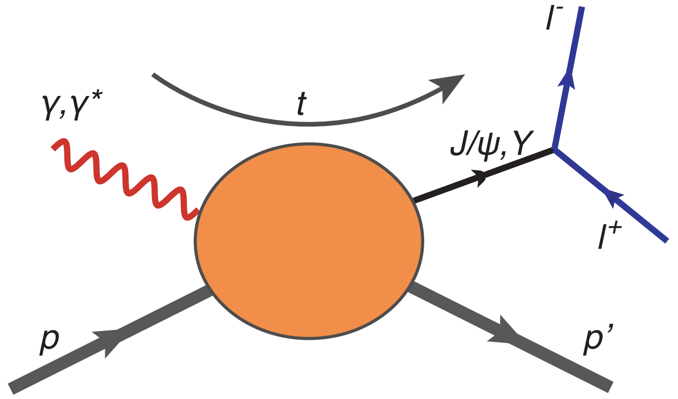
PROBING THE GLUONIC GRAVITATIONAL FORM FACTORS OF THE PROTON USING NEAR THRESHOLD J/Ψ PHOTOPRODUCTION



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MAY 15-17, 2024

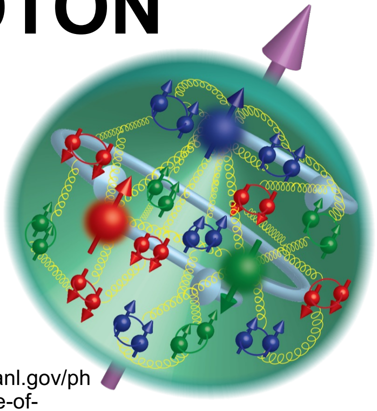
CFNS WORKSHOP, STONYBROOK UNIVERSITY

(On behalf of Hall C J/ψ-007 collaboration)

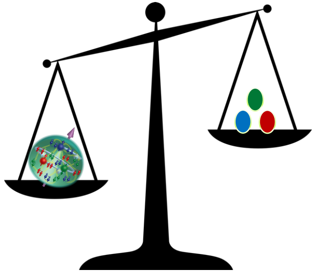
This work was supported by the U.S. Department of Energy, Office of Nuclear Physics, under Contract No. DE-AC02-06CH11357.

UNDERSTANDING THE ORIGIN OF PROTON MASS AND ITS DISTRIBUTION

- Proton's macroscopic properties – charge, spin, mass – arise from a very complex dynamics between the quarks and gluons (QCD)
- Studying its charge radius from electron scattering experiments have been an active area of research
  - Quarks carry electromagnetic charge
- Little is known about its mass density which is dominated by energy carried by gluons
  - Gluons do not carry electric charge and difficult to access via electron scattering experiments.



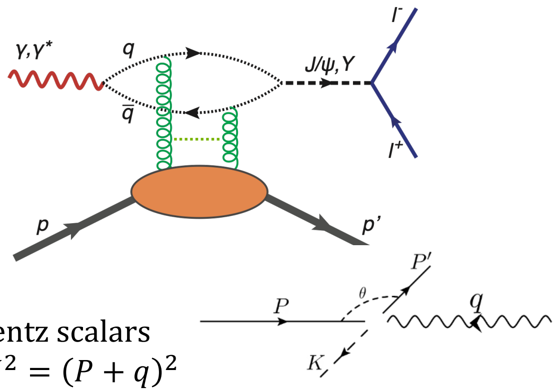
https://www.anl.gov/phy/3d-structure-of-protons-and-neutrons



NEAR THRESHOLD J/Ψ PRODUCTION

Why is it interesting?

- t-channel differential cross section of quarkonium production at threshold → promising channel to access the gluons
  - GFFs are matrix elements of the proton's energy-momentum tensor (EMT)
  - Gluon Form Factors (slope and magnitude)→ encode mechanical properties e.g., radii, pressure, shear



Lorentz scalars
$s = W^2 = (P+q)^2$
$t = (P-P')^2 = (q-K)^2$

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

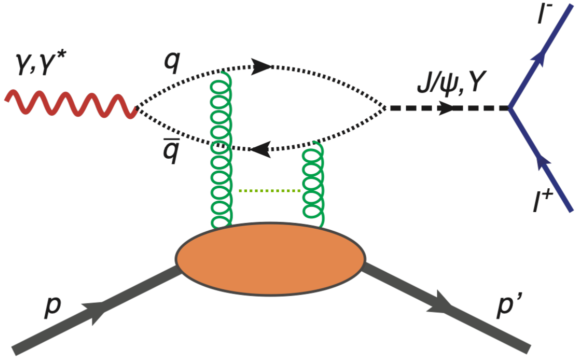
$A_{g,q}(t)$: Related to quark and gluon momentum fraction; $A_{g,q}(0) = \langle x_{g,q}\rangle$

$B_{g,q}(t)$: Total angular momentum $J_{g,q}(t) = \frac{1}{2}(A_{g,q}(t) + B_{g,q}(t))$

$C_{g,t}(t)$: Pressure and Shear distribution $D_{g,q}(t) = 4C_{g,q}(t)$

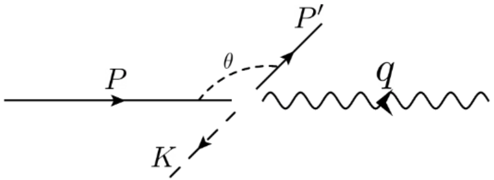
D. Kharzeev Phys. Rev. D 104, 054015
Ji et. al. Phys. Rev. D 103, 096010
Hatta et. al. Phys. Rev. D 98, 074003
Mamo & Zahed Phys. Rev. D 101, 086003

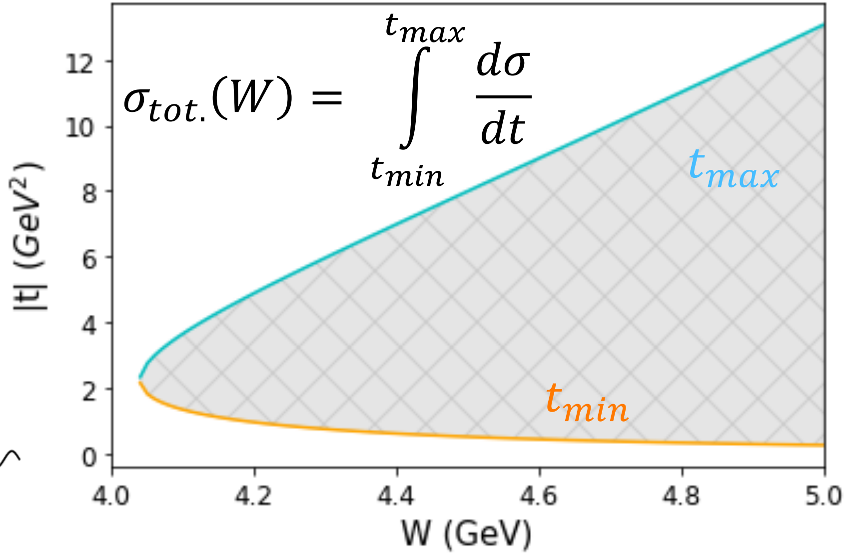
J/Ψ PHOTOPRODUCTION KINEMATICS



Lorentz scalars

$$s = W^2 = (P+q)^2$$
$$t = (P-P')^2 = (q-K)^2$$





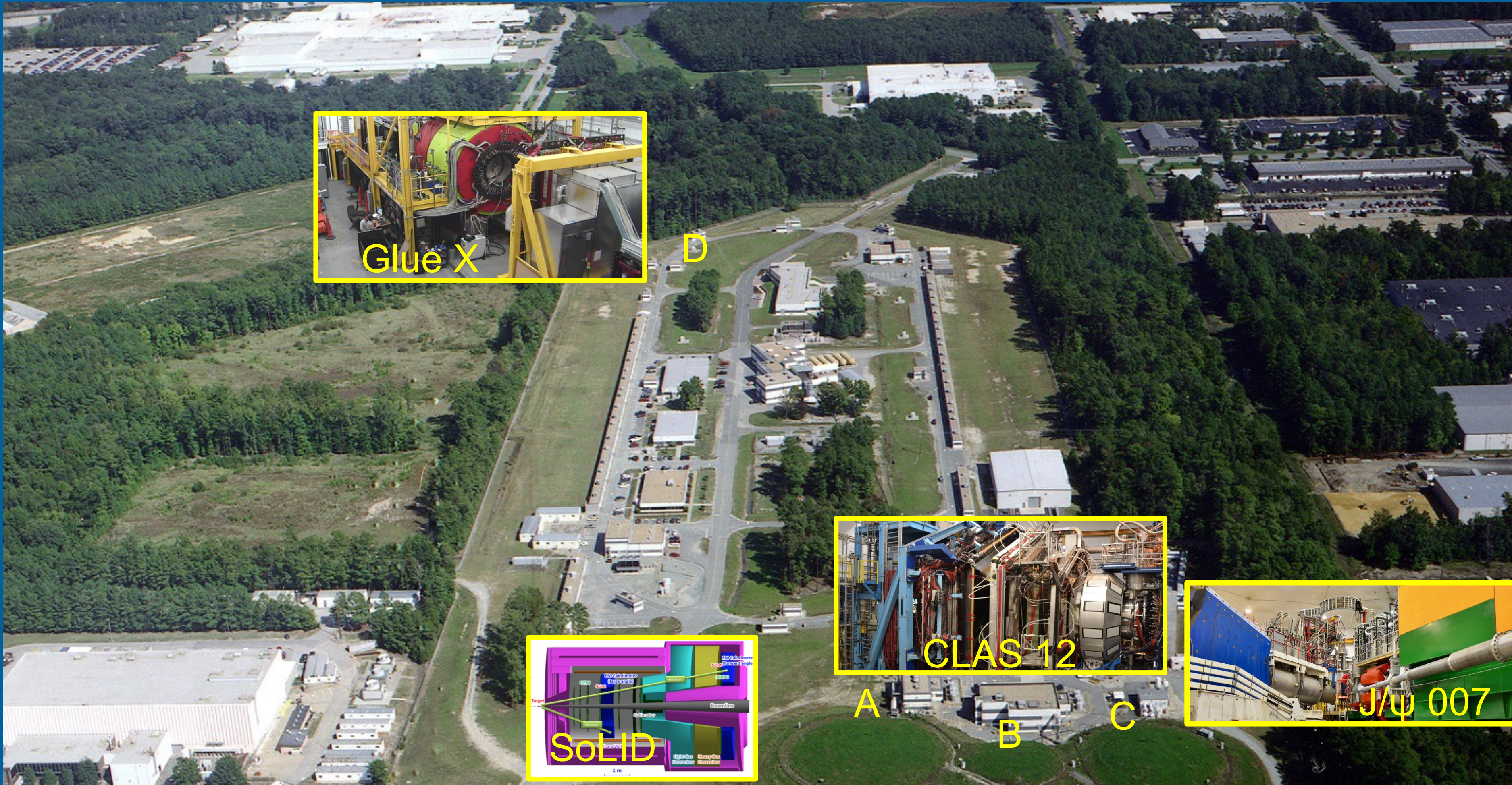
- Phase space for J/Ψ production is limited by t_{min} and t_{max}
  - t_{min} → J/Ψ in the forward/ along the direction of photon
  - t_{max} → J/Ψ in the backward/ along the direction of proton

J/Ψ threshold

$W \approx 4.04\ GeV$

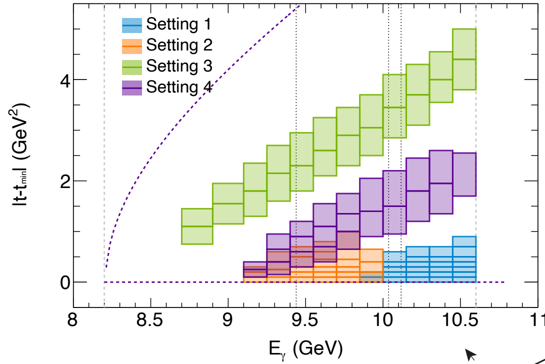
$E_\gamma^{lab} \approx 8.2\ GeV$

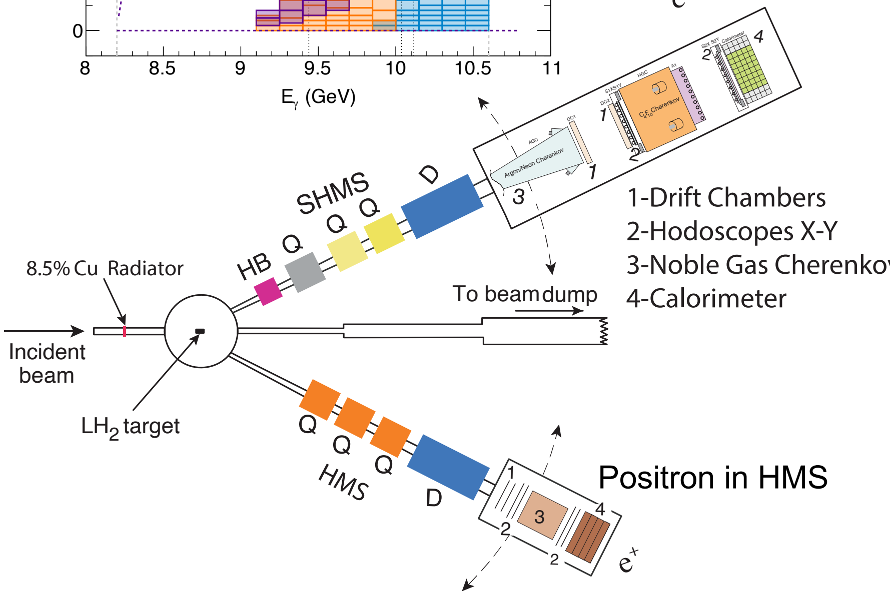
12 GEV EXPERIMENTS AT JLAB



J/Ψ-007 EXPERIMENT

- E12-06-007 (J/Ψ-007) ran in February 2019 (~ 9 PAC days) & measured exclusive J/Ψ photoproduction cross section as a function of photon energy E_γ and t (the momentum transfer from initial photon to the produced J/Ψ)
  - Scanned photon beam energy E_γ from 9.1 to 10.6 GeV and |t| up to 4.5 GeV^2.
  - High intensity real photon beam, generated from 10.6 GeV electron beam traversing through a copper radiator, was incident on liquid hydrogen target
  - HMS and SHMS used to measure the e^-e^+ or $\mu^-\mu^+$ produced in coincidence from decay of J/Ψ.

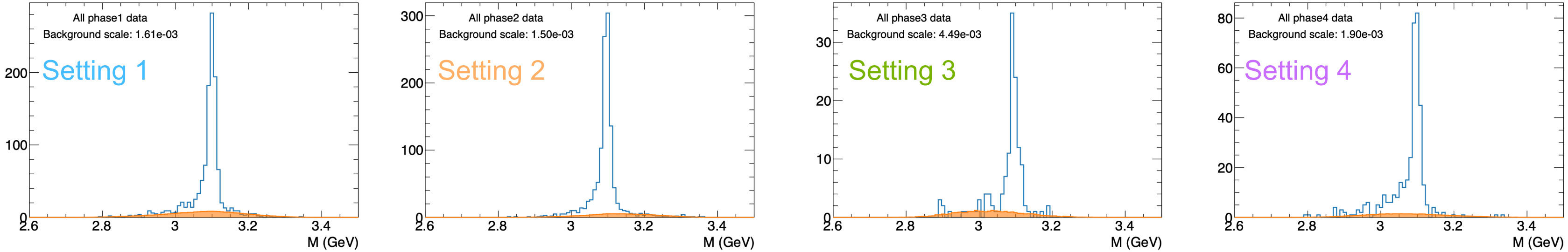




Z.-E. Meziani, S. Joosten et al., arXiv:1609.00676 [hep-ex]

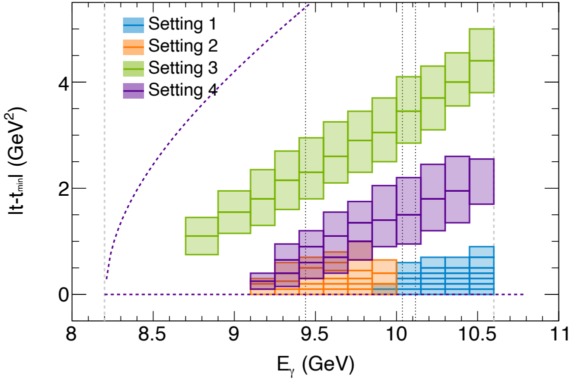
MASS SPECTRUM FROM ELECTRON CHANNEL

Settings optimized for accessing broad range of t



Clear J/Ψ signal with minimal background

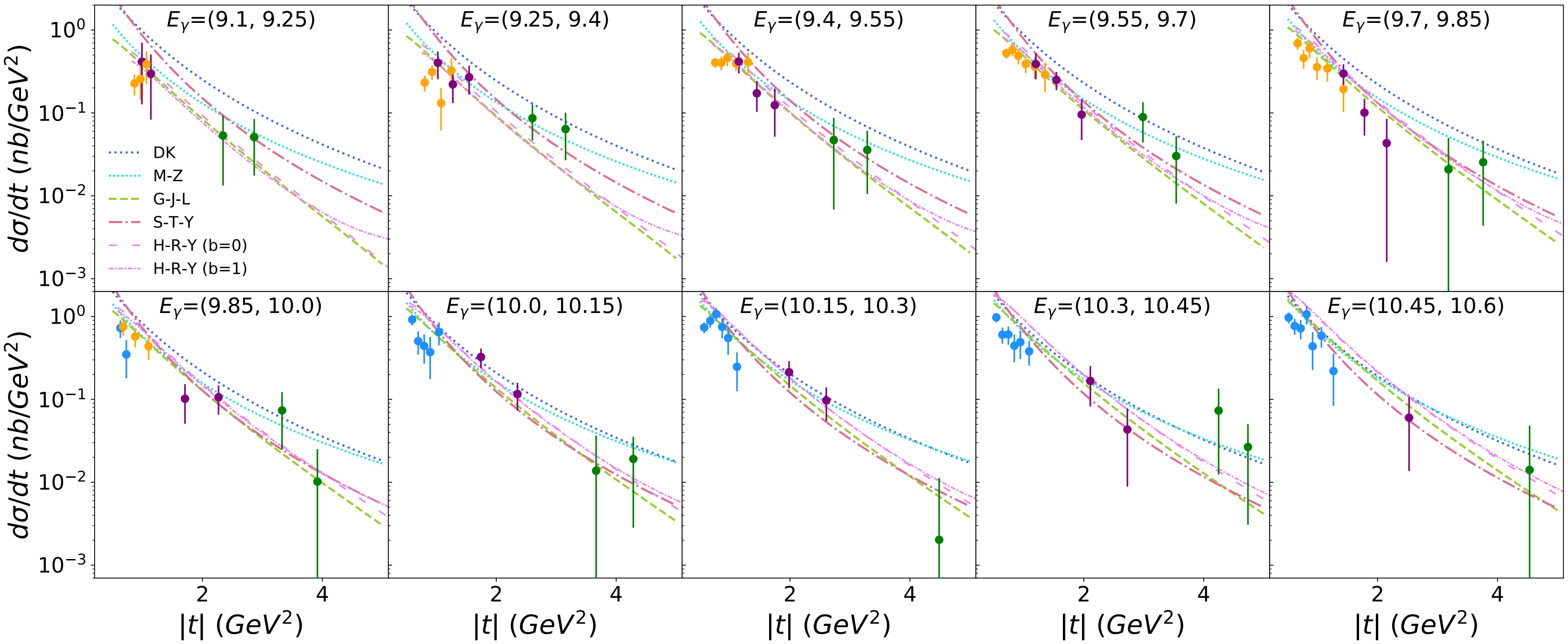
	SHMS		HMS		
Settings	p (GeV)	θ(deg.)	p (GeV)	θ (deg.)	
1	4.8	17	4.95	19.1	high E/ low t
2	4.3	20.1	4.6	19.9	mid E/ low t
3	3.5	30	4.08	16.4	high t
4	4.4	24.5	4.4	16.6	mid t



2-D CROSS SECTIONS- J/Ψ 007

Comparison with different model predictions

1. DK: Phys. Rev. D 104, 054015
2. M-Z: Phys. Rev. D 103, 094010
3. G-J-L: Phys. Rev. D 103, 096010
4. S-T-Y: Phys. Lett. B 822, 136655
5. H-R-Y: Phys. Rev. D 98, 074003, Phys. Rev. D 100, 014032 JHEP 12, 008

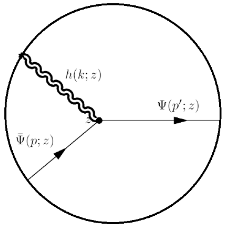


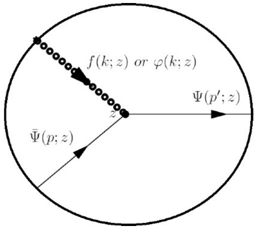
Nature **615**, pages 813–816 (2023)

MODEL DEPENDENT EXTRACTION OF GLUONIC GRAVITATIONAL FORM FACTORS

- Used two different approaches to perform extraction
  - **Holographic QCD approach** (Mamo, K. A. & Zahed, I. Phys. Rev. D 106, 086004):

    Exchange of massive 2^{++} (tensor) glueballs and 0^{++} (scalar) glueballs

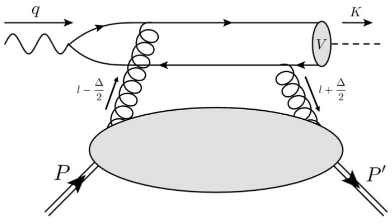


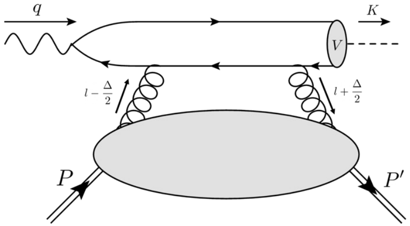


$$\frac{d\sigma}{dt} = \mathcal{N}^2 \times \frac{e^2}{64\pi(s-m_N^2)^2} \times \frac{[A(t)+\eta^2 D(t)]^2}{A^2(0)} \times \tilde{\mathcal{F}}(s) \times 8$$

  - **GPD approach** (Guo, Y., Ji, X. & Liu, Y. Phys. Rev. D 103, 096010): Gravitational form

    factors linked to the first moment of Generalized Parton Distributions.





$$\frac{d\sigma}{dt} = \frac{\alpha_{EM} e_Q^2}{4(s-m_N^2)^2} \frac{(16\pi\alpha_S)^2}{3M_V^3} |\psi_{NR}(0)|^2 |G(t,\xi)|^2$$

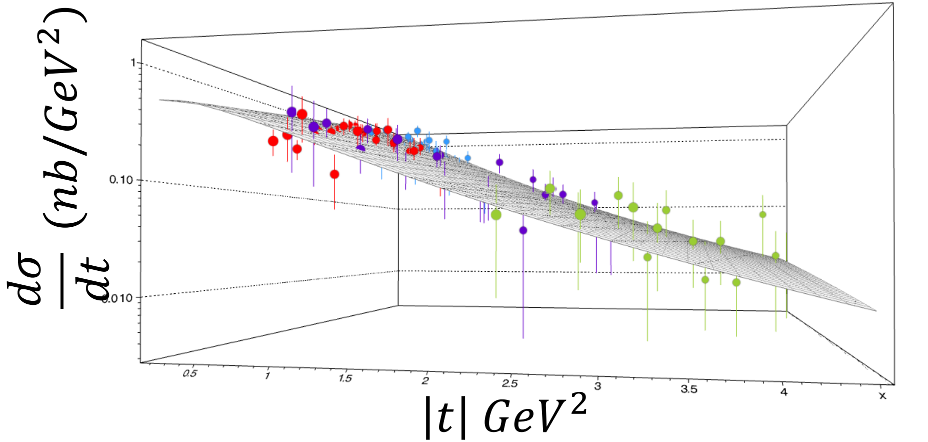
MODEL DEPENDENT EXTRACTION OF GLUONIC GRAVITATIONAL FORM FACTORS

- Two form factors (tripole form) considered.

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

- Fixed $A_g(0)$ to $\langle x_g \rangle$ = 0.414 (CT18 global fit)
  - m_A, $C_g(0)$ and m_C determined from fits
  - χ^2/n.d.f ~ 1 for both fits
- $B_g(t)$ is assumed to be negligible
- $\bar{C}_g(t)$ is not included the extraction of GFF and gluonic radii
  - $\bar{C}_g(t) + \bar{C}_q(t) = 0$ Hatta et al. JHEP 12 (2018) 008, & Tanaka, K. JHEP 03 (2023) 013

2 D fit to J/Ψ 007 data

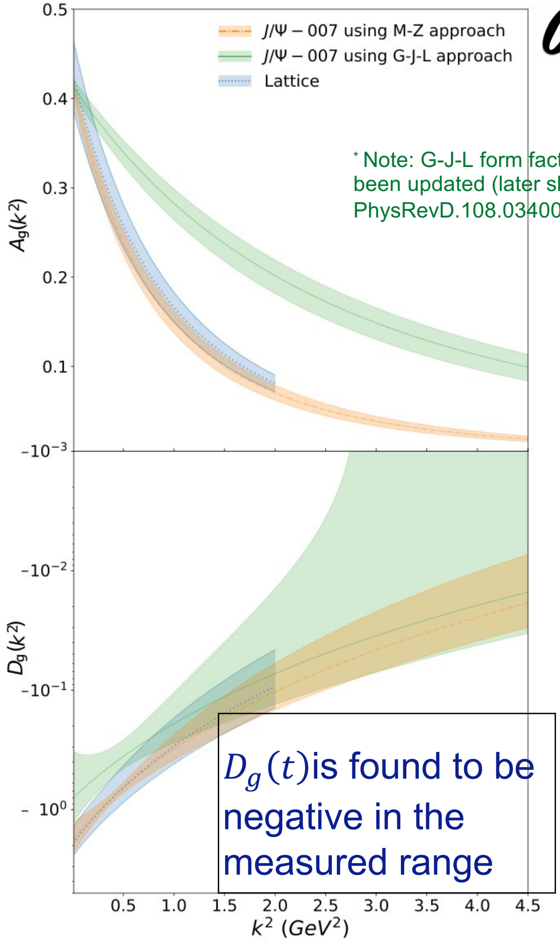


B. Duran et al., Nature volume 615, pages 813–816 (2023)

GLUON FORM FACTORS

Extraction from J/Ψ 007 experimental data

- $A_g(t)$ and $D_g(t) = 4C_g(t)$ extracted from 2 D fit to data.
  - Holographic approach (M-Z) : (Mamo, K. A. & Zahed, I. Phys. Rev. D 106, 086004)
  - GPD approach (G-J-L) : (Guo, Y., Ji, X. & Liu, Y. Phys. Rev. D 103, 096010)
- Lattice predictions: (Pefkou, D. A., Hackett, D. C. & Shanahan, P. E. Phys. Rev. D 105, 054509)
- Lattice predictions in very good agreement with extractions using Holographic QCD approach *



* Note: G-J-L form factors have been updated (later slides- PhysRevD.108.034003)

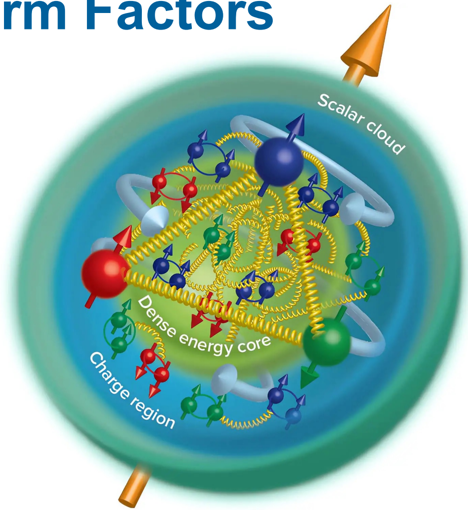
$D_g(t)$ is found to be negative in the measured range

B. Duran et al., Nature volume 615, pages 813–816 (2023)

MASS AND SCALAR RADII FROM J/Ψ 007 DATA

Using model dependent extraction of Gluon Form Factors

Theoretical approach	$\sqrt{\langle r_m^2 \rangle_g}$ (fm)	$\sqrt{\langle r_s^2 \rangle_g}$ (fm)
Holographic QCD	0.755+/-0.067	1.069+/-0.126
GPD	0.472+/-0.085	0.695+/-0.162
Lattice	0.746+/-0.055	1.073+/-0.114



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

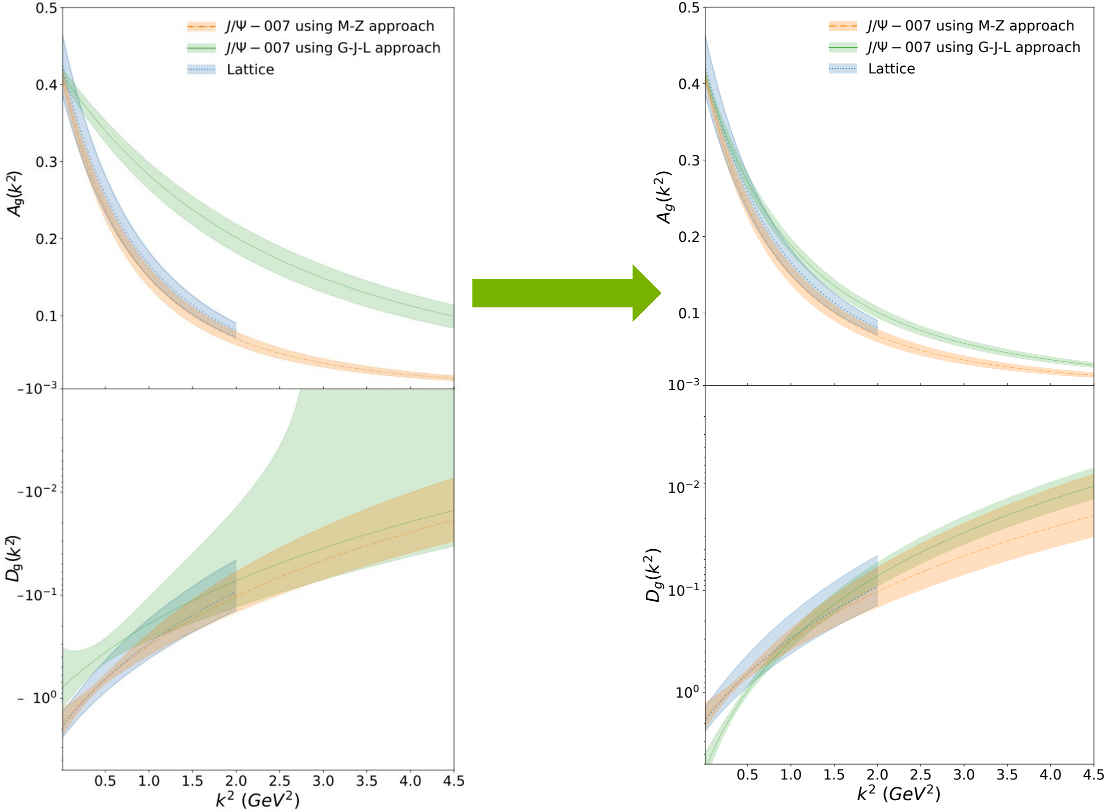
2^{++} exchange

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

0^{++} exchange

- Mass radius is found to be smaller than charge radius in both approaches!!
- Holographic QCD approach gives scalar radius close to 1 fm (larger than charge radius) –> Consistent with lattice predictions

UPDATED GPD MODEL EXTRACTION

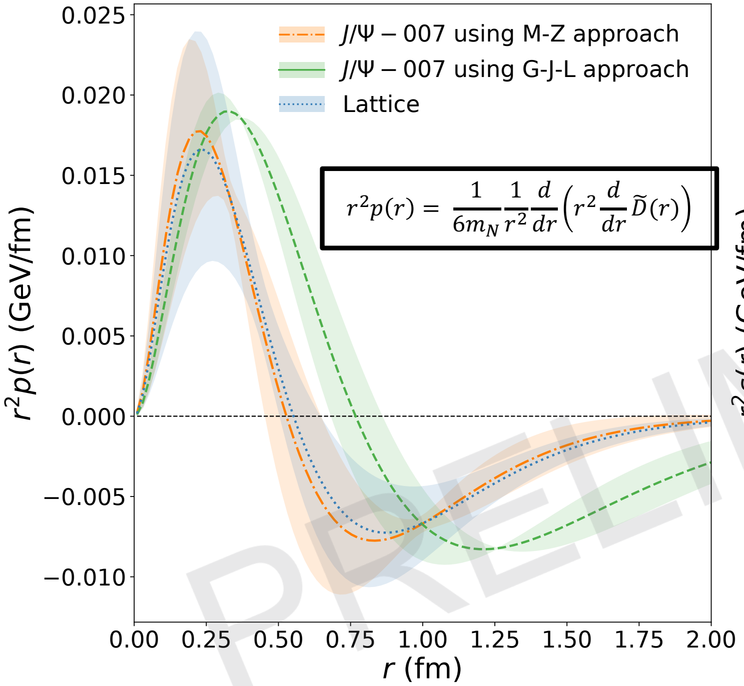


- Updates based on recent paper from Guo et. al. Phys. Rev. D.108.034003
- Factor of 2 missed in hadronic matrix element – *G(ξ,t)*
- The $A_g(t)$ in better agreement with lattice predictions and holographic model extraction
- The $D_g(t)$ uncertainty is reduced

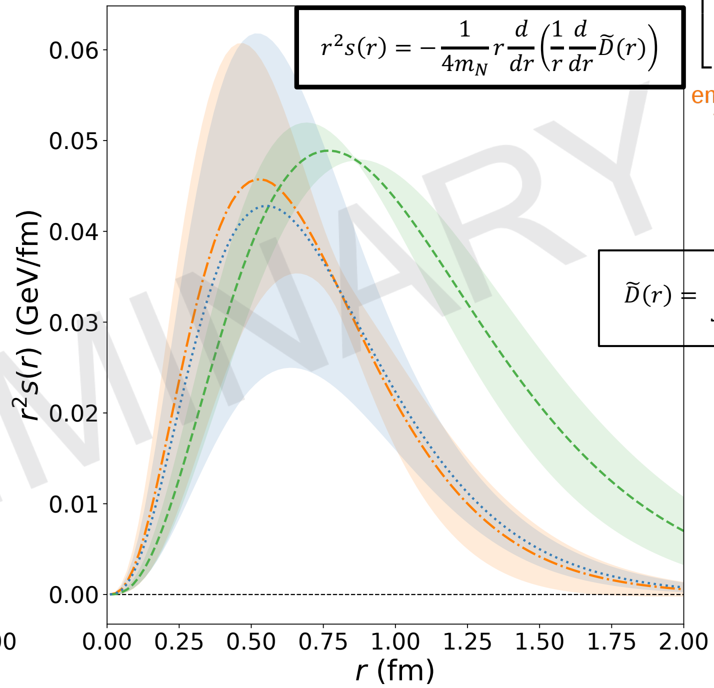
PRESSURE AND SHEAR DISTRIBUTIONS

Anisotropic spatial content of EMT

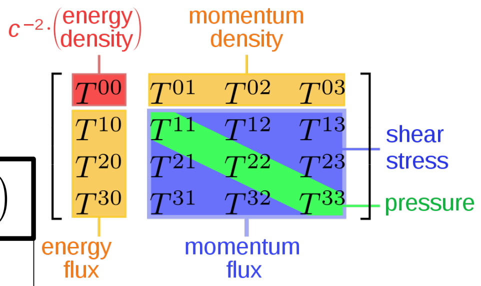
$$T^{i,j}(r) = \frac{1}{3}\delta^{i,j}p(r) + \left(\hat{r}^i\hat{r}^j - \frac{1}{3}\delta^{i,j}\right)s(r)$$



$$r^2p(r) = \frac{1}{6m_N}\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d}{dr}\widetilde{D}(r)\right)$$



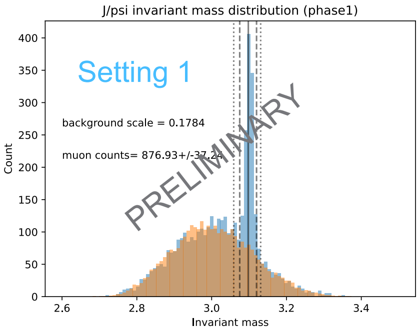
$$r^2s(r) = -\frac{1}{4m_N}r\frac{d}{dr}\left(\frac{1}{r}\frac{d}{dr}\widetilde{D}(r)\right)$$

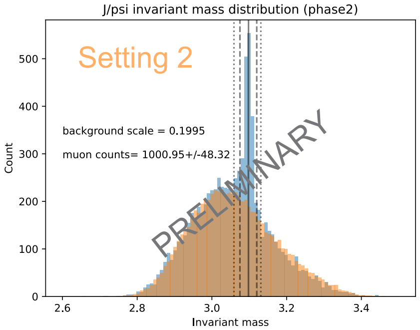


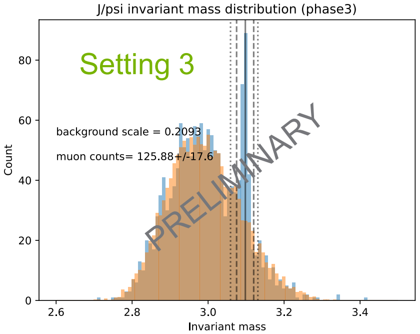
$$\widetilde{D}(r) = \int \frac{d^3\Delta}{(2\pi)^3} e^{-i\Delta.r} D(\Delta, m_C); (-t = k^2 = \Delta)$$

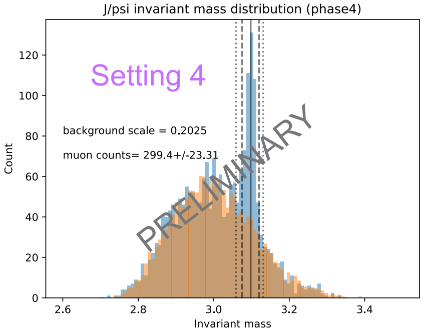
DOUBLING STATISTICS FROM J/Ψ-007 EXPERIMENT

Adding more data from muon channel









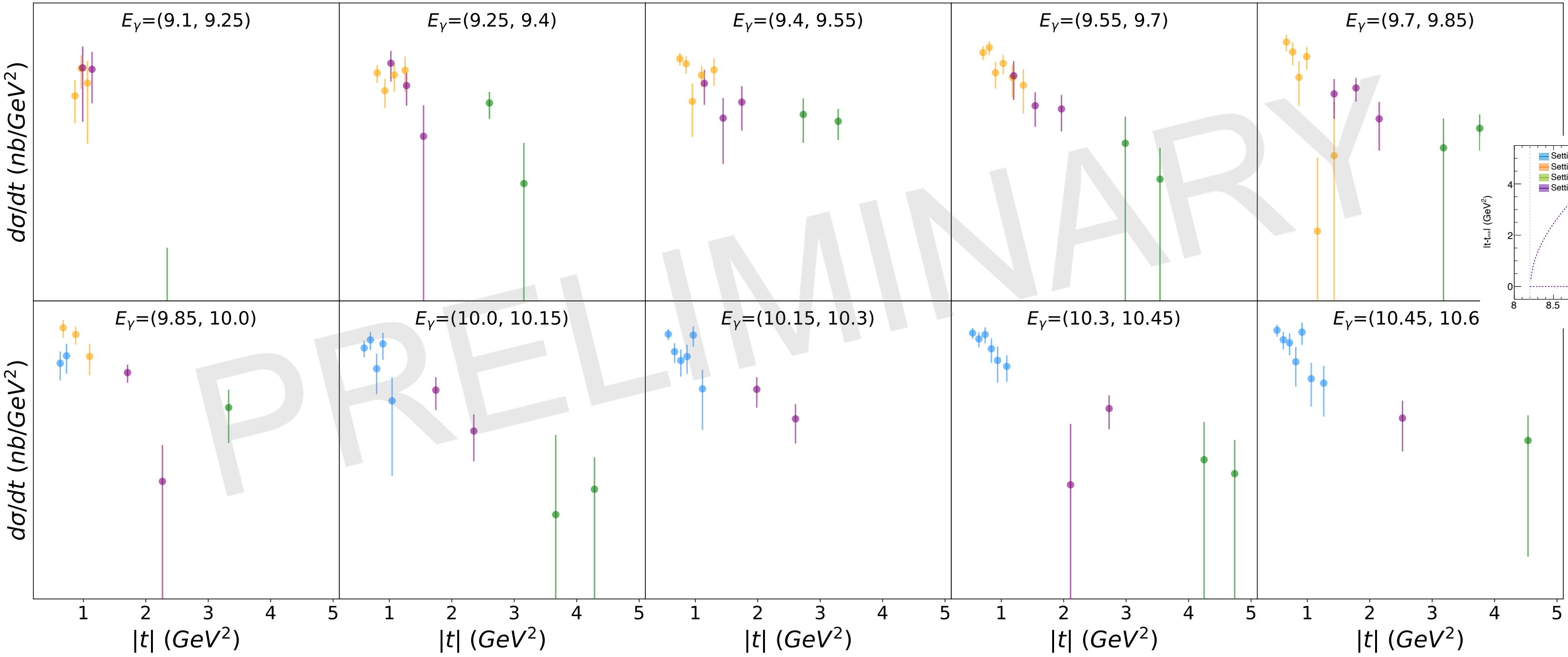
- Analysis cuts optimized to select muon sample
  - Setting 1: sweet spot for Cherenkov threshold. π's do not radiate and μ's do.

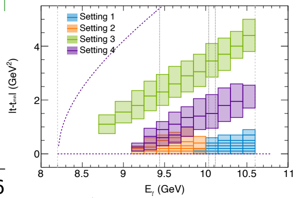
	SHMS		HMS		
Settings	p (GeV)	θ(deg.)	p (GeV)	θ (deg.)	
1	4.8	17	4.95	19.1	high E/ low t
2	4.3	20.1	4.6	19.9	mid E/ low t
3	3.5	30	4.08	16.4	high t
4	4.4	24.5	4.4	16.6	mid t

Argonne NATIONAL LABORATORY

2D CROSS SECTIONS USING MUON CHANNEL

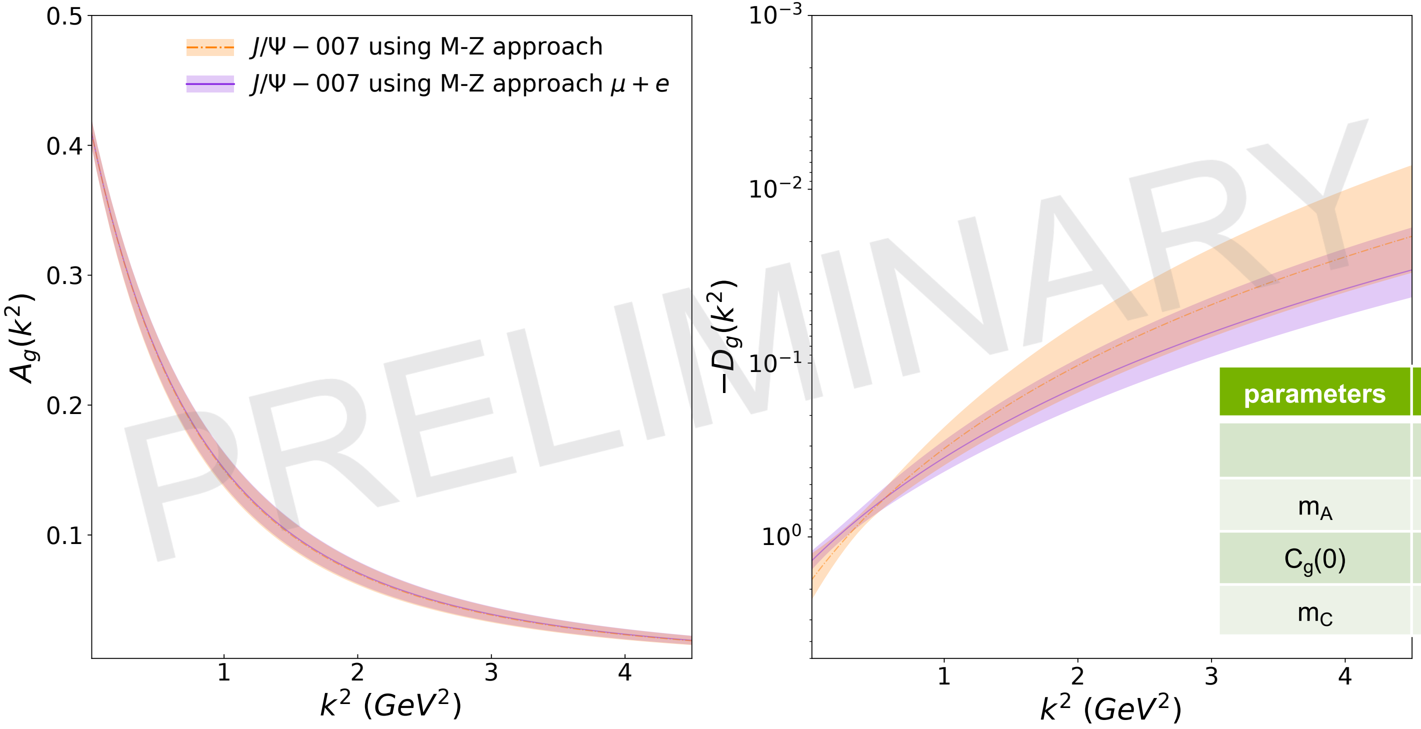
Excellent agreement with electron channel result!





FORM FACTORS - UPDATED WITH MUON CHANNEL DATA INCLUDED

Excellent agreement with electron channel result!

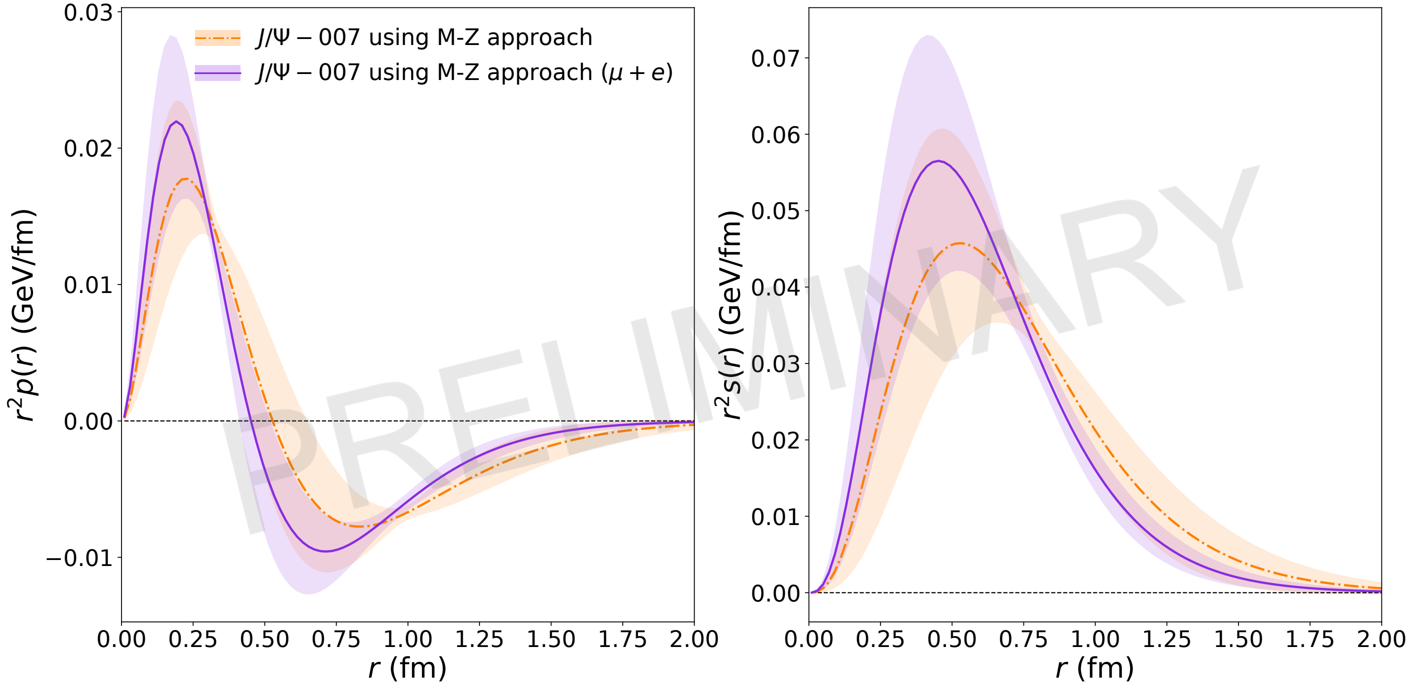


- Agrees well with electron channel results
- Significant impact on $D_g(t)$ ($=4C_g(t)$)

parameters	Relative error	
	$J/\psi \to e^-e^+$	$J/\psi \to e^-e^+$ or $\mu^-\mu^+$
m_A	4%	3.5%
$C_g(0)$	28%	12%
m_C	18%	11.3%

PRESSURE AND SHEAR DISTRIBUTIONS

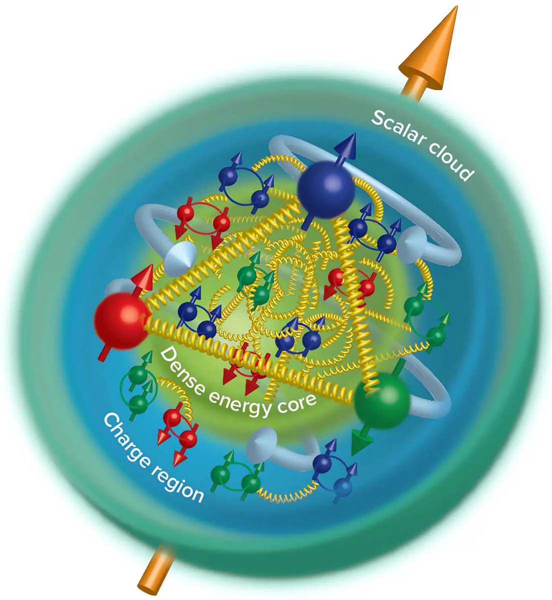
After including the muon channel data



More results from J/ψ 007 to be published soon!

SUMMARY

- Extraction of gluon Gravitational Form Factors ($A_g(t)$ and $C_g(t)$) from J/ψ 007 experiment
  - Electron channel results already published
    - Hinting towards a picture of proton with dense energetic core
    - Consistent with Lattice predictions
  - Preliminary results from analysis of muon channel
    - Nice agreement with electron channel results
    - large impact is seen on the $C_g(t)$ form factor.
- Extraction of gluonic pressure and shear distribution inside proton for first time from experiments
- Finalizing results from muon channel data
  - To be published soon!

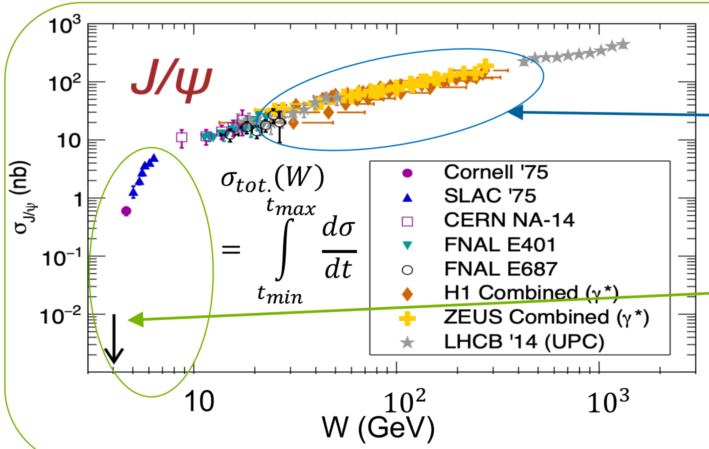


THANK YOU!

QUESTIONS?

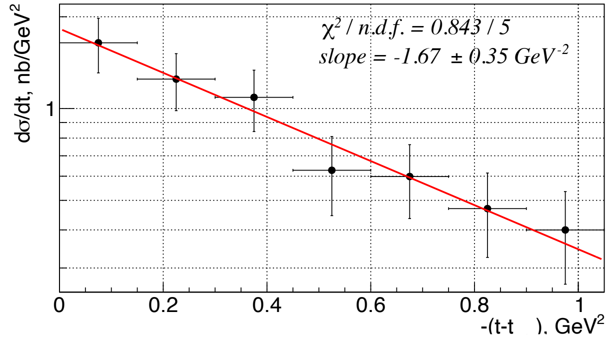
BACK UP

J/Ψ PHOTOPRODUCTION NEAR THRESHOLD AT HALL D

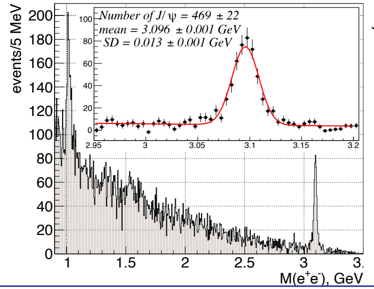


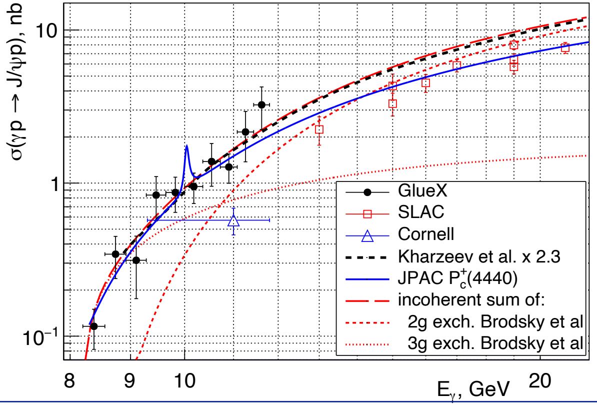
- Cross section well constrained at higher energies.
- Experimental data lacking near threshold region.

PRL 123, 072001 (2019)



- First to measure J/ψ at JLab.
- Reported 1D differential cross section $\frac{d\sigma}{dt}$ in E_γ bin (10 GeV - 11.8 GeV) upto $t = 1.4\ GeV^2$



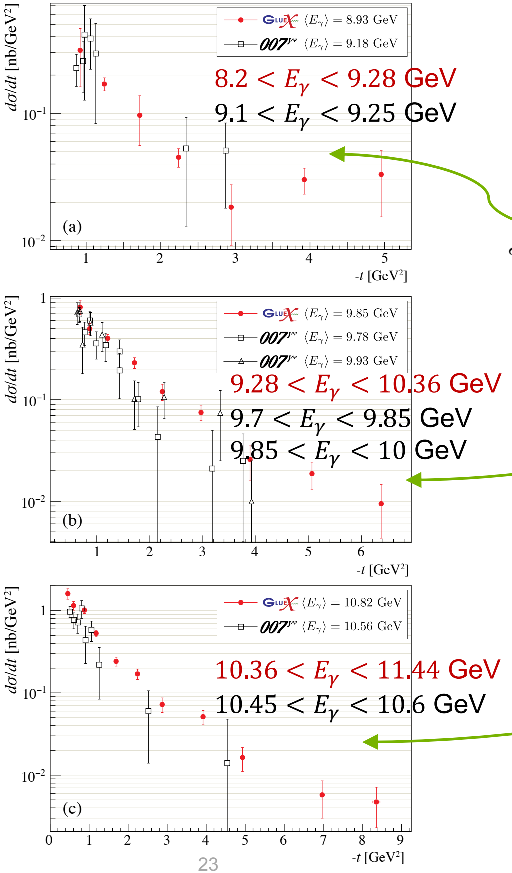


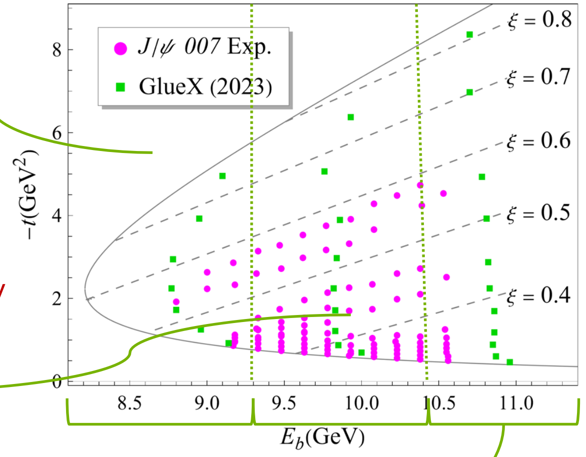
GLUEX 2023 DATA AND RESULTS

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

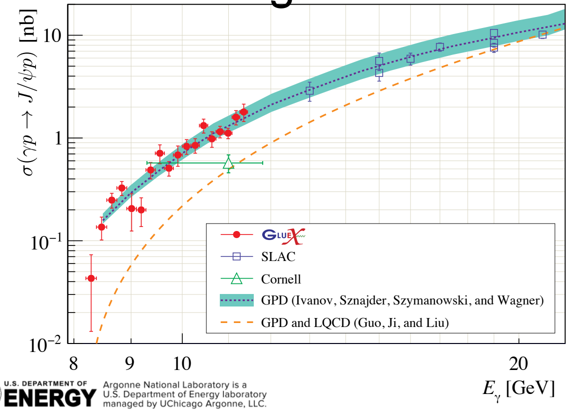
- 2 D cross section in 3 E_γ bins between 8.2 GeV – 11.4 GeV compared to closest energy bins from J/ψ 007
  - 2.2k J/ψ's (similar to J/ψ 007 experiment electron channel measurements)
- Scale uncertainty- 20% for GlueX and 4% for J/ψ 007
- Good agreement within error
  - Note differences in average energies

2 D differential CS



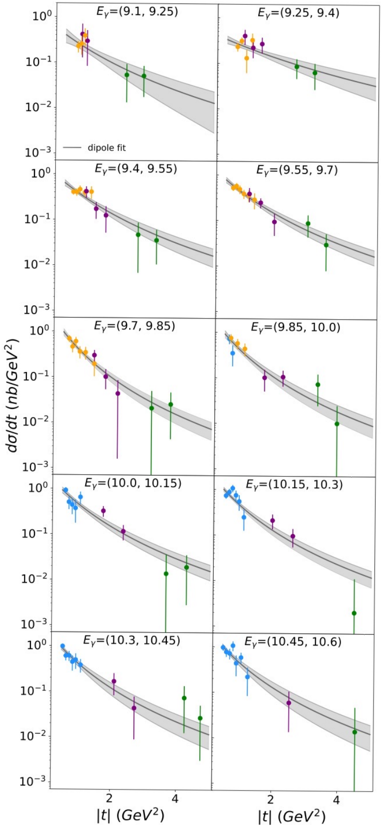


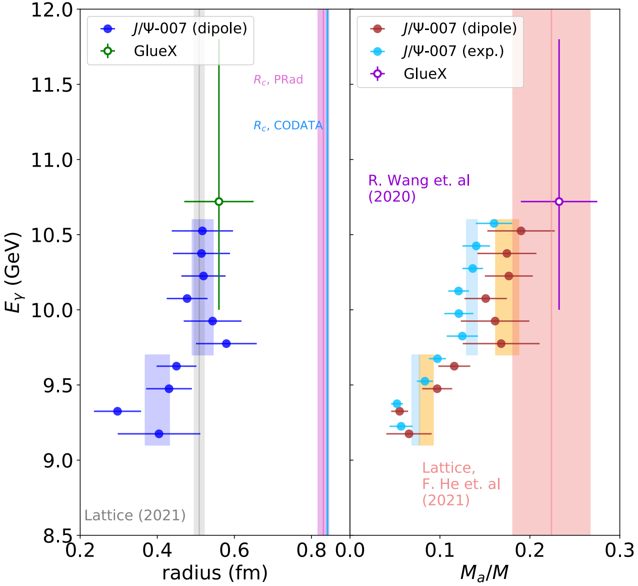
1 D integrated CS



VARIOUS MODEL DEPENDENT EXTRACTIONS

Radius (from D. Kharzeev's approach) and Ma/M (from Ji's mass decomposition)





Charge radius: CODATA
Lattice radius: Pefkou, D. A., Hackett, D. C. & Shanahan, P. E. Phys. Rev. D 105, 054509
GlueX point: Wang, R., Evslin, J., Chen, X. Eur. Phys. J. C, 80, 507 (2020)
Approach: Ji, X. Phys. Rev. Lett. 74, 1071-1074 (1995)
Lattice Ma: He, F., Sun, P., Yang, Y.-B., Phys. Rev. D 104 074507 (2021)

$$\frac{d\sigma}{dt} = \frac{1}{64\pi\, s}\frac{1}{|p_{\gamma cm}|^2}\left(Qec_2\frac{16\pi^2 M}{b}\right)^2 G(t)^2$$

$$G(t) = \frac{M}{\left(1-\frac{t}{m_s^2}\right)^2}$$

Kharzeev, D. Phys. Rev. D 104, 054015 (2021)

$$\boxed{\langle r_m^2\rangle = \frac{6}{M}\frac{dG}{dt}\Big|_{t=0} = \frac{12}{m_s^2}}$$

- Flat region at higher energies beyond $E_\gamma = 9.7\ GeV$.
- Good agreement with lattice in high energy region.
- $\sqrt{\langle r_m^2\rangle} = 0.52 \pm 0.03$ fm
- $M_a/M = 0.175 \pm 0.013$

Nature **615**, pages 813–816 (2023)

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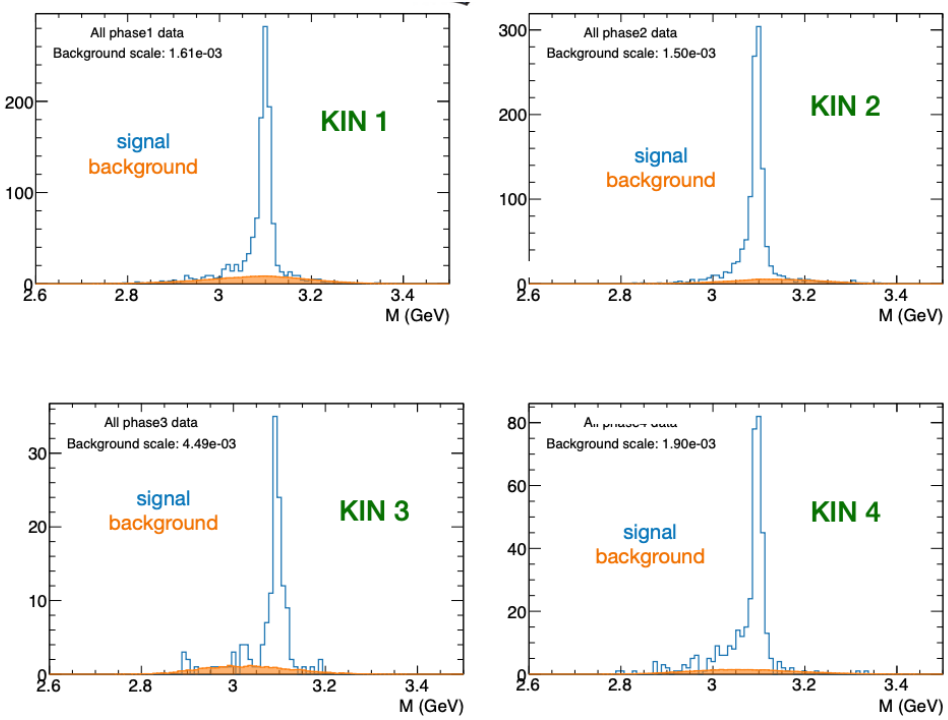
BACKGROUND CONTRIBUTION

Possible BG considerations:

- $e^-\pi^+$, $\pi^-\pi^+$ and e^-e^+
- $e^-\pi^+$ is dominant and $\pi^-\pi^+$ or e^-e^+ negligible
- Measured the background!
  - Available in the data sample due to the no PID trigger.

BG Event Selection:

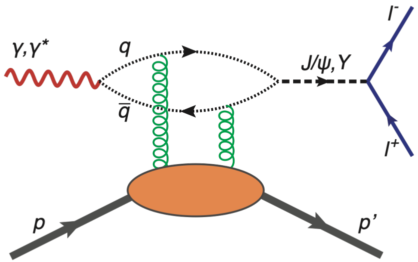
- Coincidence $e^-\pi^+$ background selected using electron PID in the SHMS and pions in the HMS.
  - **electrons:** Calorimeter
  - **pions:** Calorimeter + Cherenkov

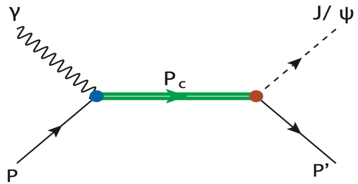


- Fit BG shape to the sidebands of the signal to obtain the BG scale.

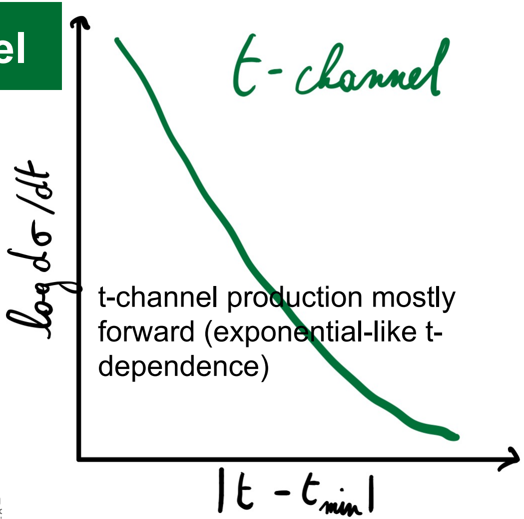
Slide from B Duran

SENSITIVITY TO T AND S CHANNEL

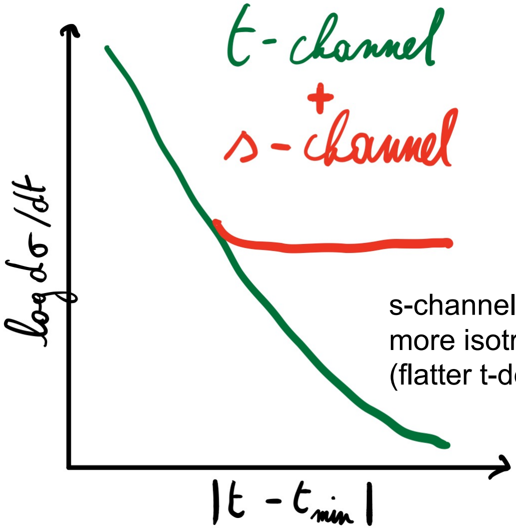




t-channel



t-channel production mostly forward (exponential-like t-dependence)



s-channel

s-channel production more isotropic (flatter t-dependence)

Slide fro Zein-Eddine

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

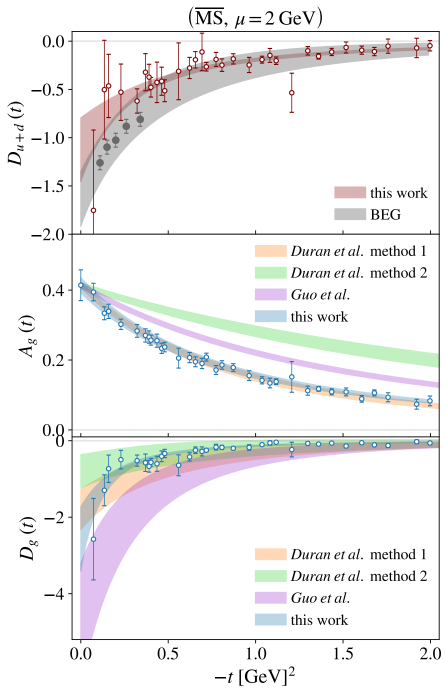
https://indico.phy.anl.gov/event/2/

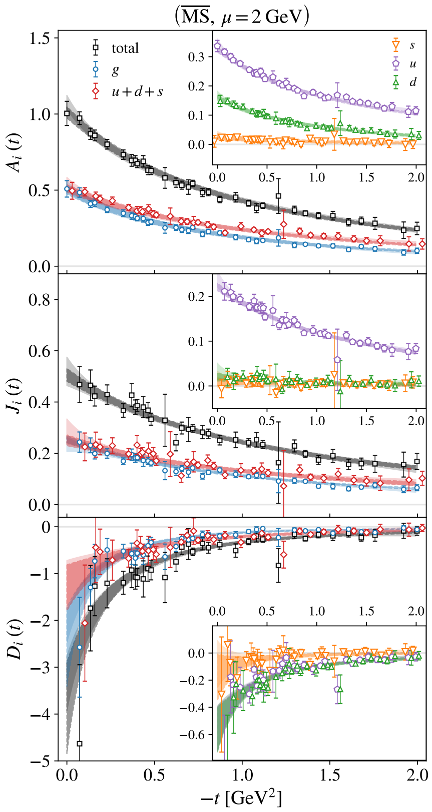
Consequence for the proton mass: About 100 MeV from the Higgs, the rest is gluon field energy

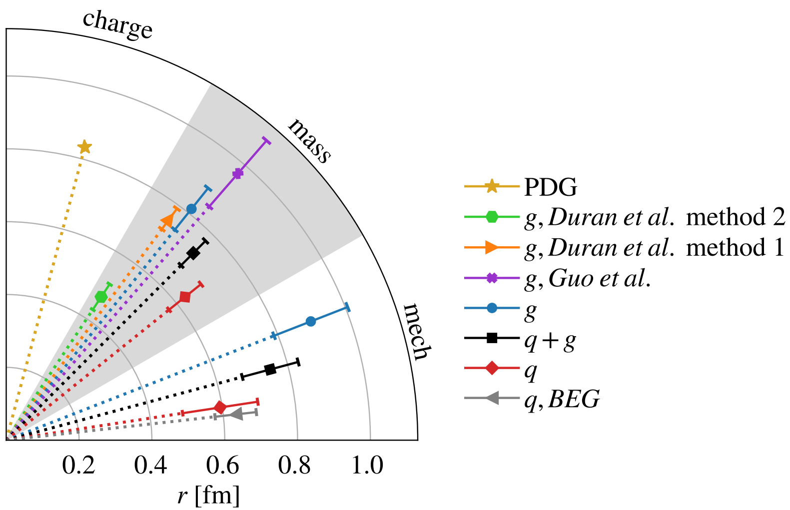
Hoferichter, Ruiz de Elvira, Kubis, Ulf-GMeißner Phys. Rev. Lett. 115 (2015) 092301 [arXiv:1506.04142] Phys. Rev. Lett. 115 (2015) 192301 [arXiv:1507.07552] Phys. Rept. 625 (2016) 1 [arXiv:1507.07552]

RECENT LATTICE RESULTS

arxiv 2310.08484







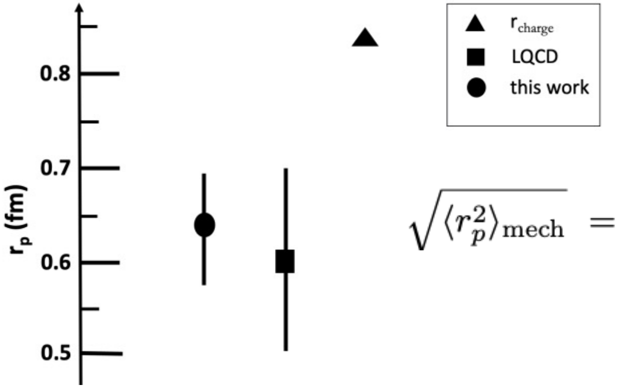
$$|G(t,\xi)|^2 = \frac{1}{\xi^4}\Bigg\{\left(1-\frac{t}{4M_N^2}\right)E_2^2$$

$$-2E_2(H_2+E_2)+\left(1-\xi^2\right)(H_2+E_2)^2\Bigg\}\,, \qquad (26)$$

where $H_2 \equiv E_2(t,\xi)$, $E_2 \equiv E_2(t,\xi)$ are defined in eq. (23). Combining with eq. (17), the cross section of heavy vector meson photoproduction can be expressed in terms of those gravitational form factors. This result agrees with the holographic QCD predictions [16, 17] that the leading contribution to the cross section is due to exchange of 2^{++} excitations, or the spin-2 twist-two operators, instead of the 0^{++} F^2 operators suggested in [3, 7]. However, in the holographic approach the twist-2 part of the gravitational form factor is dual to the graviton exchange and is free from the C_g contribution. This differs from the generic QCD parametrization in eq. (24). Because of the EMT conservation, the quantum anomalous energy F^2 form factor can be related to the twist-two ones here. If the further limit $\xi \to 0$ is taken in eq. (26), only the A form factors are leading and all the results agrees. However, this is inconsistent with our approximation here.

DVCS DATA FOR QUARK DFF

arxiv: 2310.11568



$$\sqrt{\langle r_p^2\rangle_{\mathrm{mech}}} = 0.634 \pm 0.057\ \mathrm{fm}$$

The mechanical radius of the proton

V.D. Burkert,[1] L. Elouadrhiri,[1,2] and F.X. Girod[1]

[1] *Thomas Jefferson National Accelerator Facility, Newport News, VA 23606, USA*
[2] *Center for Nuclear Femtography, SURA, Washington, DC, USA*

(Dated: November 7, 2023)

We present the first determination of the proton's mechanical radius. The result was obtained by employing a novel theoretical approach, which connects experimental data of deeply virtual Compton scattering with the spin $J = 2$ interaction that is characteristic of gravity coupling with matter. We find that the proton's mechanical radius is significantly smaller than its charge radius, consistent with the latest Lattice QCD computation.

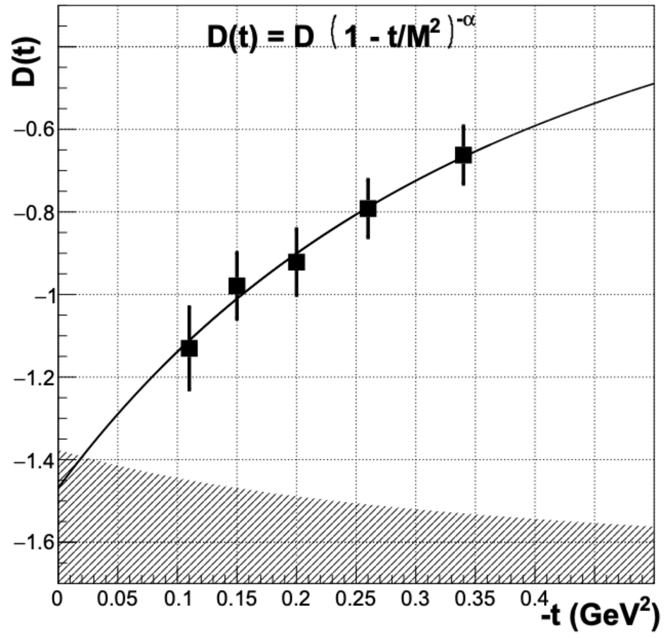


FIG. 2: The form factor $D(t)$ as determined in the fit to the DVCS data. The hatched area represents the systematic uncertainties.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