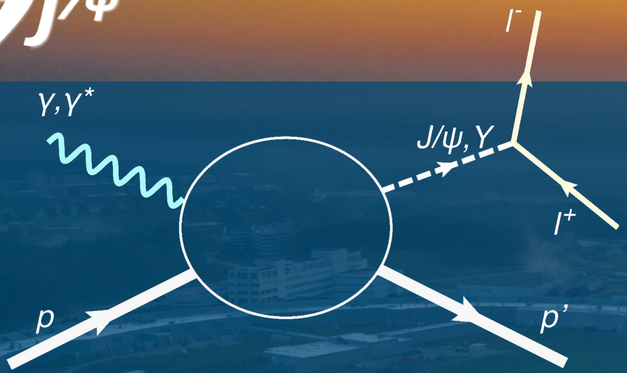
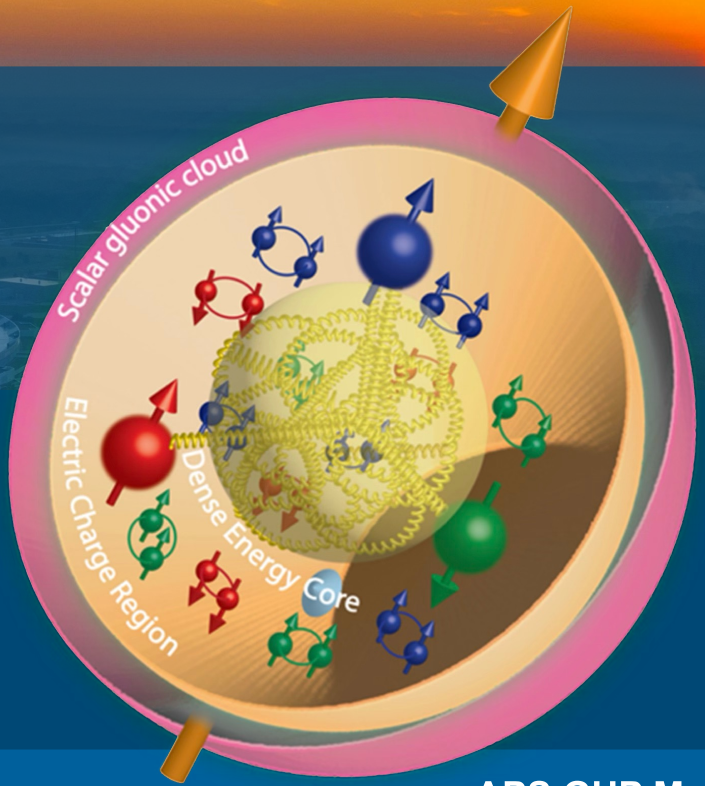


Charming Experiment Finds Gluon Mass in the Proton

Studying proton mass structure with the Hall C J/ψ-007 Experiment and beyond



Sylvester Joosten

On Behalf of the J/ ψ-007 Collaboration

With thanks to Xiangdong Ji, Dimitra Pefkou and Zein-Eddine Meziani

APS GHP Meeting

March 15, 2025, Anaheim CA

U.S. DEPARTMENT of ENERGY

This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

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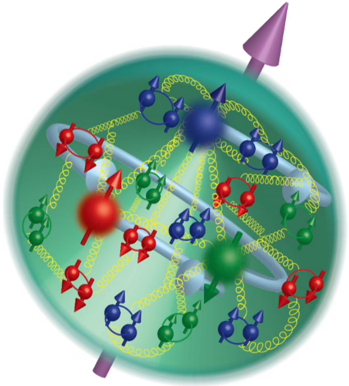
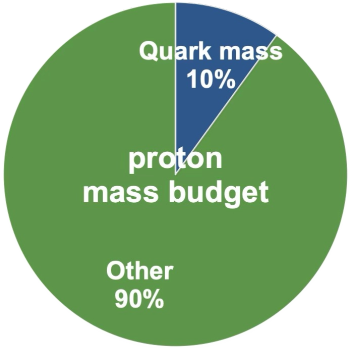
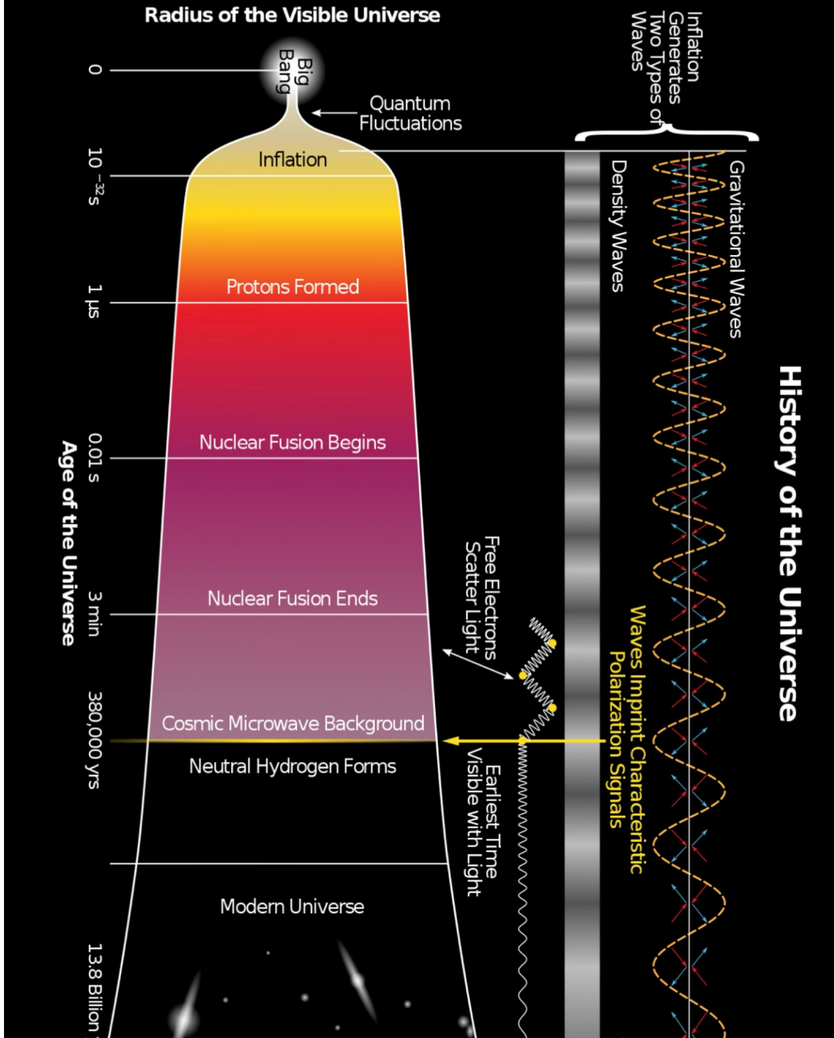
QCD in the Standard Model

The emergence of nucleon mass





- Since the formation of protons and neutrons, most of the mass of the visible universe encapsulated in protons, neutrons, and nuclei.
- Surprising: nucleon mass much larger than sum of quark masses.
- *How does QCD give rise to the 1GeV proton?*
- *How is the proton mass distributed in its confinement size?*



Adapted from an illustration by B. Sanders, NCSA, University of Illinois

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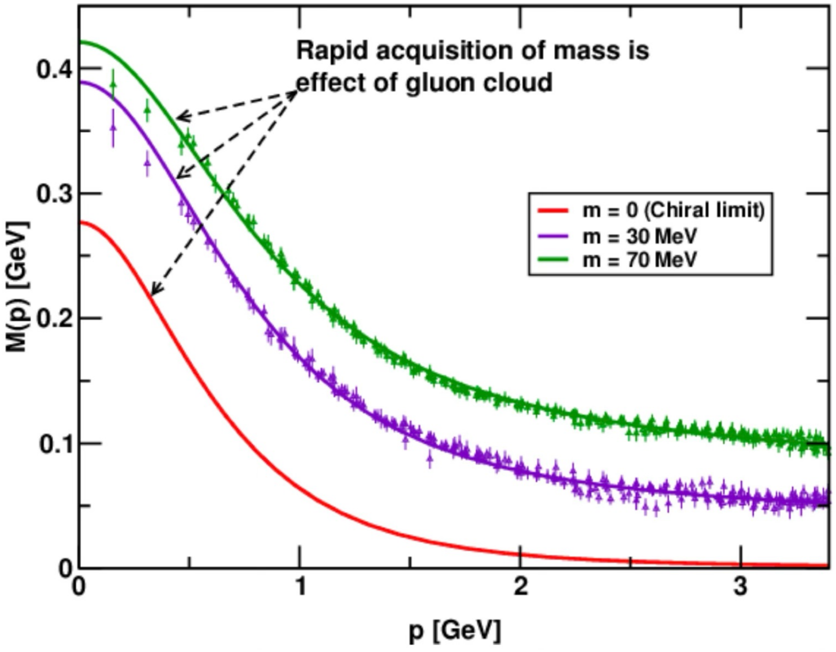
Proton Mass is an Emergent Phenomenon

QCD responsible for the proton mass



M. S. Bhagwat et al., Phys. Rev. C 68, 015203 (2003)
I. C. Cloet et al., Prog. Part. Nucl. Phys. 77, 1-69 (2014)

Most of the proton mass originates in the energy enclosed in the gluonic fields of the Strong Interaction itself

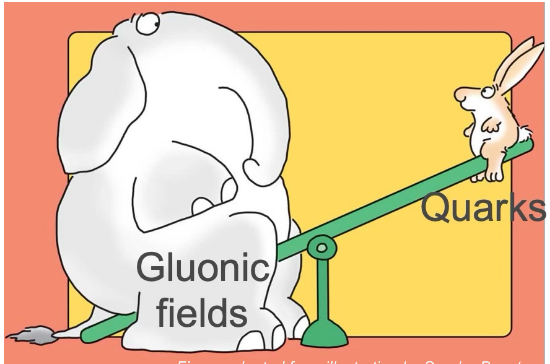


Figure adapted from illustration by Sandra Boynton

Bottom line: The Higgs mechanism is largely irrelevant for most of "normal" visible matter!

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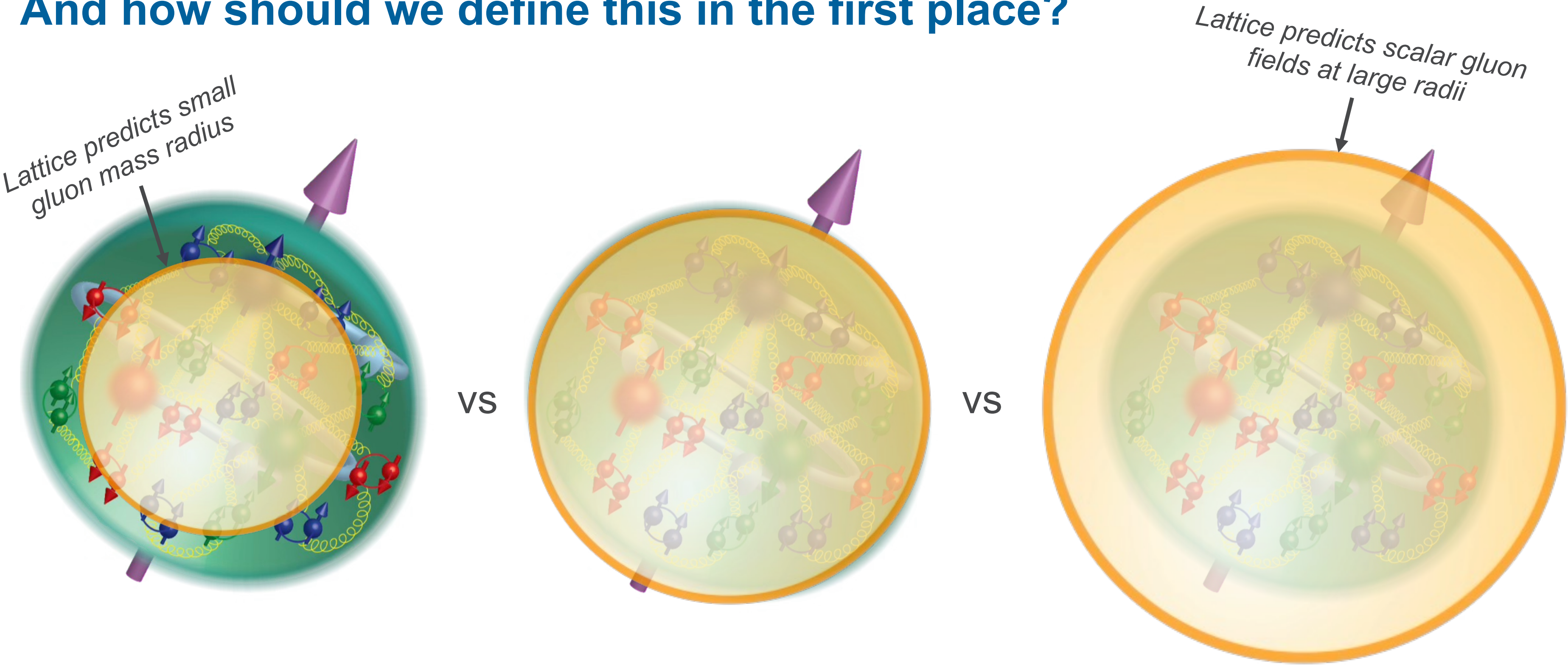
What Is the Size of a Proton?

And how should we define this in the first place?



Dense energy core?

Same as charge radius?

Energy halo beyond charge radius?

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How to measure the spatial structure of nucleons and nuclei?

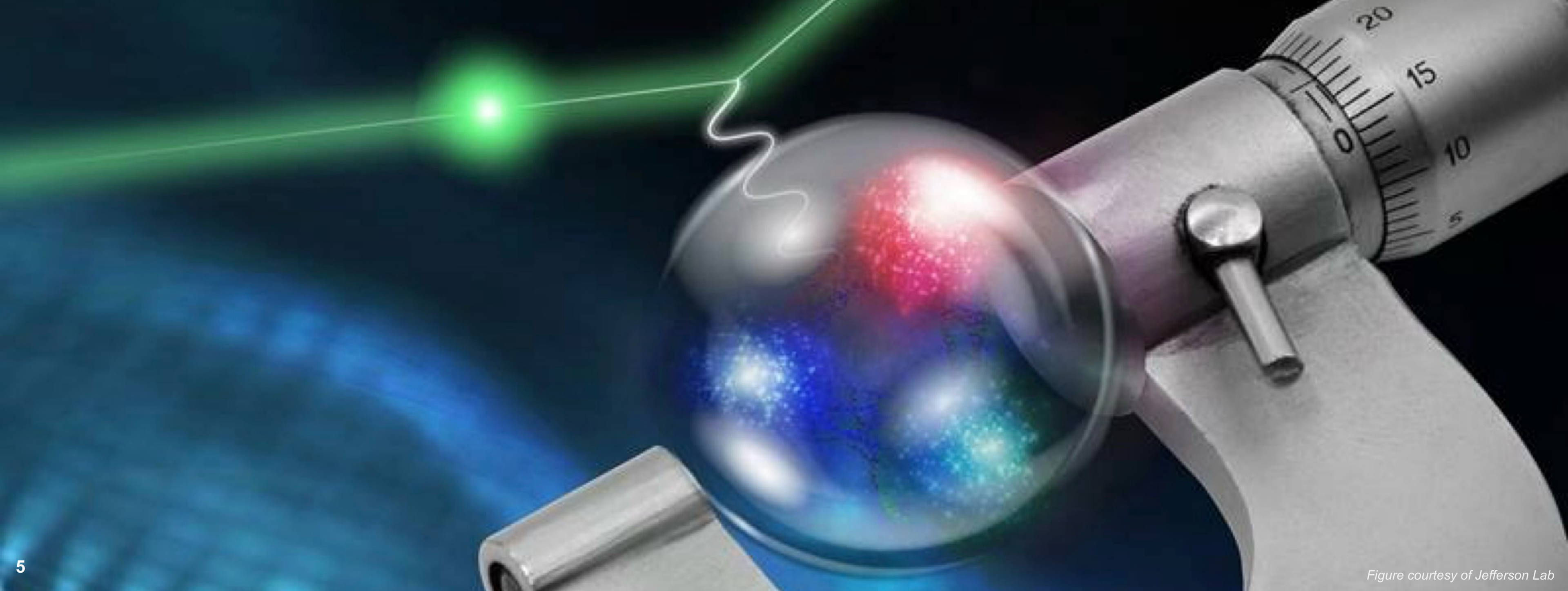
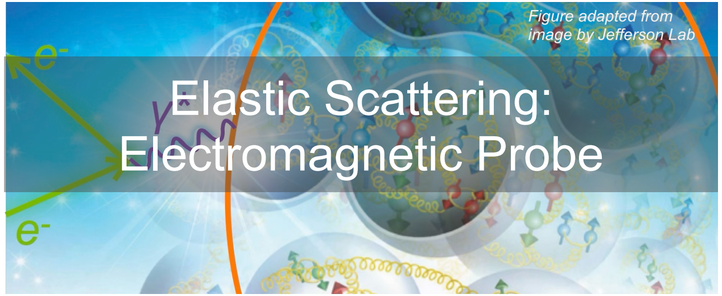
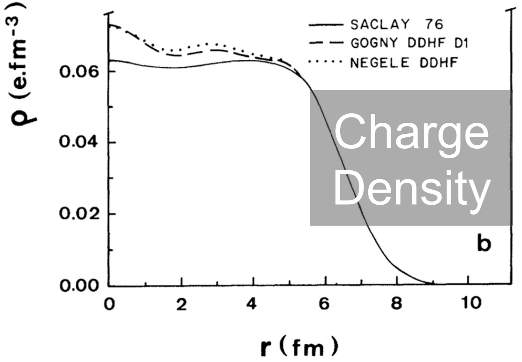


Figure courtesy of Jefferson Lab

What Is the Size of ^{208}Pb?

Analogous Example



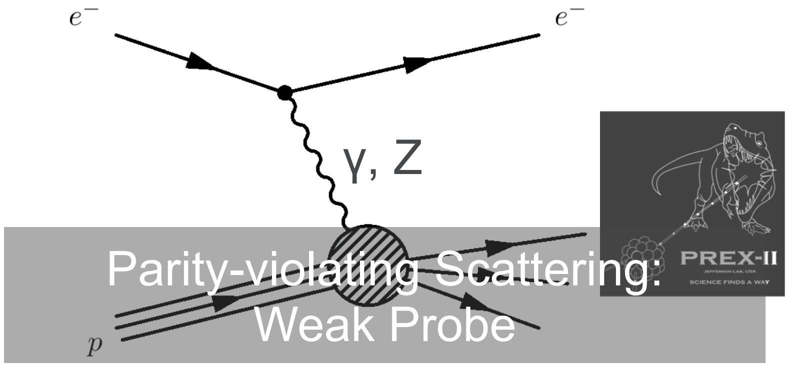


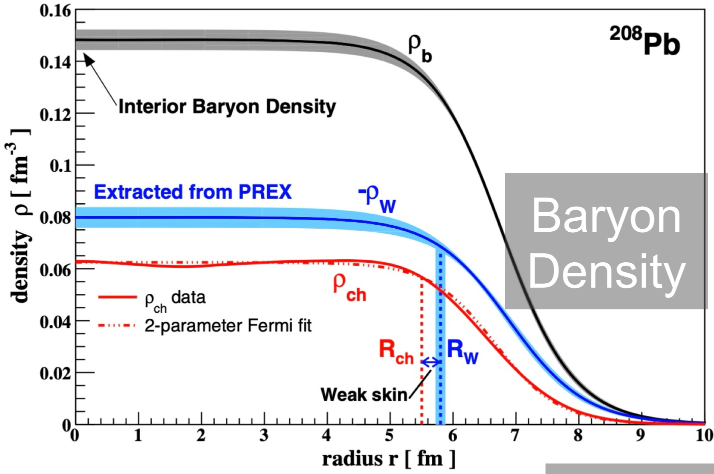
Nucleus	model	$\langle r^2\rangle^{1/2}$ [fm]
^{208}Pb*	SOG	5.503
	FB	5.4989(7)
	FB	5.503(2)

Charge Radius

B. Frois, *et al*, Phys. Rev. Lett. **38**, 576 (1977)
H. De Vries, *et al*, Atomic Data and Nuclear Data Tables 36, 495 (1987)

VS





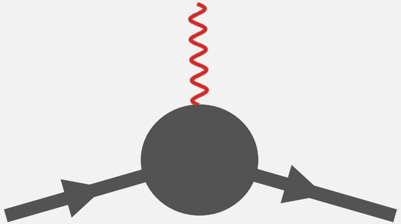
$$R_W = 5.795 \pm 0.082(\mathrm{exp}) \pm 0.013(\mathrm{theo})\ \mathrm{fm}$$
$$R_n - R_p = 0.278 \pm 0.078(\mathrm{exp}) \pm 0.012(\mathrm{theo})\ \mathrm{fm}.$$

Baryon Radius

H. Adhikari, *et al*, Phys. Rev. Lett. **126**, 172502

Gravitational Form Factors (GFFs)

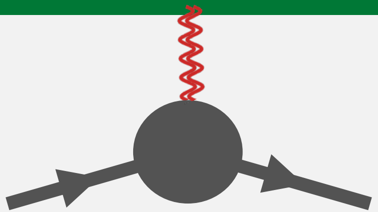
Electromagnetic FFs



$$\langle N' \mid J^\mu \mid N\rangle = \bar{u}(N')\left(F_1(Q^2)\gamma^\mu + \frac{i\sigma^{\mu\nu}q_\nu}{2M}F_2(Q^2)\right)u(N)$$

- EM FFs are the matrix elements of the electromagnetic current operator
- Map the charge and magnetization distribution in the proton

Gravitational FFs



$$\langle N' \mid T^{\mu,\nu}_{q,g} \mid N\rangle$$
$$= \bar{u}(N')\left(A_{g,q}(t)\gamma^{\{\mu}P^{\nu\}} + B_{g,q}(t)\frac{iP^{\{\mu}\sigma^{\nu\}\rho}\Delta_\rho}{2M} + C_{g,q}(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M}\right.$$
$$\left. + \bar{C}_{g,q}(t)Mg^{\mu\nu}\right)u(N)$$

- GFFs are the matrix elements of the QCD energy-momentum tensor (EMT) for quarks and gluons
- Reveal the distribution of mechanical properties of quarks and gluons in the proton, e.g. mass and internal pressure distributions

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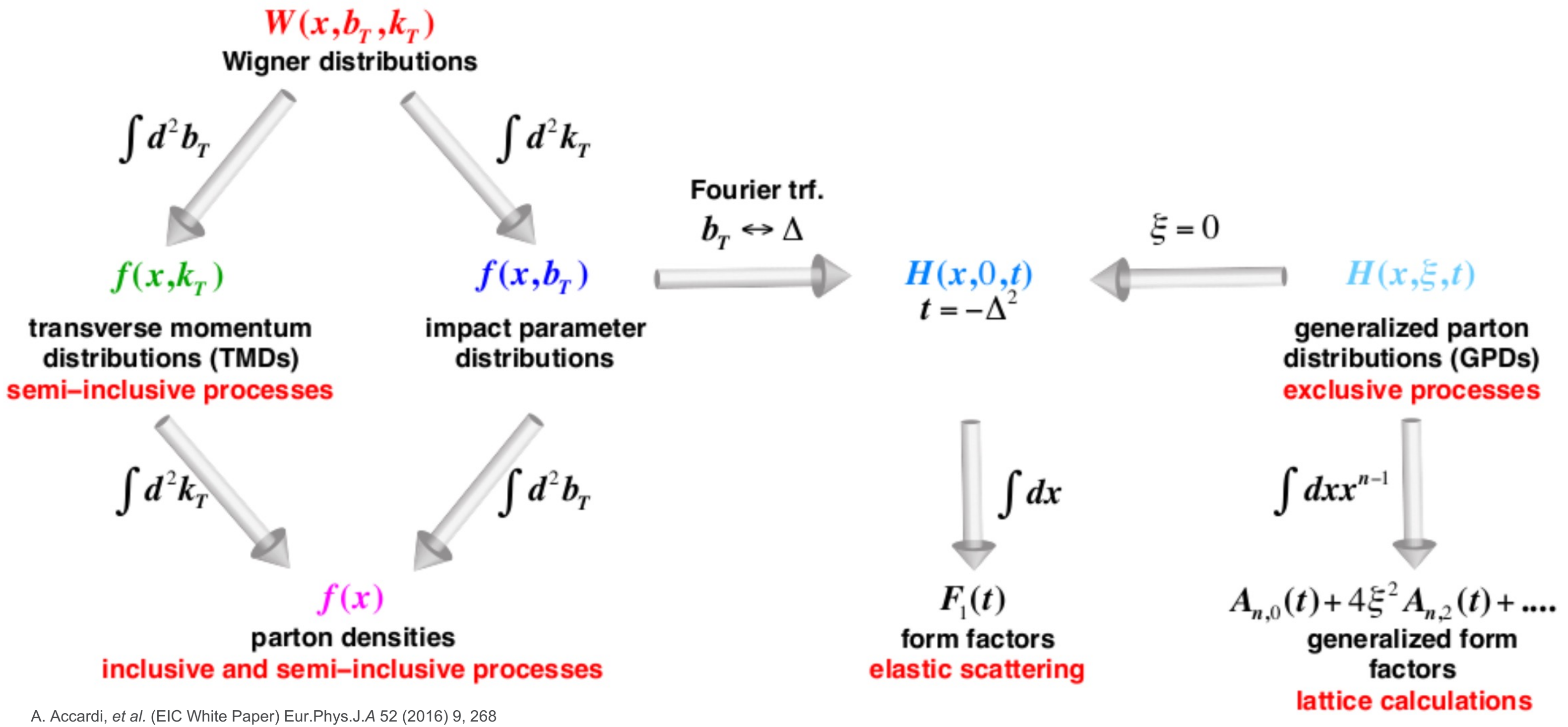
Unified View of Nucleon Structure and GFFs



A. Accardi, *et al.* (EIC White Paper) Eur.Phys.J.*A* 52 (2016) 9, 268

Gravitational FFs are generalized FFs where $n = 2$ (second moment)

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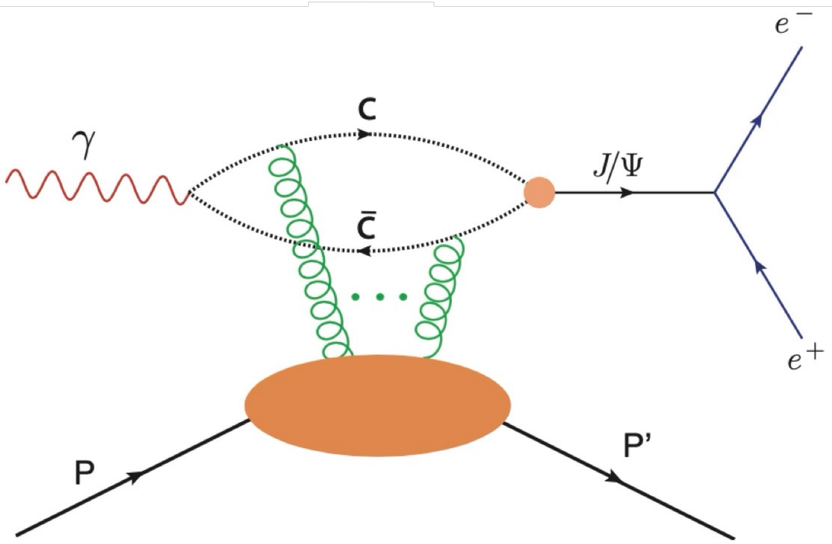
How To Measure the Gluon GFFs?

Gluons are elusive!

🛑 Cannot use Electromagnetic probe: primarily couples to quarks

🟢 Small "color" dipole made of heavy quarks well-suited

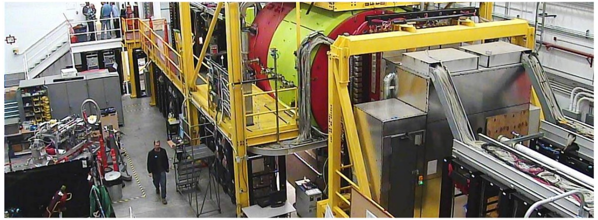


Use quarkonium photoproduction as stand-in for elastic quarkonium scattering

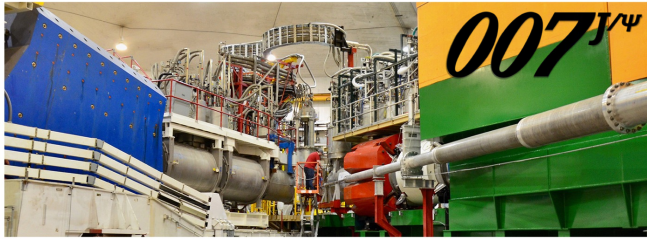
Gravitational form factors constrained by near-threshold exclusive J/ψ and Y photoproduction

Beyond GFFs: 3-D gluonic structure of nucleons and nuclei constrained by exclusive J/ψ and Y

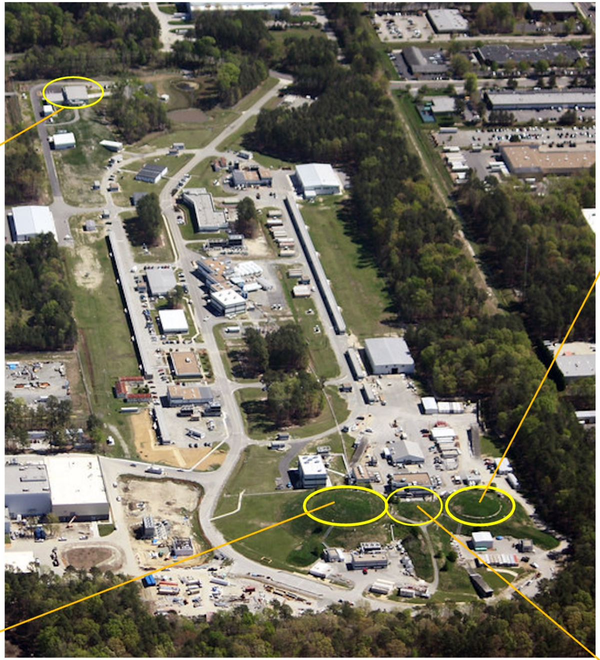
12 GeV J/ψ Experiments at Jefferson Lab

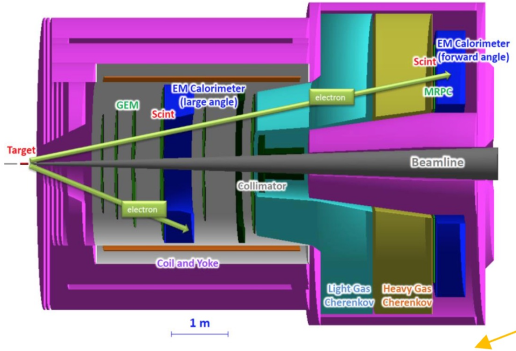


Hall D - GlueX observer the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)

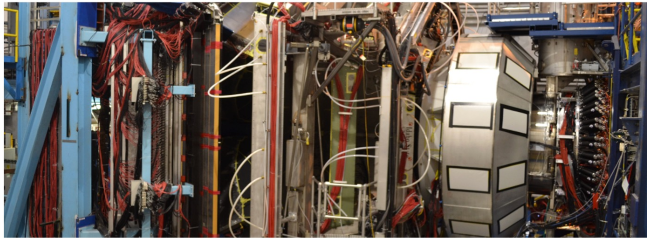


Hall C has the **J/ψ-007** experiment (E12-16-007)
LHCb hidden-charm pentaquark search





Hall A has experiment E12-12-006 at **SoLID** to measure J/ψ in electro- and photoproduction, and an LOI to measure double polarization using **SBS**



Hall B - CLAS12 has experiments to measure TCS + J/ψ in photoproduction as part of Run Groups A (hydrogen) and B (deuterium): E12-12-001, E12-12-001A, E12-11-003B

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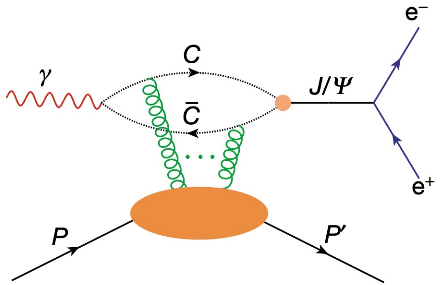
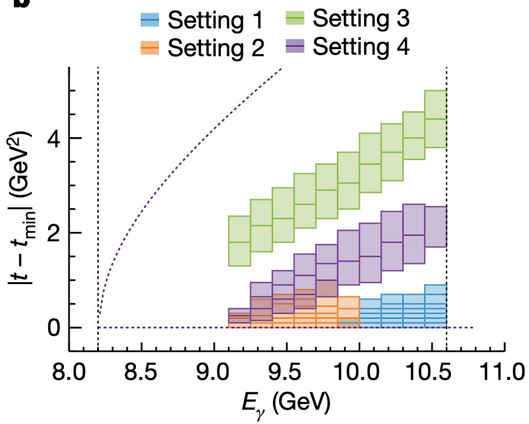
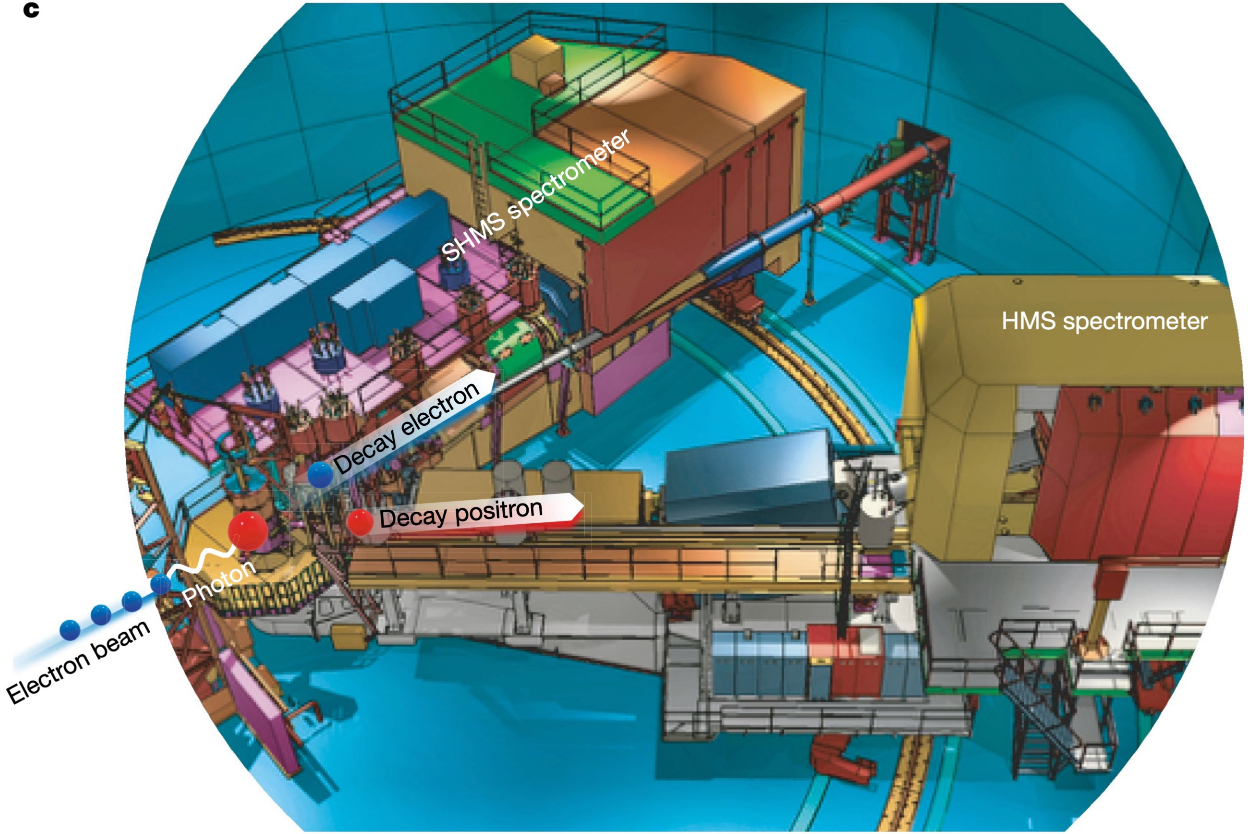
B. Duran et al., Nature volume 615, pages 813–816 (2023)

J/ψ-007 (E12-16-007) in Hall C at JLab

Near-threshold J/ψ photoproduction

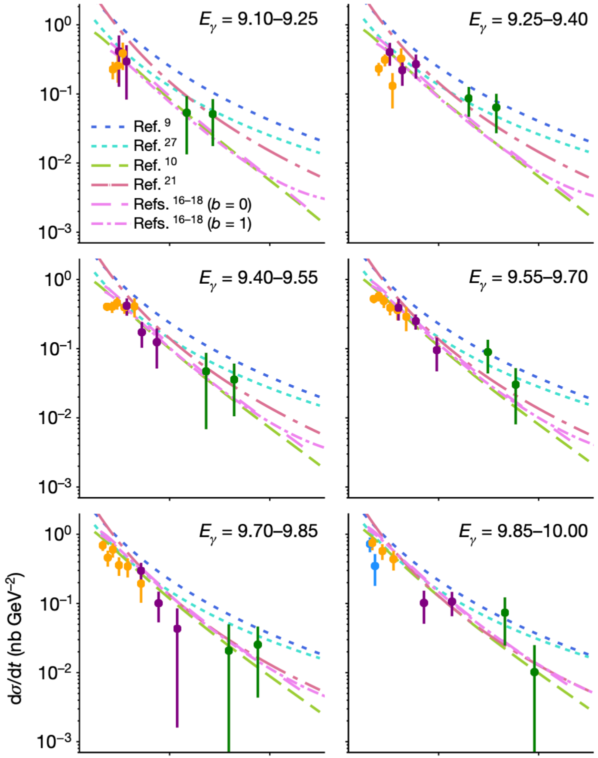


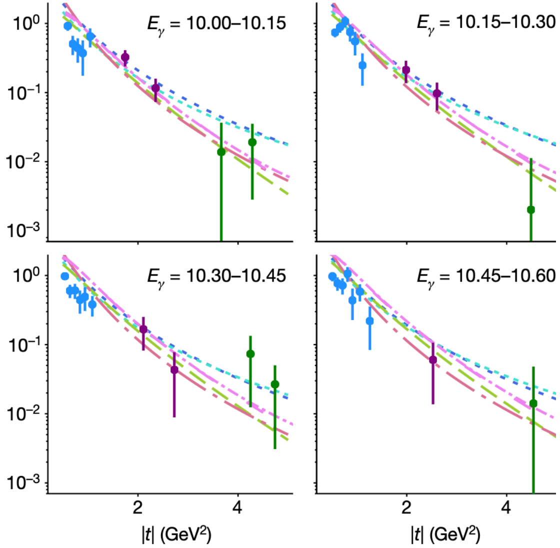




2-D J/ψ cross sections near threshold

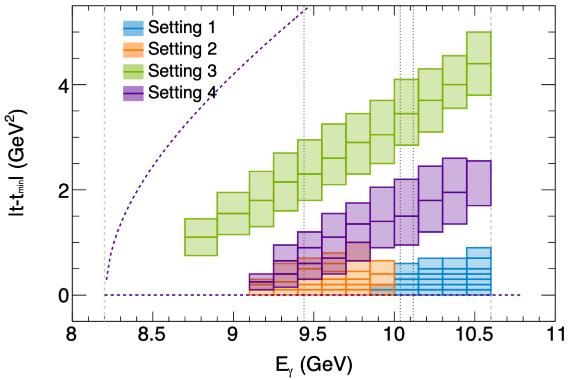
First results published in Nature in 2023





4% scale uncertainty

Ref. 9: D, Kharzeev, Phys. Rev. D 104, 054015 (2021).
Ref. 27: Mamo & Zahed, 2204.08857 (2022)
Ref. 10: Guo, Ji & Liu, Phys. Rev. D 103, 096010 (2021)
Ref. 21: Sun, Tong & Yuan, Phys. Lett. B 822, 136655 (2021)
Ref. 18: Hatta, Rajan & Yang, Phys. Rev. D 100, 014032 (2019)



Unfolded 2D cross section results compared to various model predictions informed by the 2019 1D GlueX results

All models work reasonably well at higher energies but deviate at lower energies

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Model Assumptions and Caveats

First model-dependent attempt to determine the GFFs from experiment

Assumptions

Neglect $B(t)$ - in concordance with both models and lattice QCD

Neglect $\overline{C}_g$ when evaluating the cross section and radii (*)

Assume tripole shape for $A(t)$ and $C(t)$ (**)

Fix $A(0)$ to the average gluon PDF from CT18

Both models fit the data well ($\chi^2 \sim 1$)

(*) This is appropriate for the holographic model but not the GPD model. See Hatta et al. JHEP 12 (2018) 008 & Tanaka, K. JHEP 03 (2023) 013 for a calculation of $\overline{C}_g = -\overline{C}_q$

(**) Doing the same extraction with a dipole shape, or does not impact our results

Holographic Model

K. Mamo & I. Zahed, PRD 103, 094010 (2021) and 2204.08857 (2022)

$$\frac{d\sigma}{dt} = \mathcal{N} \times \frac{e^2}{64\pi(s-m_N^2)^2} \times \frac{A(-t,\kappa_T)+\eta^2 D(-t,\kappa_T,\kappa_S)]^2}{A^2(0)} \times \tilde{F(s)} \times 8$$

N is normalized to the previous World Data (not given by the model)

GPD Model

Y. Guo, X. Ji, Y. Liu, PRD 103, 096010 (2021)

$$\frac{d\sigma}{dt} = \frac{\alpha_e m e_Q^2}{4(W^2-m_N^2)^2} \frac{(16\pi\alpha_s)^2}{3M_V^2} |\psi_{NR}|^2 |G(t,\xi)|^2$$

Assume $\xi \sim 1$ (it is less than 0.5 for most of the experimental data)

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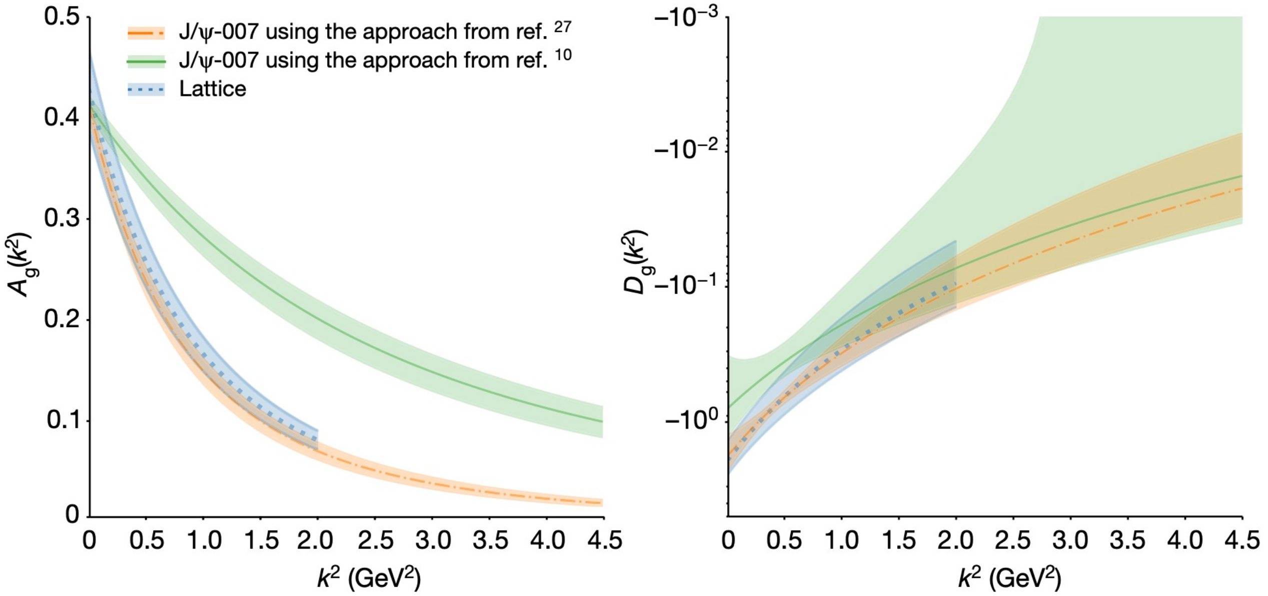
B. Duran et al., Nature volume 615, pages 813–816 (2023)

First Gluonic GFFs from Experimental Data

007J/ψ

Remarkable agreement between GFFs determined from data using the Holographic QCD approach and the direct Lattice QCD calculation!



Determined from experment

Holographic QCD approach
GPD approach

Determined from theory

Lattice QCD calculation

Ref 27 (Holographic QCD): K. Mamo & I. Zahed, PRD 103, 094010 (2021) and 2204.08857 (2022)
Ref 10 (GPD Formalism): Y. Guo, X. Ji, Y. Liu, PRD 103, 096010 (2021)
Lattice: D. Pefkou, D, Hackett, P. Shanahan, Phys. Rev. D 105, 054509 (2022).

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B. Duran *et al.*, Nature volume 615, pages 813–816 (2023)

The Proton in Three Regions?

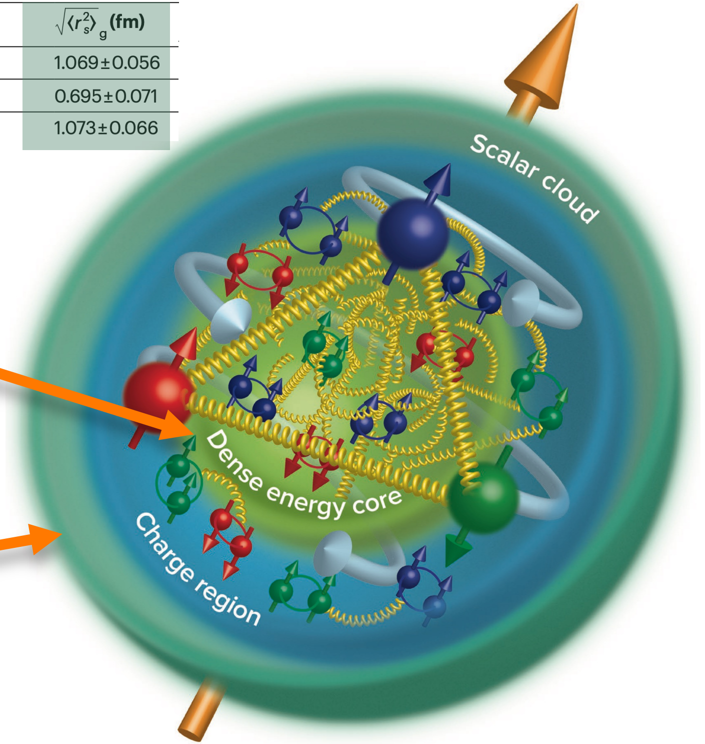
007$^{J/\psi}$

Table 1 | The gluonic GFF fit parameters, proton mass radius and scalar radius

Theoretical approach	χ^2/n.d.f.	m_A (GeV)	m_C (GeV)	$C_g(0)$	$\sqrt{\langle r_m^2\rangle_g}$ (fm)	$\sqrt{\langle r_s^2\rangle_g}$ (fm)
Holographic QCD	0.925	1.575±0.059	1.12±0.21	−0.45±0.132	0.755±0.035	1.069±0.056
GPD	0.924	2.71±0.19	1.28±0.5	−0.20±0.11	0.472±0.042	0.695±0.071
Lattice		1.641±0.043	1.07±0.12	−0.483±0.133	0.7464±0.025	1.073±0.066

The proton's mass radius seems substantially smaller than its charge radius.

The holographic QCD fit to our data and the latest Lattice calculations find a scalar gluonic cloud surrounding the charge region at about 1 fermi



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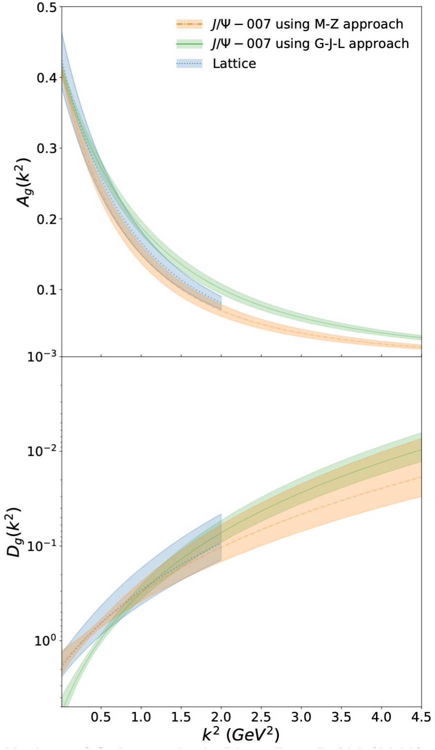
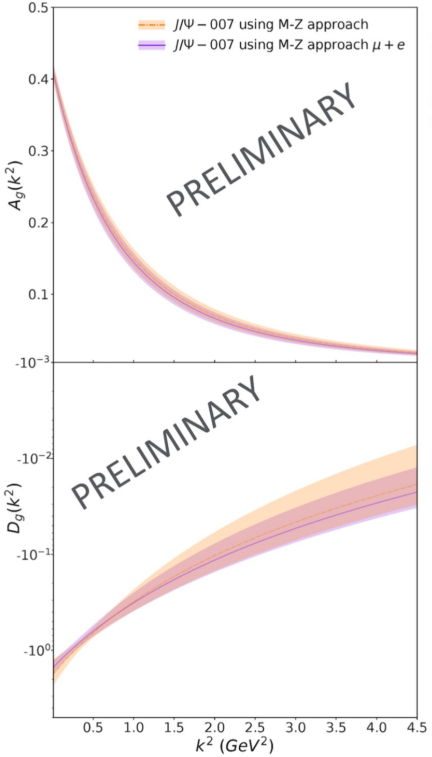
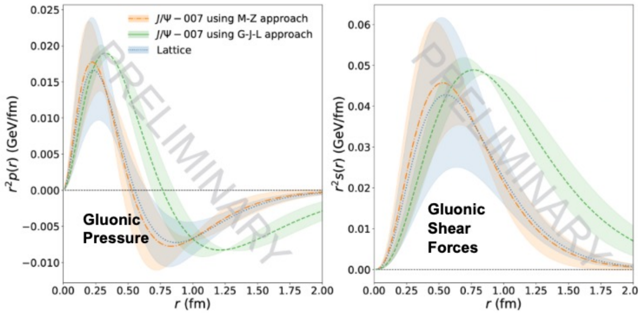
12 GeV J/ψ Experiments at Jefferson Lab

Update of G-J-L analysis PRD **108** (2023) no.3, 034003 arXiv:2305.06992



New combined electron-muon results from J/ψ-007





- Analysis with the muon decay channel results, (almost) doubling the statistics
- Consistent with the electron results
- Largest impact on the $C(t)$ form factor with improved precision

Expect more results soon: Finalizing systematics on the di-muon decay channel, preparing new manuscript to submitted to journal this month!

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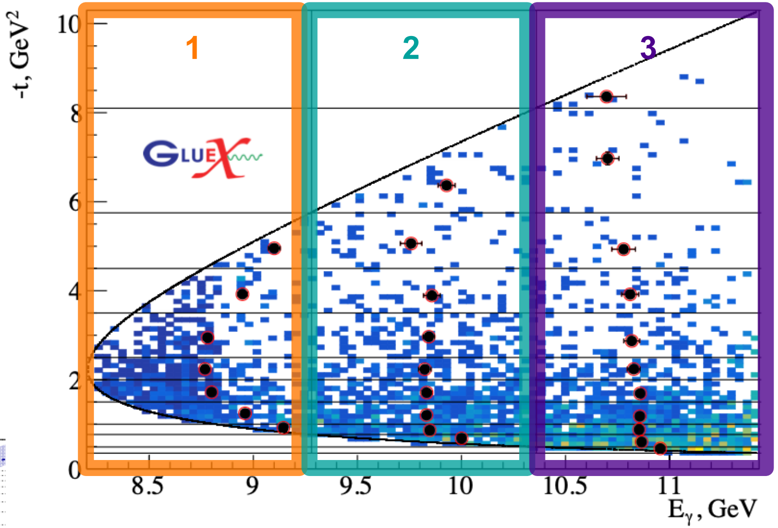
2023 Gluex Results

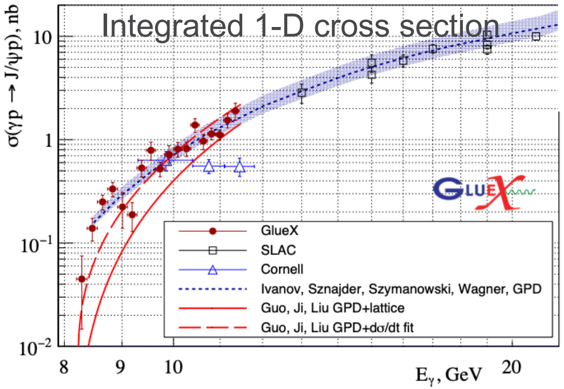
2.2k J/ψ (~ same as J/ψ-007 e+e- results)

2-D differential cross section extracted in 3 E_γ slices
E_γ ~ 8.2 - 11.44 GeV

(compared to 10 E_γ slices
E_γ ~ 9.1 - 10.6 GeV
for J/ψ-007)

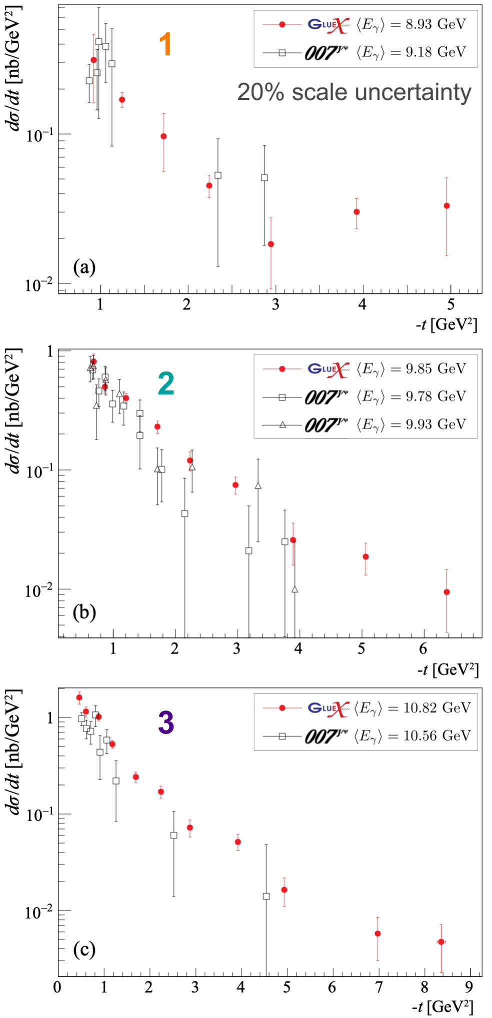
New GlueX results have 20% scale uncertainty.





Good agreement within errors with between GlueX and J/ψ-007

GlueX 2023



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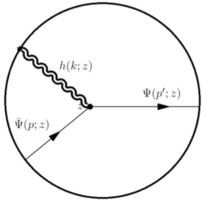
Global fit to JLab Data

2D fit to extract the *A(t)* & *C(t)* assuming *B(t)* negligible

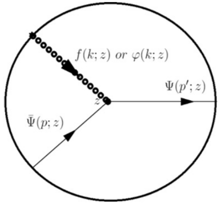
K. Mamo & I. Zahed, PRD 106, 086004 (2022) and PRD 101, 086003 (2020)

Tensor



Spin-2^{++} : $\langle p_2|T^{xy}(0)|p_1\rangle$

Scalar



Spin-0^{++} : $\langle p_2|T^{\mu}_{\mu}(0)|p_1\rangle$

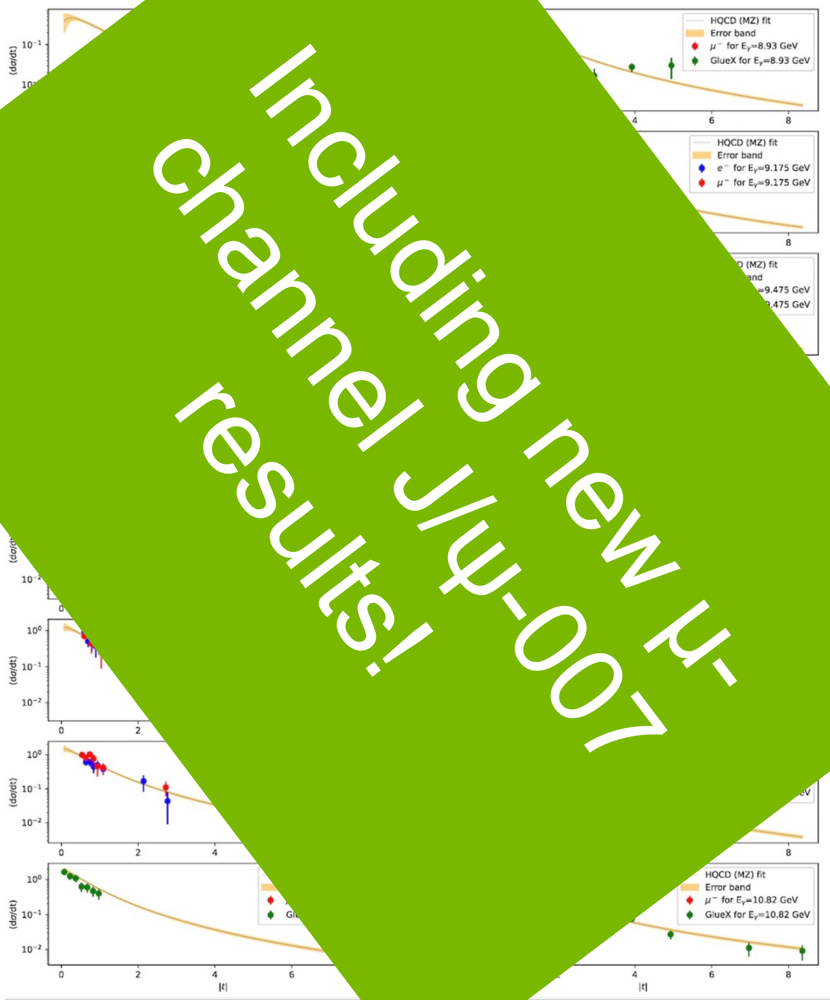
$$\frac{d\sigma}{dt} = \mathcal{N}^2 \times \frac{e^2}{64\pi(s-M^2)^2} \times \frac{\left[A(t)+4\eta^2(C(t)\right]^2}{A^2(0)} \times F(s,t) \times \frac{(2t+8M^2)}{(4M^2)}$$

$$\eta = \frac{M^2_{J/\psi}}{4p.q - M^2_{J/\psi} + t}$$

$$A_g(t) = \left(\frac{1}{1-t/\Lambda_A^2}\right)^2 \qquad C_g(t) = \left(\frac{1}{1-t/\Lambda_C^2)}\right)^3$$

- *A(t)* and *D(t)* shapes are fully calculated; However, dipole- tripole forms are assumed as very good approximations and are used in the fits to the data.
- $A_g(0)$= $\langle x_g \rangle$ is fixed to the DIS value from global fit CT18.
- *B(t)* is neglected and $\mathcal{N}$ is normalized to the cross section.

J/ψ – 007 (... d GlueX (e channel)



Including new μ-channel J/ψ-007 results!

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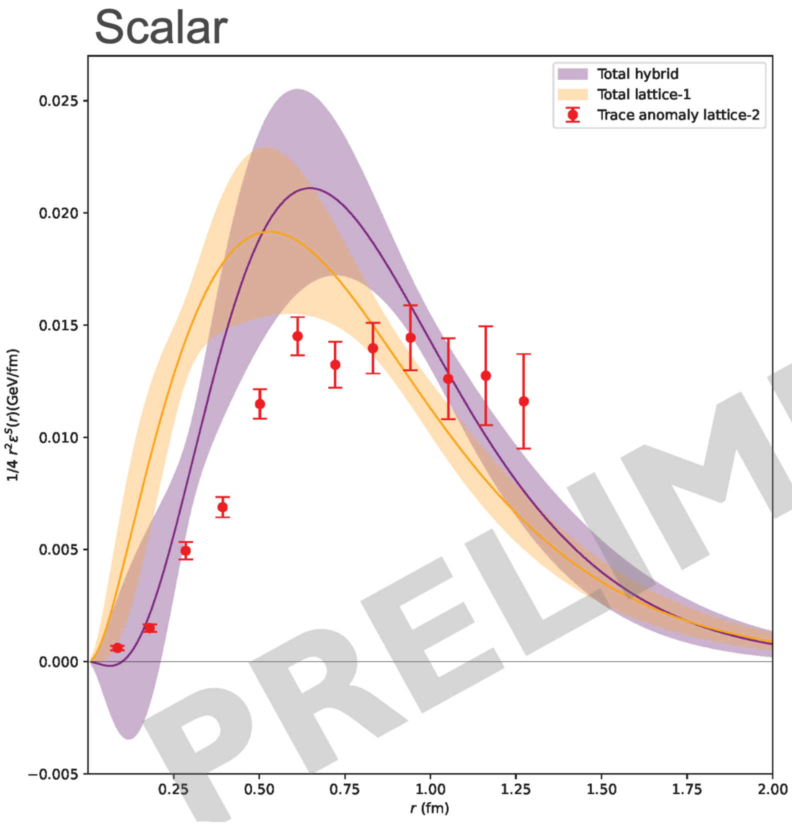
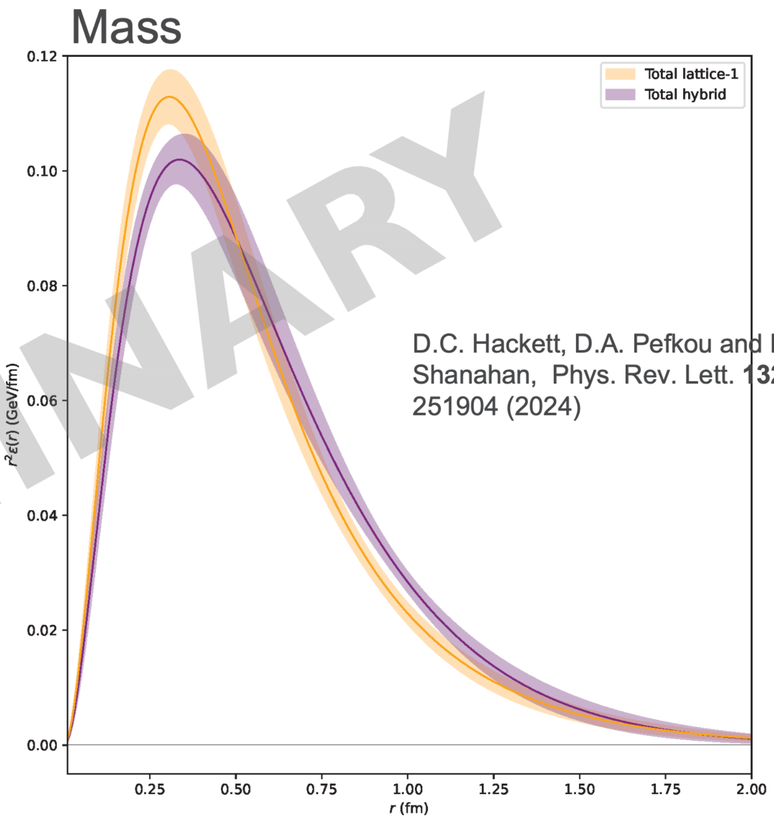
Breit-frame Scalar and Mass Densities

Hybrid quark-lattice + gluon-expt compared to pure lattice





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Extraction of Gluon Scalar/Mass Radius of the Nucleon

A Picture of Three Zones?

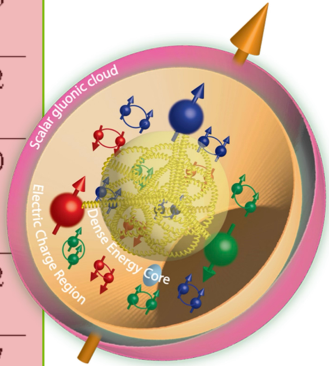
Mass Radius

$$\langle r_m^2\rangle_g = \frac{6}{A_g(0)}\frac{dA_g(t)}{dt}\Big|_{t=0} - \frac{6}{A_g(0)}\frac{C_g(0)}{M_N^2}$$

Scaler Radius

$$\langle r_s^2\rangle_g = \frac{6}{A_g(0)}\frac{dA_g(t)}{dt}\Big|_{t=0} - \frac{18}{A_g(0)}\frac{C_g(0)}{M_N^2}$$

Theoretical approach Data Set # GFF functional form	χ^2/n.d.f	m_A (GeV)	m_C (GeV)	$C_g(0)$	$\sqrt{\langle r_m^2\rangle_g}$ (fm)	$\sqrt{\langle r_s^2\rangle_g}$ (fm)	$\sqrt{\langle r_s^2\rangle_T}$ (fm)
Data set # 1 Dipole-tripole	1.21	1.153±0.018	0.967 ±0.099	-0.436±0.079	0.794 ± 0.037	1.091 ±0.074	0.999±0.036
Data set # 2 Dipole-tripole	1.08	1.158±0.013	0.895 ±0.063	-0.530±0.079	0.830 ± 0.033	1.170 ±0.067	0.984±0.052
Lattice (2024) m_π = 170 MeV Dipole-tripole		1.262± 0.018	0.845± 0.017	-0.452± 0.080	0.727 ±0.041	0.998 ± 0.086	0.897±0.060
Data set # 1 Dipole-dipole	1.15	1.212 ±0.028	0.828 ±0.106	-0.435±0.073	0.771±0.038	1.070±0.071	0.984±0.052
Data set # 2 Dipole-dipole	1.07	1.195 ±0.028	0.828 ±0.106	-0.435±0.073	0.825±0.038	1.178±0.075	0.999±0.067
Lattice (2024) m_π = 170 MeV Dipole-dipole		1.262± 0.017	0.706± 0.066	-0.552± 0.089	0.796±0.069	1.15± 0.14	1.008± 0.094



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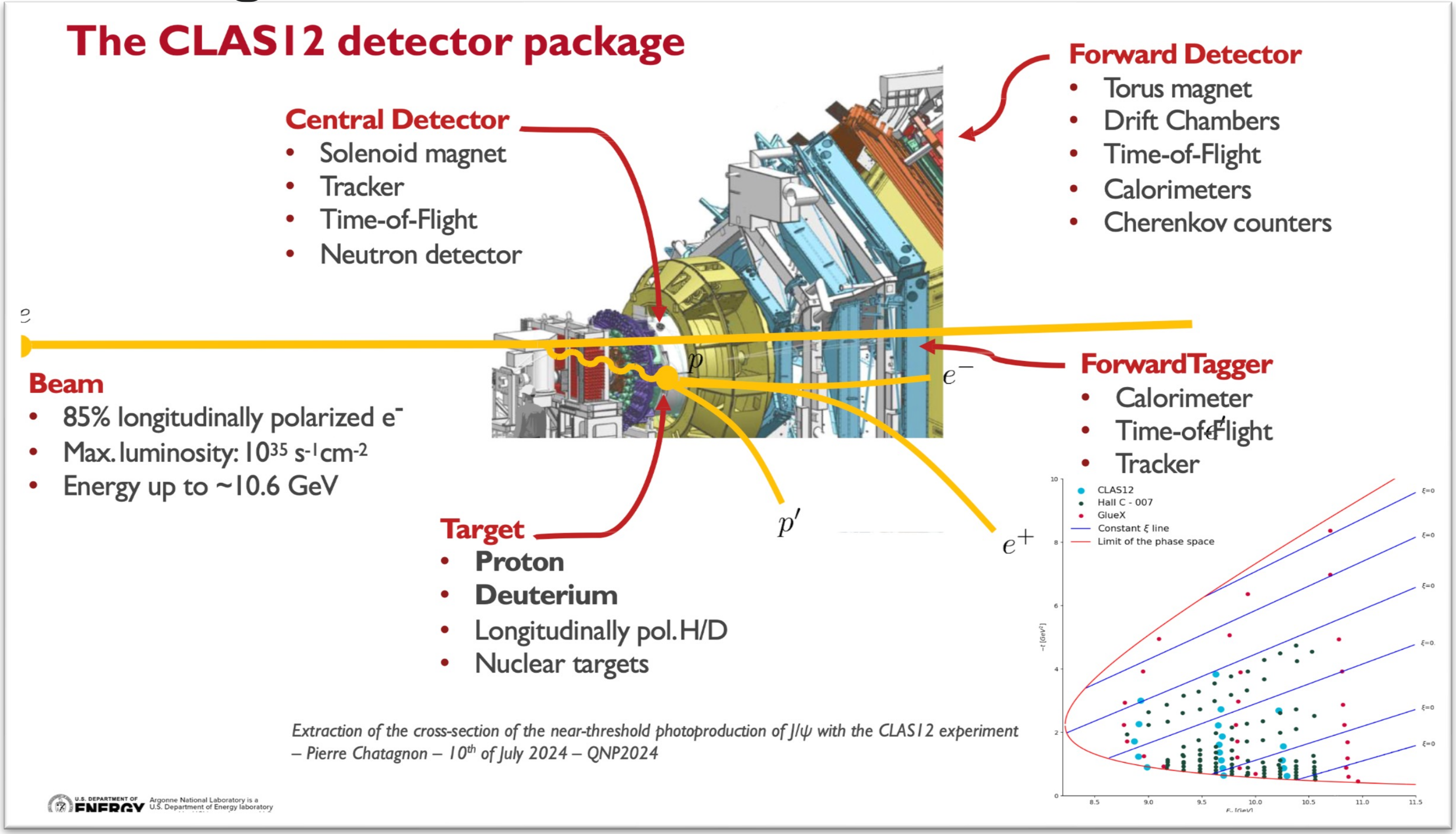
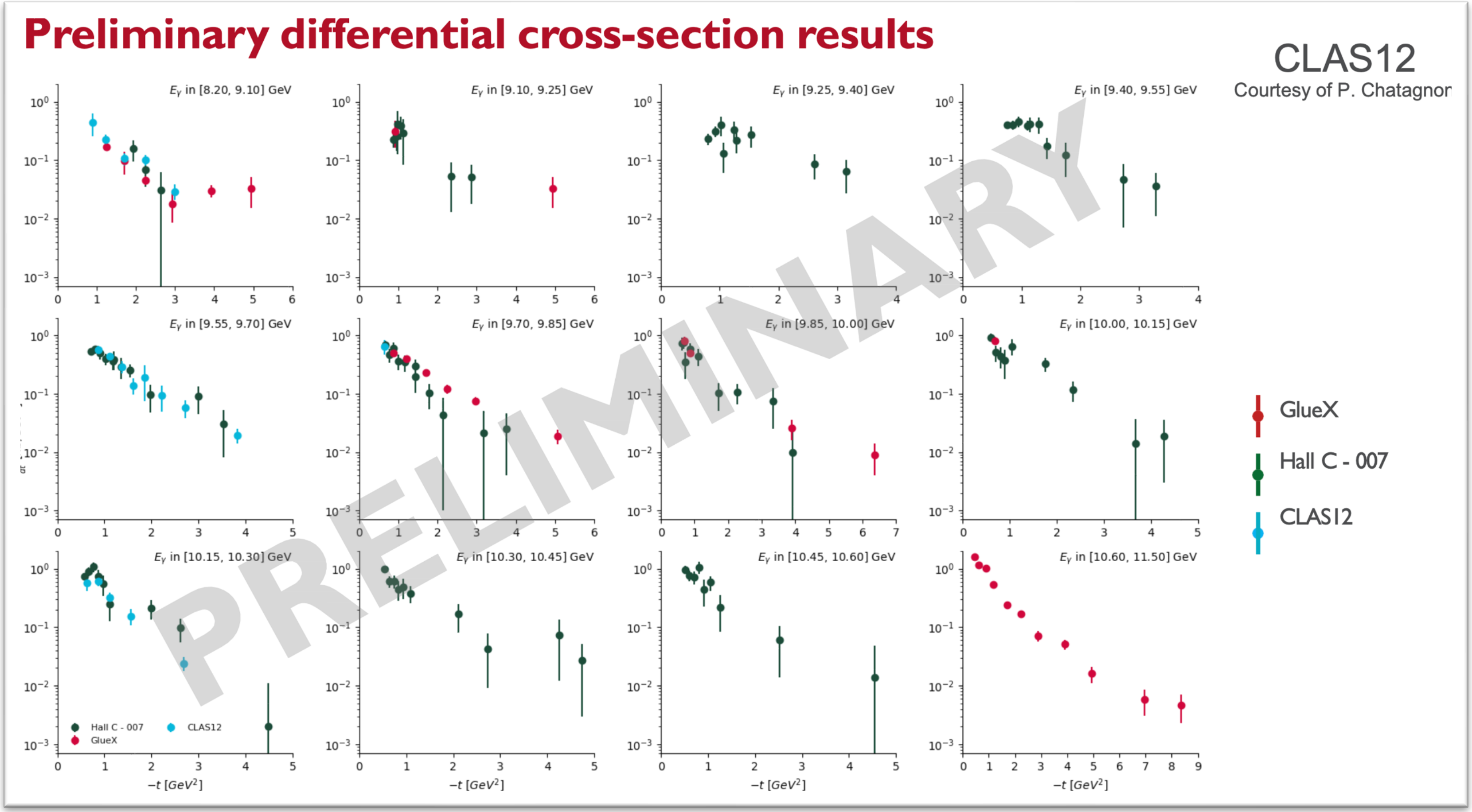
Upcoming Results: CLAS12

Courtesy of P. Chatagnon



Upcoming Results: CLAS12

From QNP2024



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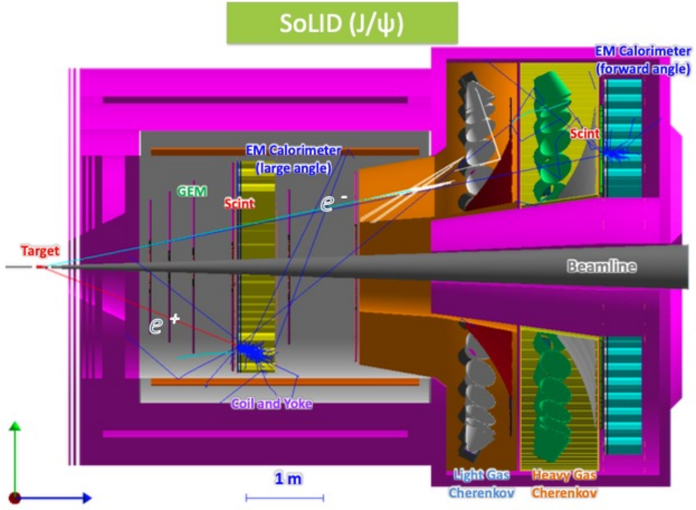
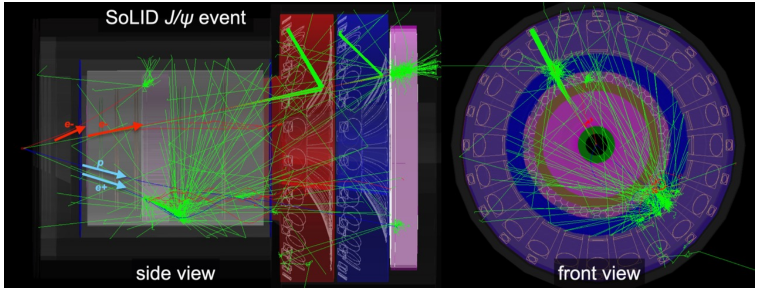
Future: SoLID-J/ψ in Hall A

Ultimate factory for near-threshold J/ψ

SoLID
SOLENOIDAL LARGE INTENSITY DEVICE

- General purpose large-acceptance spectrometer
- 50+10 days of 3μA beam on a 15cm long LH2 target ($10^{37}/cm^2/s$)
- **Ultra-high luminosity**: $43.2ab^{-1}$
- **Open 2-particle trigger,** covering J/ψ production in four channels: Electroproduction (e,e^-e^+), photoproduction (p,e^-e^+), inclusive (e^-e^+), exclusive (ep,e^-e^+)
- The electoproduction channel provides for a modest lever-arm in Q^2 near threshold





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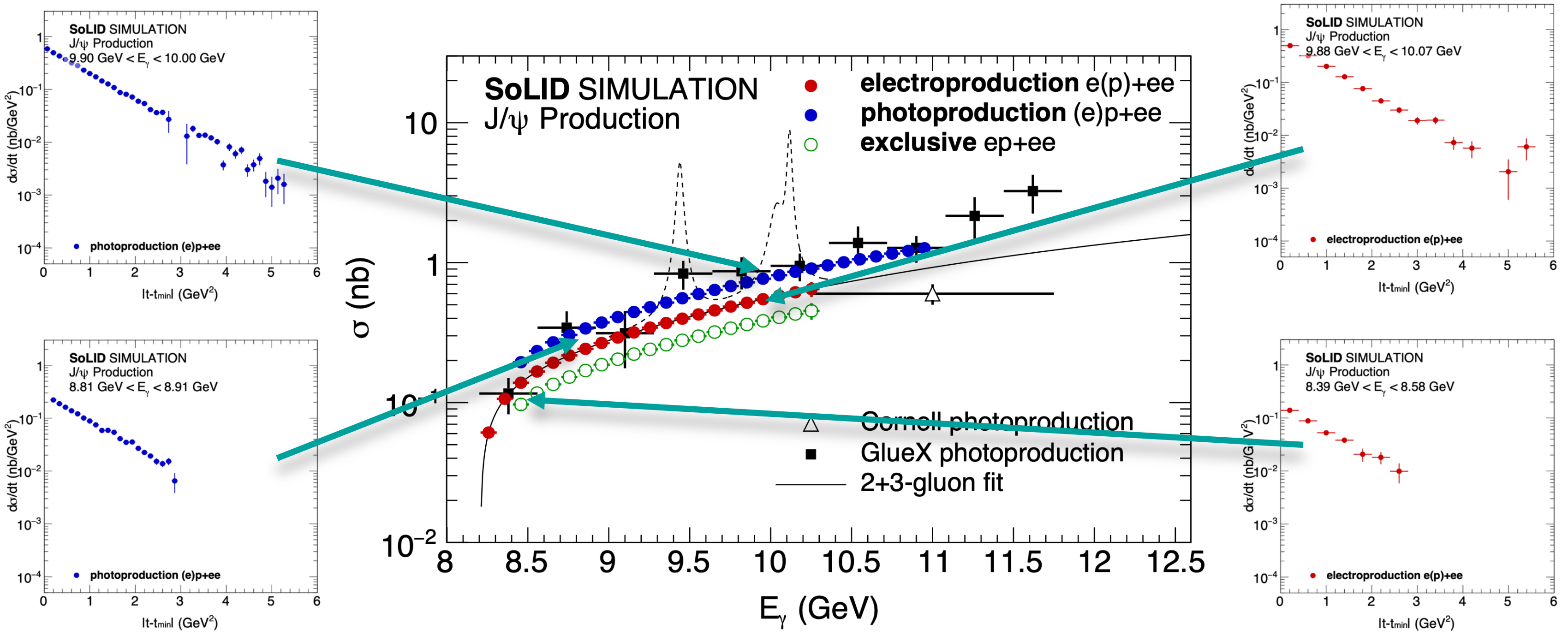
Future: SoLID-J/ψ in Hall A

High-precision 2-D cross section crucial to really connect GFFs to data



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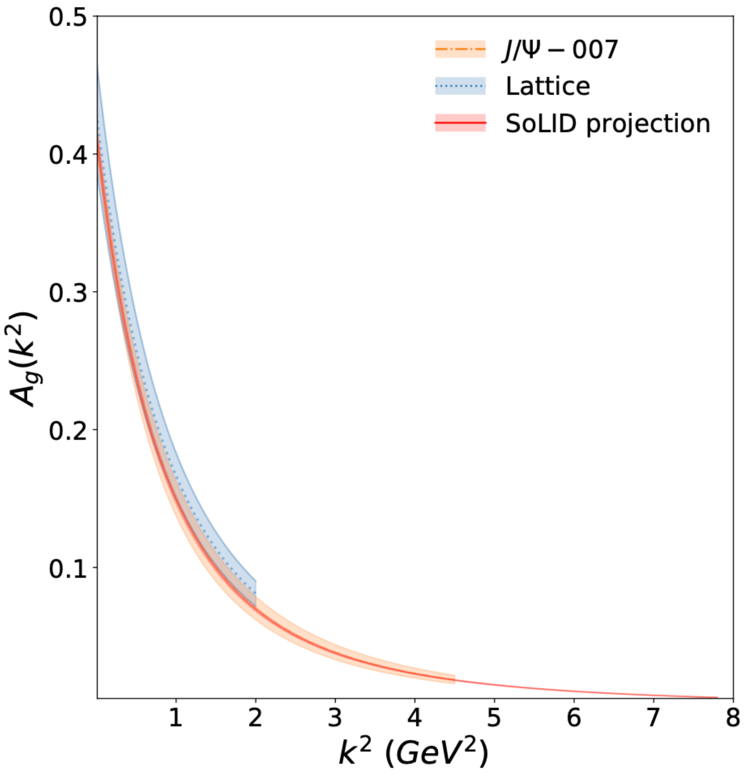
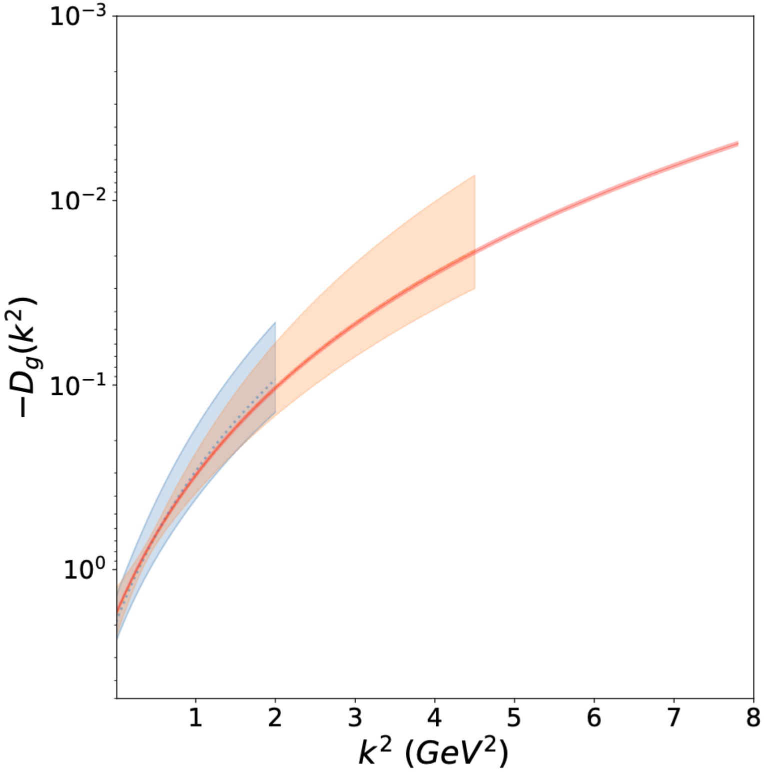
Future: SoLID Projected Impact on gluon GFFs

Comparison with J/ψ-007 (Holographic QCD approach) and Lattice





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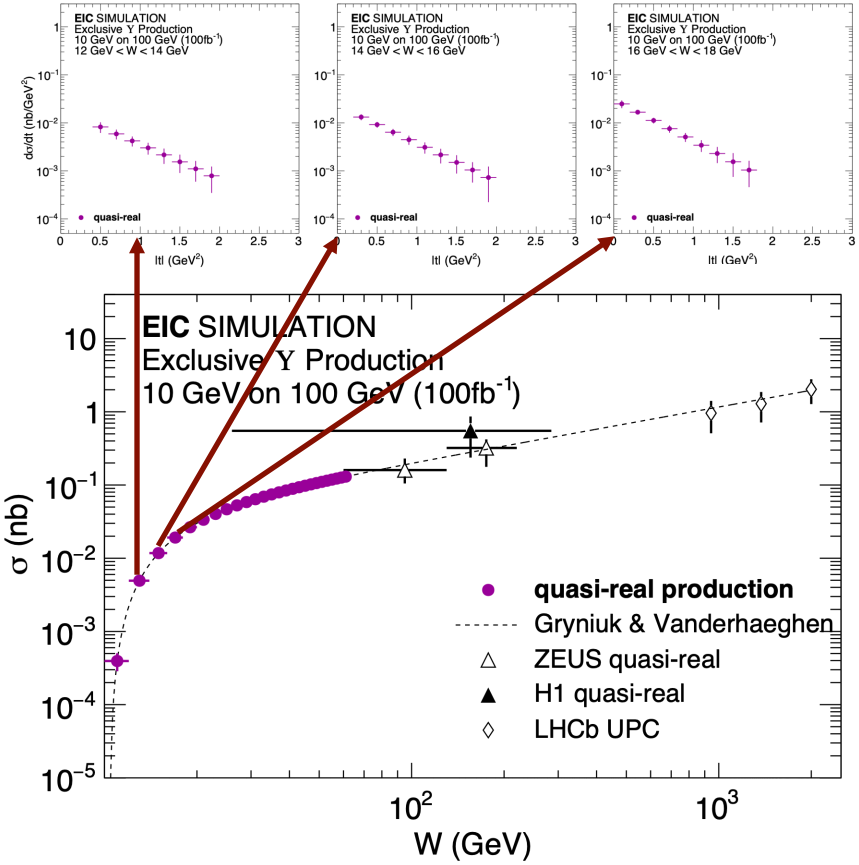
Future: Υ(1s) Near Threshold

Near-threshold quarkonium at EIC

- Υ(1S) at EIC trades statistical precision of J/ψ at SoLID for lower theoretical uncertainties and extra channel to study universality.
- Large Q^2 reach at EIC an additional knob to study production



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O. Grynyuk, S. Joosten, Z.-E. Meziani, M. Vanderhaeghen PRD 102, 014016 (2020)

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S. Joosten, GHP 2025
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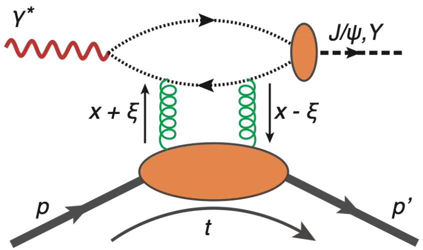
Future: Deeply-Virtual Quarkonium Production

Accessing the 3-D gluon structure



Hard scale: $Q^2 + M_V^2$

Modified Bjorken-*x*: $x_V = \dfrac{Q^2 + M_V^2}{2p \cdot q}$

average unpolarized gluon GPD related to *t*-dependent cross section (LO)

$$|\langle \mathcal{H}_g \rangle|(t) \propto \sqrt{\frac{d\sigma}{dt}(t) / \frac{d\sigma}{dt}(t=0)}$$

→

Fourier transform:
3-D transverse gluonic density

$$\rho(|\vec{b}_T|, x_V) = \int \frac{d^2\vec{\Delta}_T}{(2\pi)^2} e^{i\vec{\Delta}_T \vec{b}_T} |\langle H_g \rangle|(t = -\vec{\Delta}_T^2)$$

3-D GPDs can be related to 2-D Gravitational Form Factors

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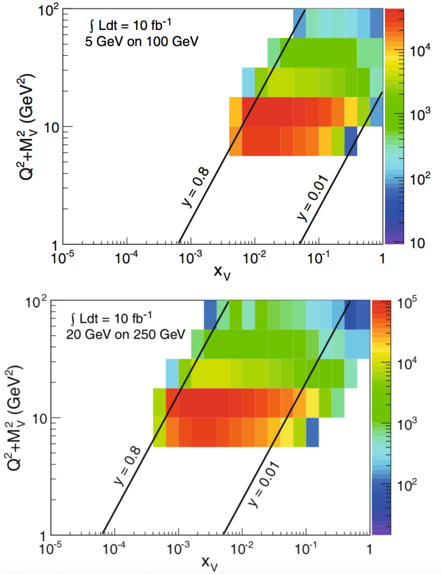
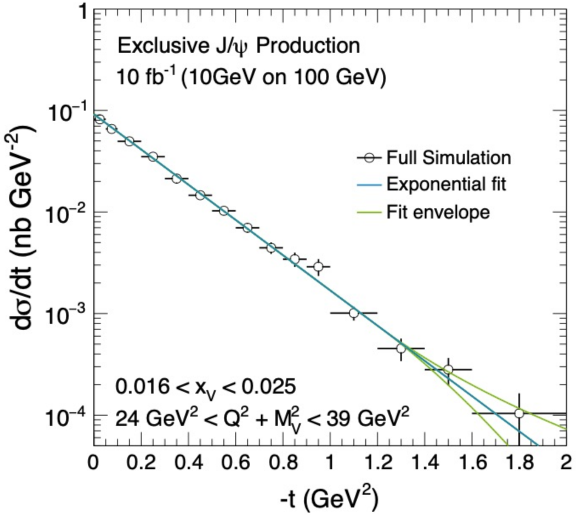
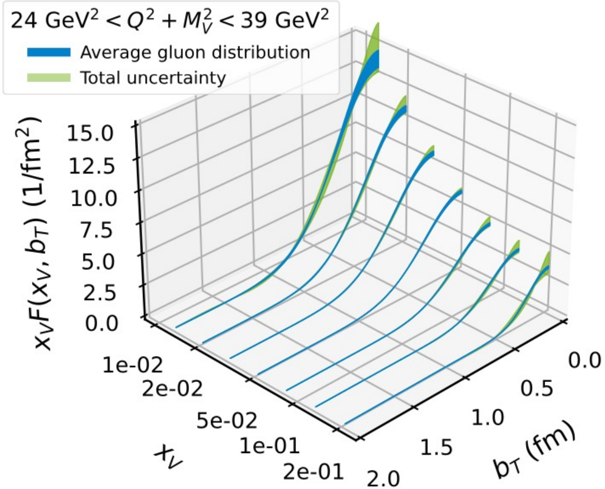
Future: Gluon Tomography at EIC

An Example







Only possible at an EIC:
from the valence region
deep into the sea!

t-spectra for each x_V-Q^2 bin → **Normalized average gluon density**

Eur.Phys.J.A 52 (2016) 9, 268
JINST 17 (2022) 10, P10019

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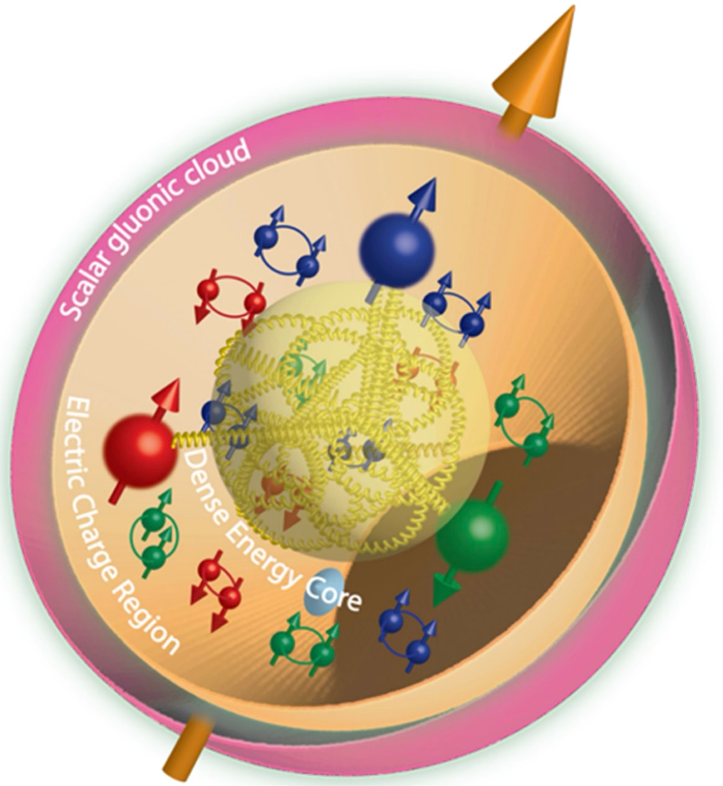
Conclusion

The JLab 12-GeV program has delivered important first results on near-threshold J/ψ production from GlueX and Hall C (J/ψ-007)

- A new window on the gluonic structure of the proton
- The proton appears to have a dense energy core
- What are the implications of a possible scalar gluonic cloud? Does the proton have a scalar gluon “skin”?

The planned near-threshold J/ψ production program at Jefferson Lab is crucial to further our understanding of the origin of mass.

- SoLID can reach J/ψ observables that cannot be achieved anywhere else, including precision measurements at high t and precision electroproduction near threshold.



The mass structure of the nucleons and nuclei is a rapidly evolving topic, reaching from Jefferson Lab to the EIC

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