Searching for New Physics at the Electron-Ion Collider

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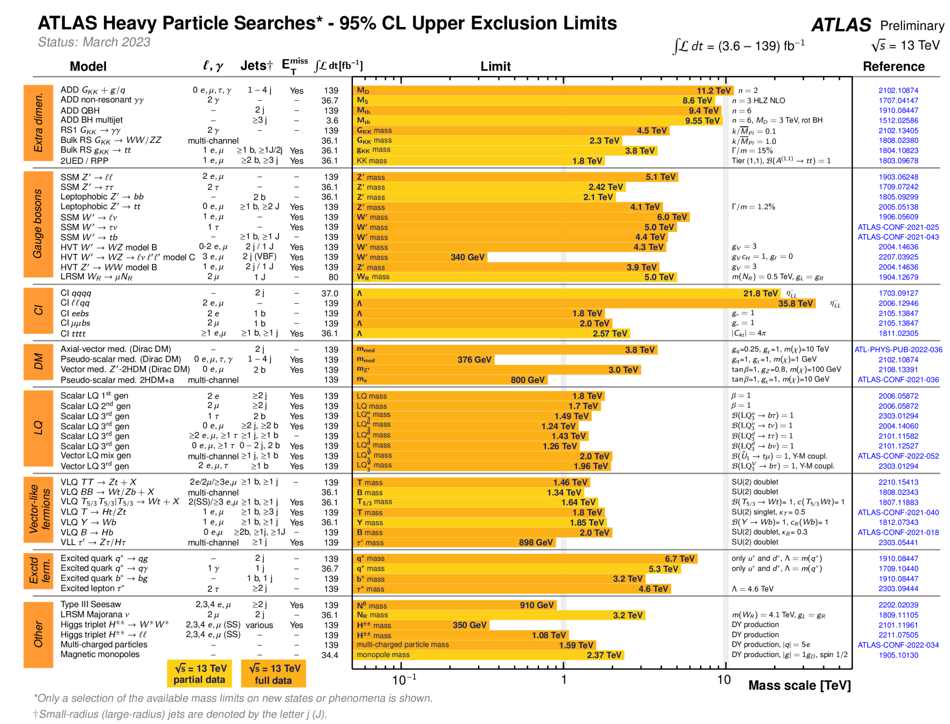
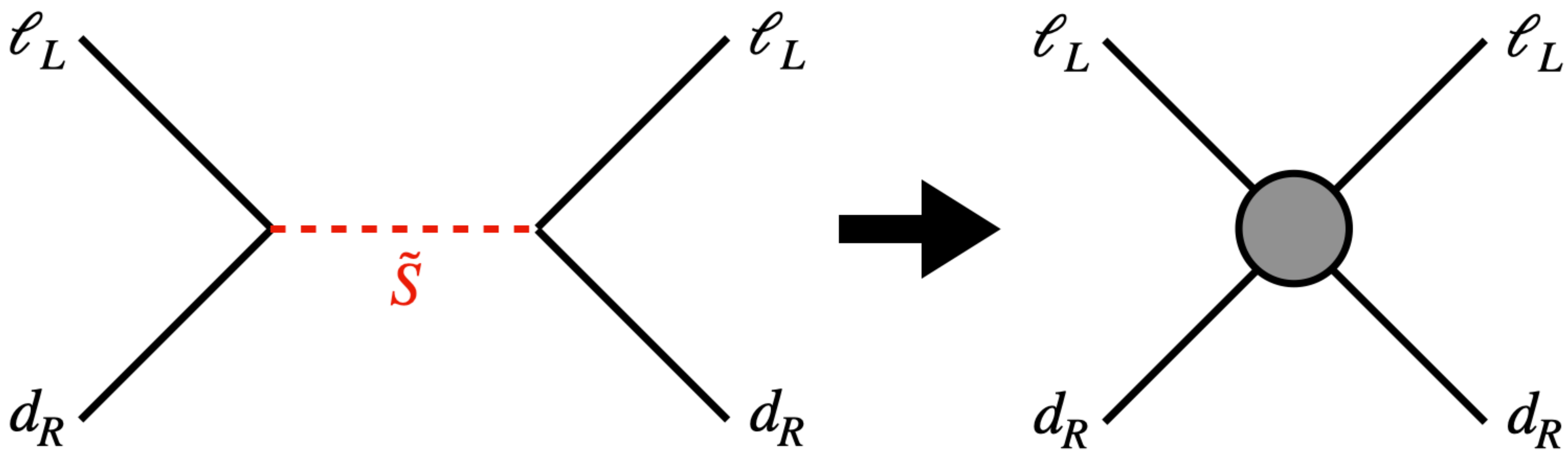
Naturalness? Baryon Asymmetry?
Strong CP? Neutrino Mass?
Flavor Puzzle? Dark Matter?
Unification? Inflation?
Quantum Gravity? ...

Where is the New Physics?



Possibilities for new physics:

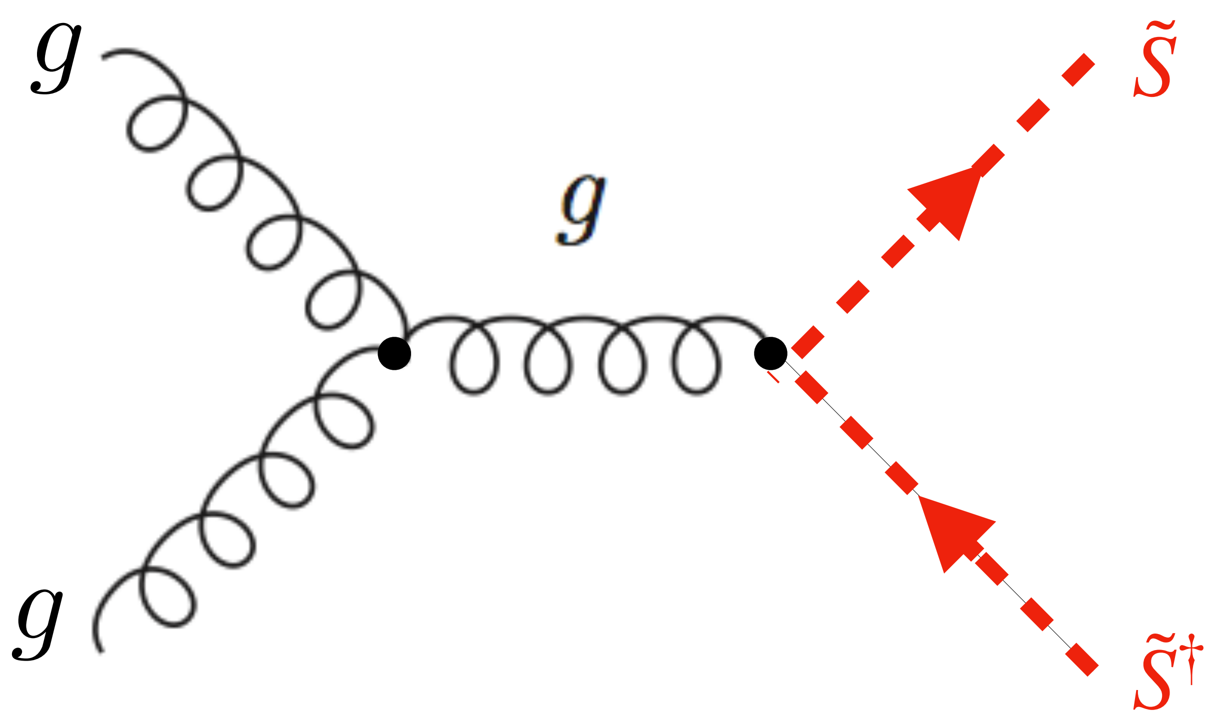
#1. New *heavy states*; masses much larger than the weak scale



Search for anomalous phenomena or rare processes
with precision measurements

Possibilities for new physics:

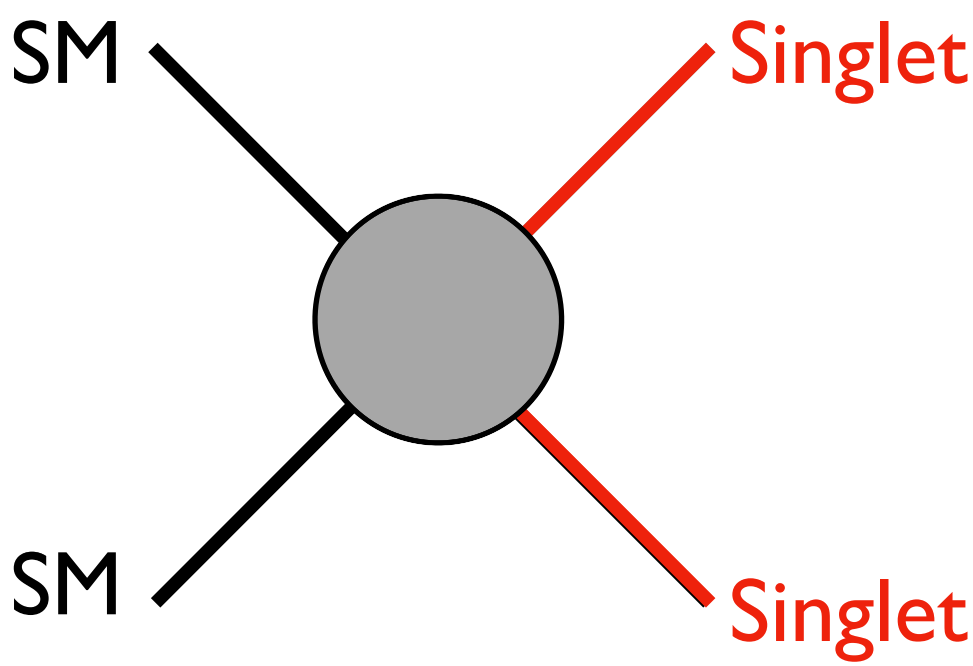
#2. New *light* charged states; masses near the weak scale ~ 1 TeV



Produce states directly at high energy colliders like LHC

Possibilities for new physics:

#3. New *light gauge singlet states*, masses can be below the weak scale



Generic "Portal"

$$\mathcal{L} \supset \frac{\mathcal{O}^{(p)}_{\rm SM}\mathcal{O}^{(q)}_{\rm singlet}}{\Lambda^{p+q-4}}$$

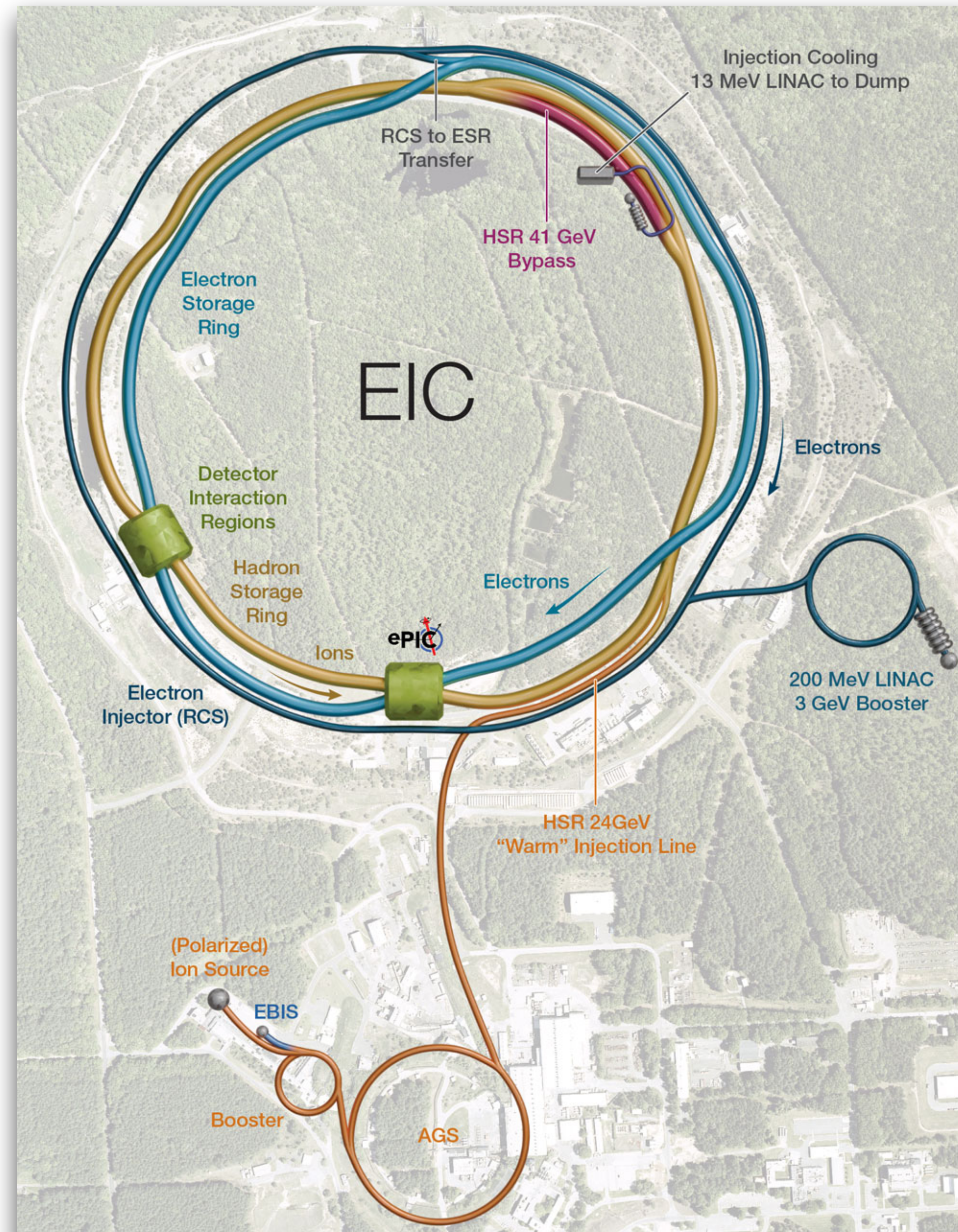
Probe these states directly using high intensity/precision experiments

The Electron-Ion Collider (EIC)

- The EIC is a new flagship collider facility being built at Brookhaven National Laboratory to study QCD and nuclear structure

- The EIC will collide polarized electrons with polarized protons and ions over a wide range of energies and with high luminosities.
  - Variable $\sqrt{s} \sim 20 - 141\,\mathrm{GeV}$
  - Luminosity goal $10^{33} - 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

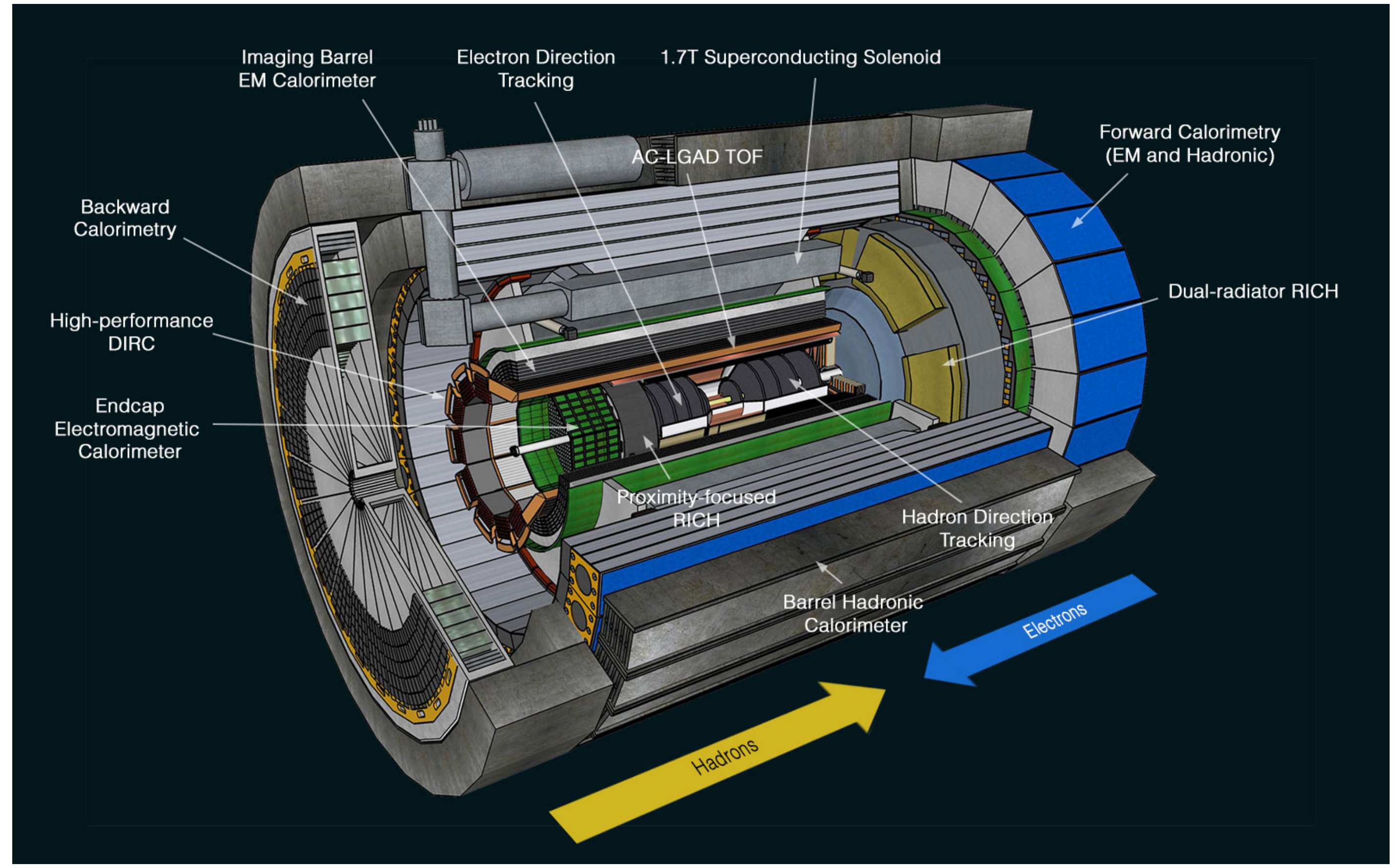
- Physics goals of the EIC:
  - 3D tomography of the proton and nuclei
  - Origin of proton spin
  - Gluon Saturation and dense QCD matter
  - Hadronization in cold nuclear matter
  - Precision QCD, fundamental symmetries
  - …



The ePIC detector

- Full acceptance design across a wide rapidity range

- Precision tracking in a strong magnetic field for accurate momentum and vertex reconstruction



- Comprehensive particle identification (PID) for distinguishing photons, electrons, hadron species over a broad momentum range

- High-resolution calorimetry for energy measurements, jet reconstruction, and missing-energy studies

- Forward and backward instrumentation to tag diffractive and low-angle particles, enabling exclusive and small-x physics

- Dedicated systems for beam-polarization and luminosity measurements

Why BSM at the EIC?

- Clean, controlled initial state
  - Polarized electron beam on (polarized) protons/nuclei, precise kinematics, controlled systematics, parity-violating & spin asymmetries for SMEFT, …

- High luminosity at moderate center-of-mass energies ($\sqrt{s} \sim 20 - 141\,\mathrm{GeV}$)
  - Ideal for light, weakly coupled states (dark photons, ALPs, HNLs, …)

- Full control of the final state
  - Measure scattered electron, tag the proton/nucleus, enables exclusive channels, missing-momentum/energy methods, invisible-decay searches, …

- Broad PID + excellent tracking/timing:
  - Displaced-vertex/timing signatures for long-lived particles
  - Heavy-flavor tagging for models with c/b or τ couplings

- Photon-rich production modes:
  - Coherent/ultra-peripheral electron-ion processes enhance production rates for certain BSM states

Precision measurements & SMEFT

Probing the SMEFT at the EIC

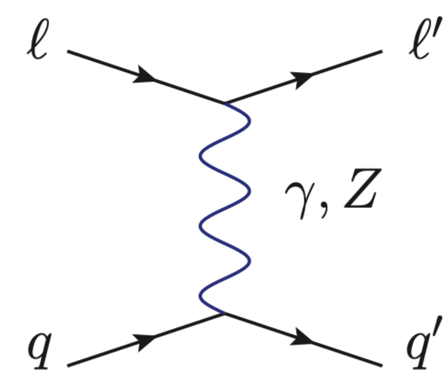
[Boughezal, Petriello, Wiigand '20]

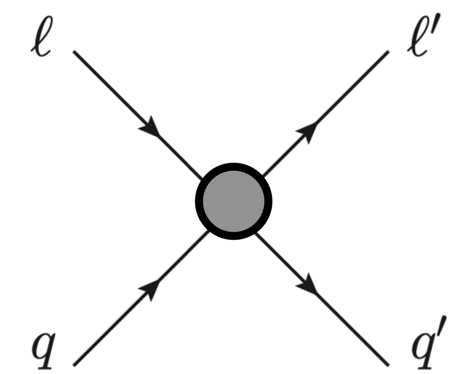
- Consider four-fermion SMEFT operators coupling leptons and quarks

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i C_i \mathcal{O}_i + \ldots ,$$

$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}\gamma^\mu l)(\bar{q}\gamma_\mu q)$	$\mathcal{O}_{lu}$	$(\bar{l}\gamma^\mu l)(\bar{u}\gamma_\mu u)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}\gamma^\mu \tau^I l)(\bar{q}\gamma_\mu \tau^I lq)$	$\mathcal{O}_{ld}$	$(\bar{l}\gamma^\mu l)(\bar{d}\gamma_\mu d)$
$\mathcal{O}_{eu}$	$(\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)$	$\mathcal{O}_{qe}$	$(\bar{q}\gamma^\mu q)(\bar{e}\gamma_\mu e)$
$\mathcal{O}_{ed}$	$(\bar{e}\gamma^\mu e)(\bar{d}\gamma_\mu d)$		

- SMEFT operators contribute to deep inelastic scattering (DIS) processes:





- Polarized DIS cross sections depend on quark, lepton polarizations, λ_e, λ_q , and probe different combinations of Wilson coefficients depending on beam polarizations, e.g.,

$$\frac{d^2\sigma_u^{\gamma SMEFT}}{dx dQ^2} = -x\frac{Q_u Q^2}{8\pi\alpha}\Big[C_{eu}(1+\lambda_u)(1+\lambda_e) + (C_{lq}^{(1)} - C_{lq}^{(3)})(1-\lambda_u)(1-\lambda_e)$$
$$+(1-y)^2 C_{lu}(1+\lambda_u)(1-\lambda_e) + (1-y)^2 C_{qe}(1-\lambda_u)(1+\lambda_e)\Big]$$

Probing the SMEFT at the EIC

[Boughezal, Petriello, Wiigand '20]

- Drell-Yan processes at the LHC provides strong constraints on SMEFT four-fermion operators, but can be flat-directions in fits to Wilson coefficients, e.g., for $C_{eu}, C_{lq}^{(1)} \neq 0,$
- Example for $C_{eu}, C_{lq}^{(1)} \neq 0:$

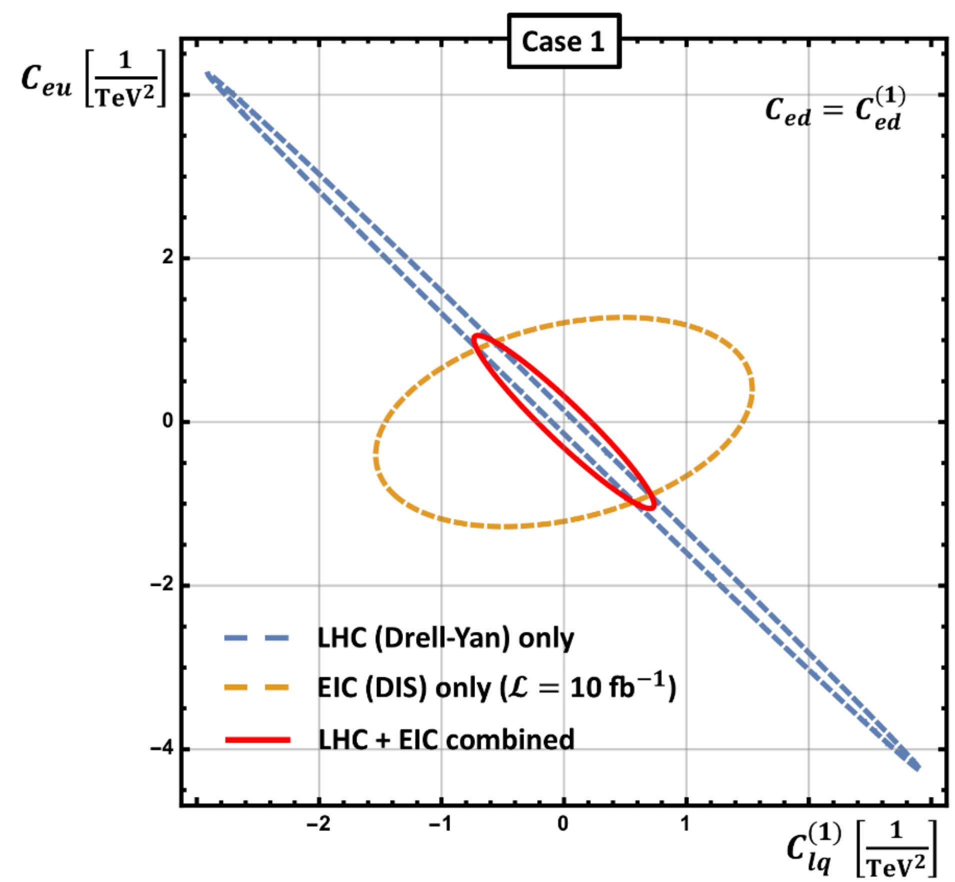
$$\frac{d\hat{\sigma}_{uu}^{\gamma\text{SMEFT}}}{dM^2 dY dc_\theta} = -\frac{8\pi\alpha Q_u}{3}\frac{(C_{eu} + C_{\ell q}^{(1)})\,\hat{u}^2}{\hat{s}}$$

$$\frac{d\hat{\sigma}_{uu}^{Z\text{SMEFT}}}{dM^2 dY dc_\theta} = \frac{2g_Z^2}{3}\frac{(g_R^u g_R^e C_{eu} + g_L^u g_L^e C_{\ell q}^{(1)})\,\hat{u}^2}{\hat{s} - M_Z^2}$$

flat direction for $\hat{s} \gg M_Z^2$

$$C_{\ell q}^{(1)} = -C_{eu}\frac{Q_u e^2 - g_Z^2 g_R^u g_R^e}{Q_u e^2 - g_Z^2 g_L^u g_L^e} \approx -0.69 C_{eu}$$

- Polarized DIS measurements at the EIC can disentangle such flat directions, providing a complementary probe of SMEFT operators.



Parity-violating asymmetries at the EIC

[Boughezal, Emmert, Kutz, Mantry, Nycz, Petriello, Şimşek, Wiegand, Zheng '22]

- In DIS experiments with electron beam polarization P_e and hadron beam polarization P_H, the differential cross section may be decomposed as

$$\mathrm{d}\sigma = \mathrm{d}\sigma_0 + P_e\,\mathrm{d}\sigma_e + P_H\,\mathrm{d}\sigma_H + P_e P_H\,\mathrm{d}\sigma_{eH}$$

$$\mathrm{d}\sigma_0 = \frac{1}{4}\Big[\,\mathrm{d}\sigma|_{\lambda_e=+1,\lambda_H=+1} + \mathrm{d}\sigma|_{\lambda_e=+1,\lambda_H=-1} + \mathrm{d}\sigma|_{\lambda_e=-1,\lambda_H=+1} + \mathrm{d}\sigma|_{\lambda_e=-1,\lambda_H=-1}\,\Big]$$

$$\mathrm{d}\sigma_e = \frac{1}{4}\Big[\,\mathrm{d}\sigma|_{\lambda_e=+1,\lambda_H=+1} + \mathrm{d}\sigma|_{\lambda_e=+1,\lambda_H=-1} - \mathrm{d}\sigma|_{\lambda_e=-1,\lambda_H=+1} - \mathrm{d}\sigma|_{\lambda_e=-1,\lambda_H=-1}\,\Big]$$

$$\mathrm{d}\sigma_H = \frac{1}{4}\Big[\,\mathrm{d}\sigma|_{\lambda_e=+1,\lambda_H=+1} - \mathrm{d}\sigma|_{\lambda_e=+1,\lambda_H=-1} + \mathrm{d}\sigma|_{\lambda_e=-1,\lambda_H=+1} - \mathrm{d}\sigma|_{\lambda_e=-1,\lambda_H=-1}\,\Big]$$

$$\mathrm{d}\sigma_{eH} = \frac{1}{4}\Big[\,\mathrm{d}\sigma|_{\lambda_e=+1,\lambda_H=+1} - \mathrm{d}\sigma|_{\lambda_e=+1,\lambda_H=-1} - \mathrm{d}\sigma|_{\lambda_e=-1,\lambda_H=+1} + \mathrm{d}\sigma|_{\lambda_e=-1,\lambda_H=-1}\,\Big]$$

- Parity-violating asymmetries:
  - *unpolarized PV asymmetry* : comparing right-handed and left-handed electron scattering from unpolarized hadrons $\quad A_{\mathrm{PV}}^{(e)} \equiv \frac{\mathrm{d}\sigma_e}{\mathrm{d}\sigma_0}$
  - *polarized PV asymmetry* : comparing unpolarized electron scattering off right-handed and left-handed hadrons $\quad A_{\mathrm{PV}}^{(H)} \equiv \frac{\mathrm{d}\sigma_H}{\mathrm{d}\sigma_0}$

Weak mixing angle at EIC

[Boughezal, Emmert, Kutz, Mantry, Nycz, Petriello, Şimşek, Wiegand, Zheng '22]

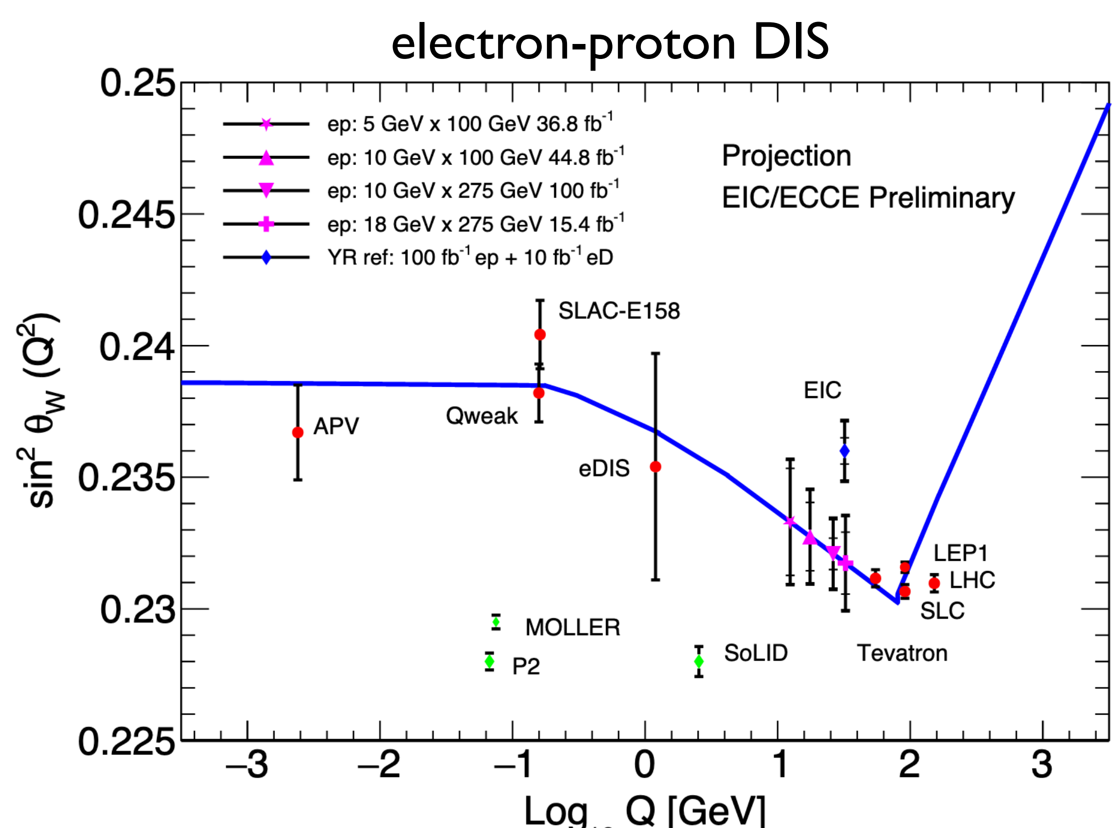
- The weak mixing angle may be extracted through a measurement of the unpolarized PV asymmetry

$$g_V^i \equiv t_{3L}(i) - 2Q_i \sin^2\theta_W \ ,$$
$$g_A^i \equiv t_{3L}(i) \ ,$$

$$A_{\rm PV}^{(e)} = \frac{|P_e|\eta_{\gamma Z}\left[g_A^e 2yF_1^{\gamma Z} + g_A^e\left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2xy}{Q^2}\right)F_2^{\gamma Z} + g_V^e(2-y)F_3^{\gamma Z}\right]}{2yF_1^{\gamma} + \left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2xy}{Q^2}\right)F_2^{\gamma} - \eta_{\gamma Z}\left[g_V^e 2yF_1^{\gamma Z} + g_V^e\left(\frac{2}{xy} - \frac{2}{x} - \frac{2M^2xy}{Q^2}\right)F_2^{\gamma Z} + g_A^e(2-y)F_3^{\gamma Z}\right]}$$

- Fit to pseudo-data of polarized DIS, 80% electron beam polarization, several different energies, $Q \sim 10 - 30\,\mathrm{GeV}$, integrated luminosities of $10 - 100\,\mathrm{fb}^{-1}$

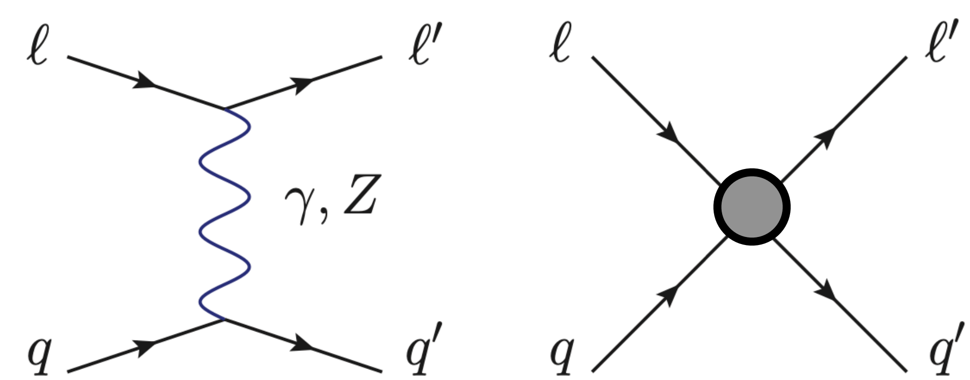
- The EIC can fill the gap in weak-mixing–angle measurements between low-energy probes and high-energy colliders.



Parity-violating asymmetries and SMEFT

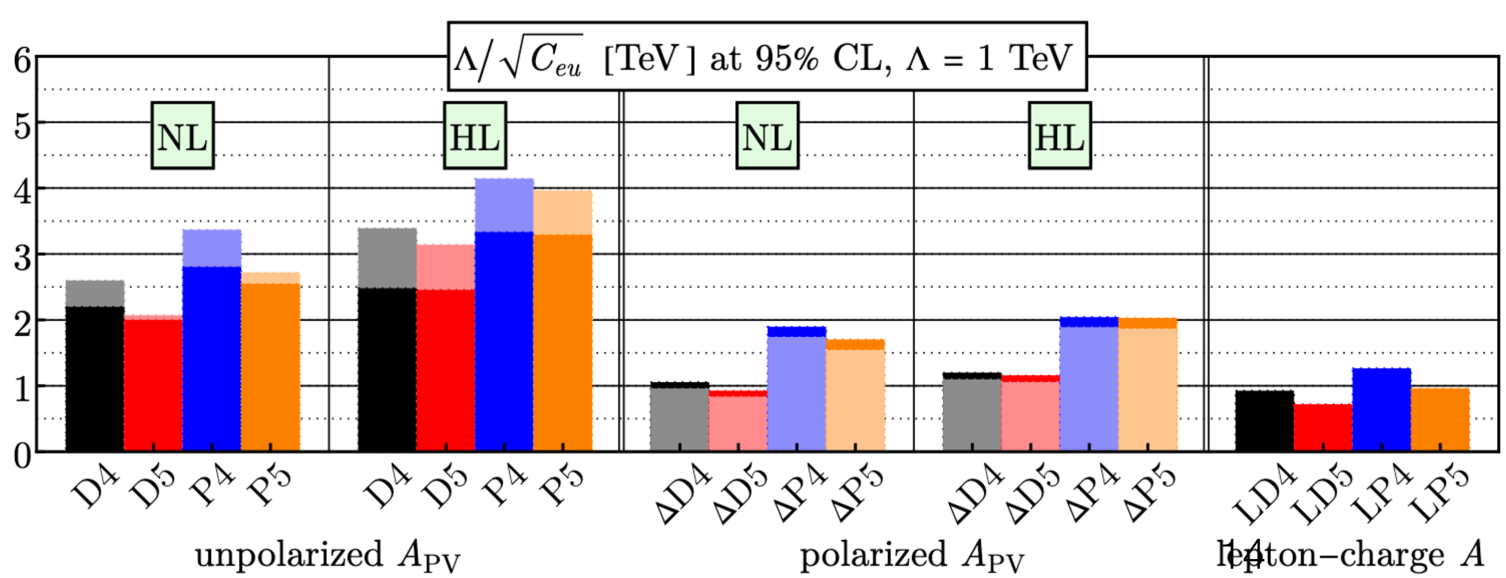
[Boughezal, Emmert, Kutz, Mantry, Nycz, Petriello, Şimşek, Wiegand, Zheng '22]

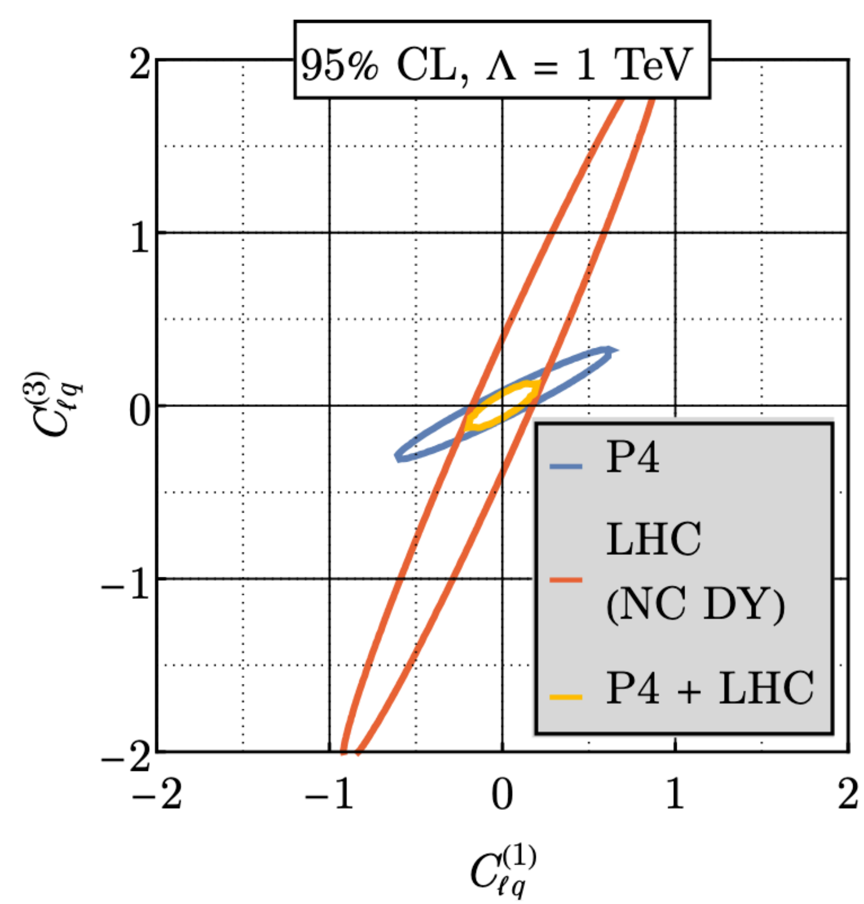
- SMEFT operators contribute to DIS and thus may be probed through PV asymmetry studies.



- EIC is capable of resolving all flat directions that appear in the LHC Drell-Yan data.

- The bounds from the projected EIC data can be much stronger than the LHC data





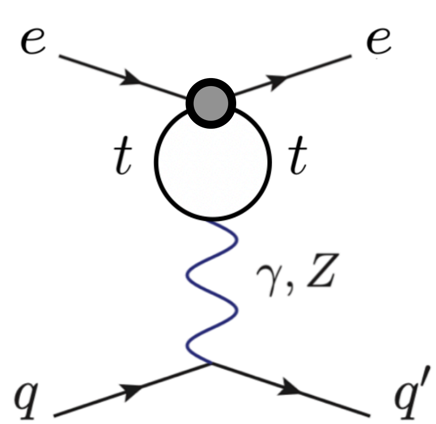
Top quark interactions at the EIC

[Bellafronte, Dawson, Giardino, Liu, 25]
[see also Jiang, Liu, Yan, 25]

- Consider SMEFT four-fermion operators involving the top-quark and leptons:

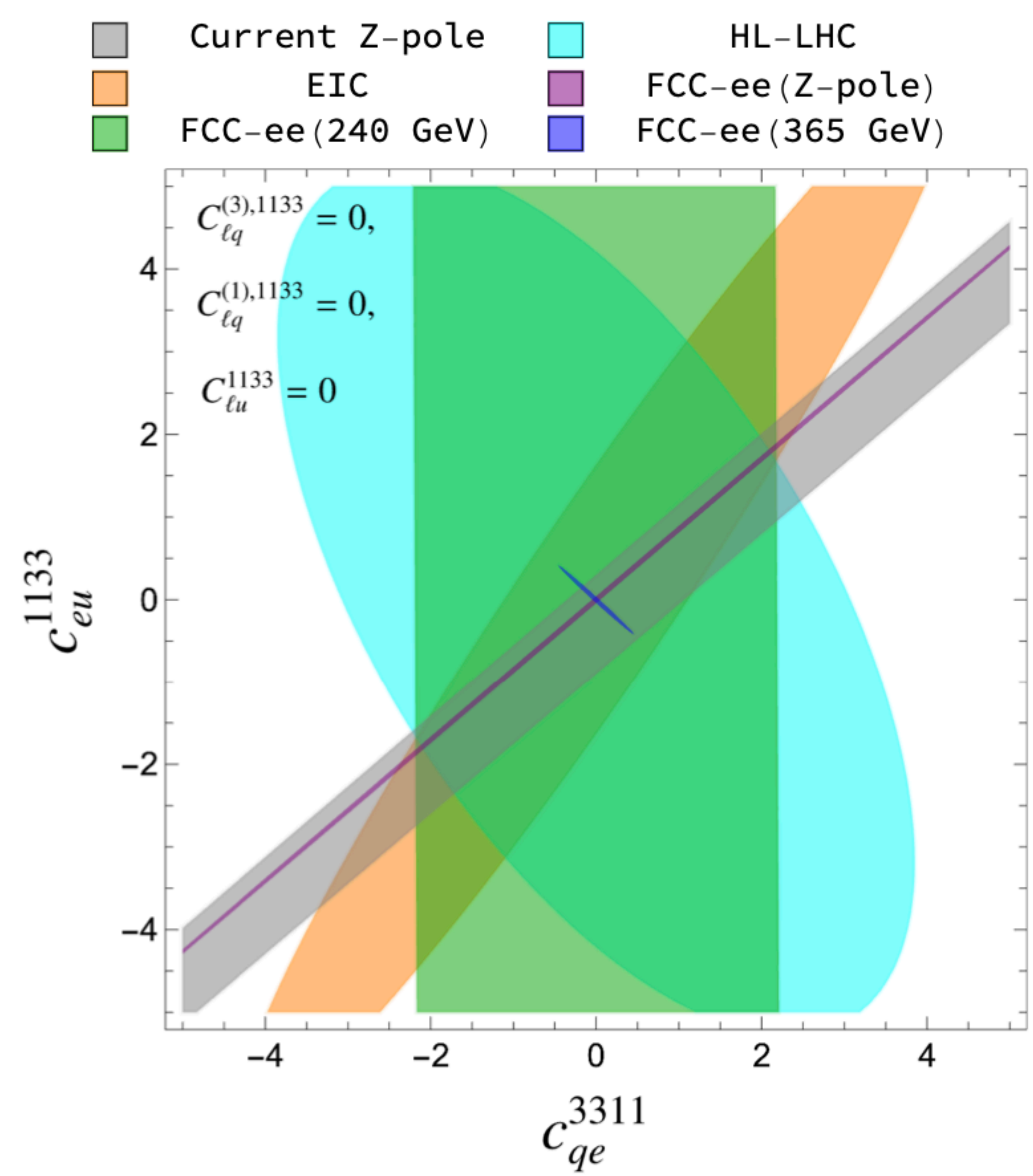
$\mathcal{O}_{\ell q}^{(3),1133} = (\bar{\ell}_L \gamma_\mu \tau^I \ell_L)(\bar{Q}_L \gamma^\mu \tau^I Q_L)$	
$\mathcal{O}_{\ell q}^{(1),1133} = (\bar{\ell}_L \gamma_\mu \ell_L)(\bar{Q}_L \gamma^\mu Q_L)$	$\mathcal{O}_{\ell u}^{1133} = (\bar{\ell}_L \gamma_\mu \ell_L)(\bar{t}_R \gamma^\mu t_R)$
$\mathcal{O}_{qe}^{3311} = (\bar{e}_R \gamma_\mu e_R)(\bar{Q}_L \gamma^\mu Q_L)$	$\mathcal{O}_{eu}^{1133} = (\bar{e}_R \gamma_\mu e_R)(\bar{t}_R \gamma^\mu t_R)$

- These operators contribute to DIS at one-loop:



- At the EIC, a promising approach is to study the left-right asymmetry in polarized DIS

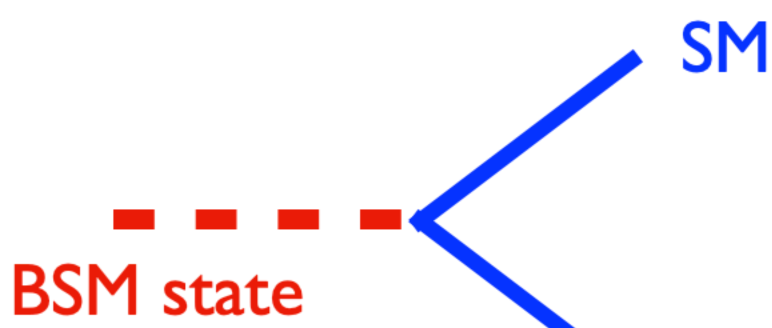
- The EIC can provide a probe that is complementary to experiments, including LEP, LHC, and future high energy colliders



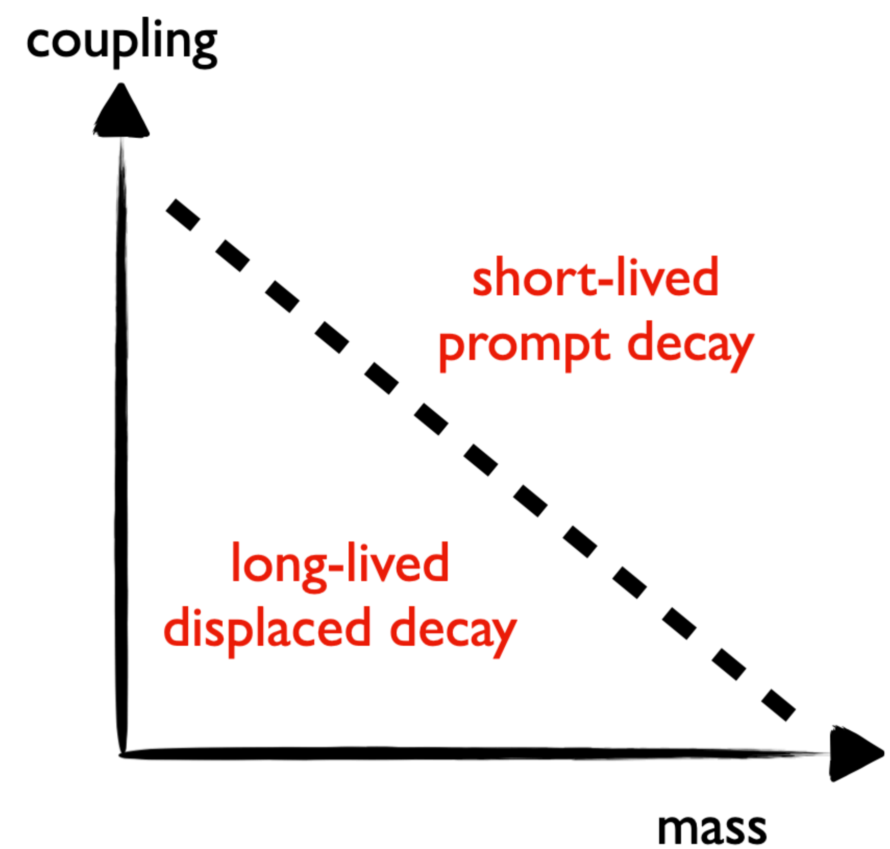
New Light Particles at the EIC

How to search for new light particles at colliders

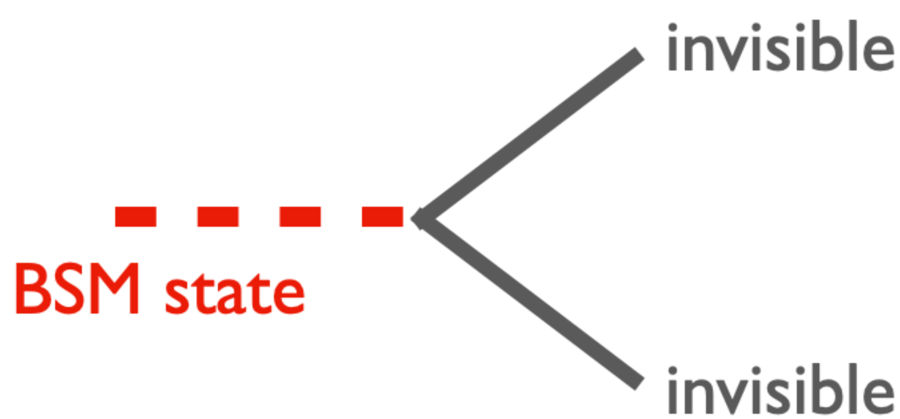
visible decay



$$\Gamma_{\rm BSM} = \tau_{\rm BSM}^{-1} \sim g_{\rm BSM}^2 m_{\rm BSM}^p$$



invisible decay



missing energy signature

Different strategies depending on decays and lifetime of particle

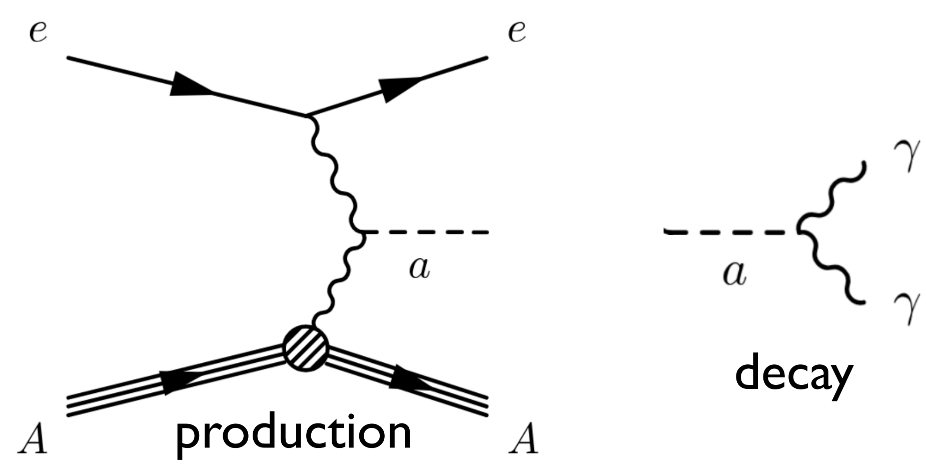
Axion-like particles at the EIC

[Balkin, Hen, Li, Liu, Ma, Soreq, Williams '23]
[see also Liu, Yan '21]

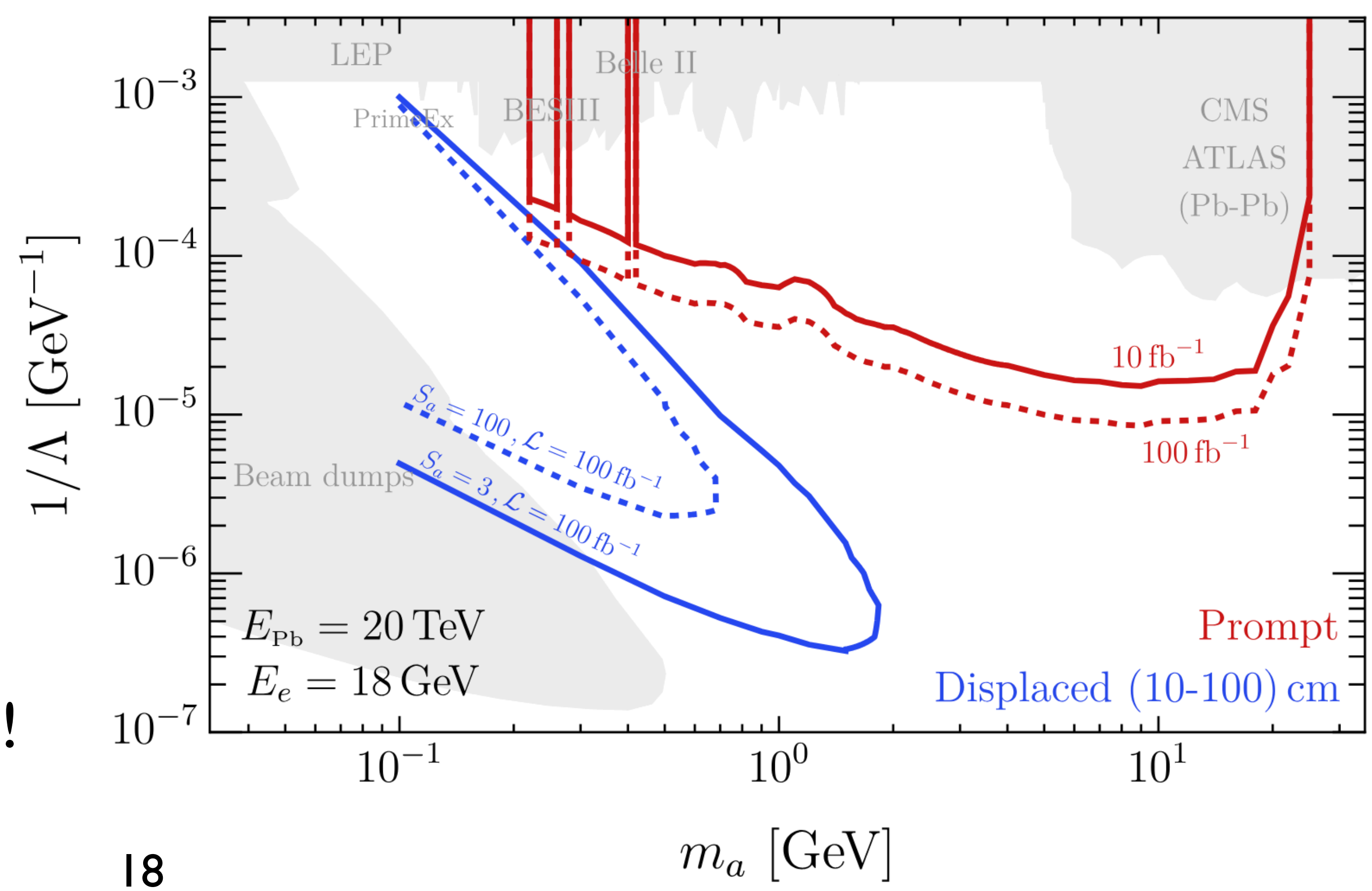
- Photon-coupled ALP benchmark model

$$\mathcal{L}_a = -\frac{1}{2}m_a^2 a^2 - \frac{a}{4\Lambda}F^{\mu\nu}\tilde{F}_{\mu\nu},$$

- Production via photon fusion, leverages coherent scattering with heavy ion (Z^2 enhancement in rate)



- Prompt ALP search (red)
  - look for a diphoton resonance
  - background: light-by-light scattering
- Long-lived ALP search (blue): reconstruct displaced diphoton vertex
- Excellent sensitivity to GeV-scale ALPs!



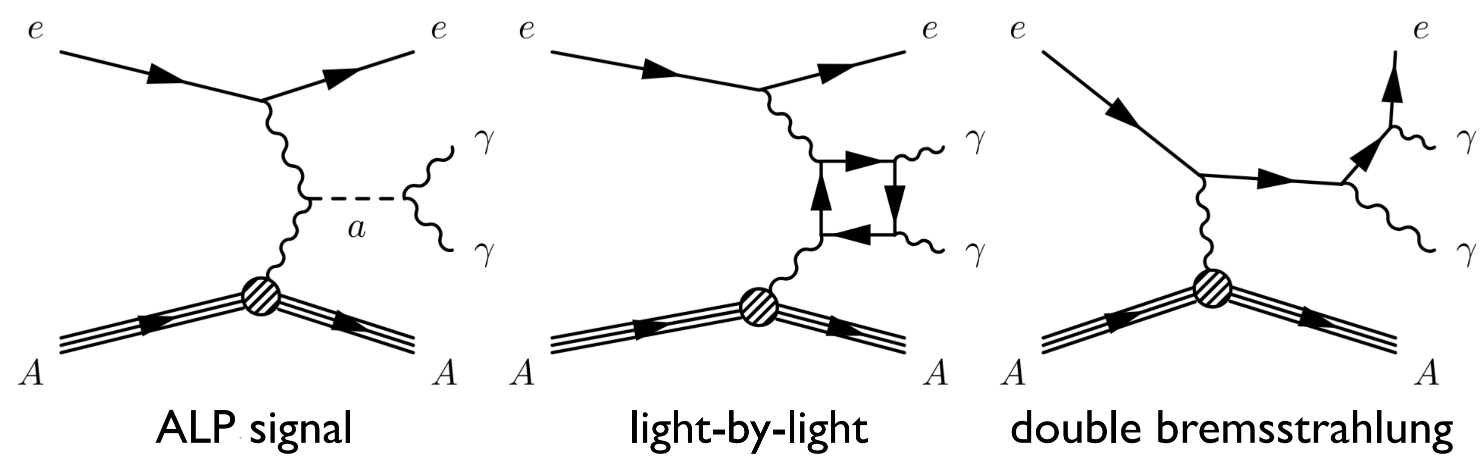
Revisiting prompt photon-coupled ALPs

[BB, Leys, Xie, to appear]

Coherent electron-ion channel

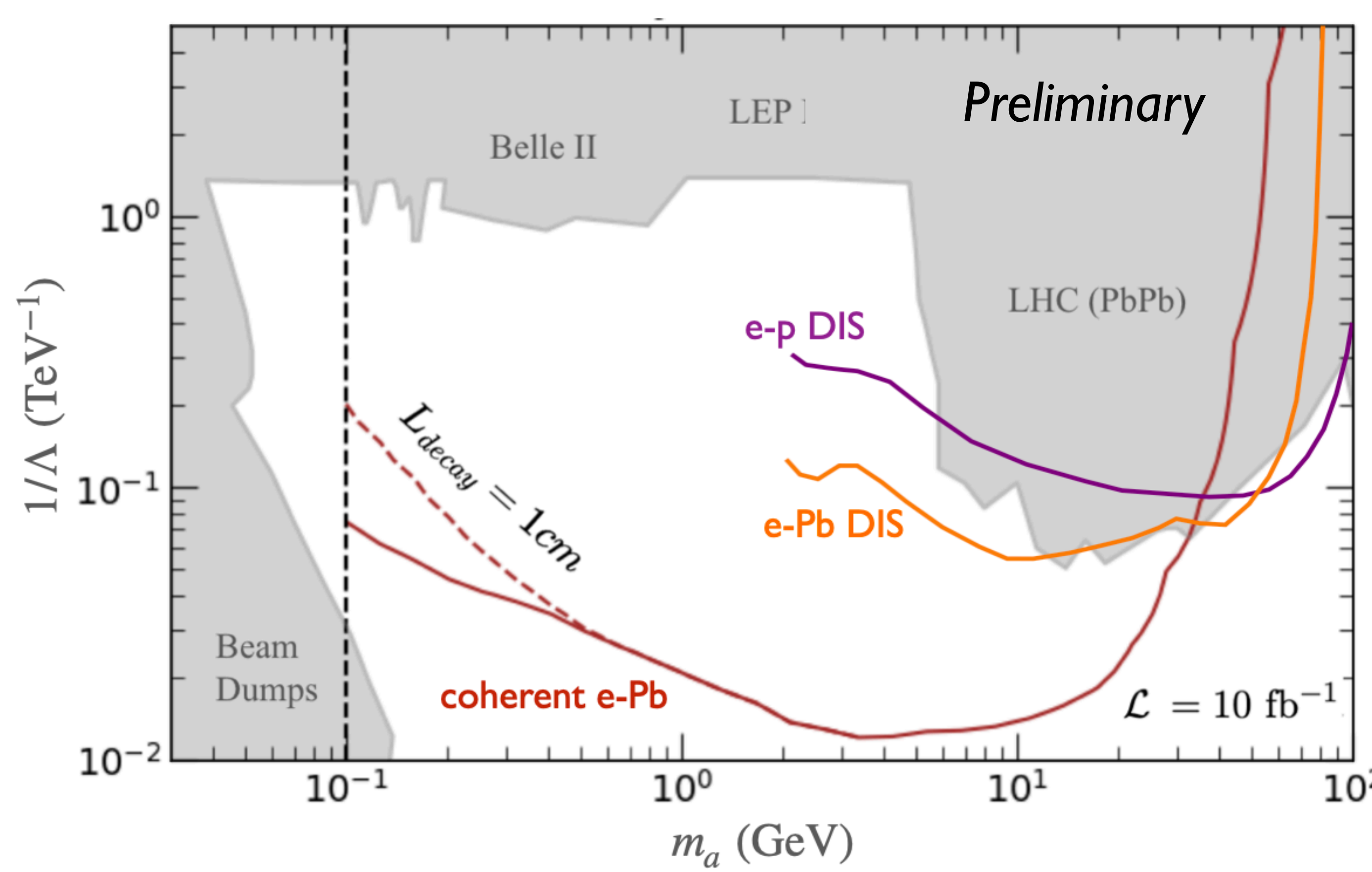
- Demonstrate that large background from double bremsstrahlung is mitigated by kinematic cuts
- Full simulation of light-by-light background with 2→3 kinematics (SuperChic) allows us to perform further optimization cuts

[Harland-Lang, Khoze, Ryskin (SuperChic) '18]



Other channels

- electron-ion DIS (orange)
  - best sensitivity at intermediate ALP masses
- electron-proton DIS (purple)
  - best sensitivity at higher ALP masses



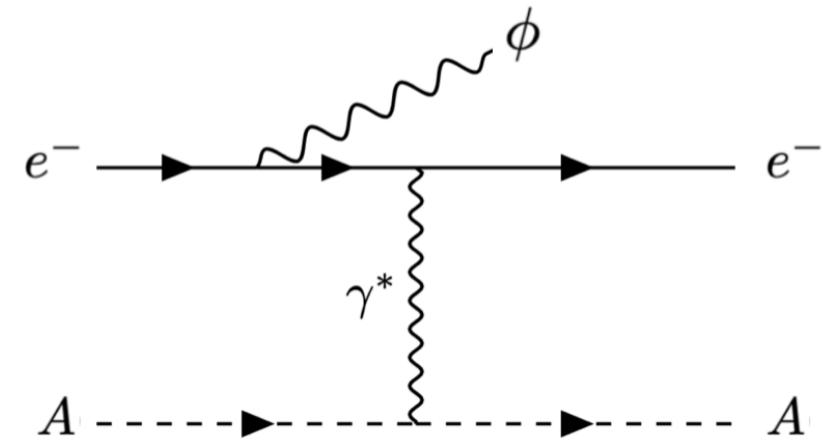
Invisible dark bosons at the EIC

[Davoudiasl, Liu, '25]

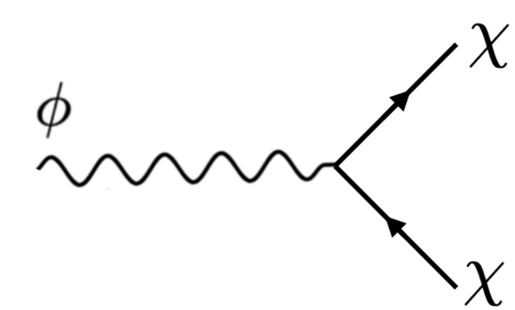
- Generic scalar ϕ and vector ϕ_μ dark boson interactions with electrons and invisible particle χ

$$\mathcal{L}_S = g_S^e\,\phi\bar{e}e + g_S^\chi\,\phi\bar{\chi}\chi\,,$$
$$\mathcal{L}_V = g_V^e\,\phi_\mu\bar{e}\gamma^\mu e + g_V^\chi\,\phi_\mu\bar{\chi}\gamma^\mu\chi\,,$$

- Production of ϕ via bremsstrahlung, coherent scattering with heavy ion (Z^2 enhancement)



production



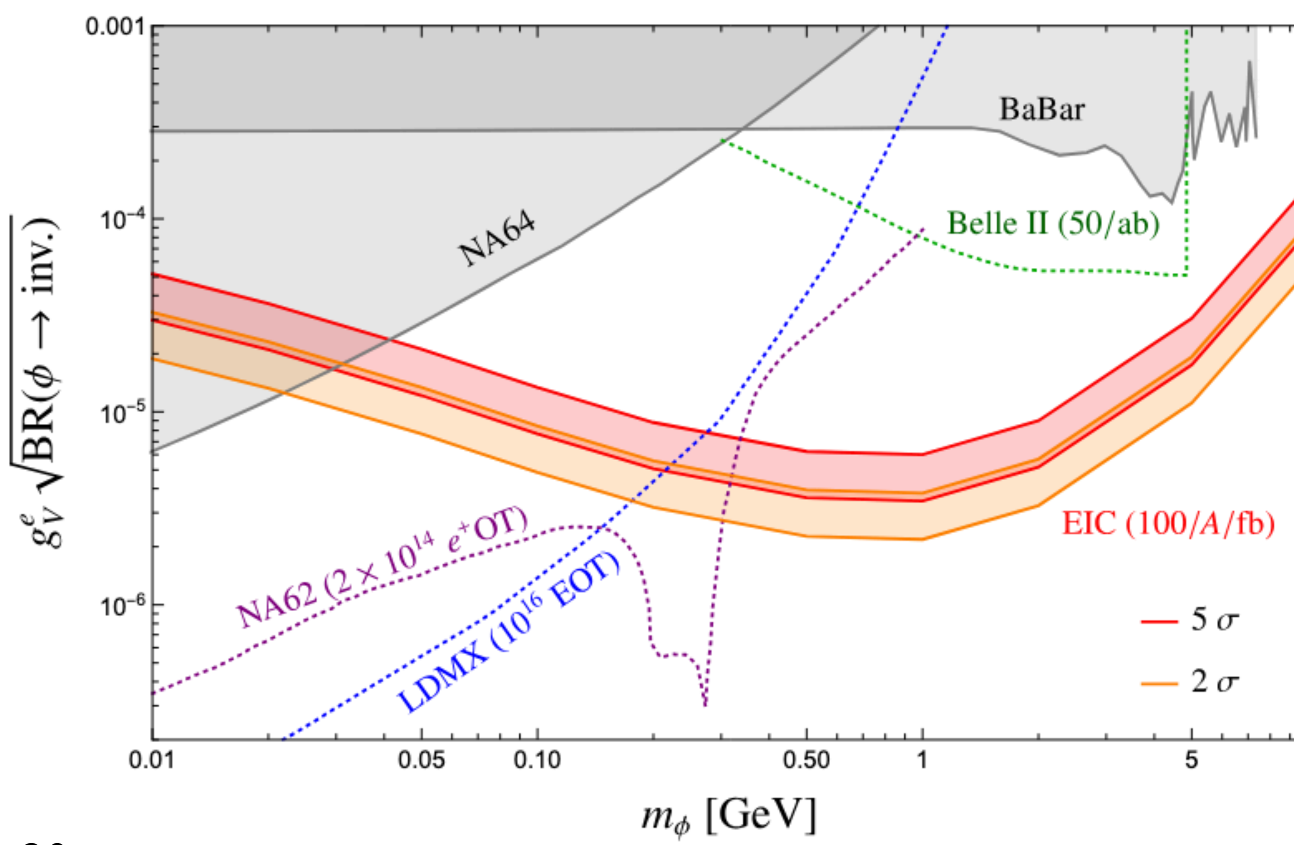
decay (invisible)

- ϕ decays invisibly, $\phi \to \chi\bar{\chi}$

- ϕ carries most of the electron beam energy, leading to a soft, central electron in the final state

- Background: QED bremsstrahlung where the photon is missed.

- The EIC has powerful sensitivity GeV-scale invisibly decaying dark bosons, complementing fixed target searches and B-factories



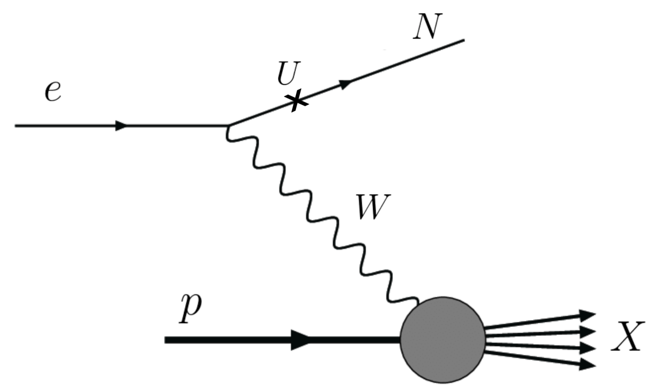
Heavy Neutral Leptons at the EIC

[BB,Ghosh, Han, Xie, '22]

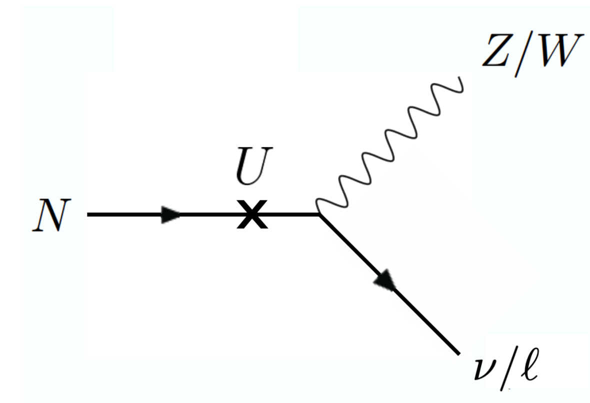
- Heavy neutral leptons (HNLs) inherit weak interactions from mixing with SM neutrinos

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

- HNL production and decay via weak interactions



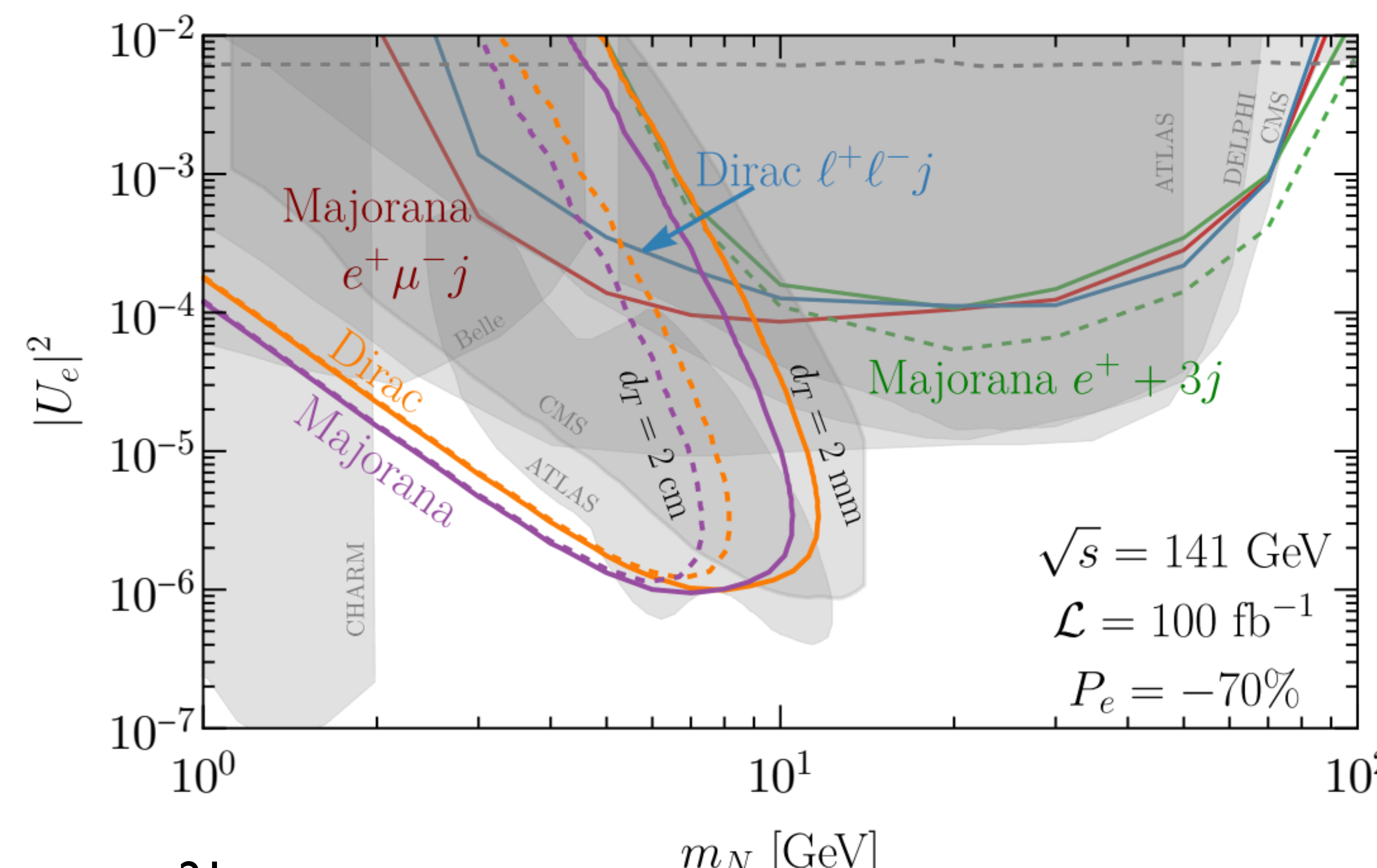
production



visible decay

- Both prompt and displaced HNL searches are possible

- Modest improvements in reach are possible at the EIC, relative to current LHC constraints

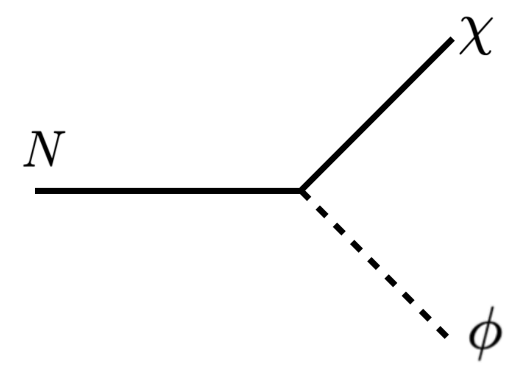


Invisible HNLs at the EIC

[Bertoni, Ipek, McKeen, Nelson '14]
[BB,Han, McKeen, Ghosh, Han '17]

- Neutrino portal dark matter — Heavy neutral leptons may serve as mediator to the dark sector

$$\mathcal{L} = -y\,\overline{L}_L\,H\,N_R - \lambda\,\phi^*\,\overline{N}\,\chi + \text{h.c.}$$



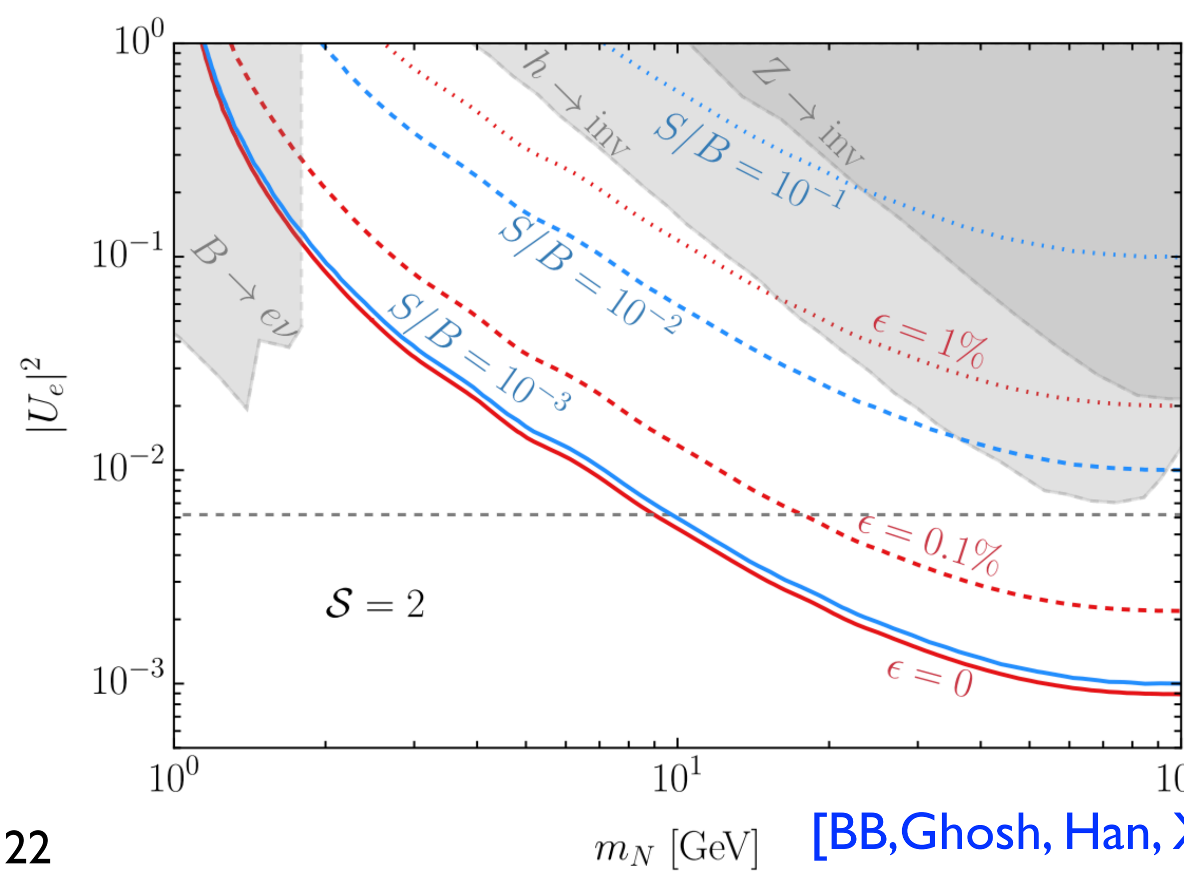
invisible decay

- In this scenario, the HNL decays invisibly, leading to a mono-jet signature at the EIC

- Signature: reduced mono-jet rate relative to SM prediction:

$$\sigma(ep \to j + \not{E}_T) = \sigma(ep \to j + \nu_e) + \sigma(ep \to j + N)$$
$$= \sigma_{\rm SM}(ep \to j + \nu_e)\,\left[(1 - |U_e|^2) + |U_e|^2\Phi(m_N)\right]$$

- EIC may have sensitivity to invisibly decaying HNLs, depending on ability to control systematic uncertainties of SM process



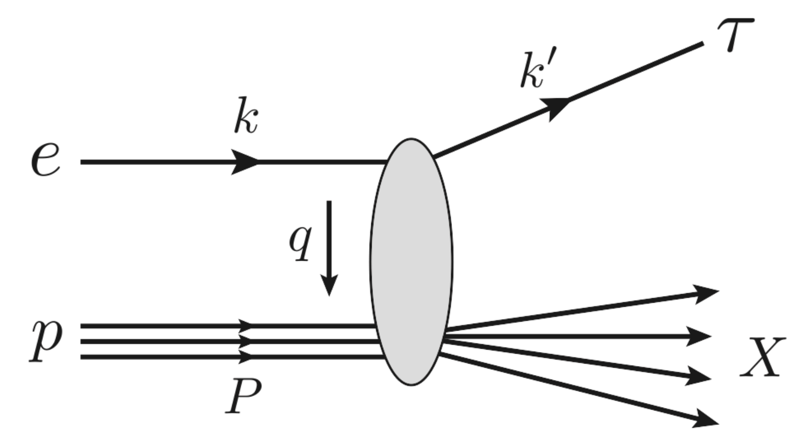
[BB,Ghosh, Han, Xie, '22]

Lepton Flavor Violation

Lepton flavor violation at the EIC

[Cirigliano, Fuyuto, Lee, Mereghetti, Yan '21]
[see also Gonderinger, Ramsey-Musolf '10]

- The EIC can search for $e - \tau$ charged lepton flavor violation (CLFV) via $e^- + p \to \tau^- + X$



- Considering backgrounds, the most promising tau decay channels are $\tau \to \mu\bar{\nu}_\mu\nu_\tau$ and $\tau \to X_H\nu_\tau$

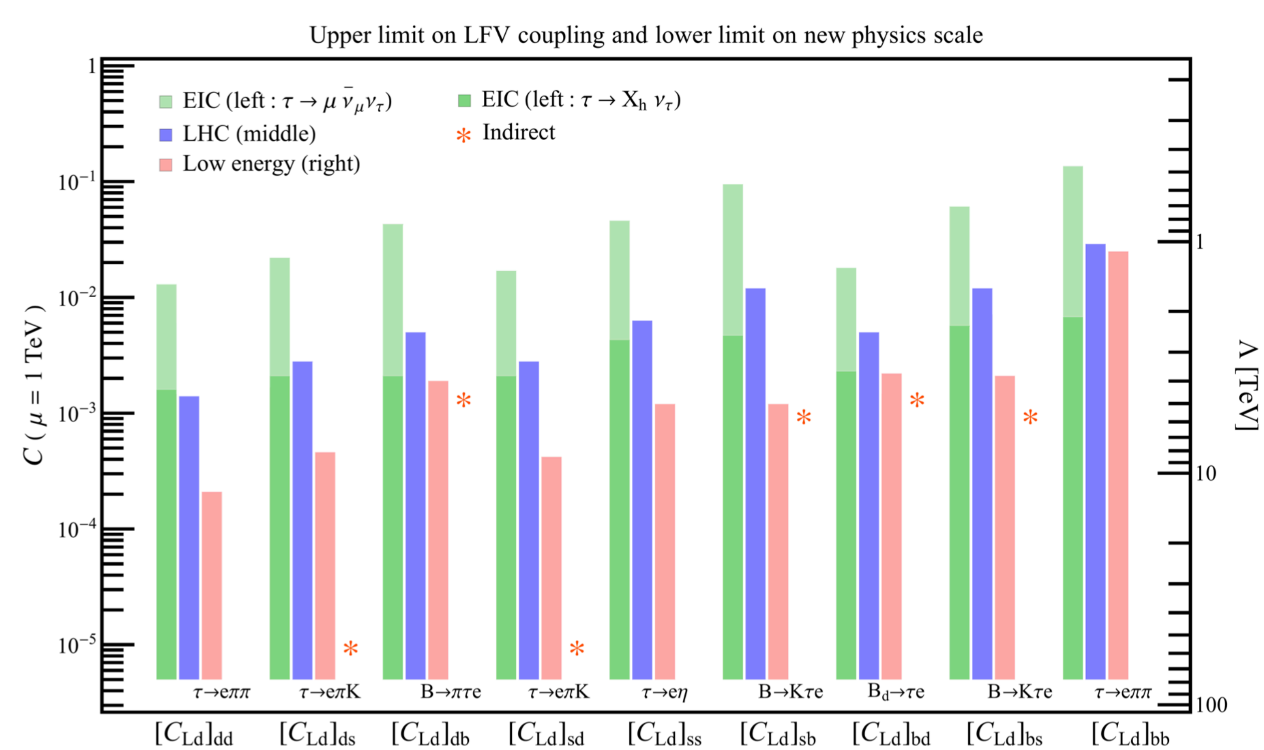
- Within SMEFT, operators leading to CLFV include
  - $Ze\tau$ and $he\tau$ contact operators,
  - $\gamma e\tau$ and $Ze\tau$ dipole operators.
  - $e\tau ff'$ four-fermion operators

$$\varphi^\dagger i D_\mu \varphi\, \bar{\ell}_L, \gamma^\mu \ell_L, \quad \bar{\ell}_L \sigma^{\mu\nu} \varphi e_R B_{\mu\nu},$$

$$\bar{\ell}_L \sigma^{\mu\nu} \varphi e_R B_{\mu\nu}, \quad \ell_L \gamma^\mu \ell_L\, q_L \gamma_\mu q_L, \quad \ldots$$

- Low energy probes (e.g., τ or meson CLFV decays) and the LHC provides stronger constraints on most SMEFT CLFV operators

- However, the EIC can have comparable sensitivity to SMEFT $e\tau ff'$ four-fermion SMEFT operators involving c or b quarks.

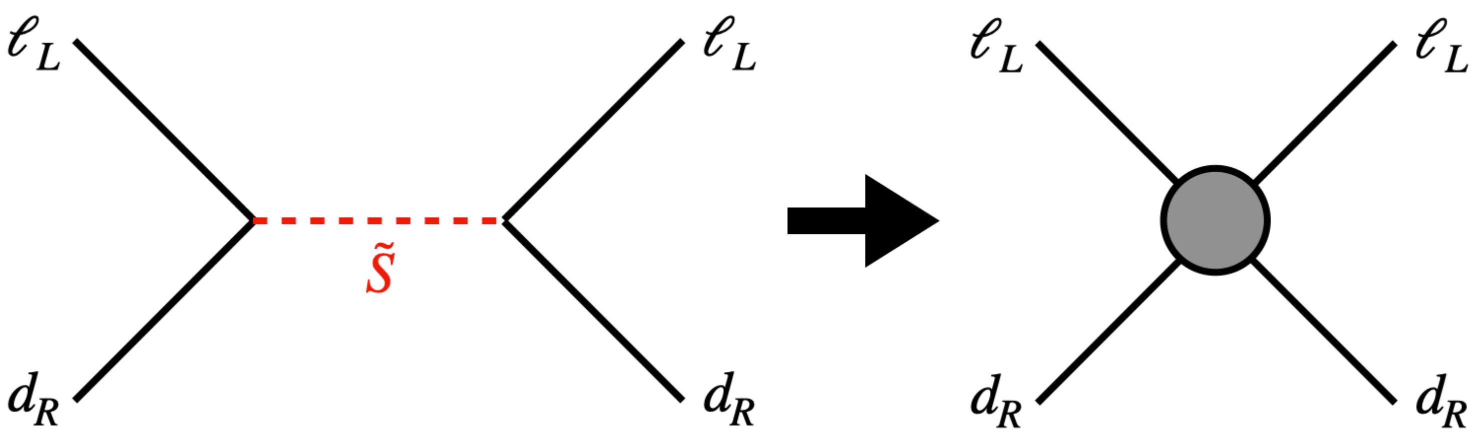


Leptoquark UV completions

[Cirigliano, Fuyuto, Lee, Mereghetti, Yan '21]

- The SMEFT operators can originate from a UV completion containing a heavy leptoquark, e.g.,

$$\mathcal{L}_{\widetilde{S}_{1/2}} = \tilde{\lambda}^{\alpha a}\, \bar{d}_R^{\alpha}\, \ell_L^{a}\, \widetilde{S}_{1/2}^{\dagger} + \text{h.c.}\ .$$

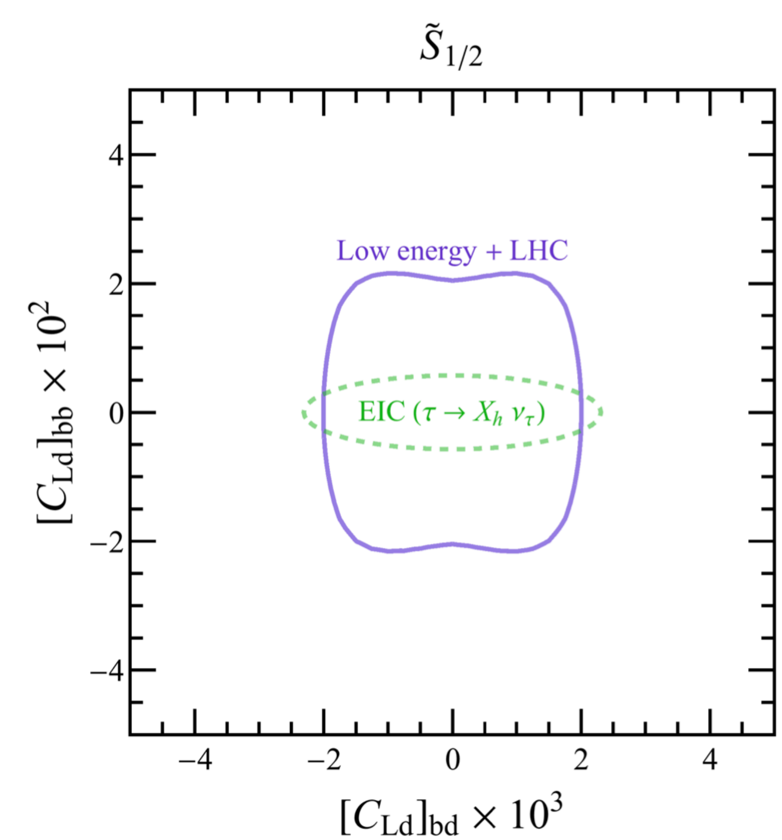


$$\frac{4G_F}{\sqrt{2}} C_{Ld}\, \bar{\ell}_L \gamma^\mu \ell_L\, \bar{d}_R \gamma_\mu d_R + \text{h.c.}$$

$$\left[C_{Ld}\right]_{\alpha\beta ab} = \frac{v^2}{4M_{LQ}^2} (\tilde{\lambda}^\dagger)^{a\beta} (\tilde{\lambda})^{\alpha b}$$

- Such UV completions, by and large, bear out the expectations obtained from the SMEFT analysis

- The EIC can provide competitive probes of leptoquarks with couplings to bottom quarks



Lepton-flavor-violating ALPs at the EIC

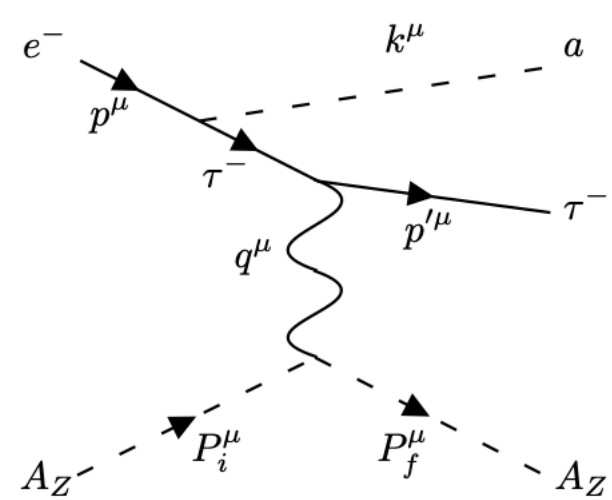
[Davoudiasl, Marcarelli, Neil '23]

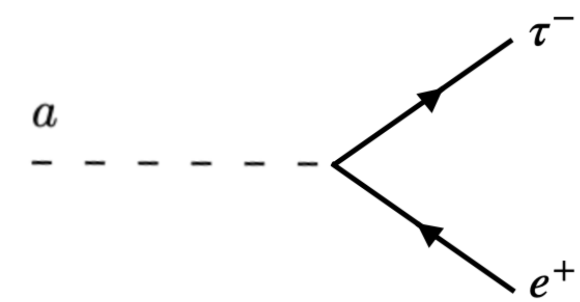
- ALPs may have flavor-violating interactions

$$\mathcal{L}_\tau \approx \frac{C_{\tau e} m_\tau}{\Lambda} a \bar{\tau} (\sin\theta_{\tau e} - \cos\theta_{\tau e}\gamma_5) e$$

- Consider e-τ-ALP coupling with lepton flavor violating signature:

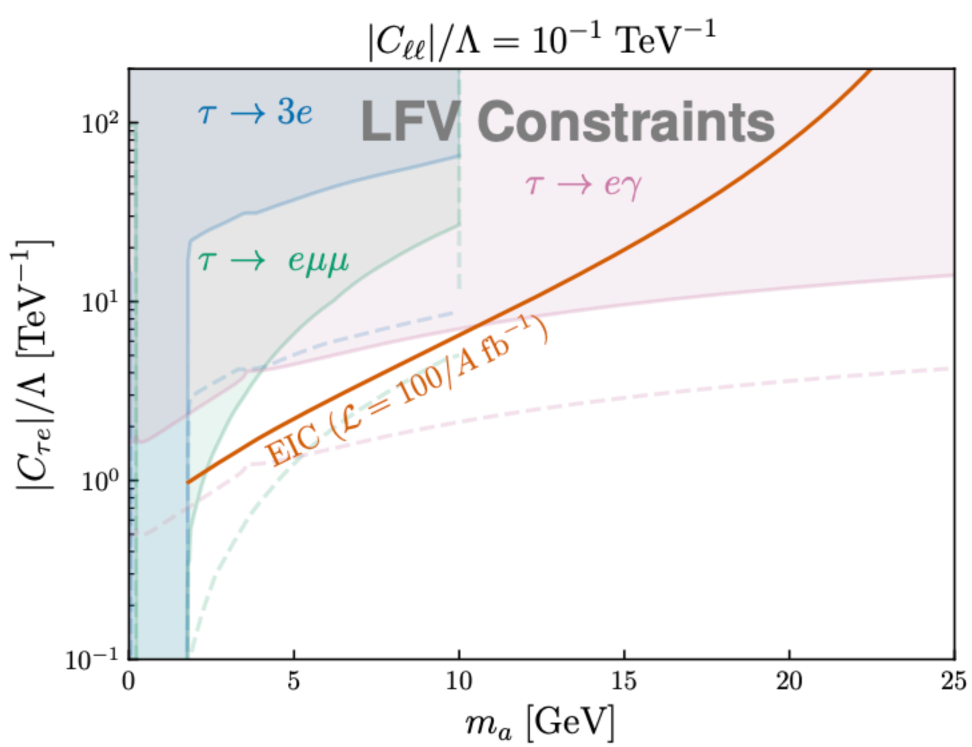
$$e^- A_Z \to a\tau^- A_Z \to (e^+\tau^-)\tau^- A_Z$$

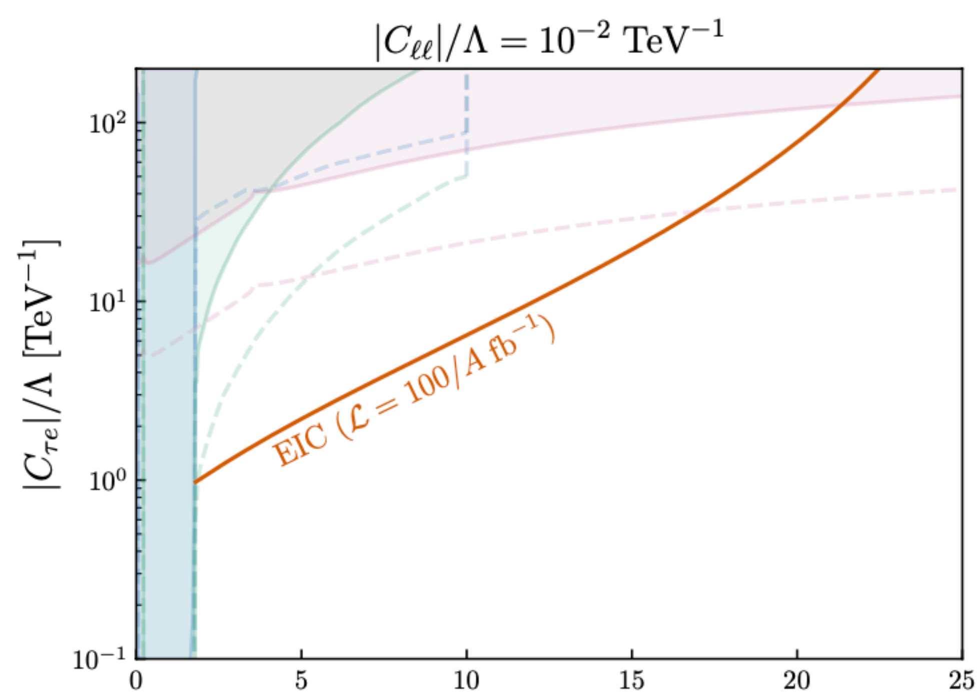




- Primary background: Bethe-Heitler production of τ pairs

- EIC searches for LFV ALPs could reach sensitivities rivaling those from rare LFV decays.





The EIC offers promising opportunities for BSM searches— its full potential remains to be explored.

<u>Resources:</u>

- EIC Yellow Paper

  https://arxiv.org/abs/2103.05419

- Snowmass 2021 White Paper: Electron Ion Collider for High Energy Physics

  https://arxiv.org/abs/2203.13199

- INT-UW workshop: "*Electroweak and BSM physics at the EIC*"

  https://www.int.washington.edu/programs-and-workshops/24-87w

- CFNS workshop at Stony Brook: "*New opportunities for BSM searches at the EIC*"

  https://indico.cfnssbu.physics.sunysb.edu/event/341/

Outlook

- The EIC @ BNL will be the flagship collider in the U.S. and will open a new frontier into QCD.
- The powerful capabilities of the the EIC and ePIC detector needed for the primary QCD program also make it well-suited to the search for new physics.
    - high luminosity, intermediate CM energies, beam polarization, clean collider environment, multi-purpose hermetic detector, excellent particle ID & tracking.
- A number of case studies demonstrate this point:
    - Precision measurements & SMEFT, new light particles, charged lepton flavor violation, …
- There is significant interest from the EIC community to expand the physics case.
- It is still very early days for BSM @ EIC. More work is needed to understand the full potential!