Search for axion-like particles at proton beam dumps

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15th March 2022

Introduction

Axion-like particle:

- BSM pseudoscalar a whose interactions respect an approximate shift symmetry $a \to a + c$
  - coupled to any SM field via dim-5 operators

$$\frac{C_{aVV}}{\Lambda} a V^{\mu\nu} \tilde{V}_{\mu\nu} \; , \; \frac{C_{aff}}{\Lambda} (\partial^{\mu} a) \bar{f} \gamma_{\mu} \gamma_5 f$$

  - ALP-Higgs coupling for dim ≥ 6

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- pseudo-Nambu-Goldstone boson (often elementary but not necessarily):
  - relic of spontaneously broken global symmetry (at $\Lambda \gg \Lambda_{\mathrm{EW}}$) of SM extension
  - (explicitly softly broken by ALP mass $m_{a,0} \ll \Lambda$)

Introduction

Motivation:

- New global symmetries ubiquitous in BSM theories:
  - Accidental symmetries in theories extending SM symmetry group
  - Compactification in theories with extra dimensions

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  - Compactification in theories with extra dimensions
- Dark matter:
  - $m_a \ll \Lambda \Rightarrow$ DM candidates or SM-DM mediators

Direct searches for ALPs

sub-MeV masses:

- helioscopes, haloscopes, light shining through wall
- effective ALP-photon coupling

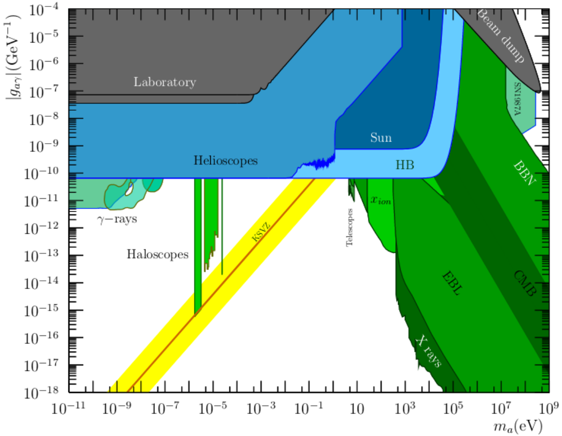

Figure: Current constraints in $(g_{a\gamma\gamma}, m_a)$ parameter space[1]

[1] I. G. Irastorza, J. Redondo, *New experimental approaches in the search for axion-like particles*, [1801.08127]

Direct searches for ALPs

sub-MeV masses:

- helioscopes, haloscopes, light shining through wall
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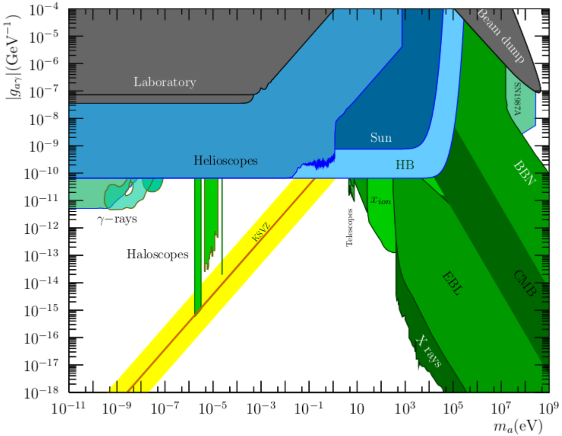
above MeV:

- collider experiments, beam dump experiments
- lots of ALP-SM interactions to investigate:
  - ALP decays: $\gamma\gamma$, $\ell\ell$, hadronic
  - many possible ALP production modes



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ALPINIST

Axion-Like Particles In Numerous Interactions Simulated and Tabulated

- A universal framework for study of ALPs at BD experiments[2]

Courtesy of B. Döbrich

Allows:

- more efficient simulation of beam-dump experiment sensitivity
- interpretation of results for any ALP model

[2] J. Jerhot, B. Döbrich, F. Ertas, F. Kahlhoefer, and T. Spadaro, *ALPINIST*, [2201.05170]

ALPINIST

Number N_{det} of expected ALPs at the detector factorizes into:

$$N_{\text{det}} = \int \mathrm{d}\theta_a \mathrm{d}E_a \boxed{\frac{\mathrm{d}^2 N\left(m_a, \mathbf{C}\right)}{\mathrm{d}\theta_a \mathrm{d}E_a}} \times \boxed{p_{\text{det}}\left(m_a, \Gamma_a, \theta_a, E_a, \mathbf{C}\right)}$$

- $\mathrm{d}^2 N/\mathrm{d}\theta_a \mathrm{d}E_a$ - ALP spectrum produced at the target
- p_{det} - probability that given ALP leads to an observable signal

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ALPs can be produced via different processes:

$$\frac{\mathrm{d}^2 N\left(m_a, \mathbf{C}\right)}{\mathrm{d}\theta_a \mathrm{d}E_a} = \sum_i \frac{\mathrm{d}^2 N_i\left(m_a, \mathbf{C}\right)}{\mathrm{d}\theta_a \mathrm{d}E_a}$$

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- coupling affects the normalisation but not the spectrum
- we can evaluate for some reference $\mathbf{C}_{\text{ref}}$ and re-scale with $f_i(\mathbf{C}, \mathbf{C}_{\text{ref}})$ later

ALPINIST - production

Primakoff process (ALP photo-production):

$$\frac{d^2N}{d\theta_a dE_a} = \boxed{\frac{C_{\gamma\gamma}^2}{\Lambda^2}} \frac{8e^4}{\sigma_N} \frac{\sin\theta_a}{\pi E_{\text{beam}}} \times$$
$$\times \int dp_t^2 d\phi_a \frac{d\sigma_{\gamma N}}{d\cos\theta_a} \boxed{\gamma(E_a, p_t^2)}$$

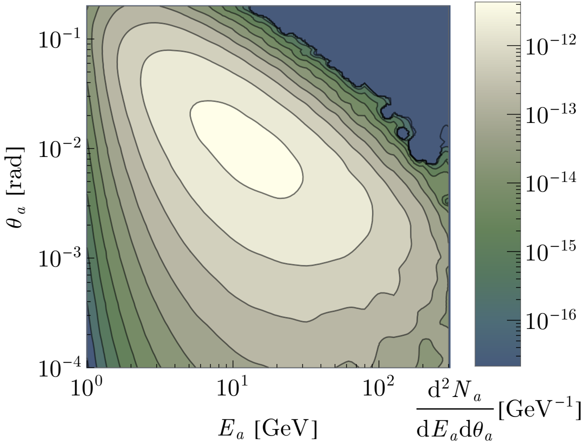

Figure: Primakoff ALP production differential yield for $m_a = 0.5$ GeV, $C_{\gamma\gamma}/\Lambda = 10^{-4}$, Cu dump, 400 GeV beam

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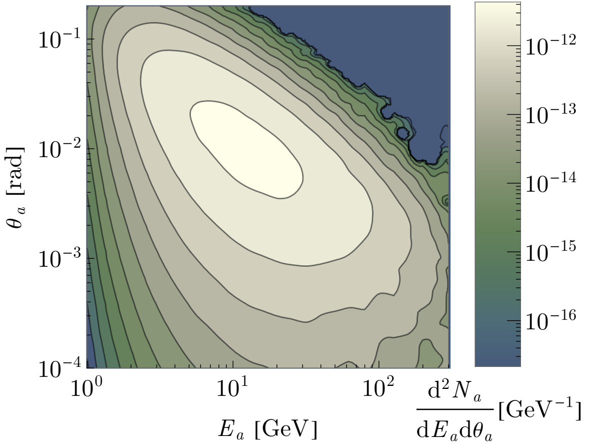

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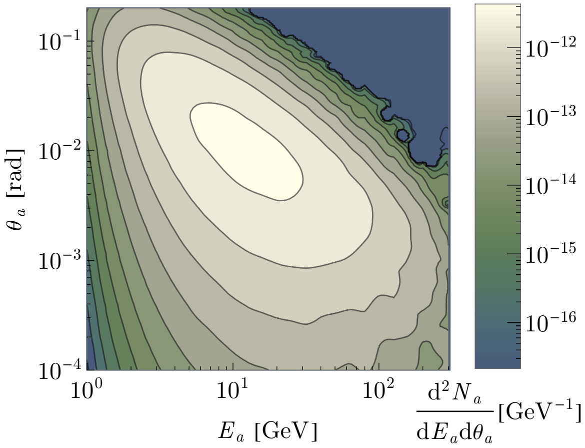
- elastic scattering of beam proton on target nuclei:
  - photon(-from-proton) distribution γ obtained using WWA



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- elastic scattering of beam proton on target nuclei:
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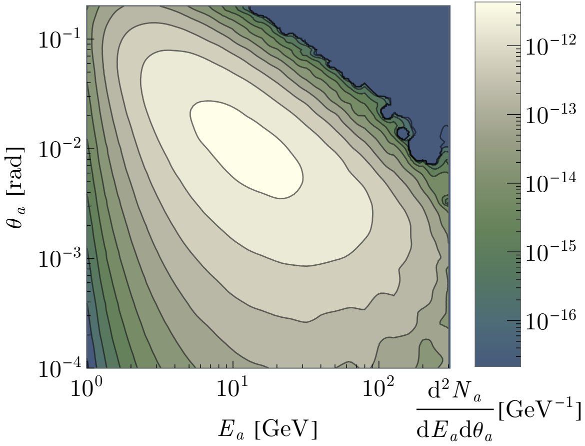
- on-shell photons from secondary π, η, η':
  - π, η, η' distributions from p-p collisions simulated with `PYTHIA`



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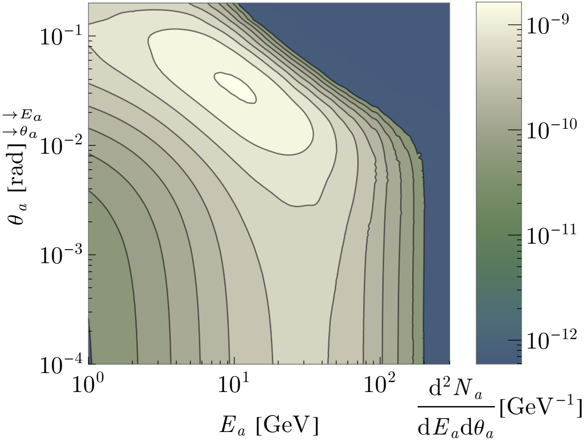
a-P mixing ($P \in \{\pi^0, \eta, \eta'\}$) production:

$$\frac{\mathrm{d}^2 N}{\mathrm{d}\theta_a \mathrm{d}E_a} = |\mathcal{F}_{\mathrm{VMD}}(m_a)|^2 \sum_P |\theta_{aP}|^2 \left. \frac{\mathrm{d}^2 N_P}{\mathrm{d}\theta_P \mathrm{d}E_P} \right|_{\substack{E_P \to E_a \\ \theta_P \to \theta_a}}$$



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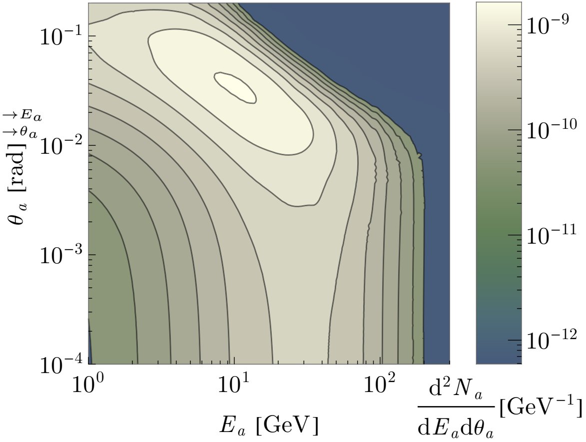

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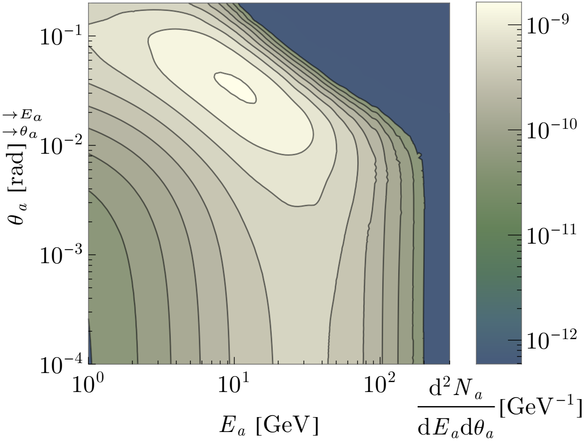

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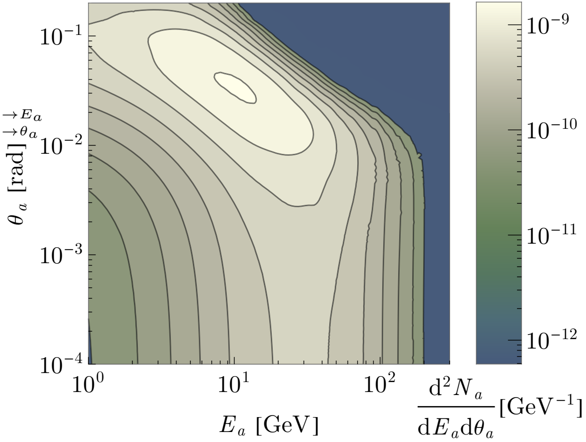

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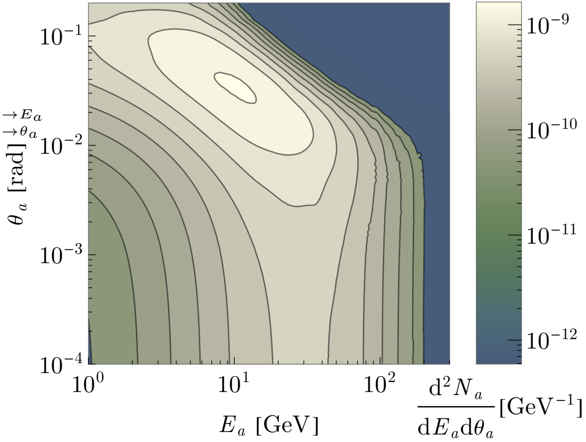
- reusing π, η, η' distribution from previous case
- $\mathcal{F}_{\mathrm{VMD}}$ to account for suppression of production cross section for $m_a \gg m_P$
- in general ALP has different mass than the original meson
  we require that $p_{a,\mathrm{cms}} = p_{P,\mathrm{cms}}$ and boost back to lab frame



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Production in rare decays:

- B and D mesons shorter decay length than nuclear interaction length of target

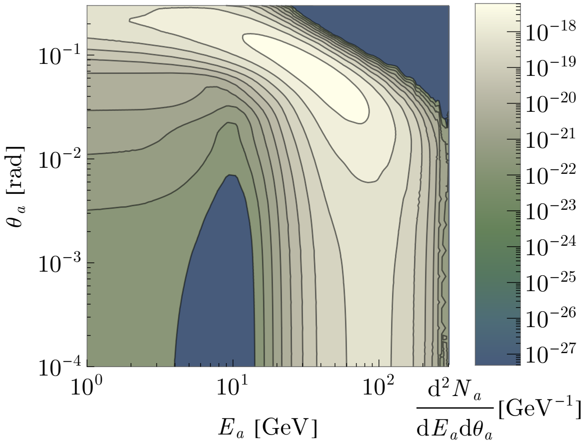

Figure: Differential yield of $m_a = 0.5$ GeV ALP produced in $B^{\pm,0} \to K^{\pm,0} + a$ assuming $\mathrm{BR}_{B\to K+a} = 10^{-10}$.

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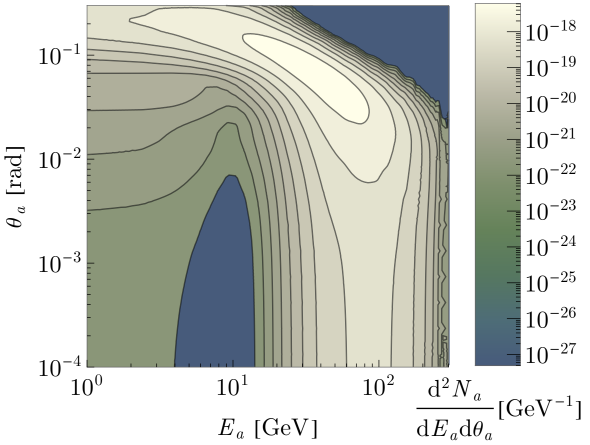

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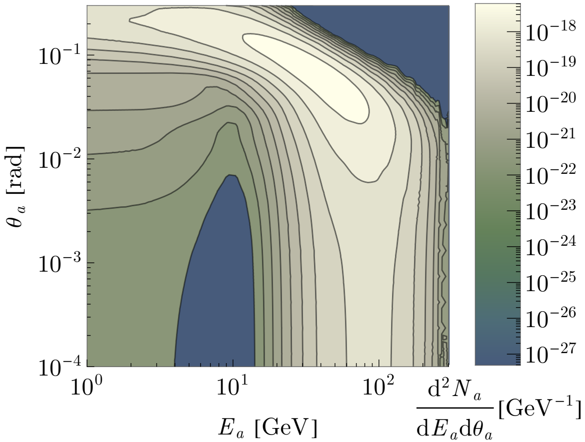

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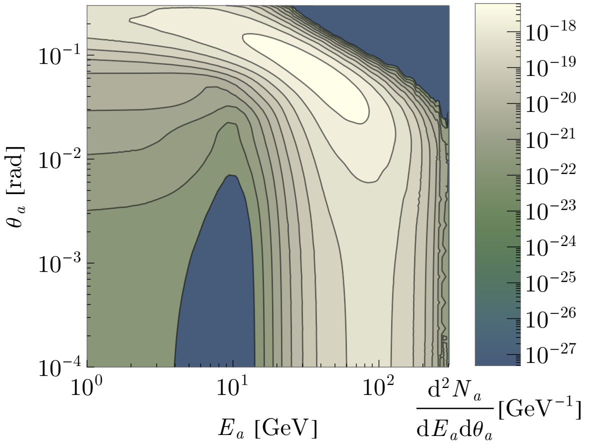
- $\mathrm{d}^2 N / \mathrm{d}\theta_a \mathrm{d}E_a$ obtained from simulation of B and D 2-body decays (B and D distribution from `PYTHIA`)

$$f_{BK}(\mathbf{C}, \mathbf{C}_{\mathrm{ref}}) = \mathrm{BR}_{B\to K+a} / \mathrm{BR}_{B\to K+a,\mathrm{ref}}$$



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detection probability depends on ALP decay final states:

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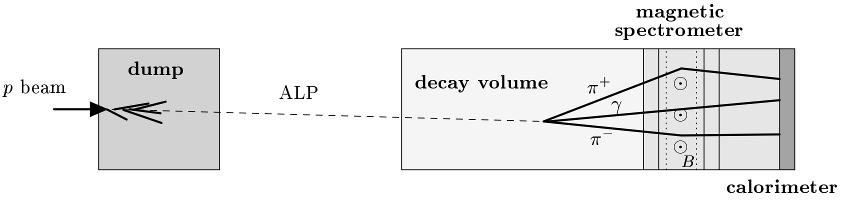
- we can re-scale with $\text{BR}_{a\to f}(m_a, \mathbf{C})$ later:

$$\begin{aligned} N_{\text{det}} &= \sum_{i,f} f_i(\mathbf{C}, \mathbf{C}_{\text{ref}}) \text{BR}_{a\to f}(m_a, \mathbf{C}) \times \int \mathrm{d}\theta_a \mathrm{d}E_a \frac{\mathrm{d}^2 N_i\left(m_a, \mathbf{C}_{\text{ref}}\right)}{\mathrm{d}\theta_a \mathrm{d}E_a} p_{\text{det},f}(m_a, \Gamma_a, \theta_a, E_a) \\ &= \sum_{i,f} M_{if}(m_a, \mathbf{C}) \times E_{\text{det},if}(m_a, \Gamma_a) \, , \end{aligned}$$

ALPINIST - decay

Evaluating $E_{\text{det},if}(m_a, \Gamma_a) = \int \mathrm{d}\theta_a \mathrm{d}E_a \frac{\mathrm{d}^2 N_i\left(m_a, \mathbf{C}_{\text{ref}}\right)}{\mathrm{d}\theta_a \mathrm{d}E_a} p_{\text{det},f}(m_a, \Gamma_a, \theta_a, E_a)$:

- $p_{\text{det},f}$ is a complicated function of final state kinematics and detector geometry



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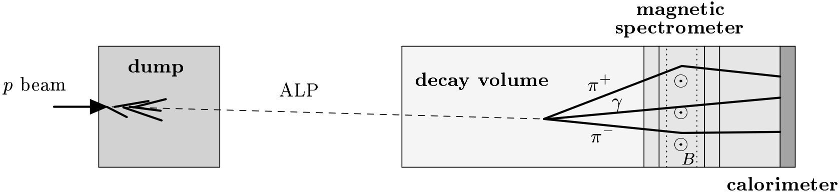
- $p_{\text{det},f}$ is a complicated function of final state kinematics and detector geometry



$$p_{\text{det},f}(m_a,\Gamma_a,\theta_a,E_a) = \sum_{k=1}^{N} \frac{\Theta_{\text{det},f}(m_a,\Gamma_a,\theta_a,E_a;\{l,a_1,..a_n\}^k_{\text{ran}})}{N},$$

in k-th simulation we pick random $\{l,a_1,..a_n\}^k_{\text{ran}}$ according to their distributions:

- l: exponential dist. $p(l) = l_a^{-1}\exp(-l/l_a)$
- 2-body decay: a_1, a_2 uniform dist.; 3-body decay: according to Dalitz-plot

ALPINIST - decay

Dalitz plot density generally non-uniform:

- momenta of outgoing particles depending on the model (χPT and VMD framework used)

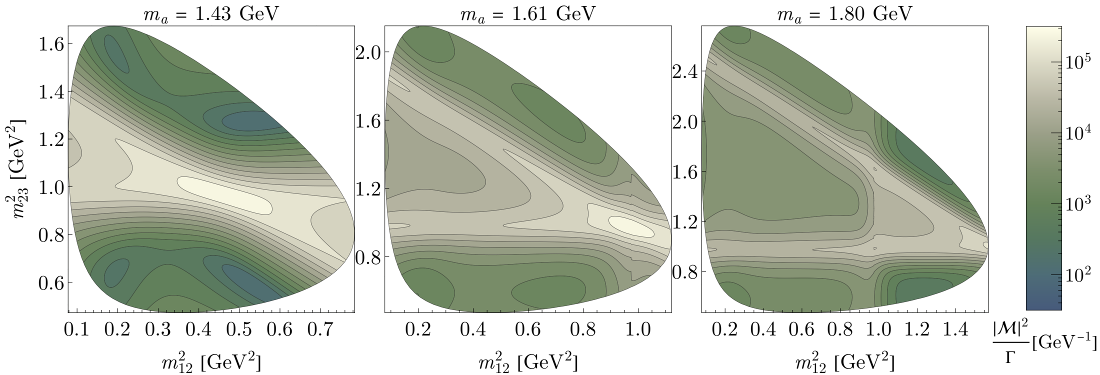
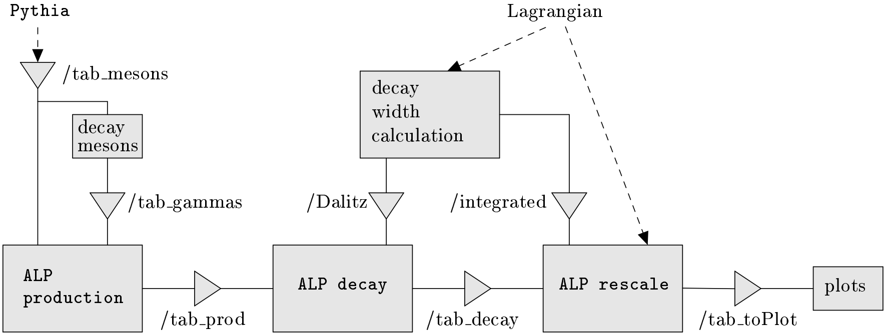


Figure: Dalitz plot density for various ALP masses used for the $a \to \pi^+\pi^-\eta$ decay.

ALPINIST - framework

Putting it all together:

- $E_{\text{det},if}(m_a, \Gamma_a)$ obtained numerically (CPU time demanding), distributions tabulated
- $M_{if}(m_a, \mathbf{C})$ analytic re-scaling



ALPINIST - experiments

Experiment	Status	E_{beam} [GeV]	N_{POT} [10^{18}]	$l_{\text{n,DV}}$ [m]	z_{DV} [m]	Ω_{cov} [μsr]
CHARM	completed	400	2.4	35	480	34
NuCal	completed	70	1.7	23	64	700
NA62	running	400	10	139	82	84
DUNE ND	proposed	120	11000	10	575	36
DarkQuest	proposed	120	1.44	13.5	5	12000
SHADOWS	proposed	400	10	26	10	9200
SHiP	proposed	400	200	50	45	4500

Table: Basic parameters for various experiments.

ALPINIST - results

Case of couplings to SM gauge bosons:

$$\mathcal{L}_{a,\text{int}} = g'^2 \frac{C_{BB}}{\Lambda} a B^{\mu\nu} \tilde{B}_{\mu\nu} + g^2 \frac{C_{WW}}{\Lambda} a W^{\mu\nu} \tilde{W}_{\mu\nu} + g_s^2 \frac{C_{GG}}{\Lambda} a G^{\mu\nu} \tilde{G}_{\mu\nu}.$$

Four different benchmark scenarios:

(i)	***B* dominance:**	$C_{BB} \neq 0;$	$C_{WW} = C_{gg} = 0$
(ii)	***W* dominance:**	$C_{WW} \neq 0;$	$C_{BB} = C_{gg} = 0$
(iii)	**Gluon dominance:**	$C_{gg} \neq 0;$	$C_{BB} = C_{WW} = 0$
(iv)	**Co-dominance:**	$C_{BB} = C_{WW} = C_{gg} \neq 0$	

ALPINIST - results

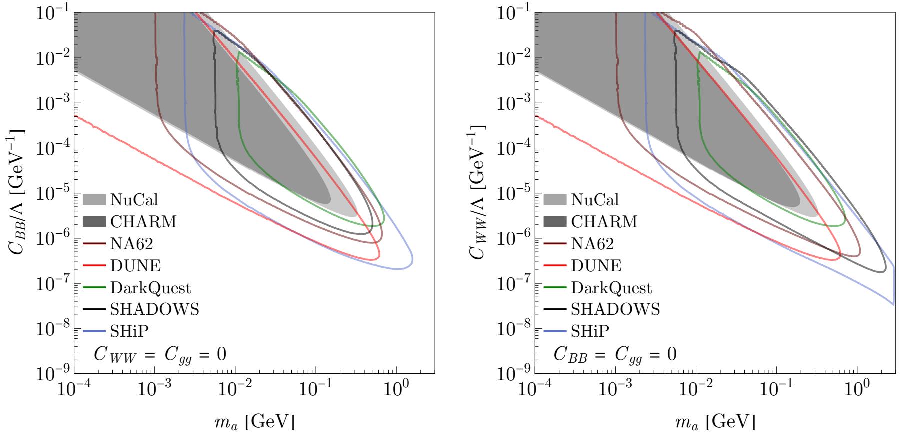


Figure: 90% CL exclusions limits for scenarios (i) (left) and (ii) (right)

ALPINIST - results

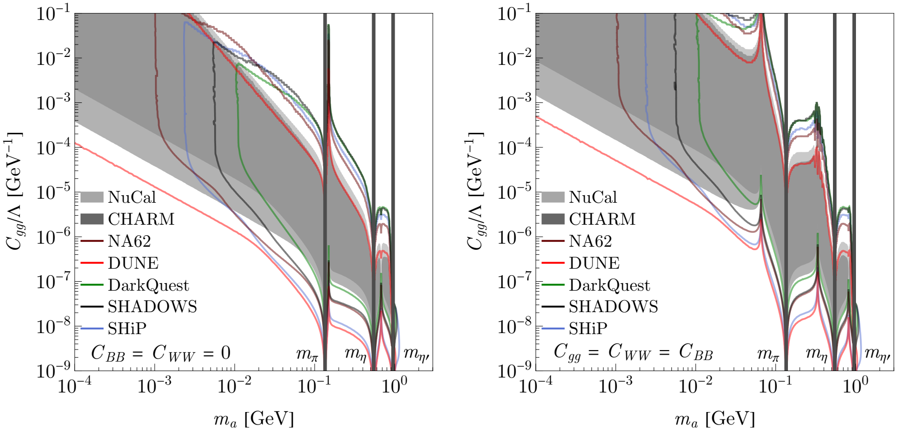


Figure: 90% CL exclusions limits for scenarios (iii) (left) and (iv) (right), 2γ decay

ALPINIST - results

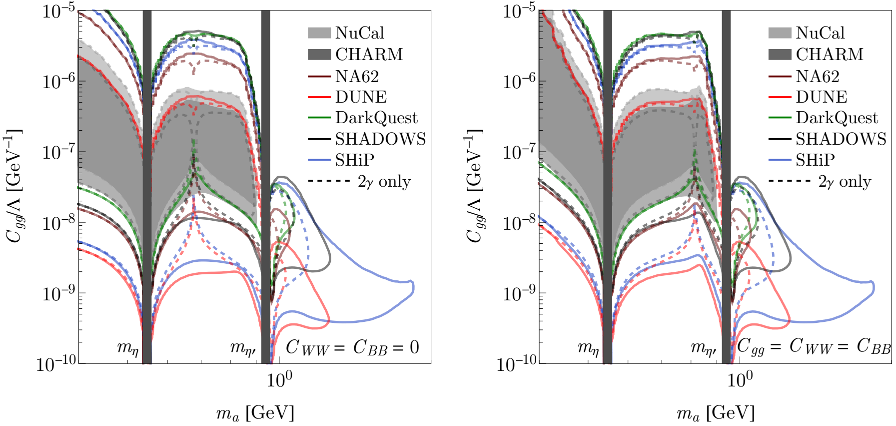


Figure: 90% CL exclusions limits for scenarios (iii) (left) and (iv) (right), hadronic decays

Conclusion

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- Beam dump experiments are among the most promising strategies to search for ALPs
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  - need for a universal framework covering wide range of possible UV completions
- Suggested approach for beam dump experiments - `ALPINIST`
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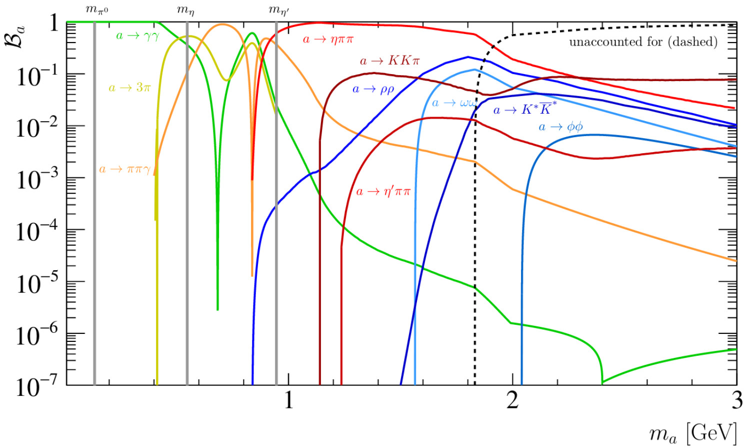
Thank you for your attention!

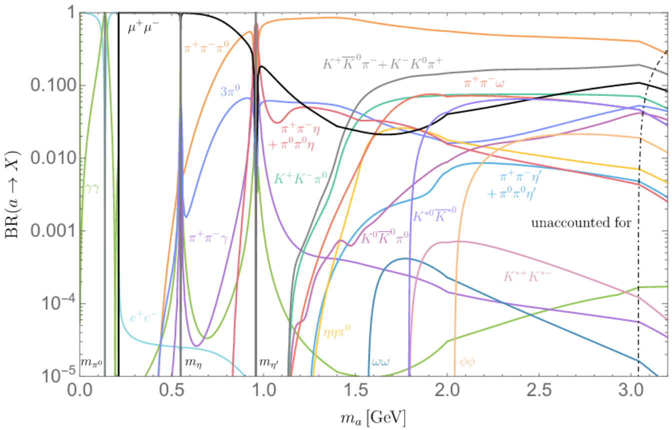
Backup slides

Branching fractions - gluonic coupling[3]



[3] D. Aloni, Y. Soreq, and M. Williams, *Coupling QCD-Scale Axionlike Particles to Gluons*, [1811.03474]

Branching fractions - fermionic coupling[4]



[4] H.-C. Cheng, L. Li, and E. Salvioni, *A Theory of Dark Pions*, [2110.10691]