PADME project at DAFNE BTF

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Outline

- Motivation
- Present status
- PADME experiment
- Expected sensitivity
- Dark photon searches at BTF
- Conclusion
Motivation: New Physics

- Standard Model is complete: 2012 LHC - Higgs boson
- Unknowns:
  - Matter-antimatter asymmetry
  - Dark matter
  - Dark Energy
- Still some places of discrepancies between theory and experiment
- The Standard Model is a low energy approximation of a more fundamental theory.
  
  But which theory?
Direct search experiment

• DAMA/LIBRA results unexplained: 9.2 \sigma
• Used to be alone, now few other indications emerged
• Seem to be possible to build a consistent picture
• If the explanation is Dark Matter, it should be relative light: \sim 10 \text{ GeV}
• Interaction with the nuclei through a mediator. Mass in the MeV range is OK
Astrophysics ...

- Positron excess: PAMELA, FERMI, AMS02
- No significant excess in antiprotons: pure secondary production

... and astronomy

Observation of 3.5keV line?
- arXiv:1402.2301
- arXiv:1402.4119
Possible interpretation: arXiv:1404.2220
If Dark Matter is the explanation to the positron excess, then the mediator should be light (\(<2 \times M_{\text{proton}}\))

- Coupling constant to DM could be arbitrary (even $O(1)$)
- The Lagrangian term can arise through
  - fermions being charged (mili) under this new gauge symmetry ($q_f \rightarrow 0$ for some flavours)
  - Kinetic mixing between ordinary photon and DM one: $\mathcal{L}_{\text{mix}} = -\frac{\varepsilon}{2} F_{\mu\nu}^{\text{QED}} F_{\mu\nu}^{\text{dark}}$
  - Using simply an effective description: $g' \cdot q'_e = \varepsilon$, $\alpha' = \alpha \times \varepsilon^2$
• About 3 $\sigma$ discrepancy between theory and experiment (3.6 $\sigma$, if taking into account only $e^+e^- \rightarrow$ hadrons)

$$a^\text{dark photon}_\mu = \frac{\alpha}{2\pi} \varepsilon^2 F(m_V/m_\mu),$$  \hspace{1cm} (17)$$

where $F(x) = \int_0^1 2z(1-z)^2/[(1-z)^2 + x^2z] \, dz$. 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
The most attractive explanation of the phenomena is the simplest one – with a single object

If this is the U-boson, it should be sufficiently light – 10-100MeV

Searches

- Beam dump experiments
  - \( A' \)-strahlung production
  - Every observed event is signal
- Fixed target
  - Peaks in the \( e^+e^- \) invariant mass spectrum
- Meson decays
  - Peaks in \( M_{e^+e^-} \) or \( M_{\mu^+\mu^-} \)
Present limits: invisible searches

- There is no published direct present limit in the $U \rightarrow \text{invisible decay}$. From $a = \frac{g^{-2}}{2}$
- The discrepancy is not in $g_{\mu}^{-2}$ itself, it's in the consistency of $g_{e}$ & $g_{\mu}$
- Alternative inputs should be used to extract information from $g_{e}$: $\alpha_{\text{EM}}$

\[
\delta a = \frac{\alpha_{\text{EM}} e^2}{2 \pi} \cdot f, \quad f = \begin{cases} 1, & \text{for } m_{l} \gg M_{U} \\ \frac{2m_{l}^2}{3M_{U}^2}, & \text{for } m_{l} \ll M_{U} \end{cases}
\]

Anomalous magnetic moment limits
- $\alpha_{\text{EM}}$ usually a determined from $g_{e} - 2$ - input
- Used further to constrain $g_{\mu} - 2$
- Dark photon contribution:

\[
|a_{e}^{\text{th}} - a_{e}^{\exp}| = (1.06 \pm 0.82) \times 10^{-12}
\]

The invisible search removes any assumption apart from coupling to leptons!


Present status

JLAB:
APEX
DarkLight
HPS

MAMI & MESA:
A1

COSY:
WASA

GSI:
HADES

VEPP3

PEPII:
BaBar

JLAB:
APEX
DarkLight
HPS

CERN SPS
spsc-p348
SHIP

DAΦNE
KLOE2,
PADME

Status: ongoing, planned, proposals
How to improve?

• Searching a U-boson in a kinematically constraint event and using full reconstruction

• Basic process: positron on a fixed target

  \[ e^+ + e^- \rightarrow \gamma + U \left\{ \begin{array}{l} \gamma + E_{\text{miss}} \quad \text{(invisible channel, U} \rightarrow \chi\chi) \\ \gamma + e^+e^- \quad \text{(visible channel, U} \rightarrow e^+e^-) \end{array} \right. \]

• Normalizing to the concurrent process - annihilation

  \[ \frac{\sigma(e^+ e^- \rightarrow \gamma U)}{\sigma(e^+ e^- \rightarrow \gamma \gamma)} = \frac{N(\gamma U)}{N(\gamma \gamma)} \times \frac{\text{Acc}(\gamma \gamma)}{\text{Acc}(\gamma U)} = \varepsilon^2 \times \delta \]

  - \(N(\gamma U), N(\gamma \gamma)\) - number of registered events
  - \(\text{Acc}(\gamma U), \text{Acc}(\gamma \gamma)\) - detection efficiency
  - \(\delta = \sigma(e^+ e^- \rightarrow \gamma U)/\sigma(e^+ e^- \rightarrow \gamma \gamma)\) at \(\varepsilon=1\) – cross section enhancement factor

Is it possible such a search to be conducted at BTF?
PADME experiment

Positron Annihilation into Dark Matter Experiment

- Small scale fixed target experiment
- Measuring both charged and neutral particles:
  - Spectrometer
  - Calorimeter
  - Beam profile
Variable beam energy
  - from \( \sim 250 \text{ MeV} \) to \( E_{\text{MAX}} \)

Variable beam intensity

Possibility for single particle beam
  - However we need statistics...

Both positron and electron beams

Small beam energy spread

Available immediately

The accessible region is limited by the maximal beam energy
  - Around 23 MeV for 550 MeV \( e^+ \) beam
Basic ideas

- Electron is at rest
- Positron momentum is determined by the accelerator characteristics – 1% resolution
- Basic contribution to the missing mass resolution – reconstruction of the photon 4-momentum
  - Interaction point inside the target – beam transverse size is small, but the time stability is not sufficient
  - Cluster position in the calorimeter
  - Energy resolution of the calorimeter

\[ M_{\text{miss}}^2 = (p_{\text{pos}} + p_{\text{elec}} - p_{\gamma})^2 \]
Event reconstruction

- Clear 2 body correlation
- Dominant process in e+/e- interactions with matter is bremsstrahlung
  - Best possible resolution on energy/angle measurement
  - Photon vetoing
  - Minimize the interaction remnants + vetoing

Closer to the real world
+ bremsstrahlung photons
+ miss-reconstruction

in ideal world
Target

- 10 diamond strips of 2 mm x 50 mm with 25um thickness
- Time resolution: below 1ns
- Sensitivity: from few to $10^9$ particles
- QDC readout and bunch-by-bunch beam spot determination
Magnetic spectrometer

- 0.6 T magnetic field, conventional dipole magnet
- Gaseous detector with 1m length, 20cm radius (10cm from the beam direction)
  - 5 layer of triple GEMs
  - Planar or cylindrical
  - Position and momentum measurements of the charged tracks (vetoing)
  - Track time resolution: ~1ns
- Readout based on custom ASIC (possibly GASTONE?)
**Calorimeter**

- Cylindrical shape, Rin = 4cm, Rout = 15cm
- 656 LYSO crystals, 1 cm x 1cm x 15-20 cm
- Energy resolution:
  \[ \sigma_E/E = \frac{1.1\%}{\sqrt{E}} \oplus \frac{0.4\%}{E} \oplus 1.2\% \]
- Angular acceptance: 1.5 – 5 degrees
  - resolution < 2mrad
- Digitizer readout
Expected sensitivity

Preliminary GEANT4 based simulation to assess the possible reach

- Rough selection based on **missing mass** cut, **veto** on extra clusters and positrons
  - 1 year of continuous running
  - 60% efficiency (data taking)
  - 50 bursts/s
  - \(10^4\) positrons/burst

- Considering the statistical uncertainty of the expected background to set the limits
Dark photon prospects at BTF

conventional electron beam and U-strahlung: $e^- Z \rightarrow e^- Z U$

**U → e^+e^- visible decay search**

- Measuring $e^+e^-$ momentum with the spectrometer
- Selection based on $M_{e^+e^-}$

- $10^7 e^-$/bunch, 50 bunch/s, 1 year
- $E_{e^-} = 750$ MeV

*Extend $M_u$ sensitivity, but model dependent*
Conclusions

- BTF machine provides unique opportunity to study possible dark photon production in annihilation channel
- Small fixed target experiment to search for dark photons in the invisible channel proposed.
- Interesting parameter space could be covered, using $10^3 - 10^5$ e$^+$/bunch.
- Preliminary studies have been initiated as a sidework activity
- Short time scale of the project
- PADME could turn BTF from a test beam facility into a fundamental physics machine
- PADME would profit from both energy and duty cycle upgrades of the BTF
Possible improvements

• Duty cycle upgrade:
  – Present: 50Hz * 10ns = 0.5*10^{-6}
  – At 10 ns all the particles in the bunch are treated as belonging to the same event
  – At 40ns (100 ns) time resolution of LYSO & Spectrometer improves the veto
  – Improvement on the repetition of equal profit!

• Energy upgrade
  – Extend the access to $M_U \sim 27$ MeV
  – Improve the results in the range 20 – 23 MeV

• Bremsstrahlung production and visible/dump detection
  – Extend the mass region
  – Extend the $\varepsilon^2$ region to lower values due to higher U-boson boost

• Beam related background (i.e. accompanying spurious particles)
  – Difficult to access in the simulation, desired to be as minimal as possible