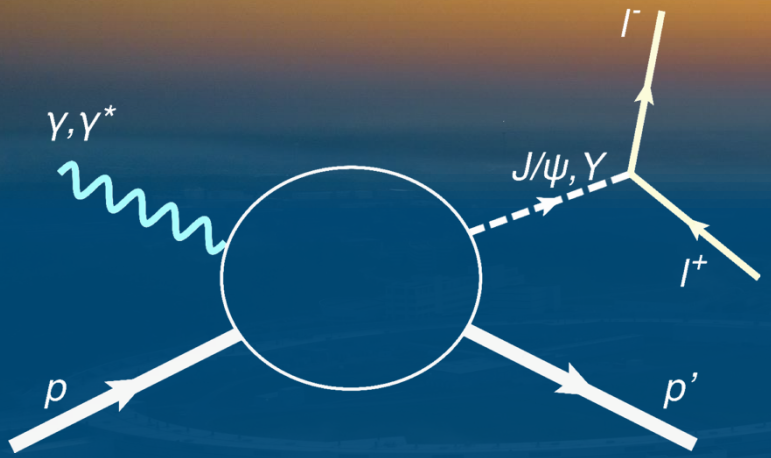
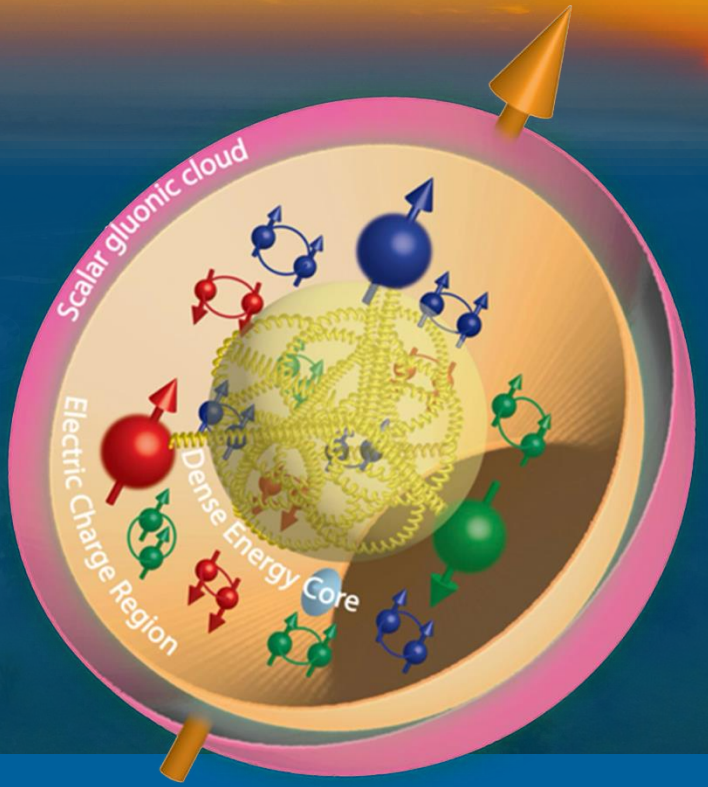


Gravitational Form Factors

And the Forces that Shape the Proton



Sylvester Joosten

With thanks to Xiangdong Ji, Yoshitaka Hatta, Henry Klest, Kiminad Mamo, Zein-Eddine Meziani, Dimitra Pefkou, and Ismail Zahed

CNF Seminar

February 26, 2026, Jefferson Lab

U.S. DEPARTMENT of ENERGY

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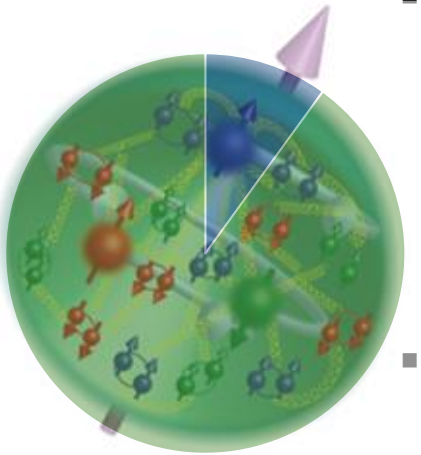
Argonne NATIONAL LABORATORY

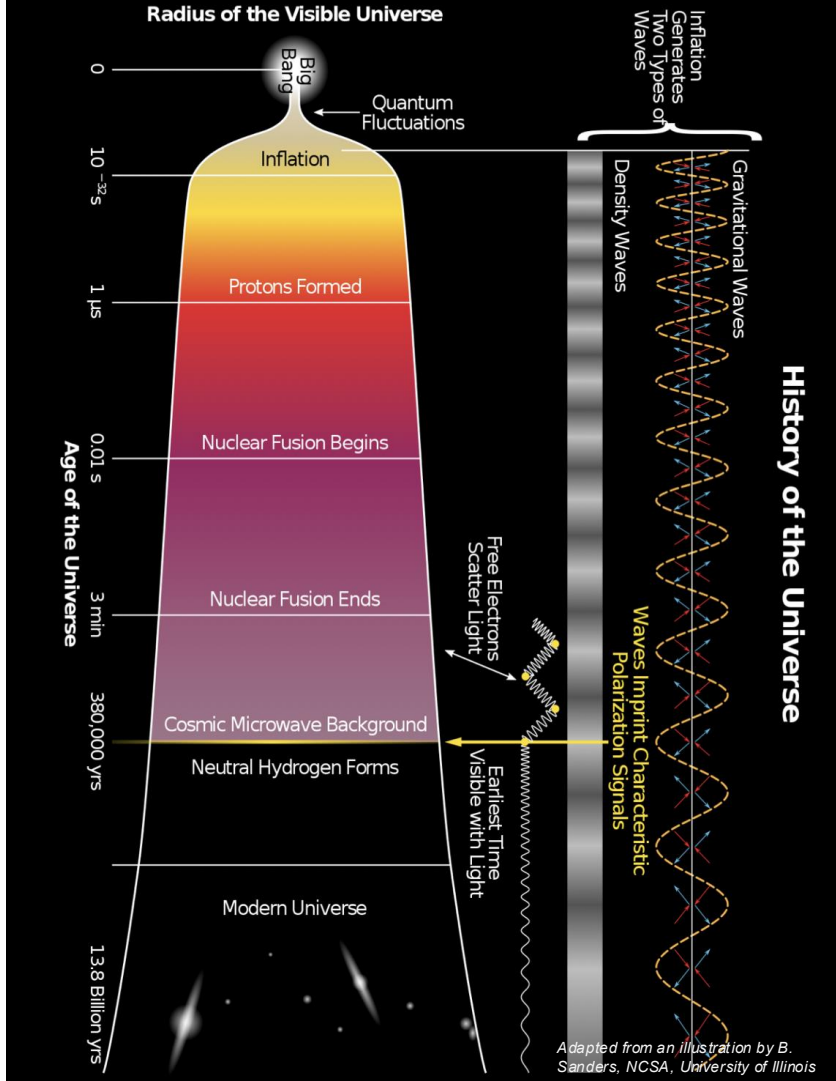
QCD in the Standard Model

The emergence of the proton



- 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?*



Why is the proton so heavy?

The proton mass is much larger than the sum of its quarks

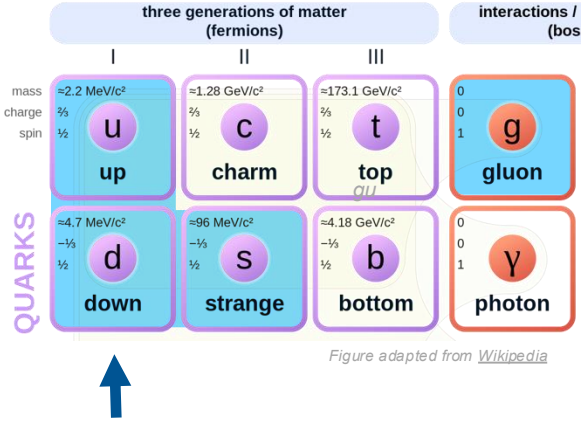
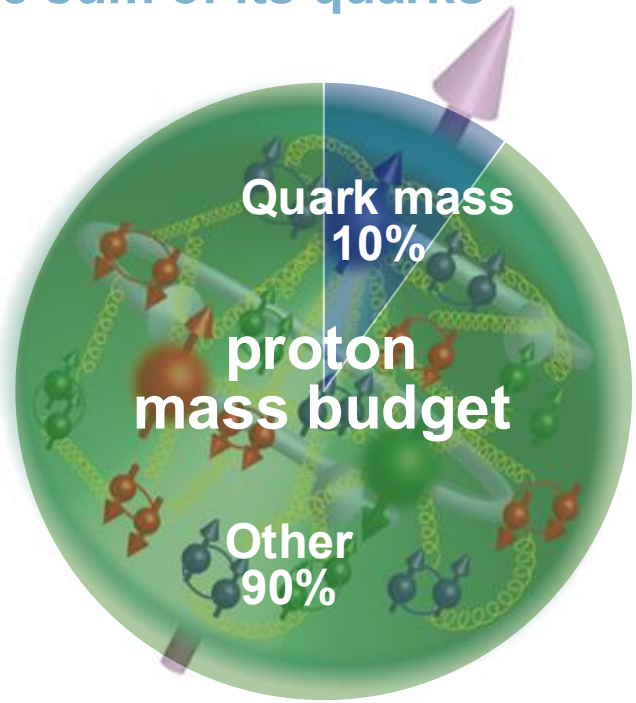


Figure adapted from Wikipedia

Gluons are **massless**

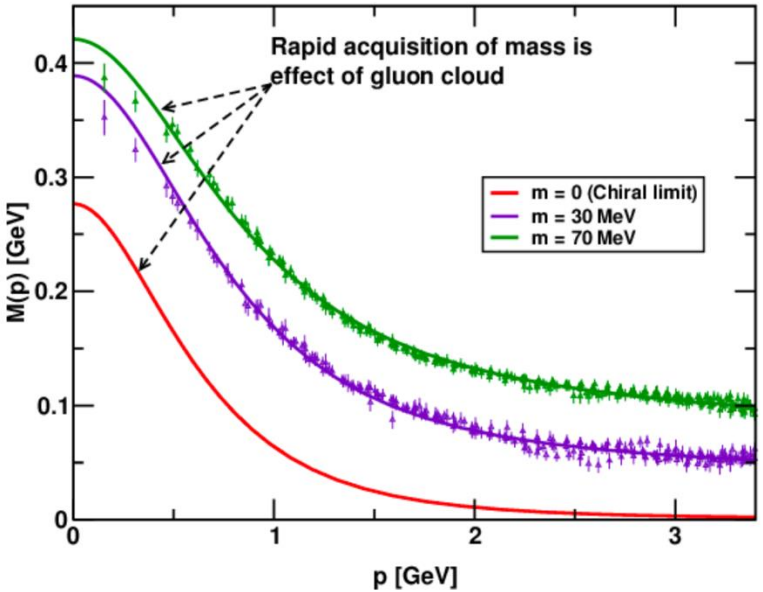
Up, down, and strange quarks are **light**



Protons are **heavy** (~ 938 MeV/c^2)

Proton mass is an emergent phenomenon

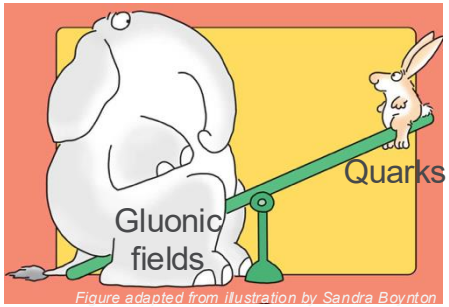
The Strong Interaction itself generates the proton mass!



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

$$E = mc^2$$

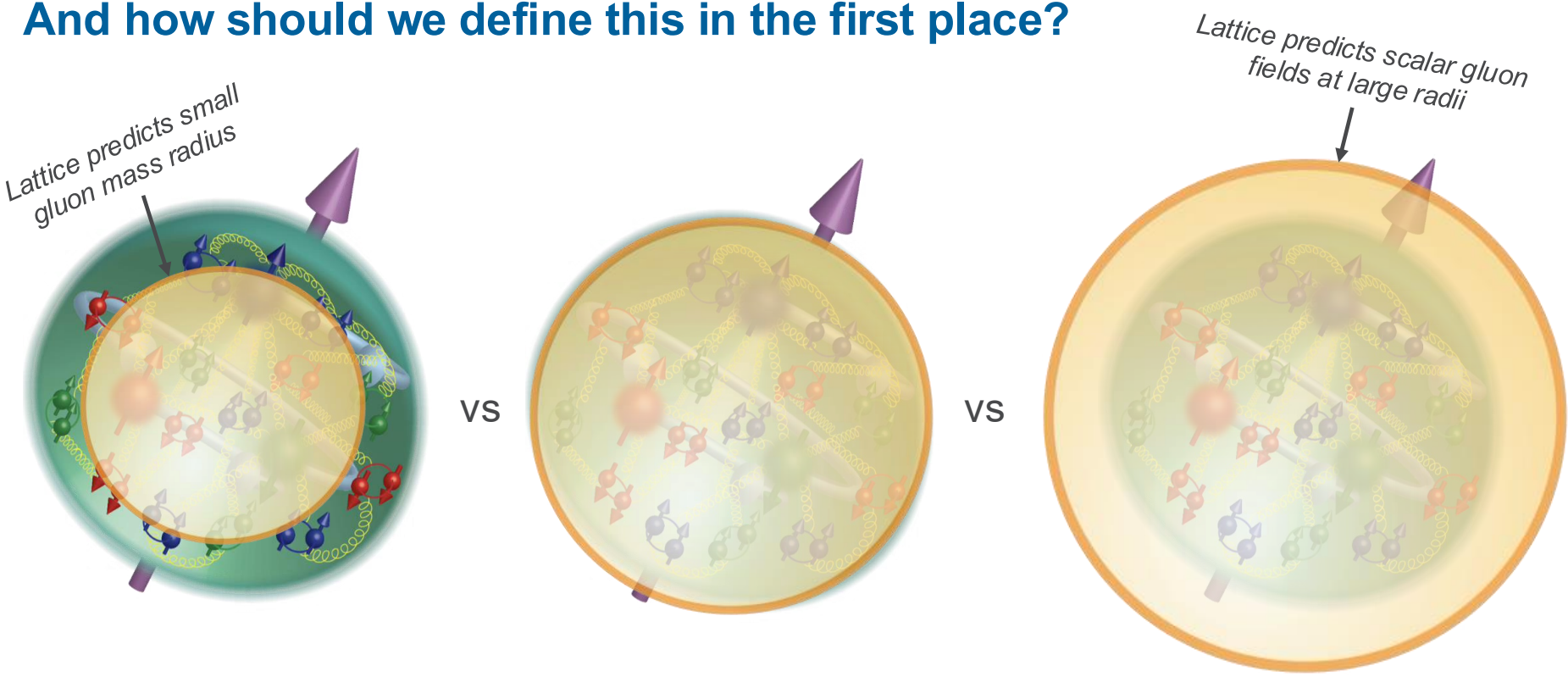


Bottom line: The Higgs mechanism seems largely irrelevant for most of "normal" visible matter!

Pefkou, Hackett, Shanahan, PRD 105 (2022) 054509
2107.10368

What Is the Size of a Proton?

And how should we define this in the first place?

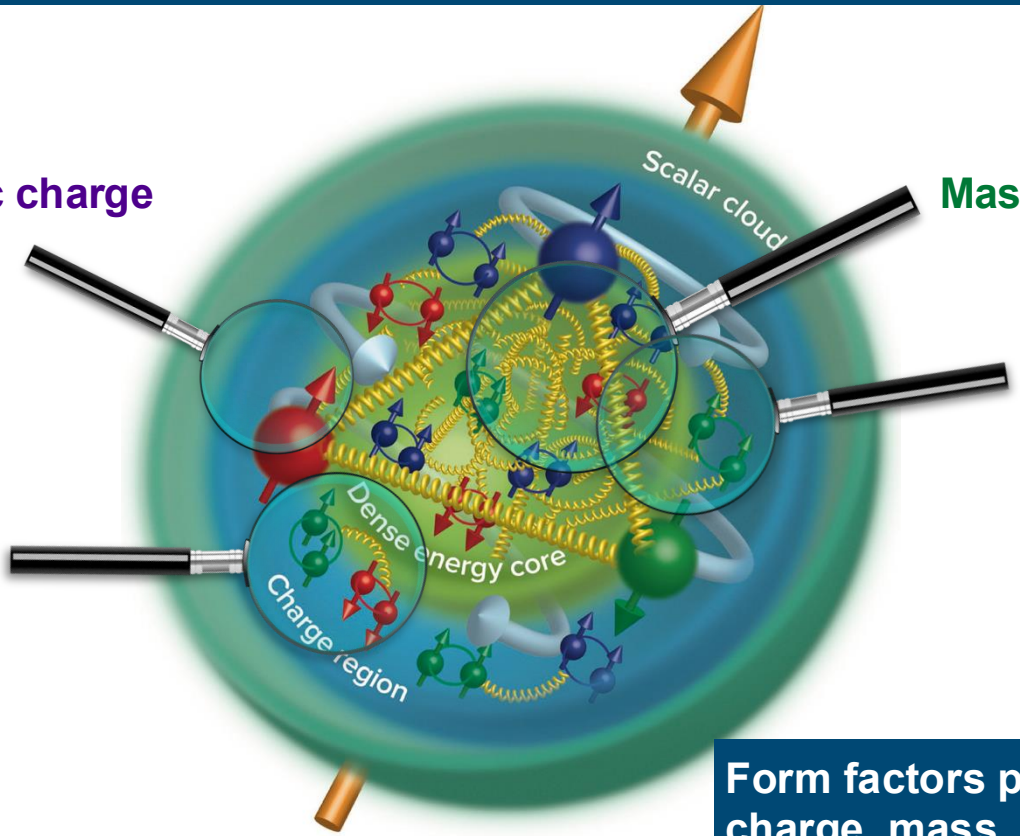


Dense energy core?

Same as charge radius?

Energy halo beyond charge radius?

Form factors: the proton in 2D



Electromagnetic charge

Mass

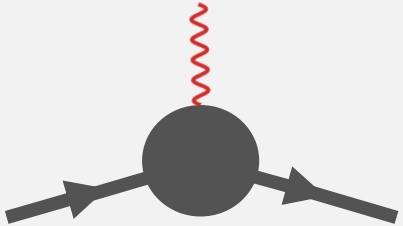
Mechanical structure and momentum current densities

Magnetization

Form factors provide a map of how charge, mass, and internal forces are distributed within the proton

Gravitational Form Factors (GFFs)

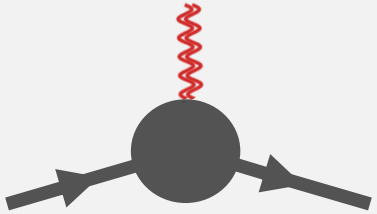
Electromagnetic FFs



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

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

Gravitational FFs



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

- GFFs parametrize 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, forces experienced by the quarks, …

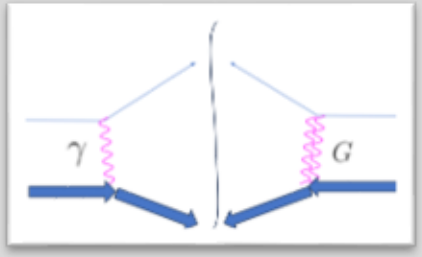
Measuring GFFs?

GFFs are not a new concept

- Introduced in the 60s
- As fundamental as EM form factors and arguably more informative
- Less ubiquitous only because we cannot measure them directly!
- One-graviton exchange **cross section is vanishingly small**

$$\frac{d\sigma}{dt} \sim G_N^2 \frac{s^2}{t^2} \qquad G_N \sim M_{Planck}^{-2} \sim 10^{-38}\,\mathrm{GeV}$$

- **Note:** Direct access may be possible in BSM scenarios with massive gravitons



  - A TeV-scale muon-ion collider would be highly sensitive beyond current collider and astrophysical bounds
  - Example observable: upward deviation from the QED prediction for elastic μ-p scattering due to through graviton-photon interference

Y. Hatta, PRD (2024), 2311.14470

$$D(t) \equiv 4C(t)$$

The quark D GFF and the pressures in the proton

Indirect measurement through DVCS

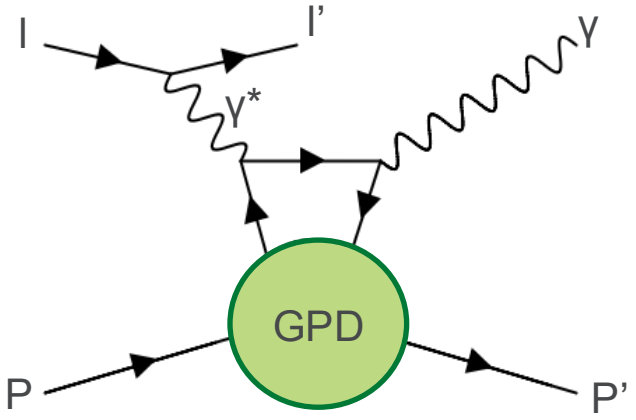
$D_i(t) \equiv 4C_i(t)$

Replacing the graviton with two photons

Based on Y. Hatta Talk at DNP2025

- Mimic a spin-2 exchange with two spin-1 photons?

$$1 + 1 = 2?$$



- Can be attempted for the quark D-term (alternative name for the C GFF)

$$D = D_u + D_d + D_s + D_g + \cdots$$

- Quark D-term related to dispersion relation for the Compton form factor (CFF) $\mathcal{H}_q$

$$\mathrm{Re}\mathcal{H}_q(\xi, t) = \frac{1}{\pi}\int_{-1}^{1} dx P \frac{\mathrm{Im}\mathcal{H}_q(x, t)}{\xi - x} + 2\int_{-1}^{1} dz \frac{D_q(z, t)}{1 - z}$$

$$D_q(t) \equiv \int_{-1}^{1} dz z D_q(z, t)$$

Teryaev (2005), hep-ph/0510031

Skewness ξ

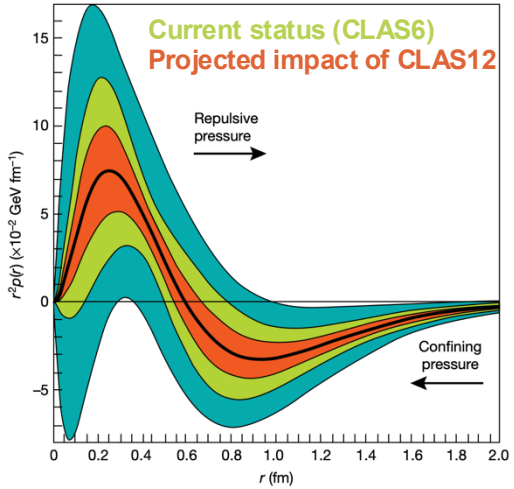
$$\xi \equiv \frac{P^+ - P'^+}{P^+ + P'^+}$$

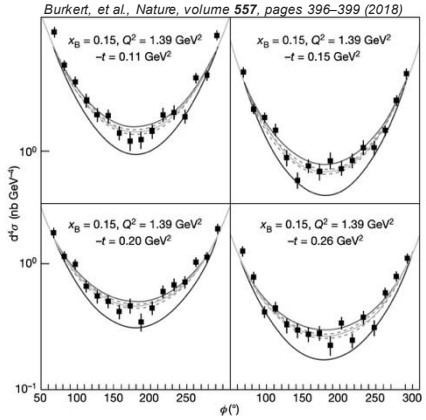
Results from DVCS

Mapping the internal pressure of the quarks

- The D-term from fits to DVCS data in leading order using a Gegenbauer expansion truncated to only its first term
  - Analysis involved fitting DVCS cross-sections and asymmetries from CLAS at Jefferson Lab
  - Primarily sensitive to valence quarks
- The extracted D-term can be related to a (Breit-frame) pressure profile inside the proton: Polyakov, Schweitzer, Int. . Mod Phys A (2018) 1805.06596
  - Repulsive pressure near the center, up to 10^{35} pascals.
- Interpretation:
  - A negative D-term is consistent with theoretical predictions
    - Burkert and collaborators argued that this confirms models of quark confinement and the stability of the proton's internal structure
  - **Open question**: how can we interpret these results without considering the role of gluons?

Burkert, Elouadrhiri, Girod, Nature 557 (2018) 396





For broader stress-tensor interpretation in QFT and many-body systems: Nielsen & Martin, PRB 32 3780 (1985); Lorcé & Schweitzer (2501.04622)

Caveat on Accessing GFFs through CFFs

A graviton isn't quite the same as two photons

Based on Y. Hatta Talk at DNP2025

$$\frac{1}{1-z} = 1 + z + z^2 + z^3 + \cdots$$

Spin-2 (EMT) — Spin-4

$$\int_{-1}^{1} dz \frac{D_q(z,t)}{1-z}$$

What we measure

$$D_q(t) \equiv \int_{-1}^{1} dz z D_q(z,t)$$

What we need

- Two-photon state couples to operators with arbitrary spin, making it impossible to formally isolate the spin-2 component…
- Truncating the expansion at $n = 1$ is unreliable, as higher-n terms (and NLO contributions) produce large uncertainties

Dutrieux, Meisgny, Mezrag, Moutarde
EPJC (2025) 2410.13518

$$1 + 1 = \text{anything}$$

Gluon GFFs
and the mass structure of the proton

How do we measure the structure of nucleons and nuclei beyond electric charge?

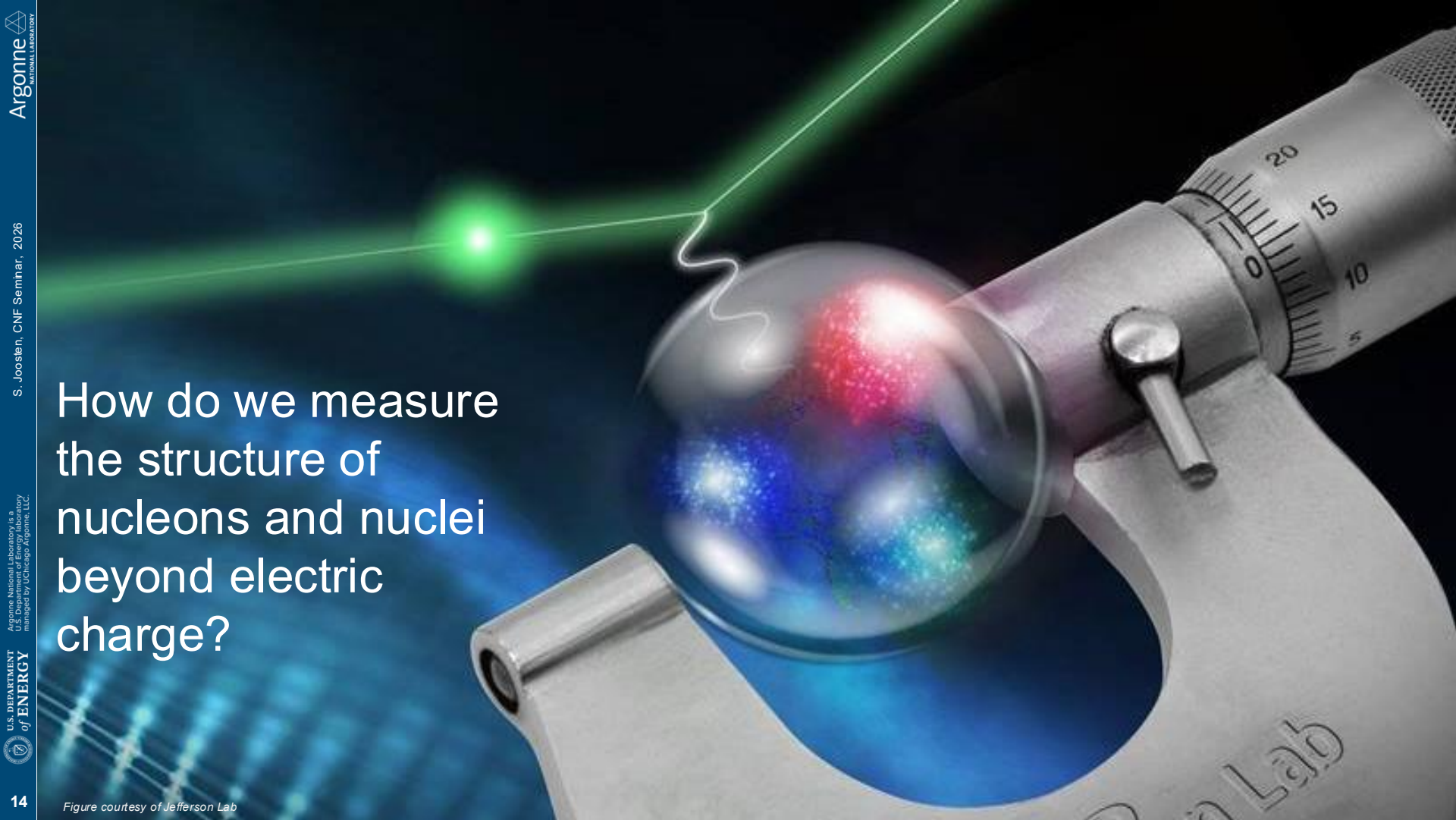
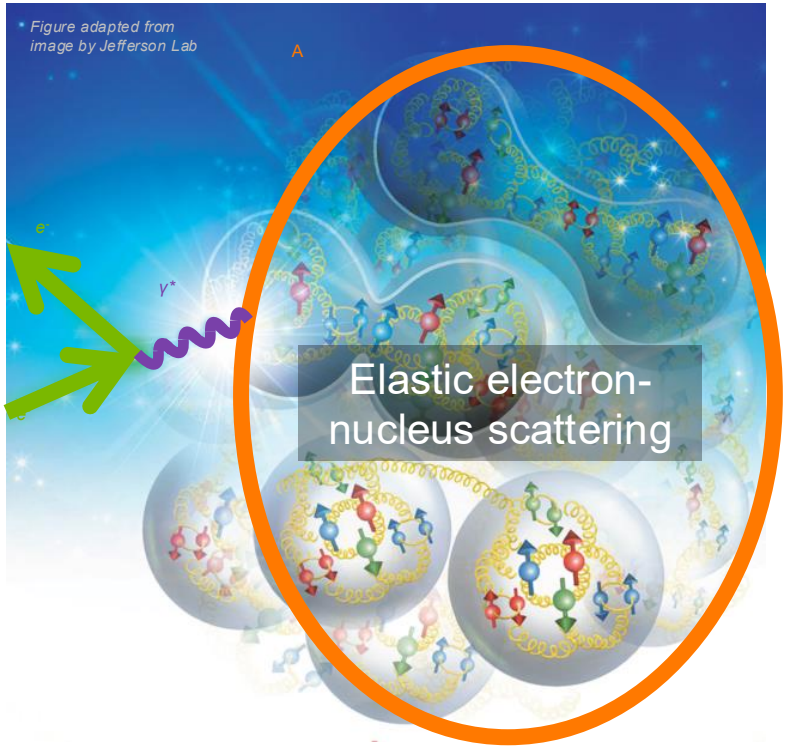


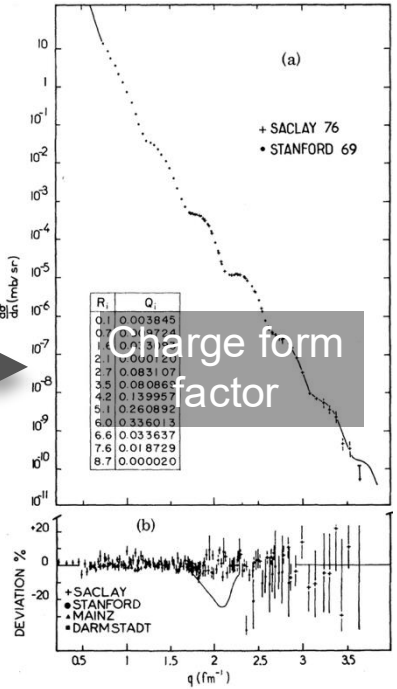
Figure courtesy of Jefferson Lab

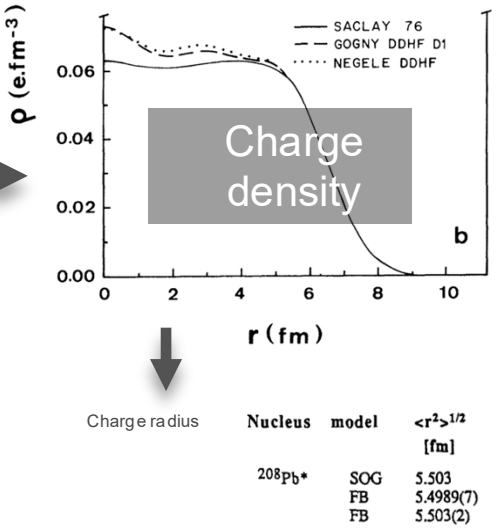
B. Frois, *et al*, Phys. Rev. Lett. **38**, 576 (1977)
H. De Vries, *et al*, Atomic Data and Nuclear Data Tables 36, 495 (1987)

Charge density through electron scattering

Example: The charge density of ^{208}Pb







Electric charge structure

Electric charge structure is easily measured through electron scattering (electromagnetic probe)

Image by Zdenek Sasek

Matter structure

The structure of objects without electric charge (gluons in the proton, neutrons in a nucleus) is much harder to study with electron scattering.

For the case of the neutron structure of ^{208}Pb, this has been accomplished by leveraging the Weak Interaction.

Accessing the neutrons in lead-208

Weak charge of protons heavily suppressed compared to neutrons.

Parity-violating scattering sensitive to the weak form-factor of the nucleus.

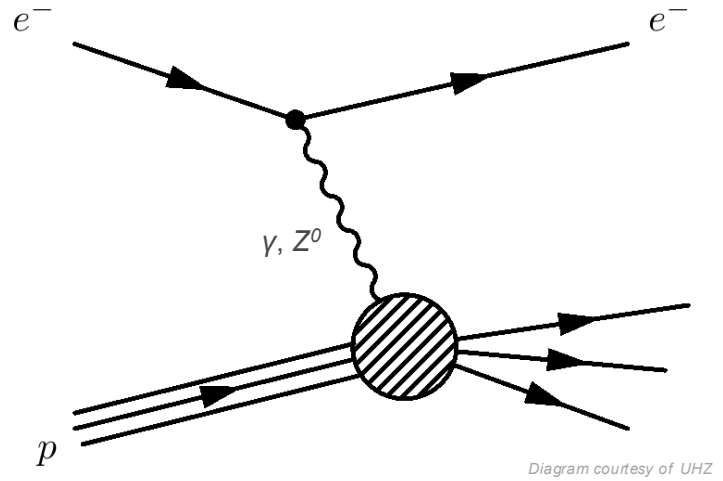
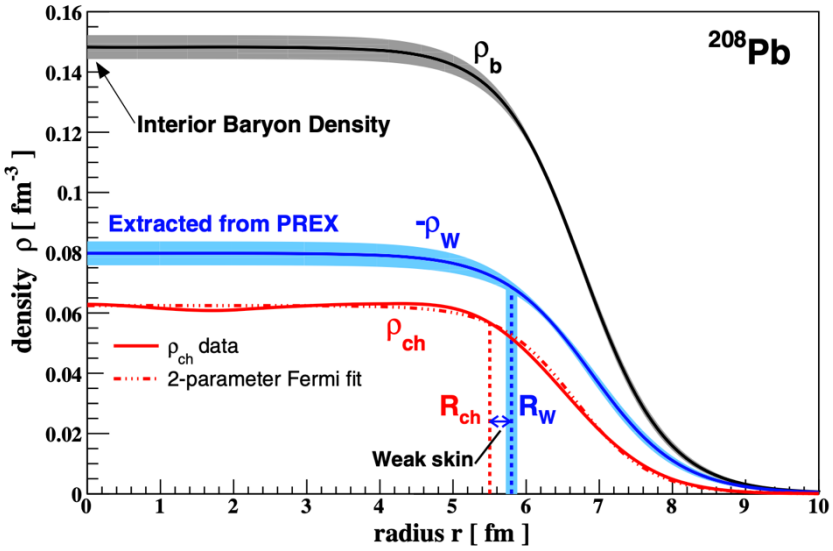


Diagram courtesy of UHZ

$$A_{\mathrm{PV}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx \frac{G_F Q^2}{4\pi\alpha\sqrt{2}} \frac{Q_W F_W(Q^2)}{Z F_{\mathrm{ch}}(Q^2)}$$

Nuclear theory predicts a neutron “skin” on heavy nuclei, which implies a neutron radius that extends beyond the charge radius.

The neutron skin of lead-208



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

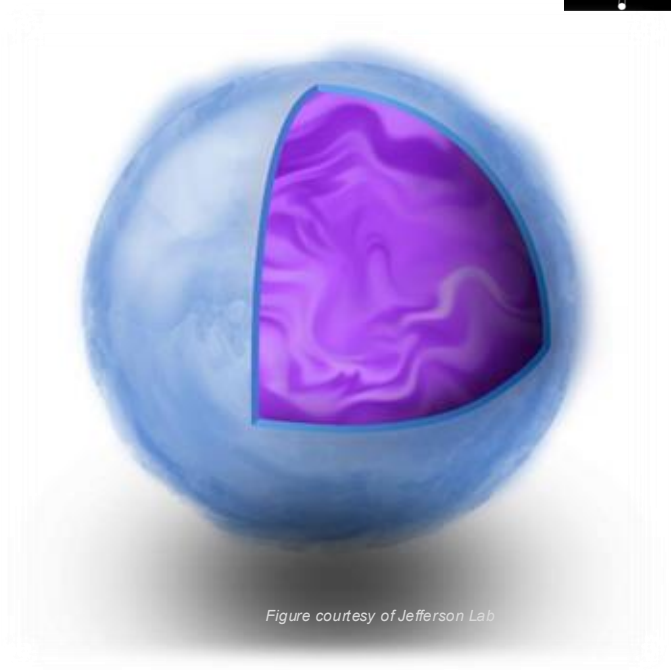


Figure courtesy of Jefferson Lab

How To Measure the Gluon GFFs?

Gluons are elusive!

- Cannot use Electromagnetic probe: primarily couples to quarks
- Cannot use Weak probe: also primarily couples to quarks
- Cannot use hadronic probe made of light quarks: primarily sensitive to quark structure
- Cannot use direct gravitational probe: interaction too weak

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- Small “color” dipole made of heavy quarks well-suited to study gluons

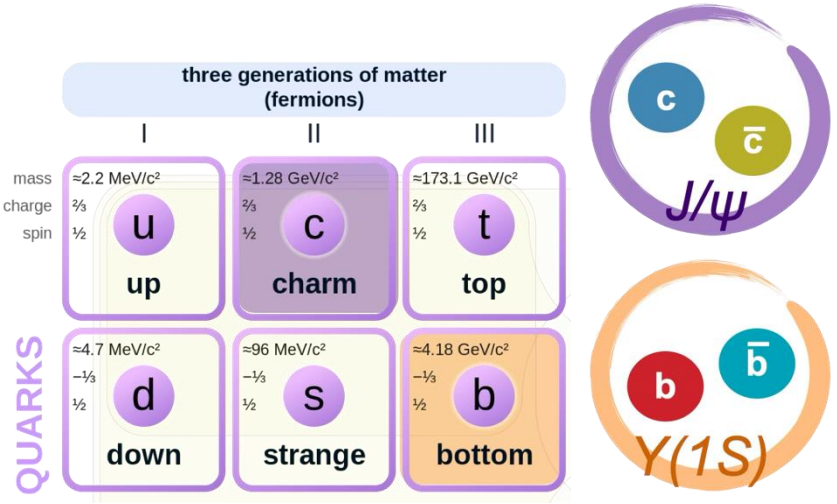

Figure adapted from Wikipedia

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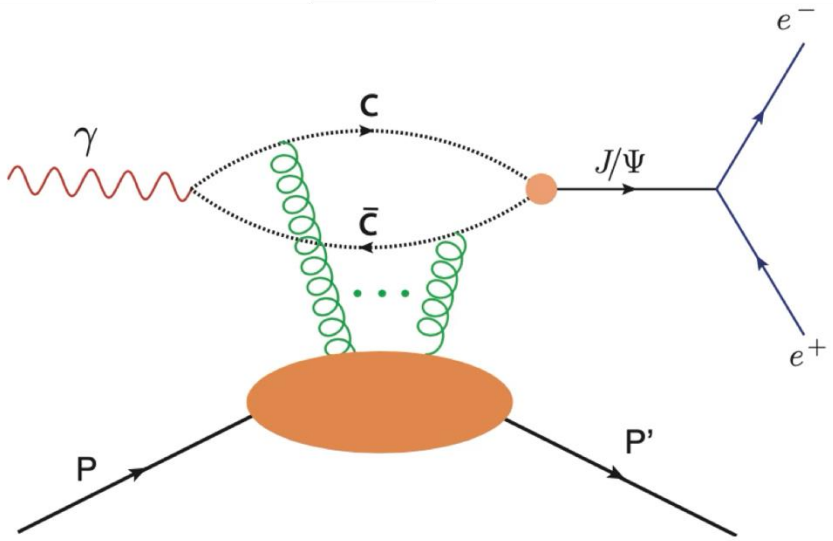


Use quarkonium photoproduction as stand-in for elastic quarkonium scattering

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

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

Quarkonium Photoproduction Near Threshold

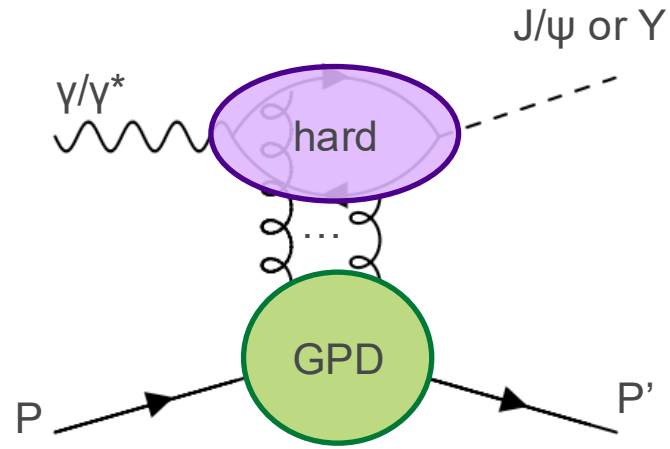
More Formally (GPD/pQCD approach)

What we measure

$$\int_{-1}^{1} \frac{dx}{x}\left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right)\mathcal{H}_g(x,\,\xi,\,t)$$

What we need

$$\int_{-1}^{1} dx\,\mathcal{H}_g(x,\,\xi,\,t) = A_g(t) + 4\xi^2 C_g(t)$$



- This is the same "problem" as the case for linking DVCS to the D-term?
- Important difference: skewness parameter ξ is tunable (large near threshold!)
- Conformal partial wave expansion is a **good approximation** for $\xi \to 1$ for gluon and strangeness GPDs (but not light quarks), has been shown in LO and NLO!

Hatta, Strikman PLB (2021) 2102.12631
Guo et al., PRD (2021) 2103.11506
Guo etal., PRD (2024) 2308.13006
Guo et al. PRL (2025) 2501.10532
Hatta, et al., PTEB (2025), 2501.12343
Hatta, Schoenleber, PRL (2025) 2502.12061

- Alternative non-perturbative approach through Holographic QCD

Mamo, Zahed PRD (2021) 2103.03186
Mamo, Zahed PRD (2022) 2204.08857

From GFFs to Mass Structure

- Mass (energy) form factor is related to the (0,0) component of the EMT:

$$\langle P' \mid T^{00} \mid P \rangle \sim G_m(t)$$

$$G_m(t) = M\left[A(t) + \frac{t}{4M^2}B(t) - \frac{t}{M^2}C(t)\right]$$

- In the Breit frame, its Fourier Transform gives an energy density. The RMS for zero momentum transfer ($t = 0$) is the mass radius $\sqrt{\langle r_m^2 \rangle}$ of the proton.

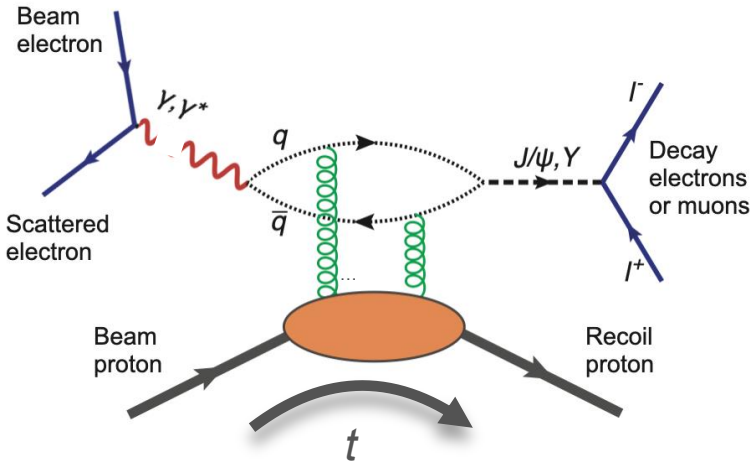
$$\langle r_m^2 \rangle \equiv \frac{\int d\vec{x} x^2 G_m(\vec{x})}{\int d\vec{x} G_m(\vec{x})}$$

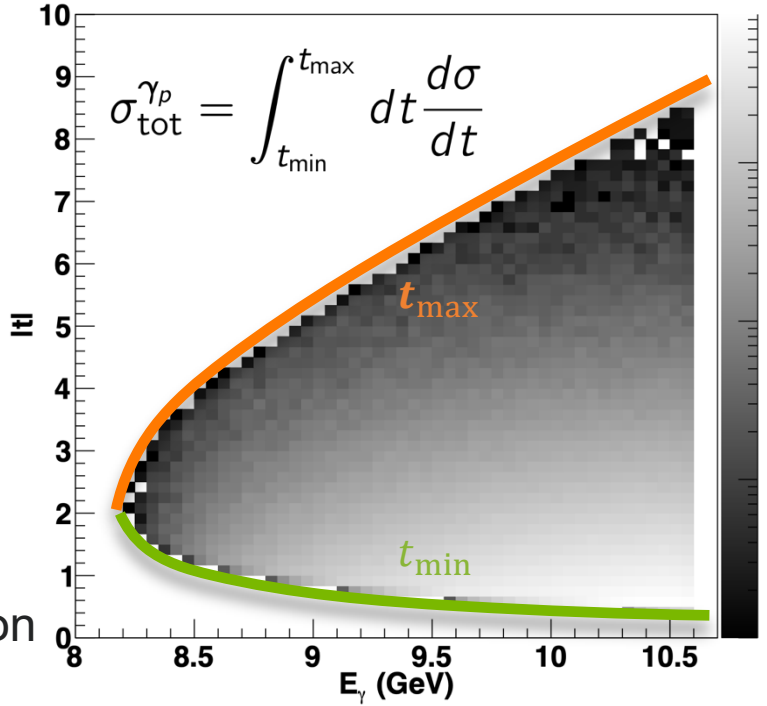
$$= 6\frac{dA(t)}{dt}\Big|_{t=0} - 6\frac{C(0)}{M_N^2}$$

Depends on slope and intercept of the GFFs at $t = 0$

Exclusive Quarkonium Photoproduction

Kinematics





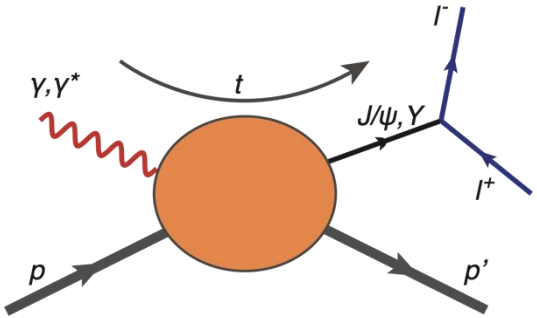
- Phase space limits bound by quarkonium direction
  - Forward (with photon): $t = t_{\min}$
  - Backward (with proton): $t = t_{max}$
- Forward direction preferred
  - $|t|$-dependence falls rapidly (exponential-like)

J/ψ threshold:
$W \approx 4.04$GeV
$E_\gamma^{lab} \approx 8.2$GeV

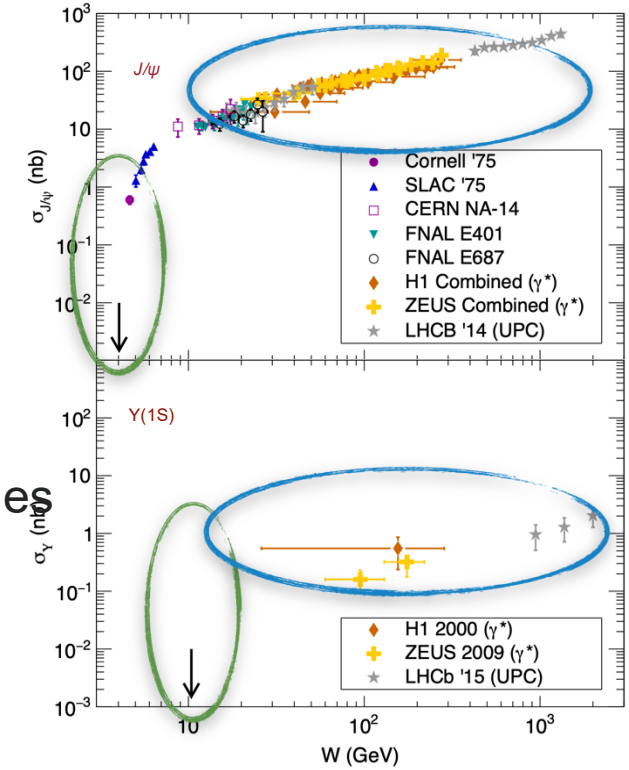
Υ(1S) threshold:
$W \approx 10.4$GeV

Exclusive Quarkonium production

Before 2019…



$$\sigma_{\text{tot}}^{\gamma p} = \int_{t_{\text{min}}}^{t_{\text{max}}} dt \frac{d\sigma}{dt}$$



- J/ψ photoproduction only constrained at higher energies
- Y(1S): not much available
- Electroproduction almost completely unconstrained
- **Almost no data near threshold**

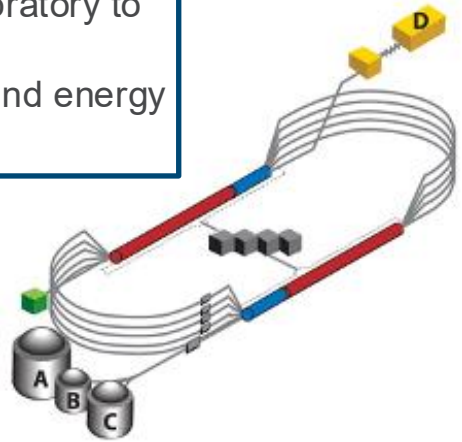
Quarkonium at Jefferson Lab and EIC

Jefferson Lab

CEBAF: very high luminosity (10^{35}-10^{39} $cm^{-2}s^{-1}$) continuous electron beam on fixed target

4 experimental halls:
- ~11GeV in Hall A, B &C
- ~12GeV in Hall D

Jefferson Lab is the ideal laboratory to measure J/ψ near threshold,
due to luminosity, resolution and energy reach



Electron-ion Collider

EIC: high luminosity (10^{33}-10^{34} $cm^{-2}s^{-1}$) polarized electron polarized ion collider

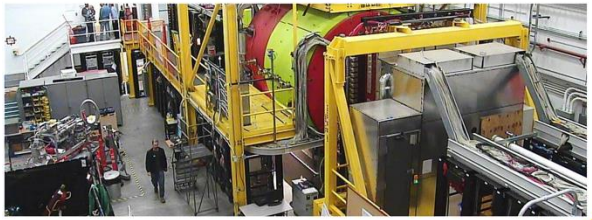
Variable CM energies: 29-140 GeV with 2 possible interactions regions

Ideally suited to study to J/ψ electroproduction at higher energies, sufficient energy and luminosity to produce Υ(1S).

Complementary programs: Jefferson Lab is the ideal laboratory to access GFFs with J/ψ production, and EIC has sufficient luminosity and energy for 3-D gluonic imaging.

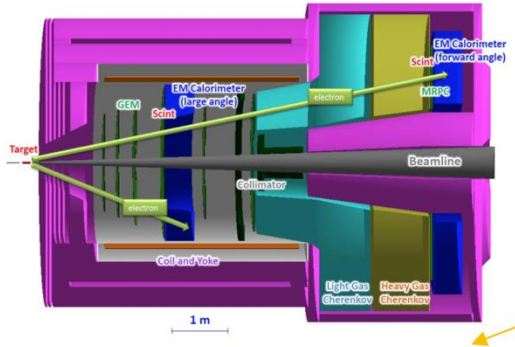
Figures courtesy of BNL (top) and Jefferson Lab (bottom)

12 GeV J/ψ Experiments at Jefferson Lab

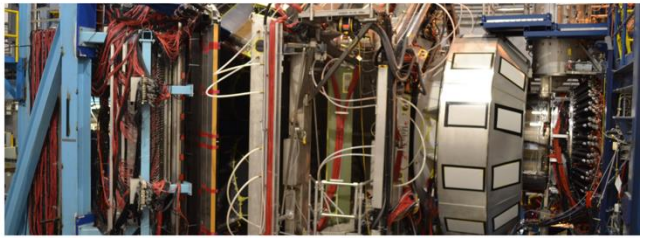


Hall D - GlueX observer the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)

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**



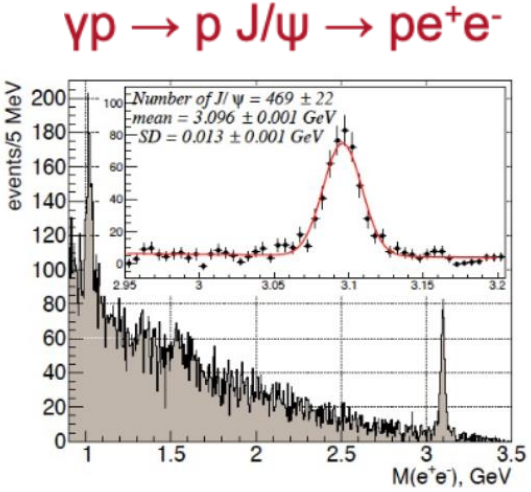
Hall B - CLAS12 has experiments to measure TCS + J/ψ in photoproduction as part of Run Groups A (hydrogen) and B (deuterium): E12-12-001, E12-12-001A, E12-11-003B

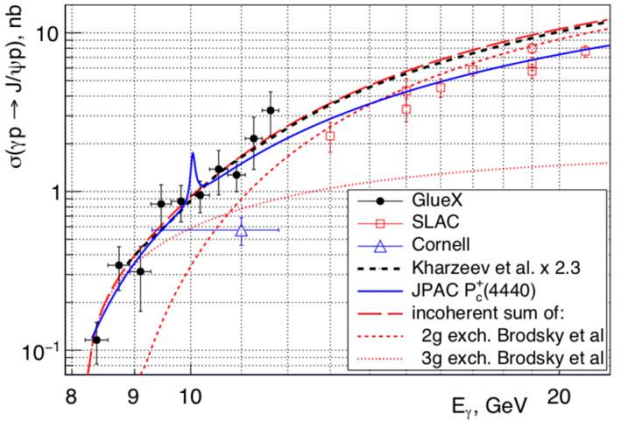
Pictures and figures courtesy of Jefferson Lab

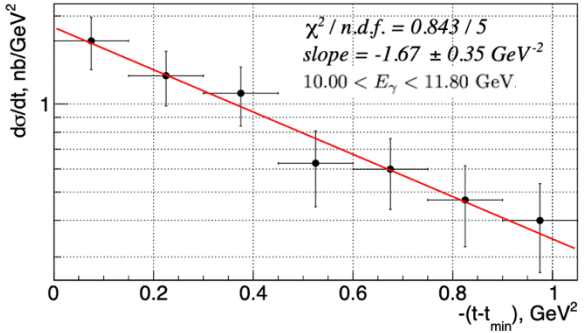
J/ψ near threshold in hall D

First J/ψ results from JLab, published in PRL 123, 072001 (2019)

- 1D cross section (~469 counts)
- Trends significantly higher than old measurements
- Single 1D t-profile spurred on many new theoretical calculations
- Did not see evidence for hidden-charm pentaquarks



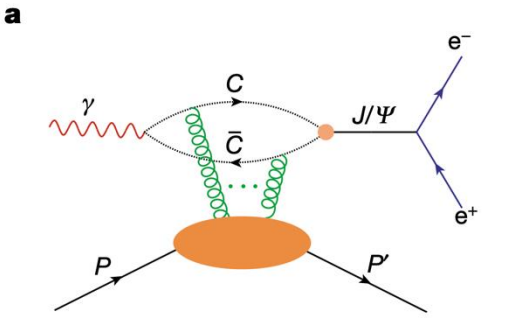


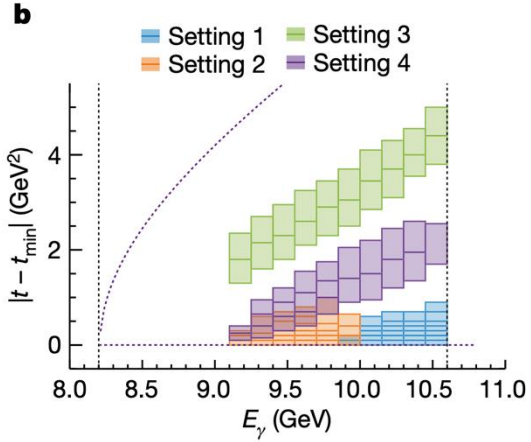


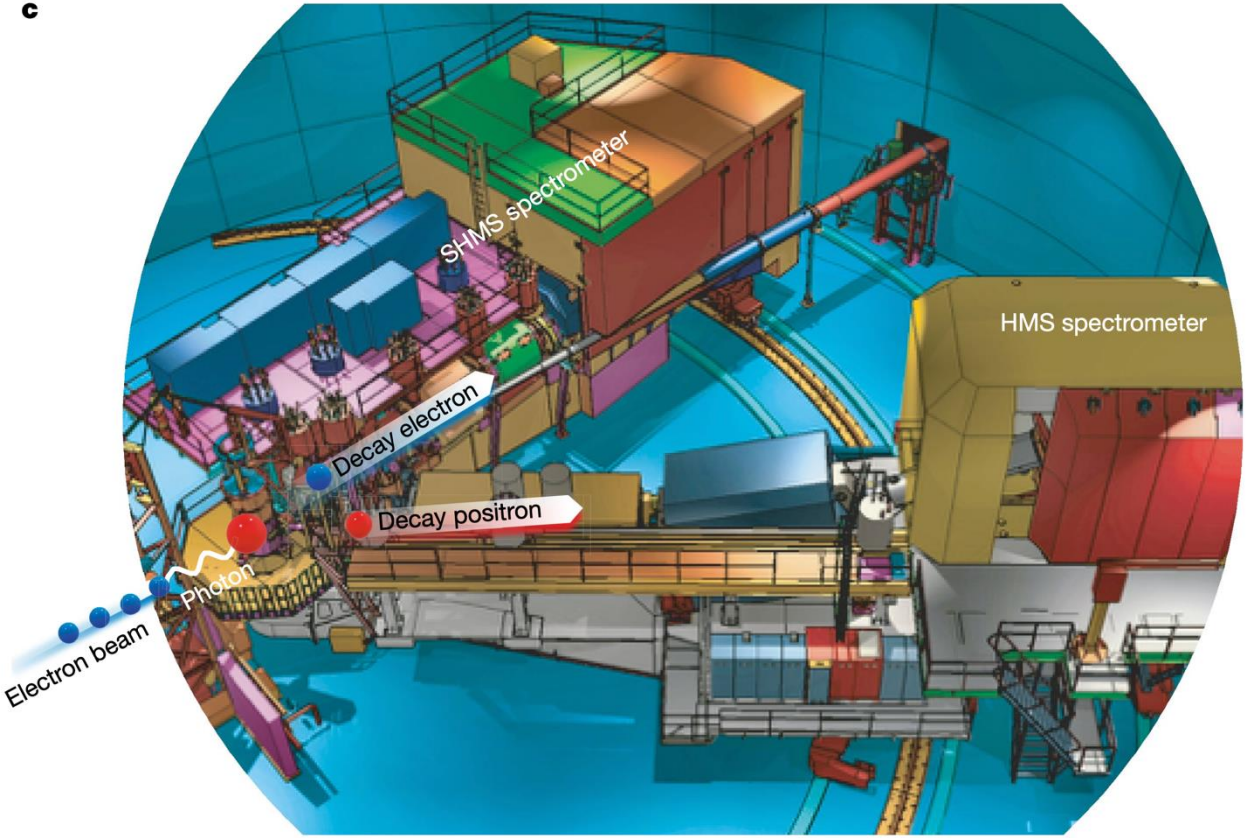
B. Duran *et al.*, Nature volume 615, pages 813–816 (2023)

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

Near-threshold J/ψ photoproduction



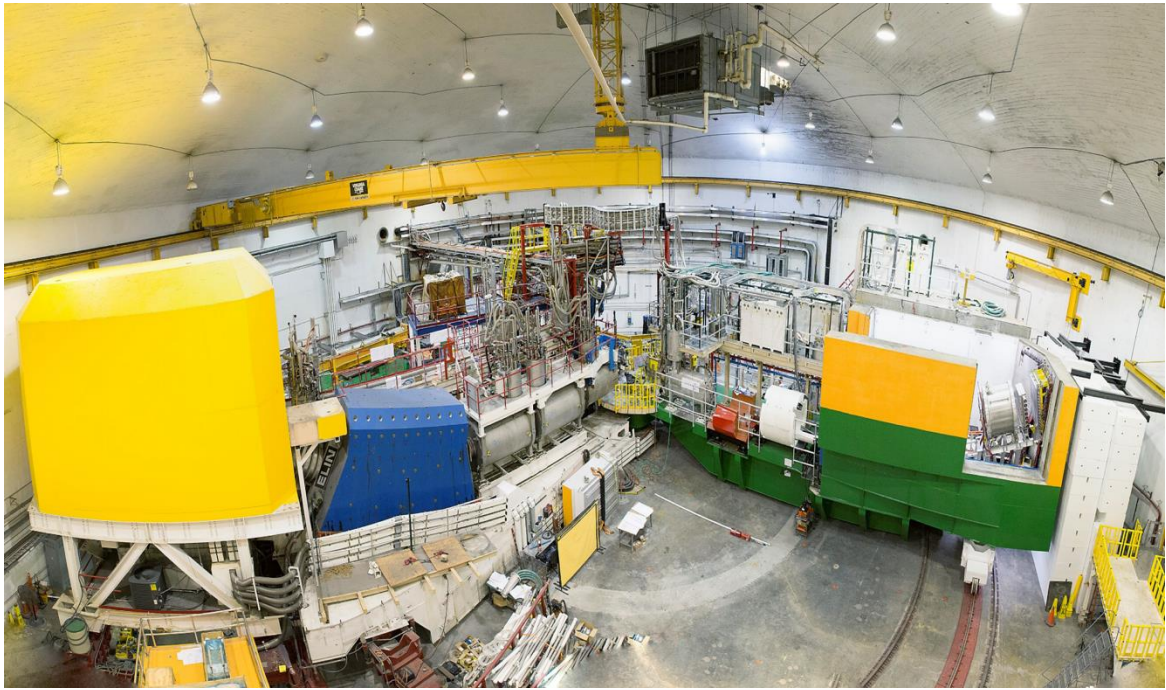




B. Duran *et al.*, Nature volume 615, pages 813–816 (2023)

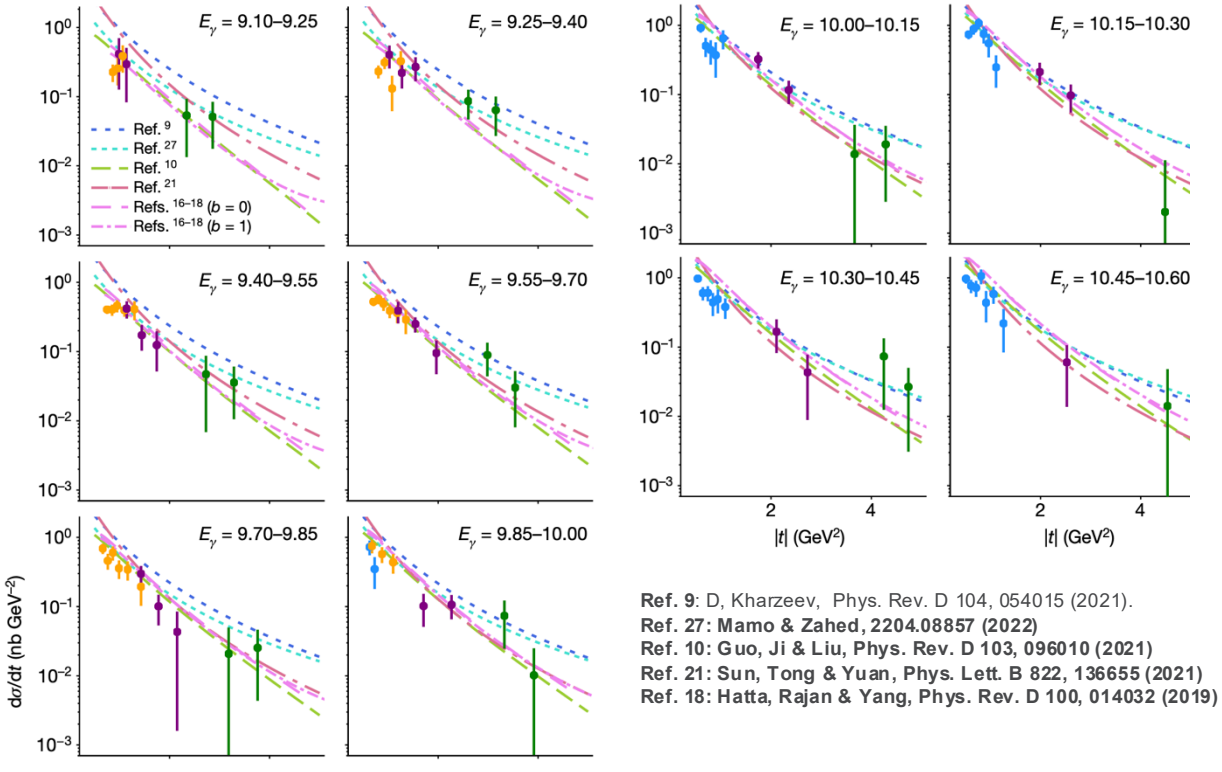
Jlab experiment E12-16-007

J/ψ-007: Search for the LHCb Pentaquark

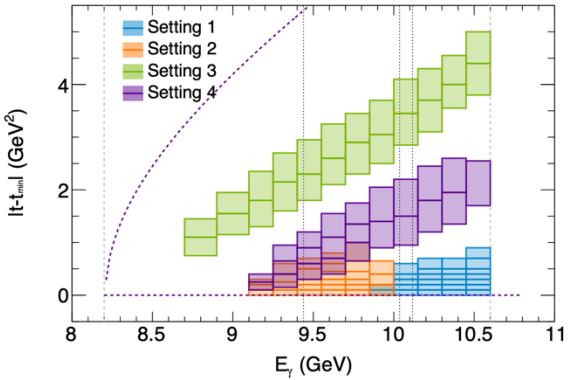


2-D J/ψ cross sections near threshold

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

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 does not meaningfully impact our results

Holographic Model

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

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

$\mathcal{N}$ is normalized to the previous World Data (not given by the model)

GPD Model

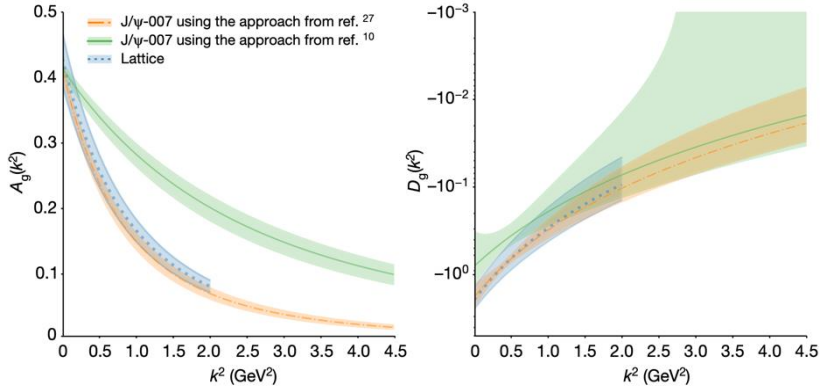
Y. Guo, X. Ji, Y. Liu, PRD 103, 096010 (2021)

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

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

First Gluonic GFFs from Experimental Data

Remarkable agreement between GFFs from data using the Holographic approach and Lattice QCD calculations!



Determined from experiment

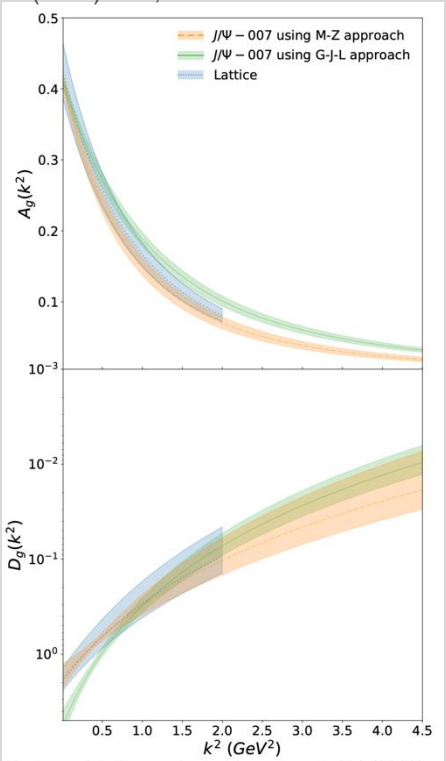
Holographic QCD approach
GPD approach

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).

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

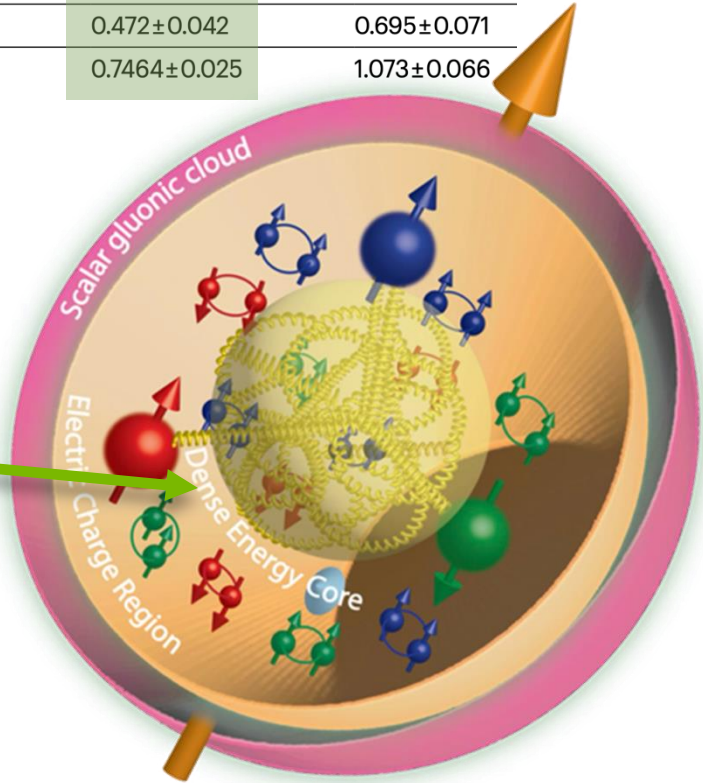


The Proton has a Dense Core?

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 is substantially smaller than its charge radius.



S. Adhikari et al. (GlueX), Phys. Rev. C 108, 025201 (2304.03845)

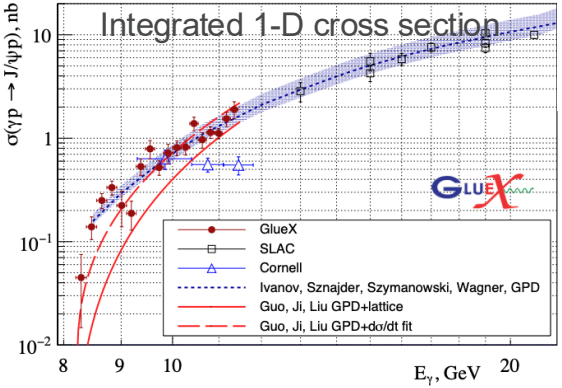
2023 Gluex Results

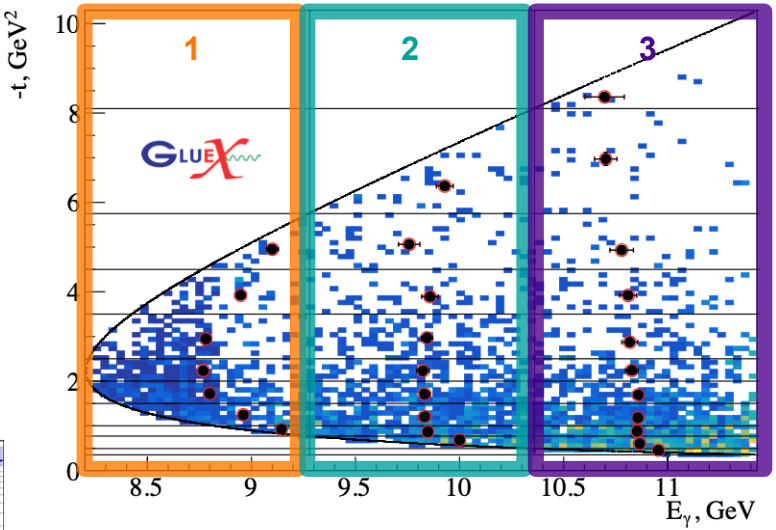
2.2k J/ψ (~ same as J/ψ-007 e+e- results)

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

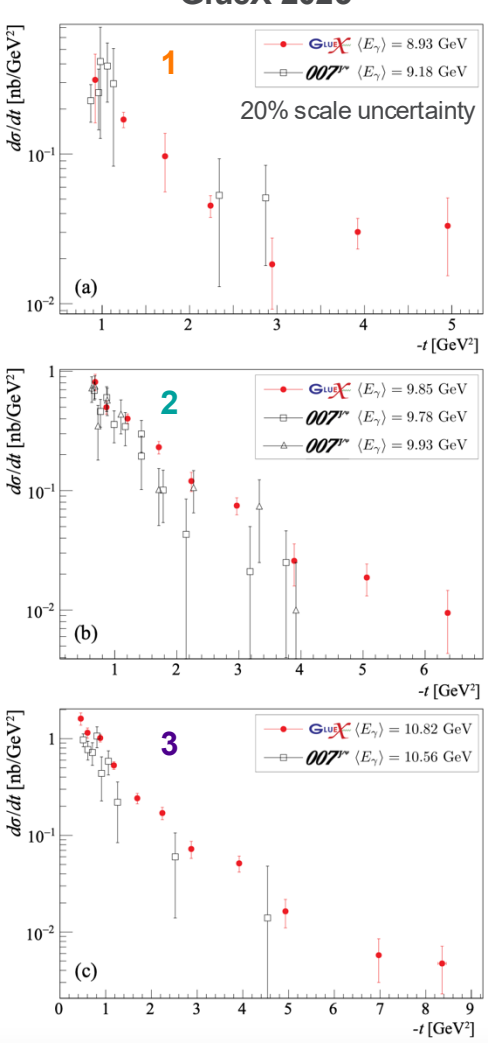
(compared to 10 E_γ slices E_γ ~ 9.1 - 10.6 GeV for J/ψ-007)

New GlueX results have 20% scale uncertainty.

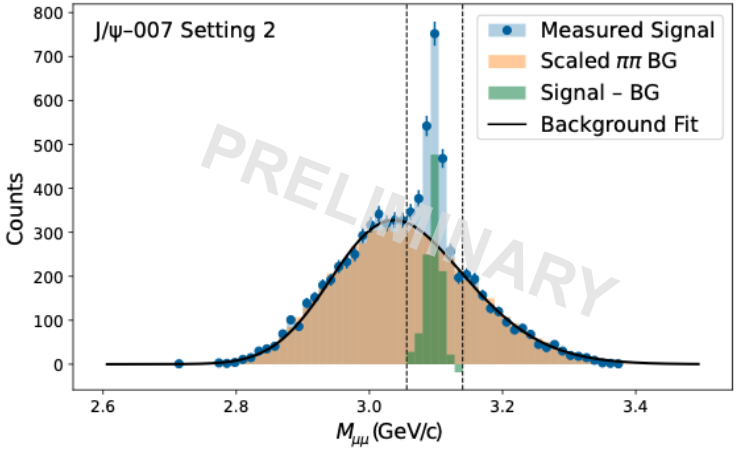


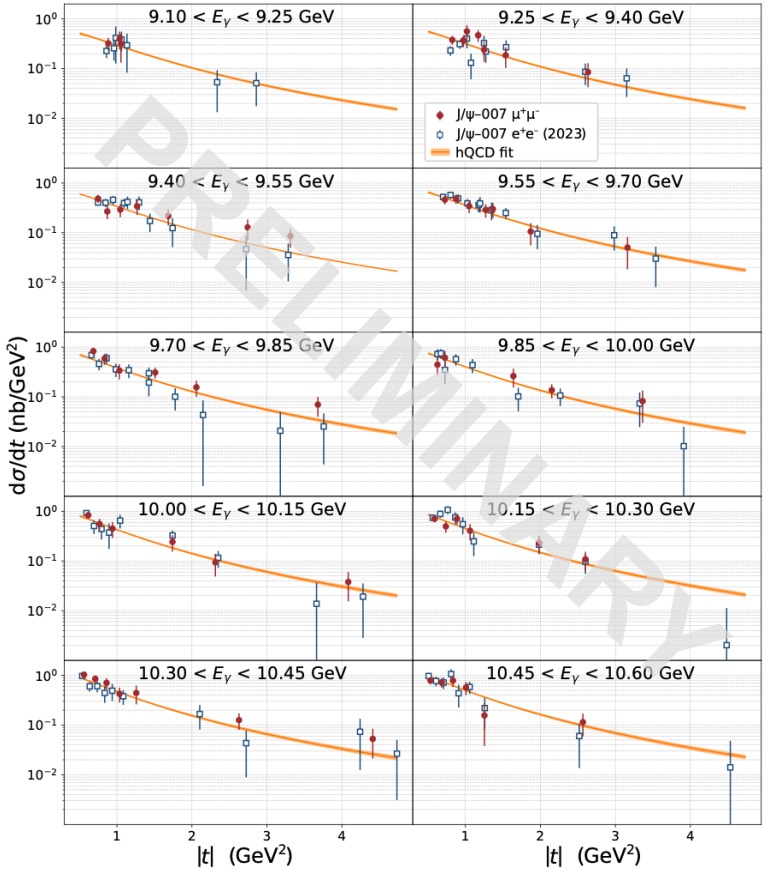


Good agreement within errors with between GlueX and J/ψ-007



Upcoming results from J/ψ-007
Di-muon channel cross section



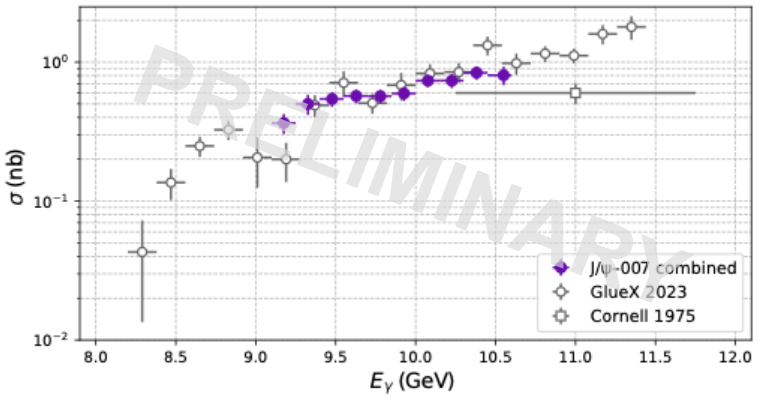


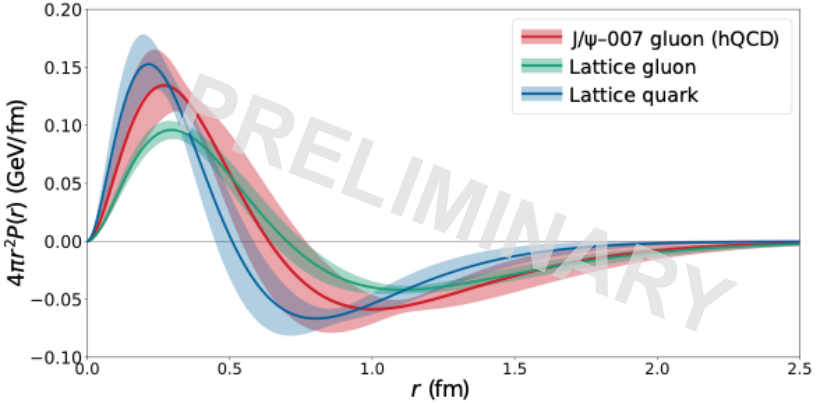
- Near-threshold J/ψ di-muon channel photoproduction cross section
- Results double the available statistics from J/ψ-007
  - Both dataset in excellent agreement
- **Manuscript currently under peer review**

SJ et al., 2602.14416 (2026, preprint)

Upcoming results from J/ψ-007

Integrated cross section and gluonic pressure





- Integrated cross section through fit of the t-dependence of combined J/ψ-007 data
  - Consistent with GlueX 2023 results
  - No evidence of fluctuations indicative of open-charm contributions
- **Manuscript currently under peer review**

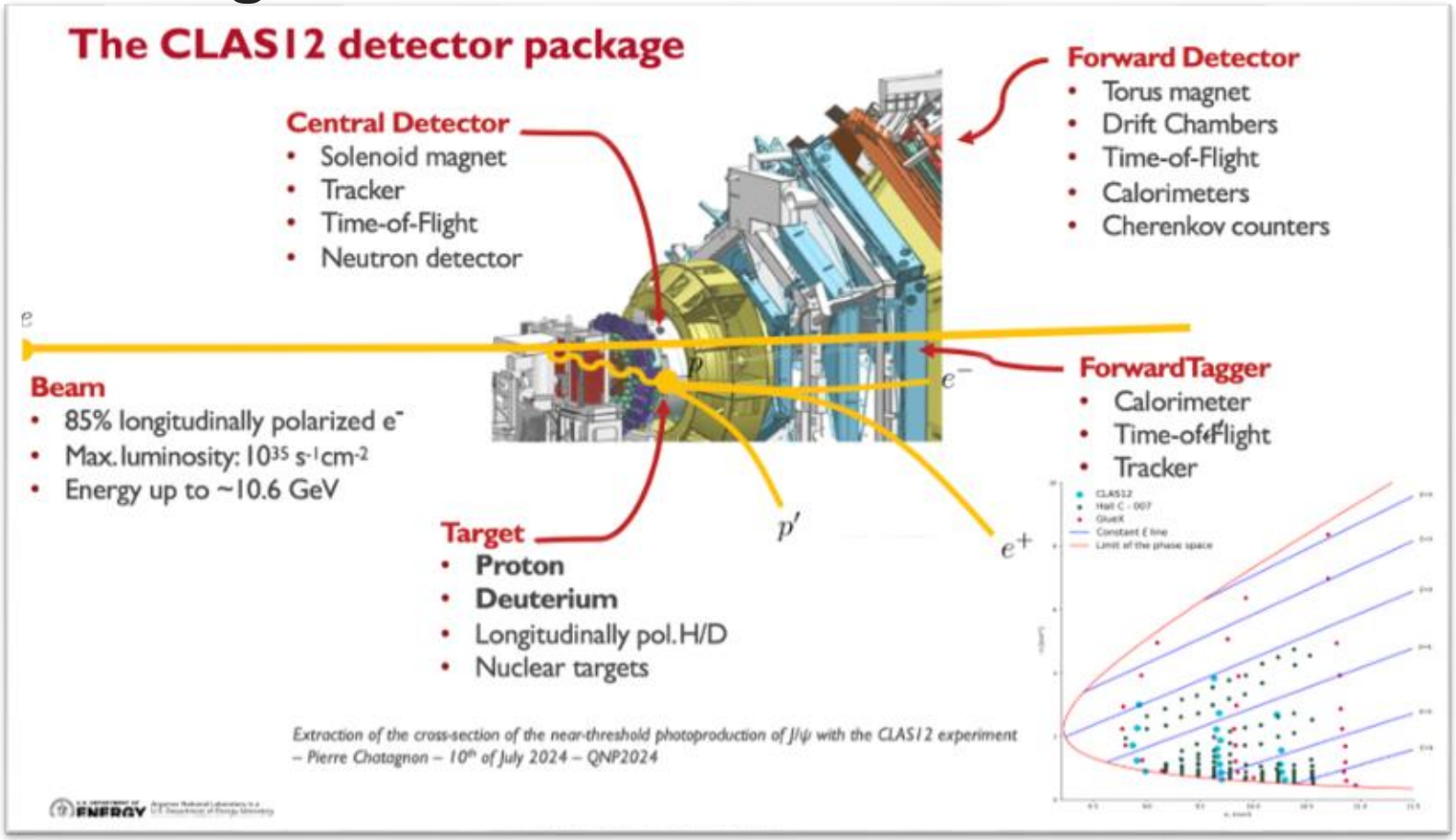
- Combined analysis of both J/ψ-007 datasets improves constraint on the C GFF
  - Demonstrate increased precision by extracting gluonic pressure
- Compared to Lattice results
  - Quarks seem to dominate at smaller radii, while gluons dominate at larger radii

SJ et al., 2602.14416 (2026, preprint)

Lattice: *D. Pefkou, D, Hackett, P. Shanahan, Phys. Rev. D 105, 054509 (2022).*

Upcoming Results: CLAS12

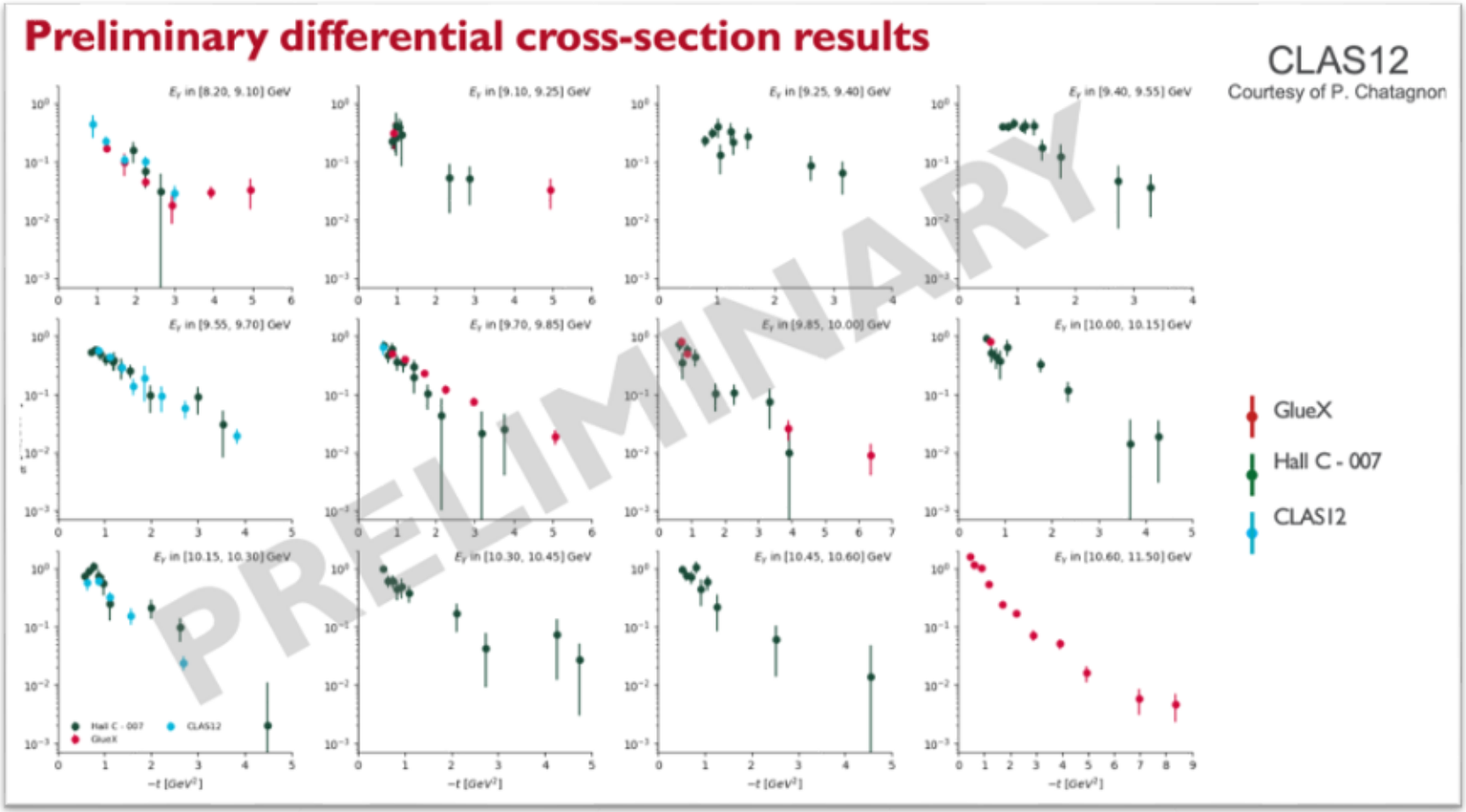
Courtesy of P. Chatagnon



Upcoming Results: CLAS12

Courtesy of P. Chatagnon

From QNP2024



What about the size of the proton?

What Sets the Scale of the Proton

Decomposing the EMT

$$T^{\mu\nu} = \hat{T}^{\mu\nu} + \bar{T}^{\mu\nu}$$

Trace part
scalar (spin-0)

$$\hat{T}^{\mu\nu} \equiv \frac{1}{4} g^{\mu\nu} T^{\alpha}_{\alpha} = \frac{1}{4} g^{\mu\nu} \left((1+\gamma_m)\bar{\psi} m \psi + \frac{\beta(g)}{2g} F^2 \right)$$

Trace anomaly

Traceless part
tensor (spin-2)

$$\bar{T}^{\mu\nu} = \bar{T}^{\mu\nu}_{q} + \bar{T}^{\mu\nu}_{g}$$

$$\mathrm{Tr}(\langle P \mid T^{\mu\nu} \mid P \rangle) = 2P^{\mu}P^{\mu} = 2M^2$$

- Scalar fields hold a special place in QFTs as they can have non-zero VEV
- The trace anomaly T^{μ}_{μ} appears to have a profound relation to the proton mass
- Non-zero value of $\langle P \mid F^2 \mid P \rangle$ could be considered a SSB of scale symmetry
  - Scalar gluon field may fill Higgs-like role in QCD

Narrative based on X. Ji Talk at DNP2025

Defining the Size of the Proton

… and what about the neutron?

- Scalar radius could be argued to be a “natural” definition for the size of hadrons
  - Invariant
  - Properly accounts for gluons
  - Electric-charge agnostic
  - Related to the emergence of scale in QCD

$$\langle P' \mid T^{\mu}_{\mu} \mid P \rangle \sim G_s(t)$$

$$G_s(t) = M\left[A(t) - \frac{t}{4M^2}B(t) + \frac{3t}{M^2}C(t)\right]$$

- The Fourier Transform now gives the scalar density, with scalar radius $\langle r_s^2 \rangle$

$$\langle r_s^2 \rangle \equiv \frac{\int d\vec{x} x^2 G_s(\vec{x})}{\int d\vec{x} G_s(\vec{x})} = 6\frac{dA(t)}{dt}\Big|_{t=0} - 18\frac{C(0)}{M_N^2}$$

Depends on slope and intercept of the GFFs at $t = 0$

Narrative based on X. Ji Talk at DNP2025

Scalar and Mass Structure from World Data

- Fit to “world” (Jlab) data on exclusive J/ψ photoproduction near threshold
  - All data from J/ψ-007 and GlueX

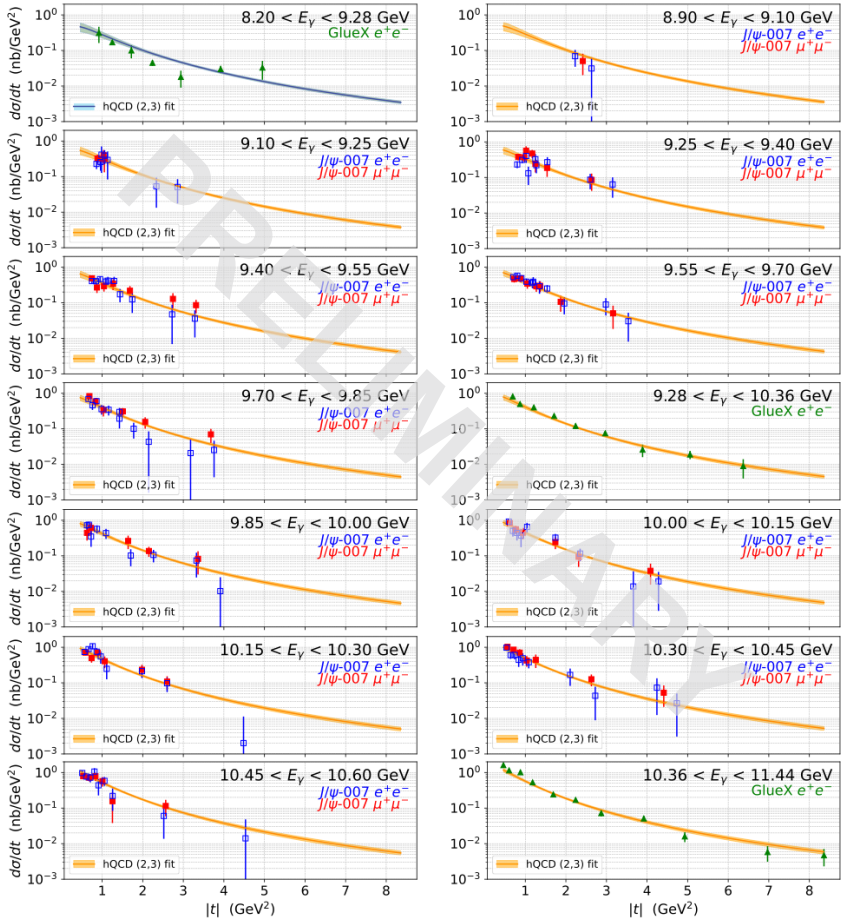
J/ψ-007, Duran *et* al., Nature volume 615, pages 813–816 (2023)
J/ψ-007, SJ et al., 2602.14416 (2026, preprint)
GlueX, Adhikari et al. (GlueX), Phys. Rev. C 108, 025201

- Holographic QCD approach, similar assumptions as before
  - Assuming dipole shape for $A_g(t)$and tripole shape for $C_g(t)$
  - Shapes are supported by theory and agree with the full functional form from holographic QCD

Mamo, Zahed PRD (2021) 2103.03186
Mamo, Zahed PRD (2022) 2204.08857

- Did not include GPD approach as due to insufficient data at $\xi > 0.5$ to acchieve stable fit results

Guo et al. PRL 135 (2025) 2501.10532

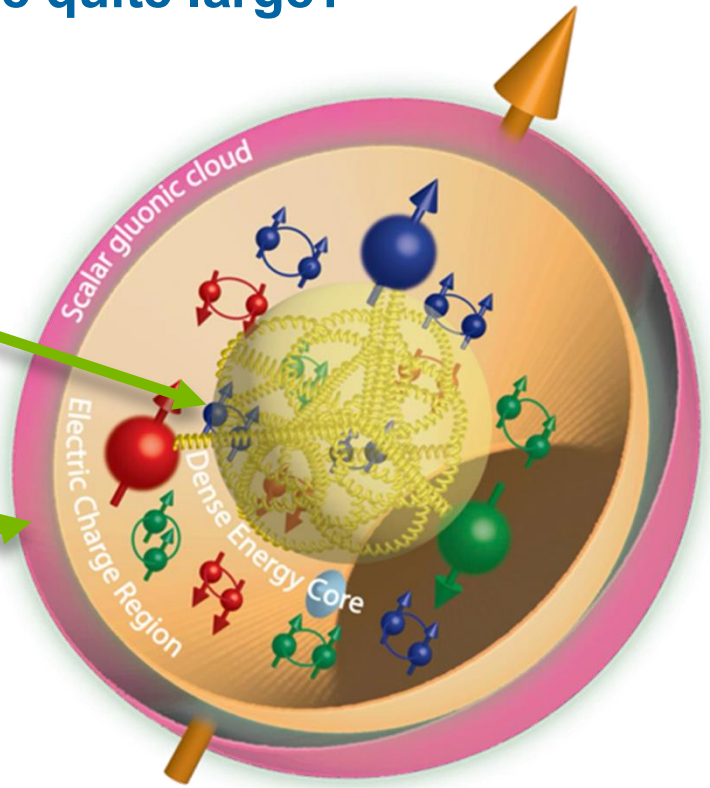


The Proton in Three Zones

The ”true” size of the proton appears to be quite large?

The proton’s mass radius is substantially smaller than its charge radius.

There may be hints of a scalar gluon cloud at larger radii



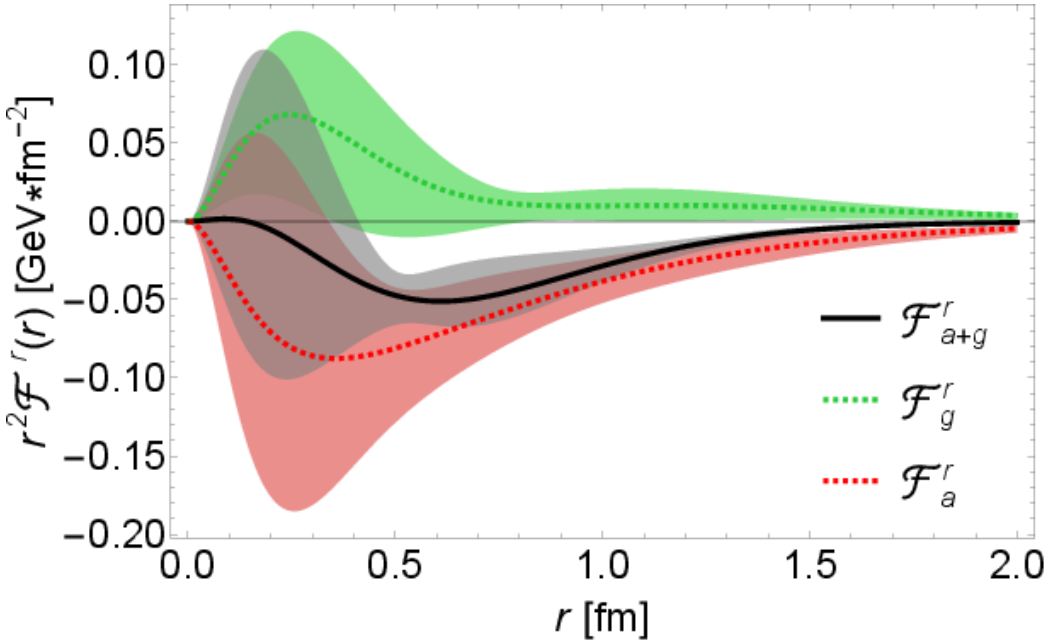
New Development: Forces on Quarks

Interpreting pressure and force densities

- Pressure corresponds to spatial components of the EMT (momentum current densities)
- The divergence of the stress tensor gives the net force density (Cauchy momentum equation)
- Balanced internal forces are encoded in the divergence-free part (related to the D-term)
- Repulsive forces from tensor gluons due to gluon radiation
- Larger attractive force from scalar gluons that appears responsible for confinement

Results from Bayesian analysis

Guo et al. PRL 135 (2025) 2501.10532



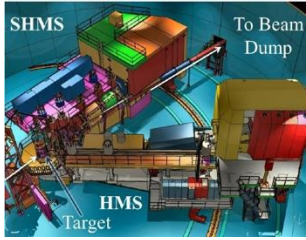
Ji and Yang, 2503.01991
Lorcé and Schweitzer, Acta Phys. Polon. B 56 (2025) 3-A17 (2501.04622)
Polyakov and Son, JHEP 09 (2018) 156 (1808.00155)
A. Freese, Phys. Rev. D 111 (2025) 034047 (2412.09664)

Future opportunities for Gluon GFFs

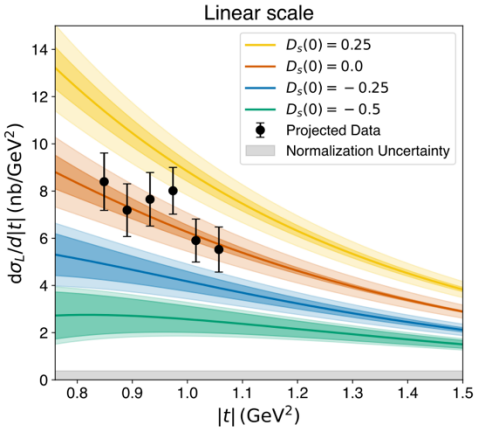
The Strangeness D-Term

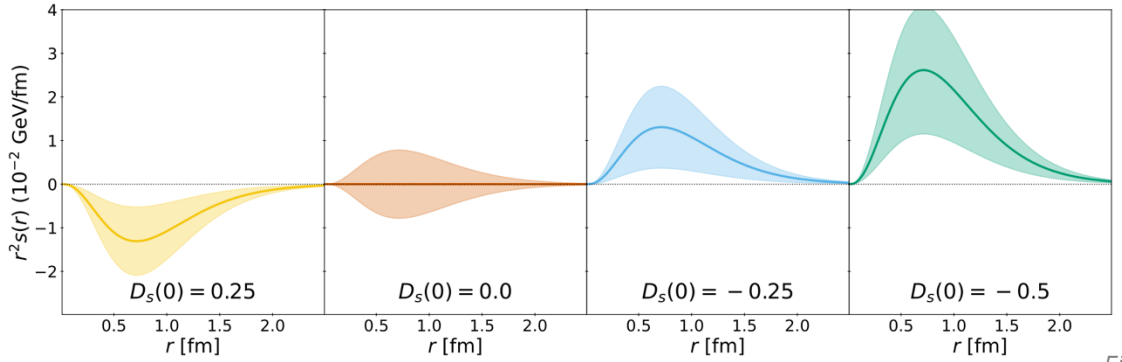
Exploring Non-Valence Contributions

Klest, et al., JLab PAC 53 (2025), 2501.01582
Hatta, et al., PTEB (2025), 2501.12343
Hatta and Strikman, PLB (2021), 2102.12631



- **Motivation**: To fully understand proton GFFs, also need to consider the role of strangeness
  - While u and d GFFs are explored through DVCS, the contribution from strange quarks is unconstrained by experiments.
  - Expectation from Lattice is that D_s could be small, and sign of D_s is yet unknown
- **Experiment**: Exclusive ϕ electroproduction near threshold in Hall C (ϕ-007), approved by PAC53
  - Measure the $|t|$-dependence of the dσ/d|t| cross-section using the reaction $H(e,e'p)\phi$
  - If ϕ-007 observes a large signal for D_s, it implies s must be considered together with u and d. Conversely, if the signal is small then ϕ becomes a good probe for gluons.



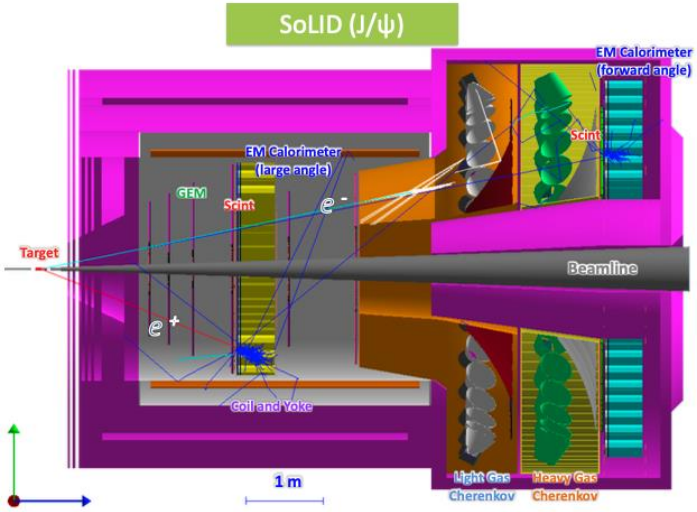


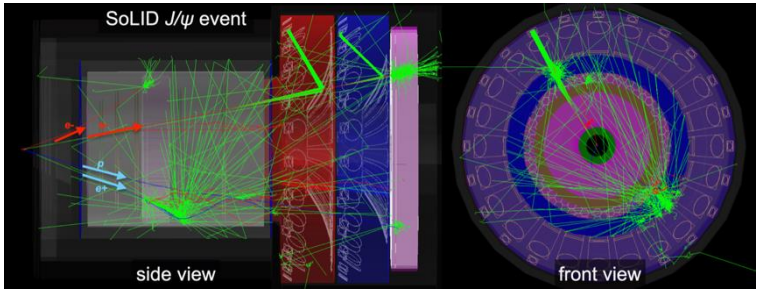
Figures by H. Klest

Future: SoLID-J/ψ in Hall A

Ultimate factory for near-threshold J/ψ

- 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

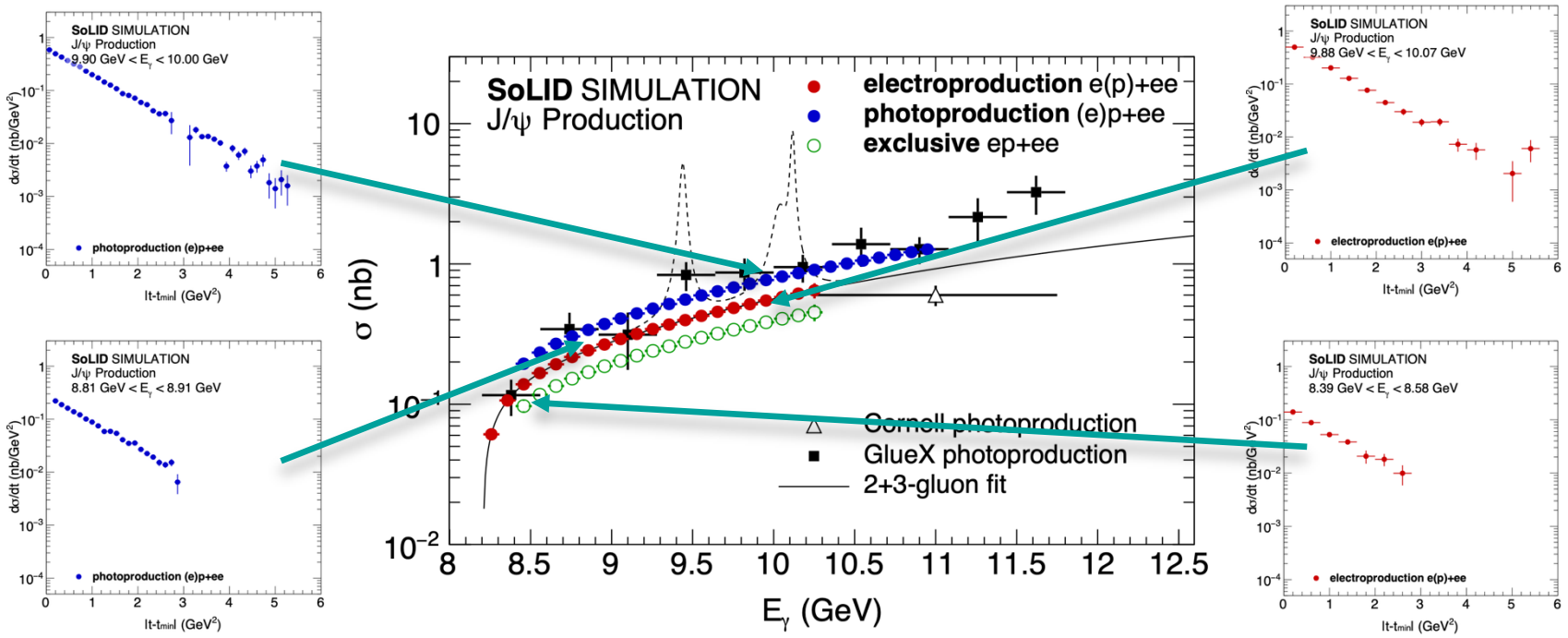




Figures courtesy of the SoLID Collaboration

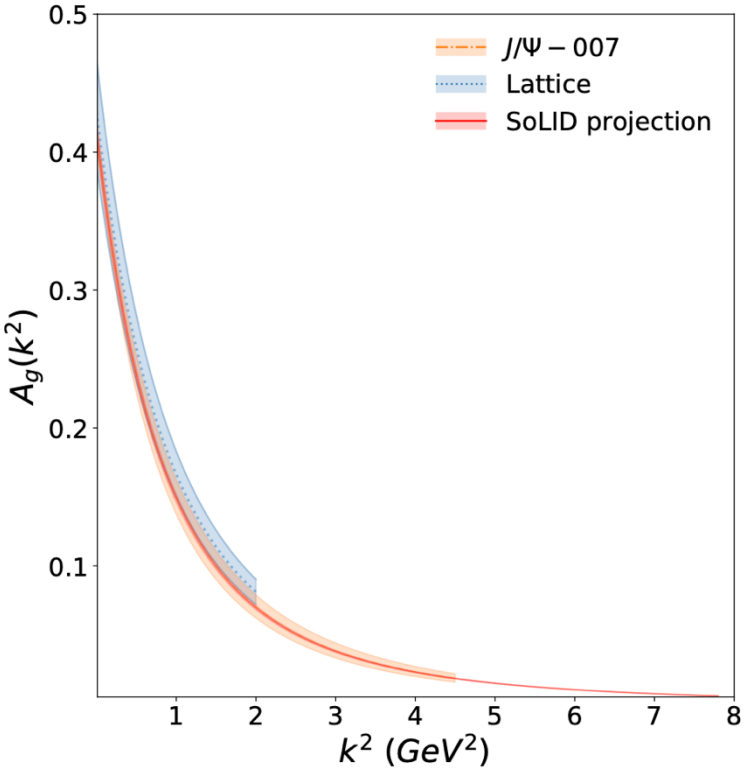
Future: SoLID-J/ψ in Hall A

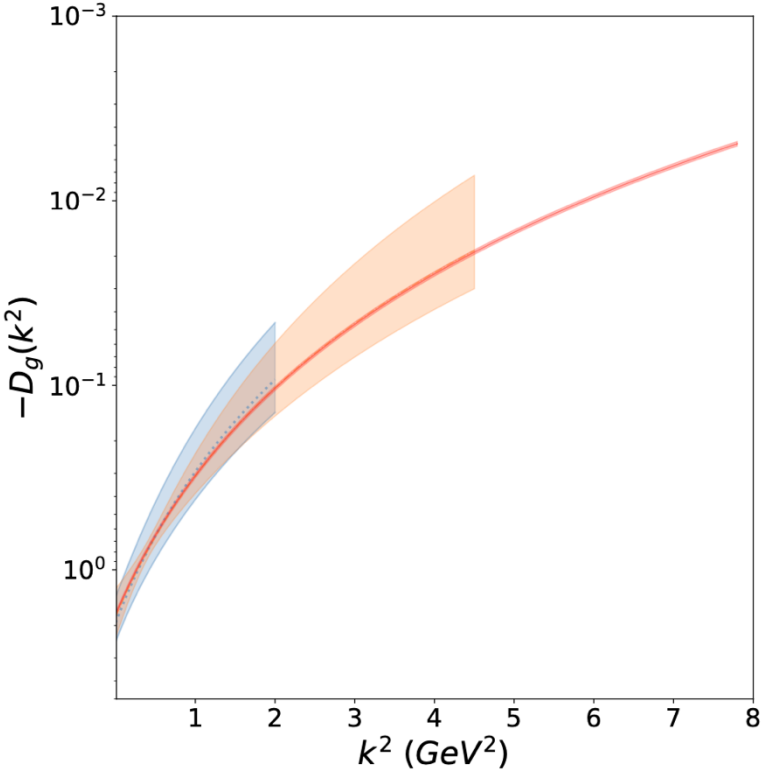
High-precision 2-D cross section crucial to really connect GFFs to data



Future: SoLID Projected Impact on gluon GFFs

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





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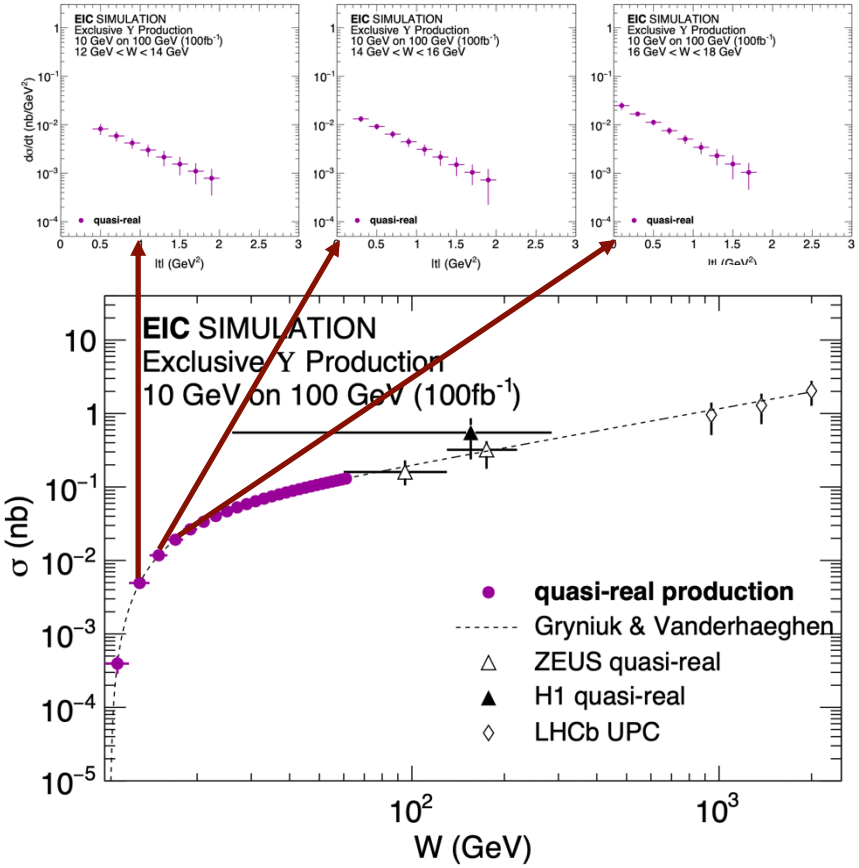
K. A. Mamo and I. Zahed, *Phys. Rev. D* **106**, no.8, 086004 (2022)
D. A. Pefkou, D. C. Hackett and P. E. Shanahan, *Phys. Rev. D* **105** (2022) no.5, 054509

Future: Y(1s) Near Threshold

Near-threshold quarkonium at EIC

- Y(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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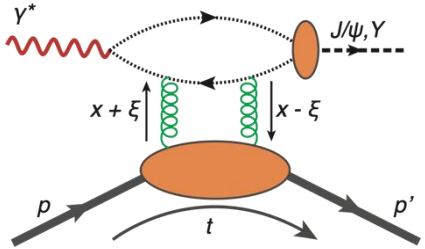
Future: Deeply-Virtual Quarkonium Production

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)

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

→

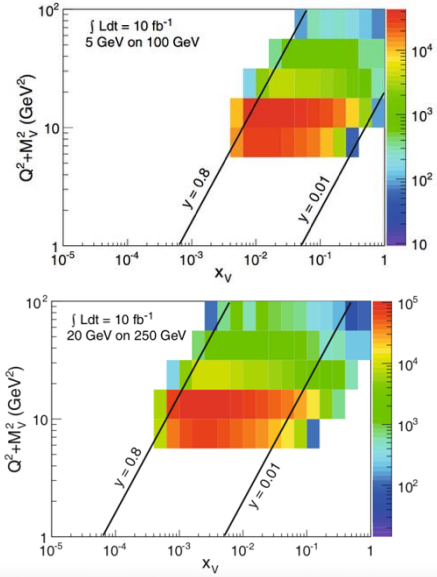
Fourier transform:
3-D transverse gluonic density

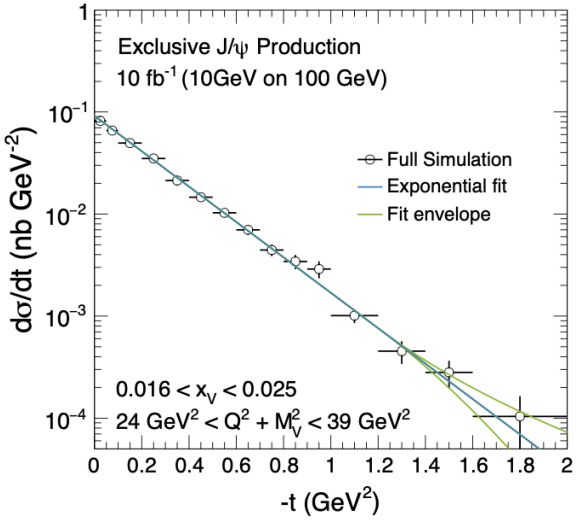
$$\rho(|\vec{b}_T|, x_V) = \int \frac{d^2\vec{\Delta}_T}{(2\pi)^2} e^{i\vec{\Delta}_T \vec{b}_T} |\langle H_g \rangle|(t = -\vec{\Delta}_T^2)$$

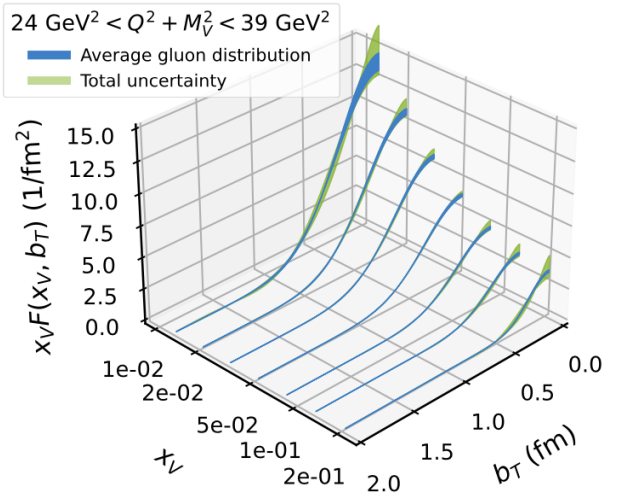
3D GPDs can be related to 2D Gravitational Form Factors

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**

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JINST 17 (2022) 10, P10019

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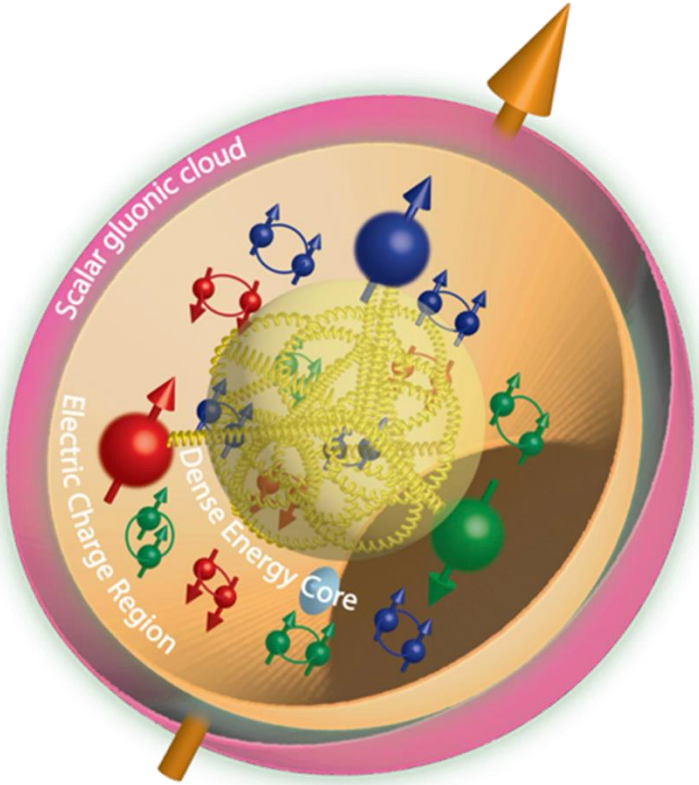
Conclusion

The JLab 12-GeV program has delivered important first results on our understanding of the mechanical structure of the proton

- 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

- Φ-007 will for the first time access the strangeness GFF
- SoLID will provide precision measurements for J/ψ near thresholds, reaching observables that cannot be achieved anywhere else



JLab 12 GeV is transforming our understanding of the proton’s mechanical structure, setting the stage for the EIC