Probing LFV, PV ALPs at the Forward Physics Facility and a Future Muon Collider

Roman Marcarelli

B. Batell, H. Davoudiasl, E. Neil, S. Trojanowski

arXiv:2403.?????

7th Annual FPF Workshop

Brookhaven National Laboratory

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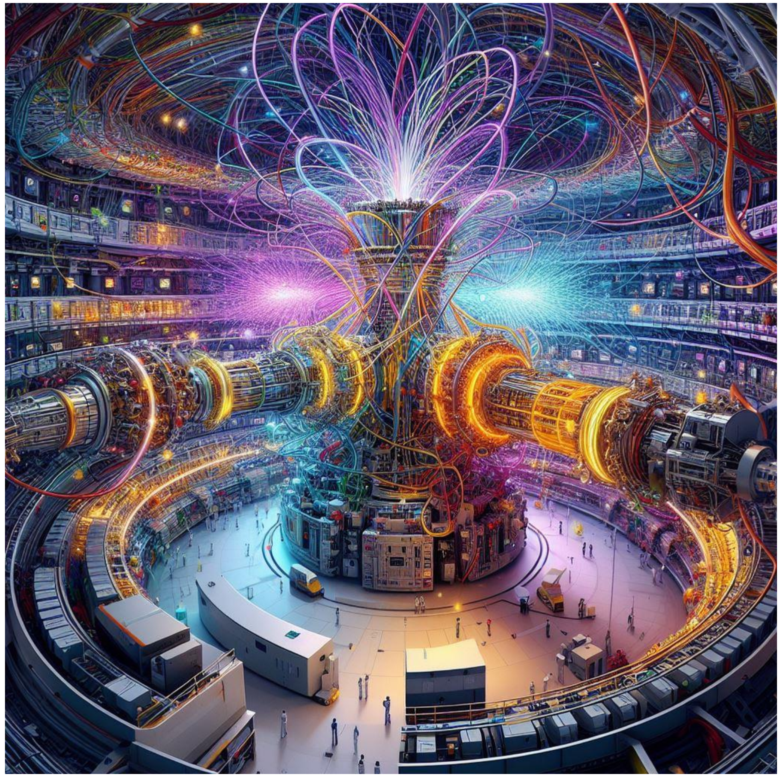

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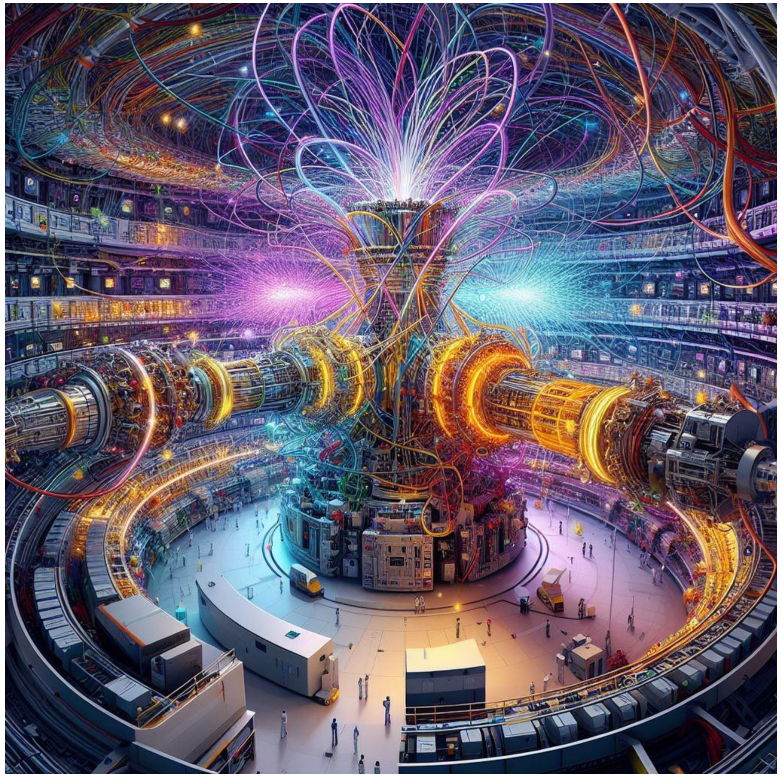

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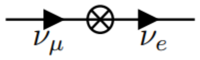

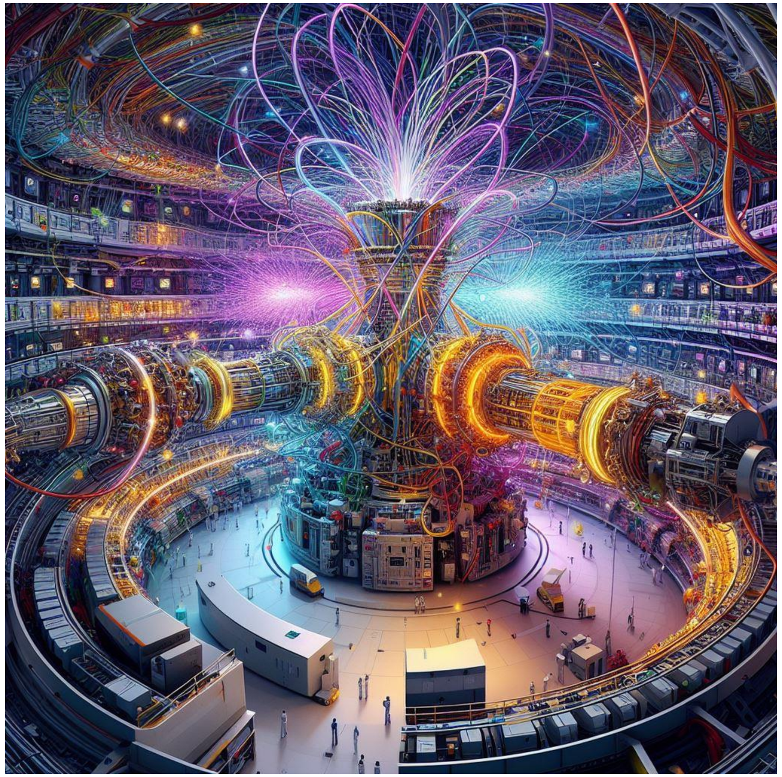

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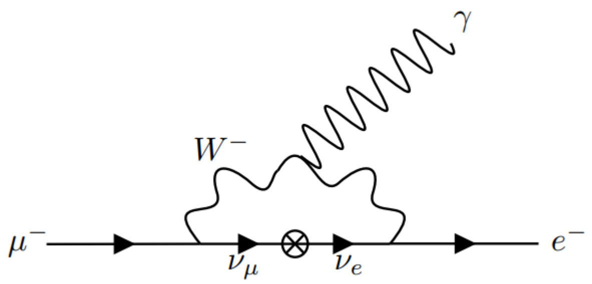

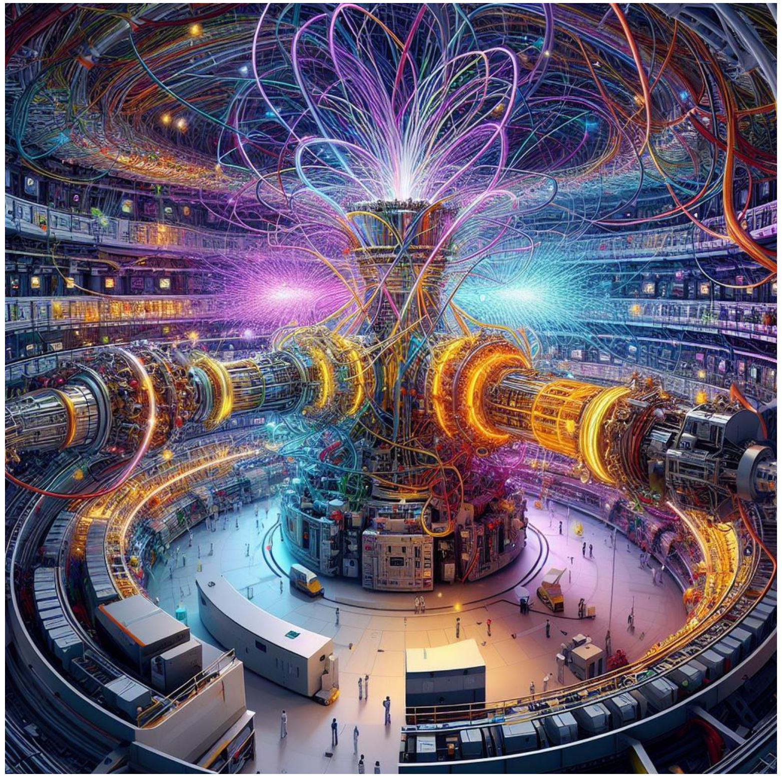

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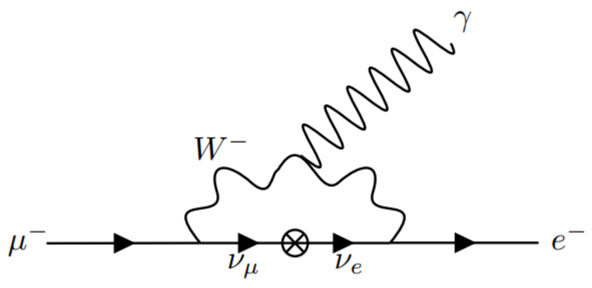

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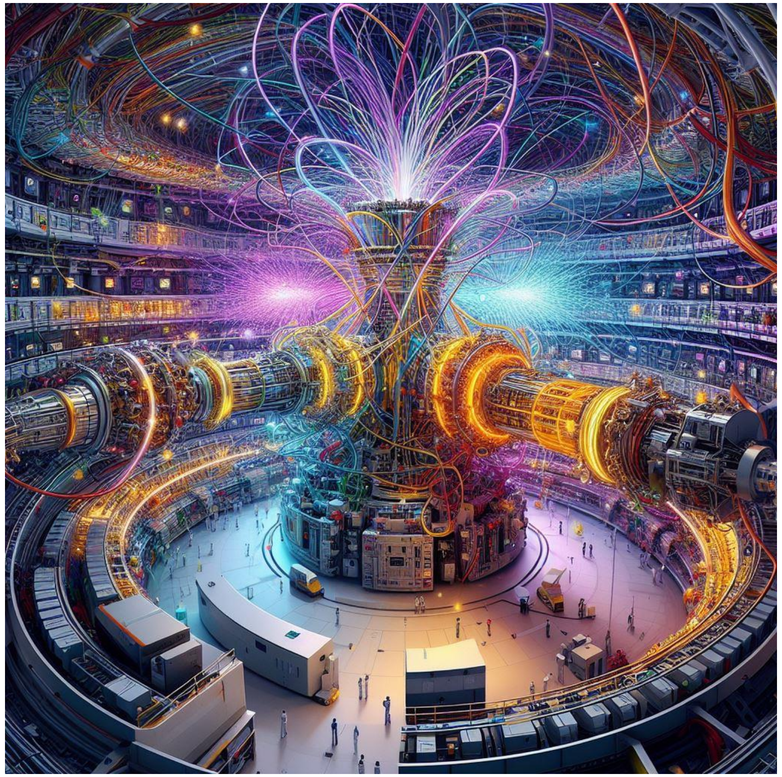

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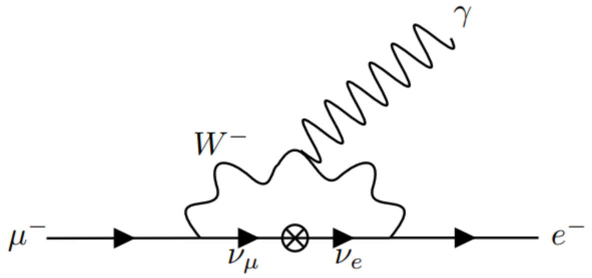

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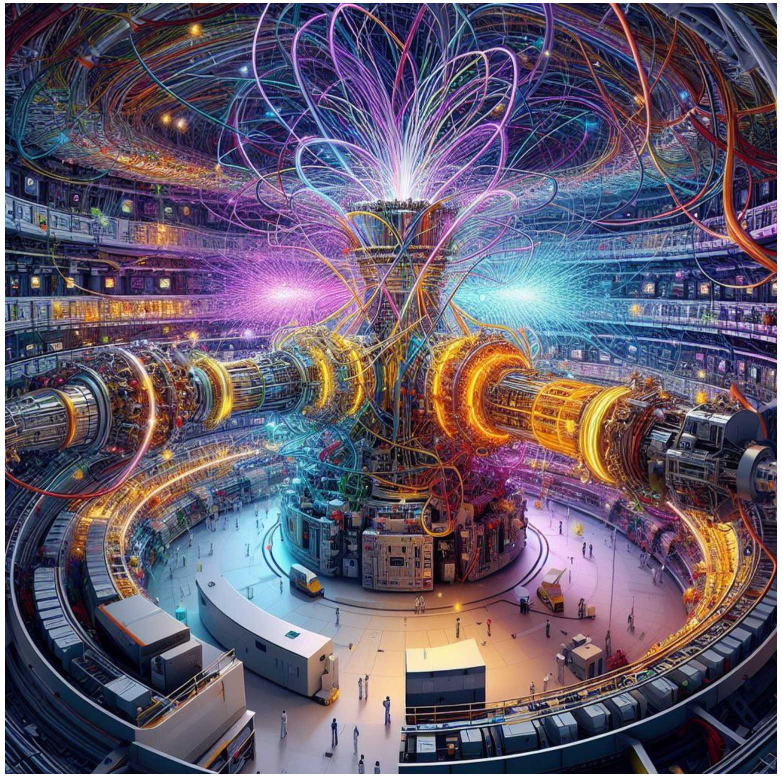

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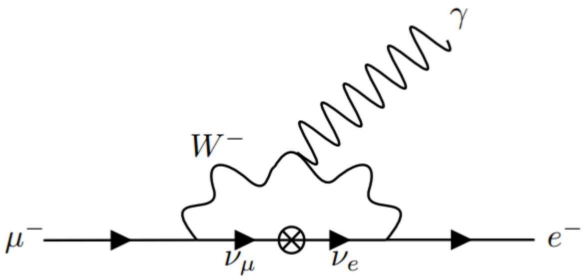

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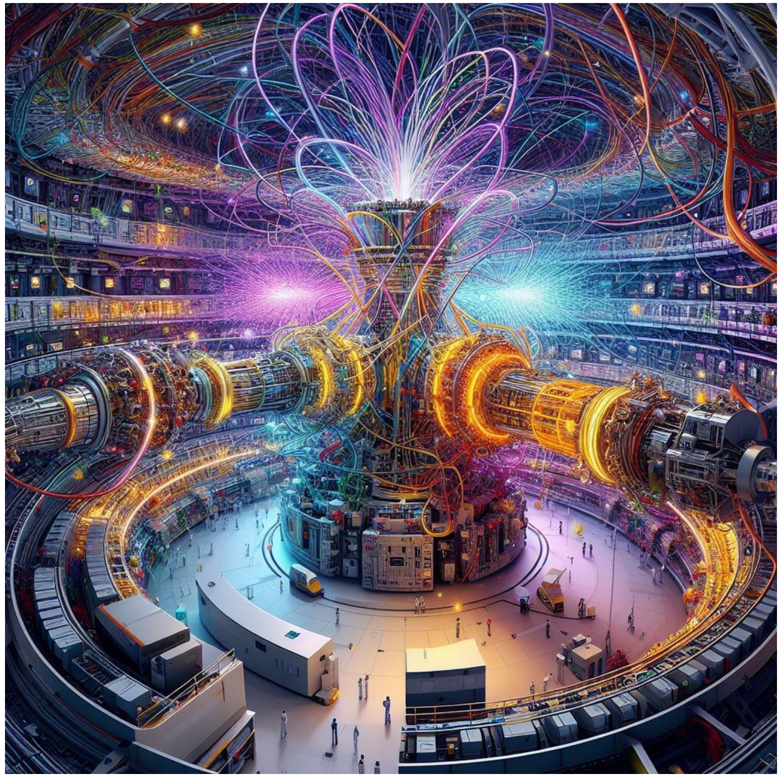

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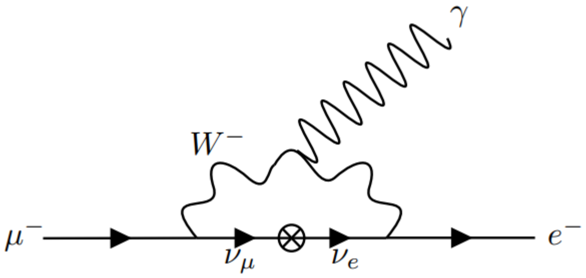
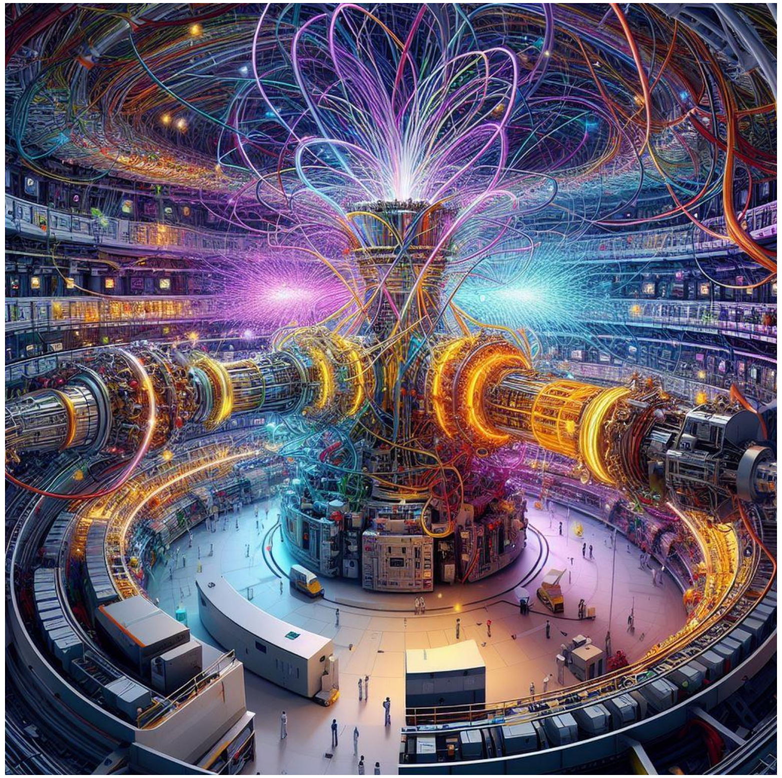


$$\sim \left(\frac{eg^2}{32\pi^2}\frac{m_\nu}{m_W}\right)^2$$

- PV: Parity-Violating
- ALP: Axion-like Particle
  - Pseudo-Nambu Goldstone modes of a spontaneously broken approximate global symmetry.
  - For our purposes: has derivative coupling to fermions
  - QCD Axion, Pion



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The Model:

- ALP Effective Lagrangian:

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu a\right)^2 - \frac{1}{2} m_a^2 a^2 + \frac{\partial_\mu a}{\Lambda} \sum_{f,f'} \bar{f} \gamma^\mu \left(V_{ff'} - A_{ff'} \gamma^5\right) f' + \cdots$$

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- Lepton sector:

$$\mathcal{L}_\ell = \frac{\partial_\mu a}{\Lambda}\sum_{\ell,\ell'} \bar{\ell}\gamma^\mu(V_{\ell\ell'} - A_{\ell\ell'}\gamma^5)\,\ell'$$

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- Lepton sector (equations of motion):

$$\mathcal{L}_\ell = \frac{a}{\Lambda} \sum_{\ell,\ell'} \bar{\ell} \left((m_\ell - m_{\ell'}) V_{\ell\ell'} - (m_\ell + m_{\ell'}) A_{\ell\ell'} \gamma^5 \right) \ell'$$

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- Two take-aways:
  - Vector current coupling vanishes for $\ell = \ell'$ ($\ell \to \ell e^{-iV_{\ell\ell}a/\Lambda}$)
  - Mass hierarchy in coupling: focus on τ

The Model:

- ALP-τ sector:

$$\mathcal{L}_{\tau\ell} \approx \frac{\partial_\mu a}{\Lambda}\left[C_{\tau\tau}\,\bar{\tau}\gamma^\mu\gamma^5\tau + \sum_{\ell=e,\mu}\bar{\ell}\gamma^\mu(V_{\ell\tau} - A_{\ell\tau}\gamma^5)\,\tau\right] + H.c.$$

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- Focus on $C_{\tau\mu}$

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- ALP- “dark-fermion” sector:

$$\mathcal{L}_\chi = \frac{\partial_\mu a}{\Lambda}\,C_{\chi\chi}\bar{\chi}\gamma^\mu\gamma^5\chi$$

- Under the right conditions, χ can be a candidate for dark matter
- If $m_a > m_\tau + m_\ell, 2m_\chi$, can decay $a \to \ell\tau$, $a \to \chi\chi$

Contribution to $(g-2)_\mu$

- Currently: Outstanding anomaly between theory and experiment for $(g-2)_\mu$
  - Fermilab + Brookhaven:

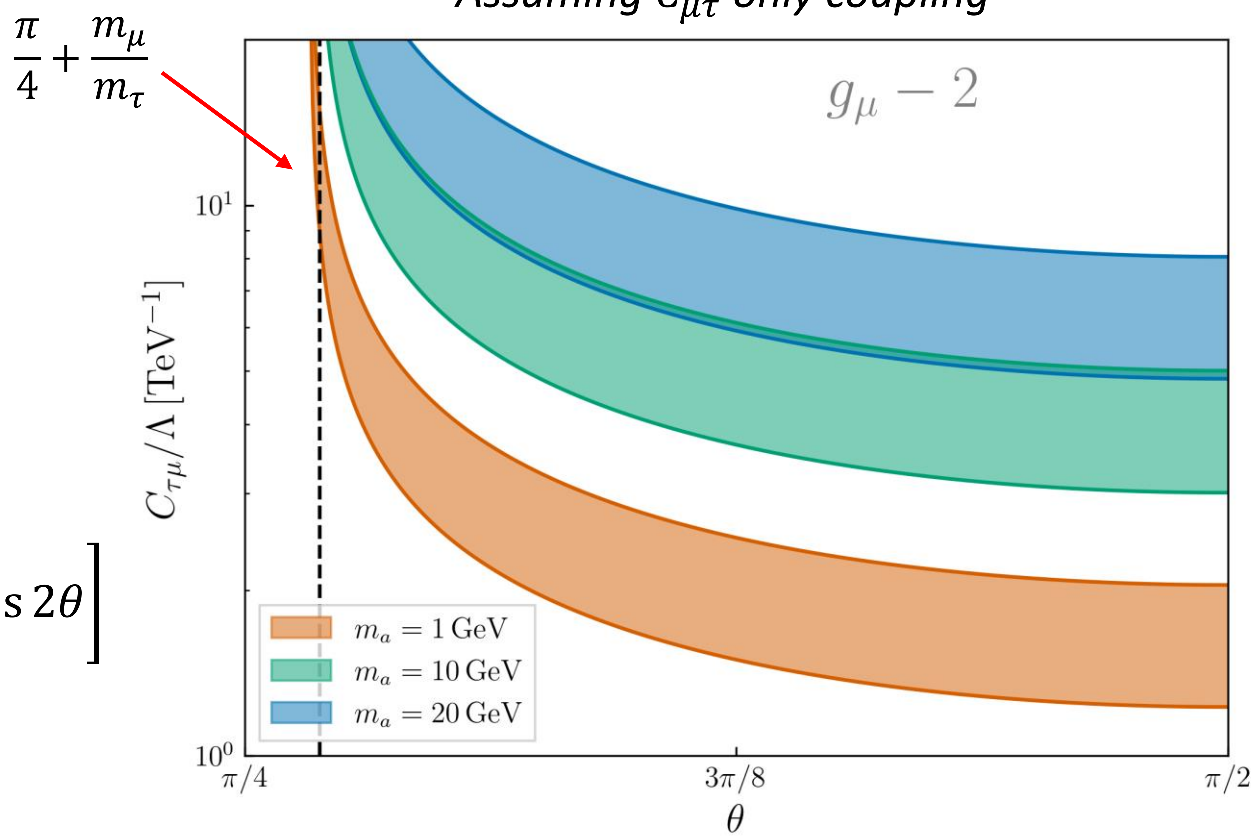
$$\Delta a_\mu = (249 \pm 48) \times 10^{-11}\ (5.1\sigma)$$

- In limit $m_\tau \gg m_\ell$

$$\Delta a_\ell = -\frac{m_\ell^2 C_{\ell\tau}^2}{16\pi^2\Lambda^2}\left[f(m_a^2/m_\tau^2) + \frac{m_\tau}{m_\ell} g(m_a^2/m_\tau^2)\cos 2\theta\right]$$

- Positive for $\theta \gtrsim \frac{\pi}{4} + \frac{m_\ell}{m_\tau}$

Assuming $C_{\mu\tau}$ only coupling

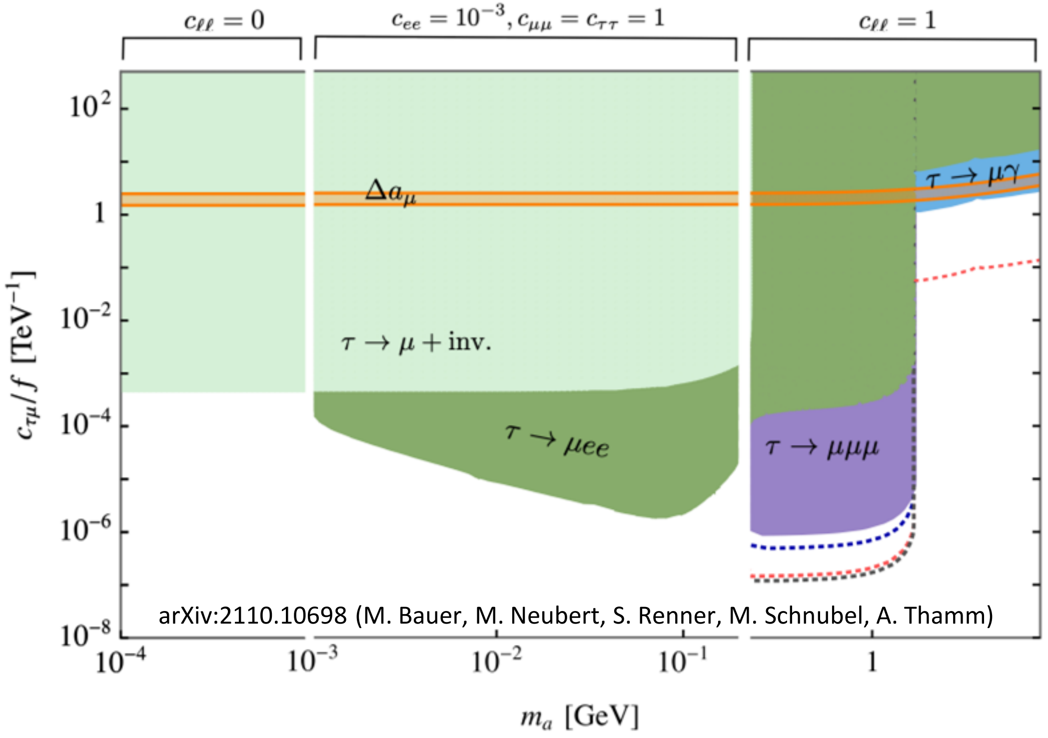


$$f(x) = \frac{2x^2\log x}{(x-1)^3} + \frac{1-3x}{(x-1)^2}$$

$$g(x) = \frac{2x^2(2x-1)\log x}{(x-1)^4} - \frac{5-19x+20x^2}{3(x-1)^2}$$

Existing Limits on LFV couplings

- Flavor-violating decays



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  - Weak for $m_a > m_\tau$
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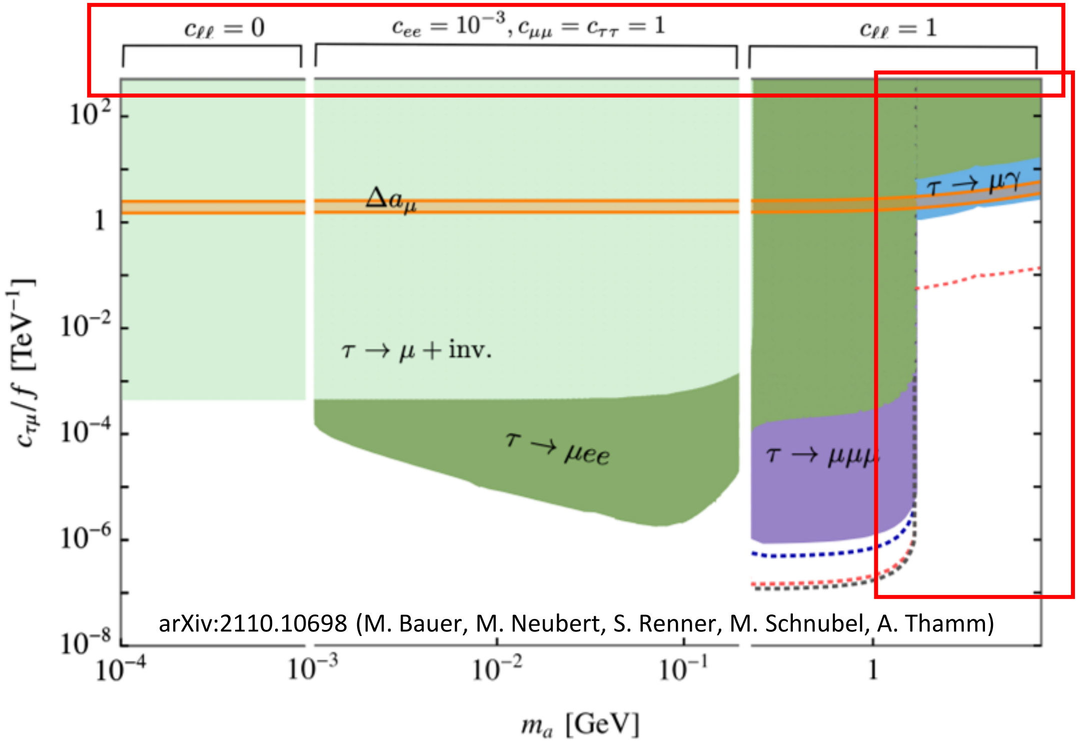

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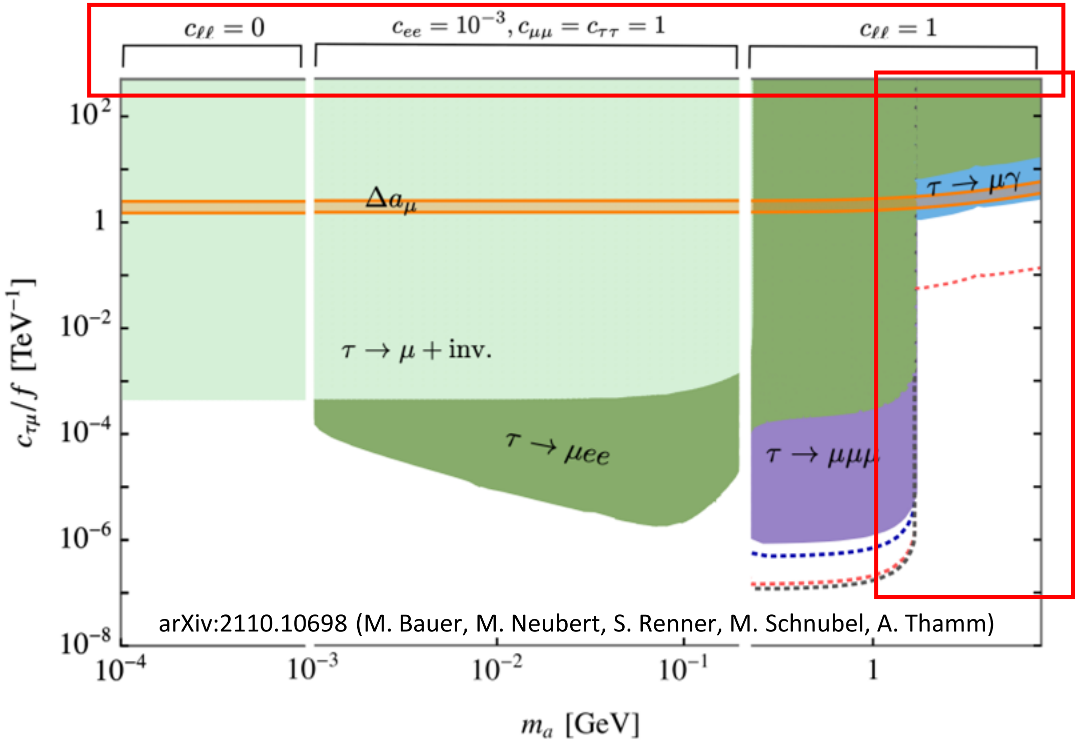

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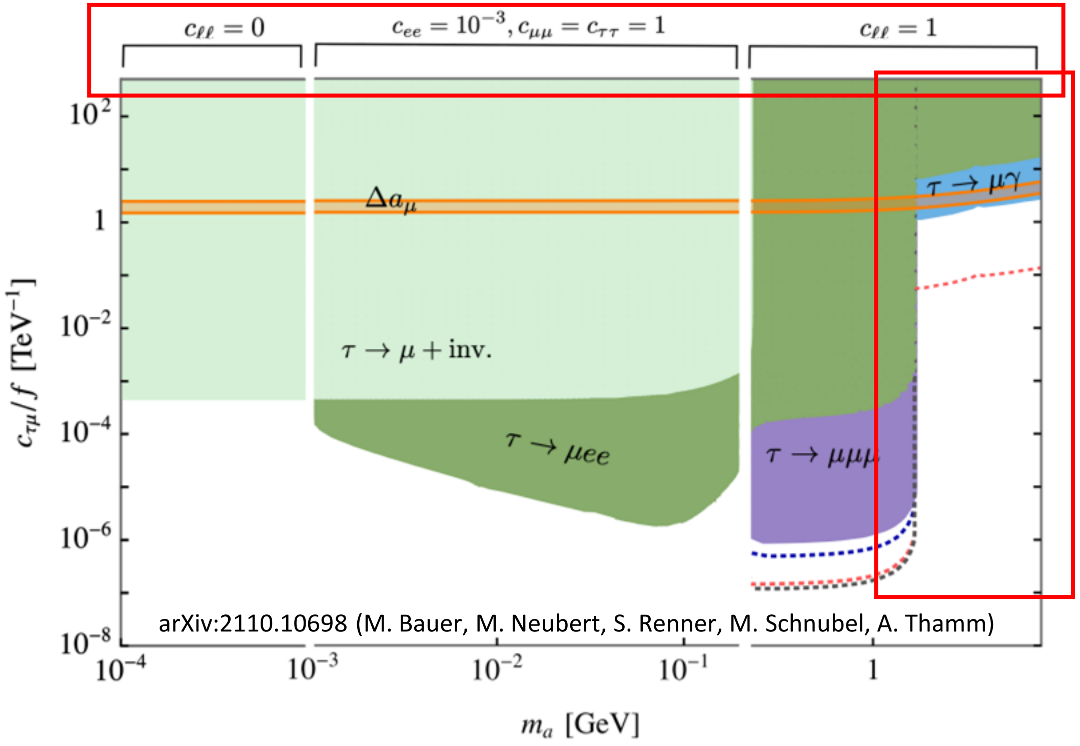

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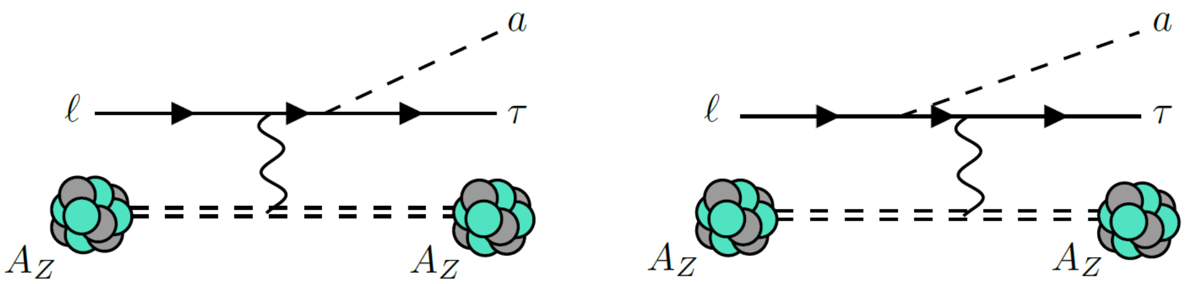

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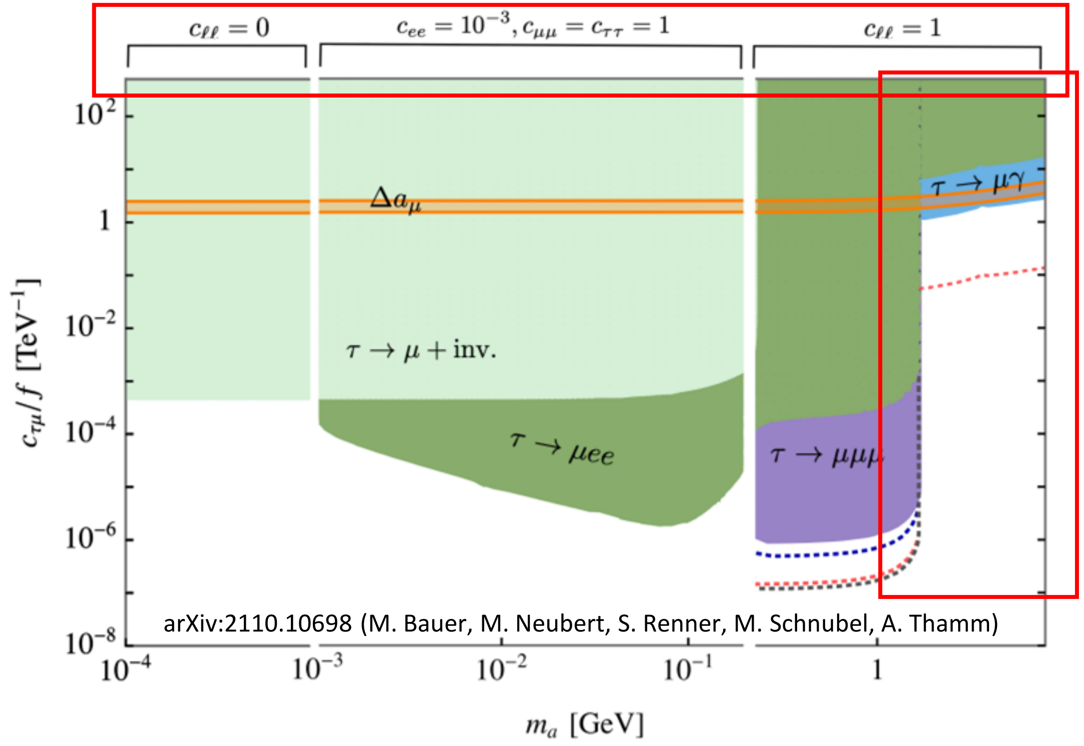

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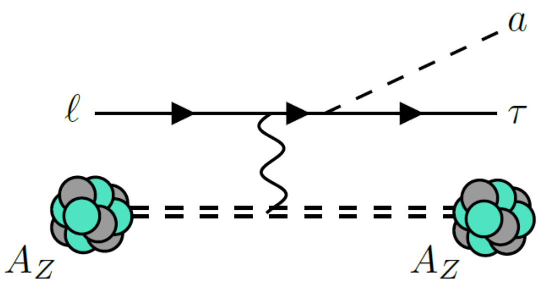

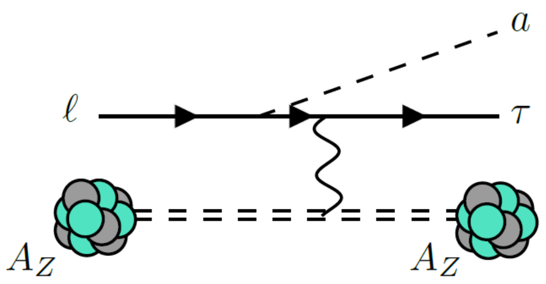

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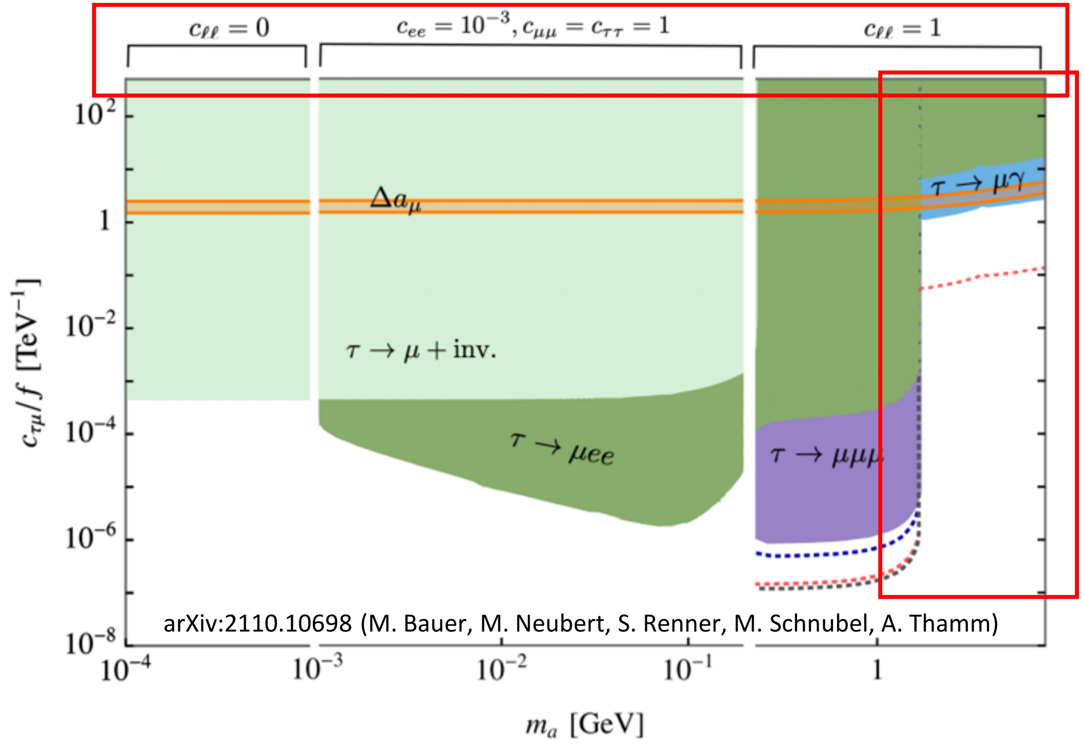

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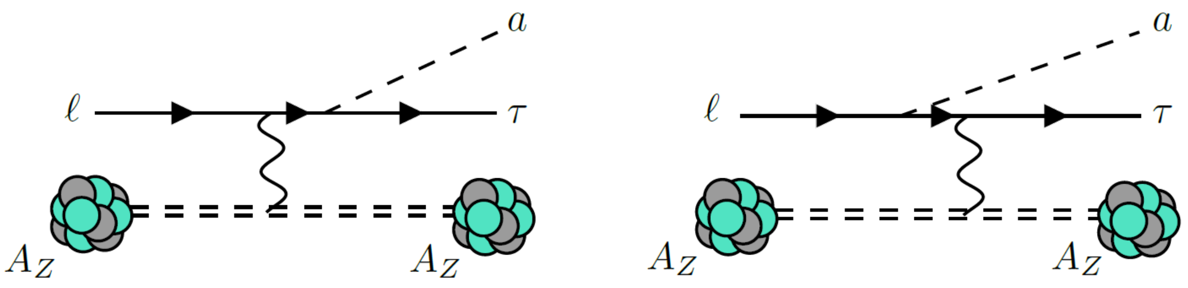

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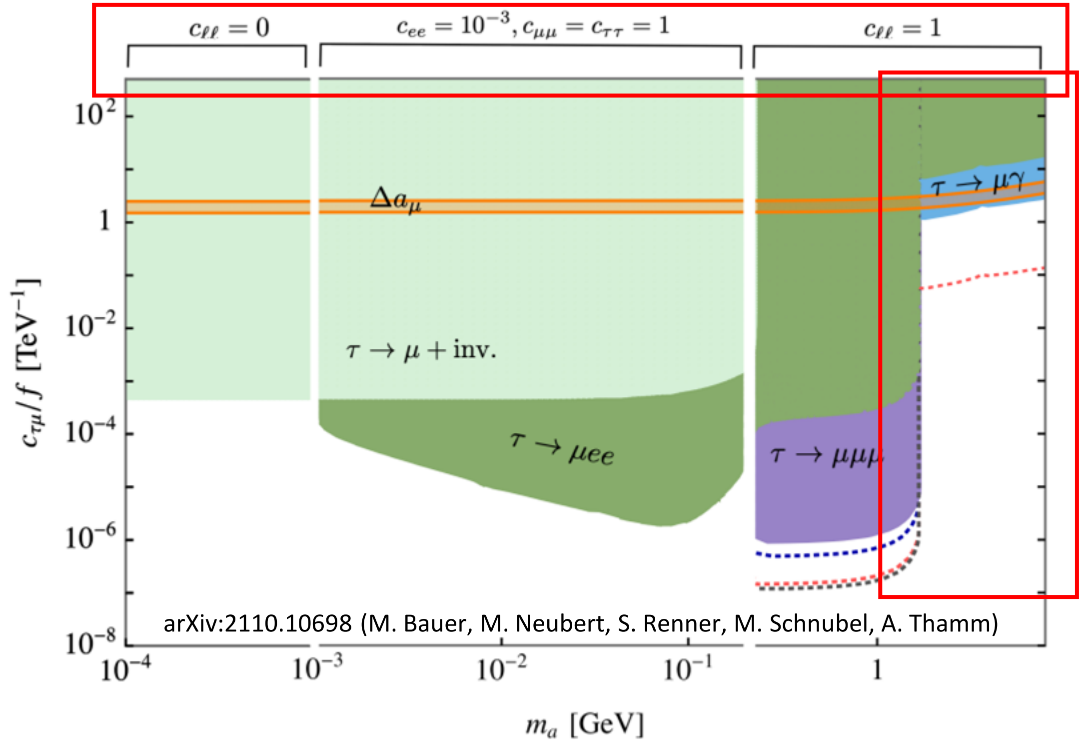

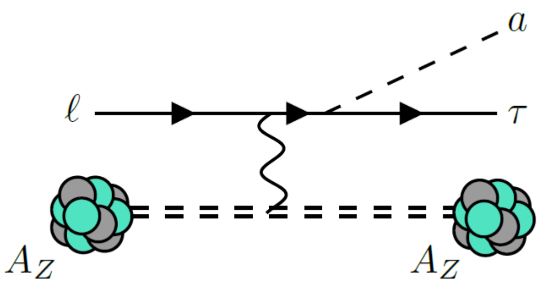

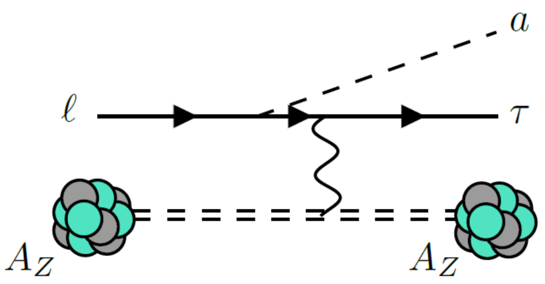

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  - $C_{\mu\tau}$:
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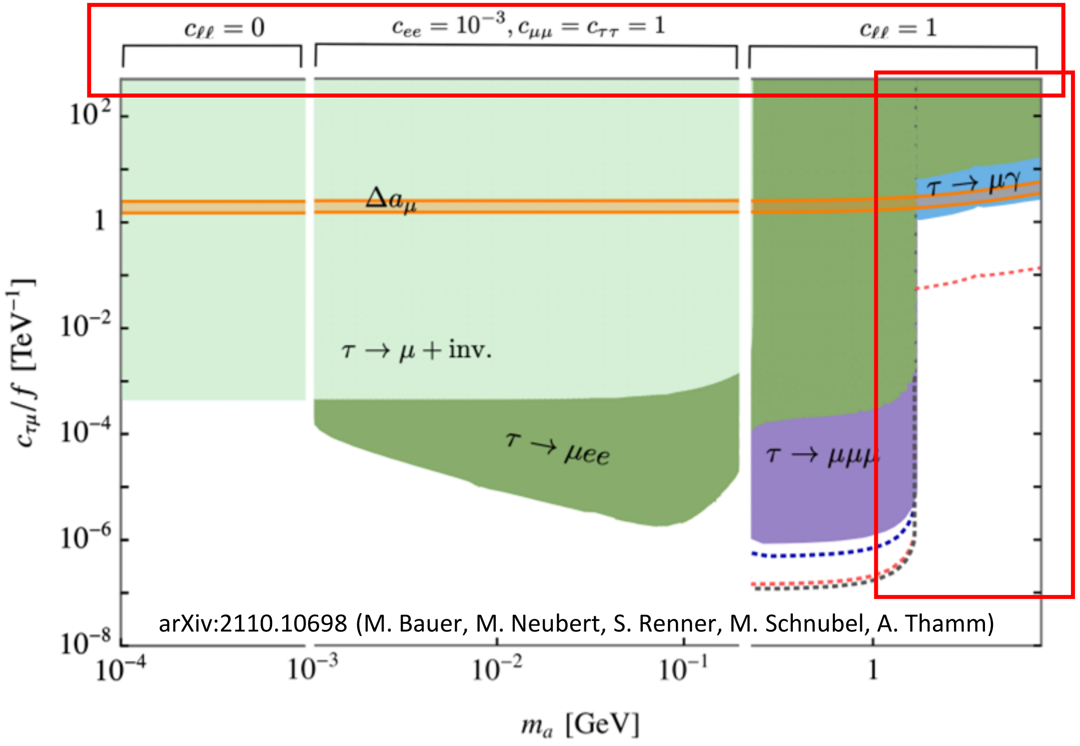

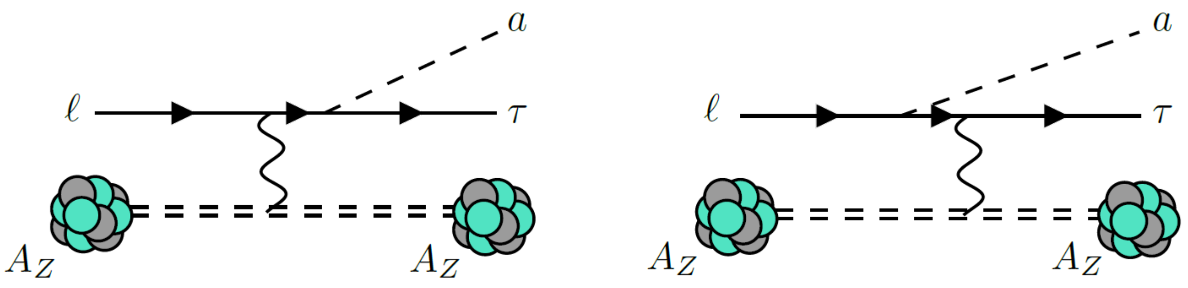

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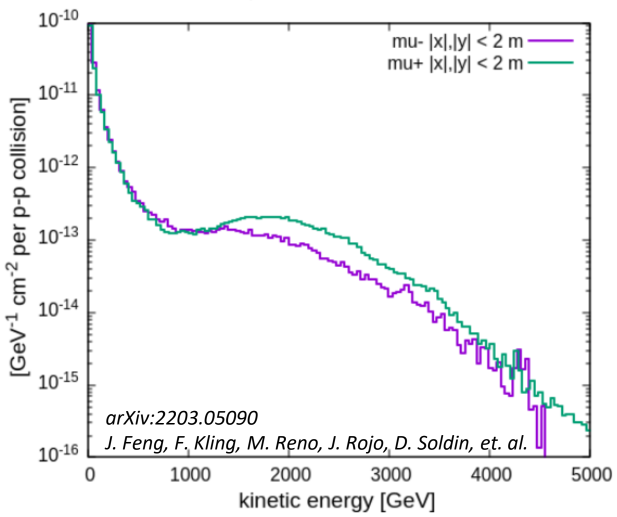
  - Energies from $10\ \mathrm{GeV}$ - $5\ \mathrm{TeV}$



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  - Thin lead plates
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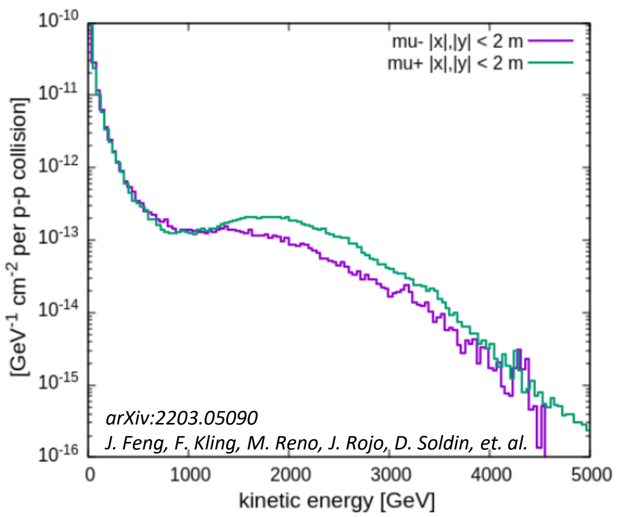
  - 20 tons of Tungsten (W) interspersed w/ emulsion layers



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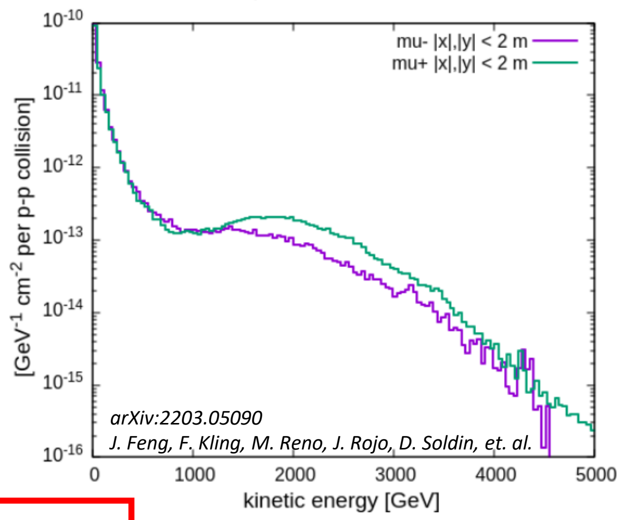

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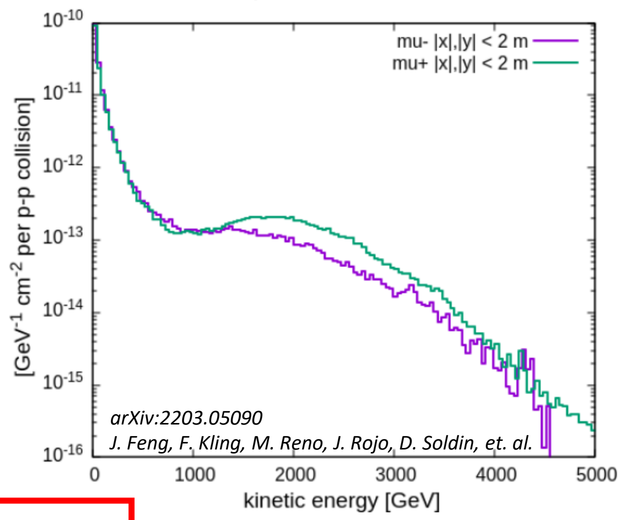

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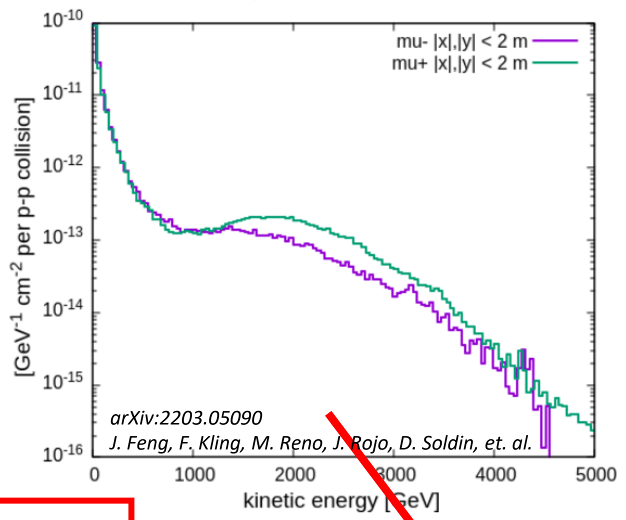
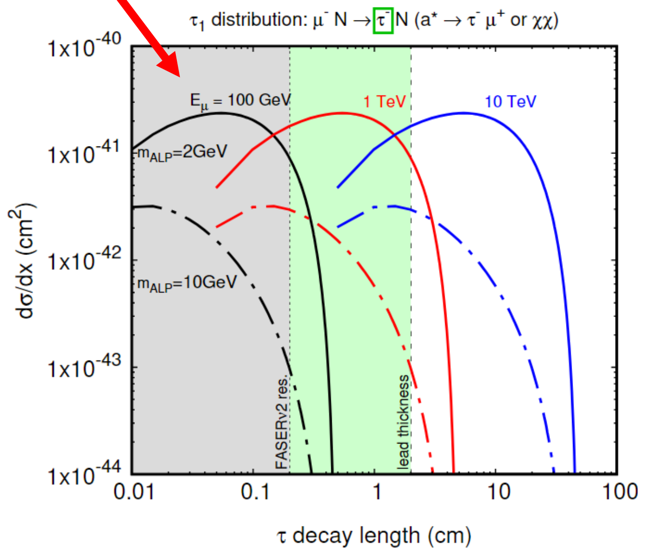
  - $\mu^- \mathrm{W} \to \tau^- \mathrm{W} a, (a \to \mu^+ \tau^-)$
    - No charge ID for f.s. leptons
    - SM background ($\mu^- \mathrm{W} \to \mu^- \mathrm{W} \tau^+ \tau^-$)
  - $\mu^- \mathrm{W} \to \tau^- \mathrm{W} a, (a \to \chi\bar{\chi})$
    - Require $\tau^- \to 3h$ or $\tau^- \to \mu^- \nu\nu$
      + 2mm τ^- track in emulsion detector

Signal at the Forward Physics Facility

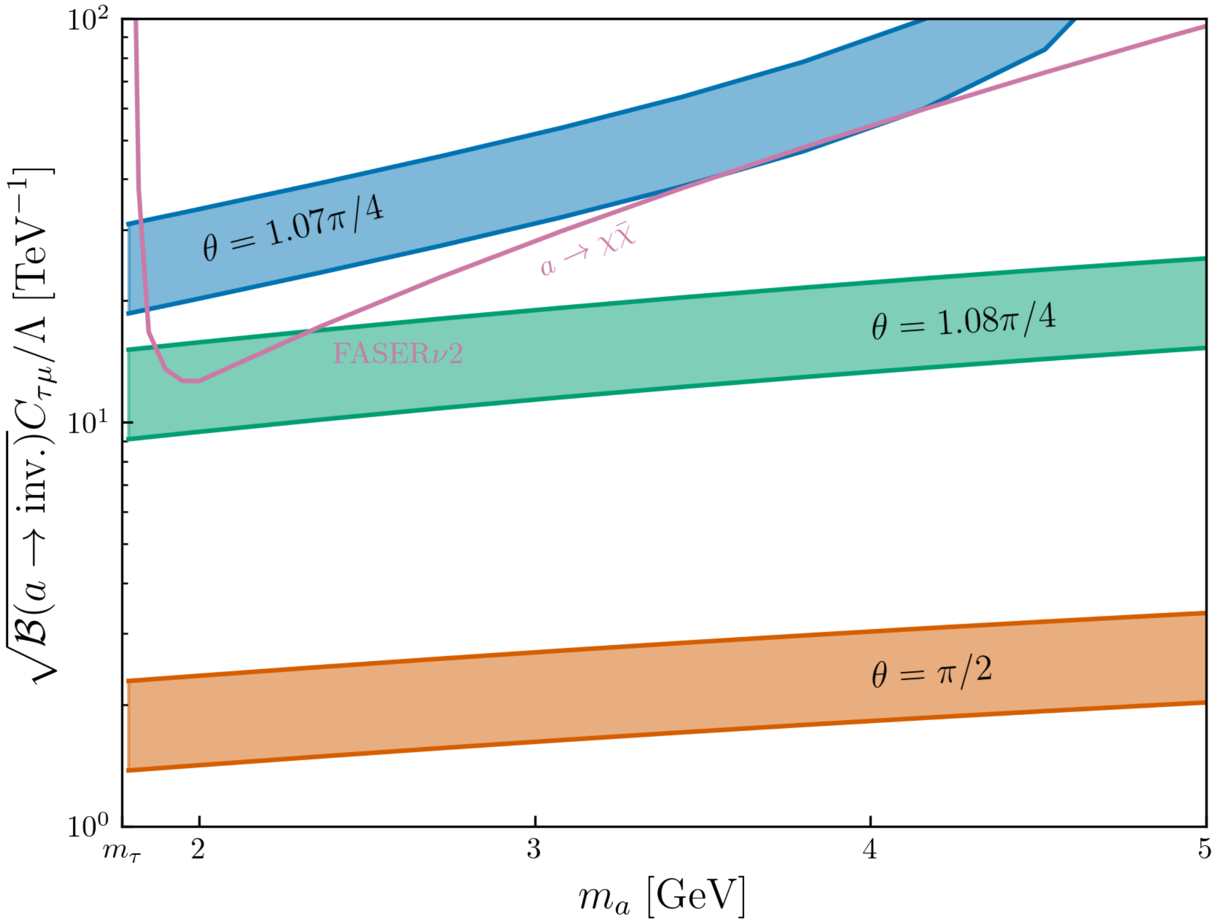
- FLUKA predictions:
  - Muons from ATLAS during HL-LHC
  - Energies from 10 GeV - 5 TeV
- FASER 2
  - Transverse size $1\text{m} \times 3\text{m}$ ($\sim$ few $\times 10^{14}$ muons)
  - Thin lead plates
- FASERν 2
  - Transverse size of $40\text{cm} \times 40\text{cm}$ ($\sim$ few $\times 10^{12}$ muons)
  - 20 tons of Tungsten (W) interspersed w/ emulsion layers
- Signal
  - $\mu^- \mathrm{W} \rightarrow \tau^- \mathrm{W} a, (a \rightarrow \mu^+ \tau^-)$
    - No charge ID for f.s. leptons
    - SM background ($\mu^- \mathrm{W} \rightarrow \mu^- \mathrm{W} \tau^+ \tau^-$)
  - $\mu^- \mathrm{W} \rightarrow \tau^- \mathrm{W} a, (a \rightarrow \chi \bar{\chi})$
    - Require $\tau^- \rightarrow 3h$ or $\tau^- \rightarrow \mu^- \nu \nu$
      + 2mm τ^- track in emulsion detector





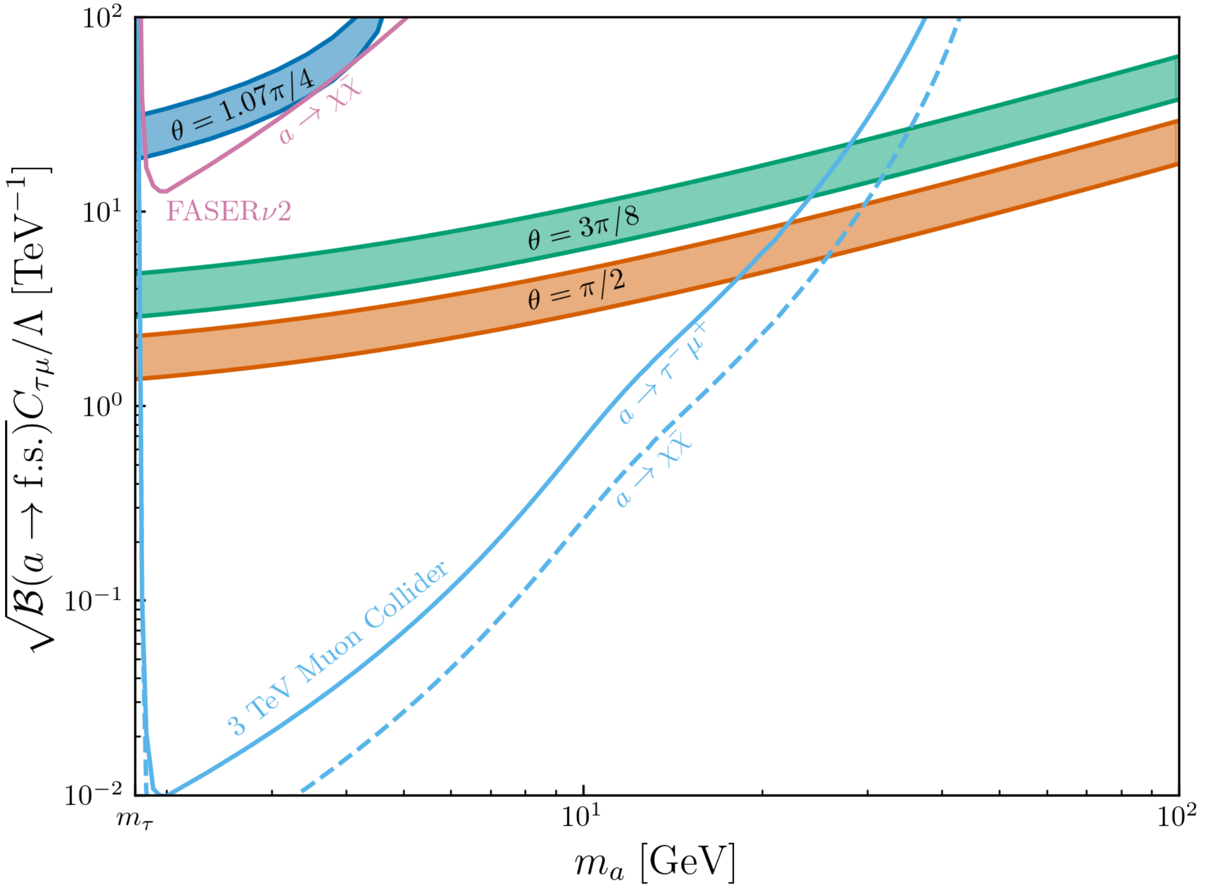
Limits from FASERν 2

- Assuming $a \to \chi\bar{\chi}$ is dominant
- Disclaimer: To be competitive, requires $C_{\tau\tau} < 10^{-2}$
- Probes explanation to muon $g-2$ anomaly in narrow range of angles
- Can be used as a pilot study for similar study at a Muon Collider



Looking Forward to a 3 TeV Muon Collider

- Consider muon thin target experiment
  - 2 cm lead (Pb) plate on beam axis
  - Assume $N_\mu = 10^{20}$ muons on target
- Signal
  - $\mu^- \mathrm{Pb} \to \tau^- \mathrm{Pb}\, a, (a \to \mu^+ \tau^-)$
    - Almost no background with charge ID
  - $\mu^- \mathrm{Pb} \to \tau^- \mathrm{Pb}\, a, (a \to \chi\chi)$
    - Almost no SM background
  - Require $\tau^- \to 3h$
- Explores large parameter space of couplings including all explanations to Δa_μ for $m_\tau < m_a < 30$ GeV



Takeaways/Concluding Remarks

- Forward-Physics Facility:
  - Flux of muons with up to 5 TeV of energy
  - Probes small region of LFV ALP parameter space
  - Potential improvements from more tau identification or higher-than-expected muon luminosity
  - Detector-environment similar to that of a Muon Collider fixed target experiment, can be used as a pilot study
  - More generically, could test viability of physics searches and inform experimental design for a future Muon Collider
- 3 TeV Muon Collider
  - Can fully probe model's explanation to muon g-2
  - Offers competitive constraints even in presence of on-diagonal couplings
  - Massive undertaking… hopefully we will see it in our lifetimes

Questions?

Phase/angle parameterization

- ALP-τ sector:

$$\mathcal{L}_{\tau\ell} = \frac{\partial_\mu a}{\Lambda}\left[C_{\tau\tau}\,\bar{\tau}\gamma^\mu\gamma^5\tau + \sum_{\ell=e,\mu}\bar{\ell}\gamma^\mu(V_{\ell\tau} - A_{\ell\tau}\gamma^5)\,\tau\right] + H.c.$$

- Useful to rewrite off-diagonal terms (assuming CP symmetry)

$$\bar{\ell}\gamma^\mu(V - A\gamma^5)\tau \longrightarrow C\bar{\ell}\gamma^\mu(\sin\theta - \cos\theta\,\gamma^5)\tau$$

where:

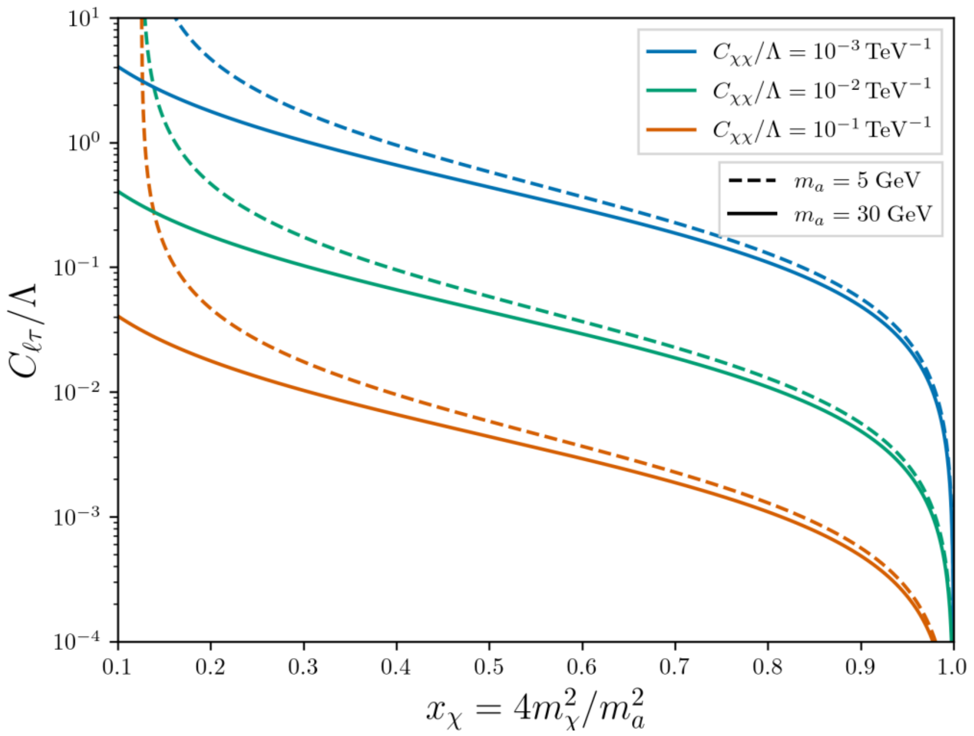
$$C = \sqrt{|A|^2 + |V|^2}$$ Magnitude of coupling

$$\theta = \tan^{-1}(|V|/|A|)$$ Parity-violating angle

Dark Matter

- If $m_\tau < m_\chi < 2m_a$, dark matter can annihilate to SM through $\chi\bar{\chi} \to a \to \ell^\pm \tau^\mp$
- Thermal averaged annihilation cross-section:

$$\langle \sigma v \rangle \sim \frac{C_{\ell\tau}^2 C_{\chi\chi}^2}{\Lambda^4} \frac{m_\tau^2 \left(4m_\chi^2 - m_\tau^2\right)^2}{\left(m_a^2 - 4m_\chi^2\right)^2} \sim 4.4 \times 10^{-26}\ \mathrm{cm^3 s^{-1}}$$

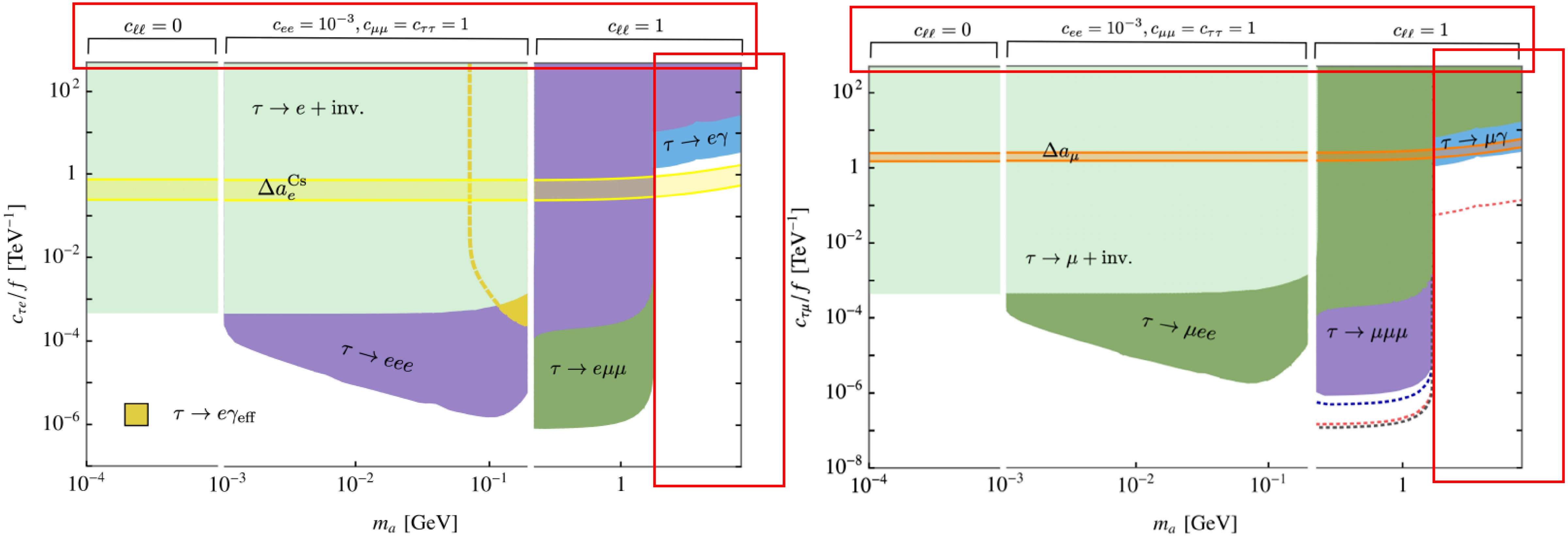


- Annihilation proceeds in s-wave
- If $m_\chi < 10$ GeV, constrained by CMB.
- Can still exist in an asymmetric dark matter scenario
- If $m_\chi > 2m_a$, dark matter mainly annihilates through $\chi\bar{\chi} \to aa$

$$\langle \sigma v \rangle \sim \frac{6}{x_{\mathrm{f.o.}}} \frac{C_{\chi\chi}^4}{24\pi} \frac{\left(m_\chi^2 - m_a^2\right)^2}{\left(2m_\chi^2 - m_a^2\right)^4} \left(1 - \frac{m_a^2}{m_\chi^2}\right)^{1/2}$$

- Annihilation proceeds in p-wave, no constraints from CMB

Existing Limits on LFV Couplings

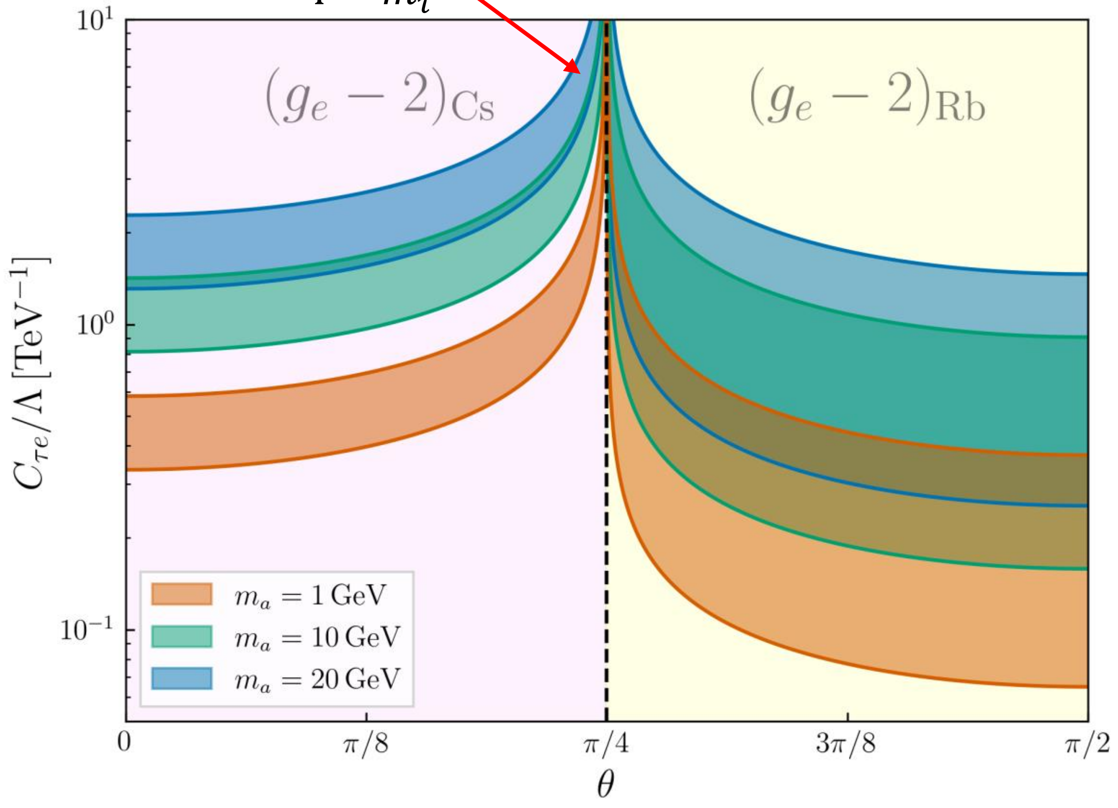


arXiv:2110.10698 (M. Bauer, M. Neubert, S. Renner, M. Schnubel, A. Thamm)

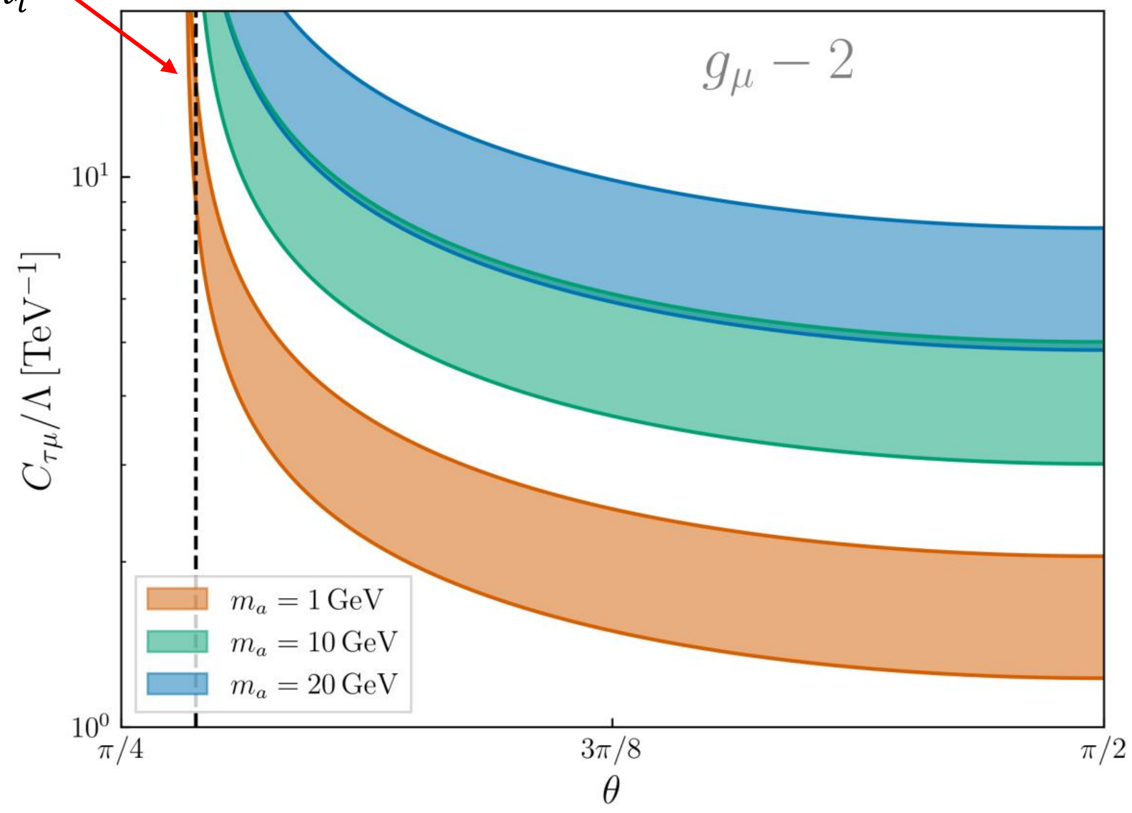
- Highly dependent on model parameters
  - As $C_{\ell\ell} \to 0$, $\tau \to \ell\gamma$ and , $\tau \to \ell\ell'$ very suppressed.
  - Weak for $m_a > m_\tau$
- Additional limits from Higgs decays (see arXiv:2105.05866 (R.M., H. Davoudiasl, E. Neil, N. Miesch))
- Can one probe $C_{\tau\ell}$ independent of other couplings?

Explanation for Δa_e and Δa_μ

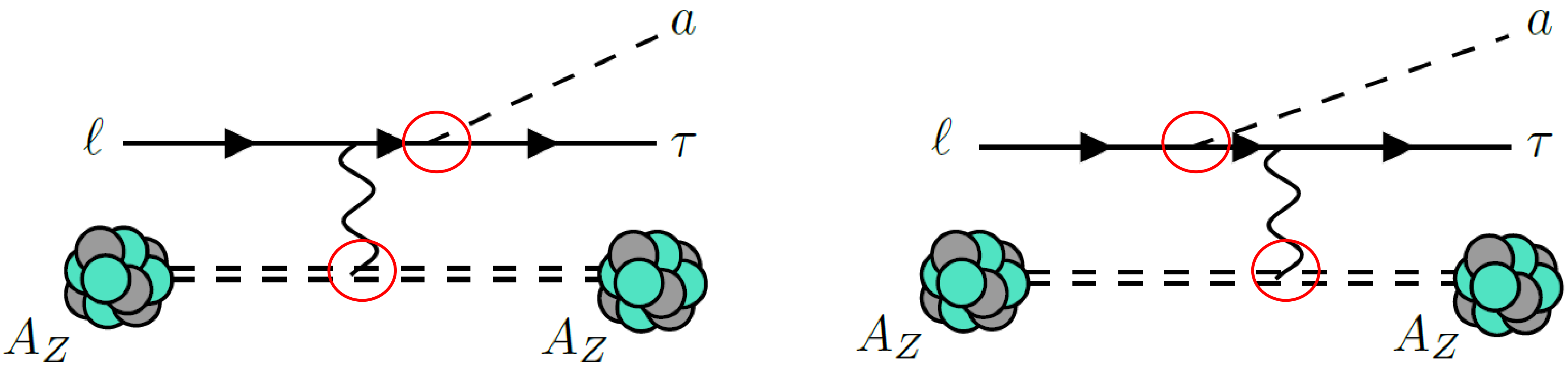
$\frac{\pi}{4} + \frac{m_e}{m_\tau}$



$\frac{\pi}{4} + \frac{m_\mu}{m_\tau}$



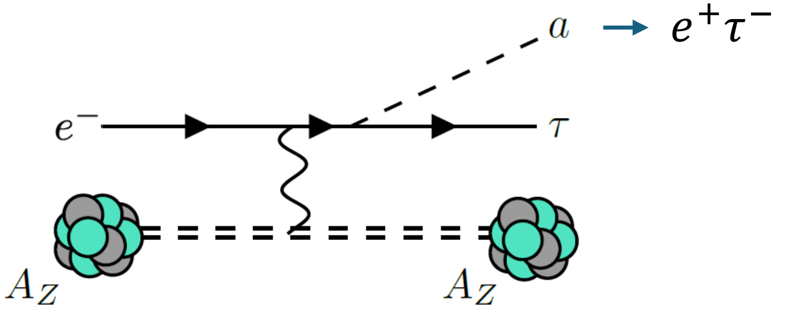
Production Process

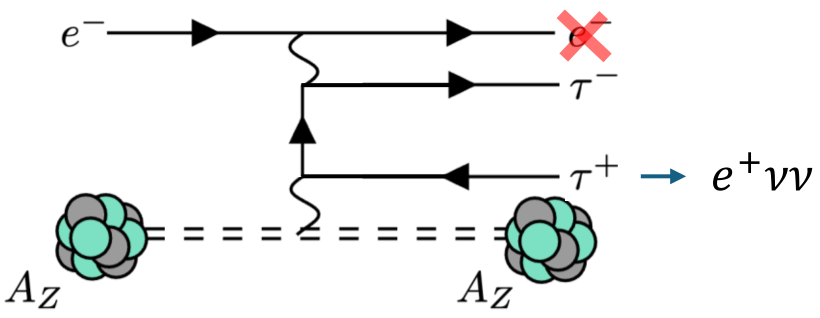


- $\sigma \propto C_{\ell\tau}^2 Z^2 F(q^2)$
  - Production proportional only to off-diagonal coupling
  - Large enhancement from charge of nucleus
  - Suppressed for large $t = q^2$
  - To produce ALP of mass m_a, need $t = (m_a^2/2E_\ell)^2$
  - $F(q^2) = F_{\text{coh}}(q^2) + F_{\text{incoh}}(q^2)/Z$

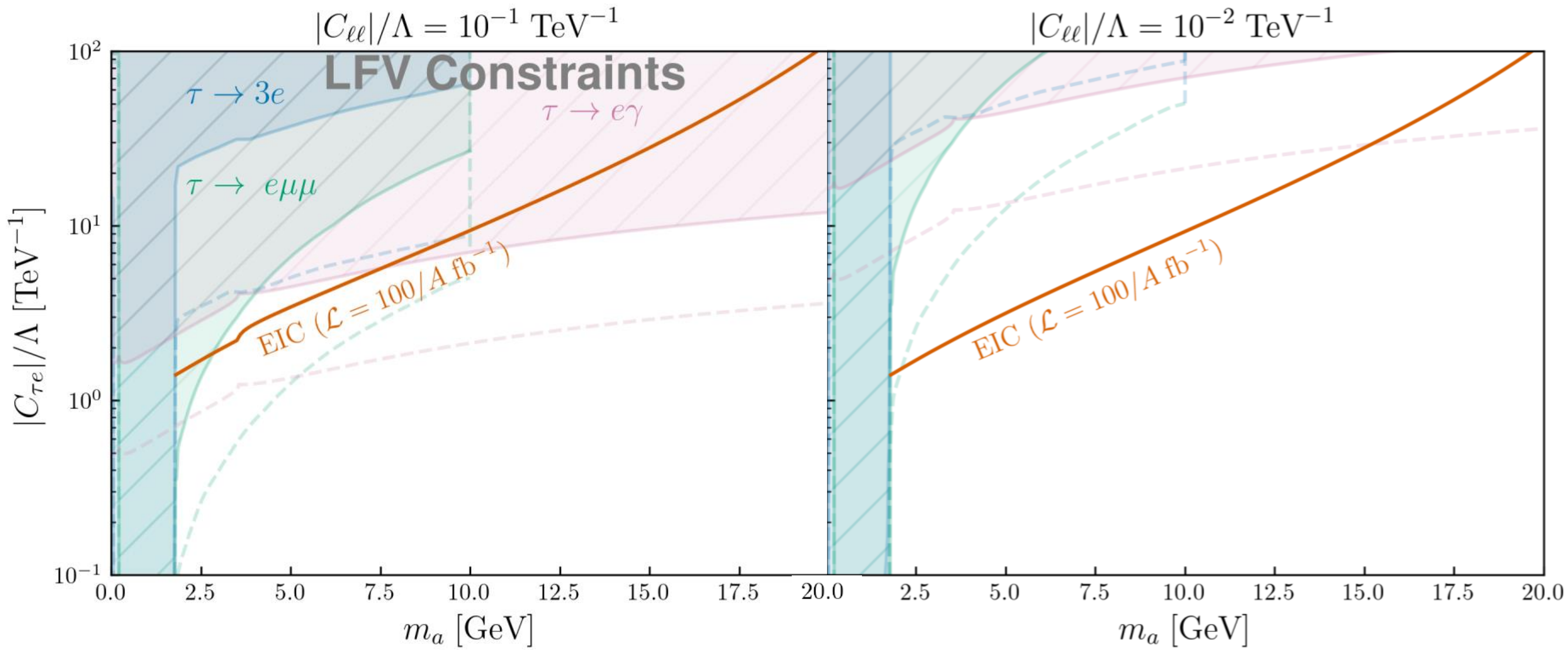
Probing $C_{\tau e}$: Electron-Ion Collider (EIC)

- High-energy electron and heavy ion beams:
  - In lab frame: $E_e^{\text{lab}} = 18$ GeV, $E_{\text{ion}}^{\text{lab}} = 110$ GeV$/A$
  - In ion frame: $E_e^{\text{ion}} \approx 4$ TeV
  - Luminosity of $\sim 3 - 15$ fb^{-1} per nucleon per month
- For clean detector environment, veto on nuclear breakup
  - cut off at $t = -q^2 = (0.1\ \text{GeV})^2$
  - Can produce ALPs up to mass $m_a = \sqrt{2E_e\sqrt{t_{\text{max}}}} = 30$ GeV
- ALP produced on-shell, consider decays $a \to e^+\tau^-$
  - Look for LFV signal: identify e^+ and one τ^-, veto on e^-
  - Main background: Bethe-Heitler process with $\tau^+ \to e^+\nu\bar{\nu}$, + loss of electron down the beam pipe.
  - Predicted ~ 400 background events, with $\sigma \sim 20$
  - Consider only $\tau \to 3h$ decays, assume efficiency $\epsilon_\tau = 1\%$ (arXiv:2207.10261).
  - Need to produce ~ 30 signal events for 90% confidence



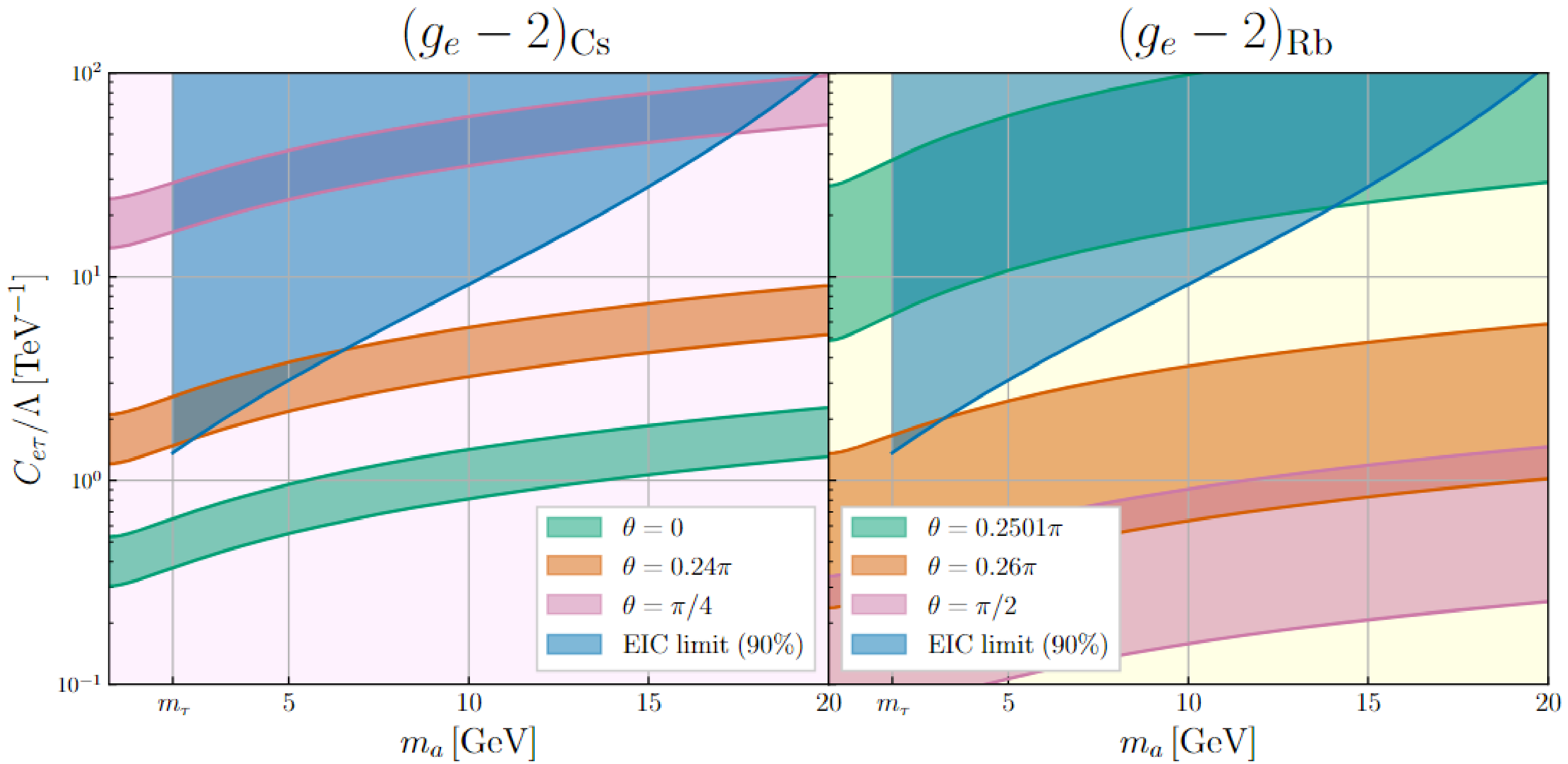


$C_{\tau e}$ limits from EIC



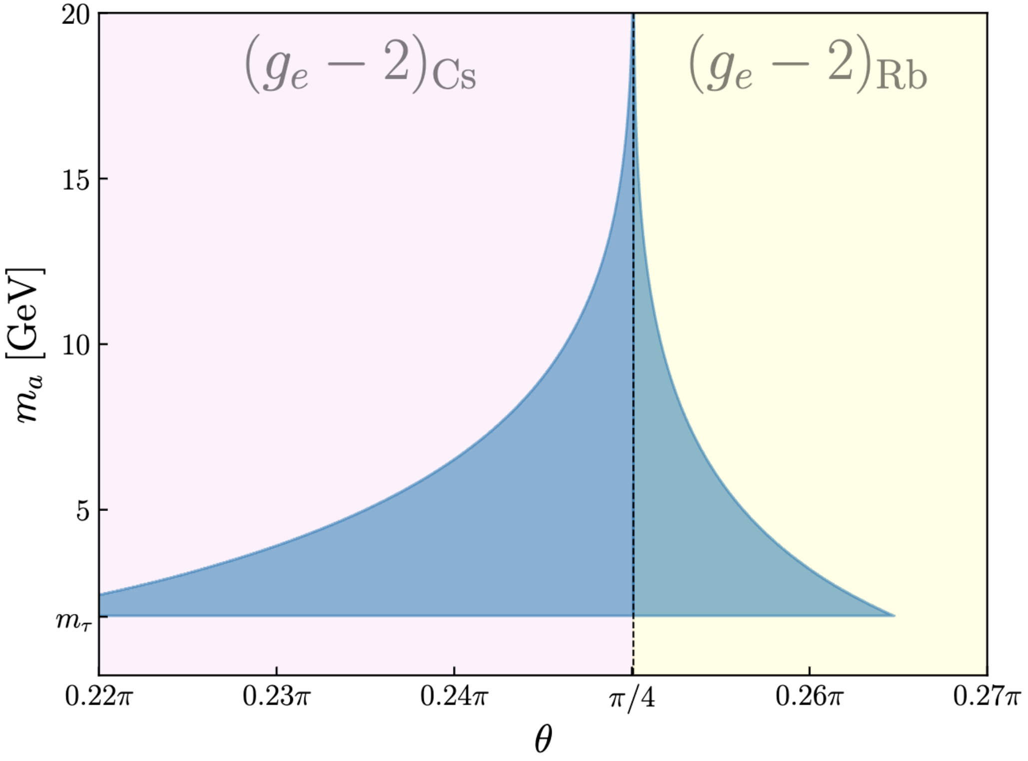
- EIC can probe $C_{\tau e}/\Lambda \sim O(1-10)/\mathrm{TeV}$
- Competitive when $C_{\tau\tau}/\Lambda < 10^{-1}\ \mathrm{TeV}^{-1}$
- Can view as complementary constraint:
  - When $C_{\tau\tau}$ large, $C_{\tau e}$ constrained with LFV
  - When $C_{\tau\tau}$ small, $C_{\tau e}$ constrained through production at EIC

EIC and electron $g-2$ anomalies



- EIC can probe near-chiral LFV explanations for either electron $g-2$ anomaly (assuming one remains)
- This analysis only considered $\epsilon_\tau \sim 1\%$ and no dedicated background mitigation. A more dedicated analysis could probe a wider range of couplings.
- Also would gain from $a \to \chi\chi$ signal

EIC in the m_a-θ plane explanation for $g_e - 2$



- EIC can probe near-chiral LFV explanations for either electron $g - 2$ anomaly (assuming one remains)
- This analysis only considered $\epsilon_\tau \sim 1\%$ and no dedicated background mitigation. A more dedicated analysis could probe a wider range of couplings.
- Would gain more from $a \to \chi\chi$ signal

Probing $C_{\mu\tau}$: m_a- θ plane explanation for $g_\mu - 2$

- FASERν2 only probes light masses with angle $\theta \sim \pi/4 + m_\mu/m_\tau$
- Muon Collider probes entire parameter space