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

Properties of BSM searches at the EIC

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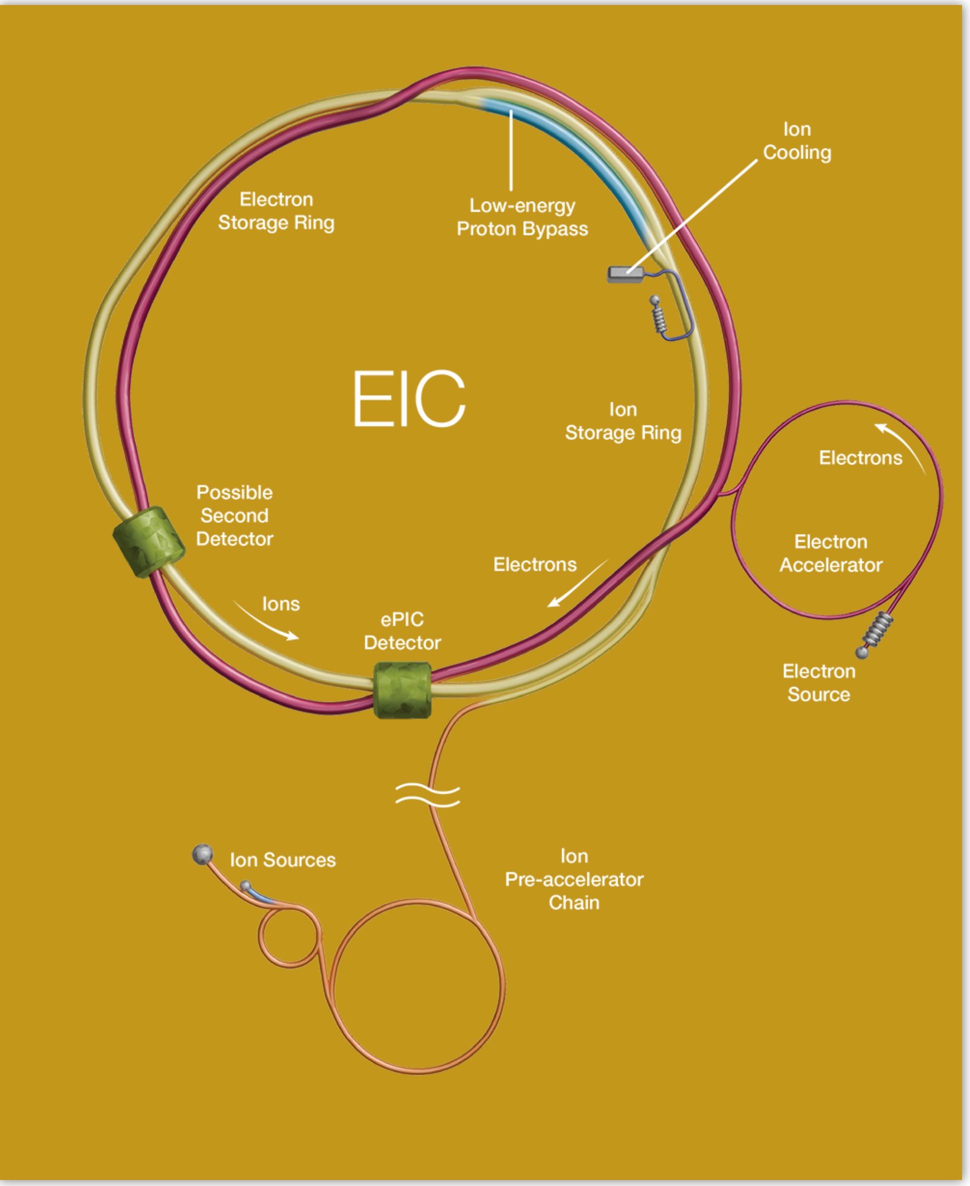
Presentation to EIC Second Detector User Group
08/14/25

Outline

- This talk will focus on some specific BSM signals at the EIC, including details of how to detect them:
  - arXiv:**2112.04513**: Direct production of lepton-flavor violating axion-like particles (**LFV ALPs**);
  - arXiv:**2307.00102**: Displaced production of **dark photons** (and other dark vector bosons).
- These are not exhaustive of all BSM physics one can study at EIC, but they are meant to be **representative** of what new-particle signals can look like.
- Lots of credit goes to my collaborators:
  - **Hooman Davoudiasl** (BNL)
  - **Dr. Roman Marcarelli** (PhD student, Colorado + BNL [DOE SCGSR])
- For many more details, see also Roman Marcarelli's PhD thesis and code (https://github.com/rmarcarelli/thesis). For *invisibly-decaying dark vectors*, see Davoudiasl and Liu, arXiv:**2505.08871**.

1. Producing new particles at the EIC

New physics at the EIC?



- Study **electron-Au mode.** Coherent scattering from gold —> **Z^2 enhancement** of cross section. (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.)
- Two types of BSM signals considered here: lepton-flavor violating (LFV) using initial-state electron; or, displaced decays.

Kinematics at the EIC

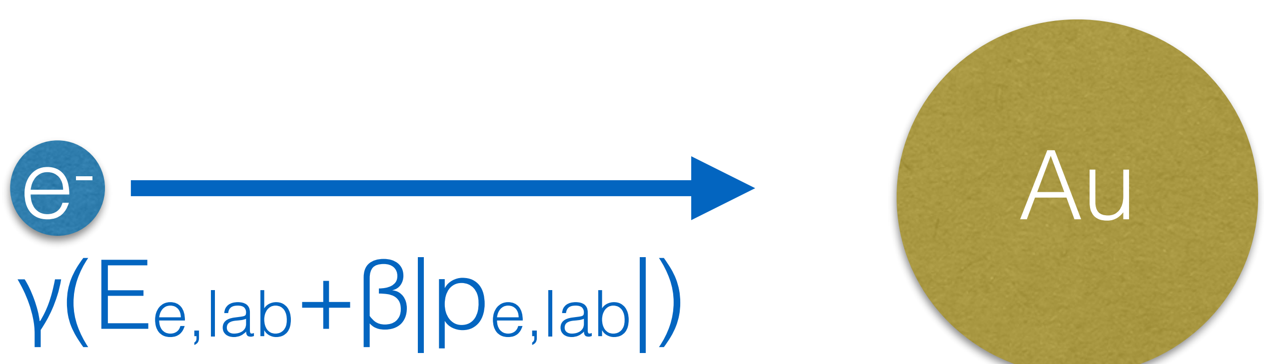
<u>Lab frame:</u>

$|p_e| = 18$ GeV

$|p_A| = 110$ GeV/A

<u>Boost:</u> $\gamma \sim 120$

<u>Ion frame:</u>

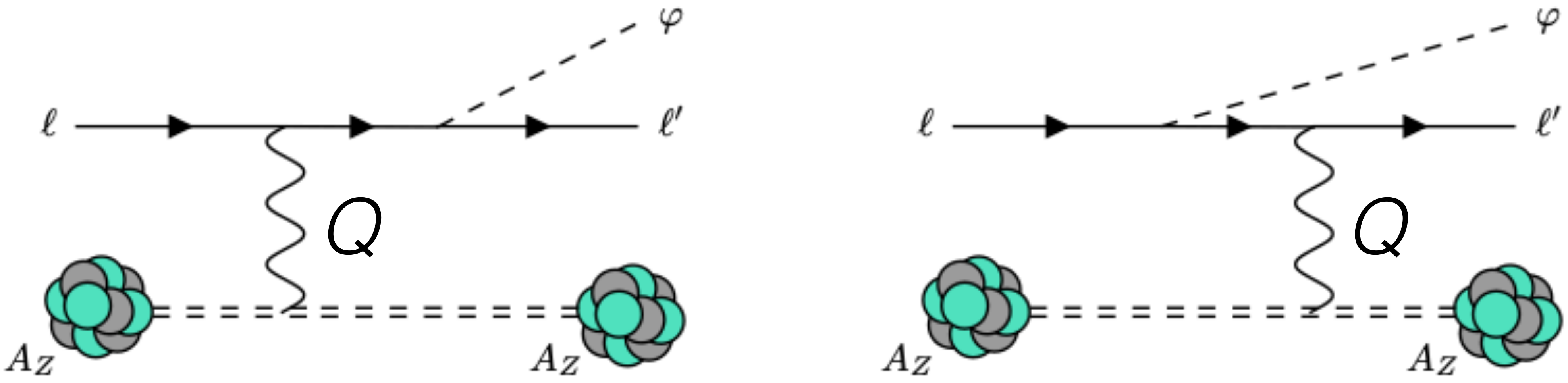


$E_e = \gamma(E_{e,lab} + \beta |p_{e,lab}|)$

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

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

- As an example, flavor-violating (pseudo-)scalar emission dominated by the following **coherent scattering** diagrams:



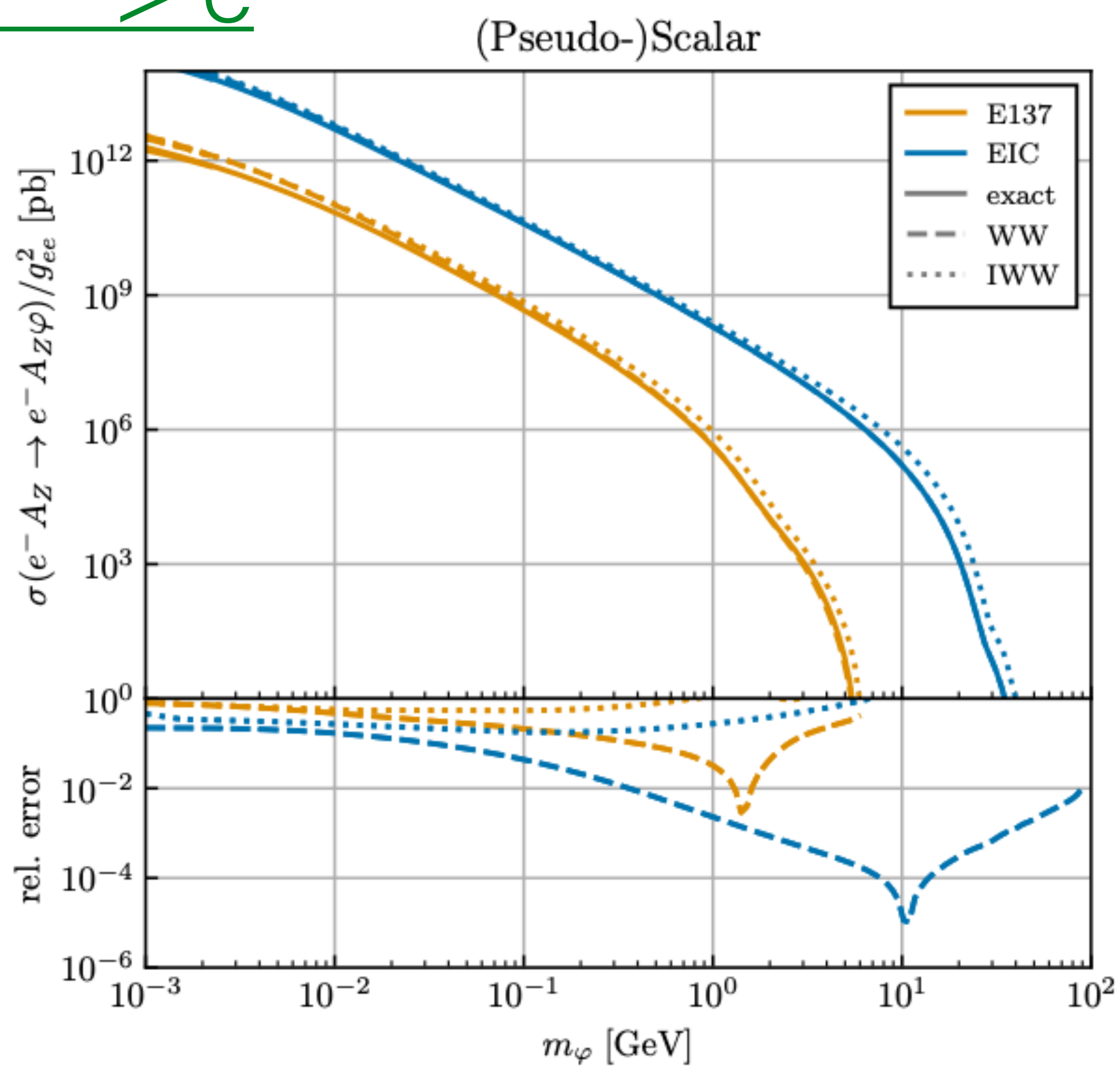
(from R. Marcarelli, PhD thesis)

- Z^2 enhancement due to ion charge apparent from diagrams. 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:

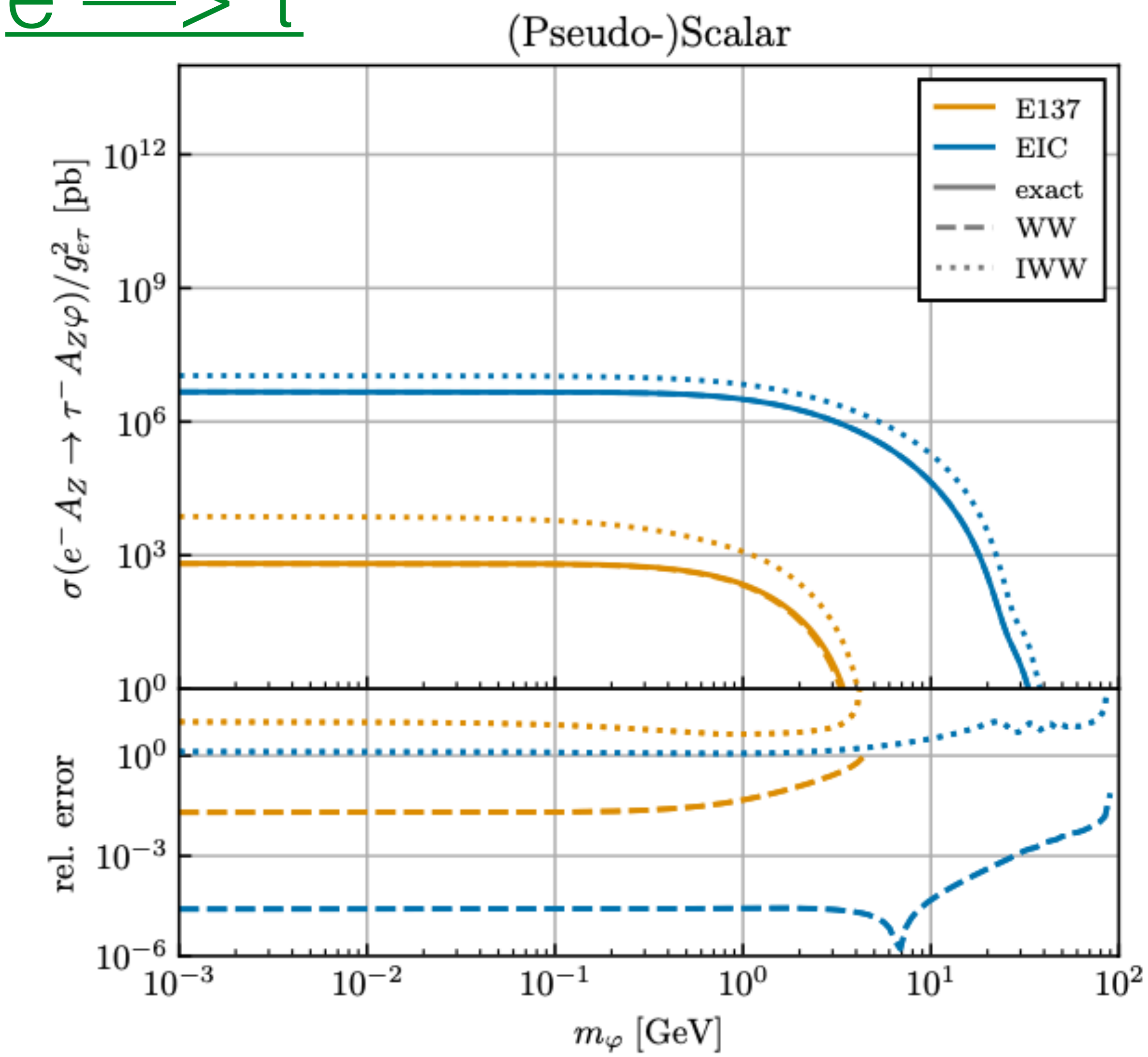
$$Q^2 \lesssim (100\ \mathrm{MeV})^2$$

e —> e



e —> τ

(from R. Marcarelli, PhD thesis)

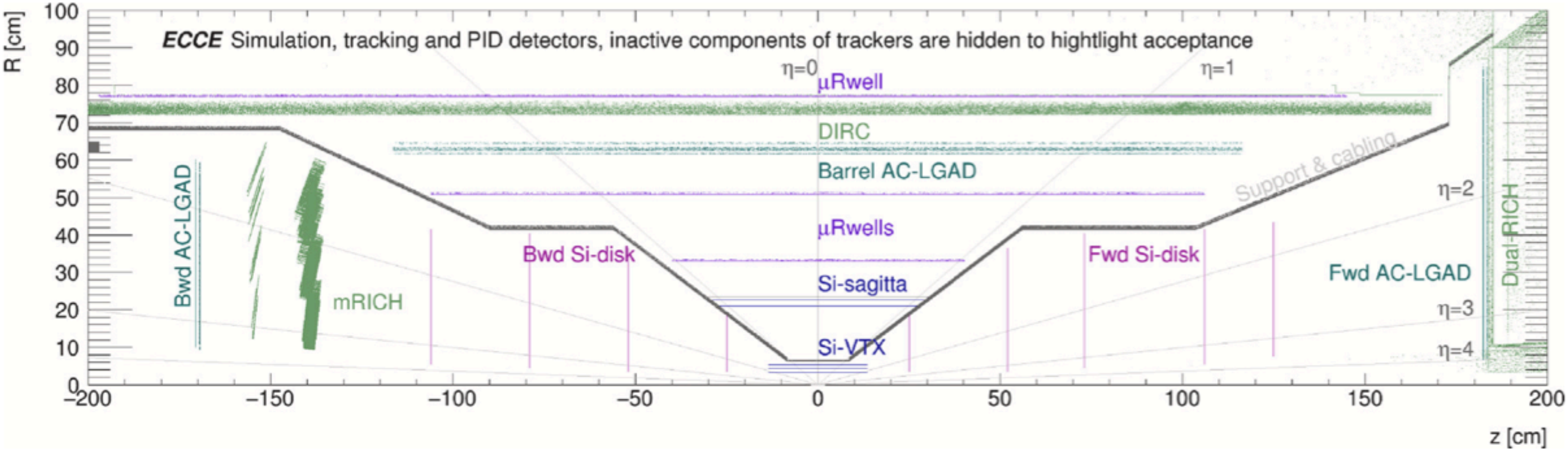


- Ion target is gold (Z=79) for the EIC, aluminum (Z=13) for E137 (SLAC beam-dump experiment circa 1980.) Higher nuclear charge on EIC target gives overall improvement to cross section.

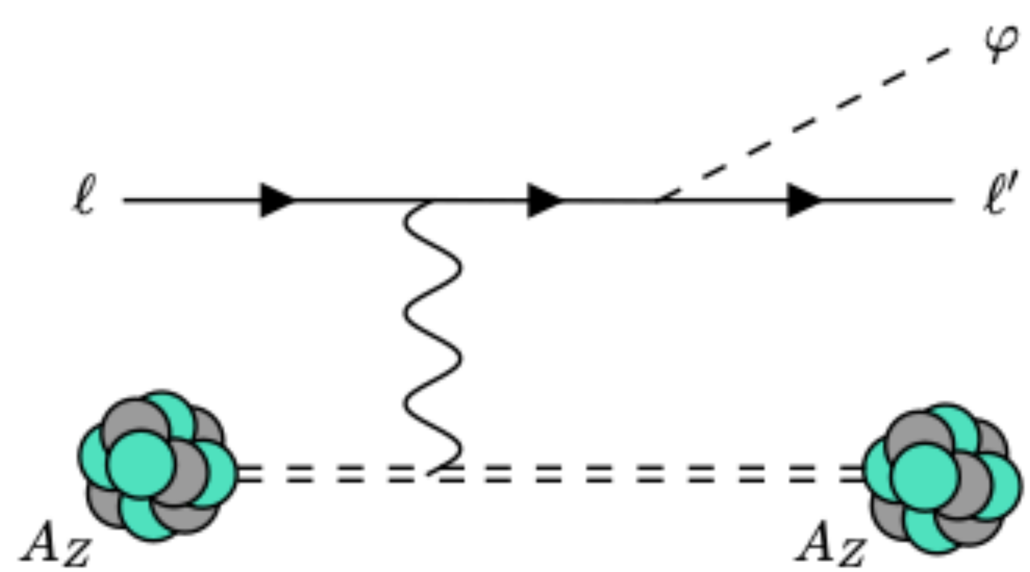
- Higher energy gives additional improvement above GeV scale; form factor cutoff apparent (Woods-Saxon form.) In ion rest frame,

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

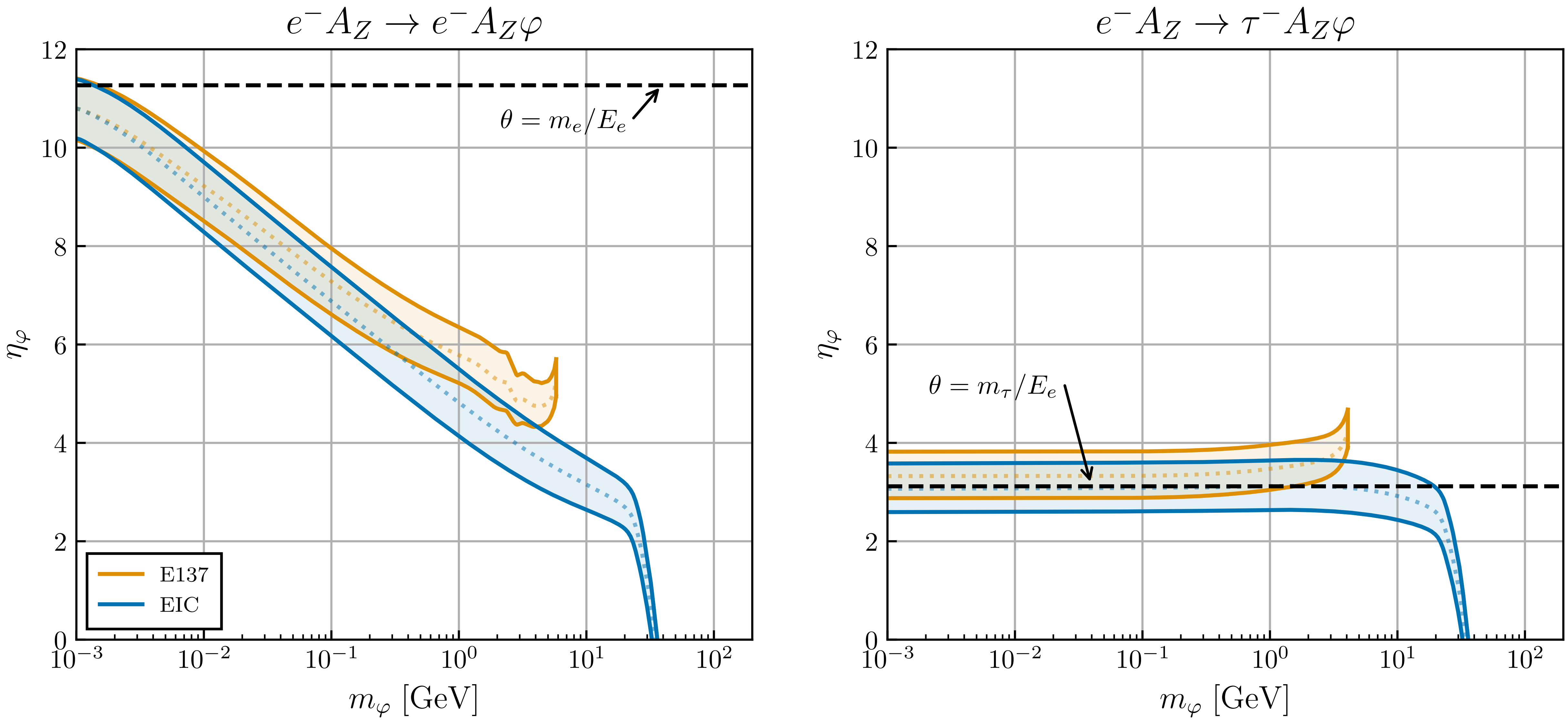
(Adkins et al., “Design of the ECCE detector for the Electron Ion Collider”, arXiv:2209.02580)



- 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”.)

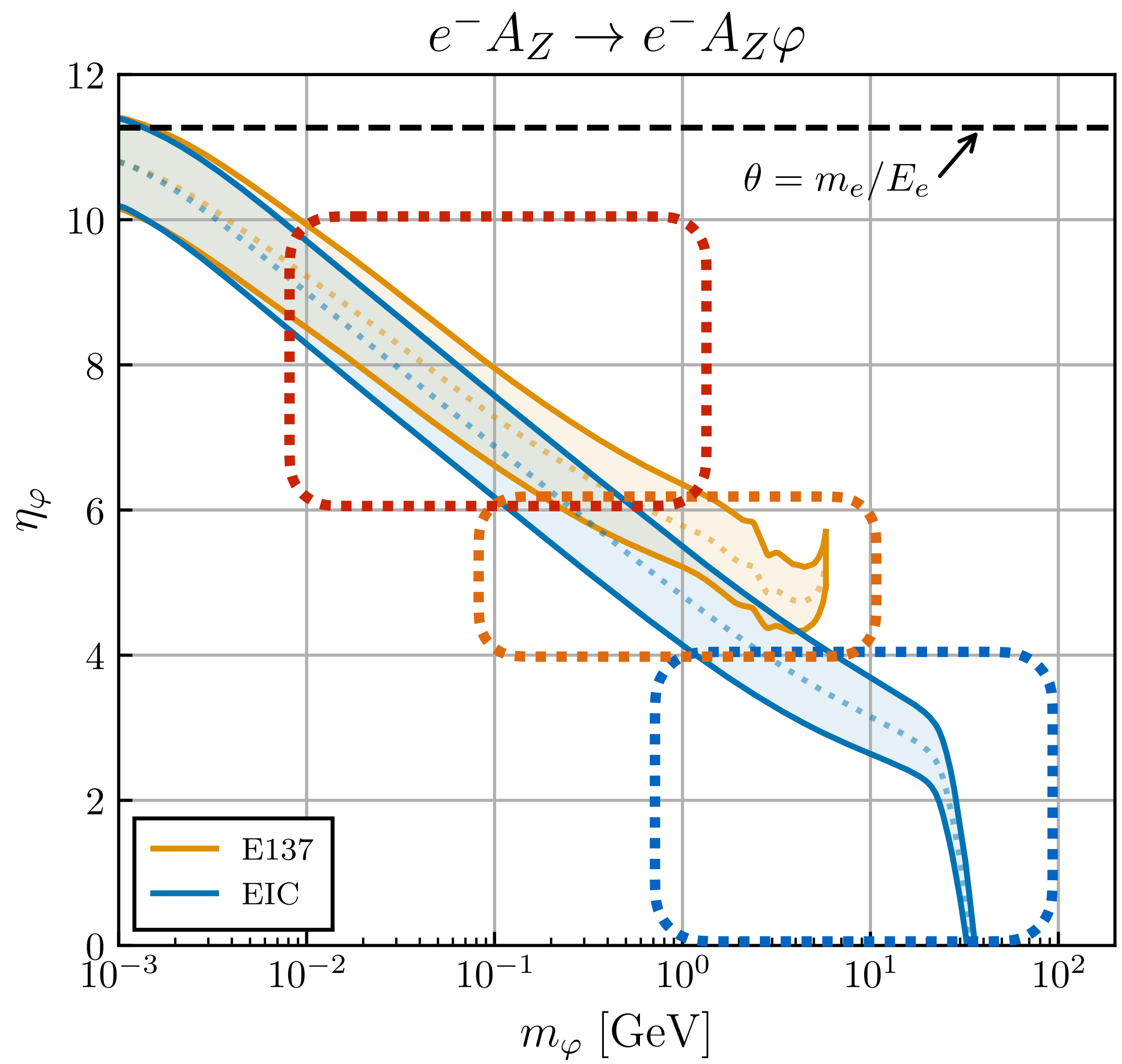


(from R. Marcarelli. PhD thesis work)



- 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)



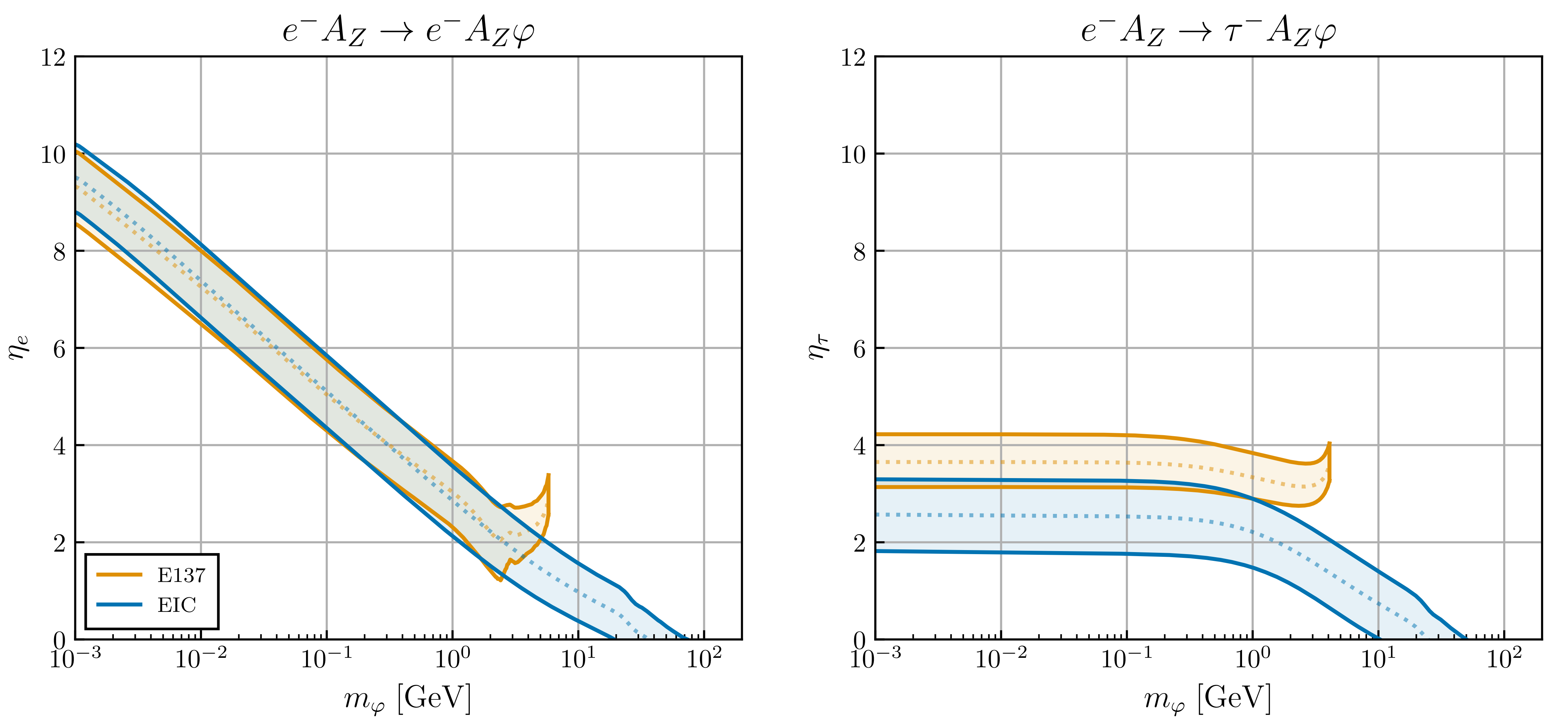
$$\eta = -\log\tan(\theta/2) \approx -\log((\Delta z)/2L)$$

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

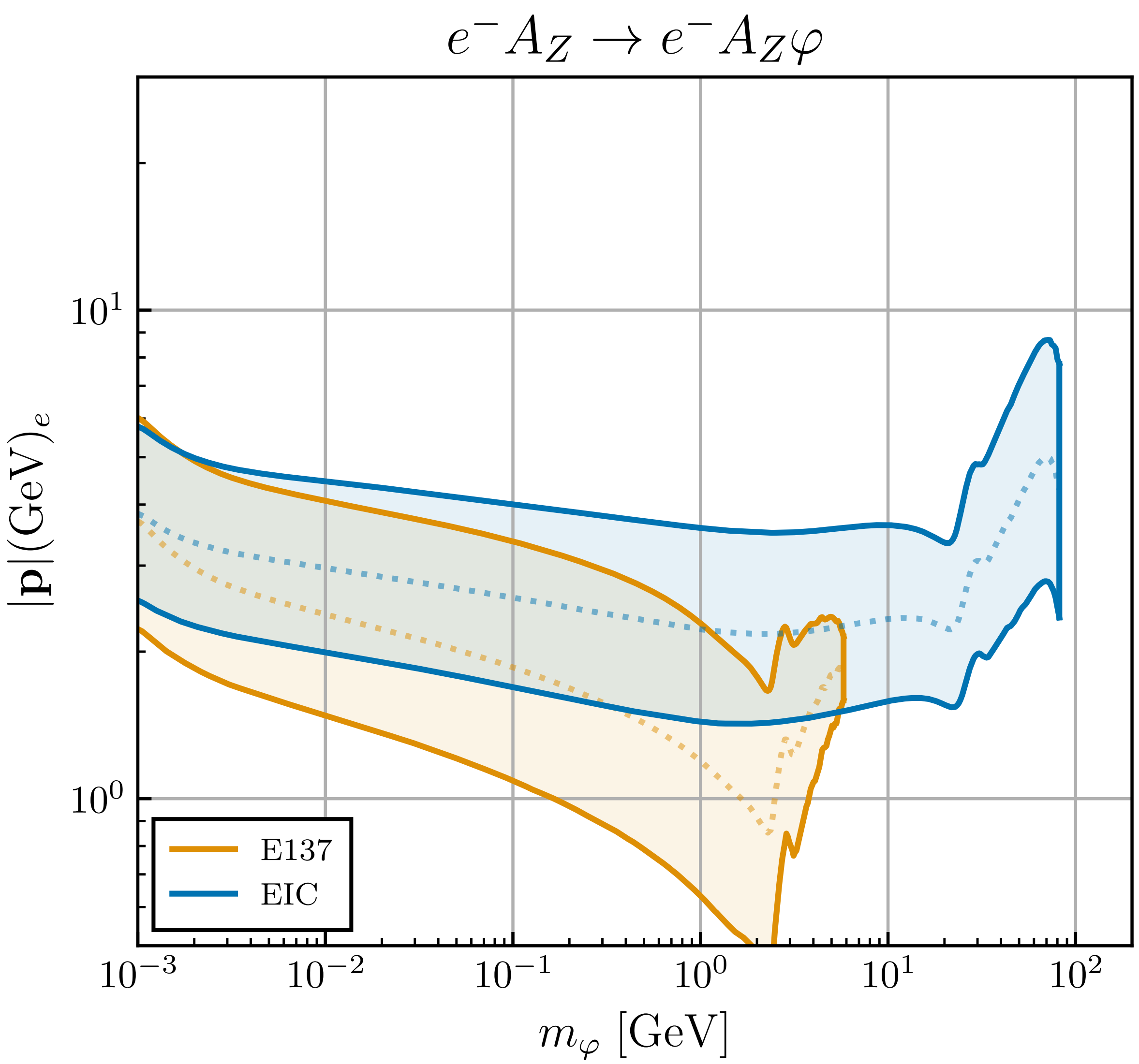
“Far backward” region

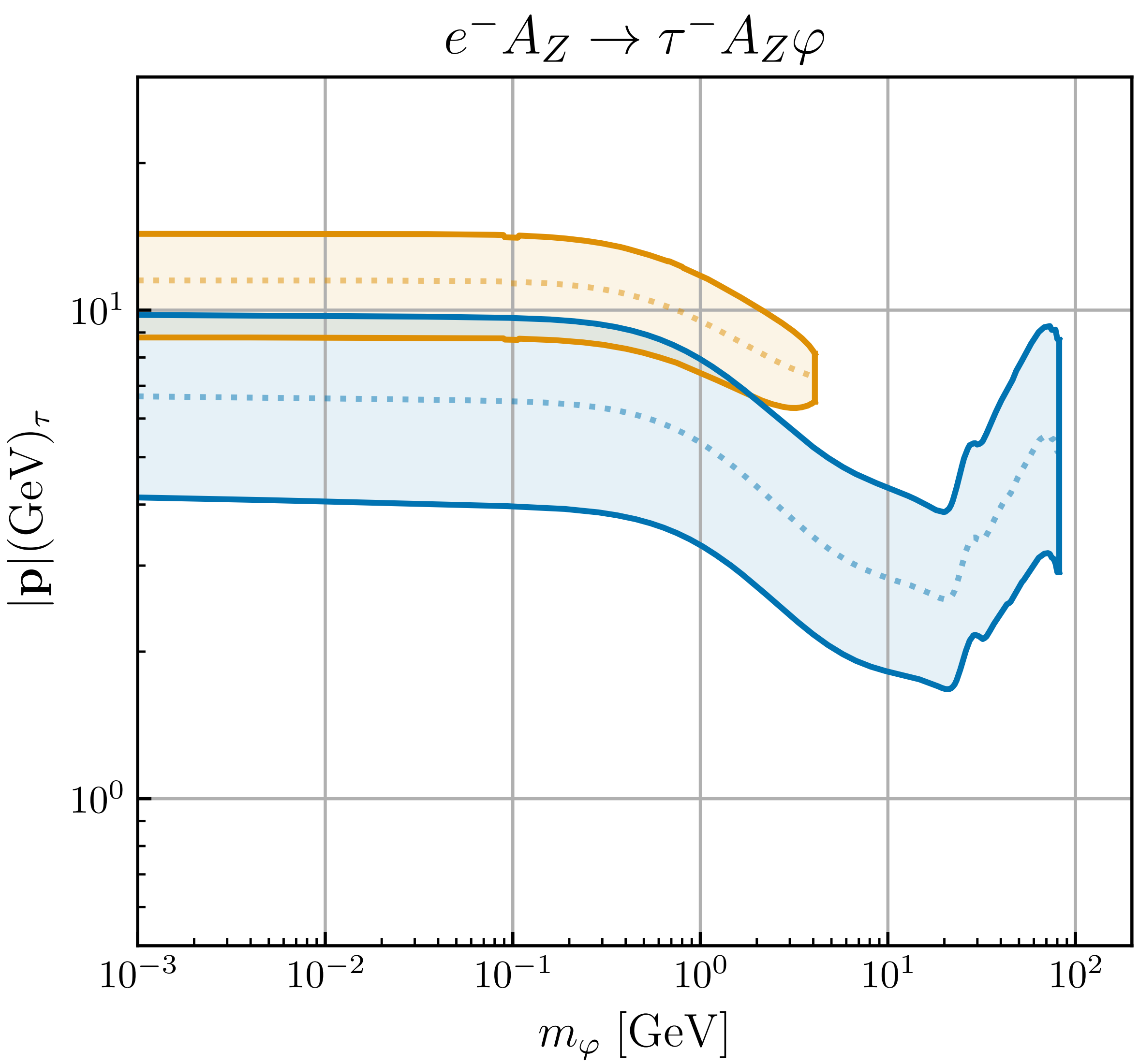
Main detector (backwards region)

- 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.
- Lightest particles are basically down the beam pipe, but also tend to have *very* displaced decays, so “beam dump” experiments tend to dominate bounds (see dark photon bounds to be shown later.)



- 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 directions.





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

2. Axion-like particles with lepton 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.

- Ignoring quarks, ALP Lagrangian has this structure:

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

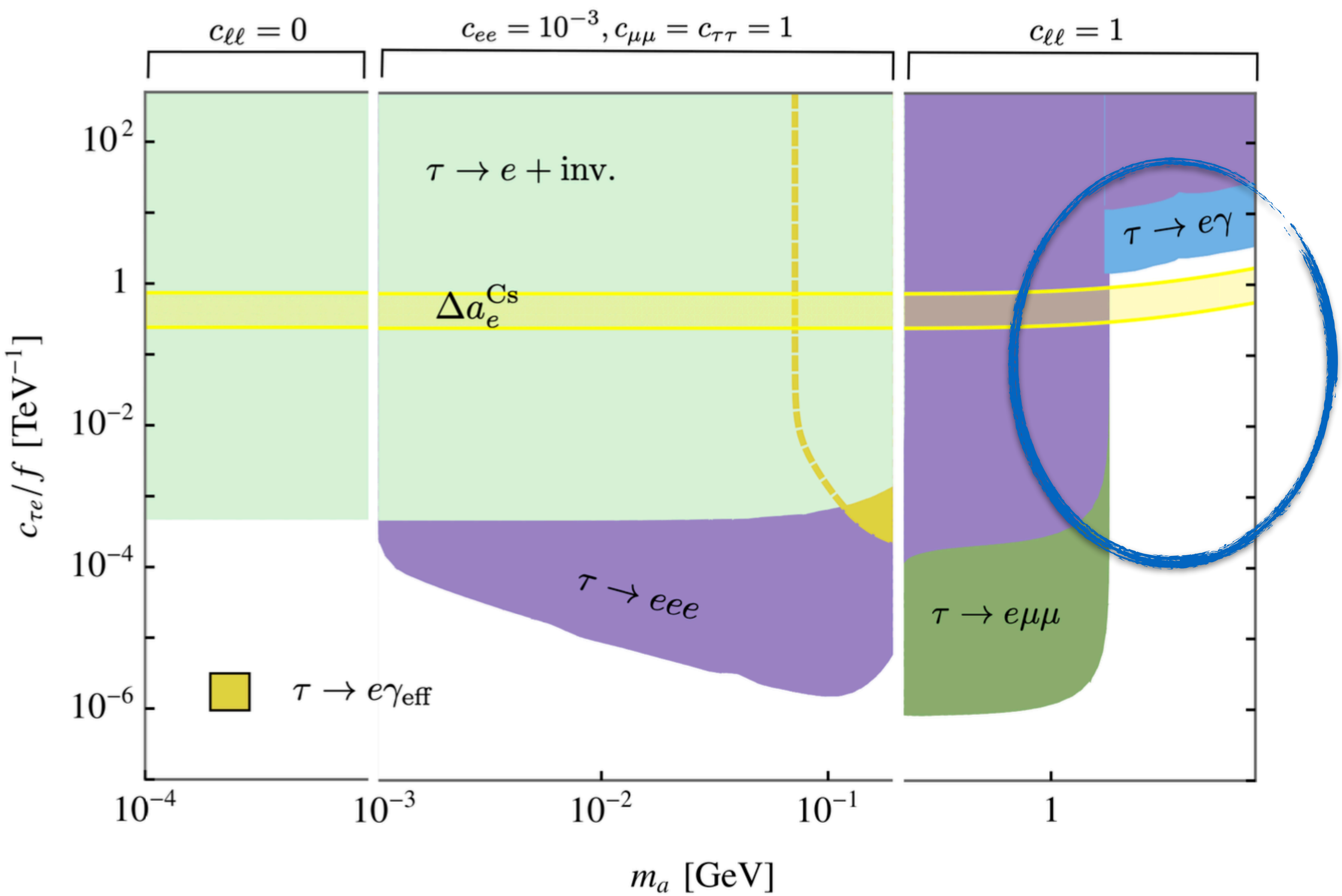
- Coupling to leptons can be written in general using equations of motion as:

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

- Important point #1: for flavor-diagonal couplings (l=l'), the **vector coupling is suppressed**! Parity-violating 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!

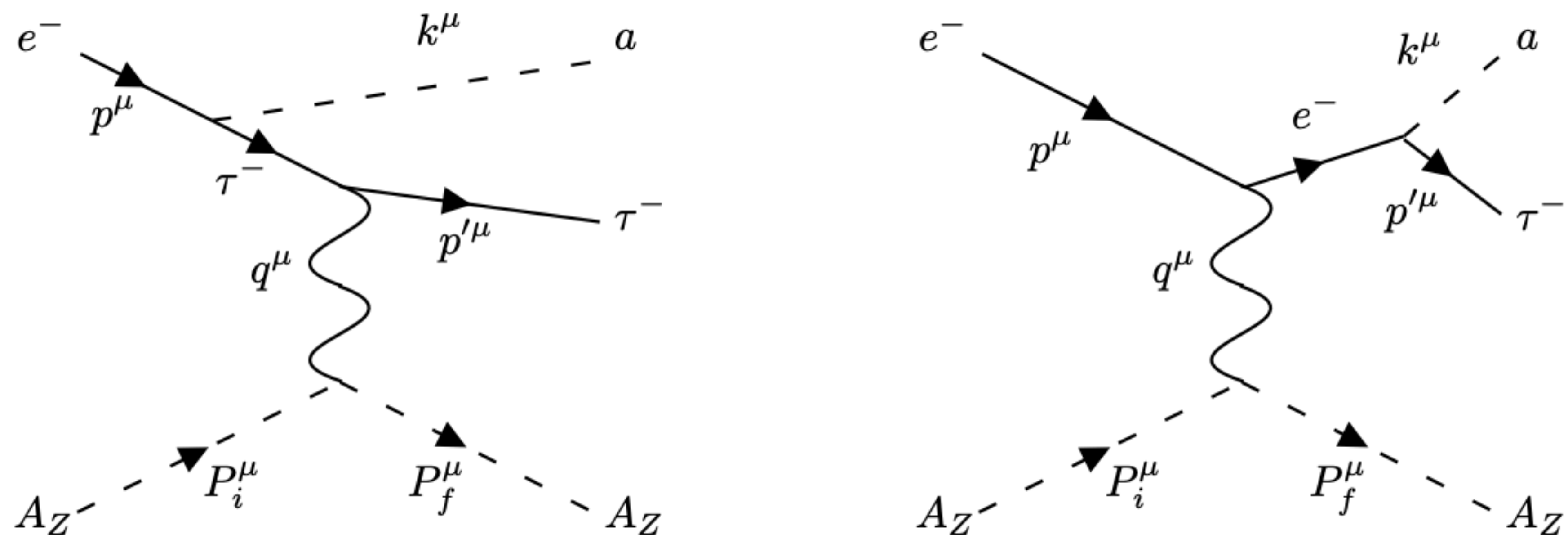
(from Bauer, Neubert, Renner, Schnubel, and Thamm, arXiv:2110.10698)
(see also: Cornella, Paradisi, and Sumensari, arXiv:1911.06279)



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

- <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.

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:** $e^- A_Z \rightarrow \tau^-(a \rightarrow \tau^- e^+) A_Z$
- 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:

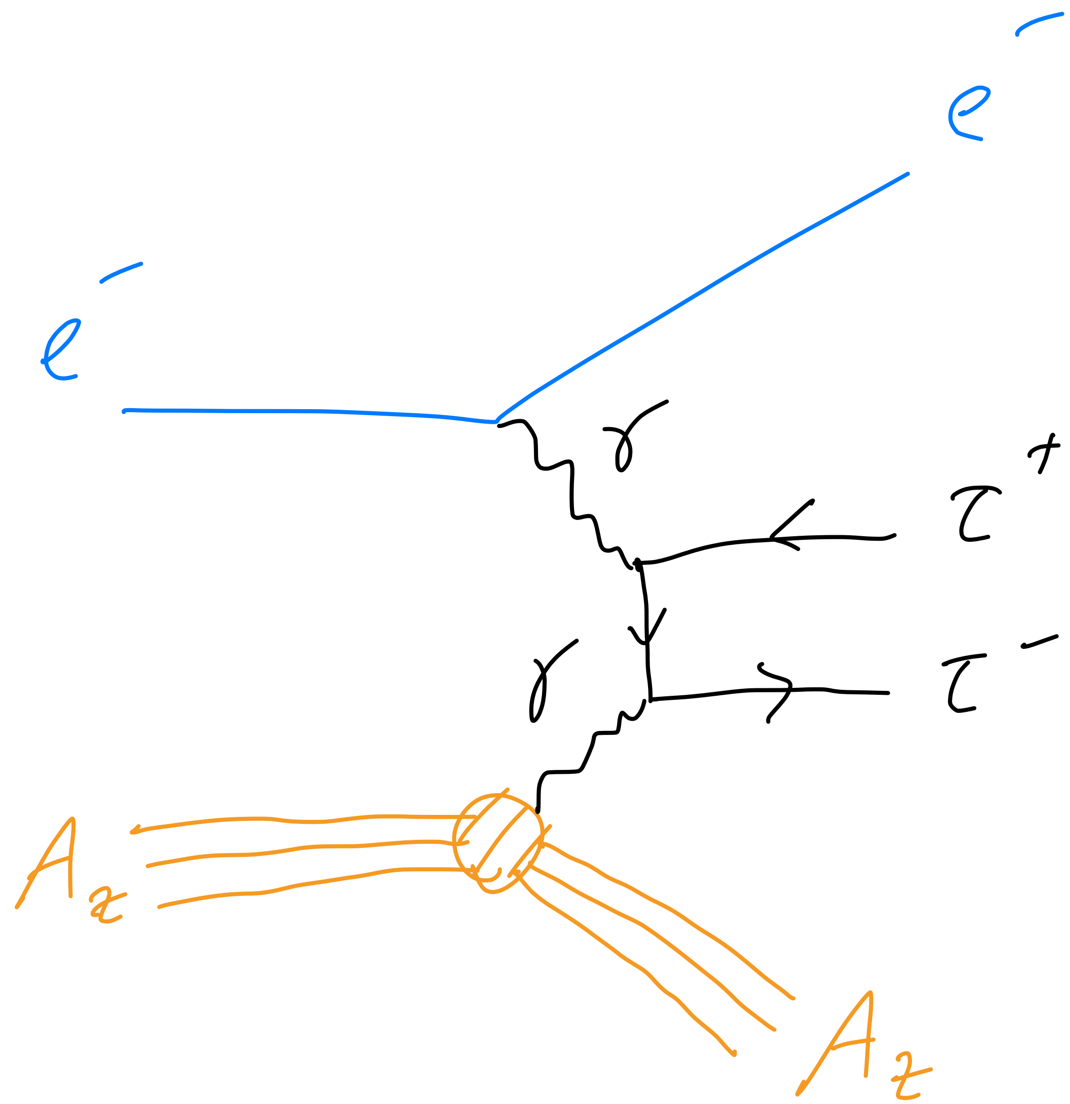
$$e^- A_Z \to \tau^- (a \to \tau^- e^+) A_Z$$
$$e^- A_Z \to \tau^- (a \to \tau^- \tau^+) A_Z$$

(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%**.

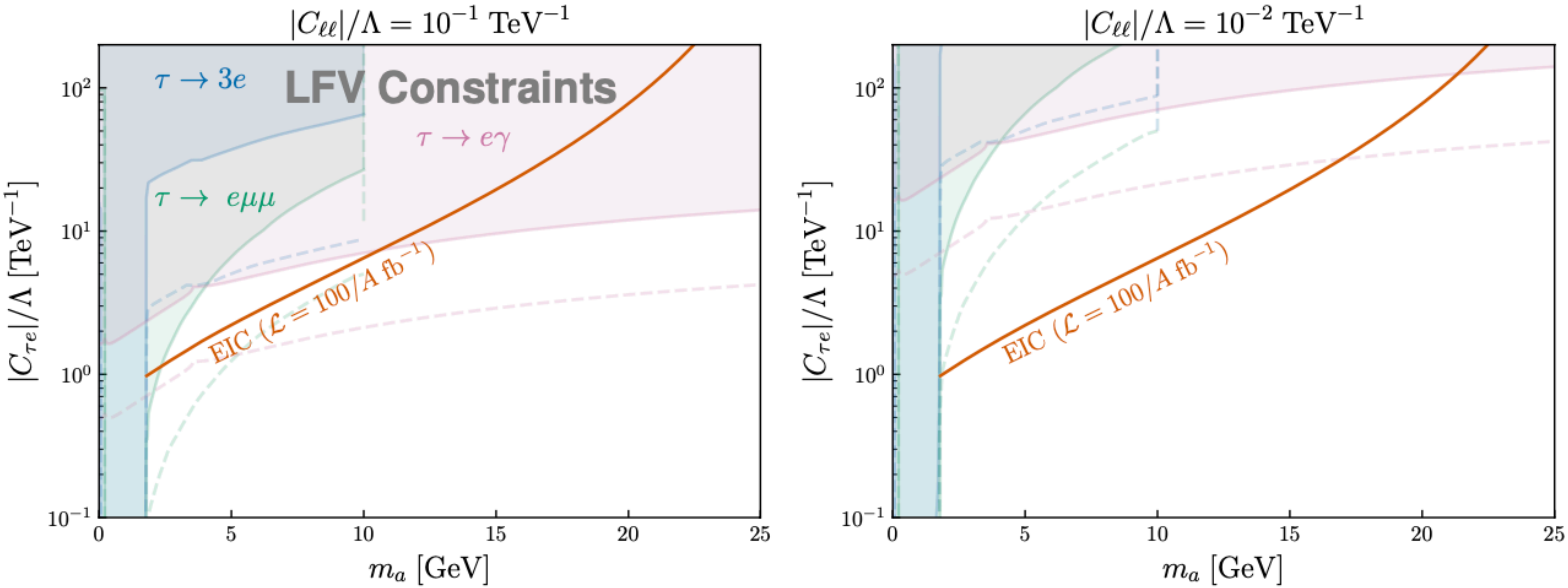


- Dominant background expected is τ pair production, specifically from the **Bethe-Heitler process** (left):

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

- 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.** Background efficiency w/cuts is about 3.6×10^{-5} —> **475 events** (so need 35 signal for 90% CL.)

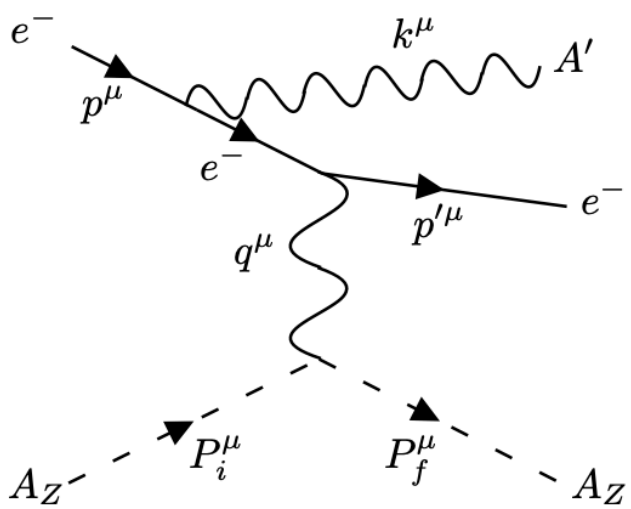
- **Side comment:** with 100/A ~ 0.5 fb-1 of luminosity in electron-Au mode, this is about **13 million** ditau events. Not competitive with Belle (~10^9 tau pairs), but still a lot! Maybe tau physics at EIC should be looked at on its own, independent of BSM applications? Can tau ID or certain aspects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

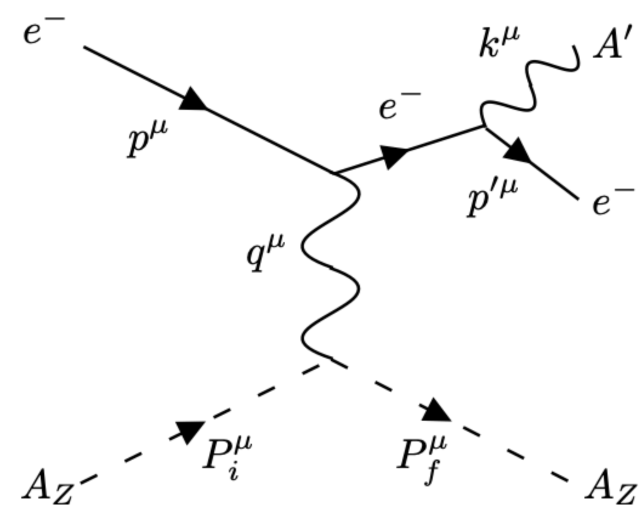


- Solid regions are current bounds; dashed lines show projections (Belle-II, 50 ab^{-1}.)
- Note that direct flavor-violation bounds for $m_a > m_\tau$ are much weaker if diagonal C_{ll} is reduced (left to right plot), but **EIC reach is unaffected**!
- Improvement in tau tagging efficiency (now 1%) or background reduction (now 475 events) could greatly improve sensitivity…(e.g. kinematic cuts to distinguish resonant signal from background might help.)

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. Dark photons are common in “dark sector” BSM scenarios; B, L combinations are valid to gauge since anomaly-free global symmetries of SM. Signal production diagrams look familiar:





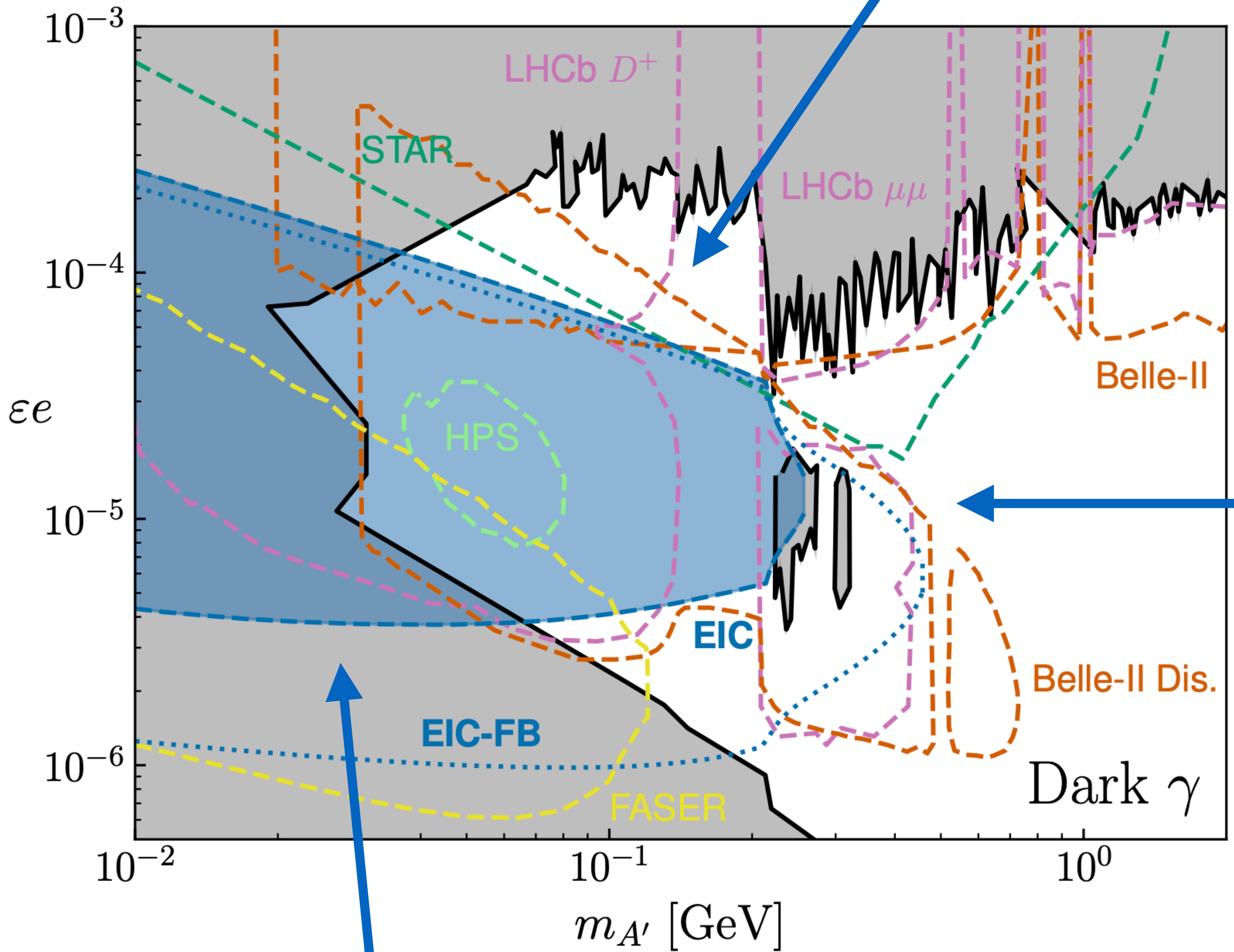
- Massive background potential in EIC, e.g. from real photon events. However, discriminate by studying only displaced decays. Sufficient displacement leads to ~0 SM background!

$$d_{A'} = \gamma v \tau_{A'} \sim \frac{120}{g_{A'}^2} \left(\frac{1\ \text{GeV}}{m_{A'}} \right) (2 \times 10^{-16}\ \text{m})$$

$g_{A'} \sim 10^{-4}$ → $\sim 20\ \mu\text{m}$

$g_{A'} \sim 10^{-6}$ → $\sim 0.2\ \text{m}$

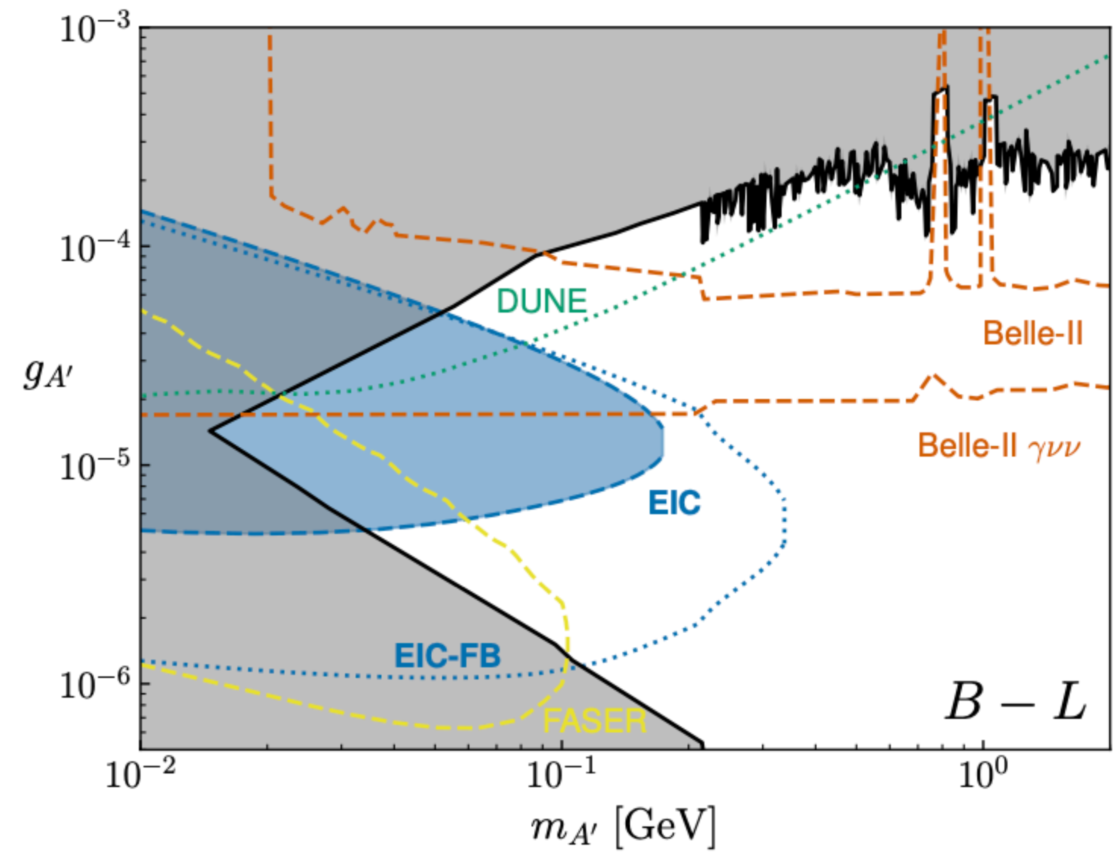
upper limit: displacement becomes too small (< 200 μm, w/geometric factors)

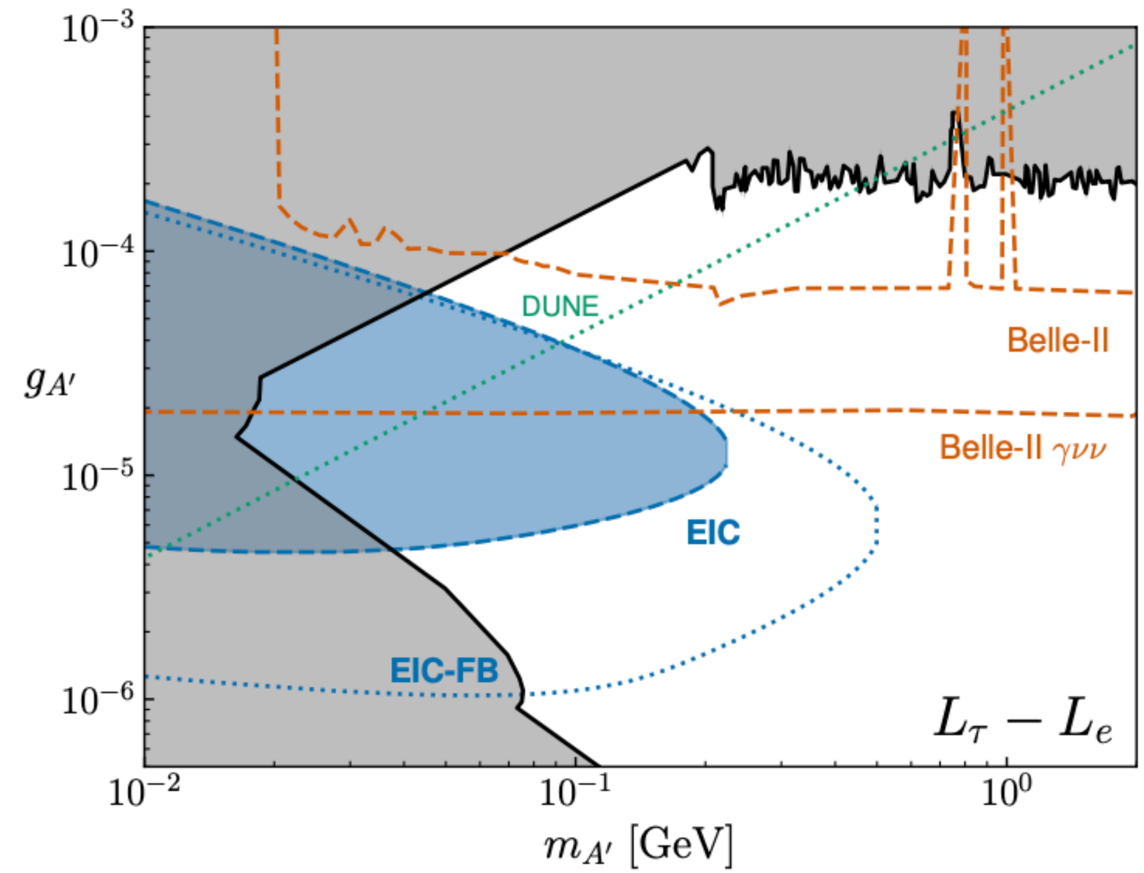


right limit: momentum transfer too large; loss of coherent enhancement. (Also, displacement reduced; boost reduces e^+e^- opening angle.)

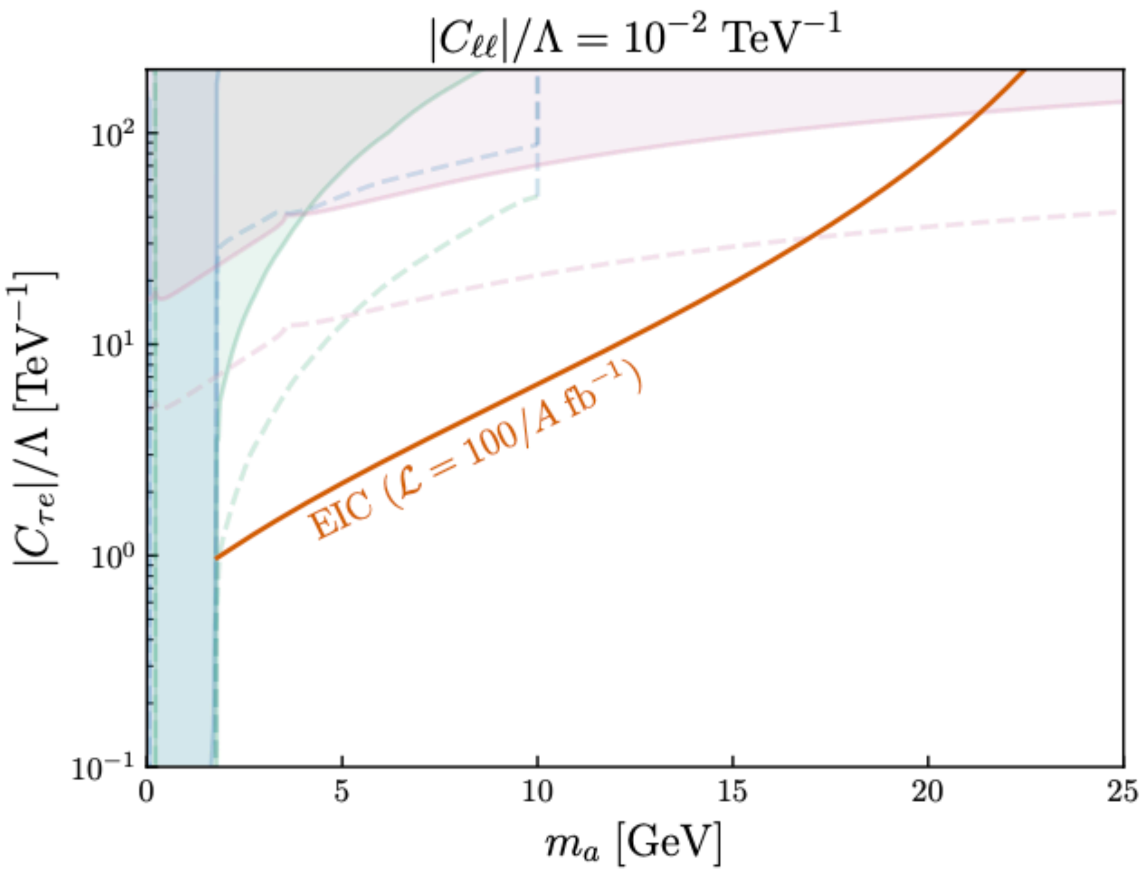
lower limit: production rate too small; displacement close to too large. (Note that **rate is peaked towards large, negative η**. "EIC-FB" scenario assumes a "B0-like" detector in electron beam direction, -4 < η < -6.

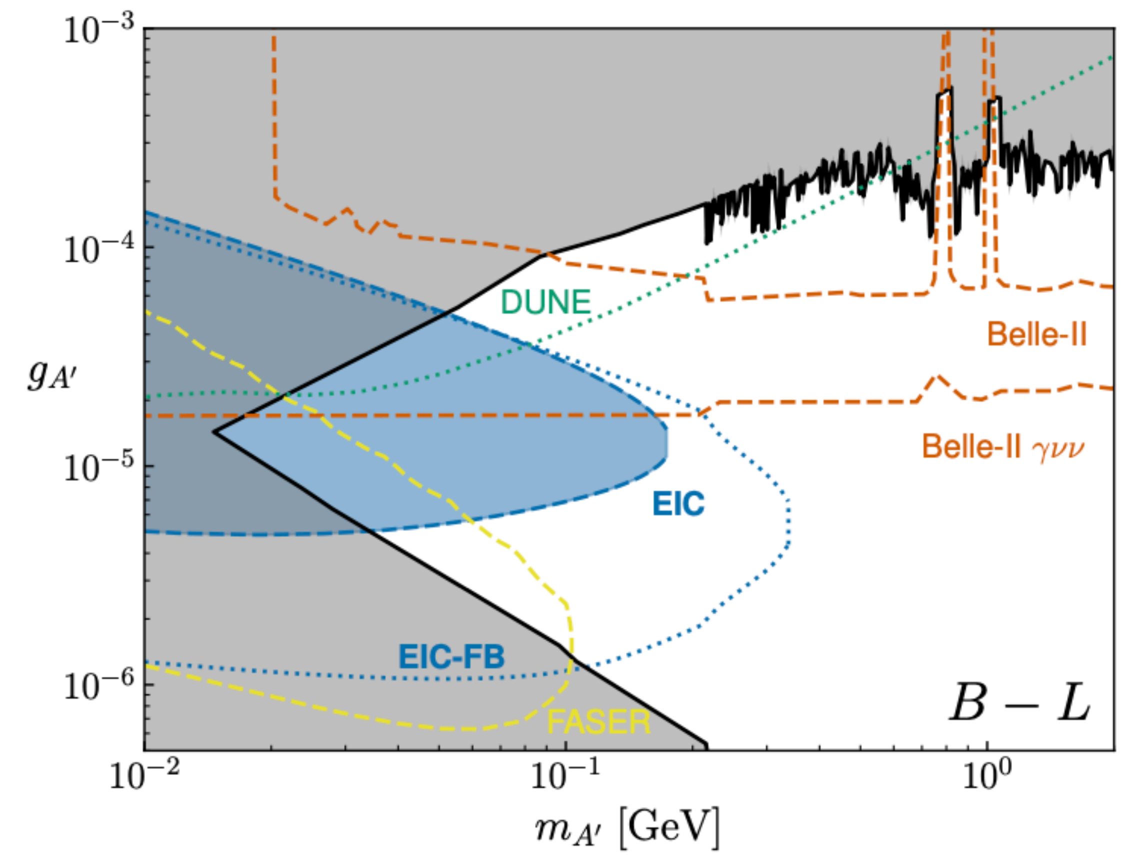
- Bounds on B-L, L_τ-L_e shown to the right; much less competition in this parameter space vs. dark photon. Can also probe L_μ-L_e (similar results to L_τ-L_e.)
- EIC is especially powerful for probing gauge bosons coupled to electron number, due to the initial-state electron.
- Other limits (beam dump, eventually astrophysics) dominate at extremely light A' masses below 10 MeV or so.
- We assumed *no muon detection capability*; being able to tag even some fraction of muons could further improve reach.





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.)
- EIC can be especially powerful for searches around 100 MeV-20 GeV or so. Lepton-coupled physics is especially motivated; muon and tau identification can be very helpful!
- More particle pheno study is needed to understand the best things to look for at EIC!

Backup slides

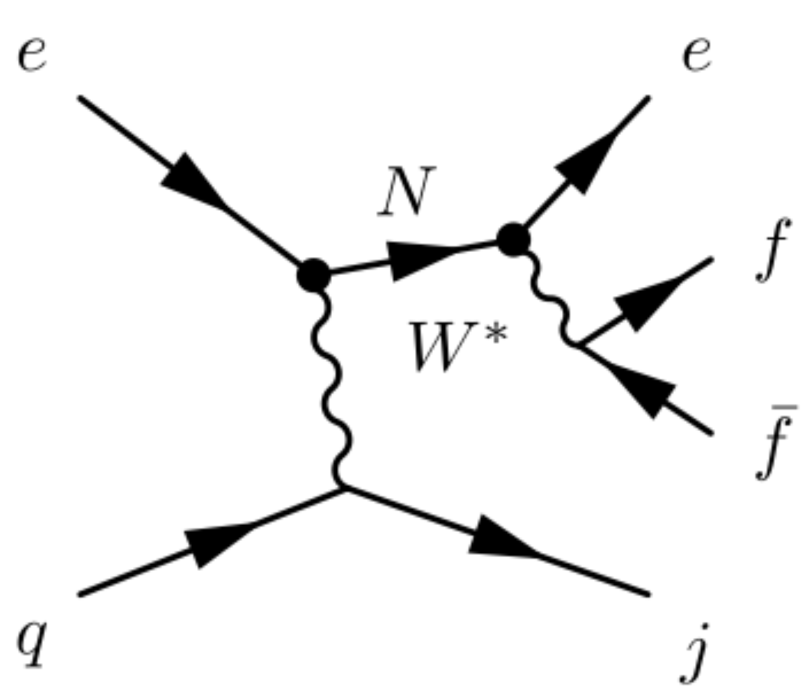
LFV beyond the SM

- 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…
- Many other searches e.g. for SMEFT or other indirect effects or effective operators (see e.g. arXiv:2102.06176), vs. direct production of BSM signals (new particles) as here.

Heavy neutral leptons

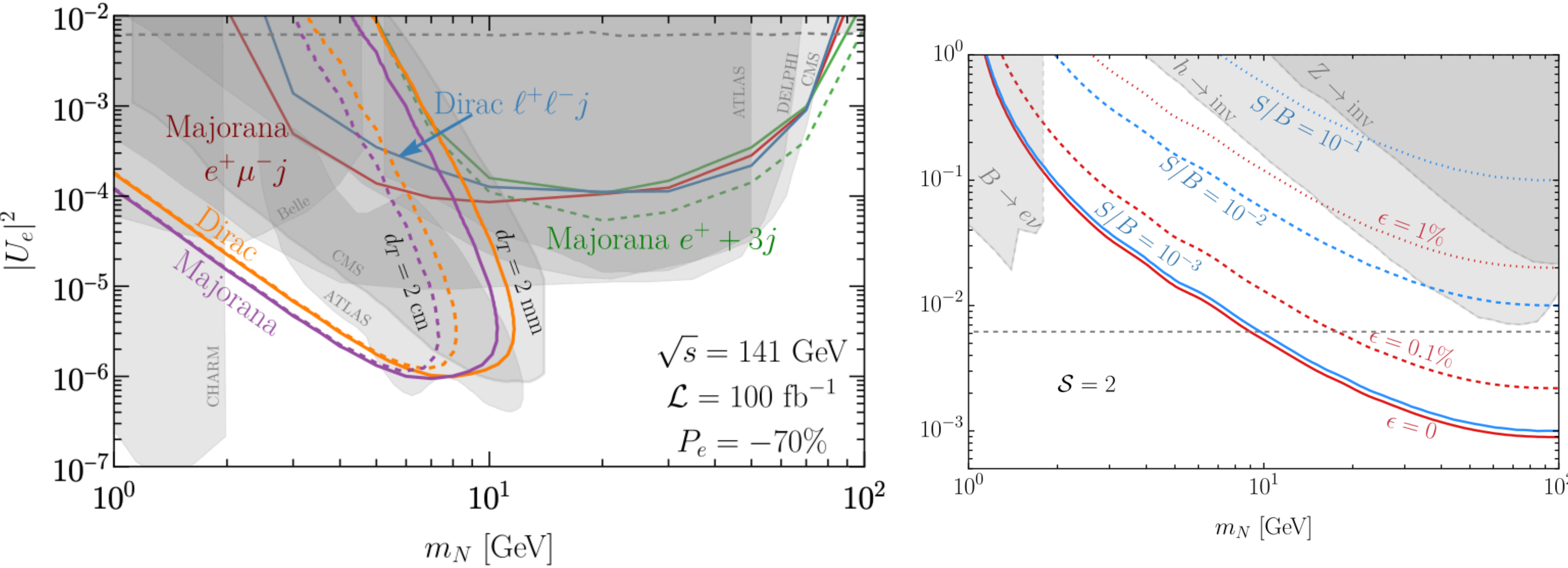
$$\mathcal{L} \supset \frac{g}{\sqrt{2}} U_{iI}\, W_\mu^-\, \ell_i^\dagger\, \overline{\sigma}^\mu N_I$$

$$+ \frac{g}{2\, c_W} U_{iI}\, Z_\mu\, \nu_i^\dagger\, \overline{\sigma}^\mu N_I + \mathrm{H.c.}$$



- *(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.

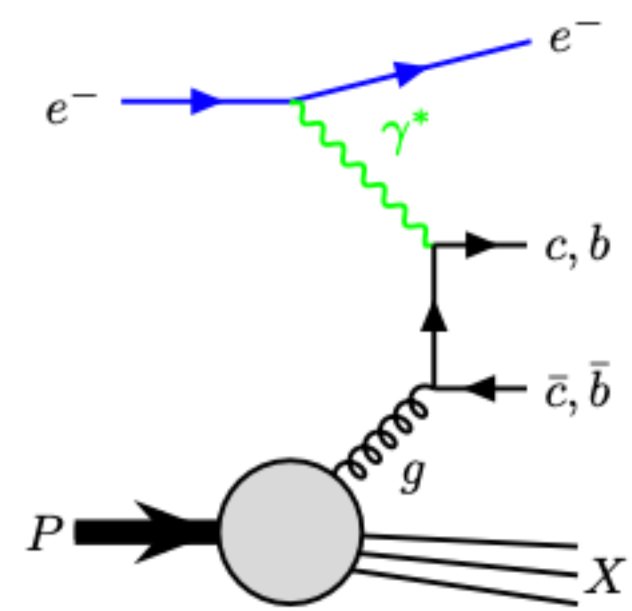
(Batell, Ghosh, Han, Xie, **arXiv:2210.09287**)



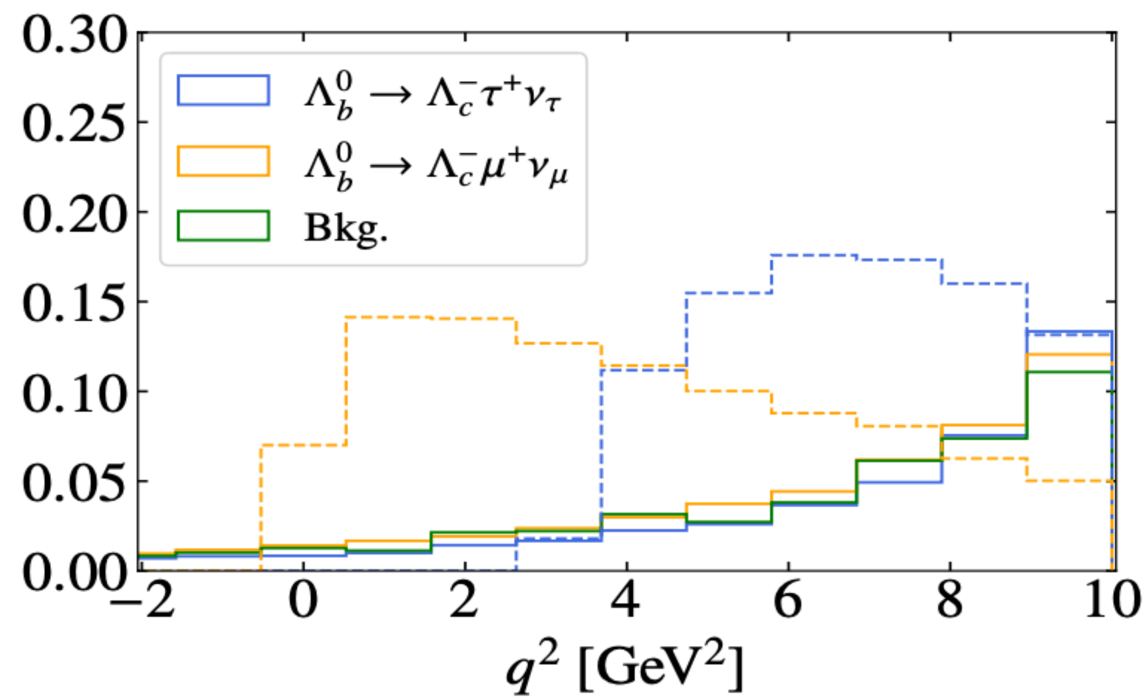
- Summary of projected reach for electron-coupling dominated case shown above. Little additional parameter space vs. other experiments in this case, but EIC still complementary. Monojet (N —> invis) can do somewhat better depending on systematics.
- Muon detection (w/muon chamber) was assumed for relevant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



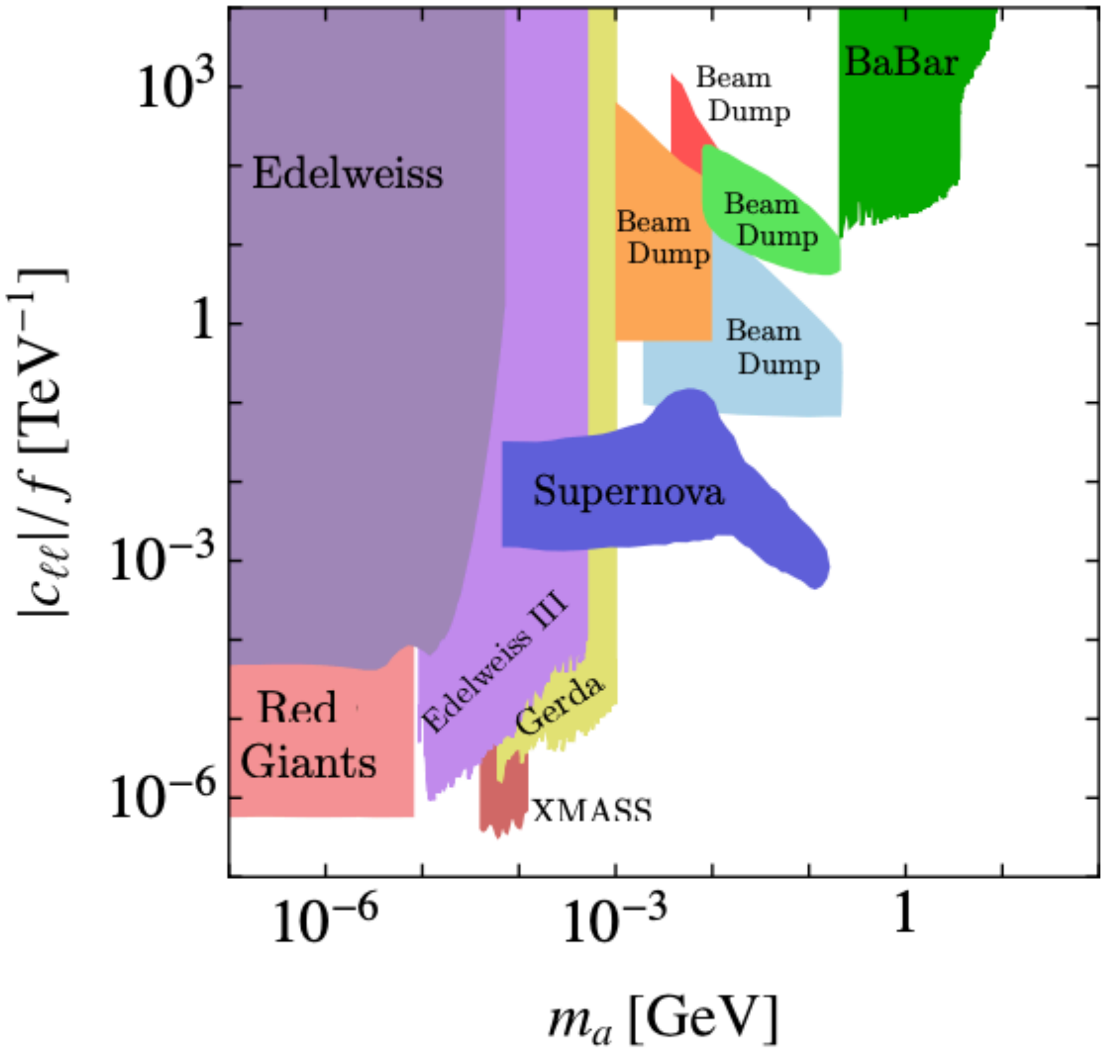
- B hadron production rates are lower vs. other expts, but clean environment + easy to make B baryons. Also, *beam polarization* at EIC provides a unique handle.

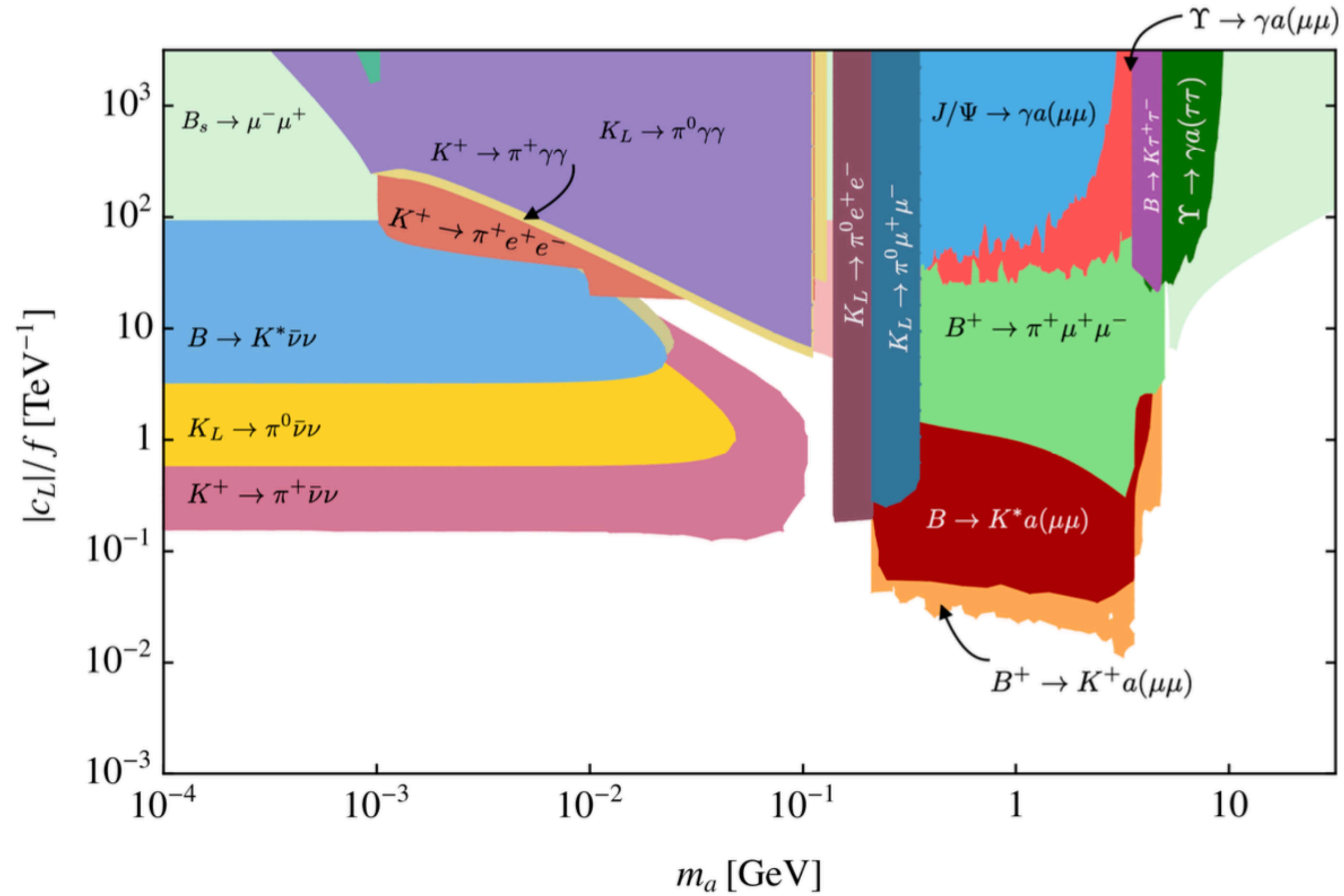


- Λ_b baryons are especially promising for EIC; can achieve comparable precision to LHCb upgrade in testing LF universality in decay (μ vs τ.) Muon or tau tagging are particularly desirable features!

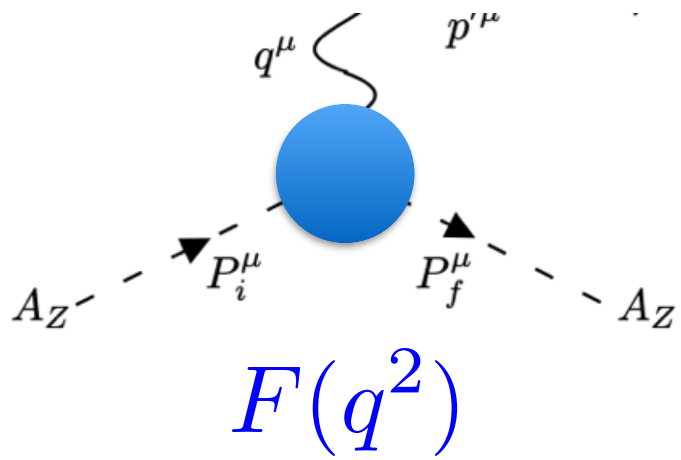
Overview of existing limits

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



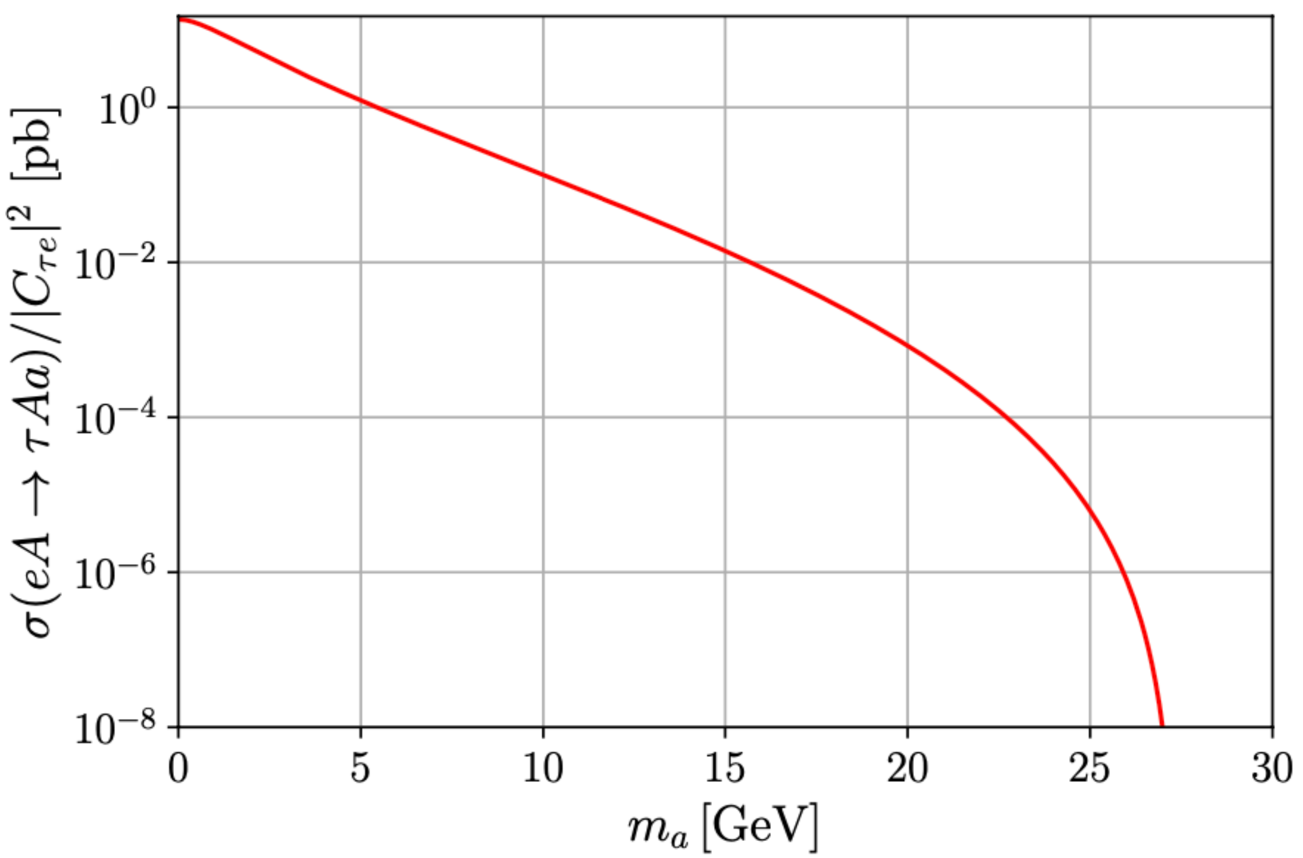


- <u>Lepton-diagonal couplings:</u> (*left*) strong astrophysical bounds at ma < 10^{-3} GeV; beam dumps below 1 GeV. (*right*) flavor-physics bounds effective above C_{ll} ~ 0.1/(1 TeV), but more model-dependent (assumes equal coupling to all LH lepton doublets.)



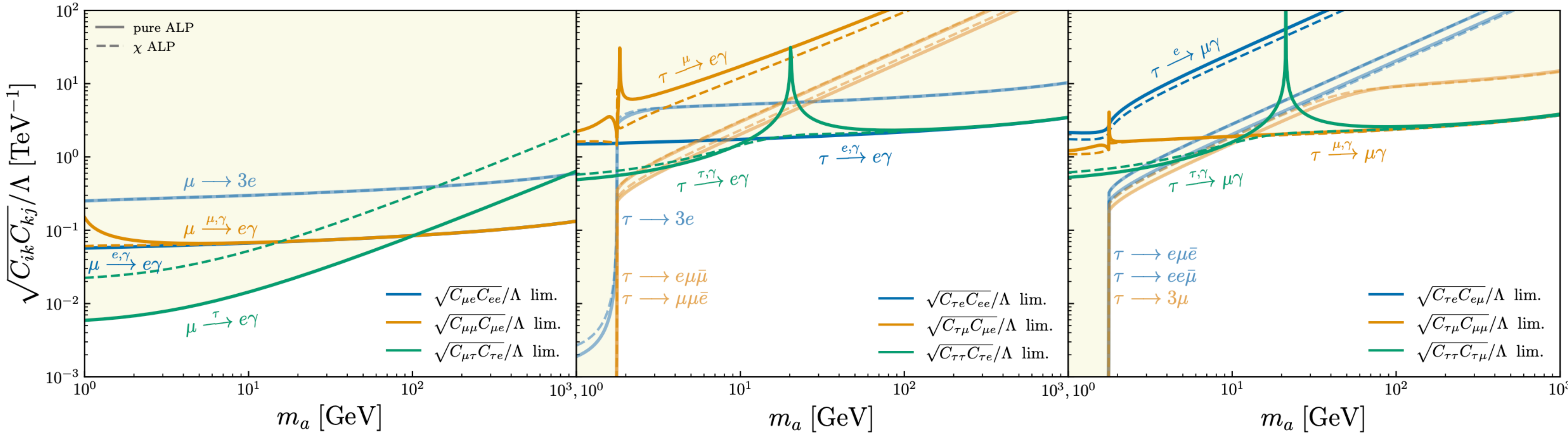
$$F(q^2) = \frac{3}{q^3 R_A^3} \left(\sin qR_A - qR_A \cos qR_A\right) \frac{1}{1 + a_0^2 q^2}$$

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



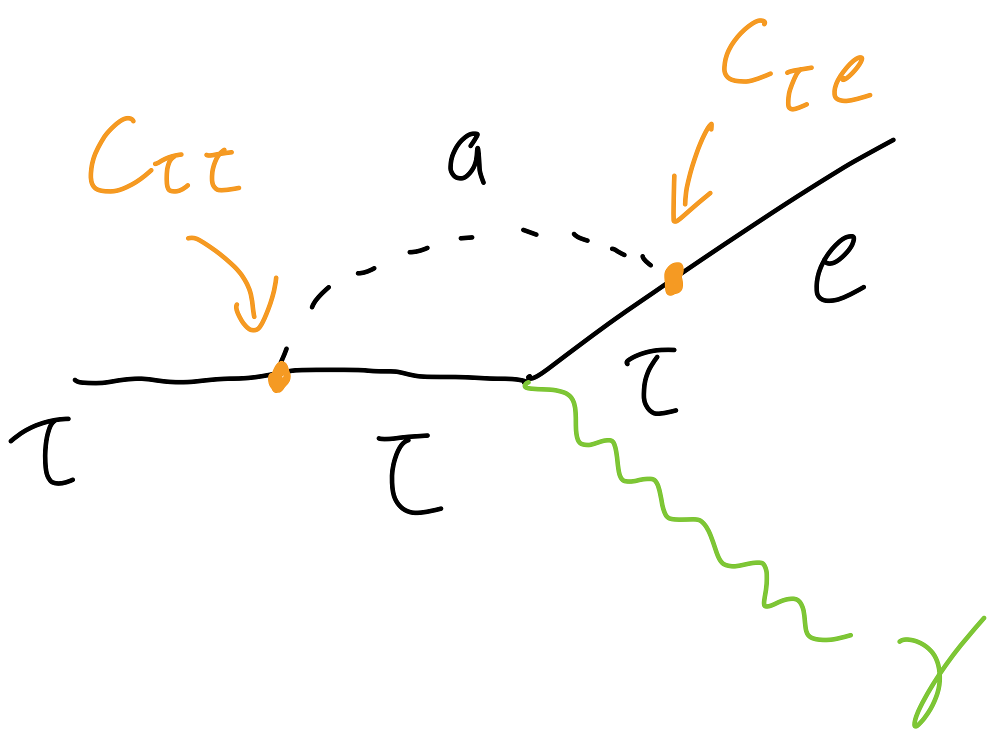
- The form factor suppression is active for m_a > 20 GeV or so (left.)
- We also impose a hard cutoff **$q^2 < (100\ \text{MeV})^2$**, to avoid nuclear breakup; this corresponds to m_a < 27 GeV. (Form factor suppression already large.)

(from R. Marcarelli, PhD thesis work)



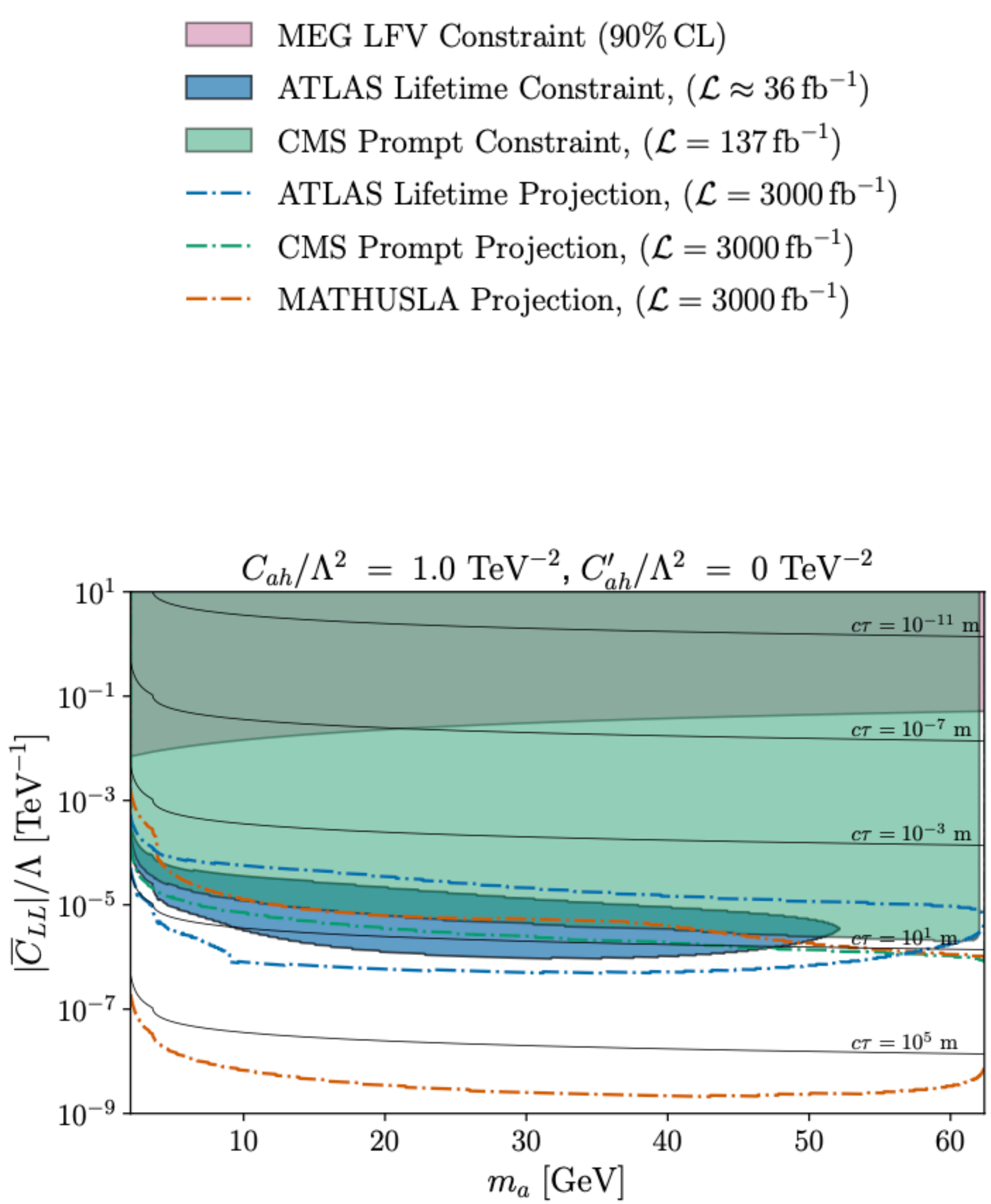
- Plot of bounds from low-energy decays of FV ALPs, above 1 GeV mass.
- Bounds all require at least two couplings at once (usually one flavor-preserving, which can be naturally suppressed for ALPs depending on chirality.)

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 $m_a > m_\tau$.

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.

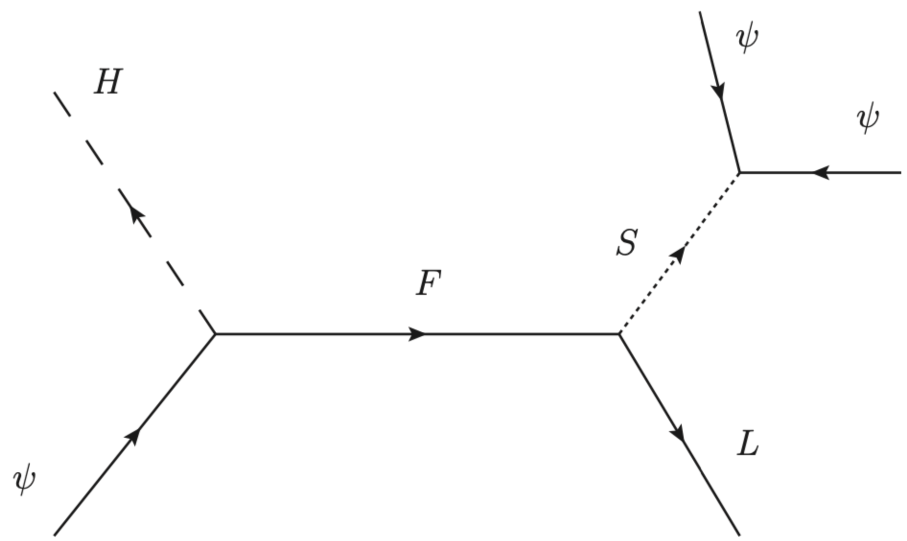
(Davoudiasl, Giardino, Neil, and Rinaldi, arXiv:1709.01082)

Example chiral ALP model

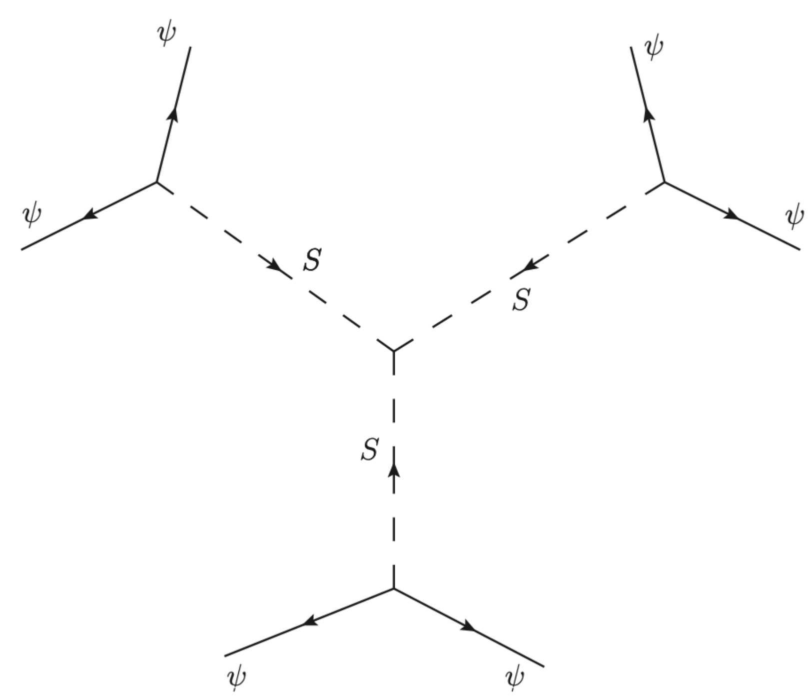
- UV-complete model for neutrino mass + composite dark sector.

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

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



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



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

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.

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

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

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.

- 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.