The Dark Matter problem

Evidences:
- spiral galaxies
- Cosmic Microwave Background
- gravitational lensing
- galaxy clusters
- Big Bang Nucleosynthesis
- large scale structures

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

Open questions:
- DM nature
- interaction(s) w/ SM
- A whole new dark sector?
- dark sector forces?
Dark Photon

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, the $A'$ could (partially) explain the $(g-2)_{\mu}$ discrepancy and the $^8$Be anomaly (see backup)

Exclusion plot assuming as $A'$ model the one presented above

Excluded as only solution of the $(g-2)_{\mu}$ problem
Dark photon production and decays

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

- **Annihilation**
  - e^- + A' → e^+ + γ

- **Bremsstrahlung**
  - e^+/- + A' → γ + N

**Visible decays**

If DM particles with m_{DM} ≤ m_{A'}/2 do not exist:
- A' → SM (visible) decays
  - up to 2m_μ, BR(e^+e^-) = 1 (if m_{A'} > 2m_e)

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

**Invisible decays**

If DM particles with m_{DM} ≤ m_{A'}/2 exist:
- A' → DM (invisible) w/ (likely) BR ≈ 1
- SM decays suppressed by a factor \( \epsilon^2 \)

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

\( \alpha_D \): A' coupling constant to the Dark Sector
The PADME approach

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

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

- known beam energy and position
- measured photon energy and position
- minimal model dependent assumptions: \( A' \) 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

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

**High energy e\(^+\)/e\(^-\) veto**
- plastic scintillator bars

**Small angle calorimeter**
- 25 3×3×14 cm\(^3\) PbF\(_2\)
- 0-20 mrad ang. cov.
- fast: 3 ns Cher. light signals

**Electromagnetic calorimeter**
- 616 2.1×2.1×23 cm\(^3\) BGO
- cylindrical shape w/ central hole
- 20-95 mrad ang. cov.
- (1-2)%/\(\sqrt{E}\)
- slow: 300 ns dec. time for scint. light

**e\(^+\) beam**
- 550 MeV
- 5000 e\(^+\) per bunch
- 40 ns bunch, every 20 ms

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

Required characteristics:

- \( \sigma_E \approx (1-2)\%/\sqrt{E(\text{GeV})} \)
  - good light yield
  - containment
- cluster time resolution < 1 ns
- angular resolution \( \approx 2 \text{ mrad} \)
- angular coverage: [20, 93] mrad
- angular acceptance: [26, 83] mrad
- central hole for brems. to SAC (faster)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( \rho )</th>
<th>MP</th>
<th>( X_0^* )</th>
<th>( R_X^* )</th>
<th>( dE/dx )</th>
<th>( \lambda_f )</th>
<th>( \tau_{\text{decay}} )</th>
<th>( \lambda_{\text{max}} )</th>
<th>( n^3 )</th>
<th>( \text{Relative output} )</th>
<th>Hygroscopic?</th>
<th>( d(LY)/dT )</th>
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</thead>
<tbody>
<tr>
<td>Units:</td>
<td>g/cm(^3)</td>
<td>°C</td>
<td>cm</td>
<td>cm</td>
<td>MeV/cm</td>
<td>cm</td>
<td>ns</td>
<td>nm</td>
<td></td>
<td>%/°C ( \uparrow )</td>
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<td>NaI(Tl)</td>
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<td>651</td>
<td>2.59</td>
<td>4.13</td>
<td>4.8</td>
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<td>1050</td>
<td>1.12</td>
<td>2.23</td>
<td>9.0</td>
<td>22.8</td>
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<td>480</td>
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<td>2.03</td>
<td>3.10</td>
<td>6.5</td>
<td>30.7</td>
<td>650(0^*)</td>
<td>300(0^*)</td>
<td>1.50</td>
<td>36(0^*)</td>
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<td>-1.9(0^*)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>CsI(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>
<td>165</td>
<td>slight</td>
<td>0.4</td>
</tr>
<tr>
<td>CsI(pure)</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>30(0^*)</td>
<td>420(0^*)</td>
<td>1.95</td>
<td>3.6(0^*)</td>
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<td>-1.4</td>
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<td>PbWO(_4)</td>
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<td>1123</td>
<td>0.89</td>
<td>2.00</td>
<td>10.1</td>
<td>20.7</td>
<td>30(0^*)</td>
<td>425(0^*)</td>
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<td>0.3(0^*)</td>
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<td>LSO(Ce)</td>
<td>7.40</td>
<td>2050</td>
<td>1.11</td>
<td>2.07</td>
<td>9.6</td>
<td>20.9</td>
<td>40</td>
<td>402</td>
<td>1.82</td>
<td>85</td>
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<tr>
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<td>788</td>
<td>1.88</td>
<td>2.85</td>
<td>6.9</td>
<td>30.4</td>
<td>20</td>
<td>356</td>
<td>1.9</td>
<td>130</td>
<td>yes</td>
<td>0.2</td>
</tr>
</tbody>
</table>

616 BGO 2.1×2.1×23 cm\(^3\) @ 3m from the target
Crystal procurement

L3 half-endcaps where crystals are... …taken
Crystal optical properties

After crystals selection the following steps are executed:

- Photosensor removal (mechanically after 48h in acetone)
- Paint removal (with 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)

Mechanical tolerances (more stringent limits are set for the square shape)

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

Slightly modified divider circuit

Typical spectral characteristics

Typical gain curve

Type B: higher linearity
PMTs test

32 PMTs at a time were tested with 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>
</tr>
</thead>
<tbody>
<tr>
<td></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

- Paint: EJ-510
  - 3 layers of white paint (≈100μm)
Scintillating Units (SU)

Maximum footprint after painting

Currently we have 580 $2.1 \times 2.1 \times 23\text{cm}^3$ painted and glued units at LNF
The LNF Beam Test Facility (BTF)

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

Experimental hall:
• < 5.5 m in length
• < 3 m in width
Calorimeter prototype performance @ BTF

Energy resolution is within the expectation, with reference to the L3 experience.

Charge spectrum:
- 250 MeV e^-
- 450 MeV e^-

Energy resolution:
- 250 MeV e^-
- 450 MeV e^-

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

Energy resolution is within the expectation, with reference to the L3 experience.

NIM A, 862 (2017) 31
**22Na setup**

- A 3×3×20 mm³ LYSO crystal read by a SiPM is used as trigger
- **22Na source** faced to each crystal, to exploit its γ 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
Reconstructed spectra w/ $^{22}$Na source

Charge is given by an integration window of 1 μs ($\approx$150 ns pre-pulse), sampled at 1GS/s
Gain curves w/ $^{22}\text{Na}$ 511 keV peak

Fitting function: $Q = \text{const} \cdot (HV)\text{slope}$

Charge $\epsilon \in [0,75] \, \text{pC}$ (depending on ch.)

HV $\in [1100,1550] \, \text{V}$ depending on ch.
Gain equalization

511 keV peak mean distributions

Equalization at 20 pC/MeV

<table>
<thead>
<tr>
<th>HV</th>
<th>Counts</th>
<th>Charge $\in$ [0,75] pC</th>
<th>Peaks distribution for fixed HVs</th>
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<tbody>
<tr>
<td>HV = 1100 V</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>HV = 1150 V</td>
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<tr>
<td>HV = 1200 V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HV = 1250 V</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>HV = 1300 V</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>HV = 1350 V</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>HV = 1400 V</td>
<td></td>
<td></td>
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<tr>
<td>HV = 1450 V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HV = 1500 V</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HV = 1550 V</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$\chi^2/\text{ndf}$: 2.345/5
Constant: 5.565 ± 2.128
Mean: 10.4 ± 0.2
Sigma: 0.7731 ± 0.2982
Reproducibility

For each SU of a group of 25 we performed 2 times the same HV scan.

Relative difference of the 511 keV peak charge as a function of the HV.
Charge relative differences distribution

- Larger relative variations are due to small absolute values
- Measurements have been done in different conditions (daylight, black cover positioning,…) that may have produced systematic variations

Distribution of the averages (red lines) of the previous slide
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 with locking screws
- equalize for different SU heights
- go to next layer

for each layer

front view

Ready for the assembly!
Conclusions

• Dark Photon is predicted by many physics models, that could explain different experimental results: 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 components of the detector and is currently under construction

• Calorimeter readout: 616 HZC XP1911 (PMTs) w/ ≃5% gain uniformity at nominal HV

• Scintillating units
  • very low threshold (≤ 0.5 MeV)
  • good reproducibility w/ variations < 3%

• ECAL prototype
  • energy resolution is compatible with the L3 results: 2%/√E(GeV)
  • good charge reconstruction linearity w/ variations < 2% up to 1 GeV
Dark Photon searches
BGO emission spectrum

Figure 1. Scintillation emission spectrum of BGO
Visible search status

Techniques:

• beam dump (bremsstrahlung)
  • A' decay products detection after high z target (A' production) + shield (SM absorption)

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

• meson decay
  • only if A' 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)
  • detect the produced DM by scattering
  • needed 4 parameters ($\varepsilon, m_{A'}, m_{DM}, \alpha_D$)

• 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

[Diagrams and plots related to DM scattering and search strategies are shown, with some notation such as $m_{A'}$, $m_{DM}$, and energy/momentum measurements.]
Beam Test Facility parasitic and dedicated modes

<table>
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<th>Parasitic mode (DAΦNE working)</th>
<th>Dedicated mode</th>
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<td></td>
<td>W/ target</td>
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<tr>
<td></td>
<td>W/o target</td>
<td>W/o target</td>
</tr>
<tr>
<td>Particle species</td>
<td>e+/e− selectable by user</td>
<td>e+/e− selectable by user</td>
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<td></td>
<td>e+/e− depending on DAΦNE mode</td>
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<td>25-700 (e+)</td>
<td>250-730 (e+)</td>
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<td>25-700 (e−)</td>
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<td>Energy spread</td>
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<td>1%</td>
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<td></td>
<td>1%</td>
<td></td>
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<td>Rep. rate [Hz]</td>
<td>10-49 depending on DAΦNE mode</td>
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<td>Pulse duration [ns]</td>
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<td>Intensity [particles/bunch]</td>
<td>1-10⁵ depending on energy</td>
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<tr>
<td></td>
<td>10⁷-1.5 · 10¹⁰</td>
<td>10³-3 · 10¹⁰</td>
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<tr>
<td>Max average flux</td>
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<td></td>
</tr>
</tbody>
</table>
Detector top view (w/ signal)

Signal:
- single $\gamma$ in the calorimeter
- nothing in the other detector components
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 $m_{A'}$)

Backgrounds geometry

Annihilation (+ISR): $e^+ e^- \rightarrow \gamma \gamma (\gamma)$

Bremsstrahlung: $e^+ N \rightarrow e^+ N \gamma$
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)
Active target

Features:
- **Diamond** (low z, reduced brems.)
- Dim.: 20×20×0.1 mm³
- 19 horiz.×19 vert. active graphitic strips (average informations on beam)
- $\sigma_{x,y}(\text{beam position}) < 2$ mm
- in vacuum w/ movement system

Test detector results *(18 h.×18 v. active strips)*

Spatial resolution: 0.2 mm (x-axis) × 0.3 mm (y-axis)
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

$E_\gamma$ in the SAC

SAC must be sensible to photons over 300 MeV and blind under 100 MeV
HV (given charge) and charge (given HV) histo

From $^{22}$Na source measurements
Cosmic ray setups

We performed CR runs with 2 different setups:

- 4×3 matrix
- 5×5 matrix with 50μm tedlar foils between crystals (see next slides)
Cosmic rays charge spectra (5×5 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 without tedlar

1% is reached at $\gtrsim 100\text{pC}$
Optical crosstalk with tedlar (4×3 matrix)

Inverse cumulative of the Side events with 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)
PMTs test station

PADME electromagnetic calorimeter - Gabriele Piperno - CALOR 2018

Seen from below
XP1911 divider new design

Voltages across resistors: measured by 10 MΩ impedance multimeter
PMTs dimensions test

GOOD CASE: Photomultiplier pass through

BAD CASE: Photomultiplier does not pass through

DIMENSIONAL TEST WITH "TUBE" ID=20,4 H8