(image credit: Invoke AI/Stable Diffusion XL Turbo)

Flavor-violating ALPs at the Electron-Ion Collider

Ethan T. Neil (Colorado)
INT Workshop, “EW and BSM Physics at the EIC”
02/15/24

Outline

- This talk will highlight results from two papers on **lepton flavor-violating ALPs:**
  - arXiv:**2112.04513**: Direct production at the EIC;
  - arXiv:**2402.XXXXX**: Electron (g-2) anomaly and EIC searches.
- Lots of credit goes to my collaborators:
  - **Hooman Davoudiasl** (BNL)
  - **Roman Marcarelli** (grad student @ CU Boulder, on leave to BNL this semester through the DOE SCGSR program)
- See also arXiv:**2105.05866**: Higgs decays at the LHC (w/Nicholas Miesch, now grad student @ Stony Brook)

1. Motivation: axion-like particles and flavor violation

Motivation: axion-like particles

- The *QCD axion* is a hypothetical solution to the strong CP problem; being tied to strong CP restricts the allowed masses/couplings.

- **“Axion-like particles” (ALP**s) don’t attempt to solve strong CP, broadening the parameter space. They are **pseudo-Nambu-Goldstone bosons** associated w/symmetry breaking.

- ALPs occur in many scenarios (ordinary pions are ALPs!) They generically 1) are light compared to Λ_{NP}, 2) couple like pseudo-NGBs.

ALPs + flavor violation?

- Flavor is one of the biggest puzzles of the Standard Model; it wouldn't be surprising for new physics to have non-trivial flavor structure.
- Flavor-violating processes are also *highly sensitive* probes of new physics, so experimental searches have great reach to high energy scales.
- This talk: **lepton** flavor violation (**LFV**). Quark FV is also interesting, but messier and more SM backgrounds (and EIC is especially relevant for lepton FV with e^-.)

- Ignoring quarks, ALP Lagrangian has this structure:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \mathcal{L}_\ell + \mathcal{L}_g + \mathcal{L}_h$$

- Coupling to leptons can be written in general as:

$$\mathcal{L}_\ell = \frac{\partial_\mu a}{\Lambda} \sum_{\ell\ell'} \bar{\ell}\gamma^\mu \left(V_{\ell\ell'} + A_{\ell\ell'}\gamma_5\right) \ell' + h.c.$$

  - Both vector and axial couplings are allowed; what makes this an ALP is the **derivative coupling**, associated with shift symmetry of *a*. Decompose into magnitude and angles:

$$\mathcal{L}_\ell = \frac{\partial_\mu a}{\Lambda} \sum_{\ell\ell'} C_{\ell\ell'} \bar{\ell}\gamma^\mu (\sin\theta_{\ell\ell'} + e^{i\phi_{\ell\ell'}} \cos\theta_{\ell\ell'}\gamma_5)\ell' + h.c.$$

  - Angle ϕ is CP violating. θ=0 gives purely axial coupling θ=π/2 is purely vector, π/4 is chiral. Set ϕ=0 for this talk. (Depending on coupling, e.g. electron EDM constrains ϕ to be very small anyway.)

$$\mathcal{L}_\ell = \frac{\partial_\mu a}{\Lambda} \sum_{\ell\ell'} C_{\ell\ell'} \bar{\ell} \gamma^\mu (\sin\theta_{\ell\ell'} + \cos\theta_{\ell\ell'} \gamma_5) \ell' + h.c.$$

- Integrate by parts, use EoM:

$$\mathcal{L}_\ell = a \sum_{\ell\ell'} \frac{C_{\ell\ell'}}{\Lambda} \bar{\ell} \left[(m_\ell - m_{\ell'}) \sin\theta_{\ell\ell'} + (m_\ell + m_{\ell'}) \cos\theta_{\ell\ell'} \right] \ell' + h.c.$$

- Important point #1: for flavor-diagonal couplings (l=l'), the vector coupling is irrelevant! PV angle θ only matters for LFV couplings.

- Important point #2: ALP-lepton couplings are proportional to the mass. Provides a natural hierarchy even if all $C_{ll'}$ ~ O(1) - τ-a couplings are largest!

- What about the other two parts of the Lagrangian?

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \mathcal{L}_\ell + \mathcal{L}_g + \mathcal{L}_h$$

- Gauge interaction Lagrangian, focus on two-photon coupling:

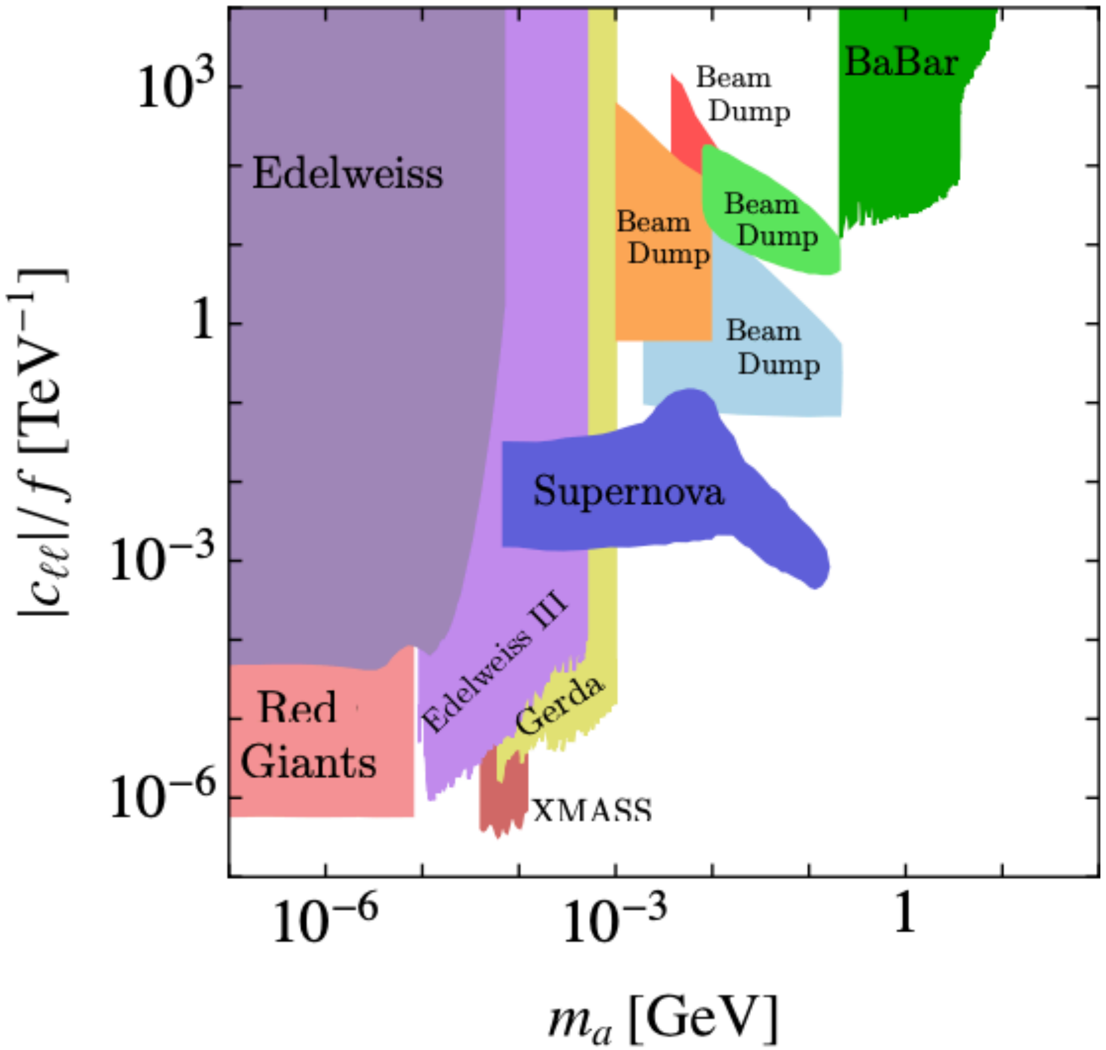
$$\mathcal{L}_g = 4\pi\alpha \frac{C_{\gamma\gamma}}{\Lambda} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \ldots$$

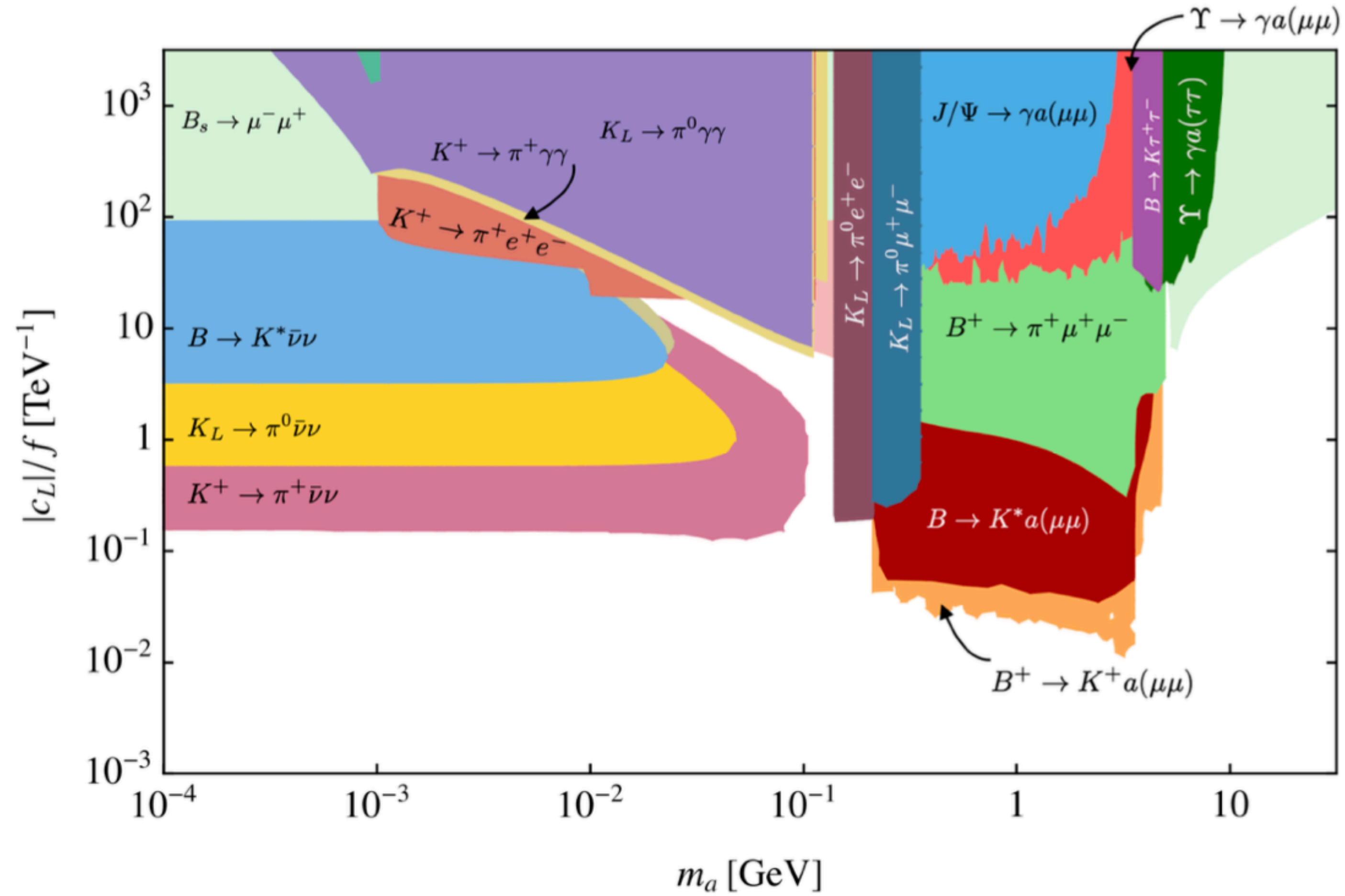
- This includes tree-level and loop-induced contributions. If we set tree-level $C_{\gamma\gamma} = 0$, loop-induced is always too small to matter (branching to two photons ~ 10^{-7} at m_a=2 GeV.)

- Last sub-Lagrangian is Higgs-ALP interactions. These are interesting - limits from rare Higgs decays are strong, see our paper 2105.05866! - but model-dependent. *Ignore* for EIC study.

Overview of existing limits

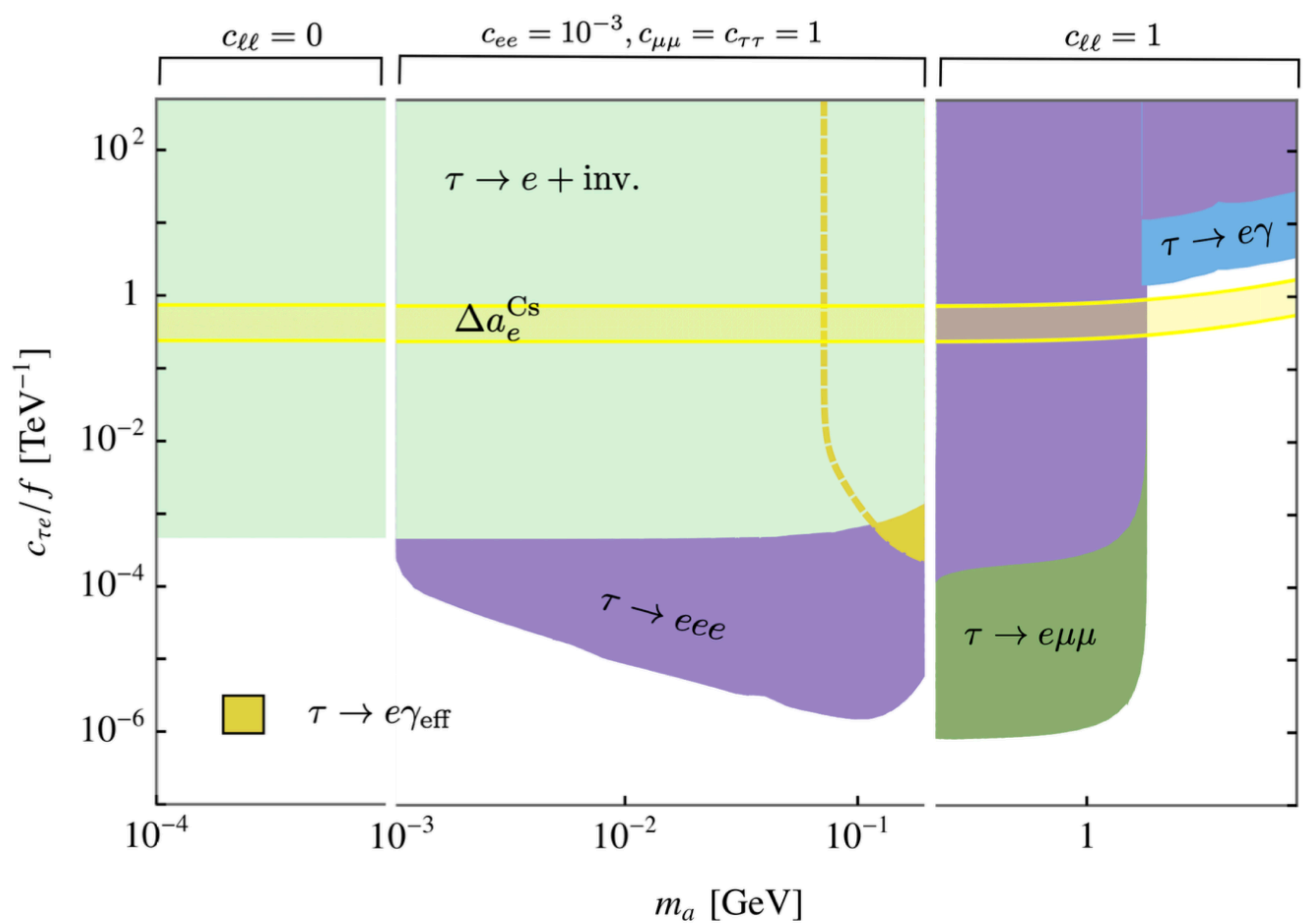
(from Bauer, Neubert, Renner, Schnubel, and Thamm, arXiv:2110.10698)





- <u>Lepton-diagonal couplings:</u> (*left*) strong astrophysical bounds at ma < 10^{-3} GeV; beam dumps below 1 GeV. (*right*) flavor-physics bounds effective above C_{ll} ~ 0.1/(1 TeV), but more model-dependent (assumes equal coupling to all LH lepton doublets.)

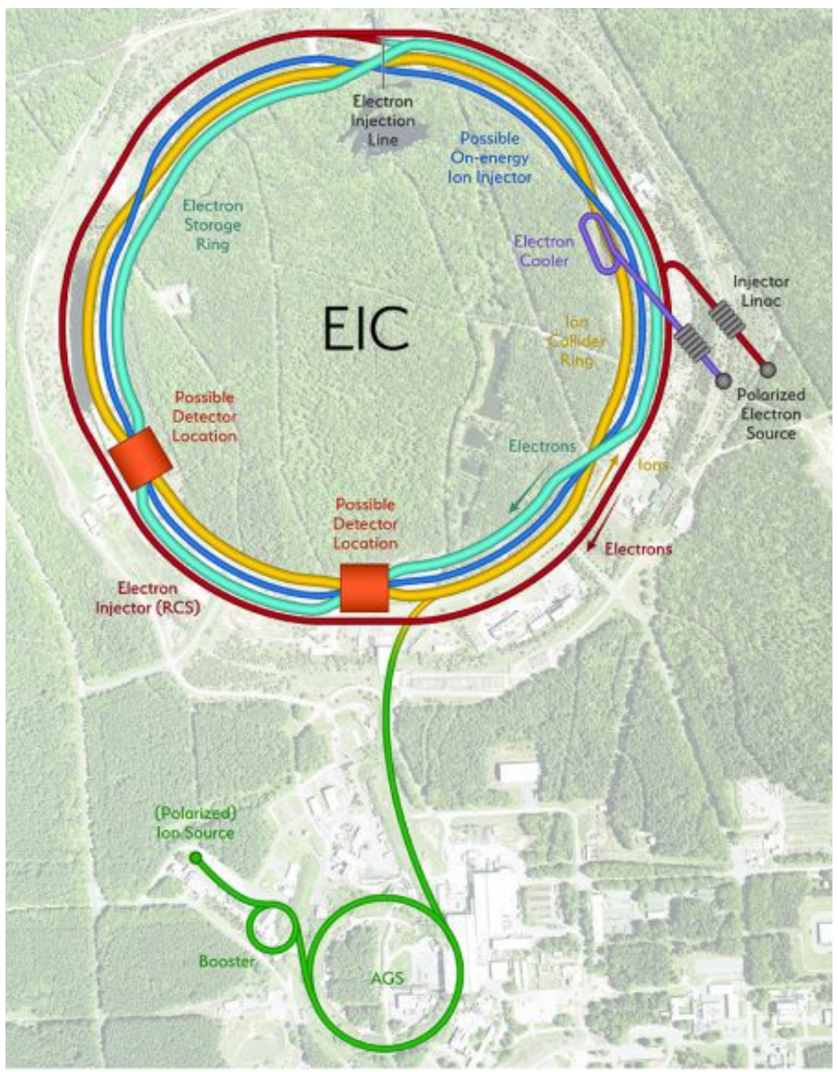
(from Bauer, Neubert, Renner, Schnubel, and Thamm, arXiv:2110.10698)
(see also: Cornella, Paradisi, and Sumensari, arXiv:1911.06279)



- LFV couplings: bounds are very strong, down to 10^{-6} / TeV. Here almost exclusively from exotic tau decays; much weaker above tau mass.
- Note the interplay between diagonal and off-diagonal lepton couplings; at heavier ALP masses, bounds are even weaker if diagonal c_{ll} are suppressed.

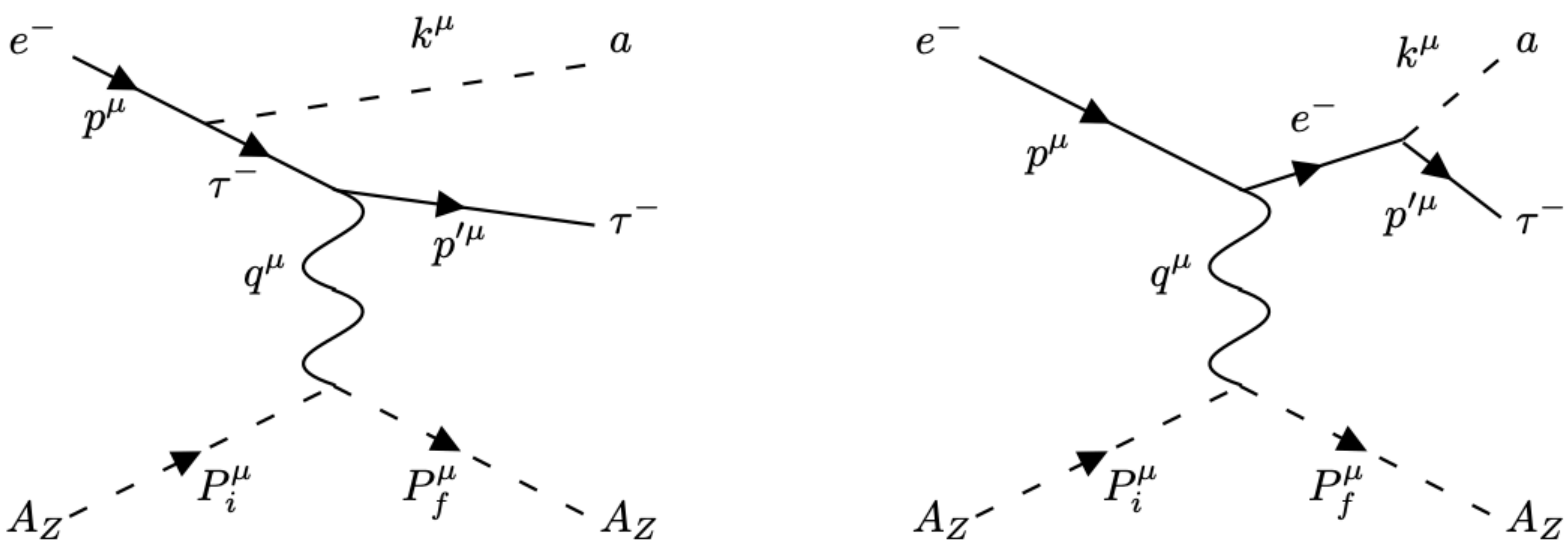
2. LFV ALPs at the EIC

New physics at the EIC?

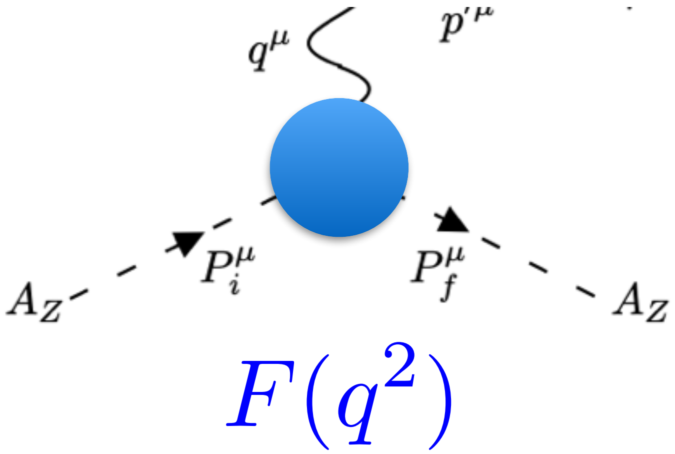


- EIC is a compelling machine for certain BSM searches, as we've heard!
- Study **electron-Au mode**: $|p_e| = 18$ GeV and $|p_{Au}| = 110$ GeV/nucleon; in the ion rest frame this resembles a fixed-target experiment with a **4.2 TeV** electron beam (!)
- Coherent scattering from gold —> **Z^2 enhancement** of cross section. (But, ion-mode luminosity (100/A) fb^{-1}, so overall Z^2/A vs. e-p mode - plus, a big CM energy boost.)
- Lower luminosity than average fixed-target/beam dump, but much better detector coverage and high CM energy; expect EIC to do best with new-physics models that are relatively *heavy* (vs. fixed-target) and have *distinctive, low-background signals* (so we only need a few events.)

Signal process

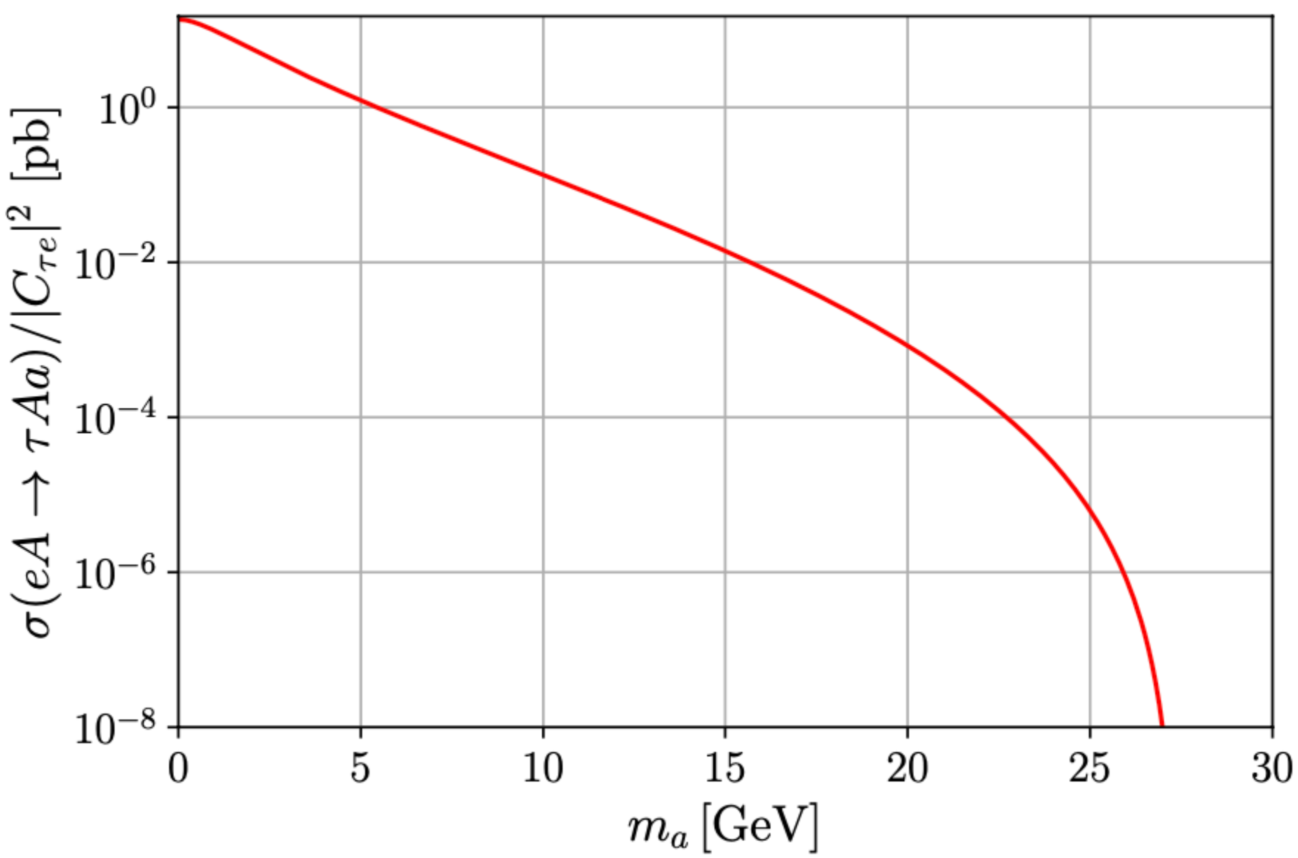


- Focus on $C_{e\tau}$ coupling. $C_{\tau\tau}$ also included, but suppressed, so Br(a —> eτ) ~ 100%. ($C_{\tau\tau}$ suppression can be natural if the parity-violating angle θ is present.)
- **Signal process:** $e^- A_Z \to \tau^- (a \to \tau^- e^+) A_Z$
- Extremely distinctive final state: two same-sign τ-, a positron, and the beam electron is gone!



$$F(q^2) = \frac{3}{q^3 R_A^3} \left(\sin qR_A - qR_A \cos qR_A\right) \frac{1}{1 + a_0^2 q^2}$$

- Woods-Saxon form factor for gold (Z=79, A=197), a0=0.79 fm, RA=(1.1 fm) $A^{1/3}$.



- The form factor suppression is active for m_a > 20 GeV or so (left.)
- We also impose a hard cutoff **$q^2 < (100\ \text{MeV})^2$**, to avoid nuclear breakup; this corresponds to m_a < 27 GeV. (Form factor suppression already large.)

Signal selection and efficiency

Signal processes:

$$e^- A_Z \to \tau^- (a \to \tau^- e^+) A_Z$$
$$e^- A_Z \to \tau^- (a \to \tau^- \tau^+) A_Z$$

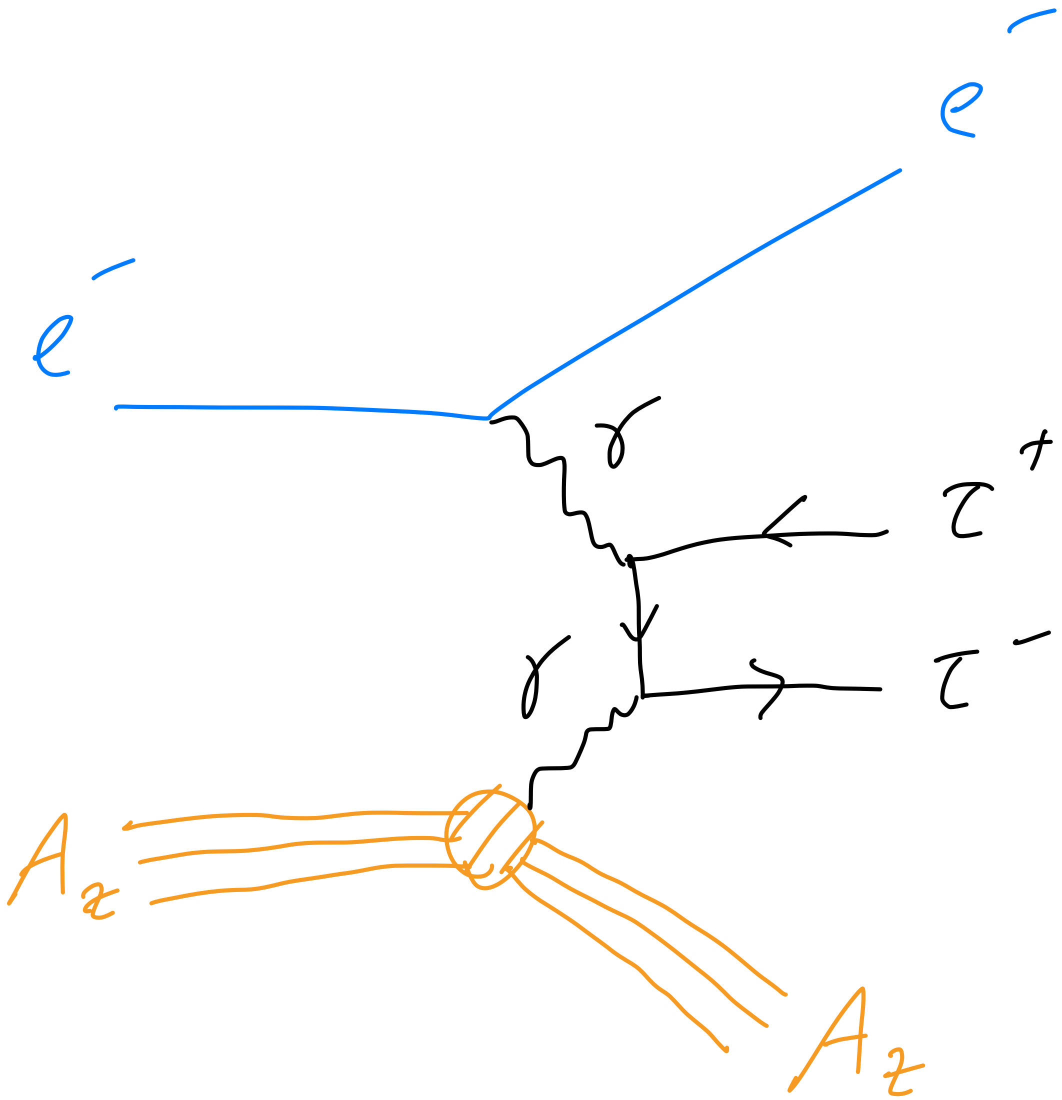
(subleading)

- **Selection criteria:**
  1. One tau identified in the final state;
  2. One e+ identified in the final state;
  3. Veto on final-state e-;
  4. Veto on nuclear breakup.

- We assume **1% efficiency** for τ identification (3-prong only; from ECCE paper, J.-L. Zhang et al., arXiv:2207.10261); see talk by A. Hurley on Wednesday.

- Can tag either final-state τ-; small additional loss when τ- gives back an electron. Overall signal efficiency **ε ~ 1.6%**.

Background



- Dominant background expected is τ pair production, specifically from the **Bethe-Heitler process** (left):

$$e^- A_Z \to e^- A_Z \tau^+ \tau^-$$

- Same Z^2 enhancement as our signal process!

- We adopt the results of Bulmahn and Reno (arXiv:0812.5008) for muons scattering on “rock” (Z=11, A=22) at ~4 TeV, and rescale by $(Z_{Au}/Z_{rock})^2$.

- Estimate: **σ_{bg} ~ 26 nb.**

BG: $e^- A_Z \to e^- A_Z \tau^+ \tau^-$

- Two ways this can pass our selection cuts:

  A. Mis-ID the beam e- as e+ (10^{-3}, guess from Yellow Report based on π/e fake rates), *and* the τ- does NOT decay to an electron;

  B. Lose the beam e- (10^{-2}, from Yellow Report), *and* τ+ decays to a positron.

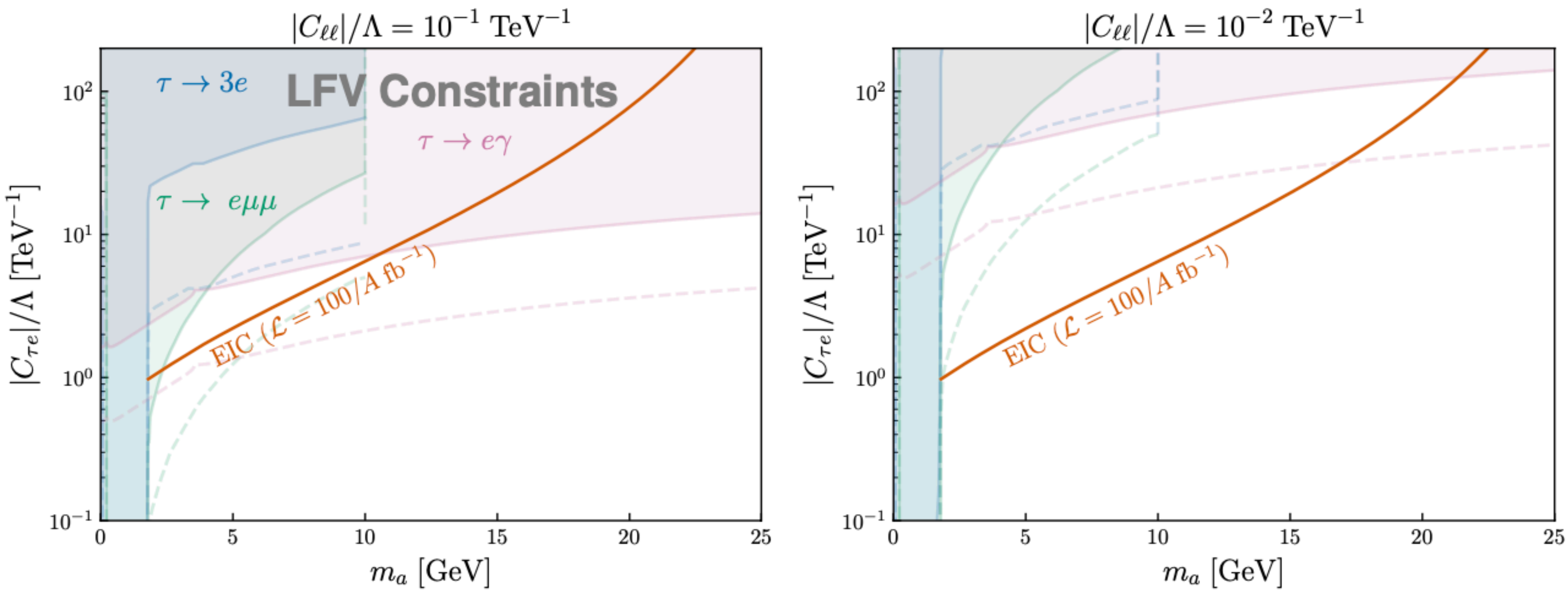
- Either scenario also requires a tagged τ at the same 1% efficiency as the signal.

$$\epsilon_{\mathrm{b.g.},A} = 10^{-3} \cdot 10^{-2} \cdot (1 + 1 - 0.18) = 1.82 \times 10^{-5}$$

$$\epsilon_{\mathrm{b.g.},B} = 10^{-2} \cdot 10^{-2} \cdot 0.18 = 1.8 \times 10^{-5}$$

Total: $\epsilon_{\mathrm{b.g.}} = 3.62 \times 10^{-5}$

- L = (100/A) fb^{-1} —> 475 background events; need 35 signal events for 90% CL.



- Solid regions are current bounds; dashed lines show projections (Belle-II, 50 ab^{-1}.)

- Note that direct flavor-violation bounds for $m_a > m_\tau$ are much weaker if diagonal C_{ll} is reduced (left to right plot), but EIC reach is unaffected!

- Improvement in tau tagging efficiency (now 1%) or background reduction (now 475 events) could greatly improve sensitivity…(e.g. kinematic cuts to distinguish resonant signal from background might help.)

Summary so far

- EIC search offers useful bounds for GeV-scale LFV ALPs; constraints are *robust* vs. small C_{ll}, unlike precision tau-decay searches.

- Muon capability? $C_{\mu e}$ is probably not competitive at EIC (down by $(m_\mu/m_\tau)^2$), and direct flavor-violation experiments are stronger.) $C_{\mu\tau}$ could be probed if $C_{e\tau}$ is also present, and final state is even more distinctive:

$$e^- A_Z \to \tau^- A_Z (a \to \tau^\pm \mu^\mp)$$

- "Far backward" capability? Versus dark photons (H. Davoudiasl's talk on Tuesday), ALPs are relatively heavy so signal is peaked at somewhat smaller $|\eta|$. Could still help, but less dramatic.

3. Electron (g-2) and LFV ALPs

*X. Fan, T.G. Myers, B.A.D.Sukra, G.Gabrielse, arXiv:2209.13084

*T. Aoyama, T. Kinoshita, M. Nio, arXiv:1712.06060

Electron (g-2) anomaly

- As mentioned before, tensions between $(g-2)_e = a_e$ measurement* and SM prediction*, depending on which input α is used:

$$\Delta a_e(\mathrm{Rb}) = (34 \pm 16) \times 10^{-14}, \quad (+2.2\sigma)$$

$$\Delta a_e(\mathrm{Cs}) = (-101 \pm 27) \times 10^{-14}. \quad (-3.7\sigma)$$

- Less significant than $(g-2)_\mu$, but cleaner SM theory: hadronic corrections are much smaller.

(arXiv:1908.00008)

Axion-like particles, lepton-flavor violation and a new explanation of a_μ and a_e

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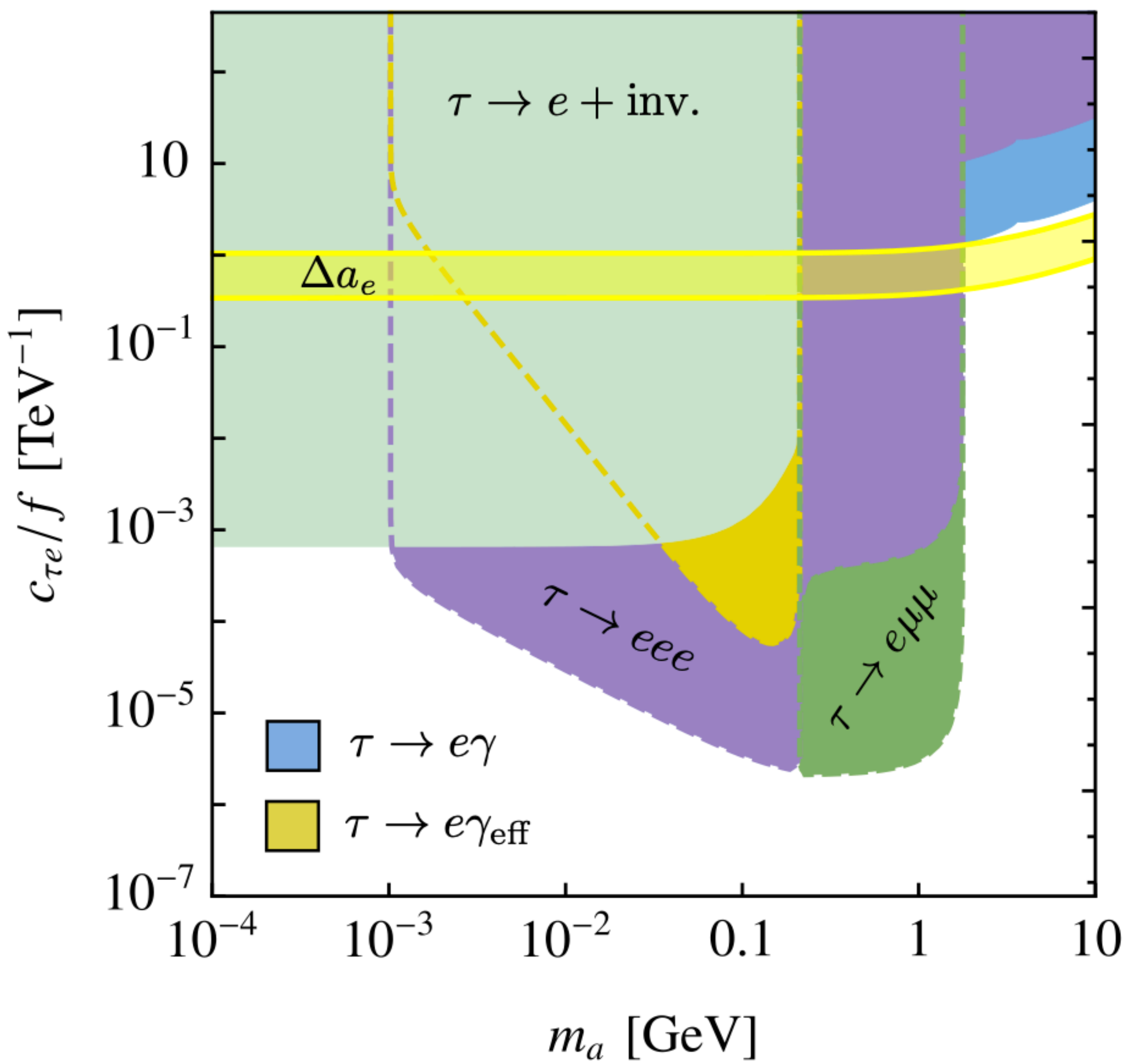
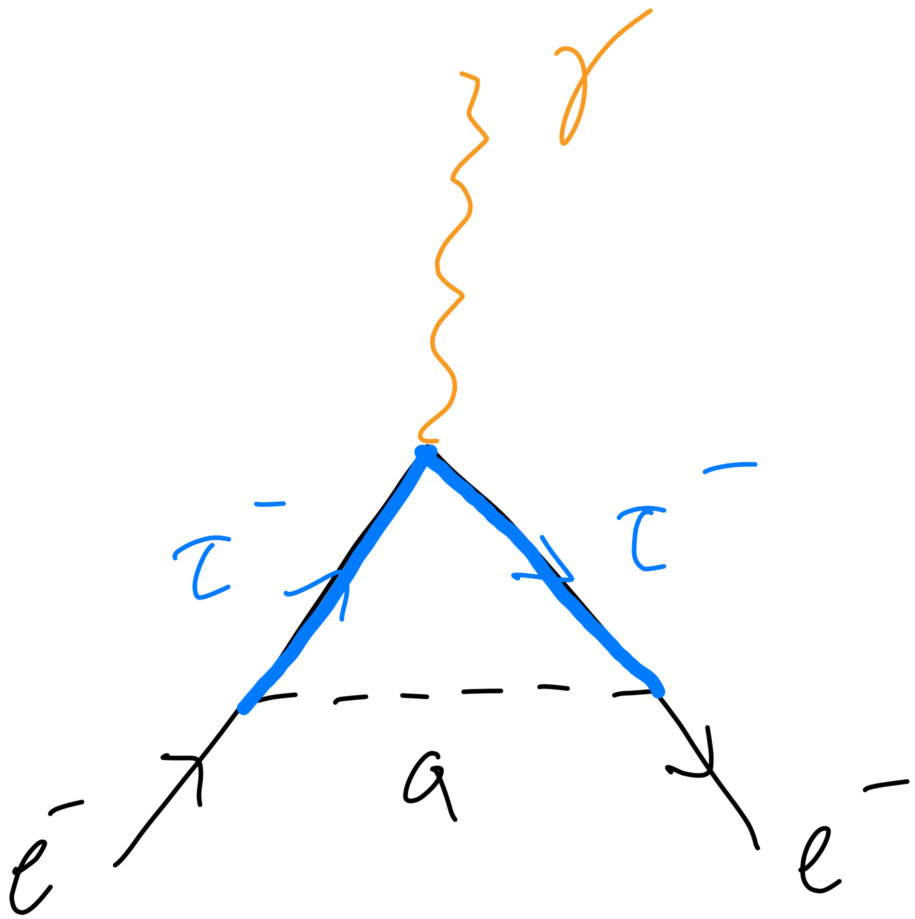


- Matching the Δa_e discrepancy using LFV ALPs has been considered before
- Solution is possible where τ decay bounds are weakest (i.e. above m_τ.)
- The solution region (left) is out of reach of EIC, but it assumes O(1/TeV) lepton-diagonal couplings, and doesn't fully explore dependence on parity-violating θ.

- Contribution to $(g-2)_e$ arises from purely the LFV $C_{\tau e}$ coupling:

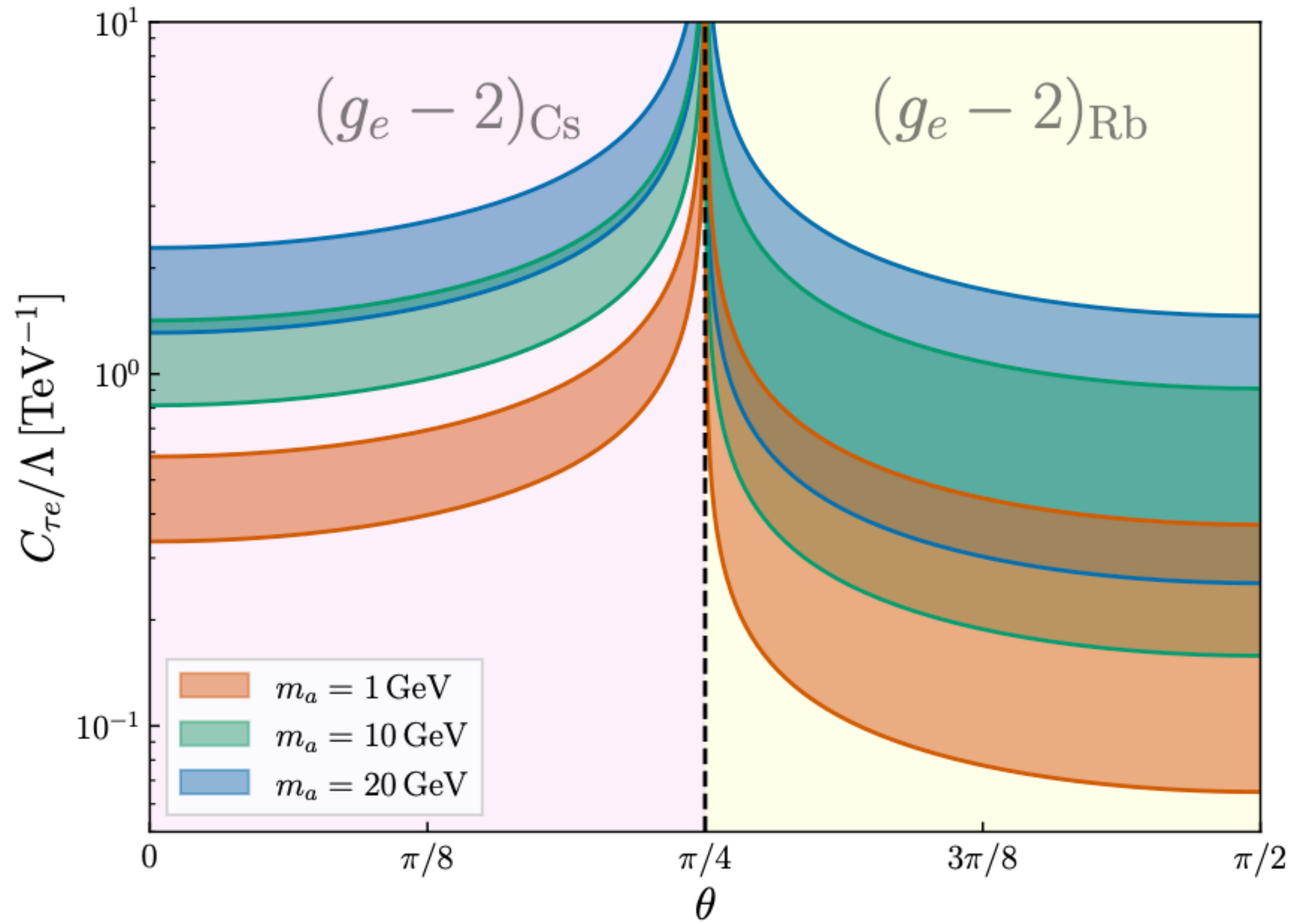


$$\Delta a_e = -\frac{m_e^2 C_{\tau e}^2}{16\pi^2\Lambda^2}\left(f(x_\tau) + \frac{m_\tau}{m_e} g(x_\tau)\cos 2\theta\right)$$

$(x_\tau = m_a^2 / m_\tau^2.)$

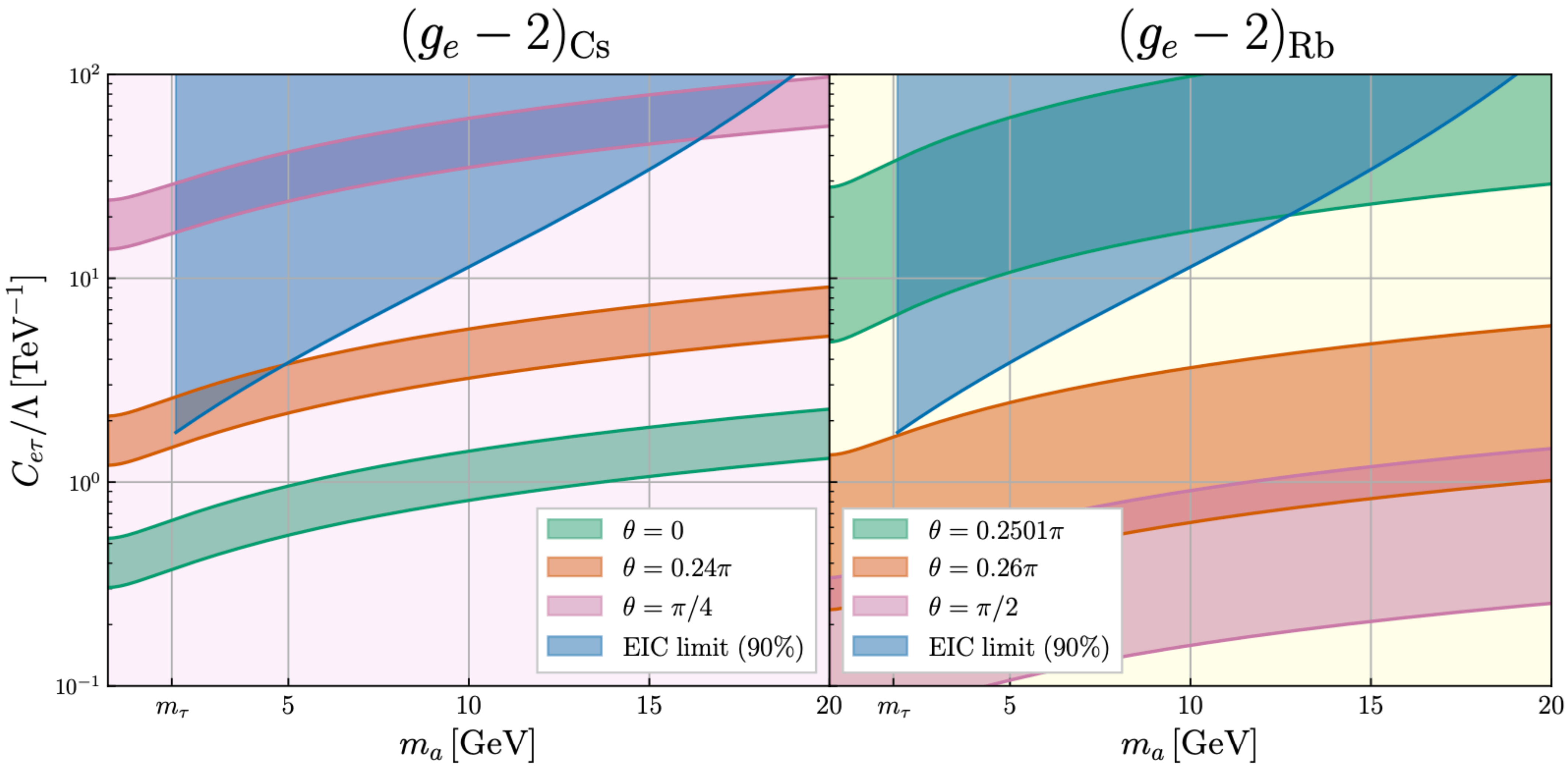
- f(x) and g(x) are kinematic factors. The f(x) term is *almost* negligible (down by $m_e/m_\tau \sim 3500$), but results in the maximum anomaly being slightly away from $\theta=\pi/4$.

- Solution regions (2σ) for the $(g\text{-}2)_e$ anomaly vs. parity-violating angle θ and coupling $C_{\tau e}/\Lambda$.
- Sign flips close to (not exactly at) θ=π/4.



$$r_{LR} = (2p-1)\frac{\sigma_L-\sigma_R}{\sigma_L+\sigma_R}$$
$$= (2p-1)\sin 2\theta.$$

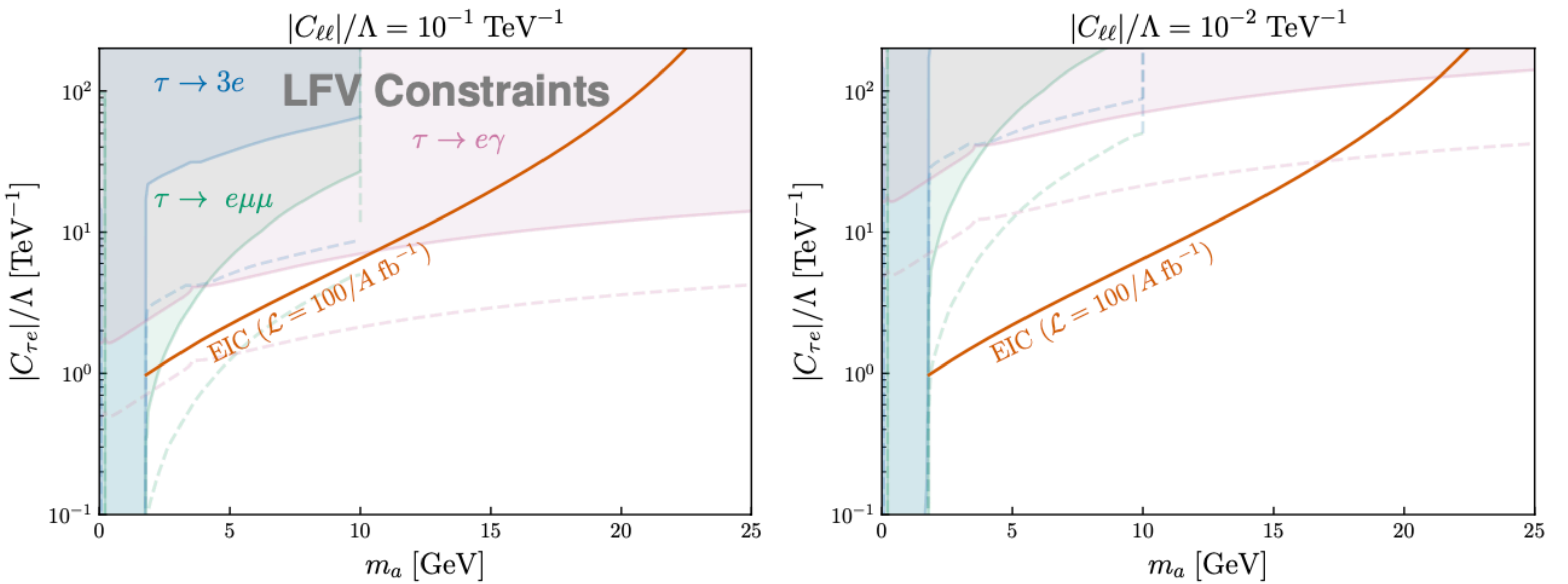
- EIC beam polarization can directly probe signal chirality, which strongly impacts Δa_e; if this model does explain the anomaly, can confirm it!



- Combine with the previously-described EIC search. θ has minimal effect on EIC reach, but large effect on $(g\text{-}2)_e$.

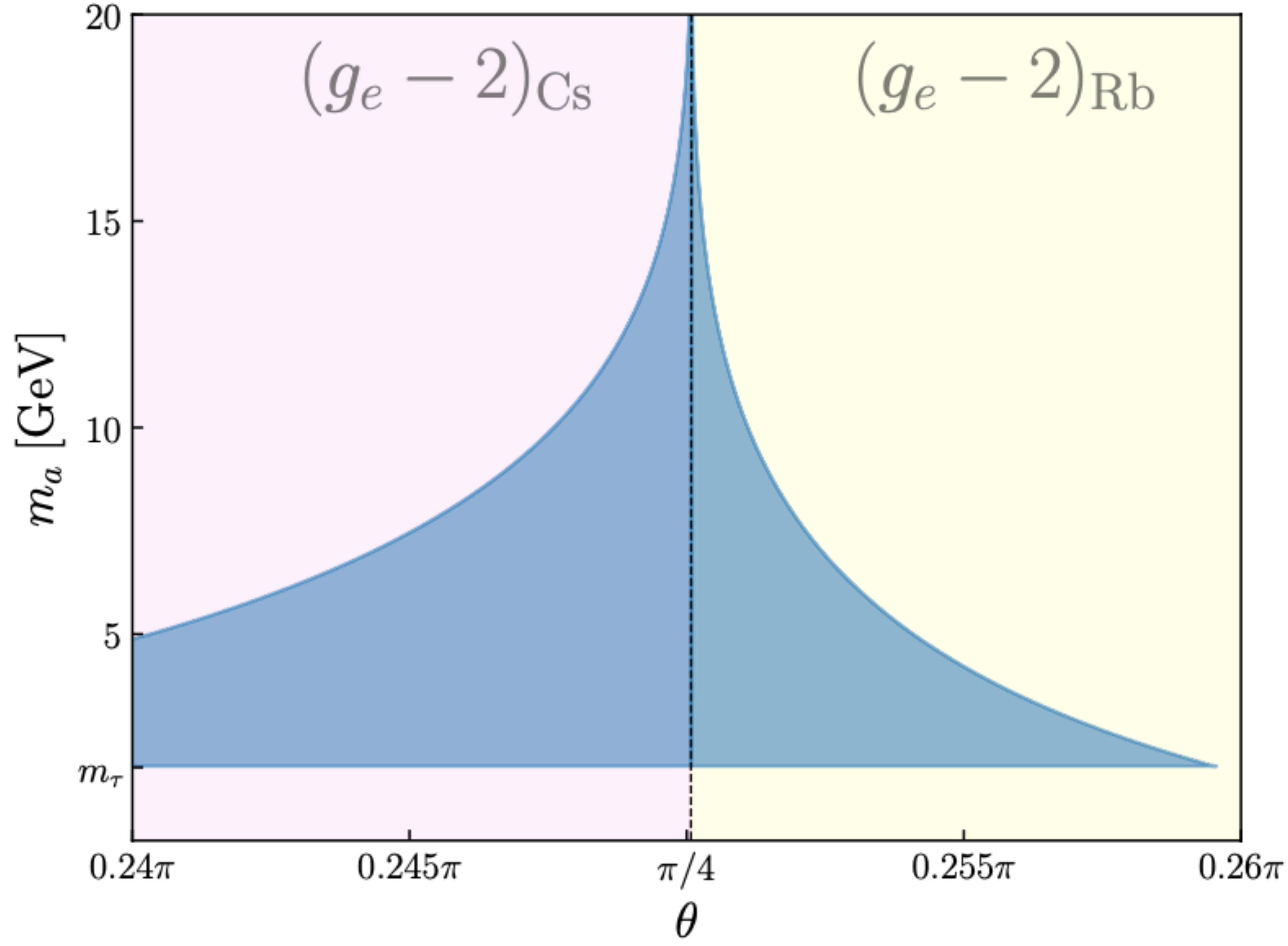
- EIC search is best at probing solutions which are "close to chiral", θ~π/4, where the corresponding coupling is strongest. If the EIC search can be improved enough, may be able to cover all possible θ (especially for α(Cs).)

Conclusions



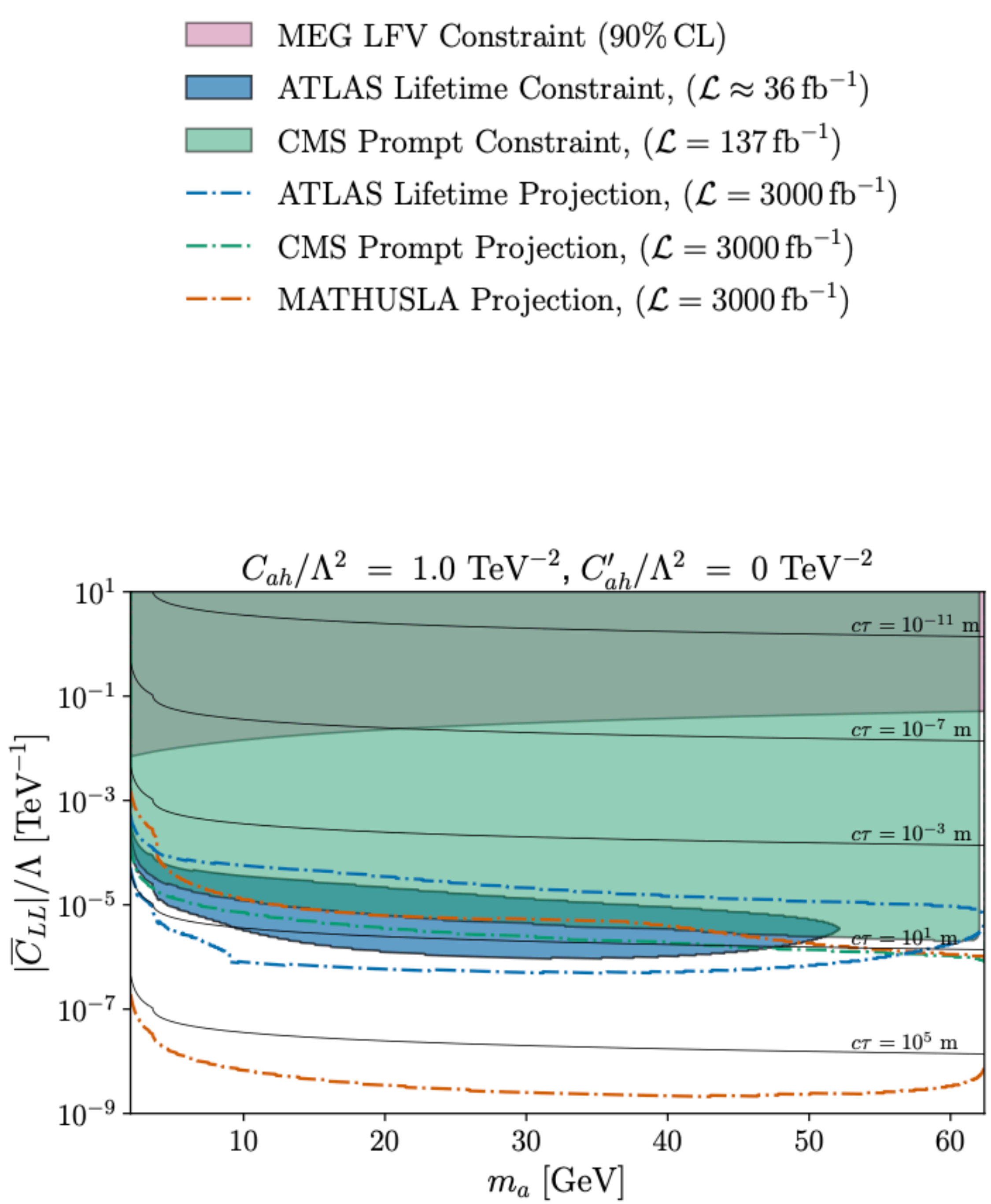
- EIC searches for ALPs with eτ coupling can probe new regions in parameter space, especially if diagonal lepton couplings are suppressed;
- Can potentially explore parameter space where the same model explains the $(g\text{-}2)_e$ discrepancy with the SM.
- Overall, EIC seems promising for a wide range of BSM searches, although not everything; more particle pheno study is needed to understand the best things to look for!

Backup slides



- Region where current EIC projected search can cover an ALP (g-2)e explanation, vs. ALP mass and θ.

Higgs decays and LFV ALPs



- Signal process:

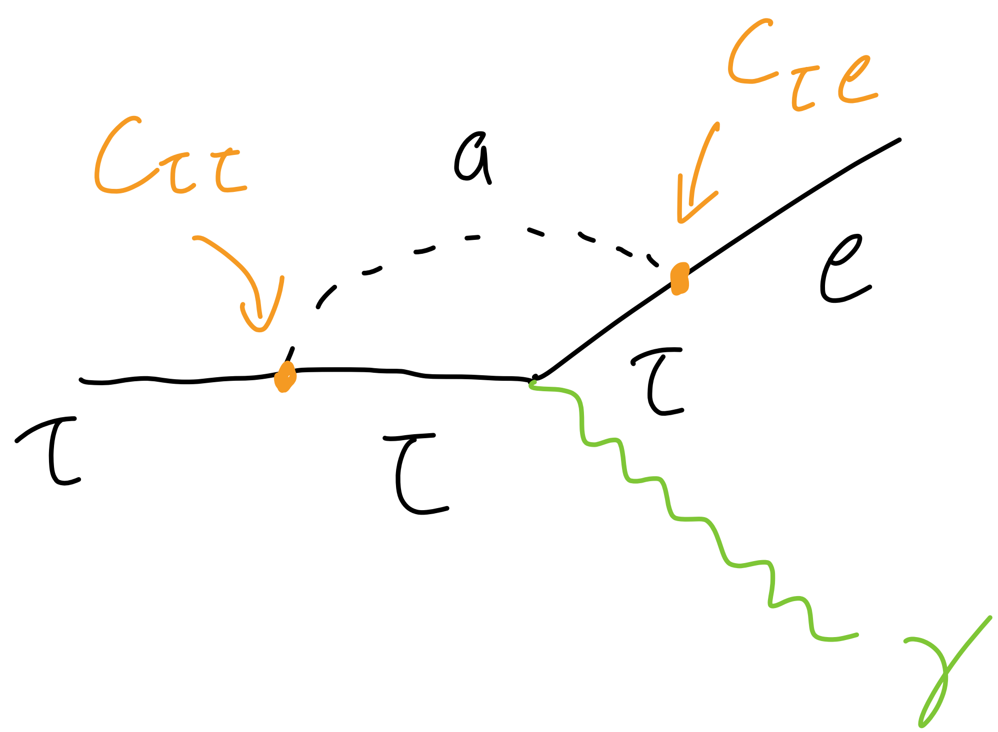
$$h \to aa \to (\tau(\tau/\ell))(\tau(\tau/\ell))$$

- Signal selection depends on channel (adapt existing searches), but same-sign lepton pairs are typical + displaced decays at some couplings.

- Projected constraints from HL-LHC, and MATHUSLA; dedicated search for signature not yet considered.

- This channel is MUCH stronger than LFV constraints - *but* depends on Higgs coupling.

Tau decay and ALP-lepton couplings



- e.g. τ->eγ, left.
- Any diagram with internal ALP needs both flavor-violating and flavor-diagonal couplings, since total # of vertices is even.
- Decays where a is on-shell only need $C_{e\tau}$, but not present for $m_a > m_\tau$.

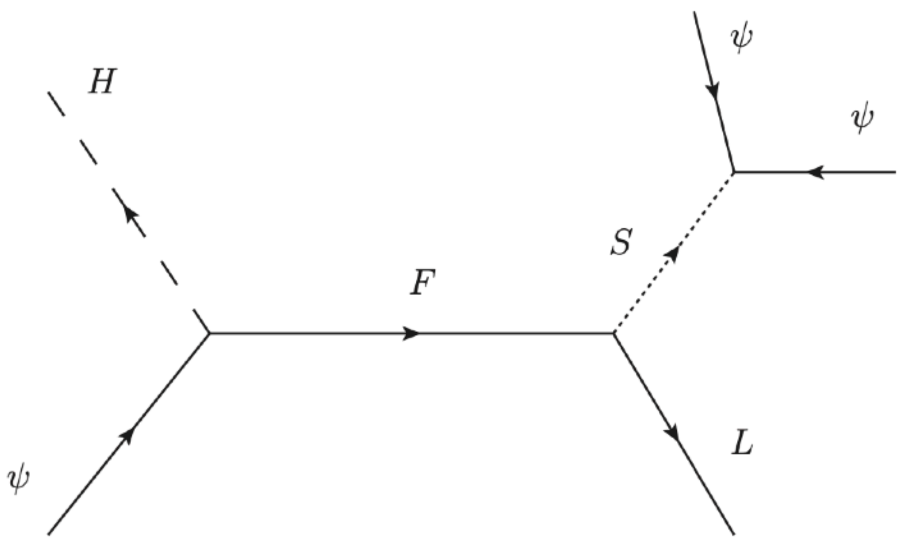
(Davoudiasl, Giardino, Neil, and Rinaldi, arXiv:1709.01082)

Example chiral ALP model

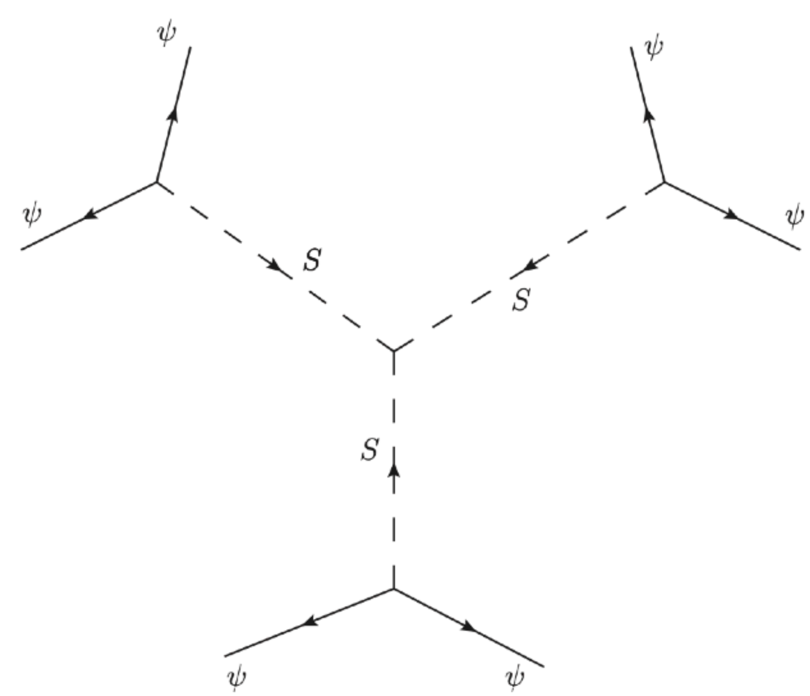
- UV-complete model for neutrino mass + composite dark sector.

$$Y^{f\alpha}\,\tilde{H}^*\bar{L}_f\,N_\alpha$$

$$\mu_N^{\alpha\beta}\,\bar{N}^c_\alpha N_\beta\ .$$



$$N \sim (\psi\psi\psi)$$
$$a \sim (\bar{\psi}\psi)$$



- Couplings to left-handed lepton doublet only leads to chiral structure —> θ = 3π/4.