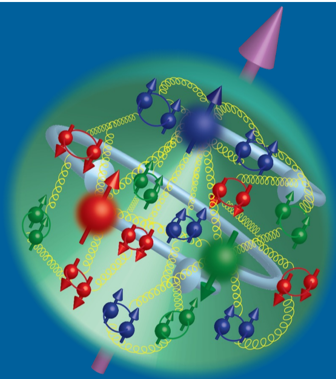
THE PROTON GLUONIC GRAVITATIONAL FORM FACTORS AND ITS MASS RADIUS



ZEIN-EDDINE MEZIANI
Argonne National Laboratory

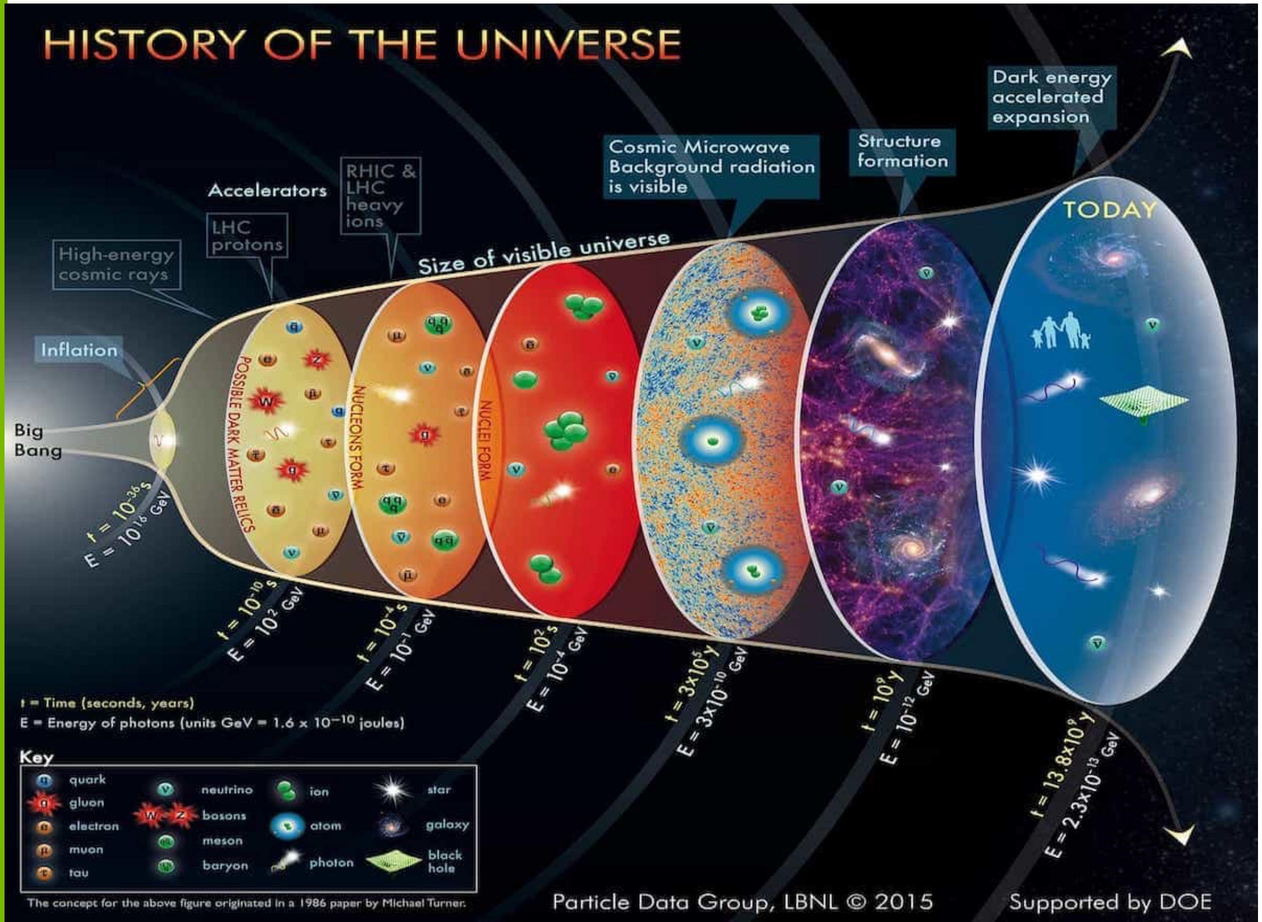
IJCLab, Orsay 03-20-2023

OUTLINE

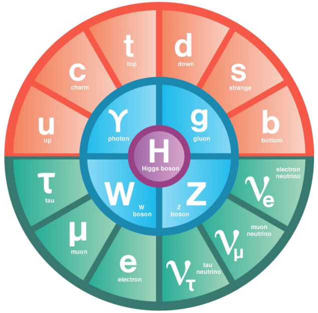
- Introduction
  - Proton mass origin
  - Proton gluonic gravitational form factors and its mass radius
- Experiment J/psi-007; J/psi threshold photoproduction on the proton
- Determination of the mass and scalar radius of the proton
- Outlook

TO KNOW YOUR FUTURE YOU MUST KNOW YOUR PAST

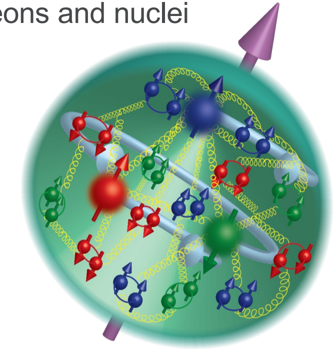
George Santanaya (American philosopher, poet and cultural critic: Born in Madrid, 1863-1952)



Standard Model of Particle Physics



Quantum Chromodynamics (QCD) is responsible for most of the visible matter in the universe providing mass and spin to nucleons and nuclei



Nucleon: A fascinating strong interacting system of confined quarks and gluons

Argonne NATIONAL LABORATORY

Science Questions

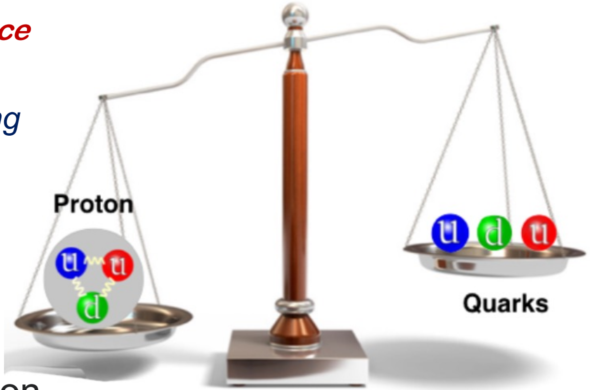
"…QCD takes us a long stride towards
the Einstein-Wheeler ideal of mass without mass
Frank Wilczek (1999, Physics Today)

Examples in nature: proton, blackhole

- What is the origin of hadron masses?
  - A case study: the proton

The 2015 Long Range Plan for Nuclear Science

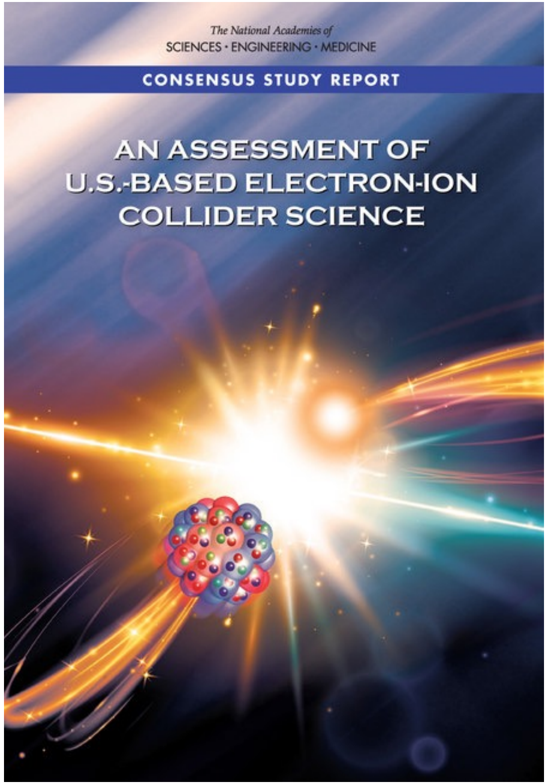
"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"



- Can we measure the gravitational form factors of the proton and determine its mass radius ?

- How does the mass radius compare with the charge radius of the proton

EXAMPLE: EIC SCIENCE ASSESSMENT BY NAS



Finding 1:

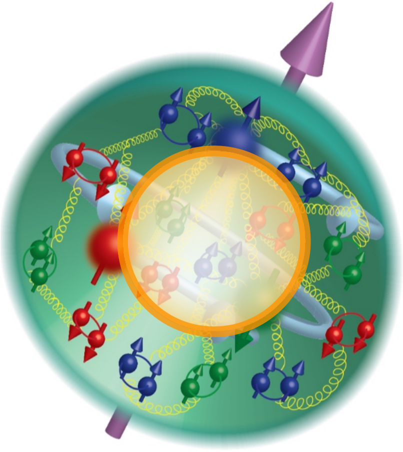
An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:

- **How does the mass of the nucleon arise?**
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

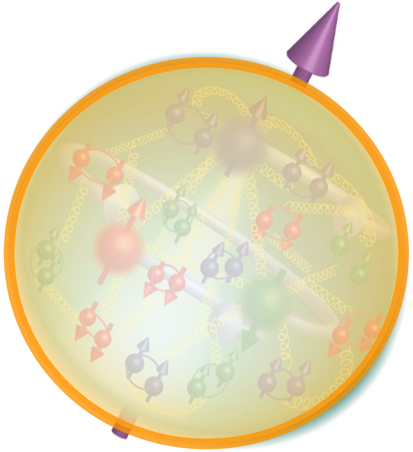
JLab and EIC will address in a truly complementary way the first two questions

WHERE IS THE ENERGY INSIDE THE PROTON?

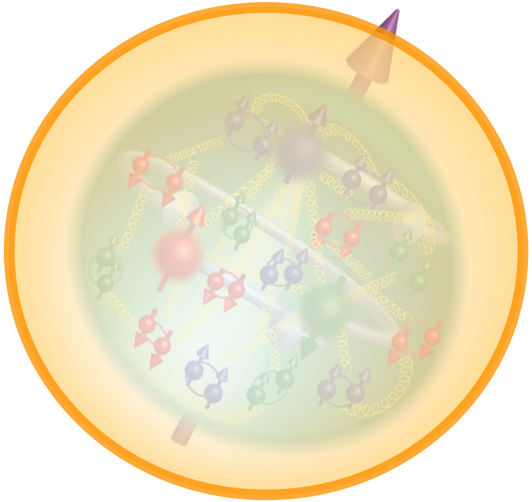
How does the mass radius compare to the charge radius?



Vs



Vs



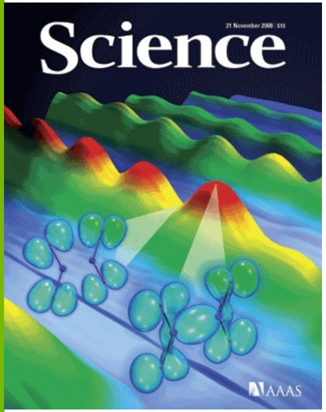
Dense energetic core?

Same as charge radius?

Energy halo beyond charge radius?

ORIGIN OF THE PROTON MASS?

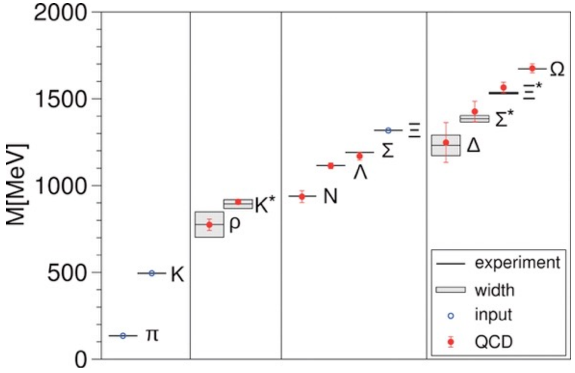
Hadron Masses from Lattice QCD



(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

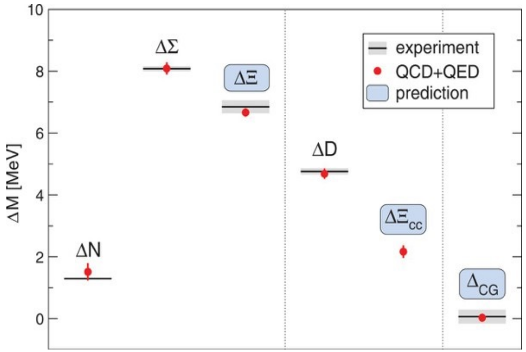
Science 322 (5905), 1224-1227
DOI: 10.1126/science.1163233



(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



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

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

See for example, **M. E. Peskin and D. V. Schroeder, An Introduction to quantum field theory, Addison-Wesley, Reading (1995), p. 682**

✧ **Trace of the QCD energy-momentum tensor:**

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

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

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

Gross, Wilczek & Politzer

At small momentum transfer, heavy quarks decouple:

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

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

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

✧ **Trace anomaly, chiral symmetry breaking, …**

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

In the chiral limit we have a finite number for the nucleon and zero for the pion

HIGGS MASS CONTRIBUTION TO THE PROTON

Pion-Nucleon Sigma Term

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

Strangeness content

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

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-GMeißner 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]

JI'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

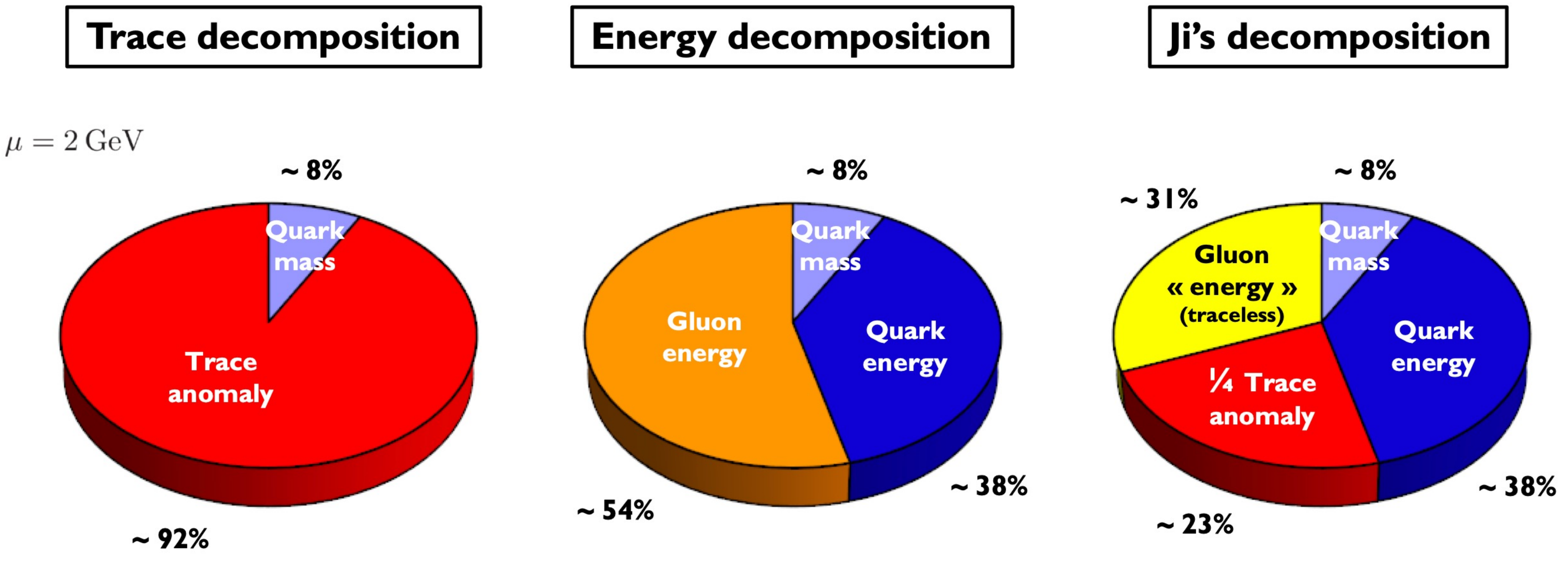
$$M_a = \frac{1}{4}(1-b) M_N$$

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

- $a(\mu)$ related to PDFs, well constrained
- **$b(\mu)$ related to quarkonium-proton scattering amplitude $T_{\psi p}$ near-threshold**

DIFFERENT MASS DECOMPOSITIONS

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



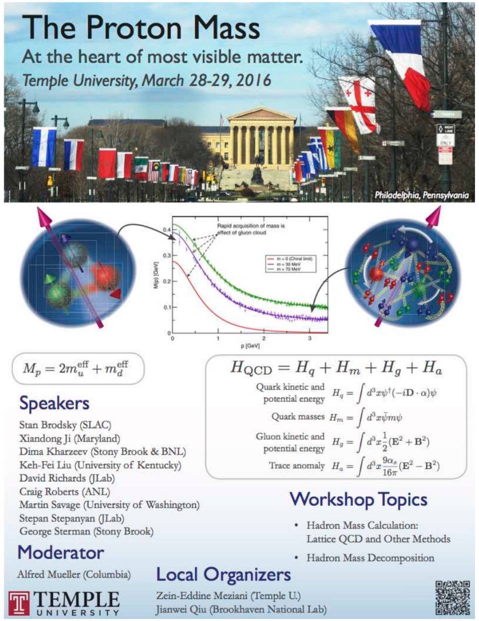
Relies on virial theorem

Independent of virial theorem

Motivated by virial theorem

THE PROTON MASS… A HOT TOPIC!

2016



2017

Jan. 2021

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

Access the trace anomaly through elastic J/psi and Upsilon production near threshold

Due to COVID-19 a 2020 Institute of Nuclear Theory in Seattle, a 4th workshop in the series: **Origin of the Visible Universe: Unraveling the Proton Mass** was delayed but held in June 2022

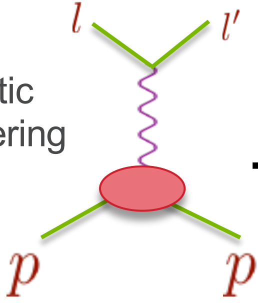
https://www.int.washington.edu/programs-and-workshops/20r-77

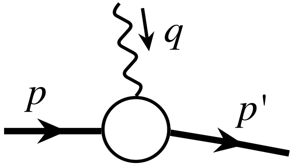
EXPERIMENTAL REACTIONS TO DETERMINE FORM FACTORS

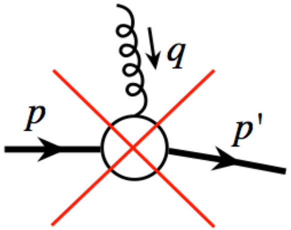
Elastic electron scattering for charge / J/psi production for gluons

Exclusive reactions

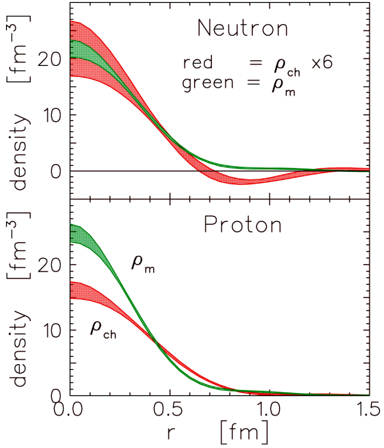
Elastic Scattering

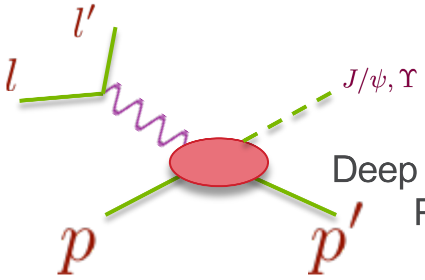




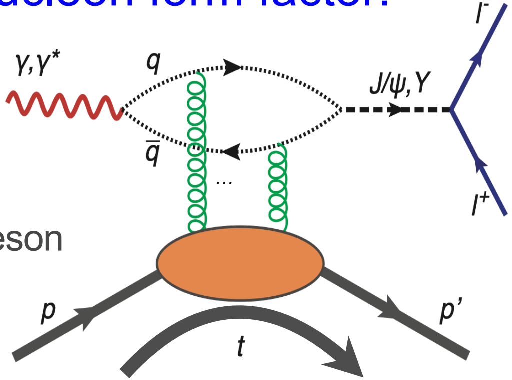


- But, NO color elastic nucleon form factor!





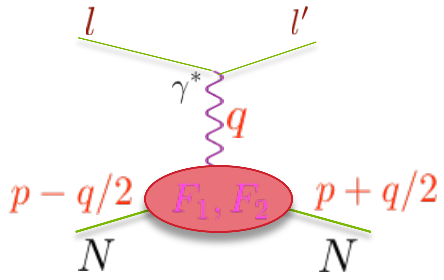
Deep Vector Meson Production (DVMP)



Threshold electro- & photoproduction of quarkonia can probe the energy distribution of gluonic fields inside the proton and nuclei

ELASTIC ELECTRON SCATTERING

- Elastic e p → e p scattering is like an electron microscope to investigate nucleon structure



R. Hofstadter
1961 Phys. Nobel Prize

- In 1-photon exchange approximation: nucleon structure parameterized by two form factors

$$\begin{aligned} A^{\mu}_{\lambda\lambda'} &= \langle p + \frac{1}{2}q, \lambda' \mid J^{\mu}(0) \mid p - \frac{1}{2}q, \lambda\rangle \\ &= \bar{u}(p + \frac{1}{2}q, \lambda')\left[F_1(Q^2)\gamma^{\mu} + F_2(Q^2)\frac{i}{2m}\sigma^{\mu\nu}q_{\nu}\right]u(p - \frac{1}{2}q, \lambda) \end{aligned}$$

Dirac Pauli

F_1 helicity conserving, F_2 helicity flip form factors

- In experiments we measure the Sachs form factors

$$\begin{aligned} G_E(Q^2) &= F_1(Q^2) - \tau F_2(Q^2) \\ G_M(Q^2) &= F_1(Q^2) + F_2(Q^2) \end{aligned}$$

$$\frac{d\sigma}{d\Omega}(E,\theta) = \sigma_M\left[\frac{G_E^2 + \tau G_M^2}{1+\tau} + 2\tau G_M^2 \tan^2(\frac{\theta}{2})\right]$$

$$\tau = \frac{Q^2}{2M} \qquad \sigma_M = \frac{\alpha^2 E' \cos^2(\frac{\theta}{2})}{4E^3 \sin^4(\frac{\theta}{2})}$$

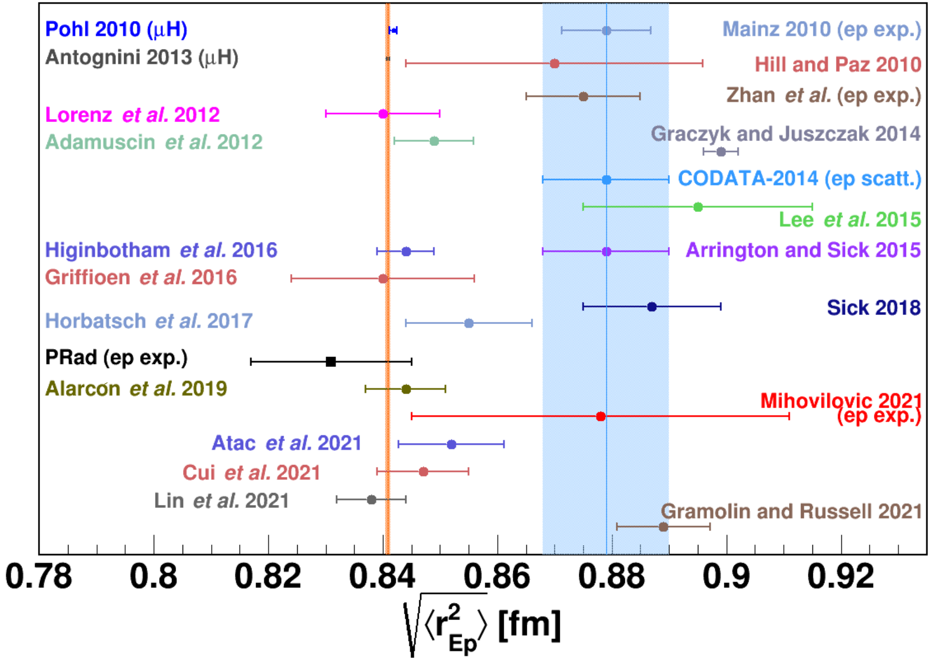
Rosenbluth Formula

PROTON ELECTRIC CHARGE FORM FACTOR AND RADIUS

PROTON CHARGE RADIUS

Various e-p scattering analyses

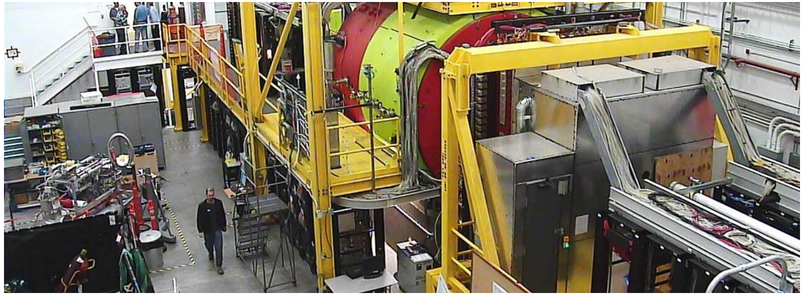
$$r_p^2 = -6\frac{dG_E}{dQ^2}|_{Q^2=0}$$



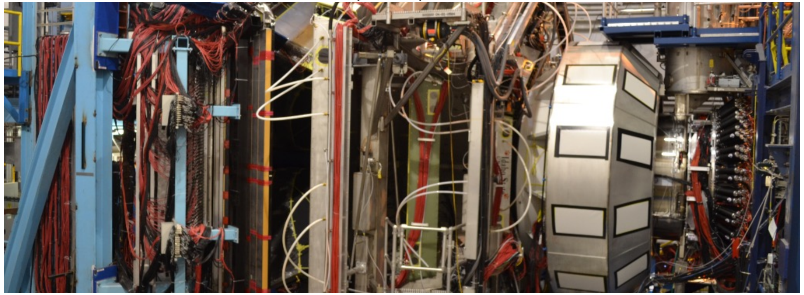
H. Gao and M. Vanderhaeghen, Rev. Mod. Phys. **94** (2022) no.1, 015002

THE PROTON GRAVITATIONAL FORM FACTORS
THE MASS AND SCALAR RADIUS

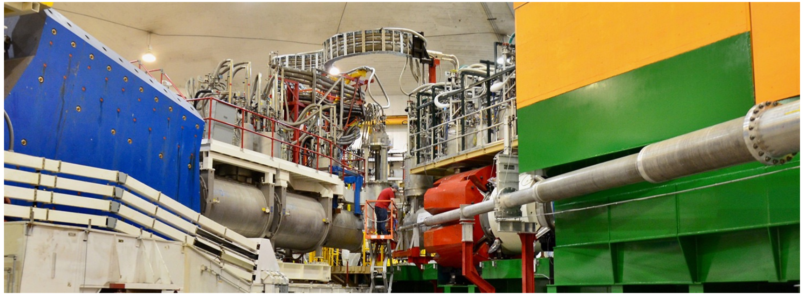
12 GEV J/Ψ EXPERIMENTS AT JEFFERSON LAB



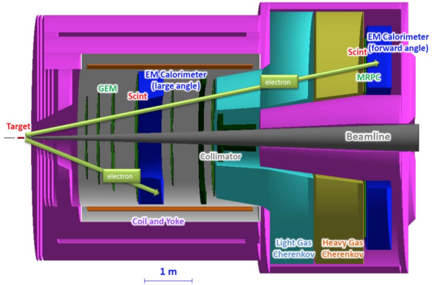
Hall D - GlueX observer the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



Hall 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



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



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**

GRAVITATIONAL FORM FACTORS (GFFS)

Towards observables of the matter structure of the proton

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

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

EMT physics encoded in these GFFs:

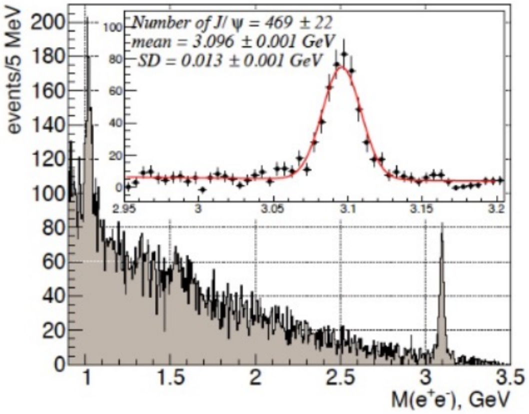
- $A_{g,q}(t)$: Related to quark and gluon momenta, $A_{g,q}(0) = \langle x_{q,g}\rangle$
- $J_{g,q}(t) = 1/2\left(A_{g,q}(t) + B_{g,q}(t)\right)$: Related to angular momentum, $J_{tot}(0) = 1/2$
- $D_{g,q}(t) = 4C_{g,q}(t)$: Related to pressure and shear forces

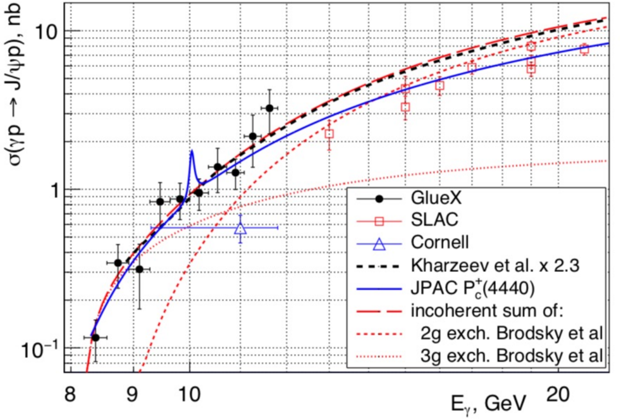
J/Ψ NEAR THRESHOLD IN HALL D

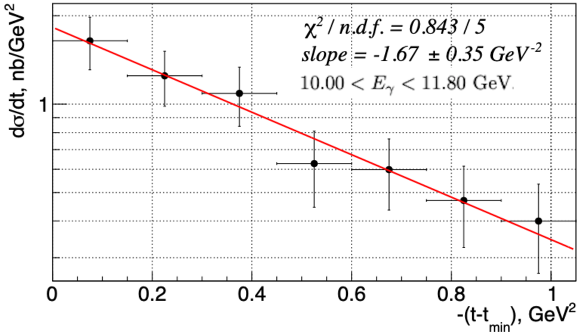
First J/ψ results from JLab, published in PRL 123, 072001 (2019)

- 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

γp → p J/ψ → pe⁺e⁻

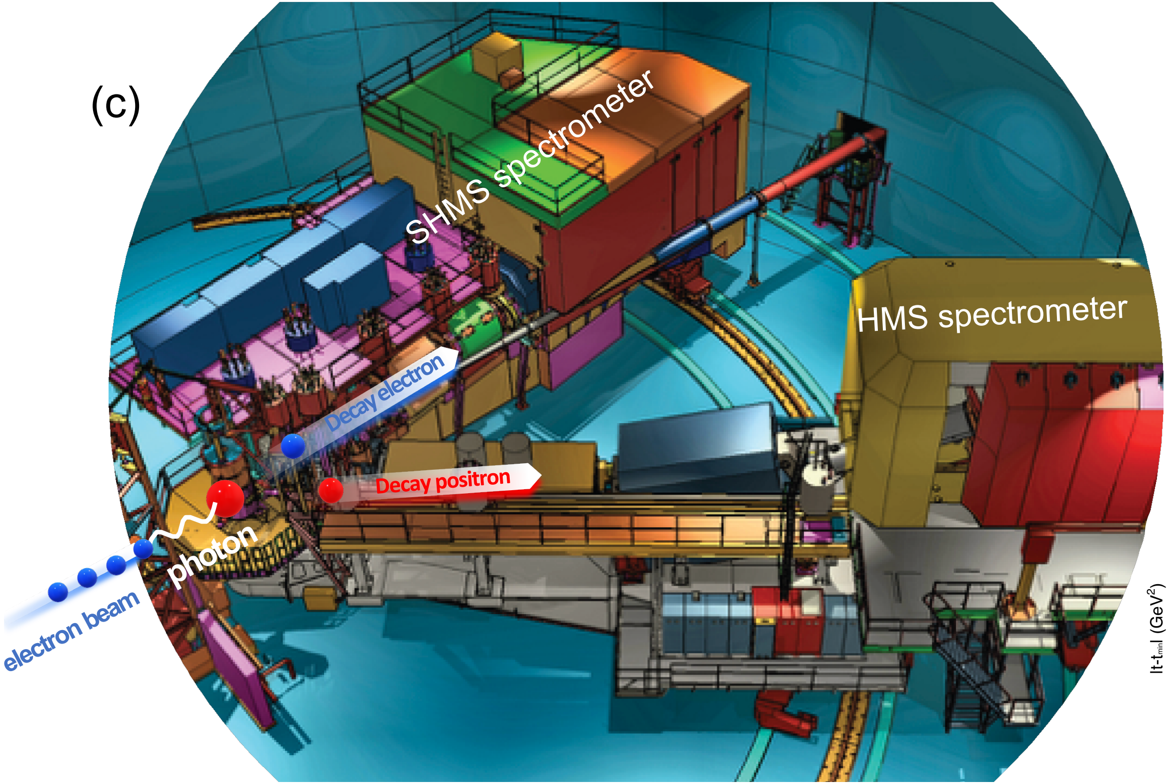


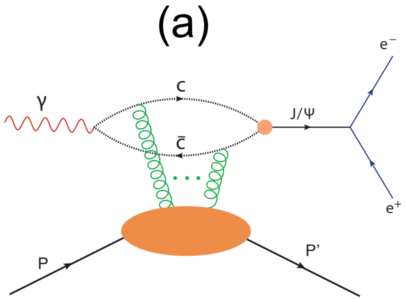


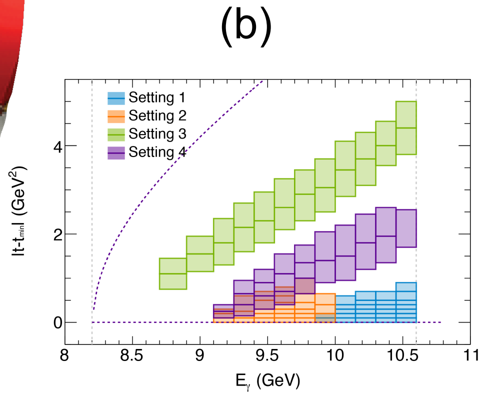


JLAB EXPERIMENT E12-16-007 IN HALL C AT JLAB

Near threshold photoproduction of J/ψ



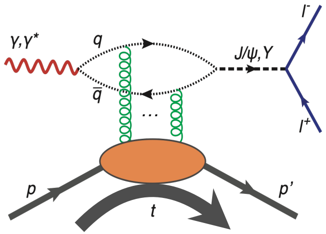




Z.-E. M, S. Joosten *et al.*, arXiv:1609.00676 [hep-ex]
K. Hafidi, S. Joosten *et al.*, Few Body Syst. 58 (2017) no.4, 141

JLAB EXPERIMENT E12-16-007

Near threshold photoproduction of J/ψ

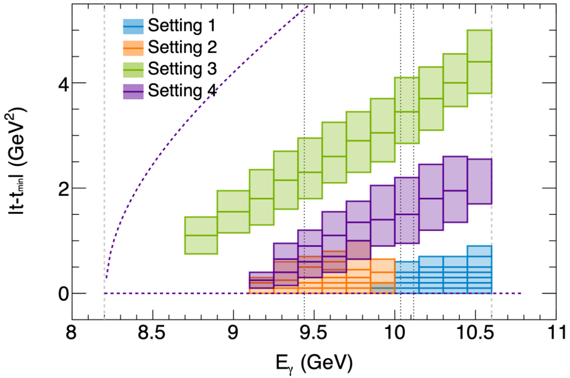


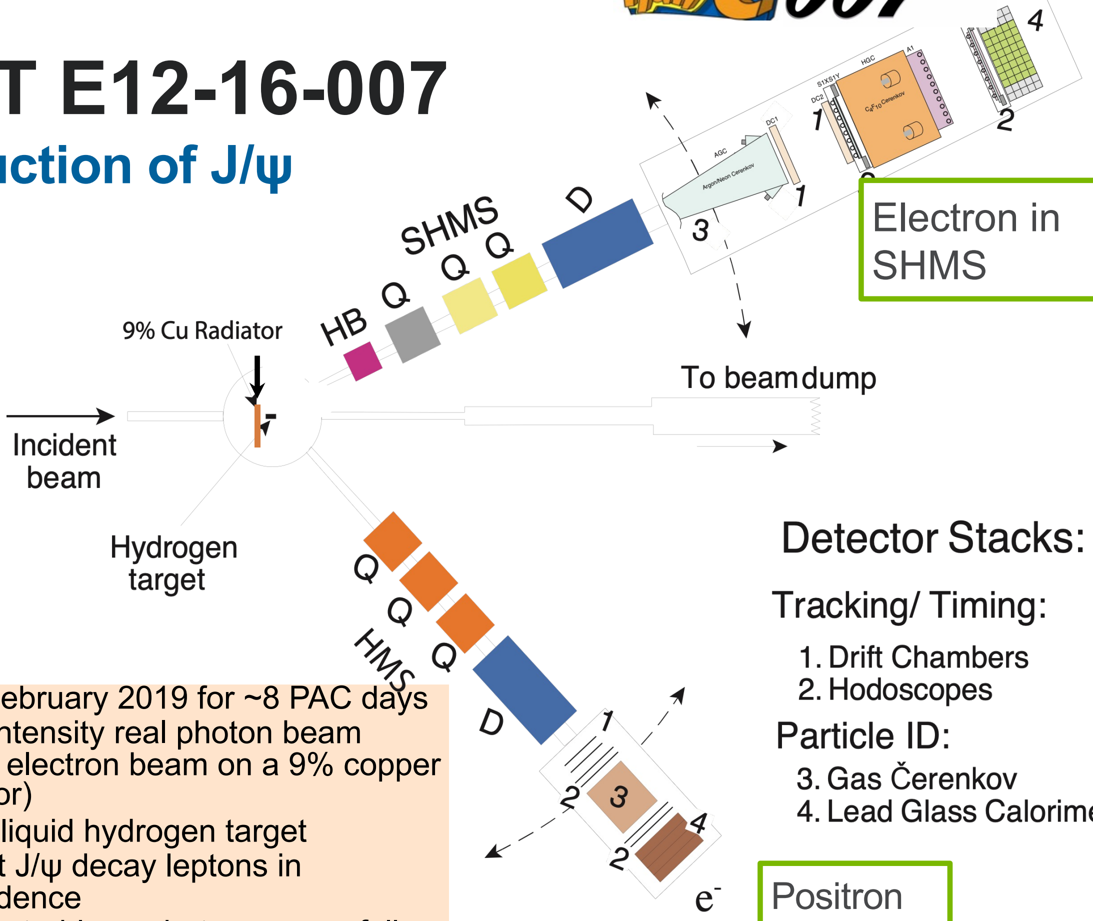
J/ψ threshold:

$W \approx 4.04\text{GeV}$

$E_\gamma^{\text{lab}} \approx 8.2\text{GeV}$

$t \approx -1.5\text{GeV}^2$





- Ran February 2019 for ~8 PAC days
- High intensity real photon beam (50μA electron beam on a 9% copper radiator)
- 10cm liquid hydrogen target
- Detect J/ψ decay leptons in coincidence
- Bremsstrahlung photon energy fully constrained

Detector Stacks:

Tracking/ Timing:

1. Drift Chambers
2. Hodoscopes

Particle ID:

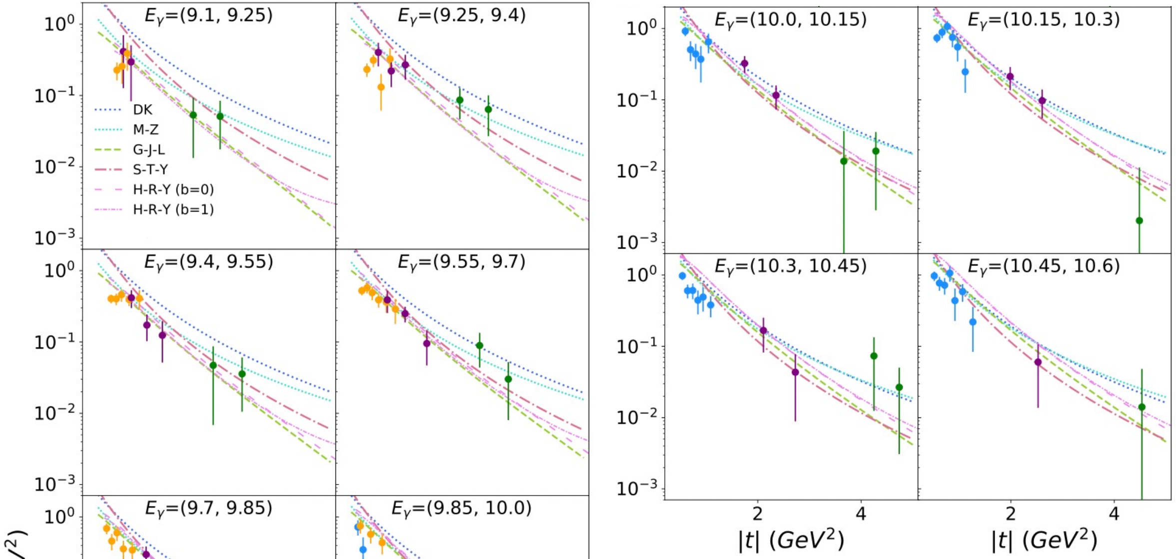
3. Gas Čerenkov
4. Lead Glass Calorimeter

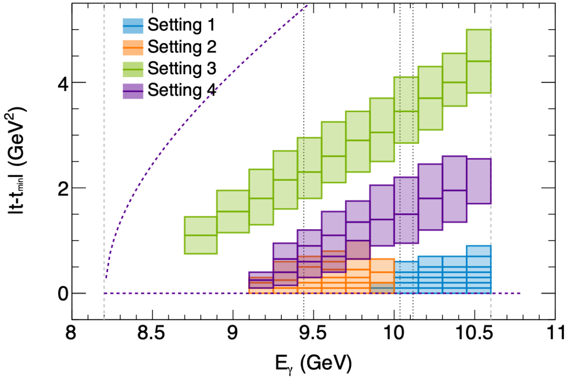
Preprint: https://arxiv.org/abs/2207.05212

$007^{J/\psi}$

Results currently under peer-review

PRELIMINARY 2D J/Ψ CROSS SECTION RESULTS





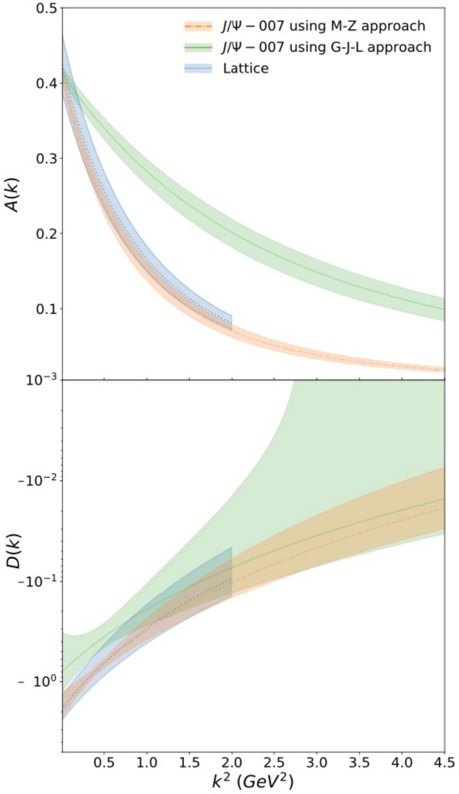
- Unfolded 2D cross section results compared to various model predictions informed by the 2019 1D GlueX results
- All models work reasonably well at higher energies but deviate at lower energies

DK: D, Kharzeev, Phys. Rev. D 104, 054015 (2021).
M-Z: Mamo & Zahed, 2204.08857 (2022)
G-J-L: Guo, Ji & Liu, Phys. Rev. D 103, 096010 (2021)
S-T-Y: Sun, Tong & Yuan, Phys. Lett. B 822, 136655 (2021)
H-R-Y: Hatta, Rajan & Yang, Phys. Rev. D 100, 014032 (2019)

Preprint: https://arxiv.org/abs/2207.05212

GLUONIC GFF RESULTS; FIRST EXTRACTION

Good agreement between Holographic QCD and Lattice results!



- Results from the 2D gluonic GFF fits
- Gluonic $A_g(t)$ and $D_g(t) = 4C_g(t)$ form factors
- $\chi^2/n.d.f.$ in both cases very close to 1
- M-Z (holographic QCD) approach fit to only experimental data gives results very close to the latest lattice results!
- GPD approach gives very different values, may indicate (expected) issues with the factorization assumption

M-Z: K. Mamo & I. Zahed, PRD 103, 094010 (2021) and 2204.08857 (2022)
G-J-L: Y. Guo, X. Ji, Y. Liu, PRD 103, 096010 (2021)
Lattice: D. Pefkou, D, Hackett, P. Shanahan, Phys. Rev. D 105, 054509 (2022).

Argonne NATIONAL LABORATORY

EXTRACTION OF GLUONIC MASS& SCALAR RADIUS OF THE PROTON

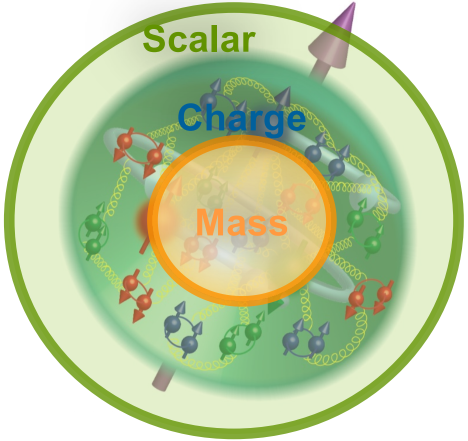
Theoretical approach GFF functional form	χ^2/n.d.f	m_A (GeV)	m_C (GeV)	$C_g(0)$	$\sqrt{\langle r_m^2 \rangle_g}$ (fm)	$\sqrt{\langle r_s^2 \rangle_g}$ (fm)
Holographic QCD Tripole-tripole	0.925	1.575±0.059	1.12±0.21	-0.45±0.132	0.755±0.067	1.069±0.126
GPD Tripole-tripole	0.924	2.71±0.19	1.28± 0.50	-0.20 ± 0.11	0.472±0.085	0.695±0.162
Lattice Tripole-tripole		1.641± 0.043	1.07± 0.12	-0.483± 0.133	0.7464±0.055	1.073±0.114

Definition of mass and scalar radius

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

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

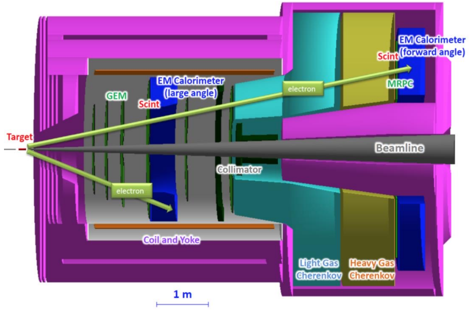
A picture of three zones?

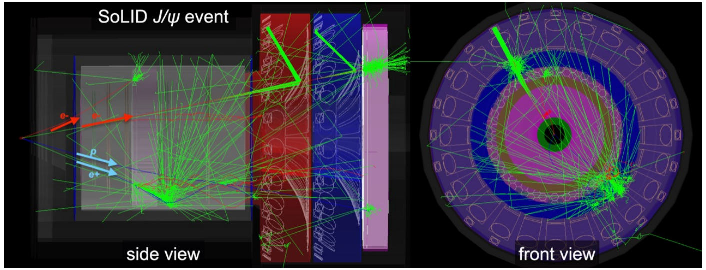


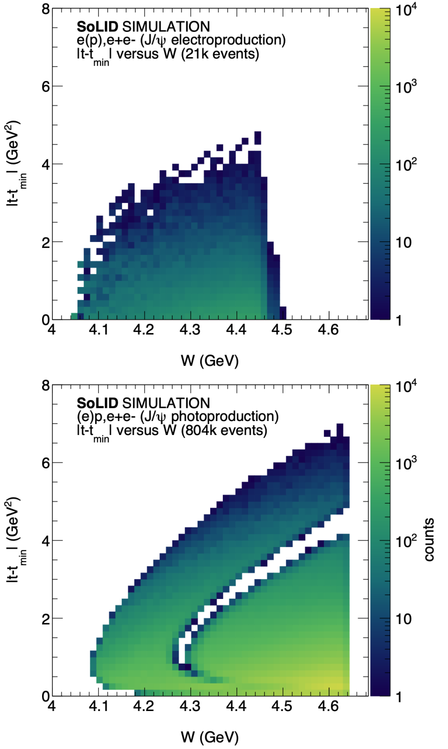
FUTURE SOLID EXPERIMENT AT JLAB

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+)**

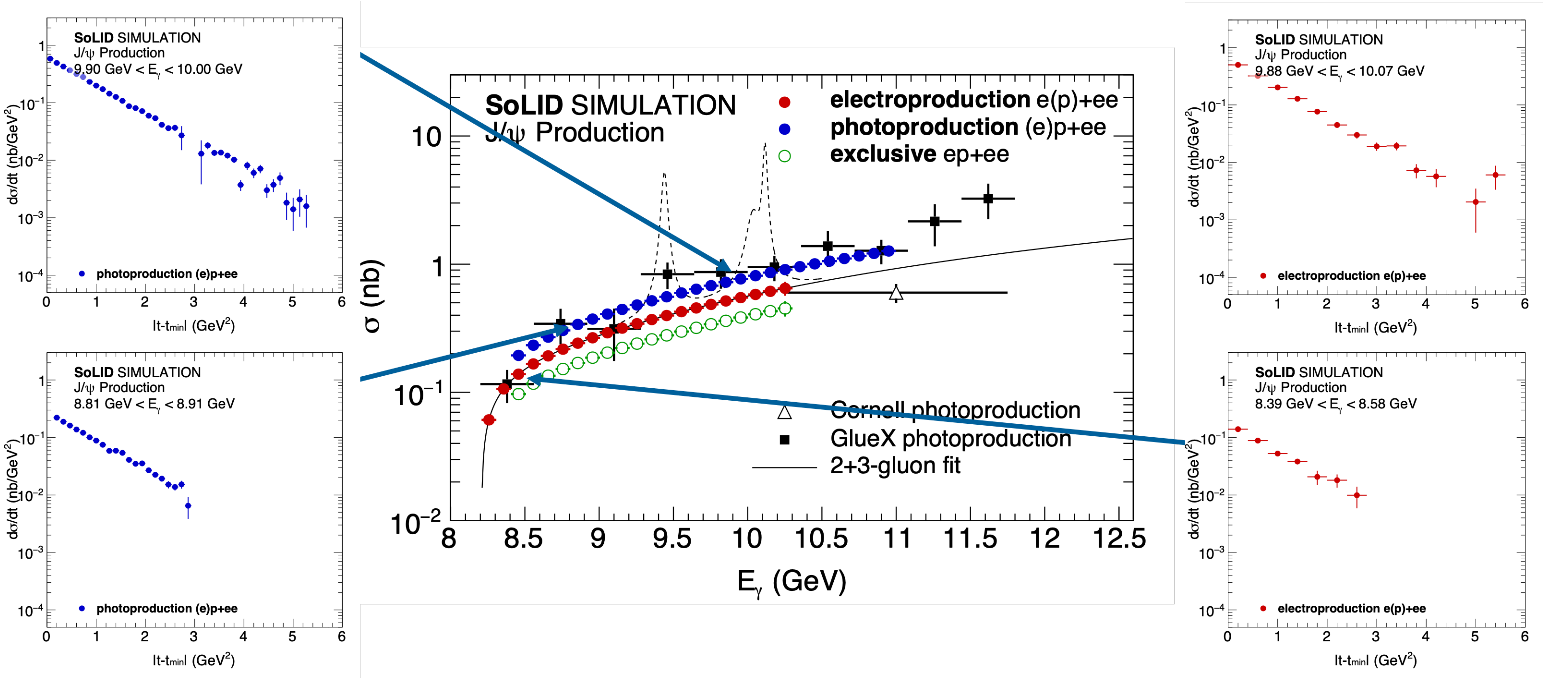






FUTURE SOLID EXPERIMENT AT JLAB

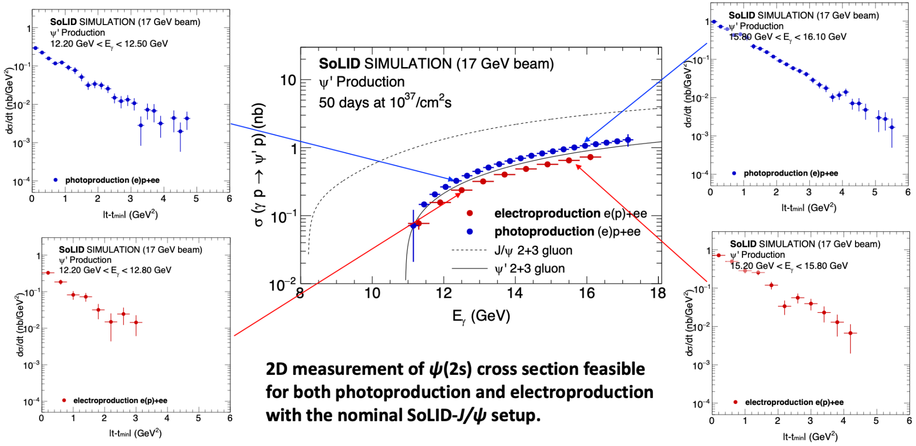
Precision measurement of J/psi near threshold



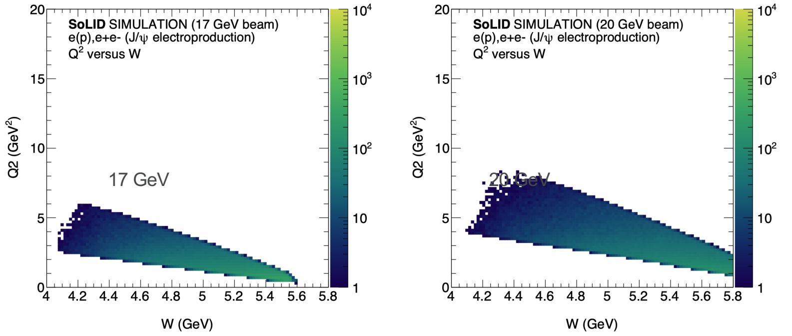
THOUGHTS ON "JLAB BEYOND"

What can be done with a JLab energy upgrade to 22 GeV at SoLID?

ψ(2s) at SoLID (17-20 GeV)



Q^2-reach for J/ψ at threshold up to ~10GeV^2 for 20 GeV beam

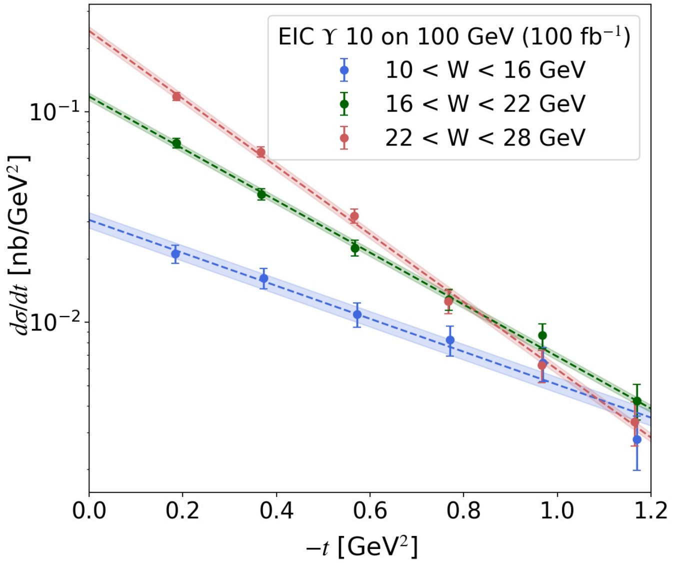


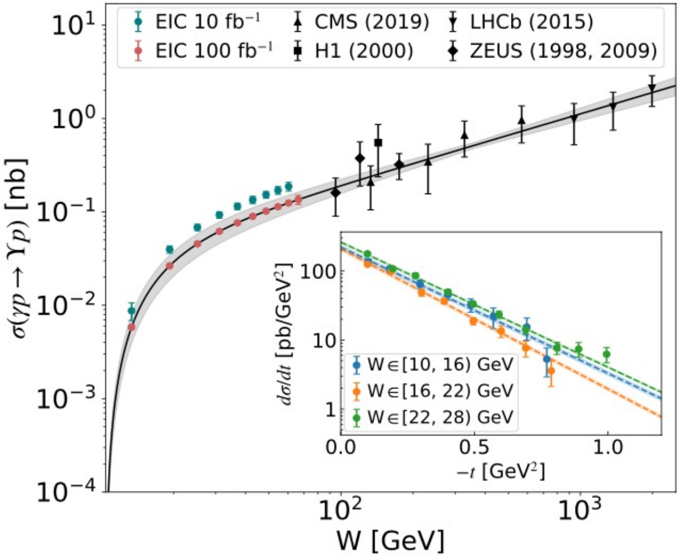
- Higher beam energy at SoLID can enable
  - Precision near-threshold **ψ(2s) production - larger color dipole** to probe the proton
  - Reach **larger values of Q^2** for J/ψ electroproduction. Modest Q^2 reach compared to EIC, but with much higher statistics near-threshold.

WHAT ABOUT THE EIC USING UPSILON PRODUCTION?

Using th ePIC detector

- 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

- Precision data in electroproduction and photoproduction of quarkonium near threshold provide a critical information to answer the following questions

  ✓ **What is the origin of hadron masses**?

  ✓ **What is the mass radius and the scalar radius?**

- Direct lattice calculations of the trace anomaly and the gravitational form factors is an important step toward understanding the proton mass different decompositions. Precision data will be able to benchmark these ab initio calculations.

- Statistical precision will help to understand the systematic uncertainties in the extractions of the anomaly, the mass radius and the scalar radius

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

- JLab and the EIC are truly complementary to address these questions.

THANK YOU!

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

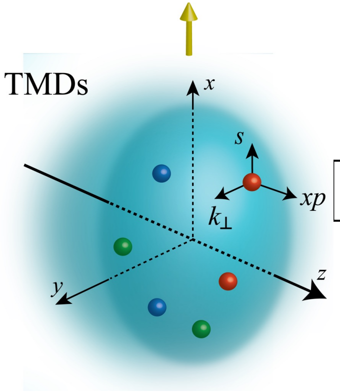
Unified View of Nucleon Structure

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

Transverse Momentum Dist. (TMD)

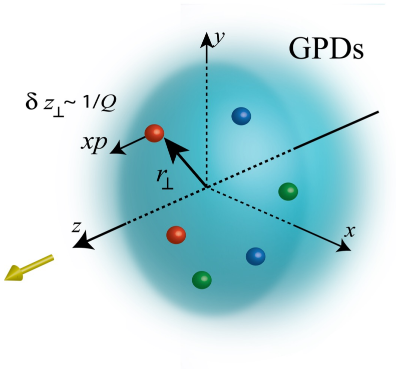
Tomography

Generalized Parton Dist. (GPD)



dr_T

d^2k_T



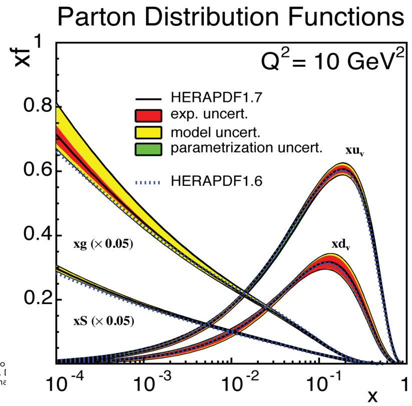
TMD $f_1^u(x,k_T)$, $h_1^u(x,k_T)$

GPD

d^2k_T

d^2r_T

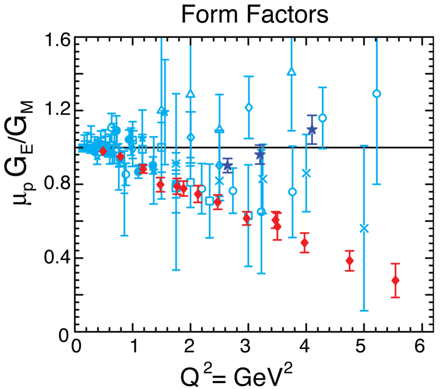
dx & Fourier Transformation



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

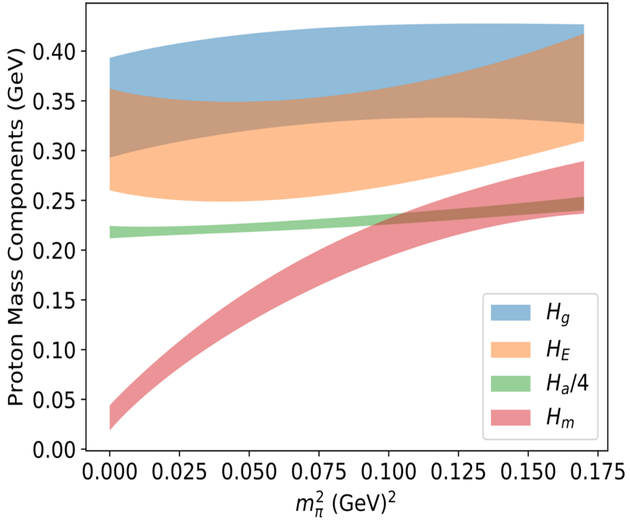
1D

Form Factors
$G_E(Q^2)$,
$G_M(Q^2)$

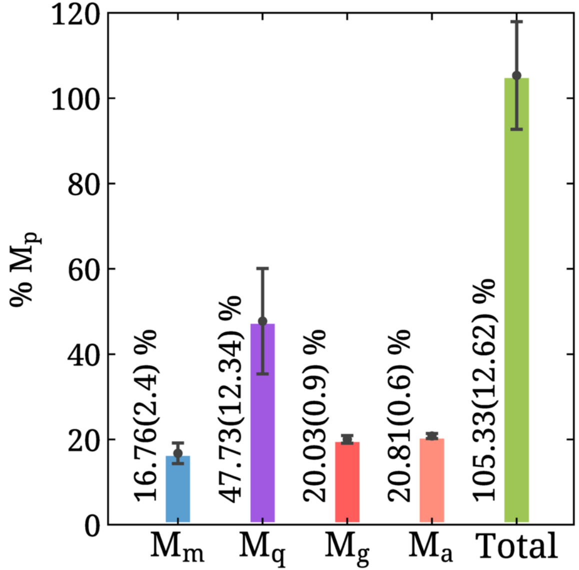


PROTON MASS ON THE LATTICE

Direct calculations of the trace anomaly were still missing until recently



Y.-B. Yang *et al.*, (χQCD), PRL 121, 212001 (2018)



C. Alexandrou *et al.*, (ETMC), PRL 119, 142002 (2017)

C. Alexandrou *et al.*, (ETMC), PRL 116, 252001 (2016)

•He Fangcheng and Sun Peng and Yang Yi-Bo, [χQCD Collaboration] “A Demonstration of Hadron Mass Origin from QCD Trace Anomaly *Phys.Rev.D* 104 (2021) 7, 074507

CHARGE AND MAGNETIZATION DISTRIBUTION

- Charge and magnetization distribution as Fourier transform of form factors
- Extracted using the Breit (center of mass) frame
- At large momentum transfer the method of extraction has been be revisited using light cone formalism to speak of true densities.
- The framework uses the Generalized Parton Distributions