Axion-like particles at accelerators

Felix Kahlhoefer
FIPs 2020
31 August – 4 September 2020
Online

Based on work by Fatih Ertas as well as collaboration with Babette Döbrich, Matthew J. Dolan, Torben Ferber, Christopher Hearty, Joerg Jaeckel, Jan Jerhot, Kai Schmidt-Hoberg and Tommaso Spadaro

Emmy Noether-Programm
DFG Deutsche Forschungsgemeinschaft

Institute for Theoretical Particle Physics and Cosmology
RWTH AACHEN UNIVERSITY

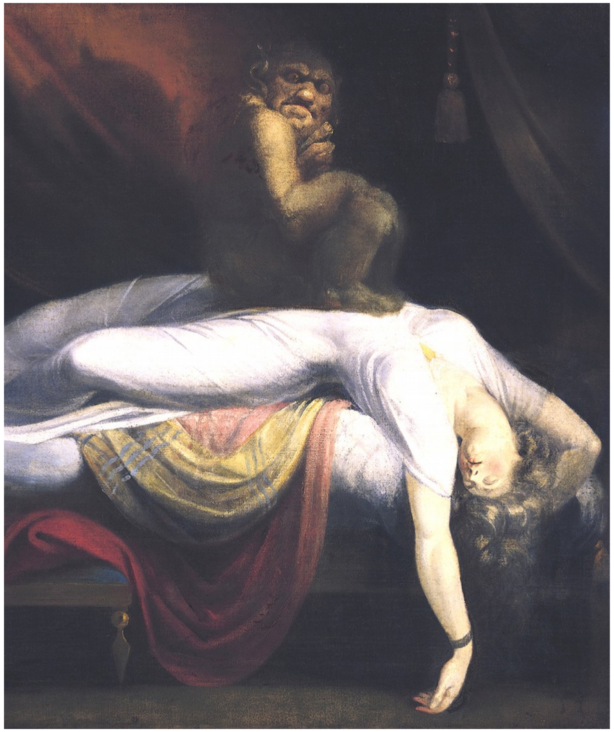
Axion-like particles (ALPs)

- Models of QCD axions typically predict specific coupling patterns and relate the coupling strength and axion mass

- **Model-independent approach:** relax assumptions
  - Couplings can vary independently
  - No relation between couplings and mass
  - Consider generic effective interactions
  - Axion-like particles (ALPs)

Brivio et al., arXiv:1701.05379;
Izaguirre et al., arXiv:1611.09355;
Bauer et al., arXiv:1708.00443;

- In general ALPs can couple to
  - Electroweak gauge bosons
  - SM fermions
  - Gluons
  - SM Higgs bosons
  - All of the above



A generic Alp causing an “Alptraum”

Part I: ALPs coupled to EW gauge bosons

- The general effective Lagrangian for an ALP coupled to EW gauge bosons is

$$\mathcal{L} = \frac{1}{2}\partial^\mu a\,\partial_\mu a - \frac{1}{2}m_a^2\,a^2 - \frac{c_B}{4\,f_a}\,a\,B^{\mu\nu}\,\tilde{B}_{\mu\nu} - \frac{c_W}{4\,f_a}\,a\,W^{i,\mu\nu}\tilde{W}^i_{\mu\nu}$$

- Such interactions arise e.g. from new heavy non-coloured fermions
- After electroweak symmetry breaking, this becomes

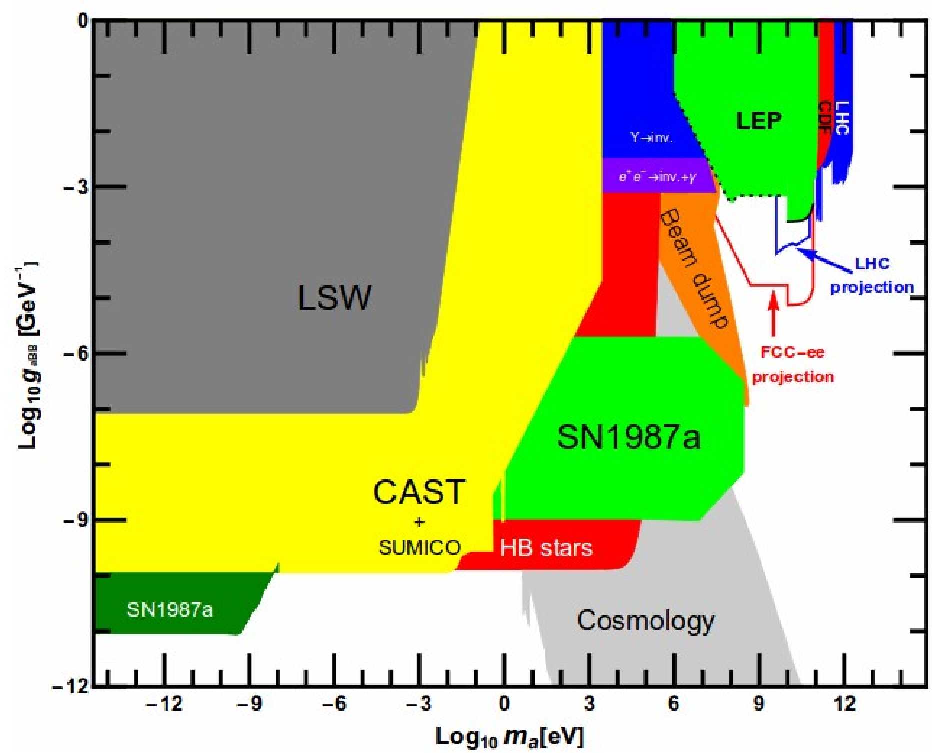
$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{g_{a\gamma Z}}{4}aF_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aZZ}}{4}aZ_{\mu\nu}\tilde{Z}^{\mu\nu} - \frac{g_{aWW}}{4}aW_{\mu\nu}\tilde{W}^{\mu\nu}$$

- Two interesting cases:
  - $c_B \sim c_W$: $g_{a\gamma Z} << g_{a\gamma\gamma}$ (photon couplings)
  - $c_B >> c_W$: $g_{a\gamma Z} \sim - g_{a\gamma\gamma}$ (hypercharge couplings)

Alonso-Álvarez et al., arXiv:1811.05466
Gavela et al., arXiv:1901.02031

Phenomenology of ALPs

- **Model-independent approach:** ALP mass and coupling strength can vary over many orders of magnitude
- ALP masses below the MeV scale
  - Very strong astrophysical constraints (cooling rates of helium burning stars)
  - Couplings to photons must be tiny
  - ALPs nearly stable – could be dark matter?

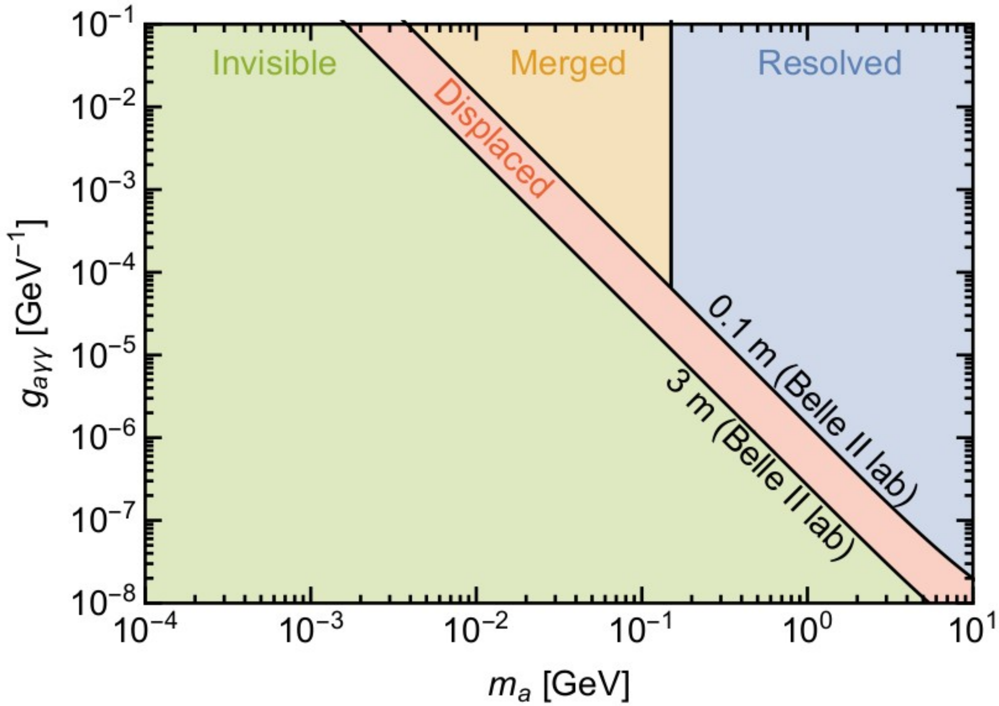


- Heavier ALPs
  - Couplings can be much larger
  - Decays happen much more quickly
  - Interesting implications for cosmology and particle physics
    - Big Bang Nucleosynthesis — Millea et al., arXiv:1501.04097, Depta et al., arXiv:2002.08370
    - Muon g – 2 — Marciano et al., arXiv:1607.01022; Bauer et al., arXiv:1704.08207
    - Mediator of dark matter interactions — Boehm et al., arXiv:1401.6458; Arcadi et al., arXiv:1711.02110; Bell et al., arXiv:1803.01574; Abe et al., arXiv:1810.01039; Ertas & FK, arXiv:1902.11070

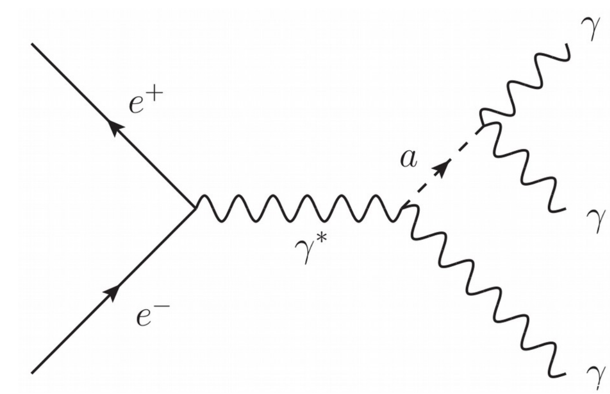
ALP decay length

- The best experimental strategy depends crucially on the ALP decay length

$$l_a = \beta\gamma\tau \approx \frac{64\pi\, E_a}{g_{a\gamma}^2\, m_a^4}$$

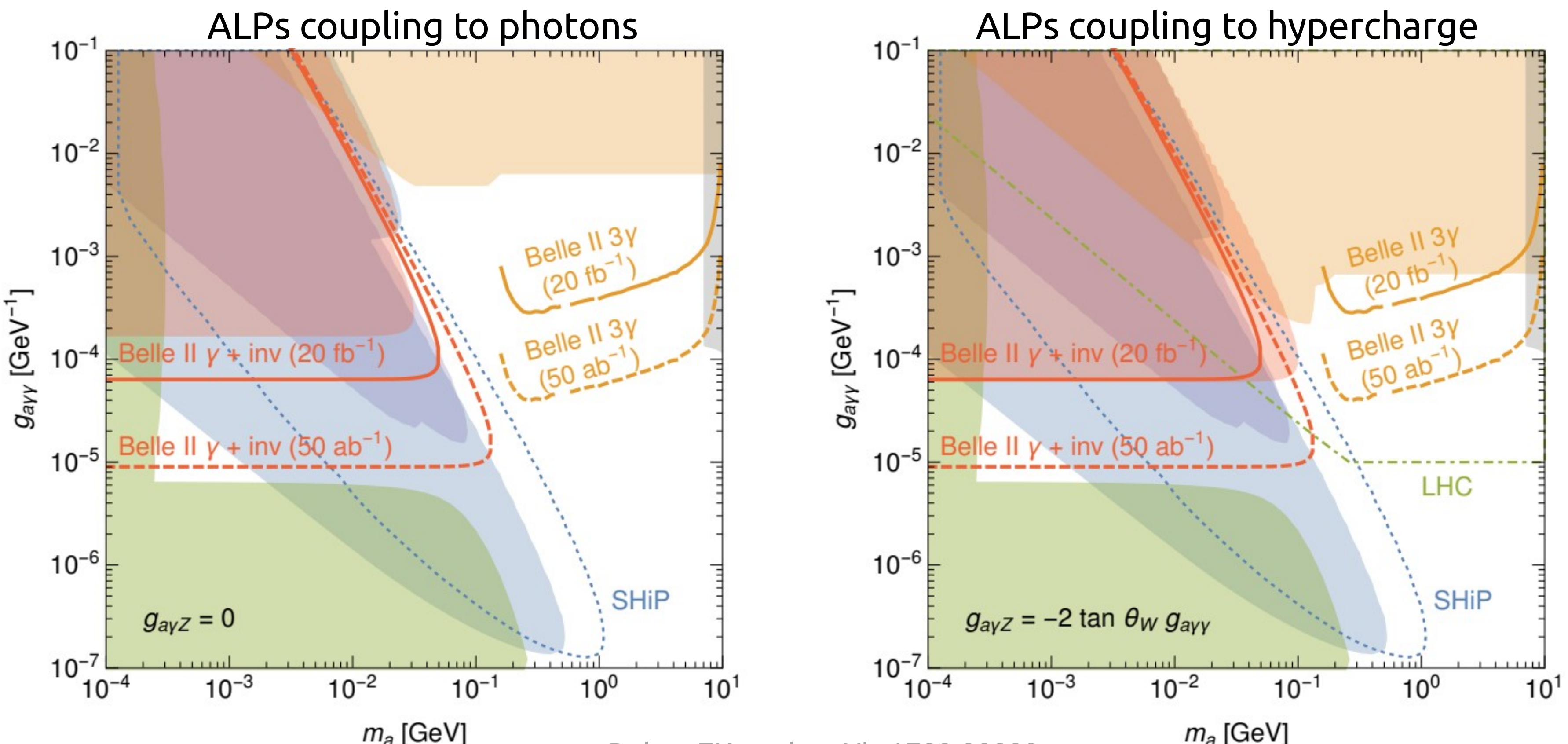


- For example, Belle II is ideally suited for exploring resolved regime (all three photons reconstructed)



- Discrimination from the dominant QED backgrounds can be achieved by searching for a peak in the di-photon invariant mass

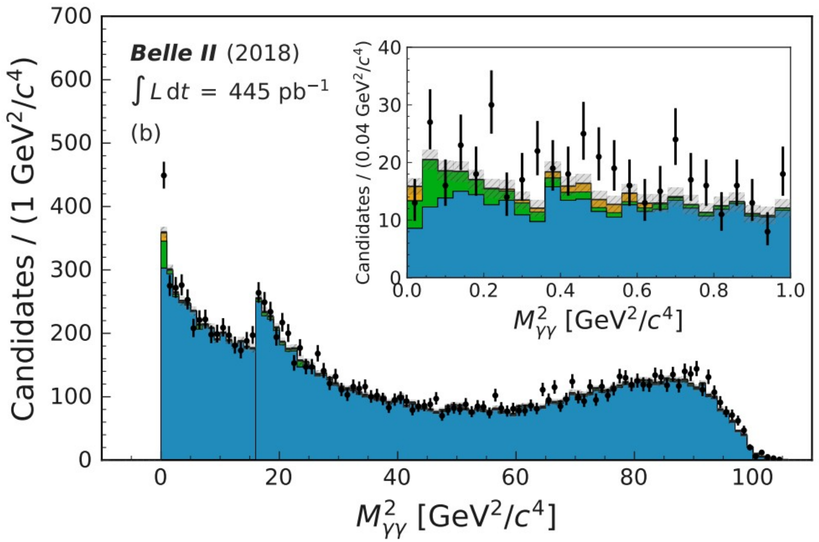
Projected sensitivities



Dolan, FK et al., arXiv:1709.00009

Important complementarity between Belle II, LHC and SHiP,
as well as between visible and invisible decay modes!

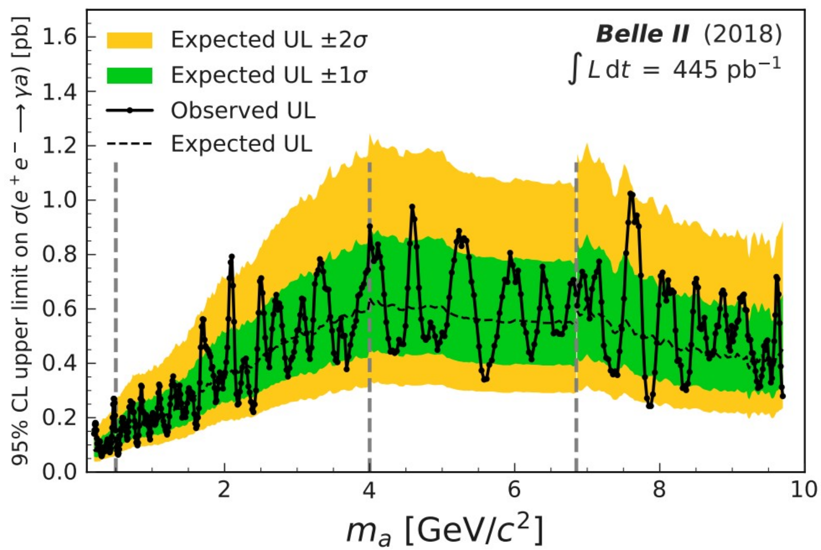
First results from Belle II

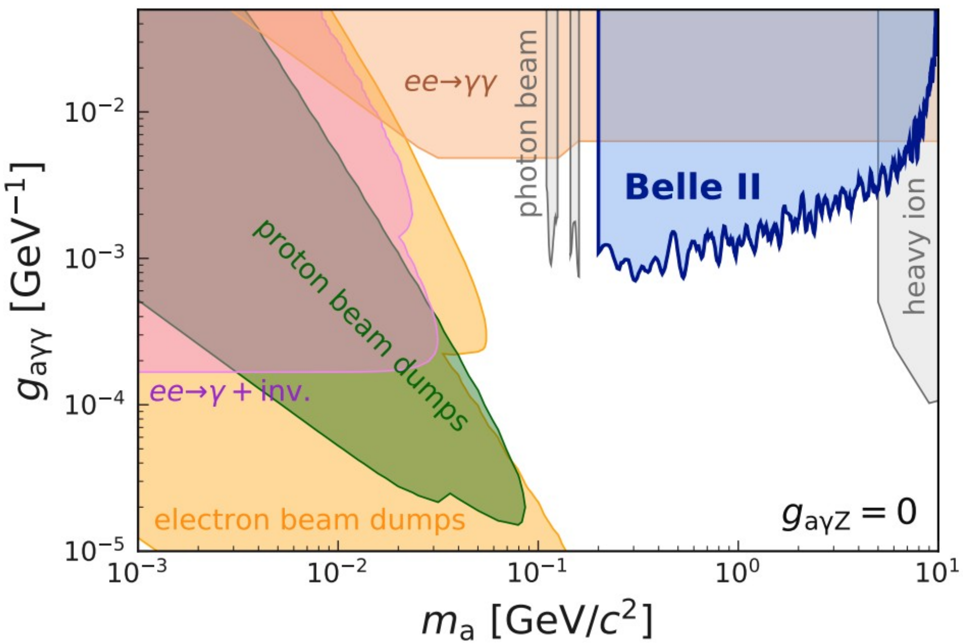


- Belle II recently published results from a first ALP search based on a luminosity of 445 pb^{-1}

arXiv:2007.13071

- Assuming sensitivity to scale proportional to √L, Belle II should be able to improve the bound on $g_{a\gamma\gamma}$ by more than an order of magnitude



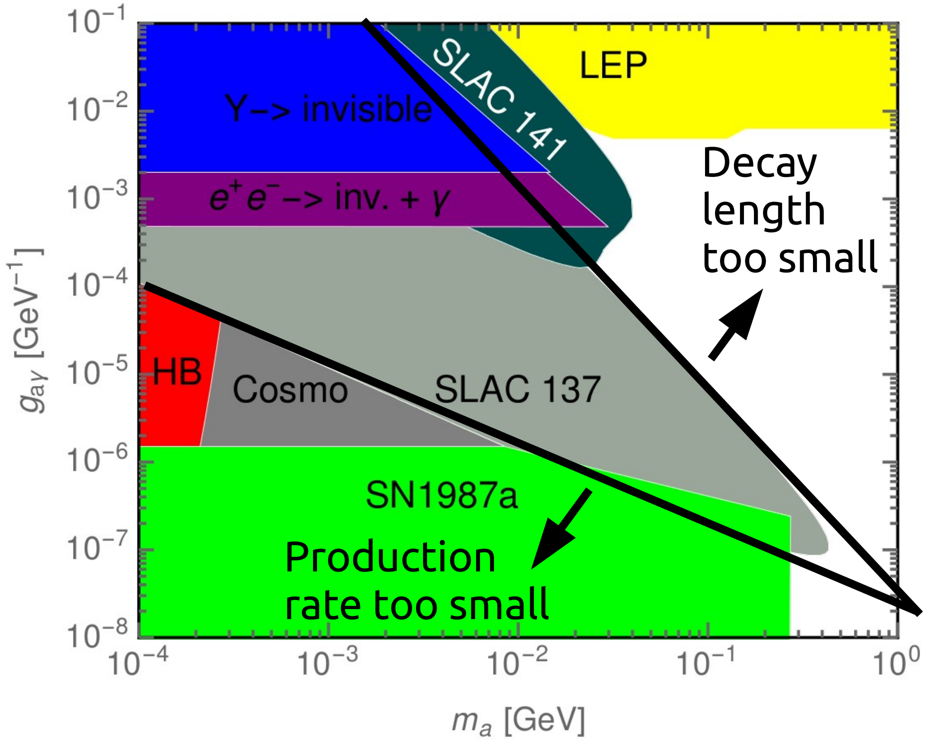


Displaced ALPs

- If the ALP decay length is of order of a few meters, interesting constraints come from beam dump experiments

Izaguirre et al., arXiv:1307.6554
Batell et al., arXiv:1406.2698

- The sensitivity of a given beam-dump experiment depends on:
  - The production cross section for ALPs in the target
  - The probability for ALPs to decay within the detector



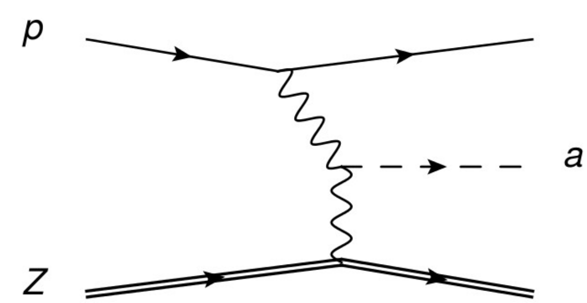
- Improve on existing bounds by increasing the beam energy

→ Proton beam dumps

ALP production in fixed-target experiments

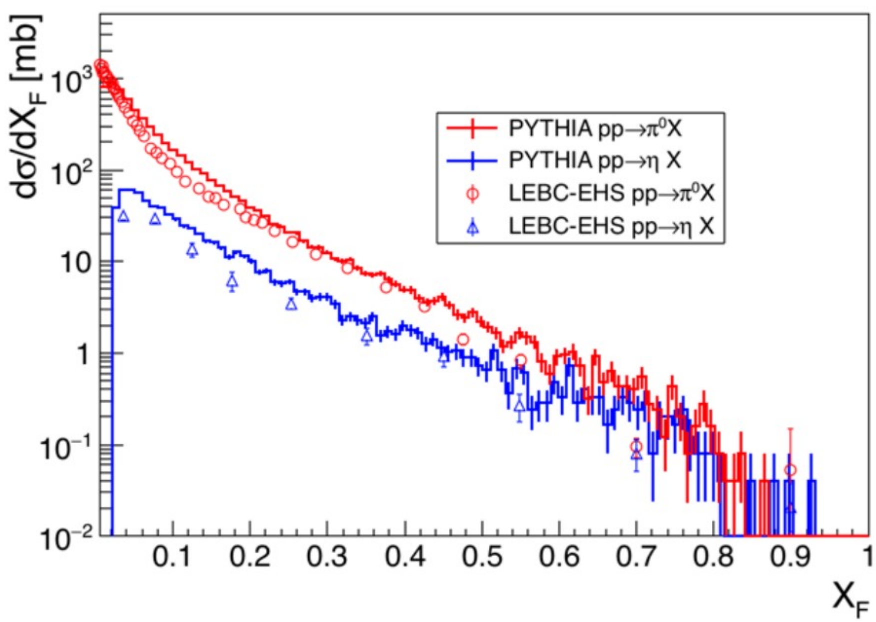
- **Conventional approach:** Replace beam of charged particles by equivalent photon distribution (Weizsäcker-Williams approximation) and consider Primakoff production

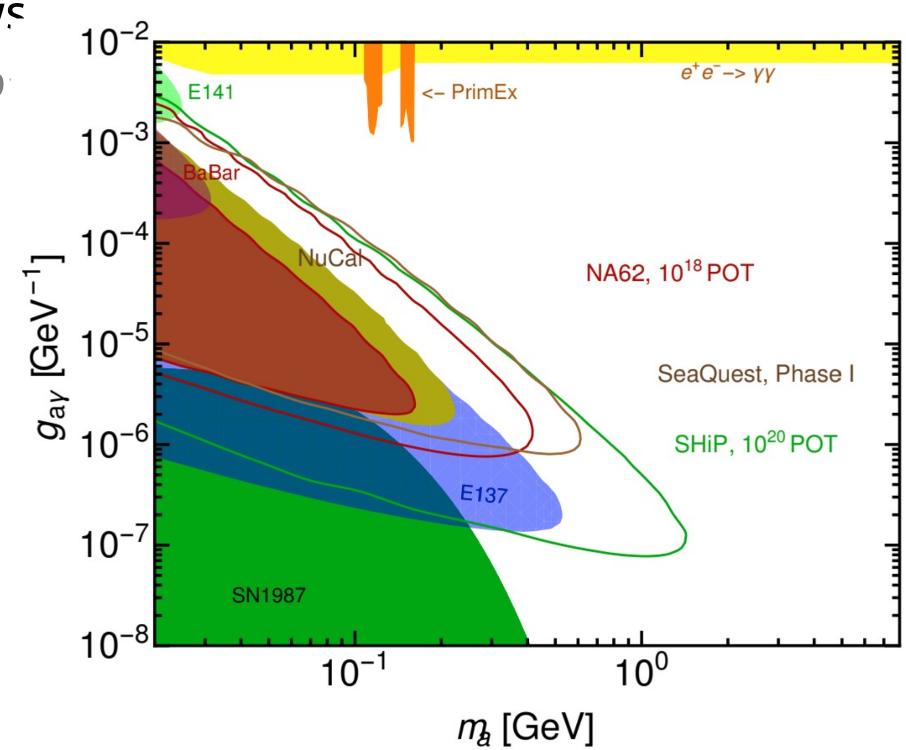
Döbrich, FK et al., arXiv:1512.03069



- For proton beams the dominant source of (hard) photons are those produced in meson decays

Döbrich et al., arXiv:1904.0209





Part II: ALPs coupled to SM fermions

- Consider the effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + \frac{\partial^\mu a}{\Lambda} \sum_F \bar{\Psi}_F \, C_F \, \gamma_\mu \, \Psi_F$$

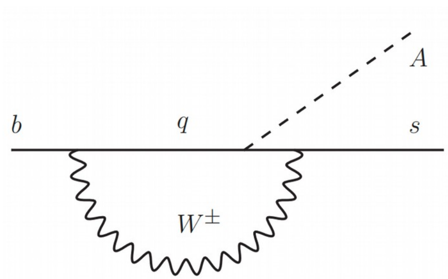
- Consequence 1: ALP-meson mixing

$$\pi^0 \to \pi^0 + \theta_{a\pi} a \approx \pi^0 + \epsilon \frac{K_{a\pi} \, m_a^2}{m_a^2 - m_\pi^2} a \,,$$

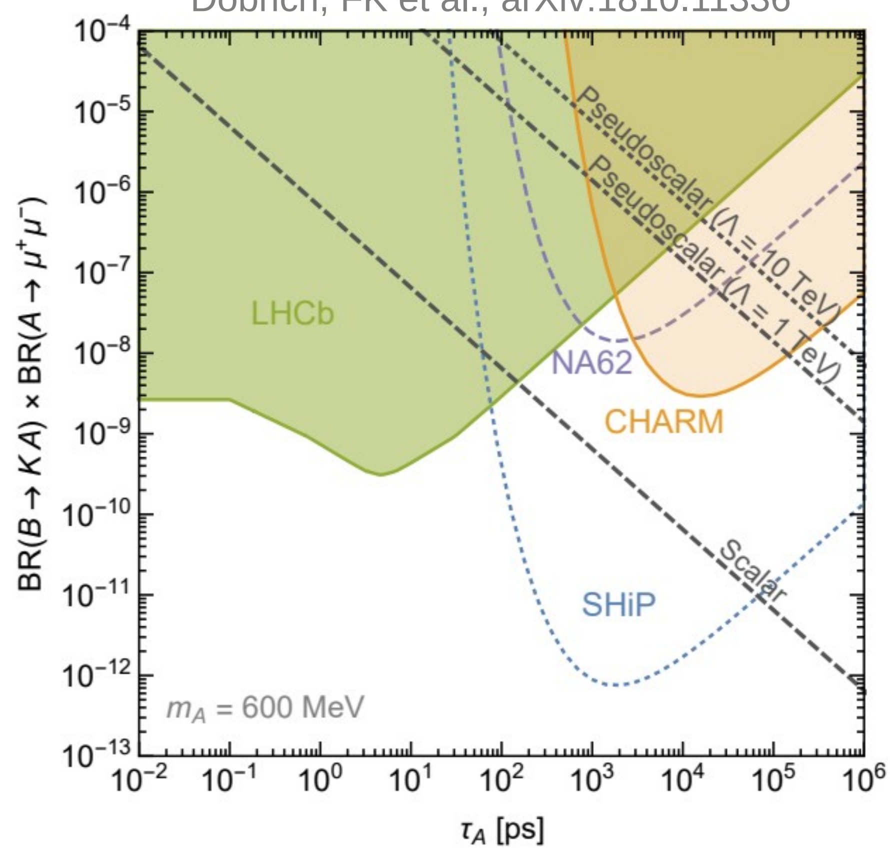
$$\eta \to \eta + \theta_{a\eta} a \approx \eta + \epsilon \frac{K_{a\eta} \, m_a^2 + m_{a\eta}^2}{m_a^2 - m_\eta^2} a \,,$$

$$\eta' \to \eta' + \theta_{a\eta'} a \approx \eta' + \epsilon \frac{K_{a\eta'} \, m_a^2 + m_{a\eta'}^2}{m_a^2 - m_{\eta'}^2} a$$

- Consequence 2: Rare meson decays



Döbrich, FK et al., arXiv:1810.11336



Searching for ALPs in kaon decays

- Tempting to estimate $B(K^+ \to \pi^+ a)$ by taking $B(K^+ \to \pi^+ \pi^0)$ and multiplying with the pion-axion mixing angle squared
- Because of the ΔI = 1/2 enhancement, the dominant contribution comes in fact from axion-eta and axion-eta' mixing:

Bardeen, Peccei & Yanagida (1987)
Alves & Weiner, arXiv:1710.03764

$$i\mathcal{M}(K^+ \to \pi^+ a)$$
$$\approx \theta_{a\pi}\, i\mathcal{M}(K^+ \to \pi^+\pi^0) + \theta_{a\eta}\, i\mathcal{M}(K^+ \to \pi^+\eta) + \theta_{a\eta'}\, i\mathcal{M}(K^+ \to \pi^+\eta')$$

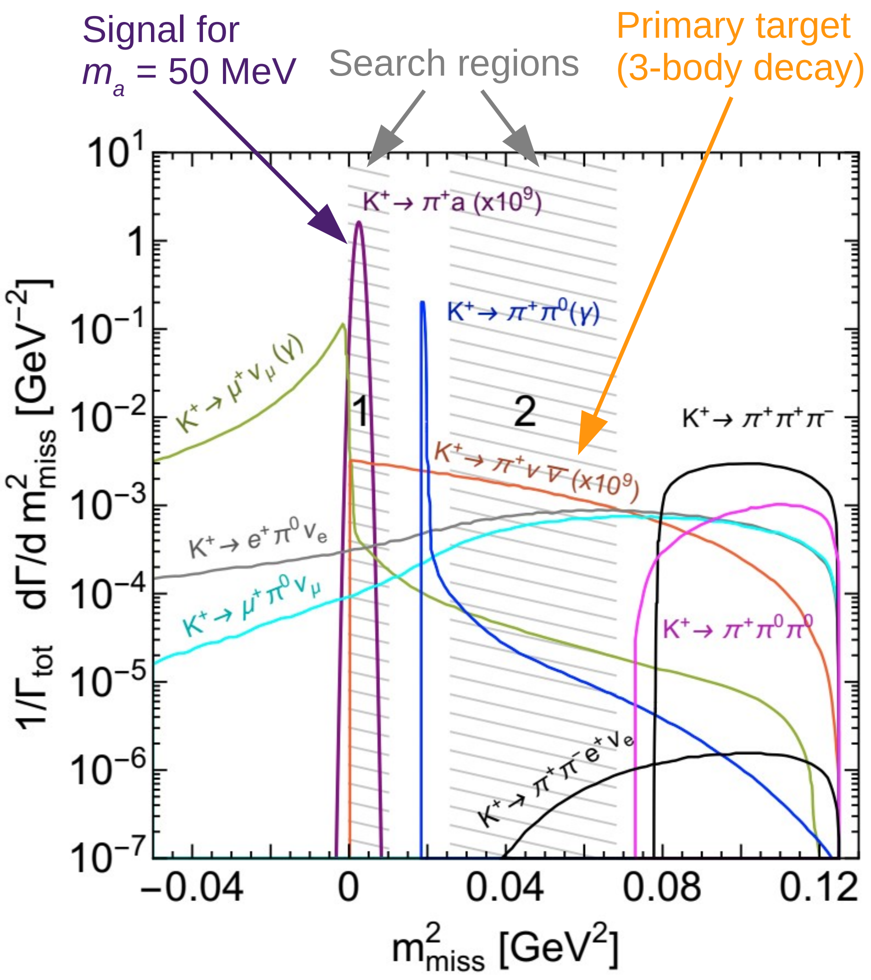
Off-shell amplitudes

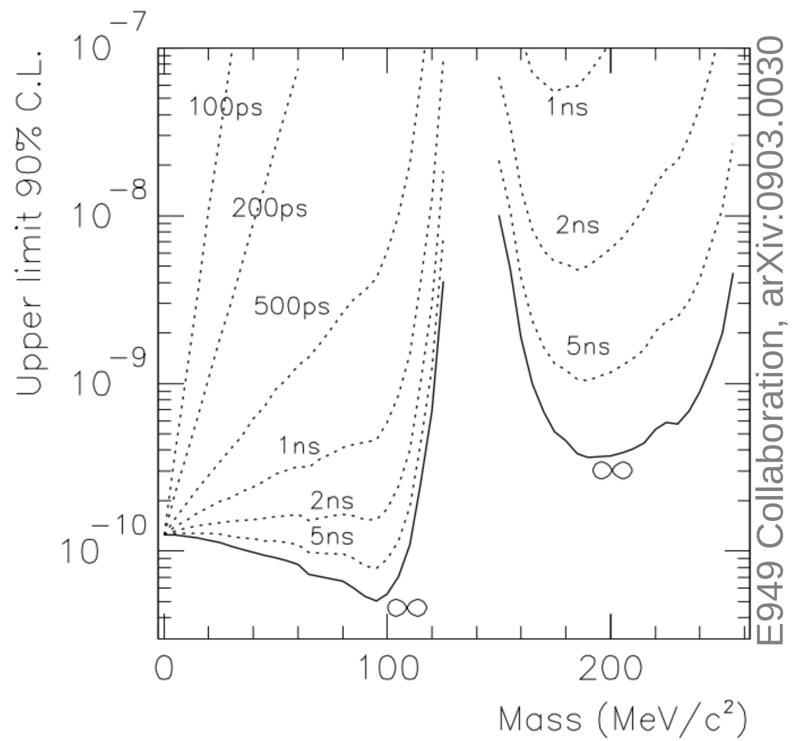
- Final result:

$$\mathrm{BR}(K^+ \to \pi^+ a) \approx |\theta_{\mathrm{mix}}|^2 \frac{\tau_{K^+}}{\tau_{K^0_S}} \mathrm{BR}(K^0_S \to \pi^+\pi^-) \frac{|\vec{p}_a|}{|\vec{p}_\pi|} D^2_{\pi\pi}$$

$$\theta_{a\pi} \frac{3A_2}{2A_0} e^{i(\chi_2-\chi_0)} + \theta_{a\eta}\sqrt{\frac{2}{3}}\left(c(\theta) - \sqrt{2}s(\theta)\right) + \theta_{a\eta'}\sqrt{\frac{2}{3}}\left(\sqrt{2}c(\theta) + s(\theta)\right)$$

Searching for ALPs with NA62





NA62 Collaboration, arXiv:1703.08501
NA62 Collaboration, arXiv:1811.08508

- NA62 should be able to improve bound on B($K^+ \to \pi^+ X$) from E787/E949 by about one order of magnitude
- First results will be published very soon…

NA62 and QCD axions

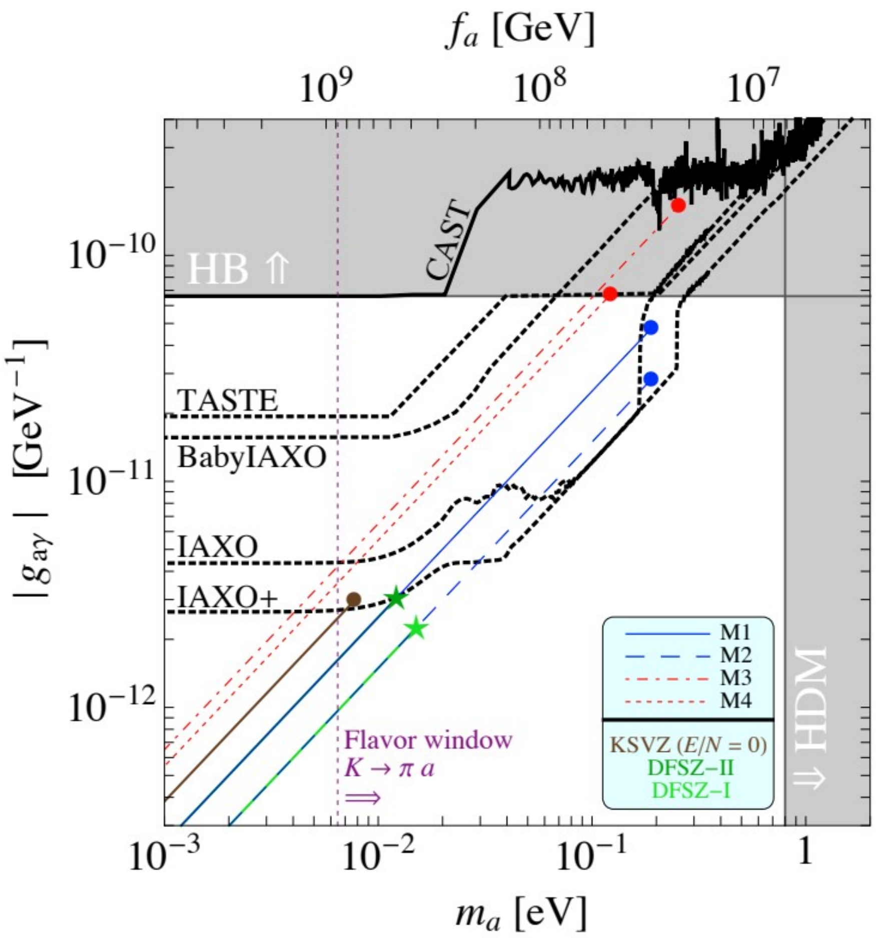
- **Common lore:** Accelerator constraints cannot compete with astrophysical constraints for QCD axions

- **Exception 1:** Suppressed astrophysical constraints (astrophobic axions)

Di Luzio et al., arXiv:1712.04940

- **Exception 2:** Enhanced rare decay rates
  - Possible even without explicit flavour violation if loop-induced processes receive large logarithmic enhancement

Alonso-Álvarez, Ertas, Jaeckel, FK and Thormaehlen, in preparation



Part III: ALPs coupled to gluons

- Coupling structure analogous to QCD axions (but with additional mass term)

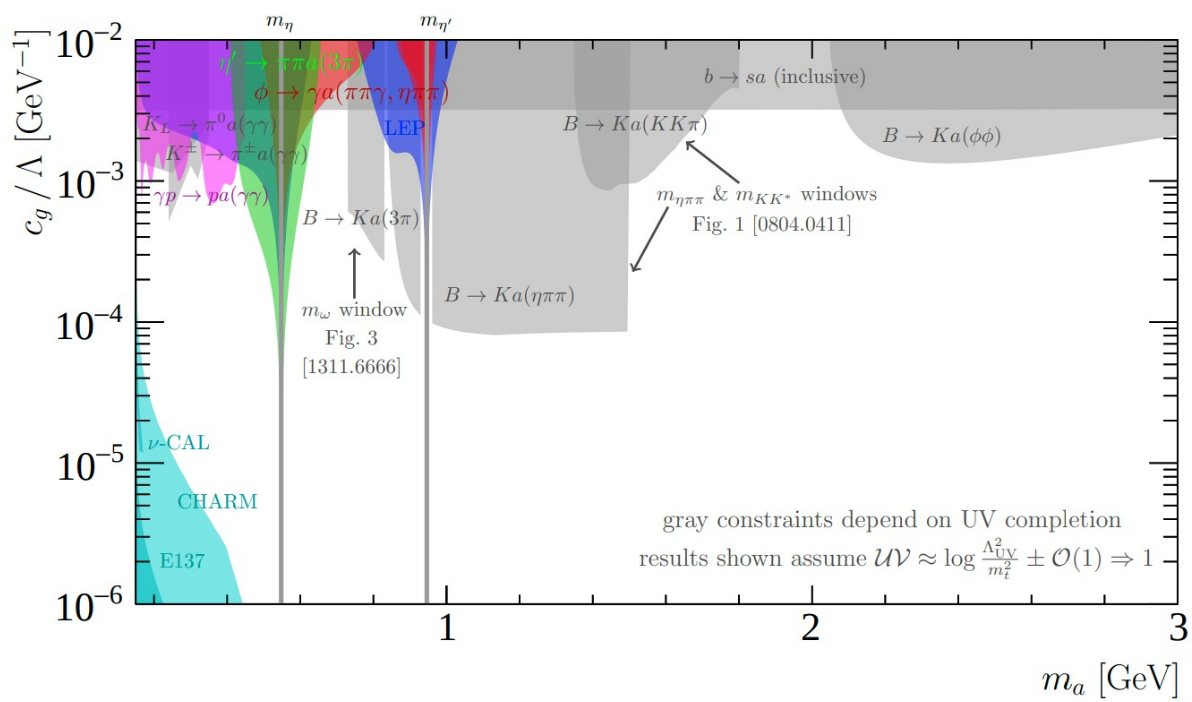
$$\mathcal{L}_{\text{eff}} \supset \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_{a,0}^2}{2} a^2 + g_s^2\, C_{GG} \frac{a}{\Lambda} G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}$$

- At low energies, this interaction induces both ALP-photon couplings and ALP-fermion couplings

→ Interesting combination of the cases discussed before

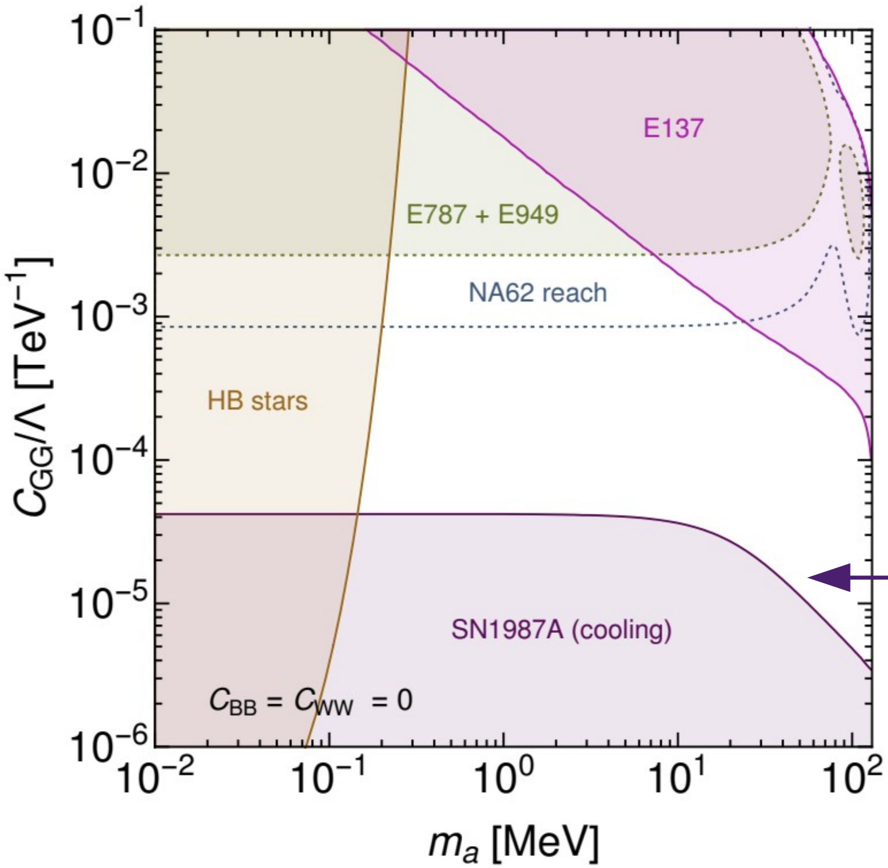
→ E.g. ALP production via rare meson decays followed by ALP decay into photons

Aloni et al., arXiv:1811.03474



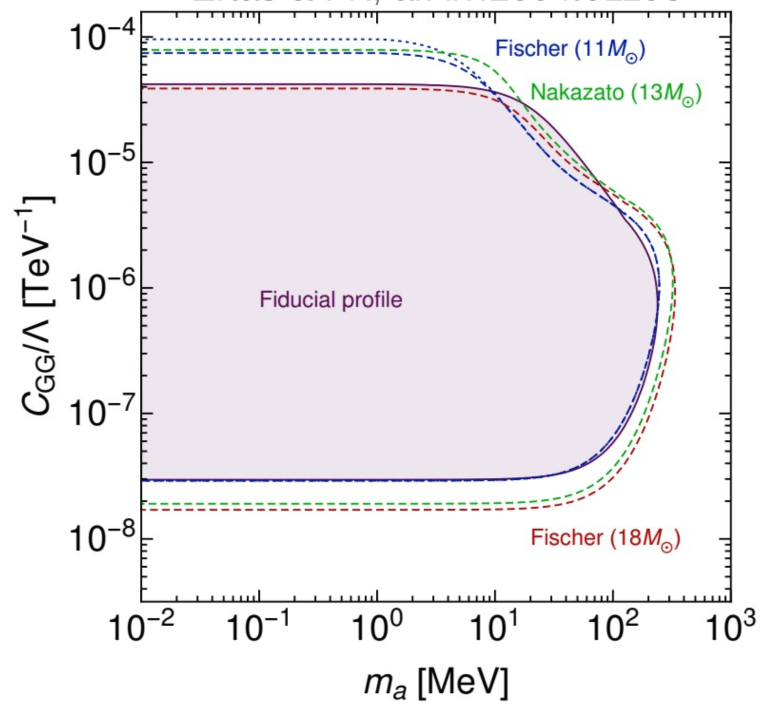
ALPs below the pion mass

- Large allowed parameter space for MeV-scale ALPs and $\Lambda \sim 10^6 - 10^7$ GeV
- Plenty of room for discovering ALPs coupled to gluons in flavour changing decays



- Conclusion robust in spite of sizable uncertainty in bound from SN1987A

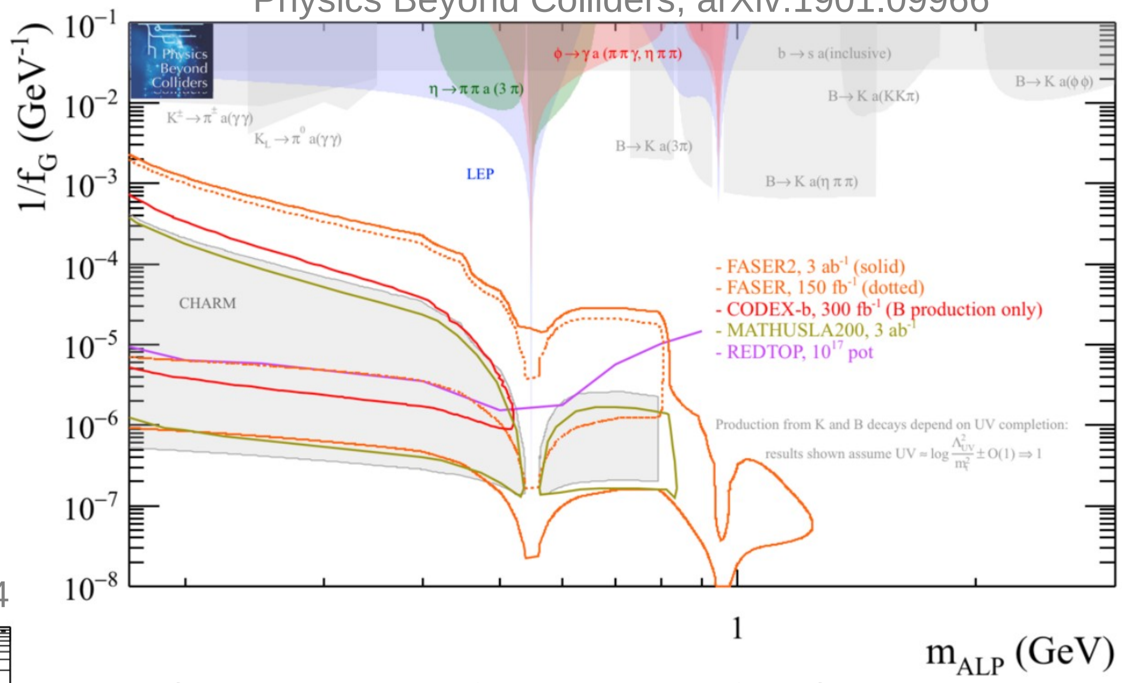
Ertas & FK, arXiv:2004.01193



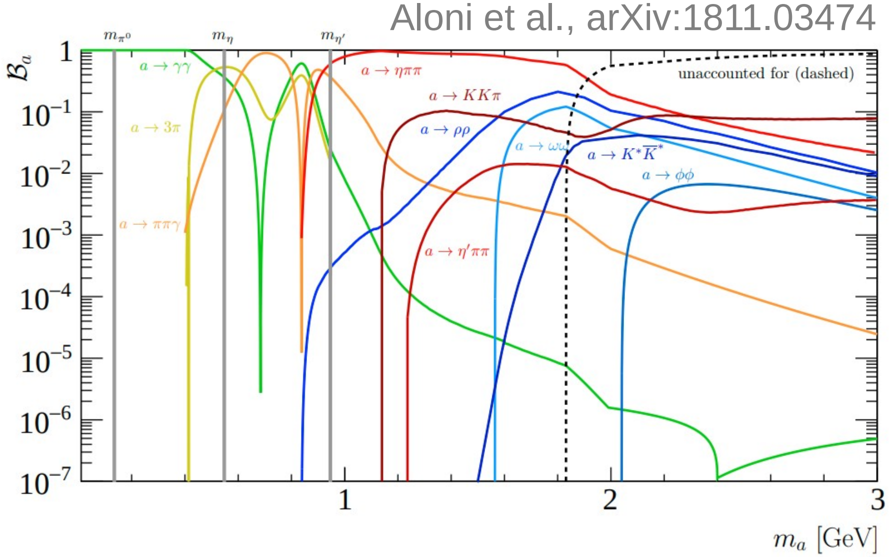
Gluonic ALPs in fixed-target experiments

- ALPs coupled to gluons can be produced in a number of different ways:
  - ALP-meson mixing
  - Primakoff production
  - Rare decays
- At the same time, many different decay modes contribute to total width

Physics Beyond Colliders, arXiv:1901.09966



Aloni et al., arXiv:1811.03474



- So far no comprehensive study of experimental sensitivities including all relevant effects
- Exciting opportunity for theory–experiment collaboration

Döbrich, Ertas, Jerhot, FK and Spadaro, in preparation

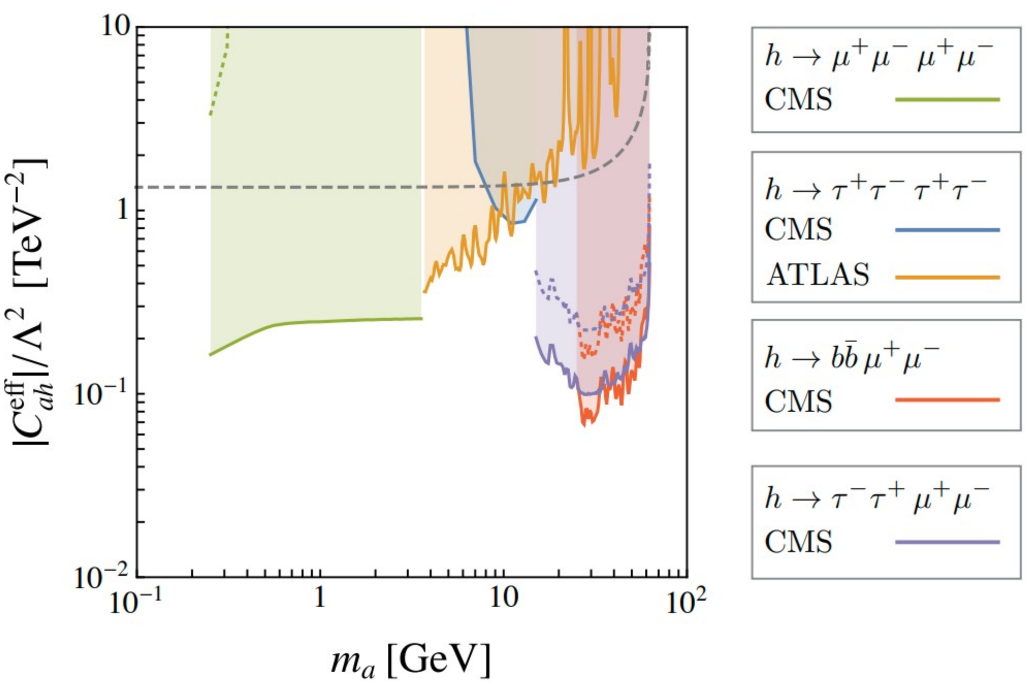
Part IV: ALPs coupled to Higgs bosons

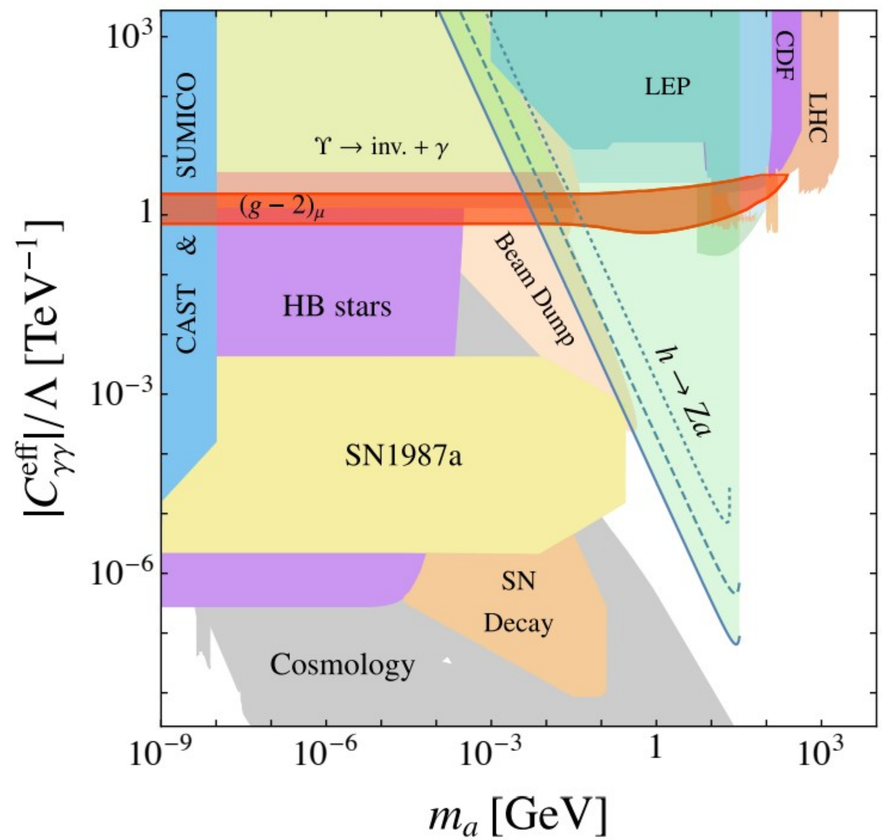
- Additional operators generated at dim 6 and 7 induce $h \to aa$ and $h \to Za$ decays

  Bauer et al., arXiv:1708.0044

- Many exciting prospects to search for ALPs at the LHC

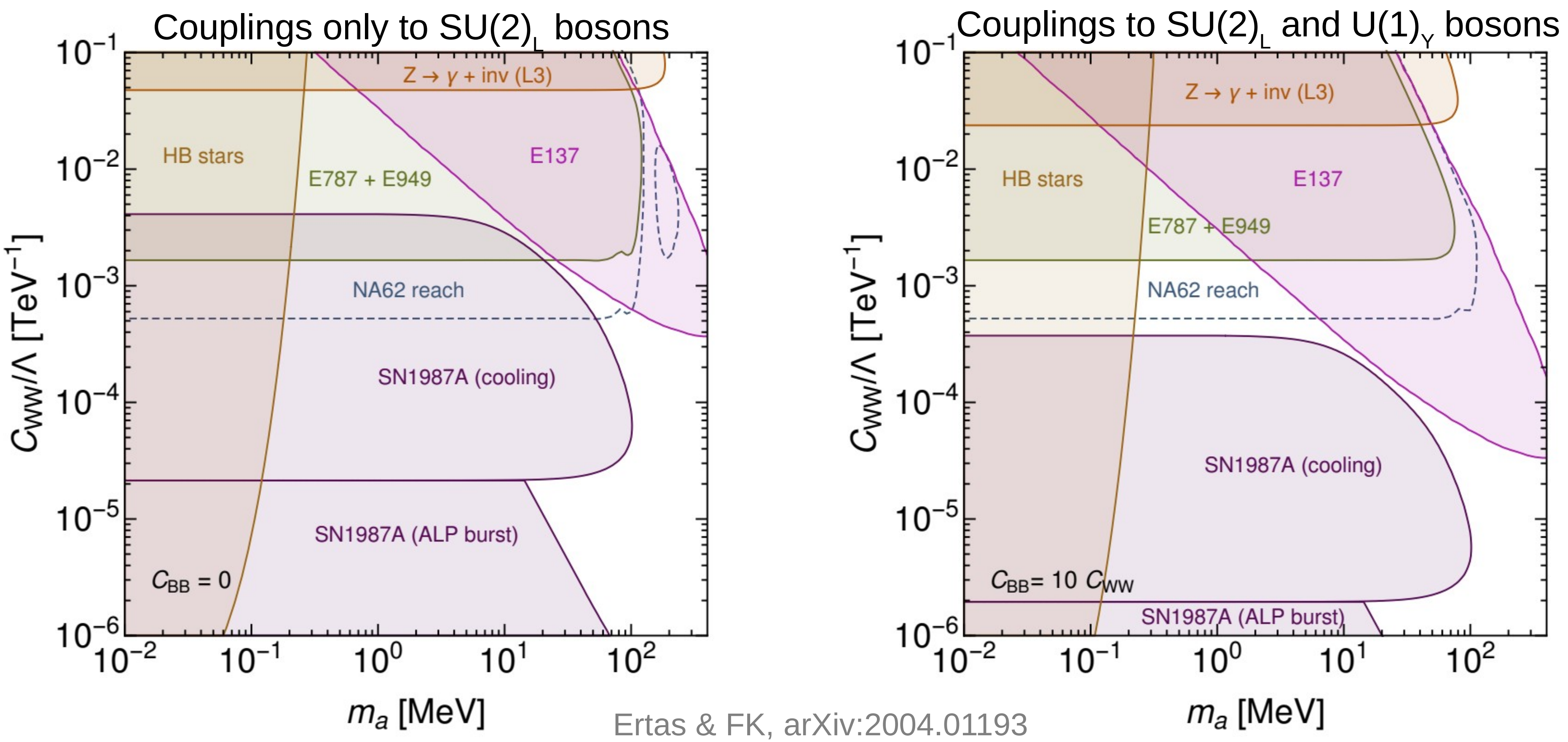
  → Next talk





Part V: ALPs with several couplings

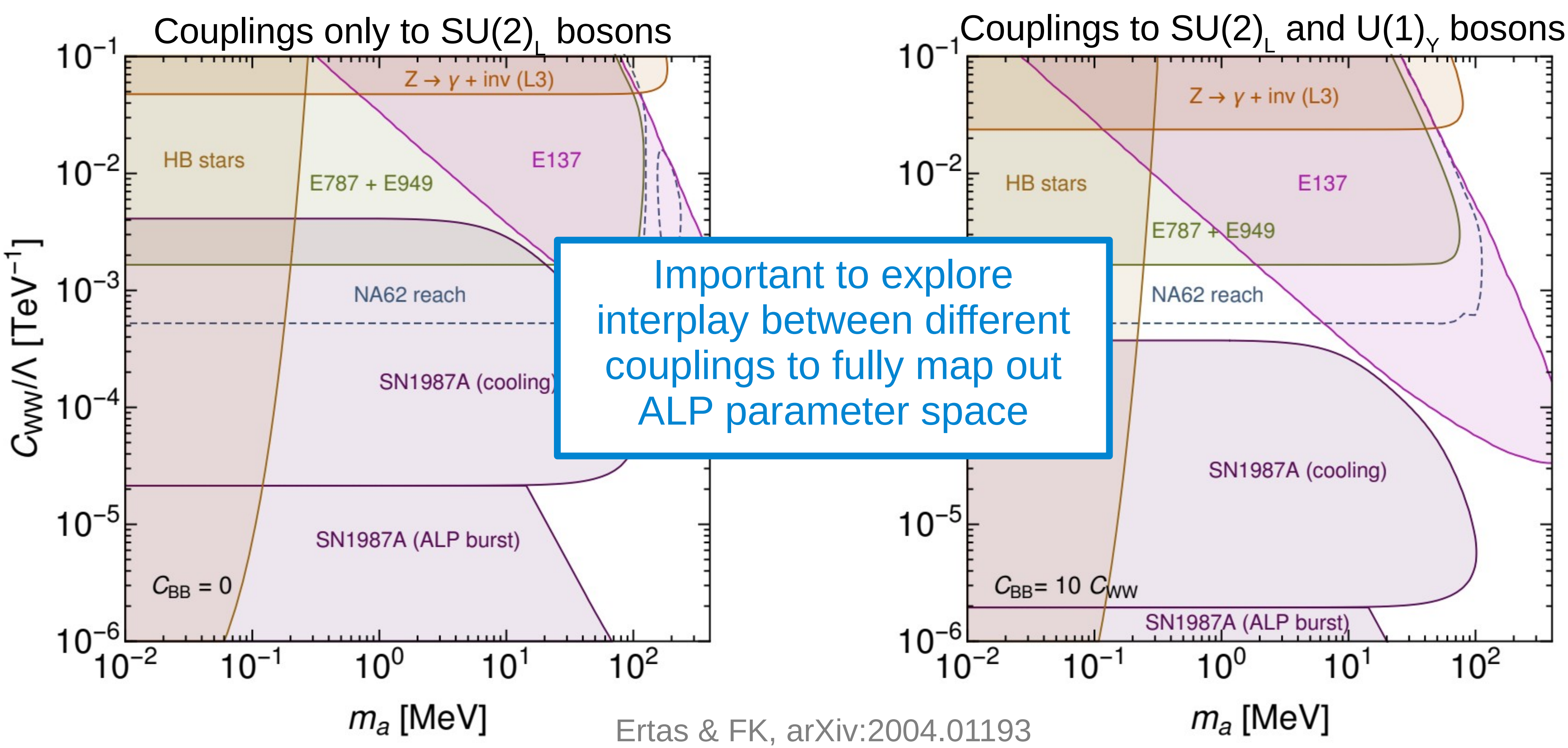
- **Naive intuition:** ALPs with several couplings are more constrained than ALPs with few couplings
- **Not true:** Some constraints are relaxed when including additional couplings



Ertas & FK, arXiv:2004.01193

Part V: ALPs with several couplings

- **Naive intuition:** ALPs with several couplings are more constrained than ALPs with few couplings
- **Not true:** Some constraints are relaxed when including additional couplings



Important to explore interplay between different couplings to fully map out ALP parameter space

Ertas & FK, arXiv:2004.01193

Conclusions

- Axion-like particles arise in many extensions of the Standard Model and can be described with effective interactions in a model-independent way
- Many different coupling structures conceivable, huge variations in the corresponding phenomenology
- Many promising experimental strategies to probe the various production modes and decay channels
- Exciting interplay between constraints from fixed-target experiments, rare decays and ee colliders as well as astrophysical bounds
- Important to consider several couplings simultaneously to identify the most interesting regions in ALP parameter space