Dark Photon search with PADME at LNF

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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 by means of “portals”.

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

Additionally the $A'$ could (partially) explain the $(g-2)_\mu$ discrepancy

$A'$ characteristics in the simplest model above:
- $1 \text{ MeV} < m_{A'} < 1 \text{ GeV}$
- $\varepsilon \gtrsim 10^{-3}$

Purely indicative numbers: it has been recently discarded as a solution
Dark Photon production

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

- **Annihilation**: $e^- + e^+ \rightarrow A'$
- **Bremsstrahlung**: $e^+ \rightarrow A' + \gamma$
- **Mesons dec. (after production)**: $\pi^0, \eta \rightarrow A' + \gamma$
Dark Photon decay

Visible decays
If DM particles w/ \( m_{\text{DM}} < m_{A'}/2 \) 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:
\[
\frac{1}{(\alpha \varepsilon^2 m_{A'})}
\]

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

\( A' \) lifetime proportional to:
\[
\frac{1}{(\alpha_{D} m_{A'})}
\]
\( \alpha_{D} \): \( A' \) coupling constant to the Dark Sector
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
Invisible search status

Techniques:

- **DM scattering (bremsstrahlung)**
  - detect by scattering the produced DM
  - needed 4 parameters ($\varepsilon, m_{A'}, m_{DM}, \alpha_D$)

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

![Diagram of Dark Photon search with PADME at LNF - Gabriele Piperno - PANIC 2017](image)

- **Not directly comparable**
The PADME approach

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

minimal model dependent assumptions: $A'$ couples to leptons

coupling of any new light particle produced in $e^+e^-$ annihilation can be limited: 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 PbF₂
  3×3×15 cm³
• 0-20 mrad ang. cov.

elempagnetic calorimeter
• 616 2.1×2.1×23 cm³ BGO
• cylindrical shape w/ central hole
• 20-95 mrad ang. cov.
• (1-2)%/√E

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

e⁺ beam
• 550 MeV
• 5000 e⁺ per bunch
• 40 ns bunch, every 20 ms
Detector top view (w/ signal)

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

[Diagram of detector setup]
Active target

Features:
- **Diamond** (low z, reduced brems.)
- Dim.: 20×20×0.1 mm$^3$
- 16 horiz.×16 vert. active graphitic strips (average informations on beam)
- $\sigma_{x-y}(\text{beam position}) < 2$ mm
- in vacuum w/ movement system
Electromagnetic calorimeter (1)

Features:
- $\sigma_E \approx (1-2\%)/\sqrt{E}$
  - high $\gamma$ statistic
  - containment
- cluster time resolution $< 1$ ns
- angular resolution $\leq 1$ mrad
- angular coverage: $[20,93]$ mrad
- angular acceptance: $[26,83]$ mrad
- central hole for brems. to SAC (faster)

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### N. 616 Scintillators BGO

616 BGO $2.1 \times 2.1 \times 23$ cm$^3$

@ 3 m from the target

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**Table 1**

| Parameter                  | $\rho$ | $\text{MP}$ | $X_0^*$ | $R_M^*$ | $dE^*/dx$ | $\lambda_f^*$ | $\tau_{\text{decay}}$ | $\lambda_{\text{max}}$ | $n^3$ | $\text{Relative output}^1$ | $d(\text{LY})/dT$ | $\%/{\circ}C^2$ |
|----------------------------|--------|-------------|---------|---------|-----------|----------------|---------------------|---------------------|------|-----------------------------|----------------|----------------|
| NaI(Tl)                    | 3.67   | 651         | 2.69    | 4.13    | 4.8       | 42.9         | 245                 | 410                 | 1.85 | 100                         | yes            | $-0.2$         |
| BGO                        | 7.13   | 1050        | 1.12    | 2.23    | 9.0       | 22.8         | 300                 | 480                 | 2.15 | 21                          | no             | $-0.9$         |
| BaF$_2$                    | 4.89   | 1280        | 2.03    | 3.10    | 6.5       | 30.7         | 650$^*$             | 300$^*$             | 1.50 | 36$^*$                       | no             | $-1.9^*$        |
| CsI(Tl)                    | 4.51   | 621         | 1.86    | 3.57    | 5.6       | 39.3         | 1220               | 550                 | 1.79 | 165                         | slight         | 0.4            |
| CsI(pure)                  | 4.51   | 621         | 1.86    | 3.57    | 5.6       | 39.3         | 30$^*$              | 420$^*$             | 1.95 | 3.6$^*$                      | slight         | $-1.4$         |
| PbWO$_4$                   | 8.3    | 1123        | 0.89    | 2.00    | 10.1      | 20.7         | 30$^*$              | 425$^*$             | 2.20 | 0.3$^*$                      | no             | $-2.5$         |
| LSO(Ce)                    | 7.40   | 2050        | 1.14    | 2.07    | 9.6       | 20.9         | 40                  | 402                 | 1.82 | 85                          | no             | $-0.2$         |
| LaBr$_3$(Ce)               | 5.29   | 788         | 1.88    | 2.85    | 6.9       | 30.4         | 20                  | 356                 | 1.9  | 130                         | yes            | 0.2            |
Electromagnetic calorimeter (2)

Dipole gap limits the angular acceptance

Results w/ a 5×5 BGO (2×2×22 cm³) matrix test

\[ \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \]

\[ \chi^2 / \text{ndf} = 6.499 / 3 \]
\[ a = 0.02013 \pm 0.001632 \]
\[ b = 2.954e-05 \pm 1.306e-05 \]
\[ c = 0.01152 \pm 0.002914 \]

250 MeV and multiples

450 MeV and multiples

M. Raggi et al., NIM 862, 31 (2017)
The LNF Beam Test Facility

PADME will be placed in the Beam Test Facility of the Laboratori Nazionali di Frascati (~Rome, IT)

| Parasitic mode (DAΦNE working) | Dedicated mode |
|---------------------------------|----------------|
| W/ target                       | W/ target      |
| W/o target                      | W/o target     |
| Particle species                |                |
| e⁺/e⁻ selectable by user        | e⁺/e⁻ selectable by user |
| Energy [MeV]                    |                |
| 25-500                          | 510            |
| Energy spread                   |                |
| 1% @ 500 MeV                    | 1%             |
| Rep. rate [Hz]                  |                |
| 10-49 depending on DAΦNE mode   | 1-49 selectable by user |
| Pulse duration [ns]             |                |
| 10                              | 1.5-40 selectable by user |
| Intensity [particles/bunch]     |                |
| 1-10⁵ depending on energy       | 10⁷-1.5 · 10¹⁰ |
| Max average flux                | 3.125 · 10¹⁰ particles/s |
| Spot size [mm]                  | 0.5-25 (y) × 0.6-55 (x) |
| Divergence [mrad]               | 1-1.5          |

A main limit to the PADME sensitivity arise from the pile-up
PADME positron beam

Beam characteristics (referring to a 550 MeV beam on a 100 μm C target):

- Energy spread ≈ 1%
- Angular divergence < 1 mrad
- Beam RMS < 1 mm
- Position RMS = 0.25 mm
- Repetition rate = 49 Hz
- Particles per bunch ≈ 5000 (limited by pile-up)
- Pulse duration = 40 ns

Increasing the pulse duration it is possible to collect more statistics maintaining the same pile-up level.

We performed some tests reaching a bunch length up to 280 ns. In principle up to 5 μs length is possible, but requires a (never tried or non-reversible) different linac configuration.
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 $m_{A'}$)
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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)

| Jan | Feb | Mar | Apr | May | Jun | Jul | Agu | Sep | Oct | Nov | Dec |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Commissioning | PADME run 1 | | | | | | DAΦNE | run 1 | | | |
Conclusions

• **Dark Photon** (DP) is predicted in a class of relatively young and general new physics models which are quickly gaining interest in the DM community

• A DP that decays into DM can (partially) explain the \((g-2)_{\mu}\) discrepancy

• **PADME** is an experiment that will search for an “invisible” (DM) decaying DP at the Laboratori Nazionali di Frascati

• The collaboration aims to collect \(10^{13}\) e\(^+\) on target by the end of 2018 testing, in a model-independent way, a DP w/ \(\varepsilon \gtrsim 10^{-3}\) and mass up to 23.7 MeV (\(E_{\text{beam}} = 550\) MeV)

• **PADME** results will apply also to other hypothetical particles like Axion Like Particles and Dark Higgs
References

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  - M. Pospelov, Phys. Rev. D 80, 095002 (2009)
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- **LNF Beam Test Facility**
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- **PADME**
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Backup
Dark Photon searches
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PADME visible

Thanks to granular e^+/e^- vetoes it is possible to search for (short lived) A' visible decaying in visible w/ the current setup

Possible future upgrades:
- high z thin target (increased A' bremsstrahlung)
- \( E_{A'} \) can be \( > \sqrt{2m_e E_{\text{beam}}} \)
- \( E_{A'} \) unknown (no closed kinematics)

Only visible decays are interesting

Bremsstrahlung

Preliminary calculations w/ \( 10^{18} \) EOT give a sensitivity on \( \varepsilon^2 \sim 10^{-7} \) in the low mass region, that worsens as \( m_{A'} \) increases
Dark Higgs at PADME

Interesting decay for PADME (depending on $m_{h'}$ and $m_{A'}$):

- if $m_{A'} < m_{h'}/2$ dominant $A' h' \rightarrow A' A' A' \rightarrow 6$ leptons (0 charge, $E_{\text{tot}} < E_{\text{beam}}$)
- if $m_{A'} > m_{h'}/2$ (or $h'$ long lived) dominant $A' h' \rightarrow A' \text{ inv.} \rightarrow 2$ leptons (0 charge)

- strong signature (no new detector component needed)
- tracking spectrometer needed
**Axion Like Particles at PADME**

An invisible decaying or long lived ALP in PADME has the same signature of a DP:
- 1 $\gamma$
- missing energy in the final state

In the visible decay $a \rightarrow \gamma \gamma$ all the production mechanisms can be explored up to $m_{\text{ALP}} \sim 100$ MeV.

Observables:
- $e^+ \gamma \gamma$
- $\gamma \gamma \gamma$