University of Colorado Boulder

“Golden” Opportunity to Search for LFV ALPs at the EIC

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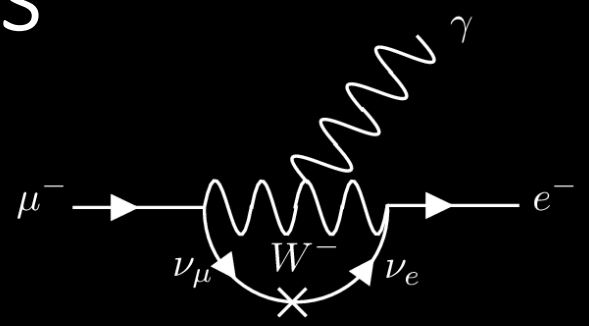
(arXiv: 21XX.XXXXX)

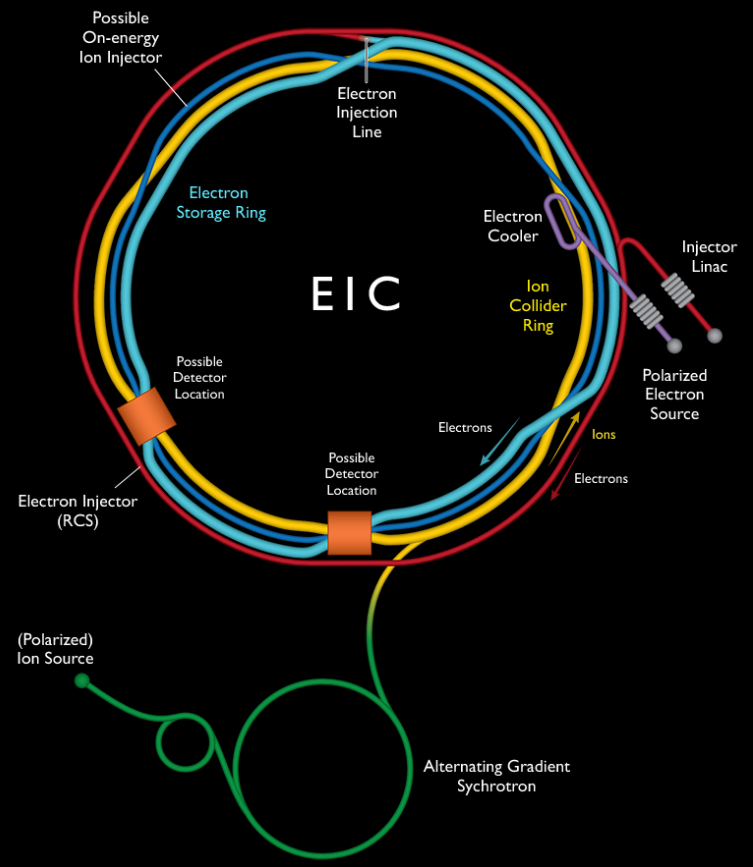
Brookhaven Forum 2021

Unpacking Acronyms



- LFV: Lepton-Flavor Violating
  - Absent from Standard Model
  - Observed experimentally (e.g. neutrino oscillations)
- ALP: Axion-Like Particles
  - pseudo-Nambu-Goldstone modes of spontaneously broken approximate global symmetry
  - QCD Axion, Pion
  - Dark pions (arXiv:1709.01082; Davoudiasl, Giardino, Neil, Rinaldi)
- EIC: Electron Ion Collider
  - "Here" at Brookhaven!
  - Collide electrons and gold ions (among others)
  - Planned to have between $\mathcal{L} = 10\ \mathrm{fb}^{-1}$ and $\mathcal{L} = 100\ \mathrm{fb}^{-1}$ in first 30 weeks

Source: bnl.gov



Model Description

- ALP Effective Lagrangian:

$$\mathcal{L} = \frac{1}{2}\left(\partial_\mu a\right)^2 - \frac{1}{2}m_a^2 a^2 + \frac{\partial_\mu a}{\Lambda}\sum_{\ell\ell'}\bar{\ell}\gamma^\mu\left(V_{\ell\ell'} - A_{\ell\ell'}\gamma_5\right)\ell' + 4\pi\alpha\frac{a}{\Lambda}C_{\gamma\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu} + \cdots$$

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- Integration by Parts and EOM:

$$\mathcal{L}_\ell = ia\sum_{\ell\ell'}\bar{\ell}\left[\frac{(m_\ell - m'_\ell)V_{\ell\ell'}}{\Lambda} - \frac{(m_\ell + m'_\ell)A_{\ell\ell'}}{\Lambda}\gamma_5\right]\ell' + h.c.$$

Model Description

$$\mathcal{L}_\ell = ia \sum_{\ell\ell'} \bar{\ell} \left[\underbrace{\frac{(m_\ell - m'_\ell)V_{\ell\ell'}}{\Lambda}}_{\text{Mass Suppression}} - \underbrace{\frac{(m_\ell + m'_\ell)A_{\ell\ell'}}{\Lambda}}_{\text{Mass Suppression}} \gamma_5 \right] \ell' + h.c.$$

- $m_\tau \gg m_\mu \gg m_e$, so only consider $\mathcal{L}_\tau$:

$$\mathcal{L}_\tau \approx \frac{iam_\tau}{\Lambda} \left[\sum_{\ell=\mu,e} \bar{\tau}(V_{\tau\ell} - A_{\tau\ell}\gamma_5)\ell - \bar{\tau}A_{\tau\tau}\gamma_5\tau \right] + h.c.$$

$$\equiv \frac{iam_\tau}{\Lambda} \left[\sum_{\ell=\mu,e} C_{\tau\ell}\bar{\tau}(\sin\theta_{\tau\ell} - \gamma_5\cos\theta_{\tau\ell})\ell + C_{\tau\tau}\bar{\tau}\gamma_5\tau \right] + h.c.$$

- $C_{\tau\ell} = \sqrt{|V_{\tau\ell}|^2 + |A_{\tau\ell}|^2}, C_{\tau\tau} = A_{\tau\tau}$
- $\theta_{\tau\ell} = -\tan^{-1}(V_{\tau\ell}/A_{\tau\ell})$

Model Description

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- $C_{\tau\ell} = \sqrt{|V_{\tau\ell}|^2 + |A_{\tau\ell}|^2}, C_{\tau\tau} = A_{\tau\tau}$
  - Characterizes interaction strength
  - Previously constrained via
    - Lepton Flavor Violation (arXiv:1911.06279; Cornella, Paradisi, Olcyr)
    - Higgs Decays (arXiv:2105.05866; R.M., Davoudiasl, **Miesch,** Neil)
  - Potential for improved constraints at EIC
- $\theta_{\tau\ell} = -\tan^{-1}(V_{\tau\ell}/A_{\tau\ell})$
  - Characterizes degree of parity violation
    - PC: $\theta = 0$, Maximal PV: $\theta = \pi/4$
  - $\theta_{\tau\ell} = \pi/4$ already seen in SM $SU(2)_L$, naturally appears in extensions
  - Can be probed with beam polarization

Why the EIC?

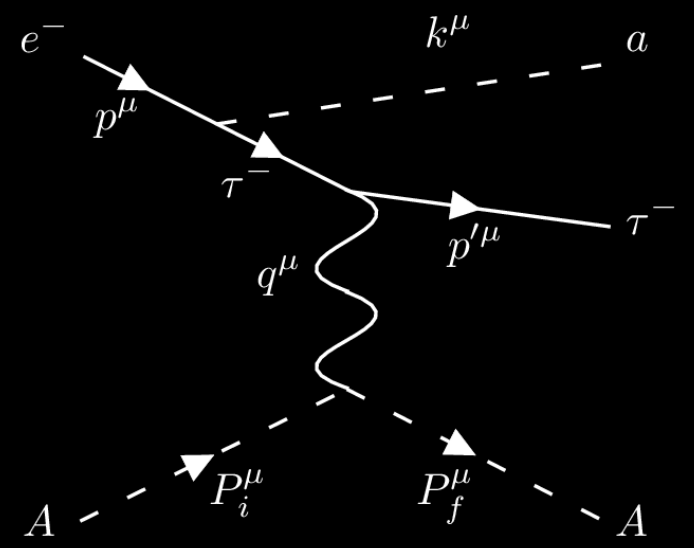
- Plans to collide Au ions with e^-
- If interaction is electromagnetic:
  - Cross section proportional to Z^2
  - For Au: $Z^2 = 79^2 \approx 6000$
  - Z^2 enhancement: can be used to probe $C_{\tau e}$
- Polarization capabilities
  - EIC Yellowbook: above 70% beam polarization
  - Great for probing $\theta_{\tau e}$
- Limits independent of other parameters of ALP model

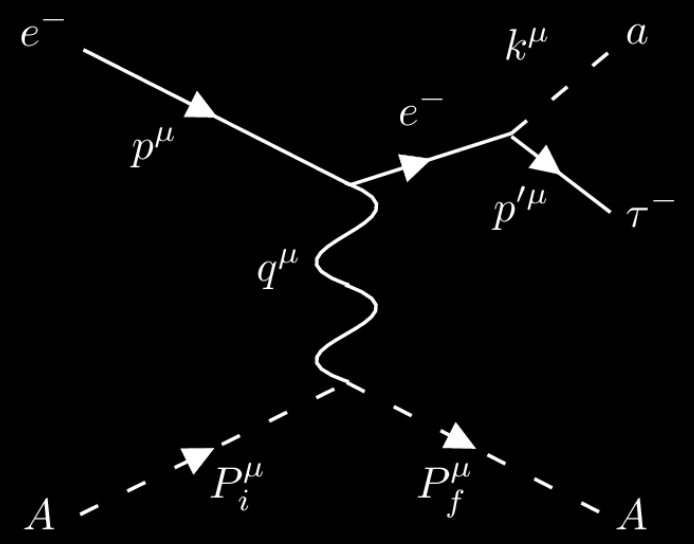
Process of Interest

- Model ion as complex scalar with mass M and charge Ze
  - Gold: $M = 183\ \mathrm{GeV}, Z = 79$
- Model photon-ion interaction via
  - $iV^{\mu}(q^2) = ieF(q^2)\left(P_i^{\mu} + P_f^{\mu}\right)$
  - $F(q^2) = Z\,\Theta(Q_{\max}^2 - q^2)\ (Q_{\max}^{\mathrm{Au}} \approx 30\ \mathrm{MeV})$
- μ^- and e^- final states ignored due to mass suppression
- EIC Yellow Book:

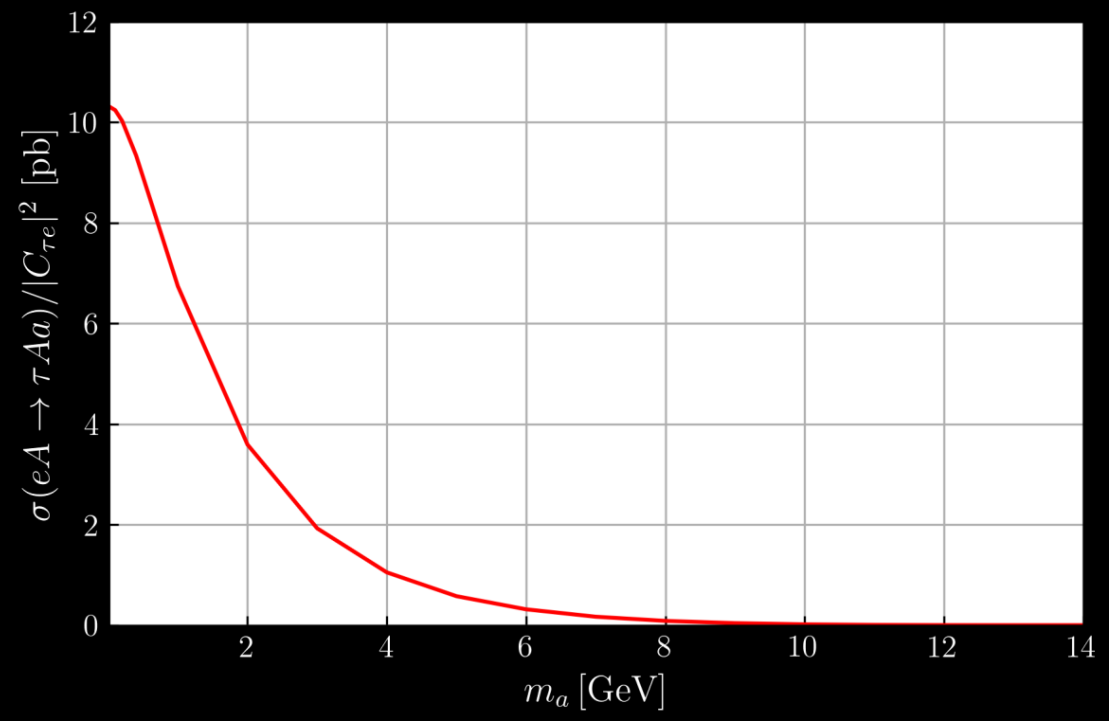
Species	Au	e
Beam energy [GeV]	110	18
$\sqrt{s}$ [GeV]	89.0	
No. of bunches	290	

  - Pseudorapidity range: $-4 \leq \eta \leq 4$
  - Angle range: $2.1° \leq \theta \leq 177.9°$
- $\overline{|\mathcal{M}|^2}$ independent of $\theta_{\tau e}$ to $\mathcal{O}(m_e/m_\tau)$





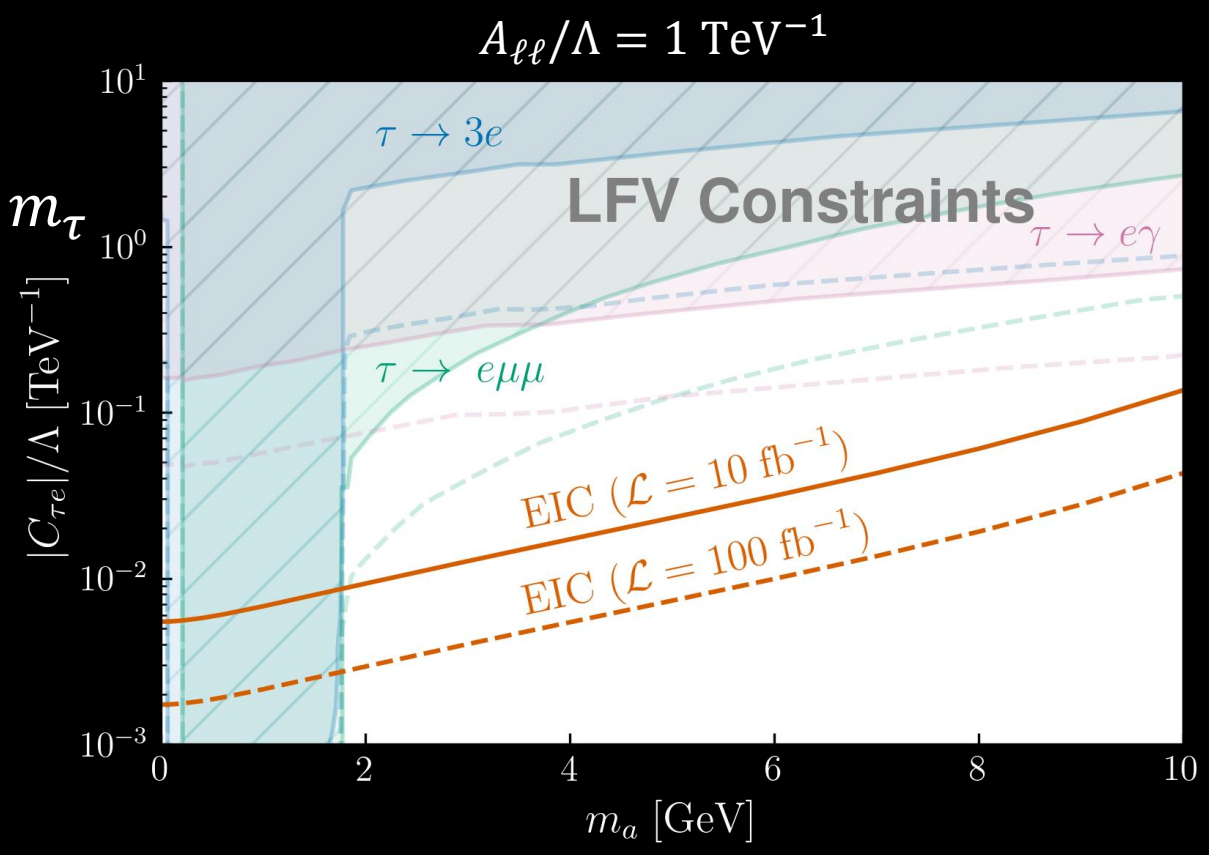
Total Cross Section



- Can use total cross section to place limits on $C_{\tau e}$
- Assumptions:
  - ALP decays leptonically inside detector
  - Zero background
  - 100% τ efficiency

Placing Limits on $C_{\tau e}$

- Compare to existing LFV Constraints (arXiv:1911.06279; Cornella, Olcyr, Paradisi)
  - Assumptions: $V_{\ell\ell'} = 0, C_{\tau\mu} = C_{\mu e} = 0, A_{\ell\ell}/\Lambda = 1\ \mathrm{TeV}^{-1}$
  - Limits from Belle ($\tau \to 3\ell$) and BaBar ($\tau \to e\gamma$)
  - Projections from Belle II (dashed lines)
- EIC outperforms LFV experiments for $m_a > m_\tau$
- Limits independent of other parameters
  - Consider $A_{\ell\ell}/\Lambda \sim 10^{-2}\ \mathrm{TeV}^{-1}$



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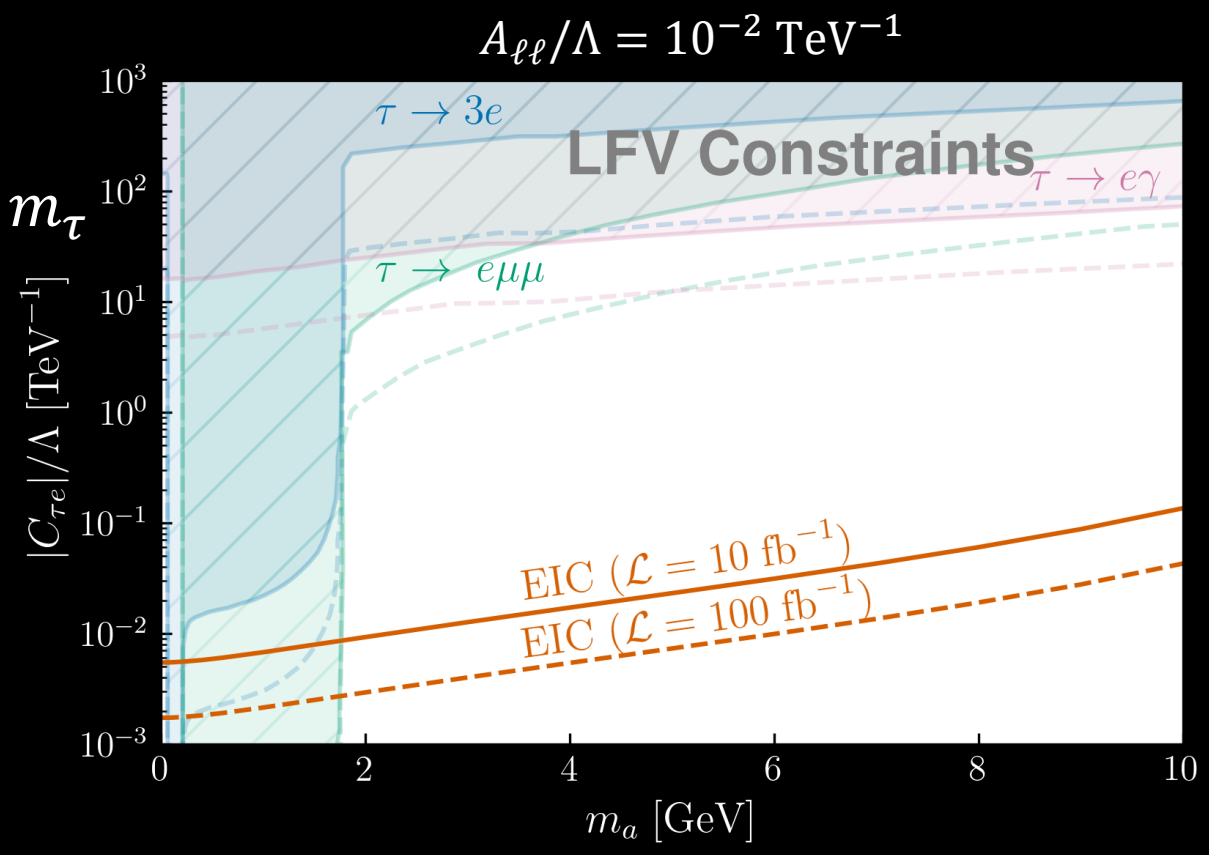
  - Free to change $\theta_{\tau e}$



What about $\theta_{\tau e}$?

- Polarized cross-section:

$$\sigma_L \approx \cos^2\left(\frac{\pi}{4} - \theta_{\tau e}\right)\sigma_0$$

$$\sigma_R \approx \sin^2\left(\frac{\pi}{4} - \theta_{\tau e}\right)\sigma_0$$

- Can probe $\theta_{\tau e}$ with left-right asymmetry:

$$r_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_0} \approx \sin 2\theta_{\tau e}$$

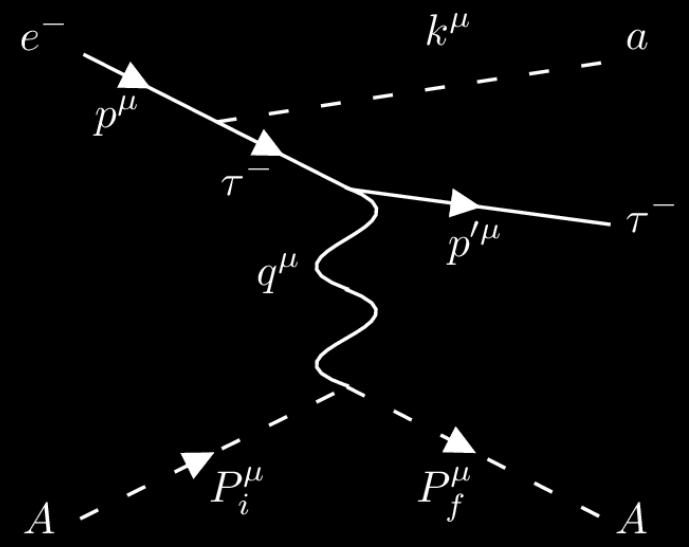
- Measurable with EIC polarization capabilities
- Specific cases:
  - $\theta_{\tau e} = 0, r_{LR} = 0$
  - $\theta_{\tau e} = \pi/4, r_{LR} = 1$

Closing Remarks

- LFV expected to occur in BSM physics
- LFV ALP model inspired by UV model, but more general
- The EIC can be used to probe the ALP model
  - Luminosity can probe $C_{\tau e}$
  - Polarization can probe $\theta_{\tau e}$
- Results:
  - EIC outperforms existing and future LFV experiments!
  - EIC limits more robust (independent of other model parameters)
- How would results change with other ions?
- What sort of constraints could EIC place on $\theta_{\tau e}$?

Questions?

Supplemental: $|\mathcal{M}|^2$ calculation

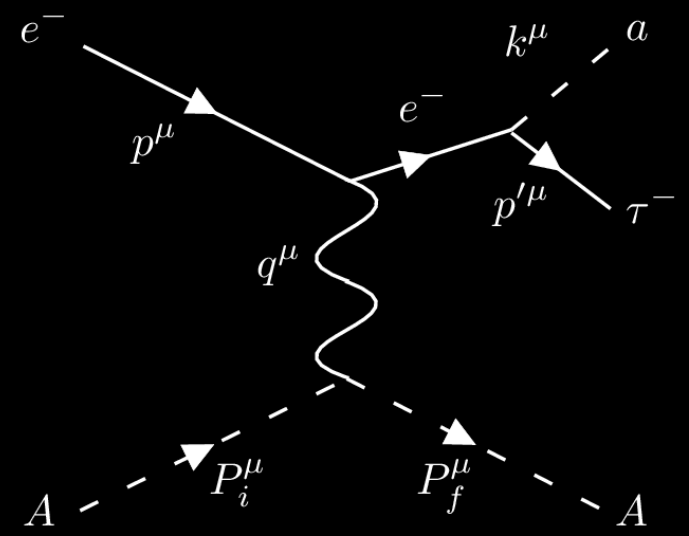


- Relevant Minkowski-like variables:
  - $q = P_i - P_f,\ P = P_i + P_f$
  - $\tilde{s} = (p' + k)^2 - m_e^2$
  - $\tilde{u} = (p - k)^2 - m_\tau^2$
  - $t = -q^2$
- Final amplitude (after lots of algebra):

$$\overline{|\mathcal{M}|^2} = \left(\frac{4\pi\alpha C_{\tau e} m_\tau}{\Lambda}\right)^2 \frac{F(q^2)^2}{q^4} \mathcal{A}^{2\to 3}$$

$$\mathcal{A}^{2\to 3} = \frac{(\tilde{s}+\tilde{u})^2}{\tilde{s}\tilde{u}} - 4\frac{t}{\tilde{s}\tilde{u}}(P\cdot k)^2 + \frac{(\tilde{s}+\tilde{u})^2}{\tilde{s}^2\tilde{u}^2} m^2(\theta_{\tau e})\left[P^2 t - 4\left(\frac{\tilde{u}P\cdot p + \tilde{s}P\cdot p'}{\tilde{s}+\tilde{u}}\right)^2\right]$$

$$m^2(\theta_{\tau e}) = m_a^2 - m_\tau^2 - m_e^2 + 2m_\tau m_e \cos 2\theta_{\tau e}$$

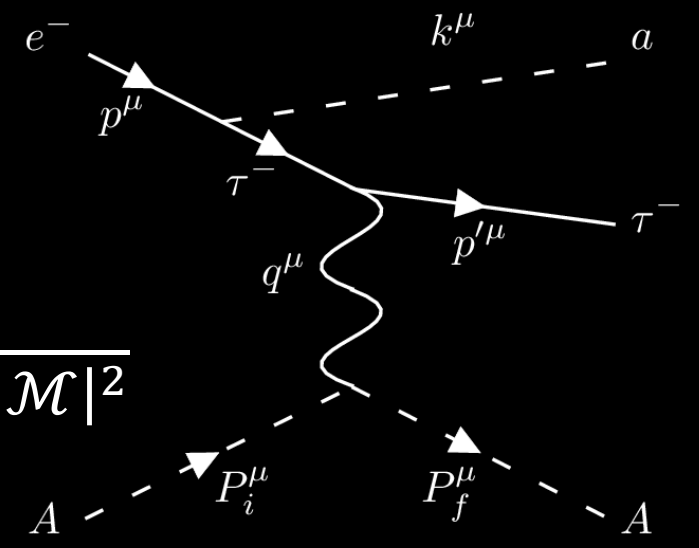


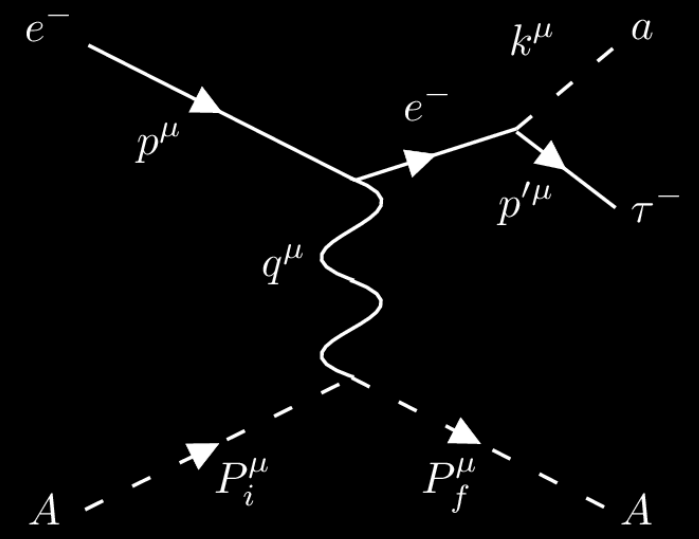
Supplemental: $|\mathcal{M}|^2$ integral

- Integrate phase space in rest frame of ion:

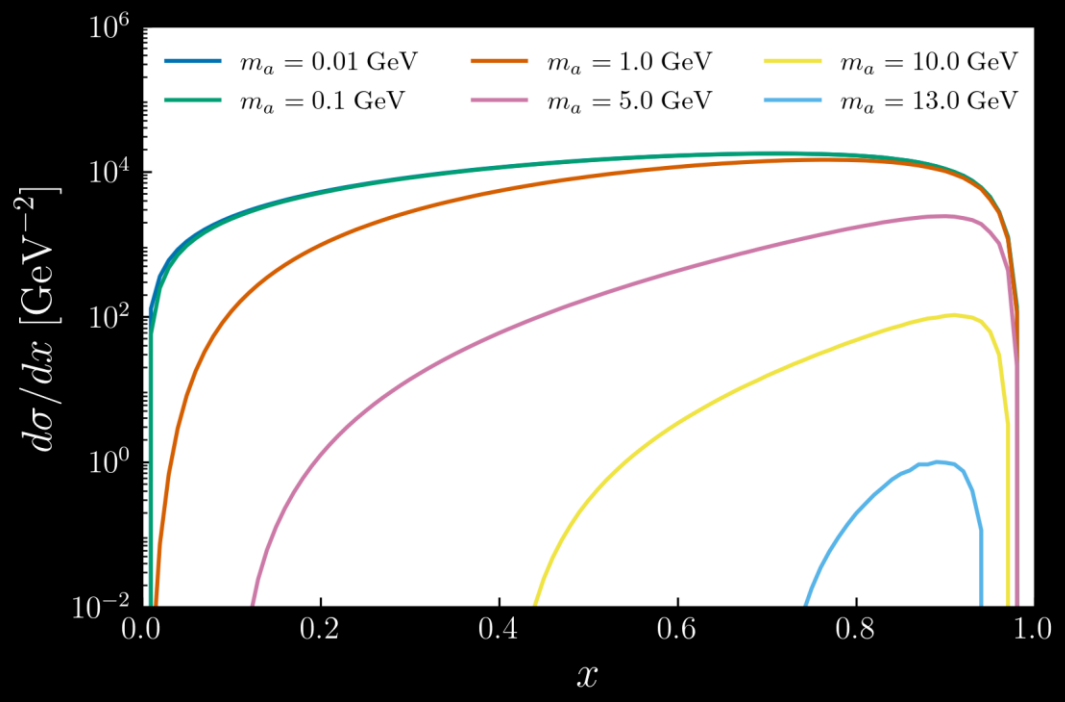
$$\frac{d\sigma}{dx\, d(\cos\theta_k)} = \frac{1}{512\pi^3 M^2} \frac{|\vec{k}| E_p}{|\vec{p}||\vec{p}-\vec{k}|} \int_{t_-}^{t_+} dt \int_0^{2\pi} d\phi_q\, \overline{|\mathcal{M}|^2}$$

- $t = -q^2,\ x = E_k/|\vec{p}|, \cos\theta_k = (\vec{p}\cdot\vec{k})/(|\vec{p}||\vec{k}|)$
- For each ALP mass:
  - Integrate ϕ_q analytically
  - Integrate $\cos\theta_k$ and t using VEGAS
    - Limits t_- and t_+ from kinematics
    - Limits on $\cos\theta_k$ from $-4 \le \eta \le 4$
  - Integrate x using trapezoid rule

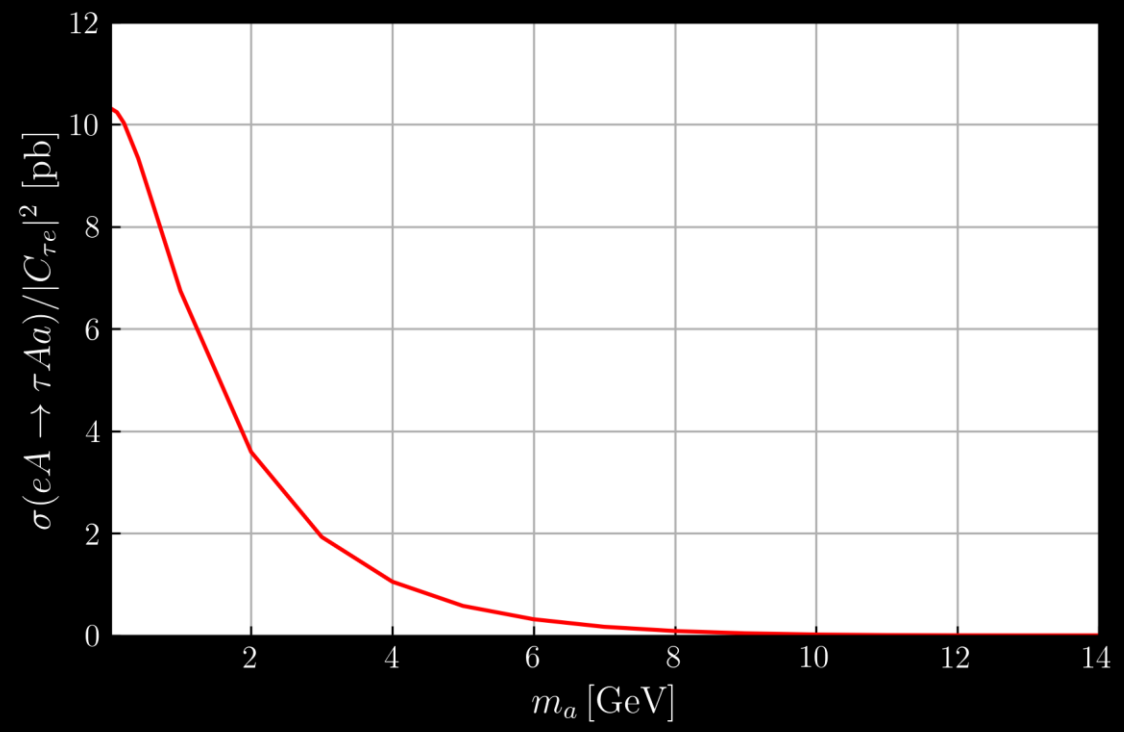




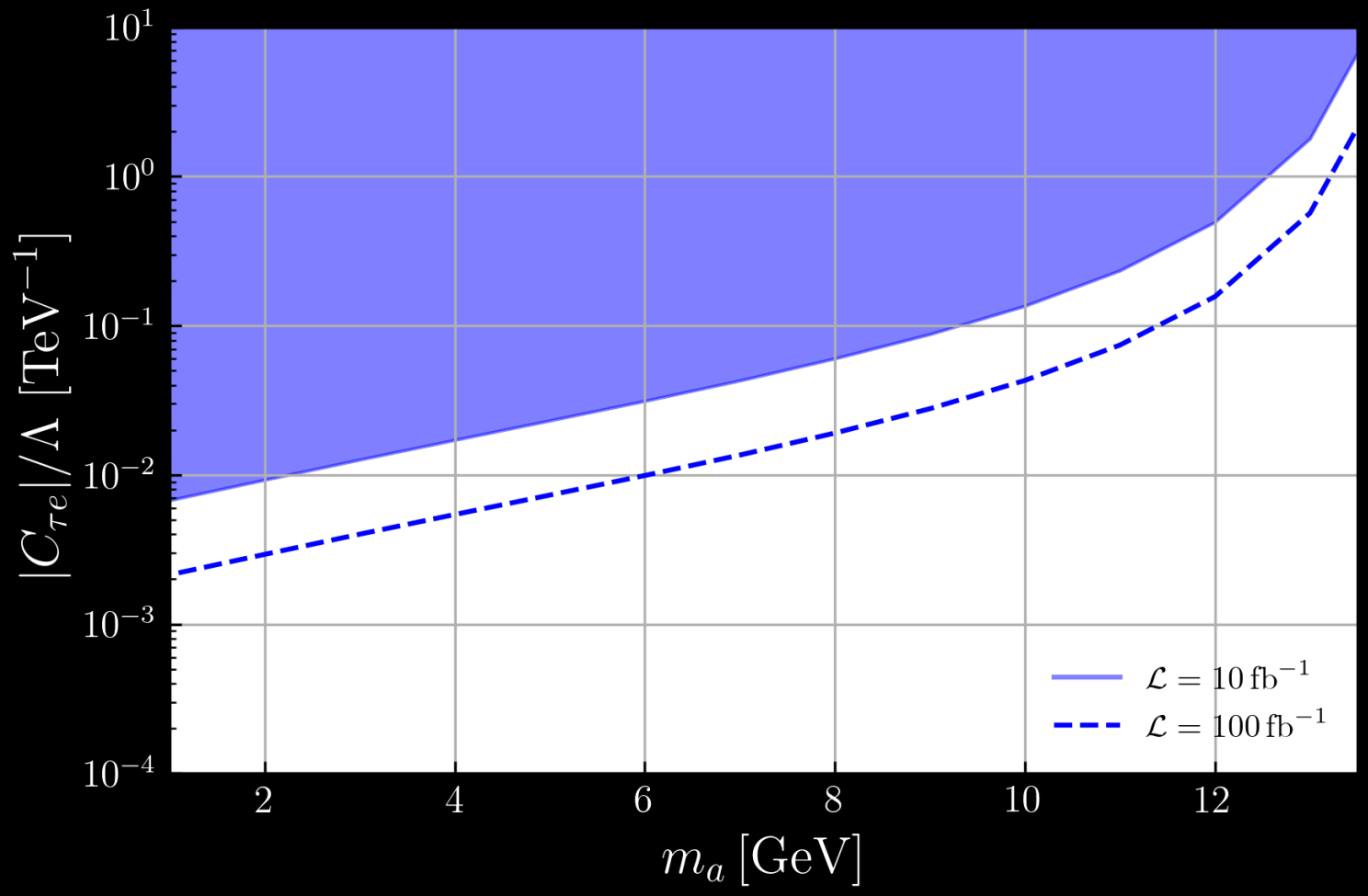
Supplemental: $d\sigma/dx$ plot



$$\int \frac{d\sigma}{dx} dx$$



Supplemental: $C_{\tau e}$ up to $m_a \approx 14$ GeV



Supplemental: Beam Polarization

- With beam polarization p:

$$r_{LR} = \frac{p \cdot \sigma_L - (1-p)\sigma_R}{\sigma_0} \approx (2p-1)\sin 2\theta_{\tau e}$$

- For EIC, $p \approx 0.7$:

$$r_{LR} \approx 0.4 \sin 2\theta_{\tau e}$$

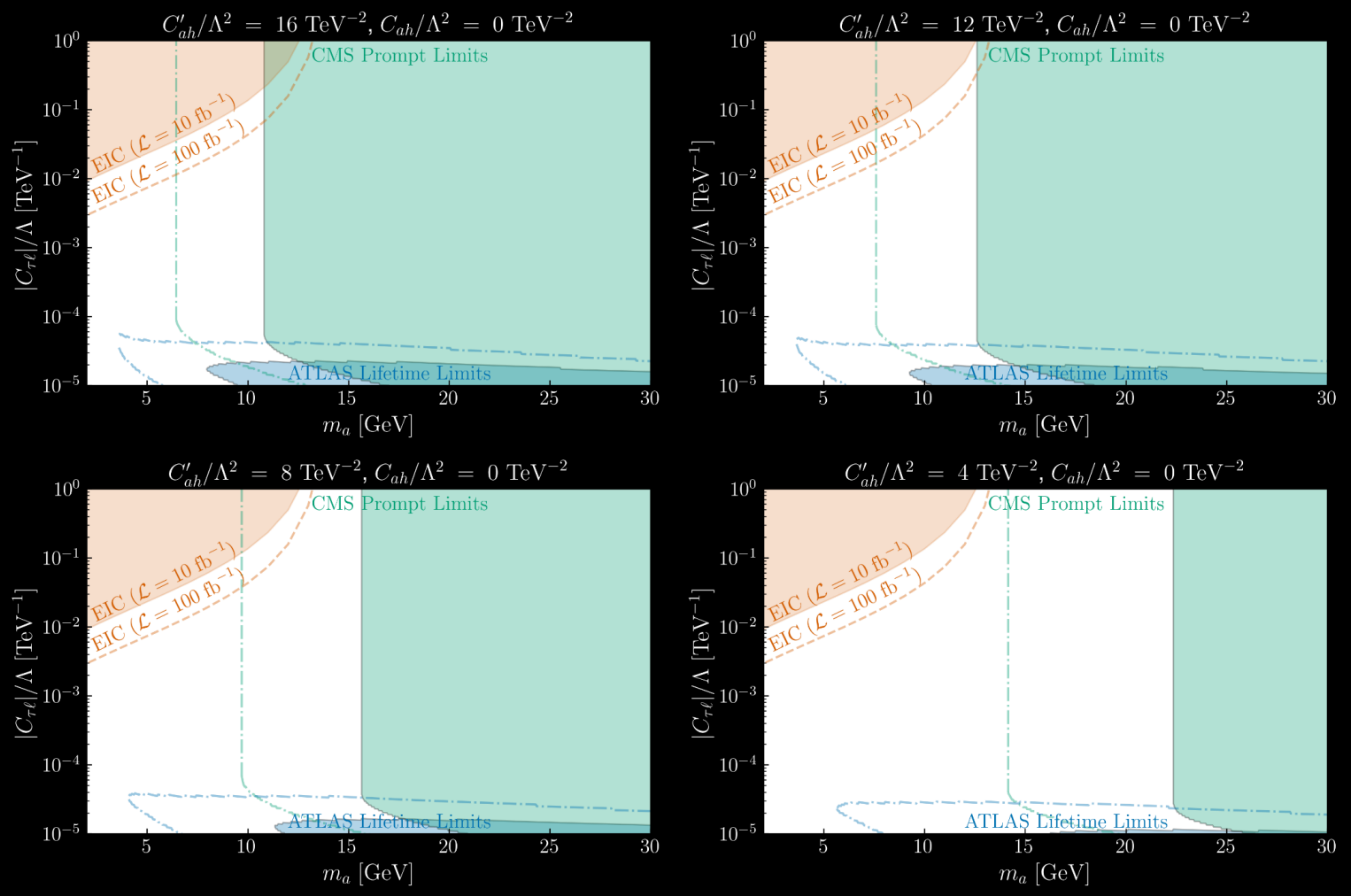
- As long as p is known precisely, can still probe $\theta_{\tau e}$

Supplemental: Higgs Lagrangian

$$\mathcal{L}_h = \frac{C_{ah}}{\Lambda^2} v \left(\partial_\mu a\right)^2 h + \frac{C'_{ah}}{\Lambda^2} v m_a^2 a^2 h$$

- In $SU(3)_C$ and other confining theories
  - C'_{ah} arises from Yukawa coupling with lighter quarks
  - C_{ah} arises from Higgs-gluon effective coupling due to heavy quark loops

Supplemental: Higgs Decay Limits



- Adapted from arXiv:2105.05866 (R.M., Davoudiasl, Miesch, Neil)
- Assumes $C_{\tau e} \approx C_{\tau\mu} \approx C_{\tau\tau}$
- CMS: $\mathcal{L} = 137\ \mathrm{fb}^{-1}$
- ATLAS: $\mathcal{L} \approx 36\ \mathrm{fb}^{-1}$
- Projections: $\mathcal{L} \approx 1000\ \mathrm{fb}^{-1}$
- Prior collider limits dependent on production of ALP pair from Higgs, so sensitive to C'_{ah} and C_{ah}
- EIC limits independent of coupling to Higgs

Supplemental: Other ALP constraints

- arXiv:1708.00443 (Bauer, Neubert, Thamm)
- $C_{\gamma\gamma}^{\text{eff}} \approx C_{\gamma\gamma} + \sum_{\ell} \frac{\alpha}{4\pi} C_{\ell\ell} B_1\left(4m_\ell^2/m_a^2\right)$