(image credit: ComfyUI/FLUX.1-dev)

Searches for flavor-violating particles at the EIC

Ethan T. Neil (Colorado)
CFNS Workshop, “New opportunities for BSM at the EIC”
07/23/25

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.
- See also Roman Marcarelli's PhD thesis and code (https://github.com/rmarcarelli/thesis)
- Lots of credit goes to my collaborators:
    - **Hooman Davoudiasl** (BNL)
    - **Dr. Roman Marcarelli** (PhD student, Colorado + BNL [DOE SCGSR])
- More flavor-violating ALPs? See also arXiv:**2105.05866**: Higgs decays at the LHC (w/Nicholas Miesch)

1. Motivation: lepton flavor violation

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^-.)

- In the SM, lepton fields are L = (N_L, E_L) [doublet, Y=-1/2] and E_R (singlet, Y=-1). Vectors over generation label {1,2,3}. Mass from Yukawa interaction:

$$\mathcal{L}_{\text{SM}} \supset \bar{L} H \mathbf{Y} E_R + \text{h.c.}$$

- In general, Yukawa matrix Y is non-diagonal. But we can always diagonalize by rotation of E_L, E_R fields:

$$v \left(\quad \bar{E}_L \quad \right) \left(\quad \mathbf{Y} \quad \right) \left(E_R \right) \rightarrow \left(\bar{e} \quad \bar{\mu} \quad \bar{\tau} \right) \begin{pmatrix} m_e & & \\ & m_\mu & \\ & & m_\tau \end{pmatrix} \begin{pmatrix} e \\ \mu \\ \tau \end{pmatrix}$$

- For quarks, this is done for both up- and down-type quarks, leaving a non-diagonal W-boson interaction (CKM matrix.) For leptons, we can rotate the neutrino field N_L independently —> diagonal W-boson interactions, no lepton flavor violation!

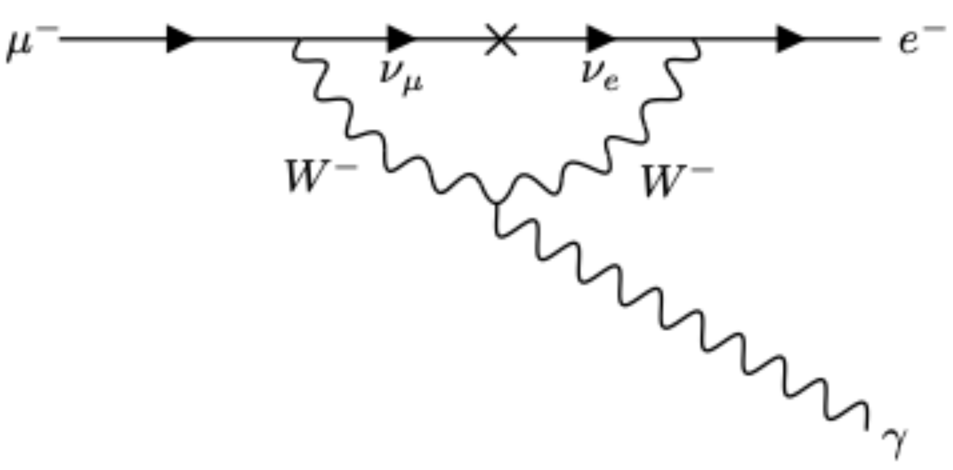
- This is the "strict Standard Model" story, but we know it's wrong - neutrinos have mass! Mixing matrix must also appear in lepton interactions, the Pontecorvo-Maki-Nakagawa-Sakata (**PMNS**) matrix:

NuFIT 5.2 (2022)

(3σ CL, from nu-fit.org)

$$|U|_{3\sigma}^{\text{w/o SK-atm}} = \begin{pmatrix} 0.803 \to 0.845 & 0.514 \to 0.578 & 0.142 \to 0.155 \\ 0.233 \to 0.505 & 0.460 \to 0.693 & 0.630 \to 0.779 \\ 0.262 \to 0.525 & 0.473 \to 0.702 & 0.610 \to 0.762 \end{pmatrix}$$

- PMNS matrix values are large ("anarchic"), but neutrino masses are very small. As a result, LFV processes exist in the SM but are extremely suppressed:



$$\mathcal{B}_{\text{SM}}(\mu \to e\gamma) \sim \frac{3\alpha}{32\pi} \frac{(\Delta m_\nu^2)^2}{m_W^4} \sim 10^{-54}$$

(MEG expt: $\mathcal{B}(\mu \to e\gamma) \lesssim 4.2 \times 10^{-13}$)

LFV beyond the SM

- Lepton flavor violation is an appealing target for experiment; heavy suppression within the Standard Model means any detection is definitely new physics!

- LFV appears in a number of concrete BSM models, particularly those with connections to flavor structure:

  - Two-Higgs doublet models (see e.g. arXiv:1106.0034, 2203.07244)

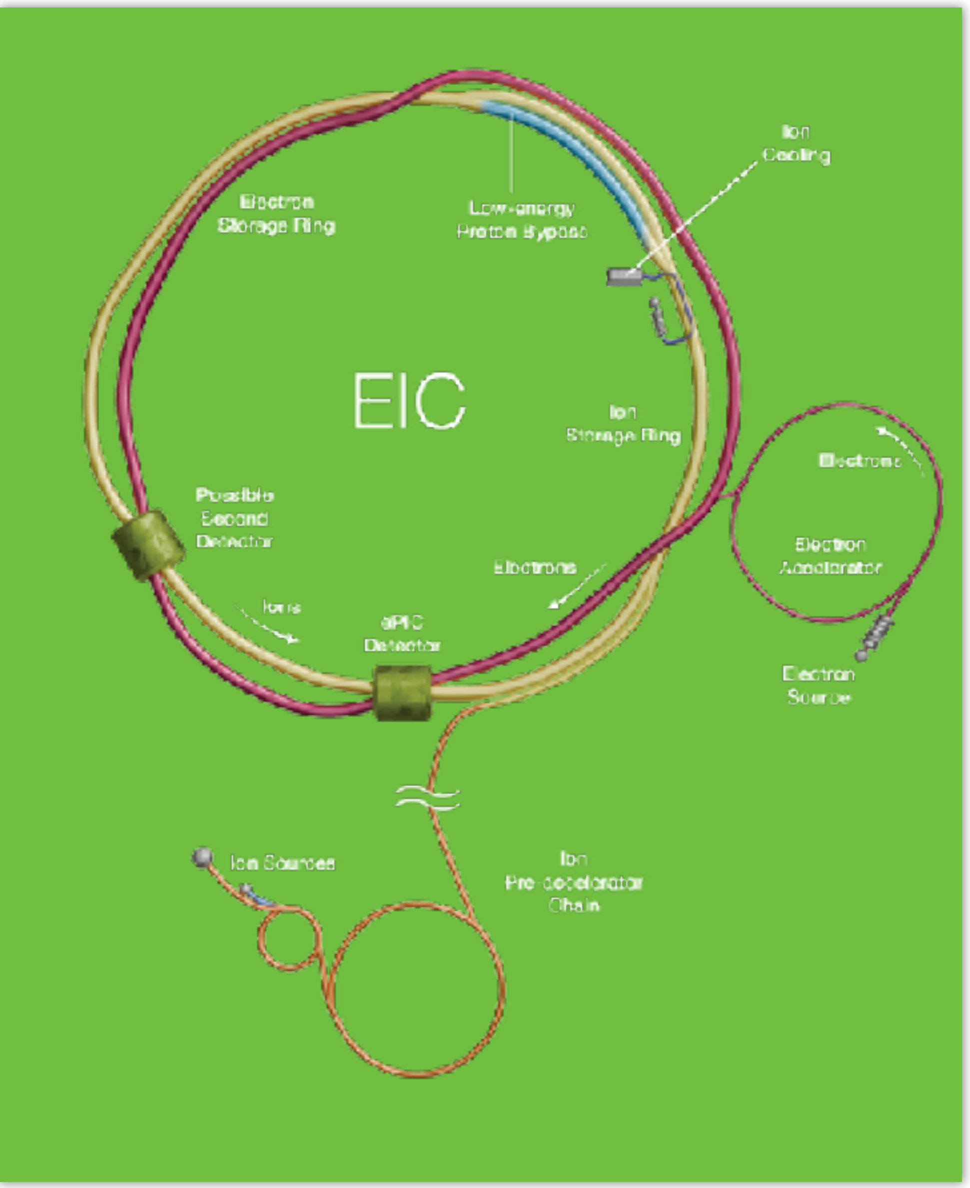
  - Froggatt-Nielsen models (see e.g. arXiv:0910.2948)

  - Axion-like particles (ALPs) - focus here! From composite Higgs, SUSY, Froggatt-Nielsen ("axiflavon"), others…

- This talk: direct production of BSM signals (new particles) with LFV, at the EIC. (*vs. probing indirect effects/effective operators; see talks by V. Cirigliano, E. Mereghetti, K. Fuyuto, A. Hurley*)

2. Producing new particles at the EIC

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.)

Kinematics at the EIC

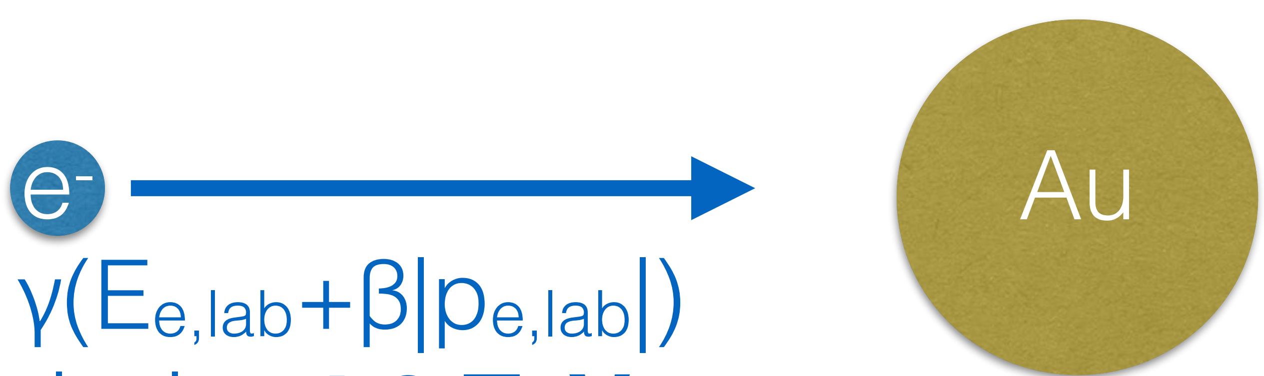
Lab frame:

$|p_e| = 18$ GeV

$|p_A| = 110$ GeV/A

Boost: $\gamma \sim 120$

Ion frame:

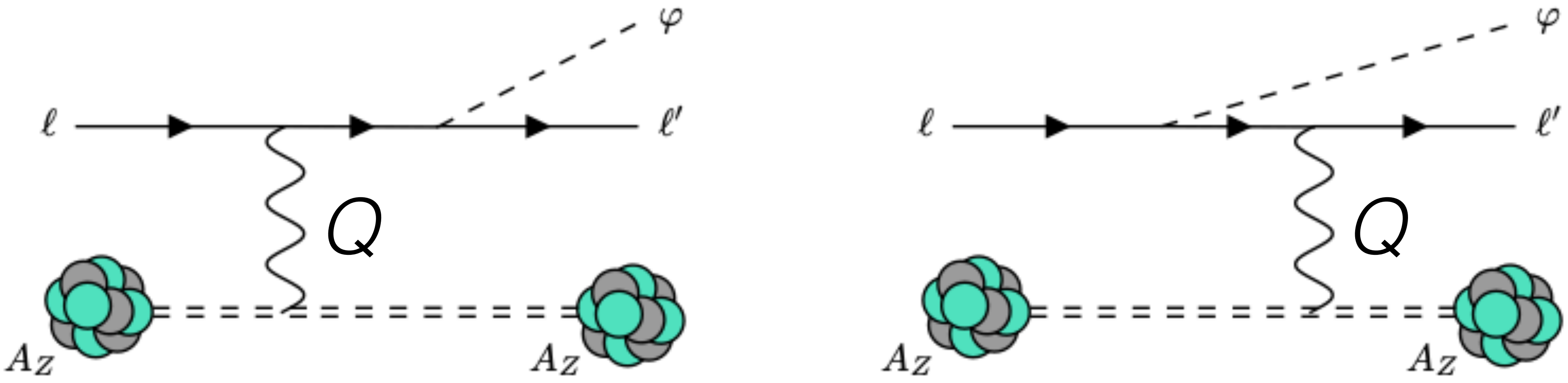


$E_e = \gamma(E_{e,lab} + \beta|p_{e,lab}|)$

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

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

- Flavor-violating (pseudo-)scalar emission dominated by the following coherent scattering diagrams:



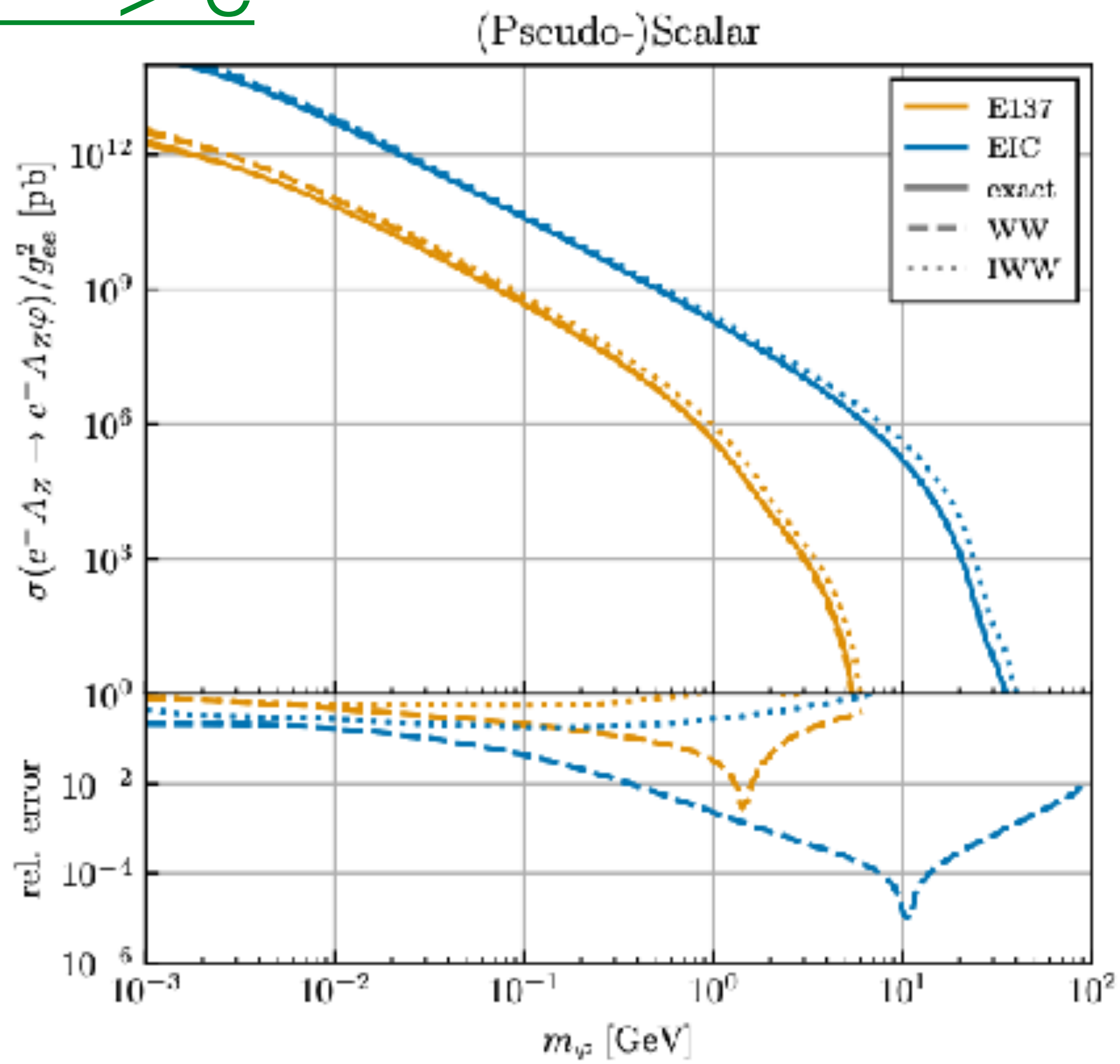
(from R. Marcarelli, PhD thesis)

- Z^2 enhancement due to ion charge apparent from diagrams. Woods-Saxon distribution for nuclear form factors. No emission from the nucleus if we impose only lepton-ϕ coupling; form factor suppression anyways unless ϕ very light.

- Requiring coherent scattering imposes kinematic limit on exchanged photon momentum:

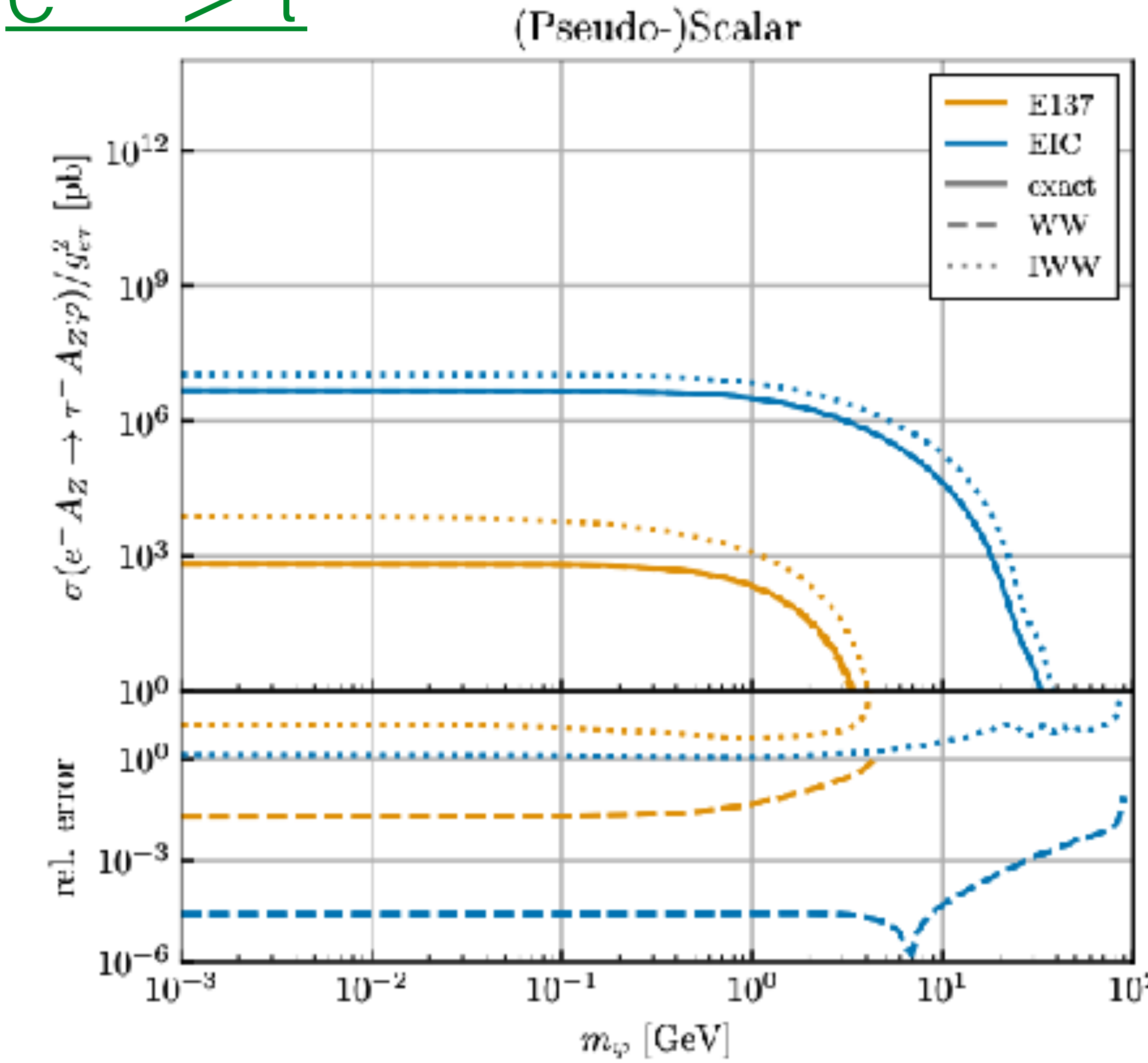
$$Q^2 \lesssim (100 \text{ MeV})^2$$

e —> e



e —> τ

(from R. Marcarelli, PhD thesis)

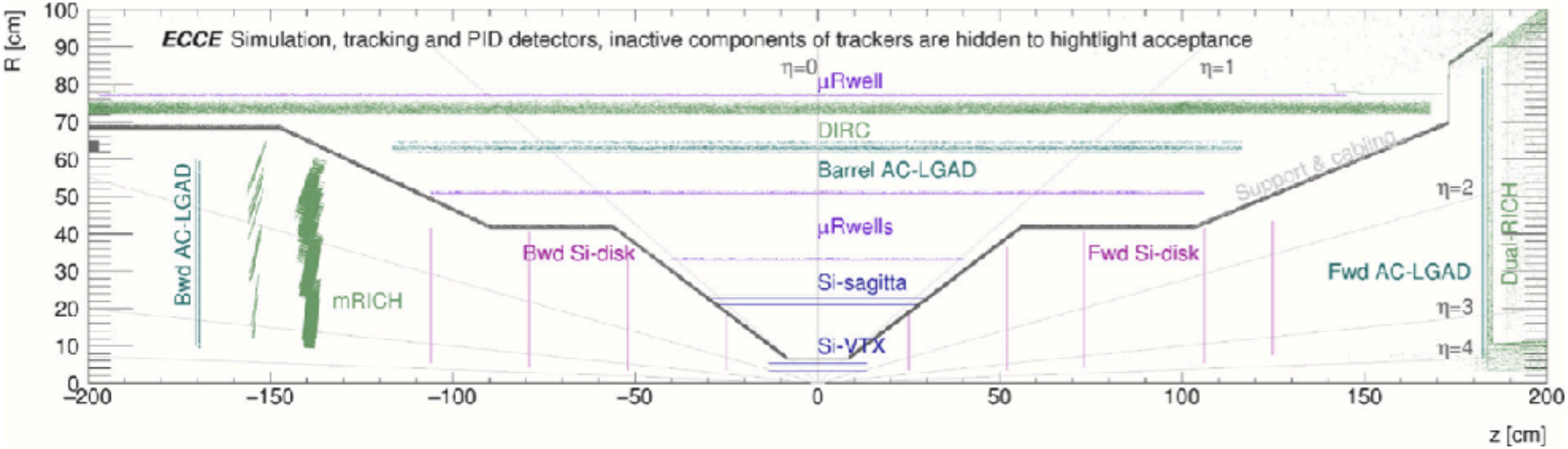


- Ion target is gold (Z=79) for the EIC, aluminum (Z=13) for E137 (SLAC beam-dump experiment circa 1980.) Higher nuclear charge on EIC target gives overall improvement to cross section.

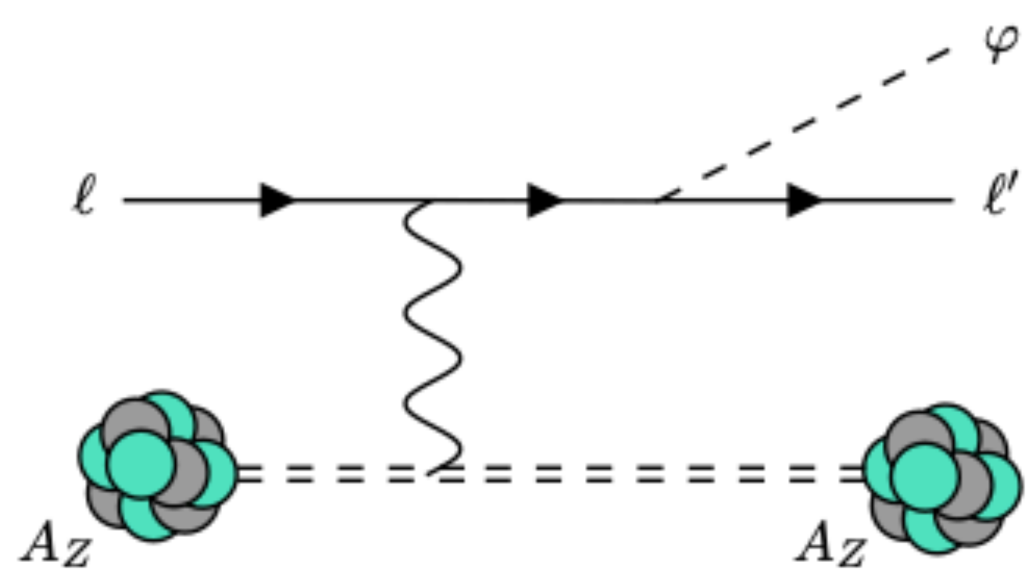
- Higher energy gives additional improvement above GeV scale; form factor cutoff apparent. In ion rest frame,

$$m_\varphi + m_{\ell'} \leq \sqrt{2Q|\mathbf{p}_\ell|} \quad \Longrightarrow \quad m_\varphi \lesssim \begin{cases} 2\ \text{GeV}\ (\text{E137}), \\ 30\ \text{GeV}\ (\text{EIC}). \end{cases}$$

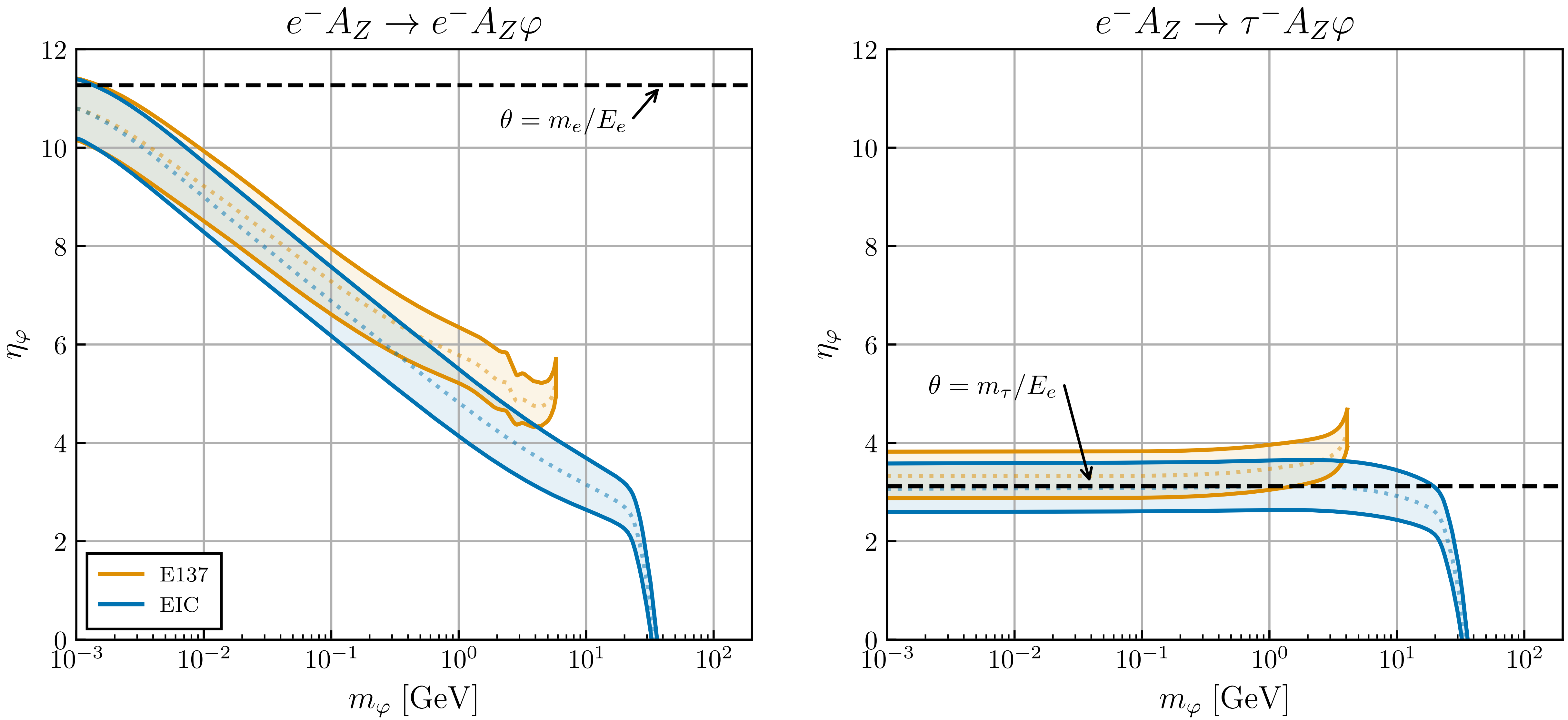
(Adkins et al., "Design of the ECCE detector for the Electron Ion Collider", arXiv:2209.02580)



- Emission of BSM particles from the e^- gives preferential η in the e^- beam direction ("backward".)
- Effect is especially pronounced for *very light* particles - heavily boosted in e^- direction ("far backward".)

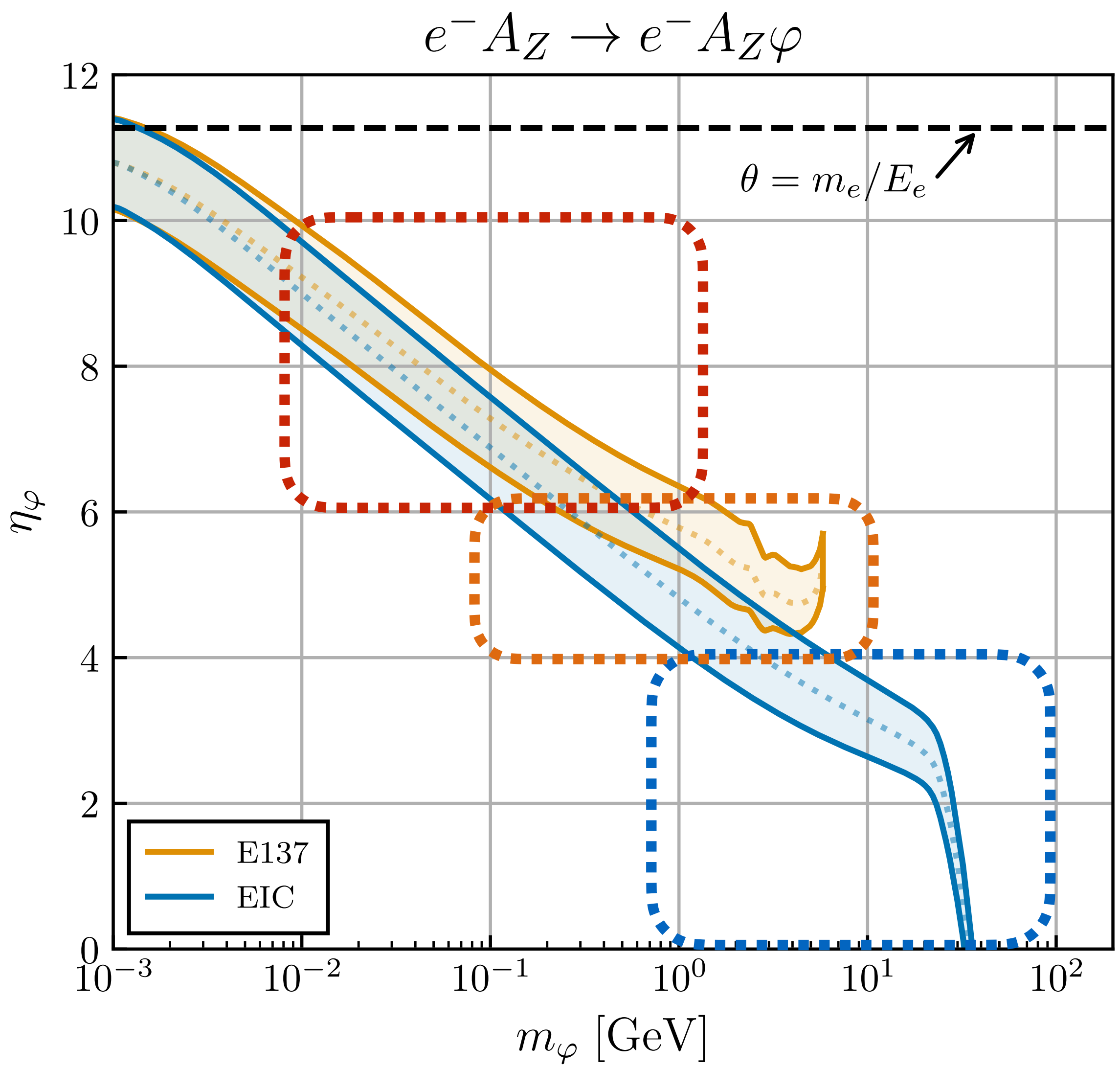


(from R. Marcarelli. PhD thesis work)



- Calculated pseudo-rapidity distributions from differential cross sections, versus BSM particle mass. Plots show "interquartile range" (i.e. 50% CL), distributions have long tails down to $|\eta|<3.5$ where EIC detector instrumentation is present.
- For heavier BSM particles, detection at extremely large η is less critical. For e —> τ conversion, η peak saturates around $\theta \sim m_\tau/E_e$, keeping signal events outside of near-beam region.

(from R. Marcarelli, PhD thesis work)



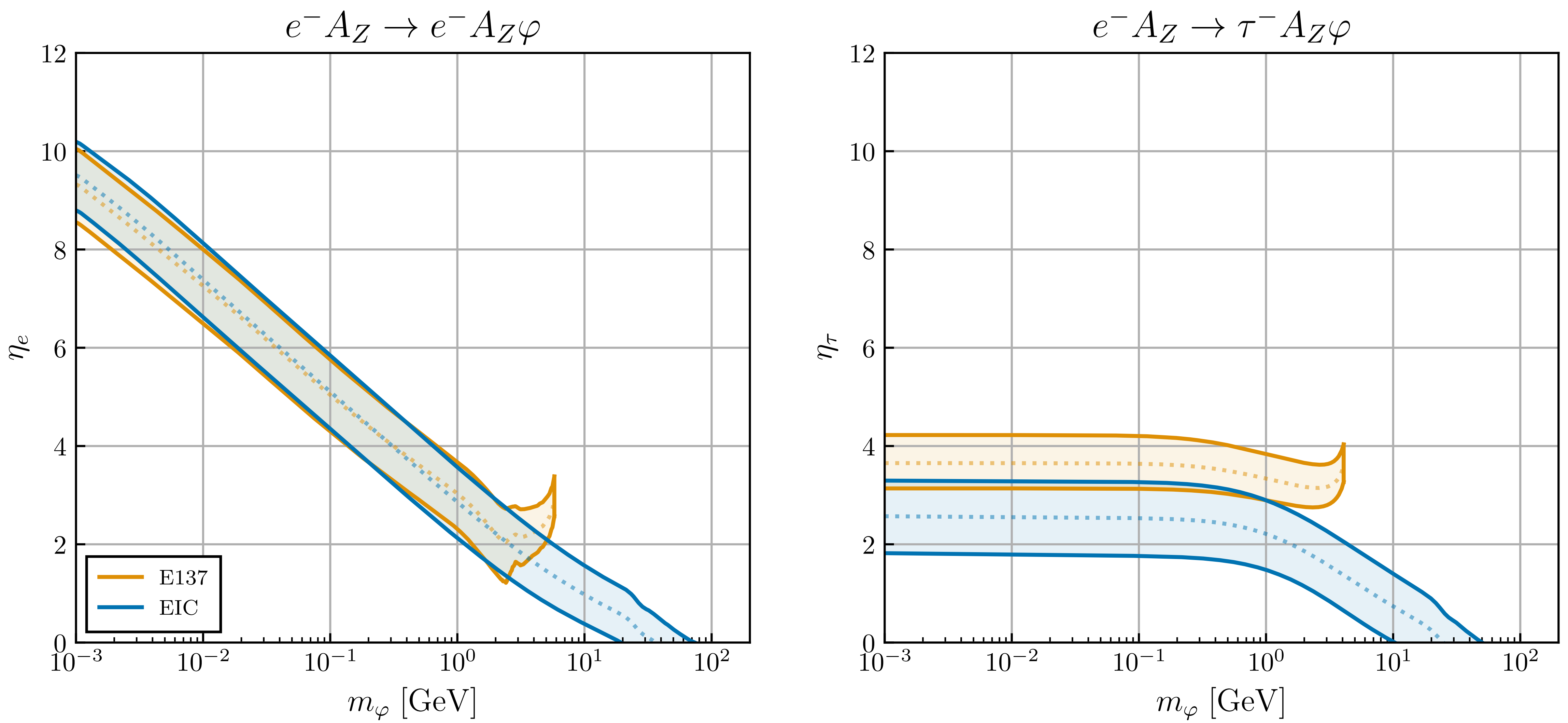
$$\eta = -\log\tan(\theta/2) \approx -\log((\Delta z)/2L)$$

"Second focus" region?
(10 mm / 40 m) —> (η ~ 9)

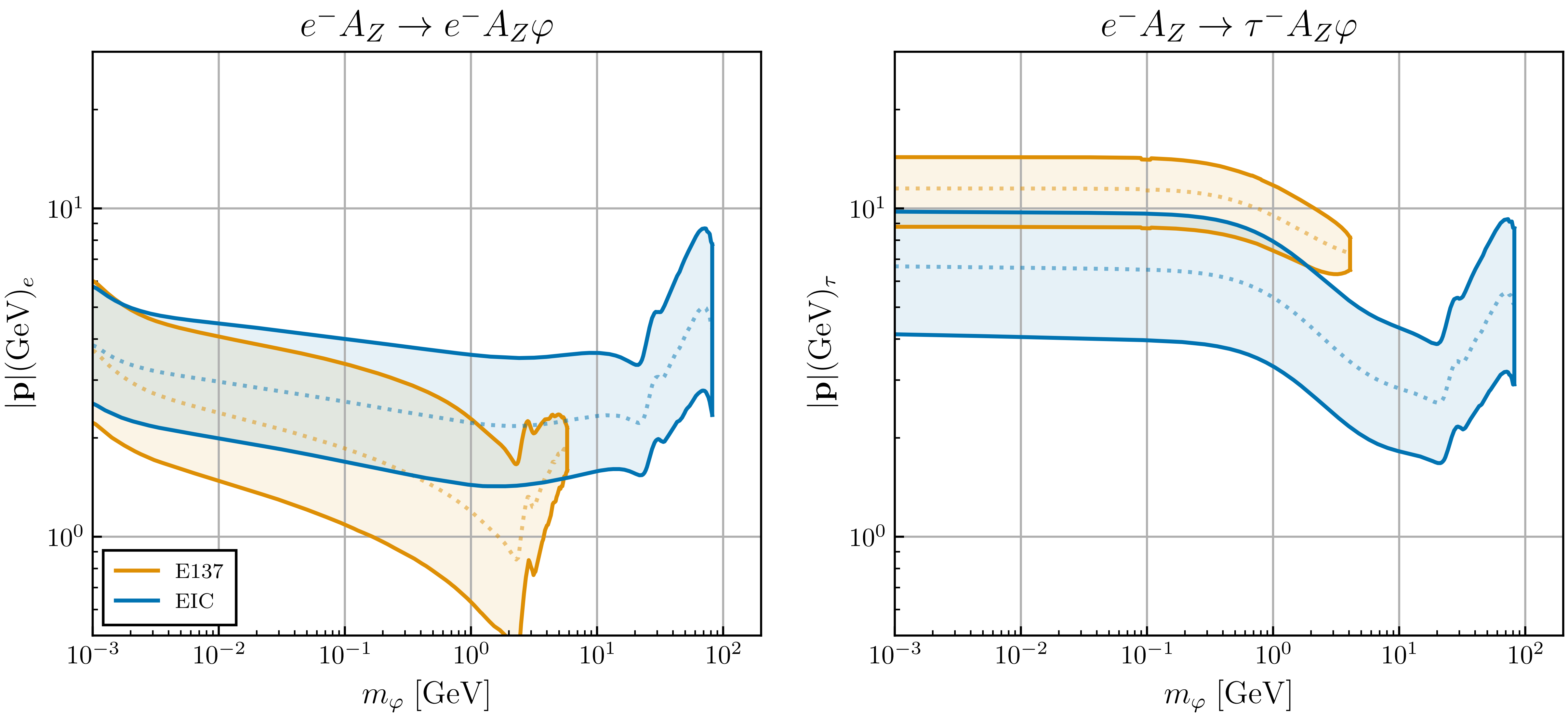
"Far backward" region

Main detector (backwards region)

- For light BSM particles *without* e —> τ conversion, the distribution becomes more and more sharply peaked in the backwards direction at large η. Below 1 GeV, not much left in the main detector!
- Possible opportunities for extra instrumentation very close to beam direction and further away to catch displaced BSM signals *(see talk by H. Davoudiasl.)*



- Similar pseudorapidity distributions, but for the final-state lepton e or τ instead of the (pseudo)-scalar ϕ. Same qualitative results; final-state particles are highly boosted in the lab frame and traveling in similar direction.



- Momentum distributions for final-state leptons, again interquartile 50% CI vs. ϕ mass. Final-state lepton momentum is typically around a few GeV.

3. Axion-like particles with LFV

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.

- 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. $\theta=0$ gives purely axial coupling $\theta=\pi/2$ is purely vector, $\pi/4$ is chiral. Set $\phi=0$ 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:

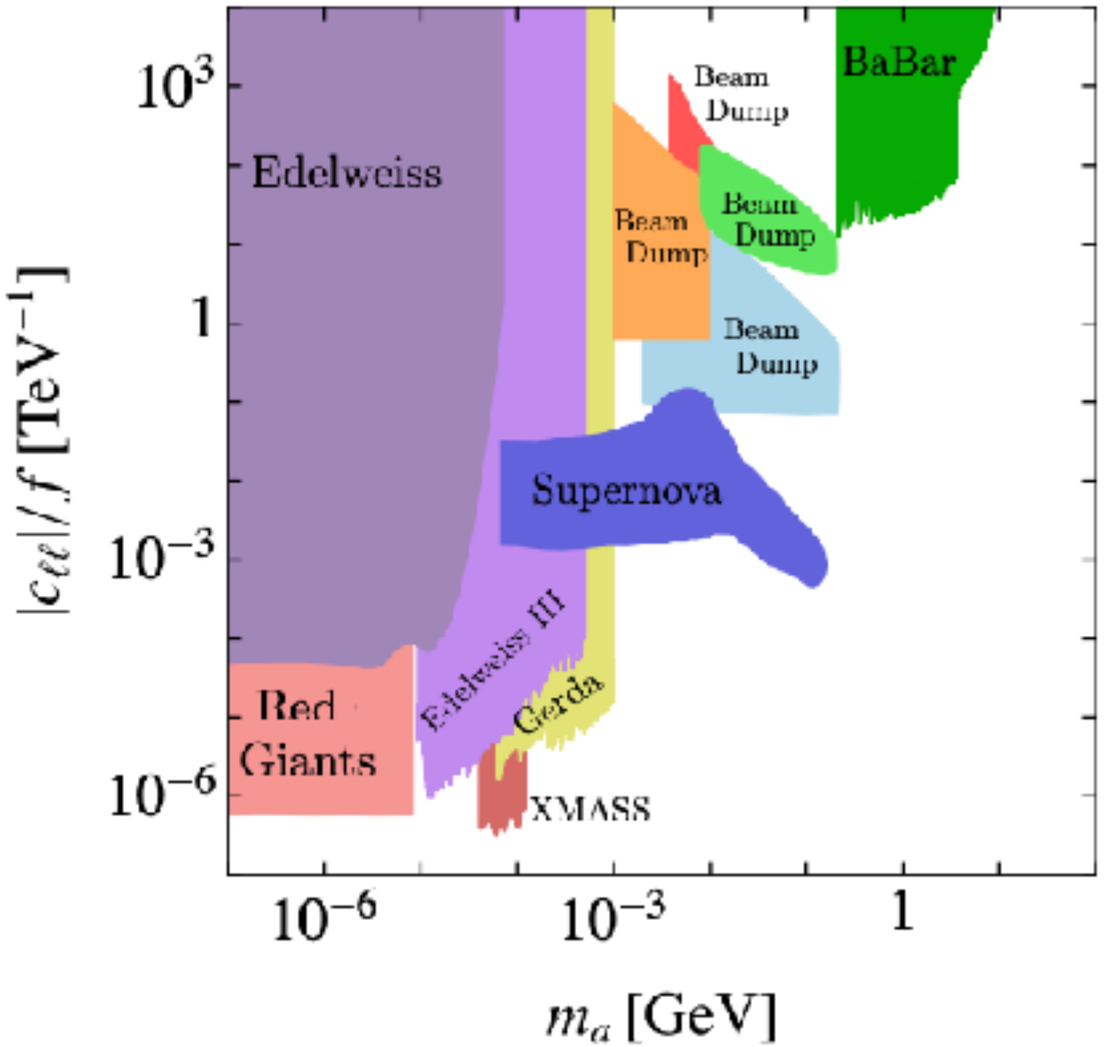
$$\mathcal{L}_\ell = a \sum_{\ell\ell'} \frac{C_{\ell\ell'}}{\Lambda} \bar{\ell} \left[(m_\ell - m_{\ell'}) \sin\theta_{\ell\ell'} + (m_\ell + m_{\ell'}) \cos\theta_{\ell\ell'} \right] \ell' + h.c.$$

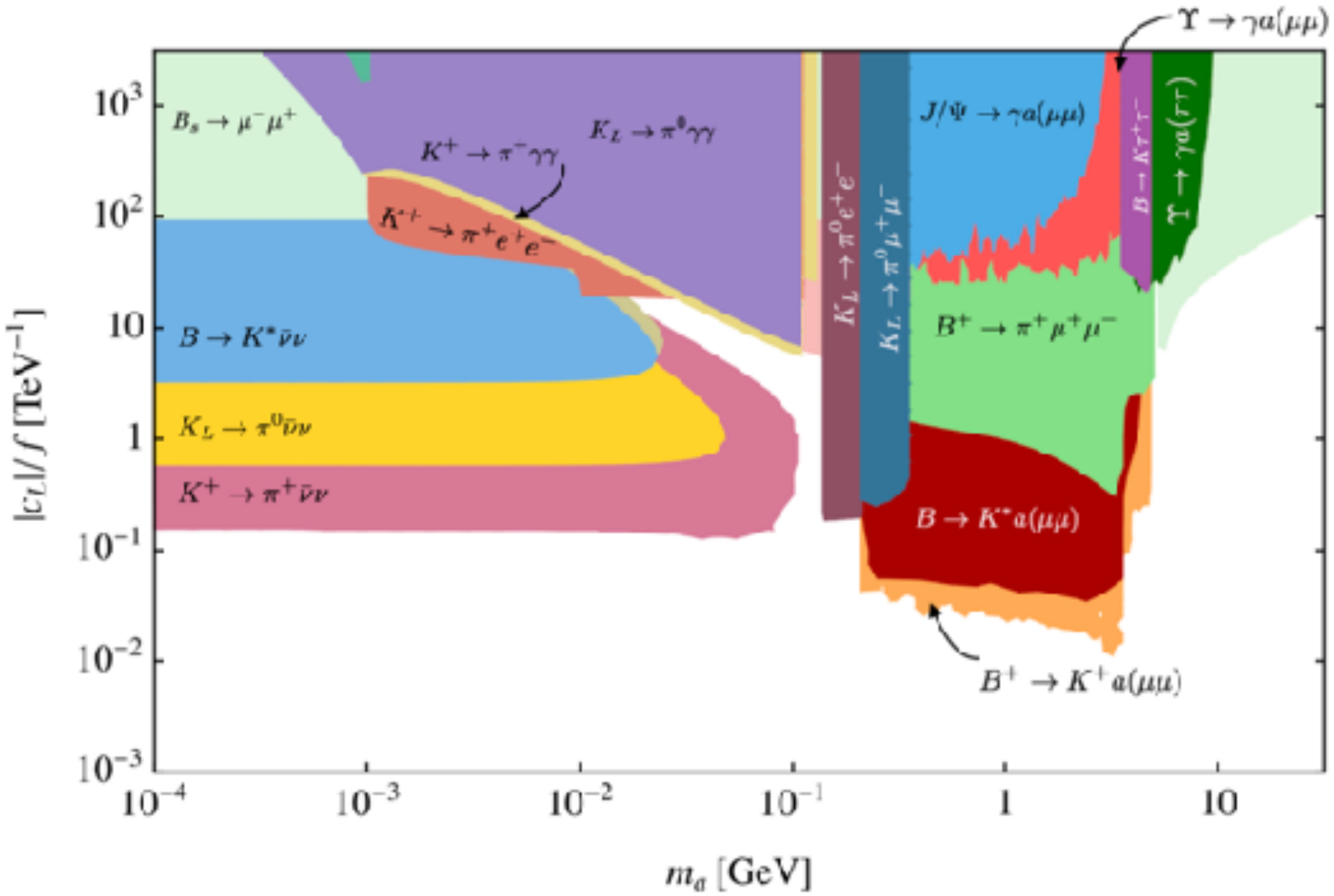
- Important point #1: for flavor-diagonal couplings (l=l'), the vector coupling is irrelevant! PV angle θ only matters for LFV couplings.

- 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!

Overview of existing limits

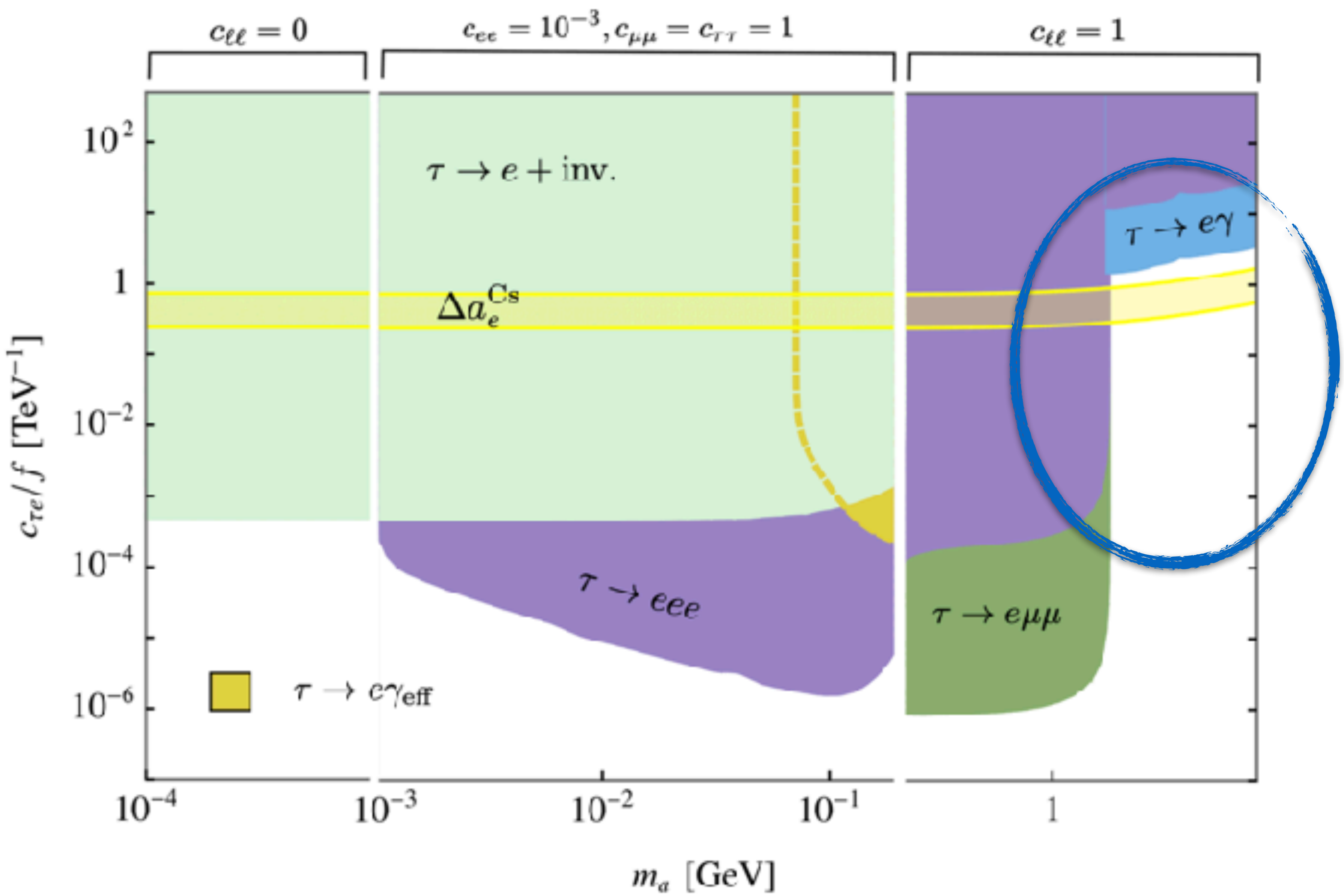
(from Bauer, Neubert, Renner, Schnubel, and Thamm, arXiv:2110.10698)





- Lepton-diagonal couplings: (*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.)

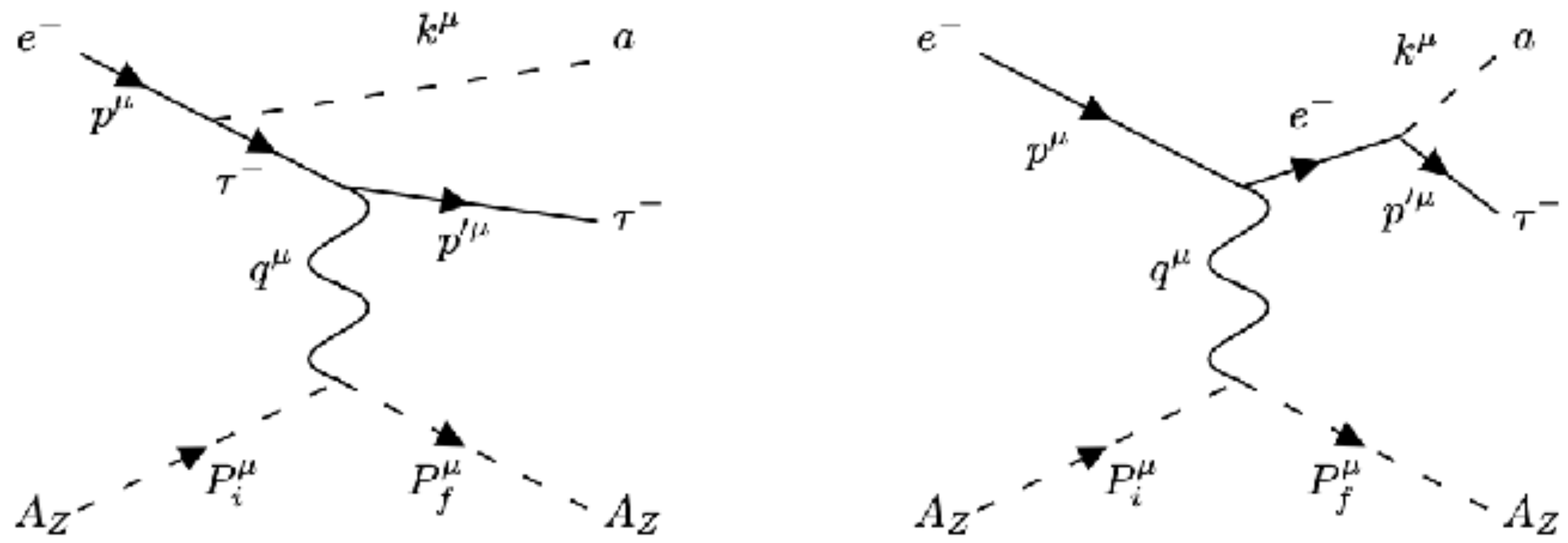
(from Bauer, Neubert, Renner, Schnubel, and Thamm, arXiv:2110.10698)
(see also: Cornella, Paradisi, and Sumensari, arXiv:1911.06279)



EIC opportunity to probe here! *(Also Δa_e solution region?)*

- 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.

EIC ALP 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!
- 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.

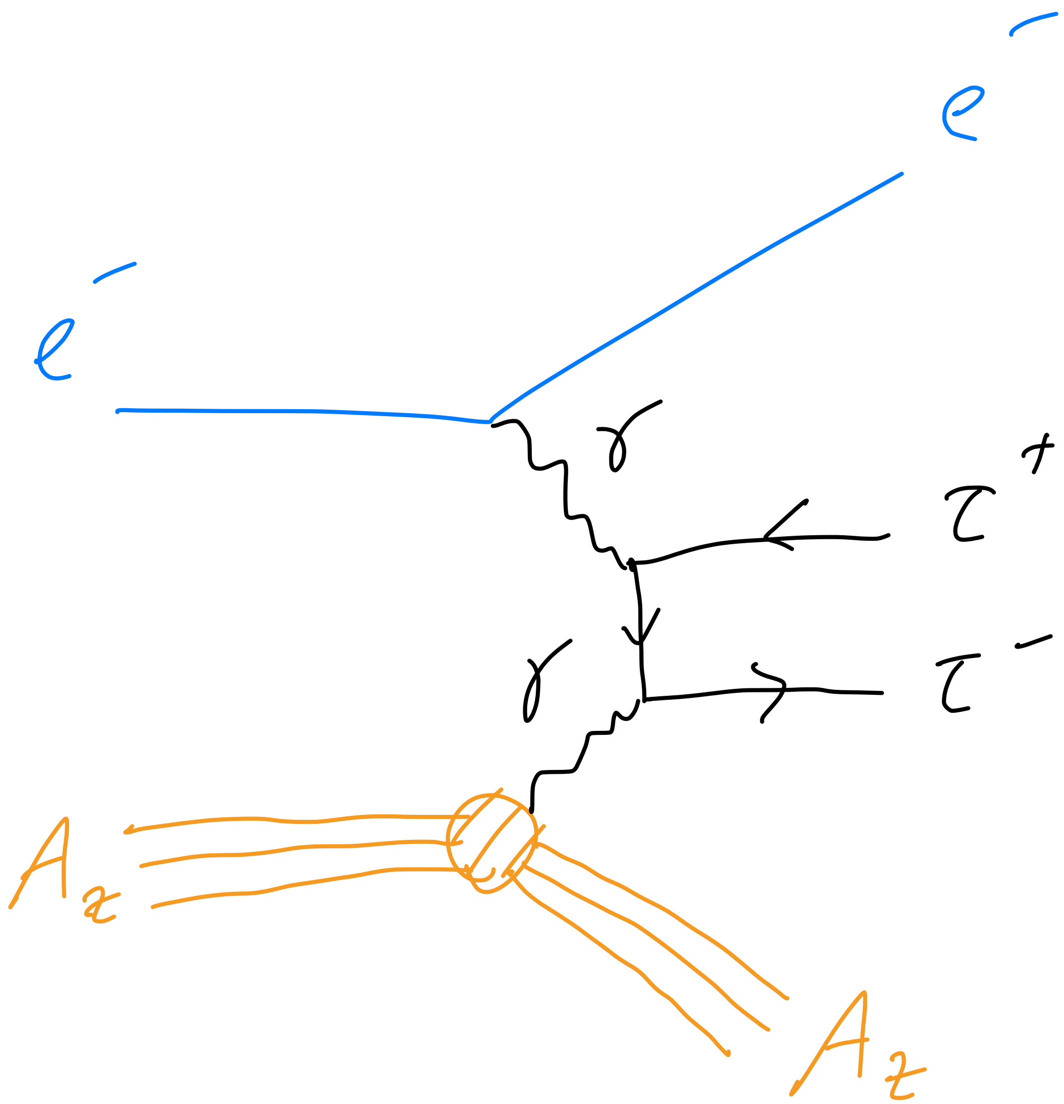
Signal selection and efficiency

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%**.



- 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.**

- **Side comment:** with 100/A ~ 0.5 fb-1 of luminosity in electron-Au mode, this is about **13 million** ditau events. Not competitive with Belle (~10^9 tau pairs), but still a lot! Maybe tau physics at EIC should be looked at on its own, independent of BSM applications?

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}, guess from Yellow Report), *and* τ^+ decays to a positron.

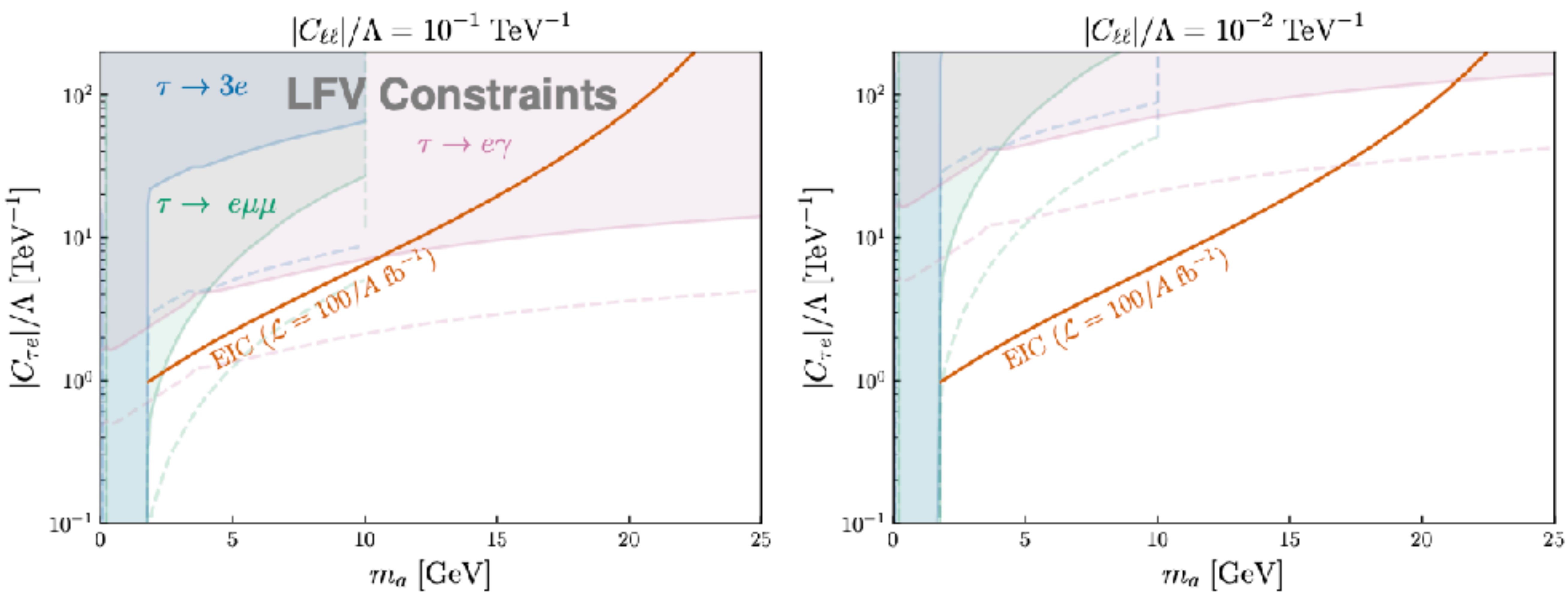
- Either scenario also requires a tagged τ at the same 1% efficiency as the signal.

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

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

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

- 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.)

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

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

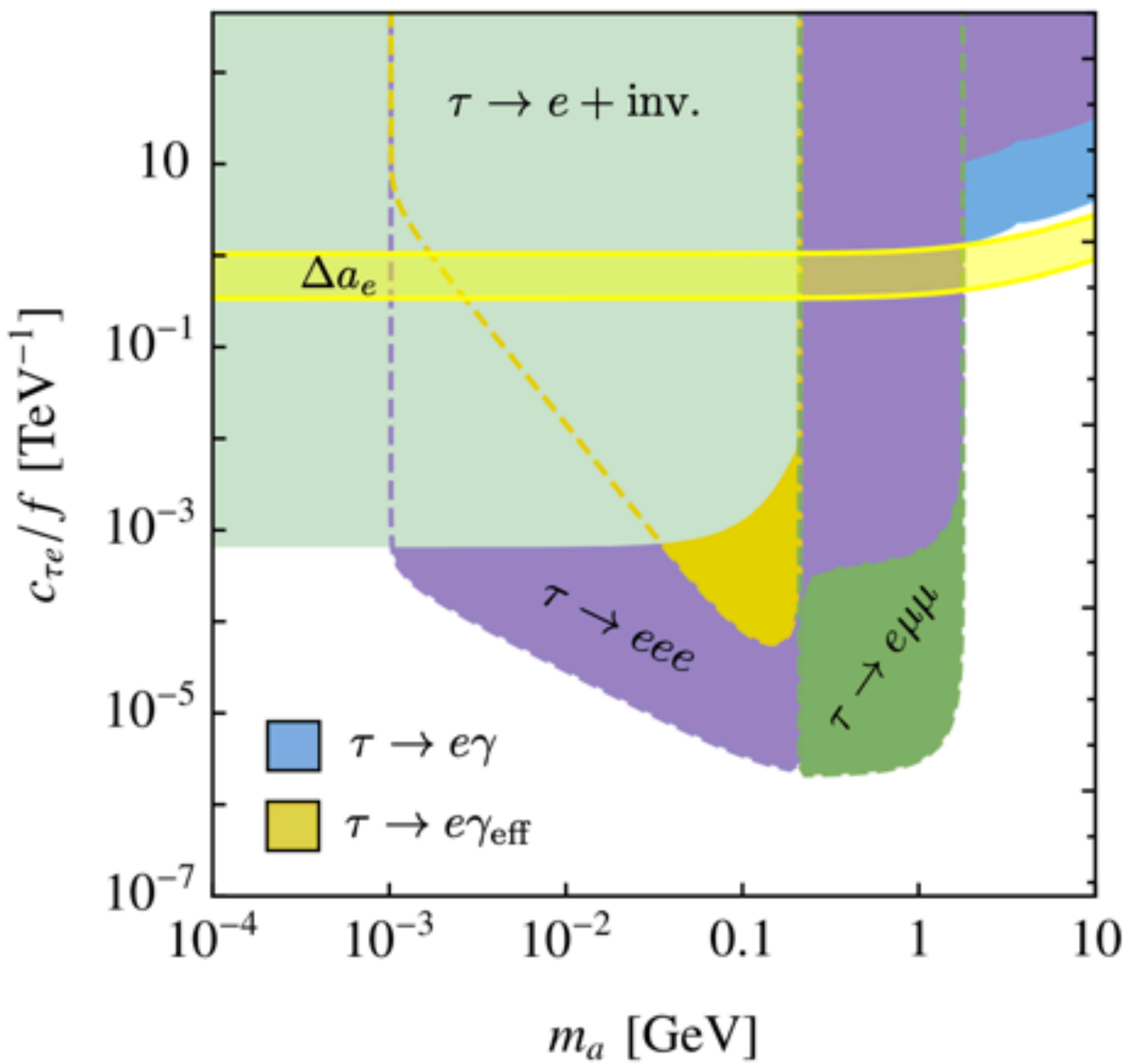
$$\Delta a_e(\mathrm{Cs}) = (-101 \pm 27) \times 10^{-14}. \quad (-3.7\sigma)$$

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

(arXiv:1908.00008)

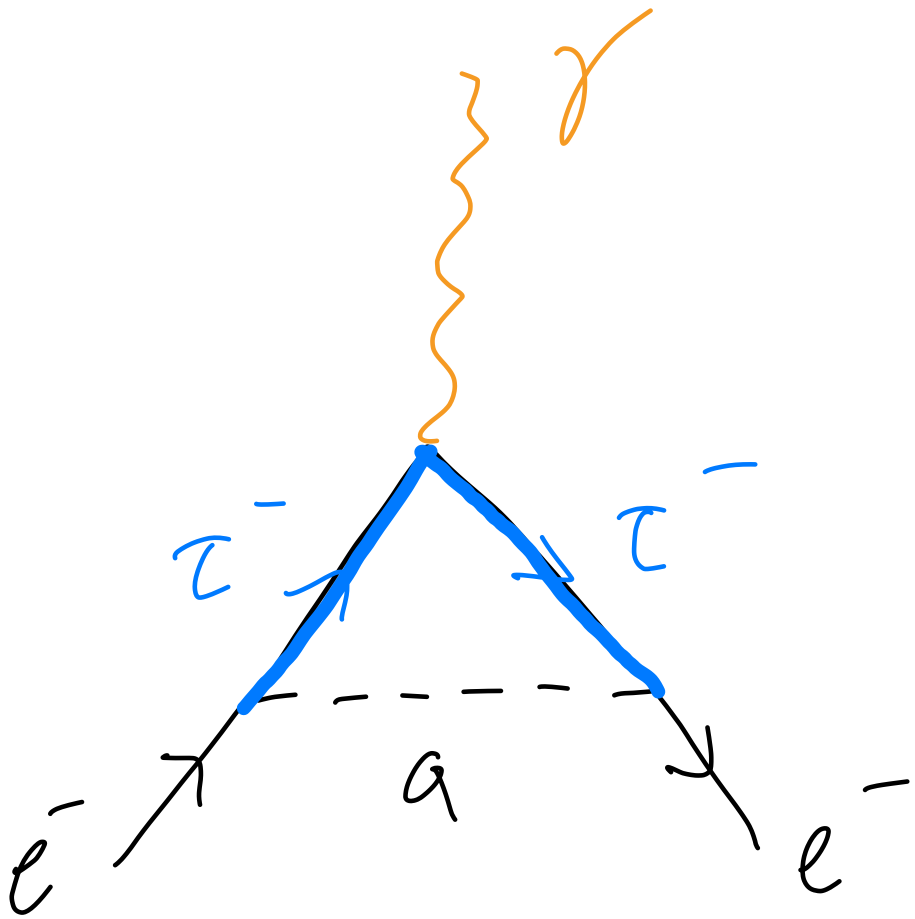
Axion-like particles, lepton-flavor violation and a new explanation of a_μ and a_e

Martin Bauer[a], Matthias Neubert[b,c], Sophie Renner[b], Marvin Schnubel[b], and Andrea Thamm[d]
[a]*Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham, DH1 3LE, UK*
[b]*PRISMA+ Cluster of Excellence, Johannes Gutenberg University, 55099 Mainz, Germany*
[c]*Department of Physics & LEPP, Cornell University, Ithaca, NY 14853, U.S.A.*
[d]*Theoretical Physics Department, CERN, 1211 Geneva, Switzerland*



- 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:

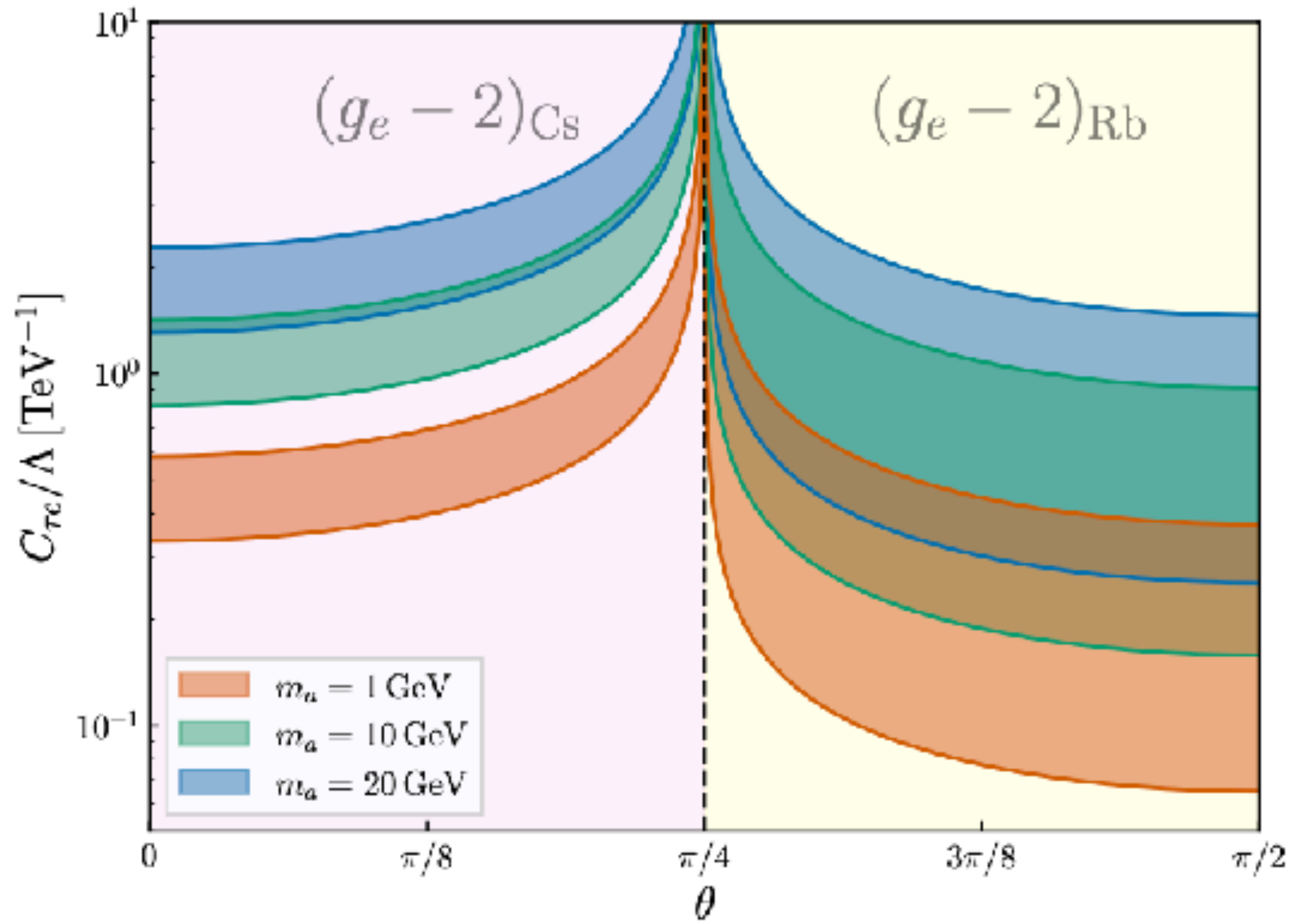


$$\Delta a_e = -\frac{m_e^2 C_{\tau e}^2}{16\pi^2 \Lambda^2}\left(f(x_\tau) + \frac{m_\tau}{m_e} g(x_\tau)\cos 2\theta\right)$$

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

- 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 $\theta=\pi/4$.

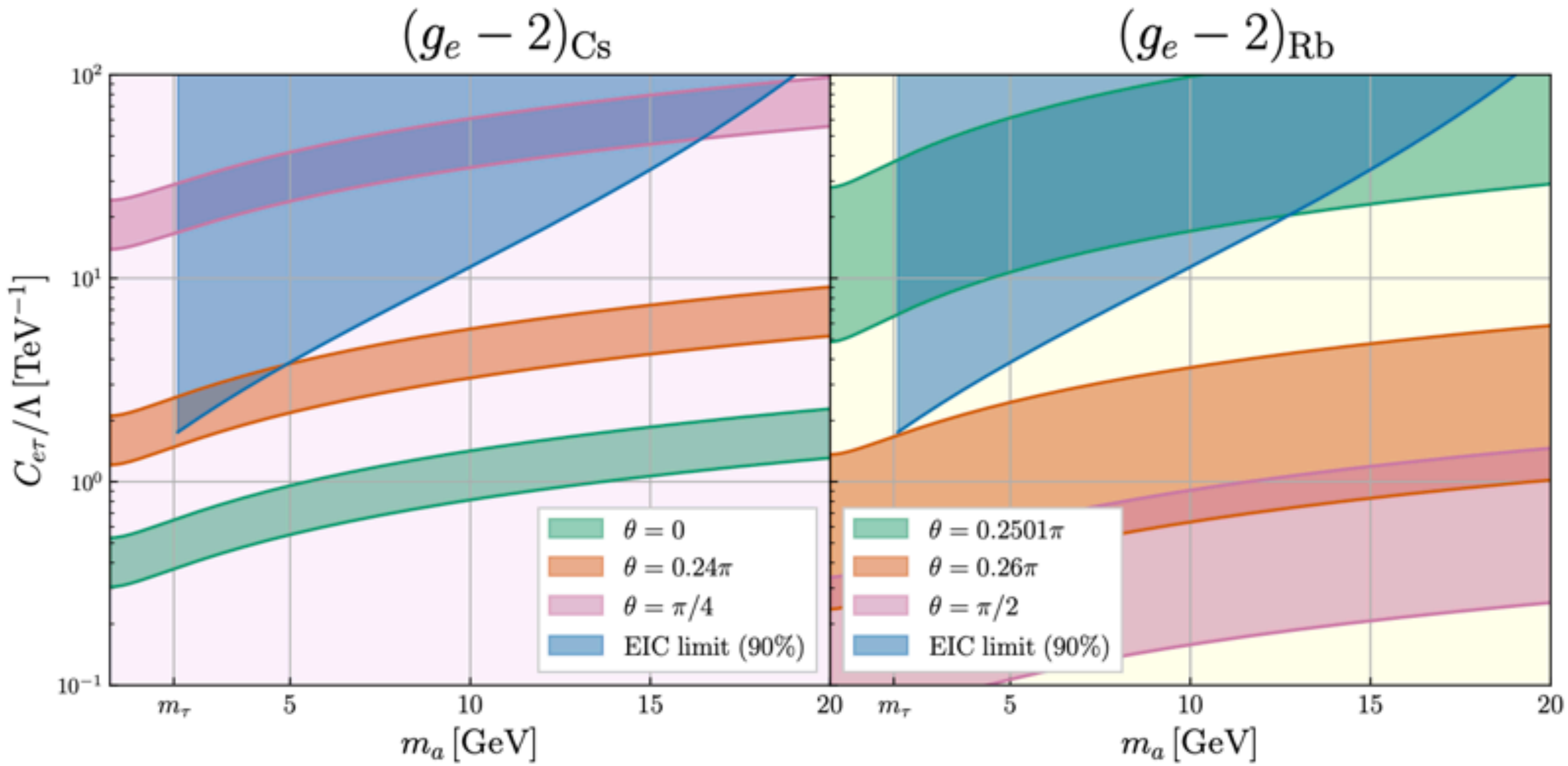
- Solution regions (2σ) for the $(g\text{-}2)_e$ anomaly vs. parity-violating angle θ and coupling $C_{\tau e}/\Lambda$.
- Sign flips close to (not exactly at) θ=π/4.



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

$$= (2p-1)\sin 2\theta.$$

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



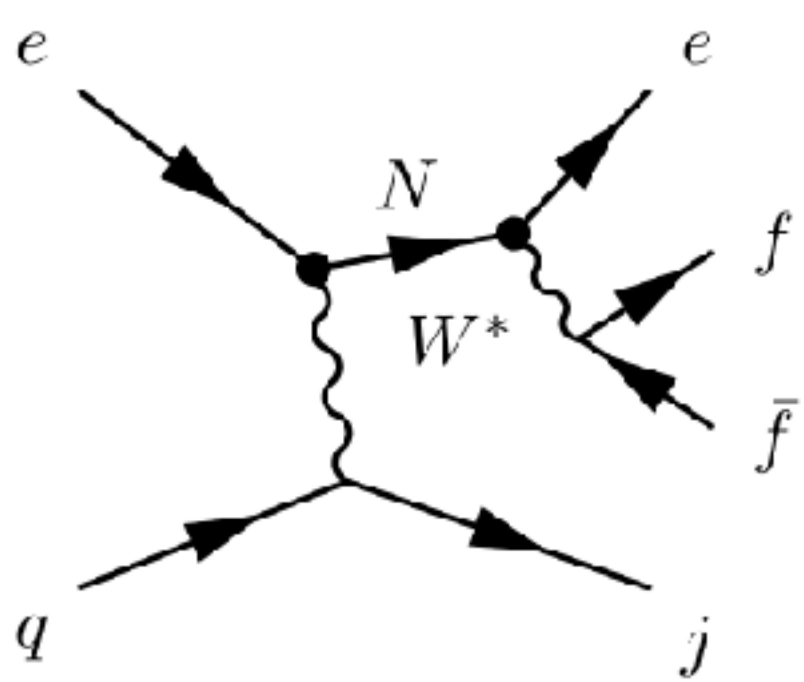
- Combine with the previously-described EIC search. θ has minimal effect on EIC reach, but large effect on $(g-2)_e$.
- EIC search is best at probing solutions which are "close to chiral", θ~π/4, where the corresponding coupling is strongest. If the EIC search can be improved enough, may be able to cover all possible θ (especially for α(Cs).)

5. Other LFV searches at EIC

(Batell, Ghosh, Han, Xie, **arXiv:2210.09287**)

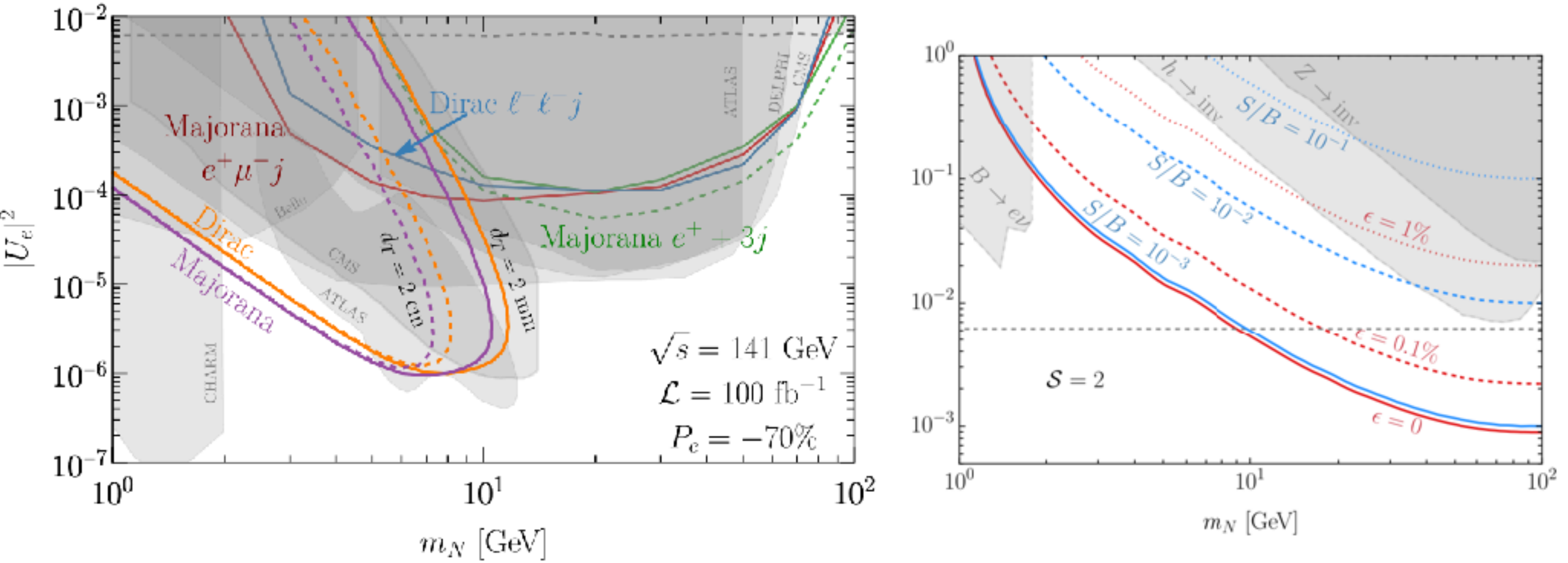
Heavy neutral leptons

$$\mathcal{L} \supset \frac{g}{\sqrt{2}} U_{iI} W_\mu^- \ell_i^\dagger \overline{\sigma}^\mu N_I + \frac{g}{2 c_W} U_{iI} Z_\mu \nu_i^\dagger \overline{\sigma}^\mu N_I + \text{H.c.}$$



- *(See also talks by S.U. Quiroga, K. Xie)*
- "HNLs" couple as right-handed neutrinos, often with Majorana mass term
- Variety of LFV processes can happen; for prompt N decay, focus on e^- —> e^+ + 3j. (Violation of L_e number due to Majorana N.)
- Can also have (eμ) final state with leptonic decay of W*, displaced decays, or monojet searches if N escapes or decays invisibly.

(Batell, Ghosh, Han, Xie, **arXiv:2210.09287**)



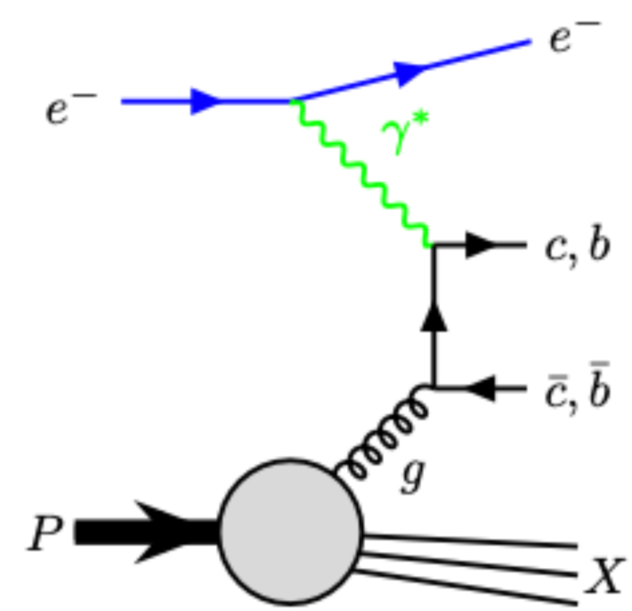
- Summary of projected reach for electron-coupling dominated case shown above. Little additional parameter space vs. other experiments in this case, but EIC still complementary. Monojet (N —> invis) can do somewhat better depending on systematics.

- Muon detection (w/muon chamber) was assumed for relevant channels; maybe muon tagging can make up for this. Tau tagging may allow other interesting search modes.

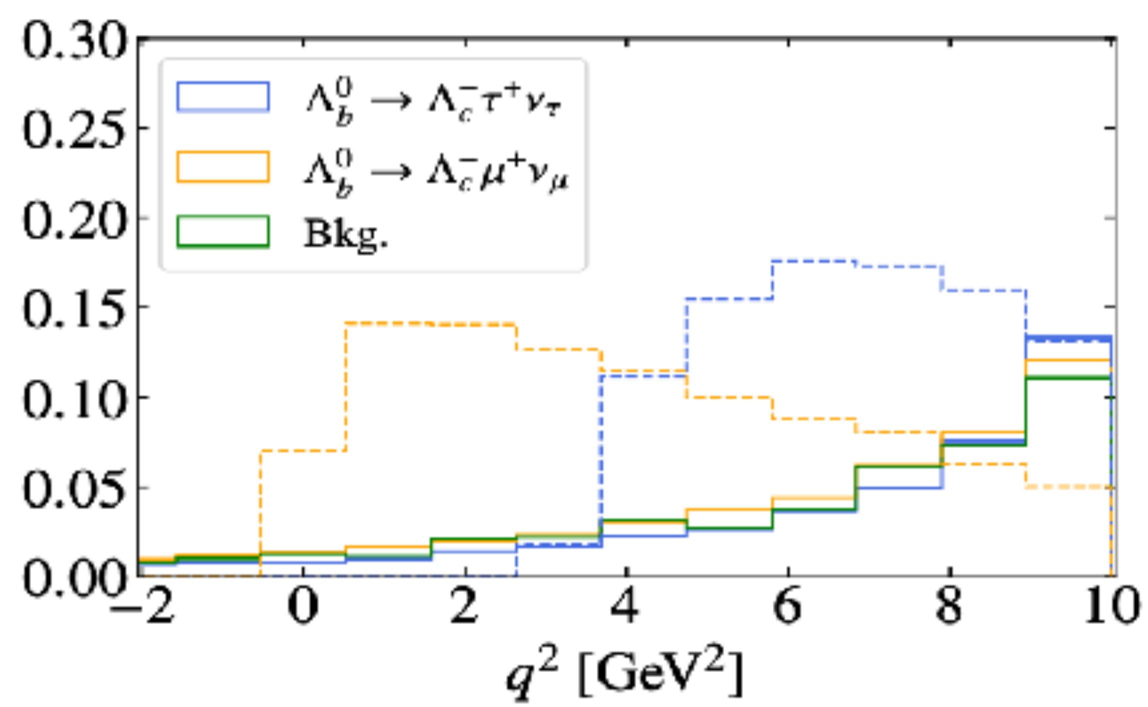
(Deng, Jiang, Liu, Yan, **arXiv:2503.02605**)

LFU in B decays:

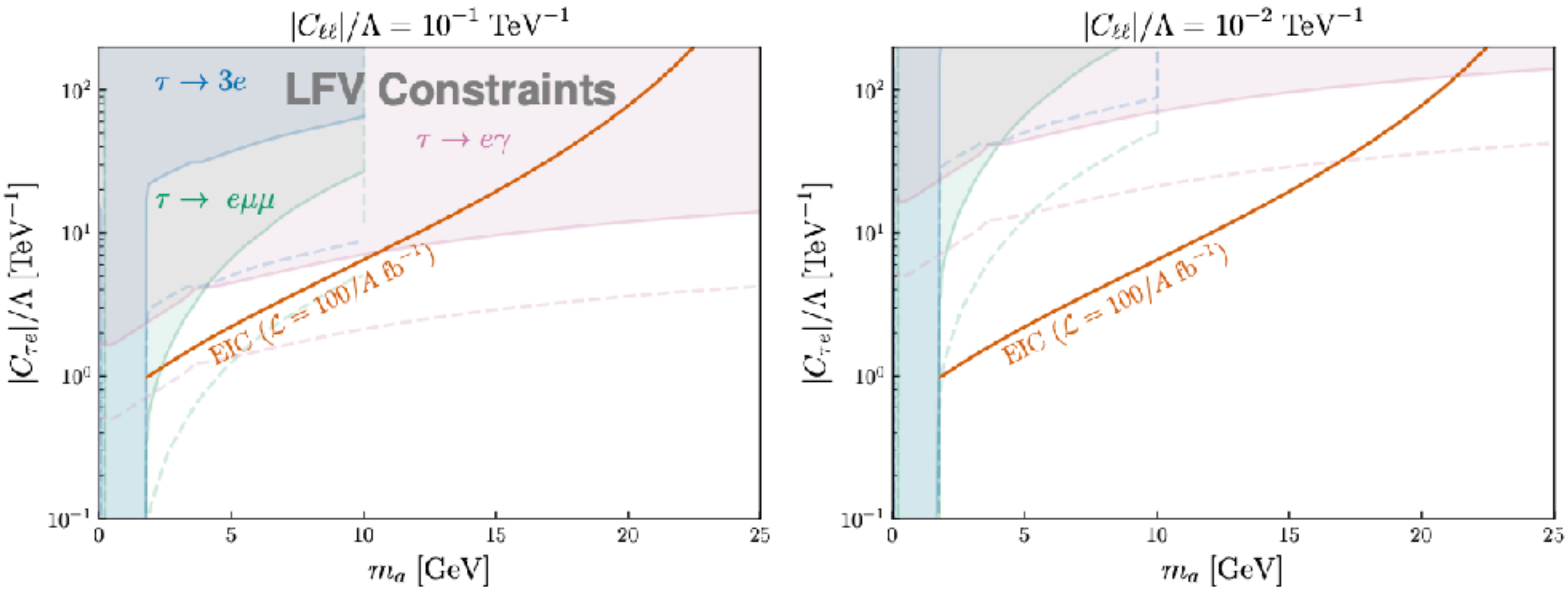
- B hadron production rates are lower vs. other expts, but clean environment + easy to make B baryons. Also, *beam polarization* at EIC provides a unique handle.



- Λ_b baryons are especially promising for EIC; can achieve comparable precision to LHCb upgrade in testing LF universality in decay (μ vs τ.) Muon or tau tagging are particularly desirable features!



Conclusions



- EIC has great potential for searches for new physics. Electron-ion mode can act like ultra-high energy fixed-target experiment, with excellent detector coverage (although *added coverage in backward region* is generally motivated by coherent production of BSM.)
- LFV searches are motivated, EIC can be powerful especially for ~1-30 GeV region. 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 $(g-2)_e$ discrepancy with the SM.
- More particle pheno study is needed to understand the best things to look for at EIC!

Backup slides

- What about the other two parts of the Lagrangian?

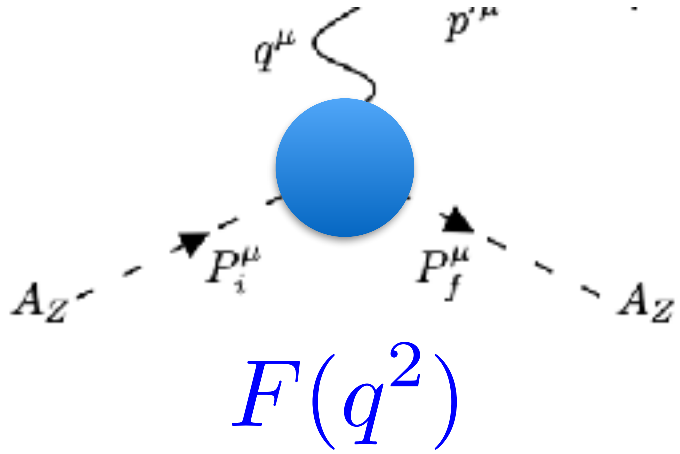
$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 a^2 + \mathcal{L}_\ell + \mathcal{L}_g + \mathcal{L}_h$$

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

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

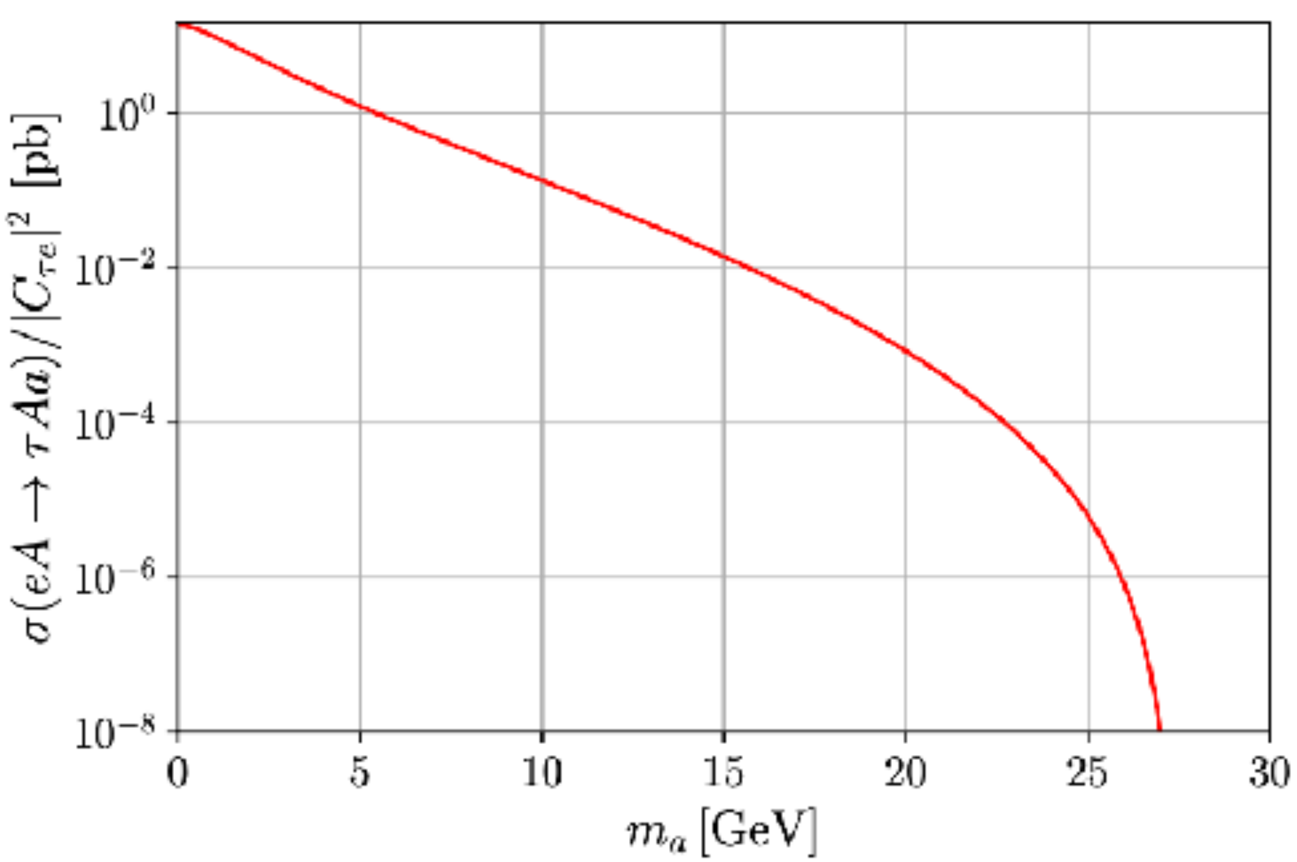
- This includes tree-level and loop-induced contributions. If we set tree-level $C_{\gamma\gamma} = 0$, loop-induced is always too small to matter (branching to two photons ~ 10^{-7} at m_a=2 GeV.)

- 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.

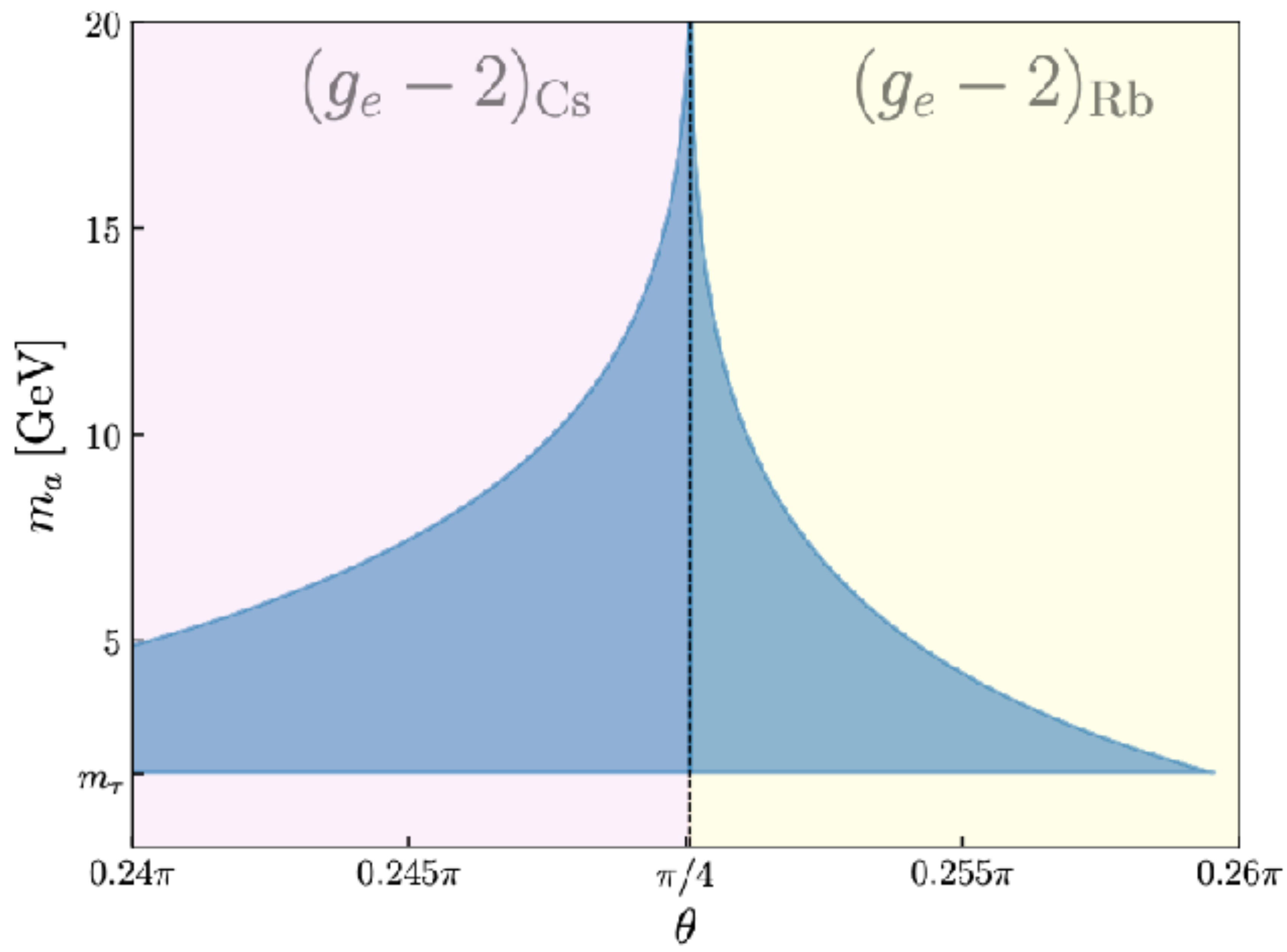


$$F(q^2) = \frac{3}{q^3 R_A^3} \left(\sin qR_A - qR_A \cos qR_A \right) \frac{1}{1 + a_0^2 q^2}$$

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

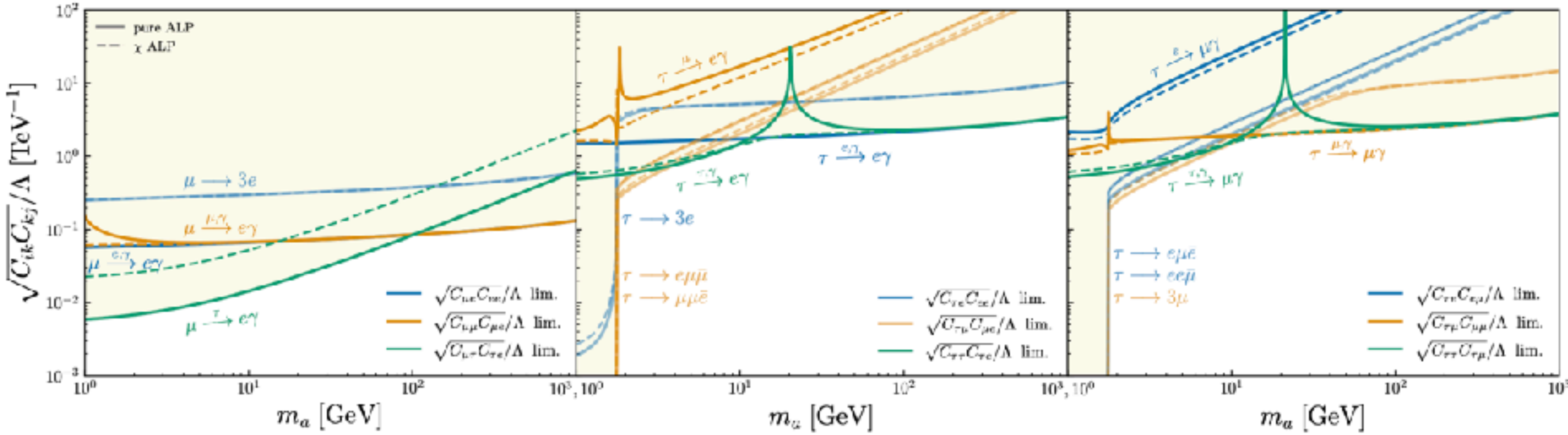


- The form factor suppression is active for m_a > 20 GeV or so (left.)
- We also impose a hard cutoff **$q^2 < (100\text{ MeV})^2$**, to avoid nuclear breakup; this corresponds to m_a < 27 GeV. (Form factor suppression already large.)



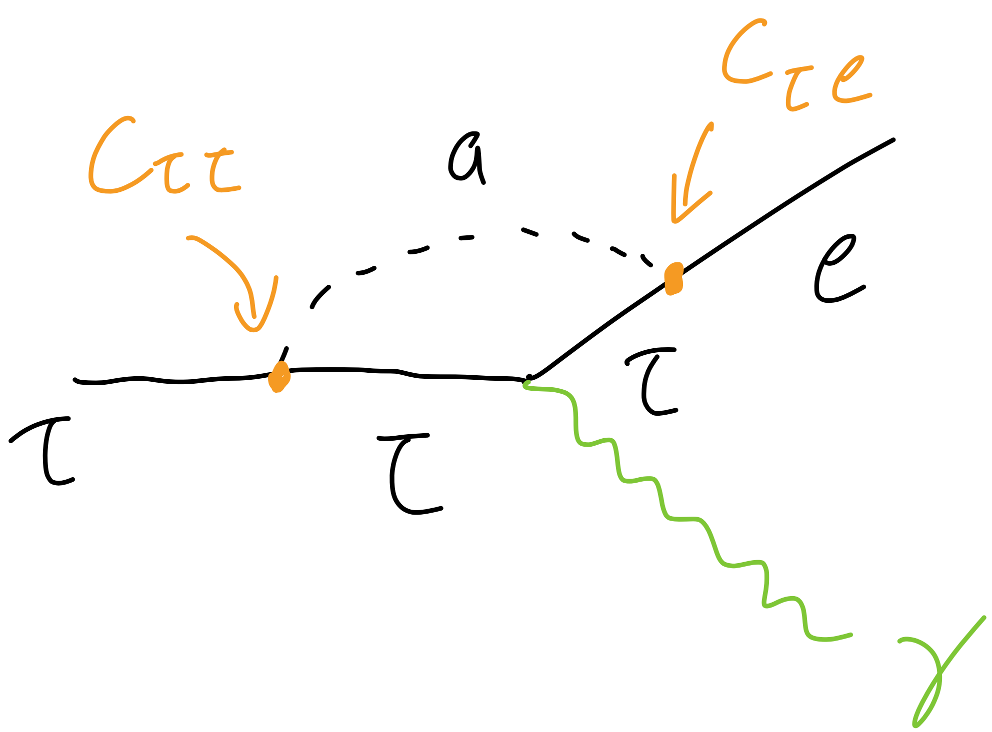
- Region where current EIC projected search can cover an ALP (g-2)e explanation, vs. ALP mass and θ.

(from R. Marcarelli, PhD thesis work)



- Plot of bounds from low-energy decays of FV ALPs, above 1 GeV mass.
- Bounds all require at least two couplings at once (usually one flavor-preserving, which can be naturally suppressed for ALPs depending on chirality.)

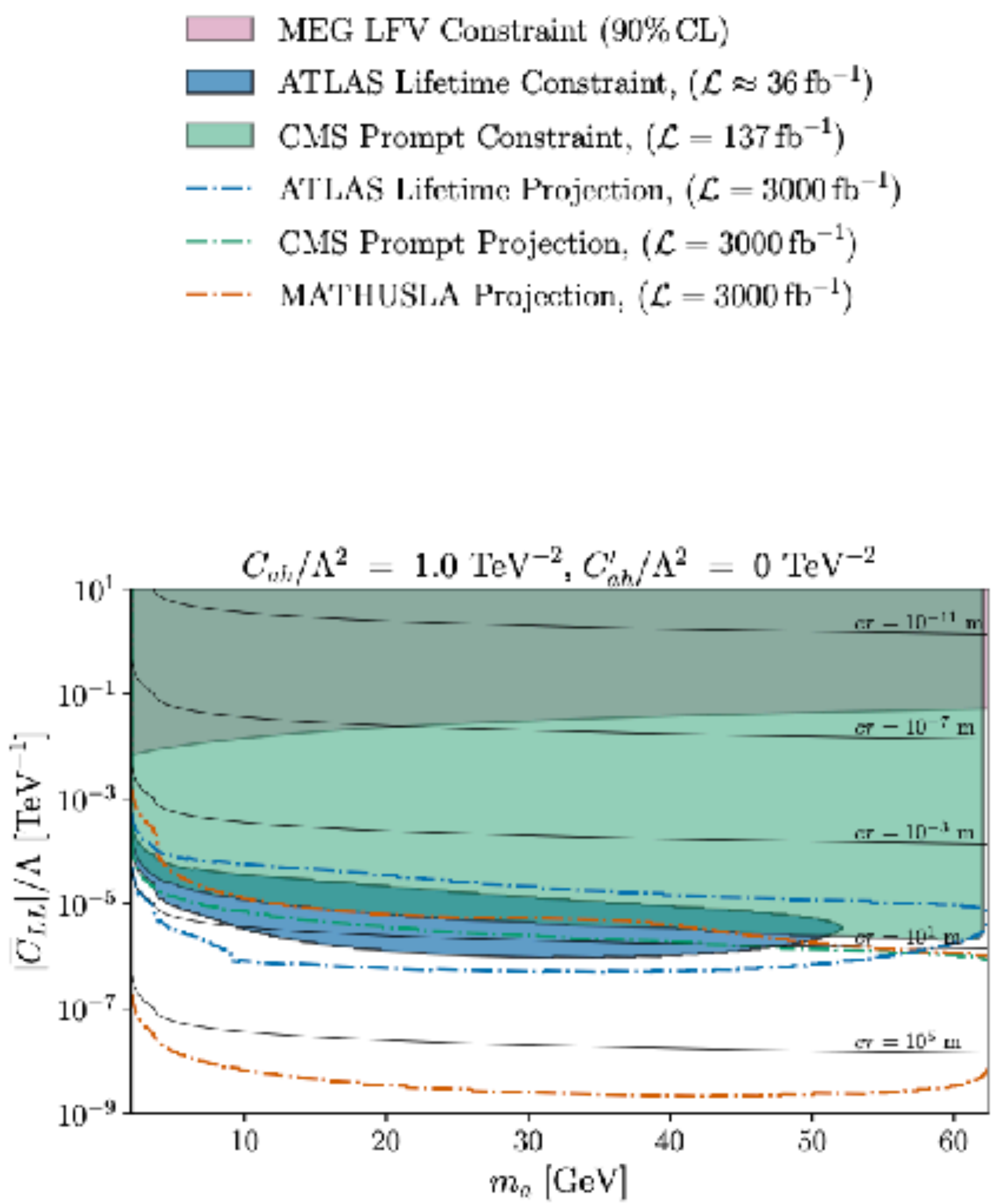
Tau decay and ALP-lepton couplings



- 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 $m_a > m_\tau$.

(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.

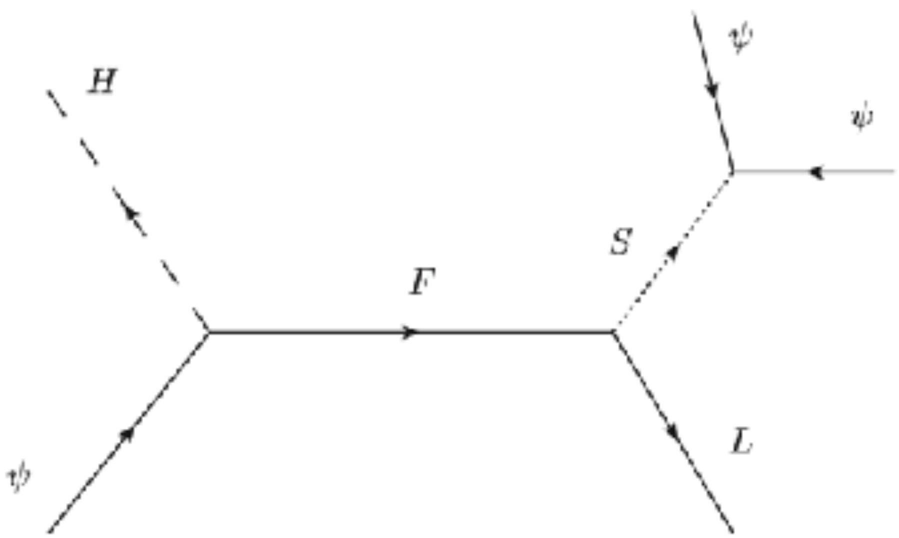
(Davoudiasl, Giardino, Neil, and Rinaldi, arXiv:1709.01082)

Example chiral ALP model

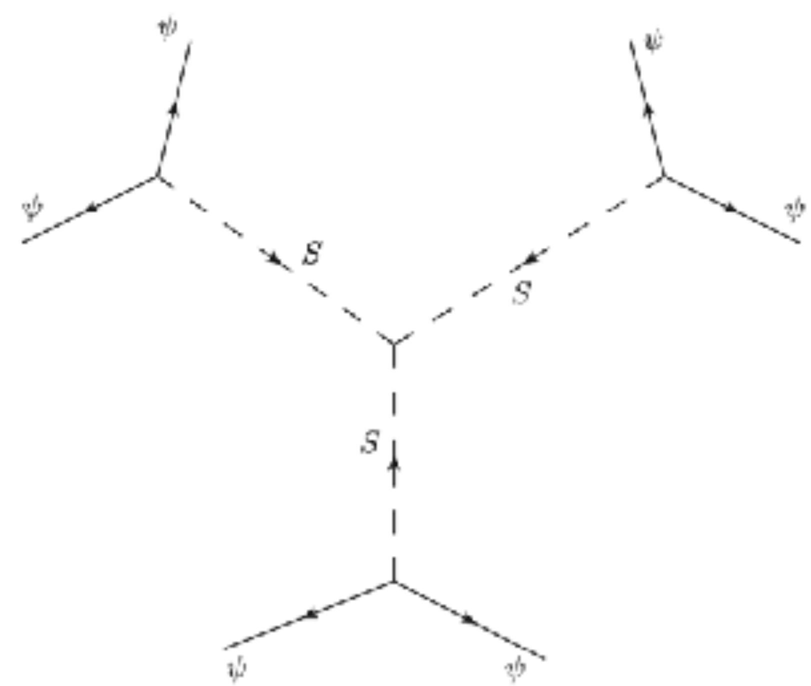
- UV-complete model for neutrino mass + composite dark sector.

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

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



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



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