Axion-like particles from proton beam dumps

Babette Döbrich (CERN)

BCTP Bonn, March 2016

Life in the `hidden sector´...
‘beam dump searches for axions’ might evoke a feeling of time travel to parts of the audience see, e.g. ‘dump chapter’ in [Rosenberg/Bibber Phys. Rept. 325]

today’s physicists regain interest for very weakly coupled with masses (well) below the need of highest-energy accelerators (‘low energy frontier’)

e.g. proposal for a dedicated dump-search at SPS (‘SHiP’, mainly meant for heavy neutral leptons) as incentive to look at prospects specifically for Axion-like particles (and others), maybe even at existing facilities (‘SHiP’ is still to be approved and built)
Brief Intro: Axions vs ALPs

- new physics is somewhere!
- could be at high mass (traditional & successfull & motivated paradigm)
- could be at ‘low’ mass and very small couplings (pragmatic & very motivated paradigm)
new physics is somewhere!

- could be at high mass (traditional & successfull & motivated paradigm)

- could be at ‘low’ mass and very small couplings (pragmatic & very motivated paradigm)

focus on “axions” coupled predominantly to photons (actually, many more possibilities!)

<table>
<thead>
<tr>
<th>Portal</th>
<th>Particles</th>
<th>Operator(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Vector”</td>
<td>Dark photons</td>
<td>$-\frac{e}{2\cos\theta_W} B_{\mu\nu} F^{\mu\nu}$</td>
</tr>
<tr>
<td>“Axion”</td>
<td>Pseudoscalars</td>
<td>$\frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i\mu\nu} \tilde{G}^{i\mu\nu}$, $\frac{\partial_a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$</td>
</tr>
<tr>
<td>“Higgs”</td>
<td>Dark scalars</td>
<td>$(\mu S + \lambda S^2) H^\dagger H$</td>
</tr>
<tr>
<td>“Neutrino”</td>
<td>Sterile neutrinos</td>
<td>$y_N L H N$</td>
</tr>
</tbody>
</table>

[from 1311.0029: Dark Sectors and New, Light, Weakly-Coupled Particles]
Brief Intro: Axions vs ALPs

cleans (detergent!)
finetuning of $\sim 10^{-10}$

- focus on “axions” coupled predominantly to photons (actually, many more possibilities!)
- pseudoscalar axion solves ‘strong CP problem as PNGB of Peccei-Quinn symmetry’ [Peccei, Quinn, 77; Weinberg, Wilczek, 78]
An “axion-like” particle (ALP) is a ‘general’ (pseudo-)scalar.
Brief Intro: Axions vs ALPs

an “axion-like” particle (ALP) is a ‘general’ (pseudo-)scalar
Axion(-like) particles coupled to two photons

- QCD axion: yellow band, ALPs possible (in principle) in all white regions
- colored is excluded
Axion(-like) particles coupled to two photons

- QCD axion: yellow band, ALPs possible (in principle) in all white regions
- colored is excluded
- interesting regions:
  - cold Dark Matter (axion and ALP)
  - some Astrophysical hints [better see Javi’s talk]
  - ‘Hidden sector’ (mediators DM, dep. coupl.)
Tackling ALPS at low and medium masses (below LHC)

↑ LSW, e.g. ALPS-II
Helioscope e.g. IAXO
Haloscope, e.g. ADMX
Tackling ALPS at low and medium masses (below LHC)


classic neutron decay: $\nu_e \rightarrow e^- + e^+$

solution: (e.g.) CAST

experimental hints

$10^{-18}$

$10^{-16}$

$10^{-14}$

$10^{-12}$

$10^{-10}$

$10^{-8}$

$10^{-6}$

$10^{-4}$

$10^{-2}$

$10^0$

$10^2$ Log Mass [eV]

$10^{-1}$ Log Coupling [GeV$^{-1}$]

$\nu_e$ vs. mass

$\nu_e$ vs. coupling

$\nu_e$ vs. ALPS

$\nu_e$ vs. ADMX

$\nu_e$ vs. LSW

$\nu_e$ vs. IAXO

$\nu_e$ vs. fixed target/dump

$ightarrow$ high mass region?

intense photon source?

accelerate charged particles!

and shield from ‘backgrounds’

and highly charged particles → fixed target/dump

Babette Döbrich (CERN)
ALP production in particle-on-target

- produce ALPs through different channels, but need clean prediction for $S/B$
- primarily: 1) Primakoff-like and 2) ‘ALPstrahlung’

- perturbative calculation requires large $p_t$
ALP production in particle-on-target

- produce ALPs through different channels, but need clean prediction for $S/B$
- primarily: 1) Primakoff-like and 2) ‘ALPstrahlung’
- 1) perturbative & can have a coherent $Z^2$ enhancement
- simple atomic and nuclear form factors (resolve charged core but not the nucleon) + ‘EPA’ (Weizäcker-Williams)

photons soft in respective rest frames

blue shifted $\gamma$s: energy for ‘heavy’ ALPs
ALP production in particle-on-target

- produce ALPs through different channels, but need clean prediction for $S/B$
- primarily: 1) Primakoff-like and 2) ‘ALPstrahlung’
- 1) perturbative & can have a coherent $Z^2$ enhancement
- simple atomic and nuclear form factors (resolve charged core but not the nucleon) + ‘EPA’ (Weizäcker-Williams)
- previous Primakoff ALP studies and madgraph MC ‘ignore’ photon $p_t$, → ALP exactly on axis ($\theta = 0$)

Babette Döbrich (CERN)
Production cross-section for ALPs in $p + N$

- assume 400GeV protons on a copper target & keep $p_t$
- most ALPs produced at $\sim 20$ mrad $\Rightarrow$ photon $p_t$ non-negligible!
- given any angle wrt beam axis, $\sigma_a$ distribution in $\theta$ and $E_a$ for each ALP mass $\Rightarrow$ we can retrace and predict a signal in an experiment (to see if it’s worth doing)
dumped MeV-GeV axion-like particles review

\[ N_{\text{det}} \sim N_{\text{pot}} \frac{\sigma_a}{\sigma_p} \left[ \exp \left( -\frac{D}{\gamma \beta \tau} \right) - \exp \left( -\frac{D + L}{\gamma \beta \tau} \right) \right] \]

- decay length \( \gamma \beta \tau \), ALP lifetime
- \( \Gamma = \tau^{-1} = g_{a \gamma}^2 m_a^3 / (64 \pi) \)

\[ p \rightarrow a \rightarrow \text{absorber} \rightarrow \text{detector} \]
dumped MeV-GeV axion-like particles review

\[ N_{\text{det}} \sim \left( N_{\text{pot}} \frac{\sigma_a}{\sigma_p} \right) \exp \left( -\frac{D}{\gamma \beta \tau} \right) - \exp \left( -\frac{D + L}{\gamma \beta \tau} \right) \]

- decay length \( \gamma \beta \tau \), ALP lifetime
  \[ \Gamma = \tau^{-1} = g_{a\gamma}^2 m_a^3 / (64\pi) \]

exclusion through dumps

- **CHARM** 400 GeV, \( N_{\text{pot}} = 2.4 \times 10^{18} \) on copper, \( D = 480 \text{m}, L = 35 \text{m} \) (off-axis: 7-12 mrad)

- **NuCal** 70 GeV, \( N_{\text{pot}} = 1.7 \times 10^{18} \) on iron,
  \( D = 64 \text{m}, L = 23 \text{m}, \text{on-axis } 0-15 \text{ mrad} \)

- **SLAC141** 9 GeV, \( N_{\text{eot}} = 2 \times 10^{15} \) on tungsten, \( D = 35 \text{m} \)

- **SLAC137** 20 GeV, \( N_{\text{eot}} = 2 \times 10^{20} \) on aluminum, \( D = 200 \text{m} \)

estimates for CHARM and NuCal newly derived for pure \( \gamma \)

[BD, Jaeckel, Kahlhoefer, Ringwald, Schmidt-Hoberg JHEP 1602, 018]
Extending the Axion-like-Particle reach at NA62?

NA62 currently taking data for measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at CERN SPS (400GeV protons)

Babette Döbrich (CERN)
Extending the Axion-like-Particle reach at NA62?

- NA62 currently taking data for measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at CERN SPS (400GeV protons)
- copper ‘TAX’ after target

Babette Döbrich (CERN)
Axion-like particles from proton beam dump
BCTP Bonn, March 2016
Extending the Axion-like-Particle reach at NA62?

- NA62 currently taking data for measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at CERN SPS (400GeV protons)
- copper ‘TAX’ after target
- can run in dump mode by closing TAX, $\gamma$s not expected!

**Diagram:**
- Protons ($p^+$) from target
- 400GeV, 75GeV
- $K^+ & more$
- Liquid Krypton calorimeter
-Muon veto
-IR
-CEDAR
-RICH
-Gigatracker
-collimator
-target
-Lar
g e an
g ... m
-at
-achromat
-vacuum
-Straw chambers
-1 m
-spectrometer
-magnet
-CHOD
-Charged anti counter
-D
-L

≈ 81m

≈ 135m
Extending the Axion-like-Particle reach at NA62?

- NA62 currently taking data for measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at CERN SPS (400GeV protons)
- copper ‘TAX’ after target
- can run in dump mode by closing TAX, $\gamma$s not expected!
- signature for ALPs: 2 coincident $\gamma$s in LKr calorimeter

Calorimeter hole for beam
Extending the Axion-like-Particle reach at NA62?

- NA62 currently taking data for measurement of $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at CERN SPS (400GeV protons)
- copper ‘TAX’ after target
- can run in dump mode by closing TAX, $\gamma$s not expected!
- signature for ALPs: 2 coincident $\gamma$s in LKr calorimeter
- decay to charged particles? $\rightarrow$ track (studies ongoing)
Acceptance for two coincident \( \gamma \)'s in toy Monte Carlo

kinematic acceptance

- angular distribution: two \( \gamma \) coincident in time in LKr

both photons in \( 0.15m < r < 1.13m \)

photon distance \( d_{12} > 0.10m \)
Acceptance for two coincident $\gamma$s in toy Monte Carlo

**short decay length $\ll$ absorber**

- $l = 40 \text{ m}$
- Both photons in $0.15 < r < 1.13$ m
- Photon distance $d_{12} > 0.10$ m

**long decay length $\gg$ absorber**

- $l = 200 \text{ m}$
- Both photons in $0.15 < r < 1.13$ m
- Photon distance $d_{12} > 0.10$ m

**kinematic acceptance**

- Angular distribution: two $\gamma$ coincident in time in LKr
- Acceptance: depends on $\tau$, $\theta$, $\gamma$
- Red: early decays $\rightarrow$ analytical estimate (mod calo hole)

---

Babette Döbrich (CERN)

Axion-like particles from proton beam dump  

BCTP Bonn, March 2016
Acceptance for two coincident $\gamma$s in toy Monte Carlo

kinematic acceptance
- angular distribution: two $\gamma$ coincident in time in LKr
- acceptance: depends on $\tau$, $\theta$, $\gamma$
- red: early decays $\rightarrow$ analytical estimate (mod calo hole)

overall acceptance
- fold acceptance with $\sigma_a$, explicit dependence on $g_{a\gamma}$ and $m_a$
- calorimeter hole little effect as $\theta$ peaks at nonzero value
- good point in evaluating probability of ALP signal
Combining computation of $\sigma_a$ with the toy MC

- red areas NA62 LKr for $>3$ events, both photons detected
- if all backgrounds can be suppressed & small losses, even $\sim$ one day of data-taking gives access to ‘uncharted territory’
- this is due to a favourable detector geometry (small $D$) and the possibility of high-energy protons on a high-Z target
- confront with data (see next slide) and full Monte Carlo as a next step
in reality: non-trivial problem (no track!), some ideas but need more thinking and testing

1h appropriate data sample taken in November 2015, TAXes closed, trigger on minimum energy in calorimeter (potentially valuable also for main physics goal: backgrounds)

start to make a proper sensitivity estimate based on this data: analysis work plan started...
Thank you for your attention!

Summary:

- ALPs with \( > (100) \) MeV motivated e.g. in DM mediator models
- suggestion to search making use of existing infrastructure: fast, cheap, complementary physics program
- novel sensitivity for NA62 in just one day, dedicated dump facility such as SHiP enormous potential
- not mentioned: collider bounds worked out [Jaeckel et al], (diphoton excess?)
- results upcoming, stay tuned!

I cordially acknowledge excellent collaboration within NA62 and especially with J. Jaeckel, F. Kahlhoefer, A. Ringwald, K. Schmidt-Hoberg, T. Spadaro
ALPs at even higher masses nearest expert: J. Jaeckel

- LEP [1509.0047] through ALPstrahlung
SHiP estimate for coherent production

- proposed dedicated Dump facility for SPS (mainly for Heavy Neutral Leptons)
- SHiP estimate based on $\sim 2 \times 10^{20}$ POT (molybdenum, $Z = 42$) $\to$ run-time of 5 years, see [1504.04956]
- $D = 70m$, $L = 50m$, calorimeter radius 2.5m
- note that the ALP sensitivity estimate in SHiP theory paper [1504.04855] is based on incoherent production, i.e. $q + \bar{q} \to a + \gamma$ (cf. next slide)
ALPstrahlung estimate from SHiP theory proposal

from SHiP theory paper, figure 5.1
note that orange region from $e^- d$umps
based on calchep (madgraph similar)

- $q + \bar{q} \rightarrow a + \gamma$
- have to deal with composite nature of proton (contrary to coherent production)
- difficult to compute reliably for ALP masses below 1GeV: for a perturbative calculation to make sense one has to require a large photon $p_t$ (proton $\rightarrow \Delta$), which implies that the ALP can fly out of acceptance
- additional photon in final state (smaller phase space)
400GeV protons on copper target (normalized to $g_{a\gamma} = 10^{-4}\text{GeV}^{-1}$)

most ALPs produced at around 10 – 20 mrad, on optimized detector should be able to cover that region
Nonzero Photon $p_t$

- A photon with energy $\omega = \times E_{\text{beam}}$ has a typical transverse momentum of order $q_t \sim \times m_p$ and hence a typical angle of $q_t/\omega = m_p/E_{\text{beam}}$. For a beam energy of 400 GeV the maximum is therefore found around $\theta \sim 2.5$ mrad.

- Produce ALP with $m_A$ and $E_A$ requires minimum momentum transfer of $q_{\text{min}}^2 = m_A^4/(4 E_A^2)$. If quantity comparable to $R_1^{-2}$ (where $R_1$ size of the target nucleus), any additional transverse momentum $q_t > 0$ strongly suppressed by the form factor of target nucleus. Peak of the differential cross section for non-zero $\theta$ disappears for large masses and small energies.
POT: flat top: 3 seconds, 2 times in each 42 seconds supercycle:
  effective factor 0.15 multiplied by $10^{12}$ protons
1 day $\sim 1.3 \times 10^{16}$ POT
1 month $3.9 \times 10^{17}$ POT (not including down-times)
Axion-like particle as DM ‘mediator’ pheno:
- could give large self-interactions in the dark sector
- DM can annihilate into mediators, which then Decay into SM
- why is DM evading direct detection? (see left)

- accessible through rare Meson decays, see e.g. 1406.5542
- could also be evoked for collider phenomenology (diphotons?)