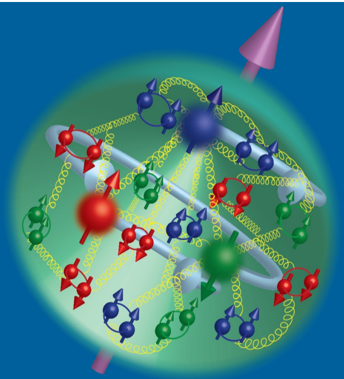
LIGHT-CONE 2023
CBPF September 18-22, 2023
Vermelha Beach

Argonne NATIONAL LABORATORY

THE PROTON GLUONIC GRAVITATIONAL FORM FACTORS AND ITS MASS RADIUS



ZEIN-EDDINE MEZIANI
Argonne National Laboratory

On behalf of the J/psi-007 collaboration

BASED ON THIS PUBLICATION AND SOME MORE

Article

Determining the gluonic gravitational form factors of the proton

https://doi.org/10.1038/s41586-023-05730-4

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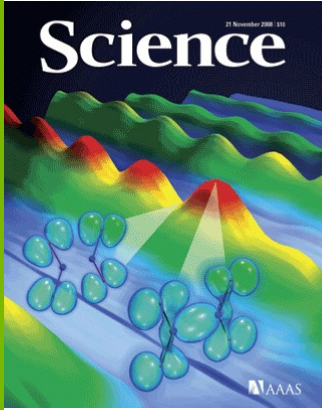
Check for updates

B. Duran[1,2], Z.-E. Meziani[1,2]✉, S. Joosten[1], M. K. Jones[3], S. Prasad[1], C. Peng[1], W. Armstrong[1], H. Atac[2], E. Chudakov[3], H. Bhatt[4], D. Bhetuwal[4], M. Boer[5], A. Camsonne[3], J.-P. Chen[3], M. M. Dalton[3], N. Deokar[2], M. Diefenthaler[3], J. Dunne[4], L. El Fassi[4], E. Fuchey[6], H. Gao[7], D. Gaskell[3], O. Hansen[3], F. Hauenstein[8], D. Higinbotham[3], S. Jia[2], A. Karki[4], C. Keppel[3], P. King[9], H. S. Ko[10], X. Li[7], R. Li[2], D. Mack[3], S. Malace[3], M. McCaughan[3], R. E. McClellan[11], R. Michaels[3], D. Meekins[3], Michael Paolone[2], L. Pentchev[3], E. Pooser[3], A. Puckett[6], R. Radloff[9], M. Rehfuss[2], P. E. Reimer[1], S. Riordan[1], B. Sawatzky[3], A. Smith[7], N. Sparveris[2], H. Szumila-Vance[3], S. Wood[3], J. Xie[1], Z. Ye[1], C. Yero[8] & Z. Zhao[7]

Hadron Masses from Lattice QCD



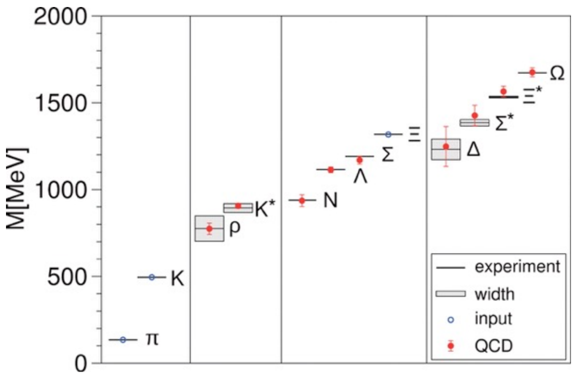
(2008)

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

589 citations



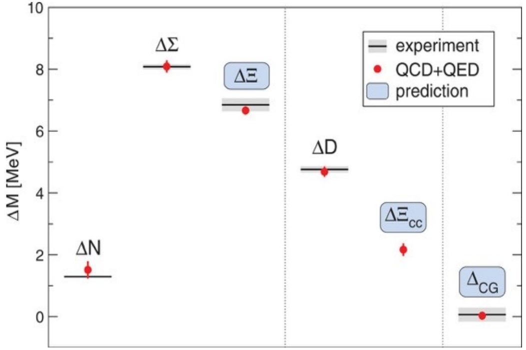
(2015)

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

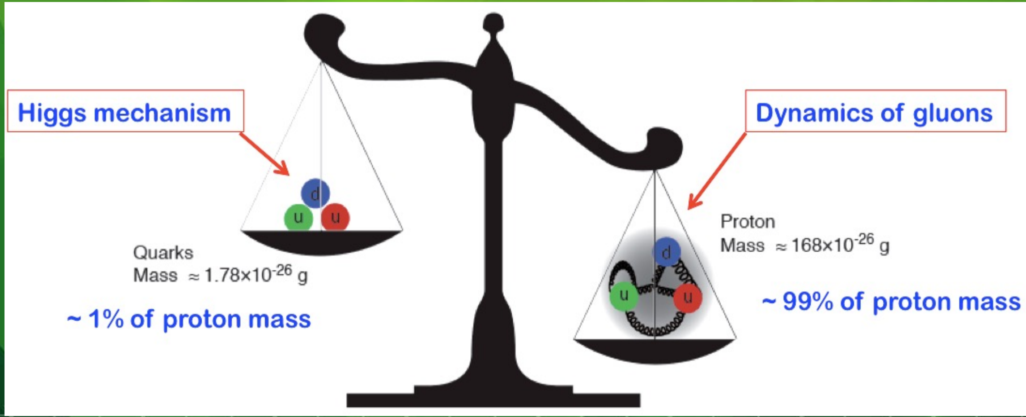
287 citations



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

Origin of Mass?

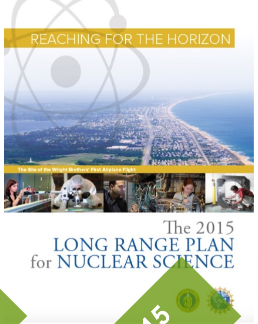
"...QCD takes us a long stride towards the Einstein-Wheeler ideal of mass without mass" Frank Wilczek (1999, Physics Today)

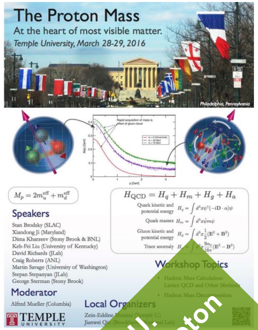


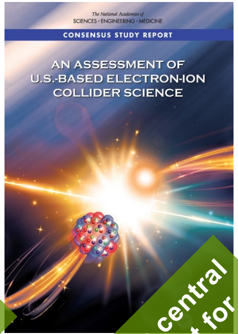
Susskind: Nothing to do with the Higgs mechanism. Examples in nature: proton, blackhole

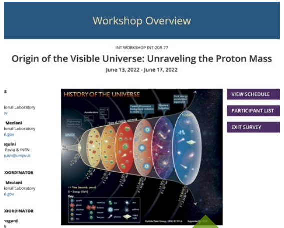
- https://youtu.be/JqNg819PiZY?t=2403

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









2012 Temple U. Workshop on heavy quarkonia

Featured in the 2015 Long Range plan

2016 Temple U. Workshop on the proton mass

2017 ECT* Workshop on the proton mass

2018 Proton mass central in NAS assessment for EIC

2021 Remote Workshop on the proton mass

2022 INT Workshop on the proton mass

2015 LHCb finds resonance in J/ψ-p channel consistent with pentaquarks

2016 Proposal for Hall C Pentaquark search

2019 First GlueX near-threshold J/ψ results

2021 First Hall C results on the pentaquark search

2022 First 2D near-threshold J/ψ results from Hall C

How does QCD generates most of 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 $\beta(g) = -b \frac{g^3}{16\pi^2} + \ldots, \qquad b = 9 - \frac{2}{3} n_h$

Gross, Wilczek & Politzer

At small momentum transfer, heavy quarks decouple:

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

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

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

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

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

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]

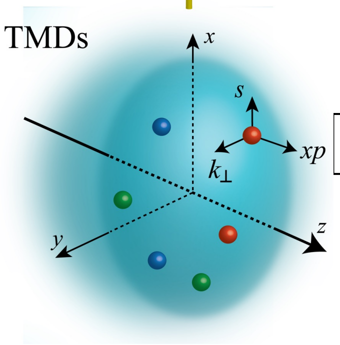
Unified View of Nucleon Structure

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

Transverse Momentum Dist. (TMD)

Tomography

Generalized Parton Dist. (GPD)

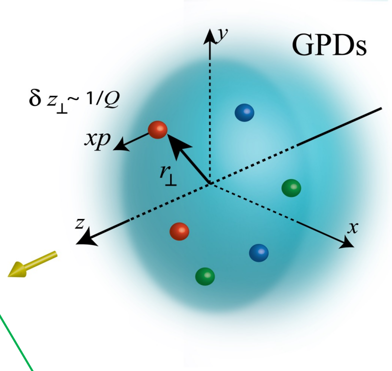


dr_T

d^2k_T

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

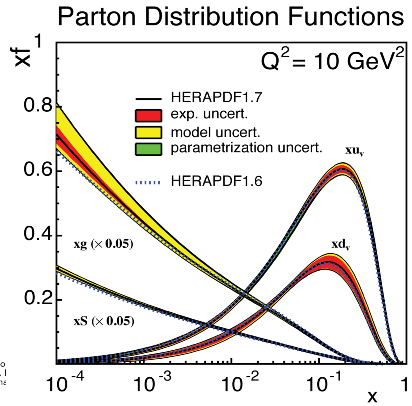
GPD



d^2k_T

d^2r_T

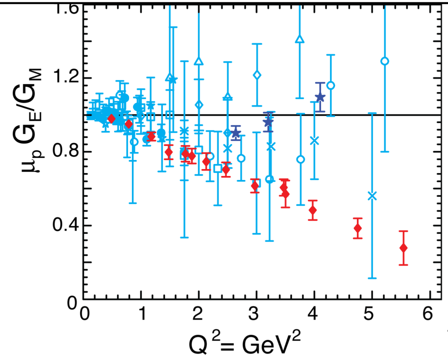
dx & Fourier Transformation



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

1D

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



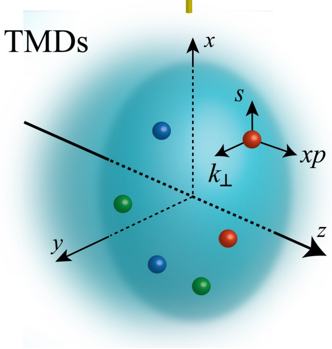
Unified View of Nucleon Structure

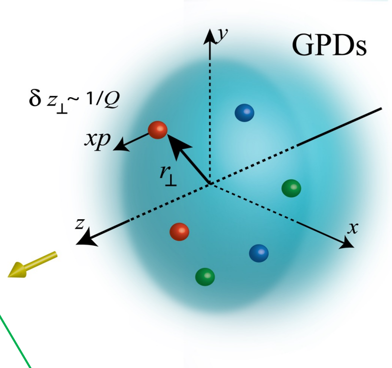
$W_p^u(x, k_T, r_T)$ *Wigner distributions*

Tomography

Transverse Momentum Dist. (TMD)

Generalized Parton Dist. (GPD)





dr_T

d^2k_T

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

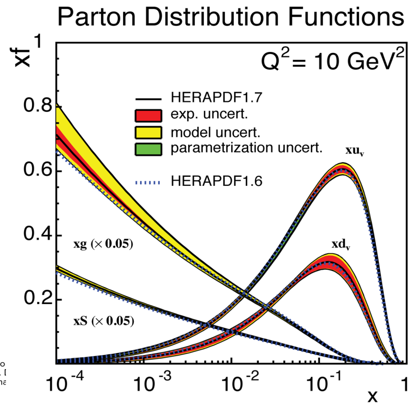
GPD

d^2k_T

d^2r_T

dx & Fourier Transformation

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



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

1D

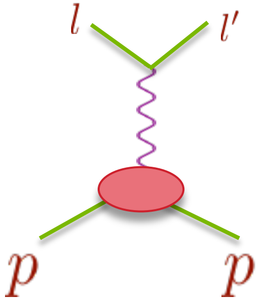
Nucleon gravitational form factors A, B, C and C_bar; (quarkonic & gluonic)
Mass density, Pressure density, Shear Forces density

The Proton Gravitational Form Factors
Mass and scalar radii

EXPERIMENTAL REACTIONS TO DETERMINE FORM FACTORS

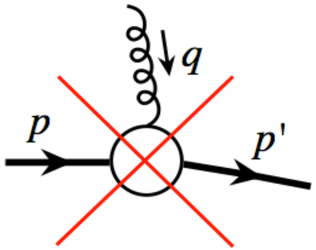
Proton electric charge distribution?

Elastic Scattering



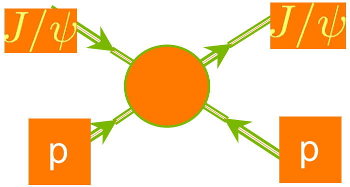
Proton color charge distribution?

Elastic color scattering

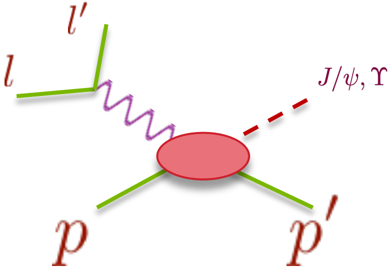


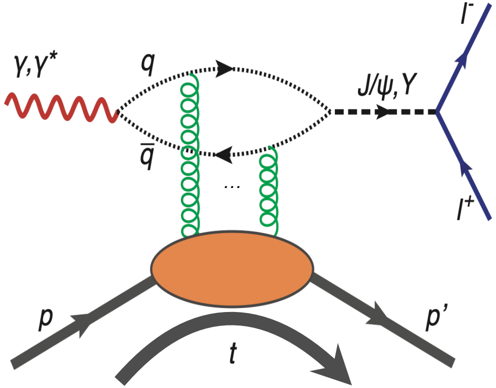
What to do? → Probe the gluon density

Elastic J/psi scattering



Deep Vector Meson Production (DVMP)





GRAVITATIONAL FORM FACTORS (GFFS)

Towards observables of the matter structure of the proton

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

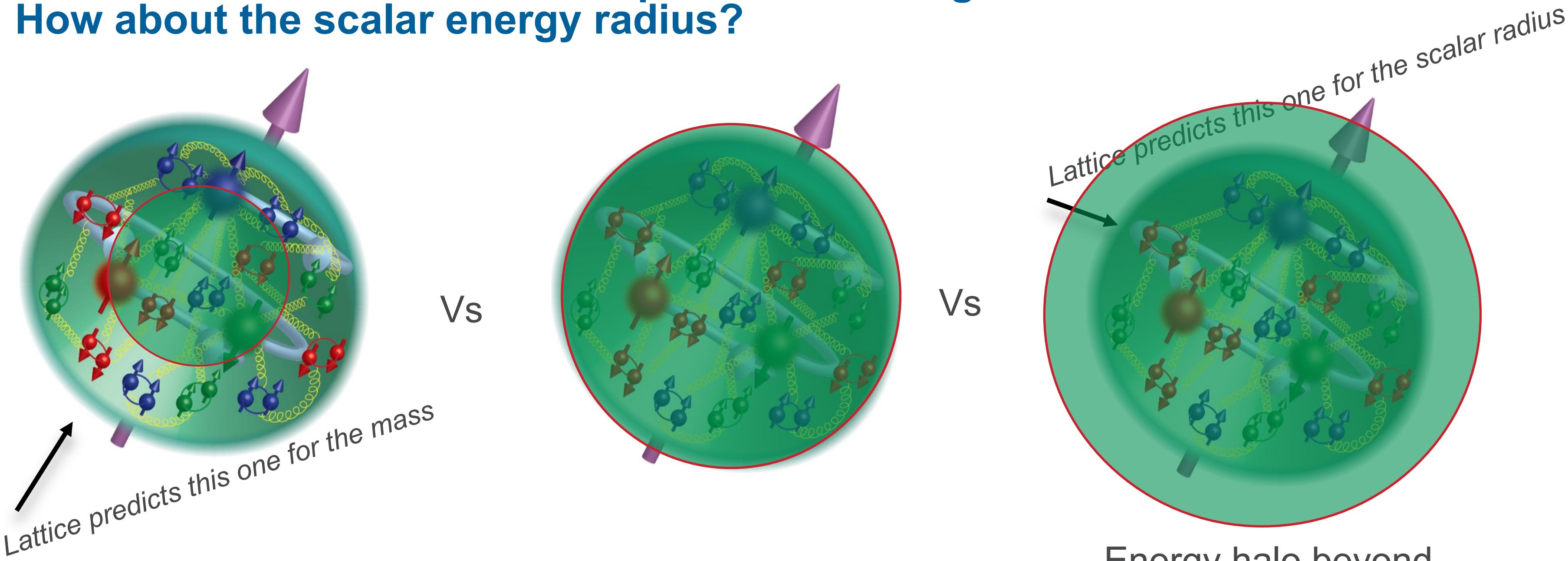
$$\langle N' \mid T^{\mu,\nu}_{q,g} \mid N \rangle$$
$$= \bar{u}(N')\left(A_{g,q}(t)\gamma^{\{\mu}P^{\nu\}} + B_{g,q}(t)\frac{iP^{\{\mu}\sigma^{\nu\}}\rho\Delta_\rho}{2M} + C_{g,q}(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M} + \bar{C}_{g,q}(t)Mg^{\mu\nu} \right) u(N)$$

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

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

WHERE IS THE GLUON ENERGY INSIDE THE PROTON?

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

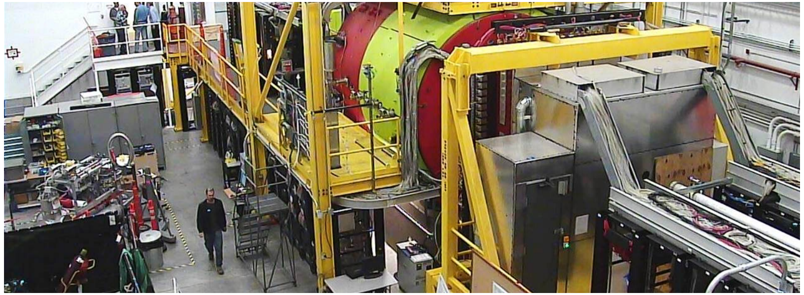


Dense energetic core?

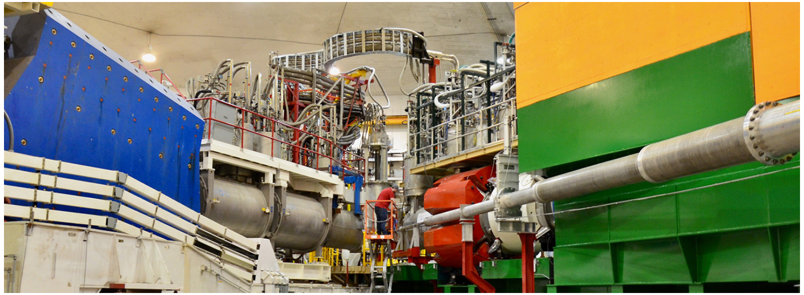
Same as charge radius?

Energy halo beyond charge radius?

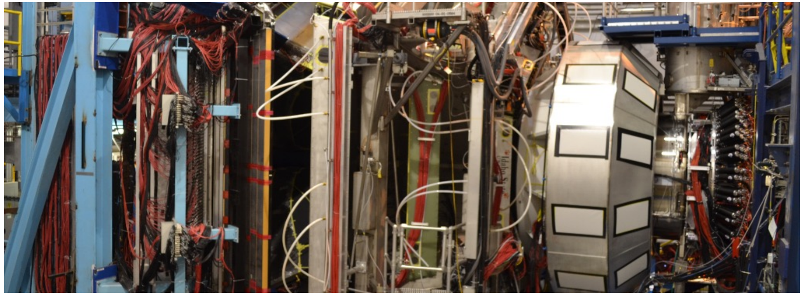
12 GEV J/Ψ EXPERIMENTS AT JEFFERSON LAB NOW AND FUTURE



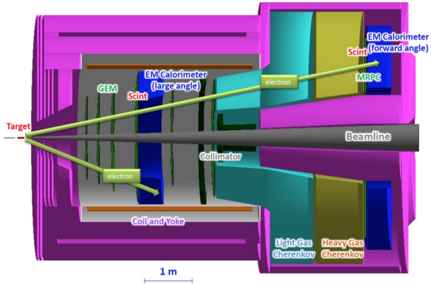
Hall D - GlueX observer the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



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



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

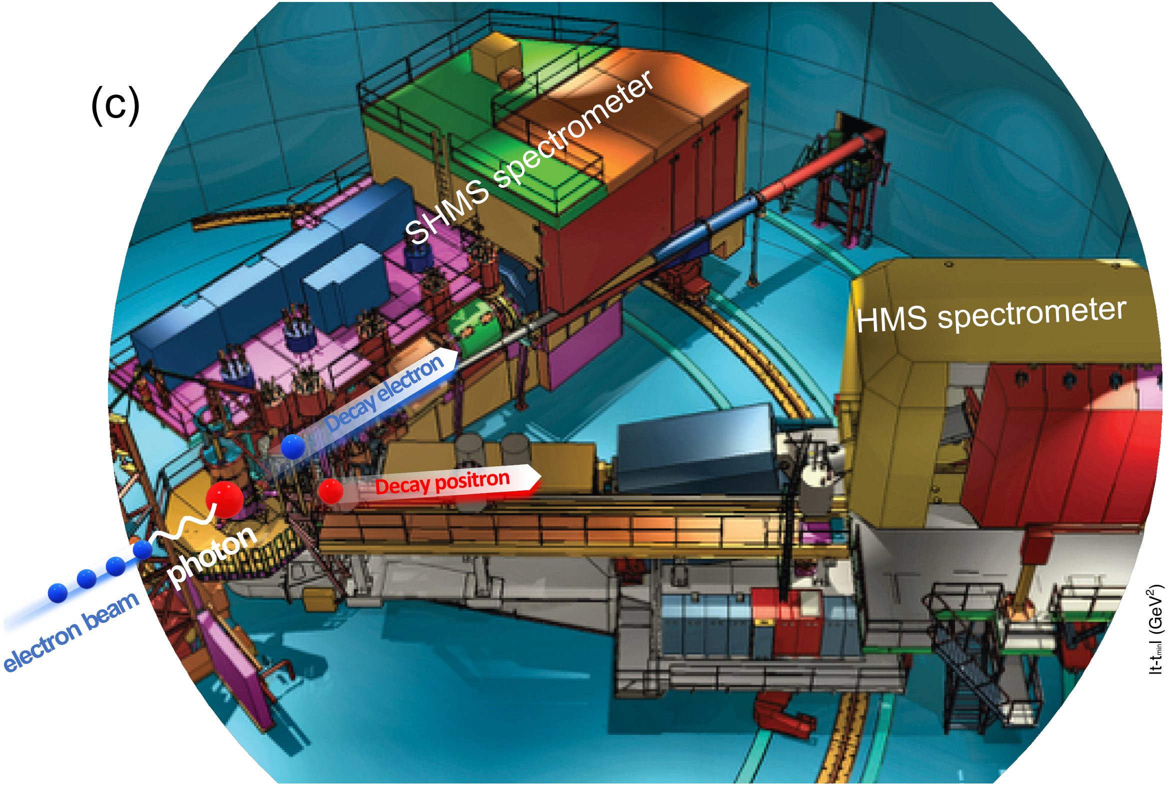


Hall A has experiment E12-12-006 at **SoLID** to measure J/ψ in electro- and photoproduction, and an LOI to measure double polarization using **SBS**

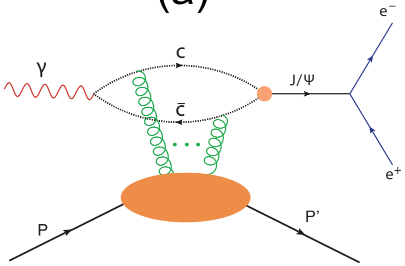
JLAB EXPERIMENT E12-16-007 IN HALL C AT JLAB

Near threshold photoproduction of J/ψ

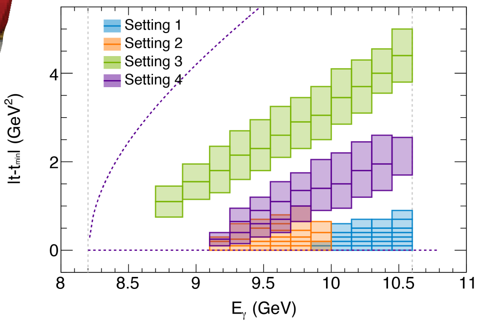
(c)



(a)



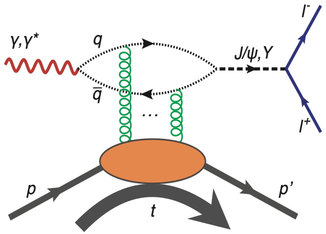
(b)



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

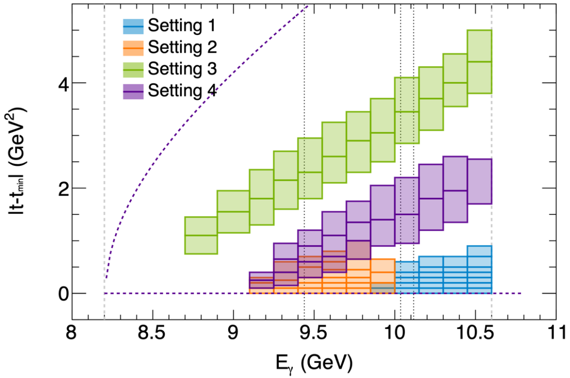


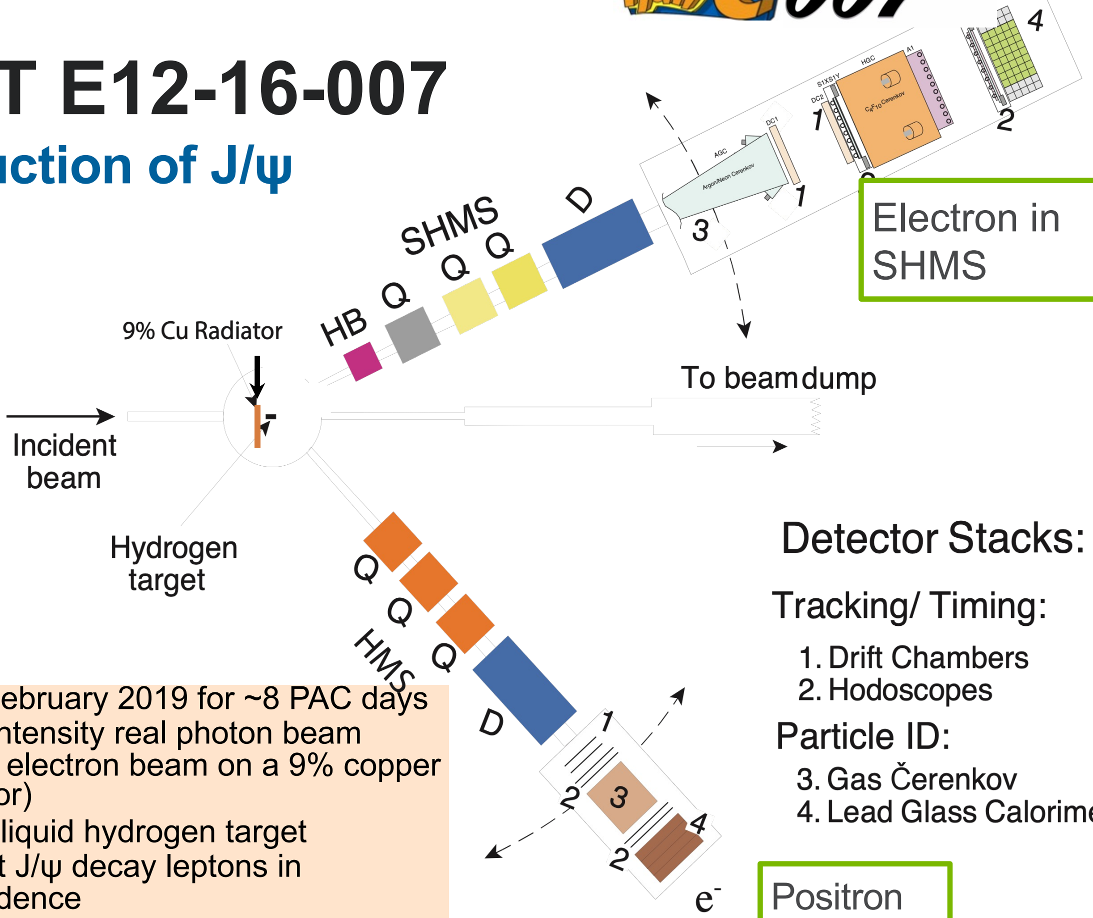
J/ψ threshold:

$W \approx 4.04\text{GeV}$

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

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





- 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

Electron in SHMS

Positron in HMS

Detector Stacks:

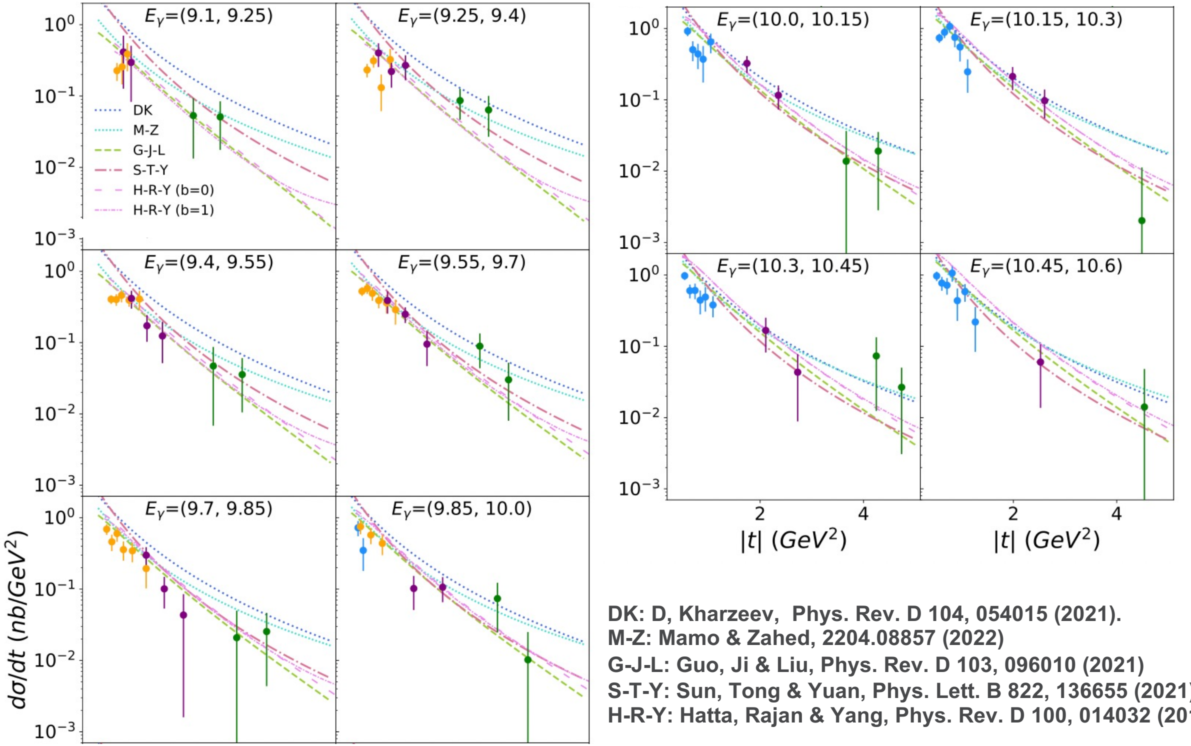
Tracking/ Timing:

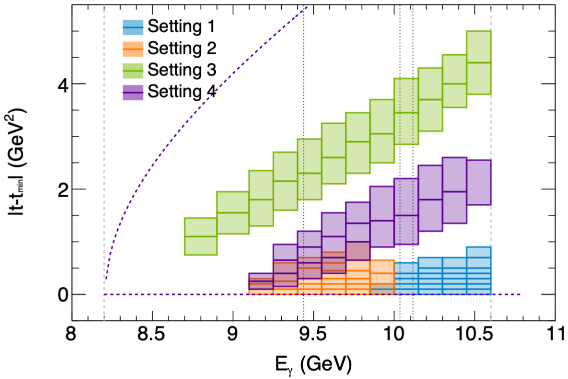
1. Drift Chambers
2. Hodoscopes

Particle ID:

3. Gas Čerenkov
4. Lead Glass Calorimeter

2D J/Ψ CROSS SECTION RESULTS



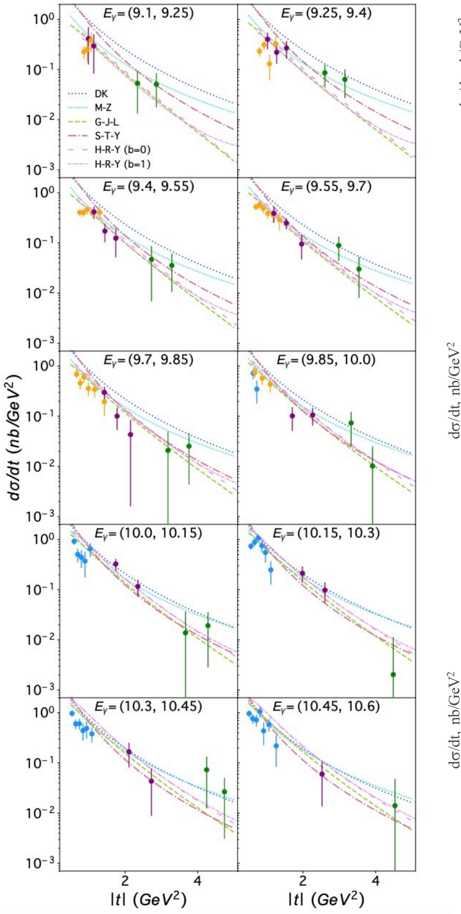


DK: D, Kharzeev, Phys. Rev. D 104, 054015 (2021).
M-Z: Mamo & Zahed, 2204.08857 (2022)
G-J-L: Guo, Ji & Liu, Phys. Rev. D 103, 096010 (2021)
S-T-Y: Sun, Tong & Yuan, Phys. Lett. B 822, 136655 (2021)
H-R-Y: Hatta, Rajan & Yang, Phys. Rev. D 100, 014032 (2019)

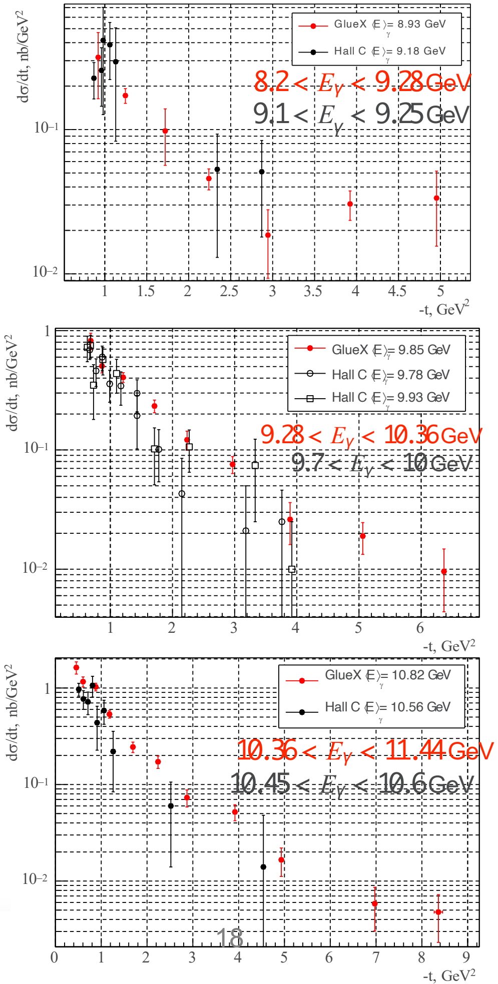
- Unfolded 2D cross section results compared to various model predictions informed by the 2019 1D GlueX results
- All models work reasonably well at higher energies but deviate at lower energies

DIFFERENTIAL CROSS SECTIONS FROM J/ψ- 007 AND GLUEX

L. Pentchev



B. Duran et al. (J/ψ-007), Nature 615 (2023)



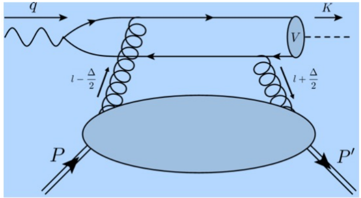
- 10 energy bins in J/ψ-007
- Results for the three **GlueX energy bins** compared to closest **Hall C (J/ψ-007) energies**
- Scale uncertainties: 20% in GlueX and 4% in Hall C results
- Good agreement within the errors; note also differences in average energies

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

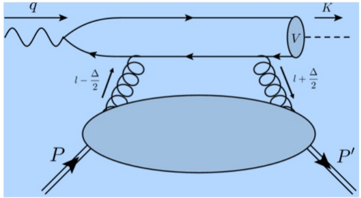
THE GENERALIZED PARTON DISTRIBUTION MODEL

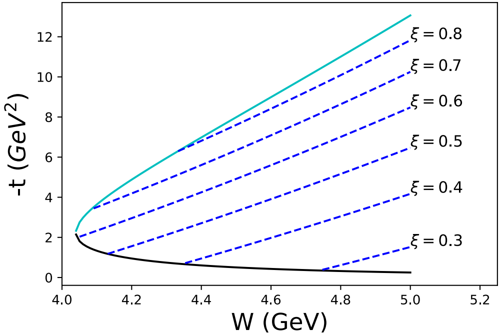
2D fit to extract *A(t)* & *C(t)* assuming *B(t)* negligible

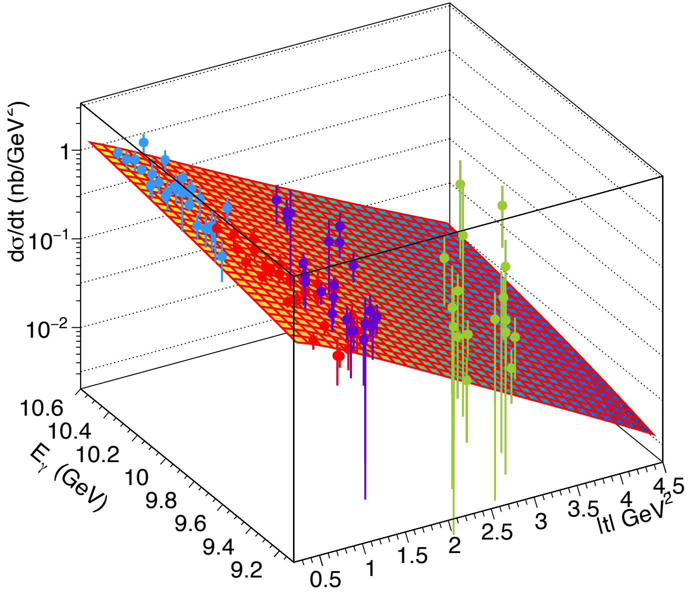
Y. Guo, X. Ji and Y. Liu,``QCD Analysis of Near-Threshold Photon-Proton Production of Heavy Quarkonium," Phys. Rev. D **103**, no.9, 096010 (2021) and [arXiv:2305.06992 [hep-ph]].



(a)







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

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

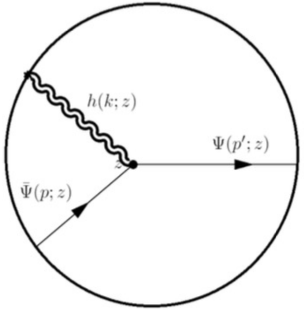
$$|G(t,\xi)|^2 = \frac{1}{\xi^4}\{(1 - \frac{t}{4m_N^2})E_2^2 - 2E_2(H_2+E_2) + (1-\xi^2)(H_2+E_2)^2\}$$

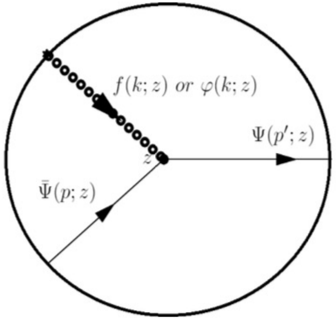
THE HOLOGRAPHIC QCD MODEL

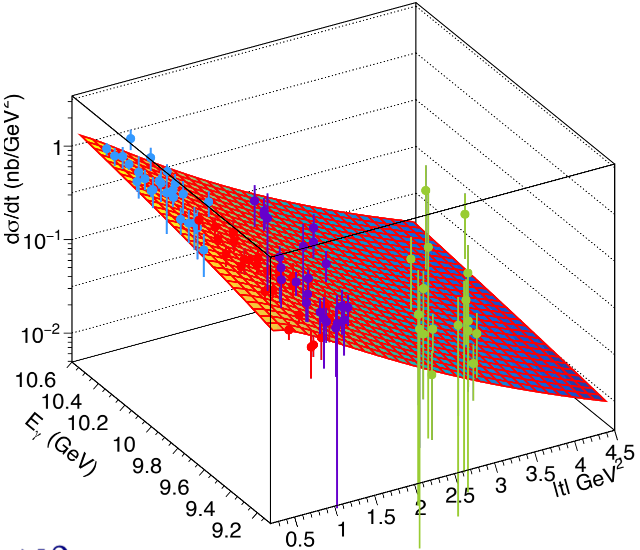
2D fit to extract the *A(t)* & *C(t)* assuming *B(t)* to be small

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

A tensor component and a scalar component







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

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

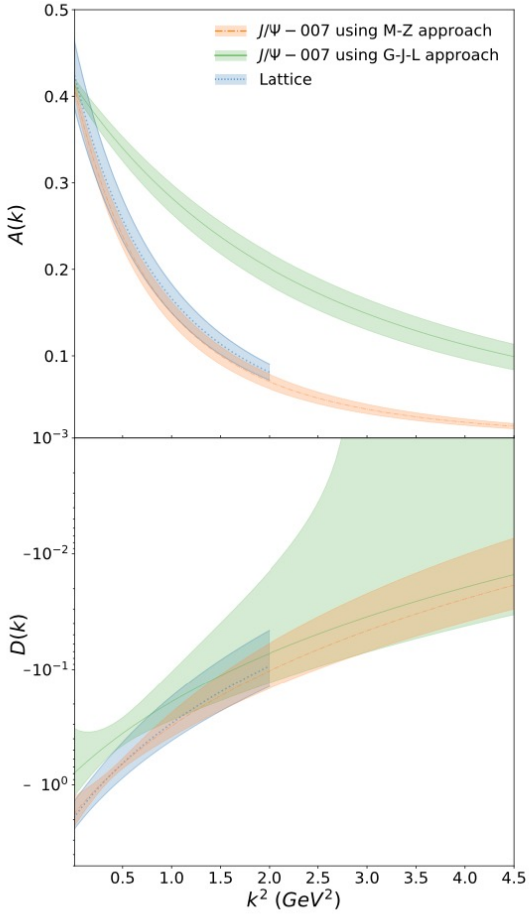
$$\frac{d\sigma}{dt} = \mathcal{N} \times \frac{e^2}{64\pi(s - m_N^2)^2} \times \frac{A(-t, \kappa_T) + \eta^2 D(-t, \kappa_T, \kappa_S)]^2}{A^2(0)} \times \tilde{F(s)} \times 8$$

- *A* and *D* shapes are fully calculated; However dipole forms are assumed as very good approximations and are used in the fits to the data. $A_g(0)$ is fixed to the DIS value from global fit CT18.
- *B(t)* is neglected

GLUONIC GFF RESULTS; FIRST EXTRACTION

007 J/Ψ

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 is 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 but………

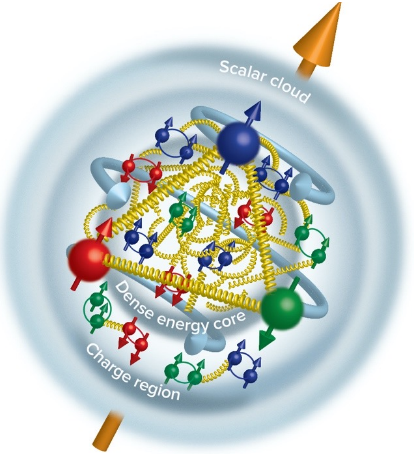
M-Z: K. Mamo & I. Zahed, PRD 103, 094010 (2021) and 2204.08857 (2022)

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).

FIRST EXTRACTION OF GLUONIC SCALAR/MASS RADIUS OF THE NUCLEON

A picture of three zones?



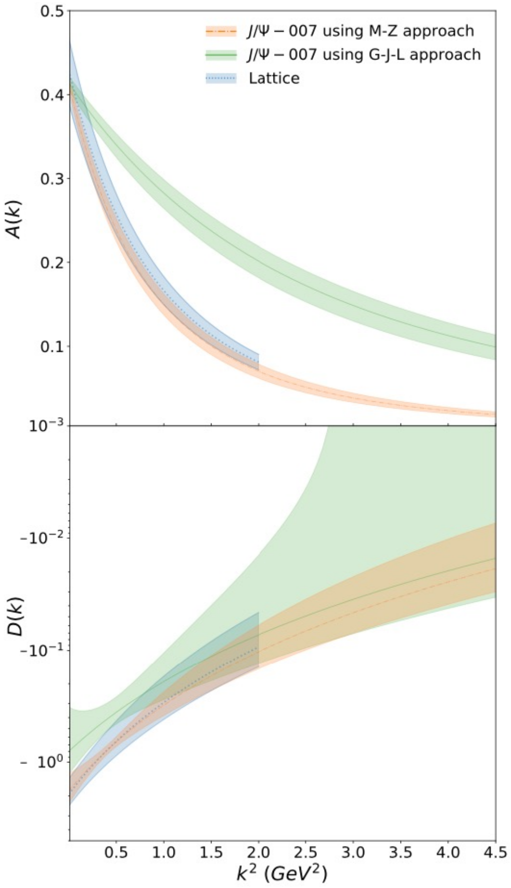
Definition of gluonic mass and scalar radius

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

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

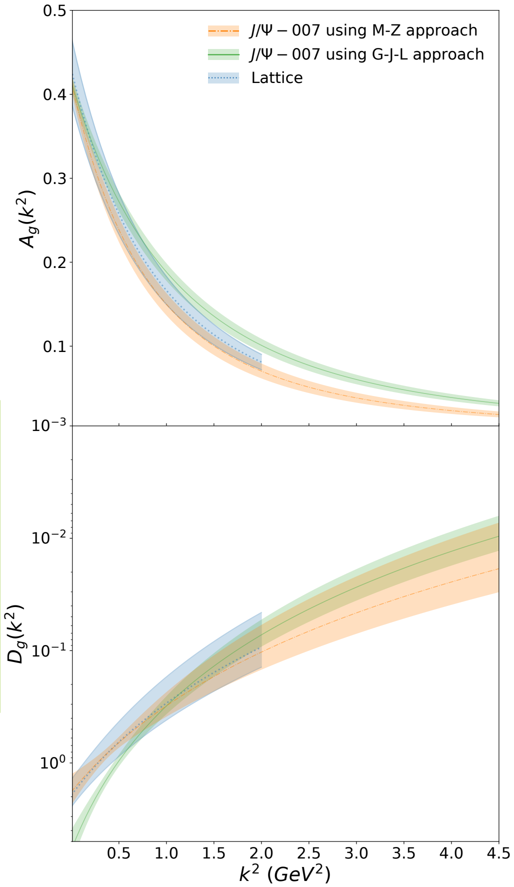
Theoretical approach GFF functional form	χ^2/n.d.f	m_A (GeV)	m_C (GeV)	$C_g(0)$	$\sqrt{\langle r_m^2 \rangle_g}$ (fm)	$\sqrt{\langle r_s^2 \rangle_g}$ (fm)
Holographic QCD Tripole-tripole	0.925	1.575±0.059	1.12±0.21	-0.45±0.132	0.755±0.067	1.069±0.126
GPD Tripole-tripole	0.924	2.71±0.19	1.28± 0.50	-0.20 ± 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

UPDATED GJL GFFS EXTRACTION RESULT (FOLLOW GREEN CURVES)



B.Duran, Z. E. M, S. Joosten, M. K. Jones, S. Prasad, C. Peng, W. Armstrong, H. Atac, et al. Determining the gluonic gravitational form factors of the proton, Nature **615**, no.7954, 813-816 (2023)

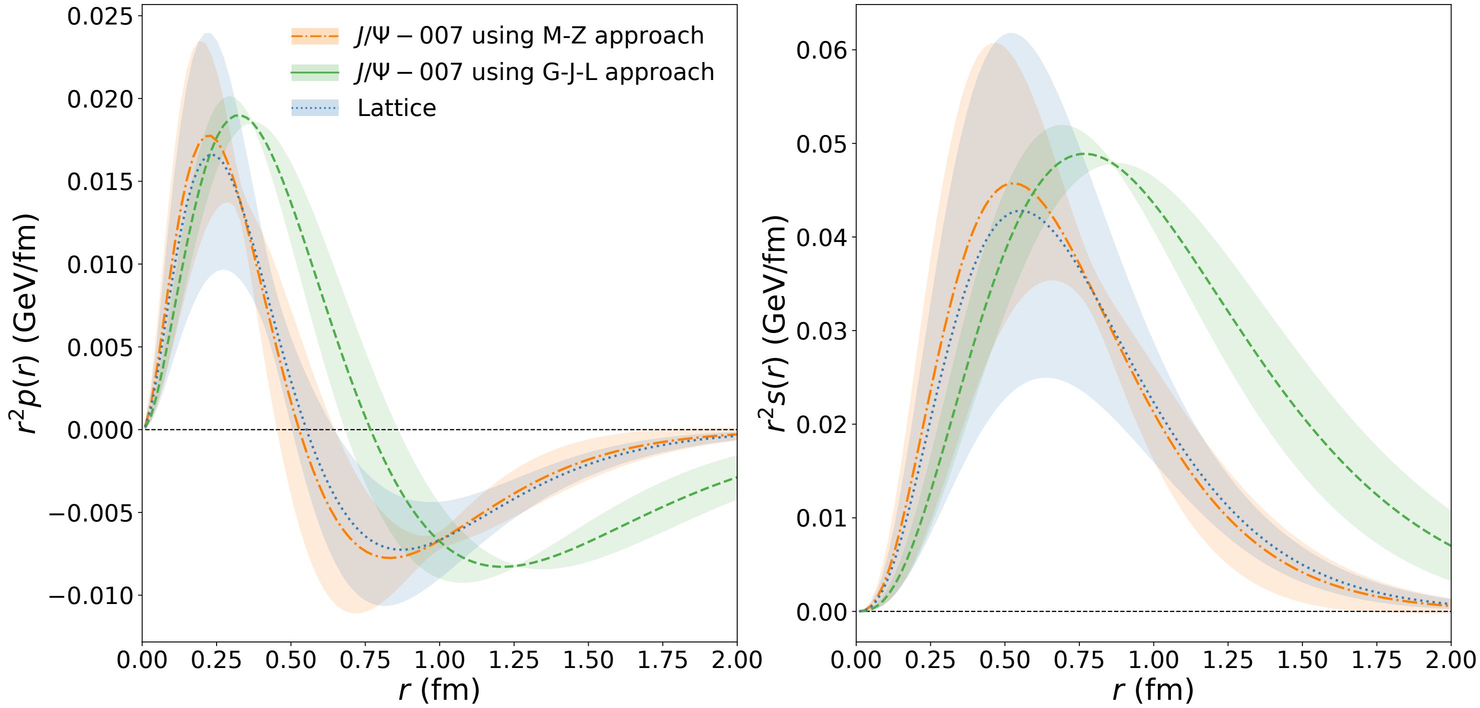
Updated analysis of near-threshold heavy quarkonium production for probe of proton's gluonic gravitational form factors
Y. Guo, X. Ji, Y. Liu and J. Yang,
Phys. Rev. D **108** (2023) no.3, 034003
doi:10.1103/PhysRevD.108.034003
[arXiv:2305.06992 [hep-ph]]



PRESSURE AND SHEAR DISTRIBUTIONS OF GLUONS

S. Prasad

Preliminary Results

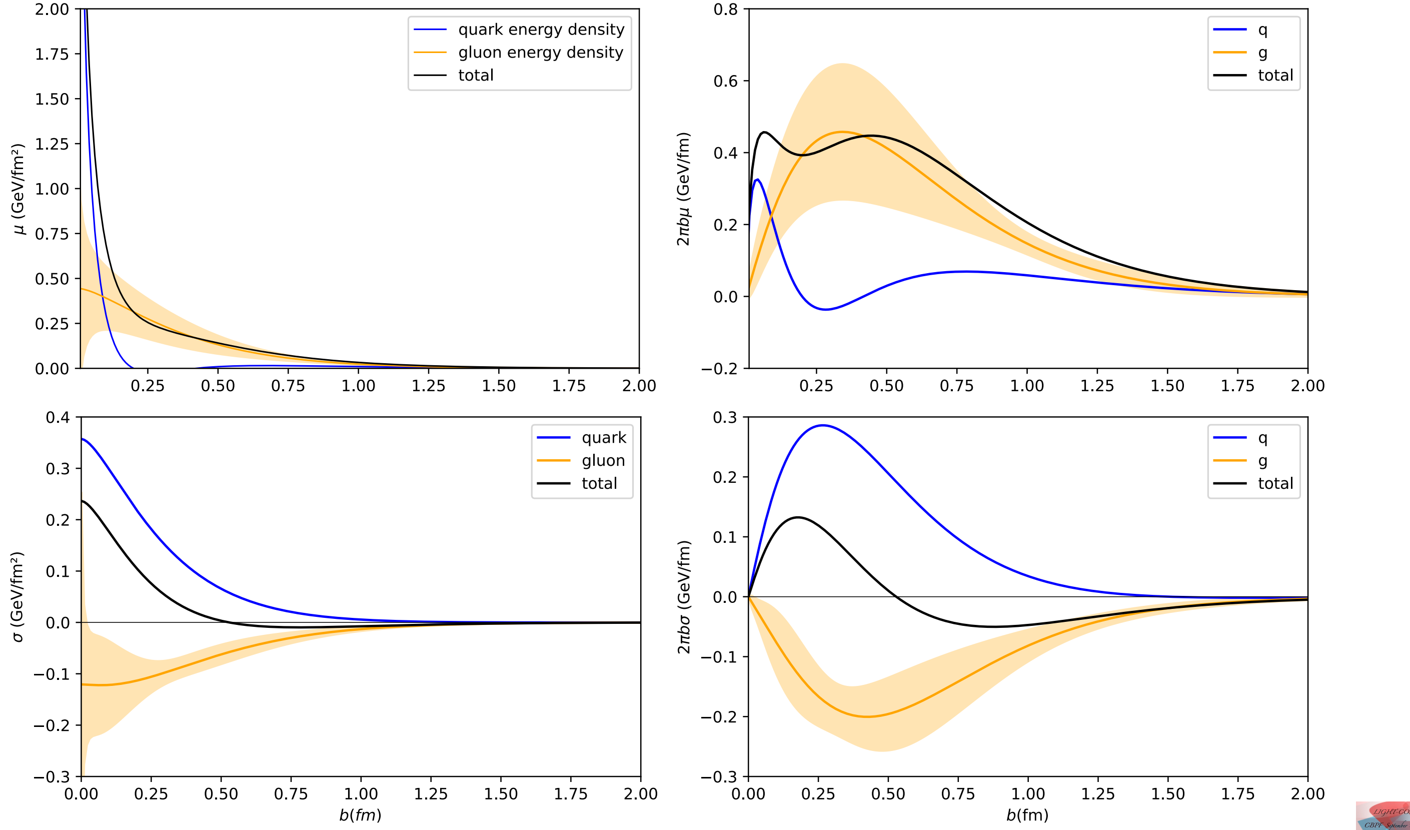


MASS, PRESSURE 2D DENSITY DISTRIBUTIONS OF GLUONS IN LC

$$\mu_g(b) = M\left\{\frac{A_g^{FT}(b)}{2} + \bar{C}_g^{FT}(b) + \frac{1}{4M^2}\frac{1}{b}\frac{d}{db}\left[\frac{B_g^{FT}(b)}{2} - 4C_g^{FT}(b)\right]\right\}$$

Lorcé et al. Eur. Phys. J. C (2019) 79

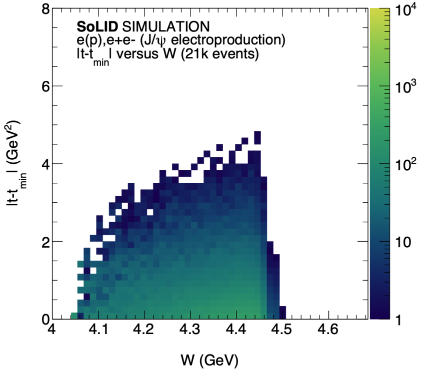
Preliminary Results

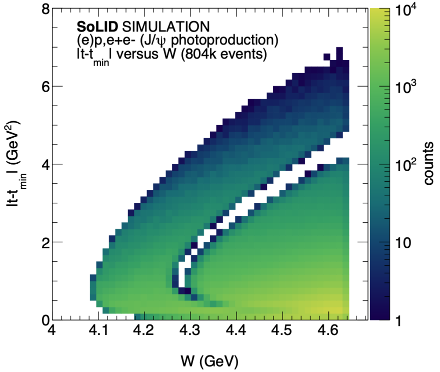


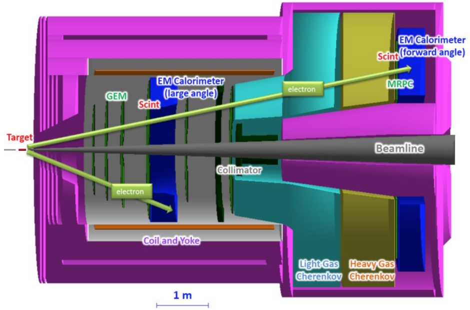
FUTURE SOLID EXPERIMENT AT JLAB

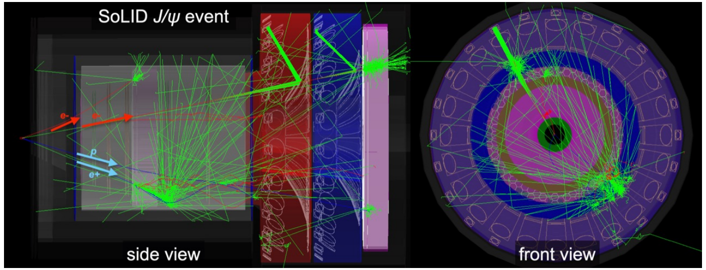
Ultimate experiment for near-threshold J/ψ production

- 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+)**





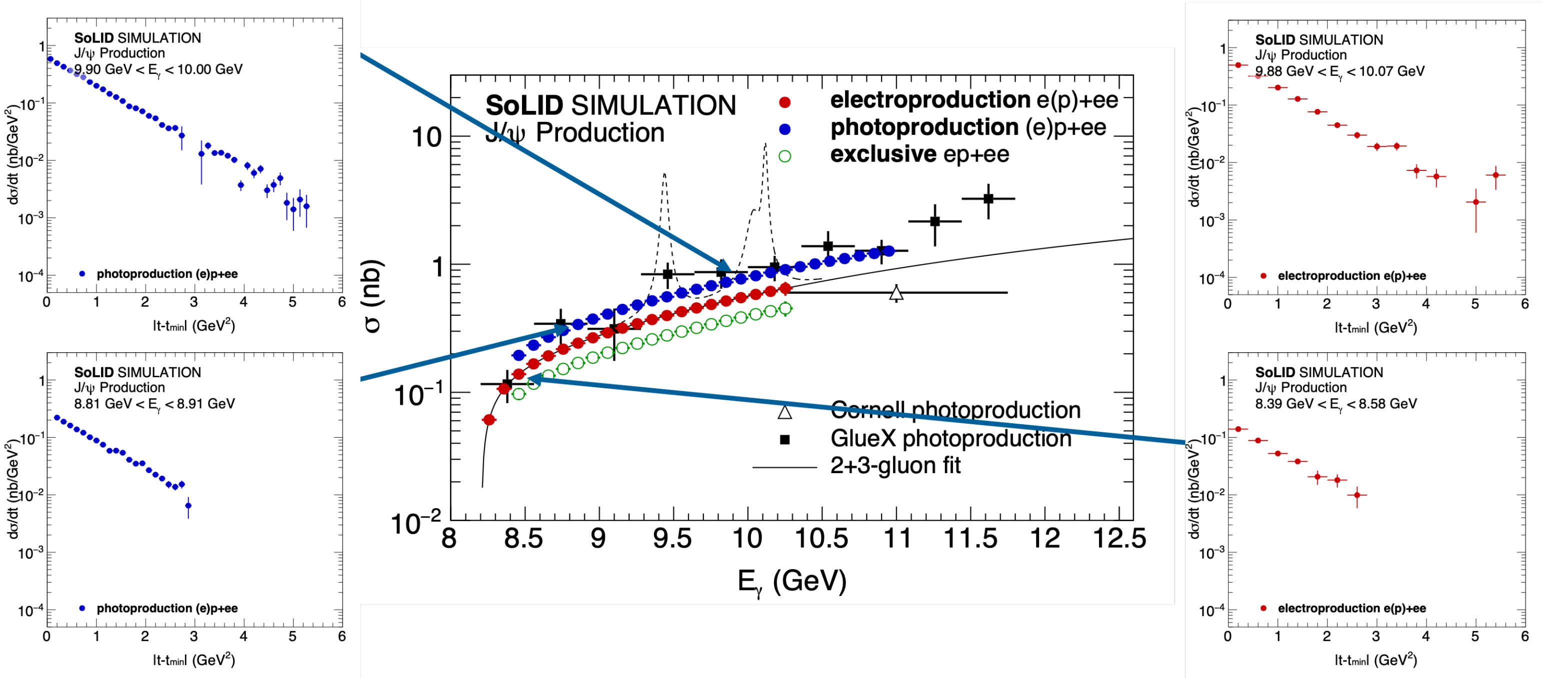




FUTURE SOLID EXPERIMENT AT JLAB

SoLID
SOLENOIDAL LARGE INTENSITY DEVICE

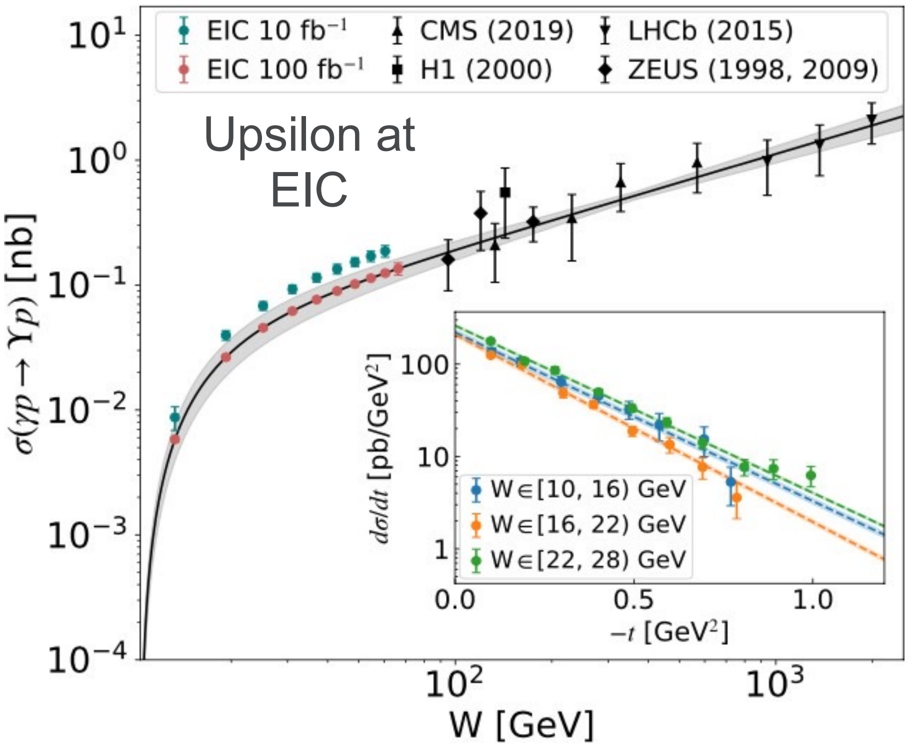
Precision measurement of J/psi near threshold



COMPLEMENTARITY WITH EIC

Upsilon production and J/psi production at large Q²

- 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 research

- Precision data in electroproduction and photoproduction of quarkonium near threshold provide critical information on

  - ✓ **The origin of hadron masses through the gravitational form factors**
  - ✓ **The gluon contribution to the mass density, the scalar density, the pressure and shear**

- Consistent will early lattice predictions we have a sneak preview of the gluonic density distribution in the proton from data with the help of models

- Statistical precision will enable an understanding of the systematic uncertainties in the extractions of the anomaly, the mass radius and the scalar radius, the pressure and shear

- In addition to photo-production measurements ePIC at EIC and SoLID at JLab will provide near threshold J/ψ (JLab at low Q^2, EIC at high Q^2) electroproduction measurements and Upsilon (EIC) precision measurements, critical for universality and the trace anomaly

THANK YOU!

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