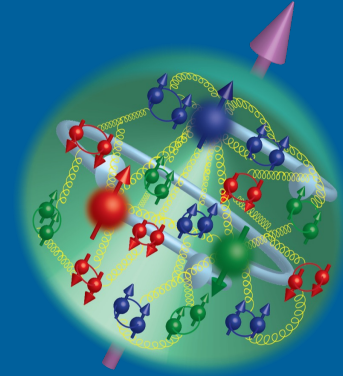


THE ENERGY MOMENTUM TENSOR FORM FACTORS OF THE PROTON: FROM JLAB TO EIC



ZEIN-EDDINE MEZIANI

Argonne National Laboratory

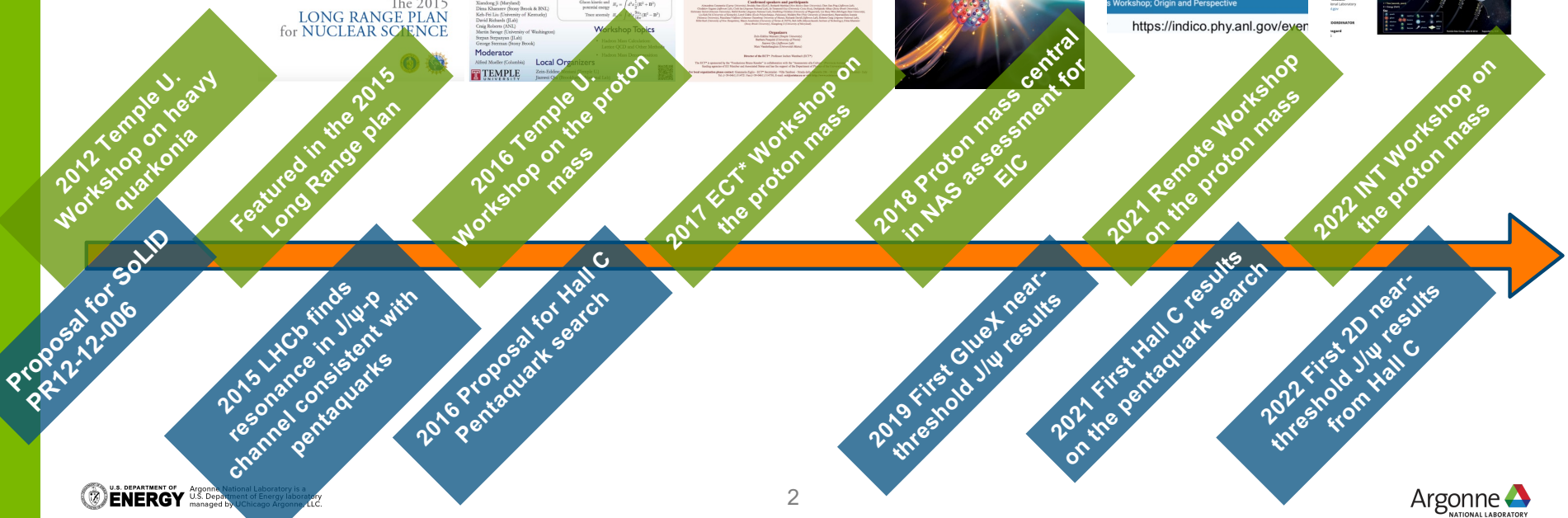
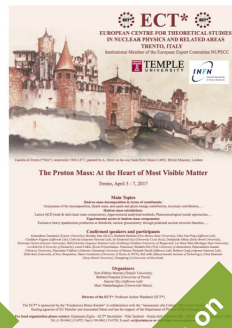
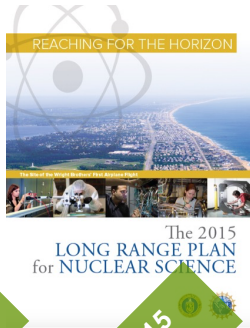
With thanks to Xiangdong Ji, Dimitra Pefkou and Sylvester Joosten, Ismail Zahed



THE PROTON MASS: AN IMPORTANT TOPIC IN CONTEMPORARY HADRONIC PHYSICS!

D. Kharzeev “Quarkonium interactions in QCD” *Proc. Int. Sch. Phys. Fermi* 130 (1996)

X. Ji, A QCD analysis of the mass structure of the nucleon *PRL* 74, 1071 (1995) & *PRD* 52, 271 (1995)



ATHENNA COLLABORATION PROPOSAL PR12-12-006 SoLID AT JLAB

Physics Motivation



- This proposal is about exploring and understanding some aspects of the strong regime of QCD
- Probes strong gluonic interaction between two color neutral objects J/Ψ and the nucleon
- Uses J/Ψ to probe color fields *in* the nucleon (minimal quark exchange)
- Tests the production mechanism of J/Ψ in a nucleon
- Probes the conformal anomaly of low energy interaction $J/\Psi - N$

A unique opportunity by exploring the **threshold region** and taking advantage of the high luminosity of CEBAF and the new energy reach namely 11 GeV



PR12-12-006, ATHENNA Collaboration, Newport News

06/19/12

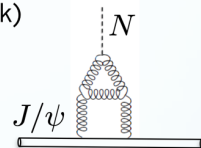
4

Statements from experts in the field!



“Low-energy J/ψ - N interaction is a probe of the scalar gluon form factor of the nucleon. This quantity is of fundamental importance since it is related to conformal anomaly of QCD and to the origin of the nucleon's mass”.

Dima Kharzeev (Stony Brook)



“I am very enthusiastic about the physics of J/ψ production at JLab” refer to:
<http://www-public.slac.stanford.edu/sciDoc/docMeta.aspx?slacPubNumber=SLAC-PUB-14985>

Stan Brodsky (SLAC, Stanford)



PR12-12-006, ATHENNA Collaboration, Newport News

6/17/12

5

MOTIVATION

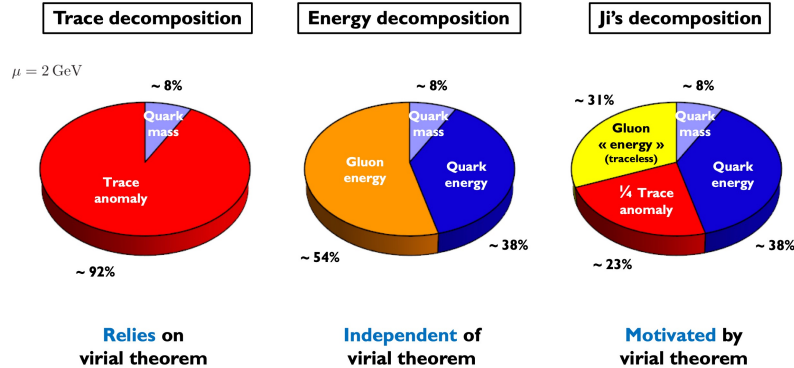
D. Kharzeev, H. Satz, A. Syamtomov, and G. Zinovjev, “ J/ψ photoproduction and the gluon structure of the nucleon,” Eur. Phys. J. C 9, 459 (1999), arXiv:hep-ph/9901375.
D. E. Kharzeev, “The mass radius of the proton,” Phys. Rev. D 104, 054015 (2021), arXiv:2102.00110.

Two questions to address

WHAT IS THE ORIGIN OF MASS?

- Is there a way to experimentally measure the trace anomaly?
- Can we verify Ji’s mass sum rule experimentally?

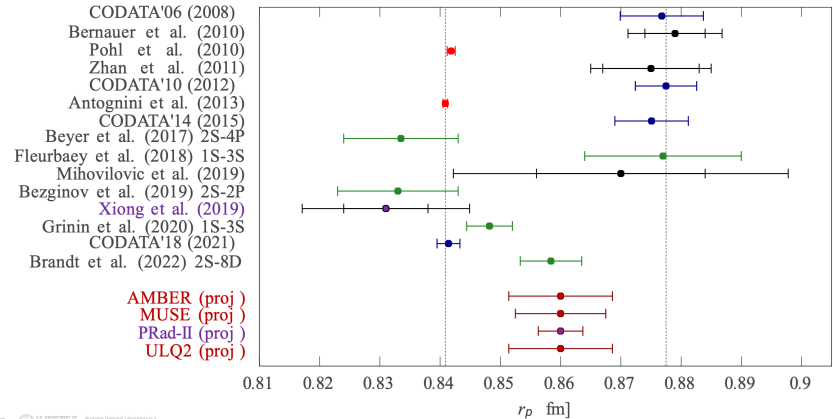
Lorcé (INT 2022)



WHAT IS THE SIZE OF THE PROTON?

- Does the electric charge radius define the proton size?
- What is the strong interaction size of the proton?

Most of us would first think of its charge radius



How does QCD generates most of the nucleon mass? Breaking of scale Invariance

Textbook: M. E. Peskin and D. V. Schroeder, An Introduction to quantum field theory, Addison-Wesley, Reading (1995)

✧ Trace of the QCD energy-momentum tensor:

D. Kharzeev Proc. Int. Sch. Phys. Fermi 130 (1996)

$$T_\alpha^\alpha = \underbrace{\frac{\beta(g)}{2g} G^{\alpha\beta a} G_{\alpha\beta}^a}_{\text{QCD trace anomaly}} + \sum_{l=u,d,s} m_l (1 + \gamma_{m_l}) \bar{q}_l q_l + \sum_{c,b,t} m_h (1 + \gamma_{m_h}) \bar{Q}_l Q_l$$

At small momentum transfer, heavy quarks decouple:

M. Shifman et al., Phys. Lett. 78B (1978)

with $\beta(g) = -b \frac{g^3}{16\pi^2} + \dots$, $b = 9 - \frac{2}{3} n_h$

Gross, Wilczek & Politzer

$$\sum_h \bar{Q}_h Q_h \rightarrow -\frac{2}{3} n_h \frac{g^2}{32\pi^2} G^{\alpha\beta a} G_{\alpha\beta}^a + \dots$$

$$T_\alpha^\alpha = \frac{\tilde{\beta}(g)}{2g} G^{\alpha\beta a} G_{\alpha\beta}^a + \sum_{l=u,d,s} m_l (1 + \gamma_{m_l}) \bar{q}_l q_l$$

✧ Trace anomaly, chiral symmetry breaking, ...

$$M^2 \propto \langle P | T_\alpha^\alpha | P \rangle \xrightarrow{\text{Chiral limit}} \frac{\tilde{\beta}(g)}{2g} \langle P | G^2 | P \rangle$$

In the chiral limit we have a finite number for the nucleon (~800 MeV) and zero for the pion

HIGGS MASS CONTRIBUTION TO THE PROTON

Pion-Nucleon Sigma Term

$$\sigma_{\pi N} = \langle N(P) | m_u \bar{u}u + m_d \bar{d}d | N(P) \rangle = (59.1 \pm 3.5) \text{ MeV}$$

Strangeness content

$$\sigma_s = \langle N(P) | m_u \bar{s}s | N(P) \rangle = 41.0(8.4) \text{ MeV}$$

A talk by Ulf-G Meißner at the 3rd Proton Mass Workshop, Jan 14-2021

<https://indico.phy.anl.gov/event/2/>

Consequence for the proton mass: About 100 MeV from the Higgs, the rest is gluon field energy

Hoferichter, Ruiz de Elvira, Kubis, Ulf-G Meißner Phys. Rev. Lett. 115 (2015) 092301
[arXiv:1506.04142] Phys. Rev. Lett. 115 (2015) 192301 [arXiv:1507.07552] Phys. Rept. 625
(2016) 1 [arXiv:1507.07552]

J/ψ'S NUCLEON MASS DECOMPOSITION: A HAMILTONIAN APPROACH

Quarks, anti-Quarks , Gluons and Trace Anomaly in the nucleon rest frame

X. Ji PRL 74, 1071 (1995) & PRD 52, 271 (1995)

$$H_{QCD} = \int d^3x T^{00}(0, \vec{x})$$

$$M_N = \frac{\langle P | H_{QCD} | P \rangle}{\langle P | P \rangle}$$

$$H_q = \int d^3x \psi^\dagger (-iD \cdot \alpha) \psi$$

Quarks & anti-quarks
kinetic and potential energy

$$M_q = \frac{3}{4} \left(a - \frac{b}{1 + \gamma_m} \right) M_N$$

$$H_m = \int d^3x \psi^\dagger m \psi$$

Quarks masses

$$M_m = \frac{4 + \gamma_m}{4(1 + \gamma_m)} b M_N$$

$$H_g = \int d^3x \frac{1}{2} (E^2 + B^2)$$

Gluons kinetic and potential energy

$$M_g = \frac{3}{4} (1 - a) M_N$$

$$H_a = \int d^3x \frac{9\alpha_s}{16\pi} (E^2 - B^2)$$

Trace anomaly

$$M_a = \frac{1}{4} (1 - b) M_N$$

$a(\mu)$ related to pdfs

$b(\mu)$ possibly related to the J/ψ production at threshold

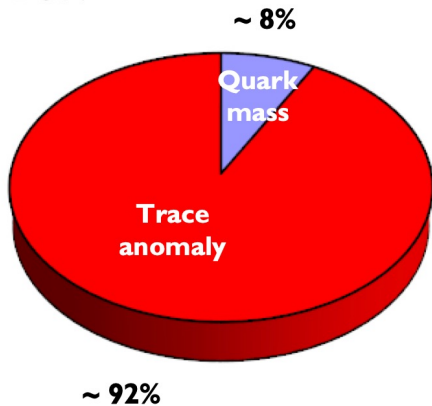
$$M_N = M_q + M_m + M_g + M_a$$

DIFFERENT MASS DECOMPOSITIONS

Proton Mass budget decompositions C. Lorcé (from 2022 INT workshop)

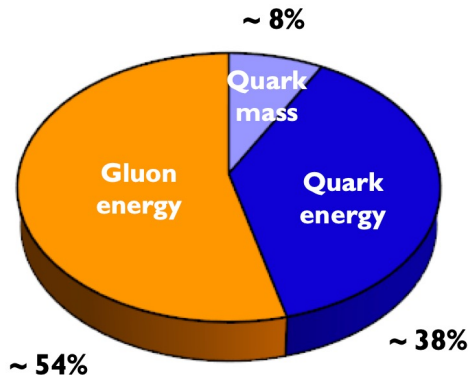
Trace decomposition

$\mu = 2 \text{ GeV}$



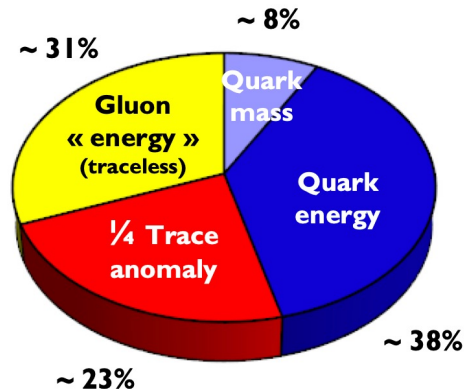
Relies on
virial theorem

Energy decomposition



Independent of
virial theorem

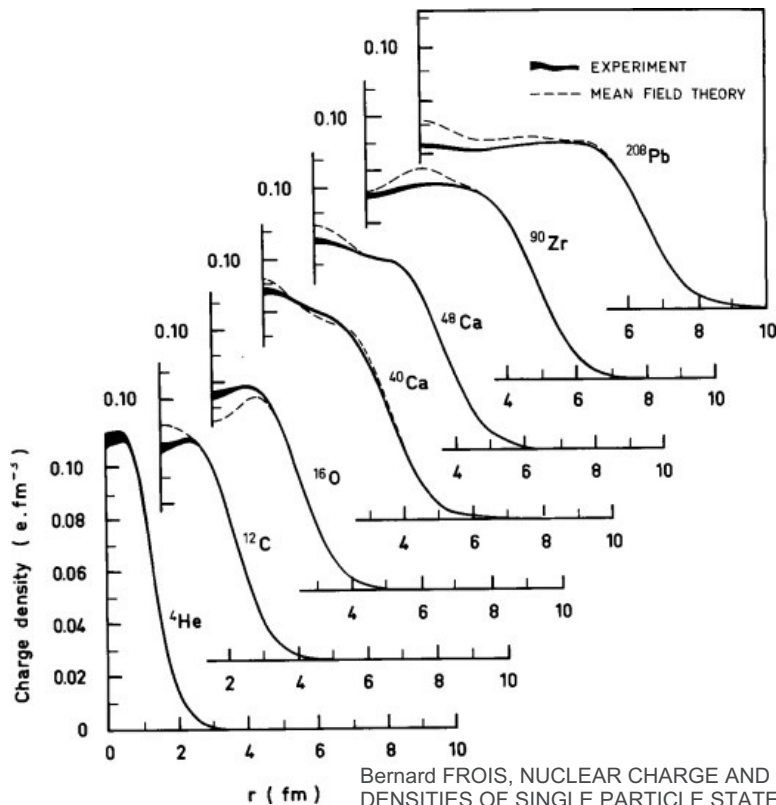
Ji's decomposition



Motivated by
virial theorem

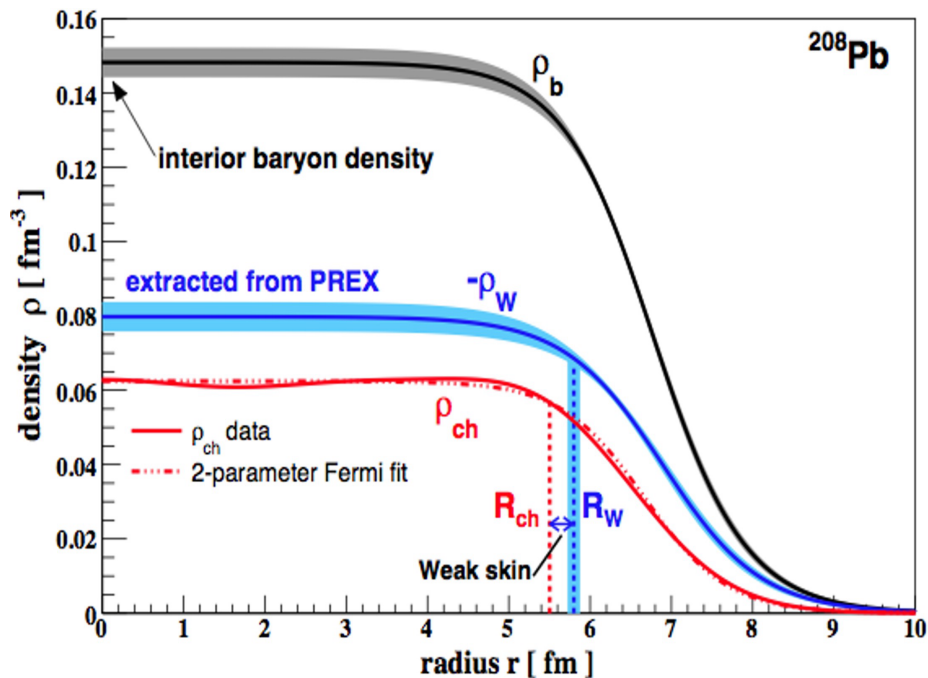
WHAT DEFINES THE SIZE OF ^{208}Pb ?-- BARYON DENSITY OF ^{208}Pb

Charge distribution of nuclei



Bernard FROIS, NUCLEAR CHARGE AND MAGNETIZATION DENSITIES OF SINGLE PARTICLE STATES,
 Editor(s): Ricardo BROGLIA, Gudrun HAGEMANN, Bent HERSKIND,
 Nuclear Structure 1985,
 Elsevier, 1985, Pages 25-43

Neutron Skin extracted from PREX ($R_n - R_p$)



D. Adhikari et. al. PRL 126, 172502 (2021)

RADIUS ZOO

Charge radius

$$\langle r^2 \rangle_c = \frac{\int d\mathbf{x} x^2 \rho_c(\mathbf{x})}{\int d\mathbf{x} \rho_c(\mathbf{x})} = \frac{6}{G_E(0)} \left. \frac{dG_E(t)}{dt} \right|_{t=0}$$

Magnetic radius

$$\langle r^2 \rangle_M = \frac{6}{G_M(0)} \left. \frac{dG_M(t)}{dt} \right|_{t=0}$$

Baryon number radius

$$\langle r^2 \rangle_B = \frac{\int d\mathbf{x} x^2 \rho_B(\mathbf{x})}{\int d\mathbf{x} \rho_B(\mathbf{x})}$$

Mass radius

$$\langle r^2 \rangle_m = \frac{\int d\mathbf{x} x^2 T^{00}(\mathbf{x})}{\int d\mathbf{x} T^{00}(\mathbf{x})} = 6 \left. \frac{dA(t)}{dt} \right|_{t=0} - \frac{3D(0)}{2M^2}$$

Scalar radius

$$\langle r^2 \rangle_s = \frac{\int d\mathbf{x} x^2 T_{\mu}^{\mu}(\mathbf{x})}{\int d\mathbf{x} T_{\mu}^{\mu}(\mathbf{x})} = 6 \left. \frac{dA(t)}{dt} \right|_{t=0} - \frac{9D(0)}{2M^2}$$

Tensor radius

$$\langle r^2 \rangle_t \equiv \frac{\int d\mathbf{x} x^2 (T^{00}(\mathbf{x}) + \frac{1}{2} T_{ii}(\mathbf{x}))}{\int d\mathbf{x} (T^{00} + \frac{1}{2} T_{ii})} = 6 \left. \frac{dA(t)}{dt} \right|_{t=0}$$

Mechanical radius

$$\langle r^2 \rangle_{mech} = \frac{\int d\mathbf{x} x^2 \frac{x_i x_j}{x^2} T_{ij}(\mathbf{x})}{\int d\mathbf{x} \frac{x_i x_j}{x^2} T_{ij}(\mathbf{x})} = \frac{6D(0)}{\int_{-\infty}^0 dt D(t)}$$

Y. Hatta, Hadron 2030

GRAVITATIONAL FORM FACTORS (GFFS)

Towards observables of the energy density structure of the proton

GFFs are matrix elements of the QCD energy-momentum tensor (EMT) for quarks and gluons

$$\begin{aligned} & \langle N' | T_{q,g}^{\mu,\nu} | N \rangle \\ & = \bar{u}(N') \left(A_{g,q}(t) \gamma^{\{\mu} P^{\nu\}} + B_{g,q}(t) \frac{iP^{\{\mu} \sigma^{\nu\}} \rho \Delta_\rho}{2M} + C_{g,q}(t) \frac{\Delta^\mu \Delta^\nu - g^{\mu\nu} \Delta^2}{M} + \bar{C}_{g,q}(t) M g^{\mu\nu} \right) u(N) \end{aligned}$$

EMT physics (mass, spin, pressure, shear forces) is encoded in these GFFs:

- $A_{g,q}(t)$: Related to quark and gluon momenta, $A_{g,q}(0) = \langle x_{q,g} \rangle$
- $J_{g,q}(t) = \frac{1}{2} (A_{g,q}(t) + B_{g,q}(t))$: Related to angular momentum, $J_{\text{tot}}(0) = 1/2$
- $D_{g,q}(t) = 4C_{g,q}(t)$: Related to pressure and shear forces

Heinz Pagels (North Carolina U.)
Published in: *Phys.Rev.* 144
(1966) 1250-1260

$$\bar{C}_q(t) + \bar{C}_g(t) = 0$$

The Proton Gravitational Form Factors A&C

Mass and Scalar–Mass Densities and their Radii

$$A^S(t) = A(t) + \frac{t}{4M}B(t) - \frac{3t}{M}C(t)$$

$$A^M(t) = A(t) + \frac{t}{4M}B(t) - \frac{t}{M}C(t)$$

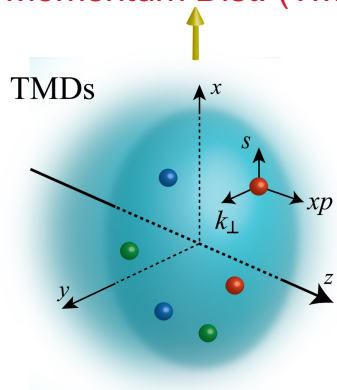
Unified View of Nucleon Structure

$W_p^u(x, k_T, r_T)$ Wigner distributions

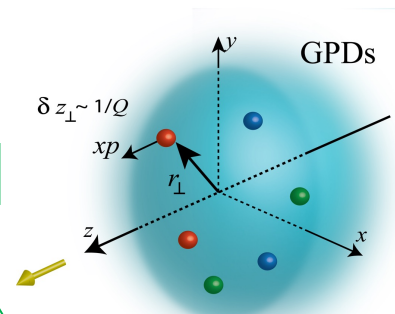
Transverse Momentum Dist. (TMD)

Tomography

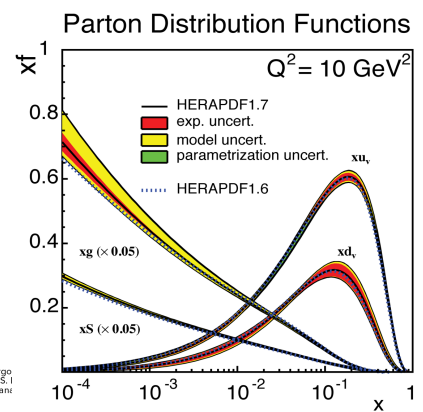
Generalized Parton Dist. (GPD)



TMD $f_1^u(x, k_T), h_1^u(x, k_T)$



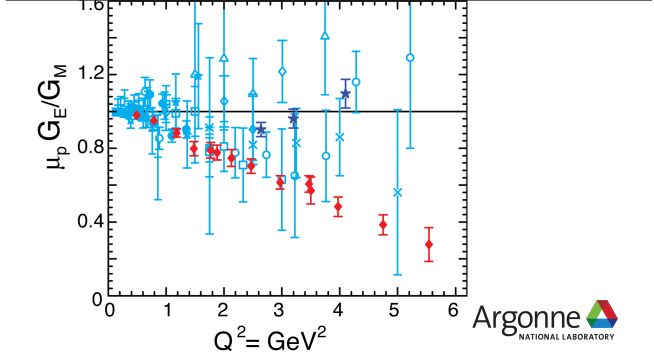
GPD



PDFs
 $f_1^u(x), \dots$
 $h_1^u(x)$

1D

Electromagnetic Form Factor $G_E(Q^2), G_M(Q^2)$



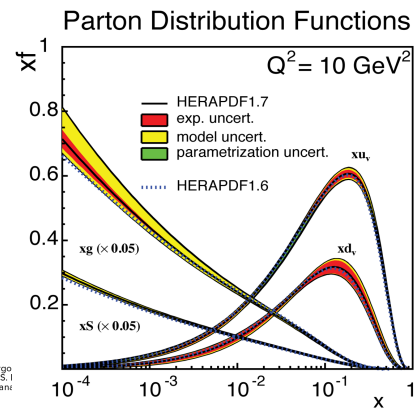
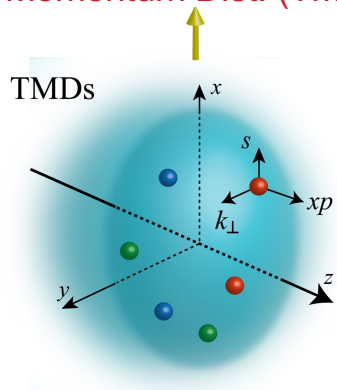
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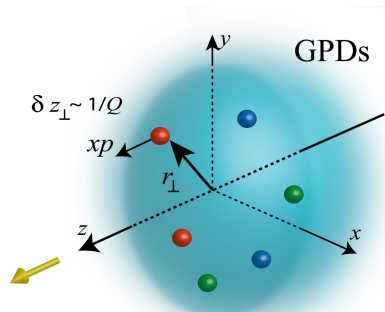
Tomography

Generalized Parton Dist. (GPD)



TMD $f_1^u(x, k_T), h_1^u(x, k_T)$

GPD



dx & Fourier Transformation

Electromagnetic Form Factor $G_E(Q^2), G_M(Q^2)$

PDFs
 $f_1^u(x), \dots$
 $h_1^u(x)$

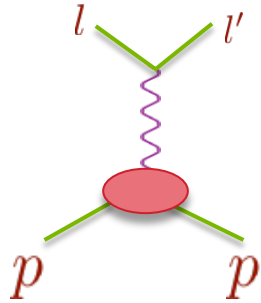
1D

Nucleon gravitational form factors A, B, C and C_bar;
(quarkonic & gluonic)
Mass density, Scalar-mass
Pressure density, Shear
Forces density

EXPERIMENTAL REACTIONS TO DETERMINE FORM FACTORS

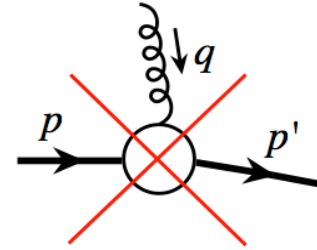
Proton electric charge distribution

Elastic Scattering



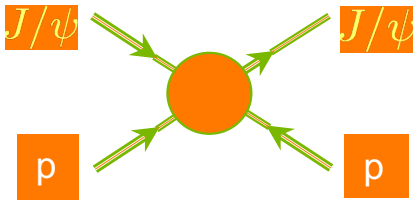
Proton color charge distribution?

Elastic color scattering; **but forbidden**

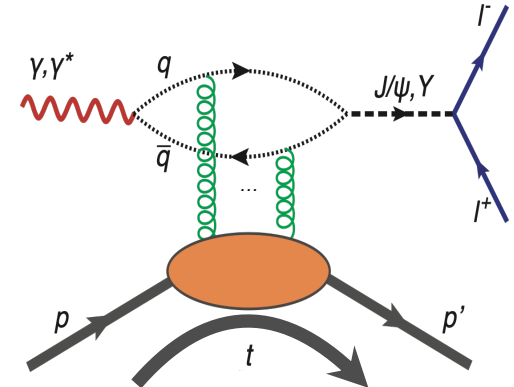
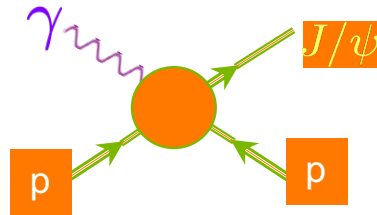


Is there an alternative to rather probe the gluon energy density in the proton?

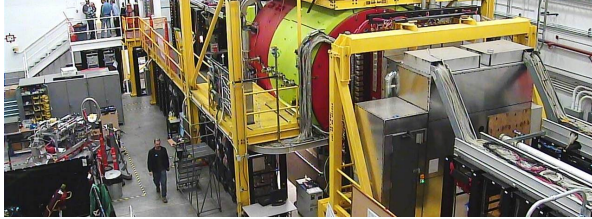
Elastic J/ψ scattering



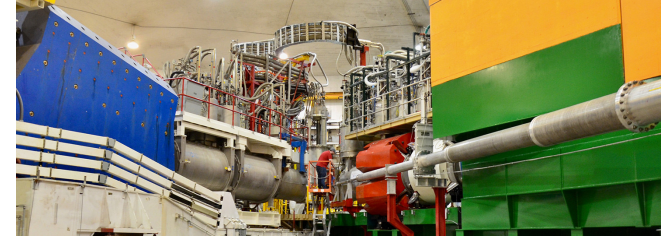
Photoproduction of J/ψ



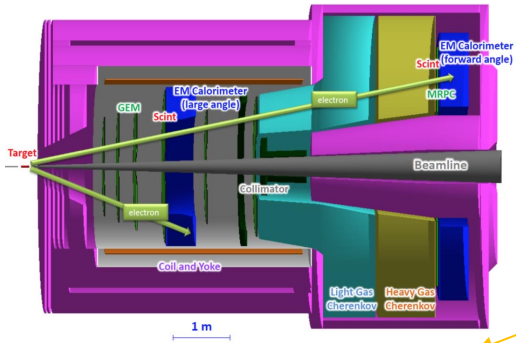
12 GEV J/ψ EXPERIMENTS AT JEFFERSON LAB NOW AND FUTURE



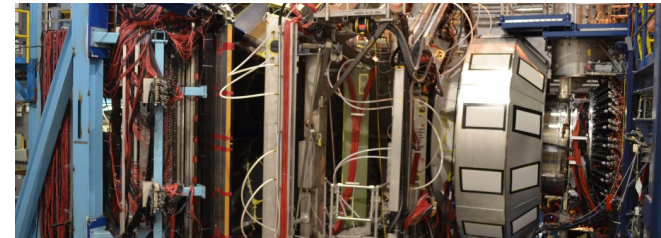
Hall D - GlueX observe the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



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



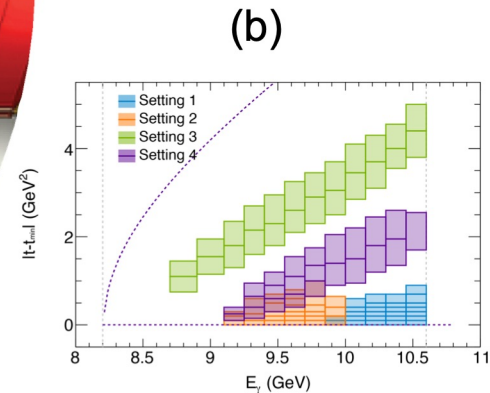
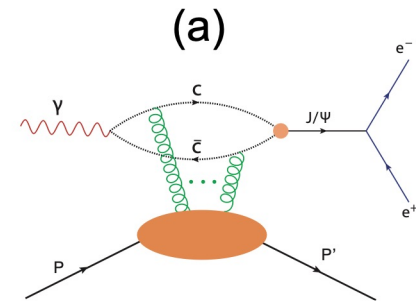
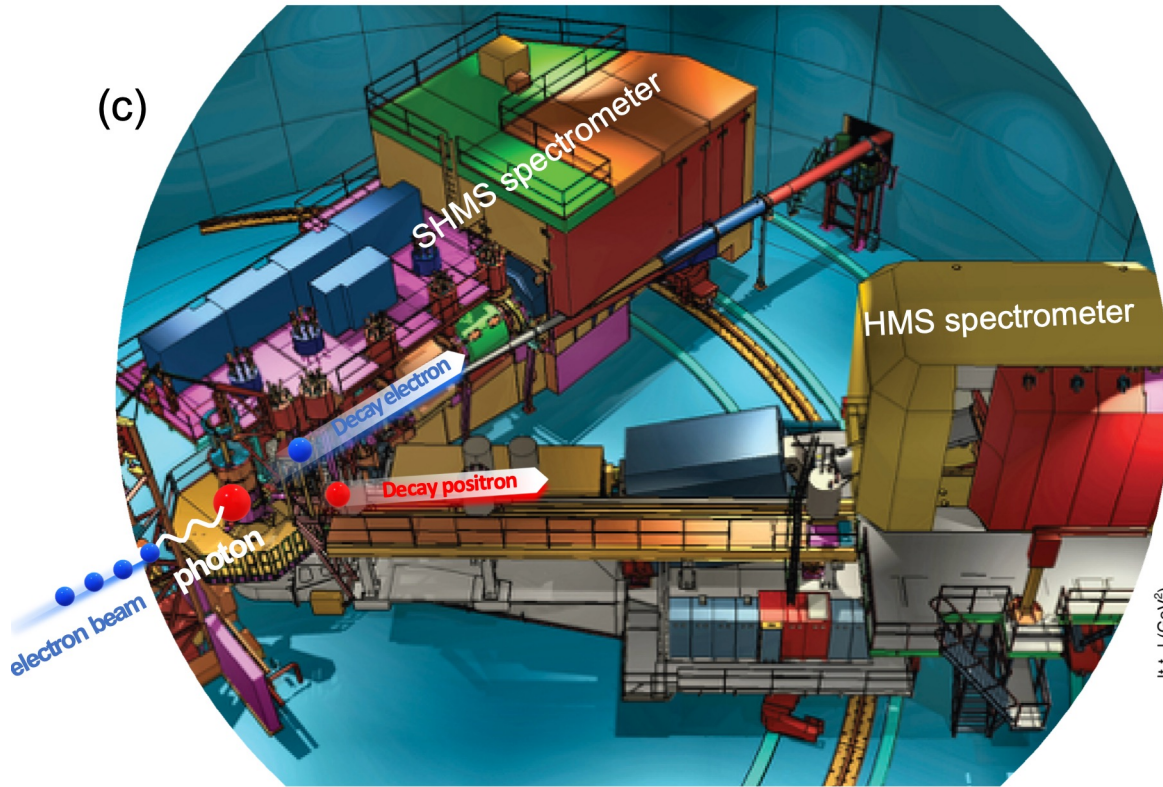
Hall A has experiment E12-12-006 at SoLID to measure J/ψ in electro- and photoproduction, and an LOI to measure double polarization using SBS



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

JLAB EXPERIMENT E12-16-007 IN HALL C AT JLAB

Near threshold photoproduction of J/ψ

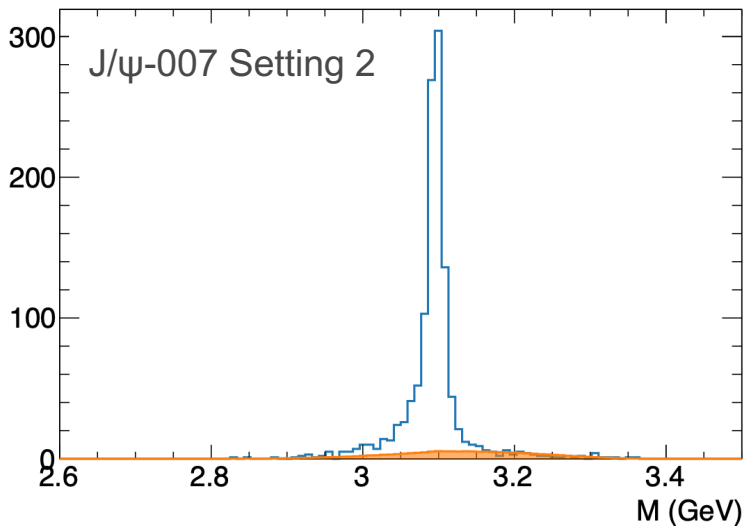


B. Duran, *et al.*, Determining the gluonic gravitational form factors of the proton.
Nature **615** (7954), 813–816 (2023), doi:10.1038/s41586-023-05730-4

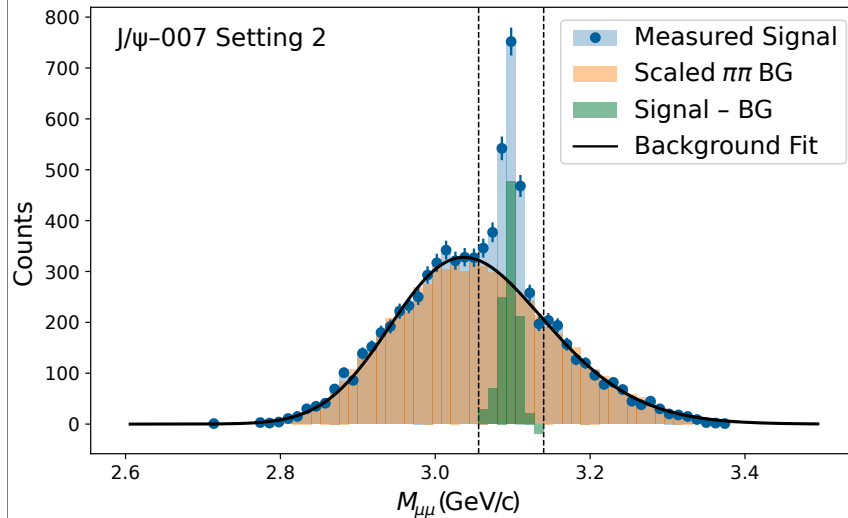
INVARIANT MASS SPECTRA IN J/ Ψ -007 EXPT.

J/ ψ -007 e⁺e⁻ and μ ⁺ μ ⁻

ELECTRON CHANNEL DECAY

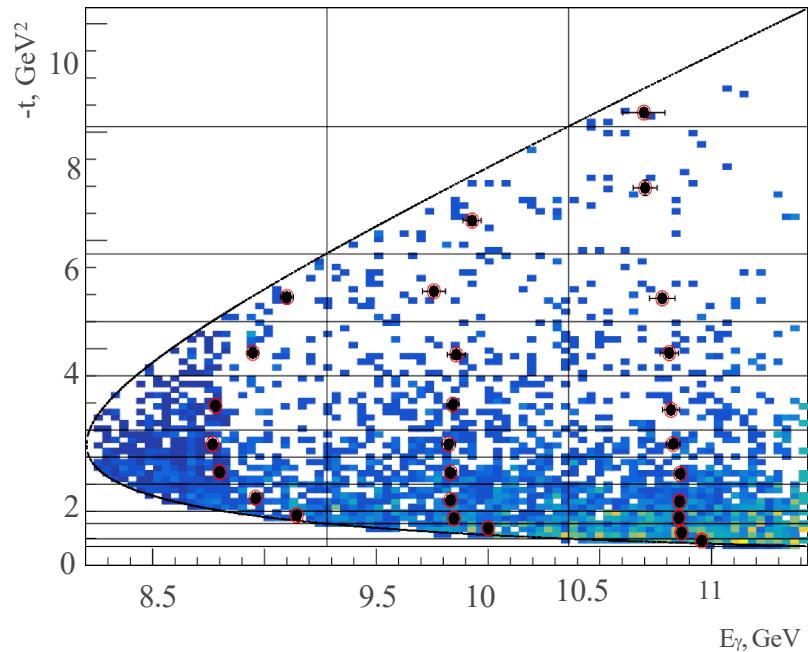
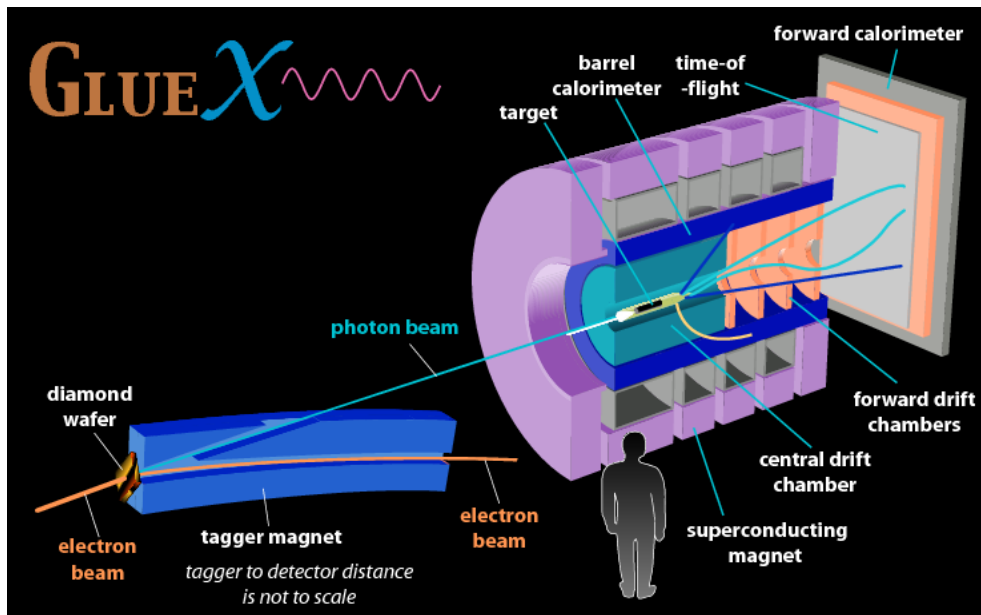


MUON CHANNEL DECAY



GLUEX EXPERIMENT IN HALL D AT JLAB

Setup and phase space

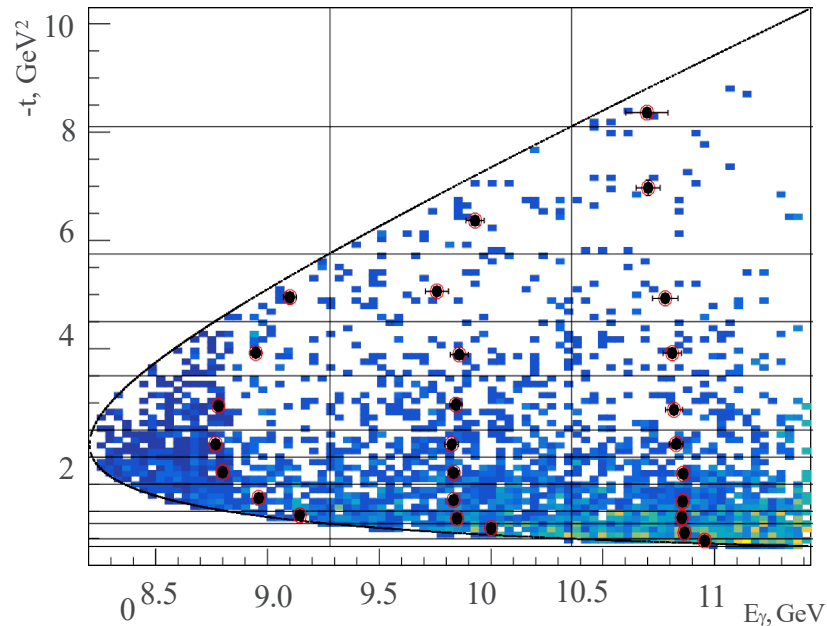
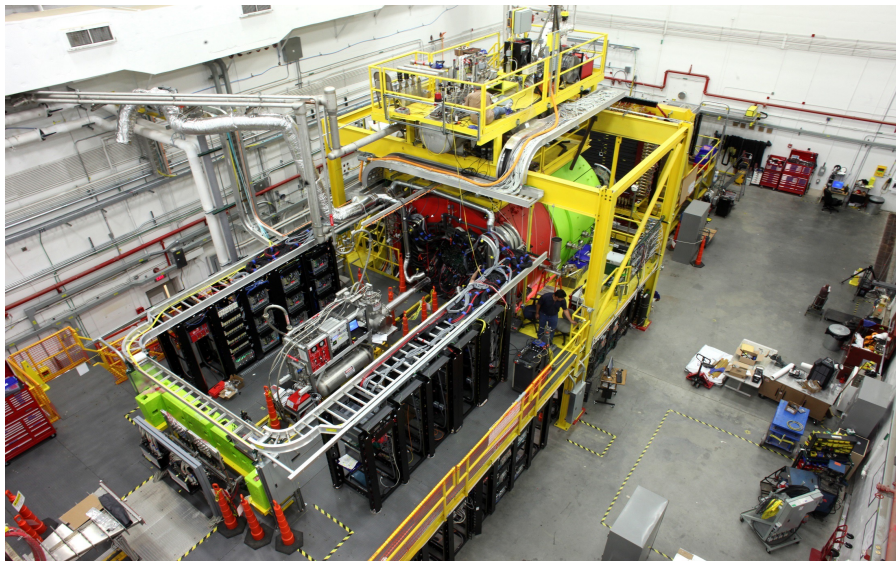


Courtesy of JLab pictures archive

Measurement of the J/ψ photoproduction cross section”, S. Adhikari *et al.*
(GlueX Collaboration). Phys. Rev. C 108, 025201, 2023, arXiv:2304.03845

GLUEX EXPERIMENT IN HALL D AT JLAB

Setup and phase space



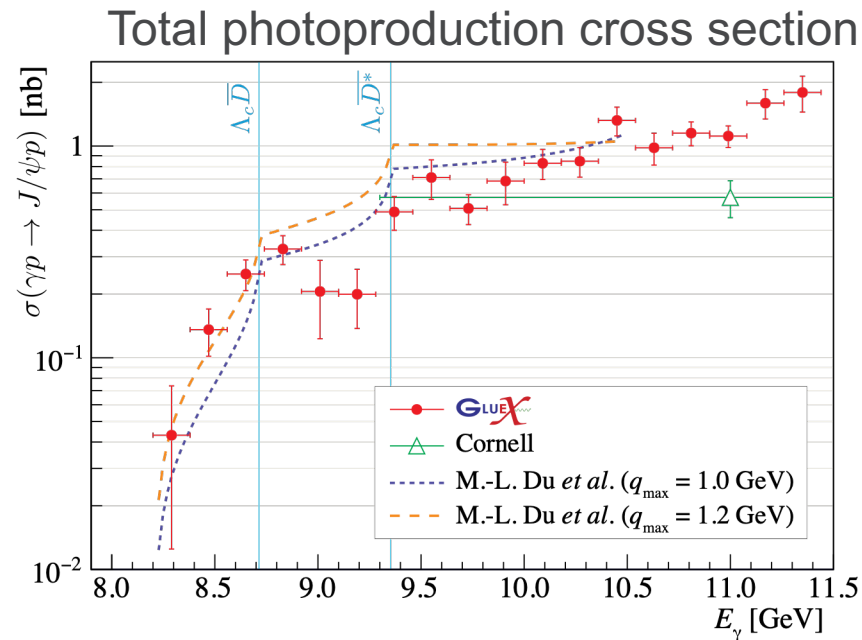
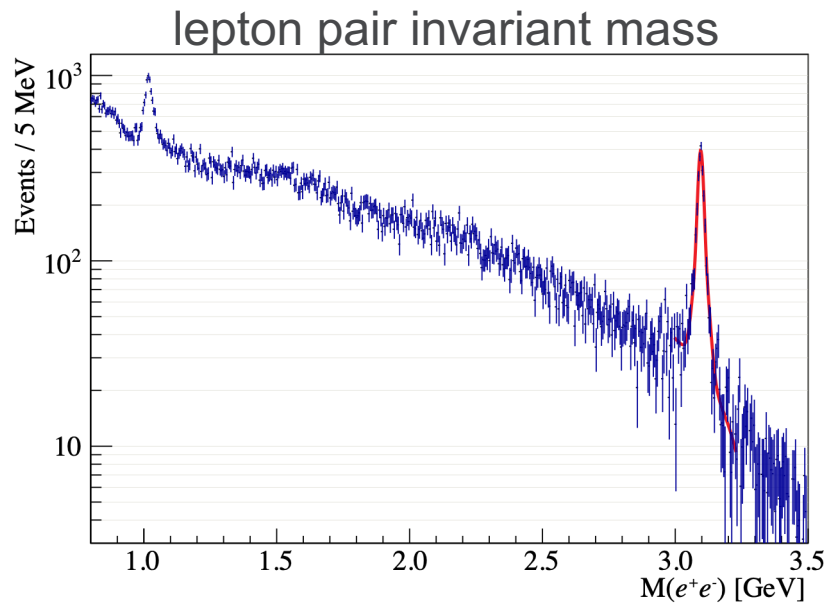
Courtesy of JLab pictures archive

Courtesy: L. Pentchev

Measurement of the J/ψ photoproduction cross section”, S. Adhikari *et al.*
(GlueX Collaboration). Phys. Rev. C 108, 025201, 2023, arXiv:2304.03845

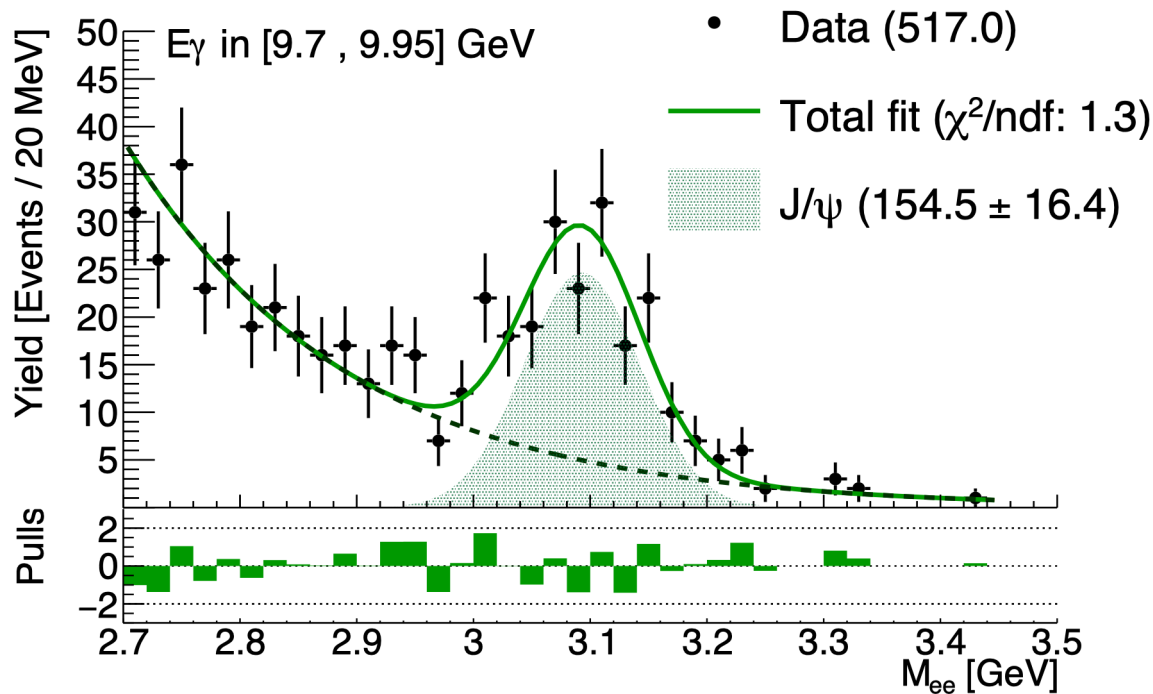
JLAB GLUEX 2023 J/ψ EXPERIMENT RESULTS

Invariant mass spectrum of e^+e^- (left) in GlueX and total photoabsorption cross section (right)



JLAB CLAS 12 TCS/J/PSI EXPERIMENT

Invariant mass spectrum for the J/psi identification in CLAS12



RECENT RESULTS FROM JEFFERSON LAB

GlueX

J/psi-007 (e- channel)

Figure from “Measurement of the J/ψ photoproduction cross section”, S. Adhikari *et al.* (GlueX Collaboration), Phys. Rev. C 108, 025201, 2023, arXiv:2304.03845

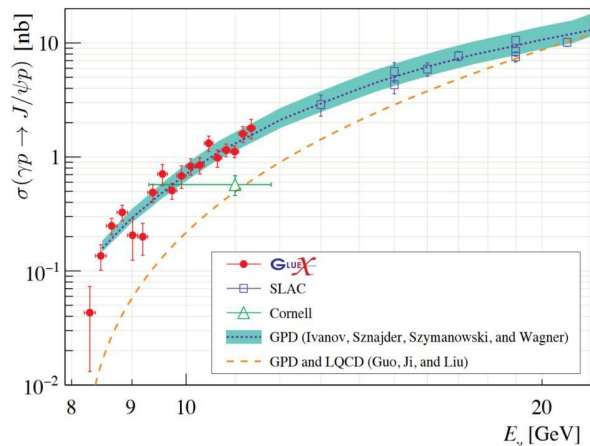


Figure from “Dynamics in near-threshold J/ψ photoproduction”, D. Winney, C. Fernandez-Ramirez, A. Pilloni, A. N. Hiller-Blin *et al.* (JPAC), Phys. Rev. D 108 (2023) 5, 054018, arXiv:2305.01449

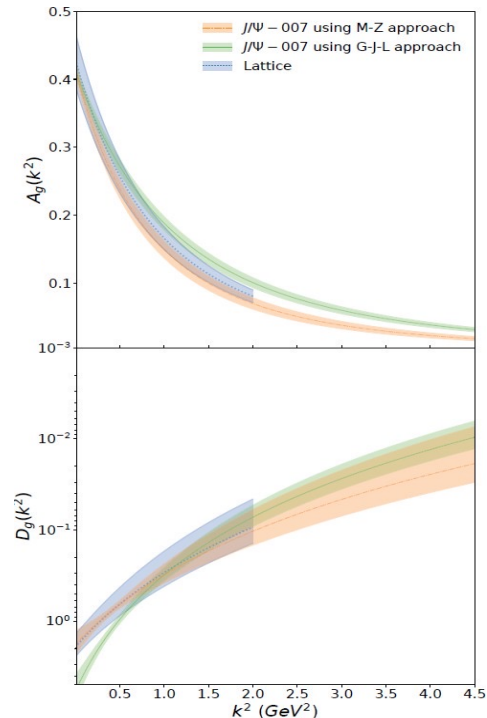
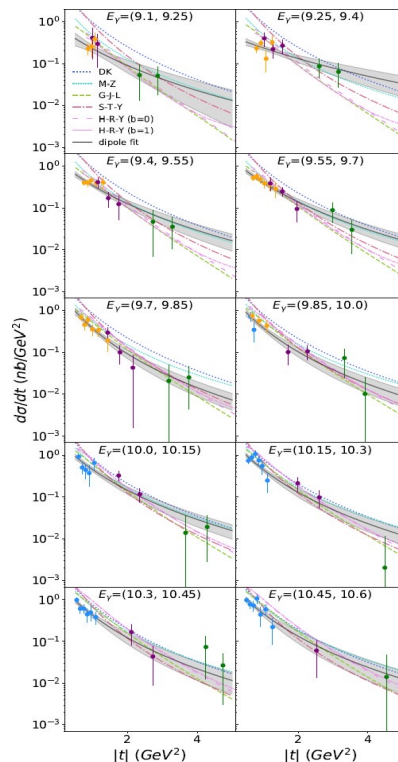
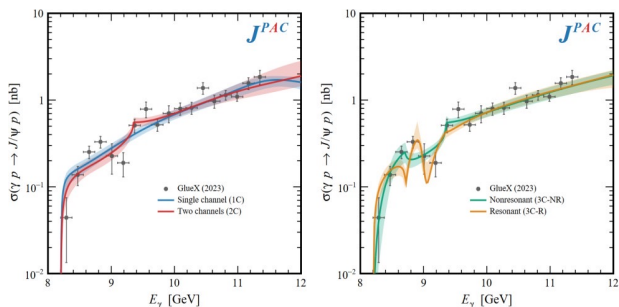
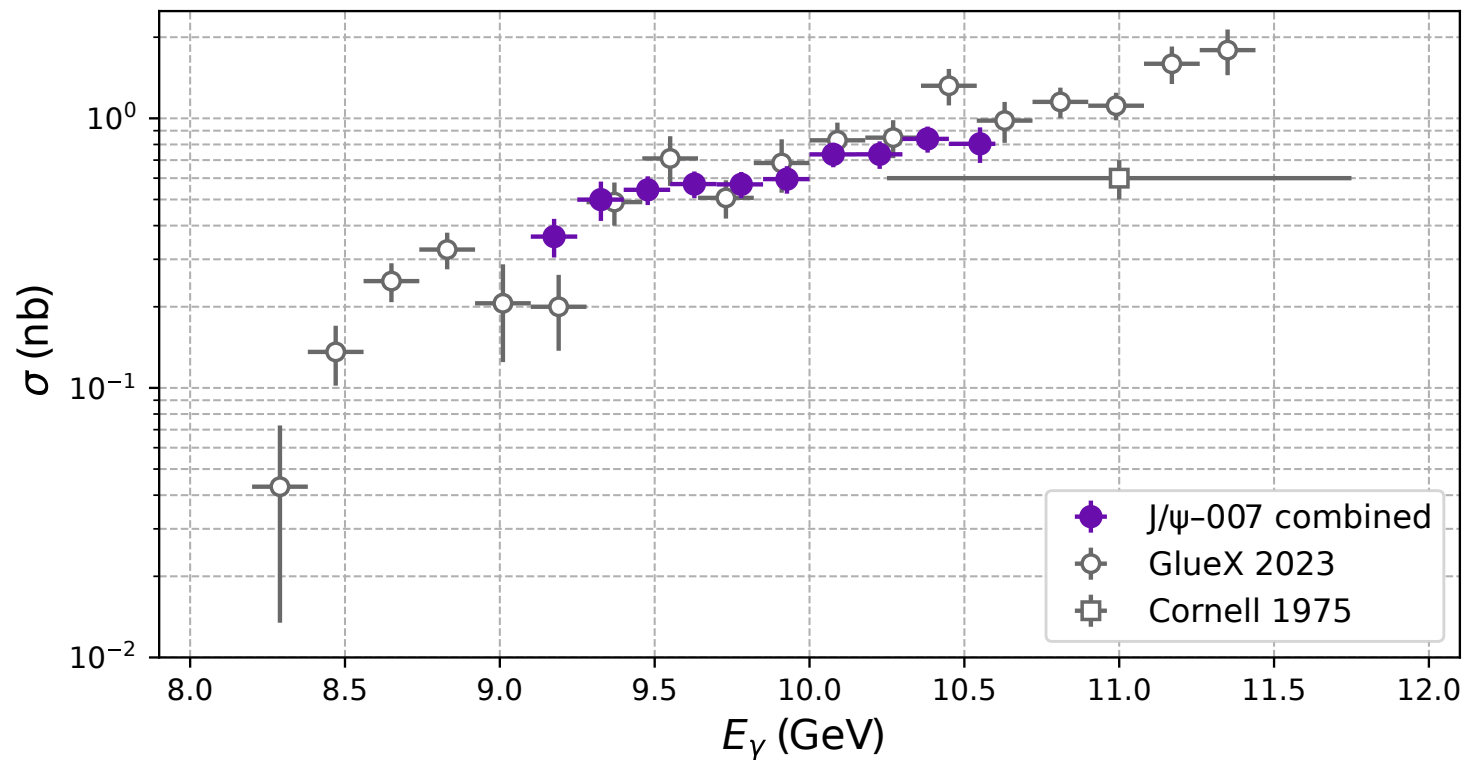


Figure from “Determining the gluonic gravitational form factors of the proton”. Duran, B., Meziani, Z.E., Joosten, S. *et al.* Nature 615, 813–816 (2023)

TOTAL J/ψ PHOTOPRODUCTION CROSS SECTION

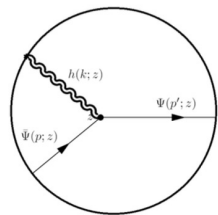
GlueX 2023 and J/psi-007 muon channel



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

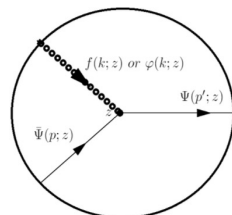
K. Mamo & I. Zahed, PRD 106, 086004 (2022) and PRD 101, 086003 (2020)

Tensor



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

Scalar



Spin-0⁺⁺ : $\langle p_2 | T_\mu^\mu(0) | p_1 \rangle$

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

$$\eta = \frac{M_{J/\psi}^2}{4p \cdot q - M_{J/\psi}^2 + t}$$

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

$$\chi^2 = 201.054$$

$$\text{nfd} = 200$$

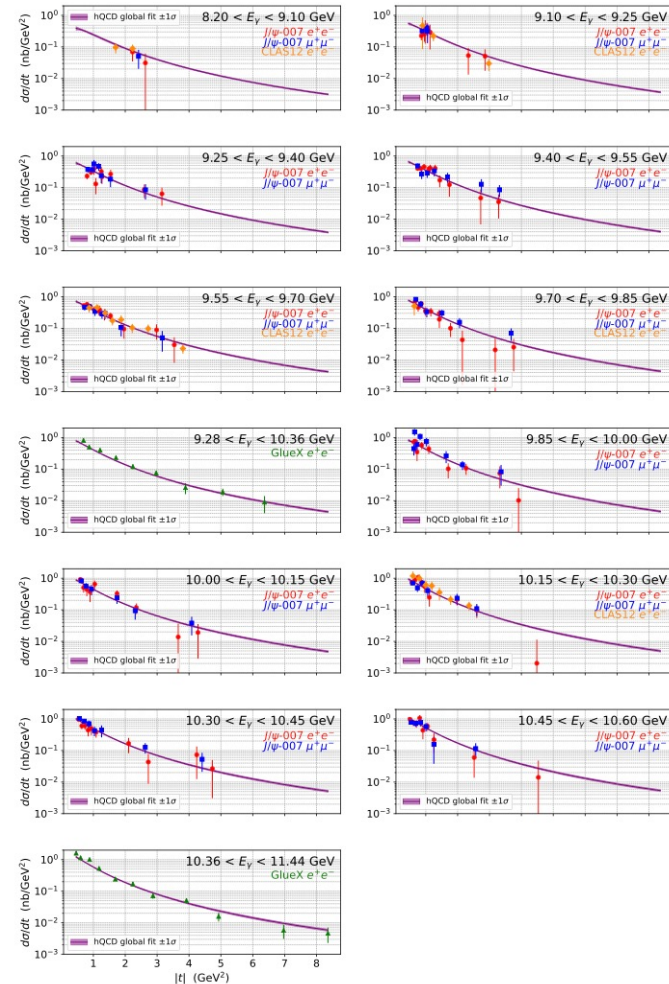
$$\chi^2/\text{nfd} = 1.005$$

$$\Lambda_A = 1.159 \pm 0.017$$

$$C(0) = -1.937 \pm 0.751$$

$$\Lambda_C = 0.914 \pm 0.151$$

- $A(t)$ 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 first GlueX cross section measurement



THE GENERALIZED PARTON DISTRIBUTION APPROACH

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

Y. Guo, X. Ji and Y. Liu, Phys. Rev. D **103**, no.9, 096010 (2021) and Y. Guo, X. Ji and Y. Liu, J. Yang, Phys. Rev. D **108** (2023) no.3, 034003

$$A_g(t) = \frac{A_g(0)}{\left(1 - \frac{t}{m_A^2}\right)^2} \quad C_g(t) = \frac{C_g(0)}{\left(1 - \frac{t}{m_C^2}\right)^3}$$

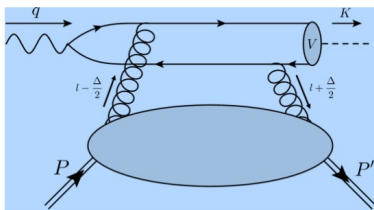
$$\frac{d\sigma}{dt} = \frac{\alpha_e m e_Q^2}{4(W^2 - m_N^2)^2} \frac{(16\pi\alpha_s)^2}{3M_V^2} |\psi_{NR}|^2 |G(t, \xi)|^2$$

$$G(t, \xi) = \sum_0^{\infty} \frac{1}{\xi^{2n+2}} \int_{-1}^1 dx x^{2n} F_g(x, \xi, t)$$

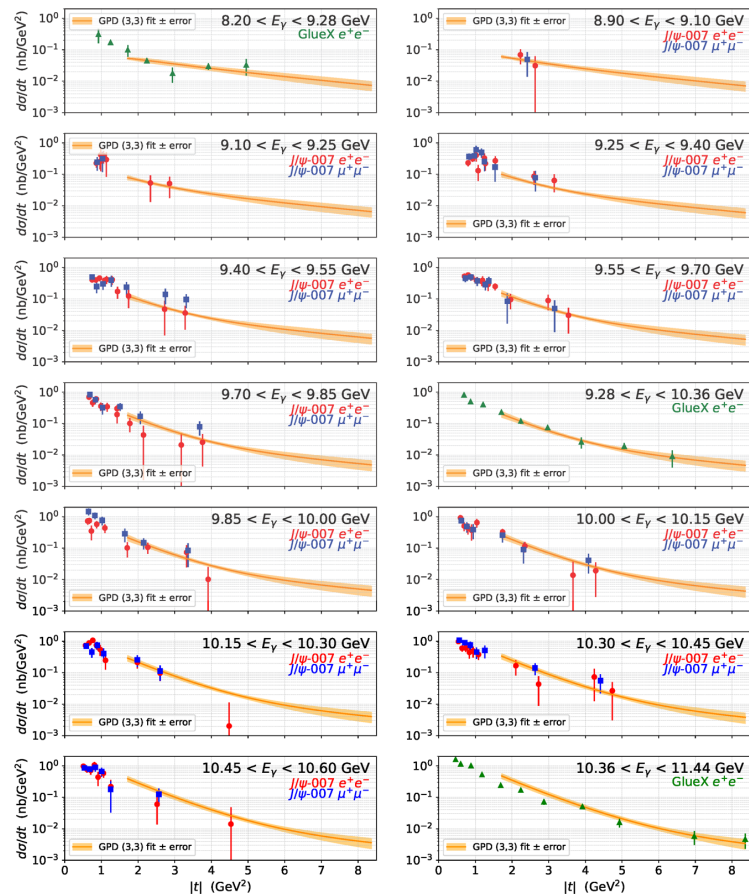
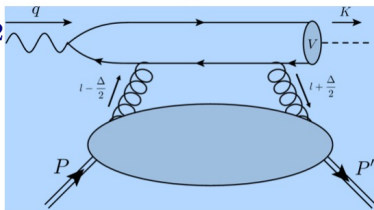
$$|G(t, \xi)|^2 = \frac{4}{\xi^4} \left\{ \left(1 - \frac{t}{4m_N^2}\right) E_2^2 - 2E_2(H_2 + E_2) + (1 - \xi^2)(H_2 + E_2)^2 \right\}$$

$$\int_0^1 dx H_g(x, \xi, t) = A_{2,0}^g(t) + (2\xi)^2 C_2^g \equiv H_2(t, \xi)$$

$$\int_0^1 dx E_g(x, \xi, t) = B_{2,0}^g(t) - (2\xi)^2 C_2^g \equiv E_2(t, \xi)$$

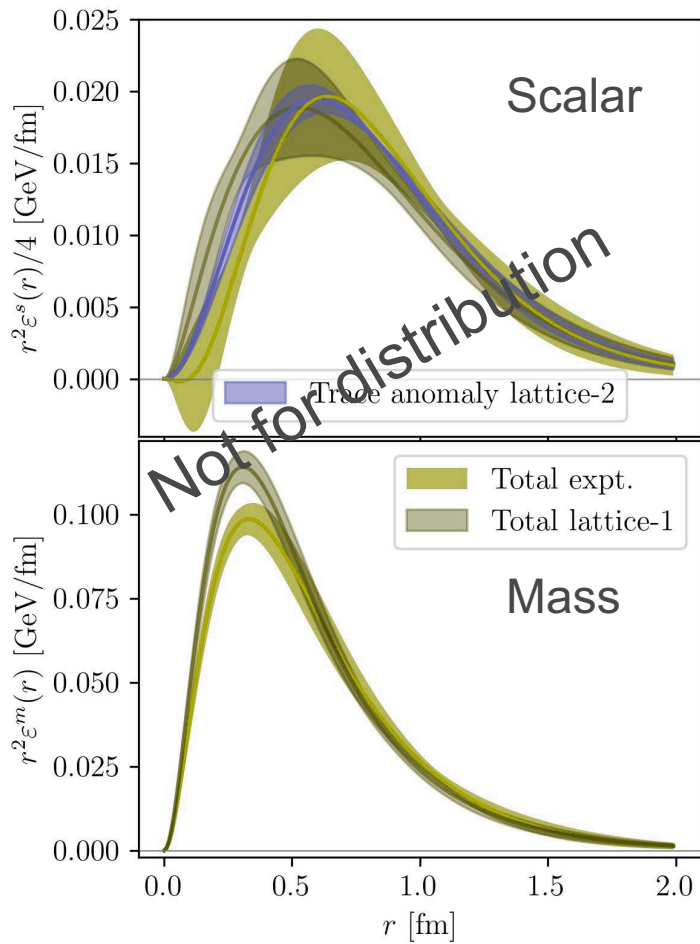


(a)



BREIT FRAME SCALAR AND MASS "DENSITIES"

Global analysis from DVCS (q) & J/psi (g) Expts. compared to lattice-1 and lattice-2



Lattice-1: D.C. Hackett, D.A. Pefkou and P.E. Shanahan, Phys. Rev. Lett. **132**, no.25, 251904 (2024)

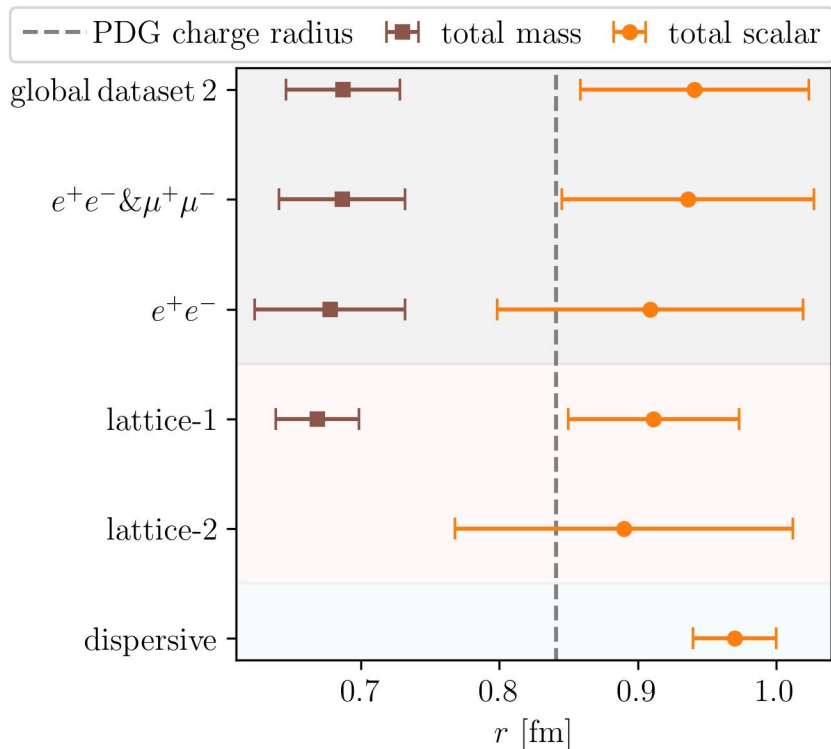
Lattice-2: B. Wang et al. [χ QCD], Phys. Rev. D **109**, no.9, 094504 (2024)
doi:10.1103/PhysRevD.109.094504 [arXiv:2401.05496 [hep-lat]].

Quark contribution to experiment: Y. Guo, F. Yuan and W. Zhao, "Bayesian Inferring Nucleon Gravitational Form Factors via Near-Threshold J/psi Photoproduction," Phys. Rev. Lett. **135** (2025) no.11, 111902 doi:10.1103/3x7r-ythq [arXiv:2501.10532 [hep-ph]].

Ji, Meziani, Joosten and Pefkou
Under review at Science

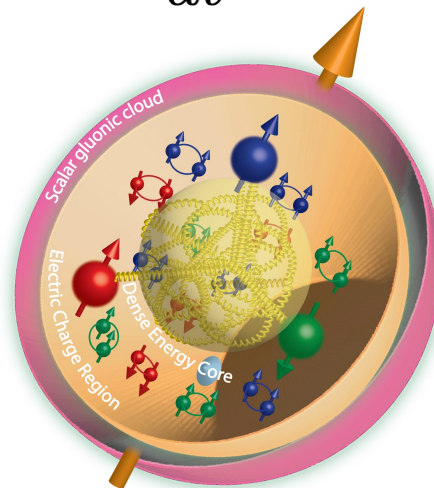
EXTRACTION OF SCALAR/MASS RADIUS OF THE NUCLEON

Gluonic mass and scalar radii



A picture of three zones?

$$\langle r_m^2 \rangle = 6 \frac{dA(t)}{dt} \Big|_{t=0} - 6 \frac{D(0)}{4M^2}$$
$$\langle r_s^2 \rangle = 6 \frac{dA(t)}{dt} \Big|_{t=0} - 18 \frac{D(0)}{4M^2}$$

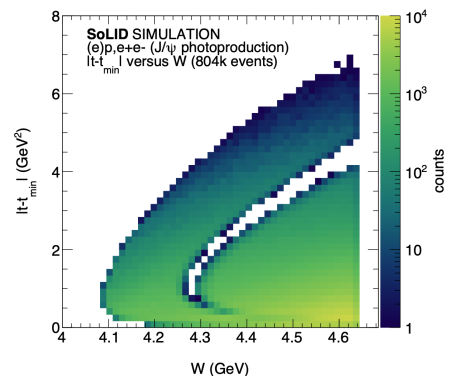
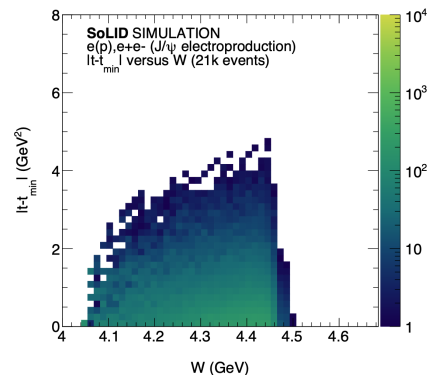
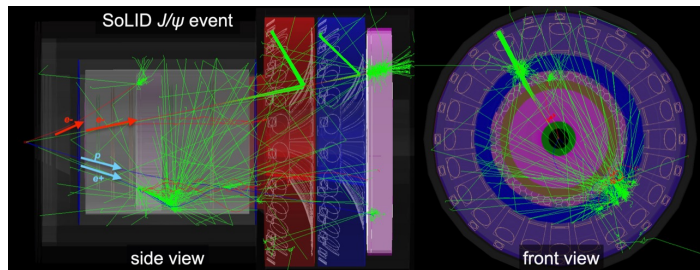
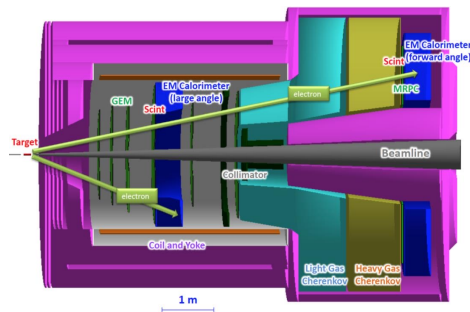


Cao, X.-H., Guo, F.-K., Li, Q.-Z. & Yao, D.-L.
Dispersive determination of nucleon gravitational form factors. Nat. Commun. 16, 6979, DOI: [10.1038/s41467-025-62278-9](https://doi.org/10.1038/s41467-025-62278-9) (2025). [2411.13398](https://doi.org/2411.13398).

FUTURE SOLID EXPERIMENT AT JLAB

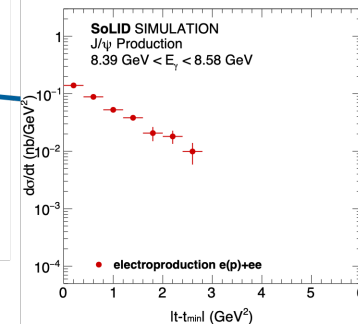
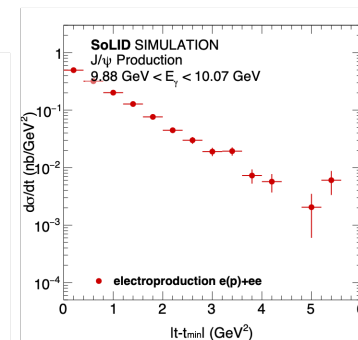
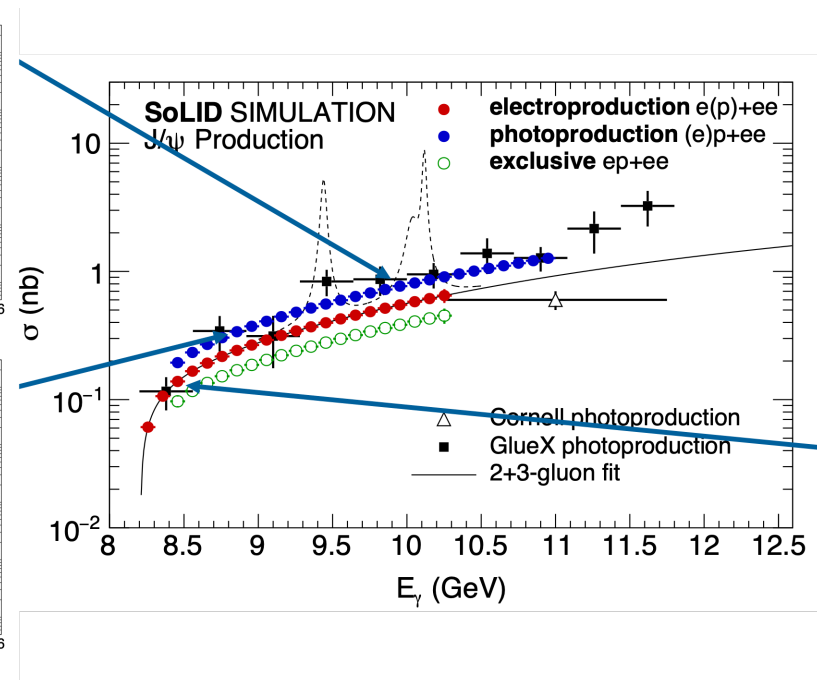
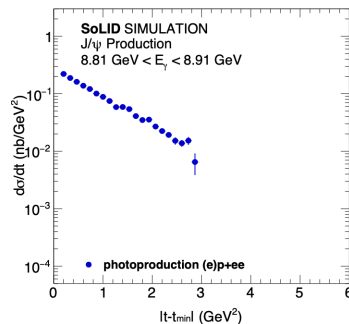
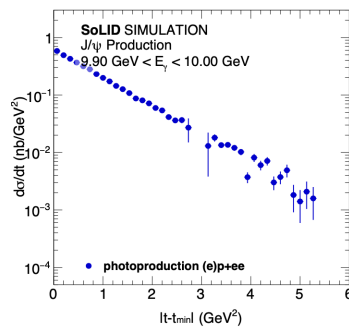
Ultimate experiment for near-threshold J/ψ production

- General purpose large-acceptance spectrometer
- 50 days of $3\mu\text{A}$ beam on a 15cm long LH2 target ($10^{37}/\text{cm}^2/\text{s}$)
- Ultra-high luminosity: 43.2ab^{-1}
- 4 channels:
 - Electroproduction ($e, e-e^+$)
 - Photoproduction ($p, e-e^+$)
 - Inclusive ($e-e^+$)
 - Exclusive ($ep, e-e^+$)



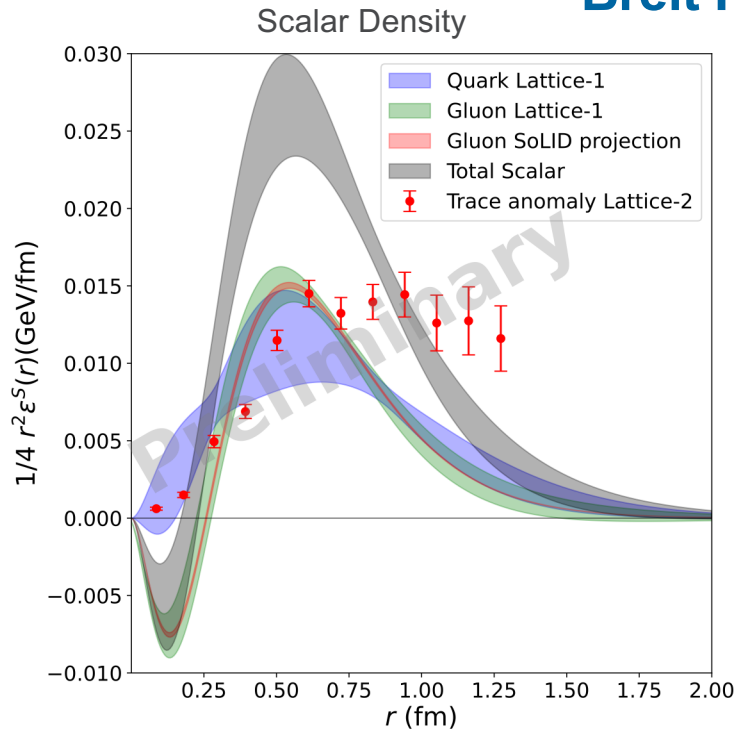
FUTURE SOLID EXPERIMENT AT JLAB

Precision measurement of J/ψ near threshold



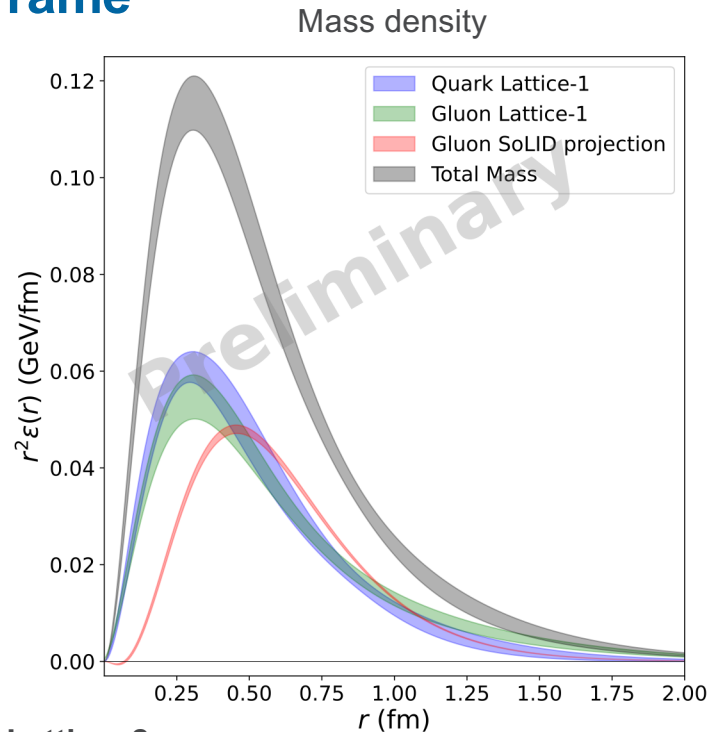
SOLID IMPACT ON GLUON SCALAR AND MASS DENSITY

Breit Frame



Lattice-1

D. C. Hackett, D. A. Pefkou and P. E. Shanahan, Phys. Rev. Lett. **132** (2024) no.25, 251904
doi:10.1103/PhysRevLett.132.251904



Lattice-2

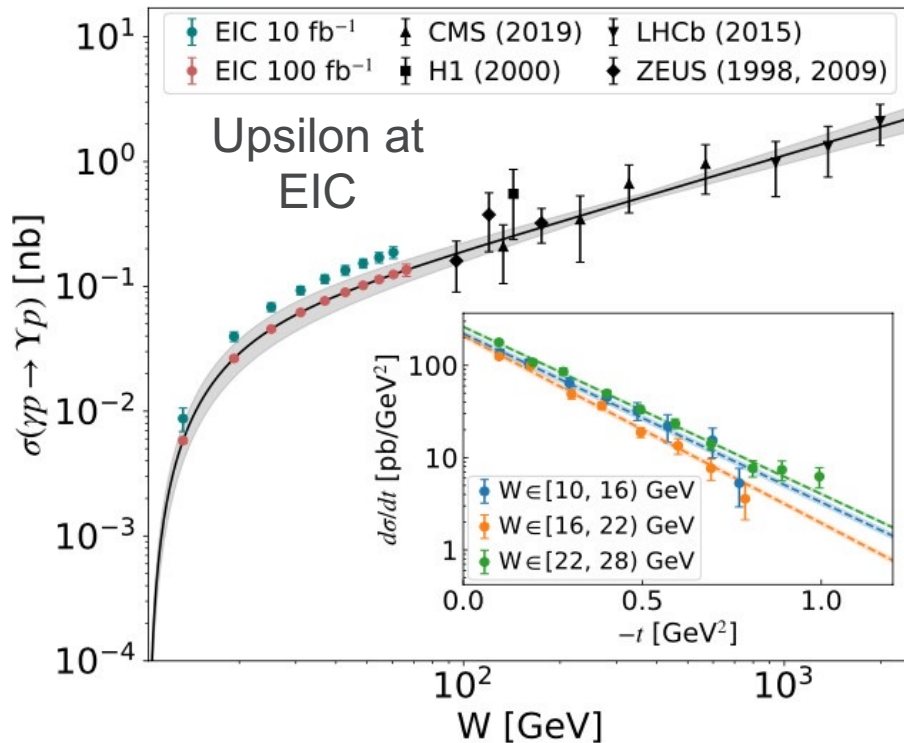
F. He et al, Phys. Rev. D **104**, no.7, 074507 (2021)
doi:10.1103/PhysRevD.104.074507 [arXiv:2101.04942 [hep-lat]]

B. Wang et al. [χ QCD], Phys. Rev. D **109**, no.9, 094504 (2024)
doi:10.1103/PhysRevD.109.094504 [arXiv:2401.05496 [hep-lat]].

COMPLEMENTARITY WITH EIC

Upsilon production and J/psi production at large Q^2

- $Y(1S)$ 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, near- threshold **J/ψ production at large Q^2** may be experimentally feasible!



CONCLUSION

- We are at the dawn of an exciting avenue of nucleon's gluonic structure research through the determination of the gluons GFFs of the nucleon.
- Present photoproduction of J/ψ data suggest a **scalar radius around 1 fm consistent with lattice QCD**.
- We have a sneak preview of the gluonic scalar density distribution in the proton from data with the help of models. **Scalar gluons configurations, at the origin of the nucleon mass, seem to define the "skin" of the nucleon.**
- Statistical precision will enable an understanding of the systematic uncertainties in the extractions of the mass radius and the scalar radius with controlled approximations.
- EIC Υ photoproduction measurements are critical **for validating the universality of the gluonic GFFs independent of models.**

Thank you!

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