New projects on dark photon search

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Overview

- Motivation
- Dark photon basics
- Searches in detectable final states
- Looking for the invisible
- Conclusions
Motivation: New Physics

- **Standard Model is complete: 2012 LHC - Higgs boson**
- Unknowns:
  - Matter-antimatter asymmetry
  - Dark matter
  - Dark Energy
- The Standard Model is a low energy approximation of a more fundamental theory.

*But which theory?*

- Despite the highest energy reach LHC did not provide any convincing evidence for new degrees of freedom … *yet?*

*Where to look? How to proceed?*

Most of those discrepancies originate from **Astrophysics and/or Cosmology**!
The smoking guns

Relatively calm and stable picture of the world

Recognize the dynamics only by looking at particular spots.
Direct search experiment

- DAMA/LIBRA results unexplained: $9.2 \sigma$
- Possible indication by other CoGeNT
- Is it possible to build a consistent picture?
- If the explanation is Dark Matter, it could be relative light: $\sim 10$ GeV
- Interaction with the nuclei through a mediator. Mass in the MeV range is OK
Astrophysics ...

- Positron excess: PAMELA, FERMI, AMS02
- Antiproton excess: AMS02

... and astronomy

Observation of 3.5keV line?

Possible interpretation: arXiv:1404.2220
About 3 \( \sigma \) discrepancy between theory and experiment (3.6 \( \sigma \), if taking into account only \( e^+e^- \rightarrow \) hadrons)

\[
d_{\mu}^{\text{dark photon}} = \frac{\alpha}{2\pi} \varepsilon^2 F(m_V/m_\mu),
\]

where \( F(x) = \int_0^1 2z(1-z)^2/[(1-z)^2 + x^2 z] \, dz \). For values of \( \varepsilon \sim 1-2 \cdot 10^{-3} \) and \( m_V \sim 10-100\) MeV, the dark photon, which was originally motivated by cosmology, can provide a viable solution to the muon \( g-2 \) discrepancy. Searches for the dark
Anomalies in nuclear transitions

- Anomalous angular and invariant mass distributions in the IPC process
- Several indications in the last few decades
- New experiment at ATOMKI
- E-ΔE plastic scintillator detector, in the plane transversal to the beam
- The anomaly observed at ~17 MeV – cannot be interpreted within nuclear physics so far...
New gauge bosons

- The effective interaction that can be studied is
  \[ \mathcal{L} \sim g'q' \bar{\Psi} (\gamma_\mu + \alpha'_a \gamma_\mu \gamma^5) \Psi A'^\mu , \text{ usually } \alpha'_a = 0 \]
  - \( q_f \to 0 \) for some flavours

- Such textbook scenario could address the \((g_\mu - 2)\) discrepancy, abundance of antimatter in cosmic rays, signals for DM scattering
  - General \( U'(1) \) and kinetic mixing with \( B \) (\( A' \), \( Z' \))
    - Universal coupling proportional to the \( q_{em} \)
      - Just single additional parameter – \( \varepsilon \)
    - Leptophilic/leptophobic dark photon

- Other messenger types possible (neutrino, higgs, ALP, see T. Spadaro talk)
- Rich dark sector?
Dark photon phenomenology

- Production mechanisms
  - Meson decays
  - Bremsstrahlung
  - Annihilation

- Decays
  - To SM model particles if nothing in the DS lighter than A'
  - $A' \rightarrow \gamma\gamma$, if $M(A') < 2m_\gamma$, small width, $A'$ quasi stable
  - To DS particles with $\text{Br}(A' \rightarrow \chi\chi) = 1$, 

Dark matter annihilation
The physics case attracted a large attention recently
Visible DP searches in BoT

- Beam dump experiments: $A'$-strahlung production
- Fixed target: peaks in the $e^+e^-$ invariant mass spectrum
- Meson decays: Peaks in $M_{e^+e^-}$ or $M_{\mu^+\mu^-}$

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**Invisible A' searches**

- Really model independent addressing of the dark gauge boson parameters is difficult
- Four parameter space to be studied: $M_{A'}$, $g'$, $g_D$, $M_\chi$
  - $g'$ could also be flavour dependent
Visible dark photons

A' production vertex

target or particle decay

- HPS
- MESA

Spectrometers looking for A':
  - produced in a thin target
  - decaying to leptons
HPS experiment

- Electron beam (2.2 and 6.6 GeV, up to 500 nA) on a thin tungsten target (0.25% $X_0$)
- A'-strahlung production
- Decay channel – $A' \rightarrow e^+e^-$
- Silicon vertex tracker (1 m long) inside dipole magnet, 6 layers (dual sensor)
  - Particle momenta, Vertices
  - 6.4 $\mu$m hit resolution, $\sigma(t) = 2.5$ ns
- Lead tungstate electromagnetic calorimeter

Fast energy measurement
Trigger definition
**HPS sensitivity**

Timothy Nelson, Dark Sectors Workshop, 28-30 Apr., SLAC

**Prompt decay**
- bump hunt
- ... background

**Displaced vertex**
- lower background
- ... lower yield

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Dark photon @ Mainz

- Tradition in dark photon physics - A1 @ MAMI
- New accelerator: MESA (Mainz Energy-recovering Superconducting Accelerator)
  - Energy up to 155 MeV
  - Current > 1 mA

Planned commissioning: 2020

Part of PRISMA cluster of excellence
The MAinz Gas Internal EXperiment

- Double arm high resolution spectrometers
  - Aim for $\Delta p/p \sim 10^{-4}$
  - Acceptance +/- 50 mrad

- Gas jet target
  - Supersonic gas /cluster jet
  - High gas density ($10^{19}$/cm$^2$)
  - O(mm) target length
  - Windowless
  - Ready in 2016
MAGIX @ MESA

- Two position detectors
  - Focal plane
  - Direction measurement
- GEM detectors considered
  - 0.7% X0
  - High rate capability
  - 2D strip readout
    - Should aim for 50μm coordinate resolution

Xe gas target
6 months data taking
preliminary
Visible dark photons status

• HPS
  – 2015 – engineering run @1.06 GeV
    • Results in the next few months
  – 2016 – physics data quality @ 2.3 GeV
    • Results expected in ~1 year
• MAGIX
  – Accelerator commissioning – 2020
• Address short and medium living DP
• Many other proposals and techniques are being tested
  – See T. Spadaro talk
Invisible dark photons

• Addressing the missing mass
  – PADME@Frascati, VEPP3@Novosibirsk, MMAPS@Cornell
  – Positron beam on a thin target
  – Annihilation production of dark photons

• Missing energy
  – NA64: leakage of energy to the dark sector in high energy shower development

• Dark matter scattering
  – BDX
**Missing mass technique**

- Positron beam on a thin target
- Positron momentum is determined by the accelerator characteristics
- Missing mass resolution: annihilation point, $E_\gamma$, $\phi_\gamma$

$$M_{\text{miss}}^2 = (p_{\text{pos}} + p_{\text{elec}} - p_\gamma)^2$$

Cross section enhancement with the approach of the production threshold
**Measurement strategy**

- **Background suppression**

<table>
<thead>
<tr>
<th>Background process</th>
<th>Cross section e@550 MeV beam</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>e+e- → γγ</td>
<td>1.55 mb</td>
<td></td>
</tr>
<tr>
<td>e^+ + N → e^+ N γ</td>
<td>4000 mb</td>
<td>E_γ &gt; 1MeV, C</td>
</tr>
<tr>
<td>e^+e^- → γγγ</td>
<td>0.16 mb</td>
<td>CalcHEP, E_γ &gt; 1MeV</td>
</tr>
<tr>
<td>e^+e^- → e^+e^-γ</td>
<td>180 mb</td>
<td>CalcHEP, E_γ &gt; 1MeV</td>
</tr>
</tbody>
</table>

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Measurement strategy

- Background suppression

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**PADME experiment**

**Positron Annihilation into Dark Matter Experiment**

- Small scale fixed target experiment
- Measuring both charged and neutral particles:
  - Charged particles detector
  - Calorimeter
  - Beam profile
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Parasitic mode</th>
<th>Dedicated mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With target</td>
<td>Without target</td>
</tr>
<tr>
<td><strong>Particle species</strong></td>
<td>e⁺ or e⁻</td>
<td>e⁺ or e⁻</td>
</tr>
<tr>
<td></td>
<td>Selectable by user</td>
<td>Depending on DAFNE mode</td>
</tr>
<tr>
<td><strong>Energy (MeV)</strong></td>
<td>25–500</td>
<td>510</td>
</tr>
<tr>
<td></td>
<td>Depending on DAFNE mode</td>
<td>25–700 (e⁻/e⁺)</td>
</tr>
<tr>
<td><strong>Energy spread</strong></td>
<td>1% at 500 MeV</td>
<td>0.5%</td>
</tr>
<tr>
<td><strong>Rep. rate (Hz)</strong></td>
<td>Variable between 10 and 49</td>
<td>1–49</td>
</tr>
<tr>
<td></td>
<td>Depending on DAFNE mode</td>
<td>1–49</td>
</tr>
<tr>
<td><strong>Pulse duration (ns)</strong></td>
<td>10</td>
<td>1.5–40</td>
</tr>
<tr>
<td><strong>Intensity (particles/bunch)</strong></td>
<td>1–10⁻⁵ Depending on the energy</td>
<td>10⁻⁷–1.5 10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>10⁻⁷–1.5 10⁻⁴</td>
<td>10⁻⁷–1.5 10⁻⁴</td>
</tr>
<tr>
<td><strong>Max. average flux</strong></td>
<td>3.125 10⁻⁷ particles/s</td>
<td></td>
</tr>
<tr>
<td><strong>Spot size (mm)</strong></td>
<td>0.5–25 (y) × 0.6–55 (x)</td>
<td></td>
</tr>
<tr>
<td><strong>Divergence (mrad)</strong></td>
<td>1–1.5</td>
<td></td>
</tr>
</tbody>
</table>
Diamond target

300 μm, graphitized strips
3mm long, 100 μm width

Polycrystalline diamonds

- 100 mm thickness:
- 16x1mm² strip and X-Y readout in a single detector
- Readout strips are graphitized by using a laser to avoid metallization
- PADME prototype 20×20mm² produced and tested in October 2015
• BGO crystals available from L3 experiment
• Crystal geometry is close to 2 x 2 cm front face
  – Cut the crystals in 1 x 1 cm and place them at 2 m
    • Requires cutting of the existing crystals, but the quantity is identified and available
  – Place the calorimeter at 3 m distance and keep the dimensions 2x2 cm
    • Agreement on the usage of extra crystals
Charged particle detector
- Plastic scintillator detector
- SiPM based readout

- CERN spare magnet: MBP-S
- Refurbished from CERN and transported to LNF
- Usage of the DAΦNE PS: 400A
Sensitivity estimation

• Assumptions:
  – 40 ns bunch length
  – 49 Hz repetition
  – 6000 e⁺/bunch

• Accessible regions:
  – E=550MeV: \( M_{A'} < 23.7 \) MeV

• Improvements possible
  – Increase beam energy
  – Extend the bunch length
MMAPS

- Approach similar to PADME: **Missing Mass A-Prime Search**
  - $E_{\text{beam}} = 1.8 - 5.3$ GeV, $I_{\text{beam}} \sim 2.3$ nA at target,
  - ~millisecond spills @ 60Hz
  - pulse structure: 168ns
MMAPS design and sensitivity

- Charged particle vetoes in front of the calorimeter
- CsI(Tl) crystal calorimeter (from CLEO), PMTs instead of photodiodes (time properties)
- Issues with overlap @ maximal luminosity: good double pulse separation necessary

Extend the accessible region up to $M_{A'} = 74$ MeV
• 500 MeV storage ring @ Novosibirsk

Proposed to construct a ByPass, allowing to utilize available space for a crystal calorimeter and shielding

Operating in parallel with the ongoing VEPP-3 activities
• CLEO CsI crystals
  – 624 crystals are assembled in a “ring”
  – placed at a distance of 8 m from the target

• CLEO measurements with 180 MeV positrons:
  – energy resolution $\sigma_E = 3.8\%$
  – spatial resolution $\sigma_x = 12$ mm $\Rightarrow$ angular resolution: $\sigma_\theta = 0.09^\circ$

• Possible operation in 3-4 years with the by-pass beam line
### Missing mass searches status

<table>
<thead>
<tr>
<th></th>
<th>PADME</th>
<th>MMAPS</th>
<th>VEPP3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Place</strong></td>
<td>LNF</td>
<td>Cornell</td>
<td>Novosibirsk</td>
</tr>
<tr>
<td><strong>Beam energy</strong></td>
<td>550 MeV</td>
<td>Up to 5.3 GeV</td>
<td>500 MeV</td>
</tr>
<tr>
<td><strong>$M_{A'}$ limit</strong></td>
<td>23 MeV</td>
<td>74 MeV</td>
<td>22 MeV</td>
</tr>
<tr>
<td><strong>Target thickness</strong></td>
<td>$2 \times 10^{22}$ e⁻/cm²</td>
<td>$O(2 \times 10^{23})$ e⁻/cm²</td>
<td>$5 \times 10^{15}$ e⁻/cm²</td>
</tr>
<tr>
<td><strong>Beam intensity</strong></td>
<td>$8 \times 10^{-11}$ mA</td>
<td>$2.3 \times 10^{-6}$ mA</td>
<td>30 mA</td>
</tr>
<tr>
<td><strong>$e^+e^- \rightarrow \gamma \gamma$ rate [s⁻¹]</strong></td>
<td>15</td>
<td>$2.2 \times 10^6$</td>
<td>$1.5 \times 10^6$</td>
</tr>
<tr>
<td><strong>$\varepsilon^2$ limit (plateau)</strong></td>
<td>$10^{-6} \text{ (10}^{-7}$ SES)$</td>
<td>$10^{-6} - 10^{-7}$</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td><strong>Time scale</strong></td>
<td>2017 - 2018</td>
<td>?</td>
<td>2020 (ByPass)</td>
</tr>
<tr>
<td><strong>Status</strong></td>
<td>Approved</td>
<td>Not funded by NSF</td>
<td>Proposal</td>
</tr>
</tbody>
</table>
Missing energy technique: NA64

- Location: SPS (CERN)
- Tagged electrons
  - clean mono-energetic electron beam of 100 GeV
  - Micromegas tracker and BGO calorimeter (synchrotron)
- Signature:
  - 100 GeV $e^-$ track.
  - < 50 GeV EM shower in ECAL
  - no energy in Veto + HCAL

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NA64 experiment

- Interesting technique
- In case of unexpected background and/or signal – not possible to disentangle
  - Can we describe particle showers in matter at $10^{-9}$ level?
    - NA64 Could test our understanding of the shower simulation
  - complementarity with the missing mass strategy
- Approved as an experiment at SPS in 2016
  - 2 + 4 weeks of data taking (tests, commissioning) in 2016, operation in 2017
**DM scattering: BDX**

**Beam Dump eXperiment**

- **χ production**
  - High-energy, high-intensity $e^-$ beam impinging on a dump
  - $\chi$ particles pair-produced radiatively, through $A'$

- **χ detection**
  - Detector placed behind the dump, $O(10m)$
  - $\chi$ scattering trough $A'$
  - Different signals depending on the interaction ($e^-$-elastic, $p$ quasi-elastic,..)

**Number of events:**

$$\frac{\alpha_D \epsilon^4}{M_A^4}$$

- Lol submitted to JLab PAC (2014) - positive feedback
- Preparation of a full Proposal ongoing
- Interesting opportunities for a phase-1 run @ other facilities
DM scattering: BDX

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Invisible perspective

- Construction of PADME
  - Aim for first tests in 2017
  - 2018: first results
- Long term
  - Improvements possible
  - VEPP3 setup
  - Increase of beam energy
    - Synergy between the labs

PADME 40 ns bunch
PADME 160 ns bunch
PADME 480 ns bunch

PADME 40 ns bunch
Conclusions

• Increased interest recently

• Many activities undergoing and many new projects are on the scene

• Covering multi-probes for Dark Photon
  – Visible in bremsstrahlung
  – Visible in meson decays
  – Invisible: missing mass, missing energy, DM scattering

• Interesting results expected before 2020

• Stay tuned