Searching for light dark matter at accelerators

Mauro Raggi, Sapienza Università di Roma e INFN Roma

Menu 2019 Workshop
1-7 June 2019 Carnegie Mellon University
The dark matter problem

Galaxies rotation curves

Strong lensing

Many solutions and open questions. Is dark matter made of new particles?

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Is the dark matter a known particle?

Dark matter has a mass.

Dark matter has gravitational interaction.

Dark matter interacts weakly with SM particles.

Dark matter contains one or more stable particles.

Is any particle we know a good dark matter candidate?
Is the dark matter a known particle?

--- strong

--- electromagn.

--- unstable

they move too fast

(hot dark matter)

to form the

observed large

scale structure

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Dark sectors a possible solution

- Standard model only includes <20% of the matter in the universe
  - We only know dark matter interacts gravitationally

- Many open questions
  - What is dark Matter made of?
  - How dark matter interact, if it does, with SM particles?
  - Does one or more new dark force exist?
  - How complex is the dark sector spectrum?
Dark sectors and portal interactions

**Dark (or hidden) sector:**  
DM particles completely neutral under SM forces, posses new interactions

**Mediator:**  
A mediator particle of the new interaction, interacting very weekly with SM particles

**Portal interaction:**  
New interaction connecting dark mediator and SM particles

The **mediator** can be scalar, fermion, vector, axion...  
The relic **dark matter (DM)** can be **either the mediator** particle or just coupled to SM via a hidden interaction

**Different portals can co-exist:**  
e.g. dark photon and Higgs, or dark photon and axion

Dark sectors can conceal **not only the DM problem, other SM anomalies:**
- Muon g–2 anomaly, proton radius, inflation, $^8\text{Be}$ anomaly, ...

The **vector portal** is the **simplest** both from the **theoretical** [additional U(1) gauge symmetry] and **experimental** point of view [just replace an ordinary $\gamma$ with a dark photon $A'$ in any QED processes]
Many candidates: how to choose?

A very wide panorama but some anomalies at low energy are interesting to guide the eye.
Simplest dark photon model

- The simplest hidden sector model just introduces one extra U(1) gauge symmetry and a corresponding gauge boson: the "dark photon" or $A'$ boson.

- The coupling constant and the charges can be generated effectively through the kinetic mixing between the QED and the new U(1) gauge bosons

$$L_{mix} = -\frac{\epsilon}{2} F_{\mu\nu}^{QED} F_{\mu\nu}^{dark}$$

- In this case the new coupling constant $= e \epsilon$ is just proportional to electric charge and it is equal for both quarks and leptons.

- As in QED, this will generate new interactions with SM fermions of type:

$$L \sim g' q_f \bar{\psi}_f \gamma^\mu \psi_f U'_\mu$$

- Not all the SM particles need to be charged under this new symmetry
- In the most general case $q_f$ is different in between leptons and quarks and can even be 0 for quarks. P. Fayet, Phys. Lett. B 675, 267 (2009)
About $3\sigma$ discrepancy between theory and experiment. Could be due to hadronic uncertainties on the Light by Light scattering?

Additional diagram with dark photon exchange can fix the discrepancy! (with sub GeV A' masses 😊)

M. Pospelov
A’ decay modes MeV-GeV scale

- If $1\text{MeV} < M_{A'} < 2m_{\chi}$ dilepton decays “visible” decays
  - $\text{Min} \ M_{A'} > 1\text{MeV}$ lifetime depends mostly on $\varepsilon^2$ long lived
- $2m_{\chi} < M_{A'}$ dark matter decays “invisible” decays
  - $\text{Min} \ M_{A'} < 1\text{MeV}$ lifetime depends mostly on $\alpha_D^2$ short lived
- Decays in $3\gamma$ are not interesting for the accelerator searches

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A’ decays in SM particles

- BR visible is =1 if dark matter is massive.

- A’ “visible” decay modes
  - A’→e^+e^-
  - A’→μ^+μ^-
  - A’→hadrons

- For \( M_{A'} < 210 \) MeV A’ only decays to \( e^+e^- \) with \( BR(e^+e^-) = 1 \)

- At higher masses hadronic decay are also allowed
How to search for $A'$ visible decays?

A) Thin target experiments

$N \propto e^2 \sim 10^{14-16}$ EOT ($e^2, M_{A'}$)

(APEX, HPS, A1)

B) $e^-$ dump experiments

$N \propto e^2 \sim 10^{19-20}$ EOT ($e^2, M_{A'}$)

(E-137, E-141, E-774, Orsay, ...)

C) Collider experiments

$N \propto e^2$ sensitive to ($\varepsilon, A'$) mass

Limited by $M_{A'} < \sqrt{s}$

(KLOE, BaBar, A1)

D) Proton dump experiments

$N \propto e^2 \sim 10^{19-20}$ POT ($e^2, M_{A'}$)

(U70, CHARM, NA62 ...)

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A’ production in “visibile” decay exp.

**Proton machines production:**
- Mesons decays \( \pi^0, \eta, D^0 \)
- QCD production lepton jets

**Electron machines production**
- e\(^-\) Bremsstrahlung
- e\(^-\)e\(^+\) annihilation + meson decays

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$A' \rightarrow \ell^+ \ell^-$ visible searches status

- Grey regions: excluded regions
- Colored lines: future experiments projections
- Green band: region in which $A'$ will explain g-2 anomaly
How to search for A’ invisible decays?

Positive evidence

A) Beam dump

\[ N \propto \varepsilon^4 \sim 10^{20} \text{ EOT (} \alpha_D \text{ and } \varepsilon^2) \]

Missing Mass

\[ N \propto \varepsilon^2 \text{ sensitive to (} \varepsilon, A' \text{) mass} \]

Limited by \( M^{A'} < \sqrt{s} \)

Negative evidence

B) Missing energy

\[ E_{e'} \ll E_B \]

C) Target/ECAL/HCAL

D) Missing momentum

\[ N \propto \varepsilon^2 (\varepsilon^2 \text{ only}) \]

\[ N \propto \varepsilon^2 \text{ contains } E_{\text{miss}} \text{ exp.} \]

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Invisible decays present status

Great progress in the beginning of 2017

- Still large regions of parameter space unexplored
- Only 1 experiment in most of the parameter space covered

New result by NA62 see P. Massarotti’s talk
Few invisible decay examples

Running experiments
- PADME
- BELLE II
- LDMX
- BDX

Future experiments
- INFN LNF
- Super KEKB
- SLAC? CERN?
- JLAB? MAMI?
First fixed target A’ experiment with positron running since October 2018
The PADME physics cases

Dark Photon
arXiv:1608.08632v1

Invisible final state:
\( e^+e^- \rightarrow \gamma A' \) and \( A' \rightarrow \chi \chi \)

ALPs and g-2
arXiv 1607.01022v2

ALPs final state \( a \rightarrow \gamma \gamma \)

BE anomaly - Fifth force
arXiv:1608.03591v1

Final state \( X \rightarrow \text{ee} \)

- Measurement of low energy (100-500 MeV) EM-cross sections
  - Bremsstrahlung cross section \( e^+N \rightarrow e^+N\gamma \)
  - Annihilation cross sections: \( e^+e^- \rightarrow \gamma \gamma \) \( e^+e^- \rightarrow \gamma\gamma(\gamma) \)

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PADME detector in a nutshell

Active target
Lecce & University Salento

Dipole magnet
(CERN TE/NSC-MNC)

C-fiber window

Veto scintillators
(University of Sofia, Roma)

BGO calorimeter
(616 L3 endcap crystals: Roma, Cornell U., LNF, LE)

PbF$_2$ calorimeter
(MTA Atomki, Cornell U., LNF)

TimePIX3 array
(ADVACAM, LNF)
Search for $e^+e^- \rightarrow \gamma + \text{nothing}$

- Measure the visible gamma missin mass
- Be sure no other photons or $e^+ e^-$ is around.
Based on 2.5x10^{10} fully GEANT4 simulated 550 MeV e+ on target events
- Number of BG events is extrapolated to 1x10^{13} electrons on target
- Using N(A'\gamma) = \sigma(NBG)

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

\delta\text{ enhancement factor: } \delta(M_{A'}) = \sigma(A'\gamma)/\sigma(\gamma\gamma) \text{ with } \varepsilon=1 \text{ due to } A' \text{ mass}
Future of the dark sector searches

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Conclusions

- Dark sectors searches are an extremely vital in the last 5-10 years
  - Recast of old experiment
  - New experiments are running
  - New experimental proposals are approved

- New generation of dedicated experiment is on the way to explore the dark sectors
  - Different techniques and different final states searches are needed to provide reliable exclusions.

A bright future is awaiting the dark sectors
Is this an evidence of a new light dark photon?

- **Sanity checks performed**
  - Excess disappears as one scans through the proton beam resonance kinetic energy of 1.03 MeV
  - Excess becomes more pronounced when restricting to the subset of events with $E > 18$ MeV and is absent for lower energy events.

$m_X = 16.7 \pm 0.35\text{(stat)} \pm 0.5\text{(sys)}$ MeV

Can only mitigate the anomaly by $1\sigma$ by improving nuclear treatment.

j.physletb.2017.08.013
π^0\text{-phobia} = \rho^+\text{-phobia}

To avoid NA48/2, prohibit π^0 decay to Xγ

FROM QUARK CONTENT

\[ \frac{1}{\sqrt{2}} (u\bar{u} - d\bar{d}) \]

\

\[ Q_u Q'_u - Q_d Q'_d = 0 \quad Q'_d = -2Q'_u \]

ProtoPhobic coupling

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The $^8$Be anomaly interpretation

Protophobic Fifth-Force Interpretation of the Observed Anomaly in $^8$Be Nuclear Transitions

Jonathan L. Feng, Bartosz Formal, Iftah Galon, Susan Gardner, Jordan Smolinsky, Tim M. P. Tait, and Philip Tanedo

**Protophobia**

Equations (5) and (8) may be satisfied with a mild $\sim$10% cancellation, provided the charges satisfy

$$-2.3 < \frac{\varepsilon_d}{\varepsilon_u} < -1.8, \quad -0.067 < \frac{\varepsilon_p}{\varepsilon_n} < 0.078. \quad (9)$$

Given the latter condition, we call the general class of vector models that can both explain the $^8$Be anomaly and satisfy pion decay constraints “protophobic.”

Strongest experimental limit on the electron coupling comes from KLOE data: $\varepsilon_e < 2E^{-3}$
Exploit the fact that you “know” where to search 17 MeV
Exploit the unique possibility to have e\(^+\) at 282.7 MeV \(\@\text{LNF}\)
Tune \(E_{e^+}\) such that \(E_{\text{CM}} = \sqrt{2m_e E_B} = 17\text{MeV}\)
Produce \(A'\) of 17 MeV on shell through direct annihilation \(e^-\rightarrow A'\)
Parametrically enhanced \(e^-\rightarrow A' O(\alpha)\) \(\text{wrt}\) \(e^-\rightarrow A' \gamma O(\alpha^2)\)
Use threshold effect to have solid evidence if \(\alpha\) Absorb any SM BG in W dump
Work ongoing on thin target reaches
PADME data taking during Run I

Primary positrons (490 MeV)

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<th>Month</th>
<th>#days</th>
<th>N_{POT}</th>
<th>N_{POT}/day</th>
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<td>2.2E12</td>
<td>0.76E11</td>
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<tr>
<td>December</td>
<td>16</td>
<td>1.4E12</td>
<td>0.875E11</td>
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<tr>
<td>January</td>
<td>15</td>
<td>1.7E12</td>
<td>1.1E11</td>
</tr>
<tr>
<td>February</td>
<td>21</td>
<td>2.1E12</td>
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<td>Total 12/02</td>
<td>82</td>
<td>7.4E12</td>
<td>0.9E11</td>
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</tbody>
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LDMX: $P_{\text{Miss}}$ experiment

Beam: individual tag of $10^{16}$ incident $e^-$
- A low-current, multi-GeV, $e^-$ beam ($10^{16}$/year $\approx 1$ $e^-$/3 ns).
Possibilities:
- DASEL@SLAC (4/8 GeV)
- CEBAF@JLab (up to 11 GeV).
- Recently SPS extracted $e^-$
- Large beam spot ($\sim 10$ cm$^2$)

Two-stage approach to LDMX:
- $4 \times 10^{14}$ “Phase I” late 2021?
- $1 \times 10^{16}$ “Phase II” late 2023-2024?

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Future $M_{\text{Miss}}$ fixed target experiments

$10^{13} e^+$ on target at LNF 2018

**PADME**

**MMAPS @ Cornell**

**EPJ Web of Conferences 142, 001 (2017)**

**PADME + MMAPS? (2020?)**

**PADME:** $E_B \sim 500$ MeV, 2 year @ INFN BTF

**Cornell:** $12 \times E_B$, $10^4 \times$ EOT

**PADME:** Better $M_{\text{miss}}$, faster detector