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GEANT4-based full simulation of the PADME experiment at the DAΦNE BTF

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Abstract. A possible solution to the dark matter problem postulates that dark particles can interact with Standard Model particles only through a new force mediated by a "portal". If the new force has a U(1) gauge structure, the "portal" is a massive photon-like vector particle, called dark photon or A'. The PADME experiment at the DAΦNE Beam-Test Facility (BTF) in Frascati is designed to detect dark photons produced in positron on fixed target annihilations decaying to dark matter ($e^+e^- \rightarrow \gamma A'$) by measuring the final state missing mass. The experiment will be composed of a thin active diamond target where a 550 MeV positron beam will impinge to produce e^+e^- annihilation events. The surviving beam will be deflected with a magnet while the photons produced in the annihilation will be measured by a calorimeter composed of BGO crystals. To reject the background from Bremsstrahlung gamma production, a set of segmented plastic scintillator vetoes will be used to detect positrons exiting the target with an energy lower than that of the beam, while a fast small angle calorimeter will be used to reject the $e^+e^- \rightarrow \gamma\gamma(\gamma)$ background. To optimize the experimental layout in terms of signal acceptance and background rejection, the full layout of the experiment was modelled with the GEANT4 simulation package. In this paper we will describe the details of the simulation and report on the results obtained with the software.

1. Introduction

The long standing problem of reconciling the cosmological evidence of the existence of dark matter with the lack of any clear experimental observation of it, has recently revived the idea that the interaction of the new particles with the Standard Model (SM) gauge fields is not direct but occurs through "portals", connecting our world with new "secluded" or "hidden" sectors. One of the simplest models introduces a single U(1) symmetry, with its corresponding vector boson, called dark photon or A'. In the most general scenario, the existence of dark sector particles with a mass below that of A' is not excluded: in this case, so-called "invisible" decays of the A' are allowed. Moreover, given the small coupling of the A' to visible SM particles, which makes the visible rates suppressed by ε^2 (ε being the reduction factor of the coupling of the dark photon with respect to the electromagnetic one), it is not hard to realize a situation where the invisible decays dominate. There are several studies on the searches of A' decaying into dark sector particles, recently summarized in [1][2].

At the end of 2015 INFN formally approved a new experiment, PADME (Positron Annihilation into Dark Matter Experiment) [3][4], to search for invisible decays of the A'. The aim of the experiment is to detect the non-SM process $e^+e^- \rightarrow \gamma A'$, with A' undetected, by measuring the final state

missing mass, using a 550 MeV positron beam from the improved Beam-Test Facility (BTF) of the DAΦNE Linac at the INFN Frascati National Laboratories [5]. The collaboration will complete the design and construction of the experiment by the end of 2017 and will collect $O(10^{13})$ positrons on target in two years starting in 2018, with the goal of reaching a $\varepsilon \sim 10^{-3}$ sensitivity up to a dark photon mass of $M_{A'} \sim 24$ MeV/c^2.

The experiment, shown in figure 1, is composed of a thin active diamond target, to measure the average position and the intensity of the positrons during a single beam pulse; a set of charged particle veto detectors immersed in the field of a 0.5 Tesla dipole magnet to detect positrons losing their energy due to Bremsstrahlung radiation; and a calorimeter made of bismuth germanium oxide (BGO) crystals, to measure/veto final state photons. As the rate of Bremsstrahlung photons in its central region is too high, the calorimeter has a hole covered by a faster photon detector, the small angle calorimeter (SAC). The apparatus is inserted into a vacuum chamber, to minimize unwanted interactions of primary and secondary particles that might generate extra photons. The maximum repetition rate of the beam pulses is 50 Hz.
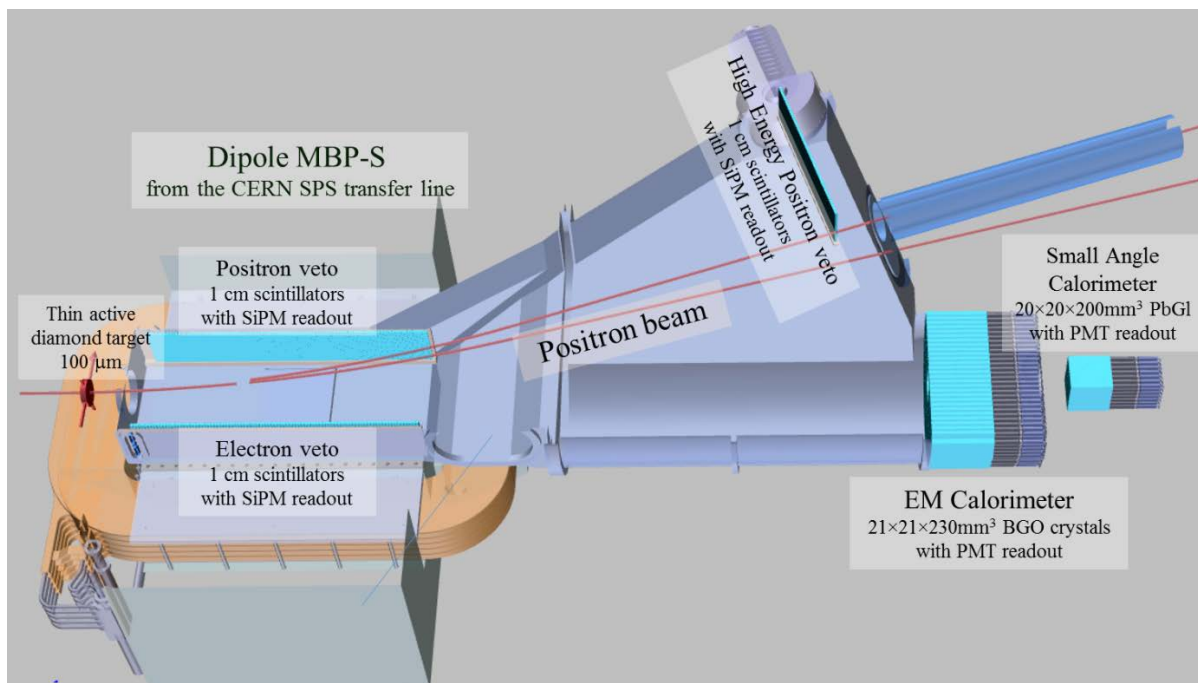

Figure 1. The PADME experiment as seen from above. The positron beam travels from left to right.

To optimize the experimental layout in terms of signal acceptance and background rejection, the full layout of the experiment has been modelled with the GEANT4 simulation package [6]. In this paper we will describe the details of the simulation and report on the results obtained with the software.

2. The PADME Detector

2.1. The diamond target
The incoming e$^+$ beam impinges on an active diamond target. The reason to choose this material is that, due to its low Z, diamond is the rigid material with the best ratio between annihilation and Bremsstrahlung processes.

The target consists of a 20×20 mm^2 polycrystalline diamond with a thickness of 100 μm. Two orthogonal sets of 19 readout strips with a pitch of 1 mm are graphitized with laser on the two sides of the diamond and used to read the X and Y coordinates of the impinging particles [7].

The final target will measure the position of the beam with an expected spatial resolution < 1 mm and its total charge with a precision better than 10%.

The first prototypes of the target were successfully tested at the BTF in 2015 and 2016 [8].

2.2. The electromagnetic calorimeter

The recoil photon from the $e^+e^- \rightarrow \gamma A'$ process will be detected by an electromagnetic calorimeter positioned 3 m downstream from the target (figure 2). It consists of 616 BGO crystals recovered from one of the electromagnetic end-caps of the L3 experiment at CERN [9]. The crystals are cut to a $21 \times 21 \times 230$ mm³ shape and arranged in a roughly cylindrical shape with ~ 60 cm diameter. To avoid the pile-up of low-angle Bremsstrahlung photons, a squared hole of 5×5 crystals is left in the central region of the calorimeter. Light coming from the crystals is read by 19 mm diameter PMTs.

The expected energy and angular resolutions of the calorimeter are $\sigma(E)/E < 2\%/\sqrt{E}$ and $\sigma(\theta) < 2$ mrad, respectively.

A prototype of the calorimeter, composed of a 5×5 array of BGO crystals, was successfully tested at the BTF in 2016 [10].
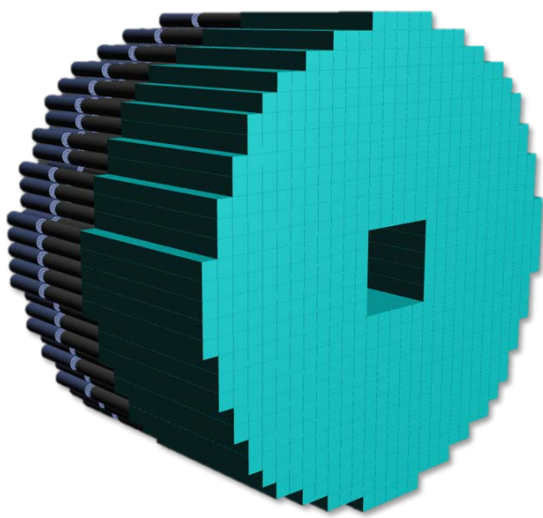

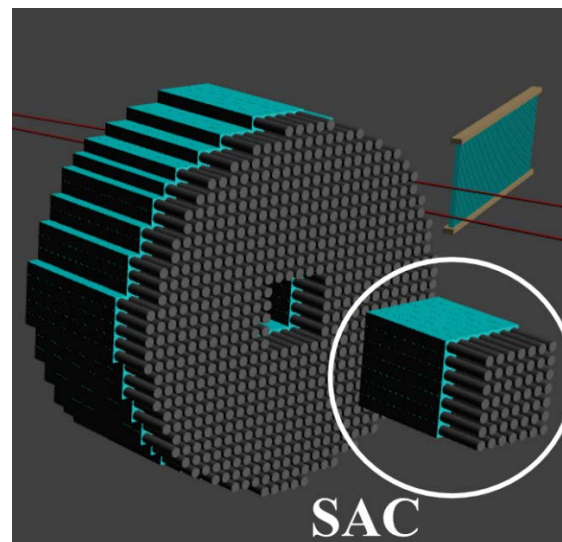**Figure 2.** The BGO electromagnetic calorimeter. Front view.

Figure 3. The Small Angle Calorimeter (SAC). Rear view.

2.3. The small angle calorimeter

In the region immediately around the axis of the incoming beam the rate of photons emitted by Bremsstrahlung process in the target is too high to be resolved by the BGO crystals, which have a relatively slow 300 ns signal decay time. The central hole of 5×5 crystals left in the electromagnetic calorimeter is therefore covered by a much faster small angle calorimeter (SAC) positioned immediately behind it (figure 3).

The SAC is composed of an array of 7×7 SF57 lead-glass blocks with a $20 \times 20 \times 200$ mm³ shape coupled with a fast PMT readout system and can resolve the foreseen rate of O(10) photons with E > 50 MeV in a single 40 ns beam spill.

2.4. The charged particles veto system

Charged particles coming from Bremsstrahlung and Bhabha scattering events, two relevant background processes, will be detected by a charged particles veto system, composed of three independent detectors: one for electrons, one for positrons with energy below that of the incoming beam, and one for positrons with energy close to that of the beam.

Each of the three detectors will be composed of a linear array of $10\times10\times184$ mm^3 plastic scintillator fingers with a SiPM readout system. The low energy electron and positron veto arrays will be positioned along the internal walls of the bending magnet, a 0.5 Tesla dipole on loan from the CERN PS, while the high energy positron veto will be positioned perpendicular to the outgoing beam direction in proximity of the beam exit duct.

The expected time resolution of the veto system is < 1 ns with a MIP detection efficiency > 99%. By measuring the impact point along the axis parallel to the direction of the incoming beam, it will also measure the charged particle momentum with a resolution of a few percent.

3. PADME experiment simulation with GEANT4

A GEANT4-based simulation of the full experiment, called PadmeMC, was developed during the early stages of the project in 2014. Since then it closely followed the evolution of the experiment design and was used to verify the effect of the proposed technical choices on the A' recoil mass measurement resolution and to optimize the construction parameters. The current version of PadmeMC is available from GitHub.[1]

3.1. Kinematics and beam simulation

The interaction of the beam particles with the active target and the resulting event kinematics are simulated using the standard GEANT4 physics libraries. The PADME physics list derives from the standard QGSP_BERT physics list provided by the GEANT4 package. It includes multiple scattering, Coulomb scattering, ionization, Bremsstrahlung emission, two photon annihilation, synchrotron radiation emission, and optionally optical photons tracking. Specific datacards allow the inclusion of photonuclear interactions and the selection of the high precision neutron transport library.

Simulation of the annihilation process with dark photon production, e⁺e⁻→γA', is handled by a custom generator which can be activated and configured via datacards, while the kinematics of three gammas final state events, e⁺e⁻→γγγ, was produced externally to GEANT4 using the CalcHEP generator [11].

A realistic description of the incoming positron beam is crucial to the correct evaluation of the resolution in the measurement of the A' recoil mass. Our simulation is based on experimental studies on the BTF beam line and allows the tuning of all relevant beam parameters:

- total duration and internal time structure of the particle bunch;
- energy spread, spatial distribution and emittance of the beam spot at the target.

The beam simulation package also includes methods to produce special events for the calibration of the electromagnetic calorimeter where fixed energy photons are directed to specific areas of the detector.

3.2. Dipole magnet and magnetic field map

The magnet used in the PADME experiment to bend the positron beam is one of the MBP-S dipoles used at CERN for the SPS transfer line. A full survey measured the dimensions of the magnet yoke, coils, and cooling system so that a very precise model of the structure could be inserted in the simulation.

The Magnetic Measures Laboratory of the INFN National Laboratory in Frascati provided a detailed map of the magnetic field produced by the dipole at nominal conditions both inside the magnet yoke and in the volumes up and downstream of it. This map was included in the simulation using the electromagnetic field package provided by GEANT4.

3.3. Detector simulation

As stated before, all detectors composing the PADME experiment were fully modeled and simulated with GEANT4 since their inception. The inclusion of datacards to control the relevant construction parameters allowed a straightforward way to study the effect of engineering choices and physical constraints on the physics results.

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[1] `https://github.com/PADME-Experiment/padme-fw/tree/master/PadmeMC`

The set of tunable parameters includes major construction choices, such as the relative positions of each detector with respect to the target, together with the dimensions of the parts composing each detector, e.g. the length of the plastic scintillator fingers in the veto system, down to tiny details, such as the thickness of the paint coating around each BGO crystal and the width of the air gap between the crystals in the electromagnetic calorimeter.

The final details of the support systems for each detector and of the vacuum chamber of the experiment are currently under study and will be included in the final version of the simulation.

4. Simulation results

PadmeMC was used to study all aspects of the experiment. Here we report about three relevant cases: the first describes a study for the optimization of the electromagnetic calorimeter construction, the second shows a comparison between real data from the testbeams and simulation results, while the third summarizes the process to evaluate the resolution on the A' recoil mass measurement.

4.1. Electromagnetic calorimeter inter-crystal gap studies

The BGO crystals composing the electromagnetic calorimeter must be packed as close as possible in order to minimize the energy lost due to the inter-crystal gap. From the practical point of view, it is not possible to reduce this gap to zero: crystals must be painted to eliminate optical cross-talk and irregularities on the crystals' surface will introduce some distance between them.

It is therefore important to evaluate the effect of this gap on the electromagnetic shower energy collection and to estimate what is the maximum acceptable gap between two crystals before this effect becomes relevant for the physics results. This information will then be used as an input to the definition of the calorimeter construction process.

After fixing the thickness of the paint around each crystal to 100 μm, as recommended by the paint datasheet for optimal light containment, we simulated samples of 30,000 photons impacting on the calorimeter with energies going from 25 MeV to 1 GeV and with the air gap between crystals varying from 50 μm to 500 μm.

The effect of the gap width on the shower energy collection and on the final energy resolution is shown in figure 4: the effect of the gap can be considered acceptable up to 150 μm while the resolution rapidly deteriorates above that value.
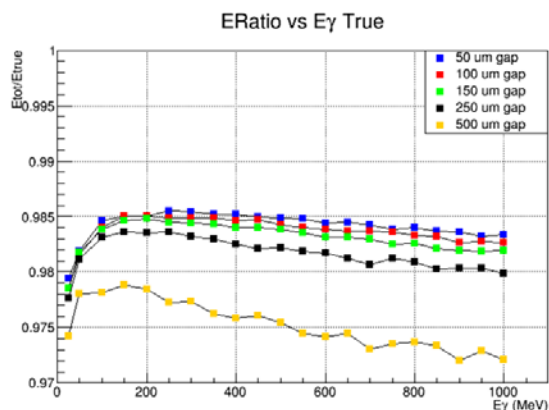

Figure 4a. Effect of the air gap between crystals on the shower energy collection.
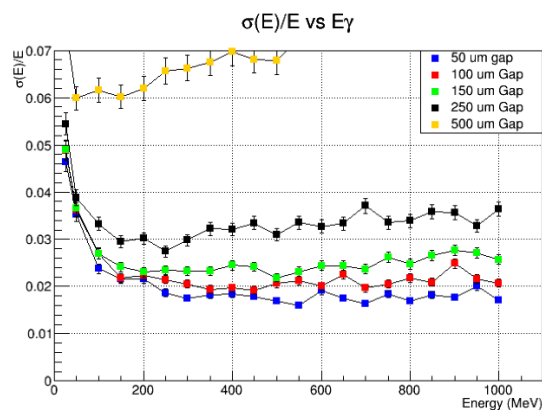
Figure 4b. Effect of the air gap between crystals on the energy resolution of the calorimeter.

4.2. Simulation comparison with testbeam data

Samples of 10,000 electrons impacting on the electromagnetic calorimeter with a spot of 1 cm radius were generated at energies varying from 50 MeV to 1 GeV in steps of 50 MeV and with an energy spread of 1%, close to the beam energy spread of the BTF beam. In order to simulate the experimental setup at the BTF testbeam (see §2.2), only the energy deposited in a 5×5 crystal matrix centered on the impact point was taken into account.

This energy was then transformed into collected charge using the formula

$$Q_{tot} = \sum_{i=0}^{N_{cry}} \left(N_{p.e.} \cdot E_i \cdot G \cdot e \right) \times C_i$$

where E_i is the energy deposited in crystal i, $N_{p.e.}$ is the conversion factor to photoelectrons, G is the nominal PMT gain, e is the electron charge and C_i is the equalization constant for crystal i. In the sum, only crystals with energy above a given threshold were considered, this in order to simulate the effect of the zero suppression algorithm applied to real data. From the data collected at the testbeams, a $N_{p.e.}$ value of ~200 p.e./MeV was estimated, while the equalization constants, not determined during the testbeam, were applied as random factors with a 10% error.

The effect of these factors on the final energy reconstruction is shown in figure 5, where the total energy released in the calorimeter (blue dots) is compared with the reconstructed energy (green dots) for the various energy values. The increasing difference at low energy is due to the effect of the minimum energy threshold.

Figure 6 shows the comparison between the experimental energy resolution of the 5×5 crystal prototype as obtained from the testbeam data analysis (black dots and red line) and the energy resolution of the released (blue dots) and reconstructed (green dots) energies obtained from the simulation.
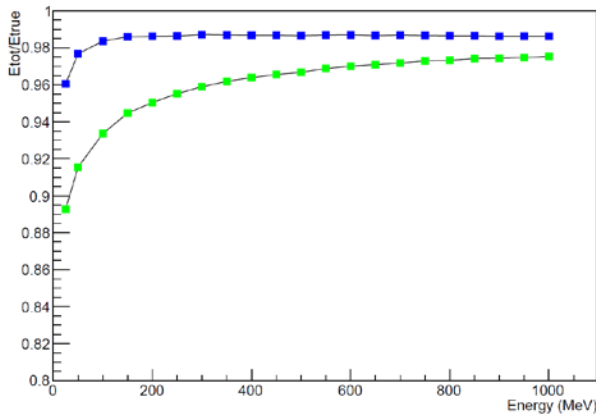

Figure 5. Comparison between the total energy released in the 5×5 BGO matrix (blue dots) and the reconstructed energy (green dots).
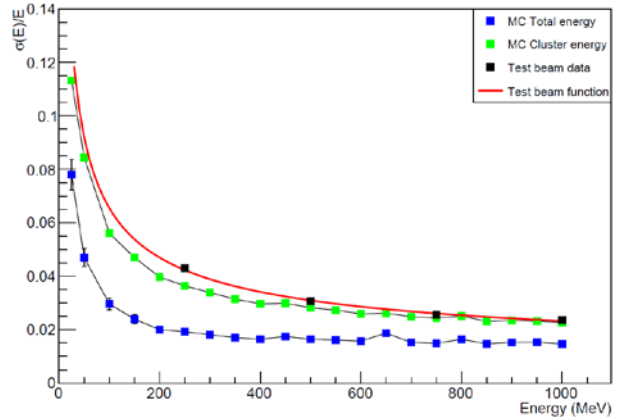
Figure 6. Energy resolution from the analysis of the testbeam data (red line) compared to the released (blue dots) and reconstructed (green dots) energy resolution from the simulation.

4.3. A' mass resolution studies

The final goal of the PADME experiment is to look for the dark photon with a mass up to $M_{A'} \sim 24$ MeV/c². Candidate events are characterized by the presence of a single photon in the electromagnetic calorimeter and nothing else. The mass of the dark photon can then be estimated by closing the kinematics with the formula $M_{miss}^2 = (P_{e^-} + P_{beam} - P_\gamma)^2$ where P_{e^-} is the four-momentum of the e⁻ in the target (considered at rest), P_{beam} is the e⁺ beam four momentum, and P_γ is the four momentum of the reconstructed photon.

In order to reduce the physical backgrounds, the candidate selection cuts must be optimized taking into account the experimental resolution in measuring the missing mass at each possible value of $M_{A'}$. To this end samples of 10,000 signal events were produced with PadmeMC for values of $M_{A'}$ going from 2 MeV to 22 MeV in steps of 2 MeV and the missing mass was reconstructed in each event. Results from this simulation are shown in figure 7.

This result allowed the definition of a set of candidate selection cuts, detailed in table 1, which were then used in all background studies. The reduction plots for the Bremsstrahlung and 3γ backgrounds are shown in figure 8.
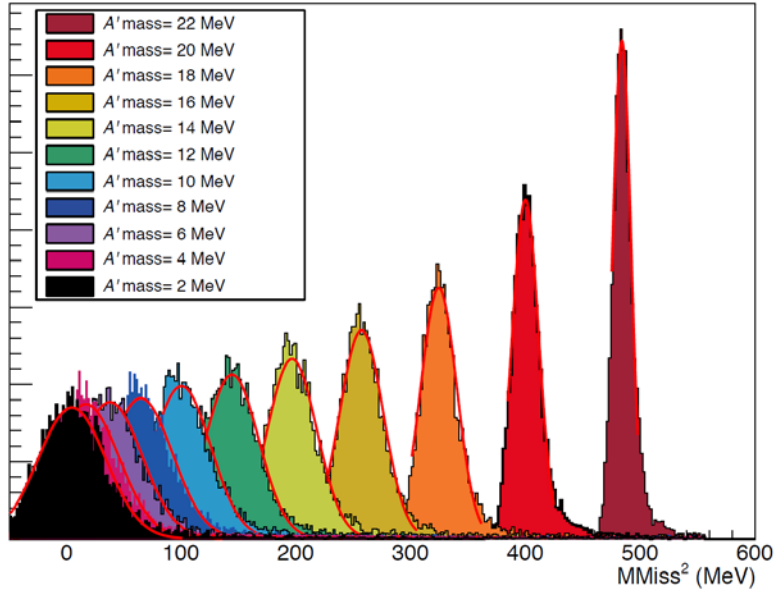

Figure 7. Missing mass squared distribution as a function of A' mass.

Table 1. Dark photon candidate selection cuts

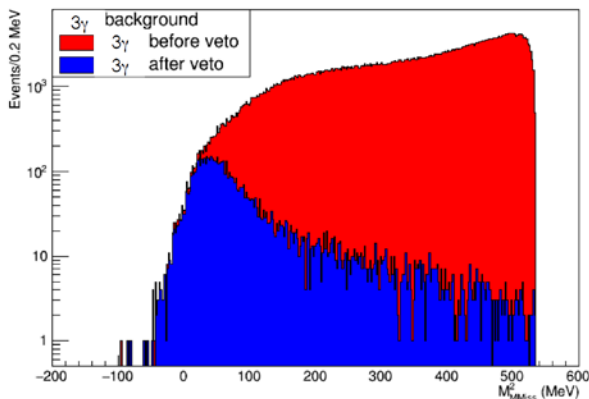|	
1 single cluster in the electromagnetic calorimeter	
$E_{min} < E_{cluster} < E_{max}$	where E_{min} and E_{max} depend on $M_{A'}$ and can be estimated from the annihilation process kinematics
30 mrad $< \theta_{cluster} <$ 65 mrad	
No in-time (i.e. ± 2 ns) charged tracks in the veto system	
No in-time (i.e. ± 2 ns) γ with E_γ > 50 MeV in the SAC	
Invariant missing mass in the range $M_{A'}^2 \pm \sigma(M_{miss}^2)$ obtained from figure 7	

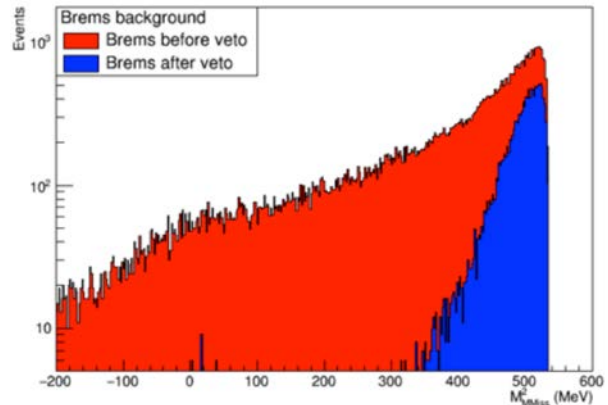**Figure 8a.** Effect of candidate selection cuts on 3γ background.

Figure 8b. Effect of candidate selection cuts on Bremstrahlung background.

5. Conclusions

The PADME experiment will search for the dark photon A' with mass up to 24 MeV in the annihilation process $e^+e^- \to \gamma A'$, with A' undetected, using the Beam-Test Facility of the DAΦNE Linac at the INFN Frascati National Laboratories. Data taking will start in 2018 and will collect $O(10^{13})$ e^+ on target in 2 years.

PadmeMC, a full GEANT4-based simulation of the experiment, has been available since the first phase of the project in 2014 and has developed into a complete package where all parameters of the PADME sub-detectors and of the positron beam can be tuned via datacards. This package is now being used to validate and optimize the technical design of the experiment.

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