# Looking Beyond the Standard Model at the EIC

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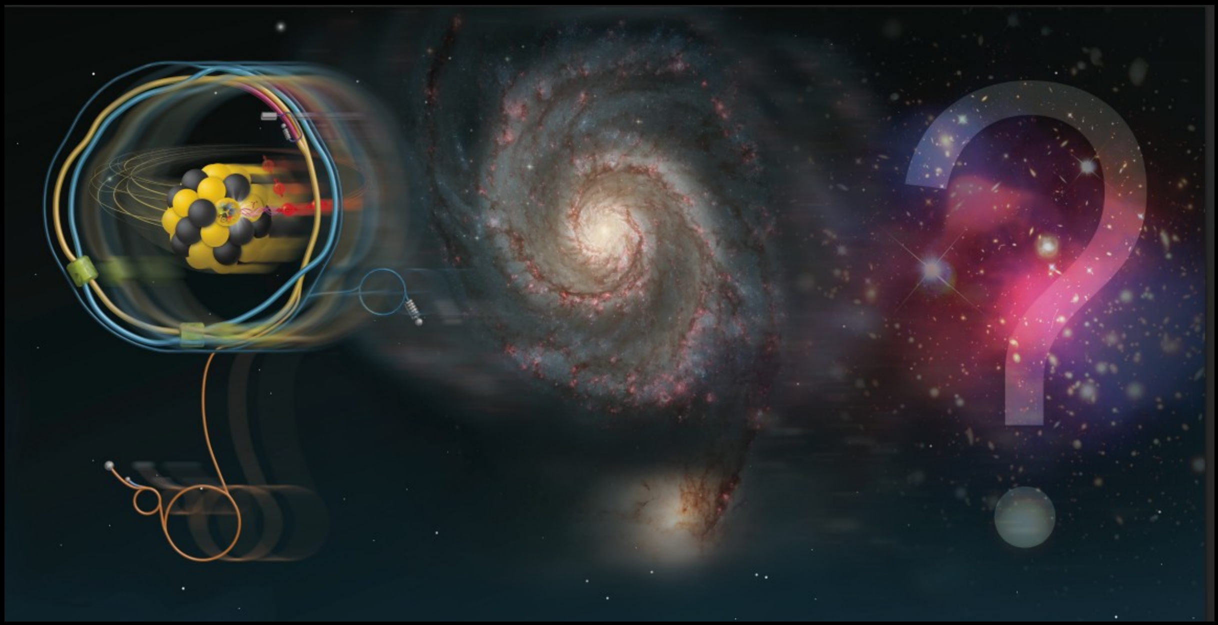
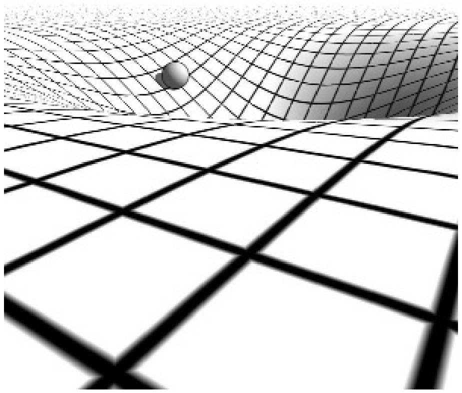
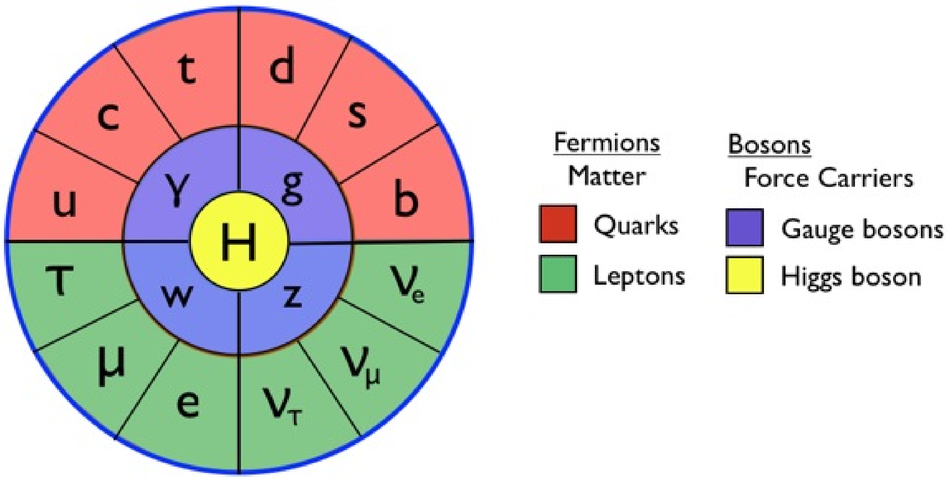


Electromagnetic Interactions with Nucleons and Nuclei (EINN 2025)
October 28-November 1, 2025, Paphos, Cyprus

## State of the art:

- Gravity: still General Relativity ($>$ 100 years!)
- Subatomic phenomena: Standard Model






Particles of the Standard Model

- There are some, often modest and transient, anomalies

**SM and GR: consistent with all "settled" tests**

**However, we are not done!**

# The Case for New Physics

- Despite great success of SM+GR, new physics is needed

- There is strong experimental evidence for this inference:

★ **Neutrino flavor oscillations $\rightarrow m_\nu \neq 0$**

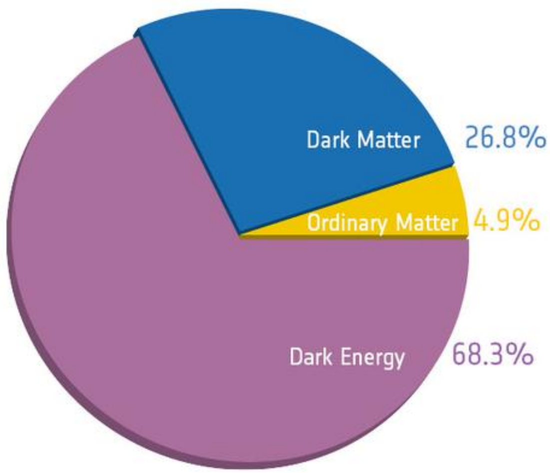
- Adding right-handed neutrinos (over a broad range of masses) can explain this
- Nature of $m_\nu$ unknown

★ **Cosmology**

- What is accelerating cosmic expansion? (dark energy; may be vacuum energy)
- What is holding galaxies together? (dark matter; may have its own sector)
- What caused ordinary matter asymmetry? (requires more CP violation,...)

**95% of the Universe is unknown to us!**

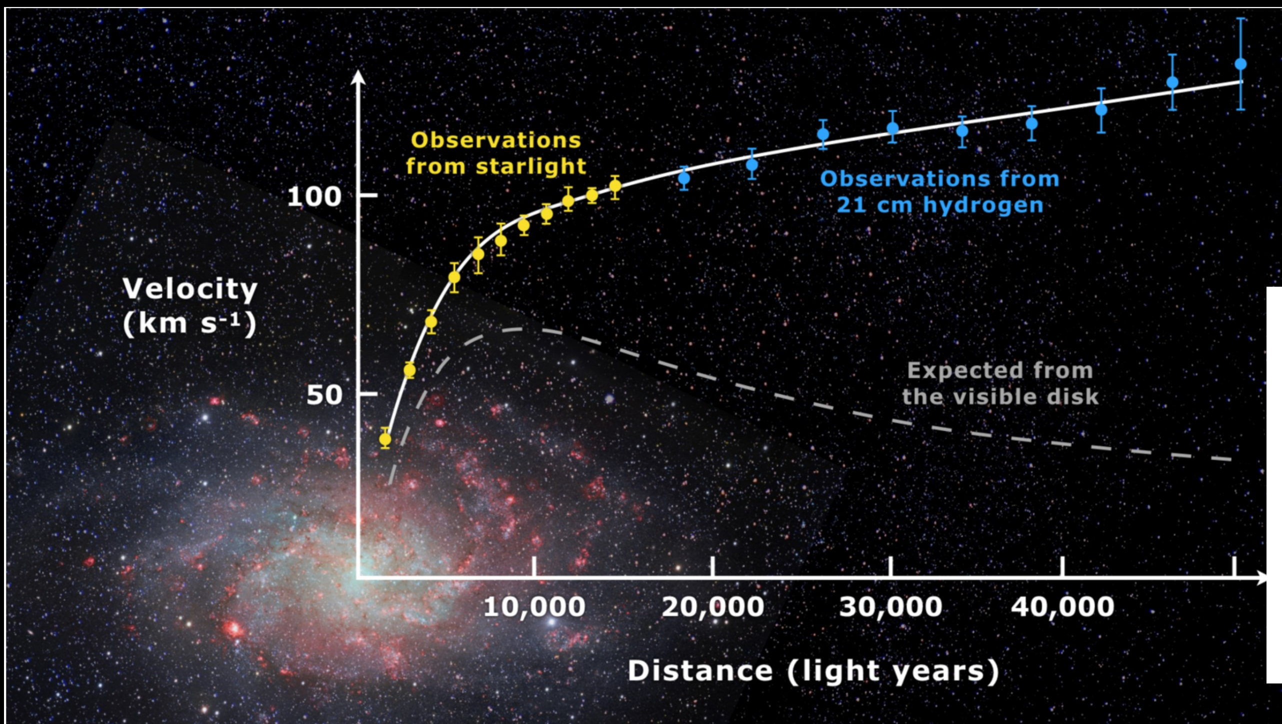
Planck



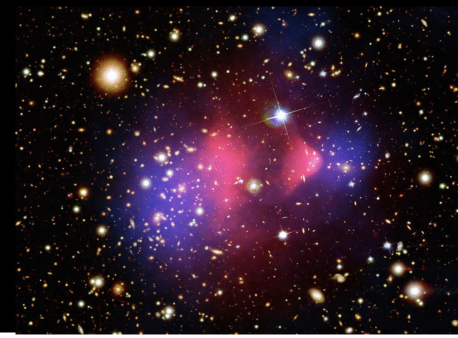

- There are also theoretical hints
- Why is gravity so weak?
- Why is CP violation so suppressed in QCD?
- . . .

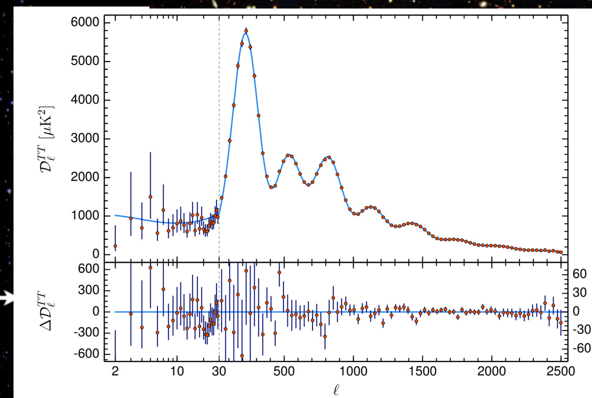
# Dark matter (DM)

- Robust evidence from cosmology and astrophysics
  - Rotation curves of galaxies, CMB, Bullet Cluster, . . .




Mario De Leo, CC BY-SA 4.0, via Wikimedia Commons



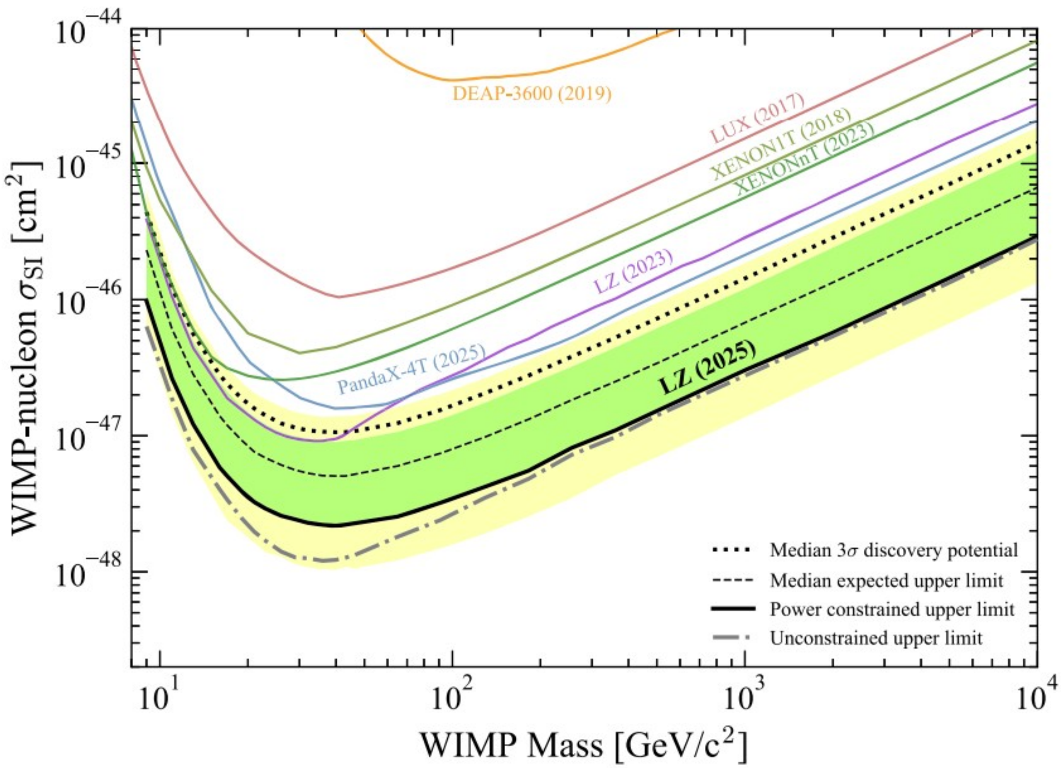



Planck Collaboration; 1807.06209

- $\sim$ 27% of energy density
- Feeble interactions with atoms, photons
- Self-interactions not strong ($\sigma \lesssim 1$ barn)
- Not explained in SM

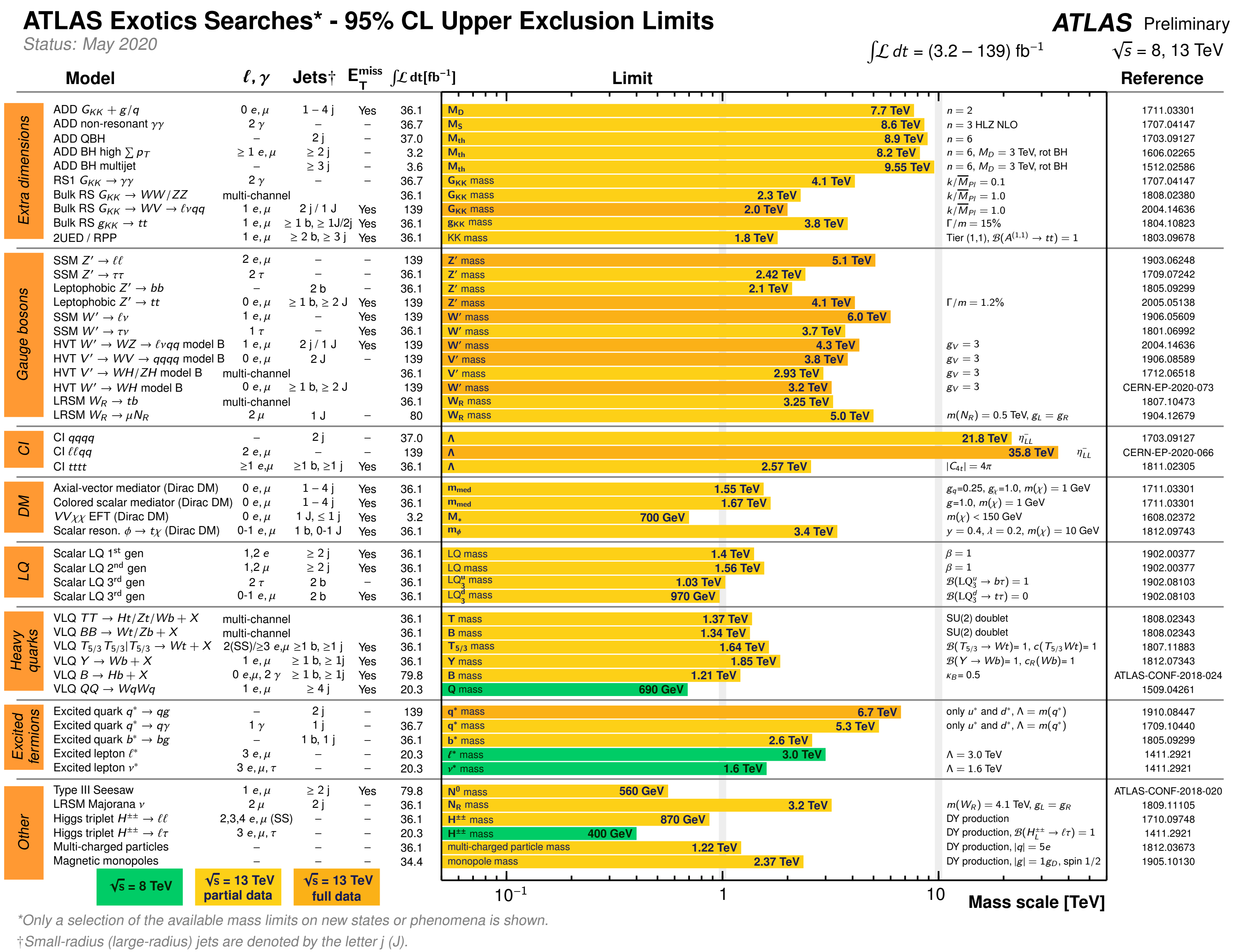
# Weak Scale and DM

- Weakly interacting massive particles (WIMPs)
- Longtime search targets
- Motivation: physics of the Higgs potential
- $M_{\text{new}} \gtrsim M_H \approx 125$ GeV (weak scale); natural thermal relics



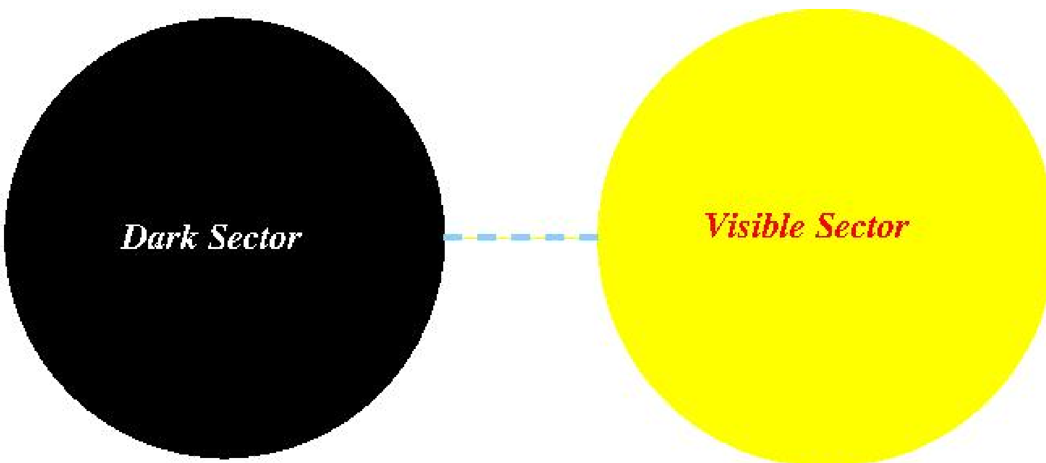

J. Aalbers *et al.*, LUX-ZEPLIN (LZ) Collab., PRL 135 (2025) 1, 011802

- New physics not close to $M_H$ (sample below, LHC Run 2)



# Dark Sectors

- With lack of evidence for new physics near weak scale ($M_H$), alternatives to WIMPs have been put forth in recent years
- DM could be light ($m \lesssim$ GeV), not associated with EW symmetry breaking (EWSB)
- DM may reside in a separate *sector* with its own forces
- Analogy with SM, the "visible sector"
- Visible and dark sectors connected by feeble interactions
- Mediators could be light, accessible to low energy experiments ($\sqrt{s} \lesssim 100$ GeV)



# The Electron Ion Collider (EIC)

2103.05419, EIC Yellow Report

- EIC, to be built at BNL: next collider with relatively large $\sqrt{s}$, luminosity

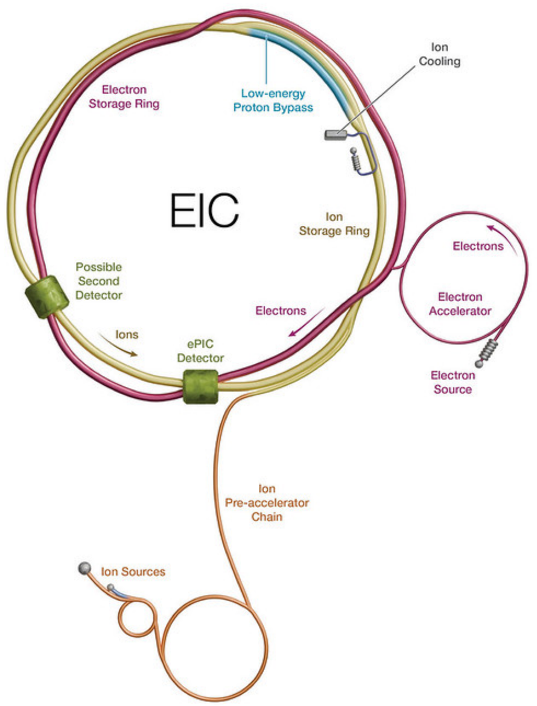
- Up to $E_e = 18$ GeV, 275 GeV proton beam

- Large nuclei (high $Z$): *e.g.* gold, lead

- 110 GeV per nucleon ion beam, *e.g.* Au

- Fixed target equivalent of $\sim 4$ TeV $e$-beam

- $\sim 100$ fb$^{-1}/A$ possible




- New frontier in studying hadronic systems

- *E.g.* spin composition and parton distribution in nucleons,....

- Unique capability: $\sim 70\%$ polarized $e$ and $p$ beams

What can we learn about new physics at the EIC?*

* This talk: only a sample of possibilities; unfortunately many interesting works not covered

# EIC and New Physics

- We will consider two large classes of beyond SM (BSM) physics:

  (I) Heavy physics, indirect signals

  (II) Light physics, perhaps from dark/hidden sectors, direct signals

- Class (I) signals generally require precision

  - Could be formulated in the language of SM effective field theory (SMEFT)

  - Beam polarization can be leveraged

- Class (II) physics could lead to direct detection of new particles

  - A variety of models

  - Access to new states around the GeV scale

  - Large atomic number ions can provide $Z^2$ enhanced coherent cross sections

We will mostly focus on Class (II) in this talk.

# Heavy New Physic and SMEFT

- Physics above weak scale, may be accessible to LHC, future colliders
- Integrate out heavy states: higher-dimension operators (point-like interactions)
- BSM encoded in SMEFT: $\Lambda > \langle H \rangle$ scale of new physics

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + c_5^1 \frac{HLHL}{\Lambda} + \sum_i c_6^i \frac{O_i}{\Lambda^2} + \ldots$$

  - Wilson coefficients $c_d^i$; operators $O_i$ of dimension $d \geq 5$, made of SM fields

Example: SMEFT Constraints at LHC and EIC Boughezal, Petriello, Wiegand, 2004.00748

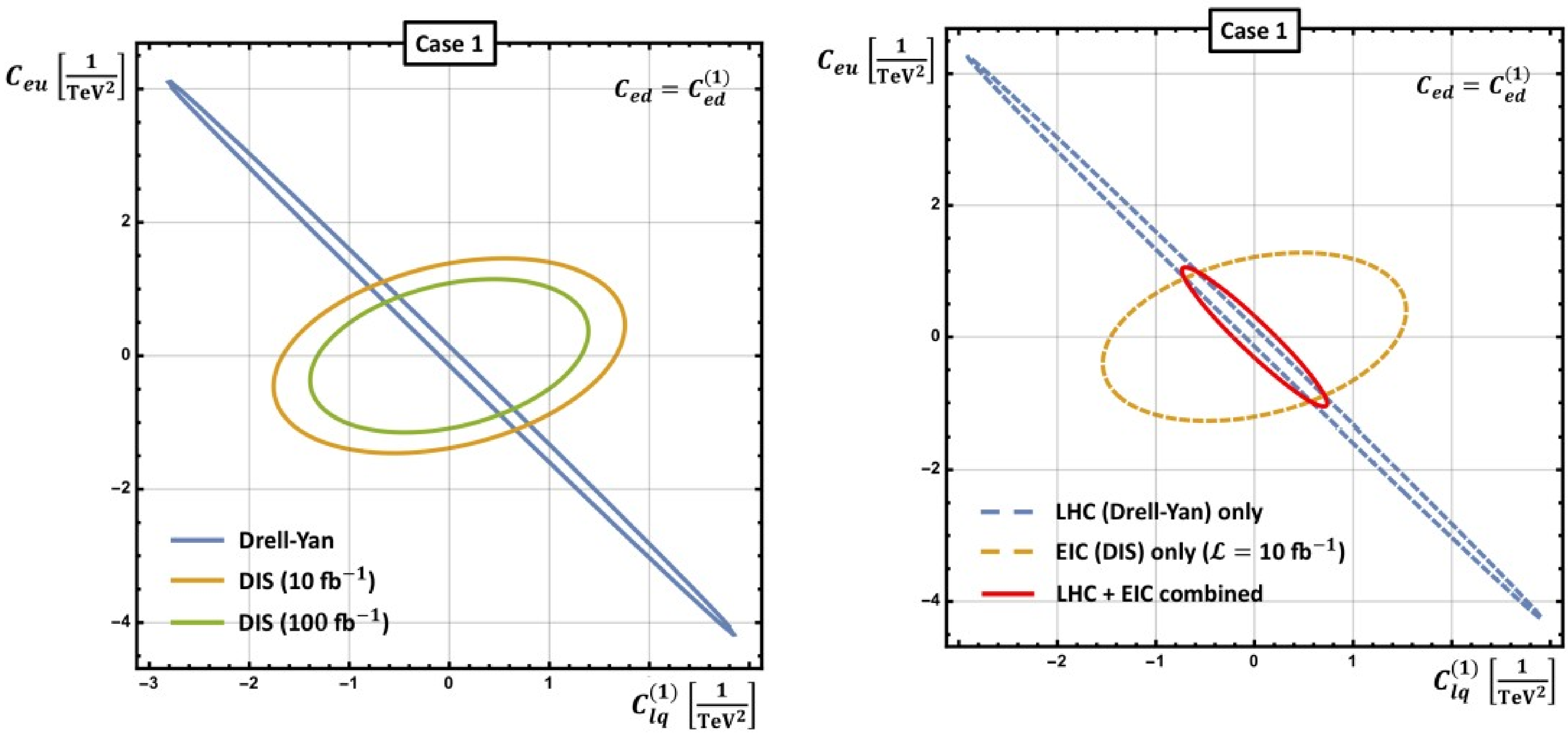
- 4-fermion operators: deep inelastic scattering (DIS) and Drell-Yan processes

- Drell-Yan: $pp \to l\bar{l}$ $(q\bar{q} \to l\bar{l})$, LHC ; DIS: $lp \to l'X$ $(lq \to l'q')$, EIC

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

From 2004.00748

- $\sim 20$ fb$^{-1}$ of ATLAS data at $\sqrt{s} = 8$ TeV (1606.01736)
- EIC: $\sqrt{s} \approx 140$ GeV, 70% $e, p$ polarization
- EIC integrated luminosity: 10 and 100 fb$^{-1}$
- DIS cross section: taking advantage of both $e$ and $p$ polarizations




From 2004.00748 (Contours: 68% C.L.)

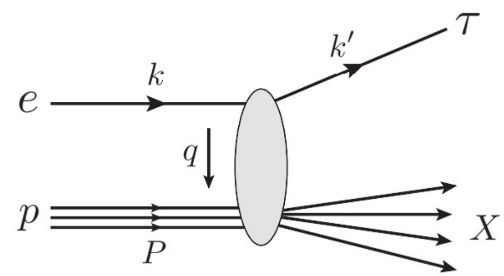
# Charged Lepton Flavor Violation (LFV)

- Could be mediated by, *e.g.*, $t$ channel heavy ($>$ 1 TeV) leptoquarks at EIC

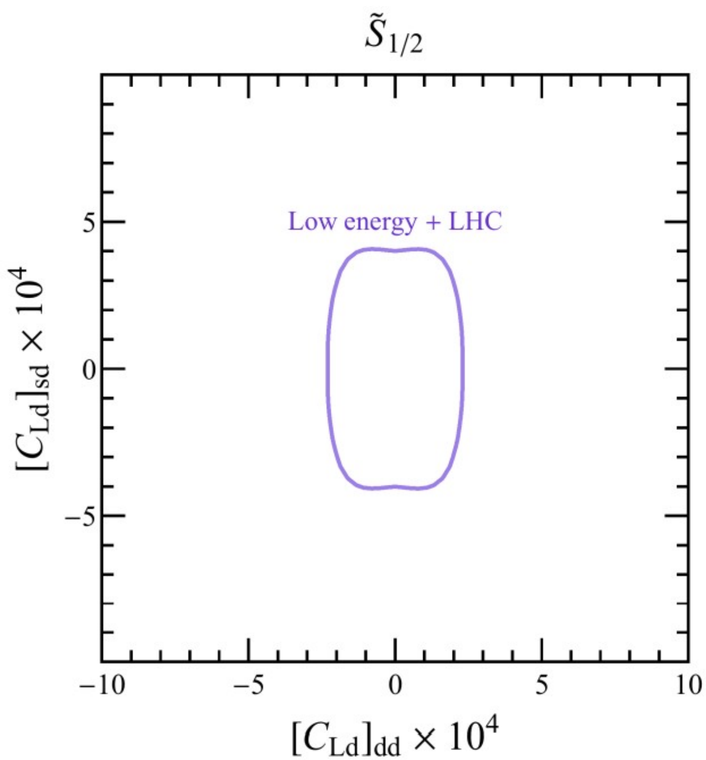
Early work by: Gonderinger, Ramsey-Musolf, 2010

  - Leptoquark: color charged; couples to quarks and lept

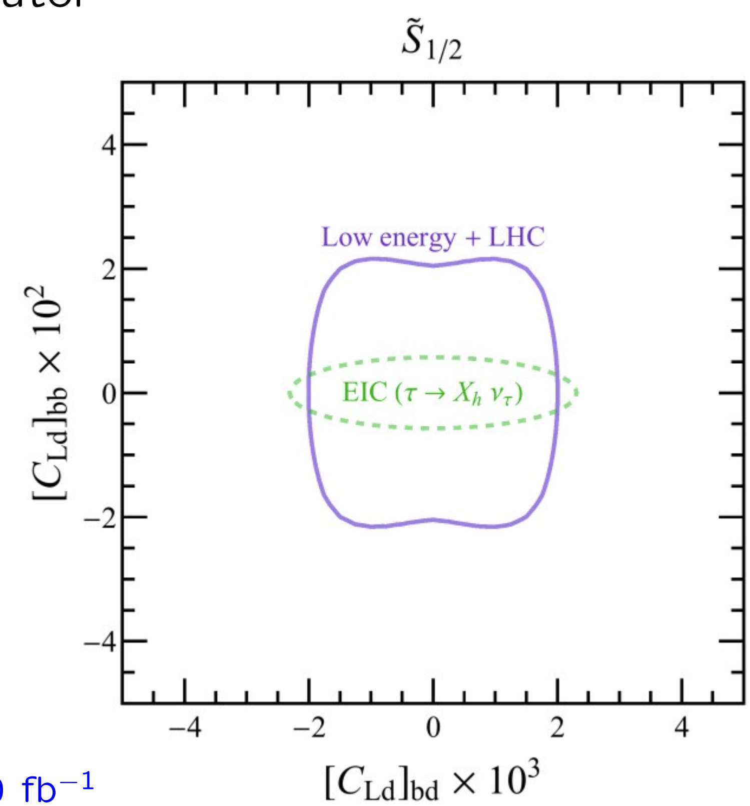
  Cirigliano, Fuyuto, Lee, Mereghetti, Yan, 2102.06176 (figures)




- Bounds on the induced dim-6 4-fermion operators
  - Bounds from LHC, low energy ($\tau$, $B$, decays)
  - Competitive EIC bounds, depending on operator



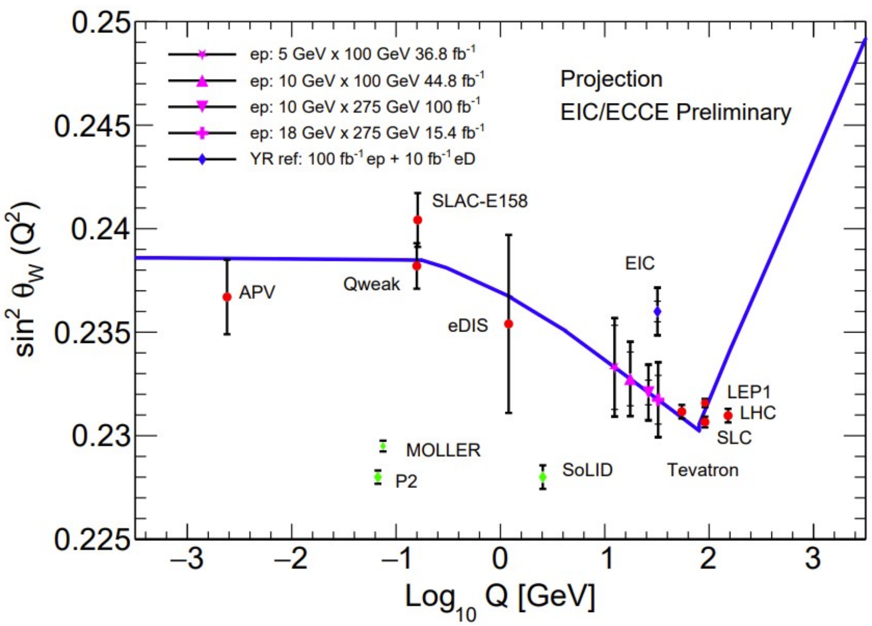

$\sqrt{s} = 141$ GeV, 100 fb$^{-1}$

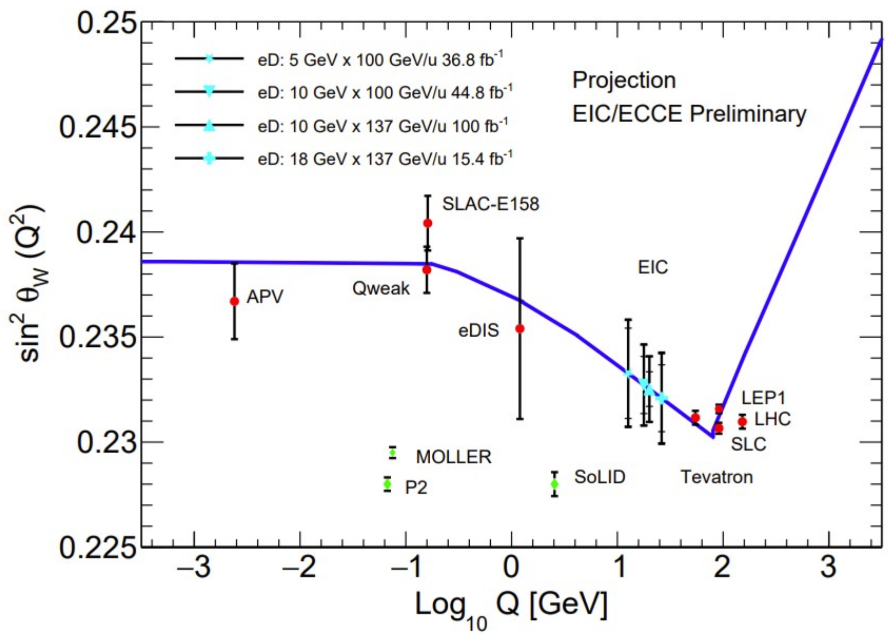


# SM Electroweak Parameters; $\sin^2\theta_W$

- Running $\sin^2\theta_W(Q^2)$: fundamental parameter of SM electroweak sector
- Has been measured in atomic, fixed target, and $Z$-pole measurements
- EIC offers access to intermediate $Q^2$ regime

From Boughezal et al., 2204.07557




Electron beam polarization: 80% with 1% uncertainty

# Direct Detection of New GeV Scale Physics

- Dark vector bosons

- Simplest case: dark $U(1)_d$, analogue of visible electromagnetism
- Dark photon (kinetic mixing) and dark $Z$ (mass mixing)
  - Coupled to SM via a small mixing parameter
- Gauge bosons with tiny gauge couplings: *e.g.* $L_e - L_\tau, \ldots$ (anomaly free)

- Dark scalars

- Axion-like particles (ALPs), analogues of QCD pions (pseudo-scalars)
  - Like pions, manifestations of spontaneously broken approximate global symmetries
  - QCD pions: broken chiral symmetry (approximate due to small quark masses)
  - ALPs can arise in a variety of models, naturally "light" (massless for exact symmetries)
- Could be a regular scalar, a "dark Higgs"

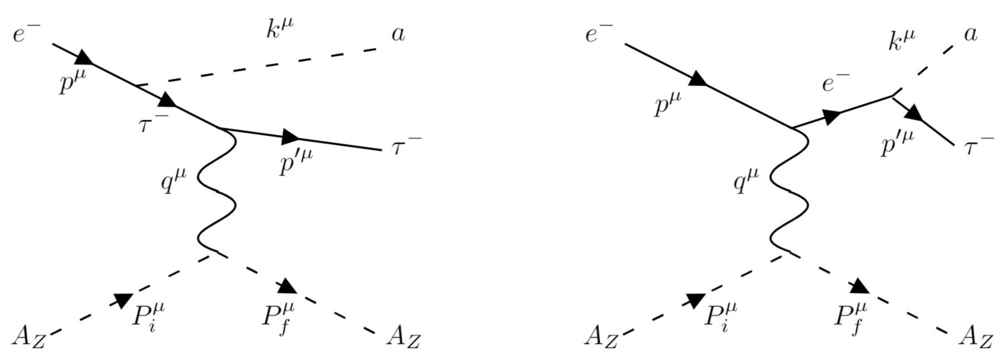
# Charged LFV via ALPs at the EIC H.D., Marcarelli, Neil, 2112.04513

- EFT for ALP interactions

$$\mathcal{L}_\ell = \frac{C_{\ell\ell'}}{\Lambda} a \sum_{\ell\ell'} \bar{\ell} \left( m^- \sin\theta_{\ell\ell'} - m^+ \cos\theta_{\ell\ell'} \gamma_5 \right) \ell' + \text{H.C.} \quad ; \quad m^\pm \equiv m_\ell \pm m_{\ell'}$$

See, *e.g.*, Bauer, Neubert, Renner, Schnubel, Thamm, 2019; Cornella, Paradisi, Sumensari, 2019

- $\theta_{\ell\ell'} = 0$: P even; maximal PV for $\theta_{\ell\ell'} = \pi/4, 3\pi/4$ (only L, R coupling)
  - Probed via polarized $e$-beams
- Search for $e - \tau$ LFV in coherent $eA_Z \to \tau A_Z a$ ; $A_Z = \text{Au}; Z = 79$




- Main decay channels: (i) $a \to \tau^- \tau^+$, (ii) $a \to \tau^- e^+$, (iii) $a \to \tau^+ e^-$
- Consider $a(\to e^+ \tau^-)\tau^-$ final state; veto on $e^-$
- Three-pronged $\tau$ decays; efficiency $\epsilon_\tau \approx 1\%$ from Zhang *et al.*, 2207.10261
  - Other decay modes and veto of ion break-up can enhance the search

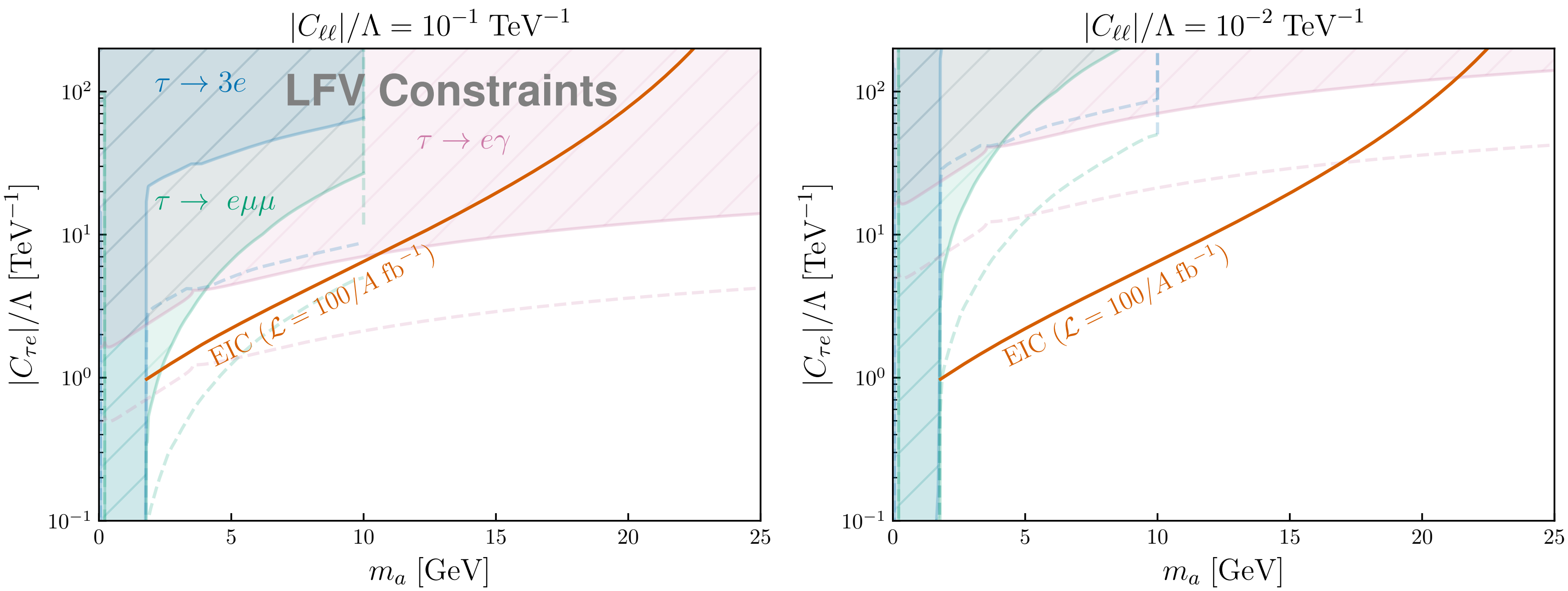
- Main background from $\tau$ pairs through Bethe-Heitler process

- Estimated from $\tau$ pair production in rock by cosmic ray muons    Bulmahn, Reno, 2008

- Good EIC prospects for probing charged LFV ALPs, especially with diagonal couplings suppressed

- Weakened $\tau$ decay constraints

- Adding $\mu$ detection may improve the search ($\tau$ identification)




Solid line BABAR, dashed line Belle II with 50 ab$^{-1}$; tree-level $a\gamma\gamma$ ignored

From H.D., Marcarelli, Neil, 2112.04513

# Heavy Neutral Leptons at the EIC

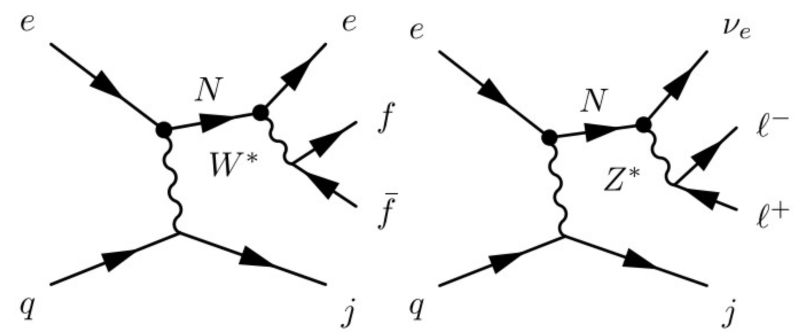
Batell, Ghosh, Han, Xie, 2210.09287

- HNLs arise in a variety of models; good example type I seesaw for $m_\nu \neq 0$
- Coupling to SM: $yHLN$

$H$ Higgs doublet $L$ lepton doublet in SM; $N$ HNL

- After EWSB: $N$ mixes with SM neutrinos

$\to \ell W N$, $\nu_\ell Z N$ couplings ($\ell = e, \mu, \tau$)




From 2210.09287

- Production in $e + p/A \to N + X$:

\- Through charged current

\- Depends on $e$-flavor mixing parameter $U_e$

\- Simplified setup: one HNL and only $U_e \neq 0$

- Phenomenological approach: mass $m_N$ and mixing $U_e$ free parameters
- Both Dirac and Majorana $N$ considered
- $N$ decays: Prompt and displaced, as well as invisible (dark sector)

- $\sqrt{s} = 141$ GeV, $\mathcal{L} = 100$ fb$^{-1}$, $P_e = 70\%$

Figures from 2210.09287

- Unpolarized PDFs, proton beam

- Visible decays:

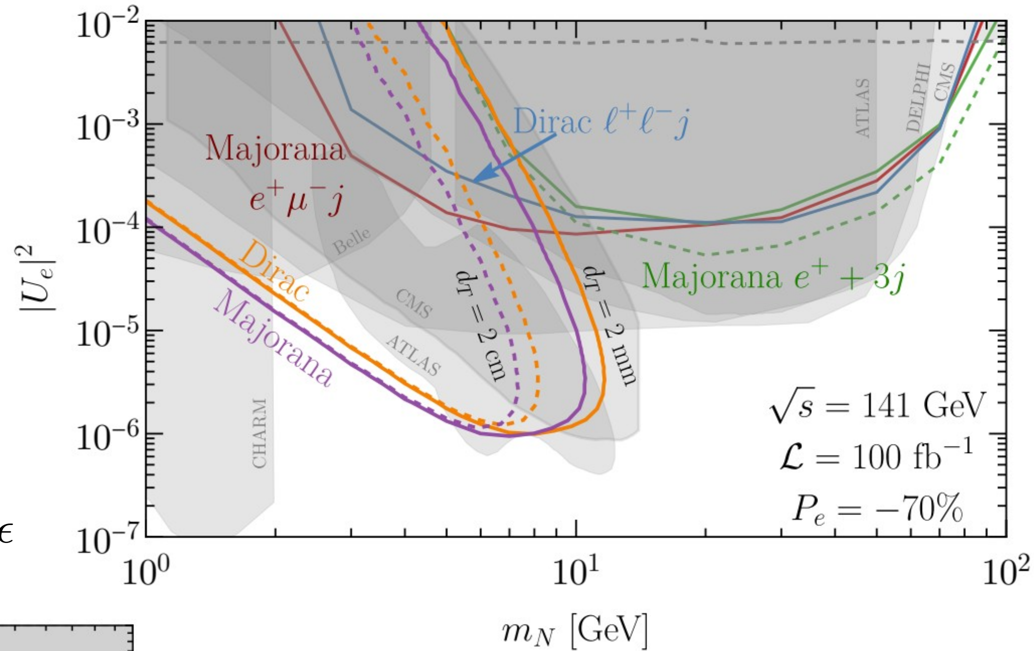
- prompt (95% CL)

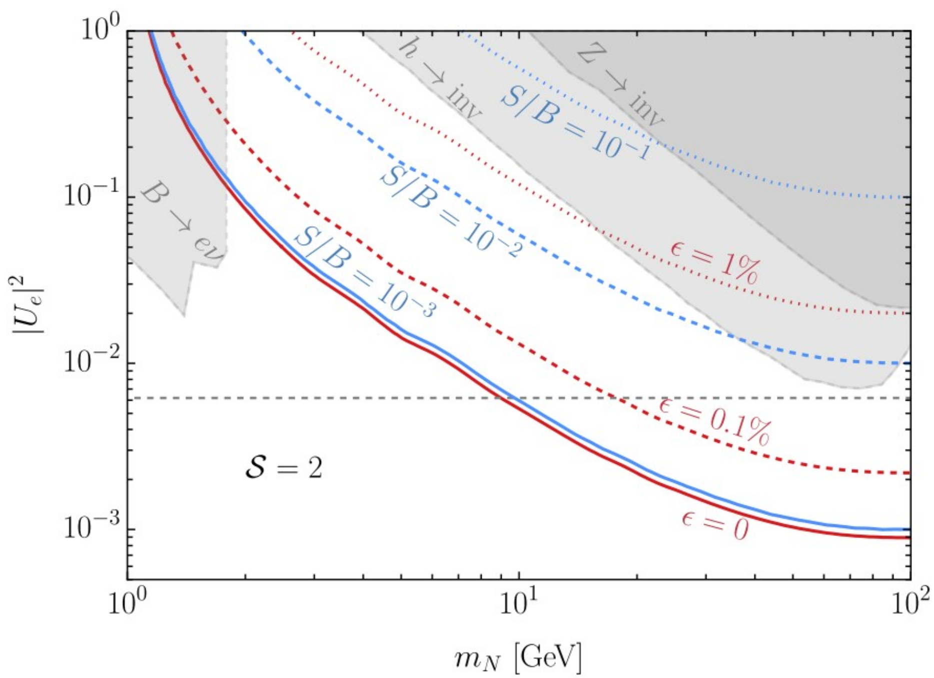
- displaced (5 events)

- Invisible decays: mono-jet

- $\mathcal{S} = S/\sqrt{B + (\epsilon B)^2}$

- fractional systematic uncertainty $\epsilon$

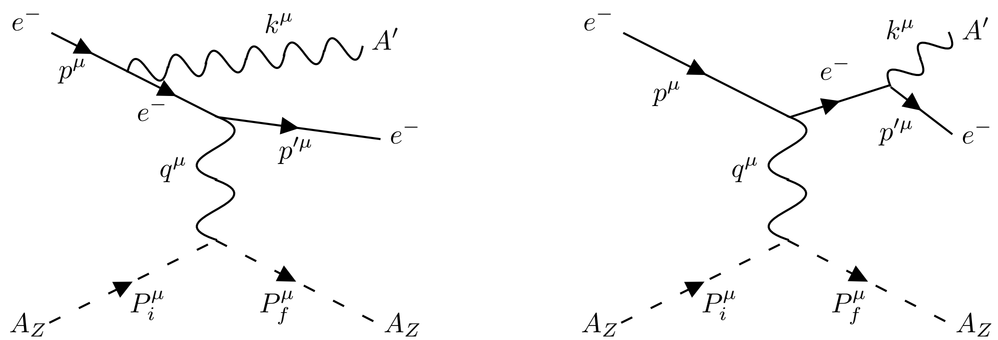


# Displaced Hidden Vectors at the EIC

H.D., Marcarelli, Neil, 2307.00102

- Coherent production from gold ion, $Z = 79$: $eA_Z \to eA_Z A'$   $(Z_d \leftrightarrow A')$
- $q^2 \lesssim \mathcal{O}$(100 MeV)
- Large $Z^2$ enhancement of electromagnetic scattering




- Probability of detection of displaced decay: $P_{\text{disp}} = e^{-d_{\text{min}}/(\gamma_k v_k \tau)} - e^{-d_{\text{max}}/(\gamma_k v_k \tau)}$
- $d_{\text{min}}$ from detector resolution, $d_{\text{max}}$ from geometry   $\gamma_k$ boost, $v_k$ velocity, $\tau$ lifetime
- Kinematic variables: laboratory frame
- Signal cross section: $\sigma_{\text{sig}}(g_{A'}) = \int P_{\text{disp}} \frac{d\sigma}{d\gamma_k\, d\eta_k} d\gamma_k\, d\eta_k\, \mathcal{B}(A' \to e^+e^-)$
- We take $E_e = 18$ GeV and $E_A = 110$ GeV/nucleon

## Signal Selection:

- Assumed EIC Comprehensive Chromodynamics Experiment (ECCE) detector

arXiv:2209.02580 [physics.ins-det]

- Now the ePIC (Electron-Proton/Ion Collider) detector, similar capabilities
- Signal requires both $e^+$ and $e^-$ from vector decay

$\mu^+\mu^-$ also available for much of the parameter space

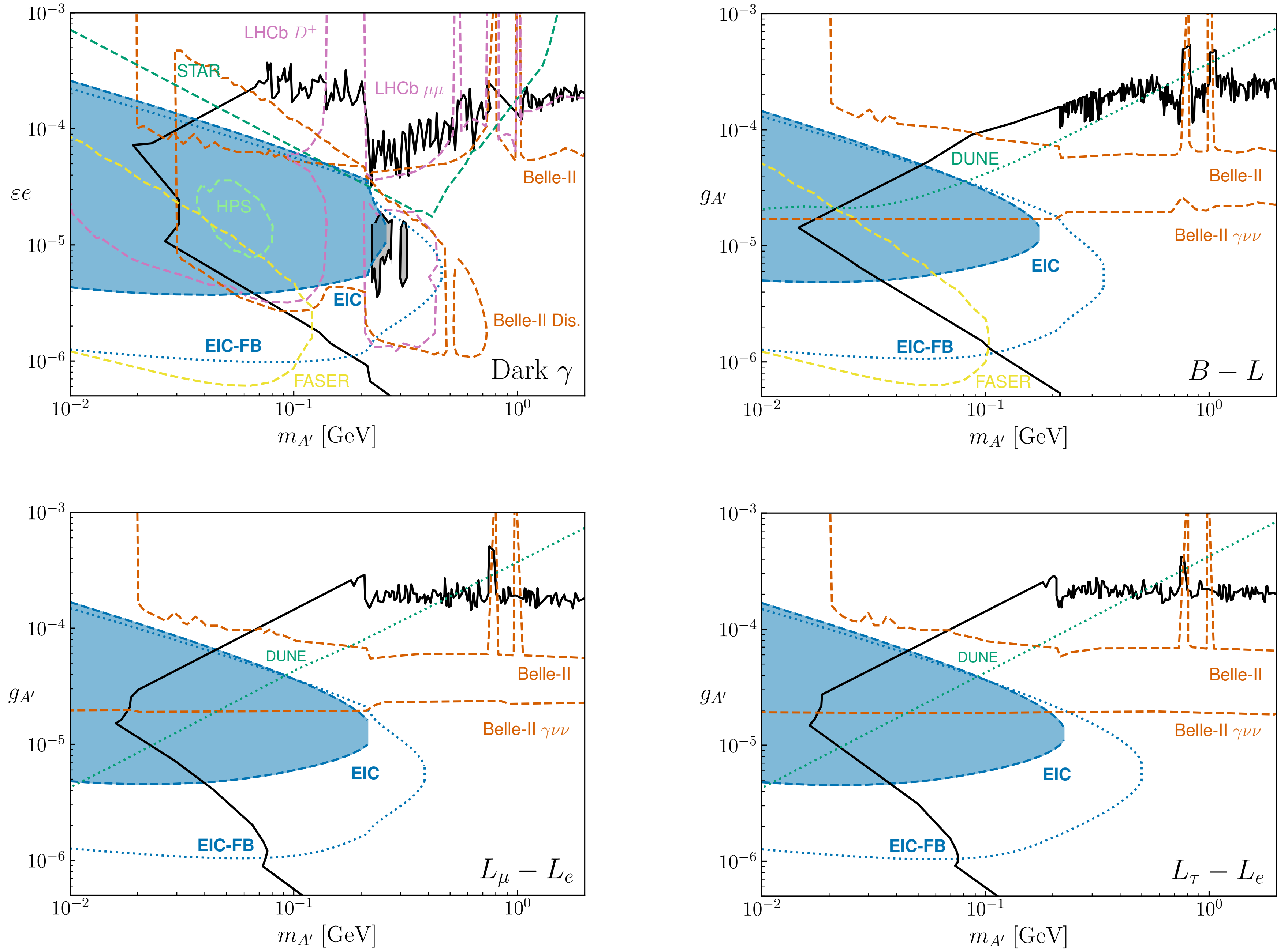
- We estimated: $d_{\rm min} \approx \gamma_k(\text{DCA}^{\rm min}_{\rm 2D})/(v_k \cos\theta_k^{\rm lab})$
- For pions: $\text{DCA}^{\rm min}_{\rm 2D} < 100\ \mu$m
- $\Rightarrow d_{\rm min} \gg 0.1$ mm, $d_{\rm max} = 1$ m

DCA: distance of closest approach

- ECCE tracking: $\boxed{|\eta| < 3.5}$
- We also considered a detector at $z = -5$ m

Further details of the current detector design may push this farther back; also a possibility for second detector

- Assumed: $\text{DCA}^{\rm min}_{\rm 2D} = 200\,\mu$m, $d_{\rm max} = 5$ m
- Covering far backwards (FB): $\boxed{-6 < \eta < -4}$

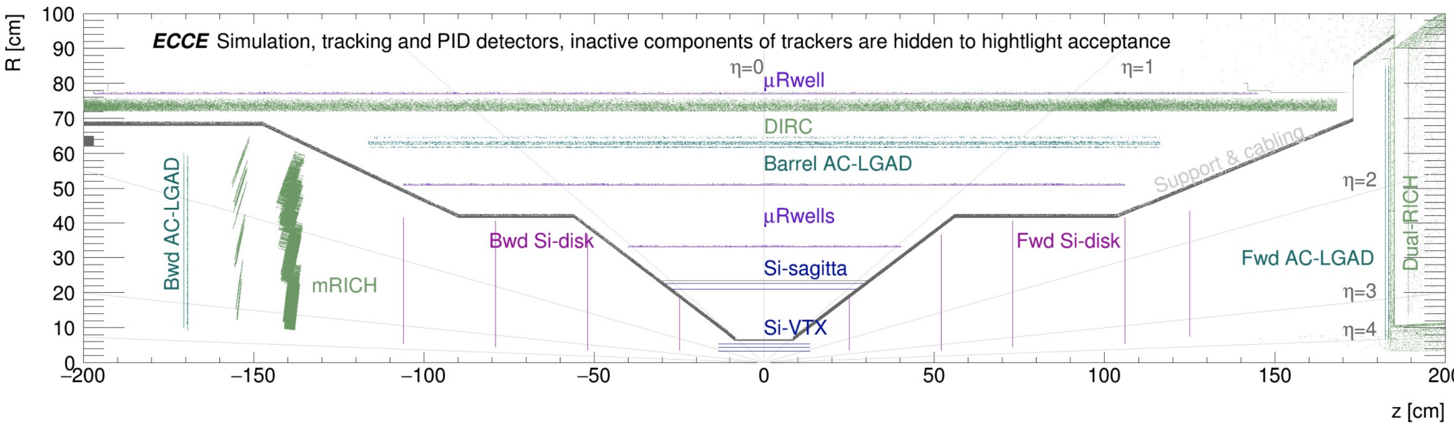



From H.D., Marcarelli, Neil, 2307.00102

# Background considerations

- We assumed zero background
- Photon conversion: sparse backwards detector systems   Adkins *et al.*, 2209.02580

- Si disks separated by $\sim 25$ cm: cut out thin regions from signal




- Misidentified pions as electrons: electron end cap fake rate $\sim 10^{-4}$

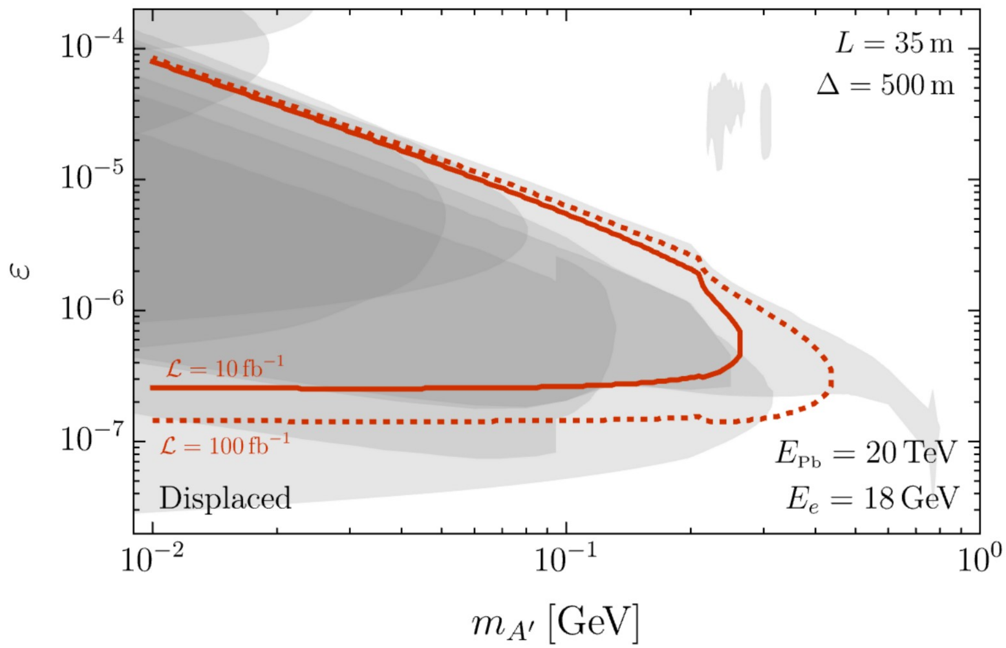
- Requiring both $e^+$ and $e^-$

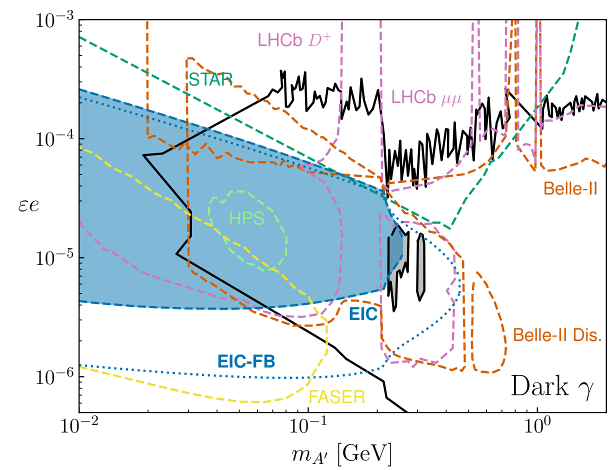
- Additional signals if muon detectors added

- Losing signal events down the beam pipe: our estimate $\sim$ (20-30) %, manageable
- These are (theorist) projections, using rough approximations

- Detailed and more realistic simulations required for definitive results

## Also Balkin *et al.*, 2310.08827, JHEP 02 (2024) 123



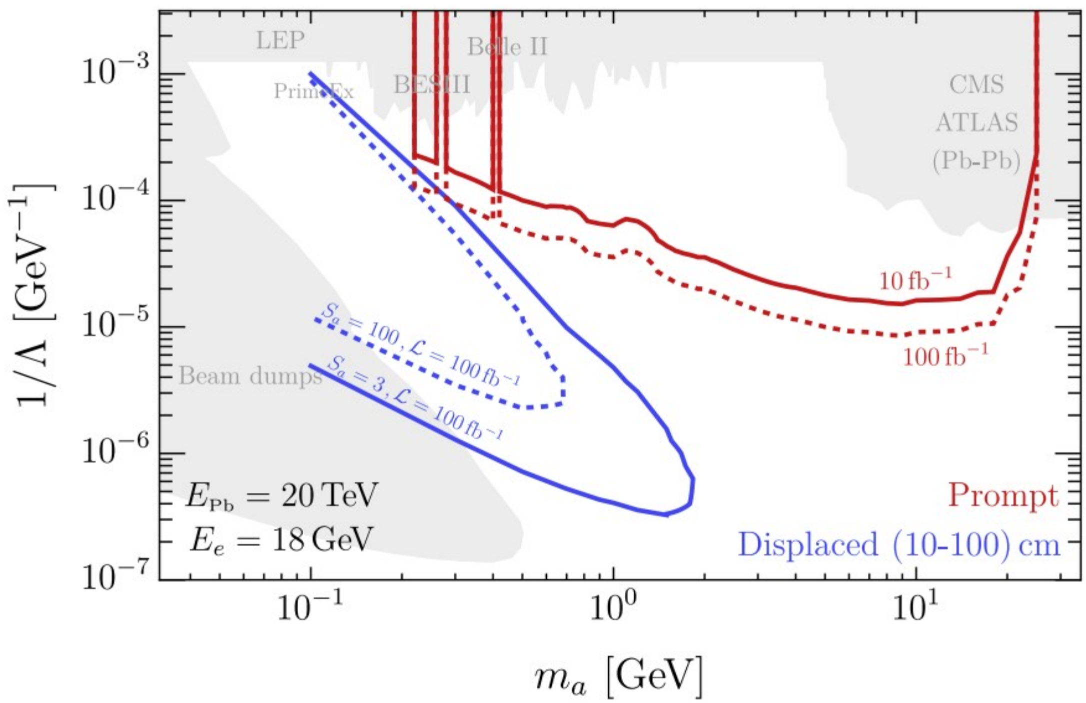




2307.00102

- $eN \to eNA'$, coherent scattering from Pb
- Dark photon decay $A' \to \mu^+\mu^-$ (to reduce background)
- Decay volume $\Delta = 500$ m long (shielded) at $L = 35$ m from interaction point
- Does not exceed current bounds
  - Our work assumed much smaller ($\gtrsim$ mm) displacement
  - Worthwhile to determine efficiency of our suggested background suppression

- Work on ALP-photon coupling using coherent scattering at the EIC

- $Z^2$ enhanced     From Balkin *et al.*, 2310.08827



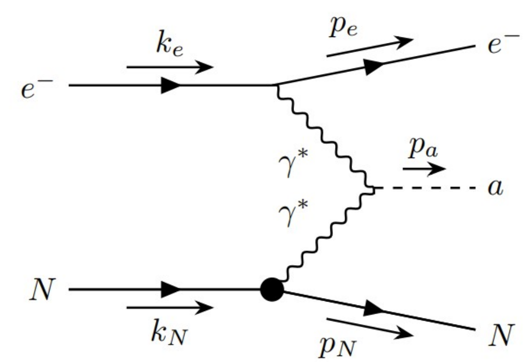




**Figure 7**: The EIC projections from the ALP searches with $E_e = 18\,\mathrm{GeV}$ and $E_{\mathrm{Pb}} = 20\,\mathrm{TeV}$. The solid (dashed) red lines show the prompt search results with 10 (100) $\mathrm{fb}^{-1}$ integrated luminosity. The solid (dashed) blue lines show the displaced search results with $S_a = 3$ ($S_a = 100$) with 100 $\mathrm{fb}^{-1}$ integrated luminosity, assuming the diphoton spatial resolution $L_R = 10\,\mathrm{cm}$ and the distance between the interaction point and the EM calorimeter $L_{\mathrm{EM}} = 100\,\mathrm{cm}$.

See also Liu, Yan, 2112.02477, Chin.Phys.C 47 (2023) 4, 043113   ($e, p$ initial states)

# Discovering Invisible Dark Bosons at the EIC

H.D., Liu, 2505.08871

- Consider dark bosons in $\sim$ 10 MeV-10 GeV mass regime
- Weakly coupled to electrons, $\mathcal{O}(1)$ invisible branching fraction:
  - $B-L$, $L_e - L_i$ with $i = \mu, \tau$, dark $Z$, ...

  - Significant invisible branching fraction from $\nu$ or "dark sector" final states
- Basic models

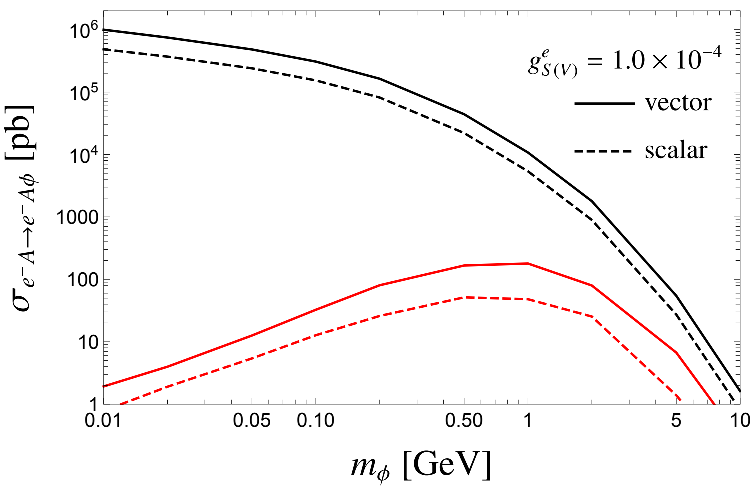
$$\mathcal{L}_S = g_S^e\,\phi\bar{e}e + g_S^\chi\,\phi\bar{\chi}\chi$$

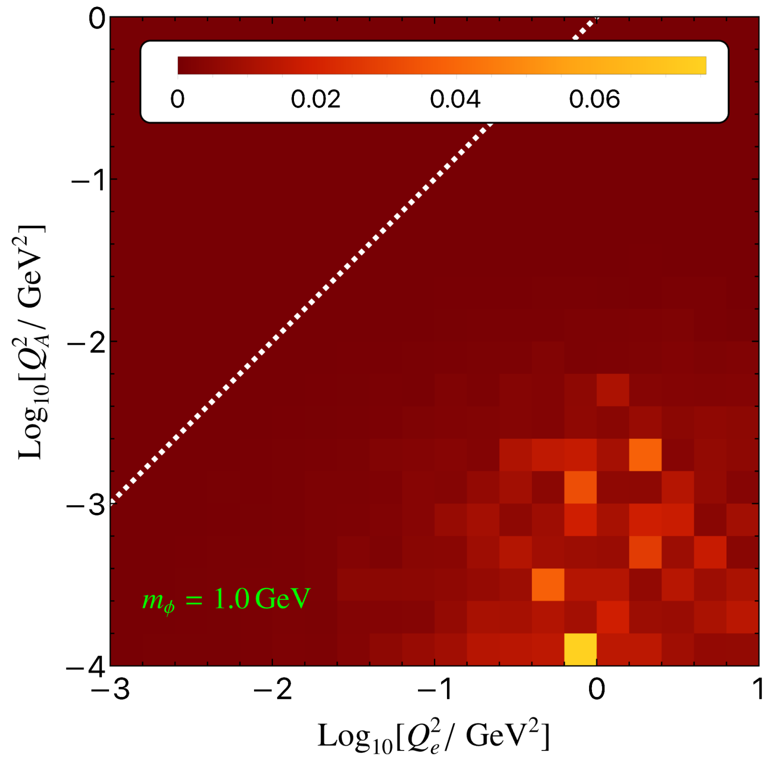
$$\mathcal{L}_V = g_V^e\,\phi_\mu\bar{e}\gamma^\mu e + g_V^\chi\,\phi_\mu\bar{\chi}\gamma^\mu\chi$$

  - $\phi$ ($\phi_\mu$) a scalar (vector)
  - $\chi$: $\nu$ or dark fermion; $\phi \to \bar{\chi}\chi$ allowed on-shell
- We consider coherent $e$-Au scattering
- $E_e = 18$ GeV, $E_A = 100$ GeV per nucleon

# Kinematics

- Emitted $\phi$ takes most of the electron beam energy
- Momentum transfer $Q^2$ mostly on the electron side
- SM background marked by soft and similar $Q^2$ from either beam



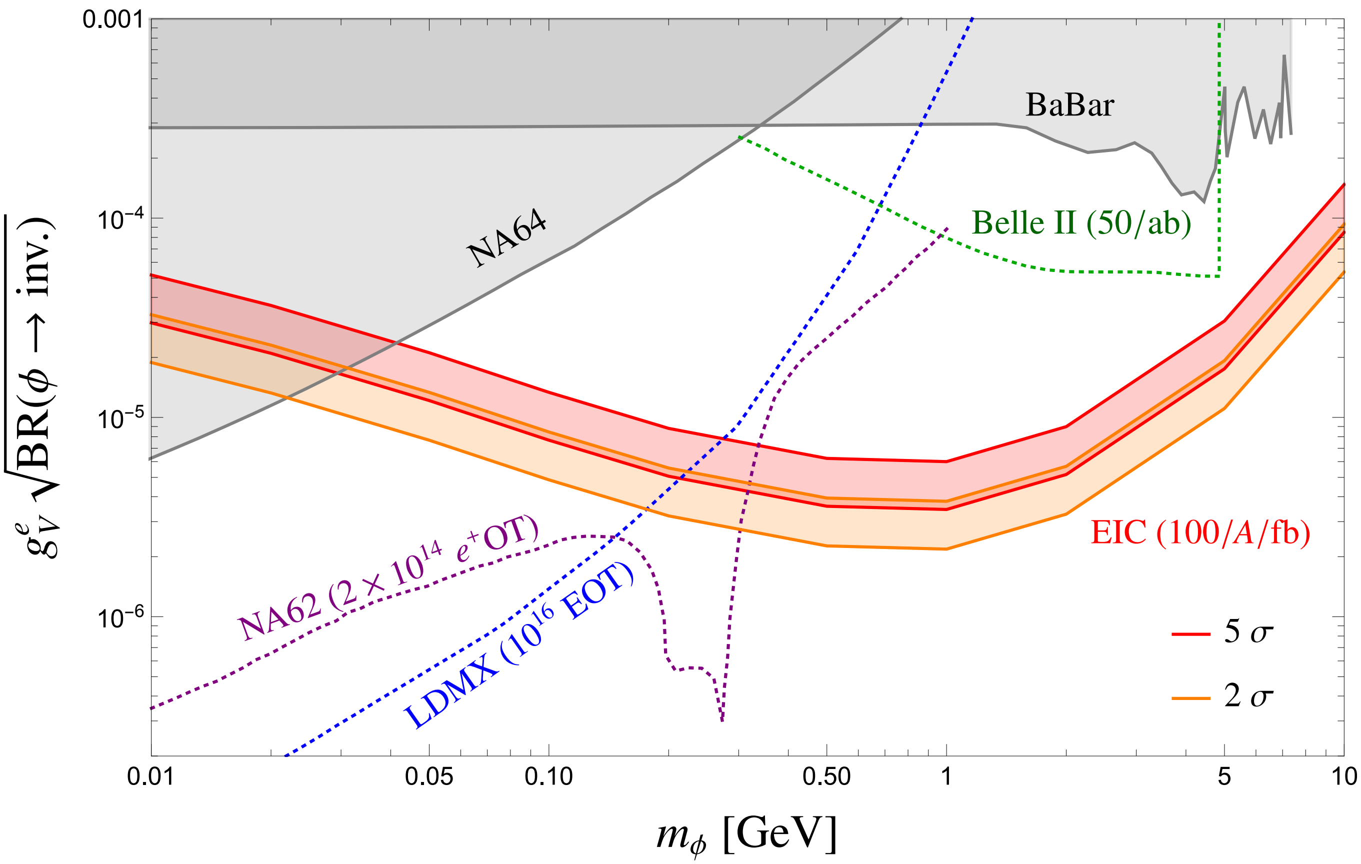




- Similar cross sections for scalars and vectors
- Red curves: after cuts
- We focus on the vector case

- A main background: coherent $e^-A \to e^-A\gamma$, with $\gamma$ missed
- Cuts: $|\,\eta_e\,| < 3.5$, $p_T^e > 1.2$ GeV, $E_e < 10$ GeV, $Q_e^2 > 4$ GeV$^2$

- $E_e$ cut $\to$ background $E_\gamma$ mostly $> 5$ GeV, *Inefficiency* $10^{-6} \leq \epsilon \leq 10^{-4}$
  - for $|\eta_\gamma| < 3.5$ (assumed missed otherwise)   Maeda *et al.*, 1412.6880; Fry *et al.*, 2501.14827
  - Background: $70 \times \epsilon/10^{-4}$ pb

- Taking similar $\epsilon$ for hard jets, DIS background $e^- A \to e^- X j$ also suppressed
  - Jet central ($|\eta_j| < 3.5$), $E_j > 8$ GeV
  - Background $\lesssim Z \times 0.2 \times \epsilon/10^{-4}$ pb (smaller than bremsstrahlung, but not negligible)
  - Additional leverage from Zero Degree Calorimeter to veto incoherent scattering



# Concluding Remarks

- Open fundamental questions strongly imply the need for new physics
- There are currently no solid hints about the nature and scale of new particles
- Longstanding theory arguments challenged, no new consensus has emerged
  - Motivates looking at a wide range of testable ideas
  - Any new facility that can help along should be leveraged
- The EIC can be a tool to probe new phenomena
  - Imprints of high scale phenomena may leave a trace (encoded via EFTs)
  - Low mass dark sectors
- We only sampled some ideas for BSM at EIC; good to have more
- Further studies are warranted and can provide
  - Optimized scientific impact for the EIC
  - Science case for extensions, *e.g.* a second detector
  - A nexus of collaboration for the high energy and nuclear physics communities