

# Searching For Dark Photon With Positrons At Jefferson Lab

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**Abstract.** The interest in the Dark Photon ( $A'$  or  $U$ ) has recently grown, since it could act as a light mediator to a new sector of Dark Matter particles. In this paradigm, the electron-positron annihilation can rarely produce a  $\gamma A'$  pair. Various experiments (e.g. PADME@LNF [1], VEPP-3 [2]) have been proposed to detect this process using positron beams impinging on fixed targets. In such experiments, the energy of the photon from the  $e^+e^- \rightarrow \gamma A'$  process is measured with an electromagnetic calorimeter and the missing mass is computed (the  $A'$  interacts weakly with Standard Model matter so it can't be detected). However, the  $A'$  mass range that can be explored with this technique is limited by the accessible energy in the center of mass frame, which goes as the square root of the beam energy.

The realization of a 11 GeV positron beam at Jefferson Lab would allow to search for  $A'$  masses up to  $\sim 100$  MeV, reaching unexplored regions of the  $A'$  parameter space. A preliminary study on the feasibility of a PADME-like experiment at Jefferson Lab has been carried out, assuming a 11 GeV positron beam with a  $\sim 100$  nA current. The achievable sensitivity was estimated, studying the main sources of background (positron bremsstrahlung, annihilation into 2 gammas) using CALCHEP [3] and GEANT4 [4] simulations.

## INTRODUCTION

Dark Matter (DM) existence is highly motivated by various astrophysical observations but its fundamental properties (interactions with the Standard Model, mass...) remain to date unknown. Experimental efforts have been mainly focused, until today, in the WIMPs search (Weakly Interacting Massive Particles): in this paradigm Dark Matter is made of particles with mass of order of  $\sim 100 - 1000$  GeV interacting with the Standard Model via Weak force. However, no unequivocal evidence of WIMP has been found to date.

Recently, the interest in new scenarios predicting DM particles with lower masses has grown. Various models [5] postulate the existence of a hidden sector of  $\chi$  particles (with masses in the MeV-GeV range) interacting with the visible world through new mediators, offering well-motivated opportunities for experimental exploration.

The simplest hidden sector model introduces one extra U(1) gauge symmetry [5] and a new gauge boson, the “Dark Photon” ( $A'$  or  $U$ ). The interaction between the hidden sector and the SM can be generated effectively by a “kinetic mixing” mechanism between the SM photon and the  $A'$ :

$$L_{mix} = -\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu},$$

where  $F_{\mu\nu}$  is the usual electromagnetic tensor,  $F'_{\mu\nu}$  is the Dark Photon tensor and  $\epsilon$  is the mixing coupling constant. In this scenario, SM particles acquire a dark “millicharge” proportional to  $\epsilon^2$ . The value of  $\epsilon$  can be so small as to preclude the discovery of the  $A'$  in the experiments carried out so far.

The decay of the  $A'$  depends on the ratio between its mass and the mass of the dark sector particles: if the dark photon mass is smaller than twice the muon mass and no dark sector particle lighter than the  $A'$  exist, it can only decay to  $e^+e^-$  pairs (“Visible Decay”). If the mass of the  $A'$  is higher than twice the mass of the  $\chi$ , it may also decay to  $\chi\bar{\chi}$  pairs (“Invisible Decay”). In this work we'll address this last scenario (see Fig. 1).

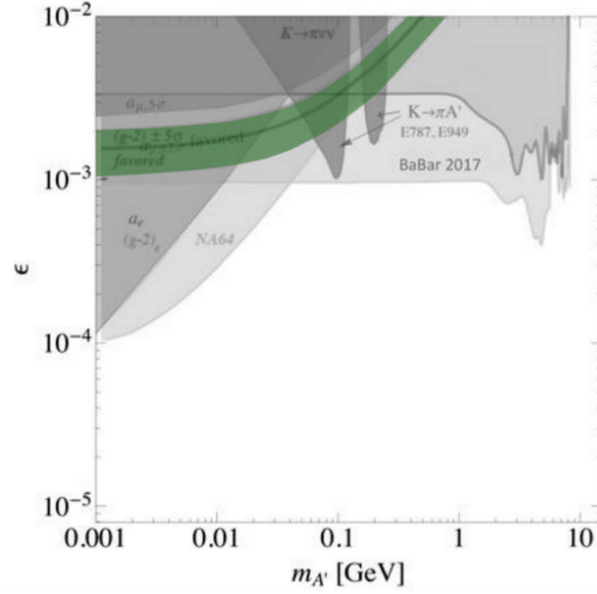


FIGURE 1. Current exclusion limits for  $A'$  invisible decay.

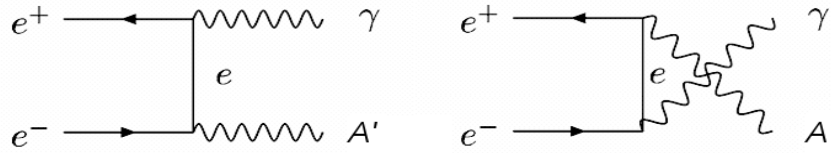


FIGURE 2.  $A'$  production via  $e^+e^-$  annihilation.

## Searching For $A'$ With Positrons - The PADME Experiment

$A'$  can be produced in  $e^+e^-$  annihilation, via the process (see Fig. 2):

$$e^+e^- \rightarrow \gamma A';$$

several experiments have been proposed to search for the production of  $A'$  in this process. PADME (Positron Annihilation into Dark Matter Experiment) [1] is one of the first  $e^+$  on target experiment searching for  $A'$ . It uses the 550 MeV positron beam provided by the *DAΦNE* linac at LNF (Laboratori Nazionali di Frascati) impinging on a thin diamond target.

The outline of the experiment is the following: the photon from the annihilation is detected with a BGO electromagnetic calorimeter placed  $\sim 2$  m downstream the target, while the  $A'$  leaves the detector area without interacting. A magnetic field of  $\sim 1$  T bends away from the calorimeter the positron beam and all the charged particles produced in the target. A single kinematic variable, the missing mass, is computed for each event:

$$M_{miss}^2 = (P_{e^-} + P_{beam} - P_{\gamma})^2$$

its distribution is peaked at  $M_{A'}^2$ , for the process  $e^+e^- \rightarrow \gamma\gamma$ .

All processes resulting in a single  $\gamma$  hitting the calorimeter represent the background for the experiment:

- Bremsstrahlung

- Annihilation into  $2\gamma$ :  $e^+e^- \rightarrow \gamma\gamma$
- Annihilation into  $3\gamma$ :  $e^+e^- \rightarrow \gamma\gamma\gamma$

To reduce the bremsstrahlung background, the PADME detector features an active veto system composed of plastic scintillating bars: positrons losing energy via bremsstrahlung in the target are detected in the vetos, allowing to reject the event. However the high bremsstrahlung rate is an issue for this class of experiments, limiting the maximum viable beam current. For this reason, a beam with a continuous structure would be the best option for PADME-like experiments.

Moreover, the sensitivity of PADME in the  $A'$  parameter space is constrained by the available energy in the center of mass frame: with a beam energy of  $\sim 500$  MeV PADME can search for masses up to 22.5 MeV. Higher energy positron beams are required to exceed these limits. In the following section, the achievable sensitivity of a Dark Photon experiment using a continuous 11 GeV  $e^+$  beam is discussed.

## Searching For $A'$ With Positrons At Jefferson Lab

### Detector Setup

The setup considered in this work, shown in Figure 3, features the following elements:

1. 100  $\mu\text{m}$  carbon target: carbon is a good compromise between density and a low  $Z/A$  ratio to minimize bremsstrahlung events.
2. 50 cm radius highly segmented ( $1 \times 1 \times 20 \text{ cm}^3$  crystals) electromagnetic calorimeter placed 10 m downstream the target. Assumed energy resolution:  $\frac{\sigma(E)}{E} = \frac{0.02}{\sqrt{E(\text{GeV})}}$
3. Active veto system with a detection efficiency higher than 99.5% for charged particles.
4. Magnet capable of a field of 1 T over a region of 2 m downstream the target to bend the positron beam.

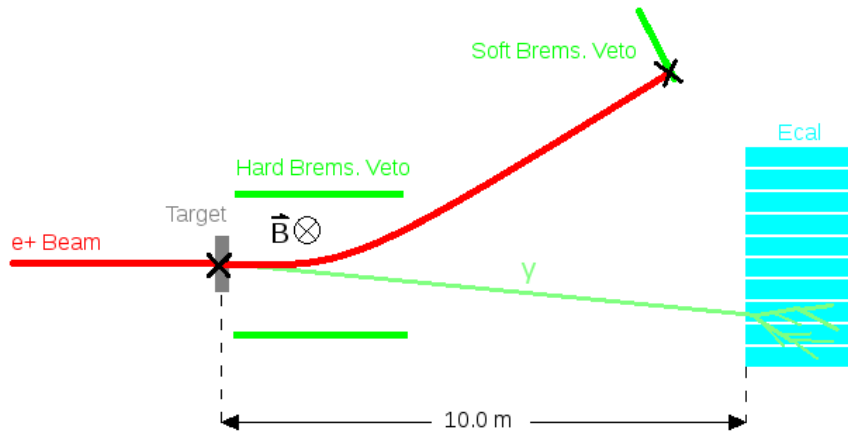


FIGURE 3. Outline of the proposed experiment at Jefferson Lab.

### Beam Parameters

The following beam parameters are assumed:

- Current: 10-100 nA;
- Energy: 11 GeV (corresponding to a maximum mass value for the  $A'$  of  $\sim 106$  MeV)
- Momentum dispersion:  $< 1\%$
- Angular dispersion:  $< 0.1$  mrad

It is important to note that momentum and angular dispersion are critical parameters for this kind of experiment, since a good knowledge of the beam particles initial state is fundamental to the missing mass computation.

## Background Evaluation

In order to evaluate the sensitivity of the experiment it is necessary to study the reconstructed missing mass distribution for the background events. As discussed previously, main background processes for such an experiment are bremsstrahlung and electron-positron annihilation into 2 or 3 gammas, which can result in a single hit in the calorimeter. To study these processes, different strategies were adopted.

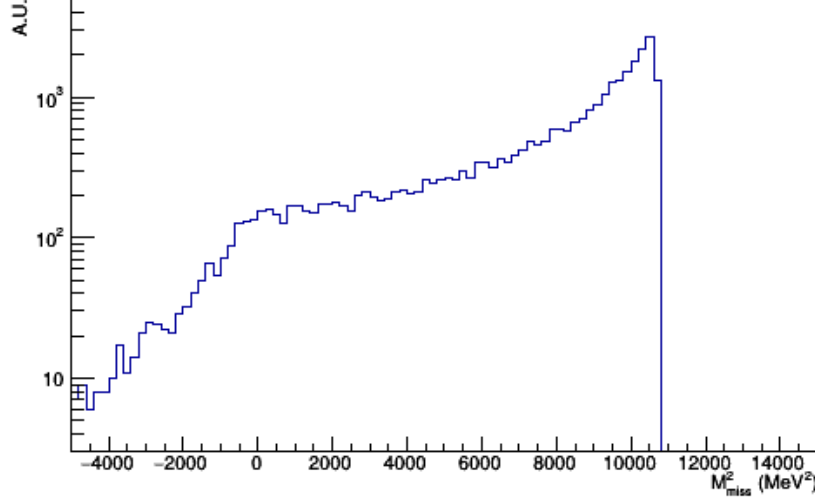


FIGURE 4. Computed missing mass spectrum from bremsstrahlung events.

For the bremsstrahlung background, a full GEANT4 [4] simulation of the positron beam impinging on the target was performed. For all bremsstrahlung photons reaching the calorimeter volume, the missing mass was computed, accounting for the detector angular and momentum resolution. Figure 4 shows the obtained spectrum. The total rate of expected bremsstrahlung events for positron on target (POT) was scaled accounting for the effect of the veto system.

The annihilation into 2 or 3 gammas is much less frequent than bremsstrahlung and was therefore studied in a different way: events were generated directly using CALCHEP [3] which provided also the total cross sections for the processes. As in the case of bremsstrahlung, missing mass spectrum was computed for event with a single gamma hit in the calorimeter. This study proved that, if an energy cut of 600 MeV is applied, the 2 gammas background becomes negligible. This is due to the closed kinematics of the  $e^+e^- \rightarrow \gamma\gamma$  process: asking for only one photon to hit the detector translates in a strong constraint on its energy. This argument is not valid for the 3 gammas: the number of background events from this process is in fact not negligible (see Fig. 5 for the missing mass spectrum).

## Signal Simulation

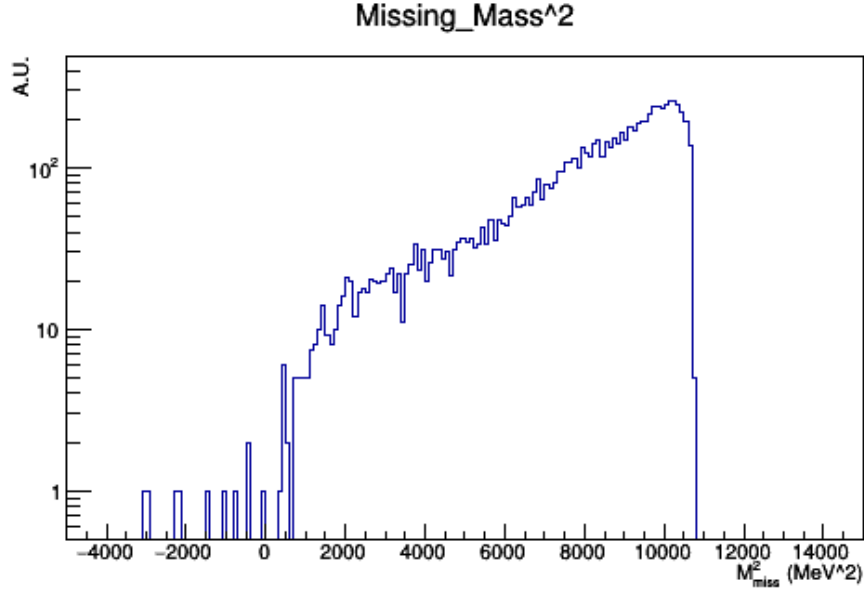
Signal events were simulated using CALCHEP. The widths  $\sigma(m_{A'})$  of the missing mass distributions of the measured recoil photon from the  $e^+e^- \rightarrow \gamma A'$  process were computed for six different values of the  $A'$  mass in the 1-103 MeV range. Figure 6 shows results for 4 mass values: the missing mass resolution for the signal is maximum for high  $A'$  masses and low for a “light”  $A'$  ( $M_{A'} < 50$  MeV).

As for the annihilation background, CALCHEP provides the total cross section of the process, for  $\epsilon = 1$ . To obtain the cross section for different values of  $\epsilon$ , it is necessary to multiply it for  $\epsilon^2$ .

## Evaluation Of The Experimental Reach

To obtain the reach of the experiment, the signal and background spectra discussed in the previous sections were used as follows:

- A measurement run of 180 days at 10 and 100 nA beam current is considered.



**FIGURE 5.** Computed missing mass spectrum from annihilation into 3 gammas events.

- Be  $N_S(m_{A'})$  the number of expected signal events for a given mass value  $m_{A'}$  and for  $\epsilon = 1$
- Be  $N_B(m_{A'})$  the number of expected background events (both from bremsstrahlung and 3 gammas annihilation) with computed missing mass in the interval:

$$[m_{A'}^2 - 2\sigma(m_{A'}^2), m_{A'}^2 + 2\sigma(m_{A'}^2)]$$

The minimum measurable  $\epsilon^2$  value is given by:

$$\epsilon_{min}^2(m_{A'}) = 2 \frac{\sqrt{N_B(m_{A'})}}{N_S(m_{A'})}$$

Curves indicating the obtainable reach are shown in Fig. 7: even with a current of 10 nA, a positron experiment searching for  $A'$  at Jefferson Lab would exceed the sensitivity of others current experiment, probing a significant region of the unexplored parameter space.

## Conclusions

A preliminary study of the achievable sensitivity for a Dark Photon experiment with a 11 GeV positron beam at Jefferson Lab was carried out. The assumptions made on the detector performance (electromagnetic calorimeter resolution, veto system efficiency) are consistent with existing detectors. This work proves that this experiment would probe unexplored regions of the parameter space, exceeding in sensitivity other missing mass experiments. The unique features of a positron beam at Jefferson Lab (high energy, continuous structure, good angular and momentum resolution) would make it the best option for this class of experiments.

## REFERENCES

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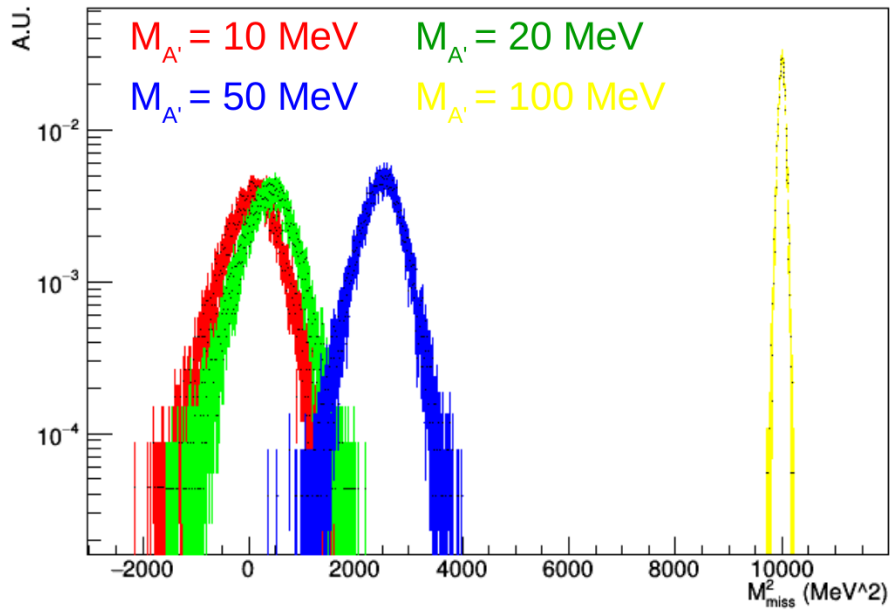


FIGURE 6. Computed missing mass spectrum for signal events with 4 different values of  $m_{A'}$ .

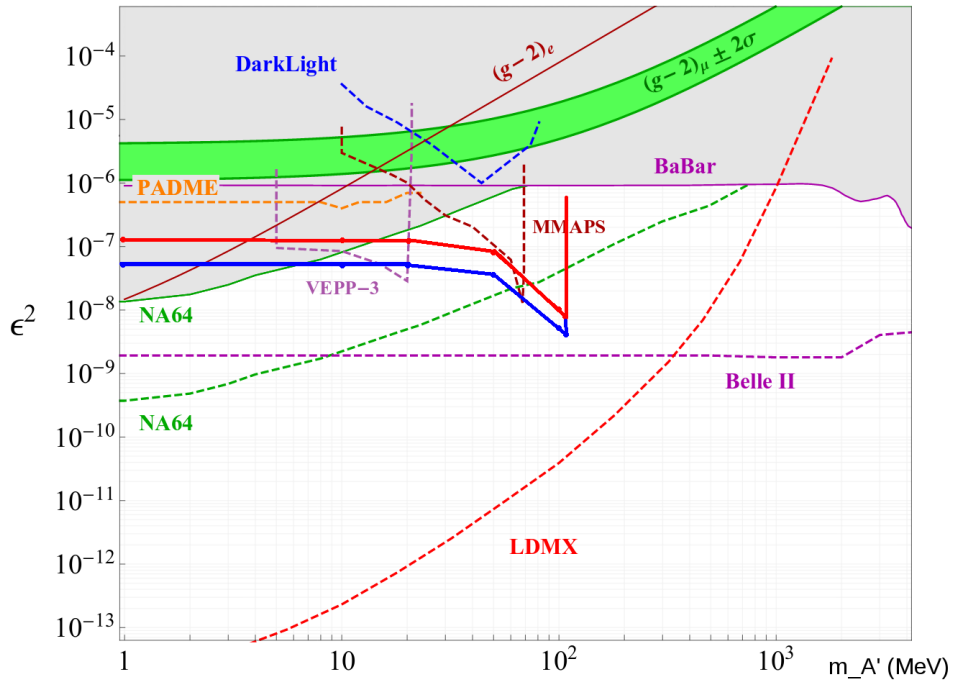


FIGURE 7. Projected exclusion limits in the  $A'$  invisible decay parameter space for a 180 days experiment with a 10 nA (red curve) and 100 nA (blue curve) 11 GeV positron beam at Jefferson Lab.