First results on the performance of the PADME electromagnetic calorimeter

Gabriele Piperno
Dark Photon as Dark Matter problem solution

**DM properties:**
- stable (half life ~ universe age)
- cold (non relativistic)
- gravitational force
- non baryonic

**DM open questions:**
- DM nature
- interaction(s) w/ SM
- A whole new dark sector?
- dark sector forces?

Possible solution to the DM elusiveness:
DM does not interact directly w/ SM, but only by means of “portals”.

The simplest model adds a $U(1)$ gauge symmetry and its boson: the Dark Photon $A'$

- SM particles are neutral under this symmetry
- new field couples to the SM w/ effective charge $\varepsilon q$

Depending on the model, in addition to DM, the $A'$ could (partially) explain the $(g-2)_\mu$ discrepancy and the $^8$Be anomaly (see backup)
Dark photon production and decays

In e+/e- collisions Dark Photon can be produced in 3 main ways:

Visible decays
If DM particles w/ \( m_{DM} \leq m_{A'}/2 \) do not exist:
- \( A' \rightarrow \text{SM (visible) decays} \)
  - up to \( 2m_\mu \), \( \text{BR}(e^+e^-) = 1 \) (if \( m_{A'} > 2m_e \))

\( A' \) lifetime proportional to:
\[
\frac{1}{(\alpha_D m_{A'})}
\]

Invisible decays
If DM particles w/ \( m_{DM} \leq m_{A'}/2 \) exist:
- \( A' \rightarrow \text{DM (invisible) w/ (likely) BR} \approx 1 \)
- SM decays suppressed by a factor \( \epsilon^2 \)

\( A' \) lifetime proportional to:
\[
\frac{1}{(\alpha_D m_{A'})}
\]
The PADME (LNF, IT) approach

\( \text{A'} \) search in e\(^+\)e\(^-\) annihilations looking for missing mass (invisible decay) in a kinematically constrained condition

- known beam energy and position
- measured photon energy and position

\[ m_{\text{Miss}}^2 = (P_{\text{beam}} + P_e - P_\gamma)^2 \]

- minimal model dependent assumptions: \( \text{A'} \) couples to leptons
- can set limits on coupling of any new light particle that can be produced in e\(^+\)e\(^-\) annihilation: Dark Photon, Axion Like Particles, Dark Higgs
The detector

**E+ beam**
- 550 MeV
- 20000 e+/bunch
- 200 ns bunch, every 20 ms

**Active target**
- diamond (low Z)
- 100 μm thickness
- info on beam time, spot size, e+ number

**High energy e+/e- veto**
- plastic scintillator bars

**TimePix3**
- 8.5 h. x 2.8 v. cm² array
- beam monitoring (high mult.)

**Small angle calorimeter**
- 25 3x3x14 cm³ PbF₂
- 0-15 mrad ang. cov.
- fast: 3 ns Cher. light signals

**Electromagnetic calorimeter**
- 616 2.1x2.1x23 cm³ BGO
- slow: 300 ns dec. time for scint. light

**MBP-S dipole** (upper part not shown)
- ≈ 0.5 T
- 1 m length. x 23 cm gap

**Two MIMOSA**
- beam monitoring (low mult.)
- can stay off-beam
Electromagnetic calorimeter (ECal) overview

Features:
- 616 2.1×2.1×23 cm³ scintillating BGO ($T_{\text{decay}} = 300$ ns)
- length = 20.5 $X_0$
- radius: ≈29 cm
- tedlar foils between crystals (no honeycomb structure) to reduce light crosstalk (see backup)
- 3.45 m from the target
- PMT: HZC XP1911
- angular coverage: [15,84] mrad
- central hole (10.5×10.5 cm²) for Brems. to SAC (faster)
- sampling: 1GS/s, 1024 samples
- w/ current gain (15.3 pC/MeV) a single SU sees photons w/ $E_\gamma < 511$ keV
Electromagnetic calorimeter pictures

Front view, open

Back view, open
$^{22}\text{Na}$ setup for Scintillating Unit (SU) calibration

- A $3\times3\times20$ mm$^3$ LYSO crystal read by a SiPM is used as trigger
- $^{22}\text{Na}$ source faced to each crystal, to exploit its $\gamma$ back-to-back emission: one in the trigger, one in the SU
- 10 HV tested on PMTs: from 1100V to 1550V in steps of 50V
- 135 SUs have been measured two times w/ the $^{22}\text{Na}$ source for reproducibility studies

\[
Q = A \cdot (HV)^s
\]
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ECal HV distribution

HV distribution for all the 616 HZC XP1911 to set SU at 15.3 pC/MeV

- Mean: 1186
- Std Dev: 52.97
HV values stability

Distribution of the HV relative difference for the 135 SU that underwent two measurements, when requiring for 15.3 pC/MeV

Preliminary

Mean 0.5878
Std Dev 0.6724
Cosmic rays in ECal

The trigger is formed of 2 paddles, each one read by 2 PMTs, one above, one below ECal.

Trigger logic:
set in this way to increase the trigger rate
SUs efficiency using CRs

At ≈17.5 MeV (CRs energy loss in SU) and 15.3 pC/MeV, ECal efficiency is ≈100%

Light yield varies w/ temperature (-0.9%/°C) → efficiency may vary

Efficiency evaluation

\[ \text{Eff}_B = \frac{A \cap B \cap C}{A \cap C} \]

It is not possible to evaluate efficiency for a SU on the border
Light yield varies w/ temp. (-0.9%/°C) → MPVs may vary → temperature monitoring
**ECal energy resolution**

Energy resolution has been evaluated using a beam w/ a single $e^+$ per bunch directly on ECal and applying a simple clusterisation algorithm.

Energy resolution at 490 MeV is $12.75/464 = 2.7\%$ (including the beam energy spread).
Conclusions

• Dark Photon is predicted by many physics models, that could explain different experimental observations: Dark Matter, $(g-2)_\mu$, $^8$Be anomaly
• PADME is an experiment hosted at the Laboratori Nazionali di Frascati searching for invisible Dark Photon decays
• The electromagnetic calorimeter is one of the most important component of the detector
• Scintillating units performances
  • very low threshold $\leq 0.5$ MeV
  • good stability w/ variations $< 3\%$ (mean value: 0.6\%)
  • efficiency (using CRs): $\approx 100\%$
• Electromagnetic calorimeter performances
  • gain equalisation at 15.3 pC/MeV from the $^{22}$Na calibration (using CRs): 11\%
  • good energy resolution: 2.7\% at 490 MeV (including the beam energy spread), even better than prototype results

Don’t miss our posters!
I. Oceano: “The performance of the diamond active target of the PADME experiment”
F. Oliva: “Performance of the charged particle detectors of the PADME experiment”
Backup
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Dark Photon searches
Visible search status

Techniques:

- **beam dump (bremsstrahlung)**
  - detection of $\Lambda'$ decay products after high $z$ target ($\Lambda'$ production) + shield (SM absorption)

- **fixed target (bremsstrahlung, annihilation)**
  - bump hunt in invariant mass spectrum, displaced vertices

- **meson decay**
  - only if $\Lambda'$ couples w/ quarks
  - old experiments reanalysis

$(g-2)_\mu$ excluded in the simplest model, but still a lot of interest. In particular the $^8\text{Be}$ anomaly.
Invisible search status

Techniques:
• DM scattering (bremsstrahlung)
  • produced DM detect by scattering
  • 4 parameters needed ($\varepsilon, m_{A'}, m_{DM}, \alpha_D$)

  \[
  A' \rightarrow Z, \bar{\chi}, \chi, \bar{\chi}, \chi, \bar{\chi} \rightarrow Z, p, n
  \]

  \[
  m_{A'} < 0.5 \text{ MeV}, \alpha_D = 0.1
  \]

  \[
  \varepsilon = 10^{-4} - 10^{-2}, m_{A'} = 10^{-2} - 10^{-1}, m_{DM} = 10^{-1} - 10^{-3}
  \]

• missing energy/momentum search (bremsstrahlung)
  • not kinematically constrained process
  • observed energy/momentum smaller than expected

• missing mass search (annihilation)
  • kinematically constrained process
  • no assumption on $A'$ decay chain

Not directly comparable
# Scintillating material selection

<table>
<thead>
<tr>
<th>Material</th>
<th>$\rho$ (g/cm$^3$)</th>
<th>$T$ (°C)</th>
<th>$X_0$ (cm)</th>
<th>$R_M^*$ (cm)</th>
<th>$dE^*/dx$ (MeV/cm)</th>
<th>$\lambda_I^*$ (cm)</th>
<th>$\tau_{\text{decay}}$ (ns)</th>
<th>$\lambda_{\text{max}}$ (nm)</th>
<th>$n^b$</th>
<th>Relative output†</th>
<th>Hygroscopic?</th>
<th>$d(\text{LY})/dT$ (%/°C‡)</th>
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</thead>
<tbody>
<tr>
<td>NaI(Tl)</td>
<td>3.67</td>
<td>651</td>
<td>2.59</td>
<td>4.13</td>
<td>4.8</td>
<td>42.9</td>
<td>245</td>
<td>410</td>
<td>1.85</td>
<td>100</td>
<td>yes</td>
<td>−0.2</td>
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<tr>
<td>BGO</td>
<td>7.13</td>
<td>1050</td>
<td>1.12</td>
<td>2.23</td>
<td>9.0</td>
<td>22.8</td>
<td>300</td>
<td>480</td>
<td>2.15</td>
<td>21</td>
<td>no</td>
<td>−0.9</td>
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<tr>
<td>BaF$_2$</td>
<td>4.89</td>
<td>1280</td>
<td>2.03</td>
<td>3.10</td>
<td>6.5</td>
<td>30.7</td>
<td>650$^s$</td>
<td>300$^s$</td>
<td>1.50</td>
<td>36$^s$</td>
<td>no</td>
<td>−1.9$^s$</td>
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<tr>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>0.9$^f$</td>
<td>220$^f$</td>
<td></td>
<td>4.1$^f$</td>
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<td>Csl(Tl)</td>
<td>4.51</td>
<td>621</td>
<td>1.86</td>
<td>3.57</td>
<td>5.6</td>
<td>39.3</td>
<td>1220</td>
<td>550</td>
<td>1.79</td>
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<td>0.4</td>
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<tr>
<td>Csl(pure)</td>
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<td>621</td>
<td>1.86</td>
<td>3.57</td>
<td>5.6</td>
<td>39.3</td>
<td>30$^s$</td>
<td>420$^s$</td>
<td>1.95</td>
<td>3.6$^s$</td>
<td>slight</td>
<td>−1.4</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>6$^f$</td>
<td>310$^f$</td>
<td></td>
<td>1.1$^f$</td>
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<tr>
<td>PbWO$_4$</td>
<td>8.3</td>
<td>1123</td>
<td>0.89</td>
<td>2.00</td>
<td>10.1</td>
<td>20.7</td>
<td>30$^s$</td>
<td>425$^s$</td>
<td>2.20</td>
<td>0.3$^s$</td>
<td>no</td>
<td>−2.5</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10$^f$</td>
<td>420$^f$</td>
<td></td>
<td>0.077$^f$</td>
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<tr>
<td>LSO(Ce)</td>
<td>7.40</td>
<td>2050</td>
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<td>85</td>
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<td>LaBr$_3$(Ce)</td>
<td>5.29</td>
<td>788</td>
<td>1.88</td>
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<td>30.4</td>
<td>20</td>
<td>356</td>
<td>1.9</td>
<td>130</td>
<td>yes</td>
<td>0.2</td>
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</table>

Notes:
- † Relative output: 1st choice (0–100%)
- ‡ $d(\text{LY})/dT$: 1st choice (0–20%)
- $^s$ and $^f$ denote scintillation and fast decay, respectively.
BGO emission spectrum

Figure 1. Scintillation emission spectrum of BGO
Crystal procurement

L3 half-endcaps where crystals are…

...taken
Crystal optical properties

After crystal selection the following steps are executed:

• Photosensor removal (mechanically after 48h in acetone)
• Paint removal (w/ water)
• Transmittance measurement
• Annealing
  • $T_{\text{amb}} \rightarrow 200 \, ^\circ\text{C}$ in 3 h
  • 200 °C for 6 h
  • 200 °C $\rightarrow T_{\text{amb}}$ “natural”
• Transmittance measurement

Everything is performed at CERN at LAB27
Transmittance before annealing
Transmittance after annealing
Crystals cut and polished at SILO (Italy)

They produced identical parallelepipeds starting from different truncated pyramid shapes (L3 endcaps geometry was pointing)

We performed a quality check at LNF on some crystals, to verify that dimensions are within specification, w/ positive results
HZC XP1911

We modified the mechanical design

Typical spectral characteristics

Gain

Type B: higher linearity

Slightly modified divider circuit
PMTs test

32 PMTs at a time were tested w/ a LED matrix (one per tube): pulsing the LEDs we see if the PMT works and its response to the light. If results are good, tubes are sent to SILO for gluing.
Global PMT results

Gain at 1680.0V

<table>
<thead>
<tr>
<th>Gain</th>
<th>Entries</th>
<th>Mean</th>
<th>RMS</th>
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<tbody>
<tr>
<td>64</td>
<td>648</td>
<td>5.413e+06</td>
<td>1.911e+06</td>
</tr>
</tbody>
</table>

Counts vs Gain

Charge [pC] vs HV [V]
Gluing and painting at SILO

- **Glue**: EJ-500

  ![Glue application diagram](image)

- **Paint**: EJ-510
  - 3 layers of white paint (≈100μm)

  ![Painting application diagram](image)
The LNF Beam Test Facility (BTF)

PADME experimental hall is the Beam Test Facility of the Laboratori Nazionali di Frascati (~Rome, IT), the same place where the test beams have been performed.

<table>
<thead>
<tr>
<th>Dedicated mode</th>
<th>W/ target</th>
<th>W/o target</th>
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<tbody>
<tr>
<td><strong>Particle species</strong></td>
<td>e⁺/e⁻</td>
<td>selectable by user</td>
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<tr>
<td><strong>Energy [MeV]</strong></td>
<td>25-700 (e⁺)</td>
<td>250-730 (e⁺)</td>
</tr>
<tr>
<td></td>
<td>25-700 (e⁻)</td>
<td>250-530 (e⁻)</td>
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<tr>
<td><strong>Energy spread</strong></td>
<td>1%</td>
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<tr>
<td><strong>Rep. rate [Hz]</strong></td>
<td>1-49</td>
<td>selectable by user</td>
</tr>
<tr>
<td><strong>Pulse duration [ns]</strong></td>
<td>1.5-40</td>
<td>selectable by user</td>
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<tr>
<td><strong>Intensity [particles/bunch]</strong></td>
<td>1-10⁵ depending on energy</td>
<td>10³-3·10¹⁰</td>
</tr>
<tr>
<td><strong>Max average flux</strong></td>
<td>3.125 · 10¹⁰ particles/s</td>
<td></td>
</tr>
<tr>
<td><strong>Spot size [mm]</strong></td>
<td>0.5-25 (y) · 0.6-55 (x)</td>
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</tr>
<tr>
<td><strong>Divergence [mrad]</strong></td>
<td>1-1.5</td>
<td></td>
</tr>
</tbody>
</table>

Experimental hall:
• < 5.5 m in length
• < 3 m in width
# Beam Test Facility parasitic and dedicated modes

<table>
<thead>
<tr>
<th></th>
<th>Parasitic mode (DAΦNE working)</th>
<th>Dedicated mode</th>
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<tr>
<td></td>
<td>W/ target</td>
<td>W/ target</td>
</tr>
<tr>
<td>Particle species</td>
<td>e⁺/e⁻ selectable by user</td>
<td>e⁺/e⁻</td>
</tr>
<tr>
<td></td>
<td>depending on DAΦNE mode</td>
<td>depending on</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DAΦNE mode</td>
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<tr>
<td>Energy [MeV]</td>
<td>25-500</td>
<td>510</td>
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<tr>
<td></td>
<td></td>
<td>25-700 (e⁻)</td>
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<tr>
<td>Energy spread</td>
<td>1% @ 500 MeV</td>
<td>1%</td>
</tr>
<tr>
<td>Rep. rate [Hz]</td>
<td>10-49 depending on DAΦNE mode</td>
<td>1-49 selecte</td>
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<tr>
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<td>d by user</td>
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<td>Pulse duration [ns]</td>
<td>10</td>
<td>1.5-40 selecte</td>
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<td>1-10⁵ depending on energy</td>
<td>10⁷-1.5·10¹⁰</td>
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<td>3.125·10¹⁰ particles/s</td>
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<td>0.5-25 (y) × 0.6-55 (x)</td>
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<tr>
<td>Divergence [mrad]</td>
<td>1-1.5</td>
<td></td>
</tr>
</tbody>
</table>
Calorimeter prototype performance @ BTF

Charge spectrum

250 MeV e\(^{-}\)

Energy resolution is within the expectation, w/ reference to the L3 experience

Linearity residuals

Linearity is within 2% up to 1GeV (gain 5\( \times \)10\(^5\))

Energy resolution is within the expectation, w/ reference to the L3 experience

NIM A, 862 (2017) 31
We performed CR runs w/ 2 different setups:

- 4×3 matrix
- 5×5 matrix w/ 50μm tedlar foils between crystals (see next slides)
Cosmic rays charge spectra (5x5 matrix)

All events
Vertical CR
Side events (vertical CR passes through a crystal on the side)

Verticality is obtained requiring that the 5 largest signals are in column

Example: μ passing through central column
Optical crosstalk without tedlar (4×3 matrix)

Inverse cumulative of the Side events w/o tedlar

1% is reached at ≥100pC
Optical crosstalk with tedlar (4×3 matrix)

Inverse cumulative of the Side events w/ tedlar

1% is reached at ~50pC

Tedlar is effective in preventing optical crosstalk

Tedlar will be used for the ECAL assembly (it also accommodates different SU heights)
Calorimeter mechanical design

ECAL (BGO + filler)

$^{22}$Na movement (calibration & transparency)

SAC

ECAL support

PMT enclosure

Support table

Inner support

Front/rear panels (light tightness)

Support structure
ECAL assembly procedure

Procedure:
- first crystal bottom left
- complete first layer
- block layer w/ locking screws
- equalize for different SU heights
- go to next layer

ECal structure before the assembly

Front view
Vertical CR in and SU efficiency

A CR is considered as passing vertically through a SU if:

- the SU above and the SU below have signal
- the 3 SU are vertically aligned
- there are only those SUs w/ a signal in these 3 layers
- if the SU is on the border the 2 crystals above or below are used

Verticality does not give any information about longitudinal point of interaction

It is not possible to evaluate efficiency for a SU on the border
BGO thermometers

Positions:
Back (rear part of crystal)
Side (2 along the crystal side)

24 + 16 thermometers:
- Pt1000
- thin film, 10mm tails
- dimensions: 1.2x1.6 mm²
- temperature range: (-50, 500°C)
- self-heating:< 0.5 °C/mW
- thermal response: 0.1 s
- stability: ±0.05%
Active target

Features:
- **Diamond** (low z, reduced brems.)
- Dim.: $20 \times 20 \times 0.1 \text{ mm}^3$
- $19 \text{ h. } \times \ 19 \text{ v. active graphitic strips (1 mm pitch, 0.15 mm interstrip distance, electric resistance } \sim 2.5\text{k}\Omega$)
- $16 \text{ h.} \times 16 \text{ v. strips are read}
- in vacuum w/ movement system
- $\sigma_{x-y}(\text{beam position}): \ 0.6\text{mm}$

Two IDEAS boards equipped w/ 16 channel AMADEUS chip to readout
Active target operations

The target has been continuously and stably operated since September 2018.

The diamond detector performances measured on situ show excellent beam monitor capability:

- single bunch X and Y beam profiles
- good spatial resolution and linearity w/ charge weighting algorithm
- linear response to beam multiplicity (many calibration runs performed using a lead glass Cherenkov calorimeter)

Timeline trends of the vert. and horiz. beam position and the number of e+ on target are provided by the experiment monitor.
Beam profile with target

Strips X3 and X5 are not working: charge linear interpolation using lateral strips (not in this plot)
Small Angle Calorimeter (SAC)

Characteristics:

- $\sigma_E \approx 10\%$
- Cherenkov $\rightarrow$ 3-4 ns signals
- angular coverage: [0,20] mrad
- crystal wrapped w/ tedlar (only direct light)

$E_\gamma$ in SAC from a $3\gamma$ event if a "good" $\gamma$ is present in ECal

SAC must be sensiple to photons over 300 MeV and blind under 100 MeV
Detector top view (w/ signal)

Signal:
- single $\gamma$ in the calorimeter
- nothing in the other detector components

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Backgrounds

Largest backgrounds:

- $e^+ e^- \rightarrow \gamma \gamma (\gamma)$
- $e^+ N \rightarrow e^+ N \gamma$
- pile-up

Cuts:

- 1 cluster in ECAL fiducial volume
- no hits in vetoes
- no $\gamma$ in the SAC w/ $E_\gamma > 50$ MeV
- $20 - 150$ MeV < $E_\gamma < 120 - 350$ MeV (depending on $m_{A'}$)
Sensitivity

Based on $2.5 \cdot 10^{10}$ fully GEANT4 simulated 550 MeV $e^+$ on target events. Number of BG events is extrapolated to $10^{13} e^+$ on target.

PADME can explore in a model-independent way the region down to $\varepsilon \approx 10^{-3}$ w/: 
- $m_{A'} < 23.7$ MeV ($E_{\text{beam}} = 550$ MeV)
- $m_{A'} < 27.7$ MeV ($E_{\text{beam}} = 750$ MeV)
- $m_{A'} < 32$ MeV ($E_{\text{beam}} = 1$ GeV)