From Ultra-Peripheral to Fixed Target: Low energy photonuclear physics at the EIC

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FIxed-target eXperiment at EIC (FIXE) initiative
September 29, 2025

Center for Frontiers in Nuclear Science

Supported in part by the U.S. Department of Energy Office of Science

Outline

- Physics motivation
  - Hadron Mass generation & QCD Trace Anomaly
- Near-threshold photonuclear production
- EIC collider mode
- Fixed Target mode
  - Photon source and approximate rates
  - Sub-threshold production
  - Lighter VM production
- Utilization of the ePIC instrumentation
- Summary & Conclusions

Trace Anomaly and the Origin of mass

>99% of all visible mass in the Universe is built from nucleons
Higgs mass accounts for a small portion, with majority resulting from the strong force self-interactions

$$T^{\mu}{}_{\mu} = \boxed{\frac{\beta(g)}{2g} G^2} + \boxed{(1 + \gamma_m)\overline{\psi} m \psi\,,}$$

Gluons $(T_g^{\mu\nu})$ Quarks $(T_q^{\mu\nu})$

$$\langle P | T_{q,G}^{\mu\nu}(0) | P \rangle = 2P^{\mu}P^{\nu}A_{q,G}(0) + 2M^2 g^{\mu\nu}\bar{C}_{q,G}(0)\,,$$

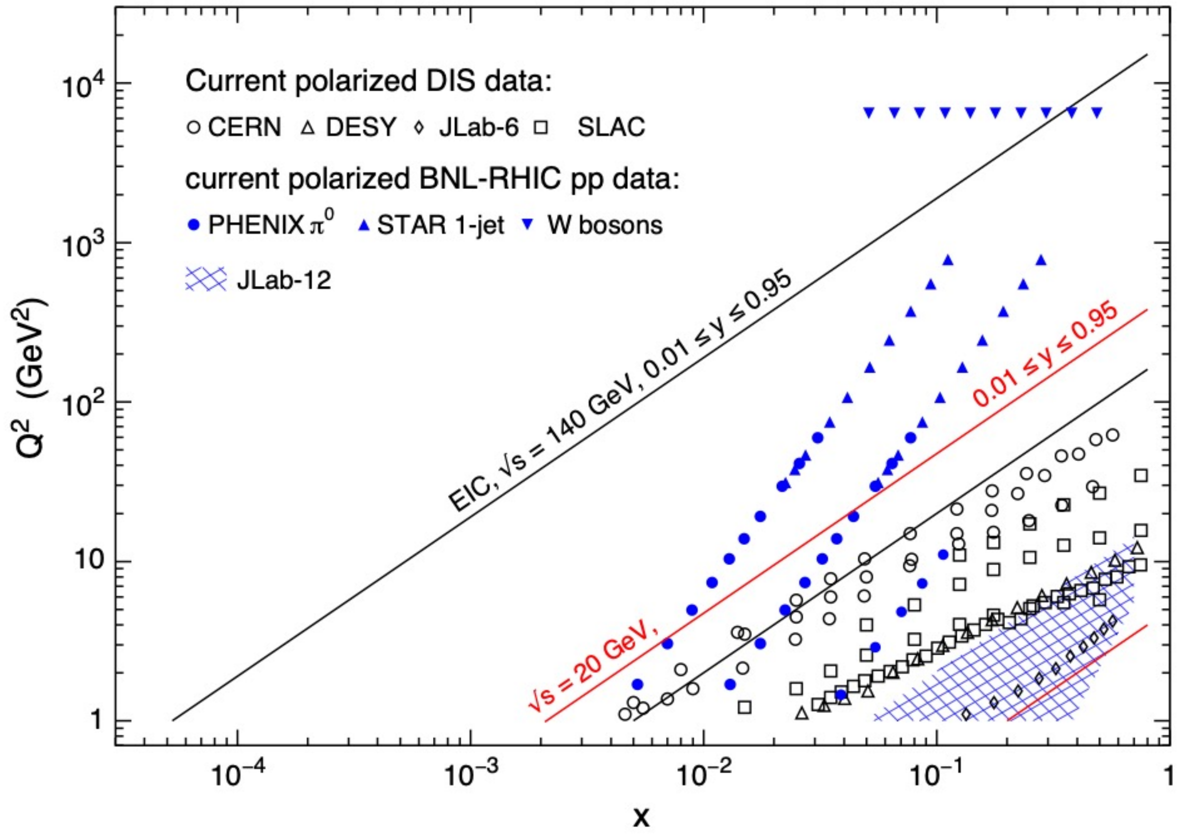
Threshold Vector Meson Production

- Probe gluonic structure of the nucleon near confinement scale (especially for heavier VMs like J/psi and Upsilon)
- Access gluonic gravitational form factors (GFFs)
- Connect to the proton mass decomposition and QCD trace anomaly
- Unique sensitivity in Upsilon, J/ψ, ϕ, and ρ near threshold, each in contribute different constraints

Wang et al. (2023) — arXiv:2308.04644, 2304.07964
Hatta et al. (2025) — arXiv:2501.12343
Du, Xie et al. (2020) — arXiv:2009.08345
Winney (2023) — arXiv:2305.01449
Kim et al. (2024) — arXiv:2411.12187

Why Threshold Production?

- **Valence (large-x) gluons & transition from non-perturbative to perturbative QCD**
- Near threshold, the produced VM is slow in the target rest frame
- Amplitude is dominated by multi-gluon exchange with $\mathbf{x \gtrsim 0.1}$, where constraints are poor.
- mapping energy and t-dependence here tests models (Regge/Pomeron, GPDs, VMD/dispersion, NRQCD).



Nucl. Phys. A 1026 (2022) 122447

Threshold Vector Meson Production

- In $\gamma p \rightarrow VM\ p$:

$$W_{thr} = m_p + m_{VM}$$

Vector Meson	Invariant Mass [GeV]	Threshold [GeV]
ρ	0.775	1.713
ϕ	1.019	1.957
J/ψ	3.097	4.035
Υ	9.46	10.398

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EDITORS' SUGGESTION

First Measurement of Near-Threshold J/ψ Exclusive Photoproduction off the Proton

A. Ali[10], M. Amaryan[22], E. G. Anassontzis[2], A. Austregesilo[3], M. Baalouch[22], F. Barbosa[14], J. Barlow[7], A. Barnes[3], E. Barriga[7] *et al.* (GlueX Collaboration)

Phys. Rev. Lett. **123**, 072001 – **(2019)**

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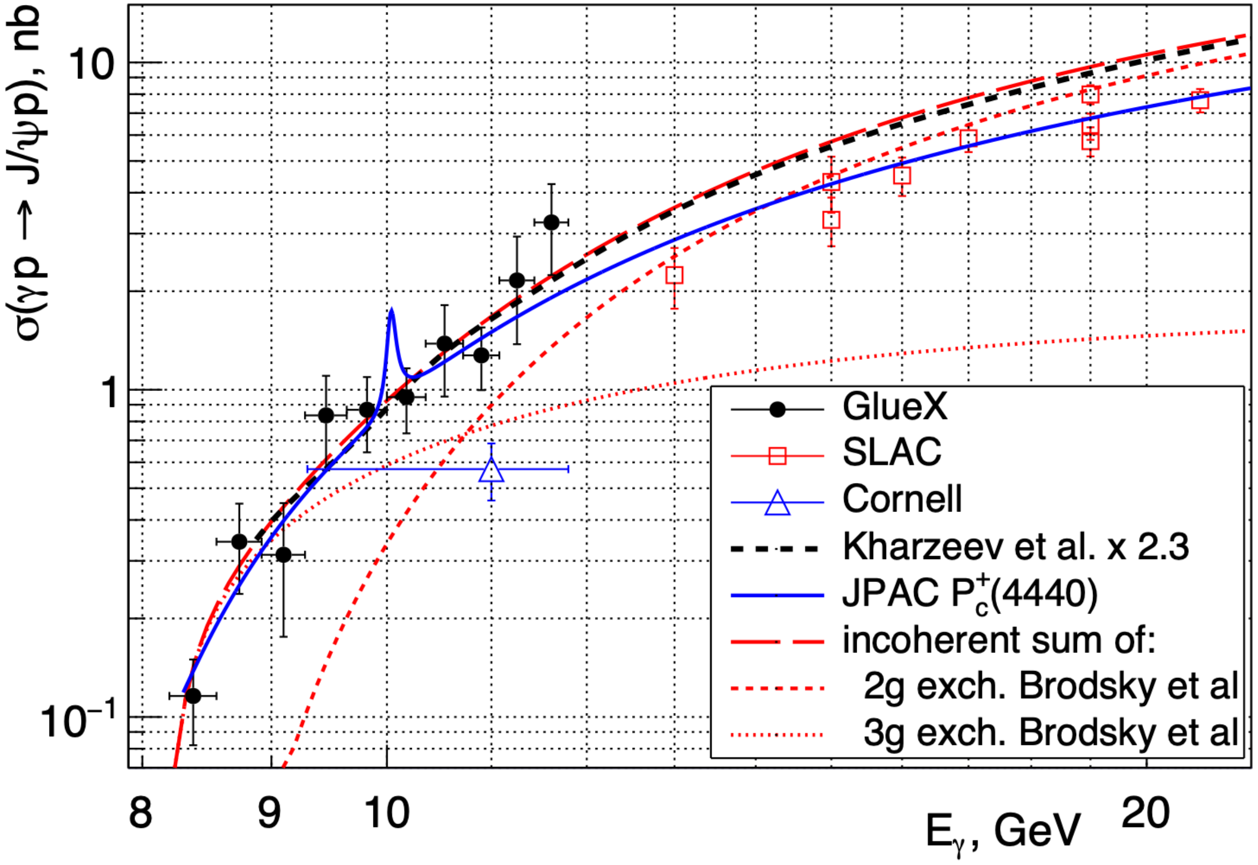
Phys. Rev. Lett. **134**, 201903 – **(2025)**



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- Similar trend but tension with some lattice calculations and models

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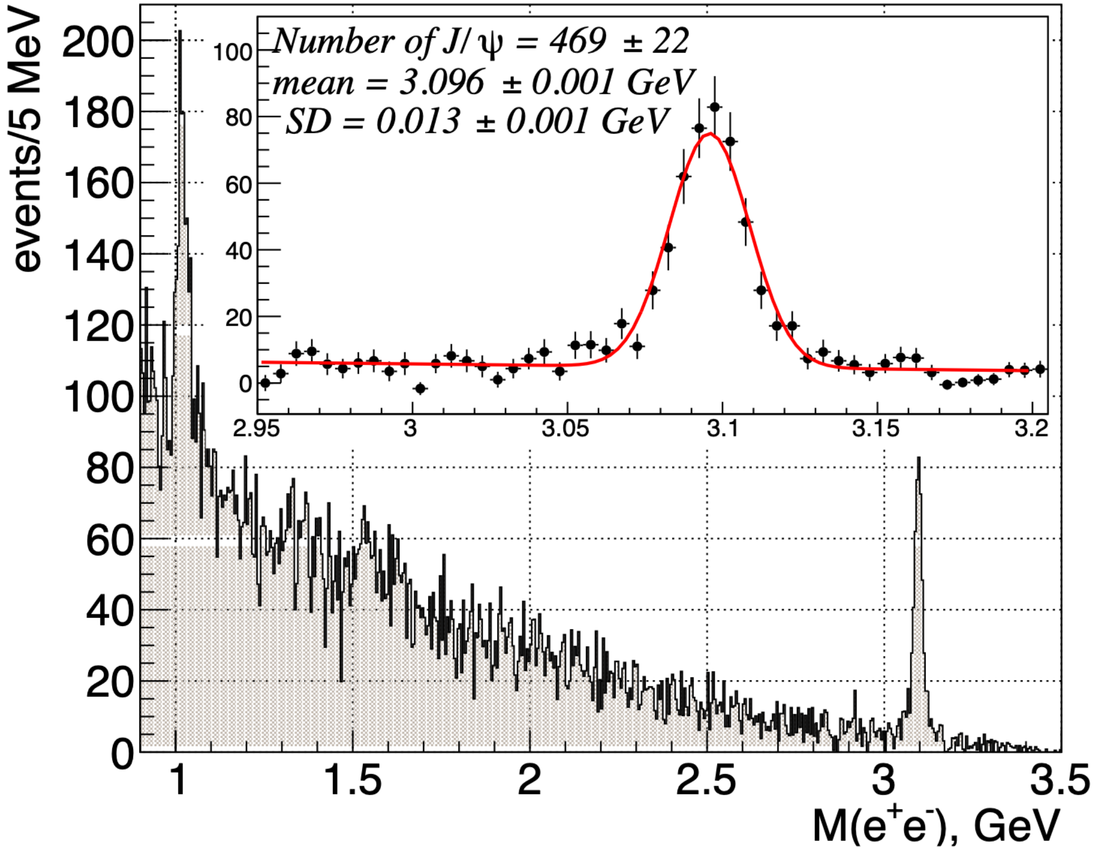

Hadron Mass: Priority for the EIC

Discussed extensively in Yellow Report, White papers, etc.

- Exclusive processes: DVCS & vector mesons (YR, Vol II)
- Heavy quarkonia: sensitivity to gluon GPDs & GFFs
- Influence forward detector concepts: Roman pots, recoil tagging (YR, Vol III)

$$W^2 \approx y\, s_{ep} + m_p^2 - Q^2$$

$$y = \frac{E_\gamma}{E_e}$$

With EIC beam configurations (5,10,18)x(41, 100, 275)

and $y_{min} \approx 0.01$, EIC collider mode can reach W_{min} ≈3-5 GeV

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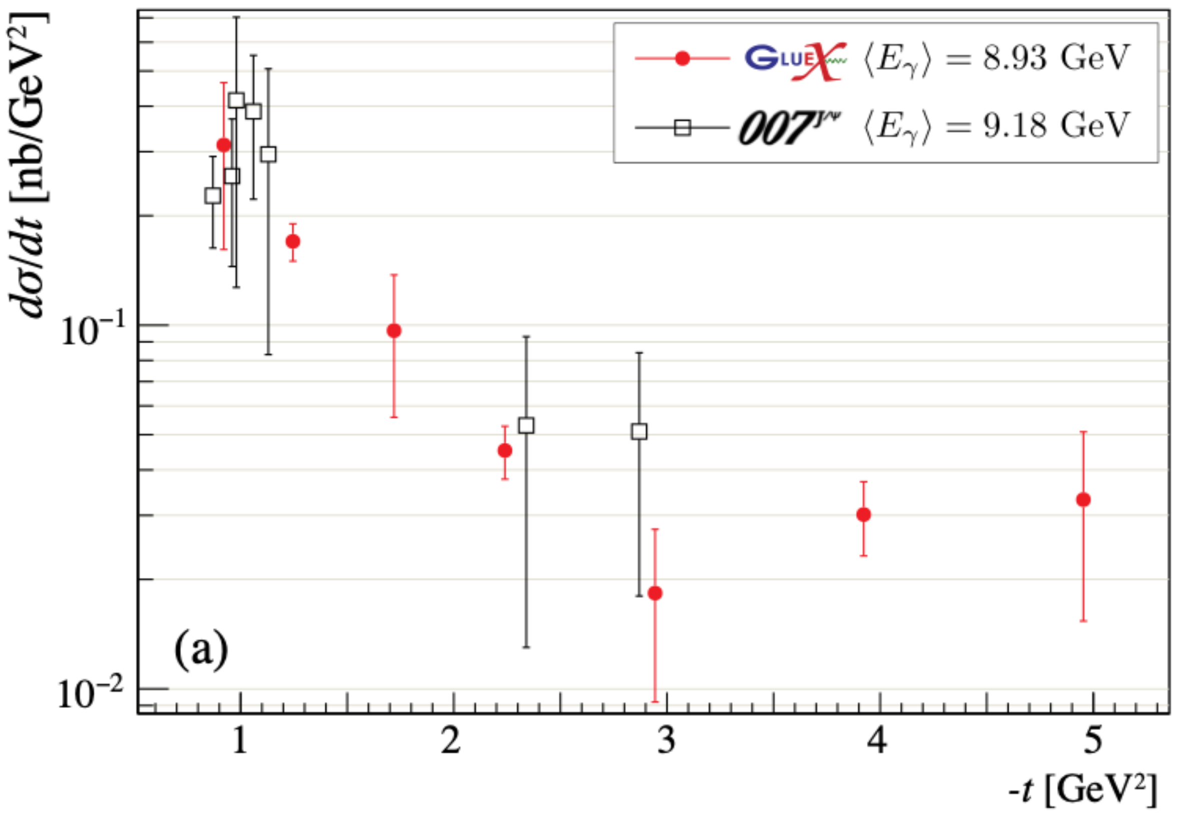
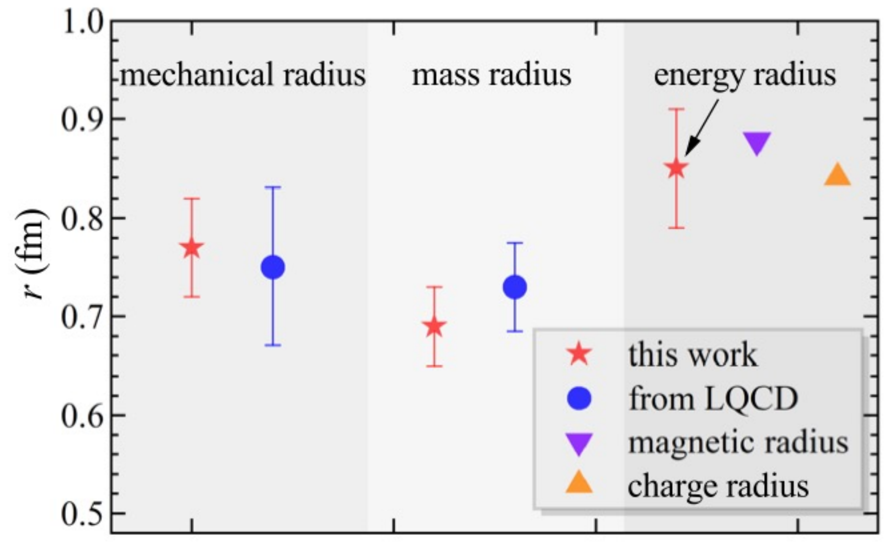
Experimental Access

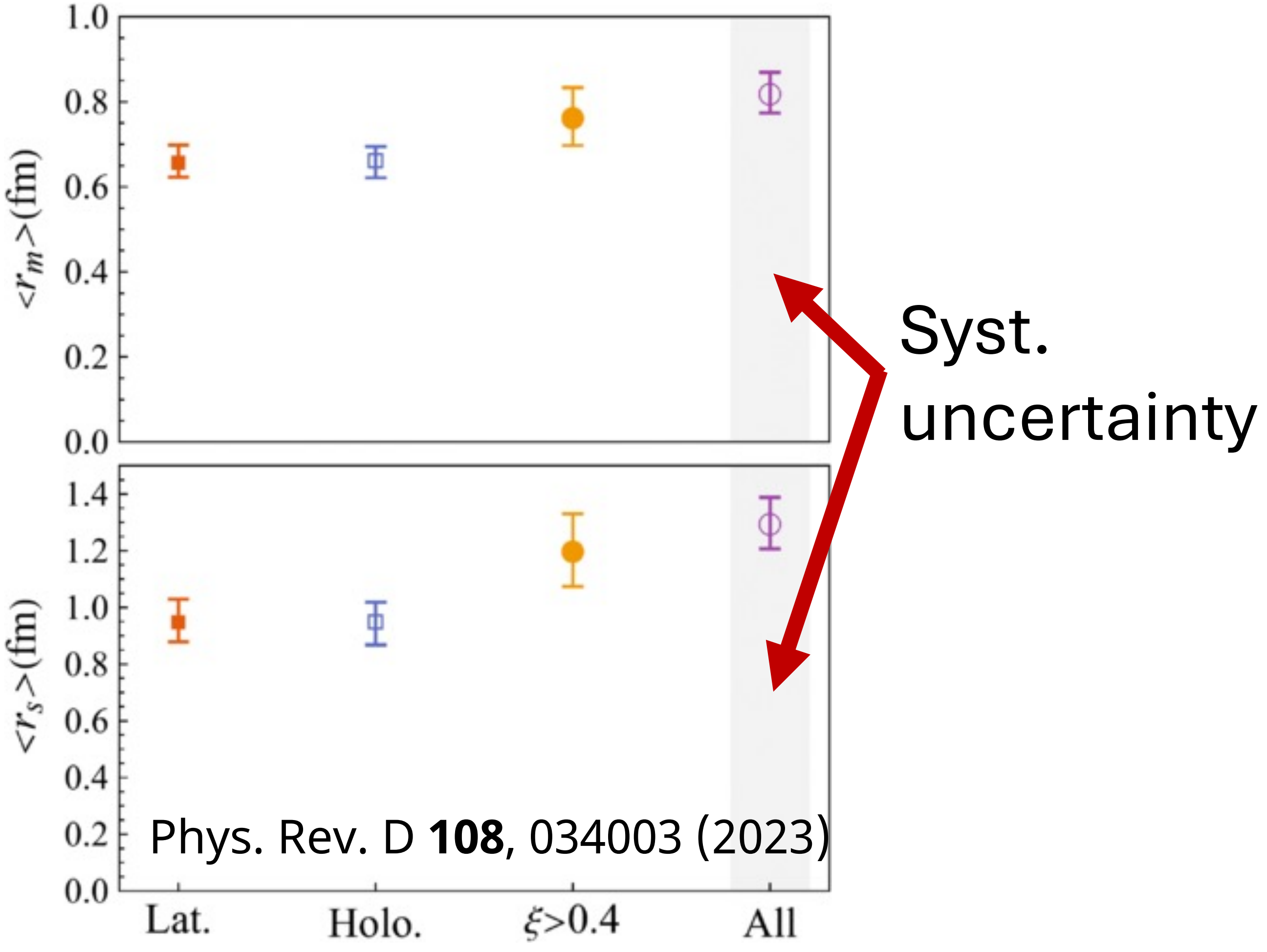
- Total cross section slope → gluon pressure & shear (GFF $C_g(t)$)
- Threshold normalization → gluon energy-momentum fraction (GFF $A_g(0)$)
- |t|-dependence of differential cross section → transverse distributions and sub-nucleonic dynamics



Proton (gluon) Radius



Chin.Phys.C 48 (2024) 5, 054102



Phys. Rev. D **108**, 034003 (2023)

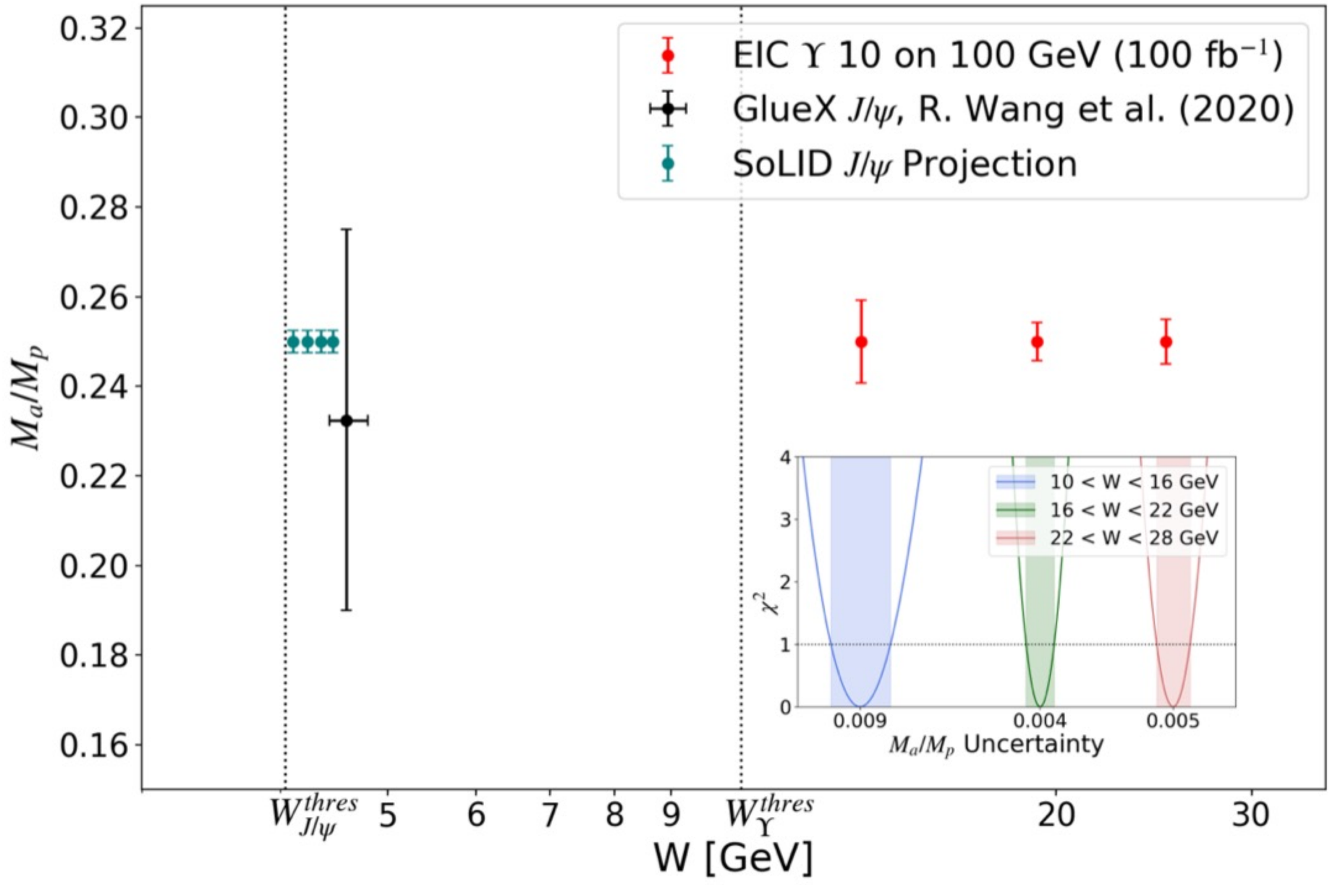
Recent data is narrowing in, but still lacks precision

EIC Collider mode (ep + eA)

$$W^2 \approx y\, s_{ep} + m_p^2 - Q^2$$
$$y = \frac{E_\gamma}{E_e}$$

J/psi may be challenging in collider mode and will likely require Q^2 >> 0, will also depend on energy resolution for y measurements

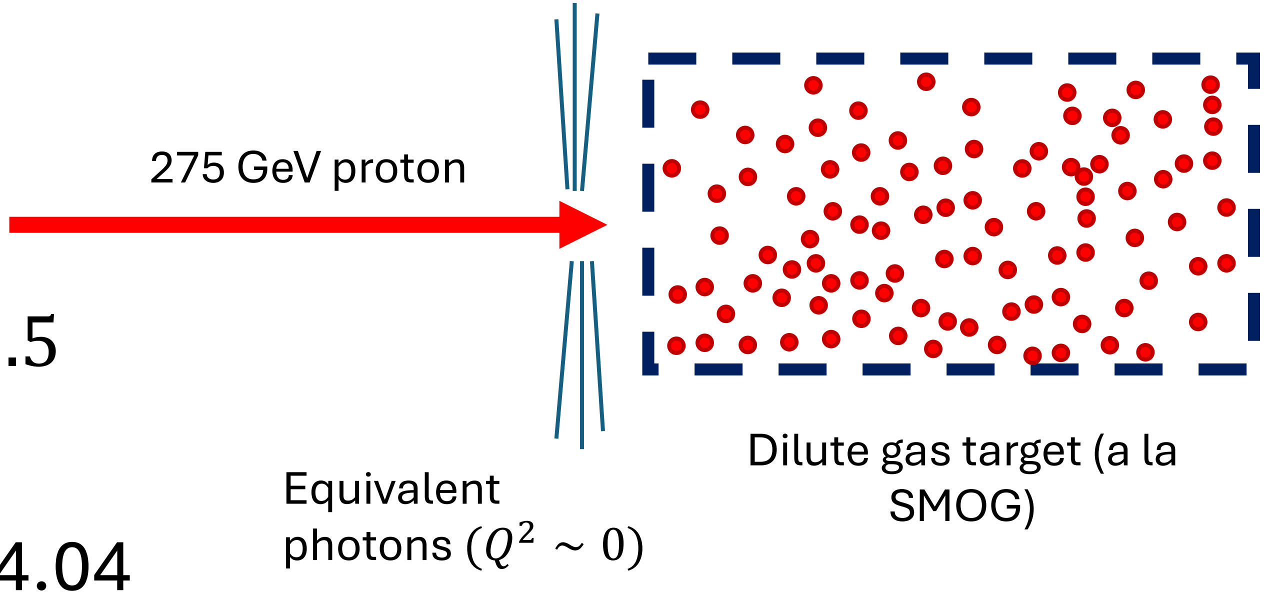
EIC collider mode will be most ideal for threshold Upsilon photoproduction (Q^2~0)



EIC Yellow Report
https://arxiv.org/pdf/2103.05419

Low-Energy Photonuclear w/Fixed Target

- 275 GeV proton beam
- EPA photon $k \leq \frac{\gamma \hbar c}{R}$
- $W_{max} \approx \sqrt{m_p^2 + 2 m_p k_{max}} \approx 12.5$ GeV
- Able to access threshold J/psi (4.04 GeV) and Upsilon (10.4 GeV)



Low-Energy Photonuclear w/Fixed Target

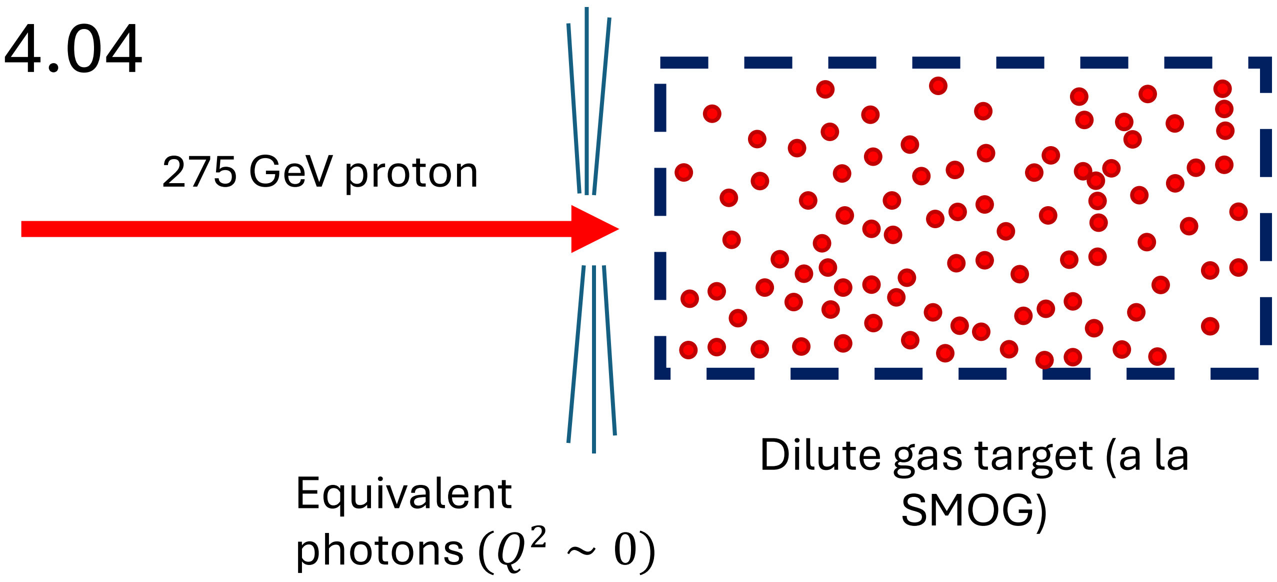
- Able to access threshold J/psi (4.04 GeV) and Upsilon (10.4 GeV)

- Production Rate:

$$L_{\gamma p} = I_p \, n_t \, N_\gamma$$
$$R \approx L_{\gamma p} \times \sigma_{\gamma p \to J/\psi p}$$

$n_t \approx 10^{13}$ cm-2, $\sigma_{\gamma p \to J/\psi p}$ ≈1-3 nb

$\mathcal{O}(100 - 1000)\, J/\psi$ per day



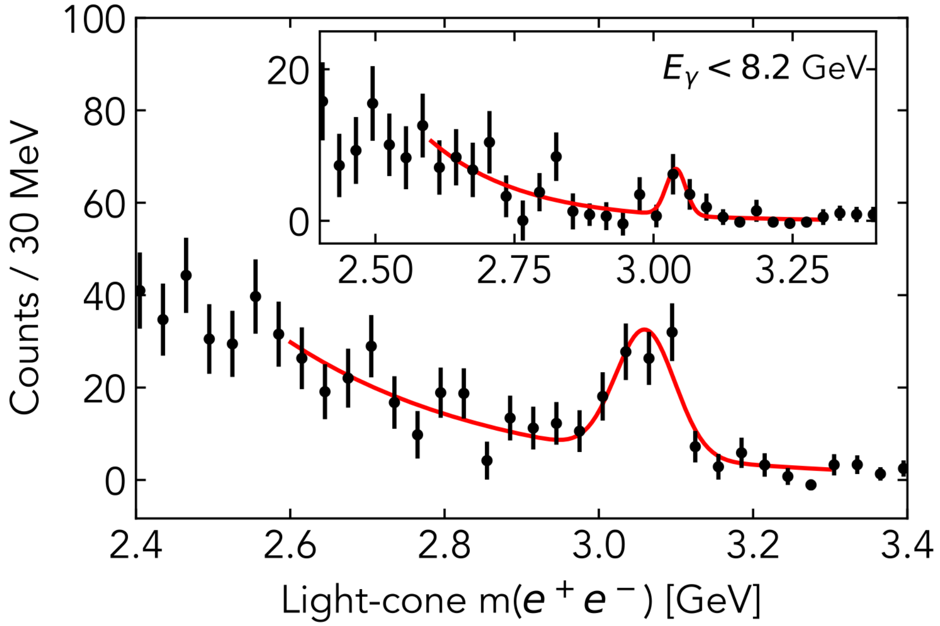
Complement EIC Collider measurements (electroproduction $Q^2 > 0$) and Jlab experiments

Sub-Threshold production and A-scan

$$k_{th} = \frac{(M_A + M_V)^2 - M_A^2}{2M_A} = M_V + \frac{M_V^2}{2M_A}$$

≈ 8.21 GeV on a proton to ≈ 3.35 GeV on ^{20}Ne

Phys. Rev. Lett. **134**, 201903 (**2025**)



Production threshold decreases for heavier targets.
Access production below the free proton threshold

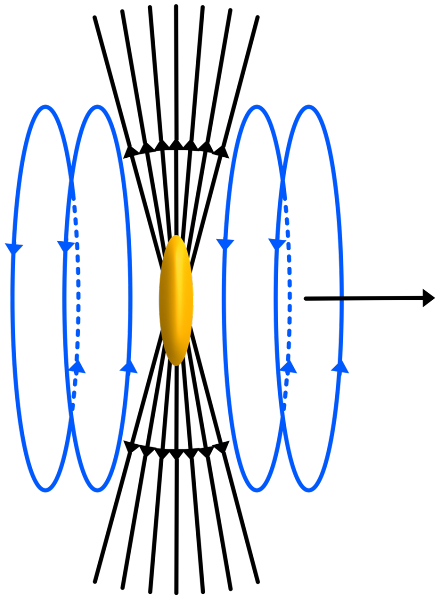
Nucleus	Plane-wave cross section	Measured cross section	Statistical uncertainty	Systematic uncertainty
^{2}H	0.24 nb	0.23 nb	0.07 nb	0.04 nb
^{4}He	0.22 nb	0.33 nb	0.06 nb	0.05 nb
^{12}C	0.24 nb	0.25 nb	0.05 nb	0.05 nb

EIC fixed target would allow scan of heavier A
And first measurements of sub-threshold Upsilon

Phys. Rev. D **108**, 054018 **(2023)**

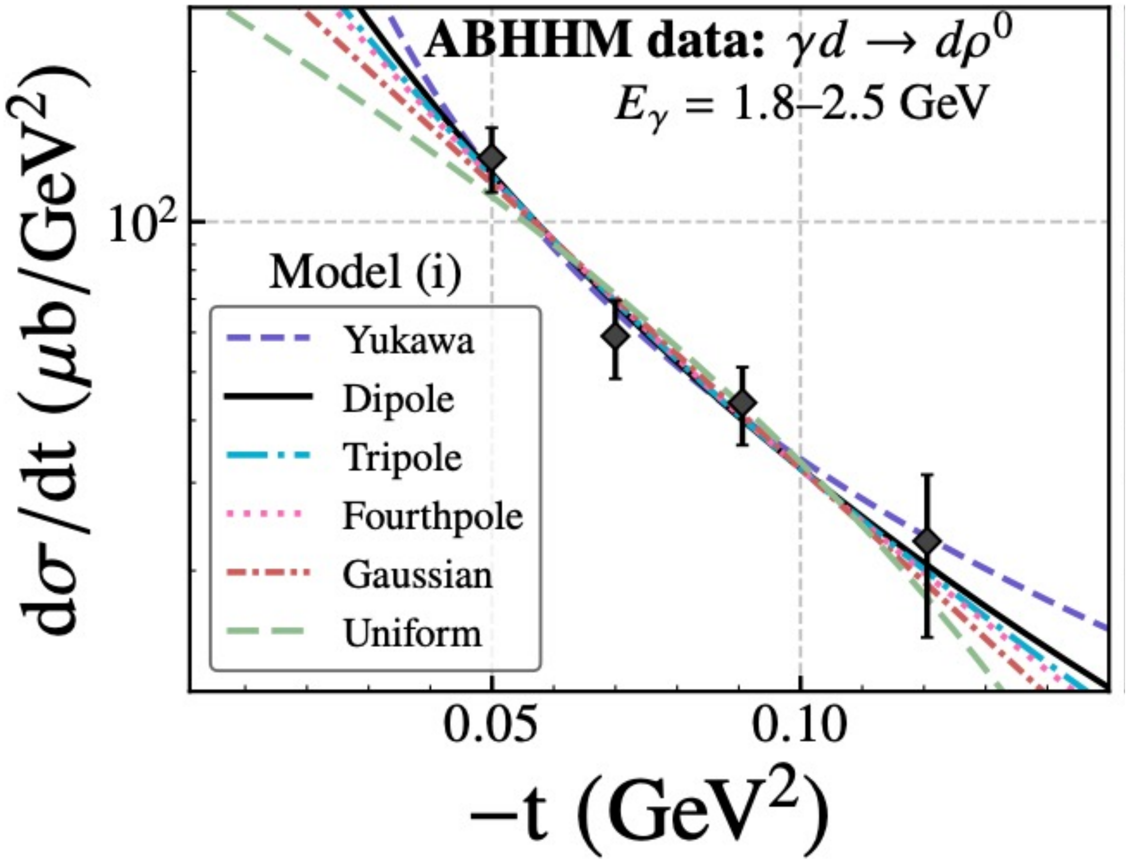
Z^2 Enhancement from Nuclear EM Fields

- Nuclear beams benefit from the Z^2 enhancement of the WW photon flux
- However, in fixed target mode, 100 GeV beam gives $W_{max} < 3$ GeV → insufficient for J/psi threshold production (even on heavy nuclear targets)
- Lighter mesons can be probed ($W_{th} \approx 2$ GeV) for ρ, ϕ
- J/psi (and Upsilon) received most attention because heavy VM are more directly related to the trace anomaly than light
- Other interesting physics in lighter mesons (ρ, ϕ)



Why study ρ, ϕ?

- Relation to trace anomaly is less direct, but benefit from much higher rate (than J/psi) and Z^2 photon flux enhancement
- Vector mesons (ρ, ϕ) probing Reggeon vs Pomeron
  - Extraction of SDME to explore non-natural contributions + look for SCHC violations
  - Strong handle on the **non-perturbative** end of the spectrum; tests of VMD and dispersion relations close to threshold
- Test models of nuclear shadowing at intermediate x

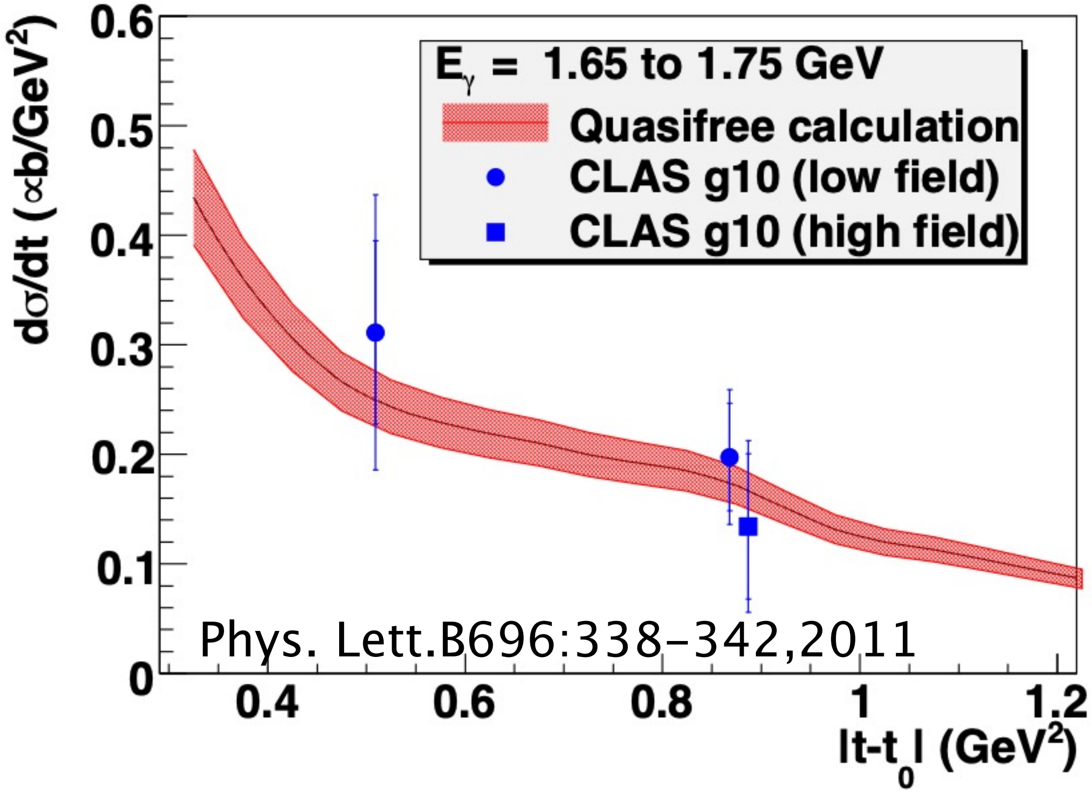


Revisiting the deuteron mass radius

arXiv:2504.10023 **[hep-ph]**

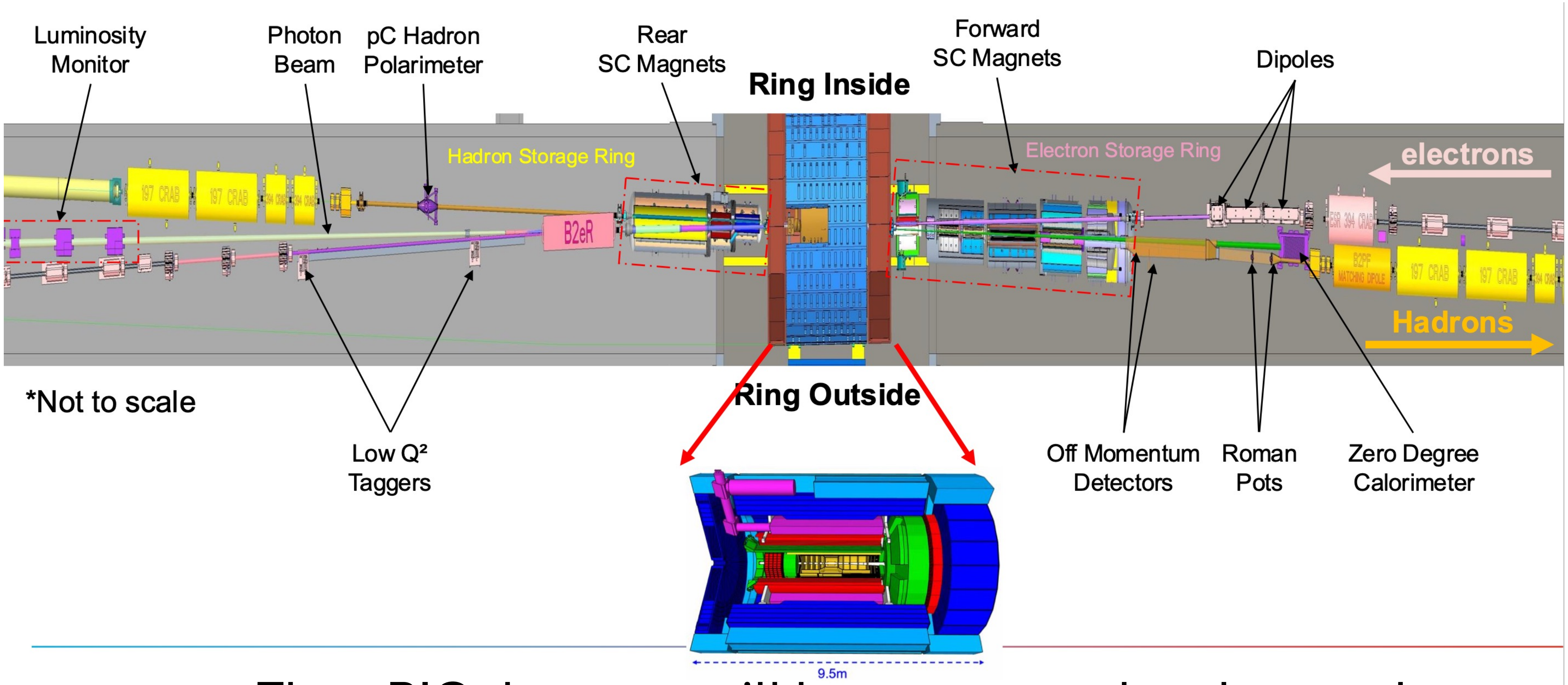
Why study ρ, ϕ?

- ϕ probes the strangeness content and is largely unconstrained at large-x
- **OZI** → enhanced sensitivity to gluonic mechanisms and to strangeness content of the nucleon (possible s $\bar{s}$ admixtures)
- Coherent ϕ on light nuclei → **A-dependence** and **small-|t| slopes** for gluon distributions at large x.



E_γ (GeV)	$\lvert t-t_0\rvert$ (GeV^2)	$\frac{d\sigma}{dt}$ ($\mu b/GeV^2$)	stat. uncer.	sys. uncer.
1.65-1.75	0.509	0.31	0.084	0.094
1.65-1.75	0.887	0.20	0.049	0.037
1.65-1.75	0.924	0.13	0.066	0.041

Use of the ePIC Detector



The ePIC detector will have extremely advanced array of far-forward/backward capabilities

Use of the ePIC Detector

- **Zero-Degree Calorimeters (both beams):** neutron/photon detection; define **Coulomb-excitation tags** and impact-parameter classes for ion beams.
- **Far-forward hadron system / Roman Pots:** detect **intact p** and diffracted nucleons; measure **t** with good resolution.
- **Off-momentum electron taggers / low-Q^2 taggers:** select **quasi-real photons** from the electron beam; define clean γ-induced samples.
- **Forward tracking + calorimetry:** reconstruct **low-p_T vector mesons**, provide exclusivity vetoes, and measure **SDMEs**.
- **Global vetoes & TOF:** suppress peripheral hadronic backgrounds; enforce exclusivity.

Thoughts on using the electron beam

- Fine photon energy control is needed for certain aspects of the near-threshold physics, i.e. structures in cross section
- Premiere experiments use thin radiators or inverse Compton scattering -> fine control on quasi mono-energetic photon beams

- At the EIC:
  - Tagged electron -> access virtual photons to lower Q^2 and higher E_γ (for displaced target with ePIC acceptance)
  - Thin radiator + photon tagger -> create a next generation version of current Jlab experiments
  - Inverse Compton Scattering -> utilize expertise and R&D for the polarimeters
  - Larger initial investment, but more topics accessible with fine photon energy control + higher rate

Summary & Conclusions

- Rich physics from vector Meson production near threshold
- Access to QCD trace anomaly and the gluonic gravitational Form Factors

$$T^{\mu}{}_{\mu} = \boxed{\frac{\beta(g)}{2g} G^2} + \boxed{(1+\gamma_m)\bar{\psi} m \psi\,,}$$

- SMOG-like fixed target at EIC would allow complementary near-threshold measurements of $\rho, \phi, J/\psi$
- Extend EIC collider kinematic reach to highest x values
- Equivalent Photons from proton beam allow threshold J/ψ, while lighter mesons benefit from Z^2 enhancement