IOP Publishing Phys. Scr. 97 (2022) 024003 https://doi.org/10.1088/1402-4896/ac41eb

Physica Scripta

RECEIVED
31 March 2021

REVISED
5 August 2021

ACCEPTED FOR PUBLICATION
10 December 2021

PUBLISHED
14 January 2022

PAPER

The physics program of the PADME experiment

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Keywords: experiments, dark matter, particle physics, dark photon

Abstract

PADME (Positron Annihilation into Dark Matter Experiment) is a fixed target experiment located at the Beam Test Facility (BTF) at the Laboratori Nazionali di Frascati (LNF) designed to search for a massive dark photon A' in the process $e^+e^- \rightarrow \gamma A'$, using a positron beam of energy up to 550 MeV. The experiment exploits the missing mass technique which allows for a search of A' in a model independent way. A sensitivity on the mixing constant $\epsilon > 10^{-3}$ for a dark photon mass in the range $1 \leqslant m_{A'} \leqslant 23.7$ MeV/c^2 can be achieved by collecting 4×10^{13} positrons on target. Run 2 data taking finished in December 2020 and allowed to reach an integrated luminosity of 5×10^{12} positrons on target.

1. Introduction: dark sector and dark photon

The strong, weak and electromagnetic interactions are described with high precision by the Standard Model (SM) of particle physics. Nevertheless, the SM is not able to explain the nature of dark matter, whose existence, demonstrated by cosmological and gravitational observations, is a compelling motivation to go beyond the SM.

A possible scenario beyond SM is a Dark Sector (DS) [1] made of dark particles which can only feebly interact with our world that we know through a portal. The existence of such a hidden sector, with new gauge groups, is well-motivated from a string theory perspective. The interactions of particles of the new sector with the SM could give rise to several interesting phenomenological signatures allowing to test the model. Analogously to the SM, the dark sector can be seen as a collection of (still unknown) particles, that are not charged under the SM strong, weak, or electromagnetic forces. A possible mediator between the SM and the DS could be the dark photon [2] which could be introduced as additional gauge symmetry $U'(1)$ to describe the interactions among the dark particles. The simplest mechanism that could determine weak couplings between SM particles and the A' field is the mixing with the standard model photon described by a kinetic mixing term in the Lagrangian:

$$\mathcal{L}_{\text{mix}} = -\frac{\epsilon}{2} F_{\mu\nu}^{QED} F_{dark}^{\mu\nu}.$$

A very small value of the mixing constant ϵ could justify the lack of experimental evidences so far.

1.1. Dark photon production, phenomenology and search

Experiments that search for the dark photon exploited several production mechanisms, in particular: Bremsstrahlung, or A'-strahlung on nuclei ($e^{\pm}N \to e^{\pm}NA'$), annihilation ($e^+e^- \to \gamma A'$), meson decays and Drell-Yan (DY) process.

The dark photon search techniques strictly depend on the dark photon phenomenology. The decay modes of the dark photon are determined by its mass and the mass of a hypothetical dark particle χ of the dark sector and can be divided into *visible* and *invisible* decays.

- *visible decays:* $A' \to SM + SM$ if $2\ m_e < m_{A'} < 2\ m_\chi$.
  If the mass of the dark photon is lower than twice the mass of any dark particle, the decay in DS particles is kinematically forbidden and the A' can only decay into SM particles if $m_{A'} > 2\ \ m_e$. The branching ratio of the decay in e^+e^- is 100% for a mass of the DP below 0.2 GeV.
  The width can be calculated as follows [3]:

  $$\Gamma_{A' \to f\bar{f}} = \frac{1}{3}\alpha\epsilon^2 m_{A'}\sqrt{1 - \frac{4m_f^2}{m_{A'}^2}}\left(1 + \frac{2m_f^2}{m_{A'}^2}\right) \tag{1}$$

  where m_f is the mass of the SM fermion and α is the fine structure constant.
  For a very low mixing constant ϵ the dark photon would be *long lived*, as the decay time is proportional to $1/\ (\alpha\epsilon^2 m_{A'})$.
  In the particular case of $m_{A'} < 2m_\chi$ with $m_{A'} < m_e$, the only accessible process is the production of 3γs in the final state, via electron box diagram. Even in this case the A' is long lived.
- *invisible decays:* $A' \to \chi\ \chi$, if $m_{A'} > 2\ m_\chi$.
  The decay width is [3]:

  $$\Gamma_{A' \to \chi\bar{\chi}} = \frac{1}{3}\alpha_D m_{A'}\sqrt{1 - \frac{4m_\chi^2}{m_{A'}^2}}\left(1 + \frac{2m_\chi^2}{m_{A'}^2}\right) \tag{2}$$

  where α_D represents the coupling of the dark photon to the dark matter.
  A reasonable assumption is $\alpha_D \gg \alpha\epsilon^2$, implying that the invisible decay dominates. The decay time in this case strictly depends on the α_D value ($\tau\ \propto\ 1/(\alpha_D m_{A'})$).

Lots of experiments around the world are currently searching for the dark photon both in the hypothesis of a visible or invisible decay. The dark photon search at accelerators allows to probe the parameter space ($m_{A'}$, ϵ), given by the mass of the dark photon $m_{A'}$ and the mixing parameter ϵ.

2. The PADME experiment

PADME (Positron Annihilation into Dark Matter Experiment) [4] is a fixed target experiment located at the Beam Test Facility (BTF) [5] at the Laboratori Nazionali di Frascati (LNF) designed to search for a massive dark photon A' in the process $e^+e^- \to \gamma A'$ (figure 1), exploiting a positron beam of energy up to 550 MeV, provided by the LINAC and delivered to the experimental hall thanks to a proper secondary beam line.

An event in PADME is represented by a bunch of about 25 000 positrons on target, with a bunch length up to 300 ns and rate 50 Hz.

The PADME detector (figure 2) is made of a thin diamond target, a magnetic dipole, which bends the beam outside the experimental acceptance, a high resolution electromagnetic calorimeter (ECAL), a small angle electromagnetic calorimeter (SAC) capable to sustain a high rate, and a charged particle veto system for positrons (PVeto) and electrons (EVeto) detection.

A positron that hits the diamond target could annihilate and produce together a SM and a dark photon with a signal event represented by an ECAL cluster, due to the SM photon shower, and nothing else in coincidence. Thanks to the close kinematics, it is possible to apply the missing mass technique, reconstructing the dark photon mass by detecting only the SM photon and imposing the 4-momenta conservation, to obtain the dark photon mass:

$$m_{miss}^2 = (P_{e^+} + P_{e^-} - P_\gamma)^2,$$

where P_{e^+}, P_{e^-} and P_γ are the 4-momentum of the beam positron, of the target electron and of the emitted photon, respectively.

The dark photon search is implemented looking for bumps in the missing mass distribution above a smooth background.

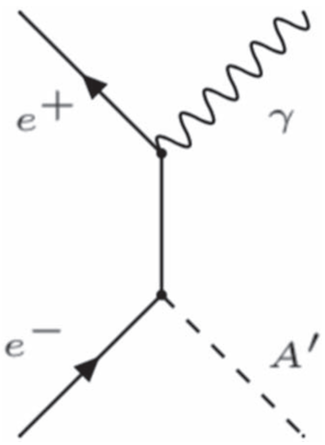

Figure 1. Feynman diagram of the process searched at PADME. The annihilation of a positron with an electron of the target producing two photons in the final state, a SM one (γ) and a dark one (A').

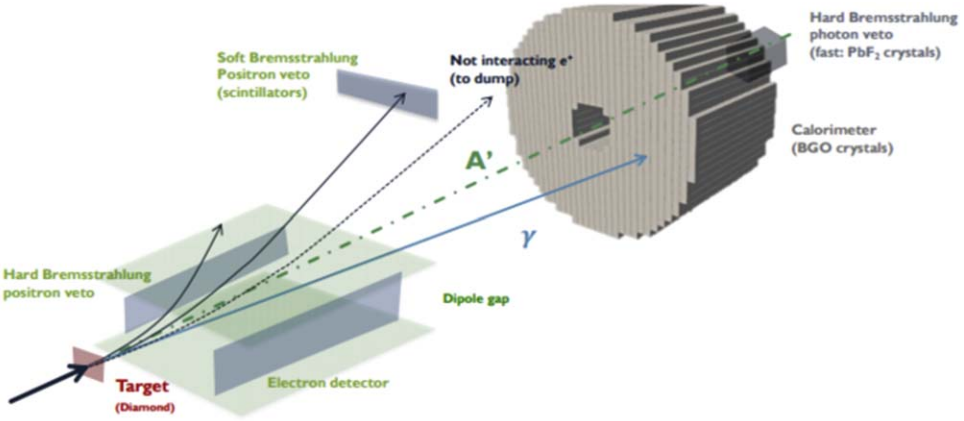

Figure 2. Layout of the PADME detector.

PADME is the first fixed target experiment designed and built to probe a particular range of the parameter space in case of invisible dark photon decay, more appealing because less investigated. In general, the peculiarity of the technique used is the total independence from the decay mode of the dark photon and model.

2.1. Signal selection

To aim a good signal selection, an important requirement is the knowledge of the A' production point on the target, together with a good measurement of the photon energy and direction.

A candidate dark photon event must satisfy the following requirements:

- one photon in ECAL inside a radial fiducial region, where the shower is well contained, and no other photons in ECAL and in SAC within ± 2 ns, to reject the annihilation final state in two or three photons;
- no positrons in the positron veto in ± 2 ns coincidence with the photon detected by ECAL and with energy summed to the photon energy compatible with the beam energy, to reject events of Bremsstrahlung.

Thus, a good background rejection is essential.

2.2. Background rejection

The SM background processes are in particular Bremsstrahlung, annihilation (in two or three photons) and Bhabha scattering.

The one with highest cross section, and so the most dangerous, is the Bremsstrahlung, where the positron of the beam interacts with the a nucleus of the target and it is slowed down, emitting a photon:

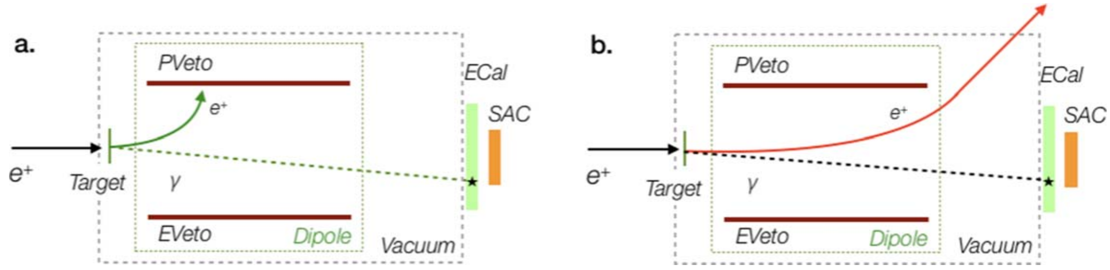

Figure 3. Bremsstrahlung process. On the left an example of background suppression, on the right the irreducible background to the dark photon signal.

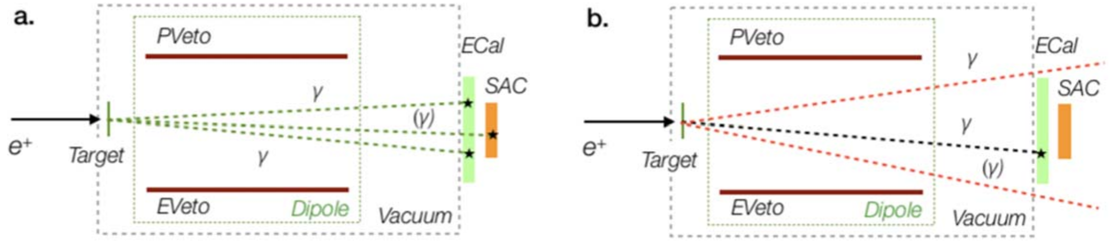

Figure 4. Annihilation (in 2 or 3γs) process. On the left an example of background suppression, on the right the irreducible background to the dark photon signal.

$$e^+N \rightarrow e^+N\gamma$$

A hole in the center of the calorimeter was foreseen to prevent the high rate of photon mostly emitted in the forward direction. In addition, the diamond target, made of a material with a low atomic number ($Z = 6$), helps to reduce the rate of Bremsstrahlung interactions ($\propto Z^2$), improving the ratio Signal/Background ($\propto 1/Z$). The veto on Bremsstrahlung interactions is performed requiring the time coincidence between the photon detected by ECAL and the positron passing through the veto bars (figure 3(a)). In addition, the sum of the particle energies should be equal to the beam energy. Unfortunately, in some cases the Bremsstrahlung photon is detected by ECAL but the corresponding positron escapes from the geometrical acceptance of the positron veto, mimicking the signal and representing an irreducible background (figure 3(b)).

The other important source of background is the annihilation in 2 or 3γs:

$$e^+e^- \rightarrow \gamma\gamma(\gamma).$$

The first can be suppressed requiring two ECAL photons in time coincidence, symmetric in the azimuthal angle and with the sum of their energies equal to the energy of the beam. The SAC allows to reject the 3γs final state, as it allows the detection of a forward photon in coincidence with the other two (figure 4(a)). The irreducible background in 3γs case is represented by a single photon detected by ECAL, with the second and third escaping not only ECAL, but also SAC (figure 4(b)).

2.3. Analysis strategy

If a peak in the missing mass distribution related to the dark photon production is observed, the mixing constant ϵ can be computed as follows:

$$\epsilon^2\delta(m_{A'}) = \frac{\sigma(e^+e^- \rightarrow \gamma A')}{\sigma(e^+e^- \rightarrow \gamma\gamma)} = \frac{N(A'\gamma)/A\ (A'\gamma)}{N(\gamma\gamma)/A\ (\gamma\gamma)} \tag{3}$$

where $N(A'\gamma) = N(A'\gamma)_{obs} - N(A'\gamma)_{bkg}$ is the number of observed events in the signal region after background subtraction, $N(\gamma\gamma)$ is the number of annihilation events, corrected by the corresponding acceptance $A(A'\gamma)$ and $A(\gamma\gamma)$, and δ is the kinematic cross section enhancement factor of the process $e^+e^- \rightarrow A'\gamma$ relative to the $e^+e^- \rightarrow \gamma\gamma$ process due to mass effects. The normalization is physics-driven, performed using the annihilation events selected directly from the analysis.

In addition, the total number of annihilations $N_{\gamma\gamma}/A(\gamma\gamma)$ can be estimated by measuring the total Number of Positrons On Target (NPOT) and the QED predicted cross section $\sigma_{\gamma\gamma}$.

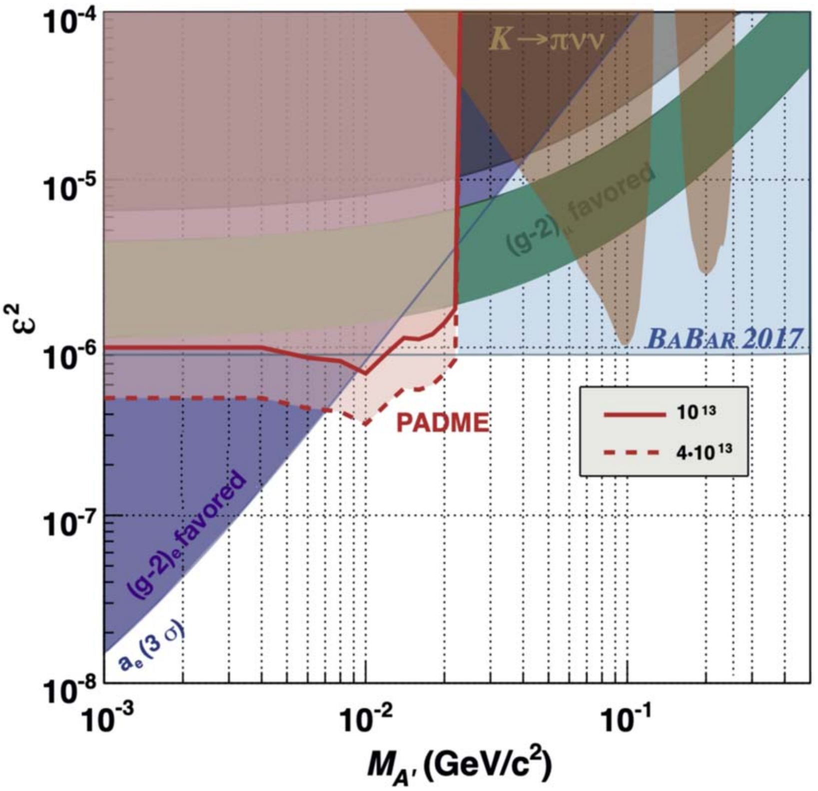

Figure 5. PADME probed region of the parameter space for invisible decays of the dark photon or long lived dark photons, for a project luminosity of 10^{13} or 4×10^{13} positrons on target, which can be reached in 6 months and 2 years, respectively, with the recent beam-line upgrades [6].

$$N_{\gamma\gamma}^{tot} = \frac{N_{\gamma\gamma}}{A\ (\gamma\gamma)} = NPOT \cdot \sigma_{\gamma\gamma} \cdot \rho_{e^-} \cdot L \tag{4}$$

where ρ_{e^-} is the density of electrons in the target and L the target thickness.

2.4. Sensitivity

The beam energy sets the limit on the mass of the dark photon, up to 23.7 MeV/c^2 for a maximum energy reachable for positrons with the existing LINAC of 550 MeV. In addition, the maximum number of positrons per bunch, compatible with a pile-up manageable by the detectors, sets the lower limit on the mixing constant ϵ in PADME, that is about 10^{-3}. Recent beam-line upgrades allowed to extend the bunch duration up to 300 ns, in such a way the multiplicity of the beam could be raised up to 30 000 positron/bunch, keeping the pile-up under control for the detectors. This feature helps to shorten the time to reach the project integrated luminosity: a data sample of 1×10^{13} POT can be collected in 6 month while in 2 years a sample of 4×10^{13} POT can be reached. The excluded region in the parameter space ($m_{A'}, \epsilon^2$) for invisible decay of the dark photon obtained for these two different values of the integrated luminosity is shown in figure 5. The dark photon mass in the range 10–100 MeV and $\epsilon < 10^{-3}$ could account for the discrepancy between the measured and the theoretical value of the anomalous magnetic momentum of the muon. The PADME sensitivity could be increased moving the apparatus to a facility that can provide a higher energy beam. The experiment could be performed at Cornell, exploiting a 6 GeV positron beam, extending the upper limit of the missing mass up to 78 MeV, or at Jefferson Lab, where a 11 GeV positron beam would help to reach a probed dark photon mass up to 100 MeV.

2.5. PADME data taking

In September 2018 the PADME detector was fully installed in the BTF experimental hall and the data taking started soon after.

The PADME data taking periods spanned more than two years and the last data taking campaign ended at the beginning of December 2020. The beam induced background and the beam features can strongly affect the data quality of the experiment. Important issues are represented by the detector efficiency, calibration, alignment and software reconstruction. For this reason some calibration runs were useful to test the detectors and all the software infrastructure.

The PADME data taking can be divided essentially in two run periods: the Run 1 from October 2018 to March 2019, with beam-test runs in July 2019, and the Run 2, acquired after some improvements on the beam line, from September 2020 to December 2020. A bunch structure as flat as possible and a long bunch length were required to keep the pile-up uniform in time and at a low level for all the detectors, allowing to run at higher multiplicity. These conditions were achieved in particular in 2020, using a positron beam directly produced by the LINAC of 430 MeV of energy.

The two most important SM background processes, the Bremsstrahlung and the annihilation, were clearly visible and several studies are ongoing to understand them and, consequently, increase the signal efficiency.

3. Additional search in PADME

PADME allows to test new physics models beyond the dark photon one. In fact, exploiting the missing mass technique, it can search for any light dark particle.

Each final state could be written as follows:

$$e^+e^- \to \gamma X$$

A light particle that can be searched in this way could be an Axion-Like-Particle or a Dark Higgs. The PADME experimental set-up could also be used to search for the visible decays of these particles.

A new approach must be exploited to search for the X boson with PADME, which requires some changes in the experimental set-up [7].

3.1. Axion-like-particles

An Axion-Like Particle (ALP) is a possible pseudo-scalar spin-0 mediator between the SM and the DS. A visible decay into a e^+e^- pair or 2γ is foreseen if no other dark sector particle lighter than the ALP, $m_{ALP} < m_{\chi}$, exists. ALPs couple to bosons (like photons with coupling $g_{a\gamma\gamma}$) and fermions (like e^- with coupling g_{aee}) and, in general, without relations between mass and coupling (unlike for QCD axions). The ALPs can be searched with the PADME experimental set-up both in visible and invisible decay [8]. In the first case, the ALP would decay into a couple of e^+e^- or two photons and the signature in PADME would be an e^+e^- pair in time with a photon or 3γs in time coincidence. The invisible decay would have the same signature of the dark photon: a single SM photon in ECAL and a missing mass component. A special visible case is the one of the long lived ALP: the decay time in such a case is long, so the signature is the same of the invisible case. In literature, it is common to refer to the long-lived case as an invisible decay. According to several models, in the mass region below 100 MeV the ALP could indeed be long lived, appearing as a missing mass in PADME.

Computations of the estimated number of ALPs produced in 2 years of data taking with 60% of efficiency and 28 000 e^+/bunch (for a total of about 4×10^{13} NPOT) report thousands events for a mass of 22 MeV and $g_{aee} = 1$, independently of the $g_{a\gamma\gamma}$ value [9]. This study for ALP search in PADME fixes the limits on free parameters for invisible channel.

3.2. Dark Higgs

One of the possibilities for the dark photon to acquire mass can be through a Higgs-like mechanism, which supposes the existence of a dark Higgs. If the dark photon and the dark Higgs have similar mass, the process $e^+e^- \to A'h'$ can be searched for. The production mechanism involves the mixing of the SM photon into a dark photon, which then emits a dark Higgs, like in a Higgs-strahlung process. Some preliminary studies have been carried out for dark Higgs decays into two dark photons ($m_{h'} > 2\ m_{A'}$) and the three dark photon decays in e^+e^-, with a final state made of 6 leptons [10]:

$$e^+e^- \to A'h' \to A'A'A' \to 3\ (e^+e^-) \tag{5}$$

PADME could search for this multi-leptons final state requiring the coincidence of three charged particles in both the PVeto and EVeto [11]. In the scenario of invisible decays of the dark Higgs and in the case of a long lived dark Higgs, the final state to be searched for becomes e^+e^-X, where the e^+e^- pair comes from a visible decay of the dark photon. The latter signature would be made of a e^+e^- pair, in both PVeto and EVeto, and missing mass.

3.3. X boson search at PADME

A recent interesting physics result that could be the smoking gun for new discoveries is an anomaly in nuclear transitions reported by the ATOMKI collaboration. The ATOMKI group built a spectrometer with the aim of performing a simultaneous energy and angular correlation measurement of electron-positron pairs in the decay of excited Beryllium nuclei [12]. The anomaly in excited ^{8}Be transitions was the first to be observed: an excess of pair production with a well defined separation angle was measured, that can be explained by the production of a new particle named X17 [13]. The most recent measurement of the ATOMKI group reports also an anomaly in

^{4}He nuclear transitions, which can be explained by the same resonance produced in the decay of the exited state [14]. The existence of such new resonance is challenged by several experimental constraints. However, a protophobic X boson with mass $m_{A'} \sim 17$ MeV could be a consistent explanation of these observed anomalies [15].

The resonant production mechanism $e^+e^- \to A' \to e^+e^-$ is the favoured production mode, being of the order of $\epsilon^2\alpha$. The decay length of the X boson so produced does not depend on the boson mass ($\ell_\epsilon \sim 3/2m_e\alpha\epsilon^2$) for a given value of ϵ. This allows to probe the range of mass up to the kinematic limit, with the same sensitivity. A few set-up changes are needed to allow PADME to search for the X boson produced in such a way, mainly concerning the target [7]. The beam energy should be reduced to about 282 MeV in the hypothesis of a mass of 17 MeV, to investigate the resonance production. The probability of resonant production would increase using a thick target of a material with large atomic number, for example Tungsten (W). Such target would allow to overcome the difficulty of producing precisely the center of mass energy corresponding to the narrow resonance. The positrons hitting the thick target would lose energy producing, through a stochastic process, a sample of positrons of almost continuously varying energy. Those with the correct energy would then annihilate with atomic electrons via a resonant s-channel exchange of the X boson. If the decay length is such that the X boson travels through the entire target and it decays next to the exit, the e^+e^- pair of the final state would be detected by the charged particle detectors. The thick target would also act as a hermetic dump for the other positrons of the beam, reducing the background from SM processes. Hence the measurement of the momentum of the positron and electron would allow to identify an excess of events at a value of the invariant mass corresponding to the A mass. The beam intensity could be increased up to about 10^{18} POT/year, close to the maximum value compatible with the possibility to stand the resulting pileup. PADME could explore a portion of the parameter space never probed so far.

4. Conclusions

The future search for physics beyond the SM is also entrusted to dedicated and small scale experiments, like PADME. This is the first experiment designed and built to search for a dark photon signal using the missing mass technique exploiting a bunched positron beam. The data taking started in October 2018 and ended in December 2020, with relatively long shutdowns of several months. In particular, the Run 2 from September to December 2020 allowed to reach an integrated luminosity of 5×10^{12} positrons on target with low background conditions. The analysis is ongoing to put some constraints for the dark photon existence. PADME could be also exploited to search light particles as Axion-Like-Particle or the Dark Higgs. Instead, changes in the set-up must be planned to aim the X boson search.

Data availability statement

No new data were created or analysed in this study.

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