors, the PVeto hosted on one side of the gap of the magnet dipole, and the HEPVeto (high energy positron veto) located next to the beam dump region, and a detector for electrons, the EVeto, parallel to the PVeto on the other side of the gap of the magnet. The scintillators reach a time resolution better than 700 ps and an efficiency for minimum ionizing particles above 99.5%. The target is also an active detector measuring the beam multiplicity with good linearity up to more than $5000e^{+}$/strip and the average position of the beam in each pulse with a resolution of 60 μm thanks to readout graphitic strips produced on both sides with a 1 mm pitch. The most abundant background process is Bremsstrahlung even if its rate is reduced by vetoing events where a photon in the main calorimeter is detected simultaneously with a low energy positron in the scintillating bars of the veto system. QED annihilation of the $e^{+}e^{-}$ pair in three photons, although physically suppressed with respect to the $\gamma\gamma$ final state, is more insidious, being less symmetric, since only one photon may falls inside the main calorimeter acceptance.

3. Run, status and prospects

PADME collected data in two runs. In RUN-1, from September 2018 to February 2019, data have been collected with a secondary positron beam of energy 545 MeV. In the last few days, a primary positron beam with energy of 490 MeV was used. RUN-2 took place in Fall 2020 with a primary positron beam accelerated at the energy of 430 MeV; in each run about 5×10^{12} positron on target were collected. In between the 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 interface between the LINAC beam line, featuring a tight vacuum, with the PADME beam line where a less stringent vacuum requirement is met. In particular the original berillium window, 250 μm thick, was replaced with a mylar window 125 μm thick located at a larger distance from the PADME target. The improved beam quality is clearly shown by the total energy per bunch in the BGO calorimeter 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-2 after the optimization of the beam line.

The reconstruction of Standard Model processes in the PADME data is of paramount importance for the physics calibration of the detector. As anticipated, the main physics background in PADME is

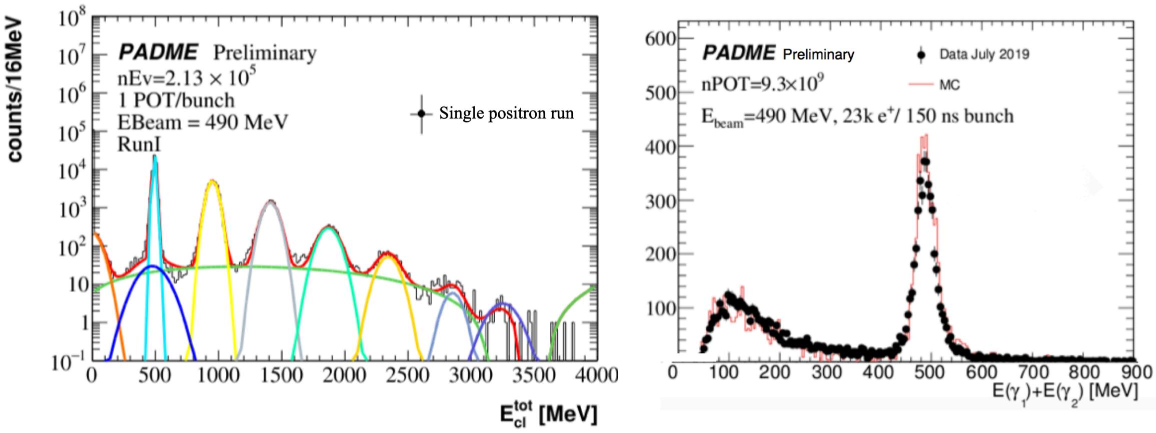

Figure 3: Left: sum of the energy of all ECal clusters reconstructed in a single positron run with beam energy of 490 MeV. Right: sum of the energies of two photons in time and back-to-back in ECal, with center of gravity compatible with a SM annihilation interaction; data are collected with a primary positron beam.

the Bremsstrahlung process. The distribution of the positrons after Bremsstrahlung in the diamond target is shown in Figure 2. The positrons are detected in the positron veto detector. The data used here come from a calibration run of July 2019 with the primary positron beam but still the old beam line. The plot shows the number of clusters recorded by the scintillating bars as a function of the scintillator channel number where the seed or the cluster is found. High channel numbers means low bending and high positron kinetic energy. The distribution is obtained after the subtraction of the large beam induced background, estimated thanks to data collected in special runs with the diamond target moved in a parking position on a side of the beam line. It is dominated by Bremsstrahlung photons and is compared with the expectation from simulation and from an analytical calculation of positron Bremsstrahlung in diamond based on the complete screening approximation. The bottom pad of Figure 2-left, shows the ratio between data and predictions, with the band representing the overall systematic uncertainty, which is consistent with 1 within 20% over most of the positron veto acceptance. The uncertainties on the momentum scale, from the knowledge of the magnetic field and geometry, and on the beam intensity, from the absolute and relative calibration of the charge measurement of the target, sum up to about 10% represented by the dark orange band. The beam background normalization and modeling are the dominant systematic uncertainties affecting the comparison between data and predictions. This is assessed through the difference between the yield in beam background simulations with and without the diamond target carrier board; when combined with the previously described errors it gives the yellow band. Finally, a 5% uncertainty is considered for the approximations in the Bremsstrahlung theoretical predictions used in `Geant4` [8] and in the calculation shown in Figure 2. The sum of the energies of a positron and a photon in time coincidence matches the beam energy for particles originating from a Bremsstrahlung interaction. The distribution of this quantity for photons reconstructed in the small angle calorimeter in a primary positron run collected during Run-2 after the beam-line commissioning is shown on the right of Figure 2. The peak at the beam energy of 430 MeV clearly stands over a limited background, demonstrating the big improvement on the beam quality achieved thanks to the line optimization.

A good understanding of the data from the precision electromagnetic calorimeter is demonstrated by the efficient reconstruction of $e^+e^- \rightarrow \gamma\gamma$ events. The SM annihilation spectrum, resulting from a loose selection ($|\Delta t| < 10$ ns, $\Delta\phi = 180° \pm 25°$, and x and y energy weighted positions within 1 cm from the beam direction) is shown in Figure 3 on the right for data collected during RUN-1. The relative energy resolution at 490 MeV of ECal, in the absence of background, has been measured in single positron calibration runs and found to be 2.6% [5]. This value is better than the resolution anticipated in previous small size prototypes, where extra fluctuations due to incomplete containement were present. The same resolution has been achieved with an algorithms allowing for a multihit reconstruction of the digitized waveform of each crystal, resolving overlapping signals in spite of the 300 ns typical decay time of BGO. The plot on the left of Figure 3 shows the sum of energies of all clusters in a single positron run; multiplicities of positrons up to 7/bunch are observed with a relative yield that is compatible with the Poissonian fluctuations of the beam intensity around the average value, derived from the fit, of 1.18±0.22 positrons / bunch. The same reconstruction algorithm gives a time resolution of about 1 ns for photons of energy above 100 MeV like those produced in SM annihilation.

4. Conclusions

The performance of the PADME detectors measured on data collected during two data taking campaigns matches or overcomes the design requirements. The physics backgrounds appear well under control. Annihilation events have been shown to provide a powerful run dependent monitor of the luminous point on the ECal reference plane. The clean sample of RUN-2 is currently being used to provide a cross section measurement of the annihilation process. A major challenge is the modeling of beam induced background. Its rate was dramatically reduced with a refinement of the PADME beam-line in between the two runs. A detailed simulation of the beam-line is being implemented in Monte Carlo to support data driven estimates exploited so far and help approaching the suppression necessary for the dark photon search.

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