Looking for Dark Particles at the EIC

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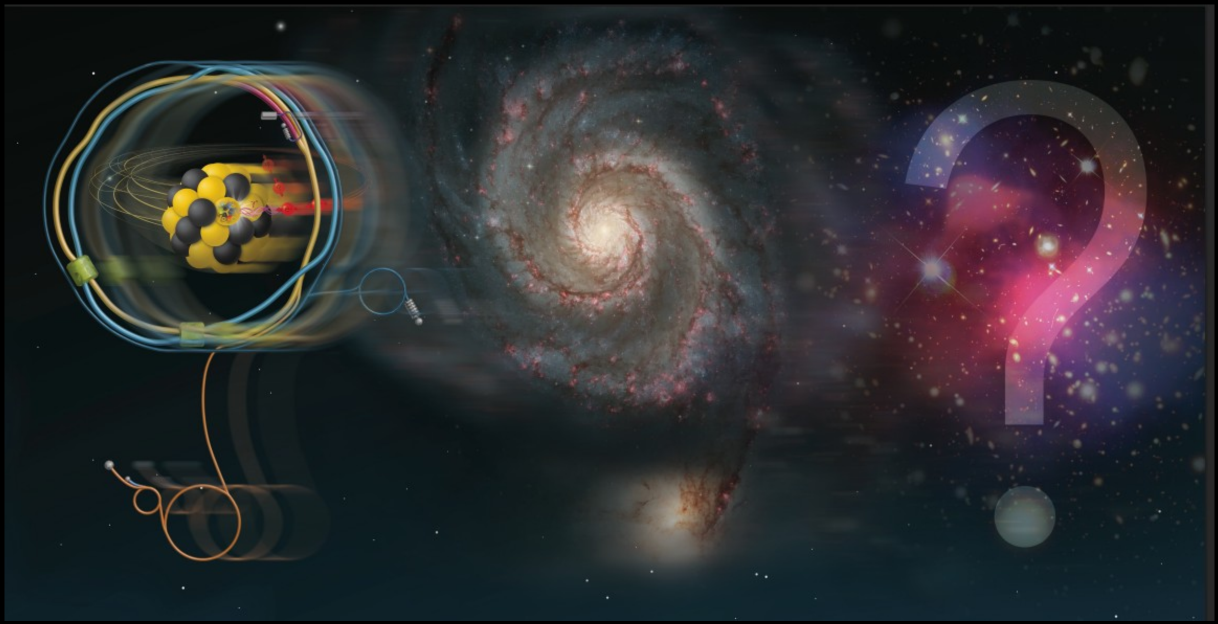


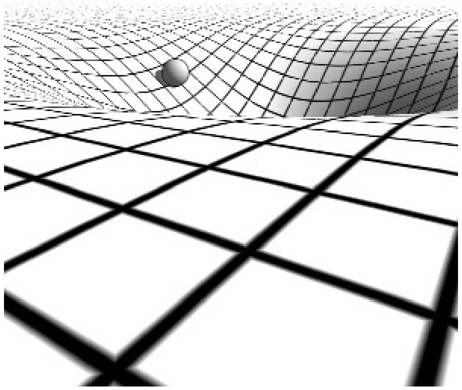
CFNS Workshop:

New Opportunities for Beyond-the-Standard Model Searches at the EIC

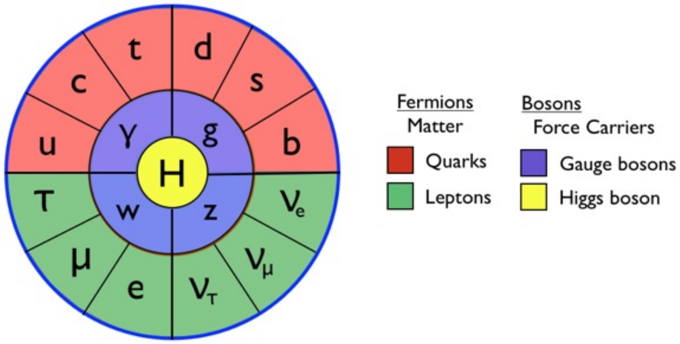
Stony Brook University, July 21-24, 2025

Brookhaven National Laboratory

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 remain consistent with “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** $\rightarrow m_\nu \neq 0$

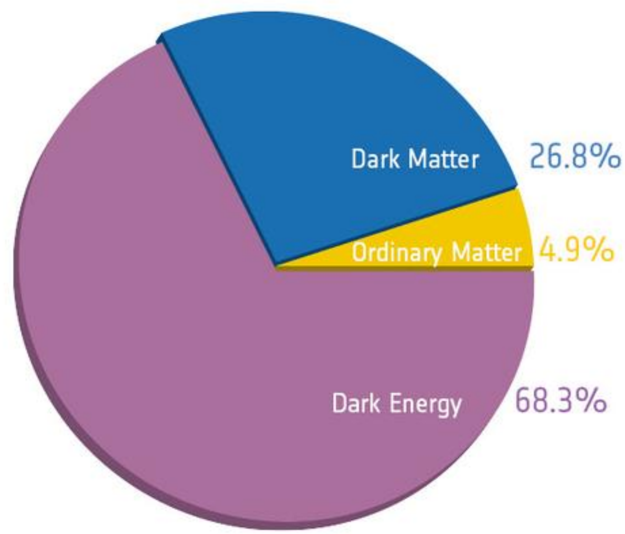
- Adding right-handed neutrinos (over a broad range of masses) can explain this

★ **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 CPV)

95% of the Universe is unknown to us!

Planck



There are also theoretical hints:

- Why is gravity so weak?

  - Hierarchy between Planck scale and Higgs mass: $\frac{M_H^2}{M_{\mathrm{Pl}}^2} \sim 10^{-34}$

  - Why is M_H stable against quantum corrections $\sim \mathcal{O}(M_{\mathrm{Pl}})$?

- Why is CP violation so suppressed in strong interactions?

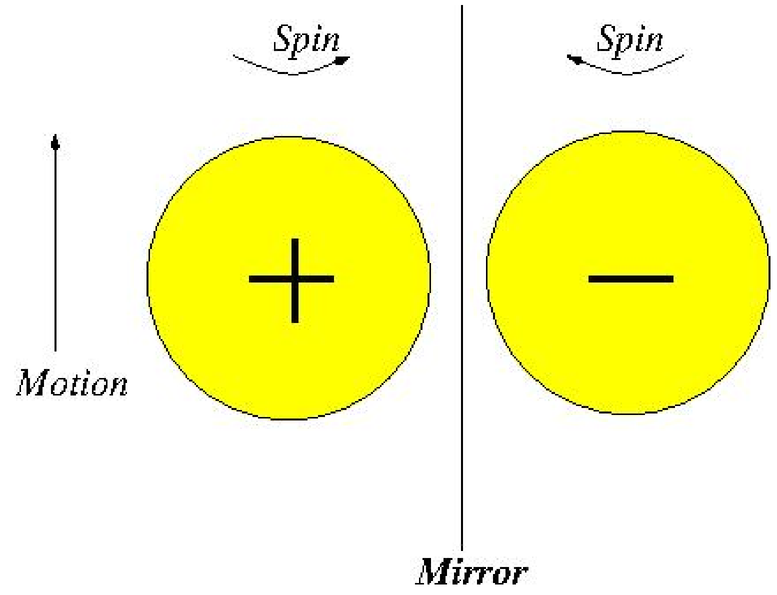
  - Neutron electric dipole moment $\lesssim 10^{-26}$ e.cm; could have been $\mathcal{O}(10^{10})$ times larger

- Why . . . ?

Aside:

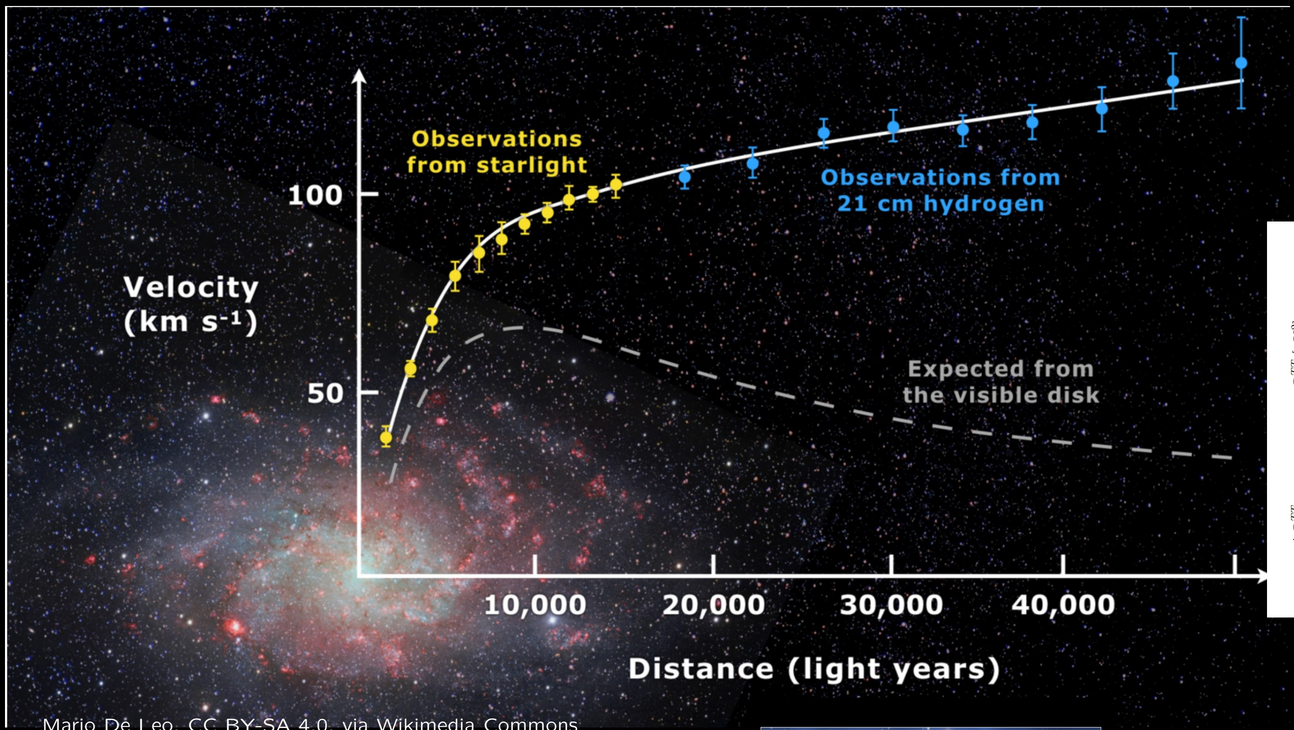
CP: Charge conjugation (particle $\leftrightarrow$ antiparticle) – Parity (mirror)

- Violated by SM weak interactions
- SM CPV: not enough to account for ordinary matter

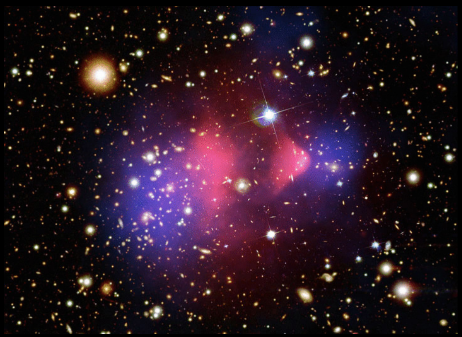


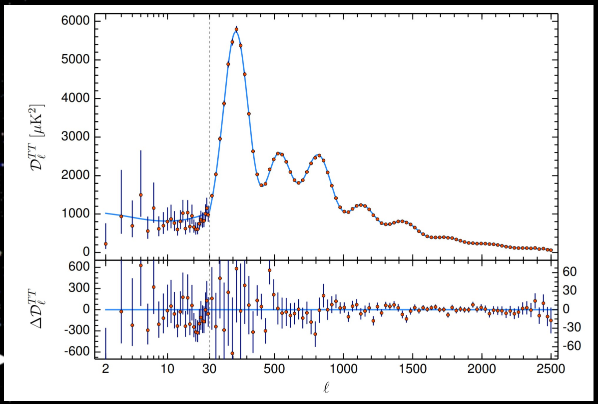
Dark matter (DM)

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



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





Planck Collaboration; 1807.06209

Dark Matter Ring in Galaxy Cluster Cl 0024+17 (ZwCl 0024+1652)
Hubble Space Telescope • ACS/WFC

NASA, ESA, and M.J. Jee (Johns Hopkins University) STScI-PRC07-17a

- $\sim 27\%$ of energy density

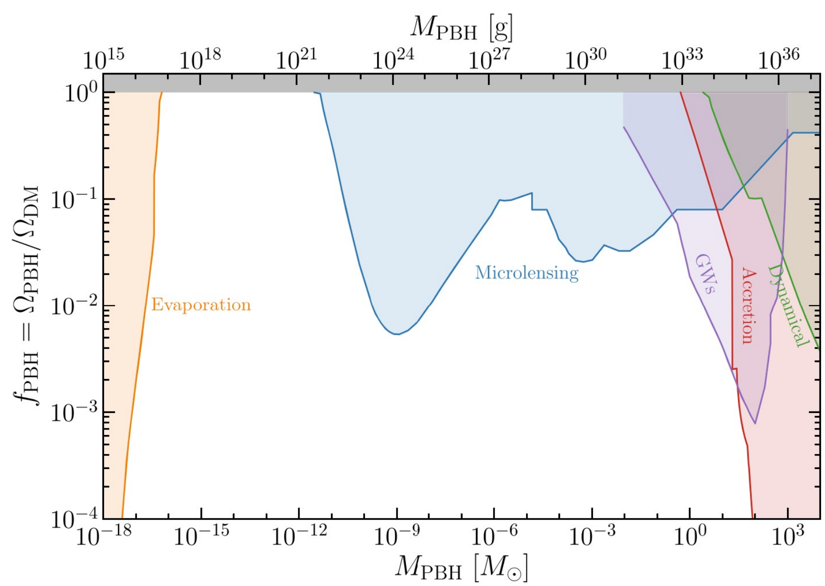
• Dark Matter: unknown substance

- Feeble interactions with atoms, photons
- Self-interactions not strong ($\sigma \lesssim 1$ barn)
- Not explained in SM
- So far, evidence only from gravity effects
- Possible mass scale: $\boxed{10^{-22}\text{ eV} \lesssim M_{\text{DM}} \lesssim 10^{55}\text{ eV}}$ 77 orders of magnitude!
- Lower bound: ultralight bosons ("Fuzzy DM," must fit within galactic structures)

Hu, Barkana, Gruzinov, 2000

- Upper bound: possibly primordial black holes (sub-solar mass) Hawking, 1971

- Formed in the early ($t \ll$ ps) Universe from over-densities

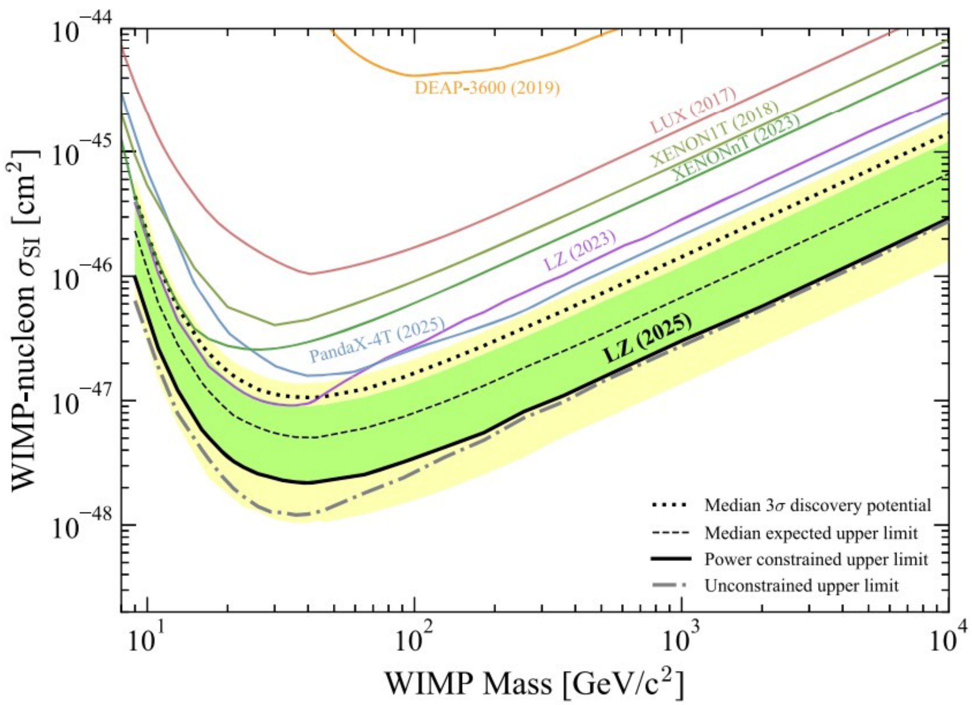


E.g., Green and Kavanagh, J.Phys.G 48 (2021) 4, 043001

Weak Scale DM

- Weakly interacting massive particles (WIMPs) longtime targets
- Motivation: The hierarchy problem in SM; $M_{\text{new}} \gtrsim M_H \approx 125$ GeV (weak scale)
- Thermal relic density: annihilation, "freeze-out"

- $\rho_{\text{WIMP}} \propto 1/\sigma_{ann}$
- $\sigma_{ann} \sim g^4/M^2$
- $g \sim g_{\text{weak}}$, $M \gtrsim$ weak scale $\rightarrow \rho_{\text{WIMP}} \sim \rho_{\text{DM}}^{\text{obs}} \Rightarrow$ *WIMP Miracle*



J. Aalbers *et al.*, The LUX-ZEPLIN (LZ) Collaboration, Phys.Rev.Lett. 135 (2025) 1, 011802

Dark Sectors

• With lack of evidence for new physics near weak scale, alternatives to WIMPs have been put forth in recent years

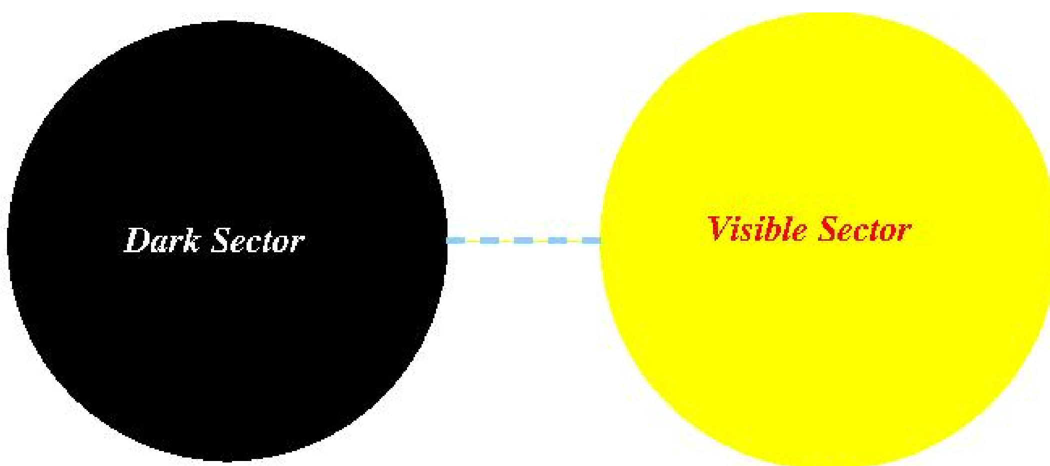
• Example: DM could be light ($m \lesssim$ GeV) and may reside in a separate sector with its own forces

• Analogy with SM

• Maybe set by an asymmetry (not a thermal relic), like ordinary matter

• Visible and dark sectors connected by feeble interactions

• Mediators could be light, accessible to low energy experiments



Examples of GeV Scale Dark Bosons

- Dark vector bosons

• Simplest case: dark $U(1)_d$, analogue of visible electromagnetism

• Dark photon (kinetic mixing) and dark Z (mass mixing)

• Very weakly interacting gauge bosons: *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)

- Can arise in a variety of models, naturally "light" (massless for exact symmetries)

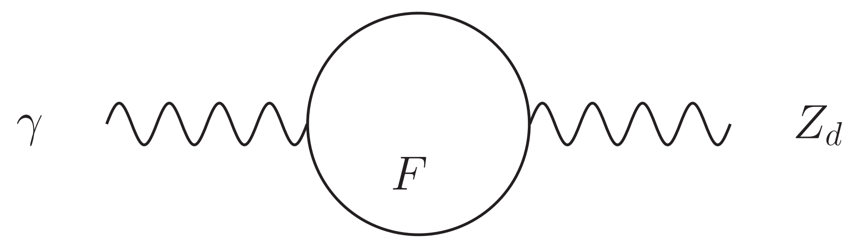
See E. Neil's talk for some of the EIC phenomenology

Dark Photon

- Kinetic mixing: $Z_{d\mu}$ of $U(1)_d$ and B_μ of SM $U(1)_Y$ Holdom, 1986

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_W}B_{\mu\nu}Z_d^{\mu\nu} - \frac{1}{4}Z_{d\mu\nu}Z_d^{\mu\nu}$$

- $X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$ (field strength tensor)
- $\tan\theta_W \equiv \dfrac{g'}{g}$ with g' and g gauge couplings of $U(1)_Y$ and $SU(2)$, respectively
- Can be loop induced: $\varepsilon \sim e g_d/(4\pi)^2 \lesssim 10^{-3}$



- F charged under both $U(1)_Y$ and $U(1)_d$

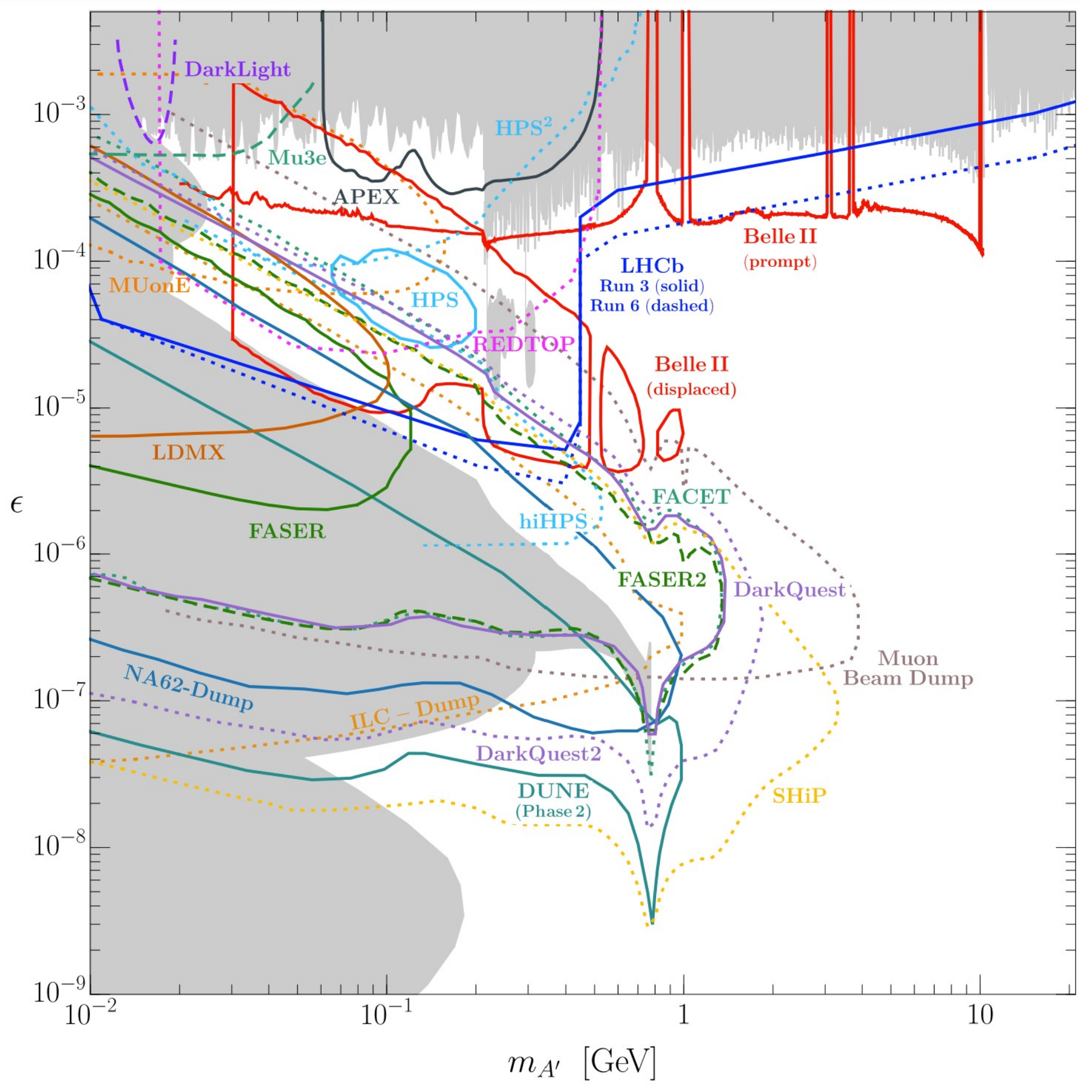
$$\boxed{\mathcal{L}_{\text{int}} = -e\,\varepsilon\, J^\mu_{em} Z_{d\mu}}$$

$J^\mu_{em} = \sum_f Q_f \bar{f}\gamma^\mu f + \cdots$ (electromagnetic current)

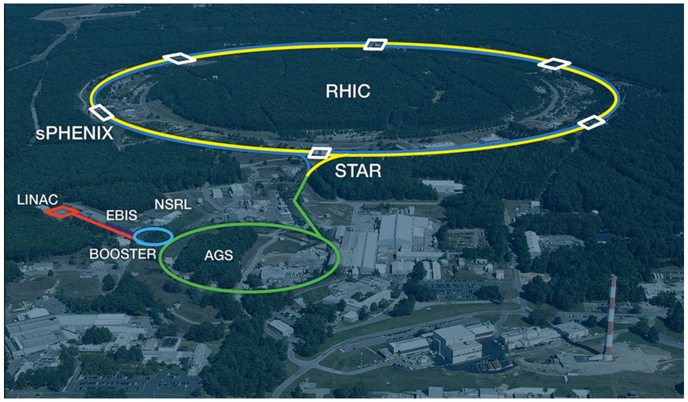
- Active experimental program to search for the dark photon

Pioneering early work by Bjorken, Essig, Schuster, Toro, 2009

From Batell, Blinov, Hearty, McGehee, 2207.06905, visibly decaying Z_d

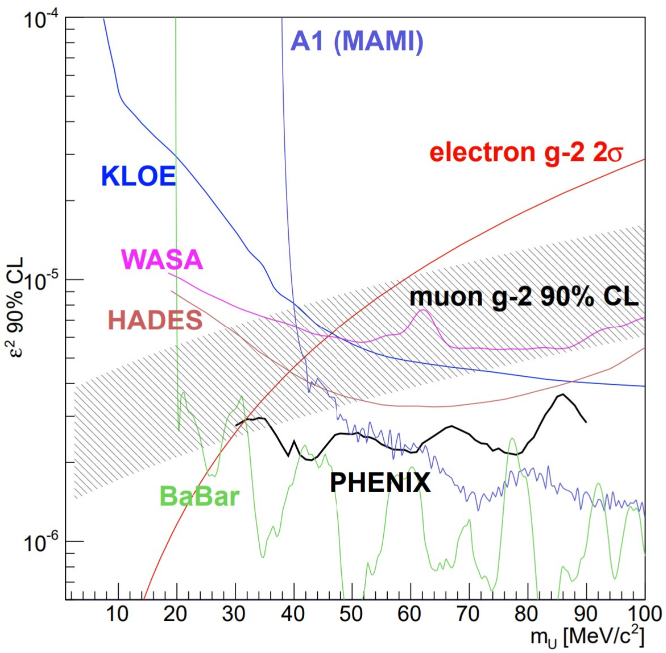


- Also a Long Island industry! (RHIC)



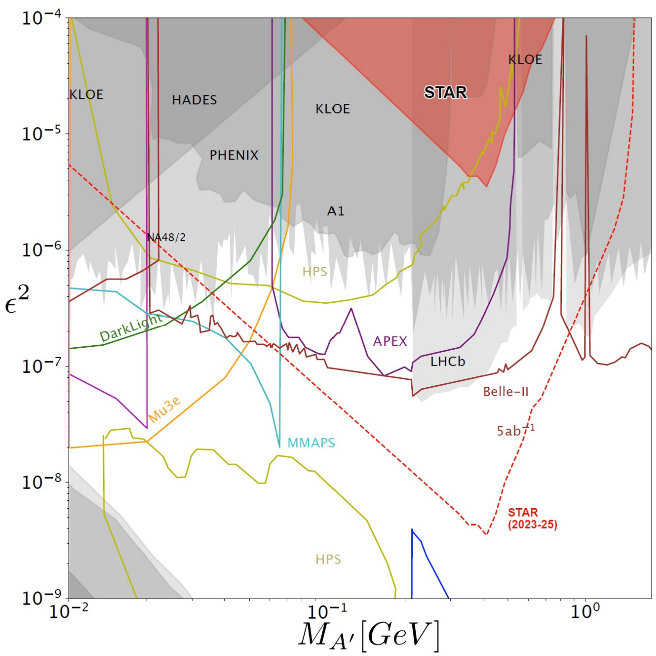
- PHENIX: $\pi^0, \eta \to \gamma A'(\to e^+e^-)$

Phys.Rev.C 91 (2015) 3, 031901, (PHENIX Collaboration)



- STAR: ultra-peripheral $\gamma A' \to e^+e^-$

Xu, Lewis, Wang, Brandenburg, Ruan, 2211.02132



Other $U(1)$ Gauge Interactions

- $B-L$; anomaly free with the addition of three right-handed neutrinos

- Leptophilic interactions: $L_i - L_j$, with $i, j = e, \mu, \tau$, $i \neq j$

- Gauge one at a time

- Anomaly free

- We will consider $m_{A'}$ at or below GeV scale

- Direct coupling to SM: gauge coupling must be tiny $g_{A'} \ll 1$

- Various experimental probes, akin to dark photons

- Light and feebly interacting states can be long-lived

- Displaced vertex or missing energy signals in collider experiments

- Good prospects for suppressing SM backgrounds

The Electron Ion Collider (EIC)

2103.05419, EIC Yellow Report

- New frontier in studying hadronic systems, to be built at BNL

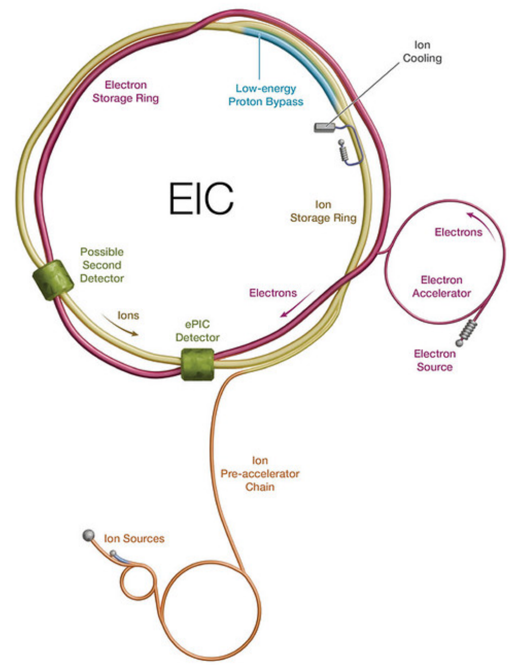
- *E.g.*, spin composition of nucleons,....

- Large $\sqrt{s}$, luminosity

- Up to $E_e = 18$ GeV and 110 GeV per nucleon (e-Au)

- Fixed target equivalent of ~ 4 TeV e-beam

- ~ 100 fb^{-1} per nucleon possible



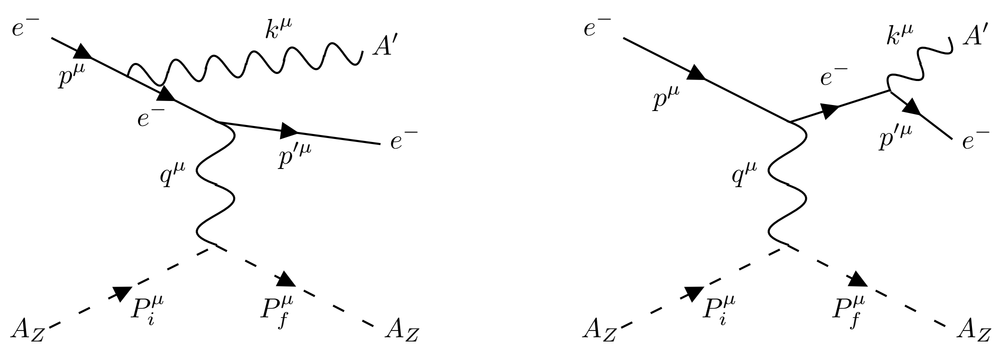
- Polarization: $\sim 70\%$ for e and p beams

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

Displaced Hidden Vectors at the EIC

H.D., Marcarelli, Neil, Phys.Rev.D 108 (2023) 7, 075017, 2307.00102

- Coherent production from gold ion, $Z = 79$: $eA_Z \to eA_Z A'$ $(Z_d \leftrightarrow A')$
- $q^2 \lesssim \mathcal{O}(100 \text{ MeV})$
- 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_{min} from detector resolution, d_{max} from geometry γ_k boost, v_k velocity, τ 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

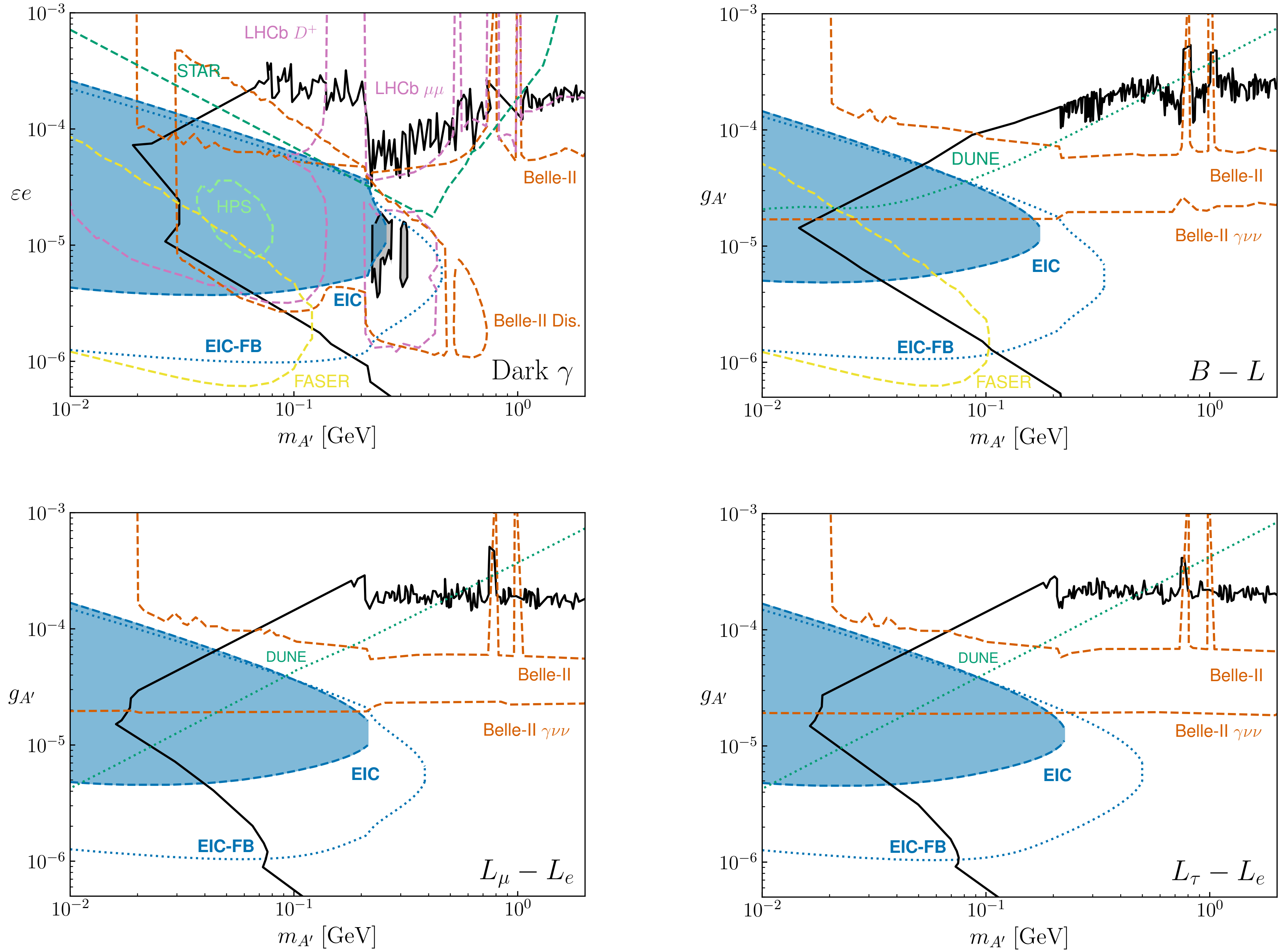
- We estimated: $d_{\text{min}} \approx \gamma_k(\text{DCA}^{\text{min}}_{\text{2D}})/(v_k \cos\theta_k^{\text{lab}})$
- For pions: $\text{DCA}^{\text{min}}_{\text{2D}} < 100\ \mu\text{m}$
- $\Rightarrow d_{\text{min}} \gg 0.1$ mm, $d_{\text{max}} = 1$ m

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

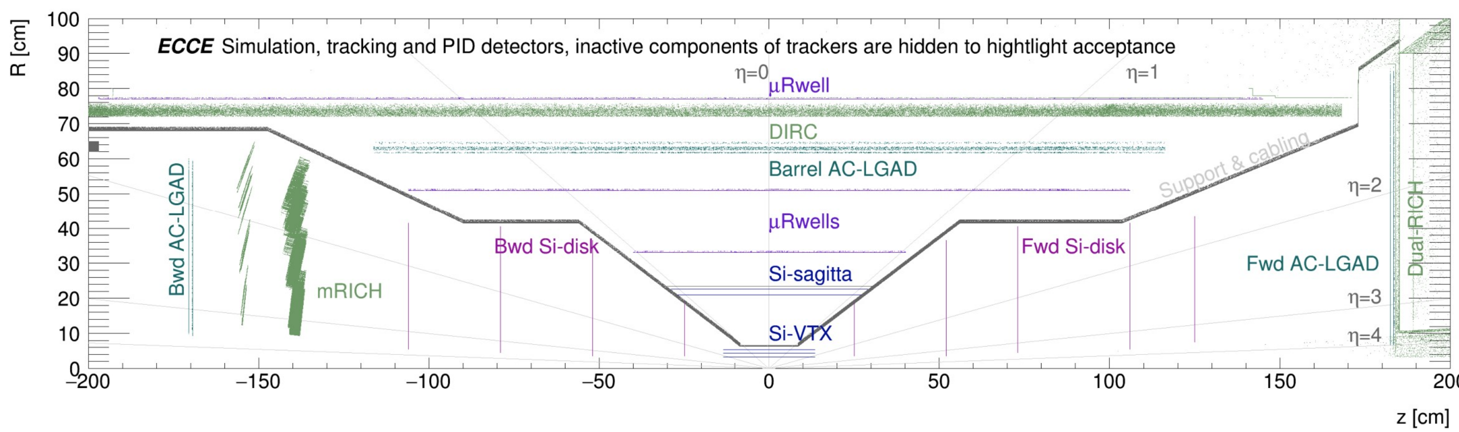


From H.D., Marcarelli, Neil, 2307.00102

Background considerations

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

- Si disks separated by ~ 25 cm: cut out thin regions from signal



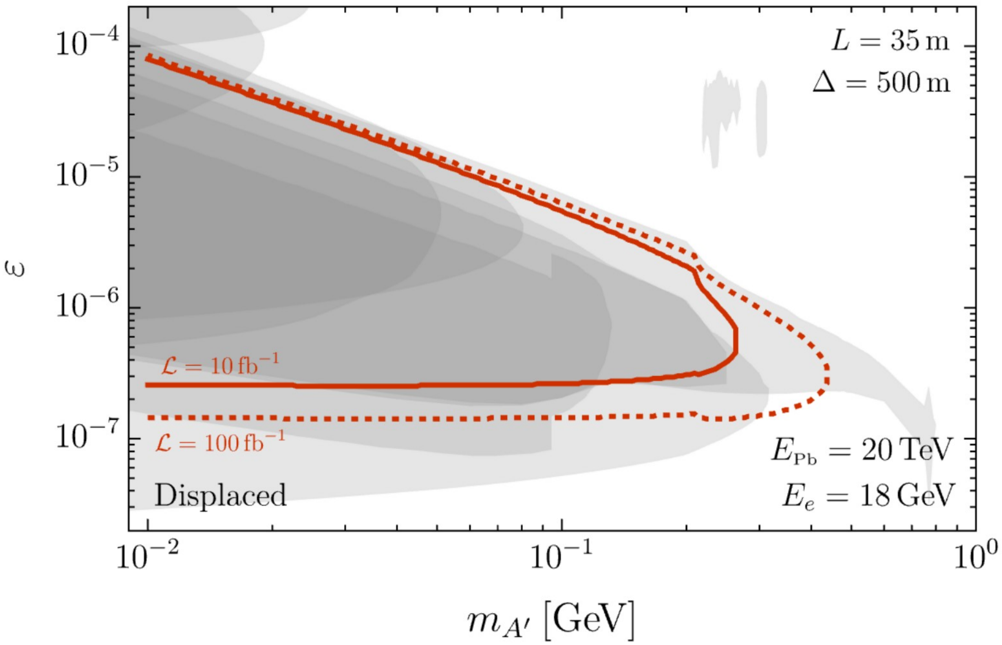
- Misidentified pions as electrons: electron end cap fake rate $\sim 10^{-4}$

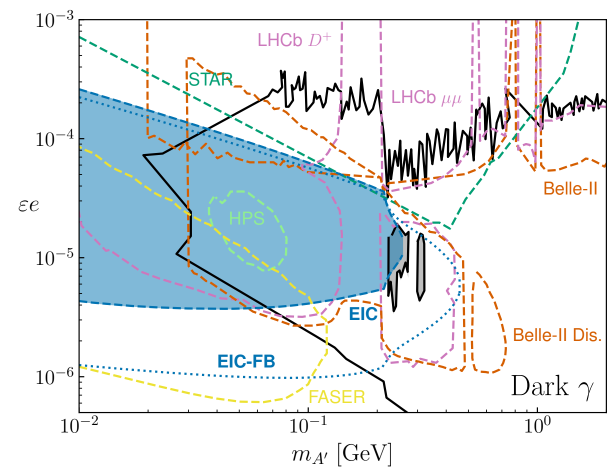
- Requiring both e^+ and e^-
- Additional signals if muon detectors added

- 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

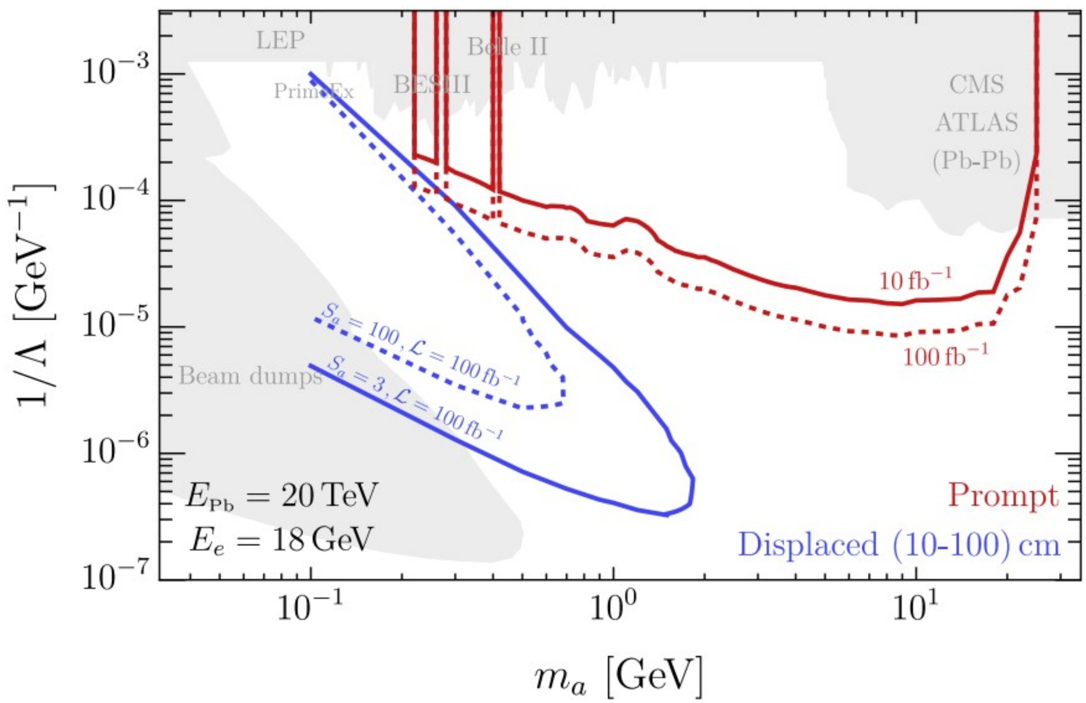
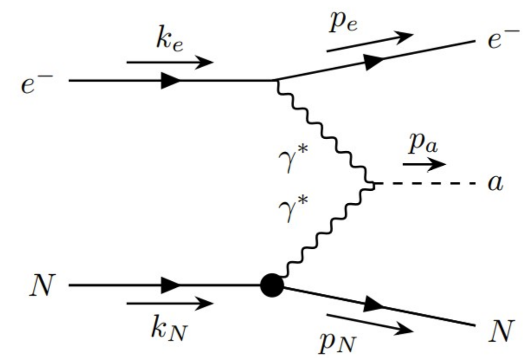


Figure 7: The EIC projections from the ALP searches with $E_e = 18\,\mathrm{GeV}$ and $E_{\mathrm{Pb}} = 20\,\mathrm{TeV}$. The solid (dashed) red lines show the prompt search results with 10 (100) fb^{-1} integrated luminosity. The solid (dashed) blue lines show the displaced search results with $S_a = 3$ ($S_a = 100$) with 100 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
- Covers a broad range of possible models
  - $B-L$, $L_e - L_i$ with $i = \mu, \tau$, dark Z

  - Significant invisible branching fraction from ν final states

  - Dark bosons coupled to light dark sector states or neutrinos
- Basic models

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

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

  - ϕ (ϕ_μ) a scalar (vector)
  - χ a neutrino or dark fermion
  - $m_\chi < m_\phi/2 \Rightarrow \phi \to \bar{\chi}\chi$ allowed on-shell

Production Process

- We consider coherent scattering

  - Enhanced by heavy ion Z^2 (mass number A)

  Nucleus mass m_A

  - Nucleus (ion) stays intact (gold, $A = 197$, $Z = 79$)

- For $m_e \ll m_\phi \ll m_A \ll \sqrt{s}$, transferred momentum to the nucleus $Q_A^2 \sim m_\phi^4 m_A^2 / s^2$

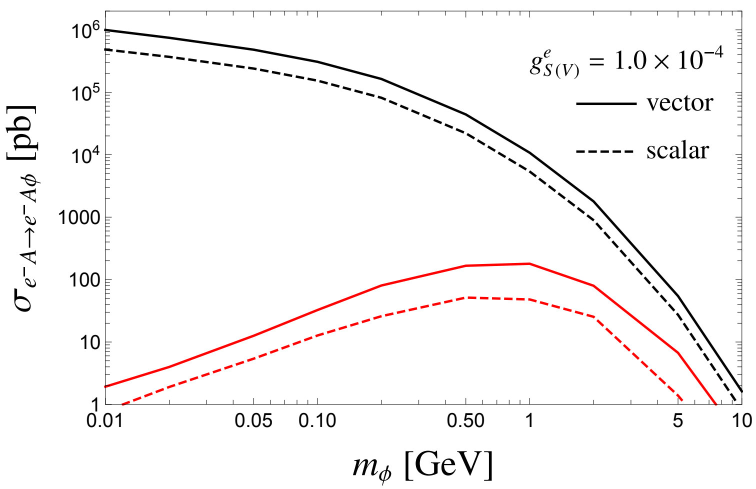
- Nuclear form factor strongly suppresses $\sqrt{Q_A^2} \gg r_A^{-1} \sim (A^{1/3}\,\mathrm{fm})^{-1}$

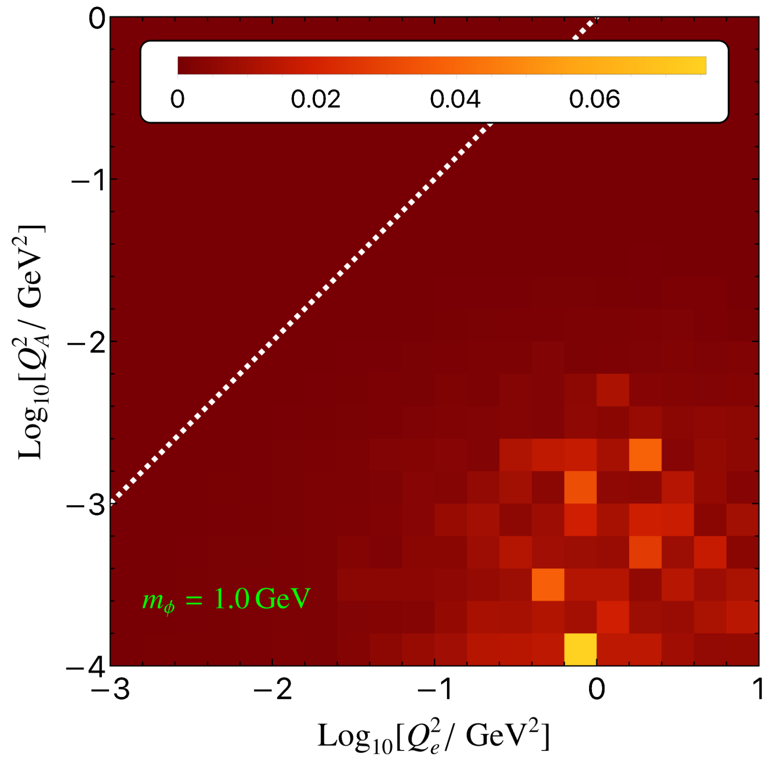
- We take $E_e = 18$ GeV, $E_A = 100$ GeV per nucleon

$$\Rightarrow \boxed{(m_\phi)_{\mathrm{max}} \sim 20\ \mathrm{GeV}(197/A)^{1/6}}$$

Kinematics

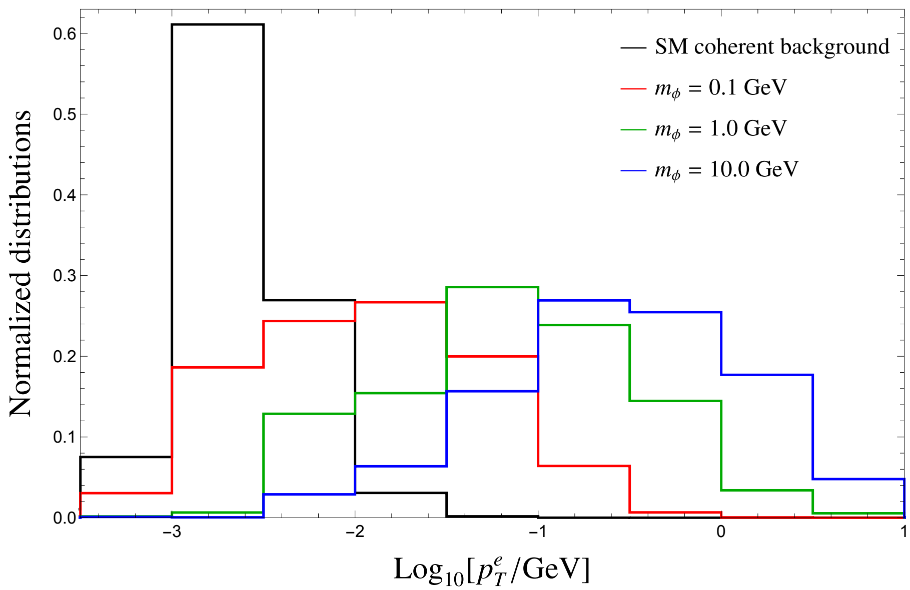
- Emitted ϕ takes most of the electron beam energy
- Momentum transfer Q^2 mostly on the electron side
- SM background marked by soft and similar Q^2 from either beam

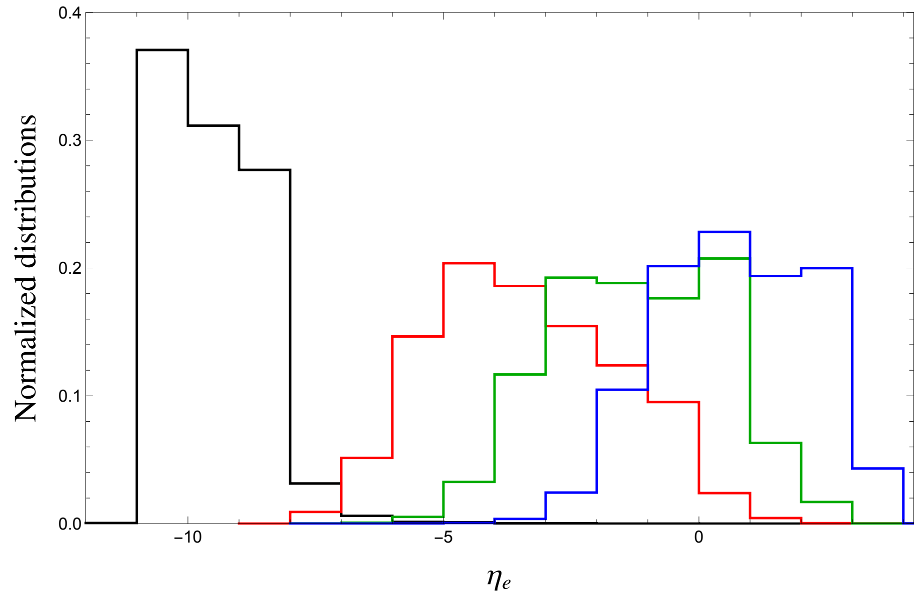




- Similar cross sections for scalars and vectors
- Red curves: after cuts
- We focus on the vector case

Suppressing the Background (p_T: transverse momentum, η: pseudo-rapidity)





- For heavier ϕ, larger p_T^e, more central recoil e
- A main background: coherent $e^- A \to e^- A\gamma$ bremsstrahlung, with the γ missed
  - Dominated by soft and collinear photons
- We hence adopt the cuts:

$$|\eta_e| < 3.5,\ p_T^e > 1.2\ \text{GeV},\ E_e < 10\ \text{GeV},\ Q_e^2 > 4\ \text{GeV}^2$$

- E_e cut $\to$ background E_γ mostly > 5 GeV, *Inefficiency* $10^{-6} \leq \epsilon \leq 10^{-4}$

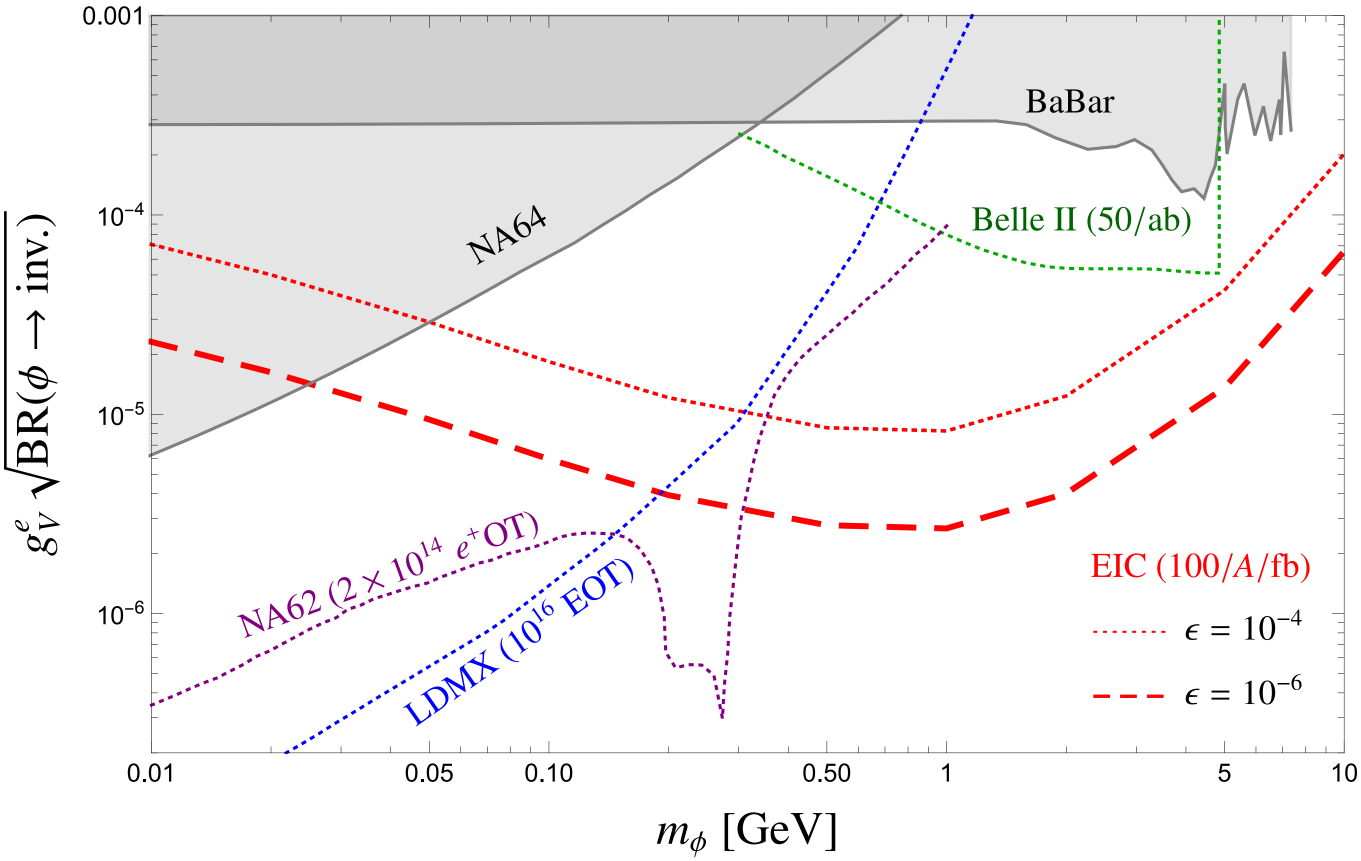
  Maeda *et al.*, 1412.6880; Fry *et al.*, 2501.14827

  - for $|\eta_\gamma| < 3.5$ (assumed missed otherwise)
  - Background: $70 \times \epsilon/10^{-4}$ pb

- Taking similar ϵ 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 background, but not negligible
  - Additional leverage from Zero Degree Calorimeter to veto incoherent scattering

Results

- EIC 3σ projections (red dashed/dotted curves):



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
- Long standing theory arguments have been challenged and no new consensus has emerged
- A good strategy seems to be 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, perhaps associated with low mass dark sectors
- Physics imprints of high scale phenomena may also leave a trace (encoded via EFTs) in EIC measurements
- Further studies are warranted and can provide

- optimized scientific impact for the EIC

- a nexus of collaboration for the high energy and nuclear physics communities