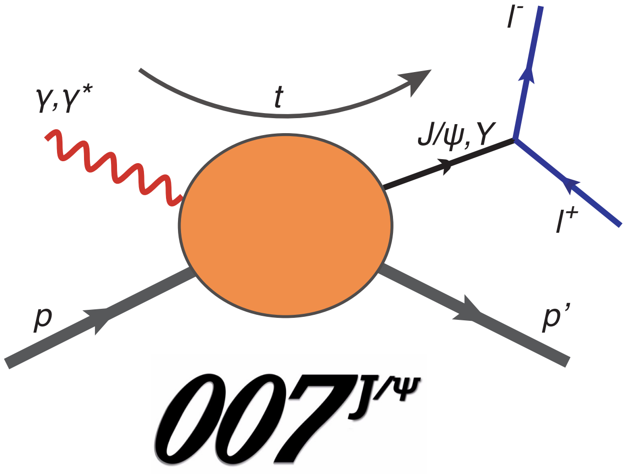
RECENT RESULTS FROM NEAR THRESHOLD J/Ψ PHOTOPRODUCTION IN HALL-C AT JLAB



SHIVANGI PRASAD
sprasad@anl.gov

On behalf of E12-16-007 collaboration

12-14 April 2023

GHP 2023 WORKSHOP

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

U.S. DEPARTMENT OF ENERGY

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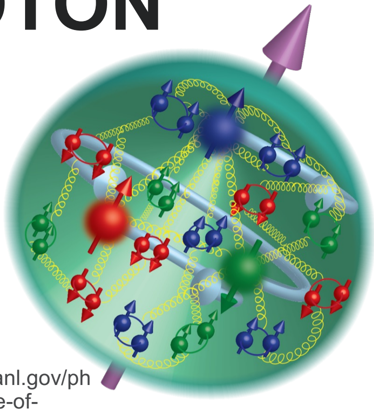
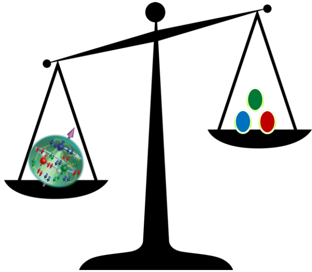
UNDERSTANDING THE ORIGIN OF PROTON MASS AND ITS DISTRIBUTION



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

- Proton's macroscopic properties – charge, spin, mass – arise from a very complex dynamics between the quarks and gluons (QCD)
- Studying its charge radius and spin from electron scattering experiments have been an active area of research
  - Quarks carry electromagnetic charge

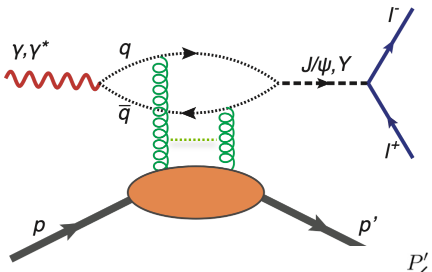


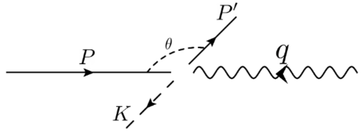
- Little is known about its mass density which is dominated by energy carried by gluons
  - Gluons do not carry electric charge and difficult to access via electron scattering experiments.

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

$s = W^2 = (P+q)^2$

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

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

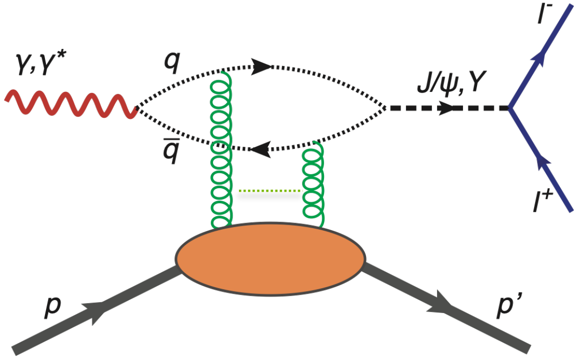
$A_{g,q}(t)$: Related to quark and gluon momentum fraction; $A_{g,q}(0) = \langle x_{g,q}\rangle$

$B_{g,q}(t)$: 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

$$s = W^2 = (P + q)^2$$

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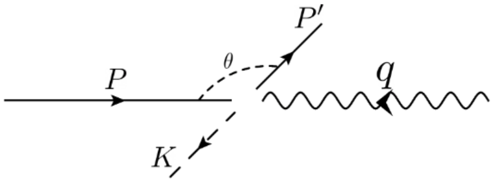
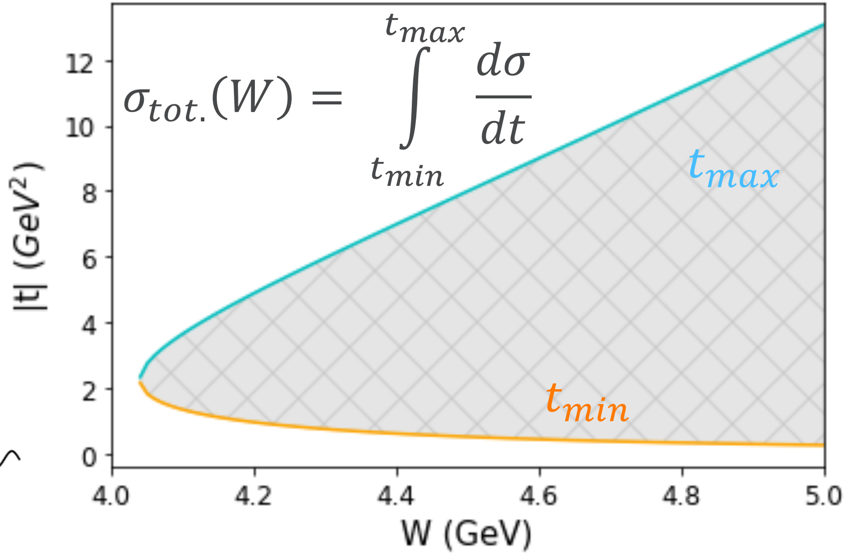




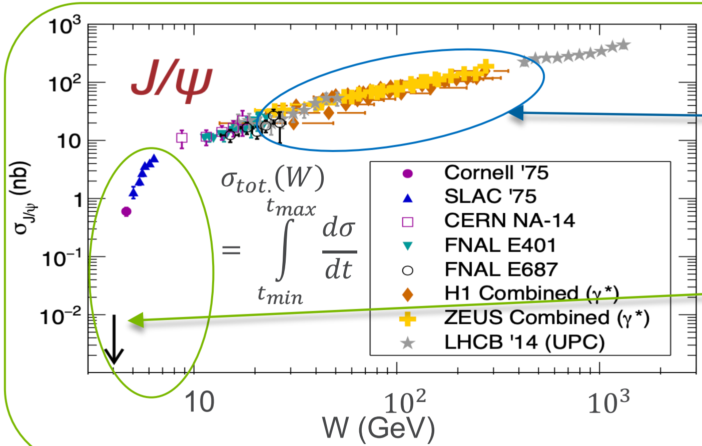
- Phase space for J/Ψ production is limited by t_{min} and t_{max}
  - t_{min} → J/Ψ in the forward/ along the direction of photon
  - t_{max} → J/Ψ in the backward/ along the direction of proton

J/Ψ threshold

$W \approx 4.04\ GeV$

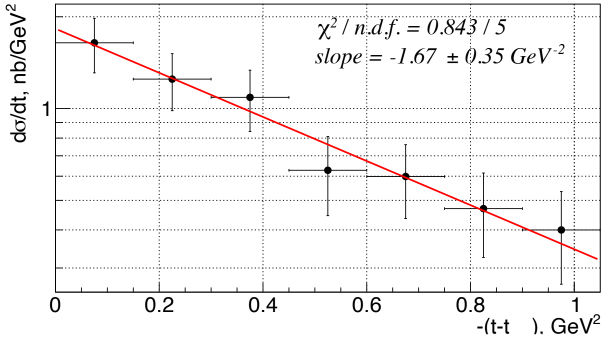
$E_\gamma^{lab} \approx 8.2\ GeV$

J/Ψ PHOTOPRODUCTION NEAR THRESHOLD AT HALL D

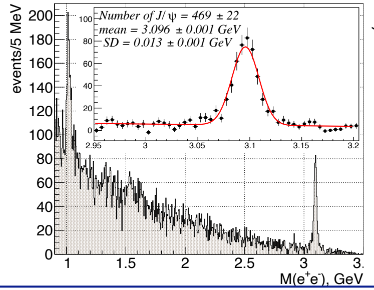


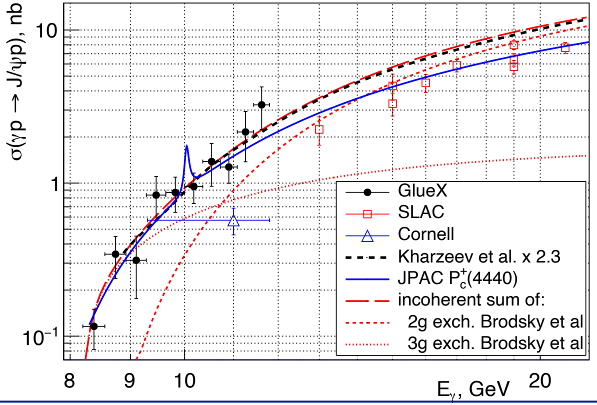
- Cross section well constrained at higher energies.
- Experimental data lacking near threshold region.

PRL 123, 072001 (2019)



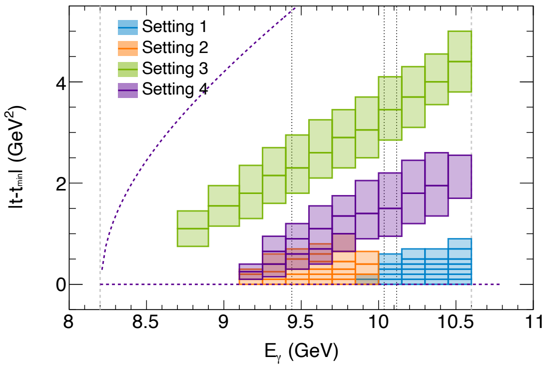
- First to measure J/Ψ at JLab.
- Reported 1D differential cross section $\frac{d\sigma}{dt}$ in E_γ bin (10 GeV - 11.8 GeV) upto $t = 1.4\ GeV^2$

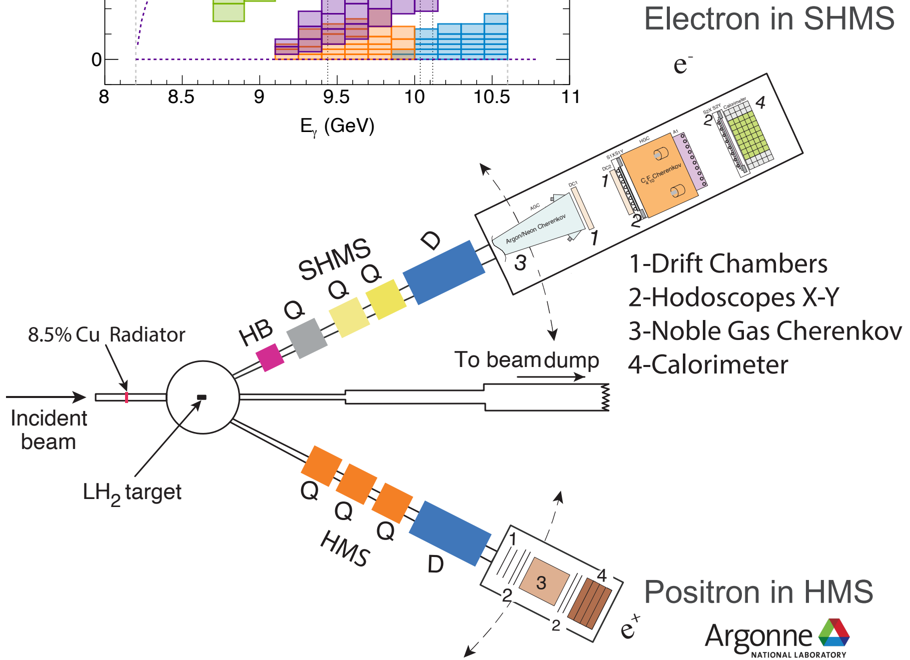




J/Ψ-007 EXPERIMENTAL LAYOUT

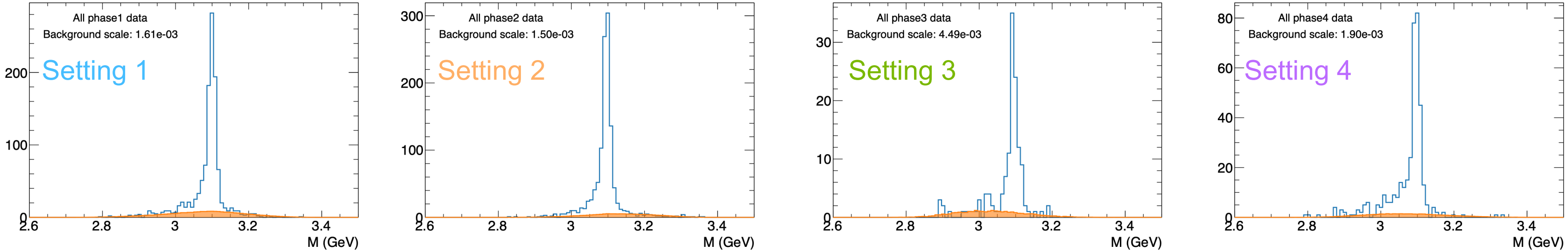
- E12-06-007 (J/Ψ-007) measured exclusive J/Ψ photoproduction cross section as a function of photon energy E_γ and t (the momentum transfer from initial photon to the produced J/Ψ)
  - Scanned photon beam energy E_γ from 9.1 to 10.6 GeV and |t| up to 4.5 GeV^2.
  - High intensity real photon beam generated 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^- produced in coincidence from decay of J/Ψ.





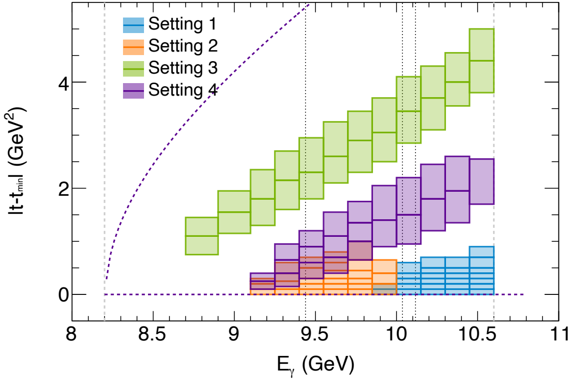
SPECTROMETER SETTINGS

Optimized for accessing broad range of t



Clear J/Ψ signal with minimal background

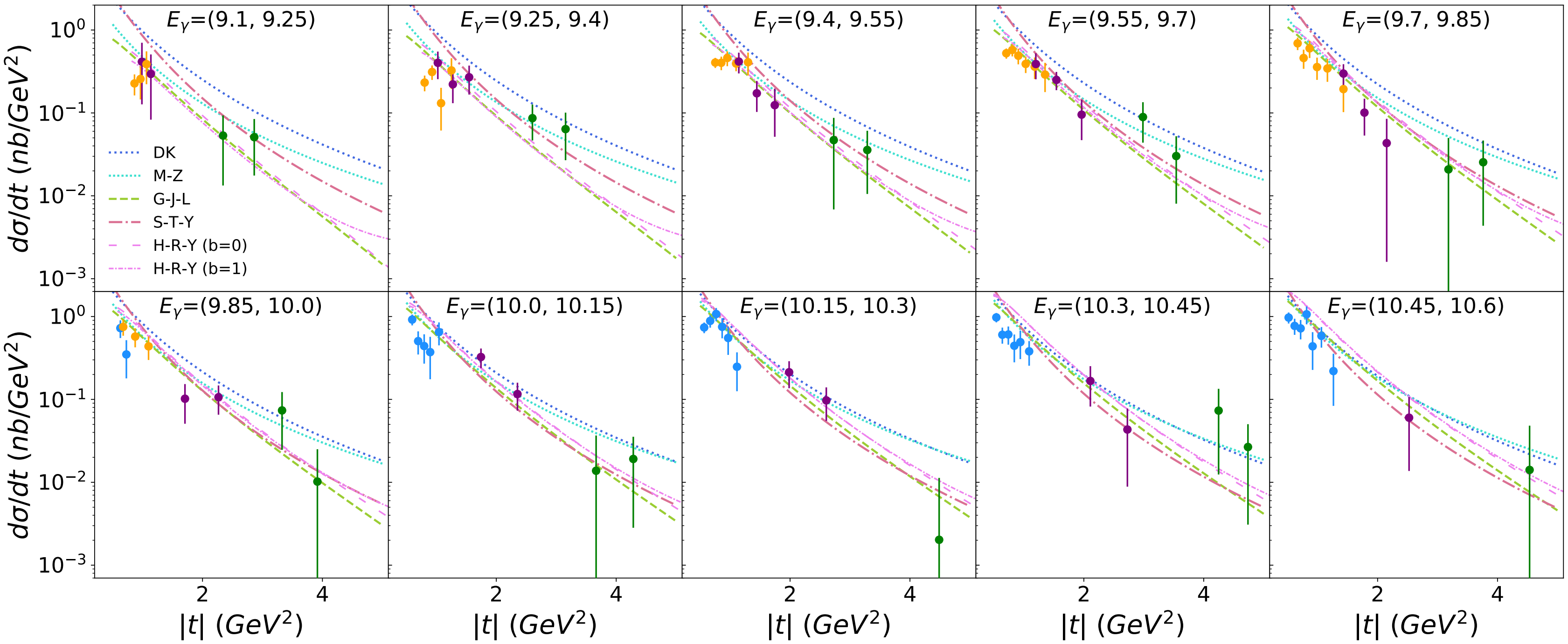
	SHMS		HMS		
Settings	p (GeV)	θ(deg.)	p (GeV)	θ (deg.)	
1	4.8	17	4.95	19.1	high E/ low t
2	4.3	20.1	4.6	19.9	mid E/ low t
3	3.5	30	4.08	16.4	high t
4	4.4	24.5	4.4	16.6	mid t



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

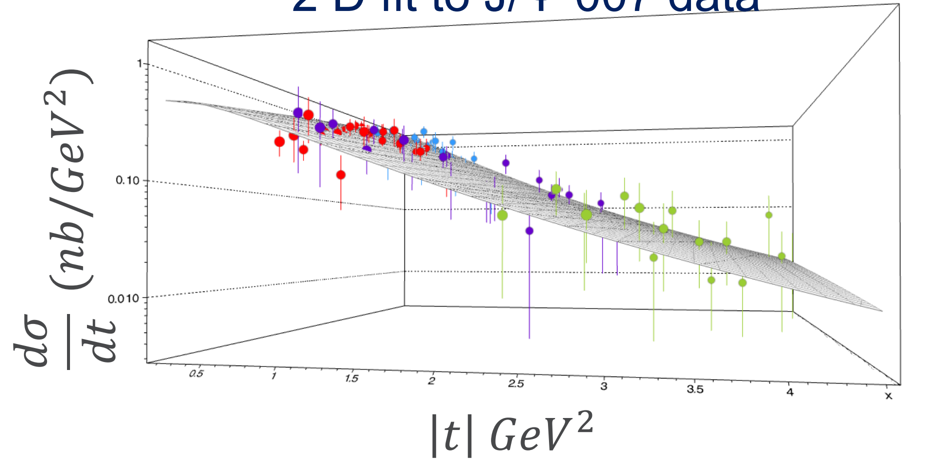
- Used two different approaches to perform extraction
  - Holographic approach : (Mamo, K. A. & Zahed, I. Phys. Rev. D 103, 094010)
  - GPD approach : (Guo, Y., Ji, X. & Liu, Y. Phys. Rev. D 103, 096010)

- Two form factors (tripole form) considered. Contribution from $B_g(t)$ is assumed to be negligible

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

- Fixed $A_g(0)$ to $\langle x_g \rangle$ → from CT18 global fit.
  - m_A, $C_g(0)$ and m_C determined from fits

2 D fit to J/Ψ 007 data

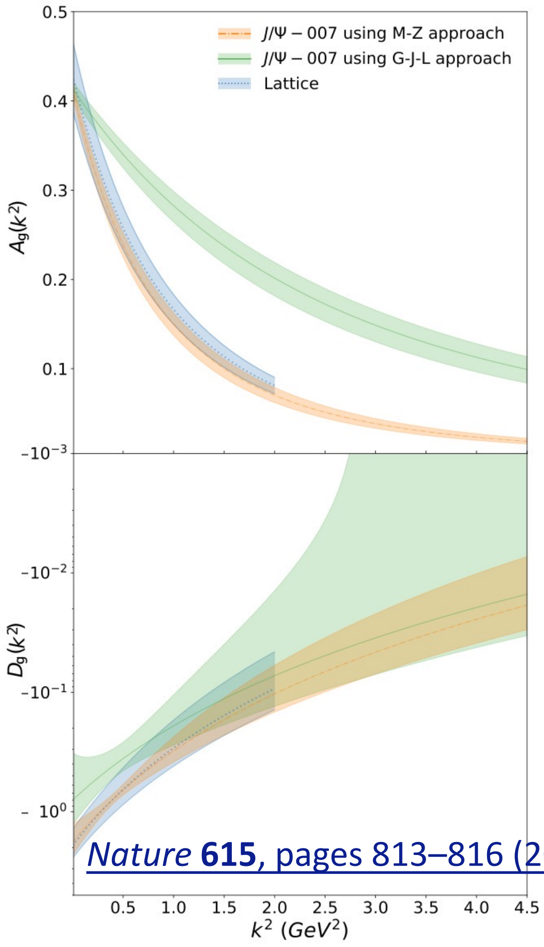


GLUON FORM FACTORS

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 103, 094010)
  - 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)

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

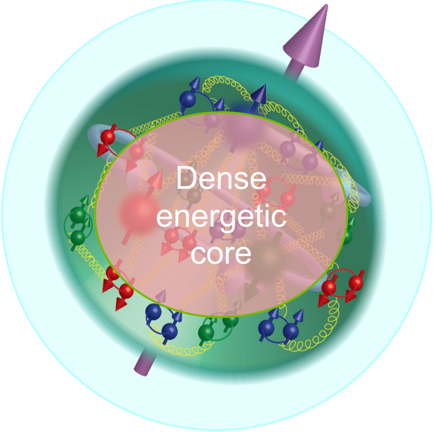


Nature **615**, pages 813–816 (2023)

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



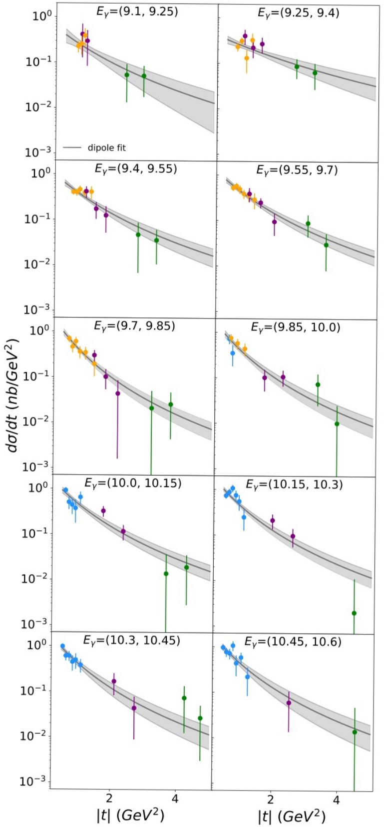
$$\langle r_m^2 \rangle = 6 \frac{1}{A(0)} \frac{dA(t)}{dt}\bigg|_{t=0} - 6 \frac{1}{A(0)} \frac{C(0)}{M_N^2}$$

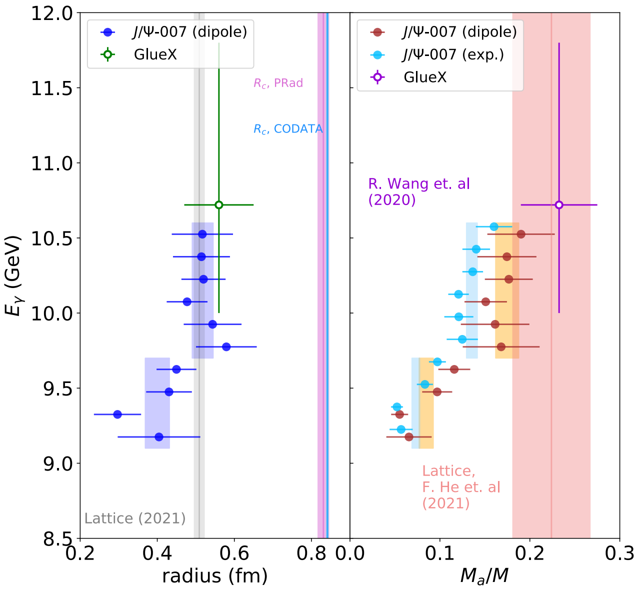
$$\langle r_s^2 \rangle = 6 \frac{1}{A(0)} \frac{dA(t)}{dt}\bigg|_{t=0} - 18 \frac{1}{A(0)} \frac{C(0)}{M_N^2}$$

- 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)

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)

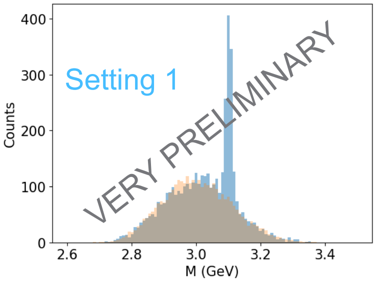
$$\langle r_m^2\rangle = \frac{6}{M}\frac{dG}{dt}\bigg|_{t=0} = \frac{12}{m_s^2}$$

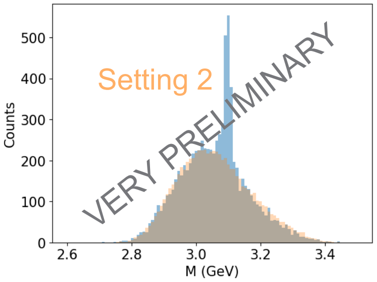
- Flat region at higher energies beyond $E_\gamma = 9.7\ GeV$.
- Good agreement with lattice in high energy region.
- $\sqrt{\langle r_m^2\rangle} = 0.52 \pm 0.03$ fm
- $M_a/M = 0.175 \pm 0.013$

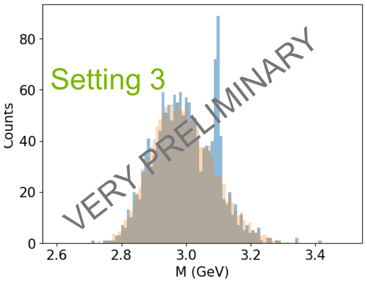
Nature **615**, pages 813–816 (2023)

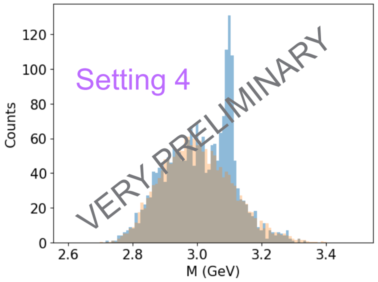
MUON CHANNEL DATA

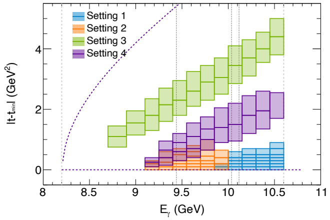
Analysis cuts optimized to select muons











Clearly see J/Ψ peak!!
Comparable statistics with electron channel data

	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

- Setting 1: sweet spot for Cerenkov threshold. π's do not radiate and μ's do.
- Using Setting 1 data to optimize the calorimeter cuts to distinguish between π and μ.
- Exploring ML techniques to distinguish between π and μ.
- Independent cross check of cross sections determined from electron channel data

SUMMARY

- J/Ψ 007 measured for the first time 2D cross section at threshold
  - Upto $t = 4.5\ GeV^2$
  - E_γ range from 9.1 to 10.6 GeV in 150 MeV bins
- Extracted GFF using two approaches
  - Holographic QCD
  - GPD
- While model dependent, preliminary results on radii extracted from the J/Ψ 007 experiment data show that mass radii is smaller than charge radius.
  - Dense energetic core
- Results published in Nature: *Nature* **615**, pages 813–816 (2023)
- Muon data (~2k events) are currently being analyzed.

THANK YOU

QUESTIONS?

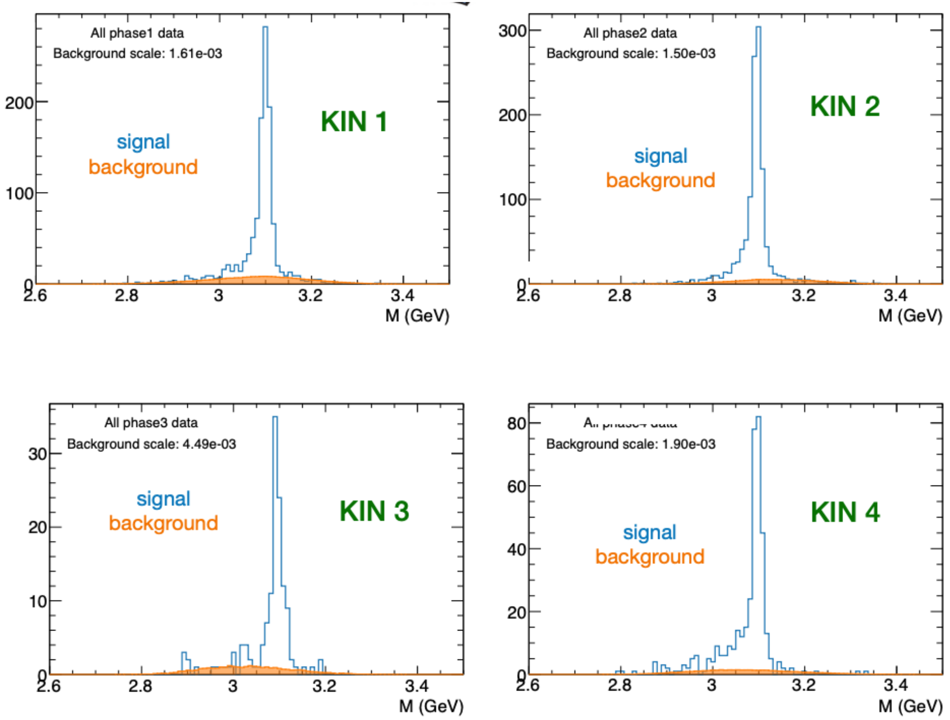
BACKGROUND CONTRIBUTION

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.

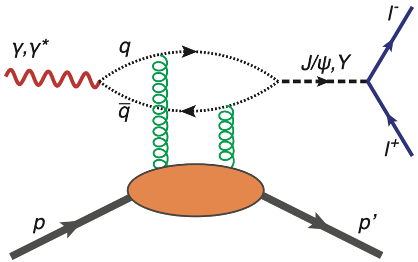
BG Event Selection:

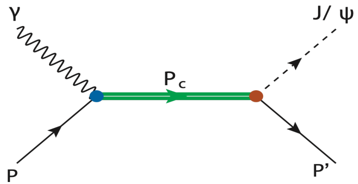
- Coincidence $e^-\pi^+$ background selected using electron PID in the SHMS and pions in the HMS.
  - **electrons:** Calorimeter
  - **pions:** Calorimeter + Cherenkov



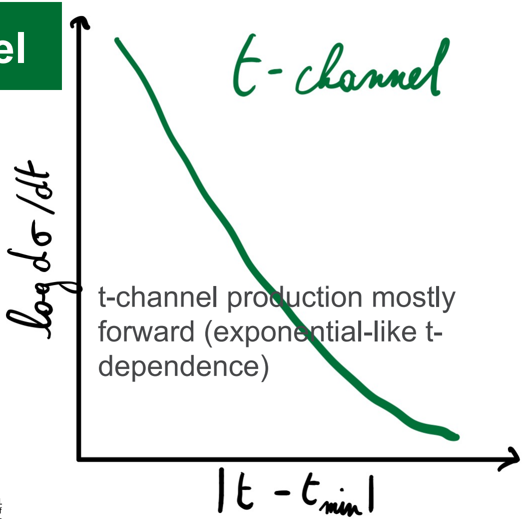
- Fit BG shape to the sidebands of the signal to obtain the BG scale.

SENSITIVITY TO T AND S CHANNEL

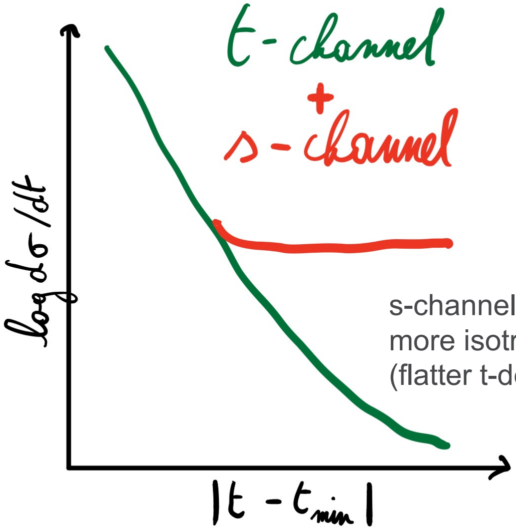




t-channel



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



s-channel

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