

# *Invisible and Displaced Signals of New Physics at the EIC*

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Based on: H.D., Liu, 2505.08871 and H.D., Liu, Neil, 2607.16400

Precision QCD Predictions for ep Physics at the EIC (IV)

September 21-25, 2026, Stony Brook University

# The Case for New Physics

- Despite great success of  $\text{SM} \oplus \text{GR}$ , new physics is needed
- There is strong experimental evidence for this inference:

## ★ Neutrino flavor oscillations $\rightarrow m_\nu \lesssim 0.1 \text{ eV}$

- Much lighter than other fermions ( $m_e/m_\nu \gtrsim 10^6$ )
- 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; no match for in the SM)
- What caused ordinary matter asymmetry? (requires new physics)

*There are also theoretical hints*

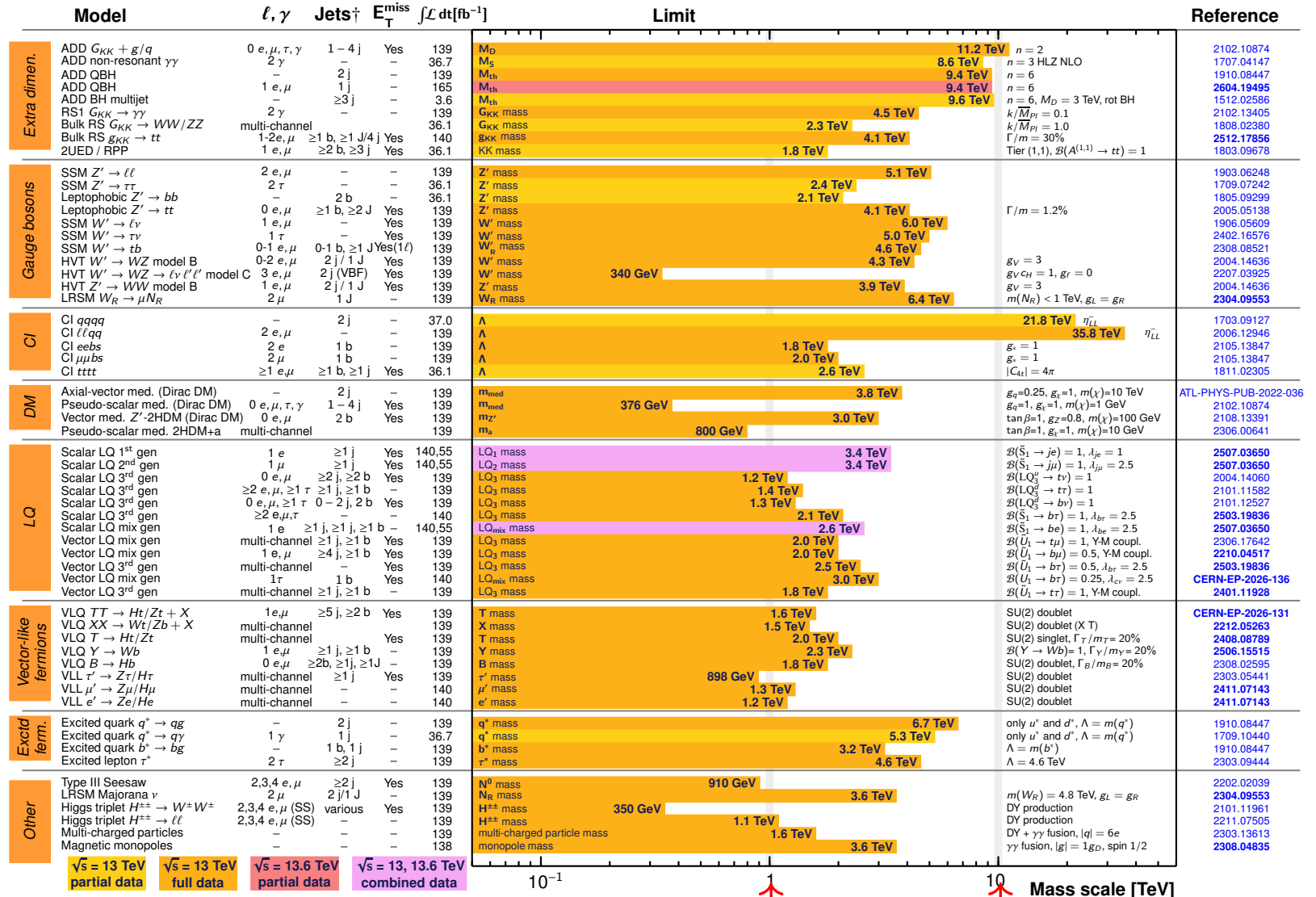
- For example: Why is gravity so weak?

# ATLAS Heavy Particle Searches\* - 95% CL Upper Exclusion Limits

Status: Spring 2026

ATLAS Preliminary

$$\int \mathcal{L} dt = (3.6 - 195) \text{ fb}^{-1} \quad \sqrt{s} = 13, 13.6 \text{ TeV}$$



\*Only a selection of the available mass limits on new states or phenomena is shown.

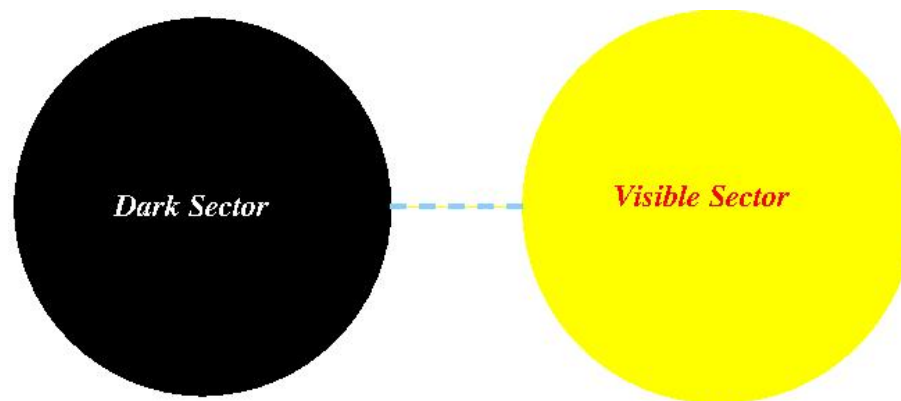
<sup>†</sup>Small-radius (large-radius) jets are denoted by the letter j (J).

1 TeV 10 TeV

- Many searches exclude new physics below  $\sim 1 \text{ TeV}$
- Some exclusions extend to  $\gtrsim 10 \text{ TeV}$

# Dark Sectors

- With lack of evidence for new physics near weak scale, alternatives to WIMPs have been put forth in recent years
  - Recent hint: LUX-ZEPLIN (LZ) single event, global significance of  $2.6 \sigma$  [2609.02823](#)
  - Could be some type of WIMP; more data needed to establish a signal
- DM could be light ( $m \lesssim \text{GeV}$ ), 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 (typically expected)
  - Mediators could be light, accessible to low energy experiments ( $\sqrt{s} \ll 100 \text{ GeV}$ )



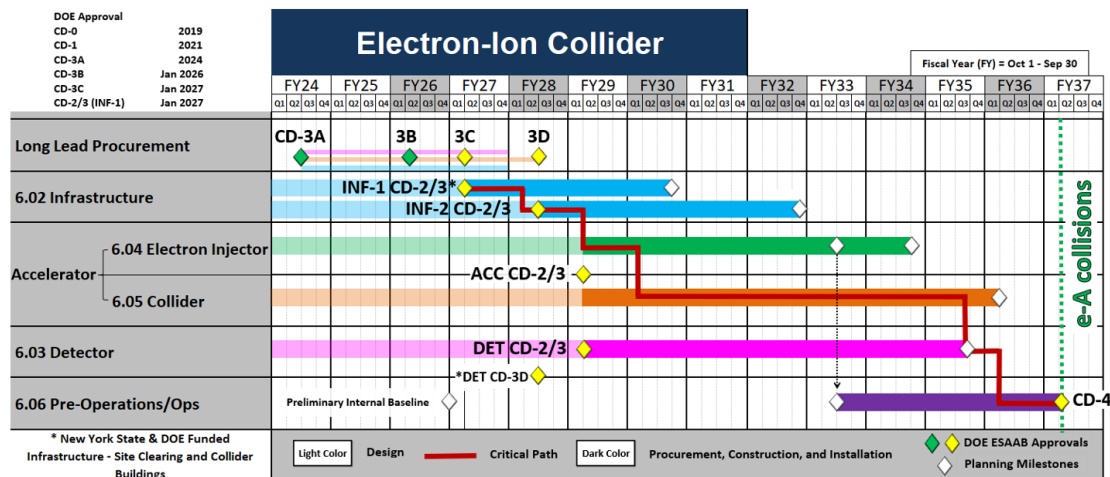
**Absent any strong evidence, one should leverage every available tool**

# The Electron-Ion Collider

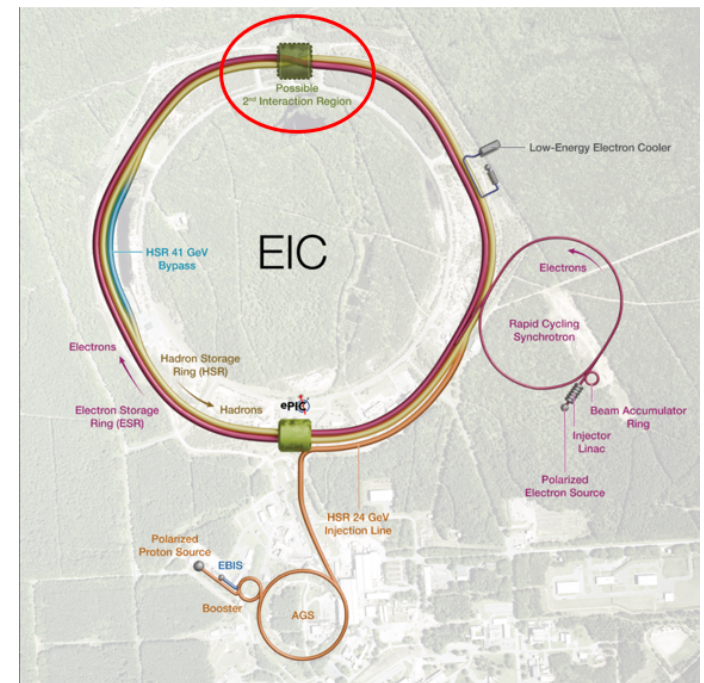
2103.05419, EIC Yellow Report

- *A future collider*, the only one to be built in the coming decade (site: BNL)
- New frontier in studying hadronic systems: spin composition of nucleons,....
- Large  $\sqrt{s}$ , luminosity
  - $E_e = 5 - 9(18)$  GeV (original design),  $\sim 40$  GeV, 100-275 GeV hadrons ( $p$  to  $U$ )
  - $\sim 100 \text{ fb}^{-1}$  per nucleon possible
- Polarization:  $\sim 70\%$  for  $e$  and  $p$  beams
- Large nuclei (high  $Z$ ): e.g. gold, lead

## Strategic EIC Schedule



Graphics from E.C. Aschenauer's talk at this meeting



What can we learn about new physics at the EIC?

# 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

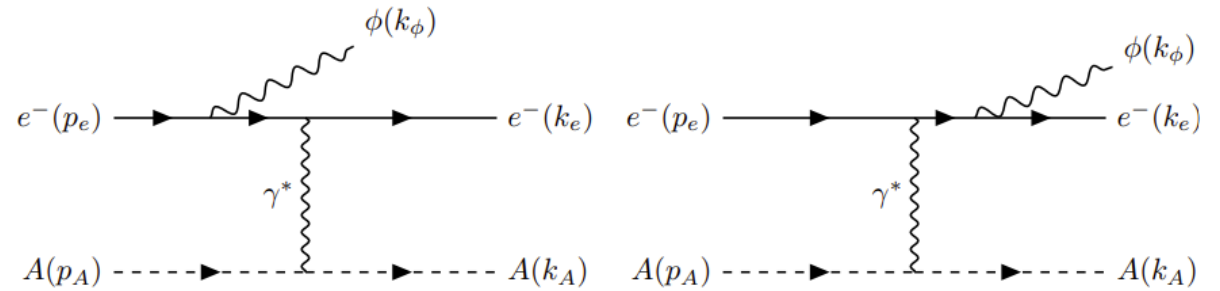
- Basic models

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

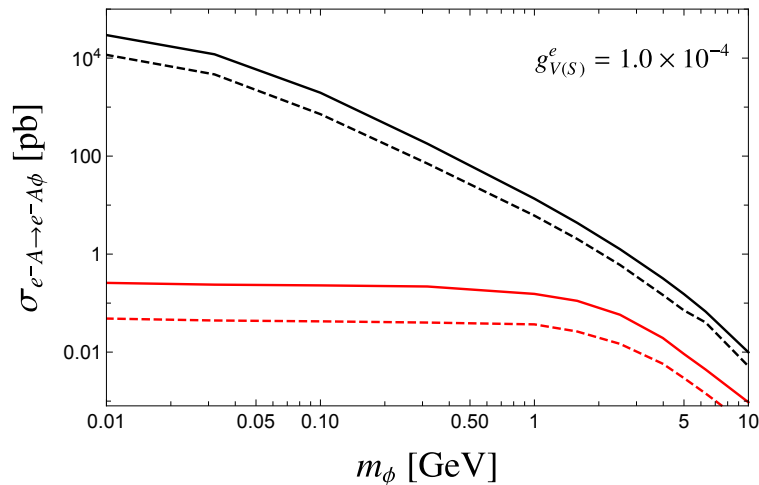
$$\mathcal{L}_V = g_V^e \phi_\mu \bar{e}\gamma^\mu e + g_V^\chi \phi_\mu \bar{\chi}\gamma^\mu \chi$$

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

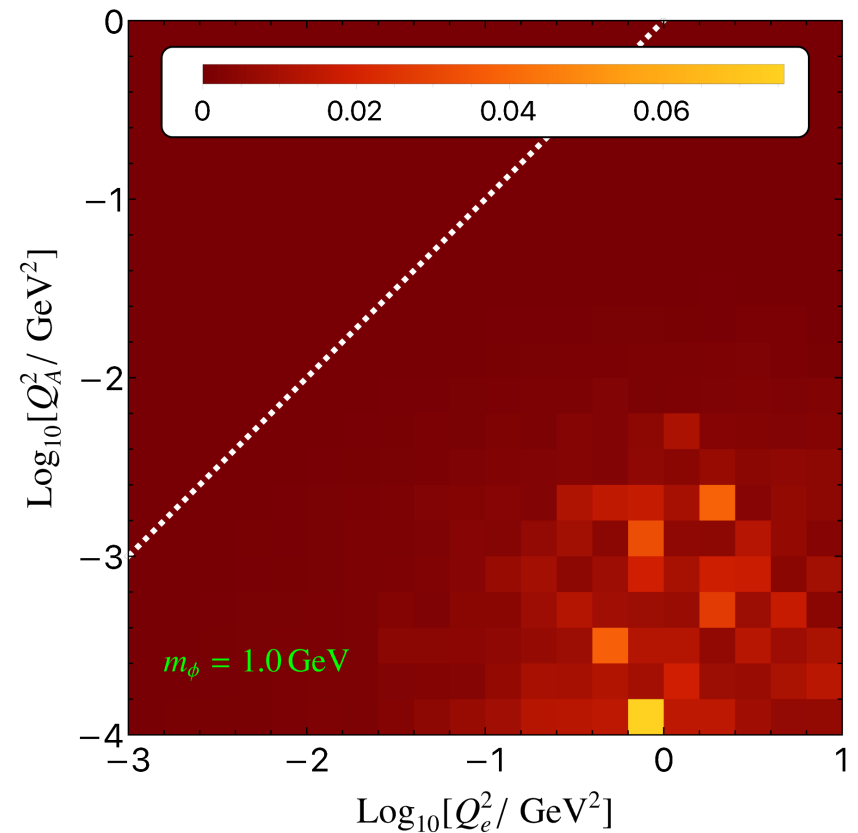
# Kinematics



- 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



- We focus on the vector case (solid black)
- Similar cross sections for scalars (dashed black)
- Red curves after cuts



# Cuts

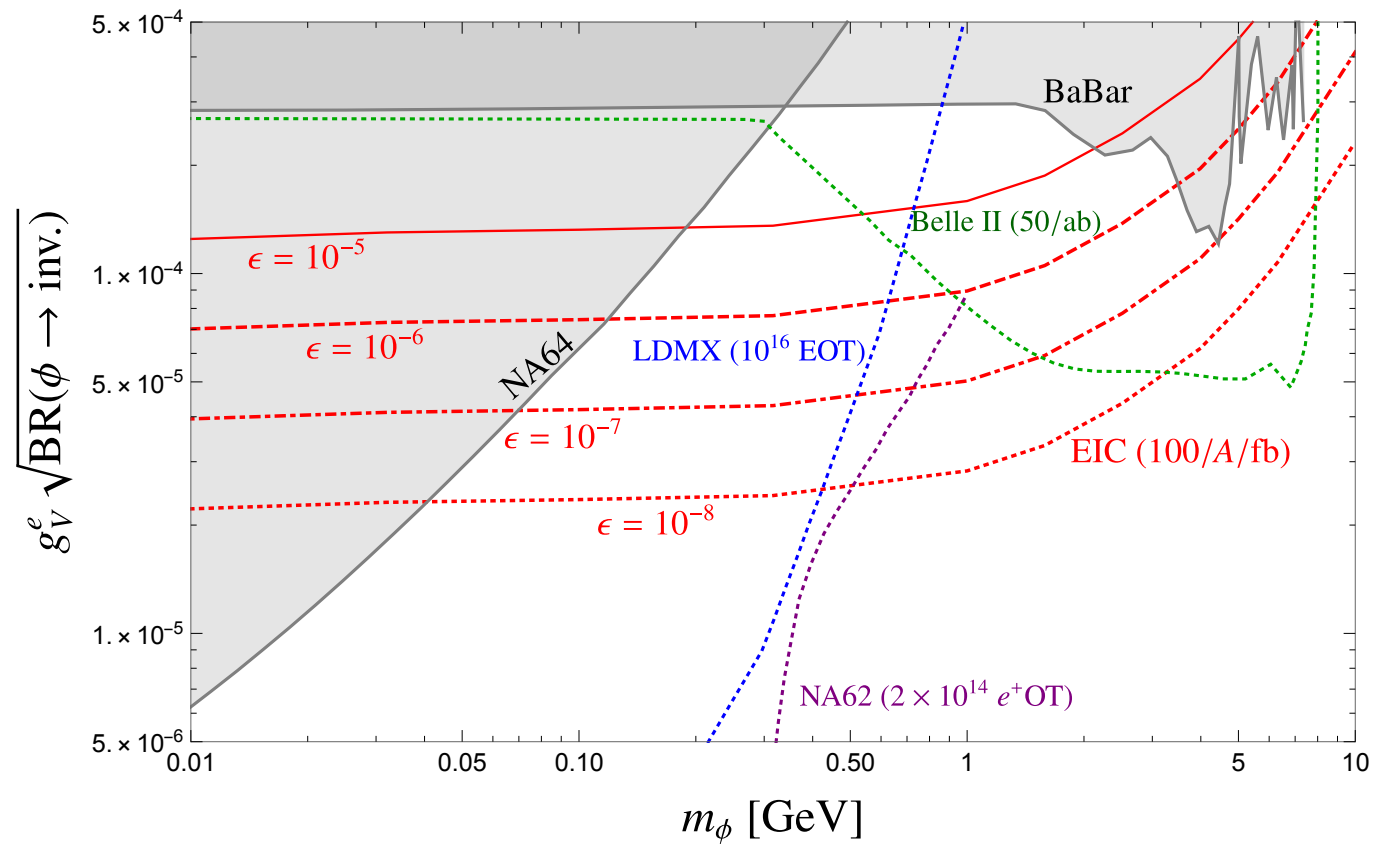
| $m_\phi$ [GeV] | $Q_{e,\min}^2$ [GeV <sup>2</sup> ] | $p_{T,e}^{\min}$ [GeV] | $\eta_e^{\min}$ | $\eta_e^{\max}$ | $E_e^{\max}$ [GeV] | $\sigma_\gamma^{\text{eff}}$ [pb] | $(1 - \epsilon_{\text{veto}}) A \sigma_{\text{DIS}}^{\text{eff}}$ [pb] |
|----------------|------------------------------------|------------------------|-----------------|-----------------|--------------------|-----------------------------------|------------------------------------------------------------------------|
| 0.010          | $10^{-0.7}$                        | 1.1                    | -3.5            | -1.5            | 10.0               | 2.06                              | 0.0310                                                                 |
| 0.032          | $10^{-0.7}$                        | 1.1                    | -3.5            | -1.5            | 10.0               | 2.06                              | 0.0310                                                                 |
| 0.100          | $10^{-0.7}$                        | 1.1                    | -3.5            | -1.5            | 10.0               | 2.06                              | 0.0310                                                                 |
| 0.316          | $10^{-0.7}$                        | 1.1                    | -3.5            | -1.5            | 10.0               | 2.06                              | 0.0310                                                                 |
| 1.000          | $10^{0.2}$                         | 1.3                    | -3.5            | 2.0             | 10.0               | 1.93                              | 0.0520                                                                 |
| 1.585          | $10^{0.5}$                         | 1.3                    | -3.0            | 2.0             | 10.0               | 1.93                              | 0.0520                                                                 |
| 2.512          | $10^{0.8}$                         | 1.3                    | -2.5            | 2.5             | 10.0               | 1.54                              | 0.0520                                                                 |
| 3.981          | $10^{1.2}$                         | 1.3                    | -2.5            | 1.0             | 10.0               | 0.70                              | 0.0330                                                                 |
| 5.000          | $10^{1.4}$                         | 1.3                    | -3.0            | 1.0             | 10.0               | 0.43                              | 0.0204                                                                 |
| 6.310          | $10^{1.5}$                         | 1.3                    | -2.0            | 3.5             | 10.0               | 0.33                              | 0.0155                                                                 |
| 10.000         | $10^{1.5}$                         | 1.3                    | -1.5            | 3.0             | 10.0               | 0.33                              | 0.0155                                                                 |

$\epsilon = 10^{-6}$  and  $\epsilon_{\text{veto}} = 95\%$

- A main background: coherent  $e^- A \rightarrow e^- A \gamma$ , with  $\gamma$  missed
- $E_e$  cut  $\rightarrow$  background  $E_\gamma$  mostly  $> 5$  GeV, *Inefficiency*  $\epsilon \gtrsim 10^{-8}$ 
  - for  $|\eta_\gamma| < 3.5$  (assumed missed otherwise) [Maeda et al., 1412.6880; Fry et al., 2501.14827](#)
  - Additional leverage from Zero Degree Calorimeter to veto incoherent scattering

We thank Rojae Mighty for pointing out numerical errors in the previous version of our results.

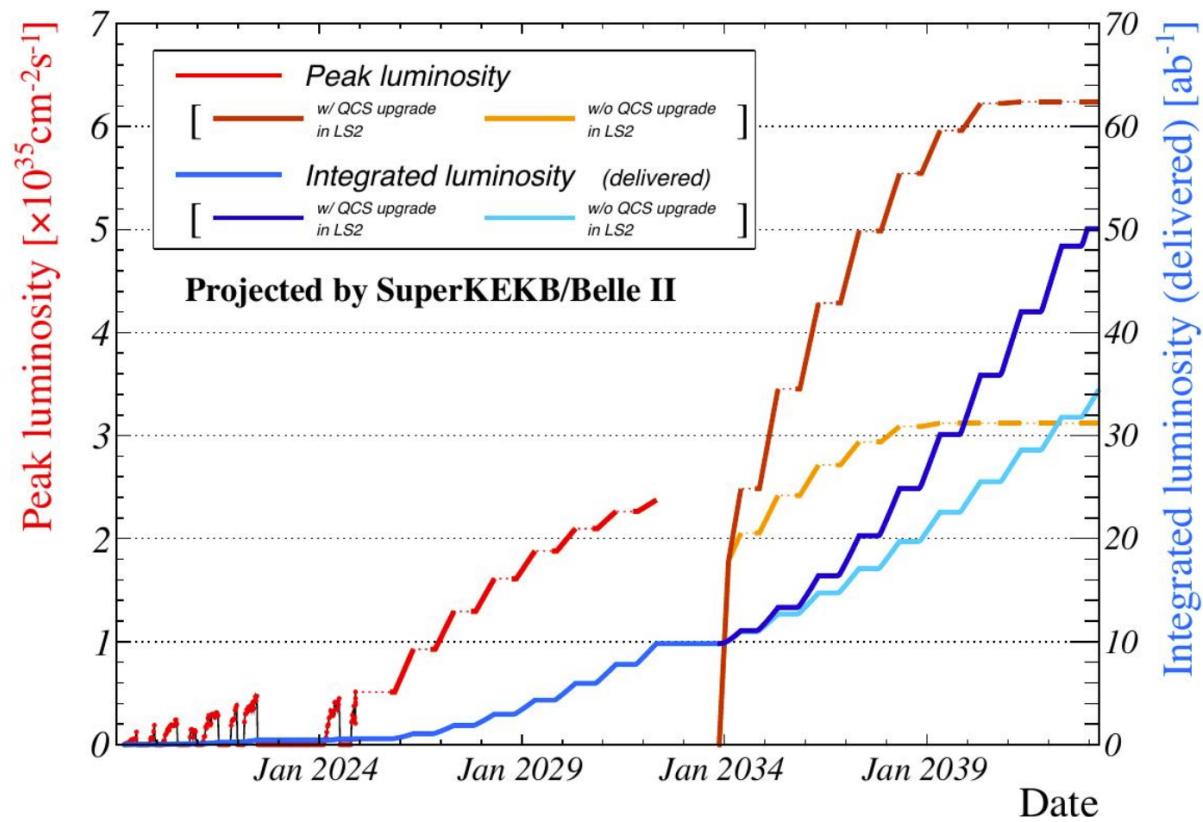
# Constraints and projections



Plot revised from v3 of H.D., Liu, 2505.08871

Belle II projection from Essig *et al.*, 1309.5084

- See also R. Mighty, A.R. Kanuganti, 2609.22484
  - Machine learning applied to this model
  - Addition of momentum transfer information (outgoing ion recoil)



From [https://www.belle2.org/info/luminosity\\_status/](https://www.belle2.org/info/luminosity_status/)

- Note:  $50 \text{ ab}^{-1}$  at Belle II, possibly circa 2043
- EIC expected to start several years earlier ( $\sim 2037$ )

# Long-Lived Dark Hadrons at the EIC

- The dark sector may include new confining dynamics
- Similar energy density of visible and dark matter:  
*Motivates asymmetric DM near nucleon mass*
- Interesting possibility: composite DM from confinement at  $\sim 1$  GeV
  - Could originate from dark and visible sectors related by approximate  $\mathbb{Z}_2$
- We consider: dark  $SU(3)_D$ , light-SM singlet quarks  $\chi_i$ , GeV scale confinement
- Dark quark  $\chi_i$  production through light mediator
- Dark showers: multiple dark pions, some decay with displacement, some escape
- Interesting target for the EIC: no hard trigger requirement
  - Sensitivity to multiple soft final states

For some early work see: Strassler, Zurek, 2006; Han, Si, Zurek, Strassler, 2007

Some recent work: Cohen, Roloff, Scherb, 2023; Cheng, Jiang, Li, Salvioni, 2024

Dark showers at BaBar and Belle II: Bernreuther et al. 2022; Lu, Xi, 2025

# Basic Model

- Complex scalar mediator  $\Phi$  sets dark sector mass scale:  $\langle \Phi \rangle = v_\Phi / \sqrt{2}$

$$\Phi = \frac{1}{\sqrt{2}} (v_\Phi + \textcolor{red}{S}) \exp\left(i \frac{\textcolor{blue}{a}}{v_\Phi}\right)$$

- $\textcolor{red}{S}$  radial mode,  $\textcolor{blue}{a}$  Goldstone mode corresponding to global U(1) breaking
- Leading interactions

$$\mathcal{L}_{\text{portal}} = \frac{1}{M} \Phi H \bar{L} e_R + y_{\chi_i} \Phi \bar{\chi}_{i,L} \chi_{i,R} + \text{h.c.}$$

- Coupling to electrons and mass generation for dark quarks  $\chi_i$ , with  $i = 1, 2$ 
  - Partial contribution to  $m_e \approx 0.511$  MeV (mild,  $\sim 20\%$ , tuning for parts of our parameter space)
  - Dimension-4 Yukawa interaction for electrons assumed
- Approximate SU(2) dark flavor symmetry
  - Two “charged” and one “neutral” dark pions:  $\pi_D^\pm, \pi_D^0$
  - $\pi_D^\pm$  not electrically charged; notation corresponds to SM isospin counterparts

# Low Energy Physics

- At low energies, we have

$$\Delta m_e = \frac{vv_\Phi}{2M} \quad ; \quad m_{\chi_i} = \frac{1}{\sqrt{2}} y_{\chi_i} v_\Phi$$

$$\mathcal{L}_{\text{int}} \supset -g_{S\chi_i} S \bar{\chi}_i \chi_i - g_{Se} S \bar{e} e - i g_{a\chi_i} a \bar{\chi}_i \gamma_5 \chi_i - i g_{ae} a \bar{e} \gamma_5 e$$

- Effective couplings

$$g_{Se} = g_{ae} = \frac{\Delta m_e}{v_\Phi} \quad , \quad g_{S\chi_i} = g_{a\chi_i} = \frac{m_{\chi_i}}{v_\Phi}$$

- We will treat  $m_S$ ,  $m_a$ , and dark confinement scale  $\Lambda_D$  as independent quantities

$\Rightarrow$  Separate production, decay, hadronization effects in our analysis

# Dark Pion Mixing with $a$

- Dark isospin violation:  $\pi_D^0$  and  $a$  mix:

$$\mathcal{L}_\chi = \frac{f_D^2 B_D}{2} \text{Tr} [(M_\chi + iaG_\chi)\Sigma_D + \text{h.c.}]$$

$$M_\chi = \text{diag}\{m_{\chi_1}, m_{\chi_2}\}, \quad G_\chi = \text{diag}\{g_{\chi_1}, g_{\chi_2}\}, \quad \Sigma_D = \exp(i\Pi_D/f_D), \quad \Pi_D = \pi_D^a \tau^a$$

$\tau^a$ : Pauli matrices;  $m_{\pi_D}^2 = B_D(m_{\chi_1} + m_{\chi_2})$  (neutral pion mass)

- Mixing term:

$$\mathcal{L}_{\text{mix}} = -\mu_{a\pi_D^0}^2 a \pi_D^0$$

$$\mu_{a\pi_D^0}^2 = B_D f_D (g_{a\chi_1} - g_{a\chi_2})$$

- Small mixing angle approximation:

$$\theta_{a\pi_D^0} \simeq \frac{\mu_{a\pi_D^0}^2}{m_a^2 - m_{\pi_D}^2}$$

- $\pi_D^0$  couples to electrons via mixing with  $a$ :

$$g_{\pi_D^0 e} \simeq \theta_{a\pi_D^0} g_{ae} \simeq \frac{\Delta m_e f_D m_{\pi_D}^2}{v_\Phi^2 (m_a^2 - m_{\pi_D}^2)} \frac{m_{\chi_1} - m_{\chi_2}}{m_{\chi_1} + m_{\chi_2}}$$

## $\pi_D^0$ Decays

- $\pi_D^0$ - $a$  mixing induces  $\pi_D^0 \rightarrow e^+e^-$  with

$$\Gamma(\pi_D^0 \rightarrow e^+e^-) = \frac{g_{\pi_D^0 e}^2}{8\pi} m_{\pi_D} \sqrt{1 - \frac{4m_e^2}{m_{\pi_D}^2}}$$

- We will fix  $m_a = 15$  MeV and  $m_{\chi_1} = 3m_{\chi_2}$
- Decay length for  $m_{\pi_D} \gg m_a$ :

$$l_{\pi_D} \simeq 0.25 \text{ m} \left( \frac{f_D}{0.1 \text{ GeV}} \right)^{-2} \left( \frac{m_{\pi_D}}{0.3 \text{ GeV}} \right)^{-1} \\ \times \left( \frac{\Delta m_e}{m_e} \right)^2 \left( \frac{g_{Se}}{5.0 \times 10^{-5}} \right)^{-4}$$

- We have used  $v_\phi = \Delta m_e / g_{Se}$  and  $g_{ae} = g_{Se}$

# General Features

- Scalar production and decay:  $eA \rightarrow eAS/a$ ;  $S/a \rightarrow \bar{\chi}\chi$ 
  - $A$  is ion of charge  $Z$ ; coherent cross section enhanced by  $Z^2$
- We focus on  $\chi$  production from  $S$  decays
  - Heavier  $S$  controls the energy available for the dark showers
  - Dark pion mass controls multiplicity and boost distribution of long-lived states
- Mass ratios:

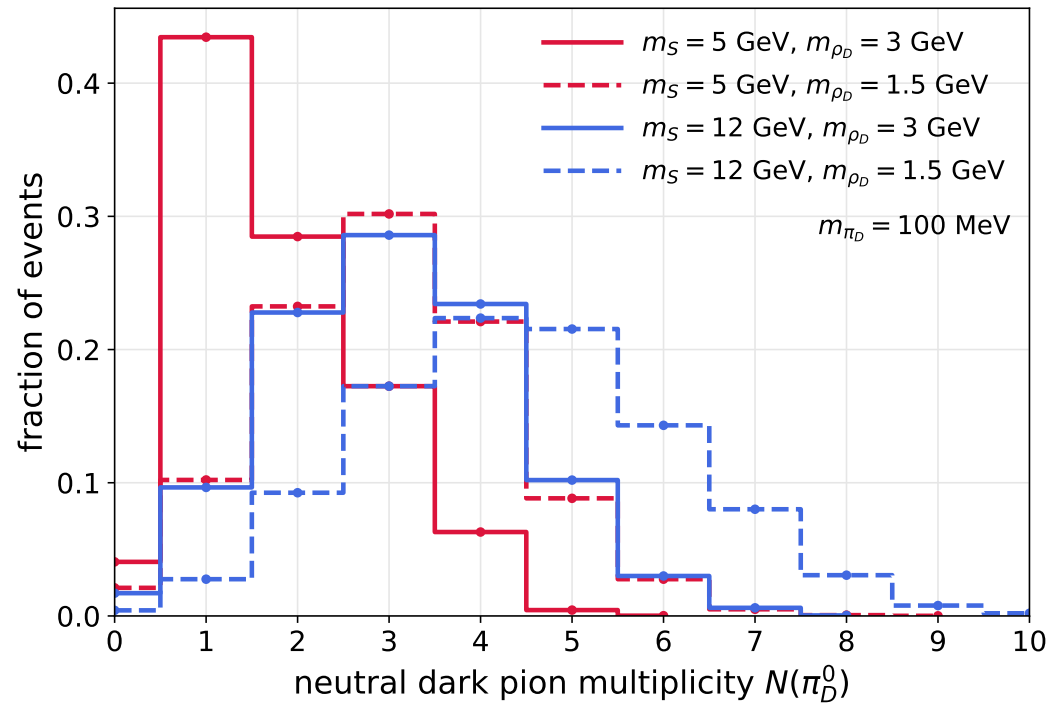
$$m_{\rho_D} = 2.0\Lambda_D, \quad f_D = 0.34\Lambda_D, \quad m_{\rho_D} > 2m_{\pi_D}$$

- Prompt decays:  $\rho_D^0 \rightarrow \pi_D^0\pi_D^0, \pi_D^+\pi_D^-, \rho_D^\pm \rightarrow \pi_D^0\pi_D^\pm$
- SU(3) gauge theory:  $m_{\rho_D}/f_D \approx 5.75$  (reflected in our benchmark choice)
  - Roughly constant for  $m_{\pi_D}$  from physical point up to  $m_{\rho_D}/2$  [DeGrand, Neil, 2019](#)
- Heaviest  $\chi$  mass fixed to be  $m_{\pi_D}^2/m_{\rho_D}$
- $\pi_D^\pm$  stable, absent flavor changing interactions  $\rightarrow$  missing energy
  - Expected to be cosmologically safe, due to rapid annihilation into  $\pi_D^0\pi_D^0$
- $\eta'_D$ : assumed heavy due to anomaly effects and integrated out

# Analysis

- Four benchmark scenarios:  $m_S = 5, 12$  GeV and  $m_{\rho_D} = 1.5, 3$  GeV
- Dark shower events generated using the Hidden Valley Module of Pythia

Carloni, Sjostrand, 2010; Carloni, Rathsmann, Sjostrand, 2011  
Bierlich et al., 2022



- Plot for fixed  $m_{\pi_D} = 100$  MeV
- $\pi_D^0$  multiplicity increases for large  $m_S$  (energy budget), smaller  $m_{\rho_D}$  ( $\Lambda_D$ )
  - Not sensitive to  $m_\chi$  for fixed  $m_{\rho_D}, m_{\pi_D}$

- Signal requirement: two neutral dark pions decay within a fiducial volume

$$L_{\min} < L_{\pi_D} < L_{\max}$$

- We adopt  $L_{\min} = 100 \mu\text{m}$  and  $L_{\max} = 1 \text{ m}$

- $L_{\min}$  based on EIC 2D distance of closest approach resolution for pions [Adkins et al., 2022](#)

- Additional reconstruction requirements on  $\pi_D^0$  energy and pseudorapidity:

$$E_{\pi_D} > 0.5 \text{ GeV} \quad , \quad |\eta_{\pi_D}| < 3.5$$

- We assume  $E_e = 10$  or  $18 \text{ GeV}$  and  $E_A = 100 \text{ GeV/nucleon}$

- Heavy ion: gold with  $Z = 79$  and  $A = 197$

- Ion form factor from [R. H. Helm, Phys. Rev. 104, 1466 \(1956\)](#).

- Mean lab-frame decay length for  $\pi_D^0$  of momentum  $p_{\pi_D}$  given by

$$\bar{L} = \frac{p_{\pi_D}}{m_{\pi_D}} l_{\pi_D}$$

- Probability of decay inside fiducial volume:

$$P_{\text{fid}} = \exp\left(-\frac{L_{\min}}{\bar{L}}\right) - \exp\left(-\frac{L_{\max}}{\bar{L}}\right)$$

- Select signals with two or more displaced  $\pi_D^0$  decays
  - Assume veto of incoherent events using zero degree calorimeter
  - Additional handle due to significant missing energy carried off by stable  $\pi_D^\pm$
- Signal features make the search nearly background free
- Expected number of signal events

$$N_S = \sigma(eA \rightarrow eAS) \mathcal{L} P(\geq 2 \text{ fiducial decays})$$

$$\mathcal{L} = 100/A \text{ fb}^{-1} \text{ assumed}$$

- We consider  $m_S = 5, 12 \text{ GeV}$ 
  - At  $m_S = 5 \text{ GeV}$ , we also include bounds from BaBar using  $514 \text{ fb}^{-1}$  of data
- BaBar analysis parameters:

$$1 \text{ cm} < r_\perp < 50 \text{ cm} \quad , \quad -1.0 < \eta_{\pi_D} < 1.9 \quad , \quad E_{\pi_D} > 0.5 \text{ GeV}$$

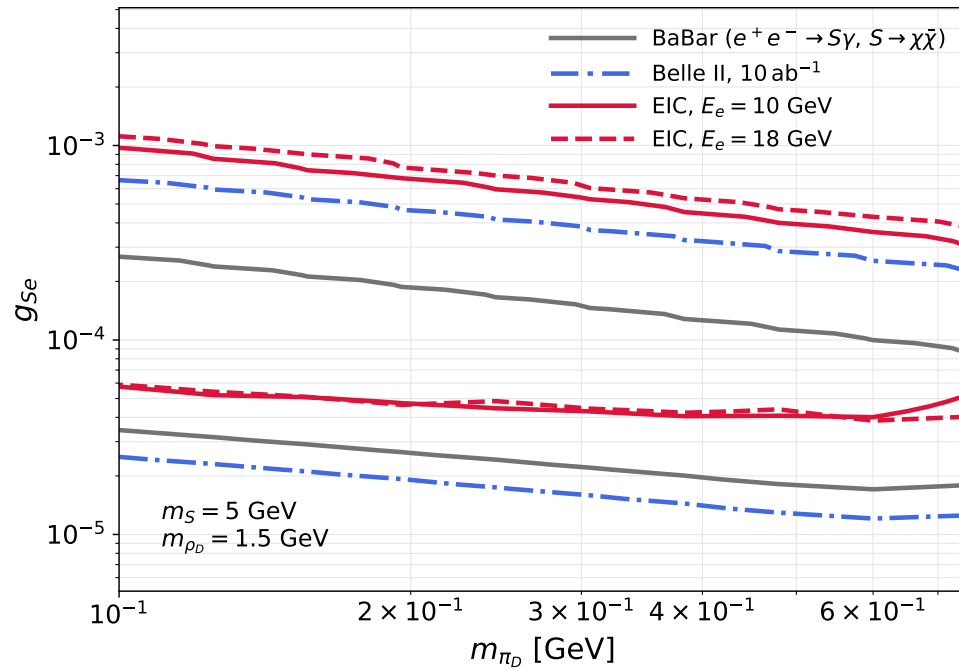
Aubert *et al.* (BaBar), hep-ex/0105044; J. P. Lees *et al.* (BaBar), 1502.02580 [hep-ex] (Search for Long-Lived Particles)

- Cuts for Belle II projections with  $10 \text{ ab}^{-1}$  of data

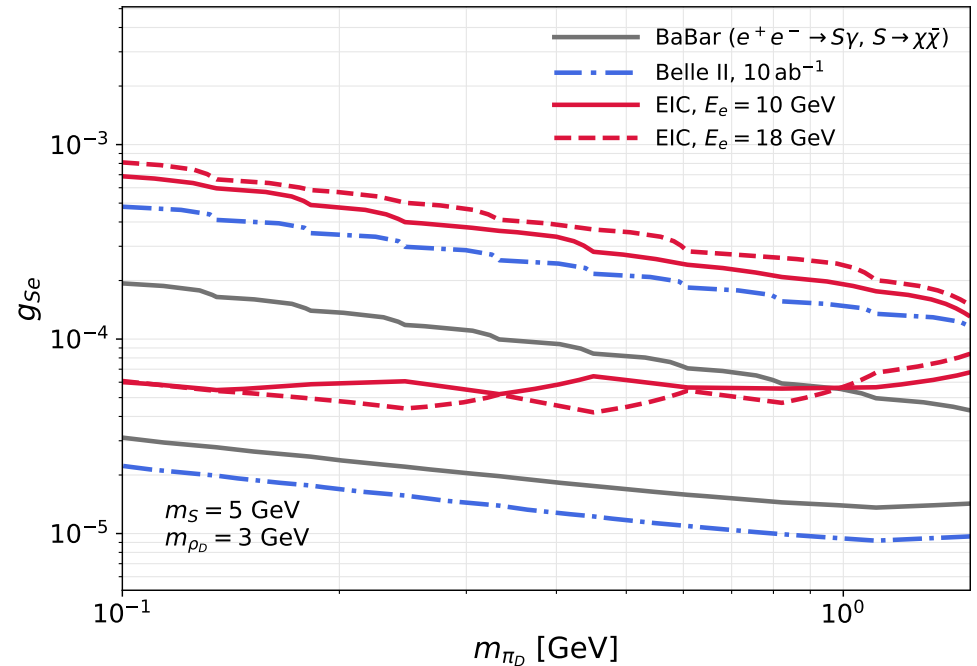
$$0.05 \text{ cm} < r_\perp < 60 \text{ cm} \quad , \quad -1.32 < \eta_{\pi_D} < 1.25 \quad , \quad E_{\pi_D} > 0.5 \text{ GeV}$$

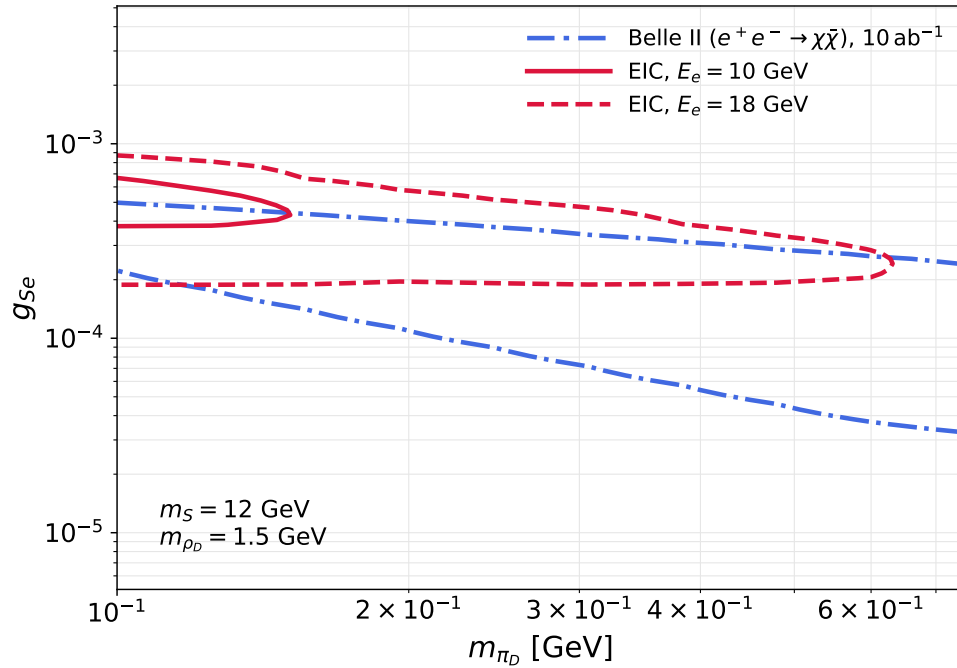
I. Adachi *et al.* (Belle-II), 2306.02830 [hep-ex] ( Search for a long-lived spin-0 mediator in  $b \rightarrow s$  transitions); Jaeckel, 2312.12522 [hep-ph] (Displaced dark photons at Belle II)

# Constraints and Projections

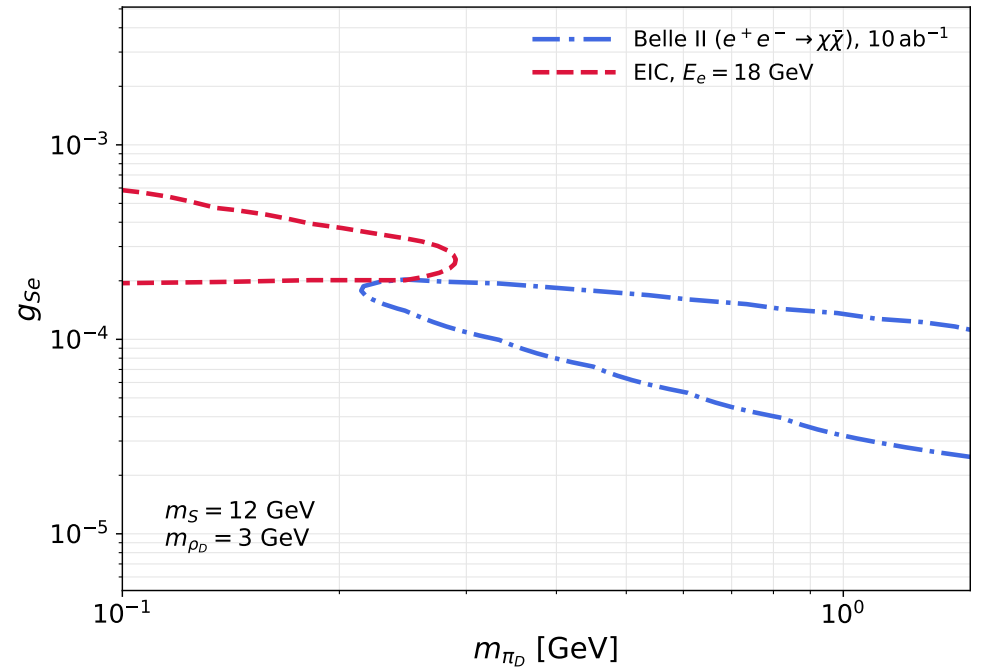


- BaBar, Belle II: smaller  $g_S$  reach than EIC's
- EIC: better vertex resolution, larger  $g_S$
- Our model:  $g_{Se} = g_{ae}$ 
  - Connects  $\pi_D$  production and lifetime





- Off-shell  $S$  production at  $B$  factories
- Smaller  $m_{\pi_D}$ : smaller  $\chi_i$  Yukawa coupling  
 → Suppressed off-shell production
- EIC: larger kinematic reach, on-shell  $S$   
 - Insensitive to small  $\chi_i$  Yukawa coupling
- EIC-Belle II *complementarity* in this regime



## *Concluding Remarks*

- DM may reside in a new sector with particles well below the weak scale
- GeV scale states can be produced in coherent scattering at the EIC
- Electron beam kinematics: a handle on invisible new physics
- Asymmetric DM may be a GeV scale composite
- We investigated signals of a “dark QCD” with two flavors
- A simple complex scalar coupled to electrons can
  - Generate dark quark masses
  - Mediate dark quark production (radial mode), leading to hadron showers
  - Provide a decay channel for flavor-diagonal dark pions (Goldstone mode)
- The dark showers could lead to nearly background-free multi-hadron signals
  - “Neutral” (flavor-diagonal) dark pions can decay with significant displacement
  - “Charged” (flavor off-diagonal) dark pions could be stable and provide missing energy signals
- More generally
  - Other final state, e.g.  $\mu^+\mu^-$ , possible: extended particle ID (second detector)
  - Good displaced vertex resolution: larger couplings