PHOTON 2019

INTERNATIONAL CONFERENCE ON THE STRUCTURE AND THE INTERACTIONS OF THE PHOTON

06/06/2019

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A LIGHT DARK MATTER PORTAL: THE AXION-LIKE PARTICLE
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- AXION-LIKE PARTICLES
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WHY DARK MATTER:

THERE IS EVIDENCE OF DARK MATTER IN A WIDE RANGE OF DISTANCE SCALES:

- Observed
- Expected


Planck 2015
OPEN QUESTIONS:

- WHAT IS THE DARK MATTER?
- INTERACTION WITH THE STANDARD MODEL?
- HOW IS THE OBSERVED RELIC ABUNDANCE PRODUCED?
- JUST ONE PARTICLE OR AN ENTIRE DARK SECTOR?
- IS IT A PARTICLE?

PROPERTIES

ITS RELIC ABUNDANCE

\[ \Omega_{DM} h^2 = 0.1198 \pm 0.0015 \]

Planck 2015
**SIMPLIFIED MODEL:**

- extension to SM w/ only the relevant parameters
- not considering what happens at UV-scale
- opening the possibility to directly produce the mediator
WEAKLY INTERACTIVE MASSIVE PARTICLES:
thermally produced in Early Universe with masses at GeV-TeV and annihilation cross-section of electroweak scale.

see also C. Weniger’ talk

BUT NO CONVINCING SIGNAL
Low-energy frontier experiments are starting to probe light masses and very feebly coupling to SM with high-intensity.

see Chu’ talk “Light Dark States associated with photons”
AXION-LIKE PARTICLE (ALP)

GENERALISATION OF AXION PARTICLE:
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- Light
- Pseudo-scalar Particle
- Derivative Coupling to SM
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pseudo Nambu-Goldstone boson of a new spontaneously broken global symmetry
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Not necessarily the QCD axion: so mass and couplings are independent parameters

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⇒ Wide Mass Range: at masses < MeV implications for cosmology and astrophysics (see Galanti’s talk), at ≳ MeV they have implications in particle physics

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Increasing interest for experimental searches at accelerators: assuming a leptophilic ALP ⇒ Lepton beam/fixed target, e.g. PADME,…
Lepton Beam/Collider, e.g. Belle II,…
The effective ALP Lagrangian [assumed valid for scales $< O(\text{TeV})$]:

$$\mathcal{L}_{alp} = \frac{1}{2} \partial^\mu a \partial_\mu a - \frac{1}{2} M_a^2 a^2 - \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} - i g_{ae\bar{e}} m_e a \bar{\psi} \gamma^5 \psi + \mathcal{L}_{DM}$$
The effective ALP Lagrangian [assumed valid for scales < O(TeV)]:

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- visible decay  $a \rightarrow l^+ l^-, \gamma\gamma$  at  $M_{dm} > M_a/2$  :

  signal: $\gamma\gamma\gamma\gamma, e^+/e^- + \gamma$
HOW TO DETECT IT? ACCELERATOR PHYSICS  (JUST ASSUME LEPTOPHILIC ALP)

The effective ALP Lagrangian [assumed valid for scales < O(TeV)]:

\[ \mathcal{L}_{alp} = \frac{1}{2} \partial^\mu a \partial_\mu a - \frac{1}{2} M_a^2 a^2 - \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} - i g_{ae \bar{e}e} m_e a \bar{\psi} \gamma^5 \psi + \mathcal{L}_{DM} \]

- visible decay \( a \rightarrow l^+ l^-, \gamma\gamma \) at \( M_{dm} > M_a/2 \):
  - signal: \( \gamma\gamma\gamma, e^+/e^- + \gamma \)

- invisible: long-lived or portal \( a \rightarrow DM DM \) at \( M_{dm} < M_a/2 \):
  - signal: \( 1\gamma + \text{missing energy/momentum/mass} \)
It is a Positron Annihilation into Dark Matter Experiment which searches the light dark particle using a positron beam on a thin diamond target, detecting the SM photon produced in the annihilation reaction:

\[ e^+e^- \rightarrow \gamma + X \]

where \( X \) is the light dark particle and therefore measuring the event as a peak in missing mass:

\[ M_{miss}^2 = (P_{e^+} + P_{e^-} - P_\gamma)^2 \]

The PADME technique is completely model independent (it only requires a lepton coupling)
Beam Energy: 550 MeV

Angular Acceptance of ECAL: \(0.026<\theta(\text{rad})<0.083\)

CUT: \(E_\gamma > 30\) MeV
PADME Cut:

- $0.026 < \theta (\text{rad}) < 0.083$ and $E_{\gamma} > 30$ MeV
- including SAC $0 < \theta (\text{rad}) < 0.083$

COMMENT:

i) AT SMALL ANGLES EASIER TO DISTINGUISH THE ALP MASSES

ii) AT SMALL ALP MASSES THE CALORIMETER RESOLUTION ENERGY IS CRUCIAL IN ORDER TO DISTINGUISH THE DARK PARTICLE
ALP–PHOTON PRODUCTION AT PADME

In PADME

\[ P = N_e \sigma_{e^+e^-\rightarrow\gamma} = 6d_{\text{target}} N_A \frac{\rho}{A} \sigma_{e^+e^-\rightarrow\gamma} \]

- \( P \): Number of events
- \( N_e \): Total number of \( e^- \) on target per unit surface area
- \( \sigma_{e^+e^-\rightarrow\gamma} \): Cross section for ALP production
- \( d_{\text{target}} \): Target thickness = 100\( \mu \)m
- \( N_A \): Avogadro's number
- \( \rho \): Diamond density = 3.5 g/cm\(^3\)
- \( A \): Atomic mass = 12 g/mol

\[ g_{ae^+e^-} = 1\text{GeV}^{-1} \]
\[ g_{\gamma\gamma} = 1\text{GeV}^{-1} \]

Number of \( e^+e^- \) in \( \gamma \) ALP events in PADME assuming \( 10^{13} \) PoT
ALP–PHOTON PRODUCTION AT PADME

with cut $M_a=5$ MeV

with cut $M_a=10$ MeV

with cut $M_a=20$ MeV

with cut $M_a=22$ MeV

$g_{\gamma\gamma}$ (GeV$^{-1}$)

$g_{\text{beam}}$ (GeV$^{-1}$)

N events

0.35
0.25
0.15
0.05

0.06
0.05
0.04
0.03
0.02
$10^{-2}$

0.08
0.06
0.04
0.02

0.010
0.005
0.000
-0.005
-0.010

0.010
0.005
0.000
-0.005
-0.010

0.010
0.005
0.000
-0.005
-0.010

0.010
0.005
0.000
-0.005
-0.010
WHAT ABOUT VISIBLE DECAYS OF ALPS IN PADME?

It depends on the ALP decay length relative to the size of the detector

\[
\Gamma_{a\rightarrow\gamma\gamma} = \frac{64\pi cE_a h}{g_{a\gamma\gamma}^2 M_a^4}
\]

\[
\Gamma_{a\rightarrow e^+e^-} = \frac{8\pi cE_a h}{g_{aee}^2 M_a^2 M_e^2}
\]

E_a=550MeV
where $\epsilon$ denotes the kinetic mixing parameter. To convert a bound on $\epsilon$ for Dark Photons into a bound on $g_{\gamma\gamma}$ for ALPs we therefore have to correct for the fact that the geometric acceptance will be very different in the two cases.

The BaBar analysis considers $-0.6 < \cos \theta < 0.6$ for $m_{E} > 5.5$ GeV and $0.4 < \cos \theta < 0.6$ for $m_{E} < 5.5$ GeV. By integrating the respective differential cross sections for ALP production and Dark Photon decay over the ranges we obtain the fiducial cross section including geometric acceptance. Using the tables, we can translate bounds on Dark Photons into the ALP parameter space under the assumption that all other selection cuts have the same efficiency for the two models. For very small masses of the invisibly decaying particle, we find that the translation is given by

$$g_{\gamma\gamma} = 1.8 \times 10^{-4} \text{GeV}^{-1} \left(\frac{\epsilon}{10^{-3}}\right).$$

Repeating this calculation for finite ALP masses and taking into account the probability that the ALP decays before leaving the detector (see above) using a detector length of $L_{D} = 275$ cm [59], we can then reinterpret the full BaBar bound in the context of ALPs.

FUTURE PADME RESULTS ARE NOT A RECAST OF DARK PHOTON MEASUREMENTS, BUT IT IS EXPLORING DIRECTLY THESE REGIONS.
CONCLUSION

- INVESTIGATE LIGHT DARK MATTER PORTALS
- AXION-LIKE PARTICLE IS A PROMISING DM PORTAL
- PADME EXPERIMENT CAN DETECT AN ALP SIGNAL
- LET’S WAIT FOR RESULTS FROM PADME
- WHAT IS THE INTERACTION WITH THE DARK MATTER?
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THANKS FOR ATTENTION!!
BACKUP SLIDES
**WIMP:** Weakly Interacting Massive Particles

\[ \Omega_{DM} h^2 \propto \frac{1}{<\sigma v>} \sim \frac{M_{DM}^2}{g^4} \]

- GeV-TeV mass scale
- weak scale cross-section

**NO CONVINCING SIGNAL IN SPITE OF SPECTACULAR IMPROVEMENTS IN DIRECT DETECTION SENSITIVITY**
PHOTON–PHOTON PRODUCTION AT PADME