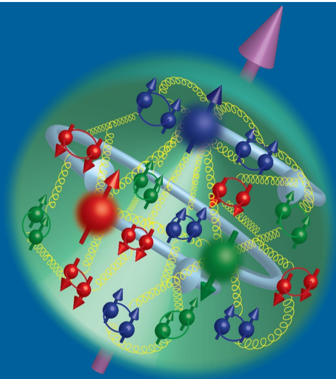
Argonne NATIONAL LABORATORY

THE PROTON GLUONIC GRAVITATIONAL FORM FACTORS

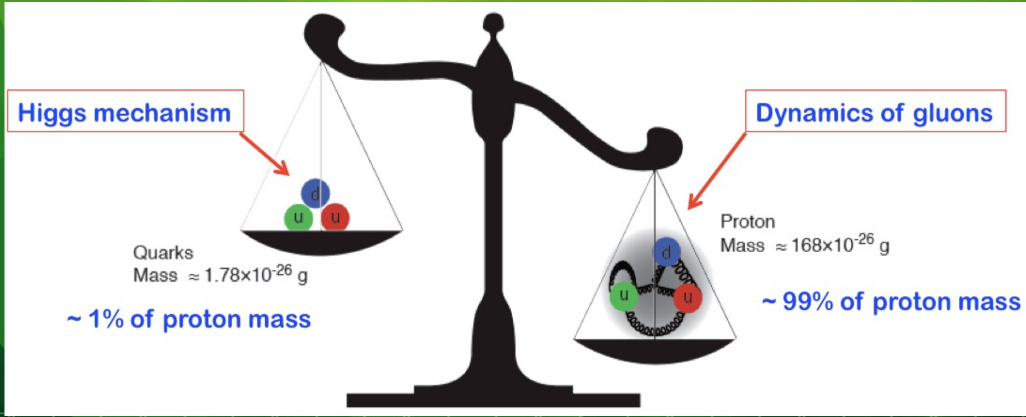


ZEIN-EDDINE MEZIANI
Argonne National Laboratory

Cairns, August 19-24, 2024

Origin of Mass?

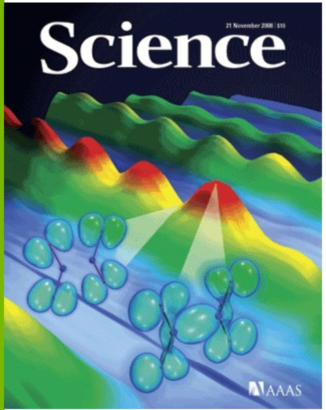
"…QCD takes us a long stride towards the Einstein-Wheeler ideal of mass without mass" Frank Wilczek (1999, Physics Today)



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

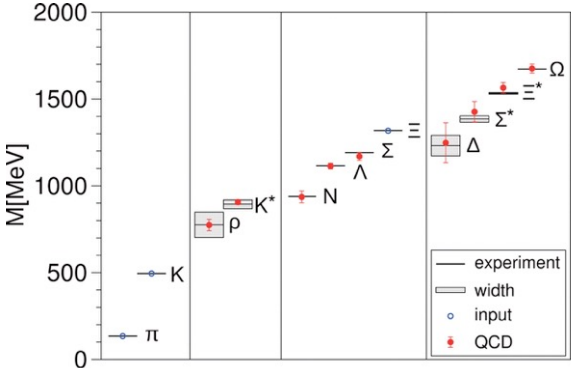


(2008)

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

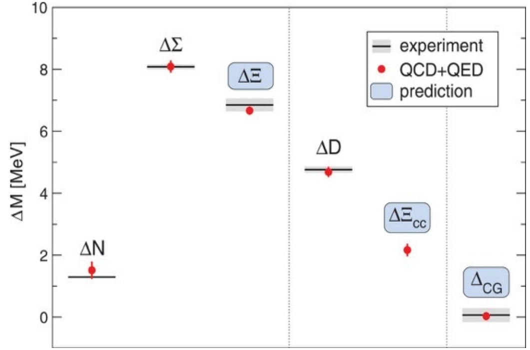


(2015)

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 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 (~800 MeV) and zero for the pion

HIGGS MASS CONTRIBUTION TO THE PROTON

Pion-Nucleon Sigma Term

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

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]

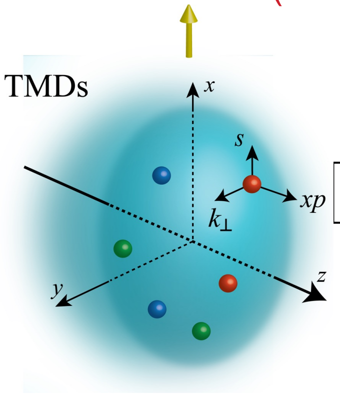
Unified View of Nucleon Structure

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

Transverse Momentum Dist. (TMD)

Tomography

Generalized Parton Dist. (GPD)

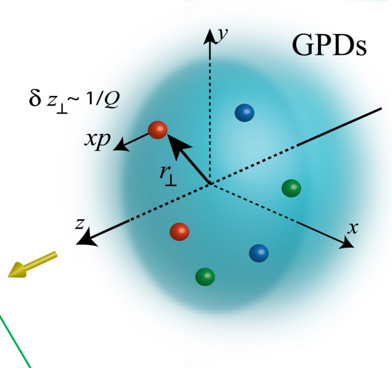


dr_T

d^2k_T

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

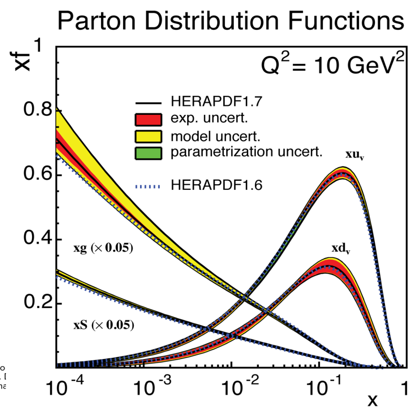
GPD



d^2k_T

d^2r_T

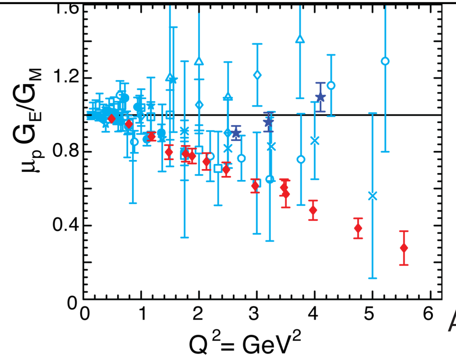
dx & Fourier Transformation



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

1D

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



U.S. DEPARTMENT OF ENERGY

Argonne NATIONAL LABORATORY

Unified View of Nucleon Structure

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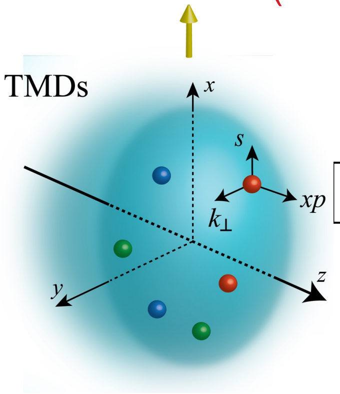
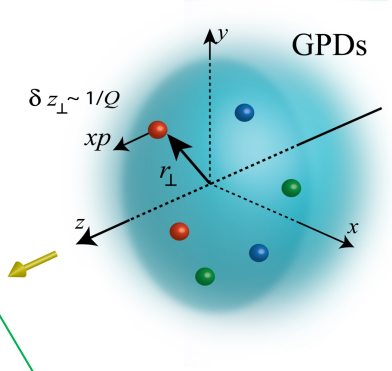


dr_T

d^2k_T

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

GPD

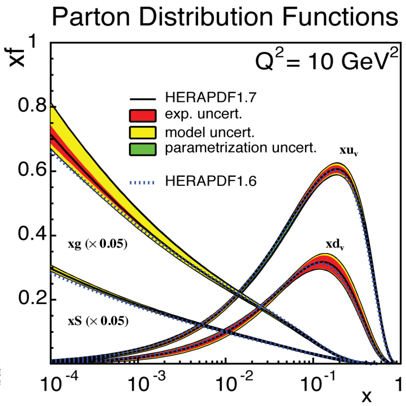


d^2k_T

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

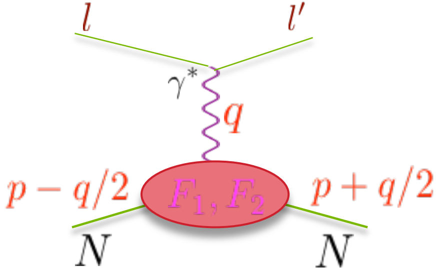
Nucleon gravitational form factors A, B, C and C_bar; (quarkonic & gluonic)
Mass density, Pressure density, Shear Forces density

The Proton Gravitational Form Factors Mass Radius and Scalar Radius

ELASTIC ELECTRON SCATTERING & ELECTROMAGNETIC FORM FACTORS

- Elastic e p → e p scattering used for more than 60 years to investigate nucleon structure
- In 1-photon exchange approximation:

  nucleon structure parameterized by two form factors



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

Dirac Pauli

F_1 helicity conserving, F_2 helicity flip form factors

- In experiments we measure the Sachs form factors

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

Rosenbluth Formula

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

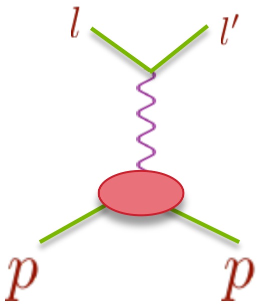
$$\tau = \frac{Q^2}{2M}$$

$$G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2)$$
$$G_M(Q^2) = F_1(Q^2) + F_2(Q^2)$$

EXPERIMENTAL REACTIONS TO DETERMINE FORM FACTORS

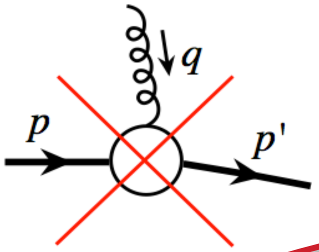
Proton electric charge distribution

Elastic Scattering



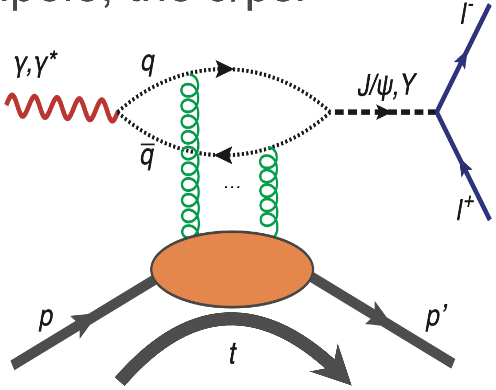
Proton color charge distribution?

Elastic color scattering; but forbidden

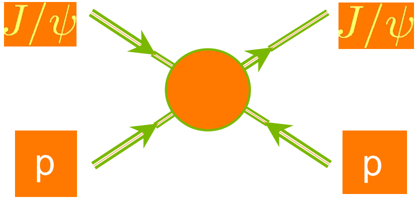


What to do to probe the gluon density?

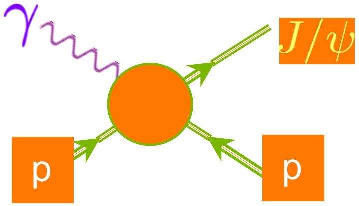
Perhaps replace the proton by a color dipole, the J/psi



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

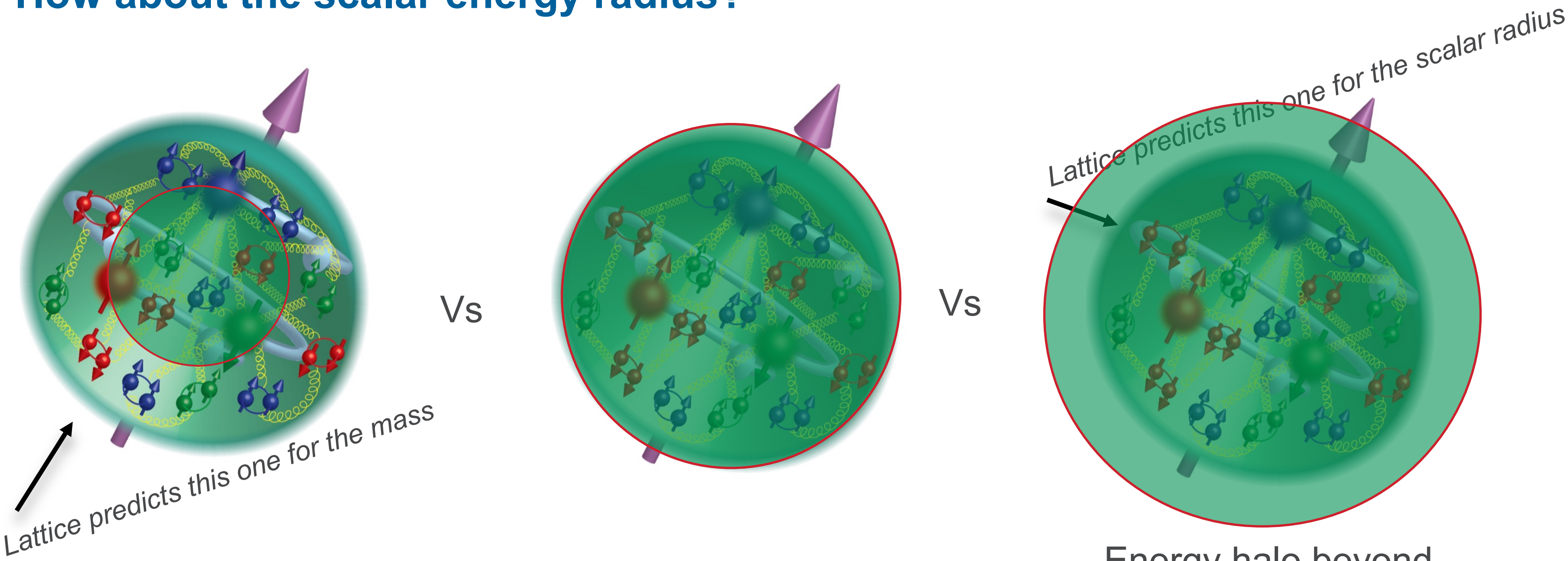
$$\langle N' \mid T^{\mu,\nu}_{q,g} \mid N \rangle$$
$$= \bar{u}(N')\left(A_{g,q}(t)\gamma^{\{\mu}P^{\nu\}} + B_{g,q}(t)\frac{iP^{\{\mu}\sigma^{\nu\}}\rho\Delta_\rho}{2M} + C_{g,q}(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M} + \bar{C}_{g,q}(t)Mg^{\mu\nu} \right)u(N)$$

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

HOW 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?

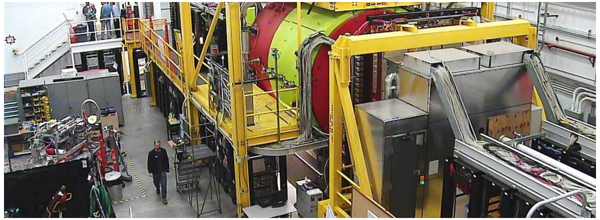


Dense energetic core?

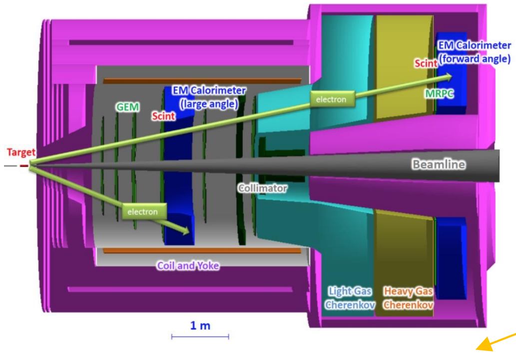
Same as charge radius?

Energy halo beyond charge radius?

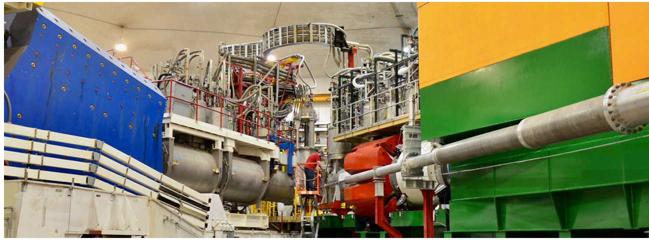
12 GEV J/Ψ EXPERIMENTS AT JEFFERSON LAB NOW AND FUTURE



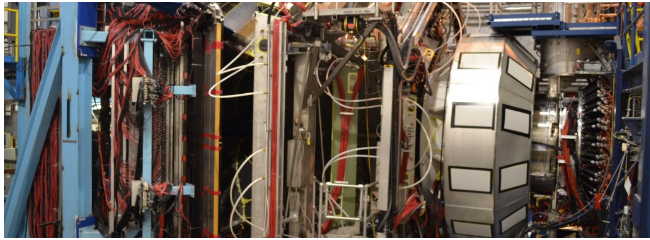
Hall D - GlueX observer the first J/ψ at JLab
A. Ali *et al.*, PRL 123, 072001 (2019)



Hall 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**



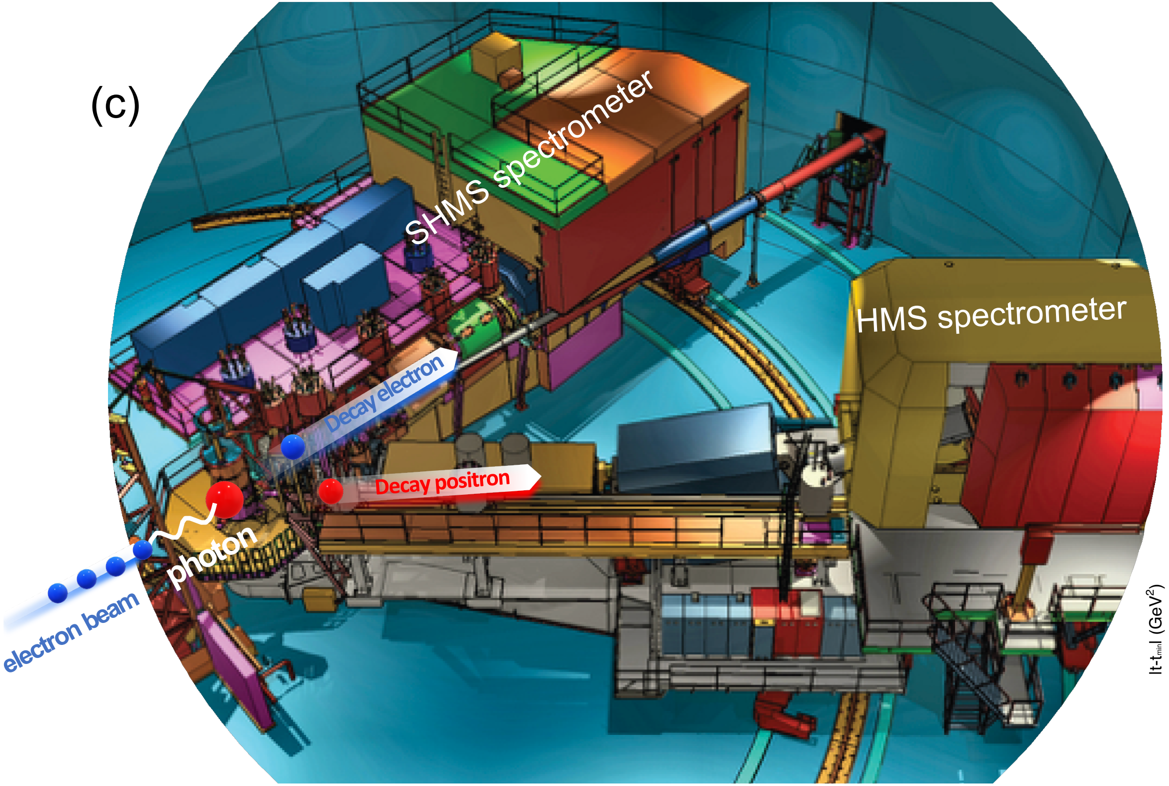
Hall C has the **J/ψ-007** experiment (E12-16-007)
LHCb hidden-charm pentaquark search

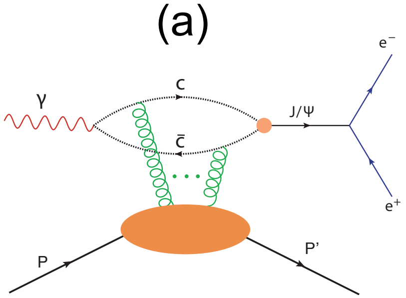


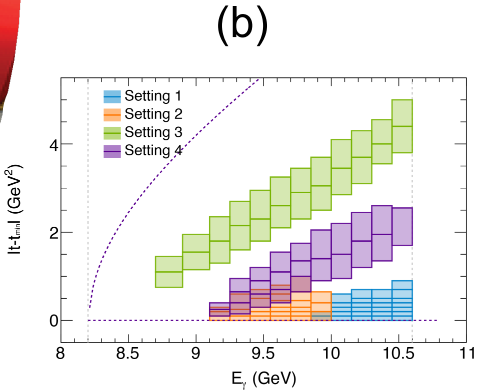
Hall B - CLAS12 has experiments to measure TCS + J/ψ in photoproduction as part of Run Groups A (hydrogen) and B (deuterium): E12-12-001, E12-12-001A, E12-11-003B

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

Near threshold photoproduction of J/ψ



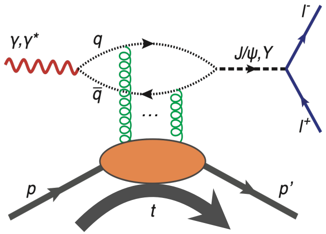




Z.-E. M, S. Joosten *et al.*, arXiv:1609.00676 [hep-ex]
K. Hafidi, S. Joosten *et al.*, Few Body Syst. 58 (2017) no.4, 141

JLAB EXPERIMENT E12-16-007

Near threshold photoproduction of J/ψ

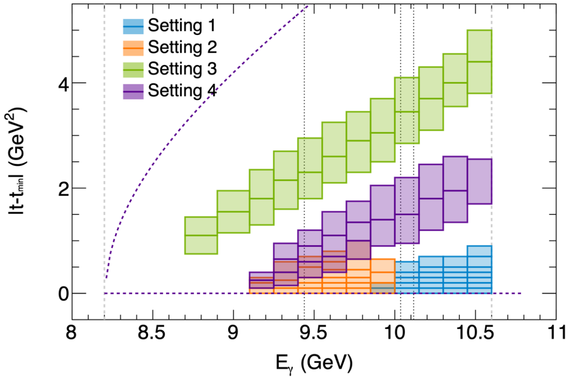


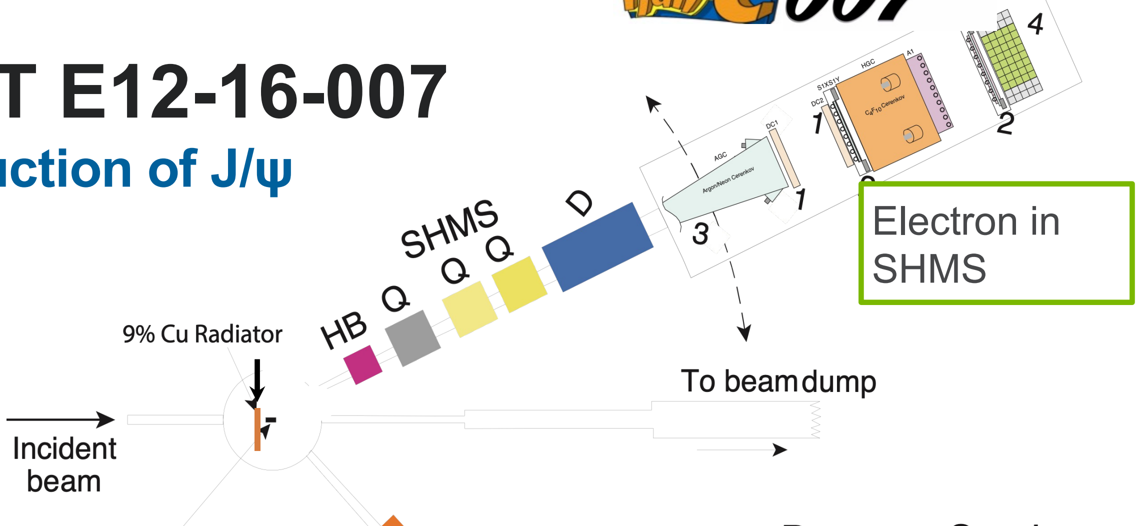
J/ψ threshold:

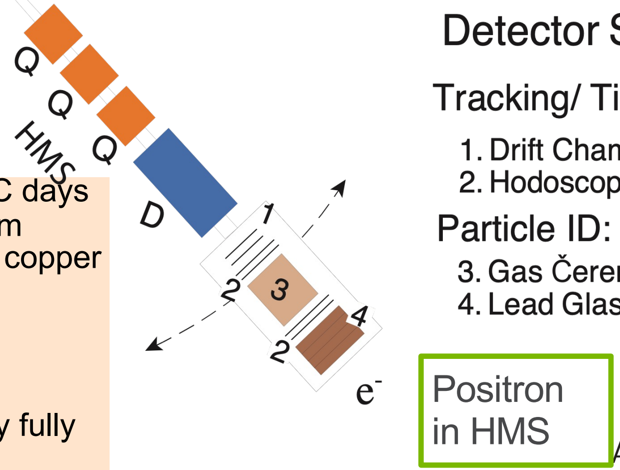
$W \approx 4.04\text{GeV}$

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

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







- 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:

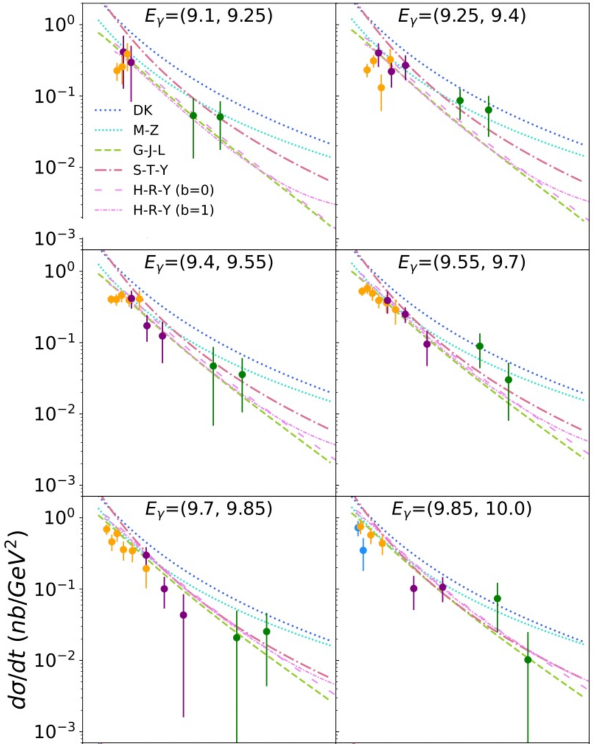
1. Drift Chambers
2. Hodoscopes

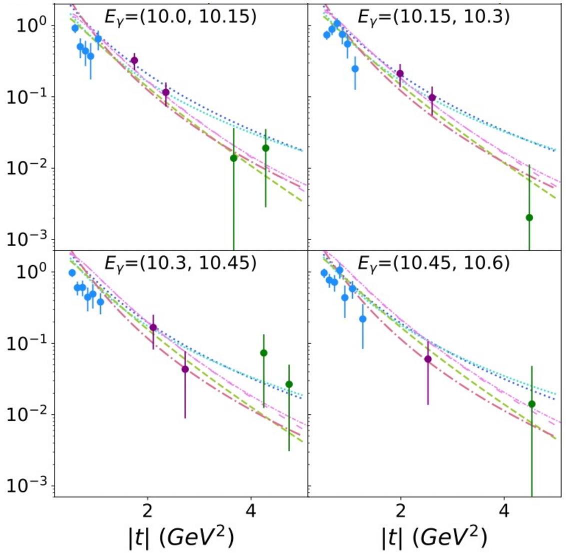
Particle ID:

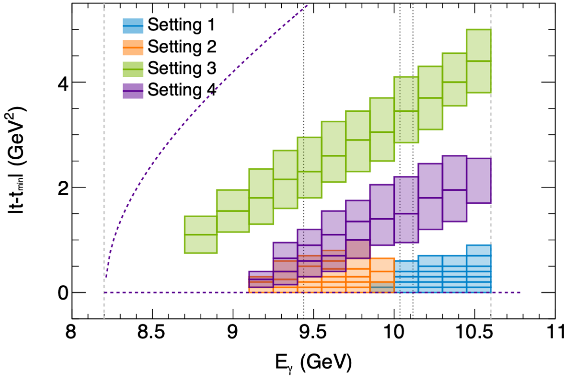
3. Gas Čerenkov
4. Lead Glass Calorimeter

2D J/Ψ CROSS SECTION RESULTS FROM 007$^{J/\psi}$

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





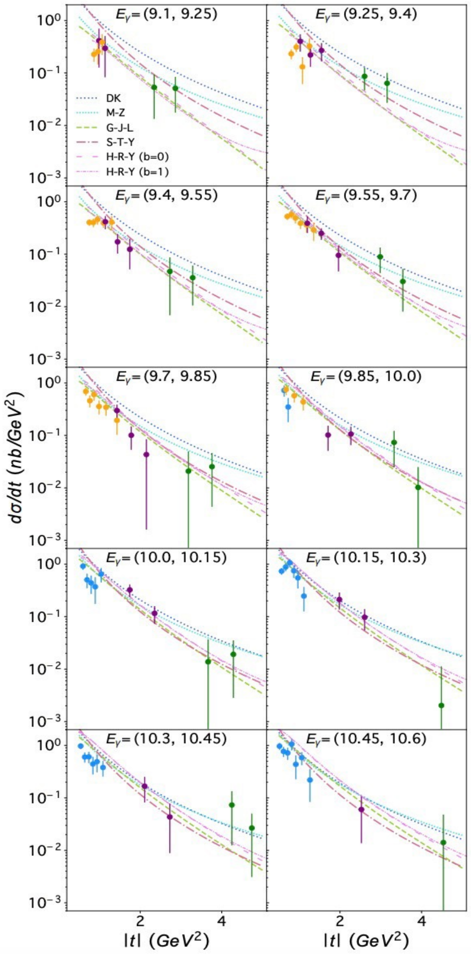


DK: D, Kharzeev, Phys. Rev. D 104, 054015 (2021).
M-Z: Mamo & Zahed, 2204.08857 (2022)
G-J-L: Guo, Ji & Liu, Phys. Rev. D 103, 096010 (2021)
S-T-Y: Sun, Tong & Yuan, Phys. Lett. B 822, 136655 (2021)
H-R-Y: Hatta, Rajan & Yang, Phys. Rev. D 100, 014032 (2019)

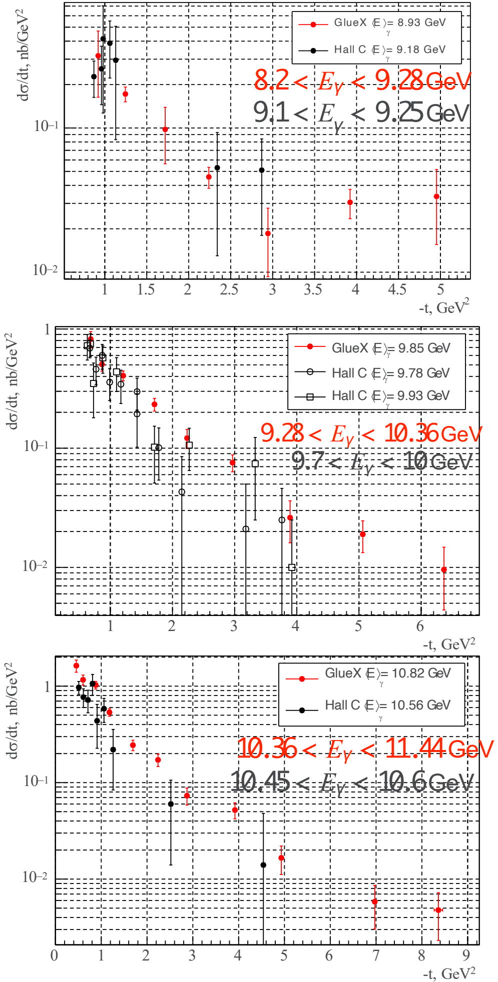
- Unfolded 2D cross section results compared to various model predictions informed by the 2019 1D GlueX results
- All models work reasonably well at higher energies but deviate at lower energies

DIFFERENTIAL CROSS SECTIONS FROM J/Ψ-007 AND GLUEX

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



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



- 10 photon energy bins of 150 MeV in *J/ψ-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/ψ-007* differential cross section results
- Good agreement within errors; note also differences in average energies

RESULTS FROM GLUEX (CONTINUED)

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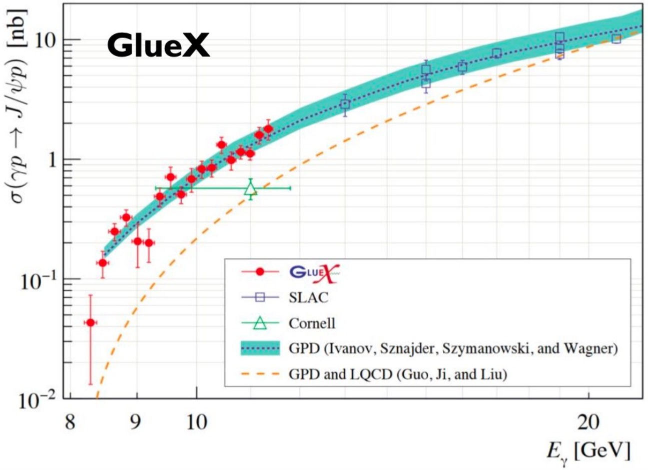
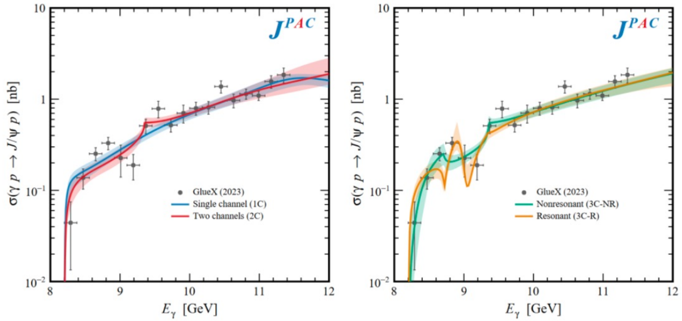


Figure from "Measurement of the J/ψ photoproduction cross section", S. Adhikari *et al.* (GlueX Collaboration). Phys. Rev. C 108, 025201, 2023, arXiv:2304.03845

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



Coupled channels and pentaquarks

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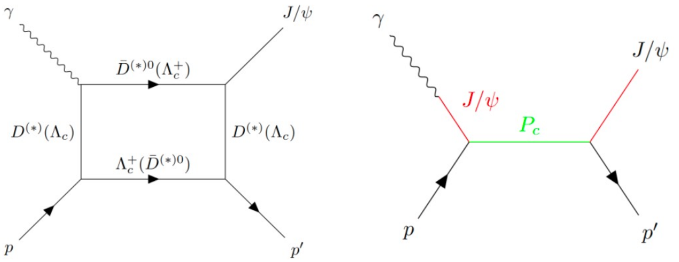
- The previous considerations rely on the application of Vector Meson Dominance.
- Thus the contribution from open-charm meson channels and potential pentaquark must be understood or ruled-out.

→ *Total cross-section as a function of photon energy*



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

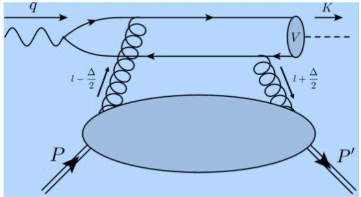
GPD Model

- 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 skewdness region
- $B_g\ (t)$ 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

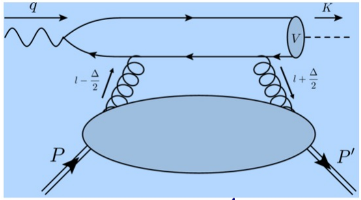
THE GENERALIZED PARTON DISTRIBUTION MODEL

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

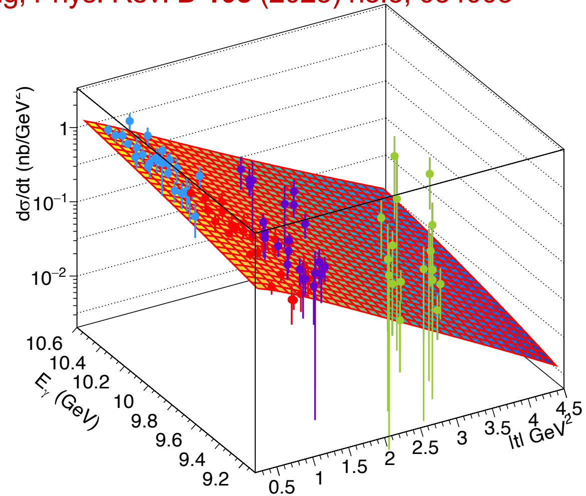


(a)



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

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



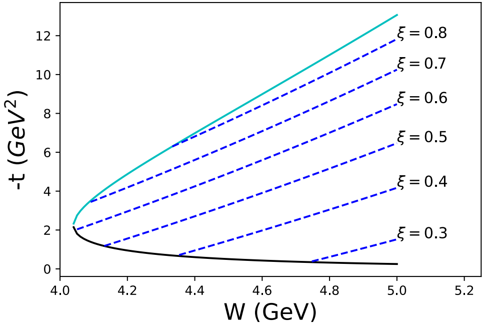
$$|G(t,\xi)|^2 = \frac{4}{\xi^4}\{(1 - \frac{t}{4m_N^2})E_2^2 - 2E_2(H_2+E_2) + (1-\xi^2)(H_2+E_2)^2\}$$

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

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

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

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

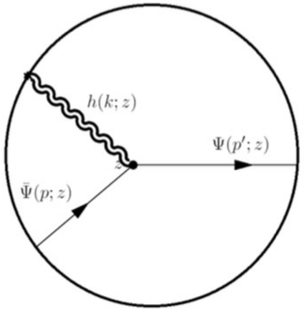


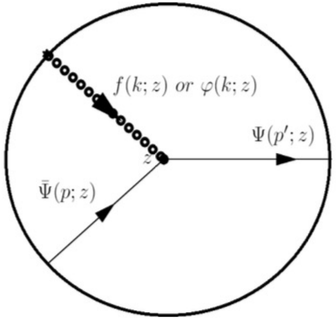
THE HOLOGRAPHIC QCD MODEL

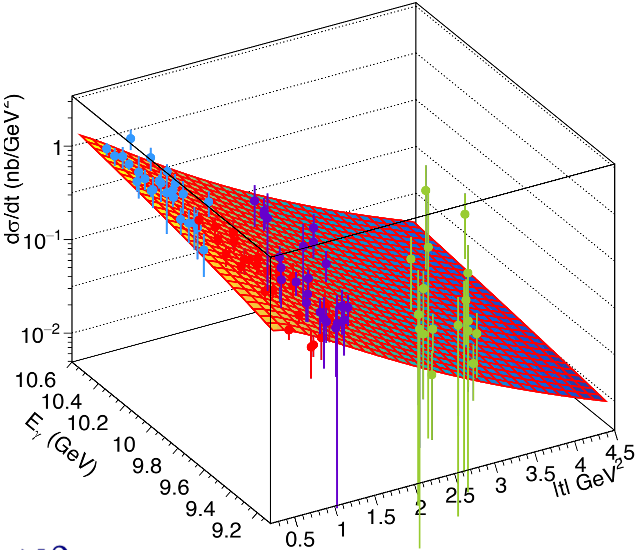
2D fit to extract the *A(t)* & *C(t)* assuming *B(t)* to be small

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

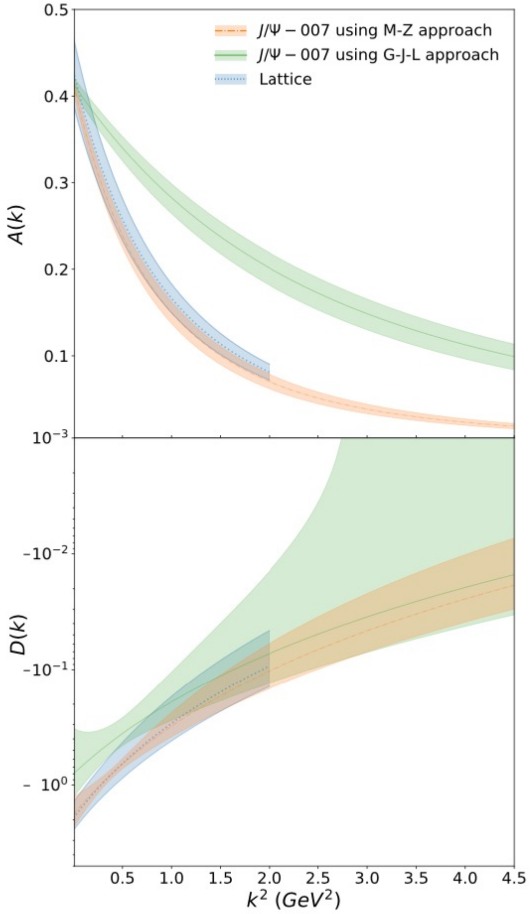
$$\frac{d\sigma}{dt} = \mathcal{N} \times \frac{e^2}{64\pi(s-m_N^2)^2} \times \frac{A(-t,\kappa_T)+\eta^2 D(-t,\kappa_T,\kappa_S)]^2}{A^2(0)} \times \tilde{F(s)} \times 8$$

- *A(t)* and *D(t)* shapes are fully calculated; However, dipole forms are assumed as very good approximations and are used in the fits to the data. $A_g(0)= <x_g>$ is fixed to the DIS value from global fit CT18.
- *B(t)* is neglected and $\mathcal{N}$ is normalized to the cross section.

GLUONIC GFF RESULTS; FIRST EXTRACTION

007 J/Ψ

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

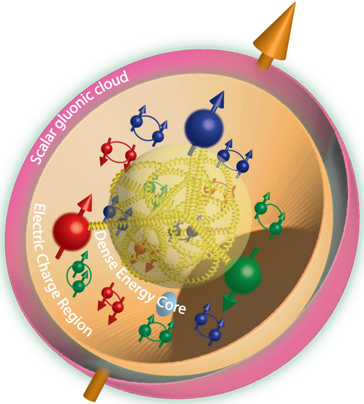
M-Z: K. Mamo & I. Zahed, PRD 103, 094010 (2021) and 2204.08857 (2022)

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?



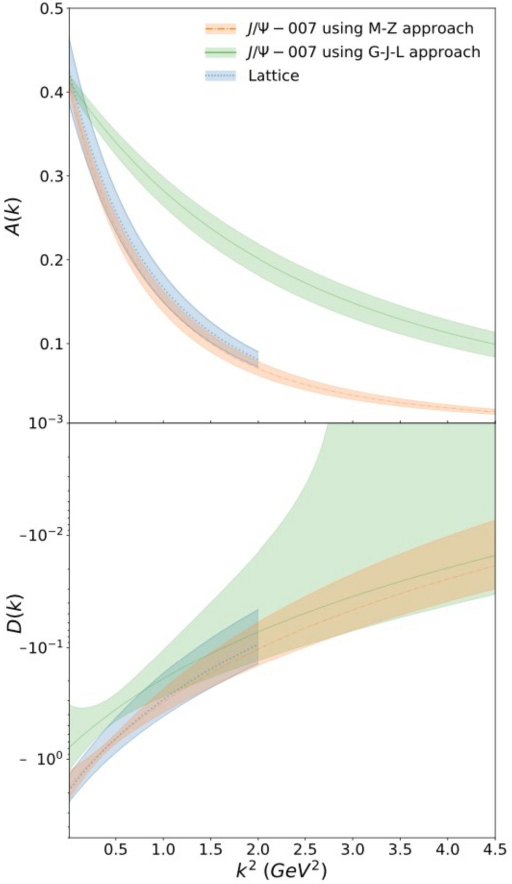
Definition of gluonic mass and scalar radius

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

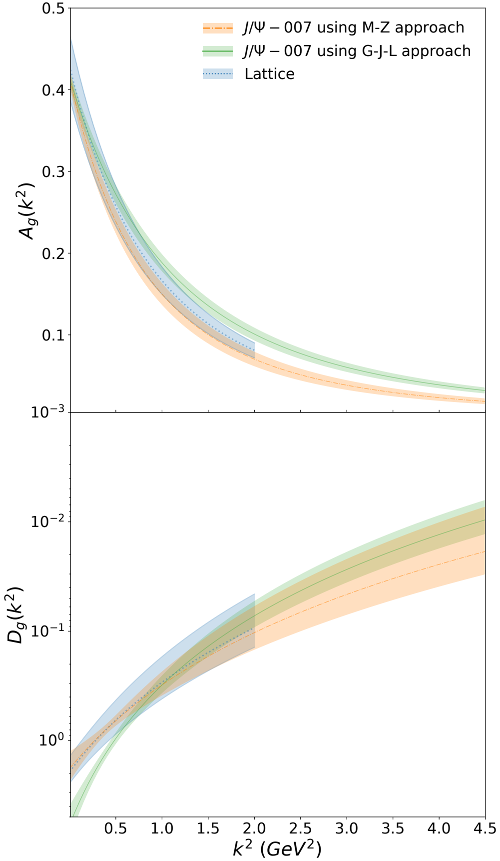
$$\langle r_s^2 \rangle_g = 6 \frac{1}{A_g(0)} \frac{dA_g(t)}{dt}|_{t=0} - 18 \frac{1}{A_g(0)} \frac{C_g(0)}{M_N^2}$$

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

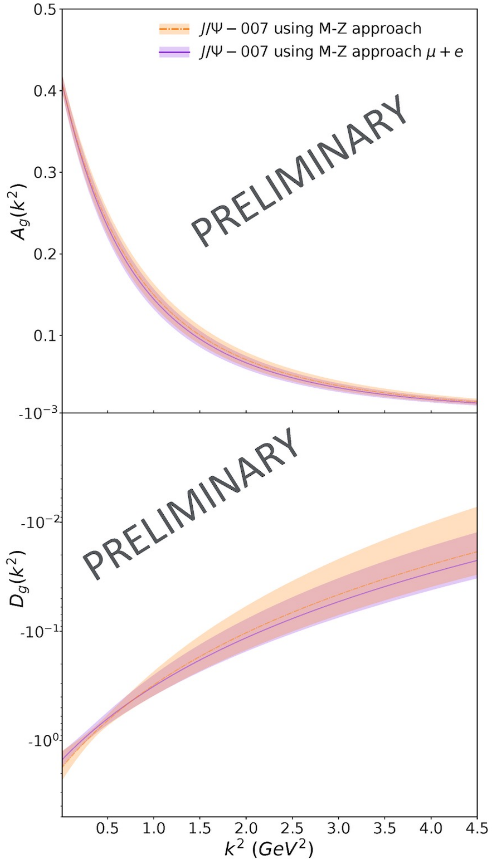
UPDATED GJL GFFS EXTRACTION RESULT (FOLLOW GREEN CURVES)



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



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

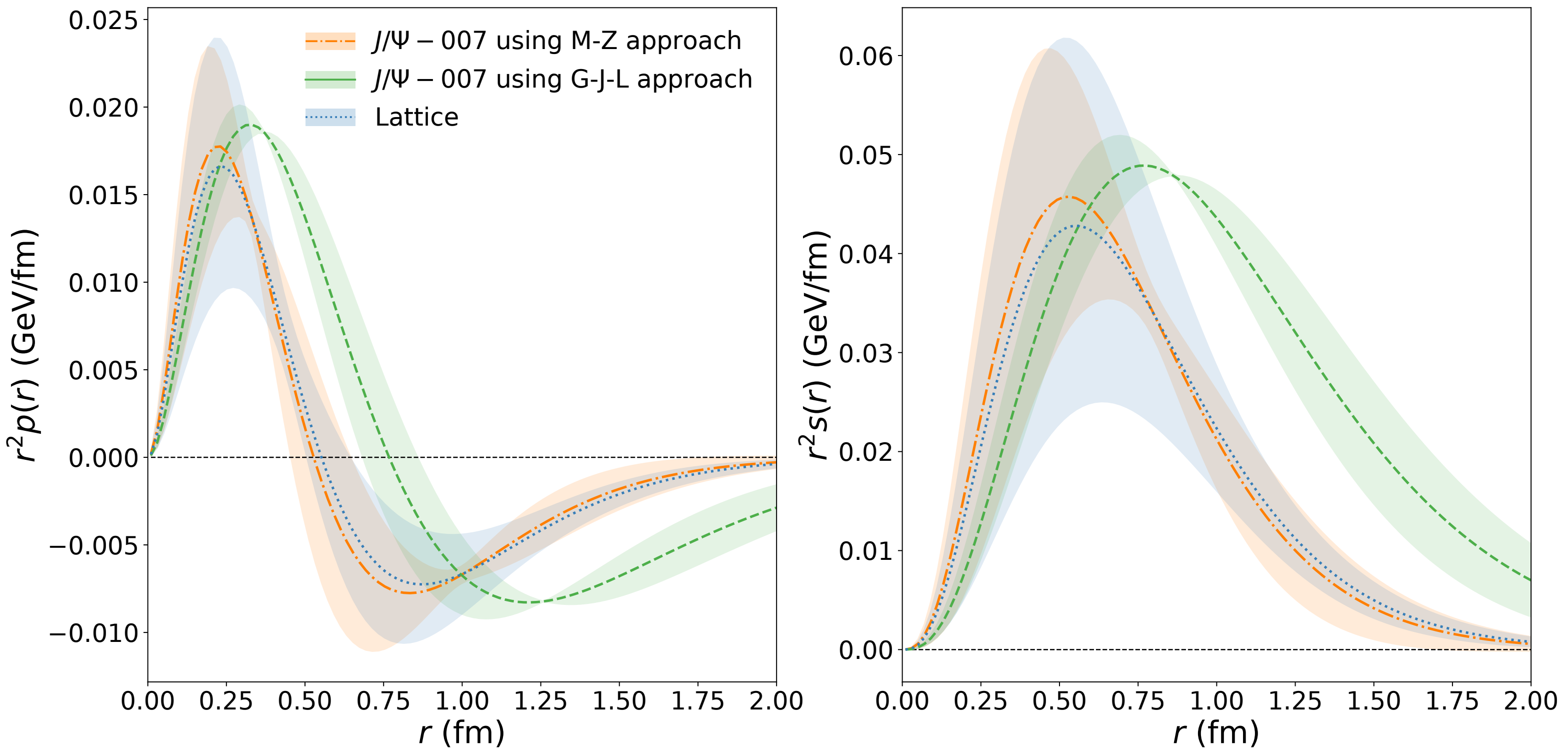


- Analysis with the muons decay channel results , doubling the statistics
- Consistent with the electron results.
- Largest impact on the *C(t)* form factor with improved precision

S. Prasad

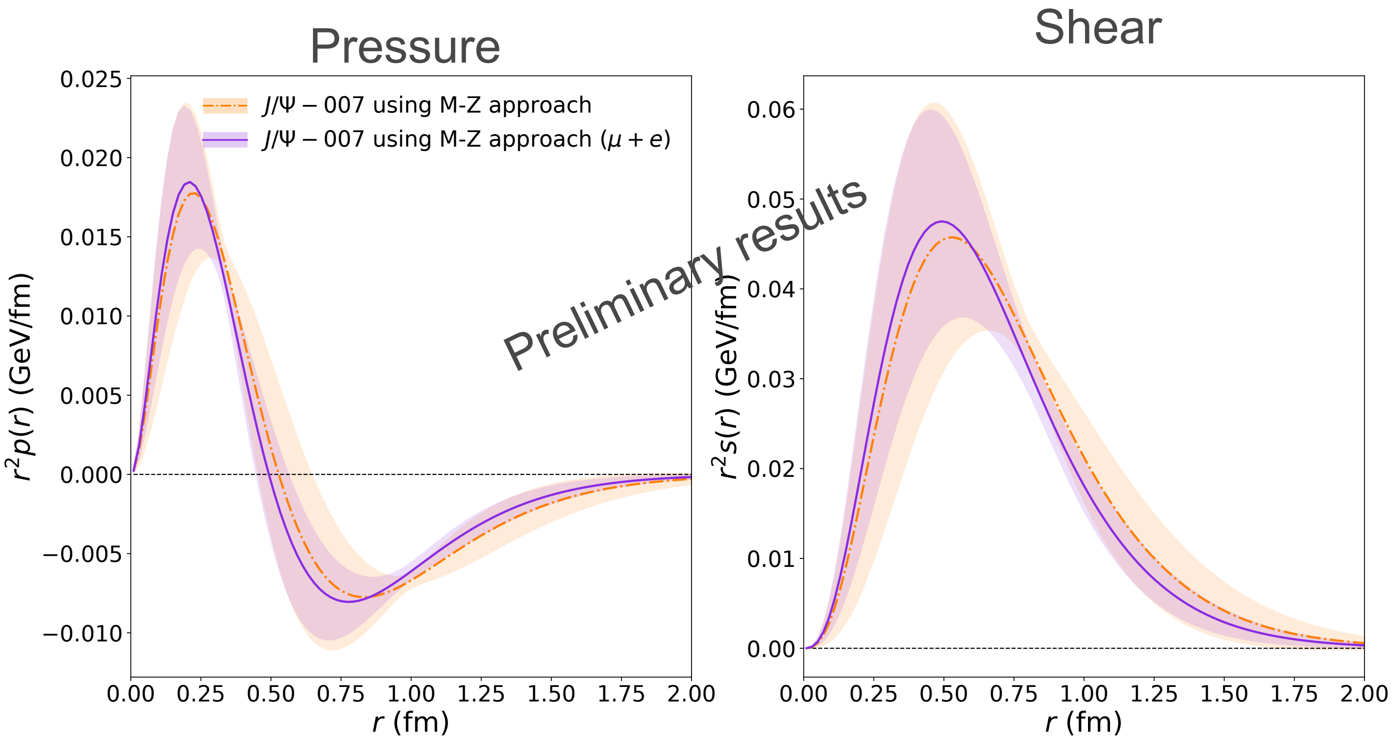
PRESSURE AND SHEAR DISTRIBUTIONS OF GLUONS

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



S. Prasad

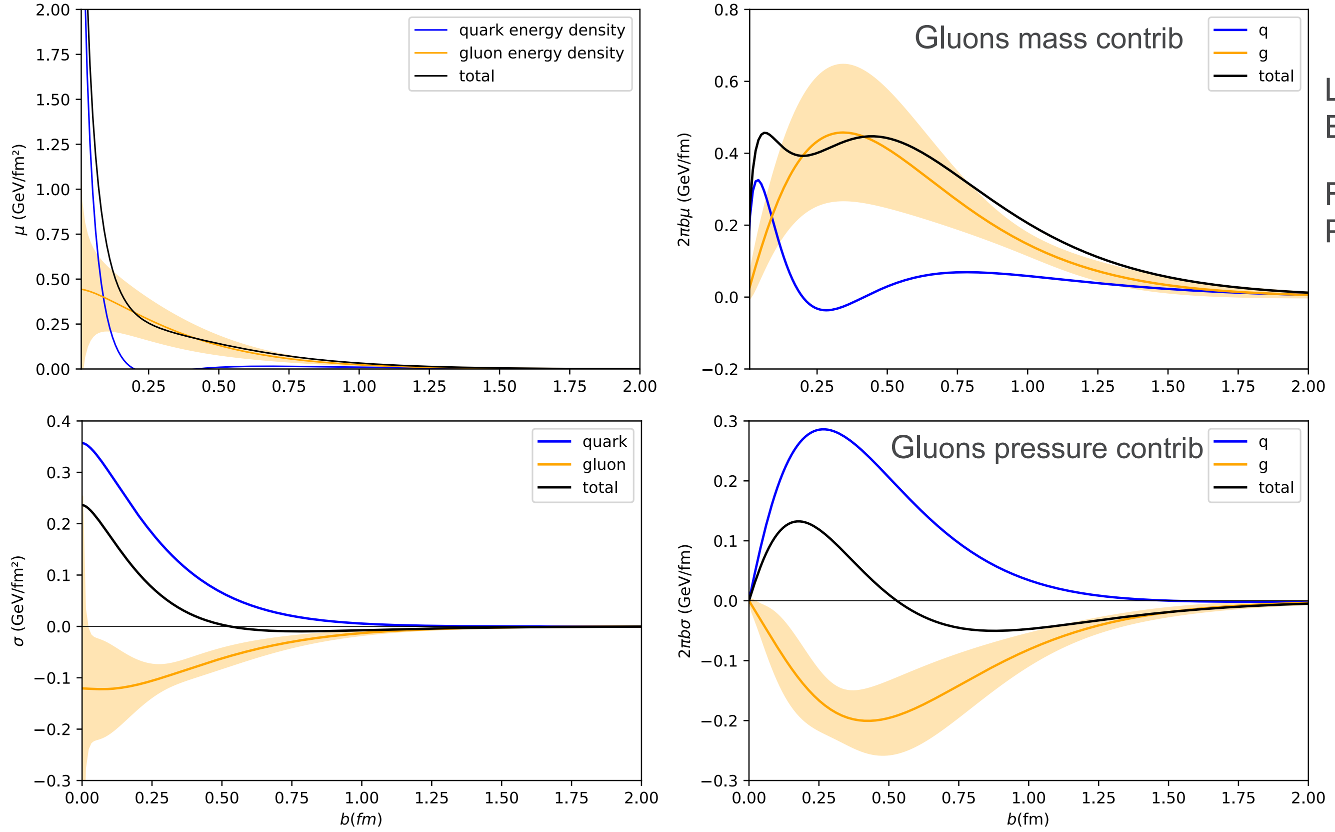
Preliminary results: Breit Frame



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



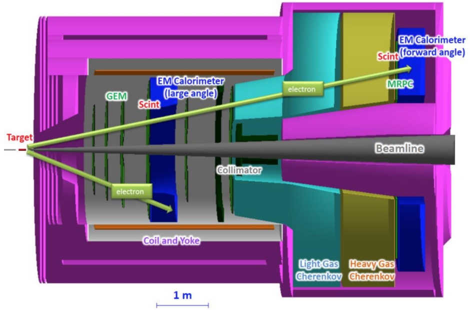
Lorcé *et al.*
Eur. Phys. J. C (2019) 79

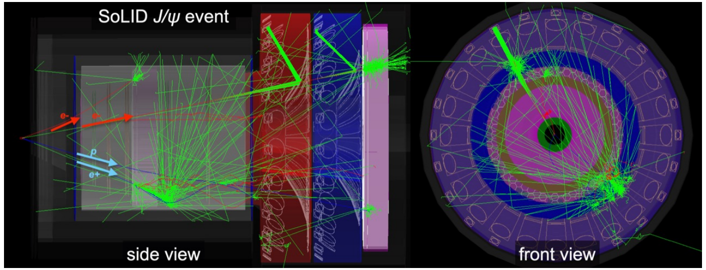
Freeze & Miller,
Phys. Rev D**103**, 094023

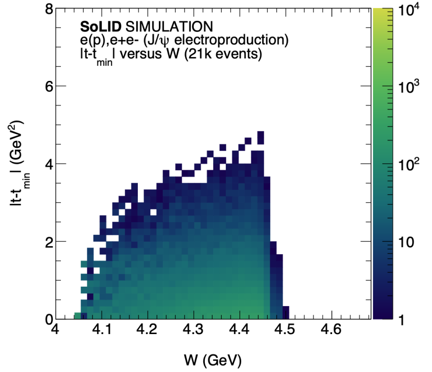
FUTURE SOLID EXPERIMENT AT JLAB

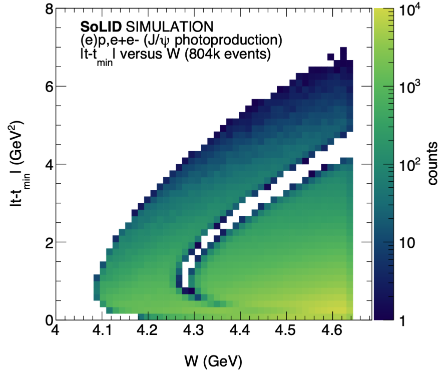
Ultimate experiment for near-threshold J/ψ production

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



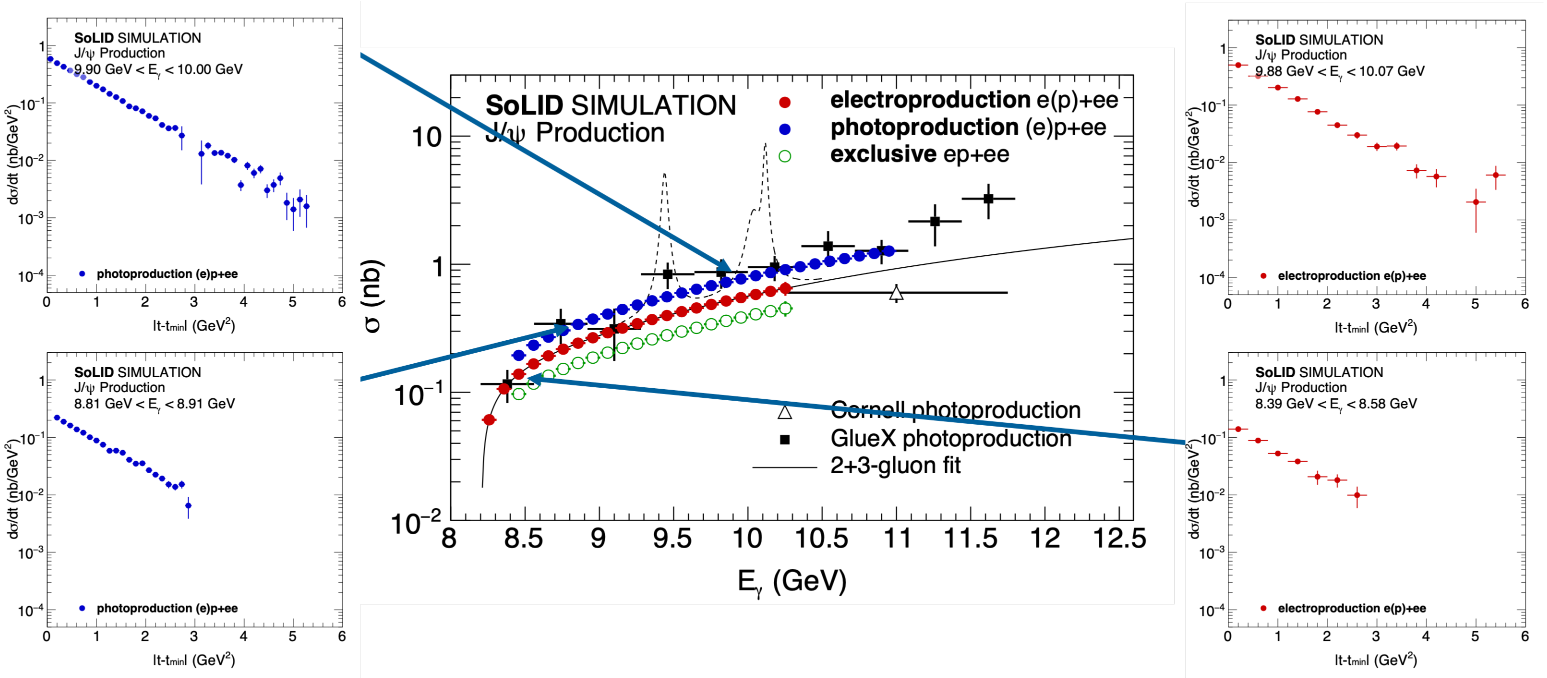






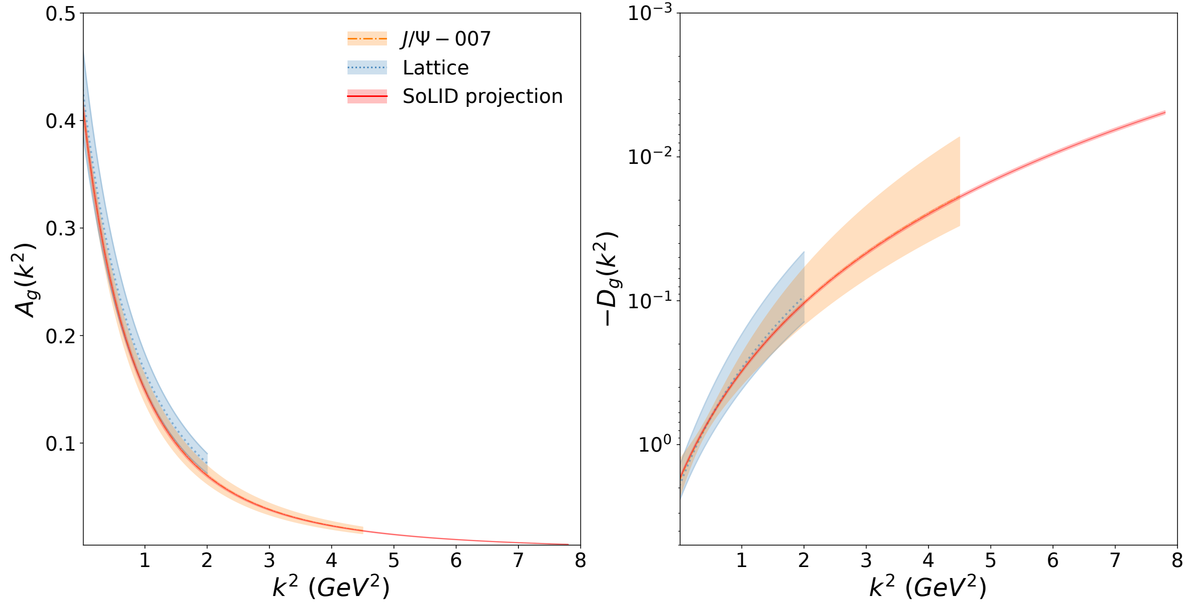
FUTURE SOLID EXPERIMENT AT JLAB

Precision measurement of J/psi near threshold



SoLID IMPACT PROJECTIONS ON GLUONIC GFFS

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



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

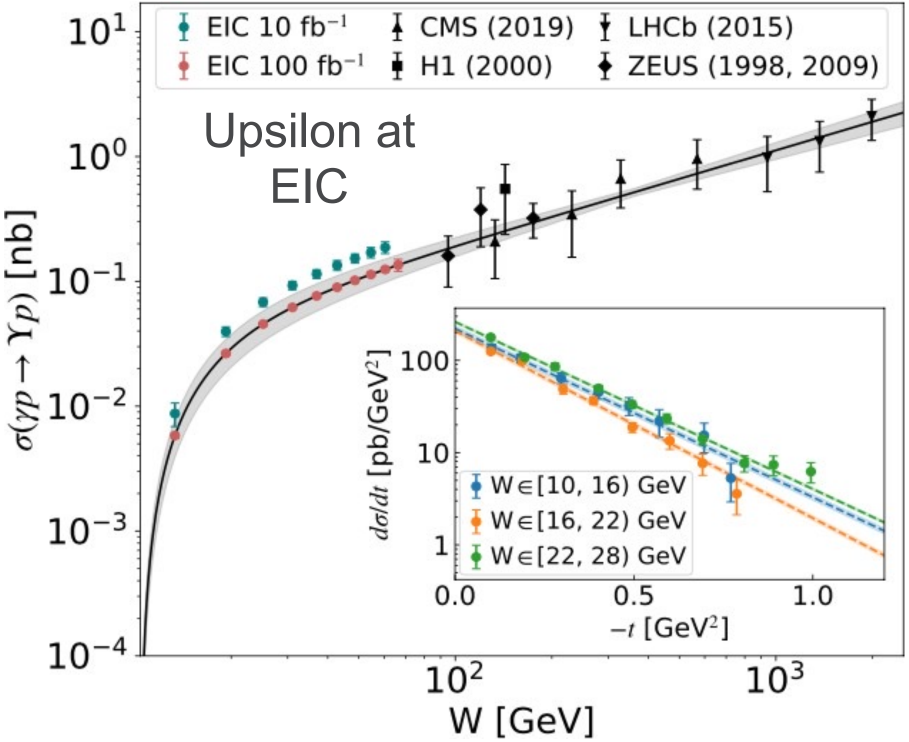
K. A. Mamo and I. Zahed, *Phys. Rev. D* **106**, no.8, 086004 (2022)

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

COMPLEMENTARITY WITH EIC

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

- Y(1S) at EIC trades statistical precision of J/ψ at SoLID for lower theoretical uncertainties, and extra channel to study universality.
- Large Q^2 reach at EIC an additional knob to study production, near-threshold J/ψ production at large Q^2 may be experimentally feasible!



CONCLUSION

- We are at the dawn of an exciting avenue of nucleon's gluonic structure research through the determination of the gGFFs of the nucleon.

- 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

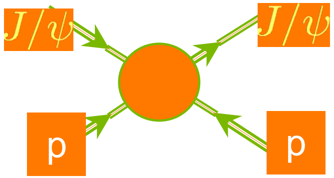
Thank you!

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

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**



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

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

$$\left|F_{J/\Psi N}\right| = \left[64\pi[m^2_{J/\psi}(\lambda^2 - m^2_N)]\frac{d\sigma_{J/\psi N\to J/\psi N}}{dt}\bigg|_{t=0}\right]^{1/2}$$

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

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

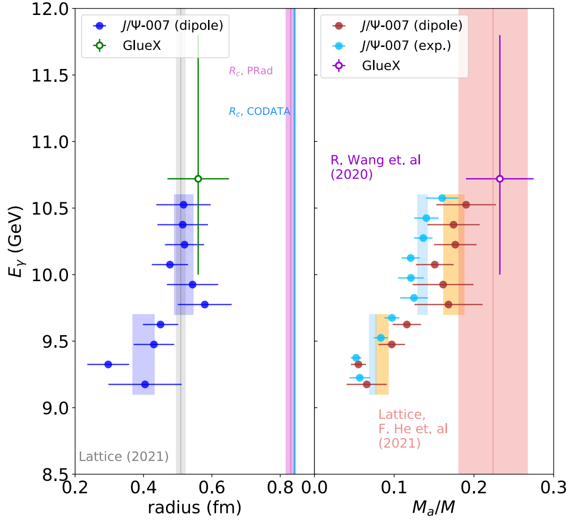
$$r_0 = \left(\frac{4}{3\alpha_s(\mu^2)}\right)\frac{1}{m_c(\mu^2)}$$

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

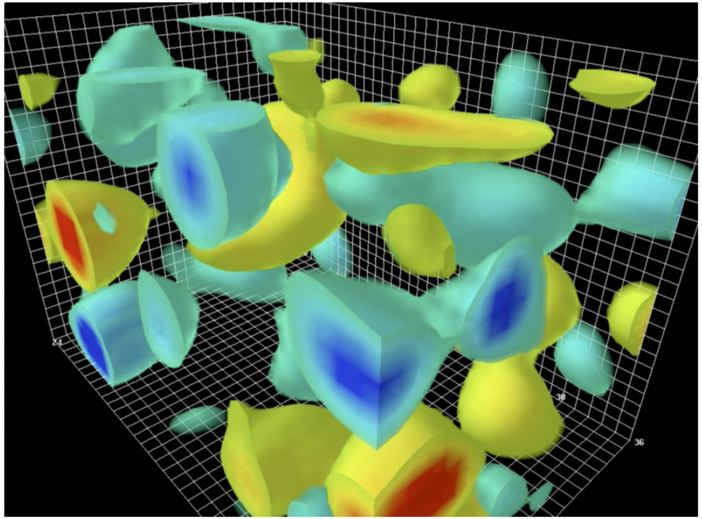
Rydberg energy squared = μ^2



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

Shuryak, Zahed

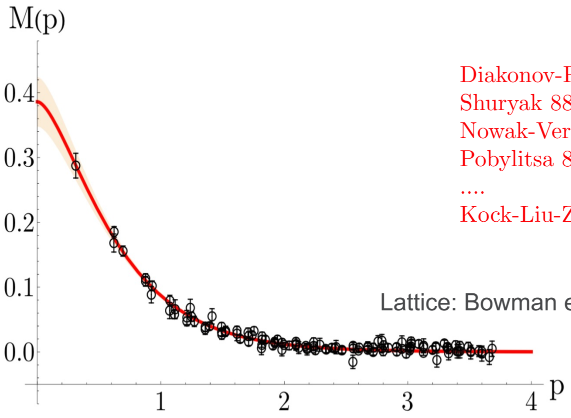
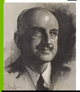


FIG. 2: Momentum dependence of the instanton induced effective quark mass in singular gauge (13) at LO (solid-curves), compared to the effective quark mass measured on the lattice in Coulomb gauge [21] (open-circles). The unit scale is GeV. We obtain a fitted parameter intervals $M(0) = 383 \pm 39$ MeV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

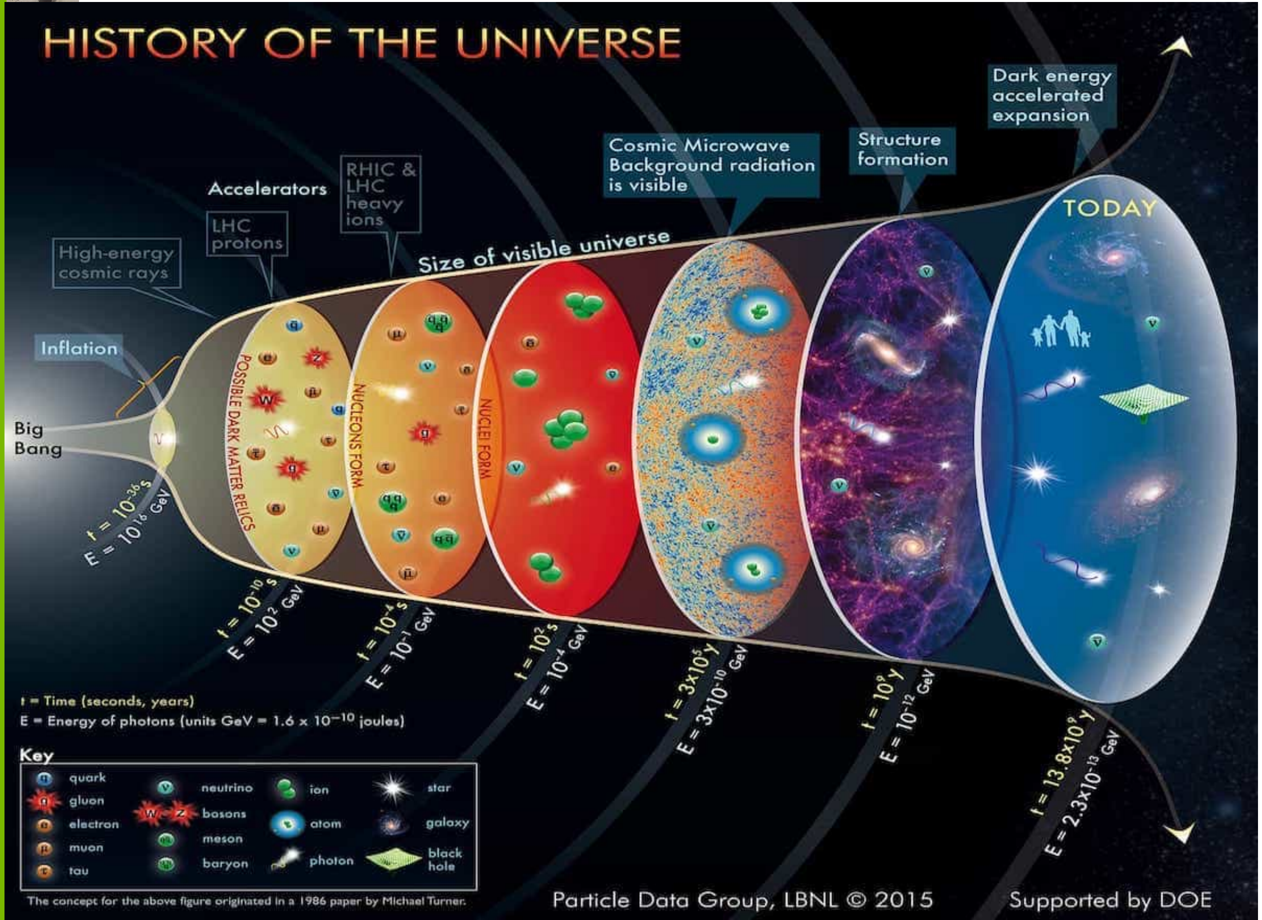
Vacuum; a liquid on Instantons
Gluon condensate in the nucleon is linked to the QCD vacuum compressibility which measures the diluteness of the QCD instanton vacuum as a topological liquid.

- 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!

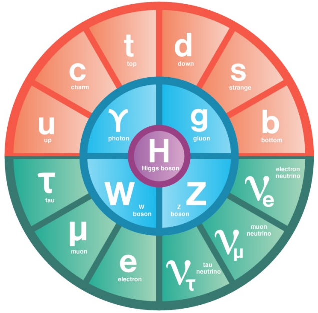
TO KNOW YOUR FUTURE YOU MUST KNOW YOUR PAST



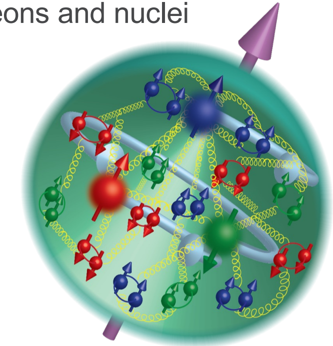
George Santayana (American philosopher, poet and cultural critic: Born in Madrid, 1863-1952)



Standard Model of Particle Physics



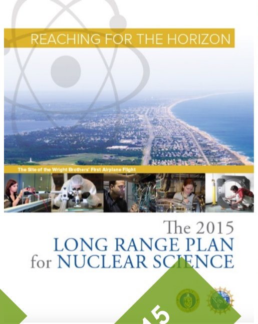
Quantum Chromodynamics (QCD) is responsible for most of the visible matter in the universe providing mass and spin to nucleons and nuclei

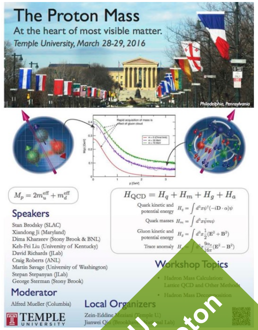


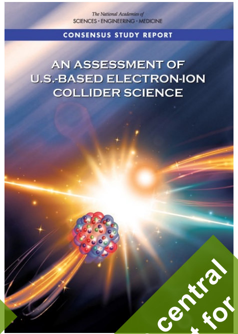
Nucleon: A fascinating strong interacting system of confined quarks and gluons

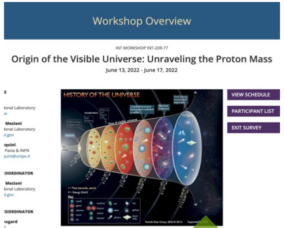
Argonne NATIONAL LABORATORY

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









- 2012 Temple U. Workshop on heavy quarkonia
- Featured in the 2015 Long Range plan
- 2015 LHCb finds resonance in J/ψ-p channel consistent with pentaquarks
- 2016 Temple U. Workshop on the proton mass
- 2016 Proposal for Hall C Pentaquark search
- 2017 ECT* Workshop on the proton mass
- 2018 Proton mass central in NAS assessment for EIC
- 2019 First GlueX near-threshold J/ψ results
- 2021 Remote Workshop on the proton mass
- 2021 First Hall C results on the pentaquark search
- 2022 INT Workshop on the proton mass
- 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)

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

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

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

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

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

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

Gluons kinetic and potential energy

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

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

Trace anomaly

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

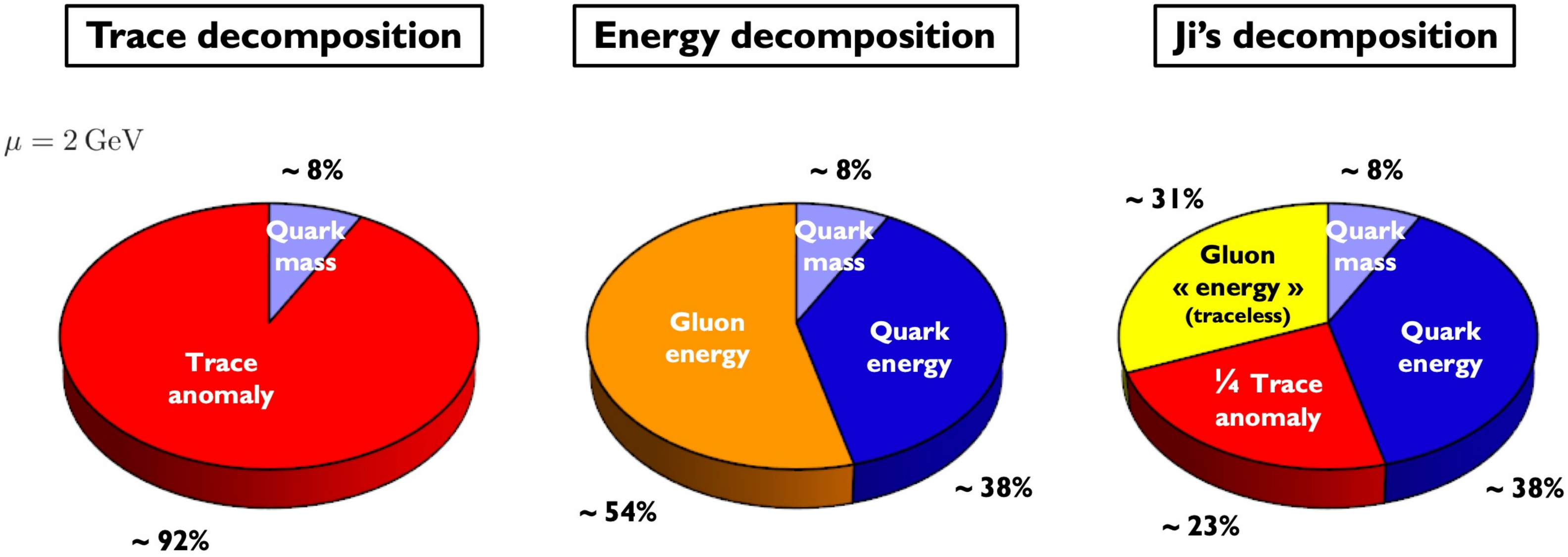
$a(\mu)$ related to pdfs

$b(\mu)$ 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)



Relies on virial theorem

Independent of virial theorem

Motivated by virial theorem