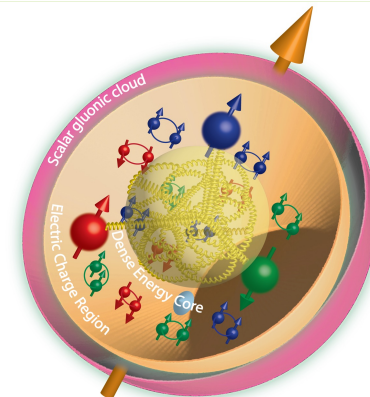


# 3D STRUCTURE OF THE NUCLEON VIA GPDS

## THE PROTON GLUONIC GRAVITATIONAL FORM FACTORS



ZEIN-EDDINE MEZIANI

Argonne National Laboratory

Article

# Determining the gluonic gravitational form factors of the proton

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

Received: 8 June 2022

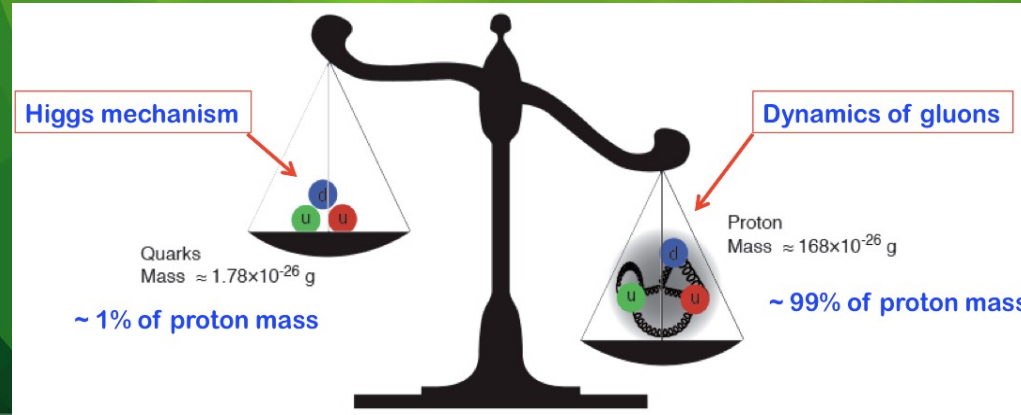
Accepted: 13 January 2023

 Check for updates

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

# Origin of Mass?

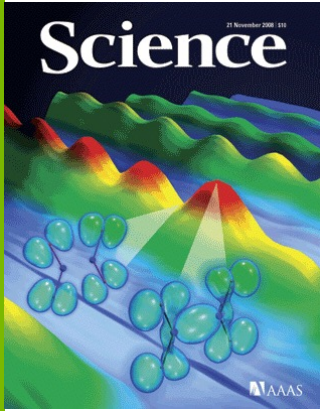
“...QCD takes us a long stride towards the Einstein-Wheeler ideal of mass without mass” Frank Wilczek (1999, Physics Today)



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

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

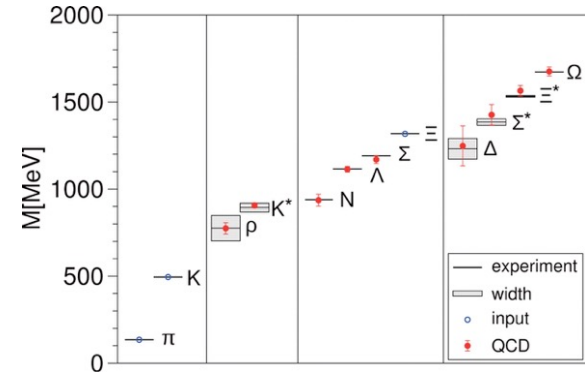
# Hadron Masses from Lattice QCD



(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

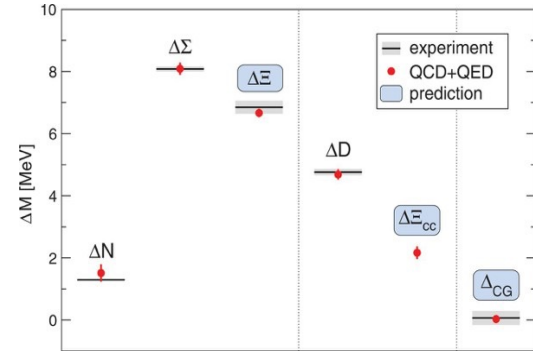
589 citations



(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?*

# 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)

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

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

Gross, Wilczek & Politzer

At small momentum transfer, heavy quarks decouple:

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

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

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

✧ 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 3<sup>rd</sup> 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]

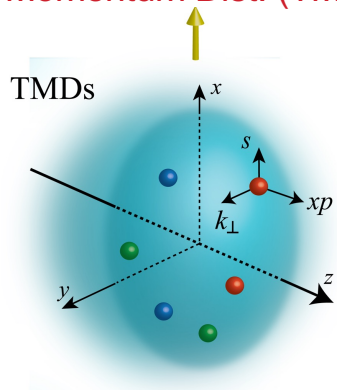
# Unified View of Nucleon Structure

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

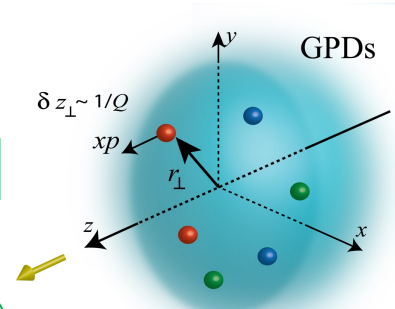
Transverse Momentum Dist. (TMD)

**Tomography**

Generalized Parton Dist. (GPD)



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



GPD

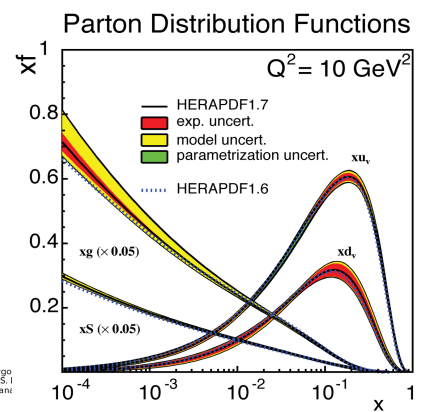
$dr_T$

$d^2k_T$

$d^2k_T$

$d^2r_T$

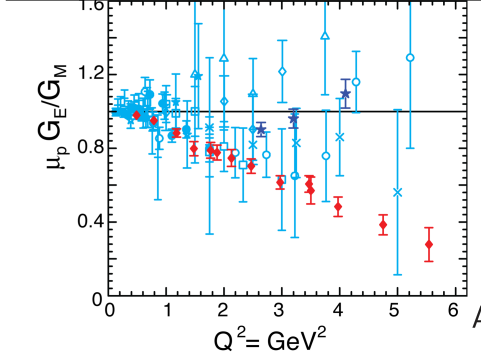
$dx$  & Fourier Transformation



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

**1D**

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



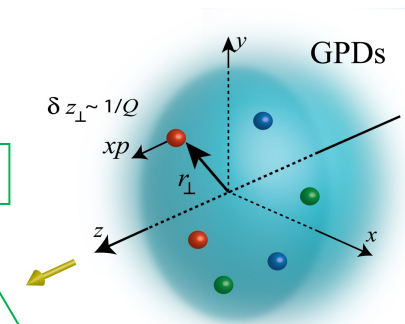
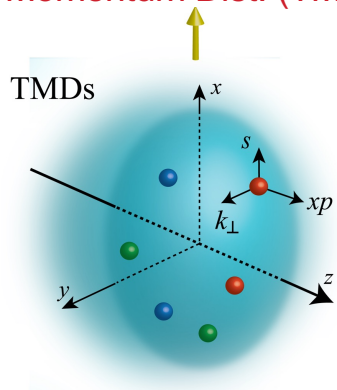
# Unified View of Nucleon Structure

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

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Generalized Parton Dist. (GPD)

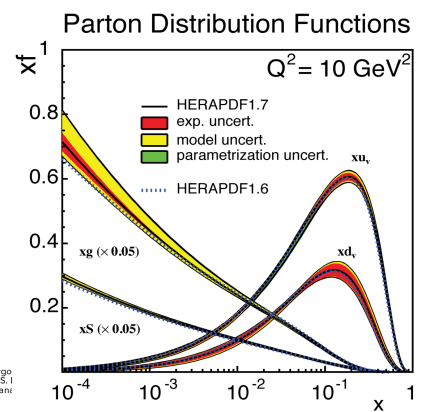


TMD  $f_1^u(x, k_T), h_1^u(x, k_T)$

GPD

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

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



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

**1D**

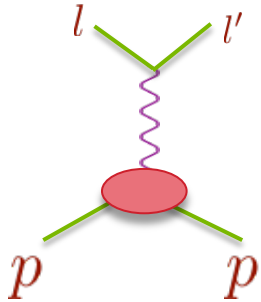


# The Proton Gravitational Form Factors Mass Radius and Scalar Radius

# EXPERIMENTAL REACTIONS TO DETERMINE FORM FACTORS

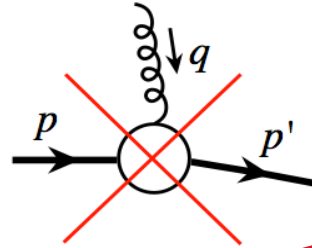
## Proton electric charge distribution

### Elastic Scattering



## Proton color charge distribution?

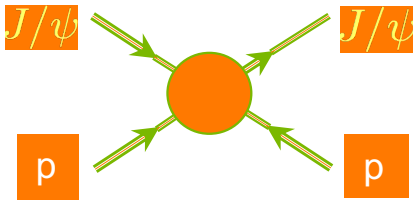
### Elastic color scattering; **but forbidden**



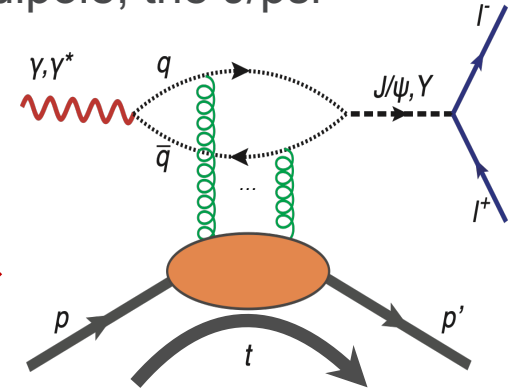
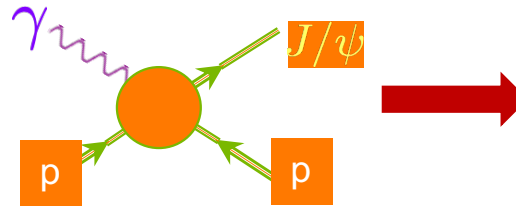
What to do to probe the gluon density?

Perhaps replace the proton by a color dipole, the  $J/\psi$

### Elastic $J/\psi$ scattering



### Photoproduction of $J/\psi$



# 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

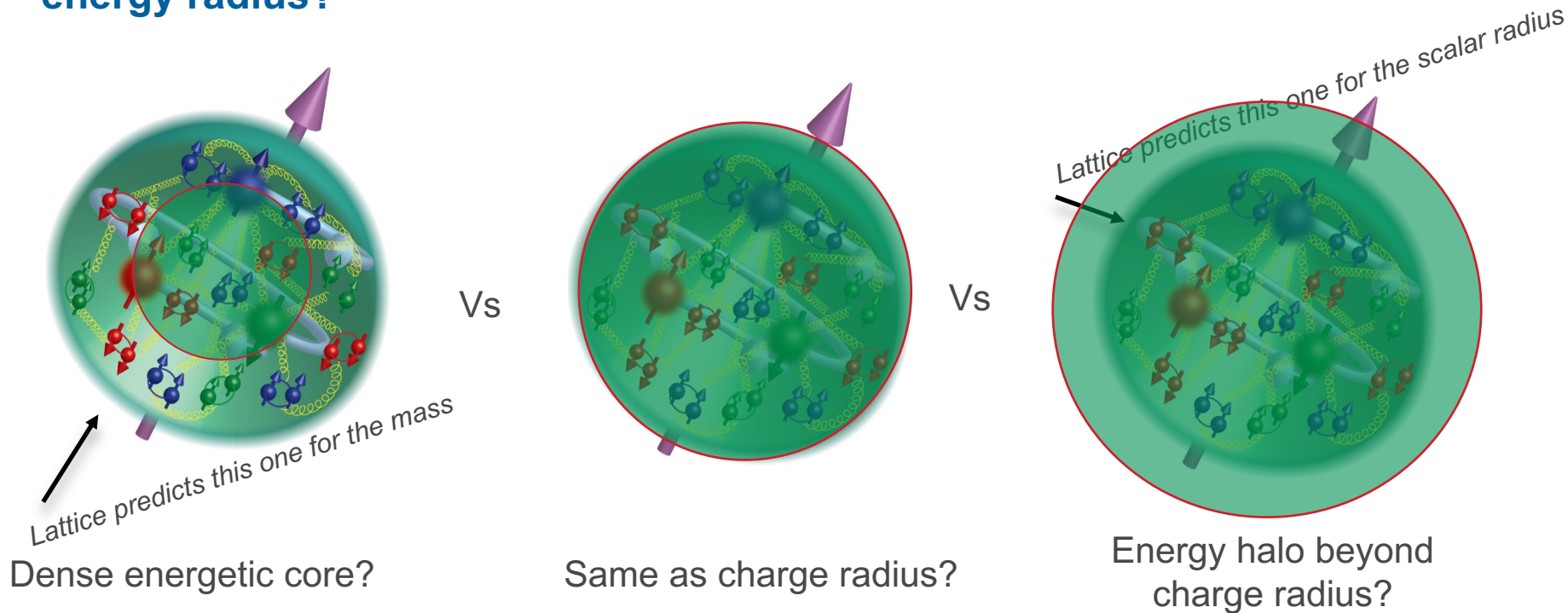
$$\begin{aligned} & \langle N' | T_{q,g}^{\mu,\nu} | N \rangle \\ & = \bar{u}(N') \left( A_{g,q}(t) \gamma^{\{\mu P^{\nu\}} + B_{g,q}(t) \frac{iP^{\{\mu \sigma^{\nu\}} \rho \Delta_\rho}{2M} + C_{g,q}(t) \frac{\Delta^\mu \Delta^\nu - g^{\mu\nu} \Delta^2}{M} + \bar{C}_{g,q}(t) M g^{\mu\nu} \right) u(N)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

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

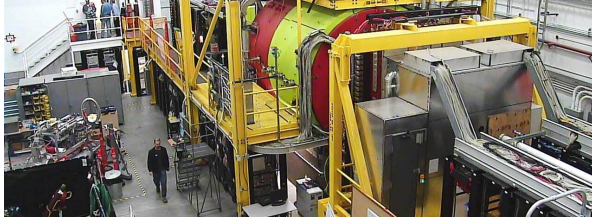
- $A_{g,q}(t)$ : Related to quark and gluon momenta,  $A_{g,q}(0) = \langle x_{q,g} \rangle$
- $J_{g,q}(t) = 1/2(A_{g,q}(t) + B_{g,q}(t))$ : Related to angular momentum,  $J_{tot}(0) = 1/2$
- $D_{g,q}(t) = 4C_{g,q}(t)$ : Related to pressure and shear forces

# HOW IS THE GLUON ENERGY DISTRIBUTED 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 and to the scalar energy radius?



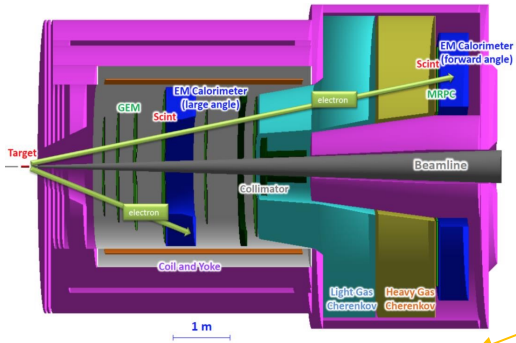
# 12 GEV J/ψ EXPERIMENTS AT JEFFERSON LAB NOW AND FUTURE



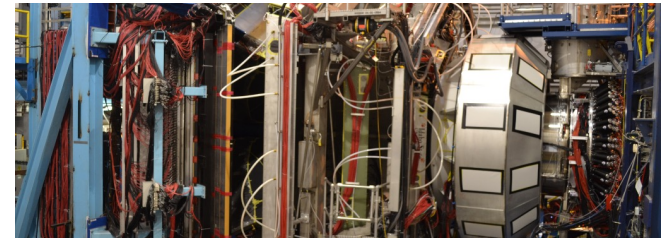
Hall D - GlueX observe the first J/ψ at JLab  
A. Ali *et al.*, PRL 123, 072001 (2019)



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



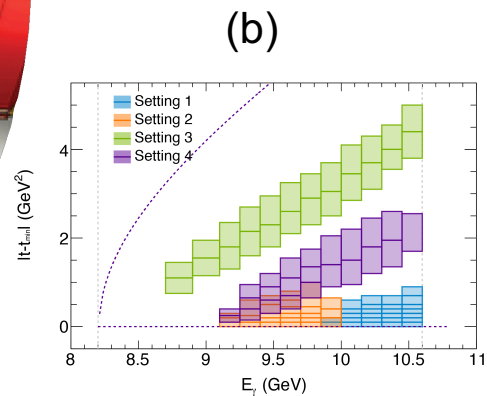
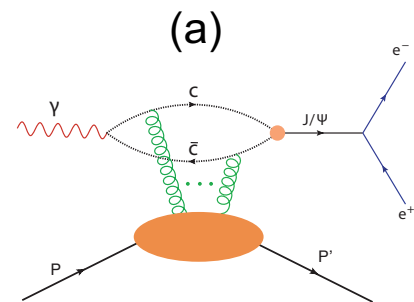
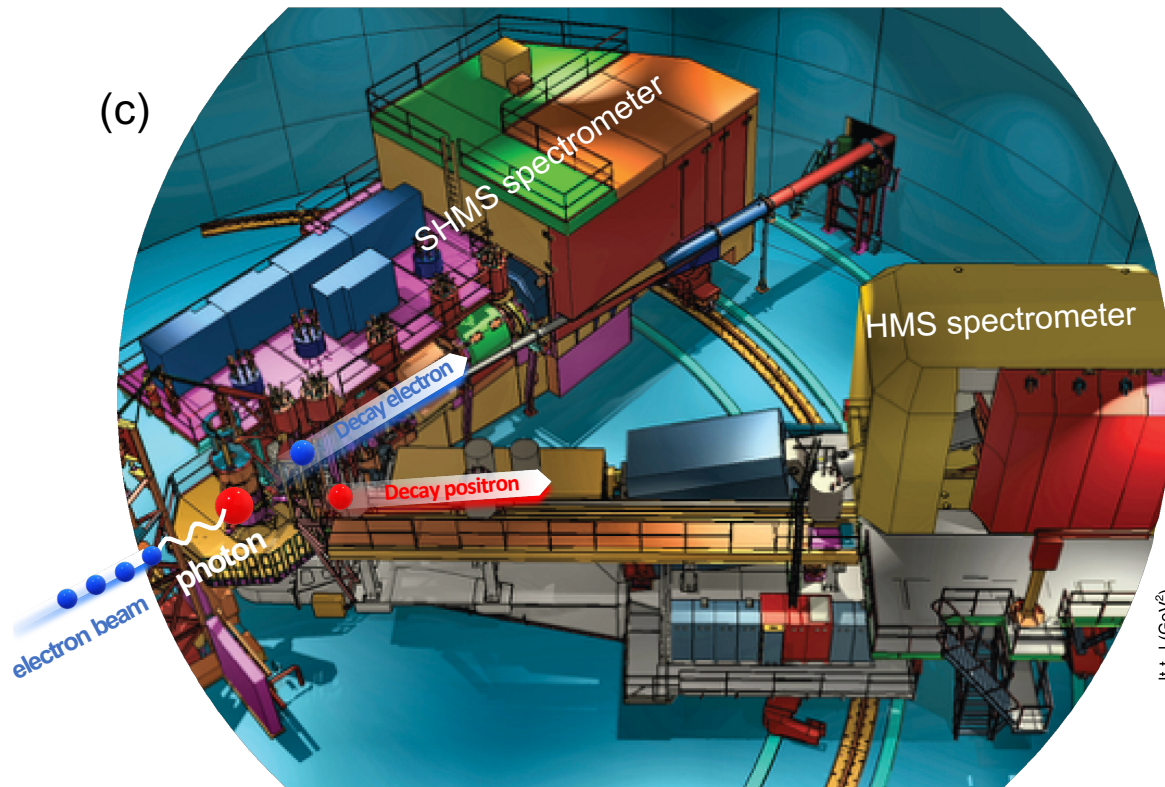
Hall A has experiment E12-12-006 at SoLID to measure J/ψ in electro- and photoproduction, and an LOI to measure double polarization using SBS



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

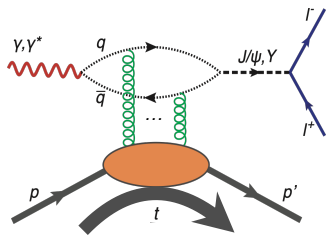
# JLAB EXPERIMENT E12-16-007 IN HALL C AT JLAB

## Near threshold photoproduction of $J/\psi$

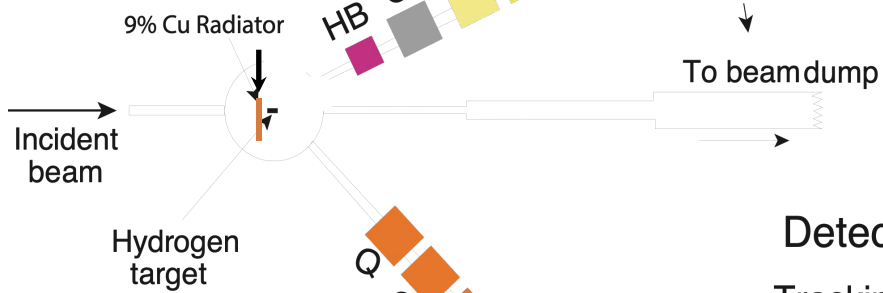


# JLAB EXPERIMENT E12-16-007

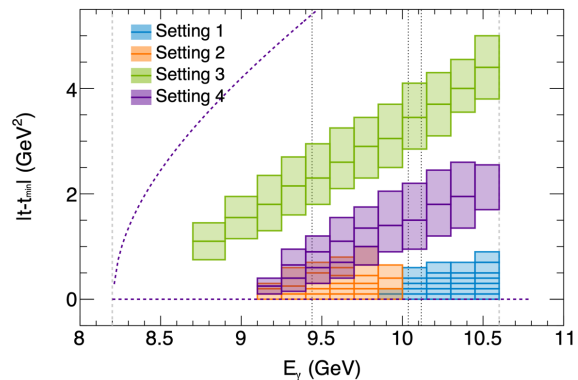
## Near threshold photoproduction of $J/\psi$



**$J/\psi$  threshold:**  
 $W \approx 4.04 \text{ GeV}$   
 $E_{\gamma}^{\text{lab}} \approx 8.2 \text{ GeV}$   
 $t \approx -1.5 \text{ GeV}^2$



Electron in SHMS



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

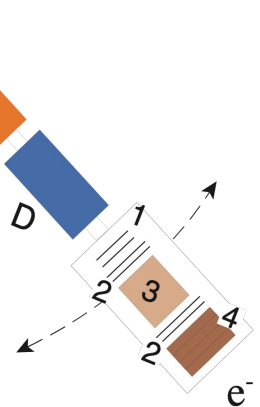
### Detector Stacks:

### Tracking/ Timing:

1. Drift Chambers
2. Hodoscopes

### Particle ID:

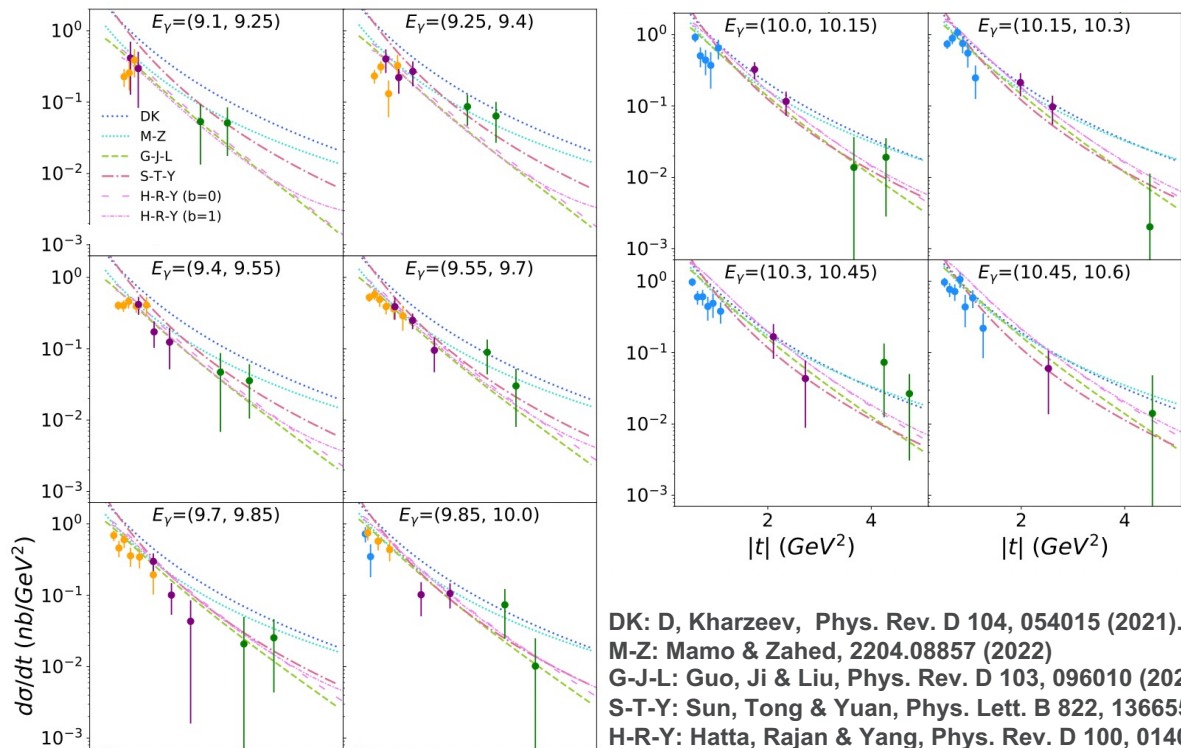
3. Gas Čerenkov
4. Lead Glass Calorimeter



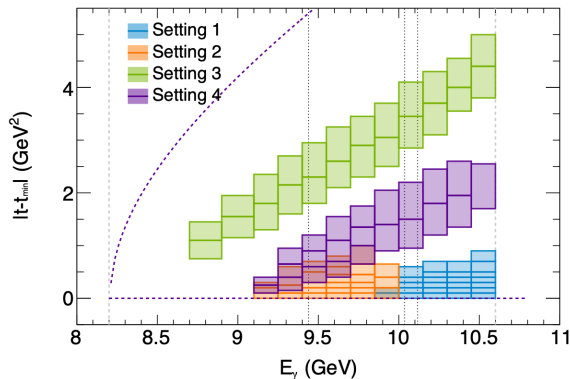
Positron in HMS

# 2D J/Ψ CROSS SECTION RESULTS FROM 007<sup>J/Ψ</sup>

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



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)



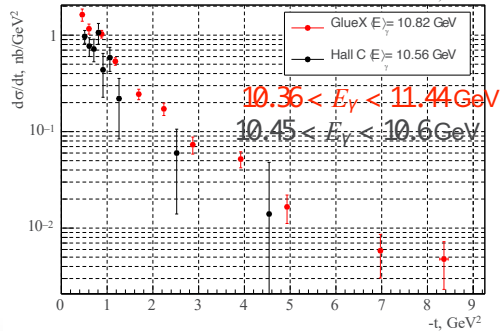
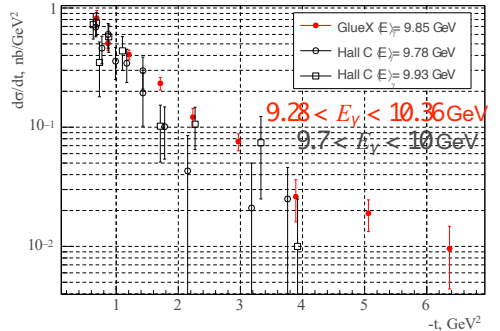
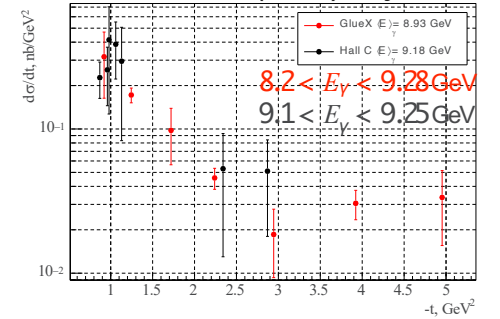
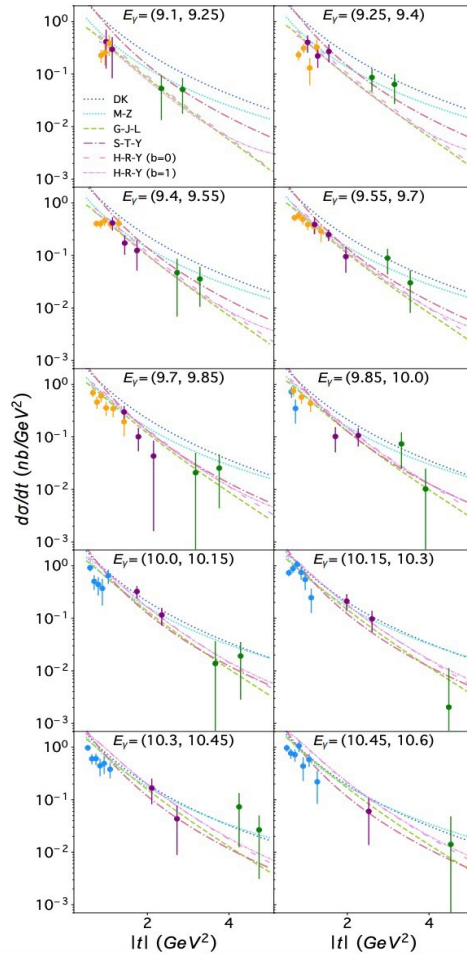
- Unfolded 2D cross section results compared to various model predictions informed by the 2019 1D GlueX results
- All models work reasonably well at higher energies but deviate at lower energies



# DIFFERENTIAL CROSS SECTIONS FROM $J/\psi$ -007 AND GLUEX

B. Duran et al. ( $J/\psi$ -007), Nature 615 (2023)

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



- 10 photon energy bins of 150 MeV in  $J/\psi$ -007
- Results for the three **GlueX energy bins** compared to the closest Hall C
- Scale uncertainties: 20% in GlueX and 4% in Hall C  $J/\psi$ -007 differential cross section results
- **Good agreement within errors**; note also differences in average energies

# CAVEATS IN THE GFFS EXTRACTION

There are certainly caveats in the extraction of the GFFs using models but this first attempt points to a promising future

## Holographic Model

- The method is suitable for threshold production, a.k.a **non-perturbative region**.
- No vector dominance model has been used
- The model seems to **track the lattice results**
- Our extraction presumes no pentaquark resonances or threshold effects in this region of cross section data
- $B_g(t)$  is neglected in the cross section expression, consistent with its smallness in lattice QCD and the holographic model
- We have neglected  $\bar{C}(t)_g$ , in the cross section expression or radii.  $\bar{C}_g(0) = -\bar{C}_q(0)$  and calculated in:

Hatta *et al.* *JHEP* 12 (2018) 008, & Tanaka, K. *JHEP* 03 (2023) 013

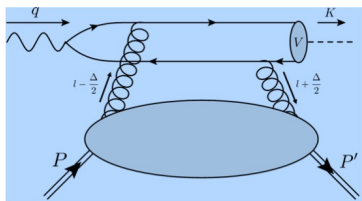
## GPD Model

- Unlike in the case of large photon-nucleon center of mass energy here  $t$  is large.
- **Two gluons** exchange is clearly not sufficient and higher order will need to be evaluated
- The GPD Model is expected to be adequate the large skewness region but most data are at small skewness
- $B_g(t)$  is neglected in the cross section expression, consistent with its smallness in lattice QCD and the holographic model
- We have neglected  $\bar{C}(t)_g$ , in the cross section expression or radii

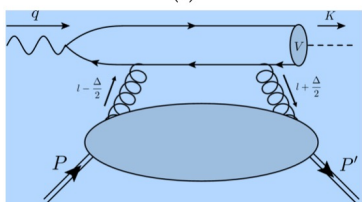
# THE GENERALIZED PARTON DISTRIBUTION MODEL

## 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)



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

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

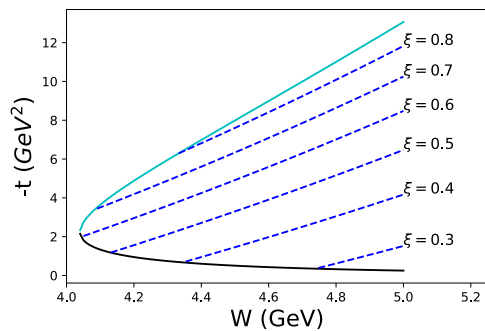
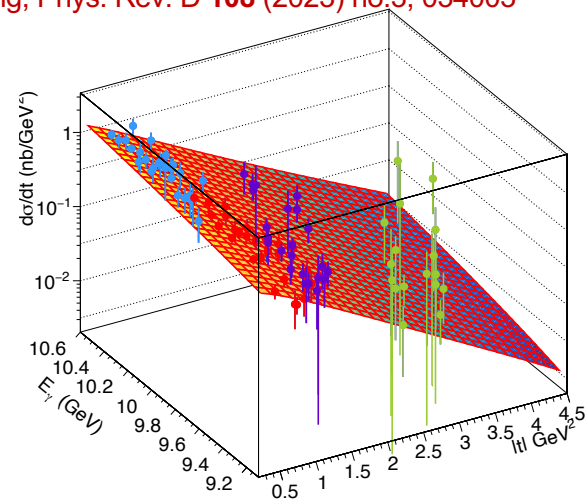
$$|G(t, \xi)|^2 = \frac{4}{\xi^4} \left\{ \left(1 - \frac{t}{4m_N^2}\right) E_2^2 - 2E_2(H_2 + E_2) + (1 - \xi^2)(H_2 + E_2)^2 \right\}$$

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

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

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

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

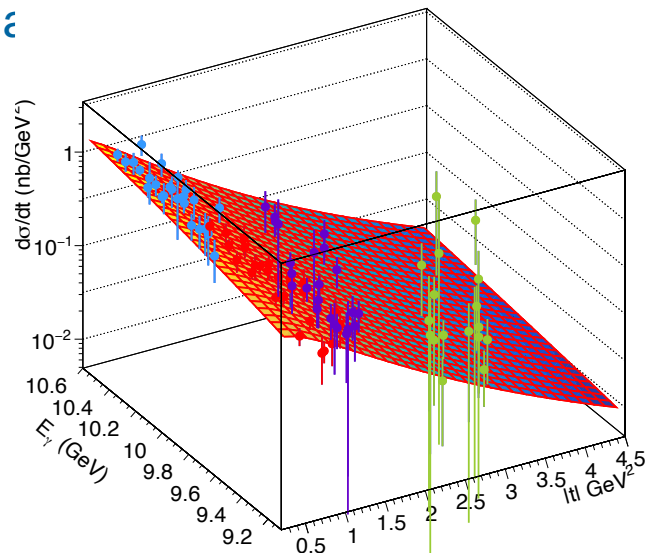
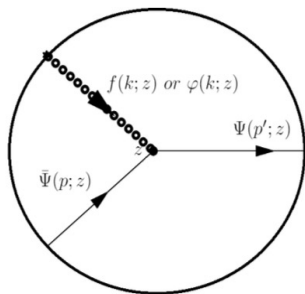
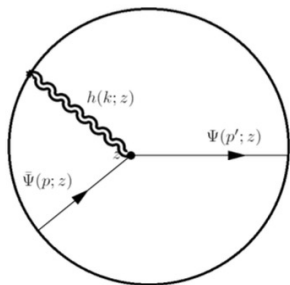


# THE HOLOGRAPHIC QCD MODEL

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** :  $\langle p_2 | T_{\mu}^{\mu}(0) | p_1 \rangle$

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

- $A(t)$  and  $D(t)$  shapes are fully calculated; However, tripole form for both A and D is used as a very good approximation 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.

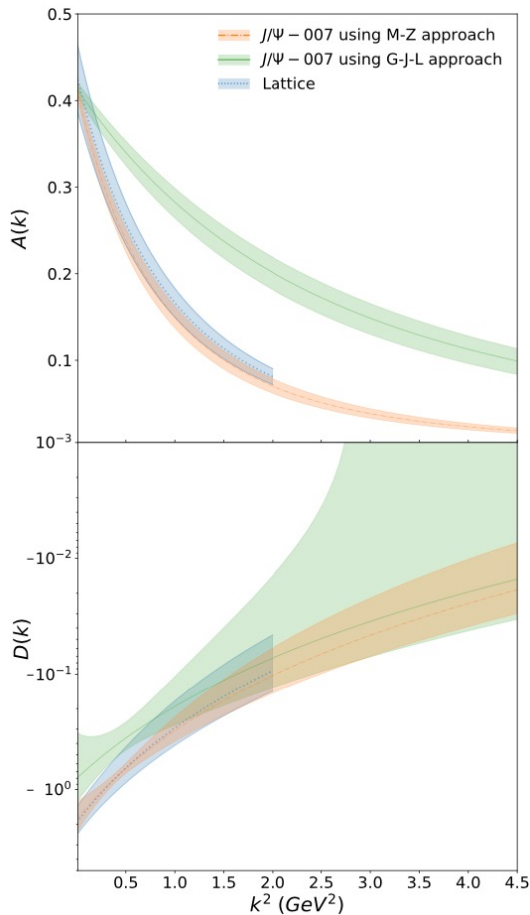
$$A_g(t) = \frac{A_g(0)}{\left(1 - \frac{t}{m_A^2}\right)^3}$$

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

# GLUONIC GFF RESULTS; FIRST EXTRACTION

007<sup>J/ψ</sup>

Good agreement between holographic QCD extraction 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).

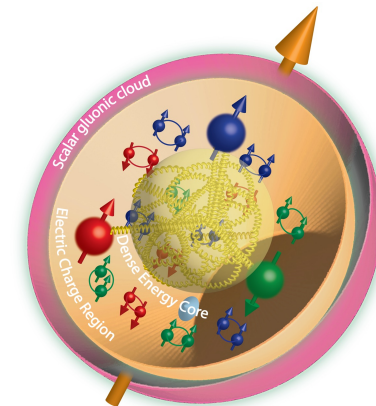
# FIRST EXTRACTION OF GLUONIC SCALAR/MASS RADIUS OF THE NUCLEON

A picture of three zones?

## Definition of gluonic mass and scalar radius

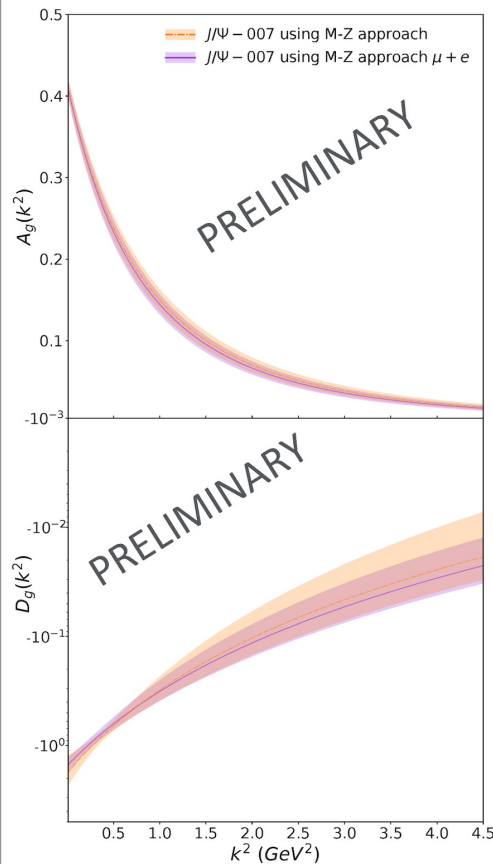
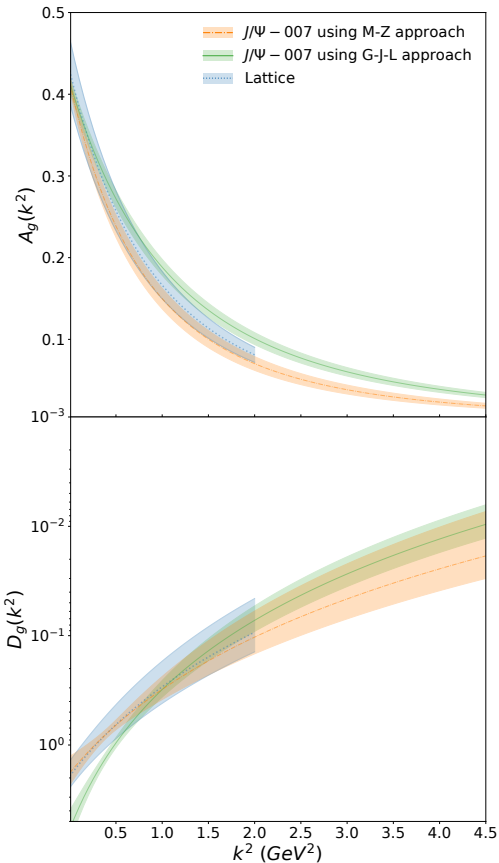
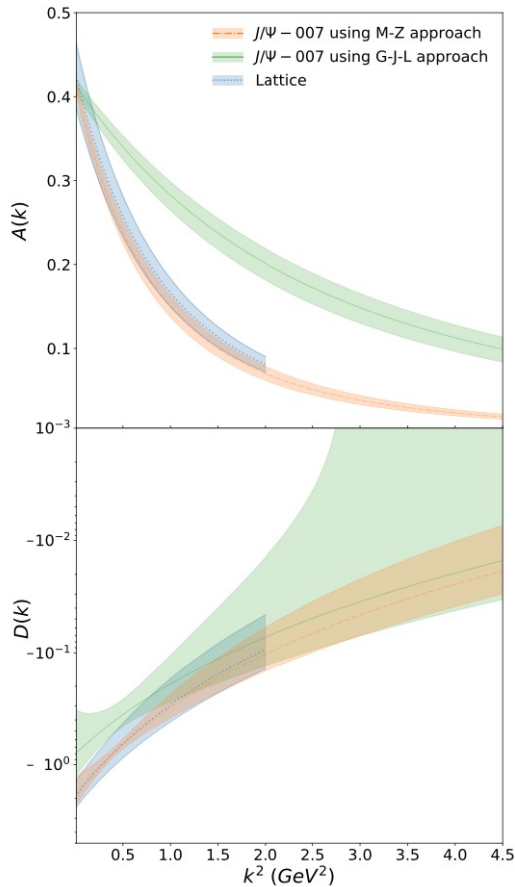
$$\langle r_m^2 \rangle_g = 6 \frac{1}{A_g(0)} \frac{dA_g(t)}{dt} \Big|_{t=0} - 6 \frac{1}{A_g(0)} \frac{C_g(0)}{M_N^2}$$

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



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

# UPDATED GJL GFFS EXTRACTION RESULT (FOLLOW GREEN CURVES)



- Analysis with the muons decay channel results, doubling the statistics

- Consistent with the electron results.

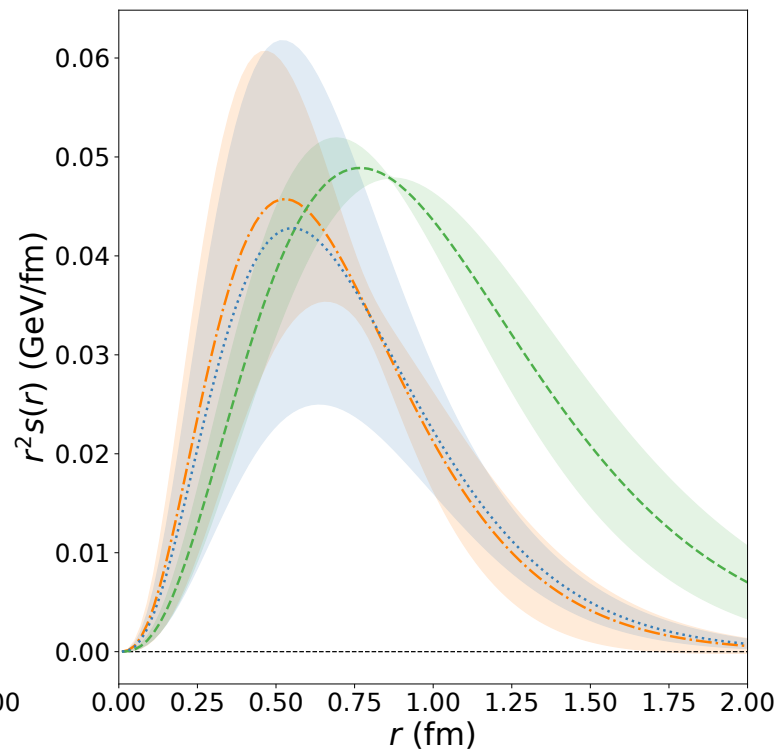
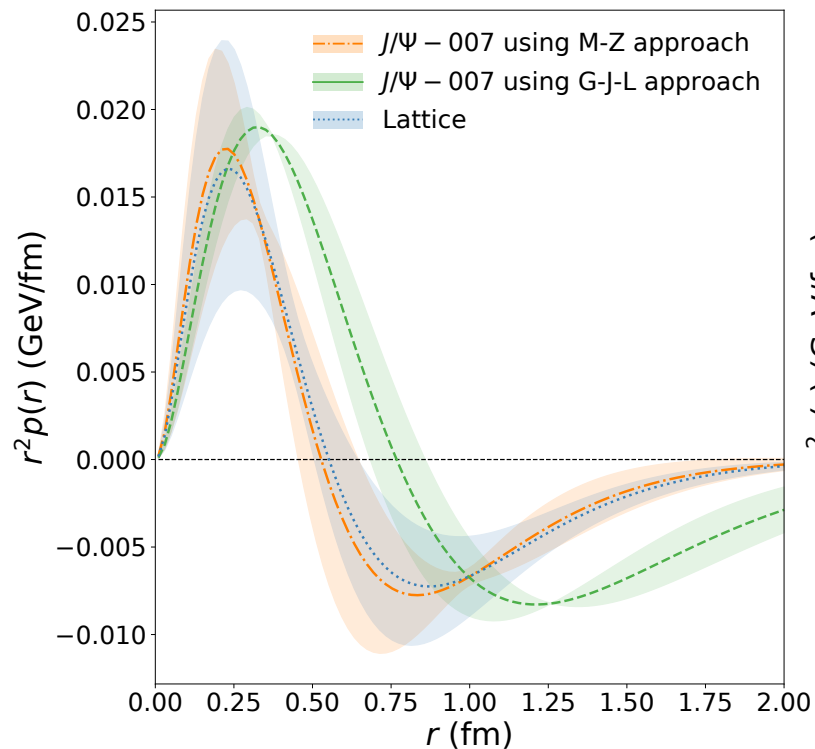
- Largest impact on the  $C_g(t)$  form factor with improved precision

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]

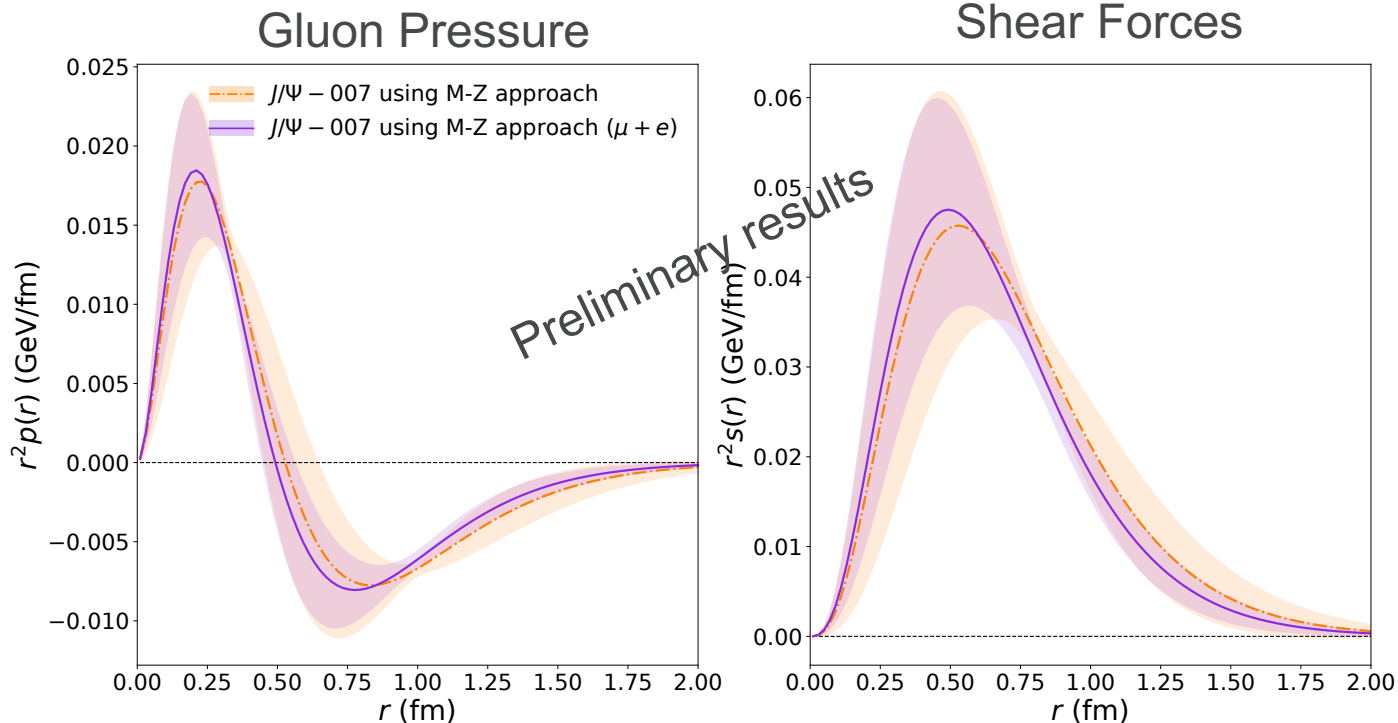
# PRESSURE AND SHEAR DISTRIBUTIONS OF GLUONS

## Preliminary Results Through Fourier Transform of the $D=4C$ GFF





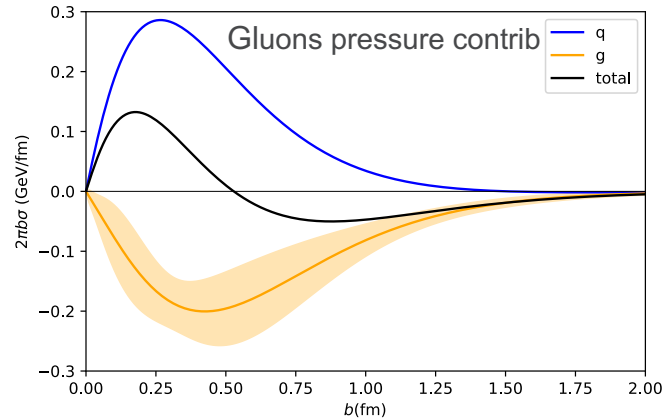
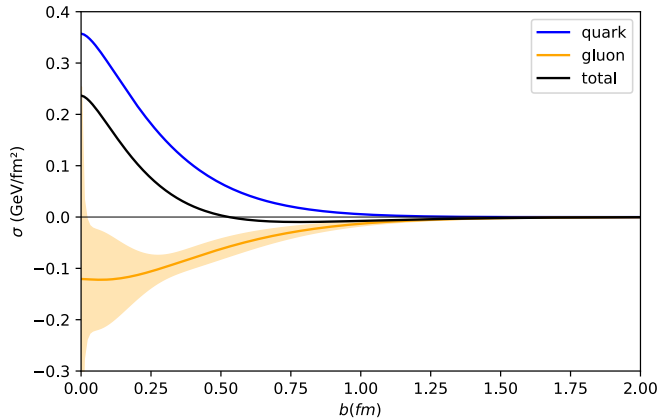
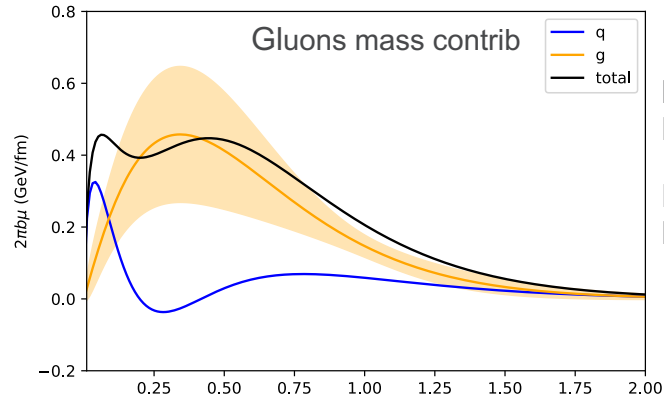
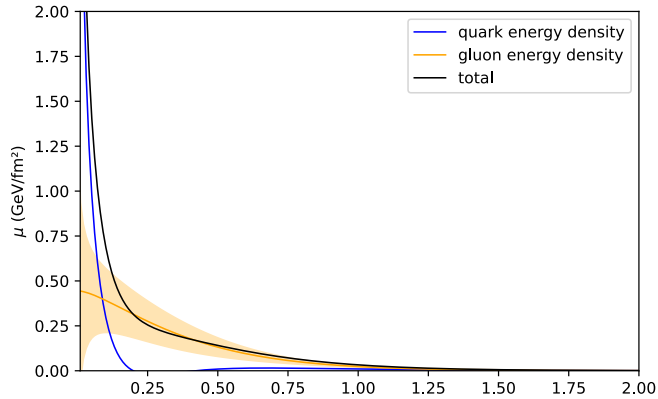
## Preliminary results: Breit Frame



# MASS, PRESSURE 2D GALILEAN DENSITY DISTRIBUTIONS OF GLUONS

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

**Preliminary Results on the Light Front**



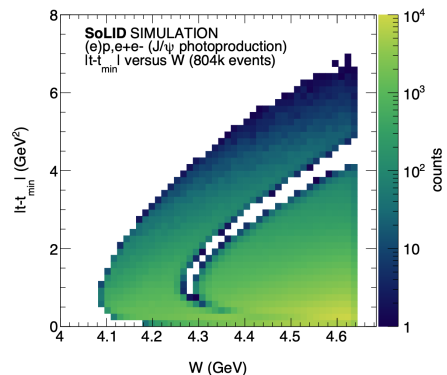
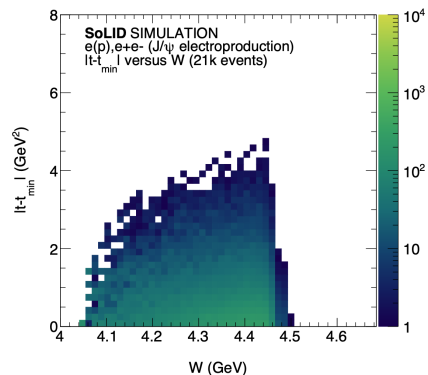
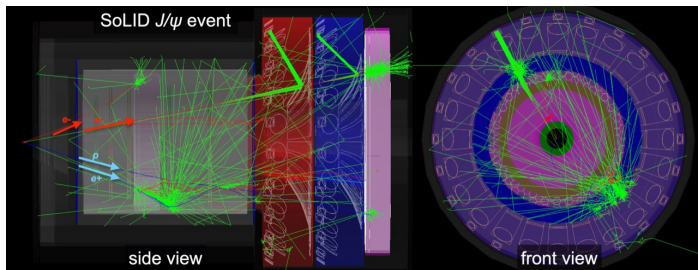
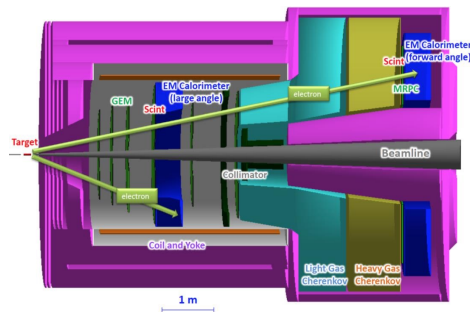
Lorcé *et al.*  
Eur. Phys. J. C (2019) 79

Freeze & Miller,  
Phys. Rev D **103**, 094023

# FUTURE SOLID EXPERIMENT AT JLAB

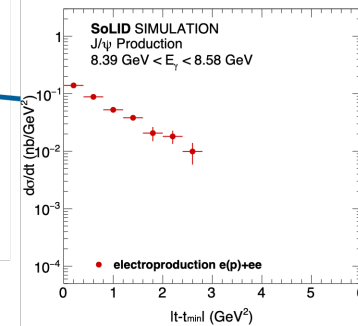
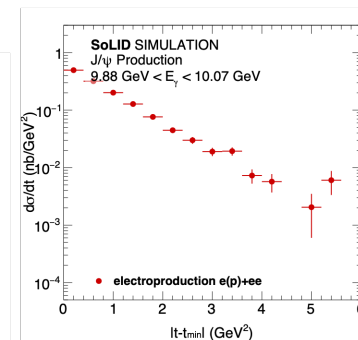
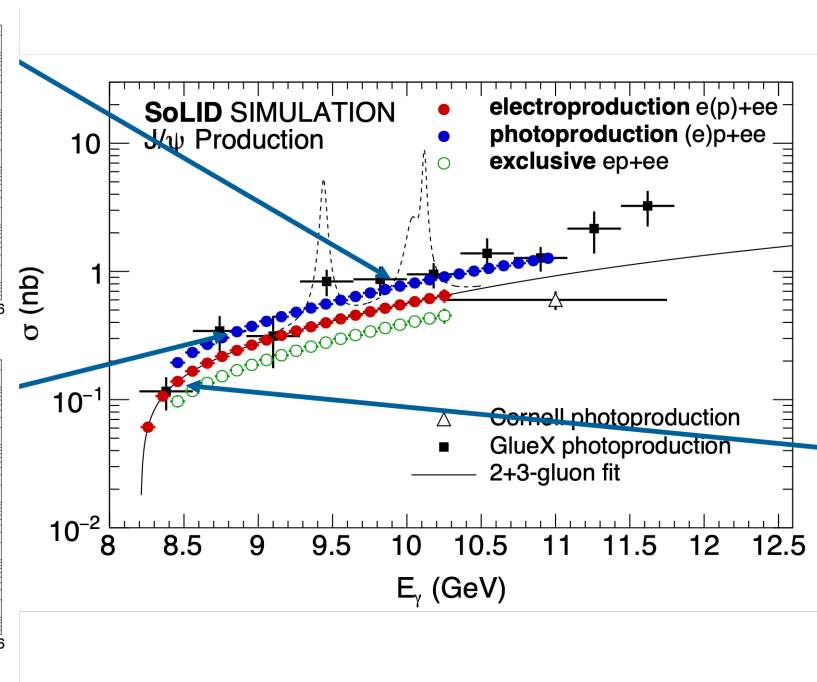
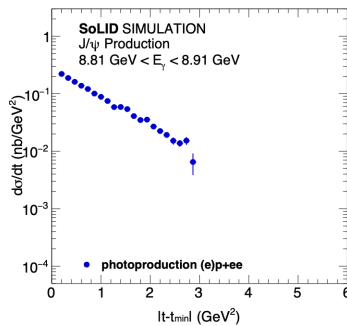
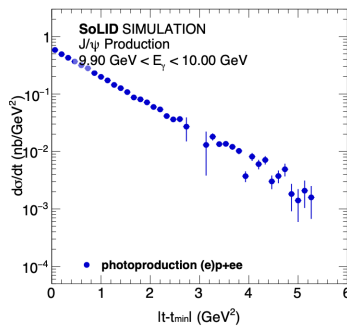
## Ultimate experiment for near-threshold $J/\psi$ production

- General purpose large-acceptance spectrometer
- 50 days of  $3\mu\text{A}$  beam on a  $15\text{cm}$  long LH2 target ( $10^{37}/\text{cm}^2/\text{s}$ )
- Ultra-high luminosity:  $43.2\text{ab}^{-1}$
- 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



# 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

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

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

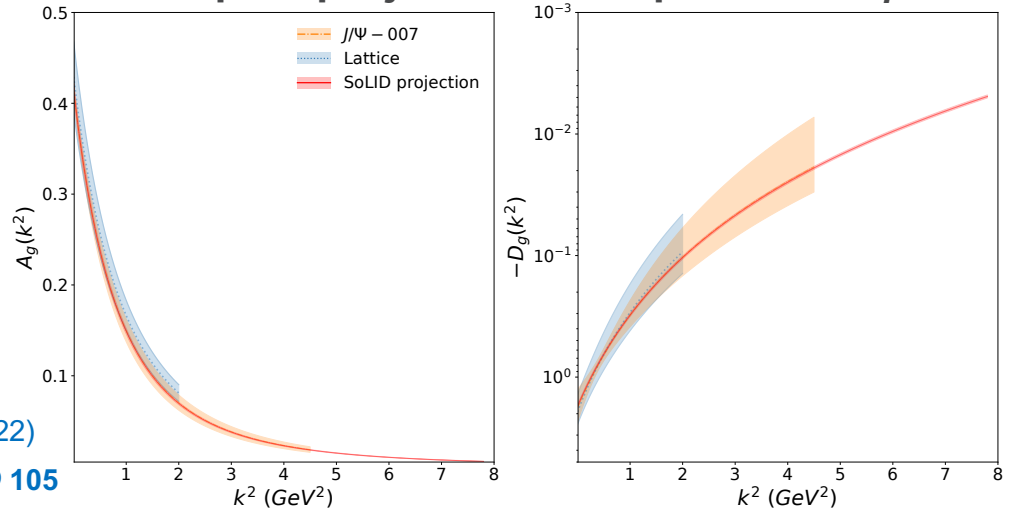
- $A_{g,q}(t)$ : Related to quark and gluon momenta,  $A_{g,q}(0) = \langle x_{q,g} \rangle$
- $J_{g,q}(t) = 1/2(A_{g,q}(t) + B_{g,q}(t))$ : Related to angular momentum,  $J_{tot}(0) = 1/2$
- $D_{g,q}(t) = 4C_{g,q}(t)$ : Related to pressure and shear forces

B. Duran, et al., *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

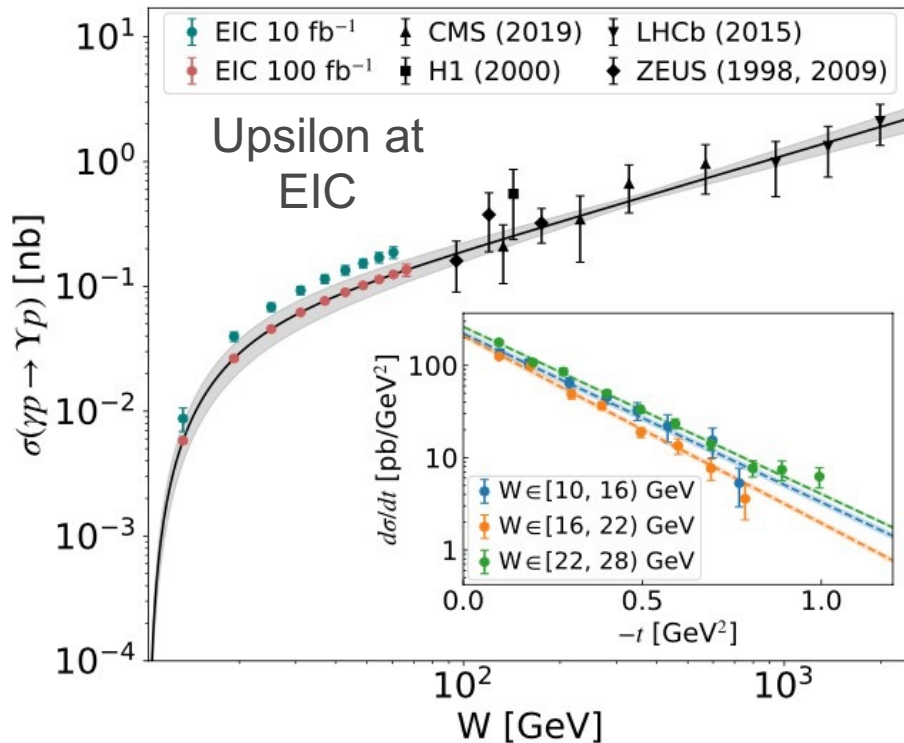
## SoLID impact projections compared to J/ψ-007



# COMPLEMENTARITY WITH EIC

## Upsilon production and $J/\psi$ production at large $Q^2$

- $Y(1S)$  at EIC trades statistical precision of  $J/\psi$  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  $J/\psi$  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
- 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 with 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  $J/\psi$  (JLab at low  $Q^2$ , EIC at high  $Q^2$ ) electroproduction measurements and Upsilon (EIC) precision measurements, critical **for universality tests and the trace anomaly**

# Thank you!

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



Argonne National Laboratory is a  
U.S. Department of Energy laboratory  
managed by UChicago Argonne, LLC.



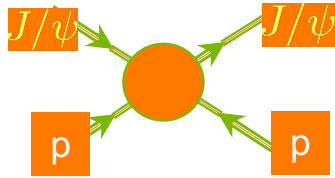


# PHOTOPRODUCTION A PATH TOWARDS THE TRACE ANOMALY

- To determine  $b$  we need the  $t$  distribution of at a given photon beam energy.

D. Kharzeev. Quarkonium interactions in QCD, 1995 nucl-th/9601029

D. Kharzeev, H. Satz, A. Syamtomov, and G. Zinovjev, Eur.Phys.J., C9:459–462, 1999



$$\left. \frac{d\sigma_{J/\psi N \rightarrow J/\psi N}}{dt} \right|_{t=0} = \frac{\alpha_{em} m_{J/\psi}}{3\Gamma(J/\psi \rightarrow e^+e^-)} \left( \frac{k_{\gamma N}}{k_{J/\psi N}} \right)^2 \left. \frac{d\sigma_{\gamma N \rightarrow J/\psi N}}{dt} \right|_{t=0}$$

Photoproduction cross section at  $t=0$  linked to the forward elastic scattering amplitude of  $J/\psi$ - $N$  through VMD

$$\left| F_{J/\psi N} \right| = \left[ 64\pi [m_{J/\psi}^2 (\lambda^2 - m_N^2)] \left. \frac{d\sigma_{J/\psi N \rightarrow J/\psi N}}{dt} \right|_{t=0} \right]^{1/2}$$

$$\lambda = (p_N p_{J/\psi} / m_{J/\psi}) \quad \text{Nucleon energy in the charmonium rest frame}$$

$$\left| F_{J/\psi N} \right| \simeq r_0^3 d_2 \frac{2\pi^2}{27} 2M_N^2 (1-b) = r_0^3 d_2 \frac{16\pi^2}{27} M_N M_a$$

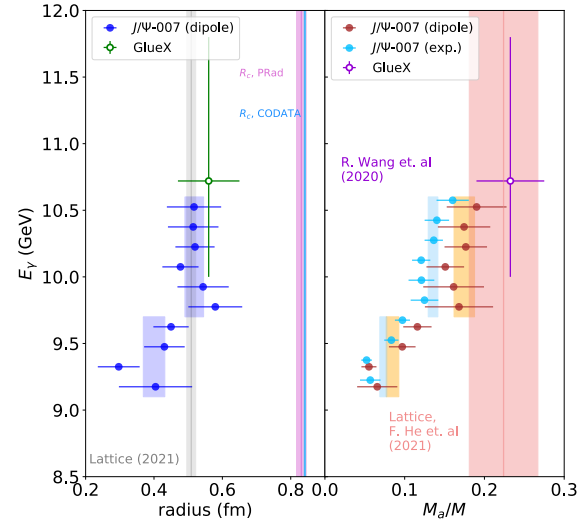
$$r_0 = \left( \frac{4}{3\alpha_s(\mu^2)} \right) \frac{1}{m_c(\mu^2)}$$

Bohr radius of charmonium

$$d_2^{(1S)} = \left( \frac{32}{N_c} \right)^2 \sqrt{\pi} \frac{\Gamma(n+5/2)}{\Gamma(n+5)}$$

Wilson coefficient

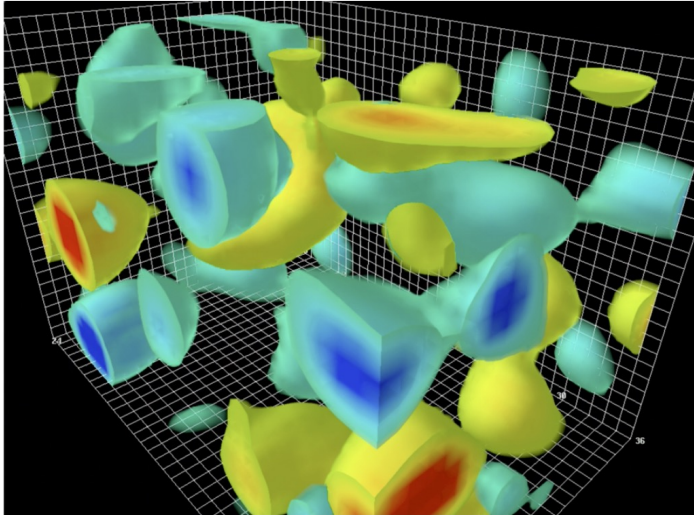
$$\text{Rydberg energy squared} = \mu^2$$



# A HOLOGRAPHIC APPROACH

- Holography provides a string-based approach dual to Yang-Mills (YM)

Instantons (yellow) and anti-instantons (blue)



Leinweber et al. 2003

Cooled Yang Mills vacuum filled with topological gauge fields

Vacuum; a liquid on Instantons

Gluon condensate in the nucleon is linked to the QCD vacuum compressibility which measures the diluteness of the QCD instanton vacuum as a topological liquid.

Shuryak, Zahed

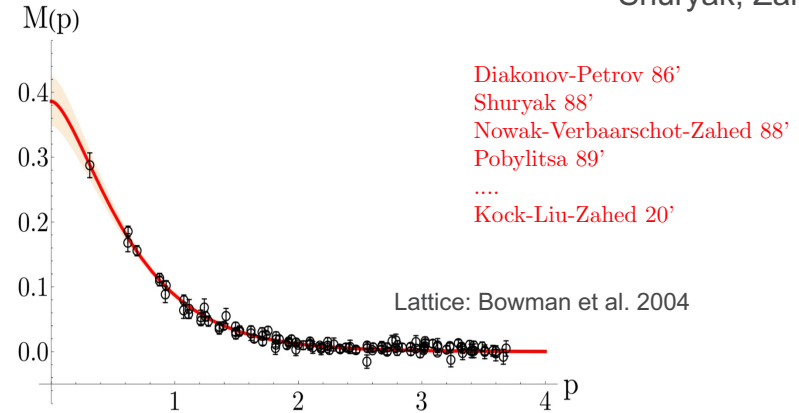


FIG. 2: Momentum dependence of the instanton induced effective quark mass in singular gauge (13) at LO (solid-curves), compared to the effective quark mass measured on the lattice in Coulomb gauge [21] (open-circles). The unit scale is GeV. We obtain a fitted parameter intervals  $M(0) = 383 \pm 39$  MeV and  $\rho = 0.313 \pm 0.016$  fm.

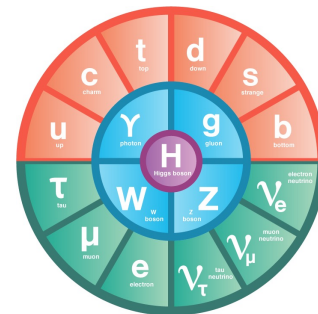
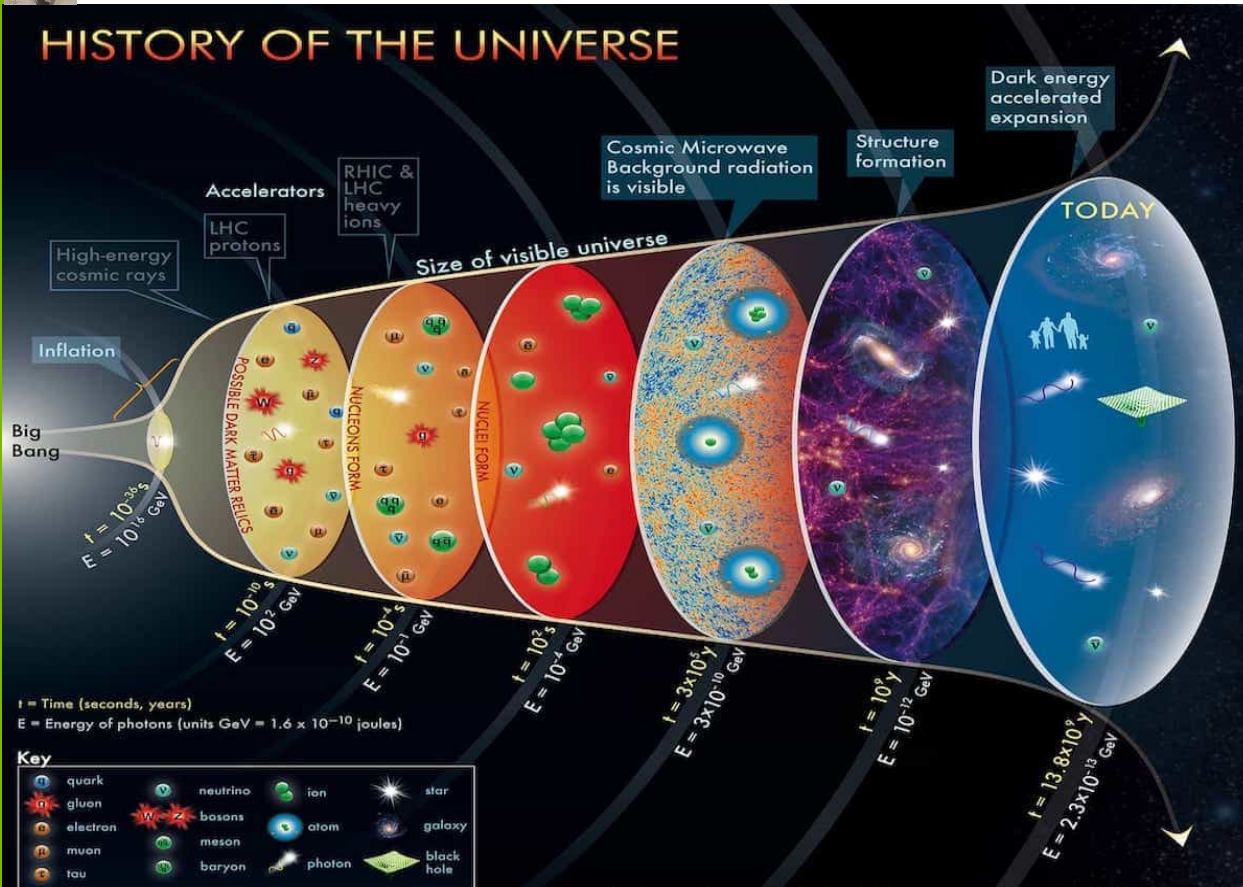
- Topological origin of mass
  - Vacuum conformal symmetry breaking by density of instantons and the rate of vacuum tunneling
  - Spontaneous chiral symmetry breaking follows simultaneously from the delocalization of the light quarks zero modes!

# TO KNOW YOUR FUTURE YOU MUST KNOW YOUR PAST

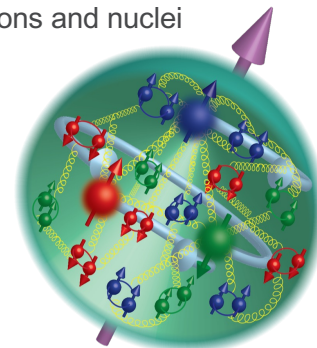


George Santayana (American philosopher, poet and cultural critic: Born in Madrid, 1863-1952)

Standard Model of Particle Physics



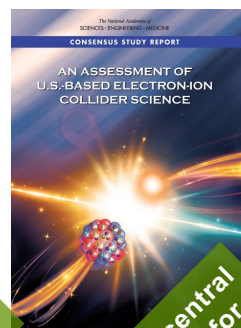
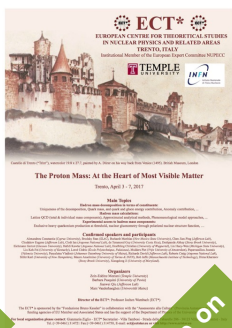
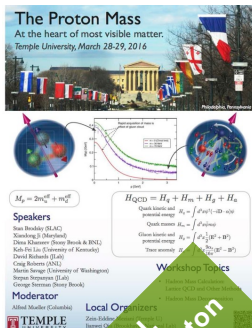
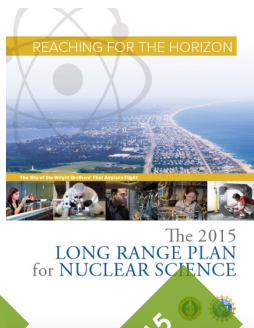
Quantum Chromodynamics (QCD) is responsible for most of the visible matter in the universe providing mass and spin to nucleons and nuclei



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

The concept for the above figure originated in a 1986 paper by Michael Turner.

# 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

# 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

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

$a(\mu)$  related to pdfs

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

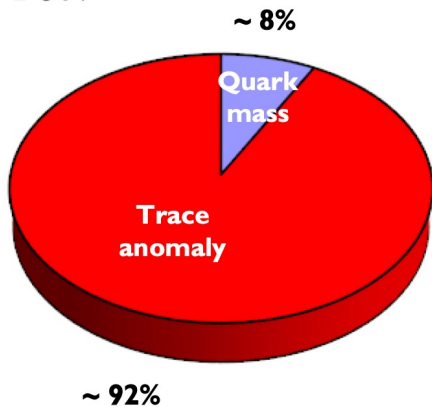
$$M_N = M_q + M_m + M_g + M_a$$

# DIFFERENT MASS DECOMPOSITIONS

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

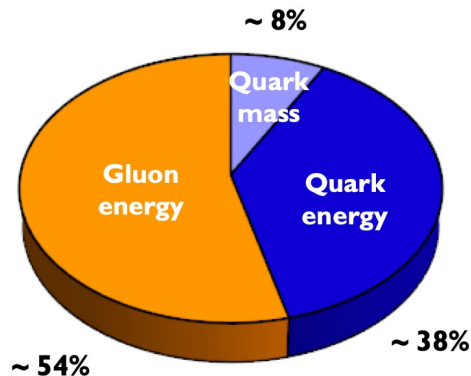
Trace decomposition

$\mu = 2 \text{ GeV}$



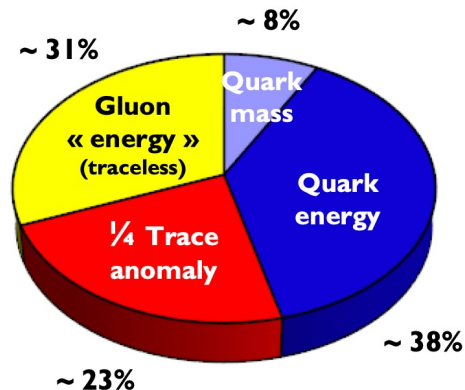
Relies on  
virial theorem

Energy decomposition



Independent of  
virial theorem

Ji's decomposition



Motivated by  
virial theorem