Particle Physics on the Plains 2019

PASSAT: Particle Accelerator helioScopes for Slim Axion-like-particle deTection

TEXAS A&M UNIVERSITY
Physics & Astronomy

Doojin Kim

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In collaboration with Walter Bonivento and Kuver Sinha [arXiv:1909.03071]
Walter Bonivento and Kuver Sinha, in progress

Motivation for Axion-like Particle Searches

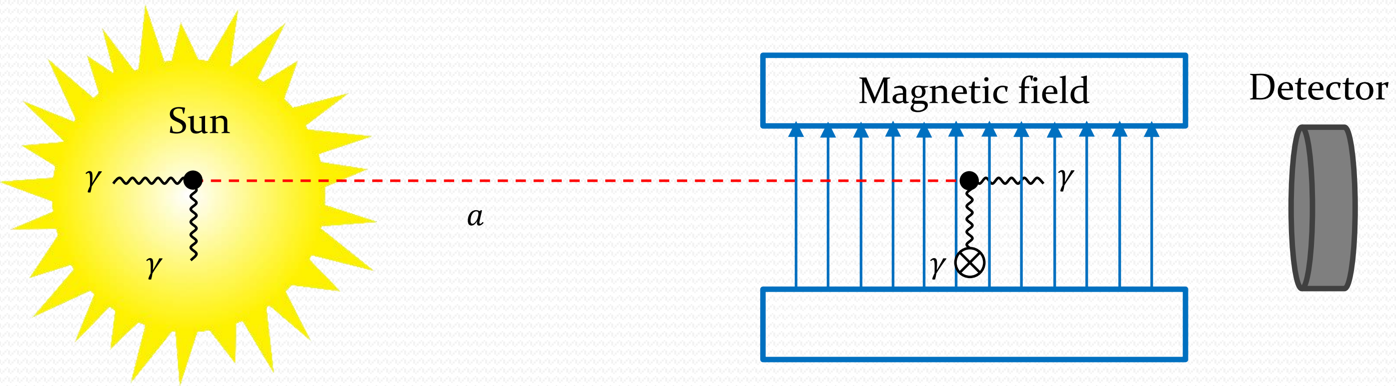
- QCD axion for solving dynamically the strong CP problem [Weinberg (1978); Wilczek (1978); Peccei and Quinn (1977)], more general pseudo-scalar axion-like particles (ALPs) which share similar properties/ pheno. wiith QCD axion, both of which are ubiquitous also in string theory [Arvnitaki, Dimopoulous, Dubovsky, Kaloper, March-Russell (2010); Cicoli, Goodsell, Ringwald (2012)]

- A plausible extension of the SM
- Axion/ALPs could be dark matter candidates.

- Axion/ALP searches in the **low-energy frontier of particle physics** (vs. new physics searches at the LHC in the (high-)energy frontier of particle physics)
- Many experimental search techniques are based on the ALP-photon coupling.

$$\mathcal{L}_{\rm int} \supset -\frac{1}{4} g_{a\gamma\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu}$$

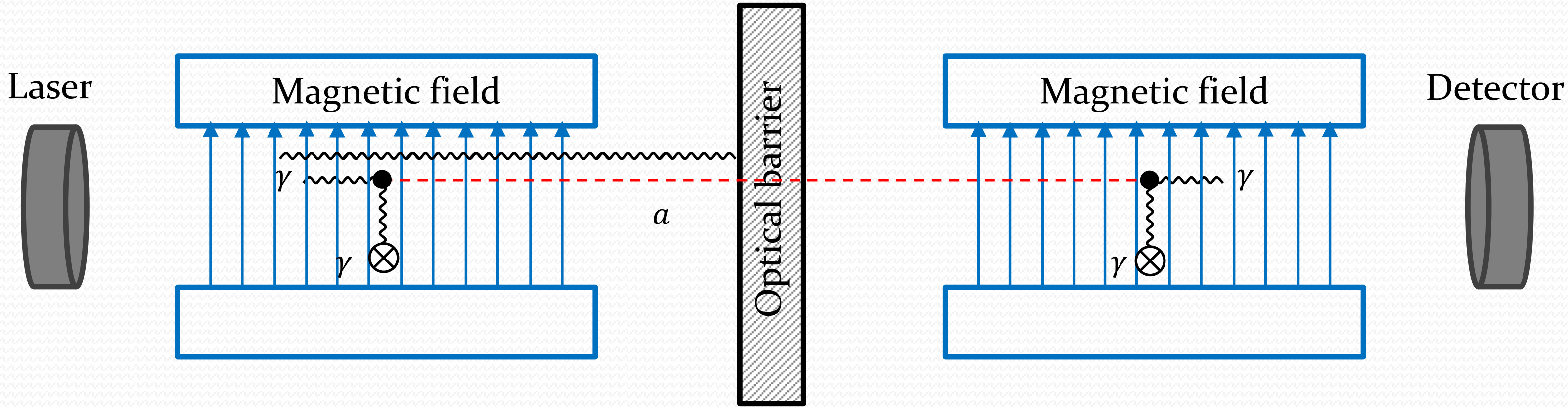
ALP Searches: CAST



- Plenty of photons inside the Sun

  $\Rightarrow$ Large signal flux expected

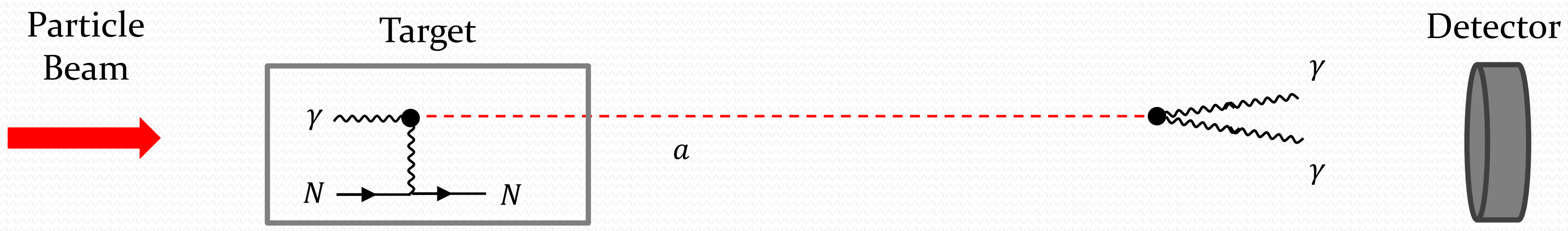
ALP Searches: LSW



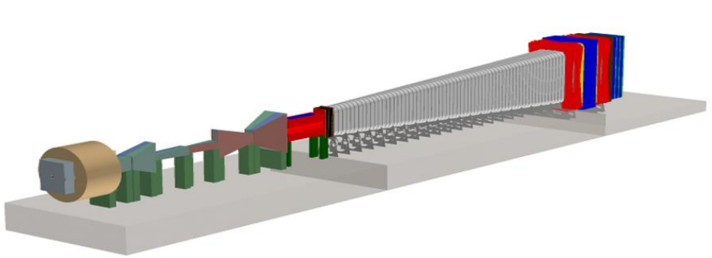
- Lab-produced ALP search, i.e., direct probe
- High intensity laser beam available
  - $\Rightarrow$ Large signal flux expected
- Accessible mass range set by the energy of the laser

[ALPS experiment]

ALP Searches: Beam-Dump Experiments



- Lab-produced ALP search, i.e., direct probe
- High intensity particle beams available
  - $\Rightarrow$ Large signal flux expected (photons from bremsstrahlung and meson decays)
- Heavier ALPs are preferred, as they can decay within detector complex



[SHiP experiment]

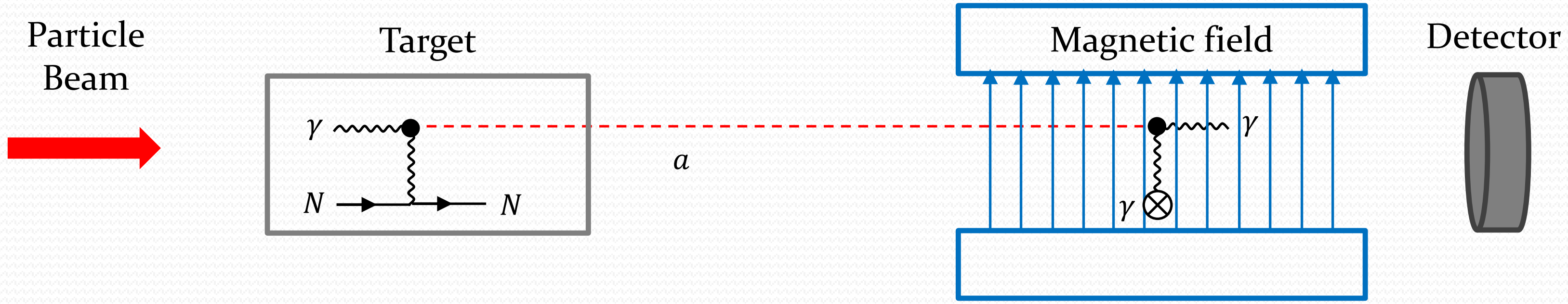
Lab-Based Searches vs. Non-Lab-Based Searches

- The PVLAS Collaboration (a polarization experiment and a lab-produced ALP search) claimed an anomaly [Zavattini et al., PRL 96 (2006) 110406] (which was later identified as a spurious effect of unknown systematics [Zavattini et al., PRD 77 (2008) 032006]) which would be explained by the oscillation of photons into ALPs.
- The preferred values for the ALP mass and the coupling were inconsistent with the astrophysical bounds (e.g., CAST), motivating a number of theoretical speculations to make the ALPs compatible with them [E.g., Jaeckel, Masso, Redondo, Ringwald, Takahashi (2006); Ahlers, Gies, Jaeckel, Ringwald (2007); Brax, van de Bruck, Davis (2007)].
- The coupling or the ALP mass can depend on a host of environmental parameters, such as the temperature, matter density, or plasma frequency, as well as the momentum transfer at the ALP-photon vertex.

Lab-based searches:

Not only complementary to astrophysical searches but also more conservative!

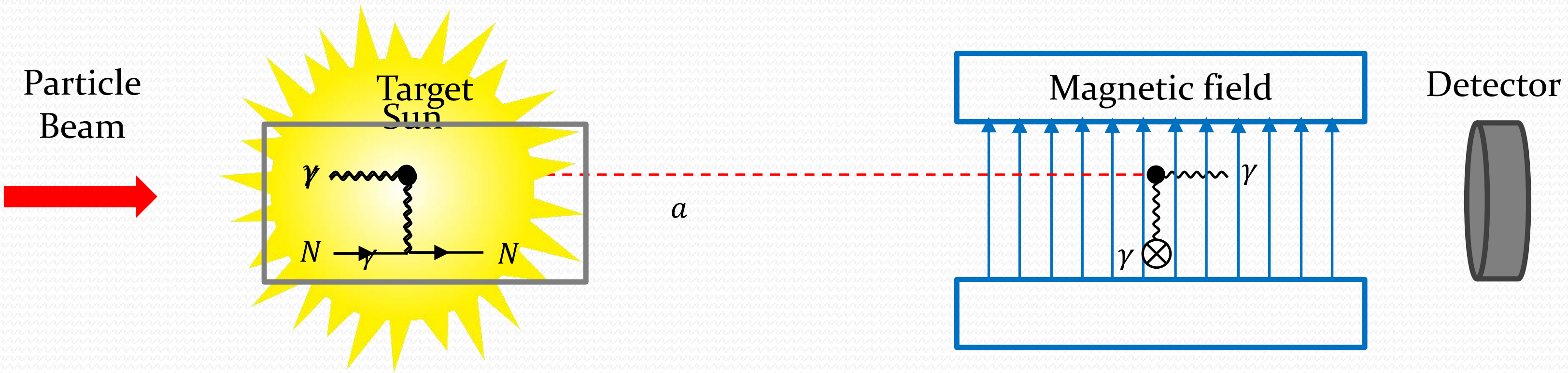
PASSAT: Main Idea



- Particle Accelerator helioScopes for Slim Axion-like-particle deTection (PASSAT): Utilizing the principle of the axion helioscope but replaces ALPs produced in the Sun with those produced in a target material.

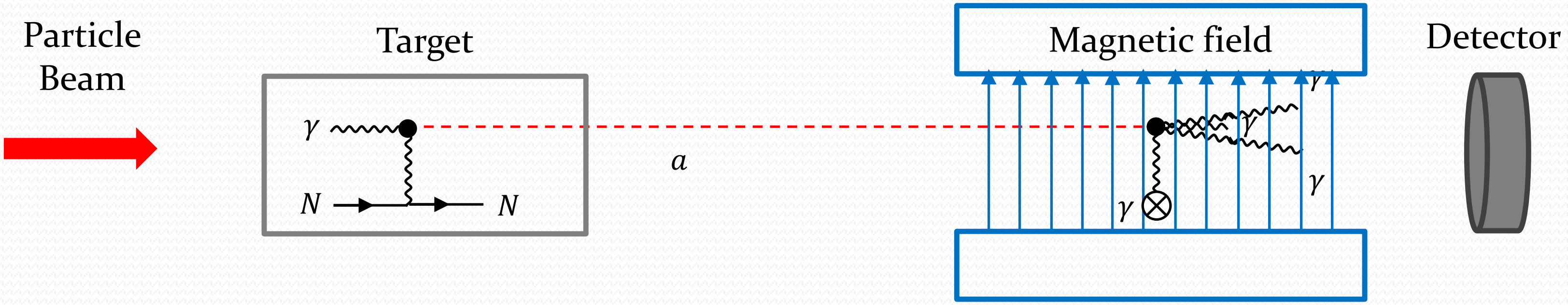
$\Rightarrow$ ALP-photon conversions: **Probing light (slim) ALPs** that are otherwise inaccessible to laboratory-based experiments which rely on ALP decay, and complements astrophysical probes that are more model-dependent.

PASSAT vs CAST



Sun is replaced by the **target material** as the source of ALPs.

PASSAT vs Beam-Dump Exp.



ALP decay process is replaced by the **ALP conversion process**.

Calculating Signal Rates

$$N_{\rm ex} = N_{\rm POT} \cdot \frac{1}{\sigma_{\gamma\to{\rm all}}} \int dE_a d\theta_a \frac{d^2\sigma_a}{dE_a d\theta_a} \cdot P_{a\to\gamma}$$

Number of protons

Cross section for photon-nucleus scattering dominated by $\gamma \to e^+e^-$ within the energy range of interest

Total cross section of the Primakoff process weighted by the photon number density profile per proton

Probability of ALP-to-photon conversion

$$P_{a\to\gamma} = \left(\frac{g_{a\gamma\gamma}BL}{2}\right)^2 \underbrace{\left(\frac{2}{qL}\right)^2 \sin^2\left(\frac{qL}{2}\right)} \quad \text{with} \quad q = 2\sqrt{\left(\frac{m_a^2}{4E_a}\right)^2 + \left(\frac{1}{2}g_{a\gamma\gamma}B\right)^2}$$

Form factor reflecting the coherence of the conversion

Calculating Signal Rates: Primakoff Process

$$\frac{d^2\sigma_a}{dE_a d\theta_a} = \int dp_T^2 d\phi\, n_\gamma(E_a, p_T^2) \frac{d\sigma_{\gamma N}}{d\theta_a}$$

Differential cross section of the Primakoff process

In the massless ALP limit,

$$\frac{d\sigma_{\gamma N}}{d\theta_a} \approx -\frac{1}{16}\alpha g_{a\gamma\gamma}^2 Z^2 F(|t|)^2 \frac{(4E_a^2 t + m_a^4)}{t^2}\theta_a$$

with

$$t = -\frac{m_a^4}{4E_a^2} - p_T^2 + 2E_a\sqrt{p_T^2}\theta_a \cos\phi - E_a^2\theta_a^2$$

Photon number density profile

Meson (e.g., π^0) decays are the dominant source of the photons.

$$n_\gamma(E_a, p_T^2) = \left|\frac{dE_\pi}{dE_\gamma}\right| \frac{dN_\pi}{dE_\pi} w(p_T^2)$$

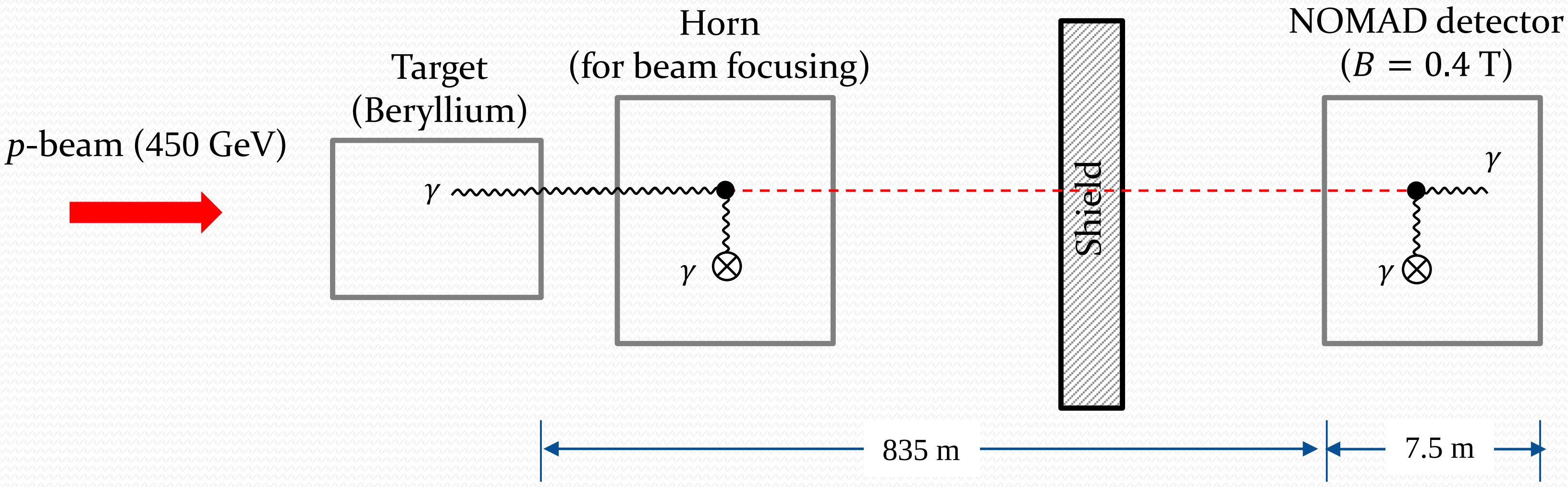
$$\frac{d\sigma}{dE_\pi} \propto E_\pi \left(1 - \frac{E_\pi}{E_{\text{beam}}}\right)^{c_\alpha} \left(1 + c_\beta \frac{E_\pi}{E_{\text{beam}}}\right) \times \left(\frac{E_\pi}{E_{\text{beam}}}\right)^{-c_\gamma},$$

$$E_\gamma = E_\gamma^*(\gamma_\pi + \sqrt{\gamma_\pi^2 - 1}\cos\theta_\gamma^*) \rightarrow E_\pi \approx \frac{m_\pi}{E_\gamma^* + \sqrt{E_\gamma^{*2} - p_T^2}} E_\gamma$$

$$w(p_T^2) = \left|\frac{d\cos\theta_\gamma^*}{dp_T^2}\right| w(\cos\theta_\gamma^*) = \frac{1}{4E_\gamma^*\sqrt{E_\gamma^{*2} - p_T^2}}$$

BMPT model [Bonesini, Marchionni, Pietropaolo, Tabarelli (2001)] for our initial estimate

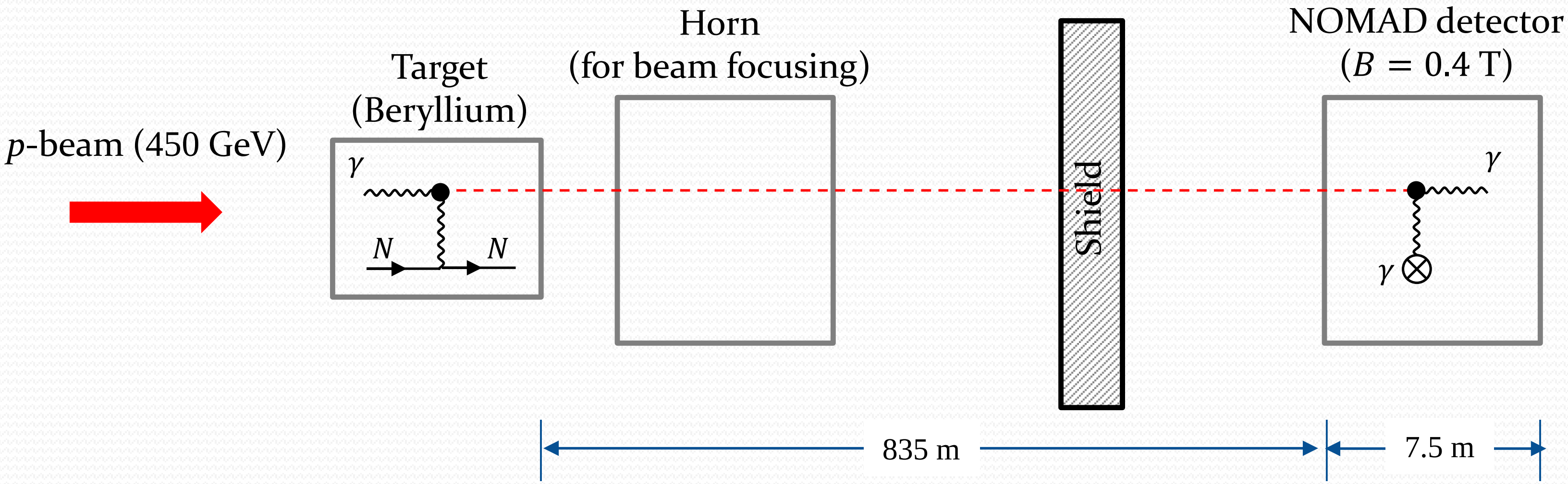
Application: NOMAD



Exp.	B [Tesla]	L [m]	A [cm^2]	θ_a^{max} [mrad]
NOMAD [33]	0.4	7.5	3.8×10^4	2.1

- Original ALP search in NOMAD: Similar to the idea of LSW, but the **laser** is replaced by the **target material**
- Selecting events with energy between 5 and 140 GeV

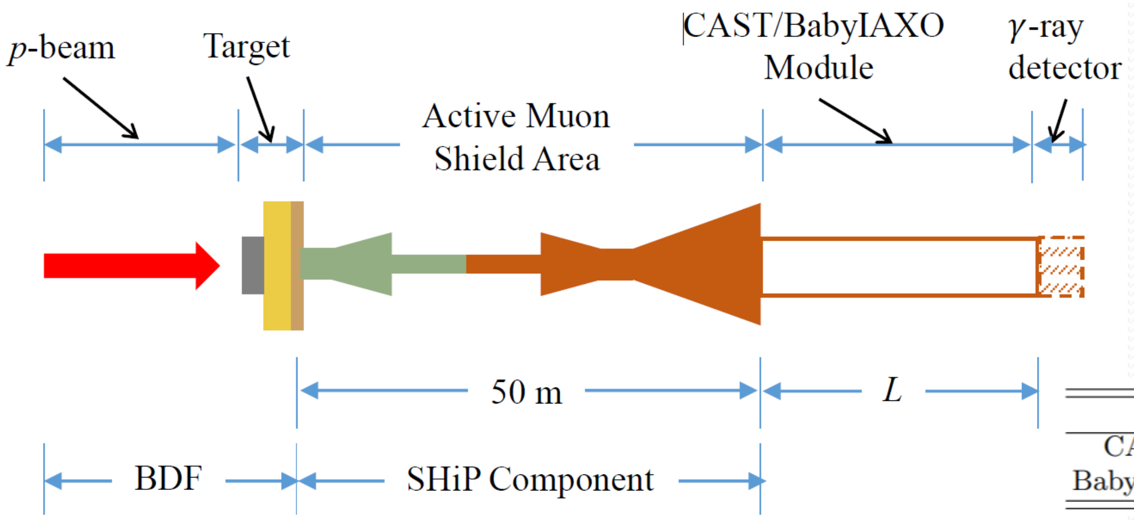
Application: NOMAD



Exp.	B [Tesla]	L [m]	A [cm^2]	θ_a^{max} [mrad]
NOMAD [33]	0.4	7.5	3.8×10^4	2.1

- Why not considering ALPs inside the target?
- Selecting events with energy between 50 and 140 GeV $\Rightarrow$ Restricting our estimates to the phase space where the negligible transverse momentum approximation and the limit of relativistic mesons are valid
- Considering the expected neutrino background 272 ± 18 events which can occur in the preshower region or in the upstream region

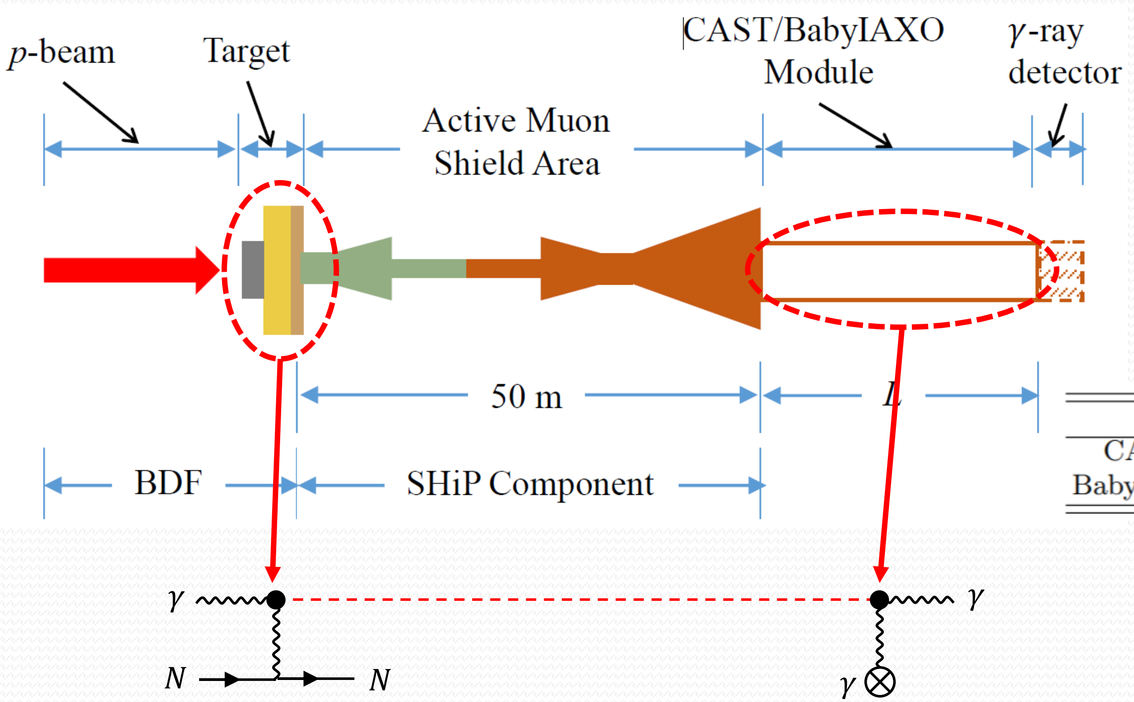
Application: BDF/SHiP+CAST/BabyIAXO



Exp.	B [Tesla]	L [m]	A [cm^2]	θ_a^{max} [mrad]
CAST [27]	8.4	9.26	14.5	0.36
BabyIAXO [28]	2	10	7.7×10^3	8.3

- Recycling the magnets from CAST or BabyIAXO experiments, after they are decommissioned, and locating them at the BDF complex (400 GeV proton beam), possibly after its first use with the SHiP experiment. ⇒ Possibly **low-cost experiments**!

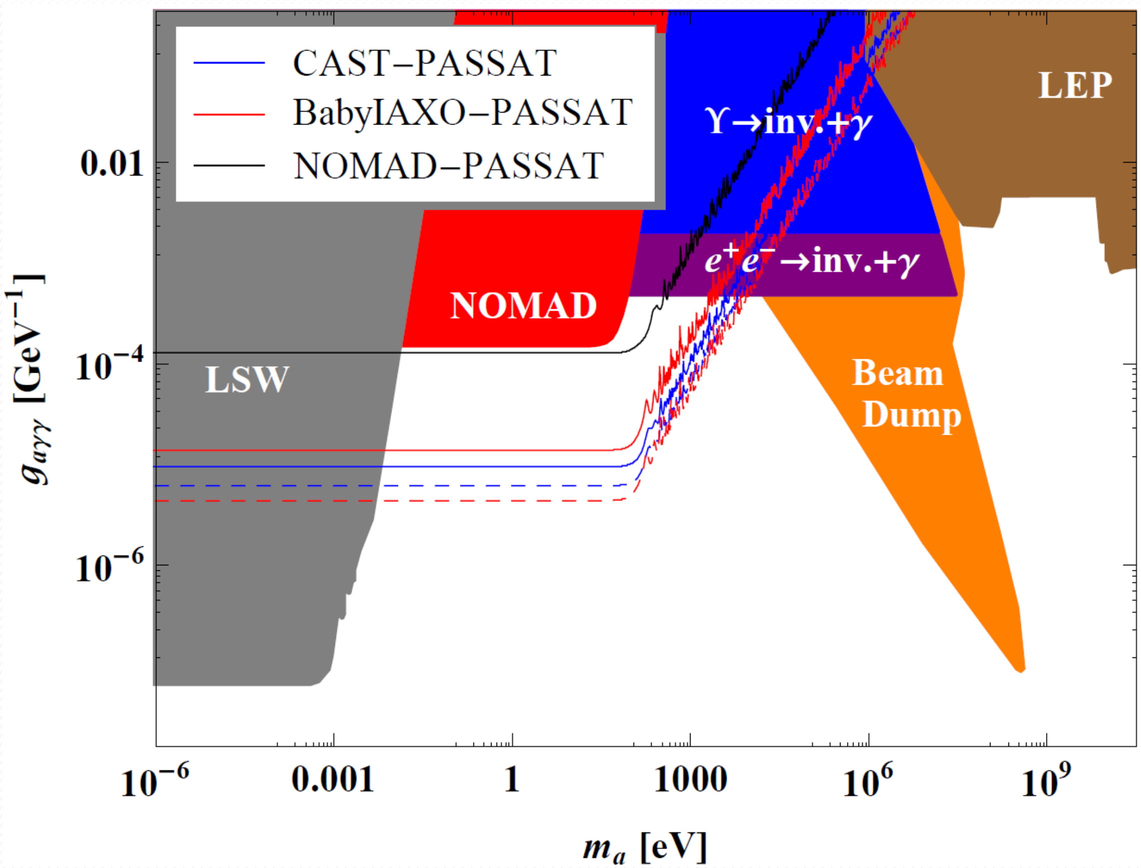
Application: BDF/SHiP+CAST/BabyIAXO



Exp.	B [Tesla]	L [m]	A [cm^2]	$\theta_a^{\max}$ [mrad]
CAST [27]	8.4	9.26	14.5	0.36
BabyIAXO [28]	2	10	7.7×10^3	8.3

- Considering signal events with $E_a > 50$ GeV $\Rightarrow$ Restricting our initial estimates to the phase space where the negligible transverse momentum approximation and the limit of ultra relativistic mesons are valid
- > 10 background events (ν elastic scattering in the detector calorimeters) expected for 2×10^{20} POT. (in-situ background estimate possible)

Expected Experimental Sensitivities



- ✓ NOMAD: 1.08×10^{19} POT collected
- ✓ CAST/BabyIAXO: 2×10^{20} POT assumed

- ✓ Showing only bounds from lab-based ALP searches
- ✓ Dashed lines are the corresponding sensitivities with prospective *B* of 20 T for CAST-PASSAT and BabyIAXO-PASSAT.

Conclusions

- We have proposed a novel method to search for ALPs at particle accelerator experiments.
- The results suggest that PASSAT should probe a wide range of parameter space that none of the lab-produced ALP search experiments have ever explored.
- The expected experimental sensitivity covers regions explored by the CAST helioscope experiment, providing a conservative and complementary probe.
- The experimental sensitivity also extends into regions that are currently solely constrained by astrophysical observations (e.g., HB stars).
- A more dedicated study with detector effects included (by GEANT and Fluka) is being prepared. Please stay tuned!