Searching for dark photons with the PADME experiment at the Frascati Linac

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for the PADME experiment
Why PADME experiment?

- Long standing problem: cosmological evidence for existence of dark matter, no clear experimental observation.
- Big boost for recent searches for Dark Matter in many sectors in last years.
- Introduction of “hidden” sector of particles and new very weak interaction with SM fermions can explain anomalies in the muon magnetic moment, results from scattering experiments searches for Dark Matter and antimatter excess in cosmic rays.
- Recently revived idea: new particles not directly connected with SM gauge fields, but only via mediator fields or “portals” connecting our world with new “secluded” or “hidden” sectors.
- Simplest scenario: additional U(1) gauge symmetry (like electromagnetism) but with massive interaction carrier: dark photon $A'$.

At the end of 2015 INFN approved a new experiment at the DAφNE BTF Linac in Frascati Laboratories: PADME (Positron Annihilation into Dark Matter Experiment) searching for invisible decays of the $A'$ produced by positrons in fixed target annihilations ($e^+e^- \rightarrow \gamma A'$) decaying to dark matter particles by measuring the final state missing mass.

PADME experiment has been financed in “What Next” program for 1.35 M€ in 2016-2018. It will be built before the end of 2017 and foreseen to take data starting in 2018.
The simplest hidden sector model just introduces one extra U(1) gauge symmetry and a corresponding gauge boson: the “dark photon” or U boson or $A'$

- Two type of interactions with SM particles should be considered:
  - As in QED, this will generate new interactions of the type:
    \[ \mathcal{L} \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu \]
  - Not all the SM particles need to be charged under this new symmetry
  - In the most general case $q_f$ can be different between leptons and quarks and can even be 0 for quarks. [P. Fayet, Phys. Lett. B 675, 267 (2009), arXiv:1408.4256]

- The coupling constant and the charges can be generated effectively through the kinetic mixing between the QED and the new U(1) gauge bosons
  \[ \mathcal{L}_{mix} = -\frac{\epsilon}{2} F_{\mu\nu}^{QED} F_{\mu\nu}^{dark} \]
  - In this case $q_f$ is just proportional to electric charge and is equal for both quarks and leptons.
Actual status
visible and invisible decays

The \((g-2)_{\mu}\) favourite band practically all excluded, in the hypotesis that the dark photon \(A'\) decays in \(e^+e^-\).

Still large parameter space to explore \(m_{A'} < 1\) GeV.

Anyhow it would be important a dedicated experiment to search for a dark photon \(A'\) in the region \(m_{A'} < 100\) MeV.

The parameter space excluded admitting the dark photon \(A'\) can decay in “dark sector” particles \(\chi\) \((M_{\chi} < M_{A'}/2)\) is very reduced.
A’ production and decays

- A’ boson can be produced in $e^+$ collision on target by:
  1. Bremsstrahlung: $e^+N \rightarrow e^+N A'$
  2. Annihilation: $e^+e^- \rightarrow \gamma A'$
  3. Meson decays

- If no dark matter candidate lighter than the A’ boson exists:
  - $A' \rightarrow e^+e^-, \mu^+\mu^-, h^+h^- \quad \text{“visible” decays}$
  - For $M_{A'} < 210$ MeV $A'$ decays only to $e^+e^-$ with BR(e+e-)=1

- If any dark matter particle $\chi$ with $2M_\chi < M_{A'}$ exists:
  - $A'$ will dominantly decay into pure DM
  - BR(l+l-) would be suppressed by $\varepsilon^2 (\approx 1\text{e-6})$
  - $A' \rightarrow \chi\chi \sim 1 \quad \text{so-called “invisible” decays}$
**PADME experiment**

PADME proposes a new technique: the **annihilation** of a positron beam on the electrons of a (thin) target, searching for a peak at $M_{\text{miss}}^2 \neq 0$ in the final missing mass, calculated from the final state $\gamma$ 4-momentum. This search is totally independent from the **dark photon** decay modes. Naturally, it's also possible to search for the “visible” decays of the dark photon $A'$ in lepton pairs.

In case of the observation of an excess, PADME may give mass and coupling of the new particle, defining the model and allowing an easy verification of the obtained result.

Participants: INFN Lecce, LNF, Padova, Roma1 + University of Salento + University of Roma “La Sapienza” + Sofia University

ATOMKI Debrecen joining
• At present all experimental results rely on at least one of the following model-dependent assumptions:
  – $A'$ decays to $e^+e^-$ (visible decays assumption) and thus $\text{BR}(A' \rightarrow e^+e^-) = 1$
  – $A'$ couples with the same strength to all fermions ($\varepsilon_q = \varepsilon_l$) (kinetic mixing)

• In the most general scenario:
  – $A'$ can decay to dark sector particles $\chi$ with $m_\chi < M_{A'}/2 \Rightarrow \text{BR}(A' \rightarrow e^+e^-) << 1$  
    Dump and meson decay experiment results suppressed by $\varepsilon^2$
  – $A'$ can couple to quark with a coupling constant smaller $\varepsilon_l$ or even 0
    Suppressed or no production at hadronic machines and in mesons decays

• **PADME** aims at detecting $A'$ produced in $e^+e^-$ annihilation and decaying into any final state by searching for missing mass in $e^+e^- \rightarrow \gamma A'$, $A' \rightarrow \chi\chi$ and $A' \rightarrow l^+l^-$ processes
  – No assumption on the $A'$ decays products and coupling to quarks
  – Only minimal assumption: $A'$ couples to leptons
  – PADME will limit the coupling of any new light particle produced in $e^+e^-$ collisions: scalars ($h'$), vectors ($A'$ and $Z'_d$), ALPs pseudoscalars
**LNF Beam Test Facility (BTF)**

<table>
<thead>
<tr>
<th>LNF Linac</th>
<th>electrons</th>
<th>positrons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximal beam energy ($E_{beam}$) [MeV]</td>
<td>800 MeV</td>
<td>550 MeV</td>
</tr>
<tr>
<td>Linac energy spread [Δp/p]</td>
<td>0.5%</td>
<td>1%</td>
</tr>
<tr>
<td>Typical charge [nC]</td>
<td>2 nC</td>
<td>0.85 nC</td>
</tr>
<tr>
<td>Bunch length [ns]</td>
<td>1.5 – 40 (planned to arrive up to 200 ns)</td>
<td></td>
</tr>
<tr>
<td>Number of bunches</td>
<td>1-50 Hz</td>
<td>1-50 Hz</td>
</tr>
<tr>
<td>Emittance [mm mrad]</td>
<td>1</td>
<td>~1.5</td>
</tr>
<tr>
<td>Beam dimension σ [mm]</td>
<td>&lt;1 mm</td>
<td></td>
</tr>
<tr>
<td>Beam divergence</td>
<td>1-1.5 mrad</td>
<td></td>
</tr>
</tbody>
</table>

- Can produce both electrons and positrons
- Duty cycle 50 Hz x 40 ns = 2x10⁻⁶ s
- Tests of 200 ns BL foreseen in 2016 - ideas to get up to 480 ns
- Request submitted at LNF MAC to get ~1 GeV beam
- May run in dedicated mode or parasitic with DAΦNE
  - With DAΦNE: $E_{e^+} = 510$ MeV, Bunch Length = 10 ns
  - Dedicated: $E_{e^+}$ up to ~600 MeV, Bunch Length > 40ns

**BTF line doubling fundamental project for compatibility of a long PADME run with test-beam activities**
The detector

Beam: $10^3-5 \times 10^4$ e$^+$ on target per bunch, at 50 bunch/s ($10^{13}-10^{14}$ e$^+$/year)

Dipole MBP-S (transfer line SPS)
Large gap, $\sim 1$ m length – $B \approx 0.6$ T

Active target
50-100 $\mu$m thick segmented diamond X.Y graphited strips

Small Angle Calo
$BaF_2$ or fast crystals $2 \times 2 \times 20$ cm$^3$
140x140 mm$^2$

EM Calorimeter
BGO Crystals $2 \times 2 \times 22$ cm$^3$
$R \approx 30$ cm

Electron-positron veto
1 m, scintillators 1 cm, SiPM readout
Inside magnet and vacuum pipe

Hep veto
60 cm, scintillators 1 cm, SiPM readout
Out of vacuum pipe

Compute the $M_{\text{miss}}^2 = (P_{e^-}^4 + P_{\text{beam}}^4 - P_\gamma^4)^2$
$P_{e^-}^4 = (0,0,0,m_e)$ and $P_{\text{beam}}^4 = (0,0,550,\sqrt{(550^2 + m_e^2)})$
Material: **BGO** - high LY, high $\rho$, small $X_0$ and $R_m$, long $\tau_{\text{decay}}$ (free from L3 calorimeter)

Cylinder: $R \sim 295$ mm, depth $220$ mm ($19.6 \times X_0$)

- Inner hole $\sim 100 \times 100$ mm$^2$ wide square
- 620 crystals each $20 \times 20 \times 220$ mm$^3$

Expected Performances:

- $\sigma(E)/E = 1.1\%/\sqrt{E} \oplus 0.4\%/E \oplus 1.2\%$ (superB calo tests@BTF - NIM A 718 (2013) 107–109)
- $\sigma(\theta) \sim 1-2$ mrad
- Angular acceptance: $(20 \div 82)$ mrad
- Timing: better than 0.7 ns (from signal shape fit)

**Full digitization of signals over $\sim 1$ $\mu$s with CAEN V1742 digitizers @ 1GS/s**
Invisible decay signal selection

Selection cuts

- Only 1 cluster in EM calo ($20 \text{ mrad} < \theta_{\text{Cl}} < 82 \text{ mrad}$)
  - Rejects $e^+e^-\rightarrow\gamma\gamma$, $e^+e^-\rightarrow\gamma(\gamma)$ final states
- $10 \text{ cm} < R_{\text{Cl}} < 26 \text{ cm}$
  - Improve shower containment and $\sigma(E)/E$
- Positron veto: no tracks in the positron vetos in $\pm2$ ns
  - Reject BG from Bremsstrahlung identifying primary positrons
- Photon veto: no $\gamma$ with $E_\gamma > 50 \text{ MeV}$ in time
  in $\pm2$ ns in the small angle calo (SAC)
  - Reject BG from Bremsstrahlung
- Cluster energy within
  $E_{\text{min}}(M_{A'}) < E_{\text{Cl}} < E_{\text{max}}(M_{A'}) \text{ MeV}$
  - Removes low energy bremsstrahlung photons and piled up clusters
- Missing mass in the region $M_{\text{miss}}^2 \pm \sigma(M_{\text{miss}}^2)$

Candidate event in PADME: 1 “good” $\gamma$
in EM Calo + NO positrons in time in vetoes + NO $\gamma$ in time in SAC
Main backgrounds

Pile-up may be controlled by cuts in $E_{cl}$ and $M^2_{miss}$

Geant4 simulation accounts for:
- Bremsstrahlung, 2 photon annihilation, Ionization processes, Bhabha and Moller scattering, and production of $\delta$-rays.
- Custom treatment of $e^+e^- \rightarrow \gamma\gamma(\gamma)$ using CalcHep generator.

New sensitivity estimates calculations under way.

Bremmstr.
PADME may explore in a model-independent way the favorite region for $(g-2)_\mu$ up to $M^2_{A'} = 2m_eE_{e^+}$

- $2.5 \times 10^{10}$ $e^+$ 550 MeV $e^+$ on target simulated with GEANT4
  #background events extrapolated at $1 \times 10^{13}$ $e^+$ on target
- Assuming $N(A'\gamma) = \sigma(N_{BG})$
- $\delta$ increase of cross section $\delta(M_{A'}) = \sigma(A'\gamma)/\sigma(\gamma\gamma)$ with $\varepsilon=1$ due to $A'$ mass

$$\frac{\Gamma(e^+e^- \rightarrow A'\gamma)}{\Gamma(e^+e^- \rightarrow \gamma\gamma)} = \frac{N(A'\gamma)}{N(\gamma)} \frac{Acc(\gamma\gamma)}{Acc(A'\gamma)} = \varepsilon \times \delta$$

**PADME** 2 years data taking with 50% efficiency and bunch length 40 ns

$10^{13}$ POT = $6000$ $e^+/bunch \times 3.1 \times 10^7$s $\times$ 49 Hz

- $E_{e^+} = 550$ MeV $M_{A'} < 23.7$ MeV/c$^2$
- $E_{e^+} = 750$ MeV $M_{A'} < 27.7$ MeV/c$^2$
- $E_{e^+} = 1$ GeV $M_{A'} < 32$ MeV/c$^2$
PADME can search for invisible decaying or long living ALP by searching for $1\gamma + M_{\text{miss}}^2$ final states.

In the visible final state $a \rightarrow \gamma \gamma$ all production mechanisms can be explored extending the mass range in the region of $\sim 100\text{MeV}$. The observables at PADME will be: $e\gamma\gamma$ or $\gamma\gamma\gamma$.
Up to now we are quite in time with this schedule.
Conclusions

➢ PADME experiment has been approved by INFN in 2015 in the “What Next” program with 1.35 M€ in 2016-2018
➢ We are starting the construction phase and making beam tests at LNF BTF for the main detector components
➢ The schedule foresees to build within end of 2017 and start taking data on the new dedicated BTF line at LNF in 2018
➢ More interesting physics channels have been identified (ALPs) and more are still to be discovered

PADME experiment promises to fulfill the design expectations and to deliver interesting data from 2018

A very exciting time awaits us all!
You are welcome to join the dark side!