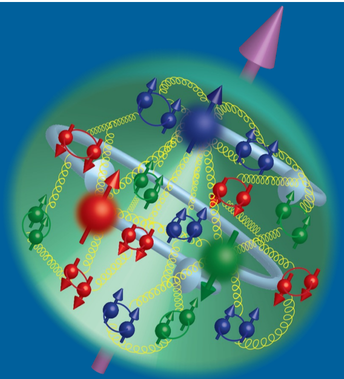
THE SCALAR ENERGY DENSITY AND THE SIZE OF THE PROTON



ZEIN-EDDINE MEZIANI

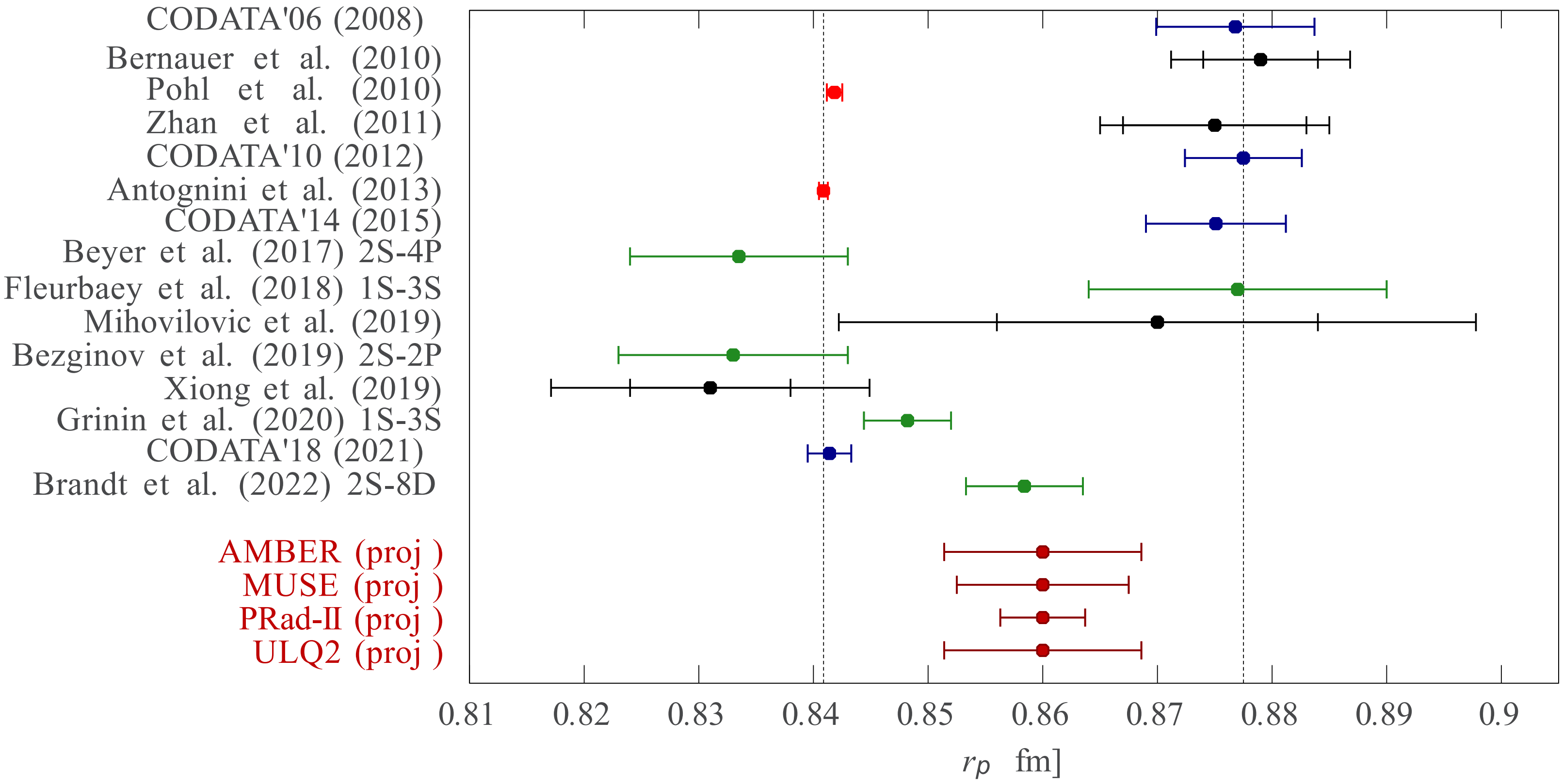
Argonne National Laboratory

With thanks to Xiangdong Ji, Dimitra Pefkou and Sylvester Joosten

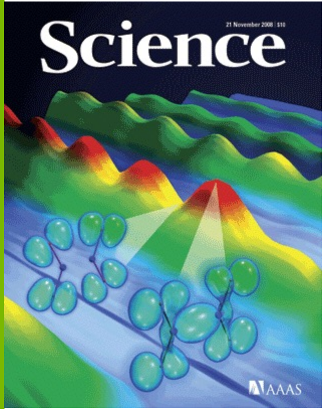
Maimi FIU February 24-28, 2024

WHAT IS THE SIZE OF THE PROTON?

Most of us would think of its charge radius



Hadron Masses from Lattice QCD



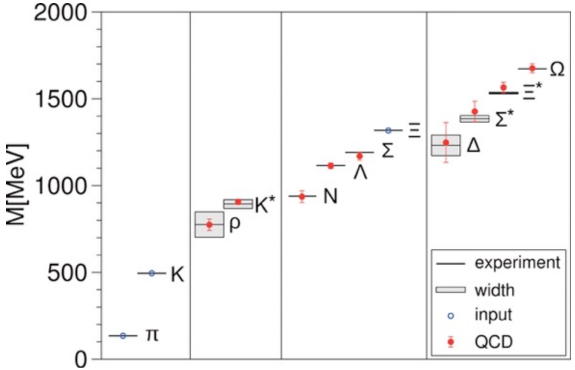
(2008)

Ab Initio Determination of Light Hadron Masses

S. Dürr, Z. Fodor, C. Hoelbling,
R. Hoffmann, S.D. Katz, S. Krieg, T. Kuth, L. Lellouch, T. Lippert, K.K. Szabo and G. Vulvert

Science 322 (5905), 1224-1227
DOI: 10.1126/science.1163233

744 citations as02/22/2025



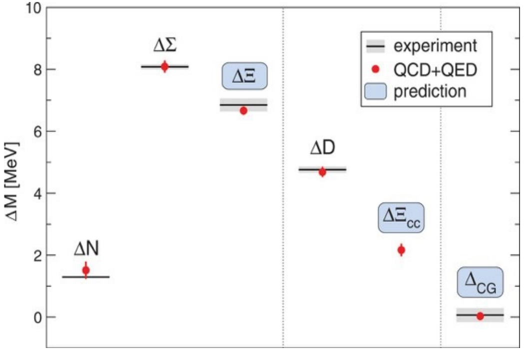
(2015)

Ab initio calculation of the neutron-proton mass difference

Sz. Borsanyi, S. Durr, Z. Fodor, C. Hoelbling, S.D. Katz,S. Krieg, L. Lellouch, T. Lippert, A. Portelli, K. K. Szabo, and B.C. Toth

Science **347** (6229), 1452-1455
DOI: 10.1126/science.1257050

433 citations

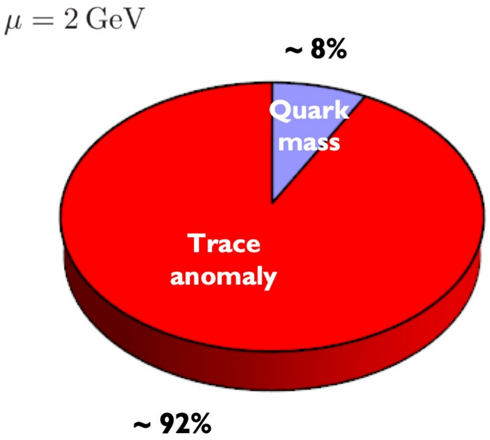


How does QCD generate this? The role of quarks and of gluons?

DIFFERENT MASS DECOMPOSITIONS

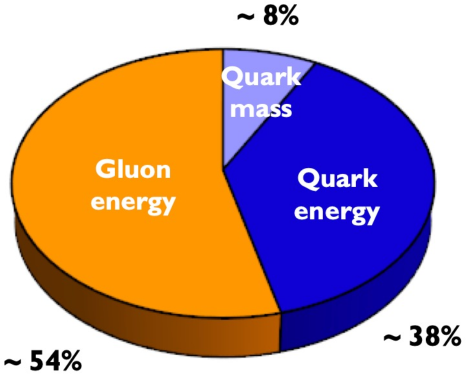
Proton Mass budget decompositions C. Lorcé (from 2022 INT workshop)

Trace decomposition



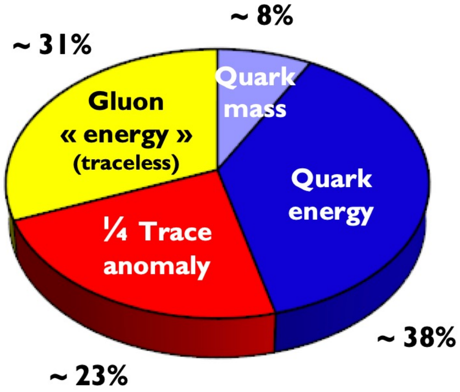
Relies on
virial theorem

Energy decomposition



Independent of
virial theorem

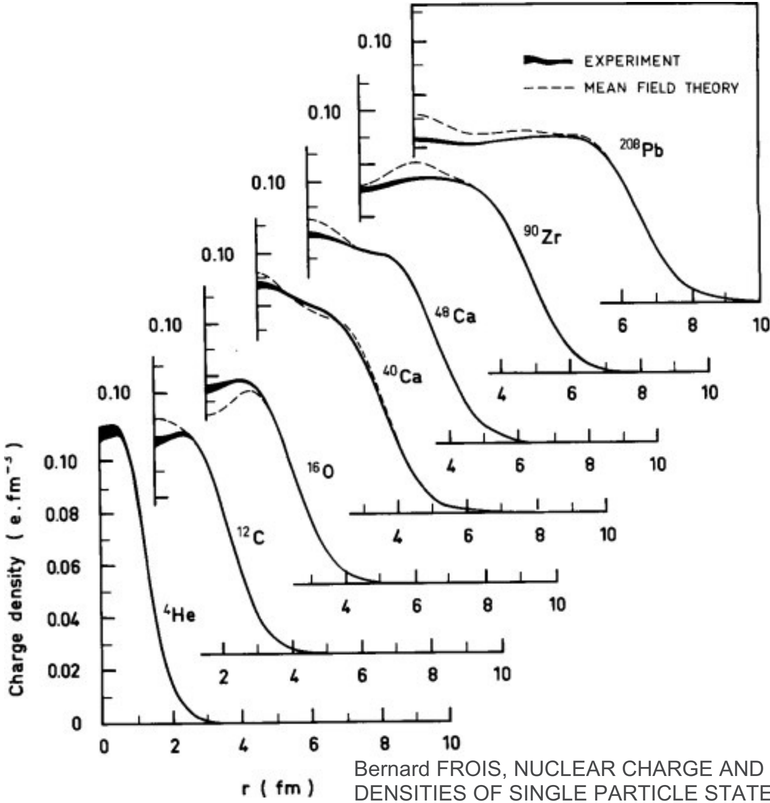
Ji's decomposition



Motivated by
virial theorem

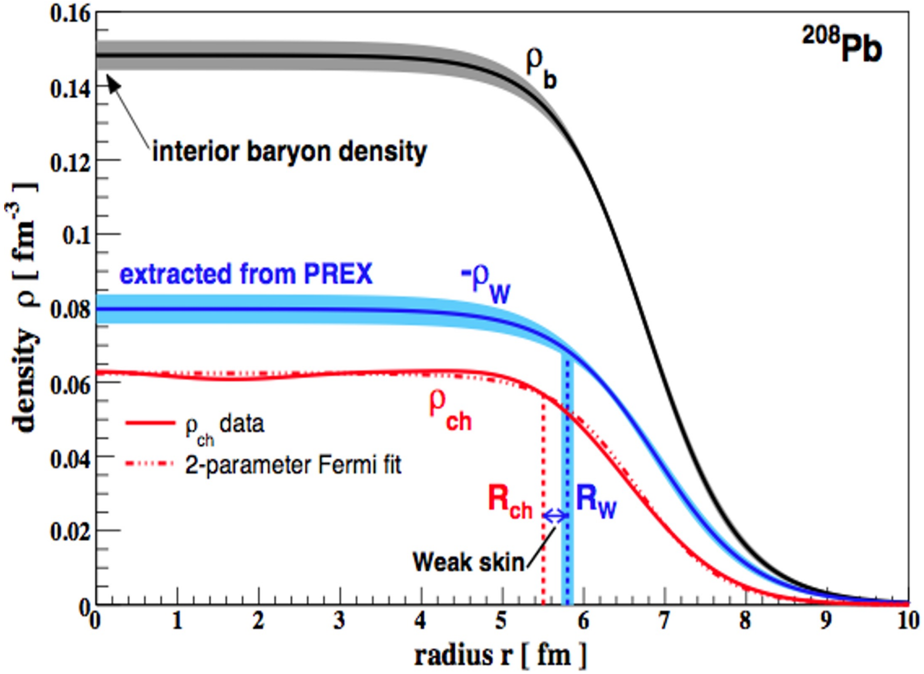
WHAT DEFINES THE SIZE OF ^{208}PB?-- BARYON DENSITY OF ^{208}PB

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

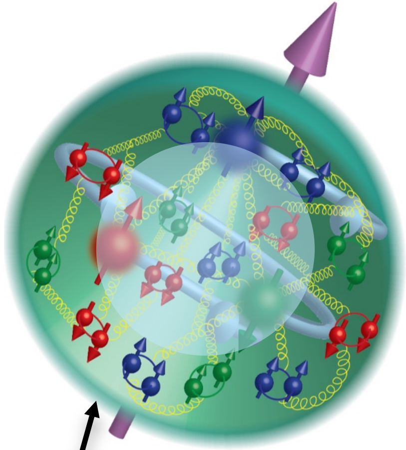
Neutron Skin extracted from PREX (R_n-R_p)



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

WHAT DEFINES THE SIZE OF A PROTON? CHARGE OR GLUON DENSITY?

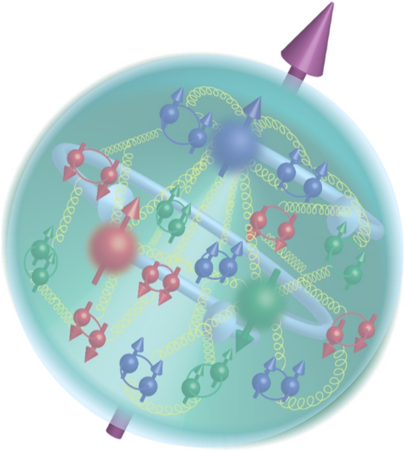
- **How is it split between gravitons-like gluons configs. and dilaton-like scalar field configs.**
- **How does the scalar gluon field radius compare to the charge radius?**
- **How about the gluon mass radius?**



Lattice predicts this one for the gluon mass contribution

Gluon energetic core?

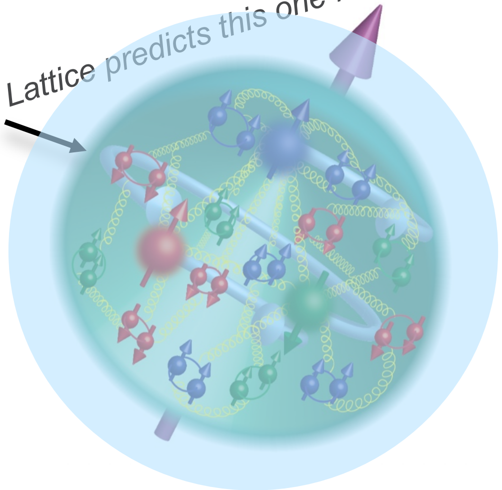
Vs



Same as charge radius?

Vs

Lattice predicts this one for the scalar radius



Energy halo beyond charge radius?

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

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

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

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

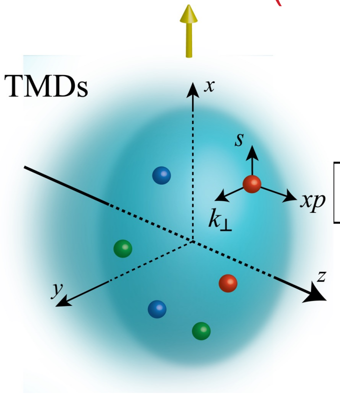
$$\bar{C}_q(t) + \bar{C}_g(t) = 0$$

Unified View of Nucleon Structure

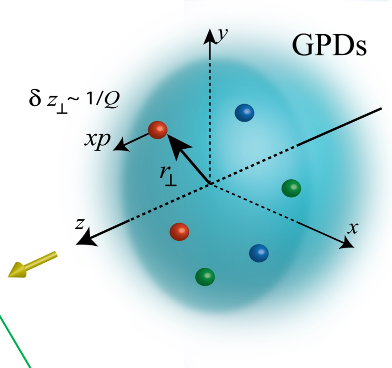
$W_p^u(x, k_T, r_T)$ *Wigner distributions*

Tomography

Transverse Momentum Dist. (TMD)



Generalized Parton Dist. (GPD)



dr_T

d^2k_T

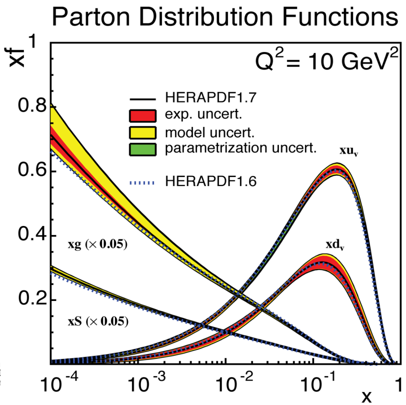
TMD $f_1^u(x, k_T)$, $h_1^u(x, k_T)$

GPD

d^2k_T

d^2r_T

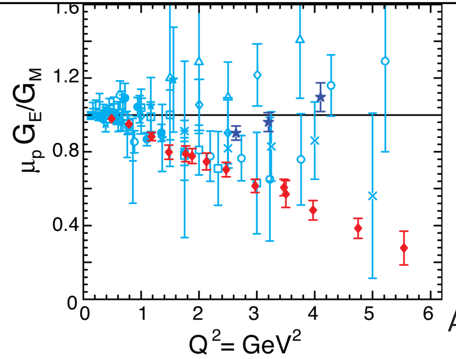
dx & Fourier Transformation



PDFs
$f_1^u(x)$, ..
$h_1^u(x)$

1D

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



U.S. DEPARTMENT OF ENERGY

Argonne NATIONAL LABORATORY

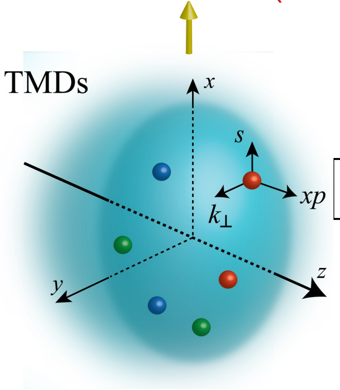
Unified View of Nucleon Structure

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

Transverse Momentum Dist. (TMD)

Tomography

Generalized Parton Dist. (GPD)

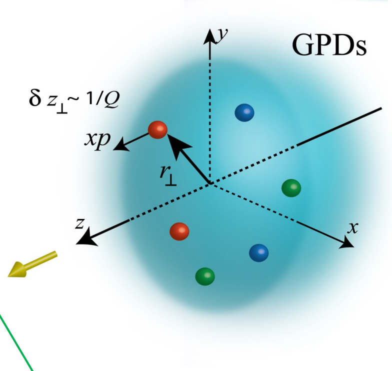


dr_T

d^2k_T

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

GPD

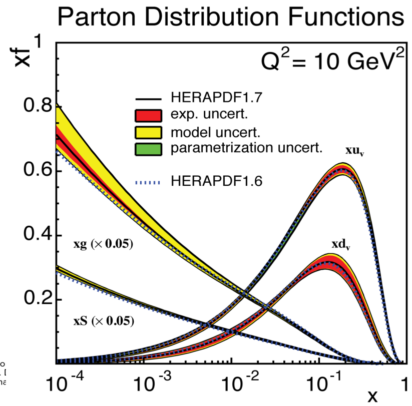


dx & Fourier Transformation

d^2k_T

d^2r_T

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



PDFs
$f_1^u(x)$, ..
$h_1^u(x)$

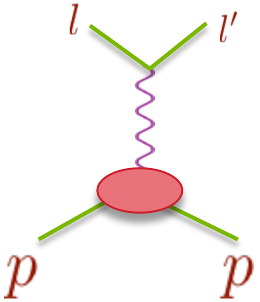
1D

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

EXPERIMENTAL REACTIONS TO DETERMINE FORM FACTORS

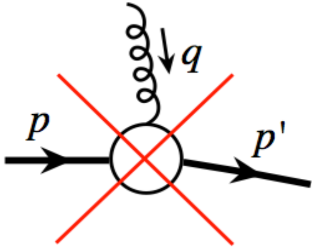
Proton electric charge distribution

Elastic Scattering



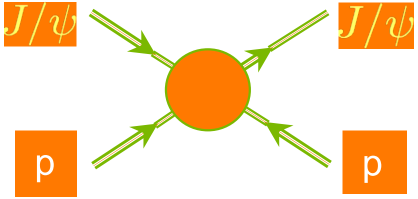
Proton color charge distribution?

Elastic color scattering; **but forbidden**

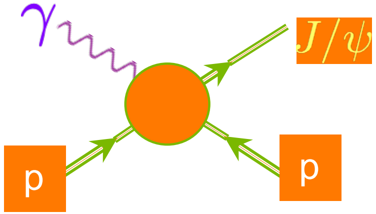


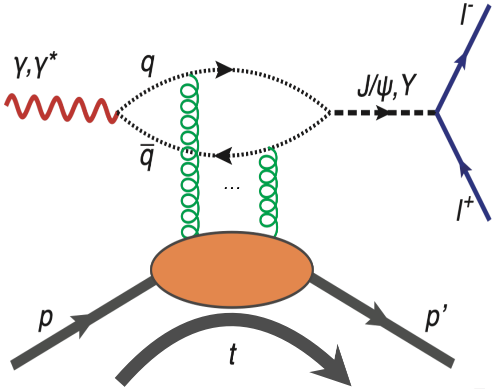
Is there an alternative to rather probe the gluon energy density in the proton?

Elastic J/ψ scattering



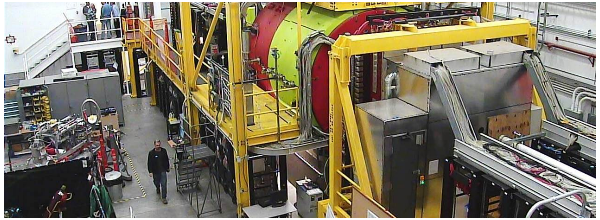
Photoproduction of J/ψ



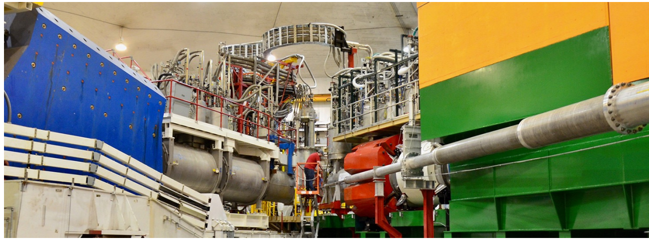


The Proton Gravitational Form Factors: Scalar and Mass Densities and their Radii

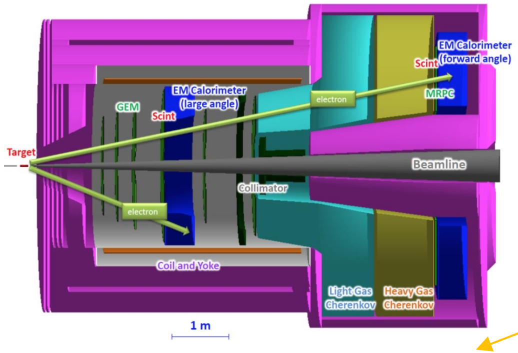
12 GEV J/Ψ EXPERIMENTS AT JEFFERSON LAB NOW AND FUTURE



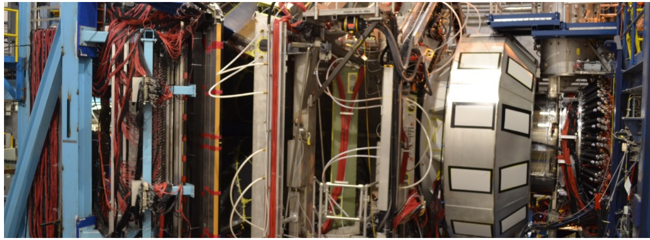
Hall D - GlueX observer the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



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



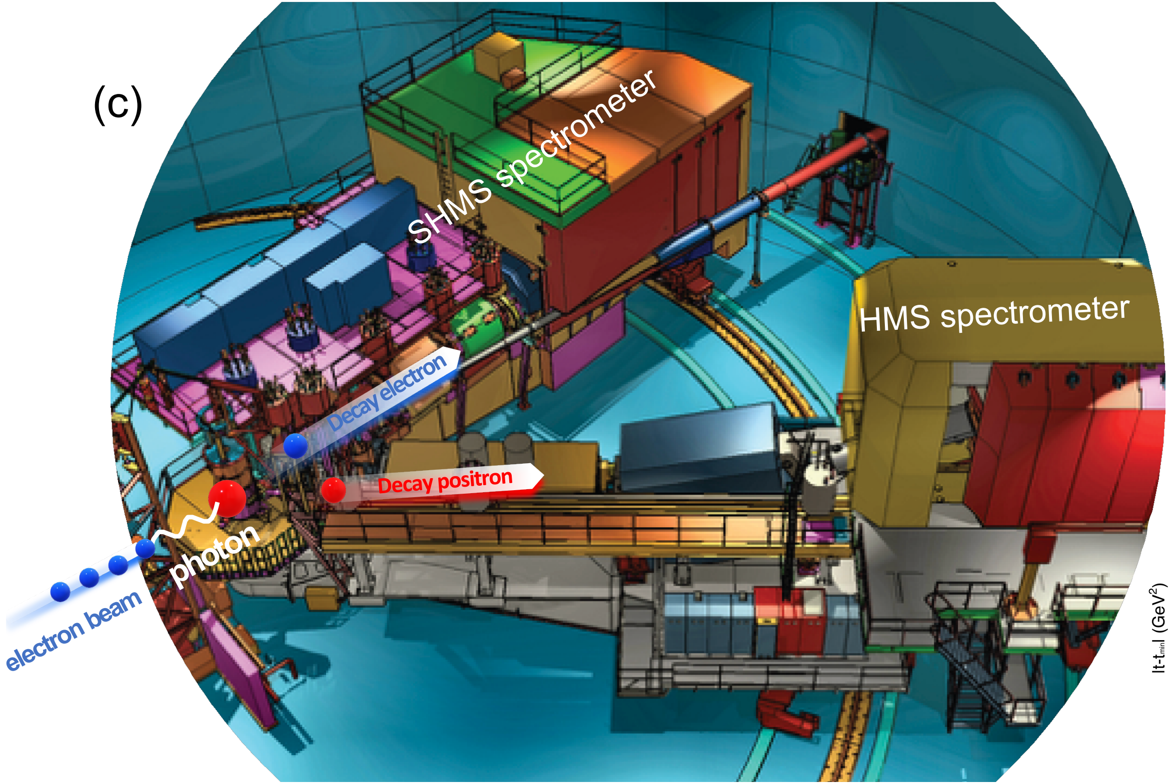
Hall A has experiment E12-12-006 at **SoLID** to measure J/ψ in electro- and photoproduction, and an LOI to measure double polarization using **SBS**

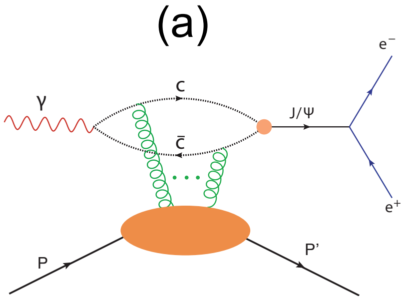


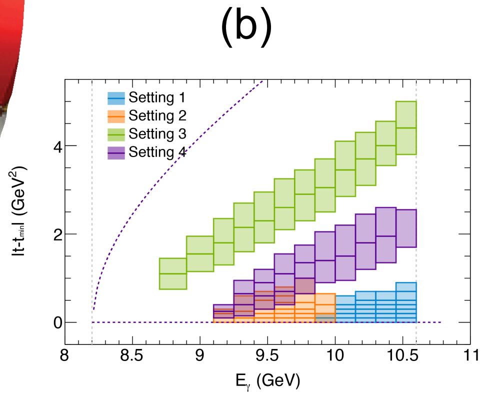
Hall B - CLAS12 has experiments to measure TCS + J/ψ in photoproduction as part of Run Groups A (hydrogen) and B (deuterium): E12-12-001, E12-12-001A, E12-11-003B

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

Near threshold photoproduction of J/ψ

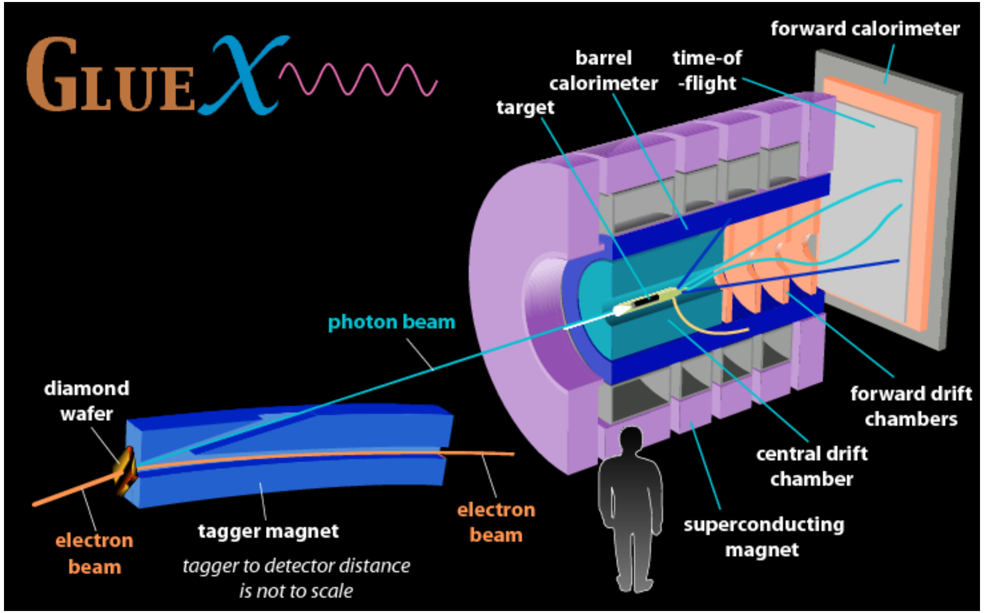




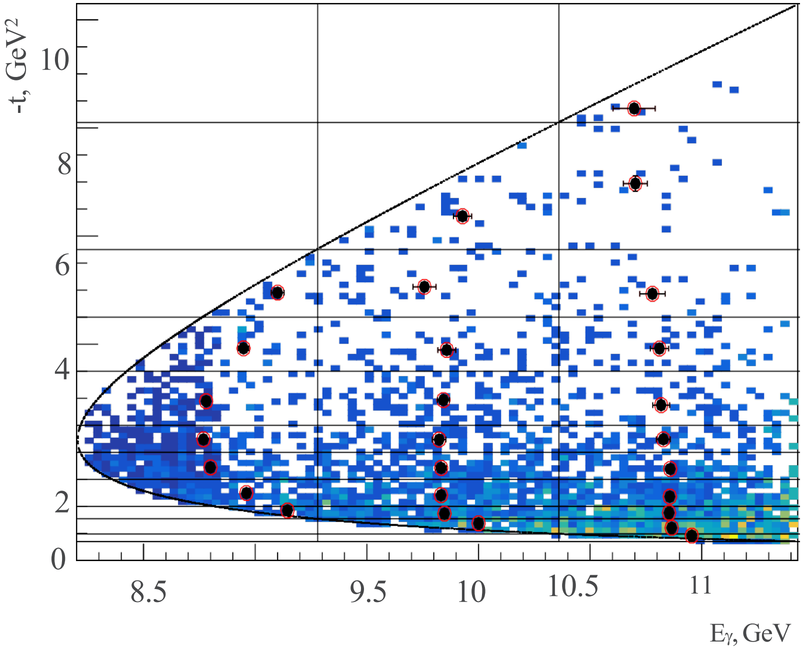


GLUEX EXPERIMENT IN HALL D AT JLAB

Setup and phase space

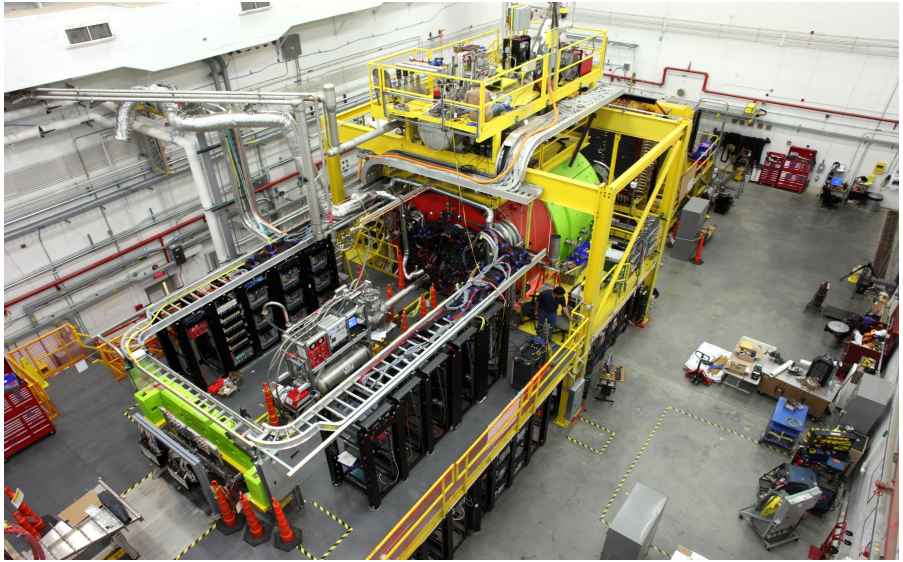


Courtesy of JLab pictures archive

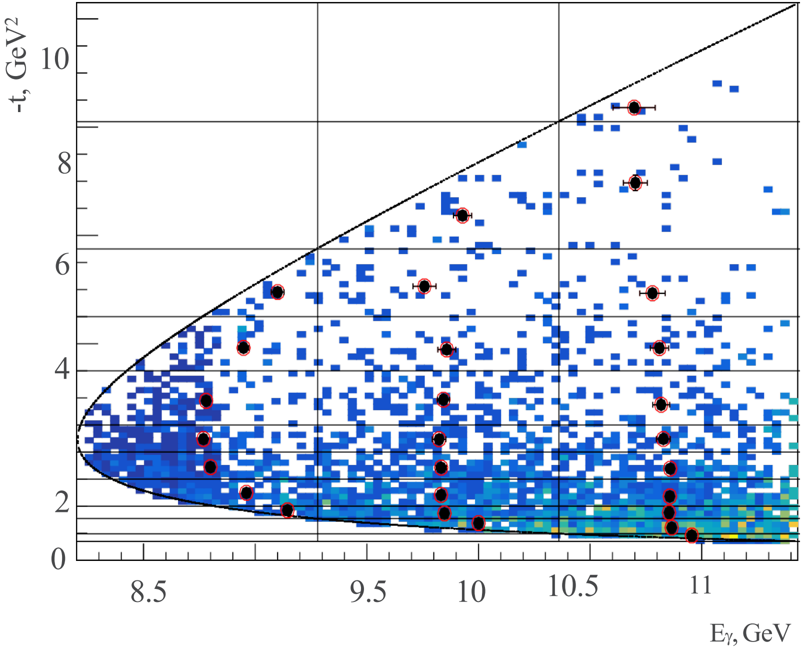


GLUEX EXPERIMENT IN HALL D AT JLAB

Setup and phase space



Courtesy of JLab pictures archive

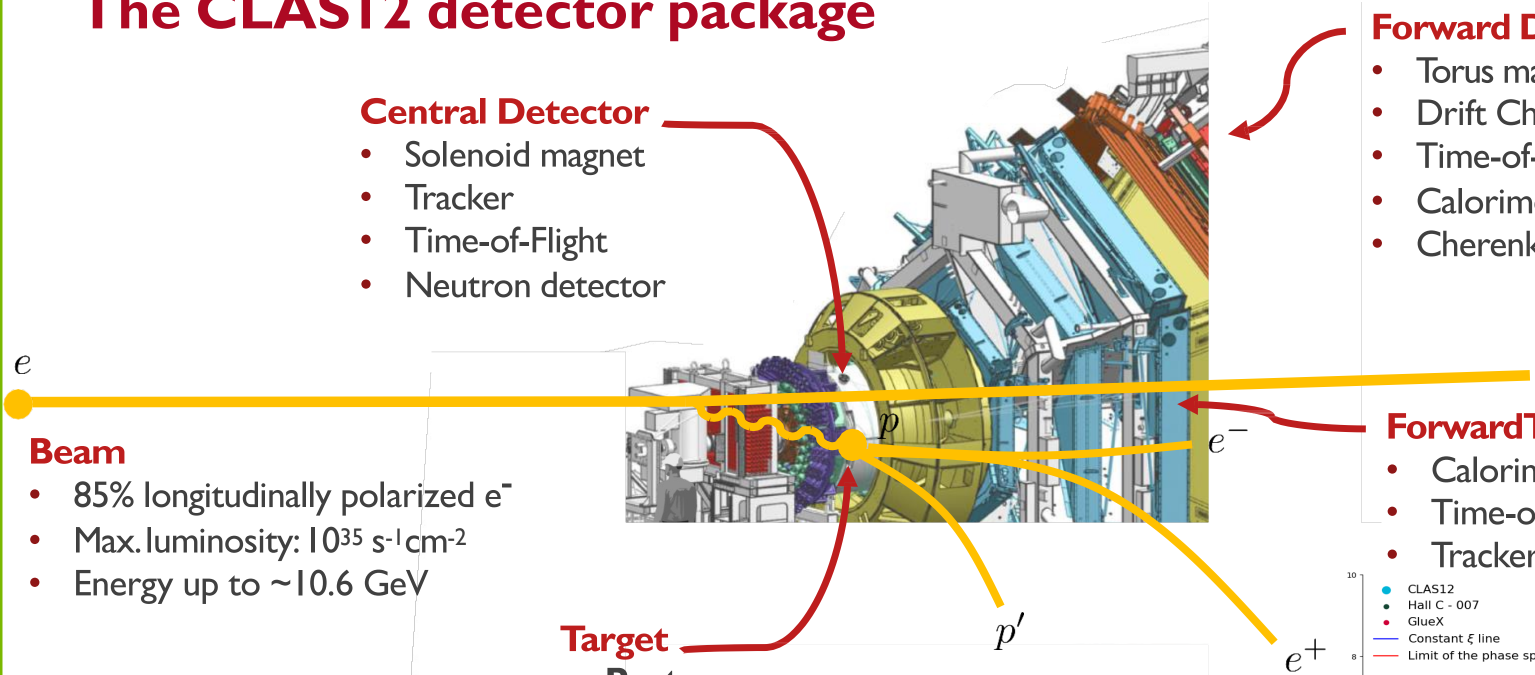


Courtesy: L. Pentchev

The CLAS12 detector package

Central Detector
- Solenoid magnet
- Tracker
- Time-of-Flight
- Neutron detector

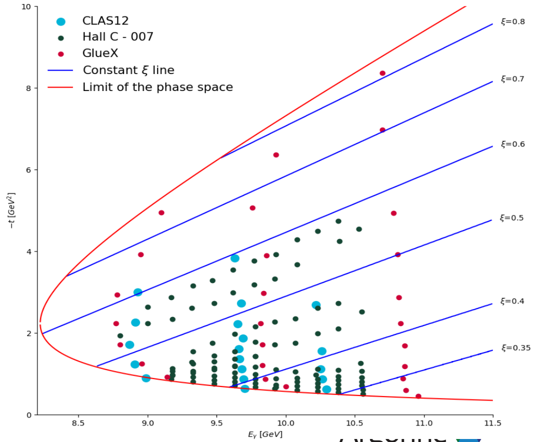
Forward Detector
- Torus magnet
- Drift Chambers
- Time-of-Flight
- Calorimeters
- Cherenkov counters



Beam
- 85% longitudinally polarized e$^-$
- Max. luminosity: 10^{35} s^{-1}cm^{-2}
- Energy up to ~10.6 GeV

Forward Tagger
- Calorimeter
- Time-of-Flight
- Tracker

Target
- **Proton**
- **Deuterium**
- Longitudinally pol. H/D
- Nuclear targets



Extraction of the cross-section of the near-threshold photoproduction of J/ψ with the CLAS12 experiment – Pierre Chatagnon – 10th of July 2024 – QNP2024

Courtesy of P. Chatagnon

RECENT RESULTS FROM JEFFERSON LAB

GlueX

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

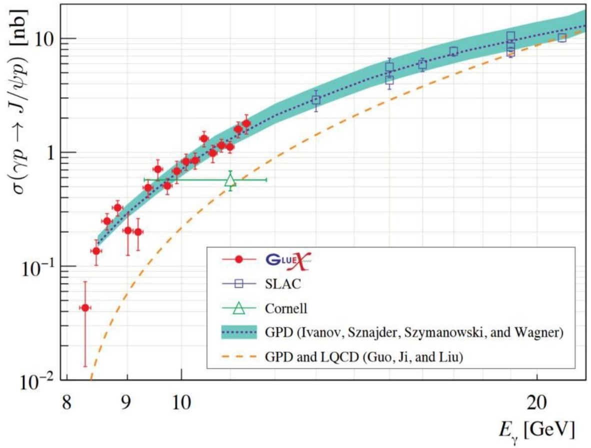
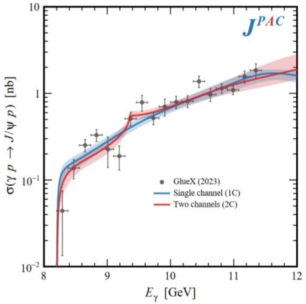
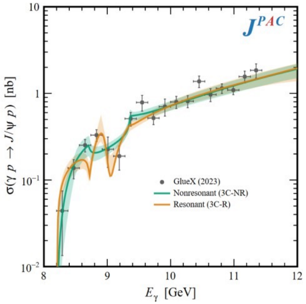
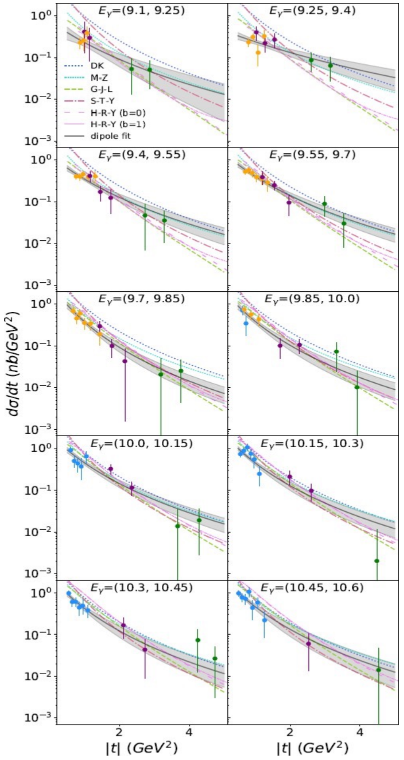


Figure from "Dynamics in near-threshold J/ψ photoproduction", D. Winney, C. Fernandez- Ramirez, A. Pilloni, A. N. Hiller Blin et al. (JPAC), Phys. Rev. D 108 (2023) 5, 054018 arXiv:2305.01449





J/psi-007 (e- channel)



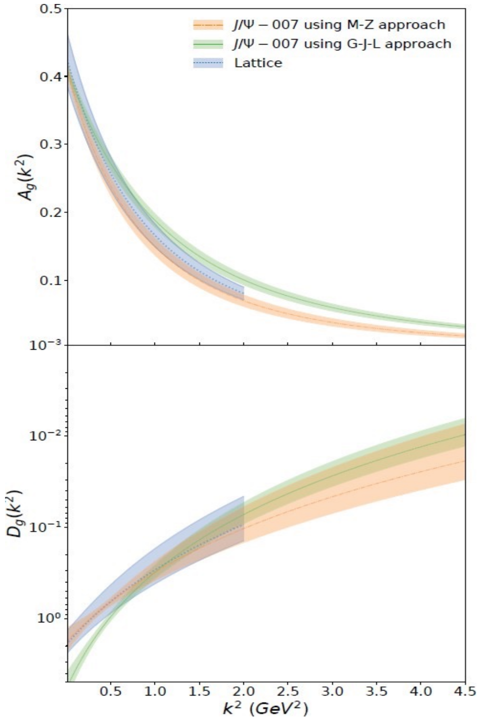
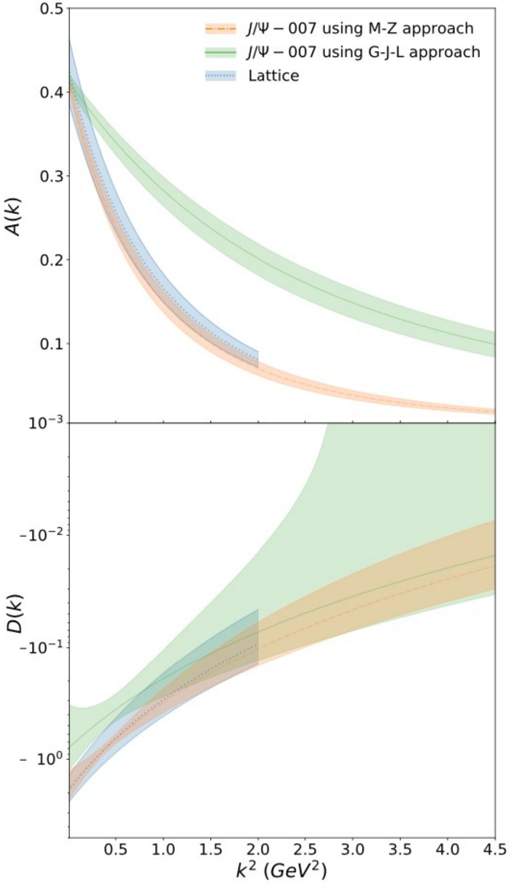
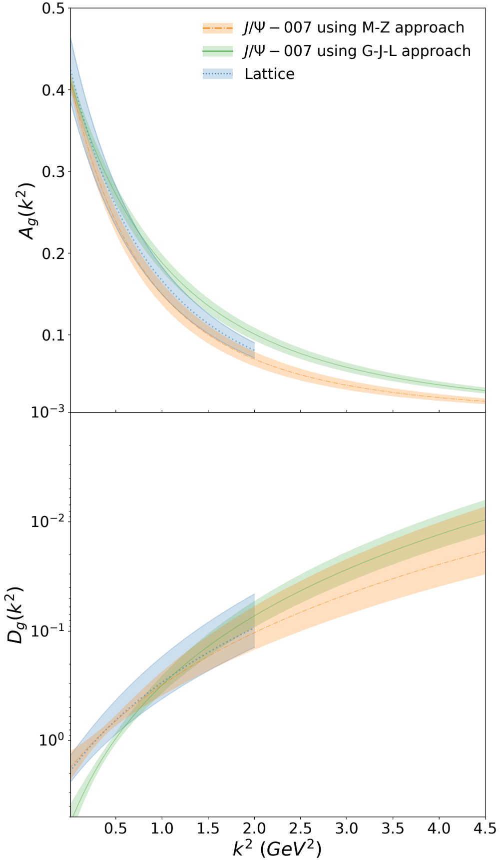


Figure from "Determining the gluonic gravitational form factors of the proton". Duran, B., Meziani, ZE., Joosten, S. *et al.* *Nature* 615, 813–816 (2023)

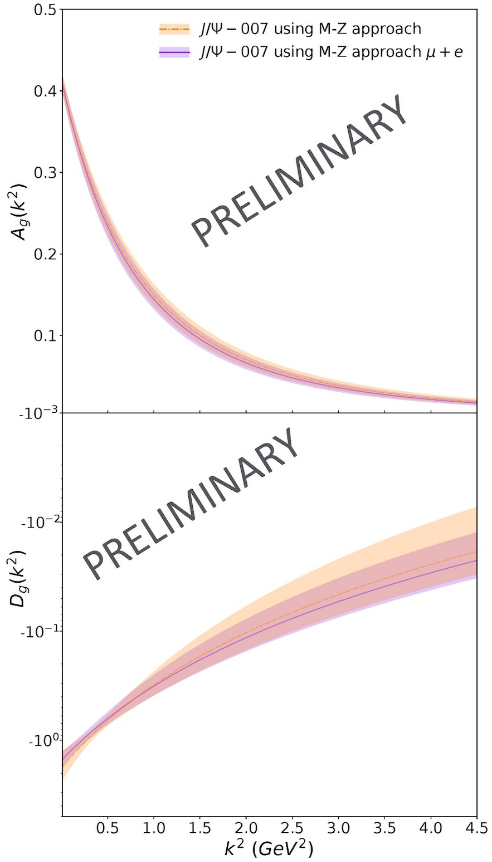
UPDATED GJL GFFS EXTRACTION RESULT (FOLLOW GREEN CURVES)



B.Duran, et al., proton, Nature **615**, no.7954, 813-816 (2023)



Update of G-J-L analysis Phys. Rev. D **108** (2023) no.3, 034003 arXiv:2305.06992 [hep-ph]



- Analysis with the muons decay channel results , doubling the statistics
- Consistent with the electron results.
- Largest impact on the *C(t)* form factor with improved precision

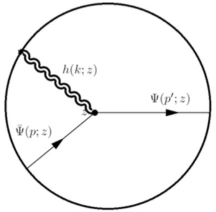
S. Prasad

JLAB J/ψ DATA: GLOBAL FIT IN THE HOLOGRAPHIC MODEL

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

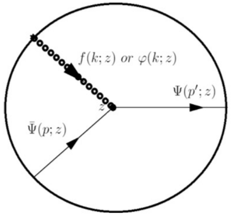
K. Mamo & I. Zahed, PRD 106, 086004 (2022) and PRD 101, 086003 (2020)

Tensor



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

Scalar



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

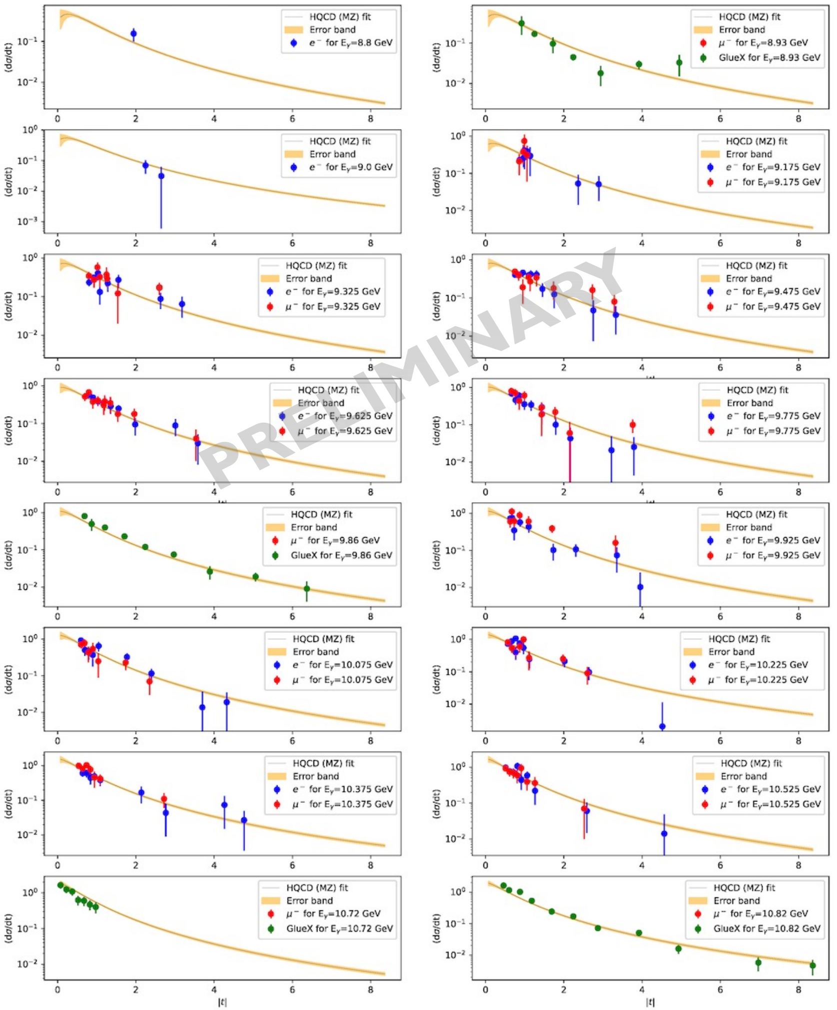
$$\frac{d\sigma}{dt} = \mathcal{N}^2 \times \frac{e^2}{64\pi(s-M^2)^2} \times \frac{\left[A(t)+4\eta^2(C(t)\right]^2}{A^2(0)} \times F(s,t) \times \frac{(2t+8M^2)}{(4M^2)}$$

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

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

- *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.

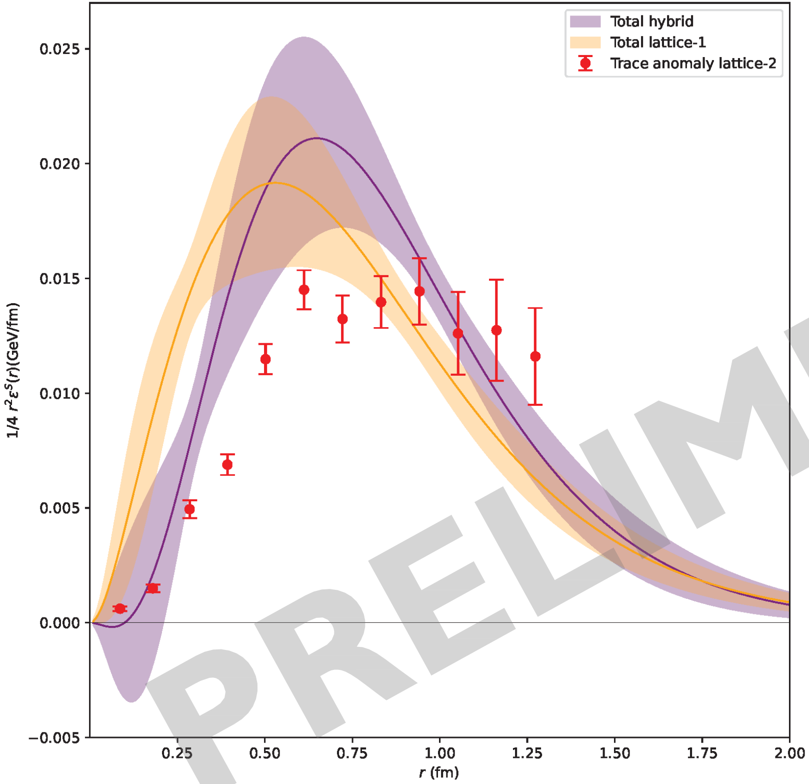
$J/\psi - 007$ (e , μ channels) and GlueX (e channel)



BREIT FRAME SCALAR AND MASS DENSITIES

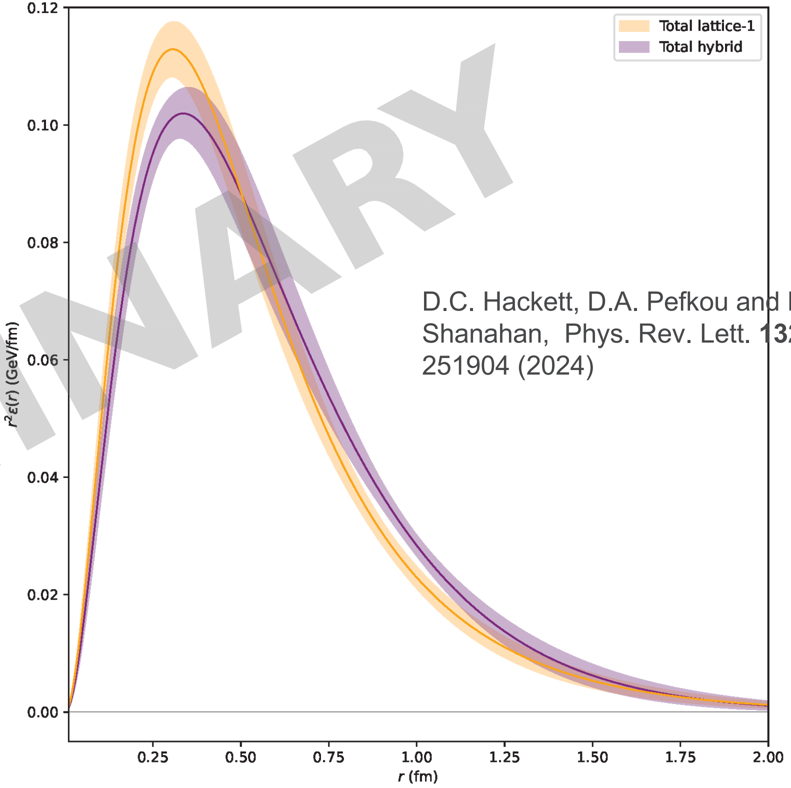
Hybrid quark-lattice + gluon-Expt. Or quark-lattice + gluon-lattice

Scalar



F. He et al. [chi-QCD],
Rev. D **104** (2021) no.7, 074507

Mass



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

Ji, Meziani, Joosten and Pefkou
Present analysis to be submitted

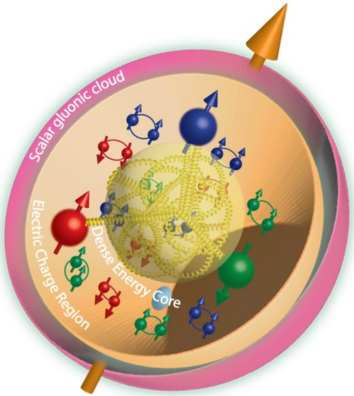
EXTRACTION OF GLUONIC SCALAR/MASS RADIUS OF THE NUCLEON

Gluonic mass and scalar radii

A picture of three zones?

$$\langle r_m^2\rangle_g = 6\frac{1}{A_g(0)}\frac{dA_g(t)}{dt}\Big|_{t=0} - 6\frac{1}{A_g(0)}\frac{C_g(0)}{M_N^2}$$

$$\langle r_s^2\rangle_g = 6\frac{1}{A_g(0)}\frac{dA_g(t)}{dt}\Big|_{t=0} - 18\frac{1}{A_g(0)}\frac{C_g(0)}{M_N^2}$$

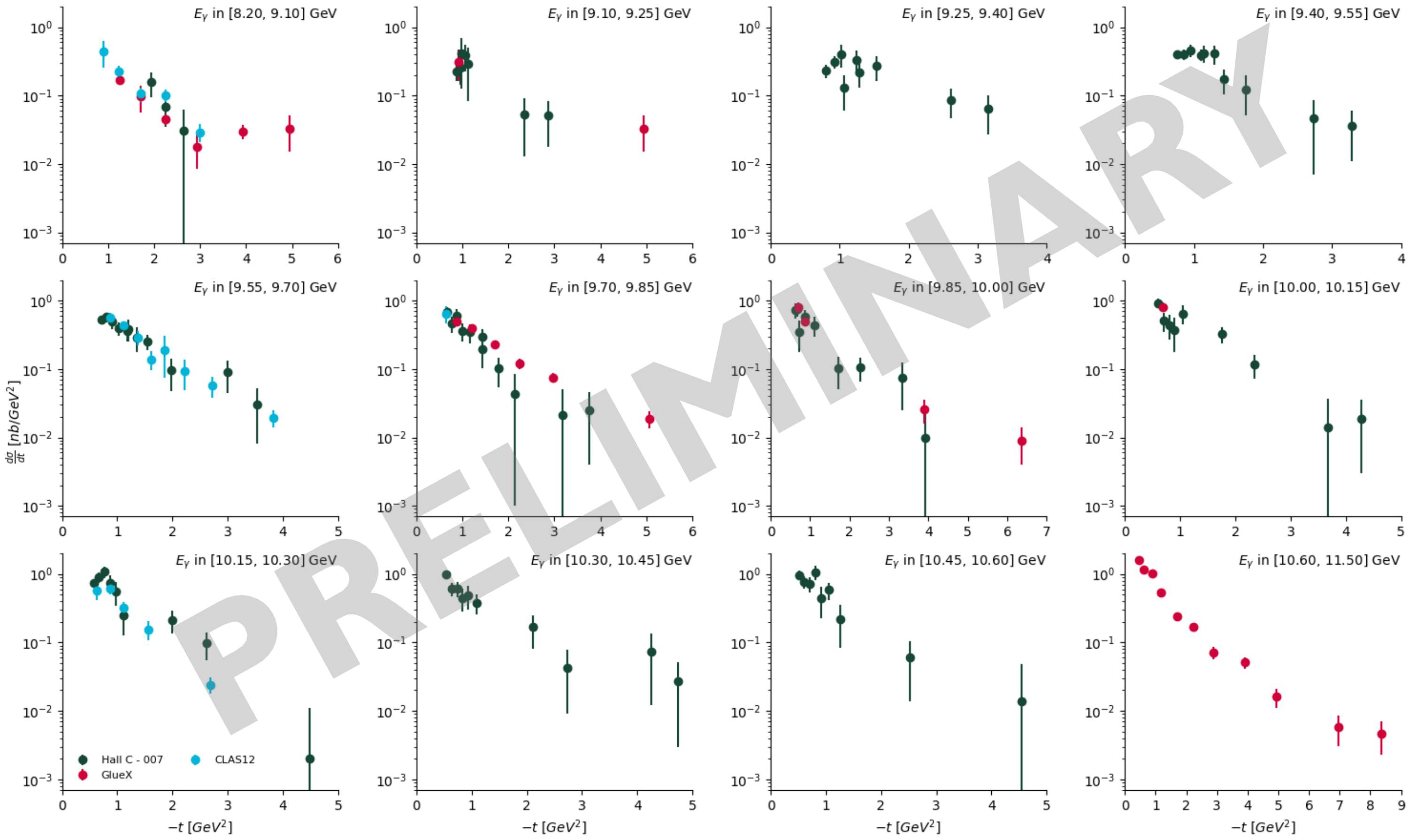


Theoretical approach Data Set # GFF functional form	χ^2/n.d.f	m_A (GeV)	m_C (GeV)	$C_g(0)$	$\sqrt{\langle r_m^2\rangle_g}$ (fm)	$\sqrt{\langle r_s^2\rangle_g}$ (fm)	$\sqrt{\langle r_s^2\rangle_T}$ (fm)
Data set # 1 Dipole-tripole	1.21	1.153±0.018	0.967 ±0.099	-0.436±0.079	0.794 ± 0.037	1.091 ±0.074	0.999±0.036
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

Argonne NATIONAL LABORATORY

Preliminary differential cross-section results

CLAS12
Courtesy of P. Chatagnon



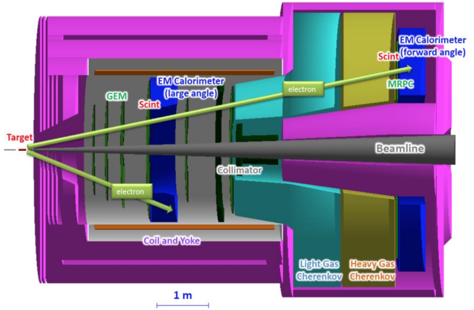
GlueX
Hall C - 007
CLAS12

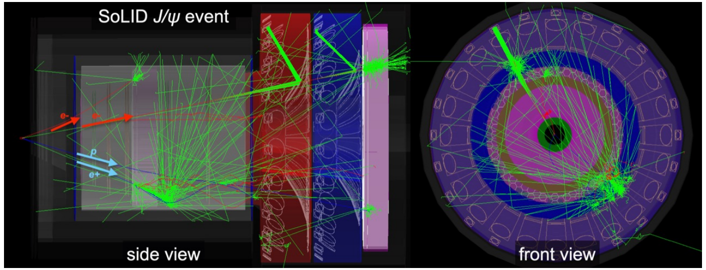
FUTURE SOLID EXPERIMENT AT JLAB

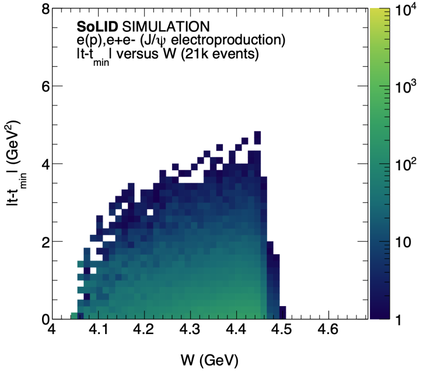
SoLID SOLENOIDAL LARGE INTENSITY DEVICE

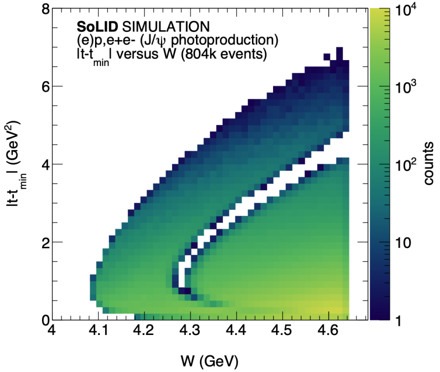
Ultimate experiment for near-threshold J/ψ production

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



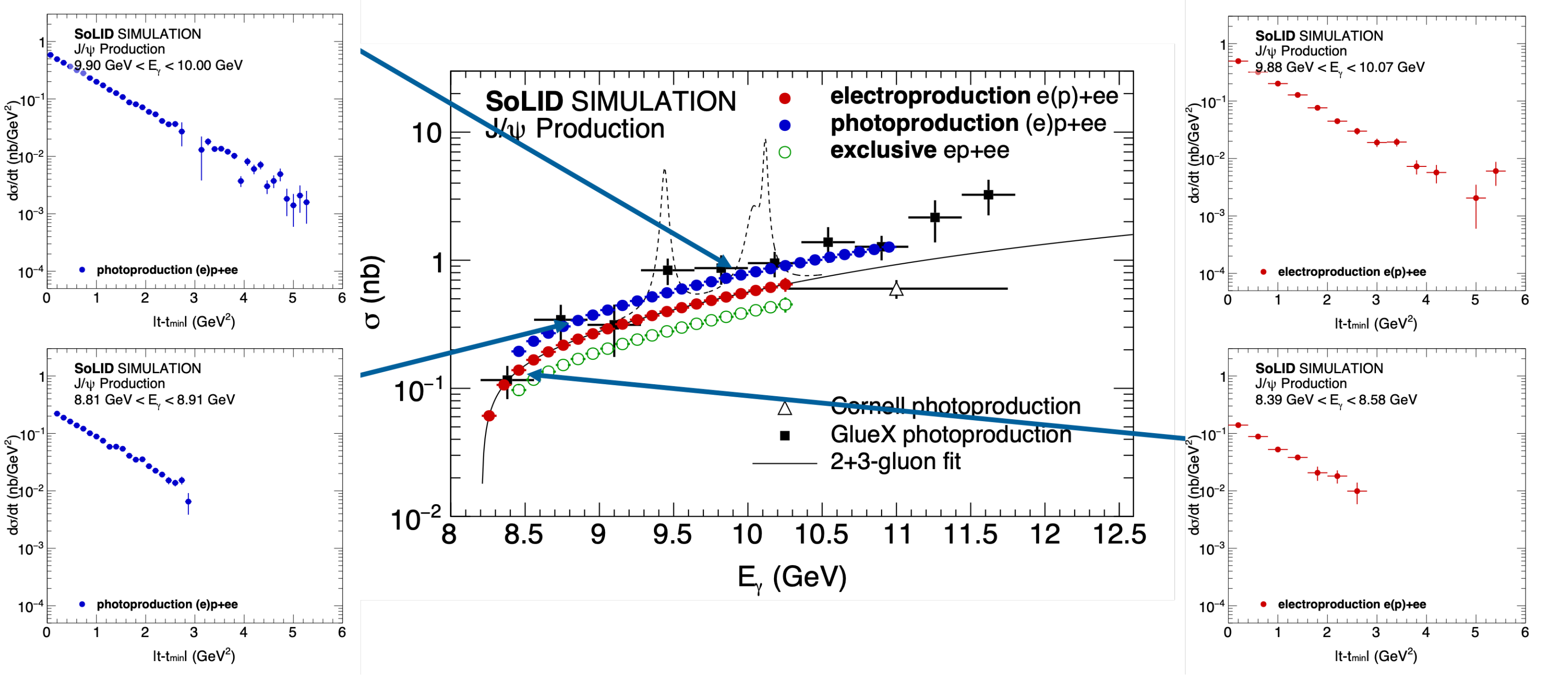






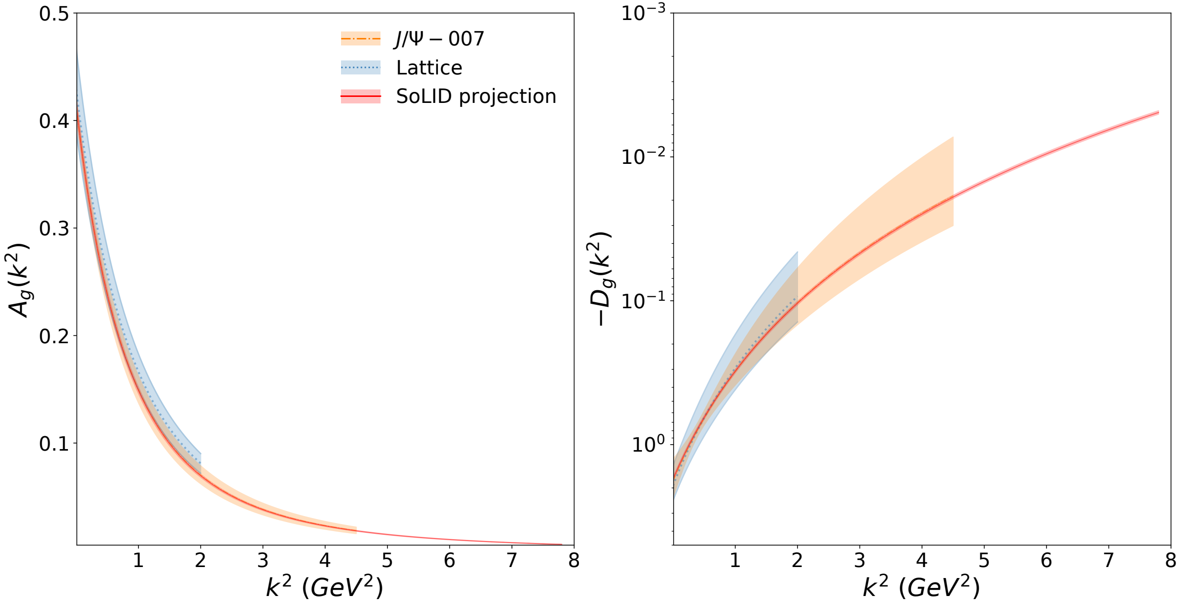
FUTURE SOLID EXPERIMENT AT JLAB

Precision measurement of J/psi near threshold



SoLID IMPACT PROJECTIONS ON GLUONIC GFFS

A(k) and -D(k) gluonic gravitational form factors compared to J/psi-007 in the holographic QCD approach and lattice predictions.



B.Duran, et al., proton, Nature **615**, no.7954, 813-816 (2023)

K. A. Mamo and I. Zahed, *Phys. Rev. D* **106**, no.8, 086004 (2022)

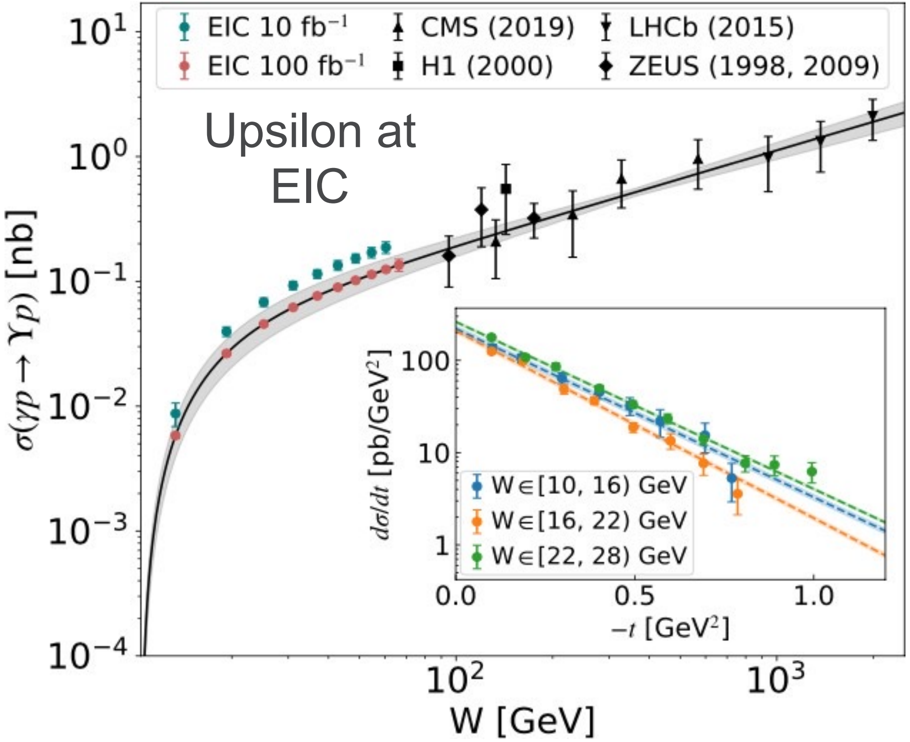
D. A. Pefkou, D. C. Hackett and P. E. Shanahan, *Phys. Rev. D* **105** (2022) no.5, 054509

COMPLEMENTARITY WITH EIC

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

- 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, 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, 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!

This was was supported in part by DE-FG02-94ER40844 and DE-AC0206CH11357