Looking Beyond the Standard Model at the Electron-Ion Collider

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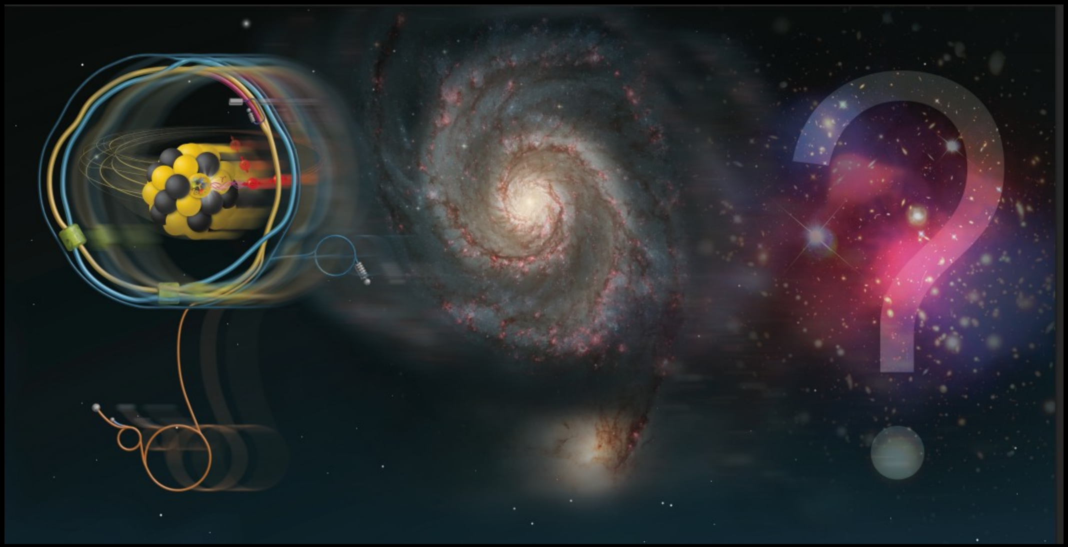


https://www.bnl.gov/hepeic/

Based on: H.D., H. Liu, 2505.08871 [hep-ph]

Phenomenology Before and After the Standard Model

University of Wisconsin-Madison, June 5, 2025

First things first

- I was at UW-Madison 2004-2006 (P.A.M. Dirac Fellow).

  - I went on to be a staff physicist at Brookhaven National Laboratory in 2006.

- Many of us who came here as junior researchers found it to be an active and supportive place to do physics.

- The Phenomenology Institute, thanks to a large degree to Vernon's vision for its place in theoretical particle physics, has left its mark on our careers and the greater community.

- Much has changed, both in Madison and in physics, since my days here.

- However, one thing has remained the same:

Vernon still writes more papers per year than most of us do at our peak!

- Seven over the last ~ 12 months by my count

Phenomenology circa 2025 (my two cents)

- Particle theory is searching for new organizing principles

\- Old arguments for new physics are getting squeezed

- So far: no obvious empirical hints or emerging theoretical consensus

\- Dark matter and neutrino masses: a large set of ideas and directions

- Casting a wide net seems like a good way forward

- Given limited resources and new high energy colliders decades away, one needs to get creative

- This attitude has been getting more attention in recent years, with many new ideas emerging to look for physics beyond the Standard Model across a wide range of scales

- If a new facility becomes available at any frontier, we should ask how it may be leveraged to advance fundamental physics

The Advent of a New Collider

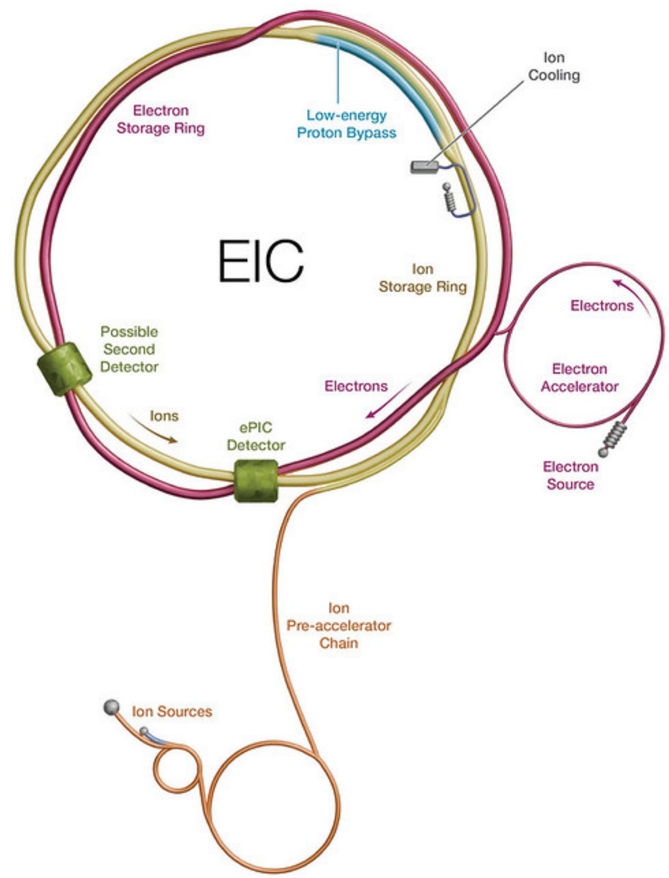
- The Electron-Ion Collider (EIC), to be built over the next $\sim$ 10 years at Brookhaven National Laboratory, will open new frontiers in studying the structure of hadrons

- EIC: relatively high center of mass energies, luminosity $\oplus$ polarized beams

EIC Yellow Report, 2103.05419

- Electron beam of up to 18 GeV
- Proton beam of up to 275 GeV ($\sqrt{s} \approx 141$ GeV)
- Heavy ion beam (Au) up to 110 GeV ($\sqrt{s} \approx 89$ GeV)
  - Au: mass number $A = 197$, atomic number $Z = 79$
- Integrated luminosity: $\lesssim 100/A$ fb^{-1}
- Proton and electron polarization goal: 70%

- Excellent electron identification
  - Baseline detector (ePIC)
- New capabilities can be envisioned
  - Implemented in a possible second detector



EIC as a Discovery Tool for Dark Bosons

- Recent interest in using EIC for probing possible new physics

For example: 1006.5063, 2004.00748, 2102.06176, 2112.04513, 2112.07747, 2204.07557, 2210.09287, 2310.08827, 2402.17821, 2503.02605.

- Here we will focus on "dark bosons": H.D., Liu, 2505.08871
  - Potentially from a "dark sector" that includes dark matter
  - With weak but non-negligible coupling to electrons
  - Having $\mathcal{O}(1)$ branching fraction into invisible final states
- Such dark bosons can originate from a variety of motivated models:

(i) Gauged $B-L$, $L_e - L_i$ with $i = \mu, \tau$, dark Z (mixing with SM Z boson)

- Invisible final states: SM neutrinos

(ii) General vector or scalar fields coupled to light dark sector states

Basic Models

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

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

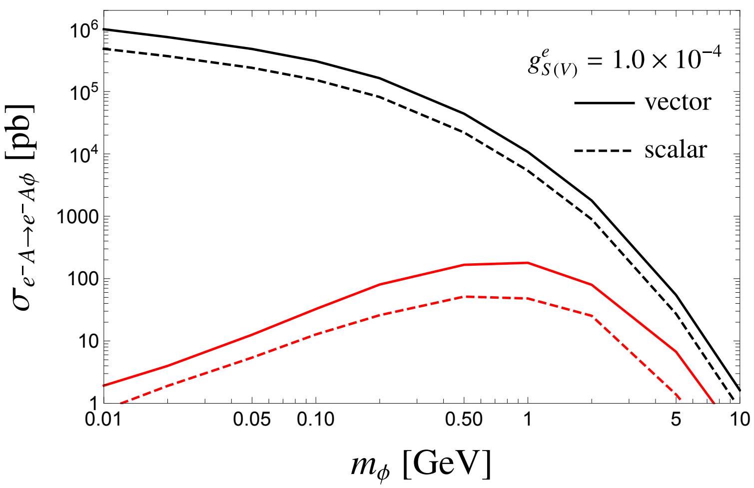
- $g^e_{S(V)}$ and $g^\chi_{S(V)}$: scalar (vector) couplings to electrons and χ
- $m_\chi < m_\phi/2 \Rightarrow \phi \to \bar{\chi}\chi$ allowed on-shell (χ: neutrino, dark state)

- We consider coherent scattering
  - Enhanced by heavy ion Z^2 (mass number A) Nucleus mass m_A
  - Nucleus (ion) stays intact
- 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 $\sqrt{Q_A^2} \gg r_A^{-1} \sim (A^{1/3}\,\text{fm})^{-1}$
- We take $E_e = 18$ GeV, $E_A = 100$ GeV per nucleon

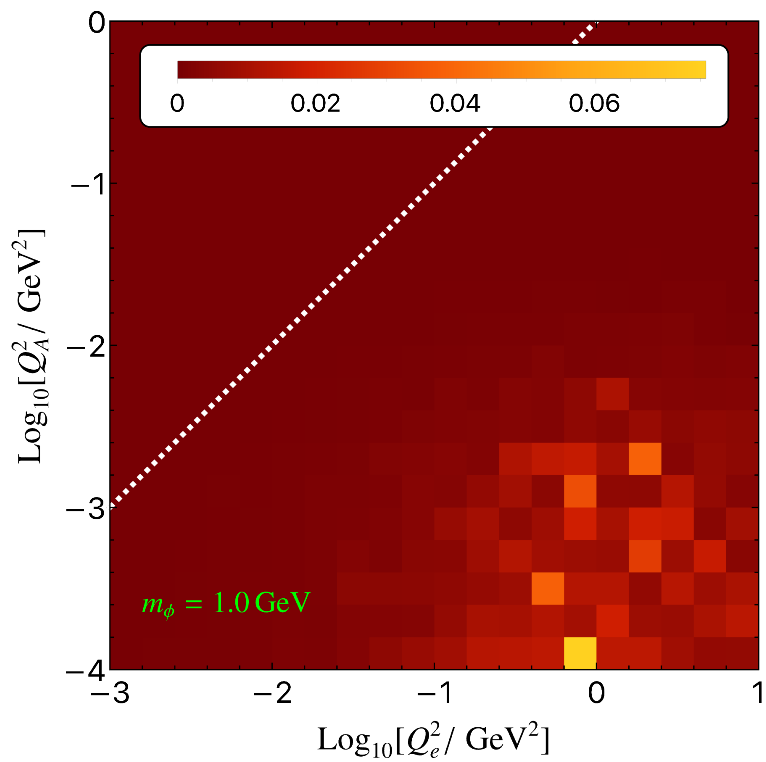
$$\Rightarrow \boxed{(m_\phi)_{\text{max}} \sim 20\ \text{GeV}(197/A)^{1/6}}$$

Kinematics

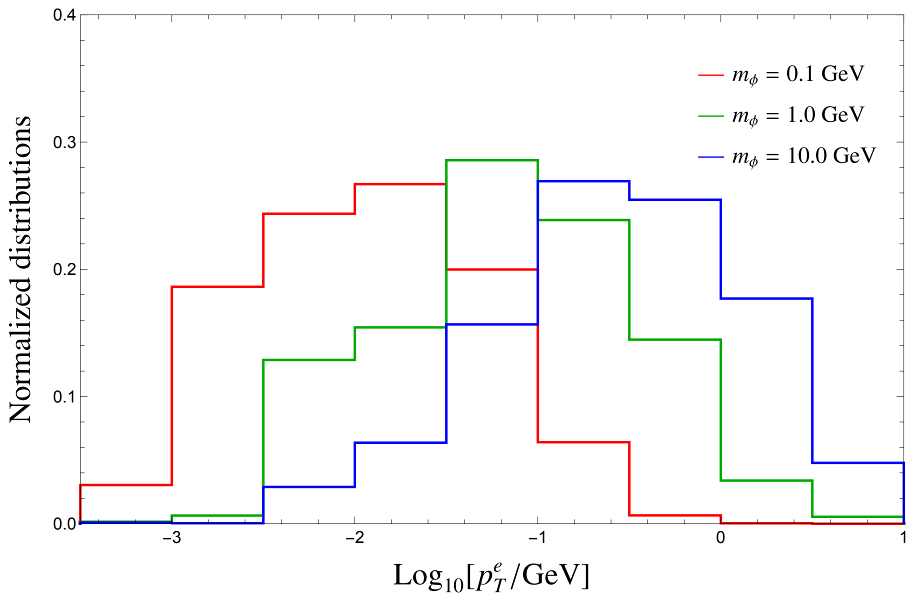
- Emitted ϕ takes most of the electron beam energy
- Momentum transfer Q^2 mostly on the electron side
- SM background marked by soft and similar Q^2 from either beam
- For heavier ϕ, momentum transfer gets larger: more central recoil e

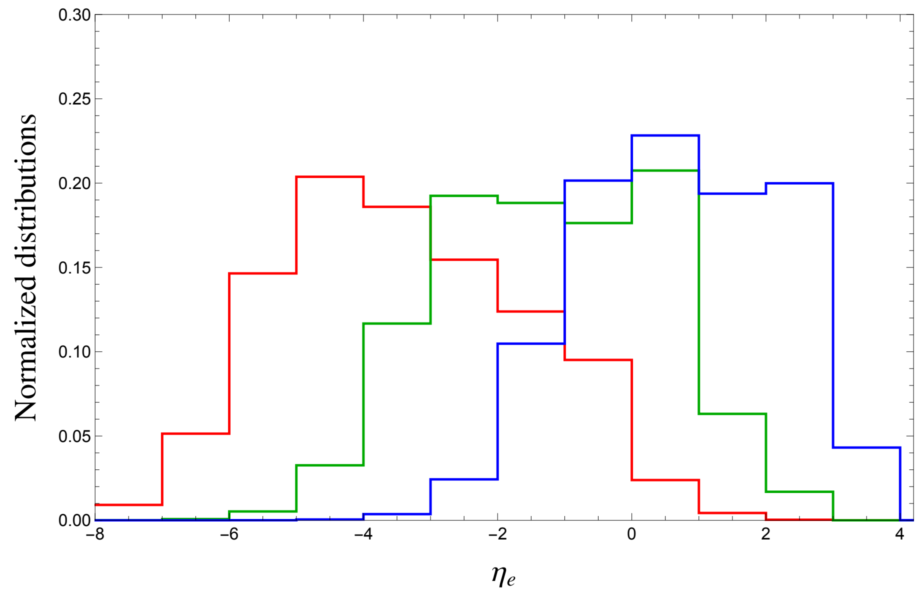


- Similar cross sections for scalars and vectors
- Red curves: after cuts
- We focus on the vector case



Cuts for Suppressing the Background





- Cuts

(p_T: transverse momentum, η: pseudo-rapidity)

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

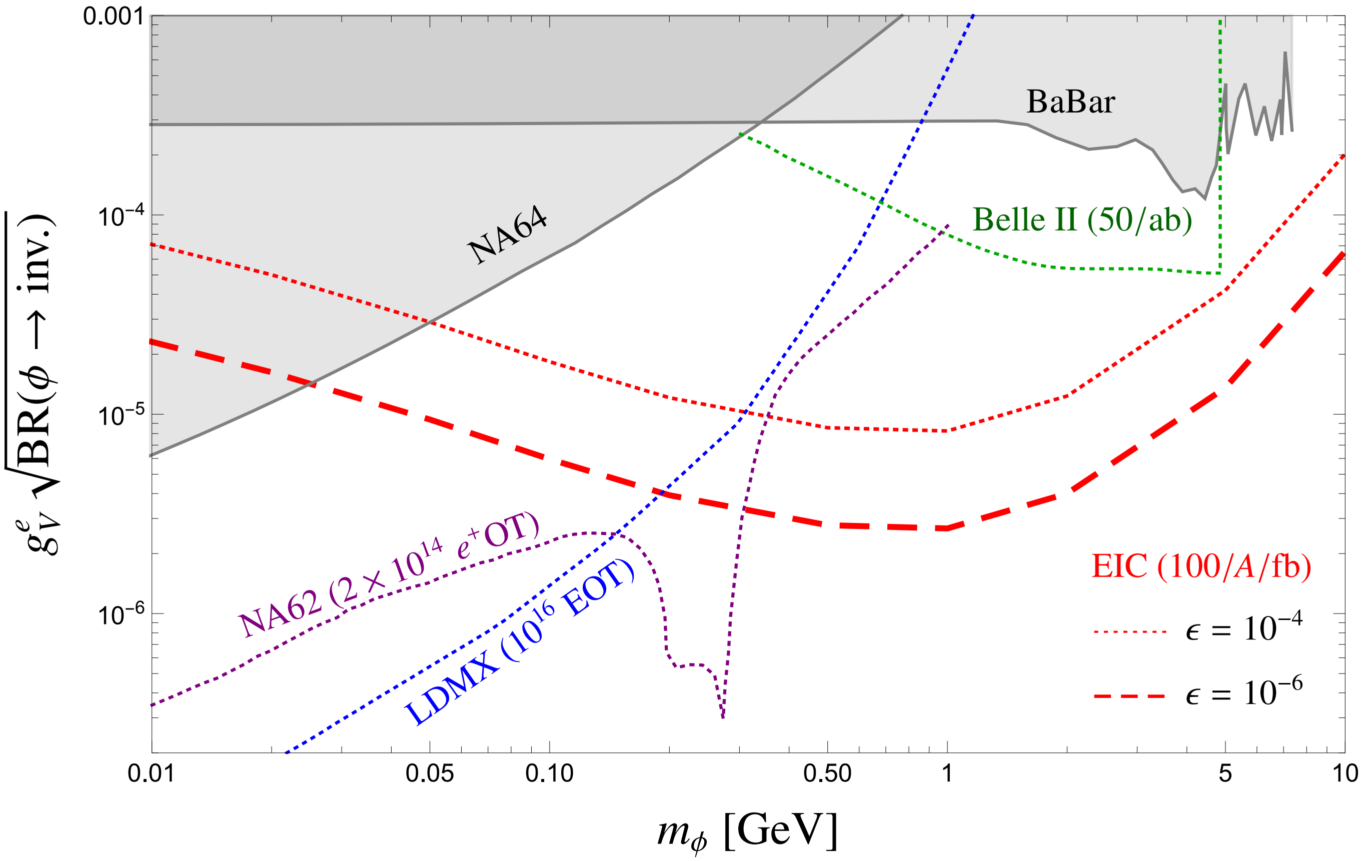
- A main background: $e^- A \to e^- A\,\gamma$ with the γ missed
- E_e cut: background bremsstrahlung γ energy mostly > 5 GeV
  - *Inefficiency* $10^{-6} \le \epsilon \le 10^{-4}$ for $|\eta_\gamma| < 3.5$ (assumed missed otherwise)

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

- Taking similar ϵ for hard jets, DIS background $e^- A \to e^- X j$ also suppressed
  - Additional leverage from Zero Degree Calorimeter to veto incoherent scattering

Results

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



- EIC: leading projections for 0.3 GeV $\lesssim m_\phi \lesssim$ 10 GeV

Concluding Remarks

- With no obvious guidance from theory and experiment all tools should be used to look for physics beyond the SM
- Perhaps new physics is not at very high scales, but hidden by feeble couplings to the SM sector
- The EIC can offer a new venue for dark sector searches
- Our results suggest the EIC can be a powerful probe of invisible light new bosons from a variety of models