Theoretical prospects of axionlike particles

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Motivation

- Issues in the SM:
  - Dark matter (DM)
  - Hierarchy problem
  - Strong CP problem
  - ...
- QCD axion solves both of them [Peccei, Quinn 1977, Dine, Fischler 1983, ...]
- More generally $\rightarrow$ Axionlike particles (ALPs): light pseudo-Nambu–Goldstone bosons that emerge from spontaneously broken approximate global symmetries
- Couplings and Mass decoupled; unlike the axion
- m_a ranges from 10^{-22} eV to several hundred GeV or even higher
- Predicted in many BSM theories: string compactifcations, supersymmetry models, Froggat-Nielsen models of flavor, ...
- Can solve the hierarchy problem (the relaxion mechanism) [Graham, Kaplan, Rajendran 2015]
- Can explain the EW baryogenesis [Im, Jeong, Lee 2022]
- The ALP is highly motivated!

Dim-5 effective field theory of the ALP

$$\mathcal{L}_5 \supset \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{m_a^2}{2}a^2 + \sum_f \frac{C_{ff}}{2}\frac{\partial^\mu a}{\Lambda}\bar{f}\gamma_\mu\gamma_5 f$$
$$+ g_s^2 C_{GG}\frac{a}{\Lambda}G_{\mu\nu}\tilde{G}^{\mu\nu} + g^2 C_{WW}\frac{a}{\Lambda}W_{\mu\nu}\tilde{W}^{\mu\nu} + g'^2 C_{BB}\frac{a}{\Lambda}B_{\mu\nu}\tilde{B}^{\mu\nu}$$

After EWSB:

$$\mathcal{L}_5 \supset e^2 C_{\gamma\gamma}\frac{a}{\Lambda}F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{2e^2}{s_w c_w}C_{\gamma Z}\frac{a}{\Lambda}F_{\mu\nu}\tilde{Z}^{\mu\nu} + \frac{e^2}{s_w^2 c_w^2}C_{ZZ}\frac{a}{\Lambda}Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$

$$c_{\gamma\gamma} = C_{WW} + C_{BB},\ C_{\gamma Z} = c_w^2 C_{WW} - s_w^2 C_{BB},\ C_{ZZ} = c_w^4 C_{WW} + s_w^4 C_{BB}$$

- Interactions with h appear only at dim-6 and higher...
- Additionally: QFV, LFV, coupled to dark photons/HNLs, ...

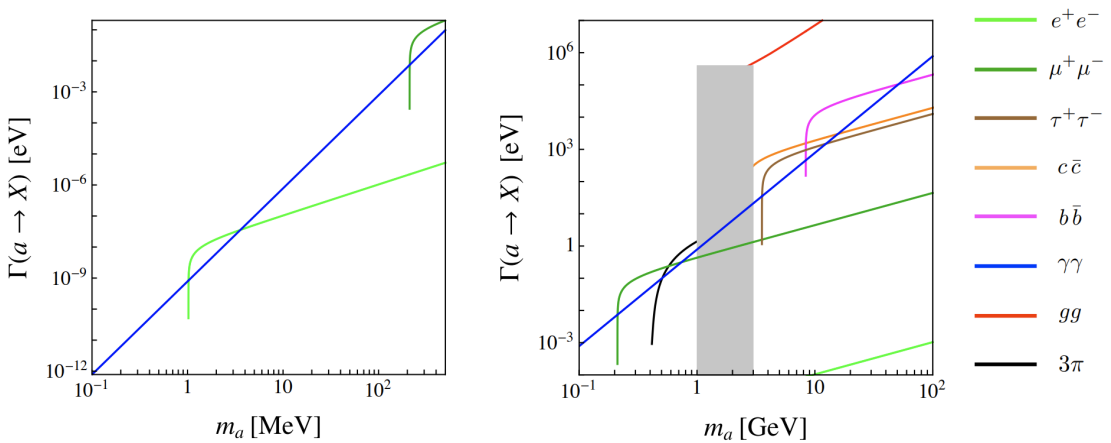
ALP decays

$$\Gamma(a \to \gamma\gamma) = \frac{4\pi\alpha^2 m_a^3}{\Lambda^2} |C_{\gamma\gamma}^{\text{eff}}|^2$$

$$\Gamma(a \to \ell^+\ell^-) = \frac{m_a m_\ell^2}{8\pi\Lambda^2} |C_{\ell\ell}^{\text{eff}}|^2 \sqrt{1 - \frac{4m_\ell^2}{m_a^2}}$$

$$\Gamma(a \to Q\bar{Q}) = \frac{3 m_a \bar{m}_Q^2(m_a)}{8\pi\Lambda^2} |C_{QQ}^{\text{eff}}|^2 \sqrt{1 - \frac{4\bar{m}_Q^2}{m_a^2}}$$

[Bauer, Heiles, Neubert, Thamm 2019]

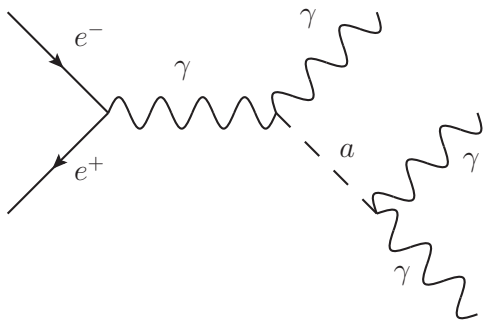


ALP decay rates into pairs of SM particles obtained by setting the relevant effective Wilson coefficients to 1

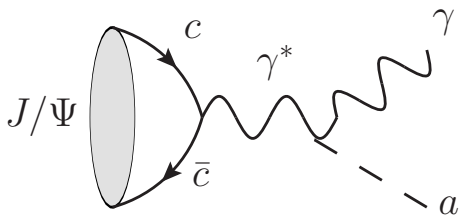
[Bauer, Neubert, Thamm 2017]

Signal processes at e^+e^- colliders

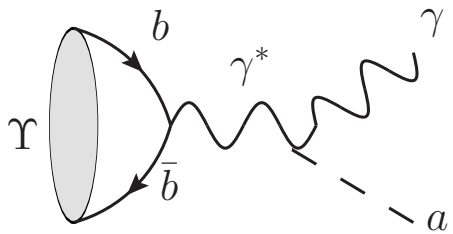
ALP coupled to photons



ALP-strahlung



Radiative decay
(BESIII, STCF)

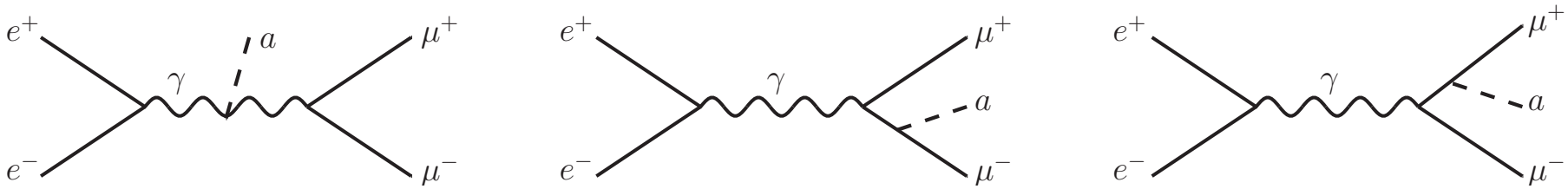


Radiative decay
(*B*-factories)

[BESIII 2023, Merlo, Pobbe, Rigolin, Sumensari 2019]

Signal processes at e^+e^- colliders

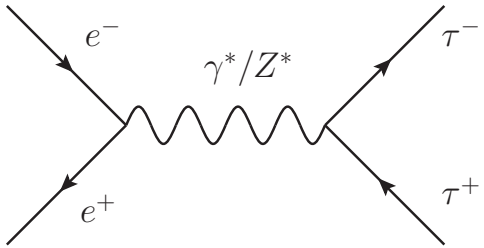
ALP coupled to leptons or photons



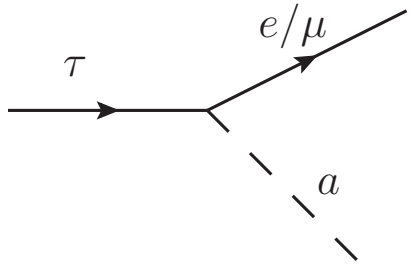
[Bauer, Neubert, Thamm 2017]

Signal processes at e^+e^- colliders

ALP coupled to leptons with cLFV



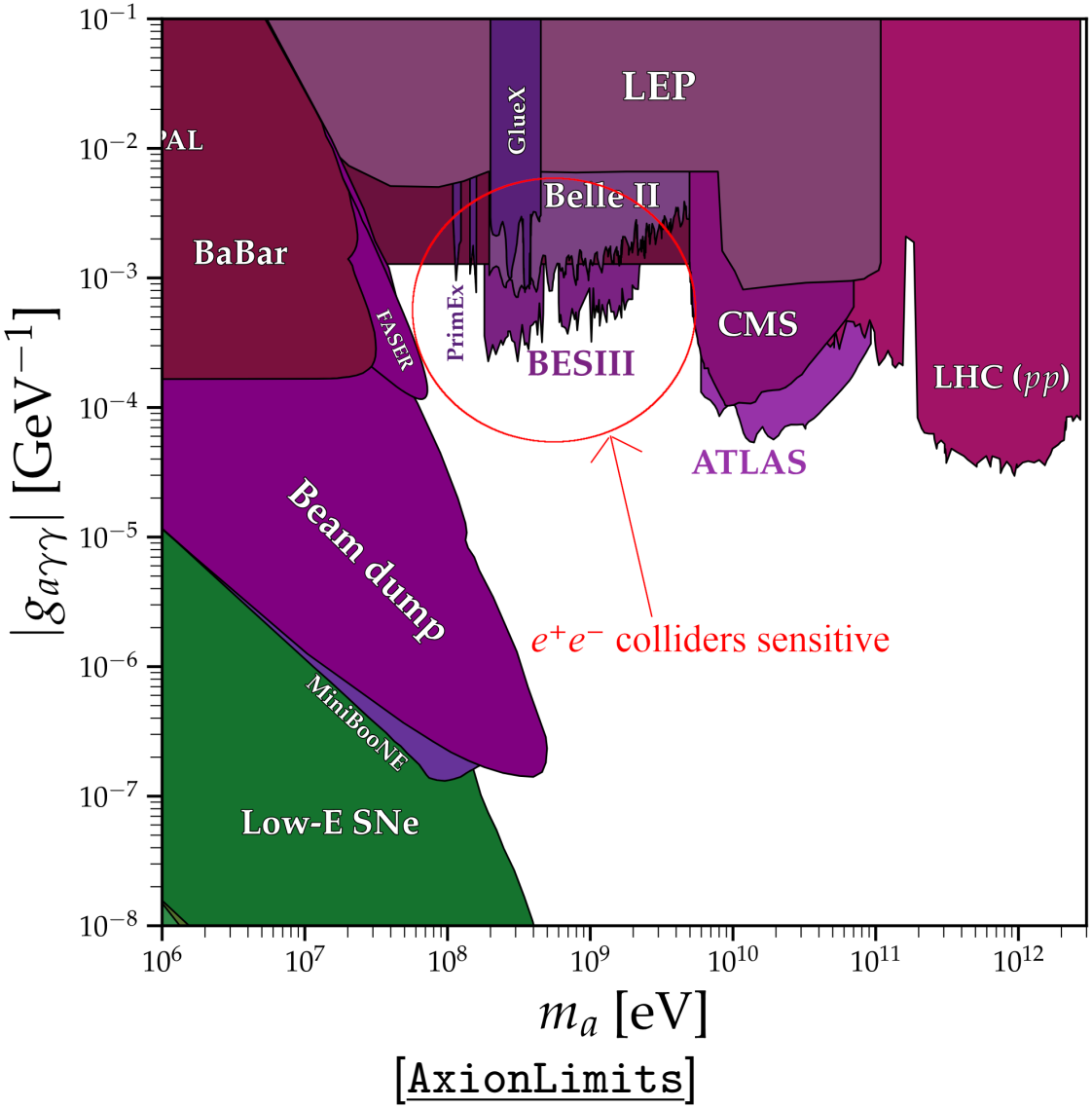
τ-pair production



ALP production from τ decays with cLFV

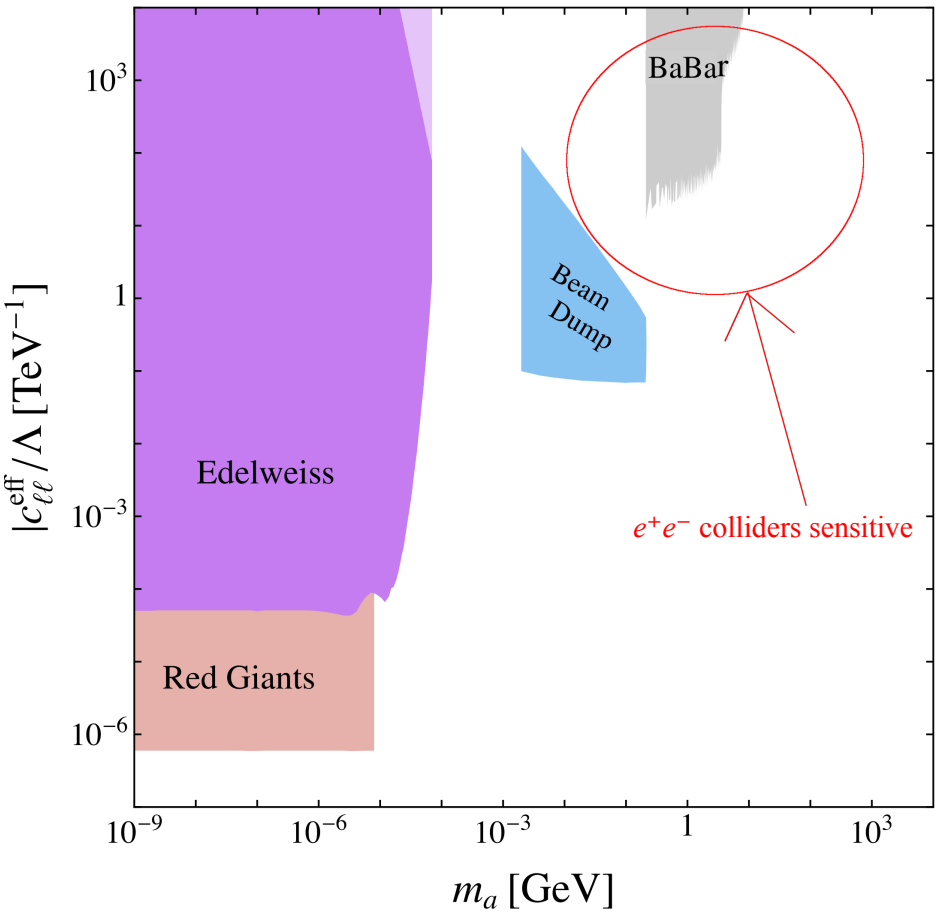
[Belle II 2019, Cheung, Soffer, ZSW, Wu 2019]

Current collider bounds on $g_{\gamma\gamma}$



[AxionLimits]

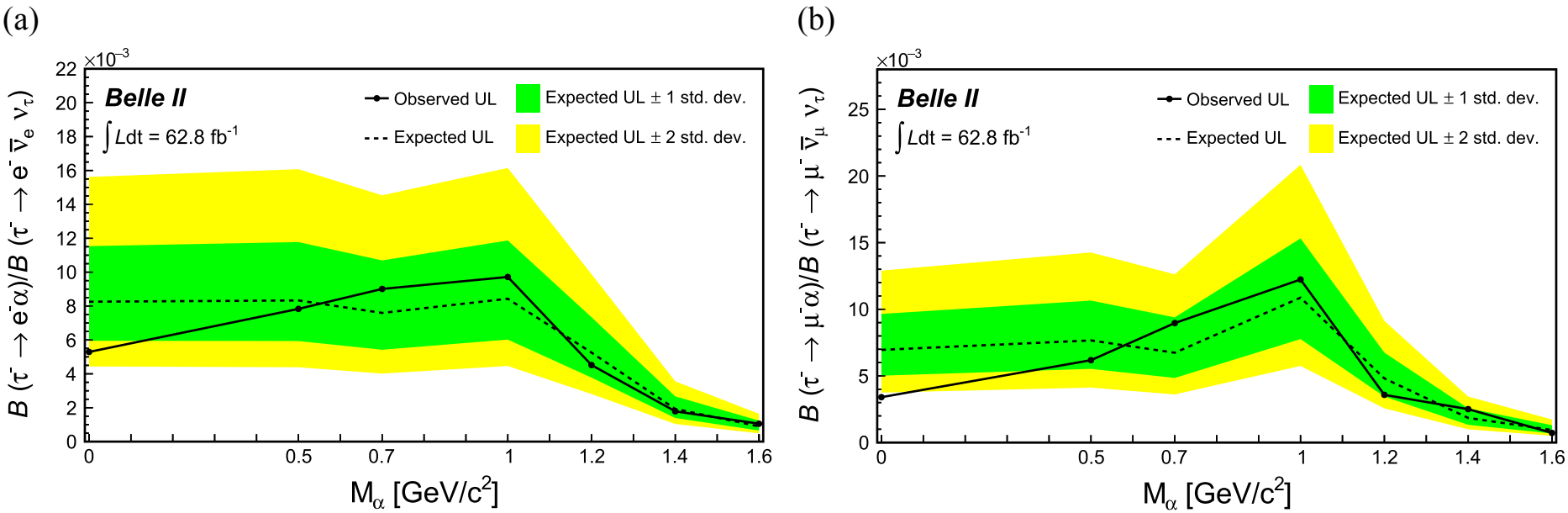
Current collider bounds on $g_{\ell\ell}$



BaBar: $e^+e^- \to \mu^+\mu^- Z'$,
with $Z' \to \mu^+\mu^-$ and reinterpreted

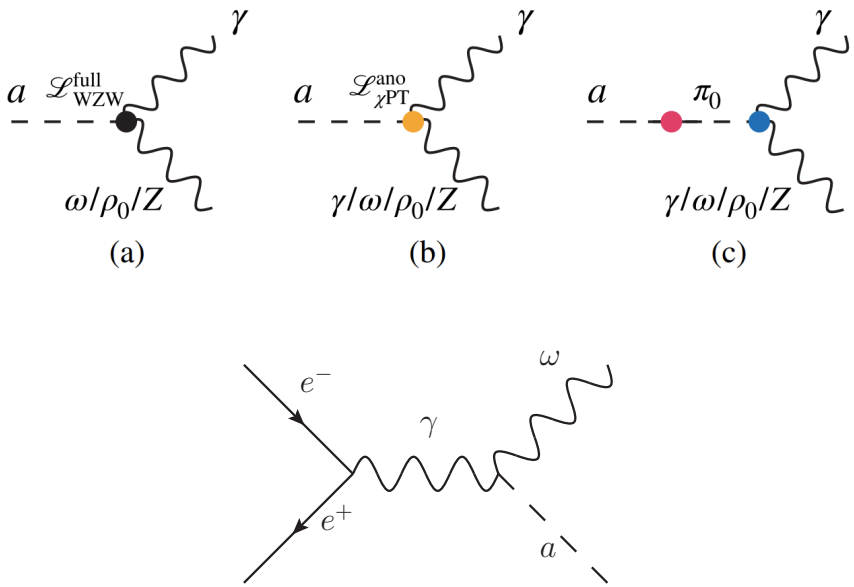
[Bauer, Heiles, Neubert, Thamm 2019]

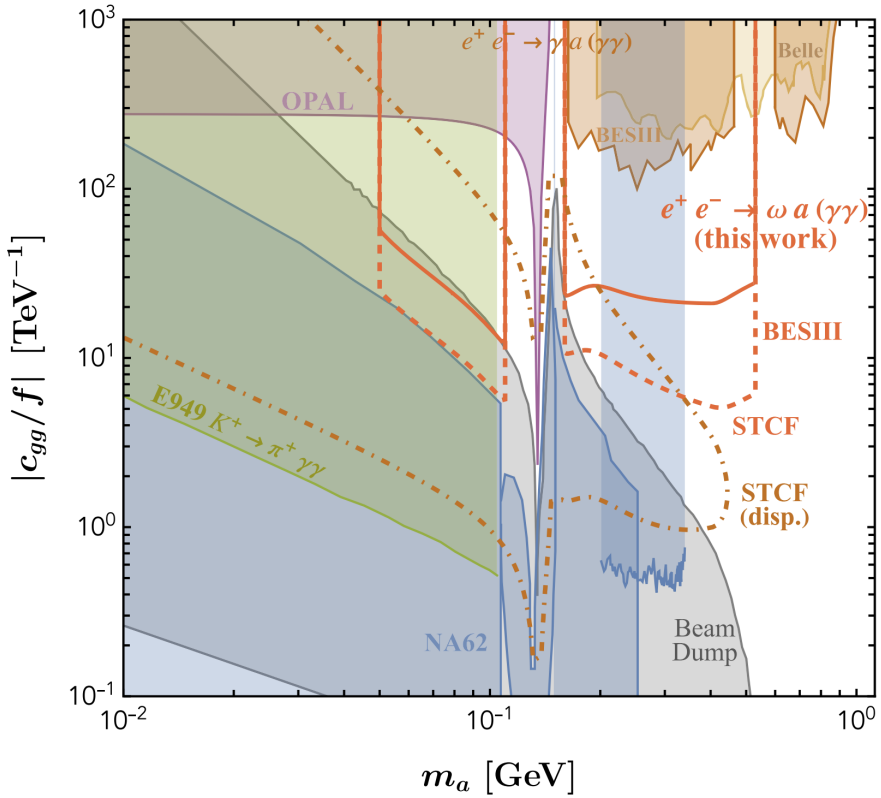
Current collider bounds on cLFV and ALP



[Belle II 2024]

BESIII and STCF sensitivities to ALP interactions with gauge bosons and vector mesons



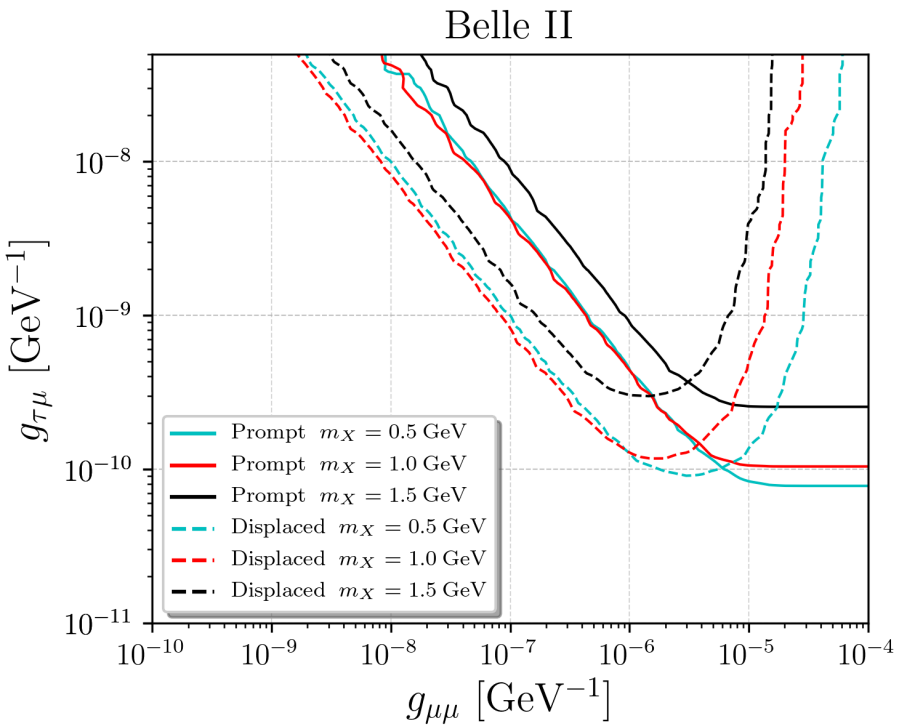


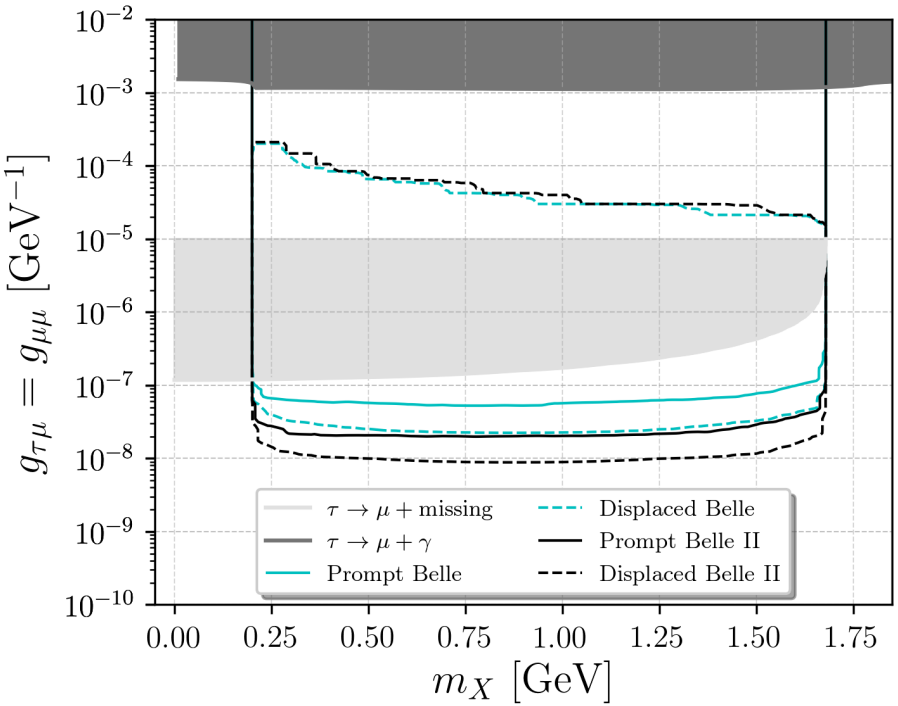
[Bai, Chen, Liu, Ma 2025]

see also [Bai, Chen, Liu, Ma 2025, Ovchynnikov, Zaporozhchenko 2025, Balkin, Coren, Soreq, Williams 2025]

Belle II sensitivity to **long-lived** ALP with cLFV

- $\tau \xrightarrow{g_{\tau\mu}} \mu\, a, a \xrightarrow{g_{\mu\mu}} \mu^- \mu^+$





[Cheung, Soffer, ZSW, Wu 2019]

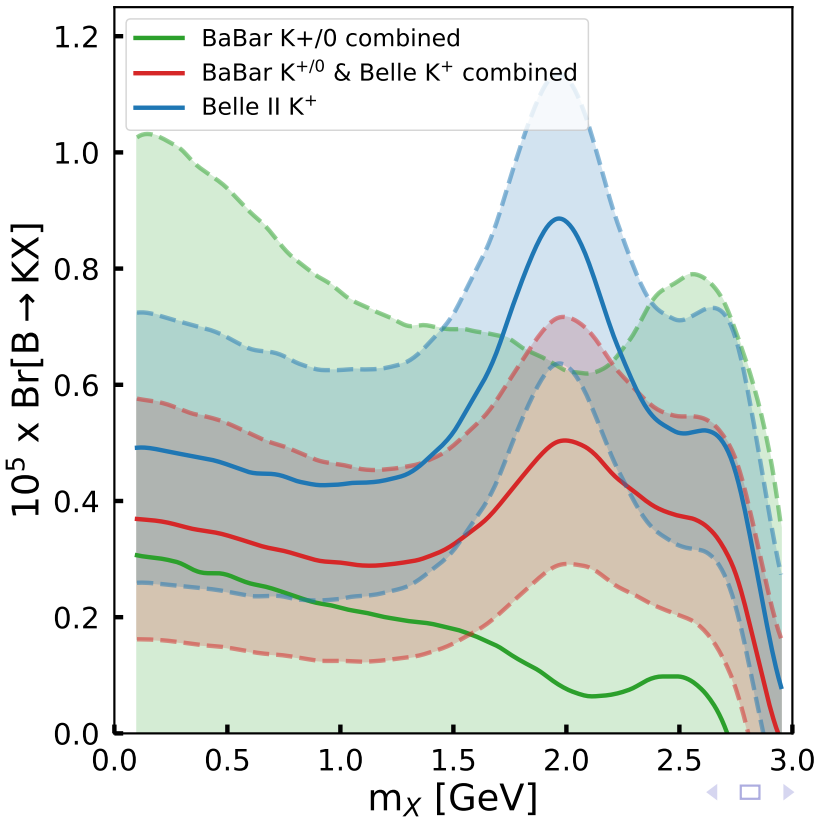
QFV ALP for explaining Belle II excess

- $\mathcal{B}(B^+ \to K^+ \not{E})_{\text{exp}} = (2.3 \pm 0.7) \times 10^{-5}$ measured at Belle II [Belle II 2024]
- 2.7σ higher than the SM prediction:
- $\mathcal{B}(B^+ \to K^+ \nu\bar{\nu})_{\text{SM}} = (4.43 \pm 0.31) \times 10^{-6}$

[Bečirević, Piazza, Sumensari 2023]

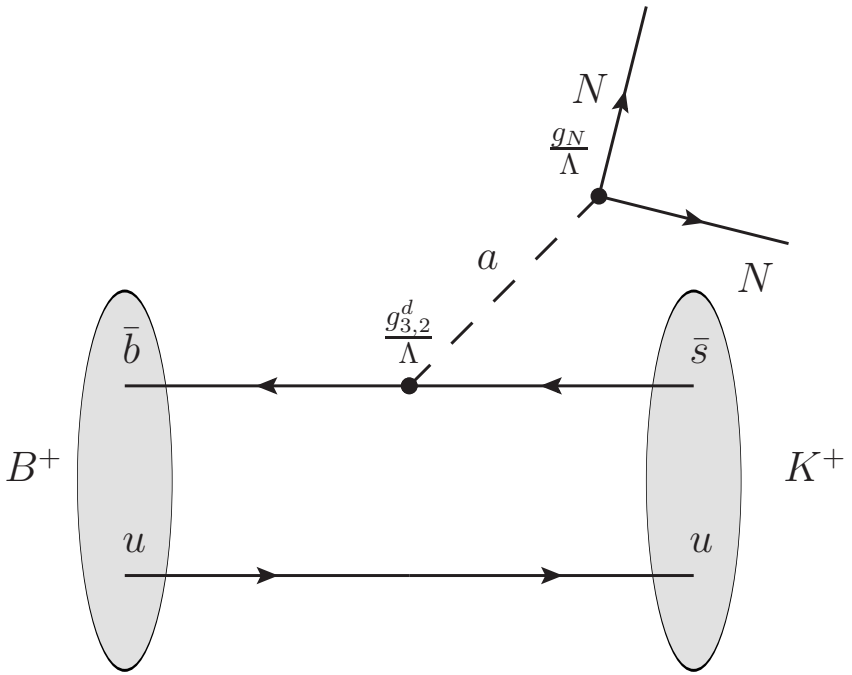
- This excess can be explained with an ALP

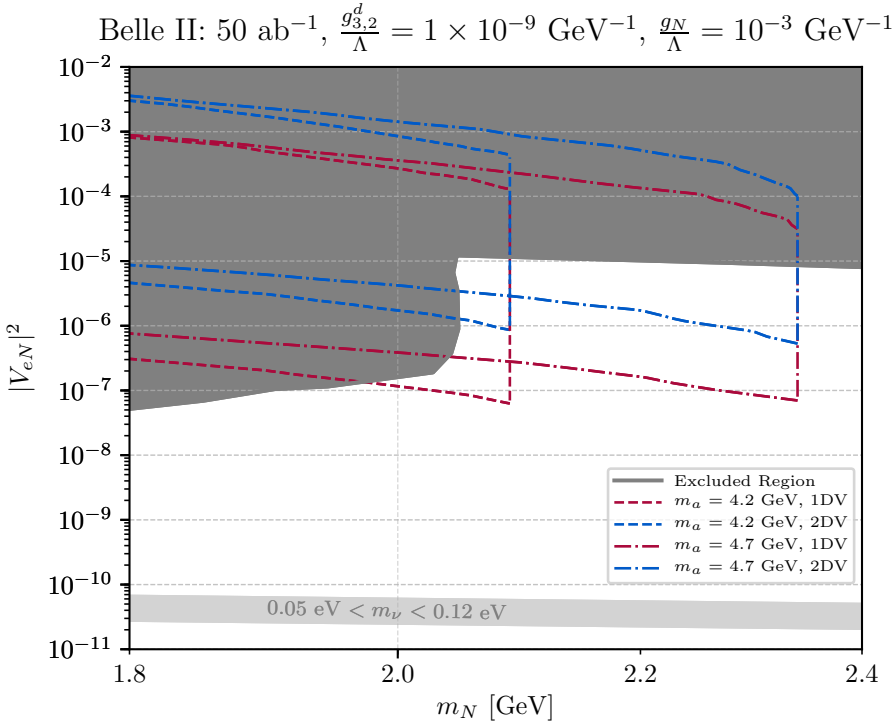
[Altmannshofer, Crivellin, Haigh, Inguglia, Martin Camalich 2024]:



Belle II sensitivity to long-lived sterile neutrinos from ALP with QFV

- $B^+ \to K^+ a, a \to NN$
- $\mathcal{O}(10^{10})$ B-mesons with 50 ab^{-1} int. lumi.





[ZSW, Zhang, Liu 2025]

Outlook

- Accumulating luminosity⇒ stronger bounds (or discovery?)
- Further BSM scenarios: dark photon, heavy neutral leptons, dark scalar, ...
- New signatures: lepton number violation, baryon number violation, missing energy, displaced vertices, ...
- BESIII and STCF: light new particle from direct collision or rare decays of D_0, D_s, J/Ψ, τ, ...

Summary

- Axions and axionlike particles highly motivated
- ALP EFT framework
- ALP can couple to all SM particles
- Showed existing bounds on ALP couplings with photons and with charged leptons (LFC and LFV)
- Displayed signal processes with Feynman diagrams
- Also *long-lived* ALPs can be constrained at low-energy e^+e^- colliders
- Extended theoretical scenarios of the ALP
- Further BSM studies possible: theory, signature, ...

Thank You! 谢谢!

Back-up slides