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

ALPs and Lepton Flavor Violation at the EIC

Ethan T. Neil (Colorado)
BNL Workshop, “Uncovering New Laws of Nature at the EIC”
11/21/24

Outline

- This talk will highlight results from two papers on **lepton flavor-violating ALPs:**
    - arXiv:**2112.04513**: Direct production at the EIC;
    - arXiv:**2402.17821**: Electron (g-2) anomaly and EIC searches.
- And (briefly) one paper on displaced decays of hidden vectors (arXiv:**2307.00102**)
- Lots of credit goes to my collaborators:
    - **Hooman Davoudiasl** (BNL)
    - **Roman Marcarelli** (grad student @ CU Boulder; visited BNL through the DOE SCGSR program)
- More flavor-violating ALPs? 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” (ALPs)** 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. *(See talk by V. Cirigliano)*

- 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^-.)

2. LFV ALPs at the EIC

Kinematics at the EIC

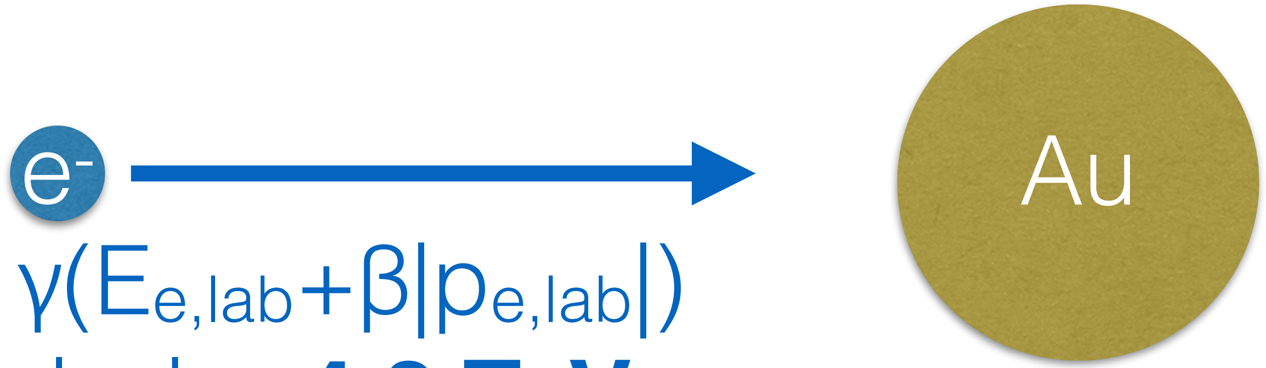
Lab frame:

$|p_e| = 18$ GeV

$|p_A| = 110$ GeV/A

Boost: $\gamma \sim 120$

Ion frame:

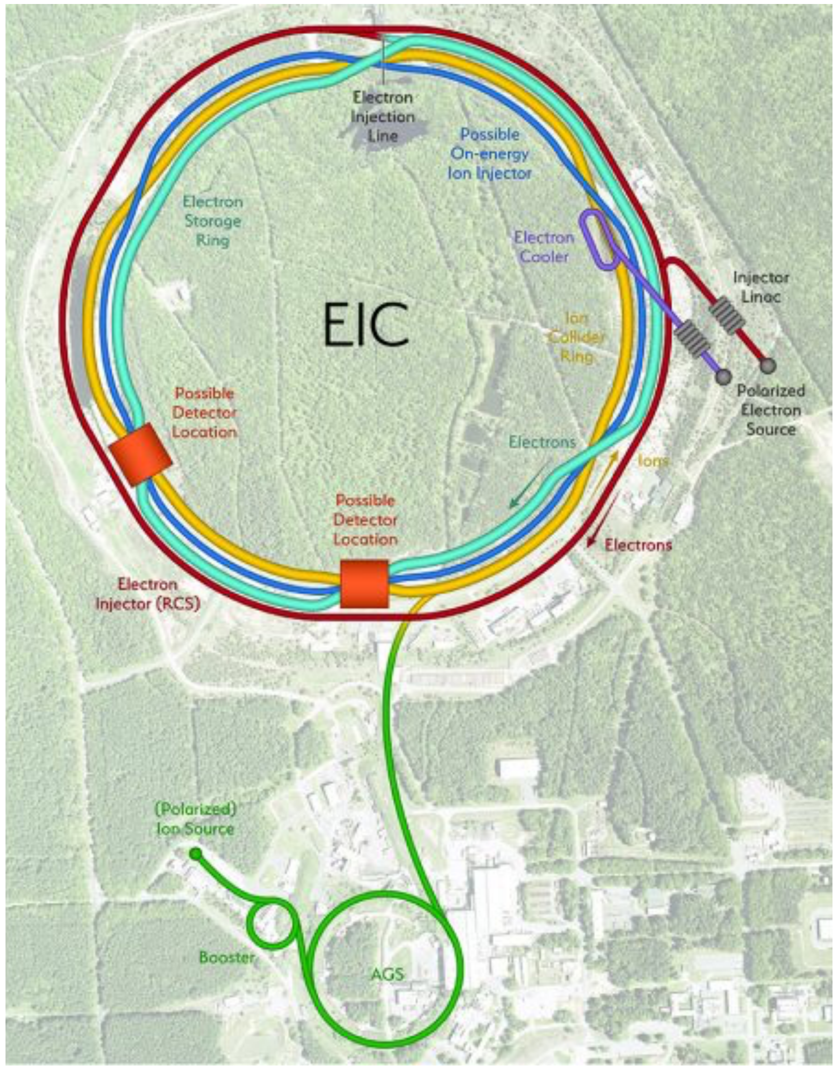


$E_e = \gamma(E_{e,lab} + \beta|p_{e,lab}|)$

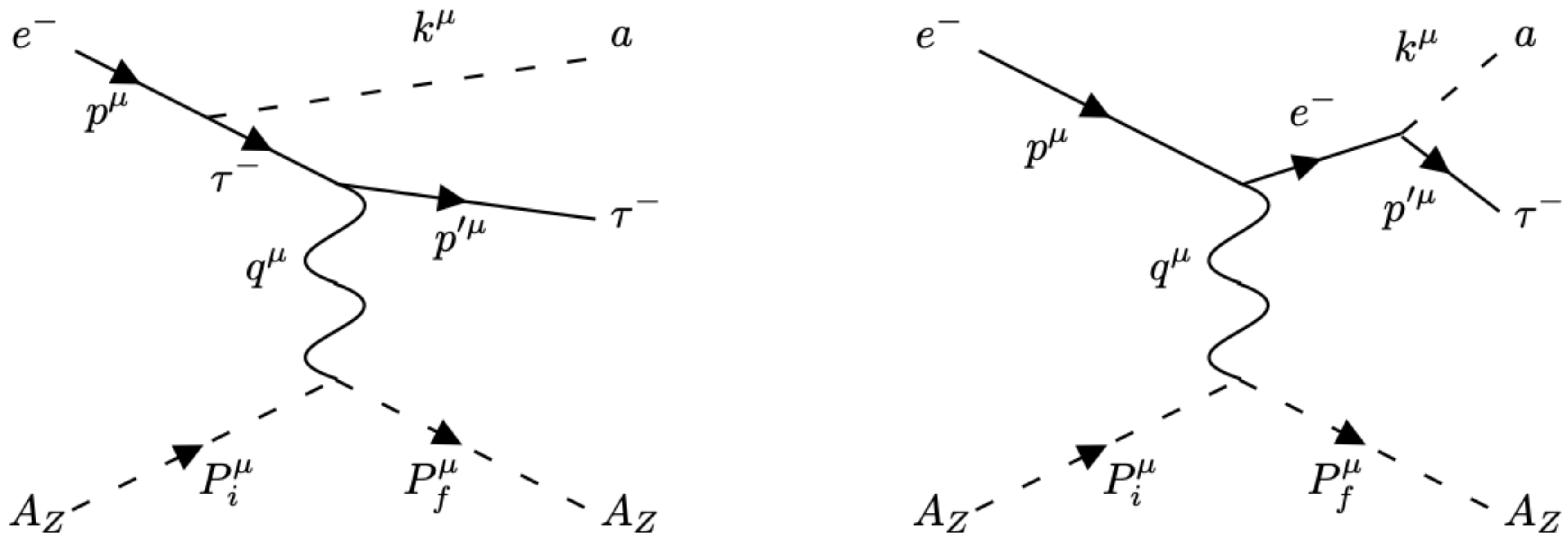
$\sim 2\gamma|p_e| \sim$ **4.2 TeV**

(higher luminosity/lower energy:
10 GeV e^- beam —> **2.4 TeV**.)

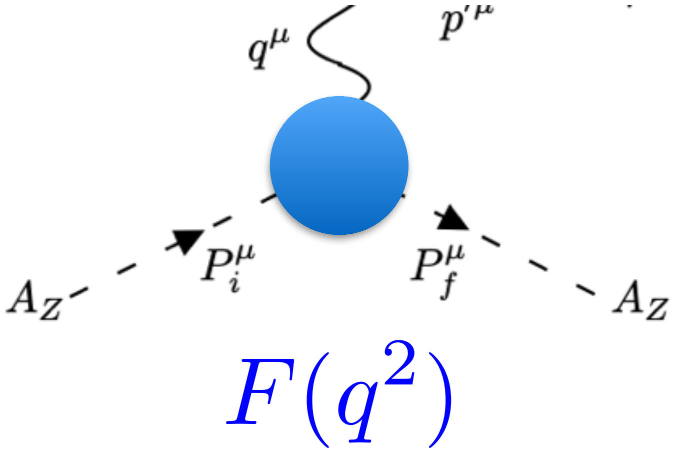
New physics at the EIC?



- Study **electron-Au mode**: ion rest frame this resembles a fixed-target experiment with a **4.2 TeV** electron beam (intensity frontier? Energy frontier!)
- 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.)
- Versus fixed-target/beam dump, lower luminosity but higher CM energy, better detector coverage. EIC does best with BSM particles that are relatively *heavy* (vs. fixed-target) and have *distinctive, low-background signals* (so we only need a few events.)

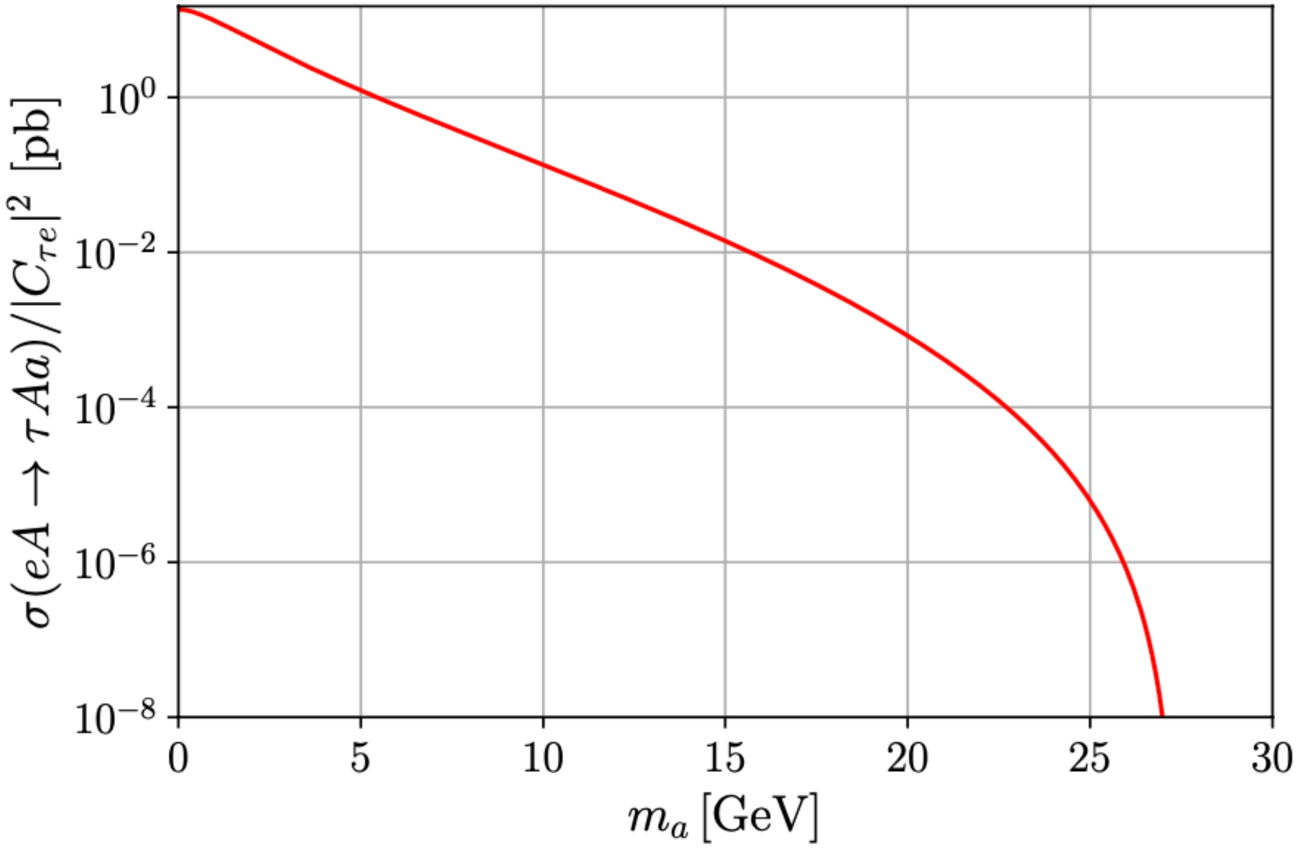


- Focus on $C_{e\tau}$ coupling. $C_{\tau\tau}$ also included, but suppressed, so Br(a —> eτ) ~ 100%. ($C_{\tau\tau}$ suppression can be natural if the parity-violating angle θ is present.)
- **Signal process:** $e^- A_Z \to \tau^- (a \to \tau^- e^+) A_Z$
- Extremely distinctive final state: two same-sign τ-, a positron, and the beam electron is gone!
- ALP is produced preferentially in the direction of the beam electron (since emission is from electron and momentum transfer is assumed small.) Significant signal can end up in "far backwards" region at large negative η.



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

- Woods-Saxon form factor for gold (Z=79, A=197), a0=0.79 fm, R_A=(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:

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

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

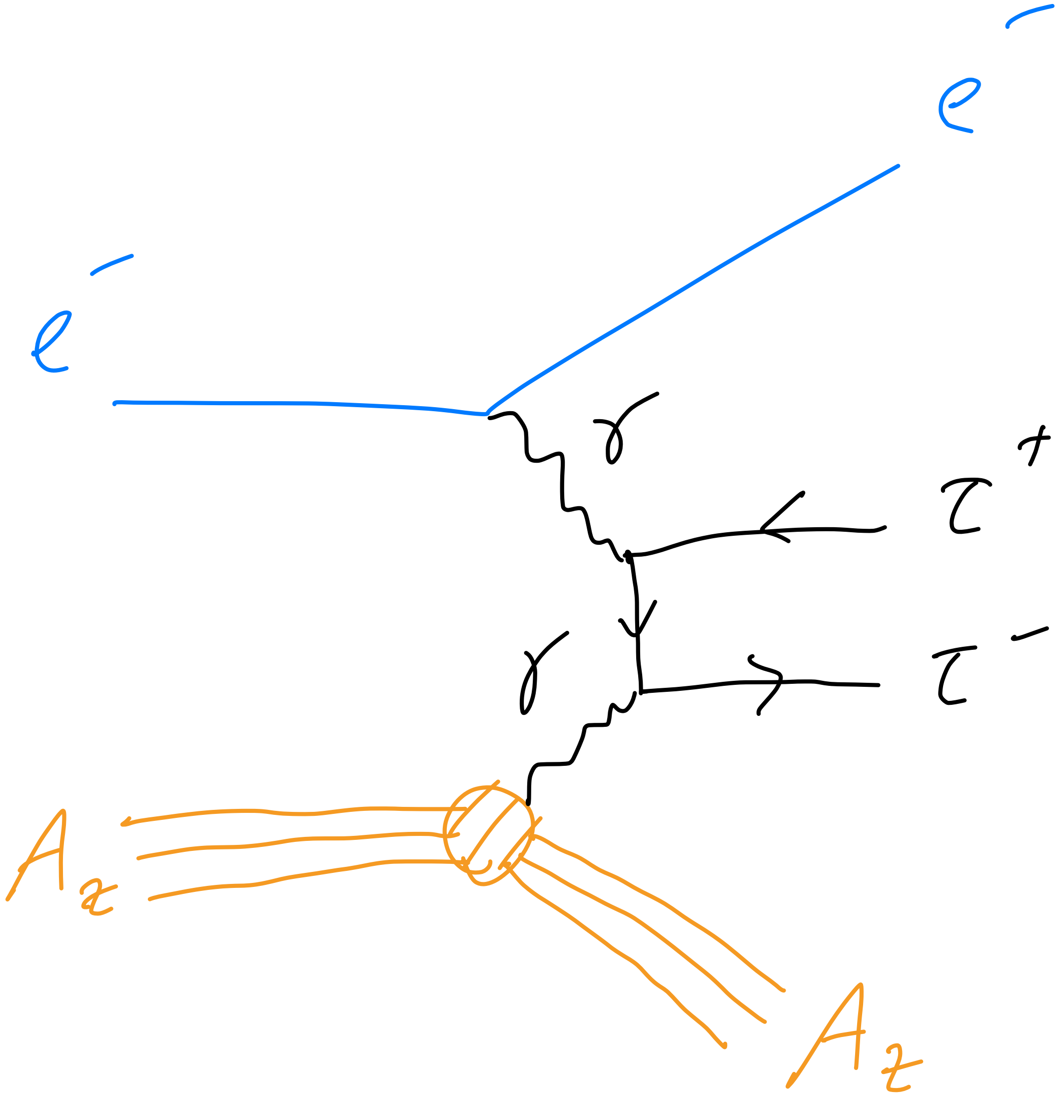
(subleading)

- **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).

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

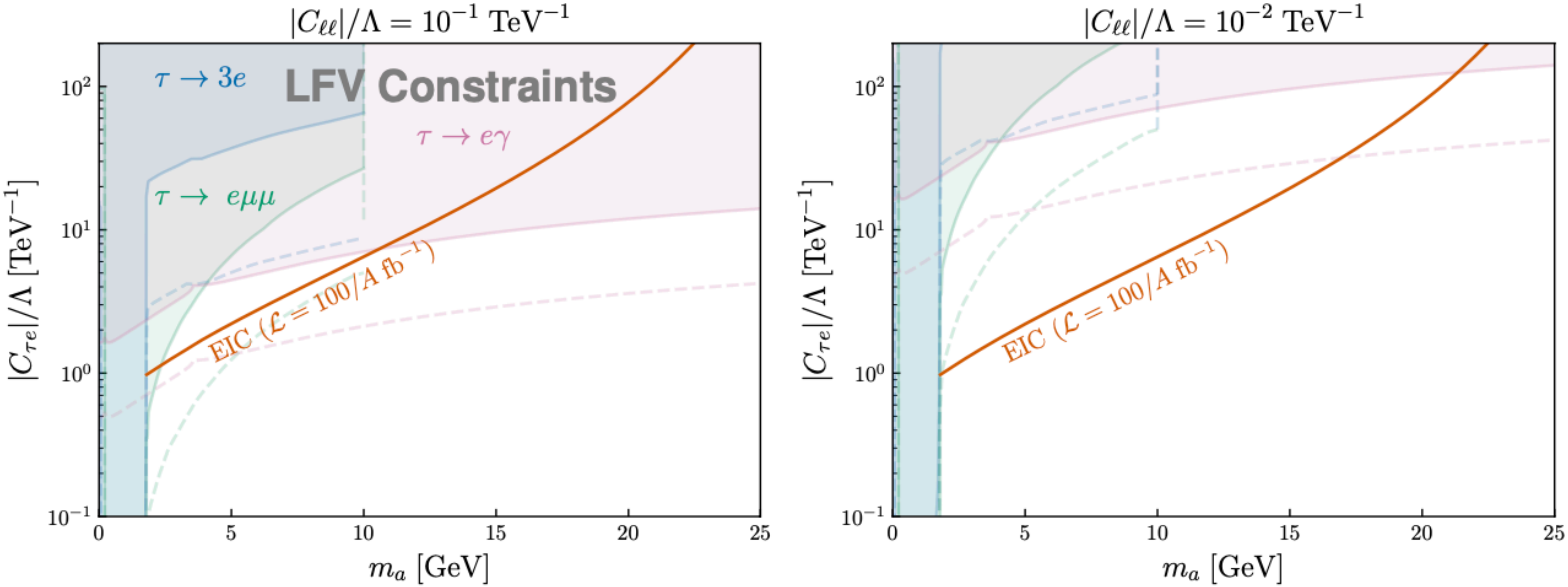
- Two ways this can pass our selection cuts:
  - A. Mis-ID the beam e^- as e^+ (10^{-3}, guess from Yellow Report based on π/e fake rates), *and* the τ^- does NOT decay to an electron;
  - B. Lose the beam e^- (10^{-2}, from Yellow Report), *and* τ^+ decays to a positron.
- Either scenario also requires 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.

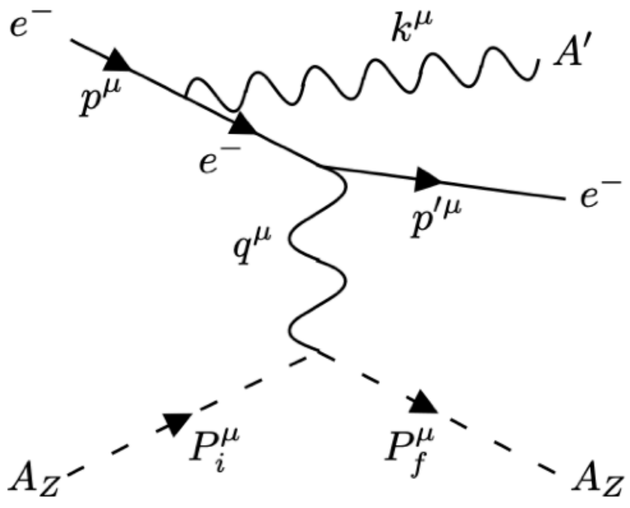
- Muon capability? $C_{\mu e}$ is probably not competitive at EIC (down by $(m_\mu/m_\tau)^2$), and direct flavor-violation experiments are stronger.) $C_{\mu\tau}$ could be probed if $C_{e\tau}$ is also present, and final state is even more distinctive:

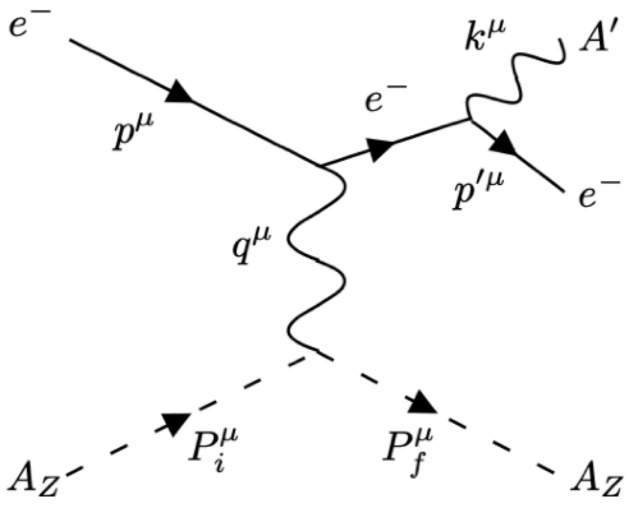
$$e^- A_Z \to \tau^- A_Z (a \to \tau^\pm \mu^\mp)$$

  - We've seen proposals for muon tagging even without dedicated muon detection capability; interesting to pursue further for BSM searches! Maybe interesting for certain QCD studies too (?)

3. Displaced decays of hidden vectors

- Search for hidden vectors: e.g. dark photon, but also B-L and L_i-L_j gauge bosons. Signal production diagrams look familiar:

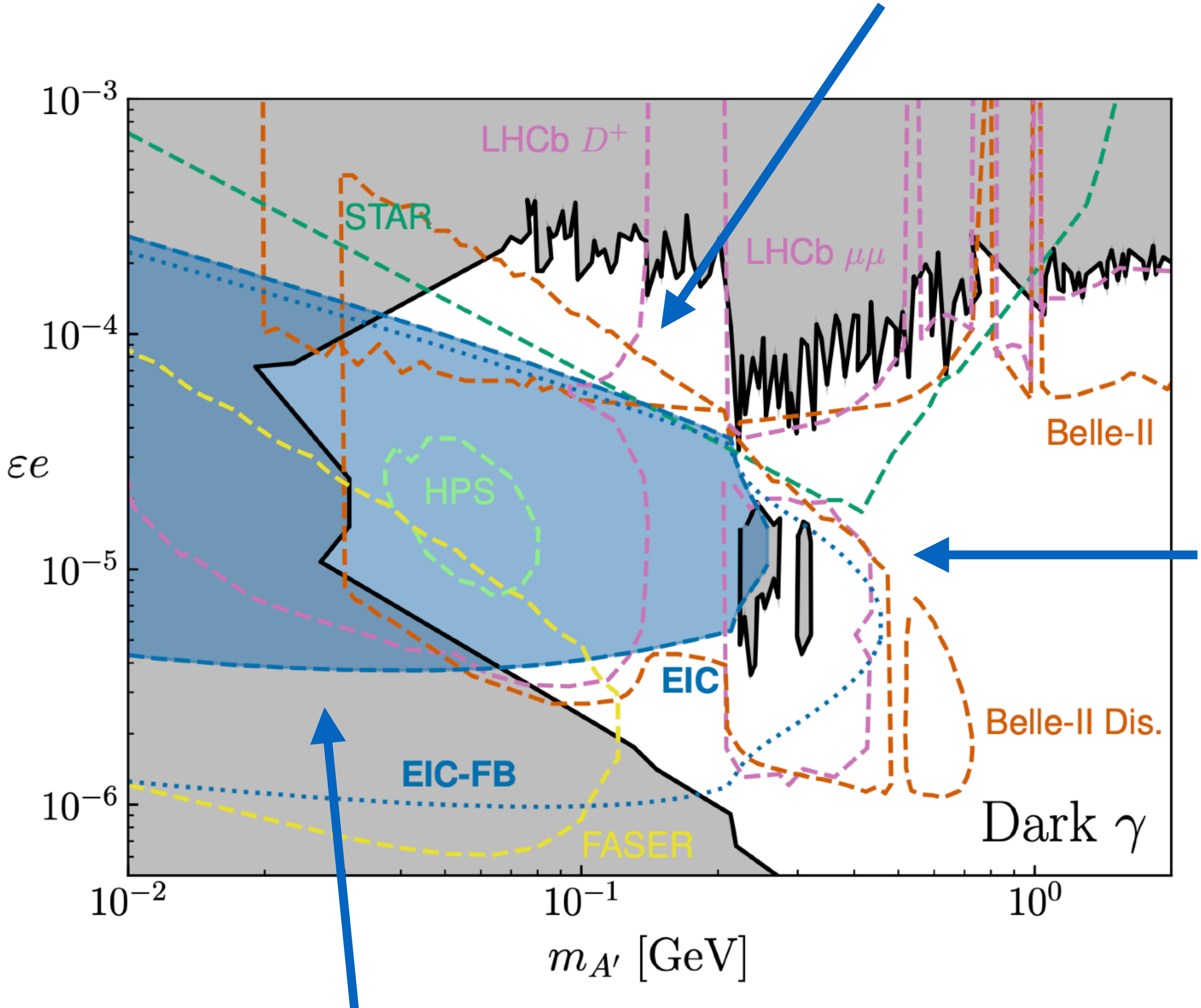




- Massive background potential in EIC, e.g. from real photon events. However, discriminate by studying only displaced decays. Sufficient displacement leads to ~0 SM background!

$$d_{A'} = \gamma v \tau_{A'} \sim \frac{120}{g_{A'}^2} \left(\frac{1\ \text{GeV}}{m_{A'}} \right) (2 \times 10^{-16}\ \text{m}) \begin{cases} \xrightarrow{g_{A'} \sim 10^{-4}} & \sim 20\ \mu\text{m} \\ \xrightarrow[g_{A'} \sim 10^{-6}]{} & \sim 0.2\ \text{m} \end{cases}$$

upper limit: displacement becomes too small (< 200 μm, w/geometric factors)



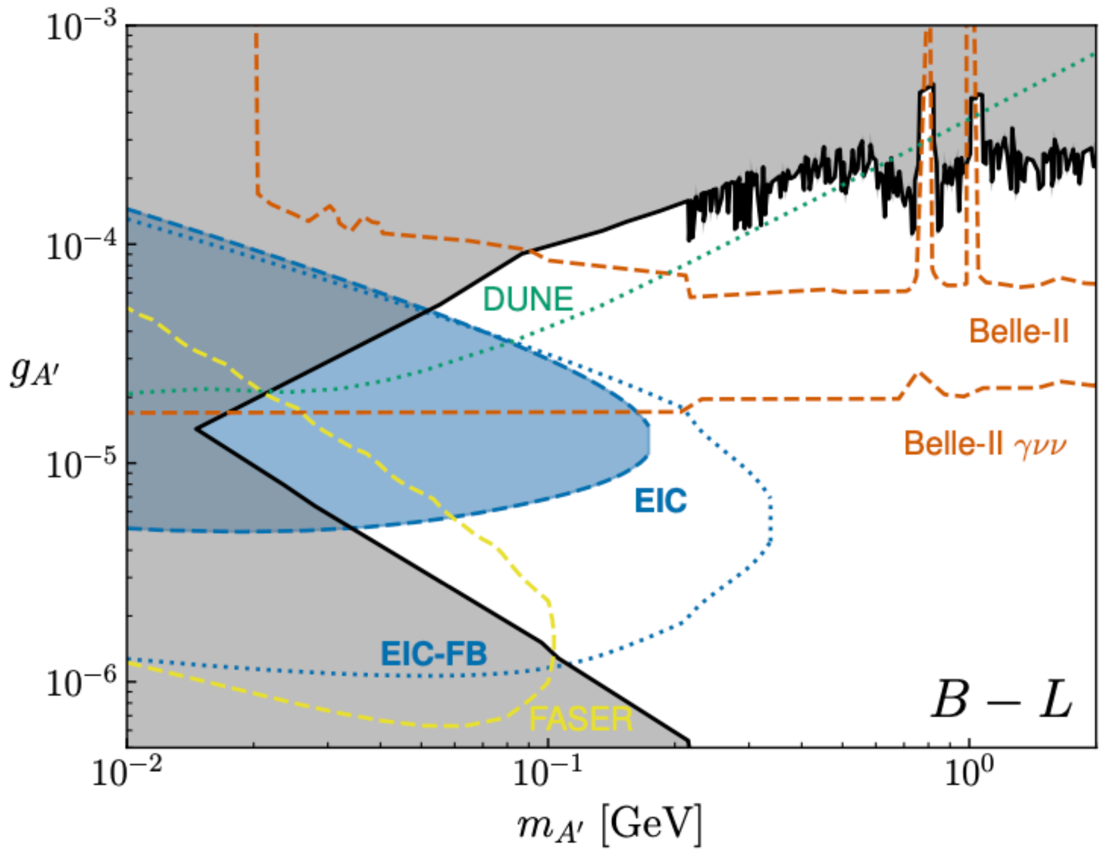
right limit: momentum transfer too large; loss of coherent enhancement. (Also, displacement reduced; boost reduces e^+e^- opening angle.)

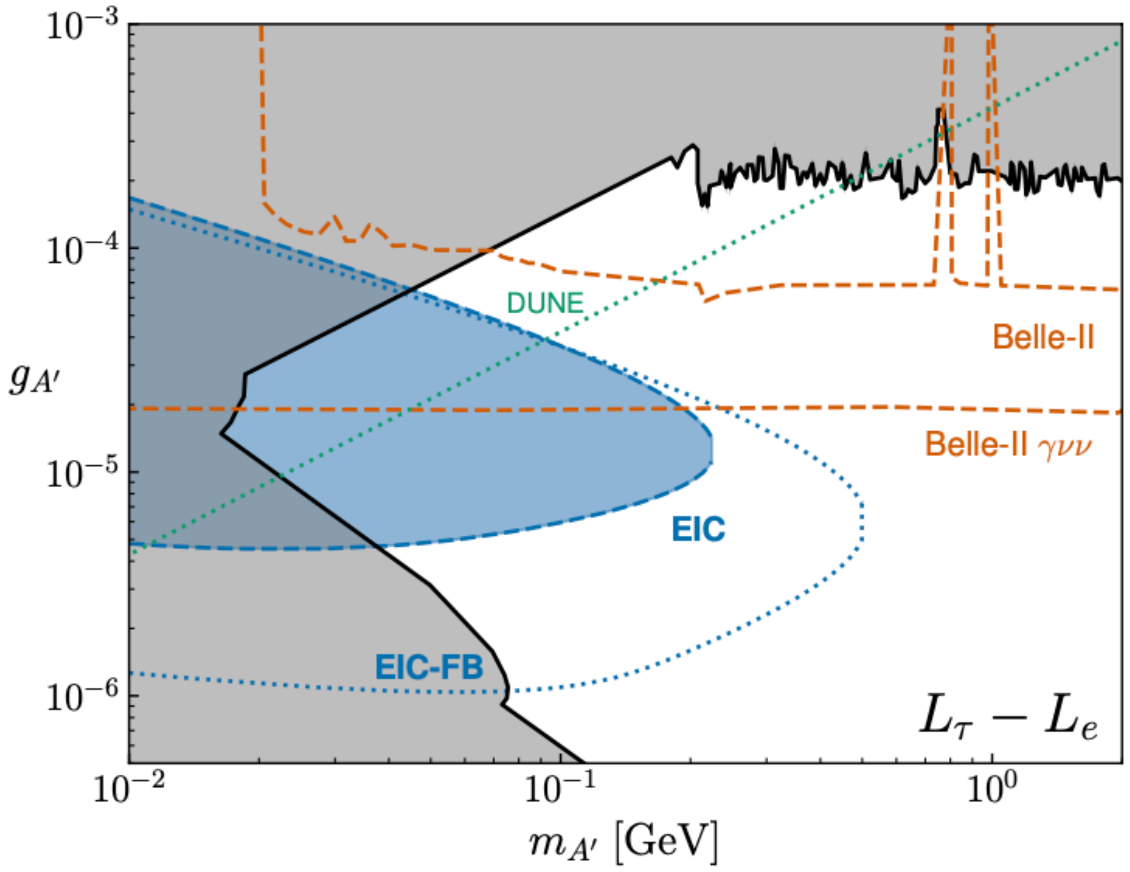
lower limit: production rate too small; displacement close to too large. (Note that **rate is peaked towards large, negative η**. “EIC-FB” scenario assumes a “B0-like” detector in electron beam direction, -4 < η < -6.

- Bounds on B-L, L_τ-L_e shown to the right; much less competition in this parameter space vs. dark photon. Also probe L_μ-L_e, similar results to L_τ-L_e.

- EIC is especially powerful for probing gauge bosons coupled to electron number, due to the initial-state electron.

- We assumed no muon detection capability; being able to tag even some fraction of muons could further improve reach.





4. 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

- Tensions are present between $(g\text{-}2)_e = a_e$ measurement* and SM prediction*, depending on which input α is used:

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

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

- Less significant than $(g\text{-}2)_\mu$, 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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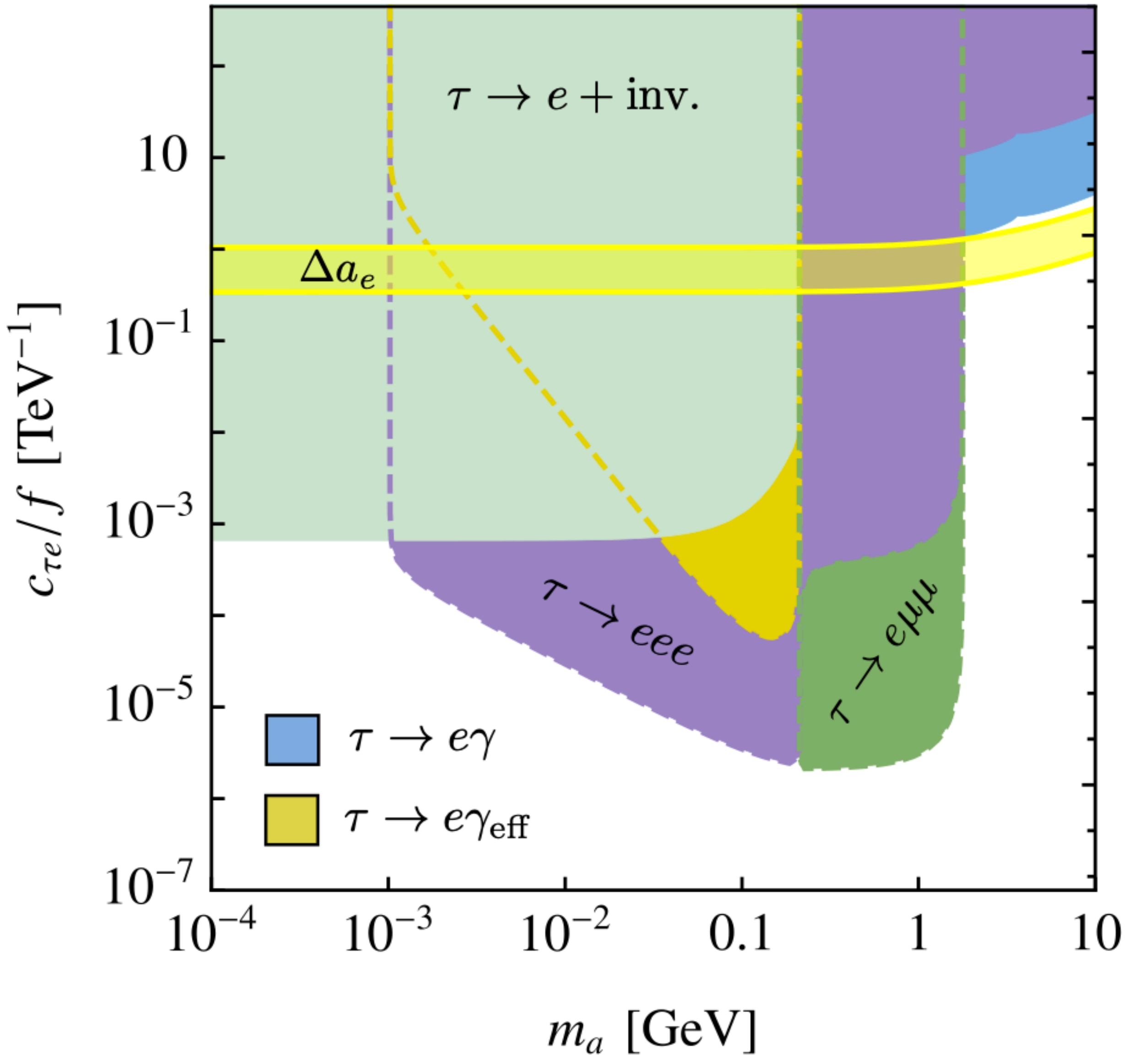
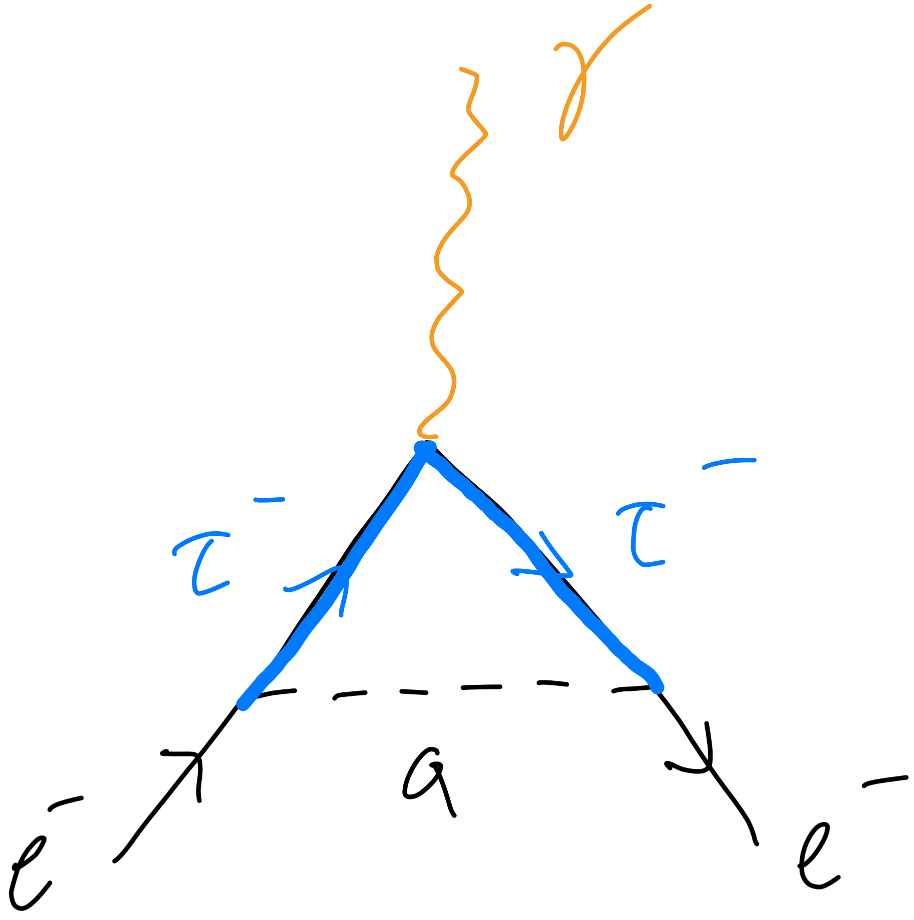


- Matching the Δa_e discrepancy using LFV ALPs has been considered before

- 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:



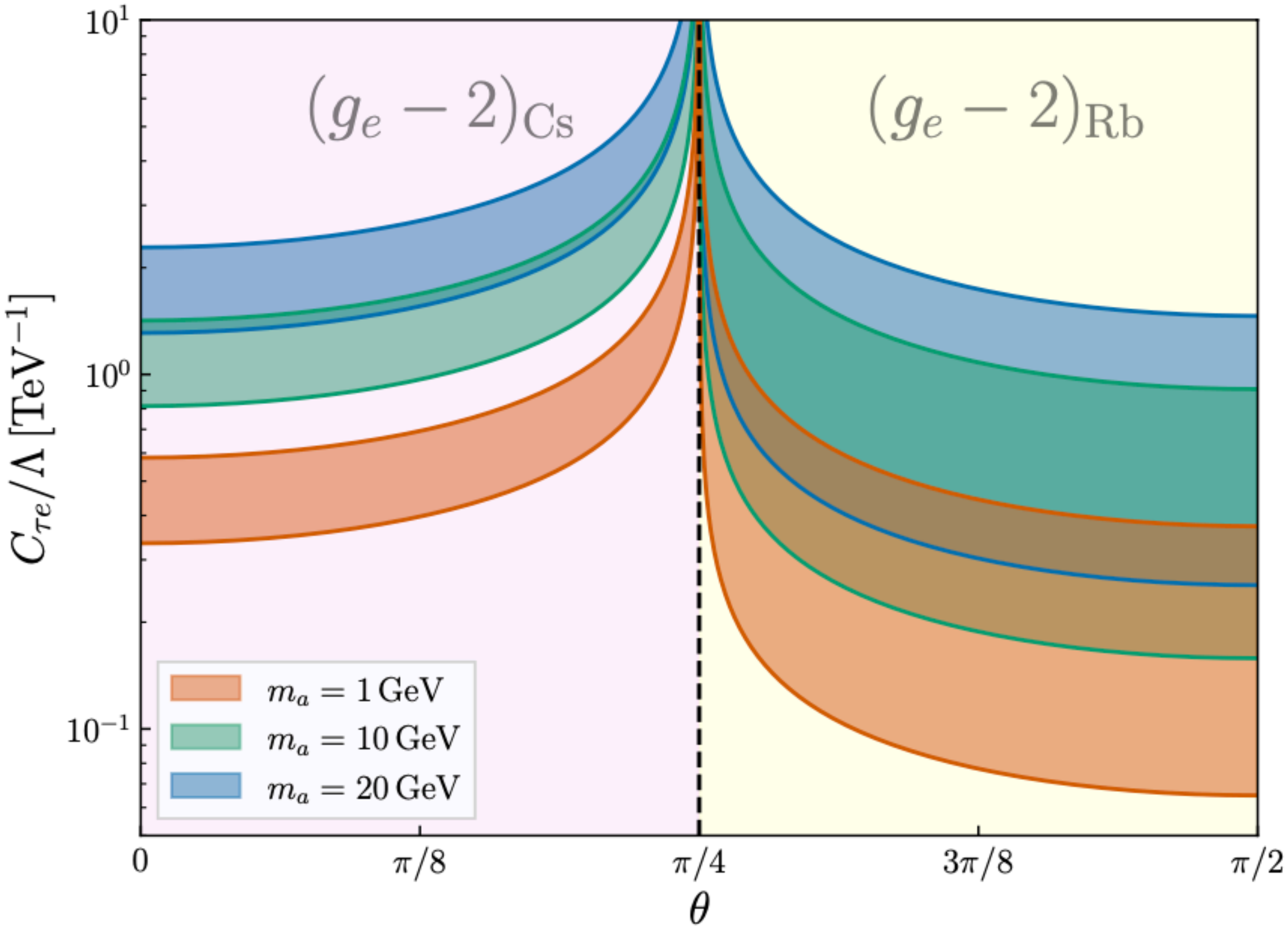
$$\Delta a_e = -\frac{m_e^2 C_{\tau e}^2}{16\pi^2\Lambda^2}\left(f(x_\tau) + \frac{m_\tau}{m_e} g(x_\tau)\cos 2\theta\right)$$

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

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

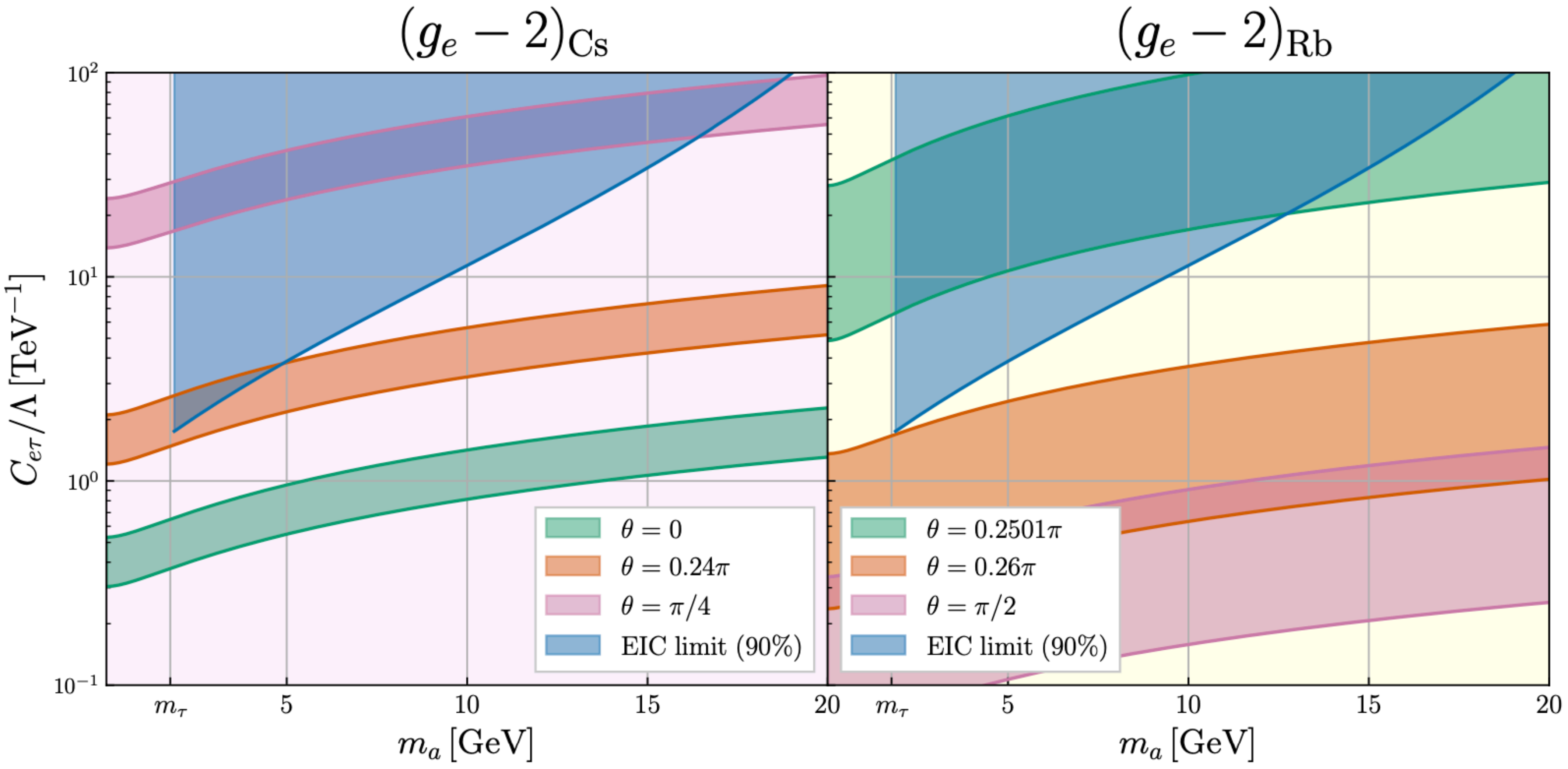
- Solution regions (2σ) for the $(g\text{-}2)_e$ anomaly vs. parity-violating angle θ and coupling $C_{\tau e}/\Lambda$.

- Sign flips close to (not exactly at) θ=π/4.



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

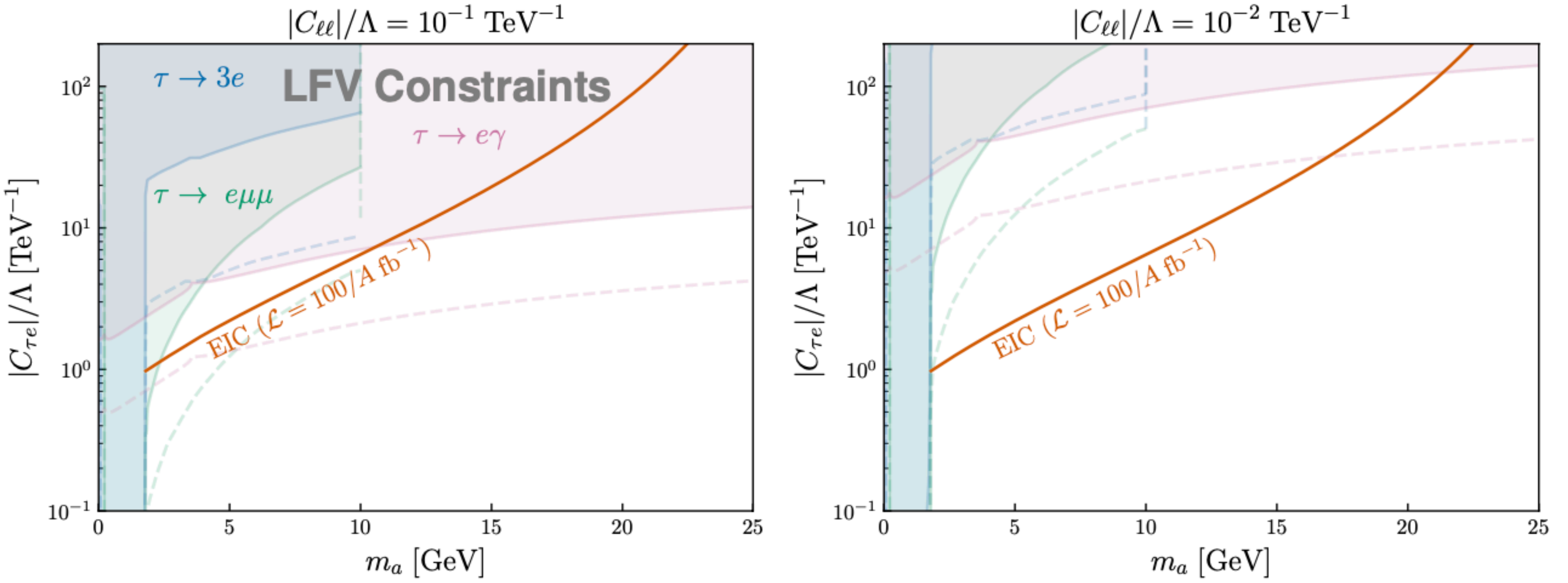
- EIC beam polarization can directly probe signal chirality, which strongly impacts Δa_e; if this model does explain the anomaly, can confirm it!



- 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 has great potential for searches for light new physics. Electron-ion mode can act like ultra-high energy fixed-target experiment, with excellent detector coverage (although *added coverage in far-backward region* could improve some searches.)

- Searches for ALPs with eτ coupling can probe new regions in parameter space, especially if diagonal lepton couplings are suppressed; also explore parameter space for $(g\text{-}2)_e$ discrepancy with the SM.

- More particle pheno study is needed to understand the best things to look for at EIC!

Backup slides

- Ignoring quarks, ALP Lagrangian has this structure:

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

- *Ignore gauge, Higgs couplings here*. 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:

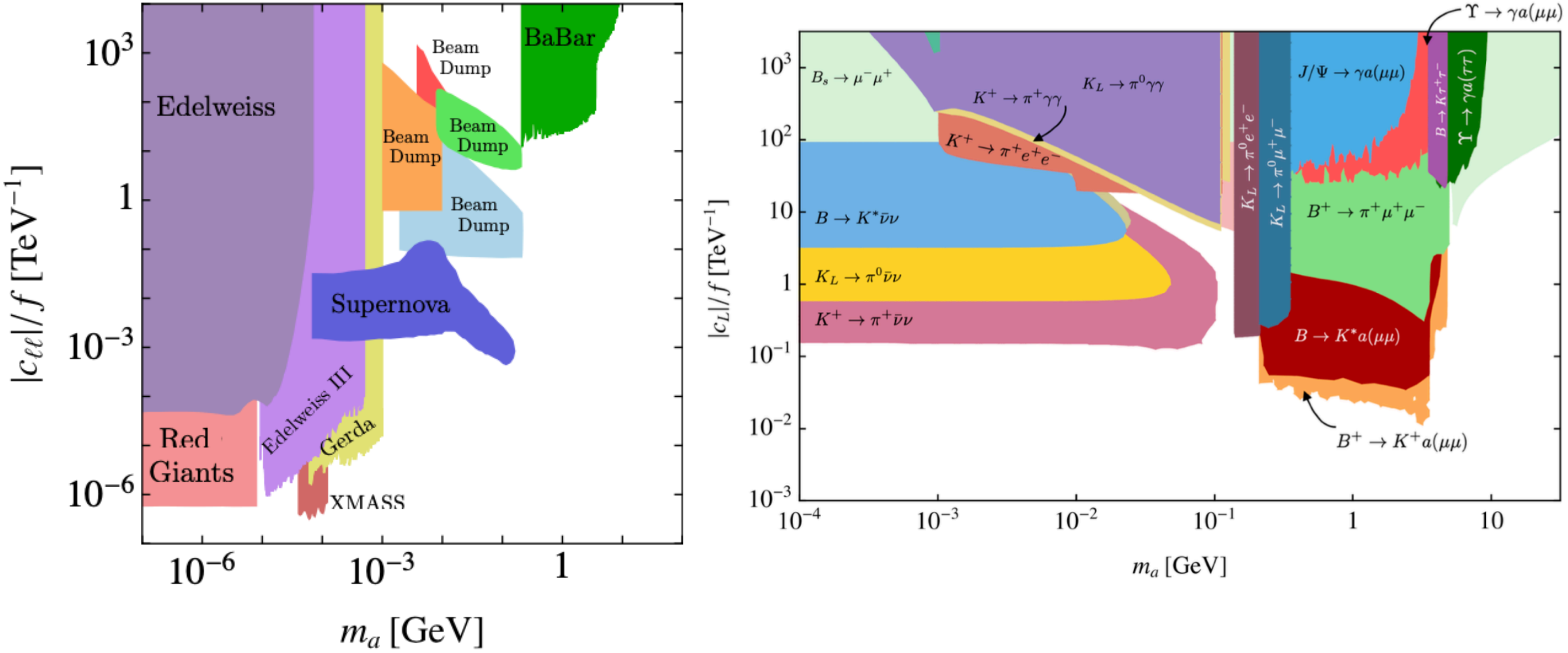
$$\mathcal{L}_g = 4\pi\alpha \frac{C_{\gamma\gamma}}{\Lambda} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \ldots$$

- 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.

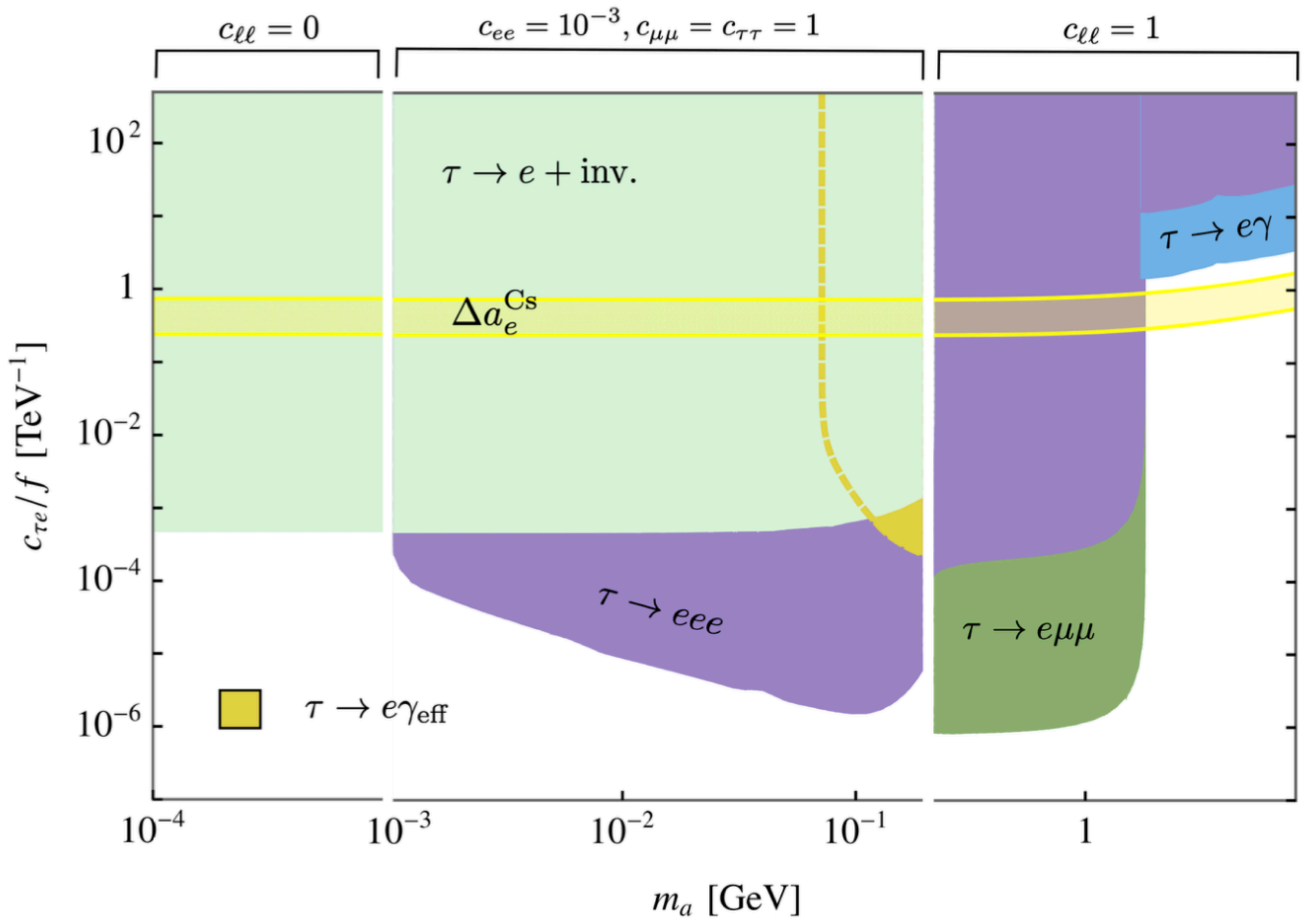
Overview of existing limits

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

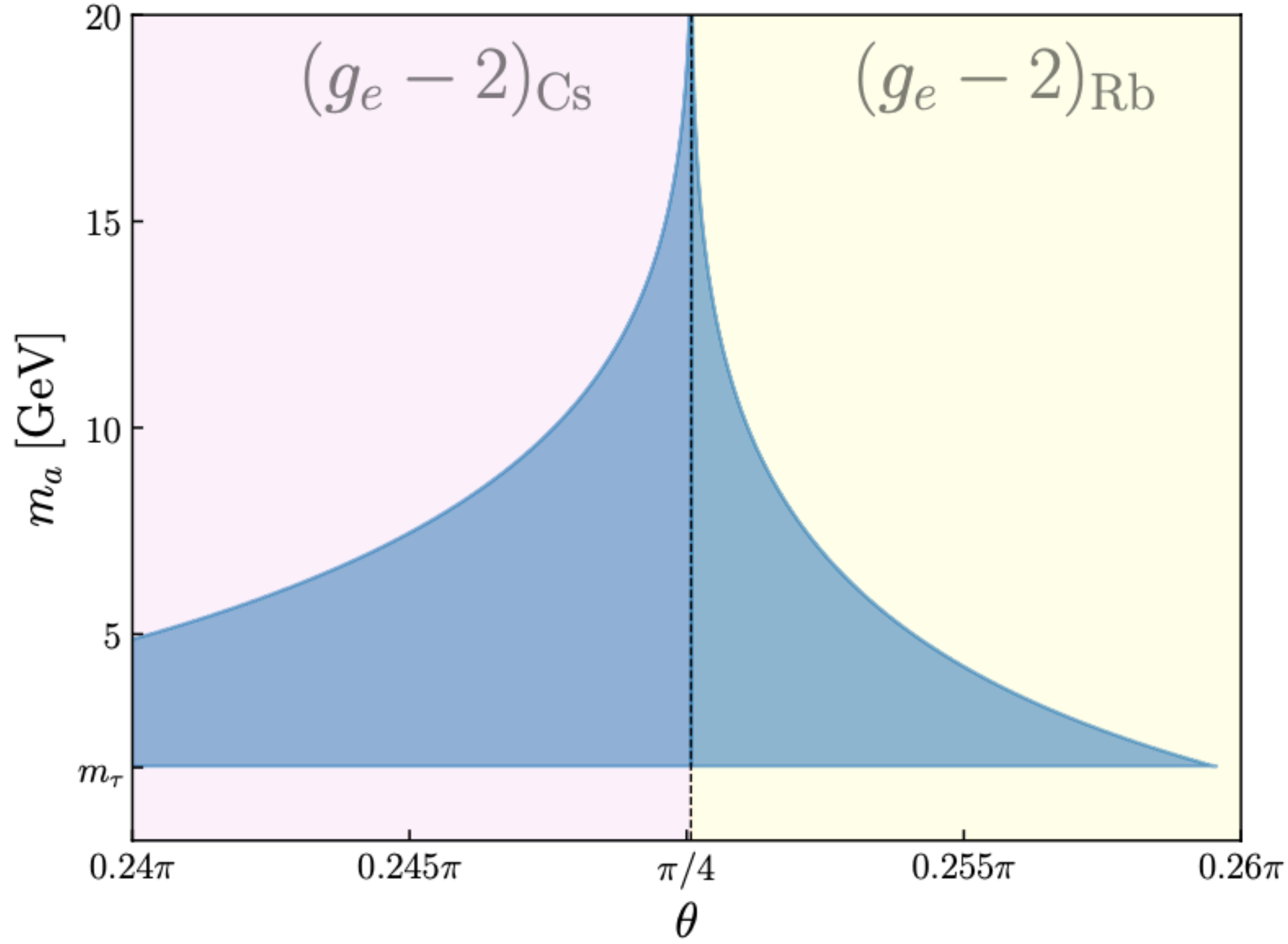


- <u>Lepton-diagonal couplings:</u> (*left*) strong astrophysical bounds at ma < 10^{-3} GeV; beam dumps below 1 GeV. (*right*) flavor-physics bounds effective above C_{ll} ~ 0.1/(1 TeV), but more model-dependent (assumes equal coupling to all LH lepton doublets.)

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



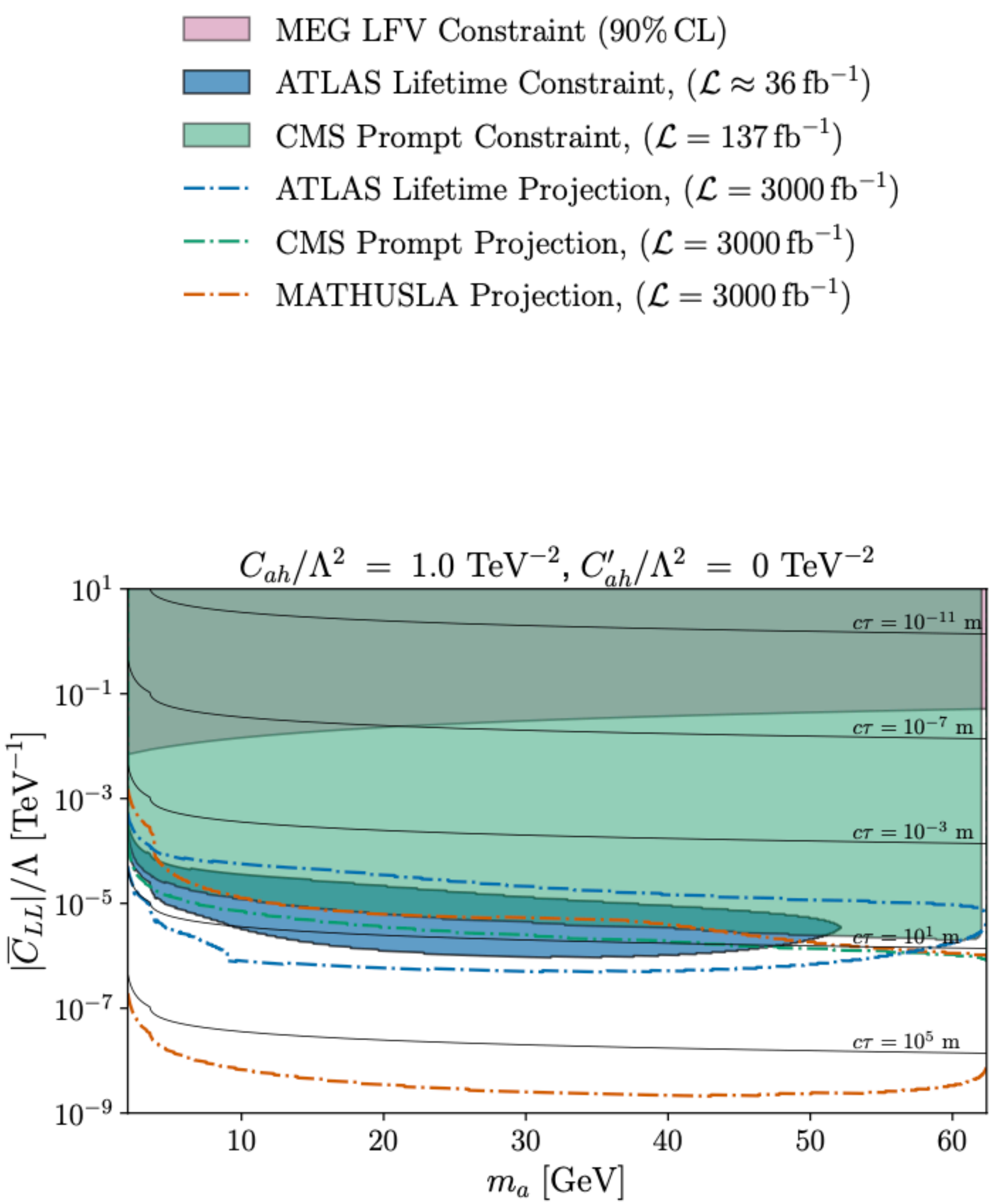
- <u>LFV couplings:</u> bounds are very strong, down to 10^{-6} / TeV. Here almost exclusively from exotic tau decays; much weaker above tau mass.
- Note the interplay between diagonal and off-diagonal lepton couplings; at heavier ALP masses, bounds are even weaker if diagonal c_{ll} are suppressed.



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

(H. Davoudiasl, R. Marcarelli, N. Miesch, ETN, arXiv:2105.05866)

Higgs decays and LFV ALPs



- Signal process:

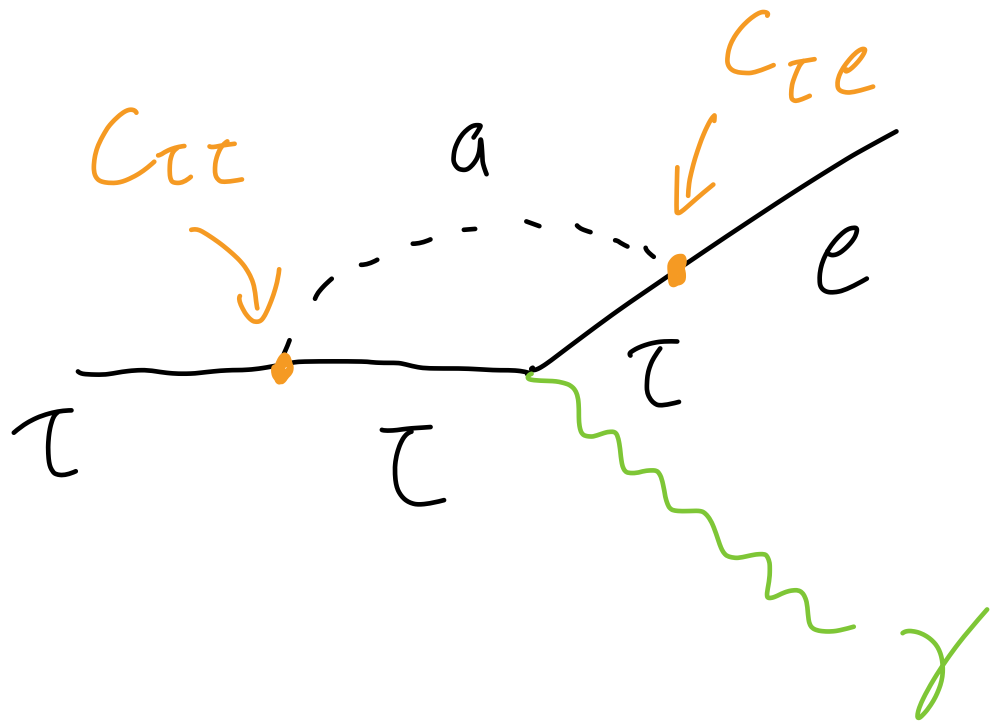
$$h \to aa \to (\tau(\tau/\ell))(\tau(\tau/\ell))$$

- 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 $m_a > m_\tau$.

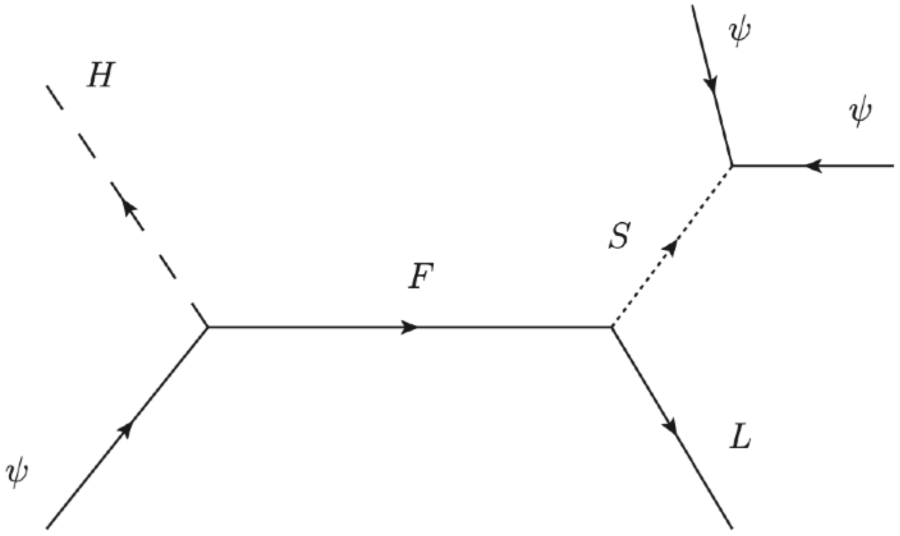
(Davoudiasl, Giardino, Neil, and Rinaldi, arXiv:1709.01082)

Example chiral ALP model

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

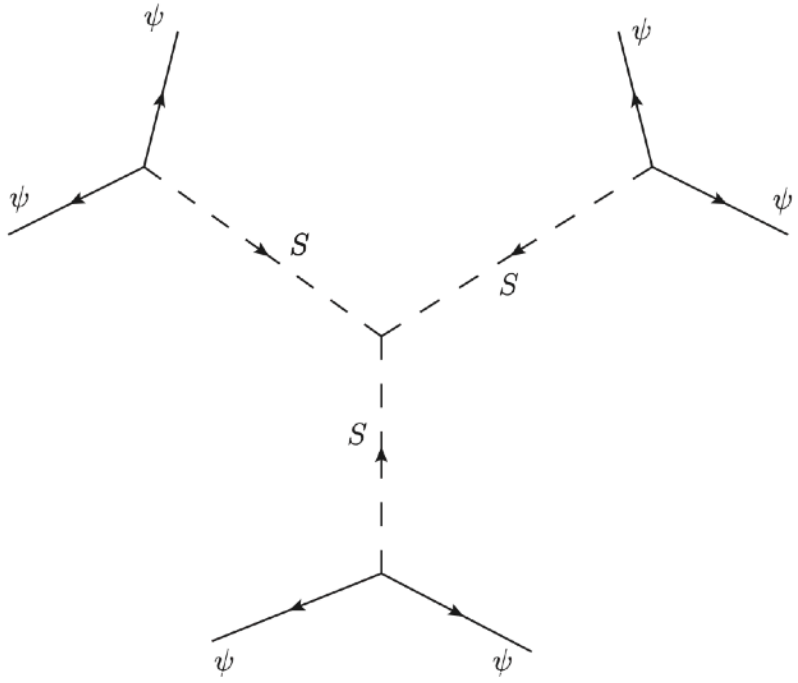
$$Y^{f\alpha}\,\tilde{H}^*\bar{L}_f\,N_\alpha$$

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



$$N \sim (\psi\psi\psi)$$

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



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