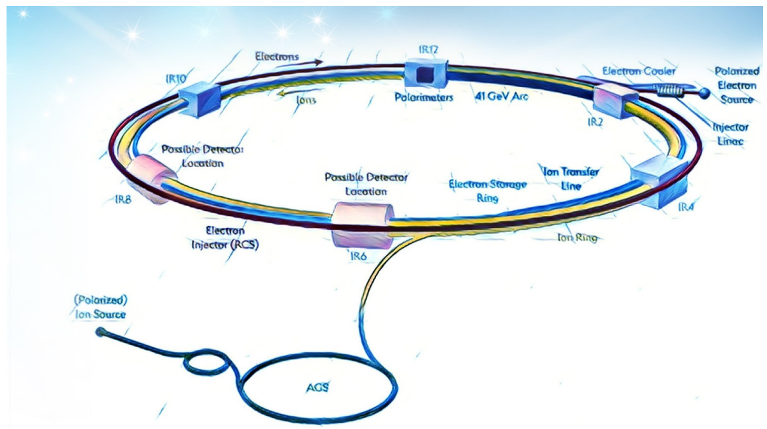
Displaced Hidden Vectors at the EIC

Hooman Davoudiasl

HET Group, Brookhaven National Laboratory



Talk at the EW and BSM Workshop at the EIC

INT, February 12-16, 2024

Based on: H.D., R. Marcarelli, E. Neil, Phys.Rev.D 108 (2023) 7, 7; 2307.00102

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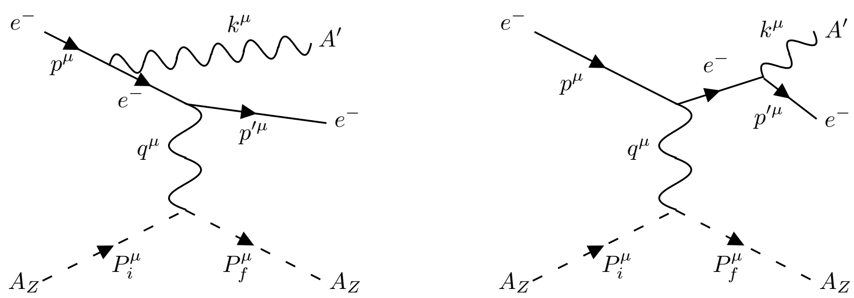

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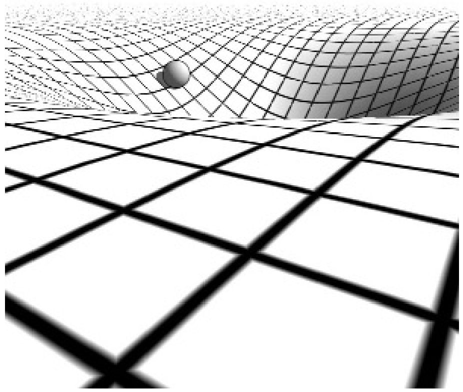
Some key developments of the recent past (incomplete list)

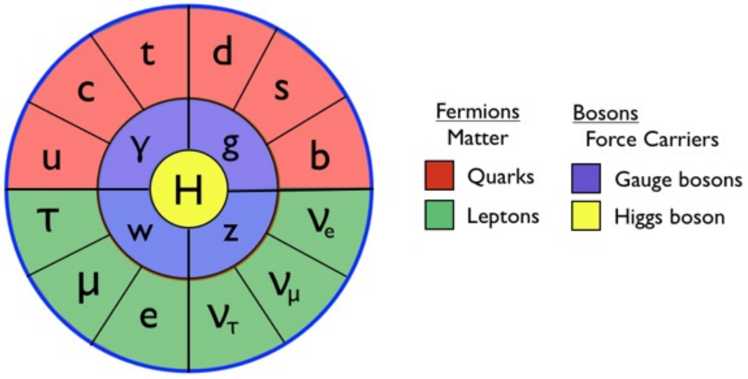
- Neutrino mixing parameter θ_{13} measurement (Daya Bay, Reno)
- Higgs discovery at the LHC (ATLAS, CMS)
- IceCube observation of astrophysical neutrinos up to $\sim 10^3$ TeV
- LIGO-Virgo detection of gravitational waves
- Multi-messenger astronomy (binary neutron star merger)
- Event Horizon Telescope imaging of supermassive black holes (M87*, SgrA*)
- Evidence for stochastic gravitational wave background
  - Pulsar timing measurements (NANOGrav, EPTA, Parkes, CPTA,...)
- . . .

Despite all that, the fundamental theories have not changed!



State of the art:

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



Particles of the Standard Model

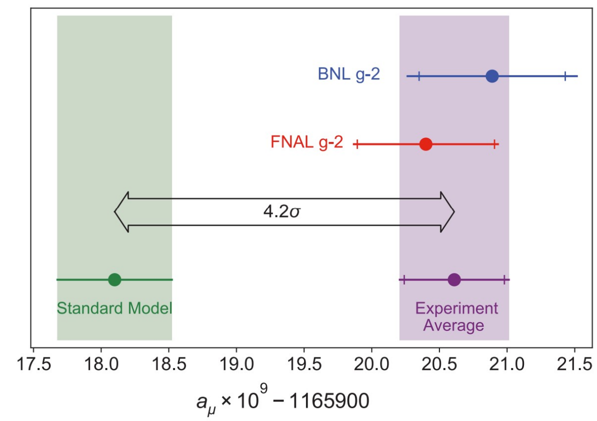
- There are some, often modest and transient, anomalies*

Aside: "*" from last page (can be a separate talk on its own)

- Two prominent instances (also others, largely less significant)

- **Muon anomalous magnetic moment ($g-2$)**
  - $g=2$ (Dirac) gets quantum corrections (SM; possibly other)
  - Theory (SM): T. Aoyama, et al., Phys.Rep. 887, 1 (2020)
  - Muon g-2 Collaboration 2023 results: discrepancy $\sim 5\sigma$
    - Above prediction under scrutiny, can change
    - Another prediction yields a smaller discrepancy

Borsanyi et al., Nature 593 (2021) 7857, 51-55

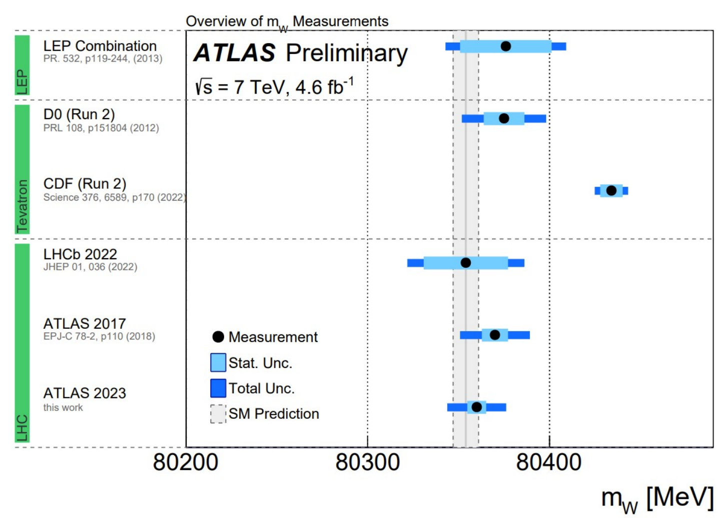


Phys.Rev.Lett. 126 (2021) 14, 141801

- **W mass**
  - CDF II result: $\sim 7\sigma$ discrepancy!

CDF Collaboration, Science 376 (2022) 6589, 170-176

  - Are there unaccounted for uncertainties?
  - More data from the LHC can be illuminating



ATLAS-CONF-2023-004

Stay tuned!

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 $\rightarrow m_\nu \neq 0$**

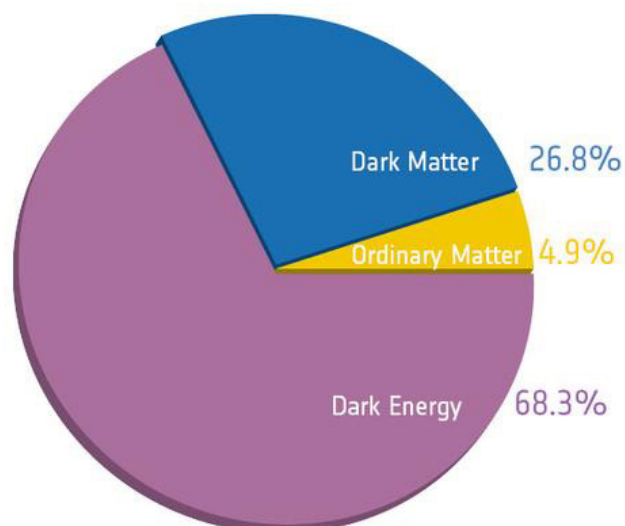
- Adding right-handed neutrinos (of a broad range of masses) can explain this

★ **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

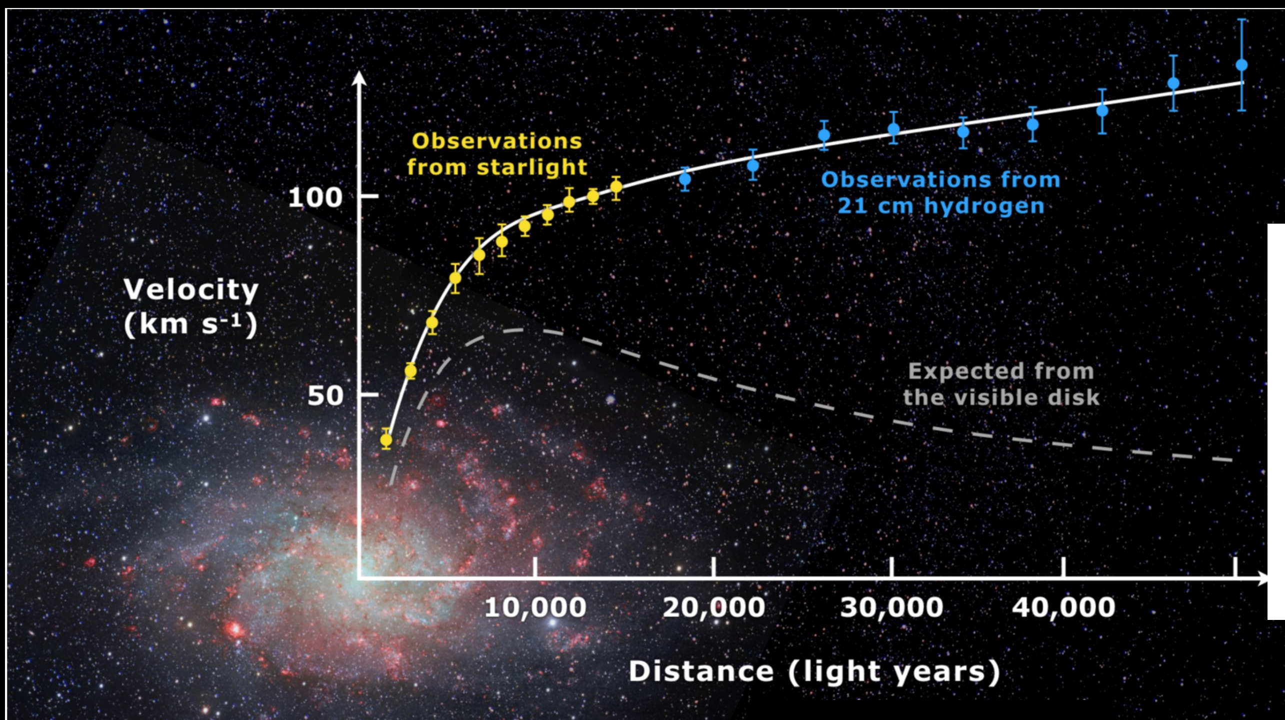


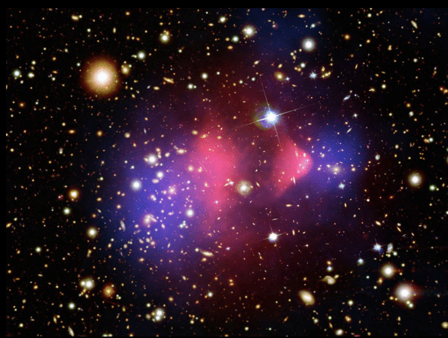
There are also theoretical hints:

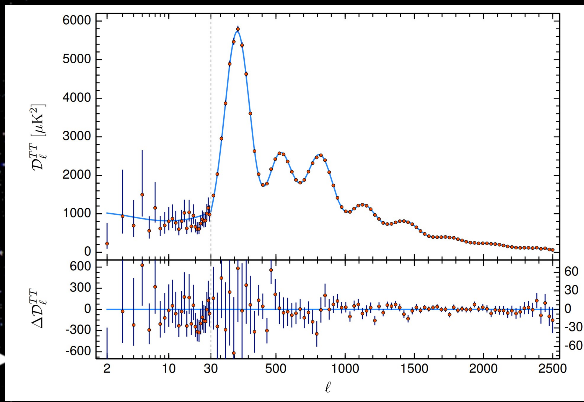
- Why is gravity so weak (Higgs mass hierarchy problem)?
- Why is CP violation so suppressed in strong interactions?
- Why . . . ?

Dark matter (DM)

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







Planck Collaboration; 1807.06209

- $\sim$ 27% of energy density

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

Dark Sectors

- With lack of evidence for new weak scale physics, alternatives to Weakly Interacting Massive Particles (WIMPs) have been put forth in recent years

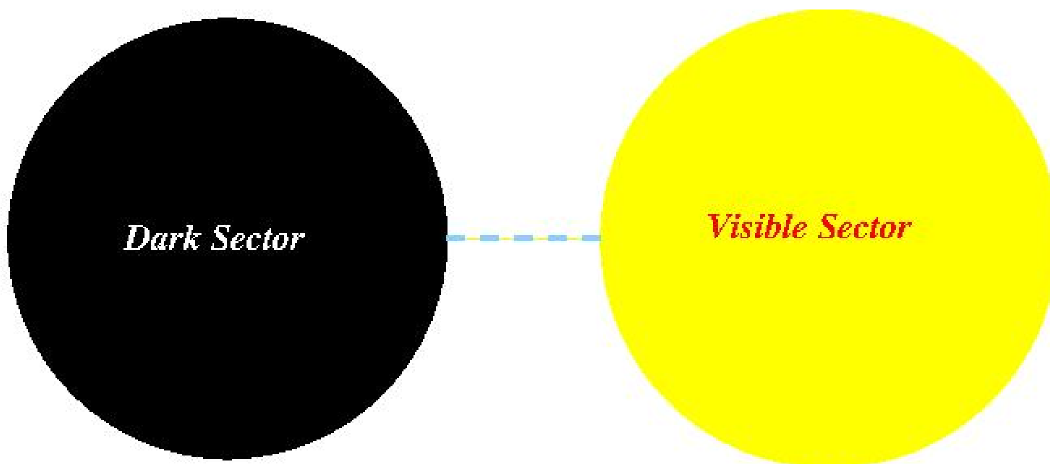
- Example: DM could be light ($m \lesssim$ GeV) and may reside in a separate sector with its own forces

- 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: $B - L$, $L_e - L_\tau, \ldots$ (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)

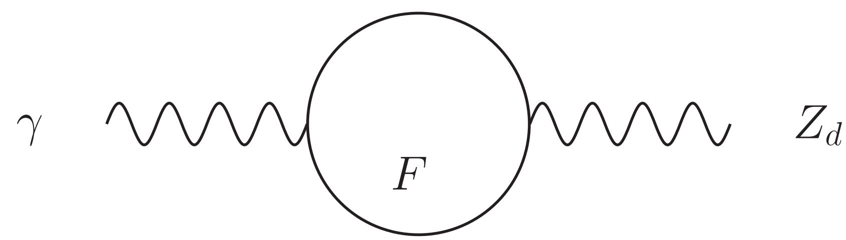
Hongkai Liu's talk on Monday; Ethan Neil's talk on Thursday

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)
  - $\tan\theta_W \equiv \frac{g'}{g}$ 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 $U(1)_d$

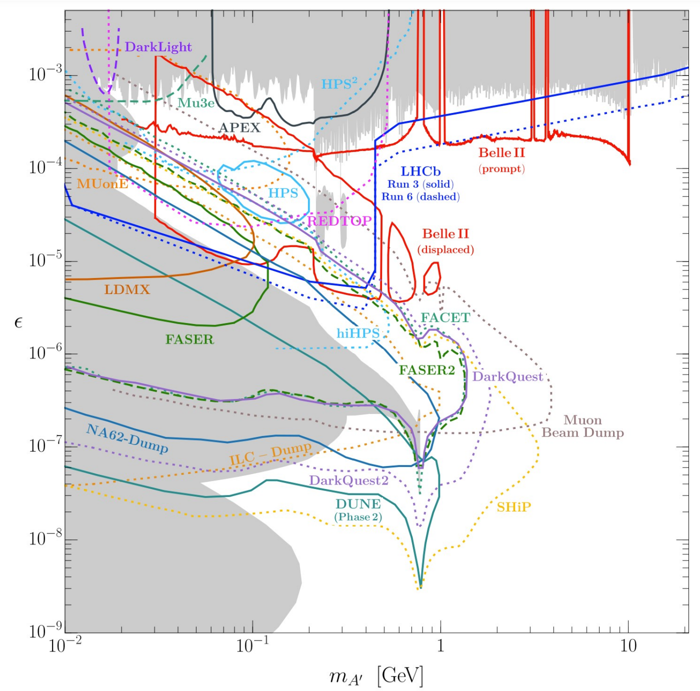
$$\boxed{\mathcal{L}_{\text{int}} = -e\,\varepsilon\, J^\mu_{em} Z_{d\mu}}$$

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

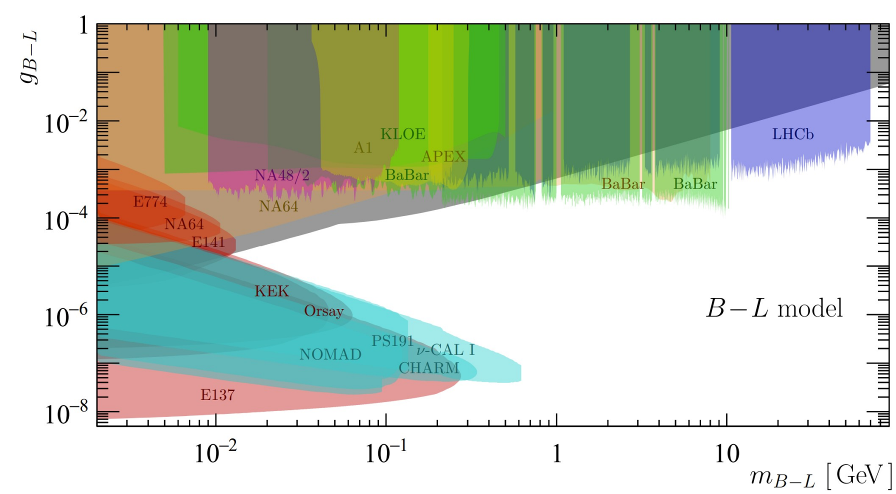
- Active experimental program to search for hidden vector bosons

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

From Batell, Blinov, Hearty, McGehee, 2207.06905, visibly decaying dark photon



From Ilten, Soreq, Williams, Xue, 1801.04847, JHEP 06 (2018) 004



Other $U(1)$ Gauge Interactions

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

- Also what is needed to provide Dirac neutrino masses

- 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

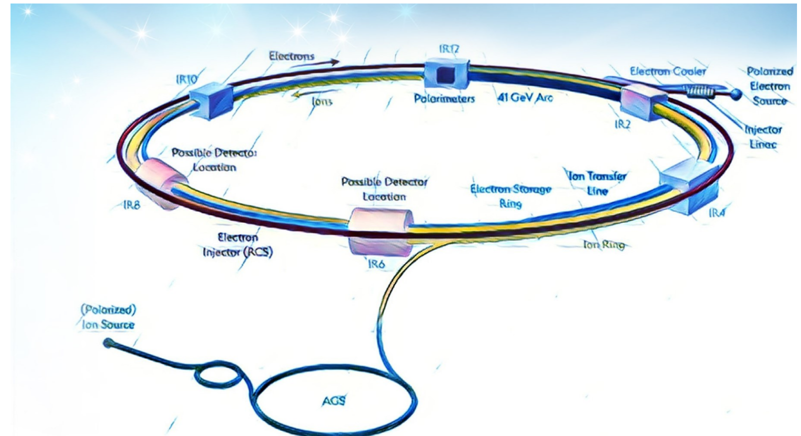
- Light and feebly interacting states can be long-lived

- Displaced vertex signals in collider experiments

- Good prospects for suppressing SM backgrounds

The Electron Ion Collider (EIC)

2103.05419, EIC Yellow Report



- New frontier in studying structure of hadronic matter, 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 A (atomic mass)

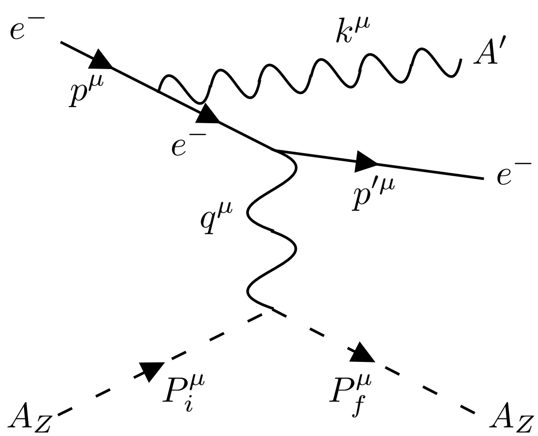
- Polarization: $\sim 70\%$ for e and p beams

- 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, $Z = 79$: $eA_Z \to eA_Z A'$ $(Z_d \leftrightarrow A')$
- $q^2 \lesssim \mathcal{O}(10\text{ MeV})$
- Large Z^2 enhancement of electromagnetic scattering



- Consider only emission from e^-

- Suppressed emission from ion (form factor) except for well constrained low $m_{A'}$

- Form factor: approximate Fourier transform of the Woods-Saxon distribution applied to Au ion

Klein, Nystrand, 1999

$$F(q^2) = \frac{3}{q^3 R_A^3} (\sin qR_A - qR_A \cos qR_A) \frac{1}{1 + a_0^2 q^2}$$

$a_0 = 0.79$ fm and $R_A = (1.1 \text{ fm}) A^{1/3}$.

- 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
- A' boost γ_k, velocity v_k, lifetime τ
- Kinematic variables: laboratory frame
- Signal cross section:

$$\sigma_{\text{sig}}(g_{A'}) = \int P_{\text{disp}} \frac{d\sigma}{d\gamma_k \, d\eta_k} d\gamma_k \, d\eta_k \, \mathcal{B}(A' \to e^+ e^-)$$

Pseudo-rapidity $|\eta| < 3.5$ (Ecce tracking)

- Focus on $A' \to e^+ e^-$ (EIC: good electron tracking)

Signal Selection:

- Based on EIC Comprehensive Chromodynamics Experiment (ECCE) detector

Adkins *et al.*, 2209.02580

- Now the ePIC Collaboration detector

- Signal requires both e^+ and e^- from vector decay

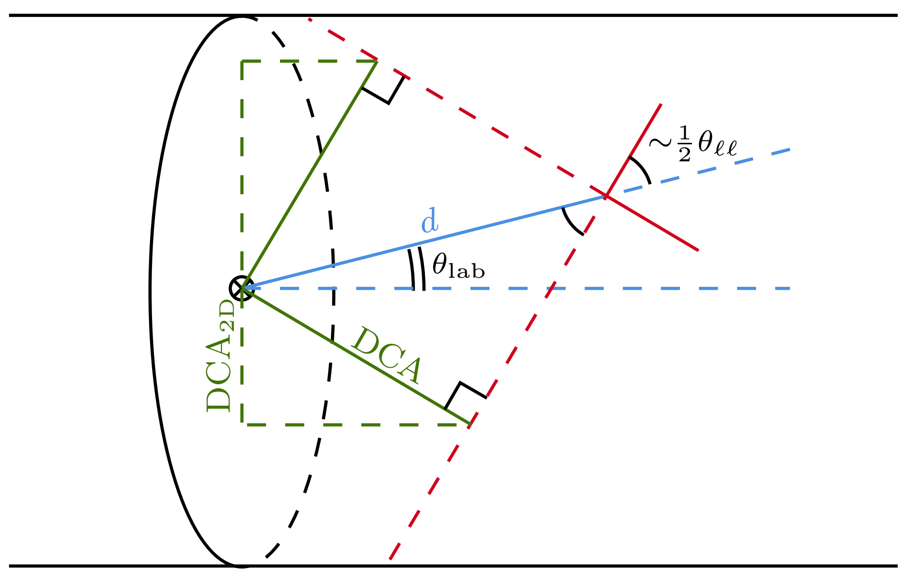
- $\mu^+\mu^-$ also available for much of the parameter space

- We estimated: $d_{\text{min}} \approx \gamma_k(\text{DCA}^{\text{min}}_{\text{2D}})/(v_k \cos\theta^{\text{lab}}_k)$

- For pions: $\text{DCA}^{\text{min}}_{\text{2D}} \lesssim 100\ \mu\text{m}$

- $\Rightarrow d_{\text{min}} \gg 0.1$ mm, $d_{\text{max}} = 1$ m

DCA: distance of closest approach



- ECCE tracking: $\boxed{|\eta| < 3.5}$

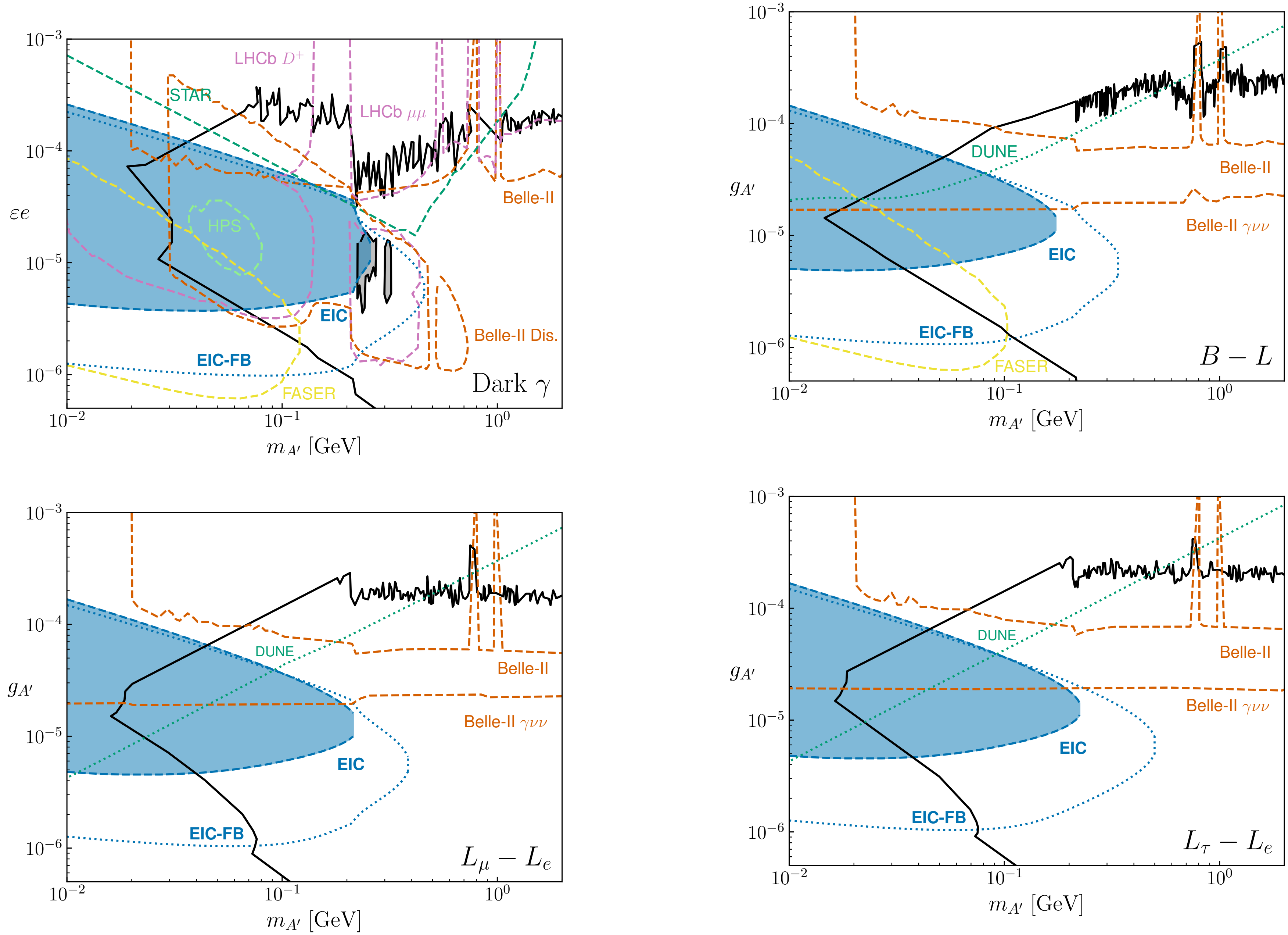
- We also considered a detector at $z = -5$ m

- Assumed: $\text{DCA}_{\text{2D}}^{\text{min}} = 200\,\mu$m, $d_{\text{max}} = 5$ m

- Covering far backwards (FB): $\boxed{-6 < \eta < -4}$

- Coupling limits: $\mathcal{L}\sigma(g_{A'}) \geq n_{\text{max}}$

- $n_{\text{max}} = 3.09$, upper limit of the 95% confidence interval on the mean number of signal events for zero expected background



- FB capability well-motivated for these searches

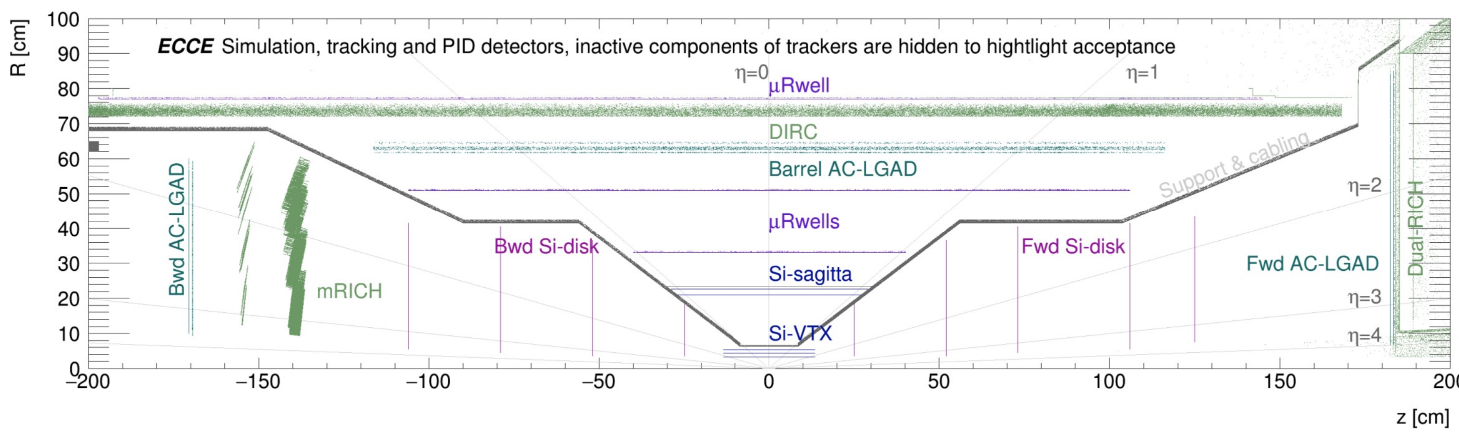
From H.D., Marcarelli, Neil, 2307.00102

- Generic for light satates emitted from the e-beam at low Q^2

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 $\sim 10^{-4}$

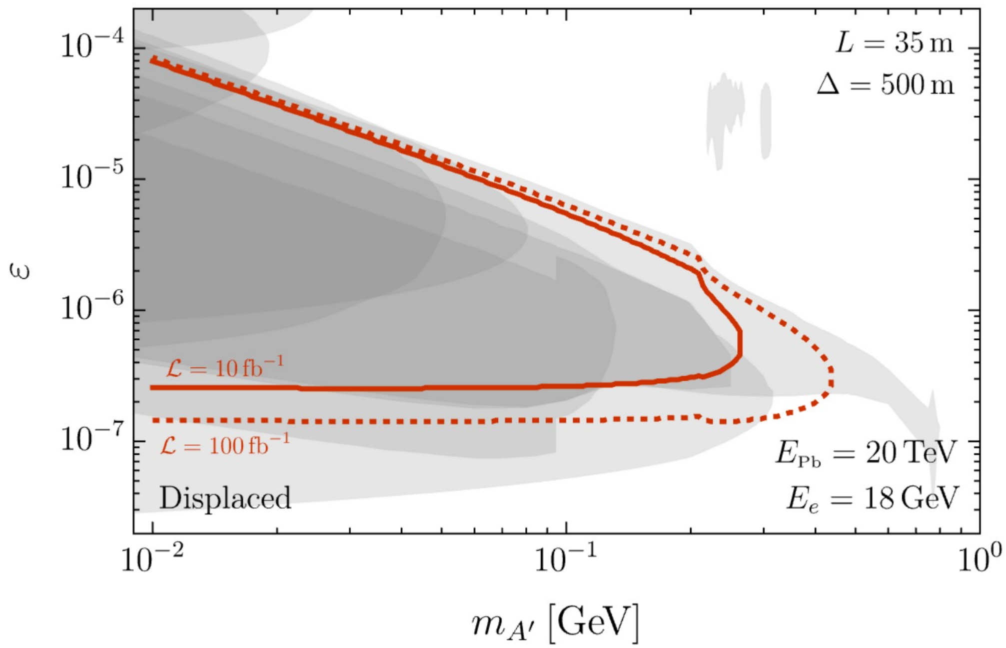
- Requiring both e^+ and e^-

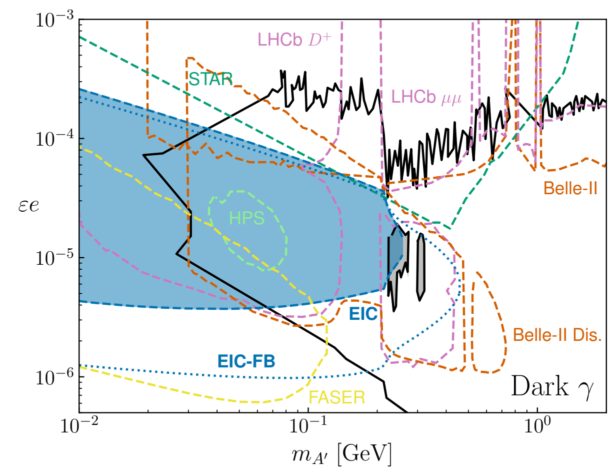
- Additional signals if muon detectors added

- 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

Recently, also [Balkin *et al.*, 2310.08827]





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

Concluding Remarks

- EIC: a frontier machine for studying hadronic structure

- Given its relatively large center of mass energy and luminosity one can leverage its capabilities to search for new physics

- "Hidden" weakly coupled vectors below the GeV scale can be produced in coherent electromagnetic scattering from large Z ions
  - Large effective luminosity $\sim Z^2$
  - Displaced "backwards" decays
  - Background may be suppressed (photon conversion) due to sparse backwards detector structure

- We examined a variety of such models and found competitive or better reach compared to other projections

- Future realistic detector simulations necessary for definitive projections

- A "far backward" (~ -5 m) detector can significantly enhance the reach
  - Muon detection capabilities can also help enlarge signal sample by $\mathcal{O}(1)$ factors