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The PADME experiment at DAΦNE LINAC

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The long standing problem of reconciling the cosmological evidence for the existence of dark matter with the lack of any clear experimental observation of it, has recently revived the idea that the new particles are neutral under the Standard Model (SM) gauge interactions, and only mediator fields or "portals", connect our world with new "secluded" or "hidden" sectors. One of the simplest models just adds an additional $U(1)$ symmetry, with its corresponding vector boson, A'. All SM particles will be neutral under this symmetry, while the new field will couple to the charged particles of the SM with an effective charge εe, so that this new particle is often called "dark photon". Additional interest arises from the observation that A' in the mass range 1 MeV$/c^2$ to 1 GeV$/c^2$ and coupling $\varepsilon \sim 10^{-3}$, would justify the discrepancy between theory and observation for the muon anomalous magnetic moment, $(g-2)_\mu$. This possibility has been recently disproved in the hypothesis that the A' decays to SM particles only, on the contrary if A' decays to dark sector particles, almost all of the available experimental constraints can be evaded and the dark photon is still a viable explanation for the $(g-2)_\mu$ anomaly. Due to the weak experimental signature, the search for invisibly decaying A' requires a carefully designed dedicated experiment: at the end of 2015 INFN has approved PADME, searching for invisible decays of the A' at the DAΦNE LINAC in Frascati. The experiment is designed for detecting dark photons produced by the annihilation of a 550 MeV positron beam onto a thin target, by measuring the final state missing mass by reconstructing only the recoiling photon in $e^+e^- \to A'\gamma$ events, regardless of the decay channel of the A'. The collaboration aims at completing the costruction by the end of 2017 and collecting $\approx 10^{13}$ positrons on target by the end of 2018, in order to reach a sensitivity at the level of 10^{-3} for ε, up to a dark photon mass of <23 MeV$/c^2$.

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1. Introduction

The failure of detecting the otherwise well motivated dark matter, in particular the exclusion up to the TeV scale of weak-interacting massive particles, has recently revived the idea that the new particles are neutral under Standard Model (SM) gauge interactions, and only mediator fields, or "portals", connect with new "secluded", "hidden" or "dark" sectors, via extremely weak interaction with the known particles.

Dark sectors could consist of rich phenomenology and states, while the mediator particle(s) should possess both SM and dark sector quantum numbers. Alternatively, the SM fields could have charge (either direct of an effective charge induced through loops or mixing) under the newly introduced interactions among the dark sectors. Both scenarios are viable and a few categories of models depending on the spin and parity of the mediator are available. The simplest of those models just add an extra $U(1)$ gauge symmetry, with a corresponding massive boson, A' or ”dark photon”.

One of the most common dark photon models is the so-called “kinetic mixing” model, in which the charges are generated effectively by the mixing with the photon; in this case the coupling of SM particles would be universal and just proportional to the electric charge through a parameter, ε, parametrizing the strenght of $A' - \gamma$ mixing. Alternatively, at least a fermion can be charged under the new gauge interaction, so that the coupling with the A' appears at tree level, leading to the possibility of different couplings for different kind of fermions.

In both cases other dark sector particles can be present, coupling without suppression with the dark photon, so that if any of those dark particles, χ is lighter than $m_{A'}/2$, then $A' \rightarrow \chi\bar{\chi}$ will be the dominant decay channel. If the so-called "invisible decay" channels is open, all the other possible decays into pairs of SM fermions – also called "visible" decays – will be strongly suppressed. In the recent years a very rich research activity in many laboratories around the world has improved the limits on the visible decays (mainly in the e^+e^- channel), down to a $\varepsilon^2 \approx 10^{-6}$ level for the coupling, while no direct measurement has been yet published for the invisible decays, as shown in Fig. 1; a recent comprehensive review can be found in Ref. [1].

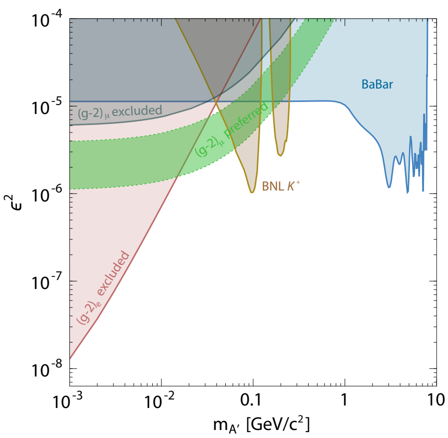

Figure 1: Invisible decays status.

2. The PADME experiment

2.1 Missing mass search for the dark photon

The most favorable production mechanism for the dark photon in the interaction of a high-intensity, mono-energetic electron beam with a target is the analogue of the standard Bremsstrahlung: $e^-(N) \to e^-(N)A'$. However, in the case in which one does not try to detect SM fermion pairs in the final state, which is the approach of the majority of the experiments to date, it is very difficult to look for the production of the A' by looking for the missing energy taken away by the dark photon and its invisible decays products. The other possible production mechanism, i.e. the e^+e^- annihilation, on the contrary has a well defined initial state, allowing the search for the A' by precisely measuring the recoil photon in $e^+e^- \to A'\gamma$ events, regardless of the decay mode of the dark photon [2, 3].

Together with the MMAPS experiment proposed at Cornell University [4], using a new positron extraction line from the CESR accelerator complex, and the Novosibirsk proposal at the VEPP-3 e^+e^- machine [5], PADME plans to exploit this technique in Frascati (LNF), using positrons produced by the DAΦNE LINAC, extracted and manipulated by the Beam-Test Facility (BTF) line [6]. The PADME sensitivity for $4 \cdot 10^{13}$ events is compared to the expectations for the Cornell and Novosibirsk experiments in Fig. 2.

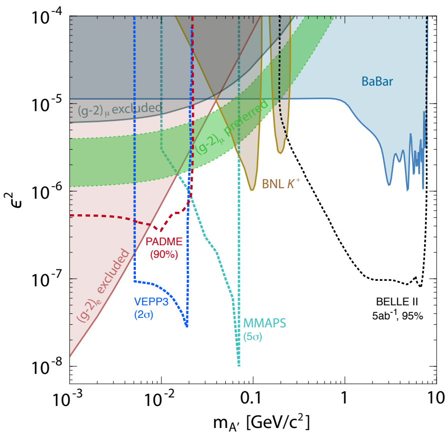

Figure 2: Invisible decays status and sensitivity of proposed experiments, compared to the PADME one for $4 \cdot 10^{13}$ events.

The Frascati LINAC can accelerate electrons and positrons up to 750 and 550 MeV/c momentum, respectively, at a maximum repetition rate of 50 Hz, with typical beam pulses of 10 ns duration and 1 nC charge, optimized for the injection into the DAΦNE collider rings. The PADME experiment will require lower density, longer pulses of positrons, at the highest possible energy, in order to manage the pile-up in the calorimeters for the detection of the recoil photon, and in the veto detectors for the suppression of the Bremsstrahlung background. Recently a number of improvements have been achieved, allowing to extend the pulse width to 250 ns, while keeping a good momentum resolution; at the same time, the alternative production of the medium-intensity, high-energy positron beam using the BTF attenuation target has been tested [7].

2.2 The PADME setup

In order to keep the Bremsstrahlung production at an acceptable rate with respect to the annihilations, the target has to be a low Z material. At the same time the missing mass technique relies on the precise knowledge of the kinematics, in particular it assumes that the target electrons are at rest, the well measured distance between the target and the photon detector measuring the energy and angle of the recoil photons. Finally, the density determines the number of target nuclei and thus the expected number of dark photon events. We have chosen as a compromise Carbon, under the form of a thin ($\sim 100\ \mu$m) diamond polycrystalline detector with graphite readout strips, thus also capable of monitoring the incoming positron beam intensity and spot size, using a fast readout of the analog signal.

The photons from the $e^+e^- \to A'\gamma$ process will be detected by a calorimeter, placed at a distance from the target sufficient for sweeping away the non-interacting positrons by means of a dipole magnet. Thanks to CERN, we can use a spare dipole from the SPS transfer line, modified to provide ~ 0.55 T over a gap of 23 cm. The choice of the distance will also determine: together with the calorimeter cell size, the missing mass resolution, and together with the lateral dimensions of the calorimeter (as well as the headroom between the magnet poles), the acceptance. Thanks to the possibility of re-using part of the end-caps of the L3 experiment ECAL, the PADME calorimeter will be a ~ 60 cm cylinder made up of 616 BGO crystals $2.1 \times 2.1 \times 22$ cm^3, read-out by 3/4” photo-multiplier tubes, placed at a 3 m distance from the target. A 10×10 cm^2 central hole will allow the most part of Bremsstrahlung photons to reach a smaller and faster Cherenkov detector, made by SF57 lead-glass bars, allowing better time resolution and reduced dead time.

The rejection of events with an irradiating positron will mainly rely on detectors made of scintillating bars, intercepting lower momentum trajectories inside the magnetic field of the dipole: a set of scintillators will be placed along the pole of the magnet, catching larger bending radii, i.e. lower momentum positrons, while another set will be placed outside the magnet, close to the nominal trajectory, for detecting higher momentum positrons. The entire path from the target to the veto detectors and to the front face of the main calorimeter will be in vacuum, in order to minimize interactions of photons and charged particles, so that a relatively large and asymmetrically shaped vessel is needed. An overall view of the PADME setup is shown in Fig. 3.

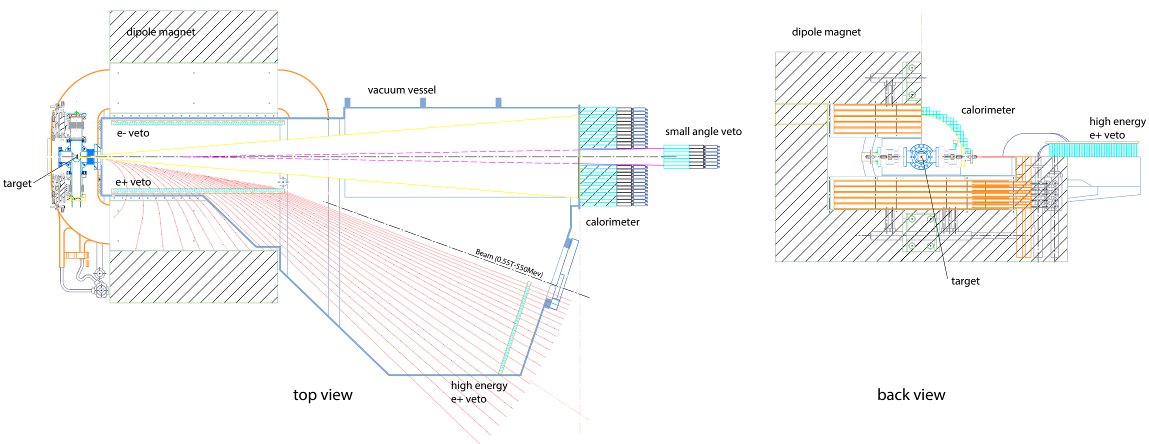

Figure 3: PADME experiment schematic setup.

The different detectors of the PADME experiment will be readout with high-speed switched capacitors digitizer, with variable sampling frequency in the 1–5 GS/s range, connected with optical links to an online PC farm, while the trigger will be distributed starting from a master signal generated by the LINAC timing system. The PADME vessel will be kept separated from the LINAC vacuum by means of a thin Beryllium window, and kept at a lower vacuum level by an independent pumping system.

2.3 PADME sensitivity for invisible decays

The sensitivity of the PADME experiment has been estimated using a detailed Monte Carlo simulation, based on GEANT4, assuming 40 ns long beam pulses, each consisting of 5,000 positrons of 550 MeV$/c \pm 1\%$ momentum, an angular divergence of ~ 1 mrad, and a Gaussian beam spot with $\sigma_{x,y} \sim 1$ mm.

Realistic performance of the detectors has been simulated: in particular for the reconstruction of clusters in the calorimeter, $\sim 2\%\sqrt{E(\mathrm{GeV})}$ energy resolution, with a minimum detectable energy of 1 MeV, and ~ 1 ns timing resolution have been used. A sub-ns timing resolution has been also considered for the scintillating bars veto detectors, and the effect of the pile-up of multiple clusters in the same beam pulse has been considered for estimating the inefficiency of the veto system as a function of the beam intensity and timing resolution.

A basic but very conservative event selection has been implemented in order to estimate the effect of the main backgrounds to the $e^+e^- \to \gamma$ + missing energy signal – i.e. Bremsstrahlung, annihilation into two and three photons, Bhabha and radiative Bhabha – namely requiring just one cluster in the calorimeter, with no in-time (< 2 ns) activity in the veto detectors.

The resulting sensitivity is shown in Fig. 4 for different values of the accumulated statistics starting from the benchmark value of 10^{13} positrons on target, corrisponding to two years of dedicated data taking at 60% efficiency, using 40 ns pulses from the DAΦNE LINAC ($4 \cdot 10^7$ s $\times$ 49 Hz). The effect of the residual background is evident by comparing the sensitivity curve for 10^{13} positrons on target and the corresponding one expected for a zero-background experiment, showing a margin for improvement of one order of magnitude in the full mass range.

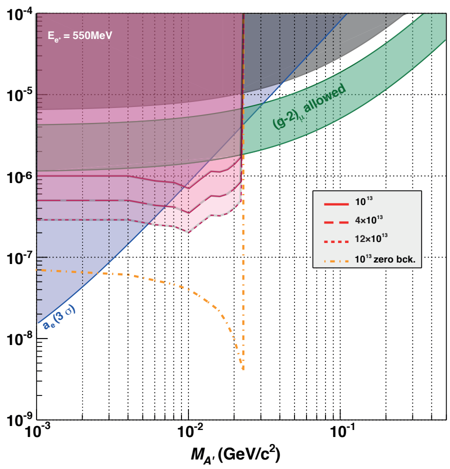

Figure 4: Estimated PADME sensitivity for different integrated statistics.

3. Conclusions

The PADME experiment is currently under construction, and plans to be ready for data taking by the end of 2017. The projected sensitivity for a benchmark statistics of 10^{13} positrons on target should allow to access the $(g-2)_\mu$ preferred band in the parameter space of the dark photon models, i.e. below 10^{-6} in the squared mixing parameter ε^2 in the mass range 1–23 MeV/c^2, using for the first time the missing mass technique, and without any assumption on the decay mode of the A' (invisible decays).

4. Acknowledgments

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