Belle-II sensitivity for axion-like particles.

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Based on
arXiv:1709.00009
with Matthew J. Dolan, Torben Ferber, Christopher Hearty and Kai Schmidt-Hoberg

Motivation for axion-like particles

- Axions and axion-like particles (ALPs) occur in many SM extensions
  - Solutions to the strong CP problem — Hook, arXiv:1411.3325; Fukuda et al., arXiv:1504.06084
  - String compactifications — Arvanitaki et al., arXiv:0905.4720, Cicoli et al., arXiv:1206.0819,
  - Supersymmetry breaking — Bellazzini et al., arXiv:1702.02152

- As Pseudo-Nambu-Goldstone bosons they are naturally light and weakly coupled
  - Difficult to detect at the LHC — Mimasu & Sanz, arXiv:1409.4792; Jaeckel & Spannowsky, arXiv:1509.00476
  - ALP with mass below the MeV scale: strongly constrained by astrophysics — Cadamuro & Redondo, arXiv:1110.2895
  - ALPs in the GeV mass range: interesting implications for particle physics
    - Muon g-2 — Marciano et al., arXiv:1607.01022; Bauer et al., arXiv:1704.08207
    - Relaxion mechanism — Flacke et al., arXiv:1610.02025
    - Mediator of dark matter interactions — Boehm et al., arXiv:1401.6458

ALPs coupled to gauge bosons

- Let's focus on the following interactions:

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

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

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

$$\mathcal{L} \supset -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} - \frac{g_{a\gamma Z}}{4} a F_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{g_{aZZ}}{4} a Z_{\mu\nu} \tilde{Z}^{\mu\nu} - \frac{g_{aWW}}{4} a W_{\mu\nu} \tilde{W}^{\mu\nu}$$

- Two interesting cases:
  - $c_B \sim c_W$: $g_{a\gamma Z} \ll g_{a\gamma\gamma}$ (photon couplings)
  - $c_B \gg c_W$: $g_{a\gamma Z} \sim -g_{a\gamma\gamma}$ (hypercharge couplings)
- In general, there may also be couplings to SM fermions, gluons and the Higgs boson, but these are strongly constrained

Dolan, FK et al., arXiv:1412.5174

ALPs as dark mediators

- In addition to the couplings to gauge bosons, ALPs can also couple to DM:

$$\mathcal{L}_{\rm DM} = g_{a\chi\chi}\,\bar{\chi}\gamma^\mu\gamma^5\chi\,\partial_\mu a$$

- Crucially, such derivative couplings are suppressed in the non-relativistic limit
- Light pseudoscalars can therefore communicate the interactions of DM particles with SM states without conflicting with direct detection experiments
- The observed DM relic abundance can be easily reproduced if annihilations in the early Universe are resonantly enhanced
- For $m_\chi \sim m_a / 2$ this requires approximately $g_{a\gamma\gamma} \sim (10^{-5} – 10^{-4})\ \mathrm{GeV}^{-1}$
- Can we test such couplings in the laboratory?

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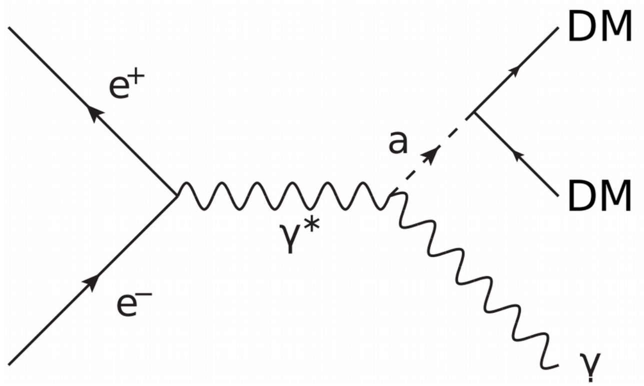
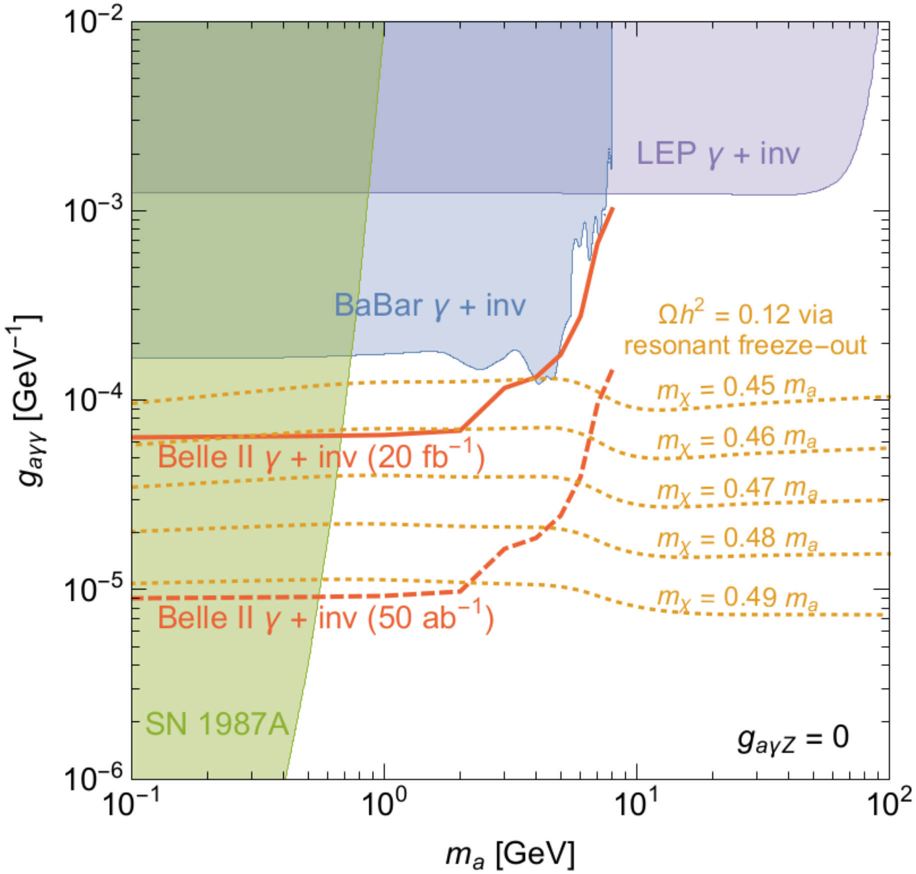
Single-photon searches at e^+e^- colliders

- For invisibly decaying ALPs a promising experimental signature is obtained if the ALP is emitted from a SM gauge boson
- One then obtains a high-p_T photon in association with missing energy.
- This signature has been searches for (e.g. in the context of hidden photons) at LEP and BaBar



- Significant improvements of sensitivity expected for Belle II.
  - Integrated luminosity of up to 50 ab^{-1} with a trigger on $E_\gamma > 1.8$ GeV.
  - Dominant background from QED processes with undetected photons
  - Depends sensitively on detector geometry, which will be improved significantly in Belle II (more homogeneous calorimeter)

Belle II sensitivity for invisibly decaying ALPs



- LEP bound from a reanalysis of a mono-photon search at DELPHI
- BaBar bound from a reanalysis of a search for hidden photons

BaBar collaboration, arXiv:1702.03327

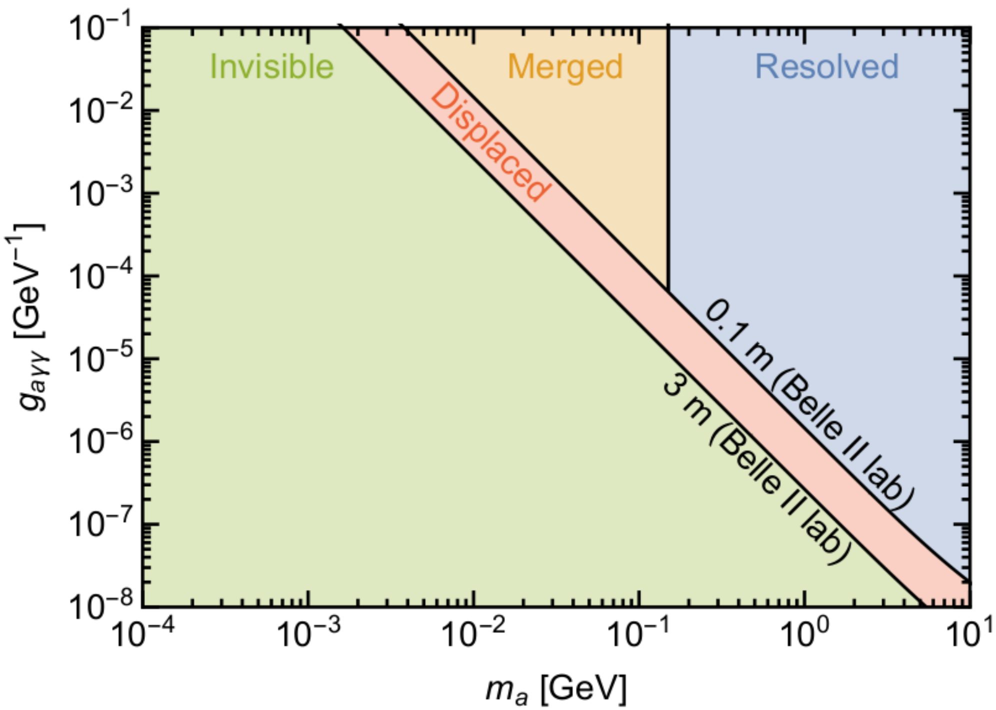
- SN 1987A bound from the length of the neutrino signal (bound on exotic energy loss mechanisms)

Jaeckel et al., arXiv:1702.02964

- Belle II has a unique potential to probe the parameter regions of particular interest

What about visibly decaying ALPs?

> The answer depends on the ALP decay length relative to the size of the detector

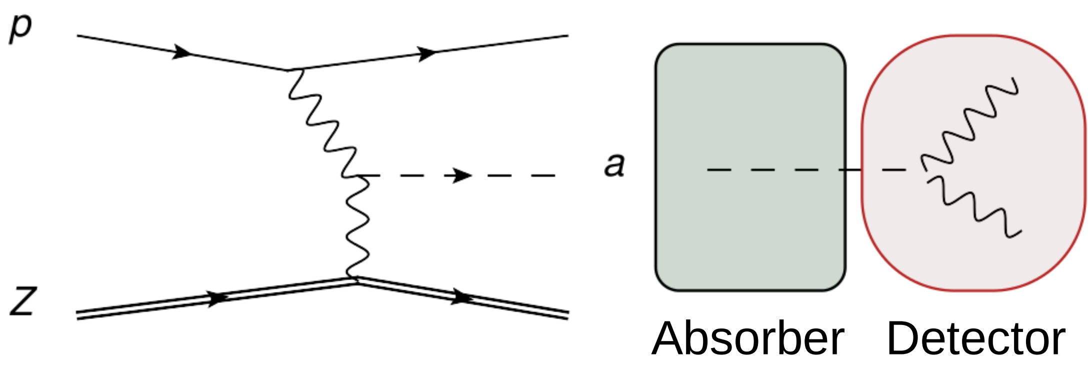


- If the ALPs escape from the detector without decaying, the signature is identical to the case of invisible decays
- More interesting signatures can occur of the ALPs decay promptly or from a displaced vertex

> Remainder of this talk: Searches for visibly decaying ALPs

Existing constraints: Beam-dump experiments

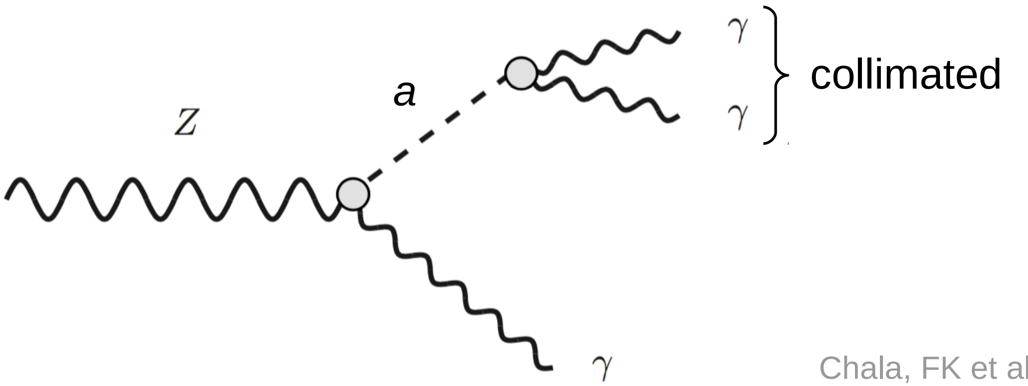
- If the ALP decay length is of order of a few meters, interesting constraints come from
  - Proton beam dump experiments (CHARM, NuCal) — Döbrich, FK et al., arXiv:1512.03069
  - Electron beam dump experiments (E137, E141) — Izaguirre et al., arXiv:1307.6554; Batell et al., arXiv:1406.2698
- Dominant production mode: Primakoff process



- Significant progress expected from the planned SHiP facility

Existing constraints: LEP, Tevatron and LHC

- Highly boosted ALPs with a short lifetime decay into a pair of highly collimated photons, which may mimic a single photon in the detector
- This signature may for example mimic the forbidden process $Z \to \gamma\gamma$

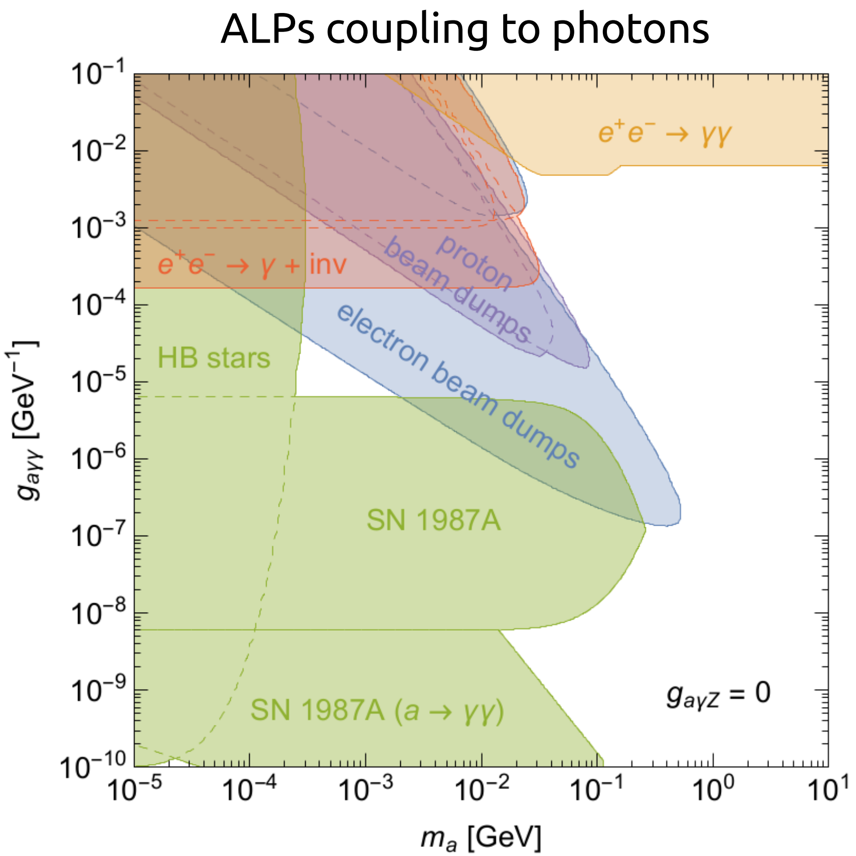


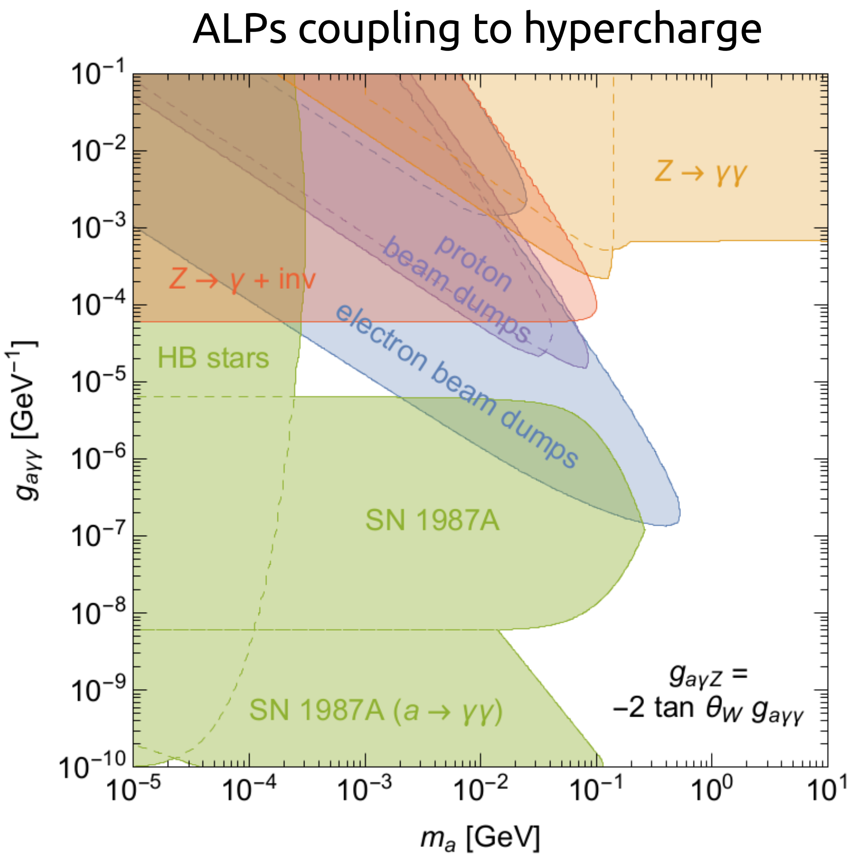
Chala, FK et al., arXiv:1512.06833

- Relevant constraints from LEP and Tevatron
- Significant improvements expected from future LHC searches

Bauer et al., arXiv:1708.00443

Existing constraints: Summary

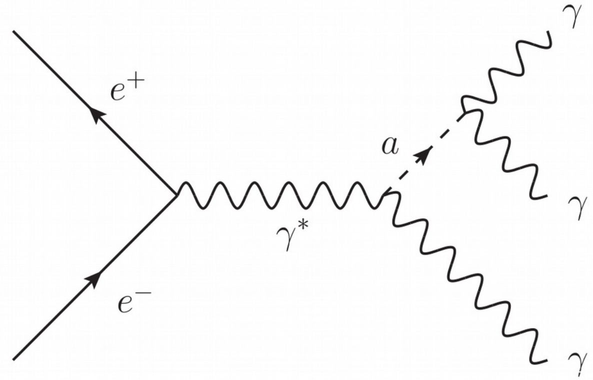


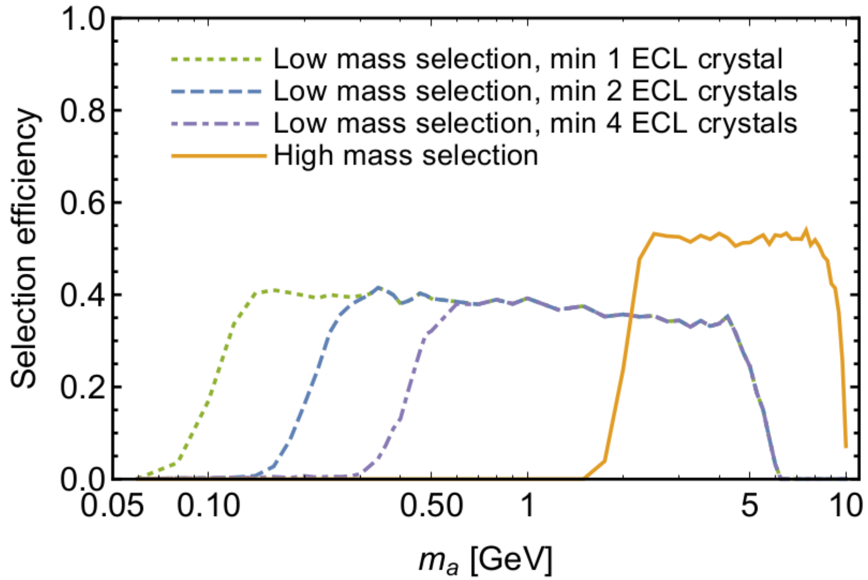


(These plots update the constraints from Masso & Toldra, arXiv:hep-ph/9503293, arXiv:hep-ph/9702275)

Belle II sensitivity for visibly decaying ALPs

- Belle II ideally suited for exploring resolved regime (all three photons reconstructed)

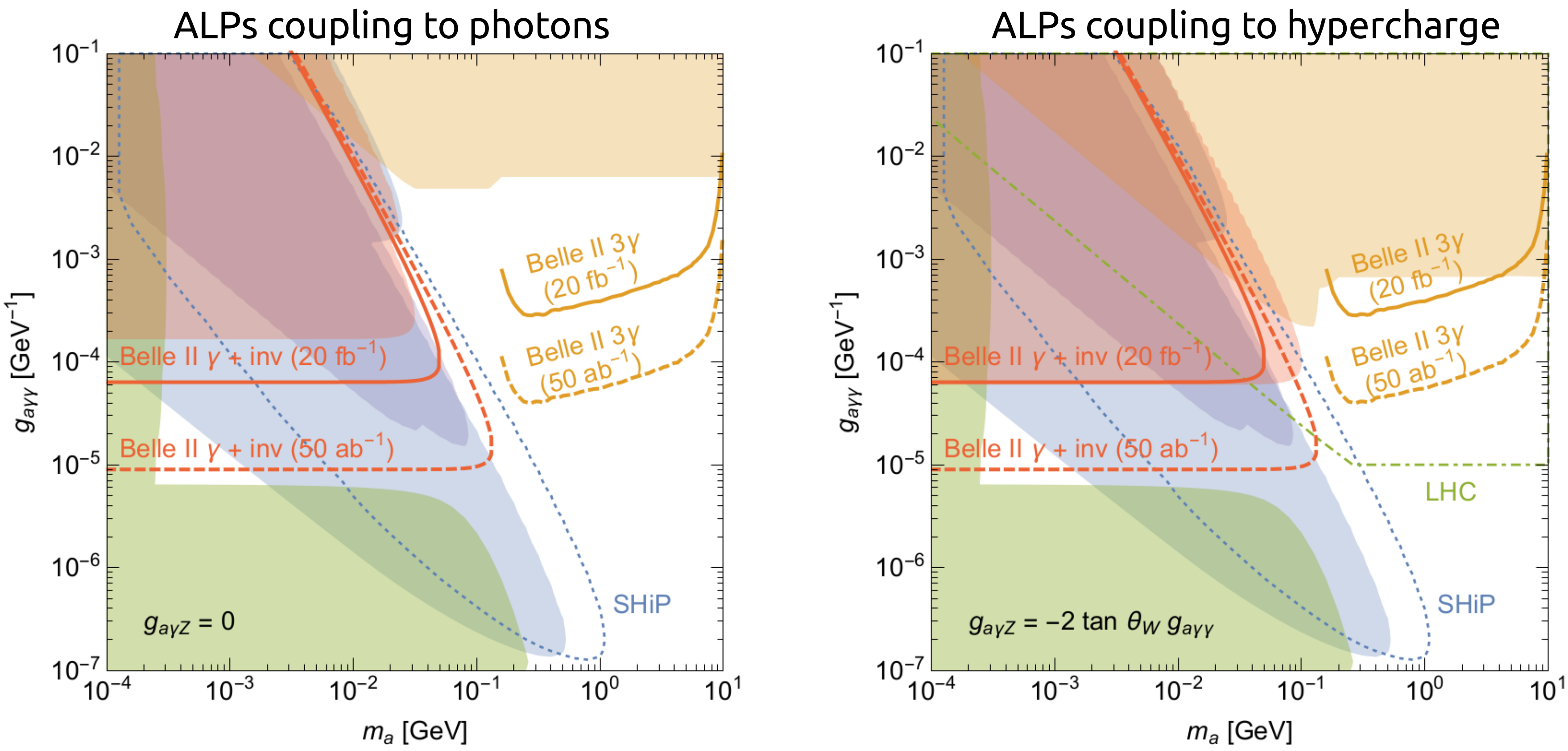




- To resolve the two photons from the ALP decay, we require a separation of at least two crystal in the electromagnetic calorimeter
- This yields a good selection efficiency for ALP masses above 200 MeV

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

Projected sensitivities: Summary



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

Conclusions

- Searches for axion-like particles in the MeV to GeV range are a promising and exciting new direction for particle physics
- Single-photon searches at Belle II can explore both invisibly decaying ALPs (e.g. DM mediators) and long-lived ALPs
- Belle II searches for three resolved photons can cover wide ranges of new ALP parameter space
- Initial data sets (20 fb^{-1}) will already be sufficient to set world-leading limits in both cases
- Let's go and discover ALPs!