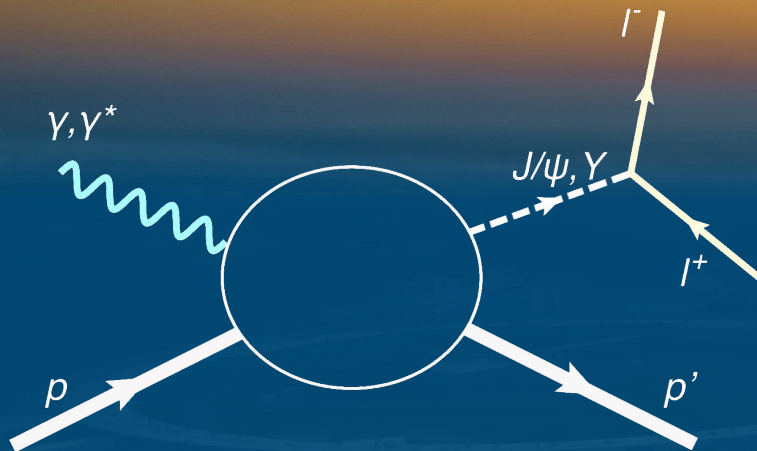
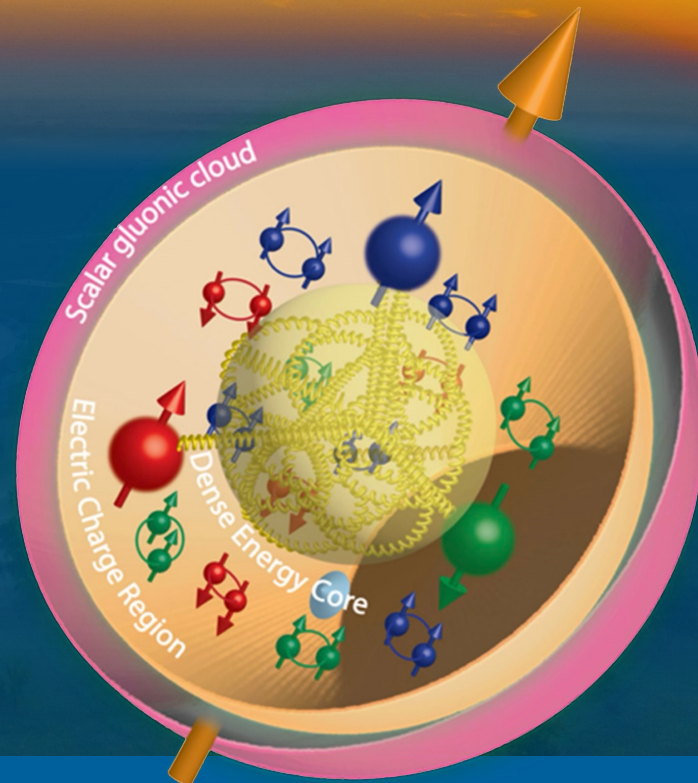




Charmonium in Hall A & C



Sylvester Joosten

007^{J/ψ} *007_{≡II}^{J/ψ}*

High-Luminosity Workshop
October 6, 2026, Jefferson Lab



U.S. DEPARTMENT
of ENERGY

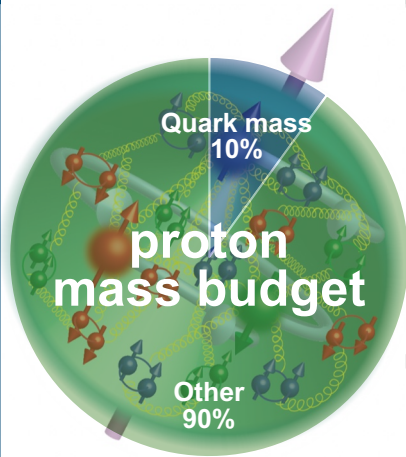
This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.



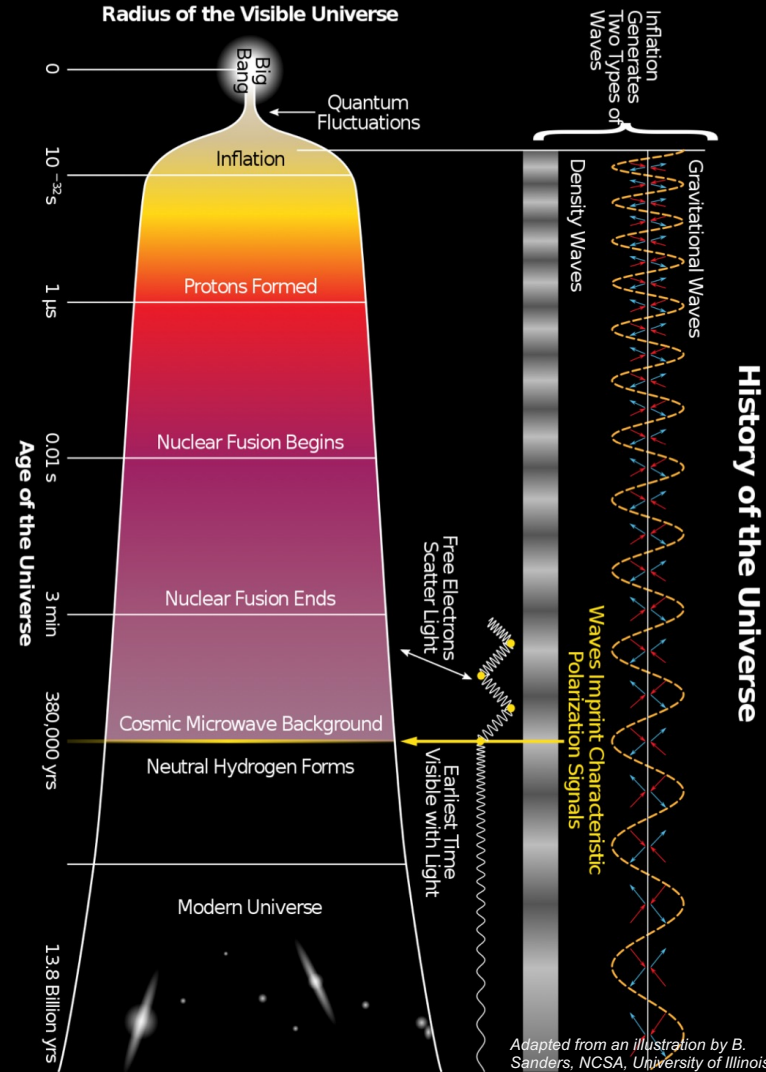
Argonne
NATIONAL LABORATORY

QCD in the Standard Model

The emergence of the proton



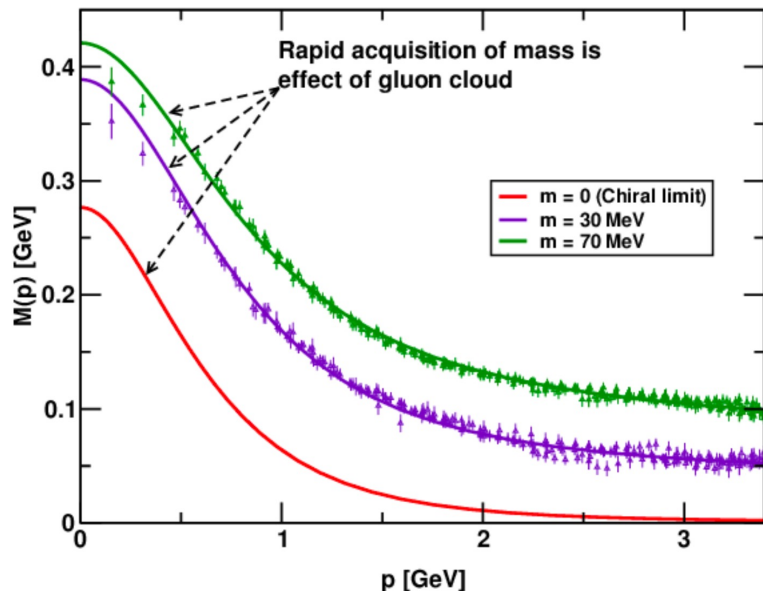
- Since the formation of protons and neutrons, most of the mass of the visible universe encapsulated in protons, neutrons, and nuclei.
 - Surprising: nucleon mass much larger than sum of quark masses.
-
- *How does QCD give rise to the 1GeV proton?*
 - *How is the proton mass distributed in its confinement size?*



Adapted from an illustration by B. Sanders, NCSA, University of Illinois

Proton mass is an emergent phenomenon

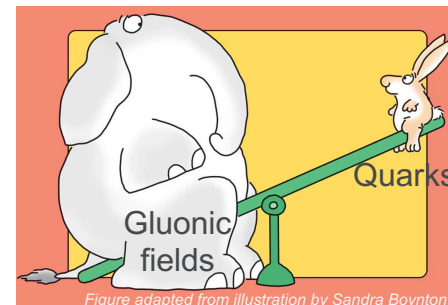
The Strong Interaction itself generates the proton mass!



M. S. Bhagwat et al., Phys. Rev. C 68, 015203 (2003)
I. C. Cloet et al., Prog. Part. Nucl. Phys. 77, 1-69 (2014)

Most of the proton mass originates in the energy enclosed in the gluonic fields of the Strong Interaction itself

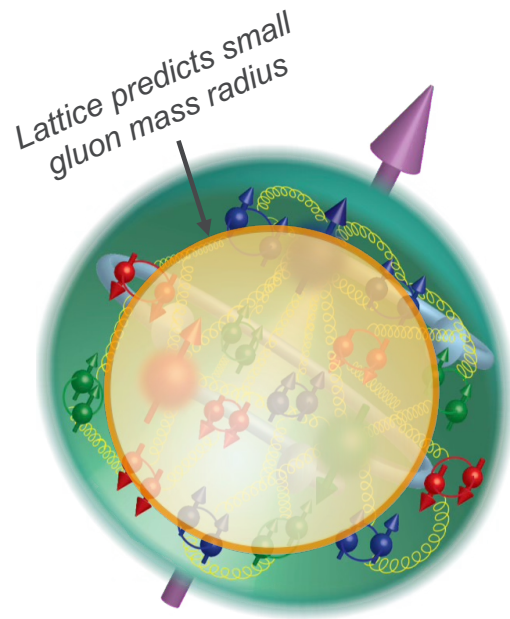
$$E = mc^2$$



Bottom line: The Higgs mechanism seems largely irrelevant for most of “normal” visible matter!

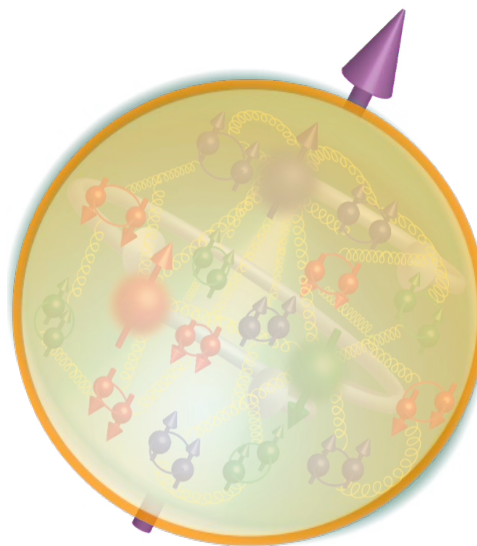
What Is the Size of a Proton?

And how should we define this in the first place?



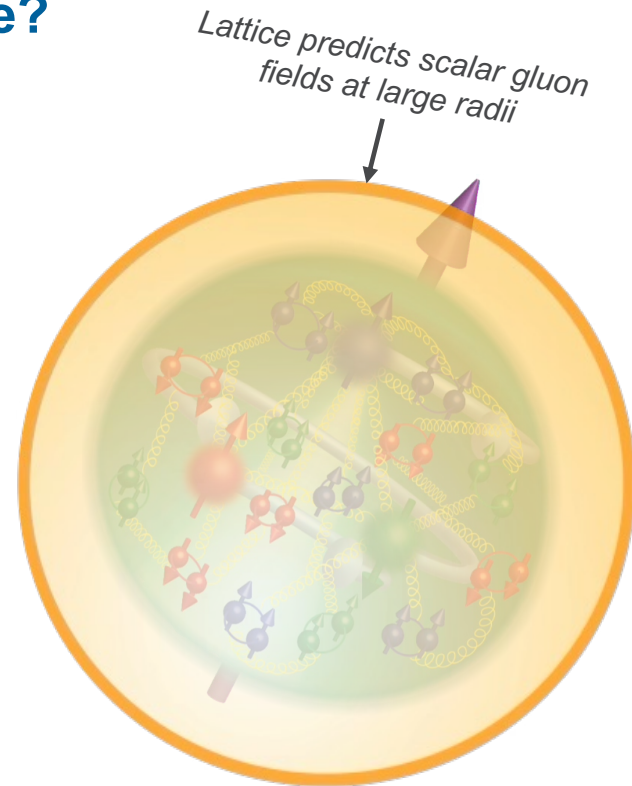
Dense energy core?

VS



Same as charge radius?

VS



Energy halo beyond charge radius?

How do we measure
the structure of
nucleons and nuclei
beyond electric
charge?

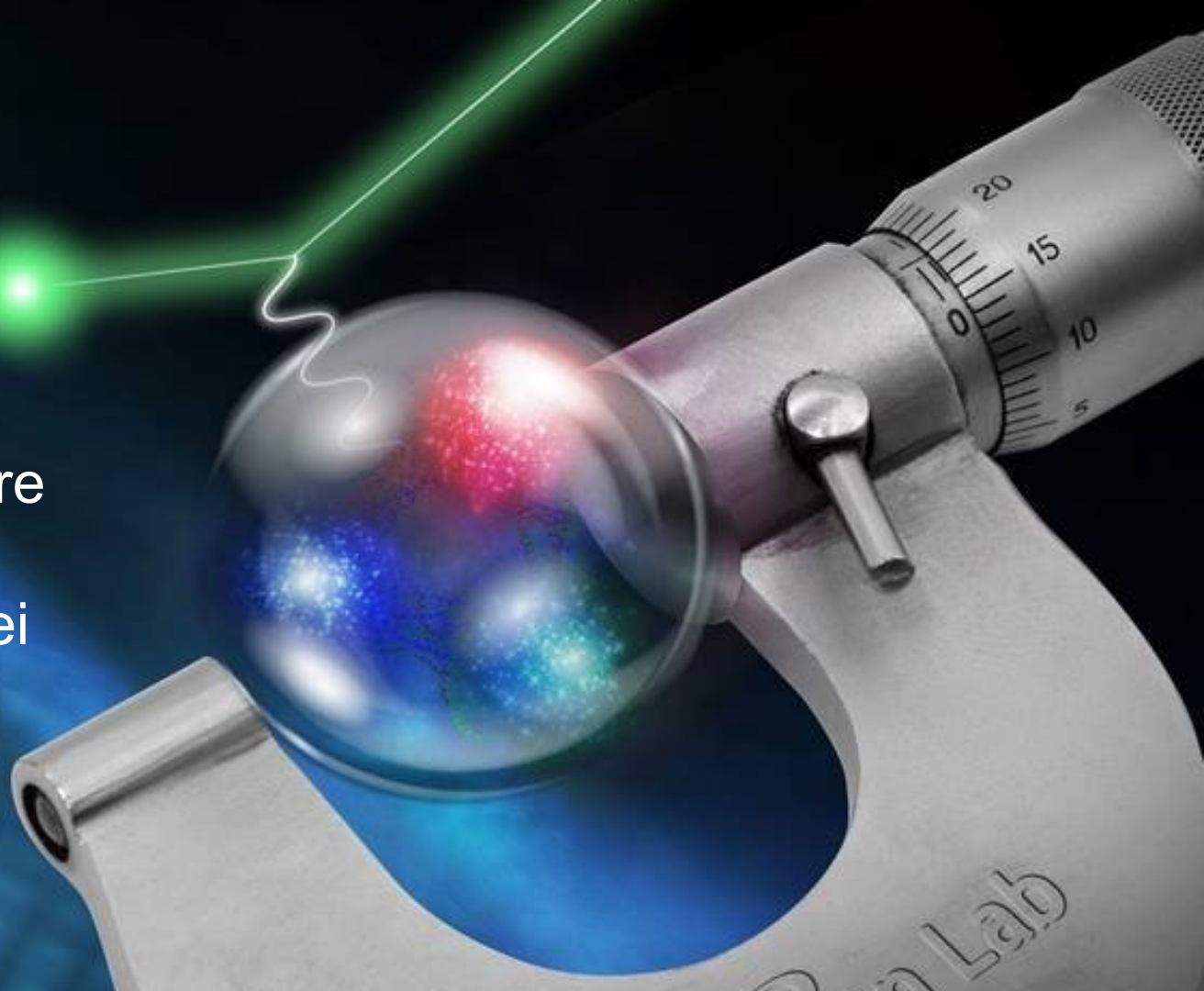
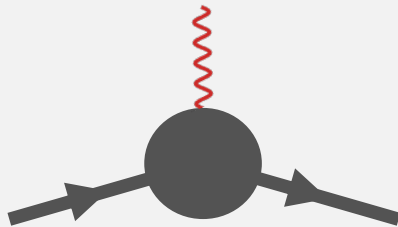


Figure courtesy of Jefferson Lab

Gravitational Form Factors (GFFs)

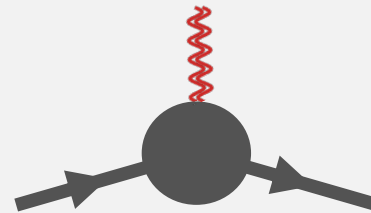
Electromagnetic FFs



$$\langle N' | J^\mu | N \rangle = \bar{u}(N') \left(F_1(Q^2) \gamma^\mu + \frac{i\sigma^{\mu\nu} q_\nu}{2M} F_2(Q^2) \right) u(N)$$

- EM FFs are the matrix elements of the electromagnetic current operator
- Map the charge and magnetization distribution in the proton

Gravitational FFs



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

- GFFs parametrize the matrix elements of the QCD energy-momentum tensor (EMT) for quarks and gluons
- Reveal the distribution of mechanical properties of quarks and gluons in the proton, e.g. mass, forces experienced by the quarks, ...

How To Measure the Gluon GFFs?

Gluons are elusive!

- Cannot use Electromagnetic probe: primarily couples to quarks
- Cannot use Weak probe: also primarily couples to quarks
- Cannot use hadronic probe made of light quarks: primarily sensitive to quark structure
- Cannot use direct gravitational probe: interaction too weak

- Small “color” dipole made of heavy quarks may be well-suited to study gluons

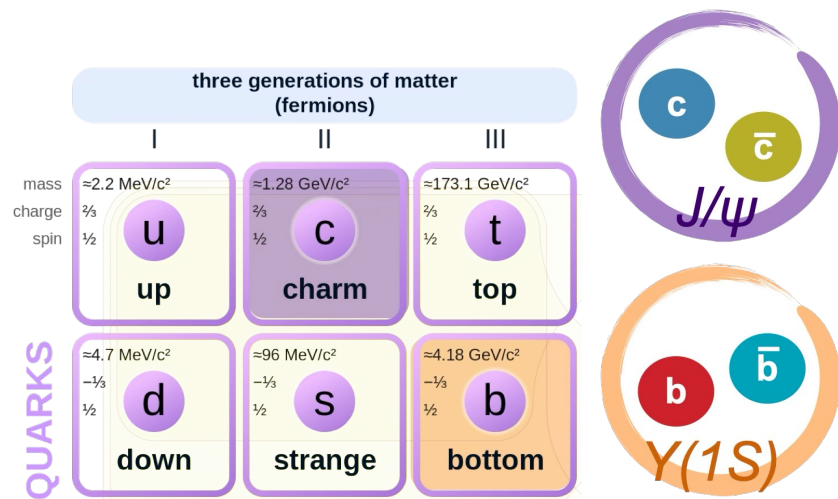


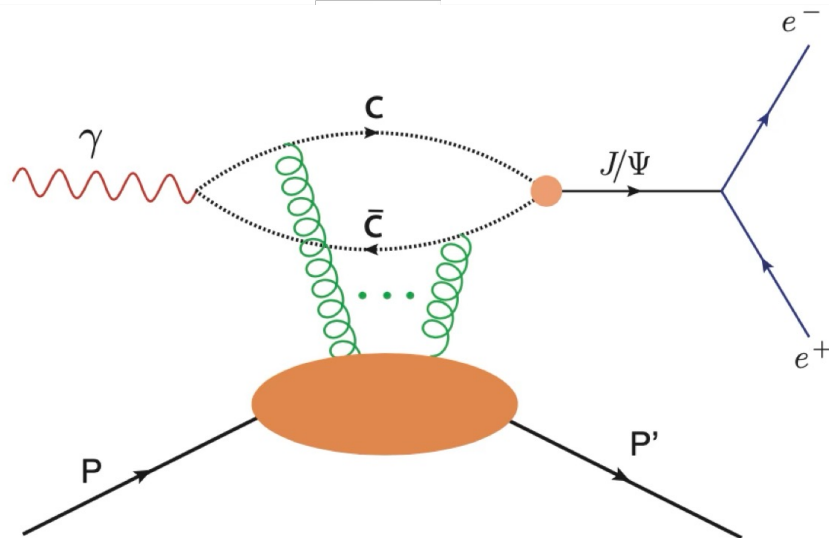
Figure adapted from [Wikipedia](#)

How To Measure the Gluon GFFs?

Gluons are elusive!

❖ Cannot use Electromagnetic probe:
primarily couples to quarks

● Small “color” dipole made of
heavy quarks may be well-suited to



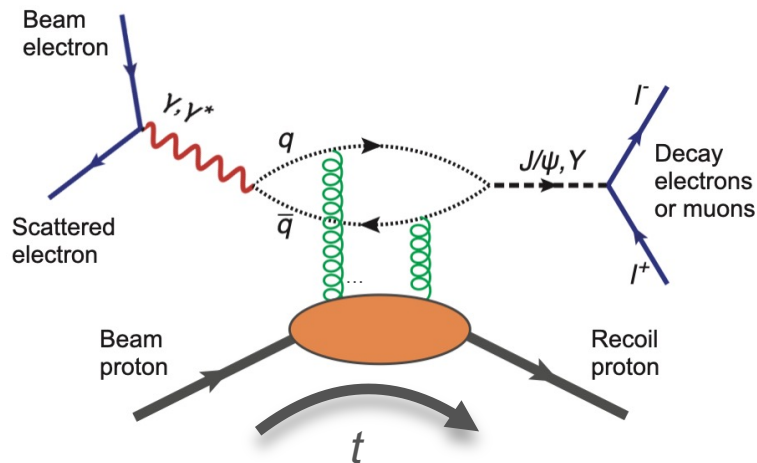
Use quarkonium photoproduction as
stand-in for elastic quarkonium scattering

Gravitational form factors constrained by
near-threshold exclusive J/ψ and Y
photoproduction

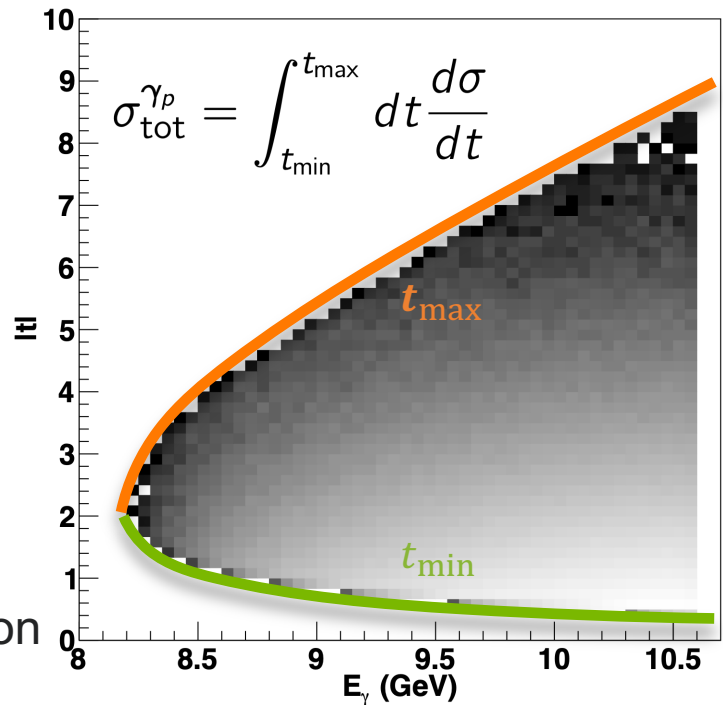
Beyond GFFs: 3D gluonic structure of
nucleons and nuclei constrained by
exclusive J/ψ and Y

Exclusive Quarkonium Photoproduction

Kinematics



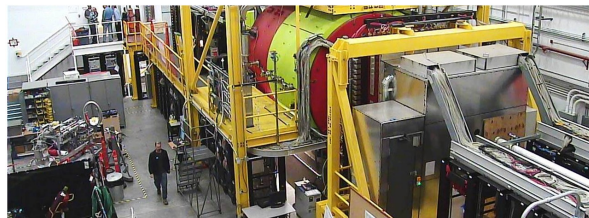
- Phase space limits bound by quarkonium direction
 - Forward (with photon): $t = t_{\min}$
 - Backward (with proton): $t = t_{\max}$
- Forward direction preferred
 - $|t|$ -dependence falls rapidly (exponential-like)



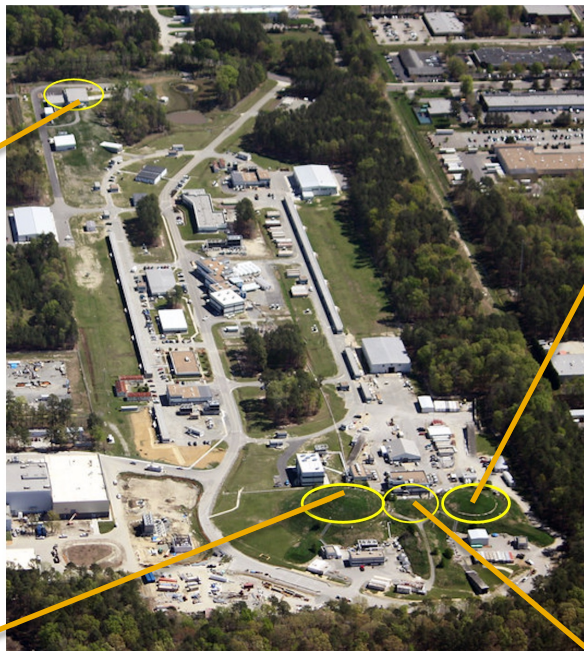
J/ψ threshold:
 $W \approx 4.04 \text{ GeV}$
 $E_{\gamma}^{\text{lab}} \approx 8.2 \text{ GeV}$

$Y(1S)$ threshold:
 $W \approx 10.4 \text{ GeV}$

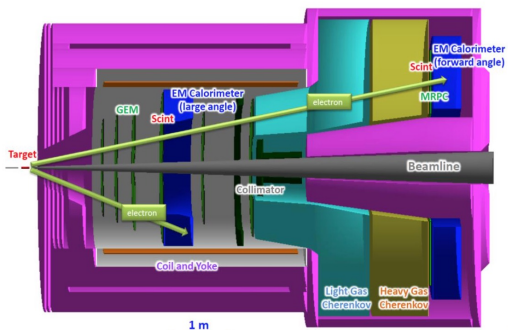
12 GeV J/ψ Experiments at Jefferson Lab



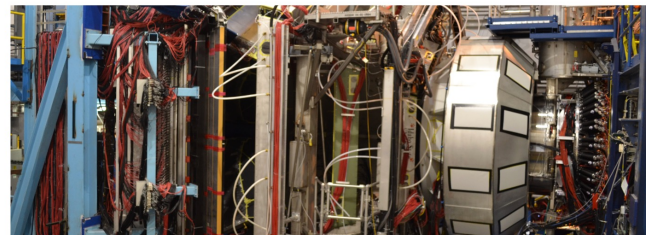
Hall D: GlueX
See Lubomir's talk



Hall C: J/ψ-007 and J/ψ-007-II
This talk



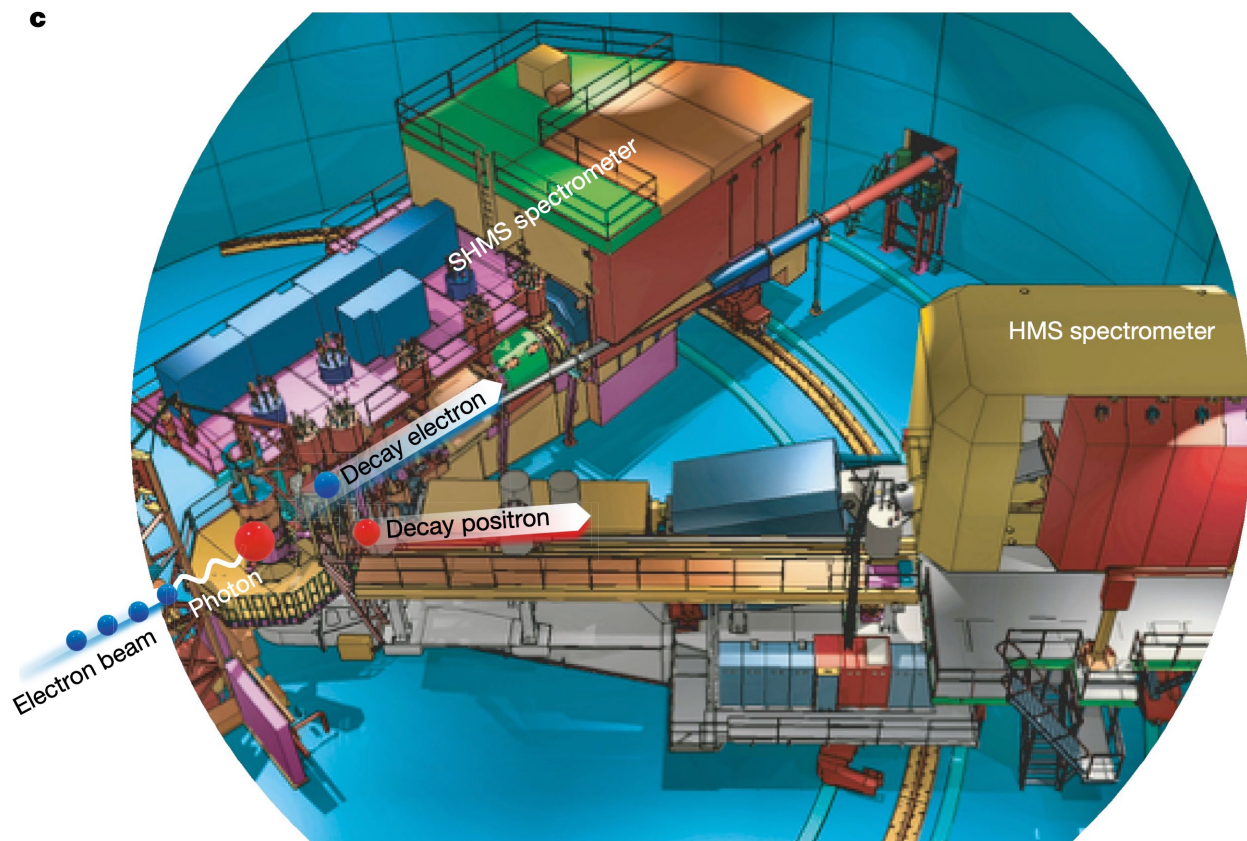
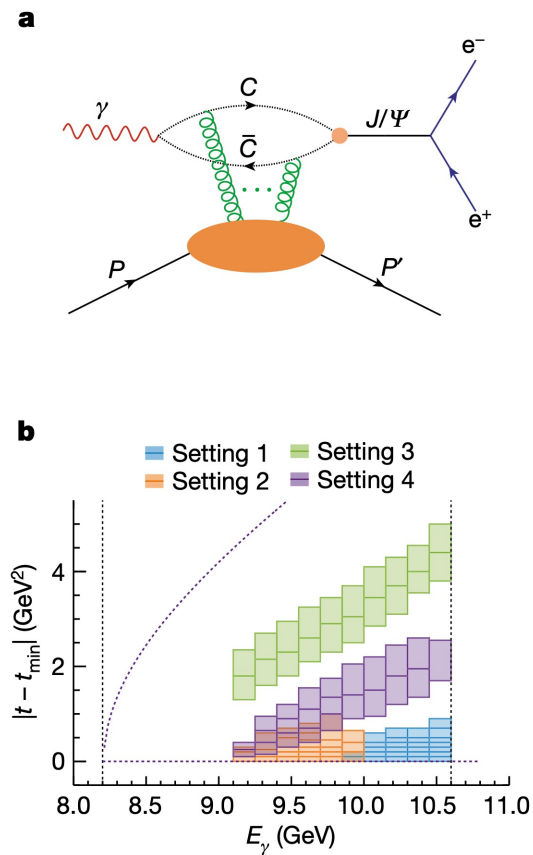
Hall A: SoLID & (not) SoLID-lite
This talk



Hall B: CLAS12 & μCLAS
See Pierre's talk

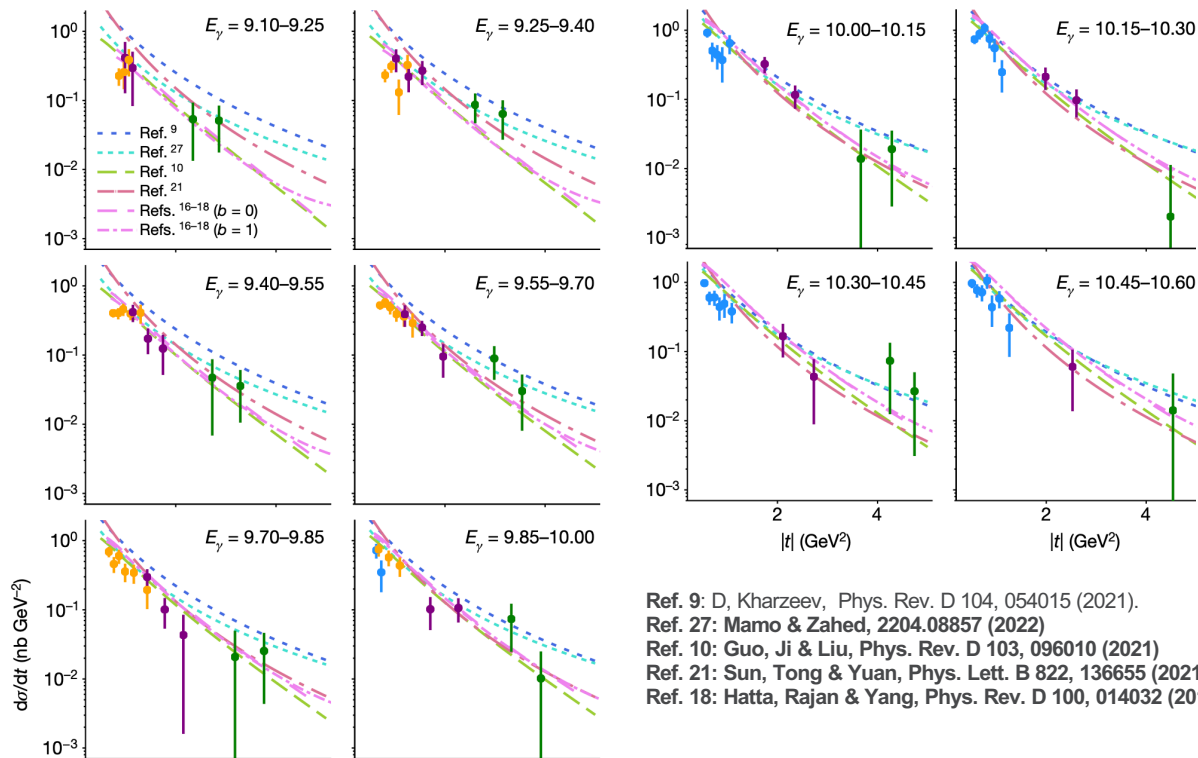
J/ ψ -007 (E12-16-007) in Hall C at JLab

The original high-luminosity J/ ψ experiment.



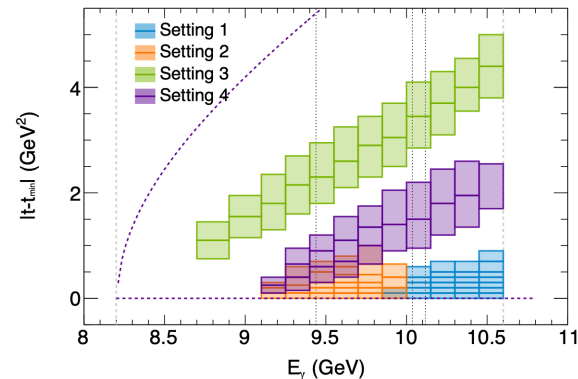
2-D J/ ψ cross sections near threshold

First results published in Nature in 2023

007^{J/ ψ} 

4% scale uncertainty

Ref. 9: D. Kharzeev, *Phys. Rev. D* 104, 054015 (2021).
Ref. 27: Mamo & Zahed, 2204.08857 (2022)
Ref. 10: Guo, Ji & Liu, *Phys. Rev. D* 103, 096010 (2021)
Ref. 21: Sun, Tong & Yuan, *Phys. Lett. B* 822, 136655 (2021)
Ref. 18: Hatta, Rajan & Yang, *Phys. Rev. D* 100, 014032 (2019)



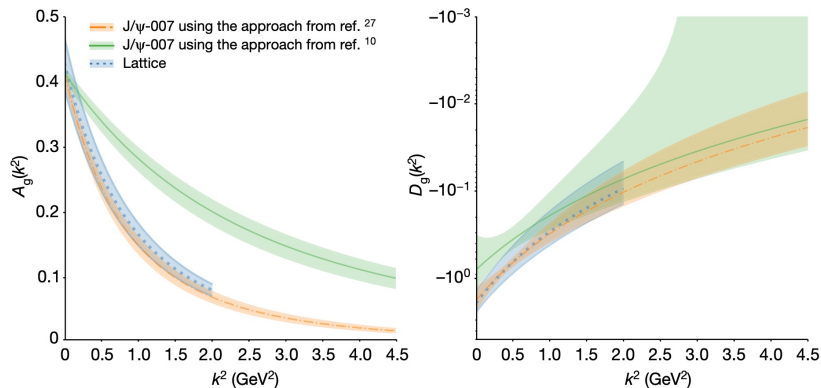
Unfolded 2D cross section results
compared to various model predictions
informed by the 2019 1D GlueX results

All models work reasonably well at higher
energies but deviate at lower energies

First Gluonic GFFs from Experimental Data

 $007^{J/\psi}$

Remarkable agreement between GFFs from data using the Holographic approach and Lattice QCD calculations!



Determined from experiment

Holographic QCD approach
GPD approach

Determined from theory

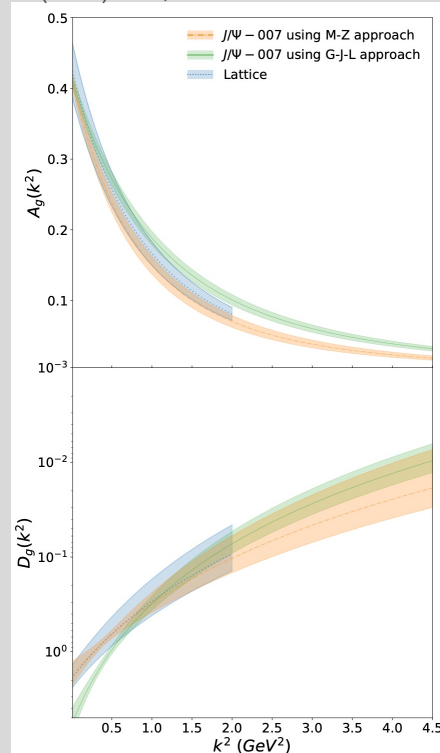
Lattice QCD calculation

Ref 27 (Holographic QCD): K. Mamo & I. Zahed, PRD 103, 094010 (2021) and 2204.08857 (2022)

Ref 10 (GPD Formalism): Y. Guo, X. Ji, Y. Liu, PRD 103, 096010 (2021)

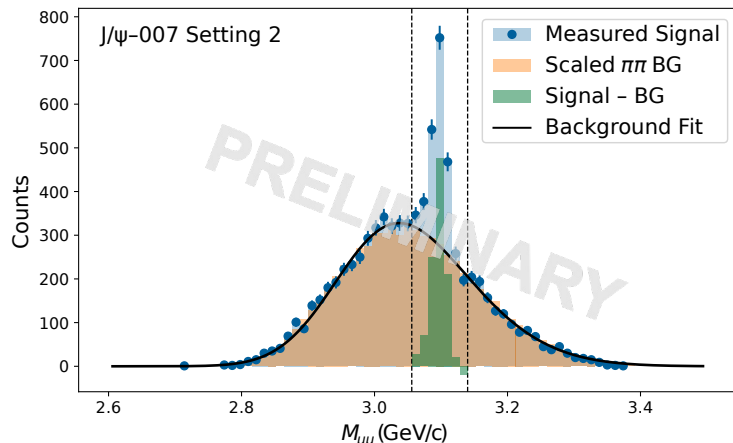
Lattice: D. Pefkou, D. Hackett, P. Shanahan, Phys. Rev. D 105, 054509 (2022).

Update of G-J-L analysis PRD 108
(2023) no.3, 034003 arXiv:2305.06992

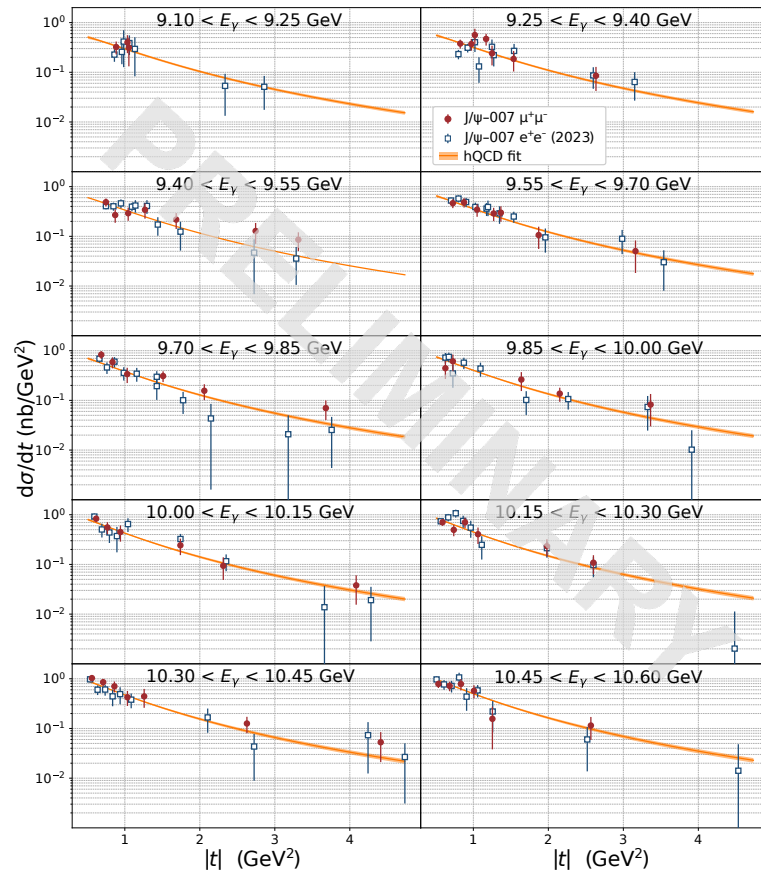


New results from J/ψ-007

Di-muon channel cross section

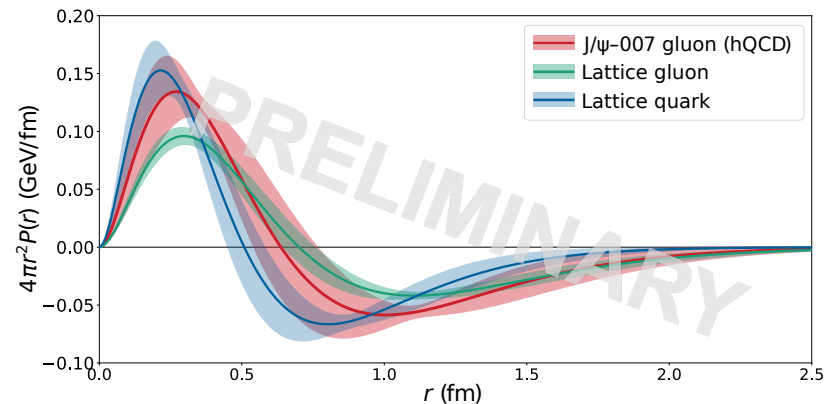
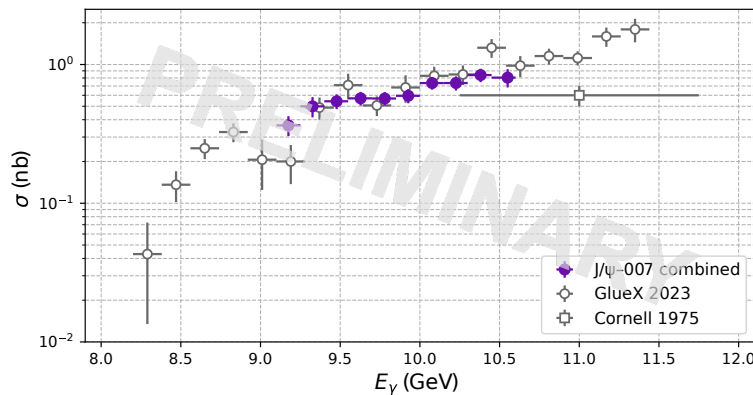
007^{J/ψ}

- Near-threshold J/ψ di-muon channel photoproduction cross section
- Results double the available statistics from J/ψ-007
 - Both dataset in excellent agreement
- Manuscript under peer review



New results from J/ψ-007

Integrated cross section and gluonic pressure

007^{J/ψ}

- Integrated cross section through fit of the t-dependence of combined J/ψ-007 data
 - Consistent with GlueX 2023 results
 - No evidence of fluctuations indicative of open-charm contributions
- **Manuscript under peer review**

- Combined analysis of both J/ψ-007 datasets improves constraint on the C GFF
 - Demonstrate increased precision by extracting gluonic pressure
- Compared to Lattice results
 - Quarks seem to dominate at smaller radii, while gluons dominate at larger radii

Future Plans for Charmonium in Hall A+C

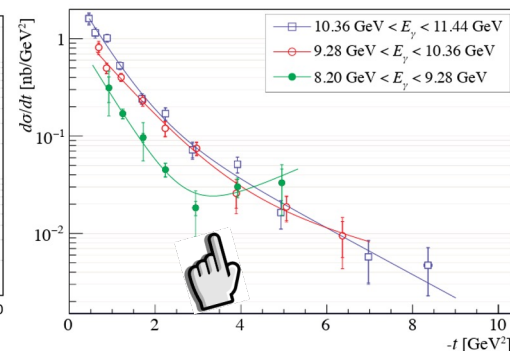
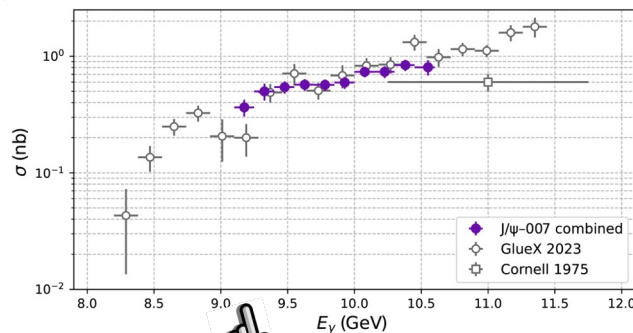
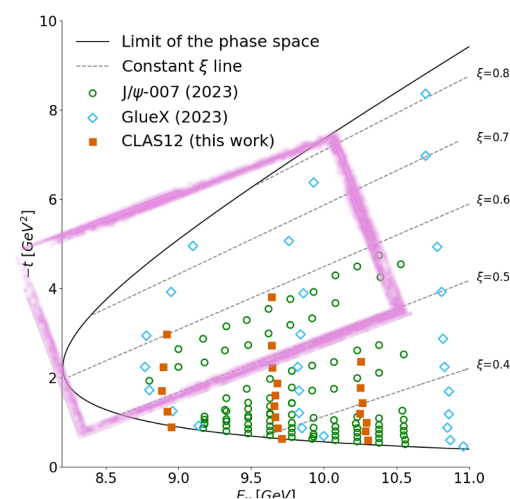
J/ ψ -007-II in Hall C

Let's focus on the high- t region

- World data lacks precise measurements at large $|t|$ and high $\xi > 0.5$
 - More constraint on theoretical assumptions
 - Better GFF extractions (e.g. 4-5x better uncertainty on C_g with holographic QCD fit)
 - Sensitive to signatures u-channel onset and open charm production

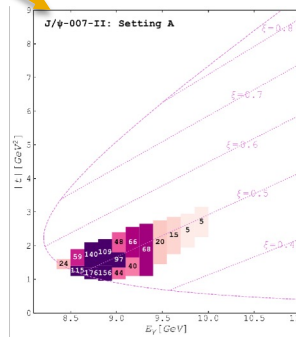
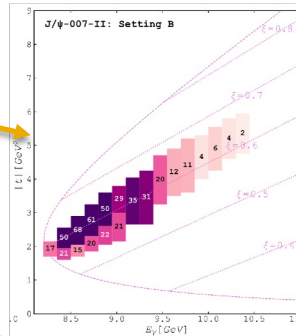
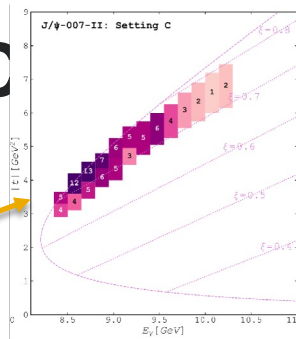
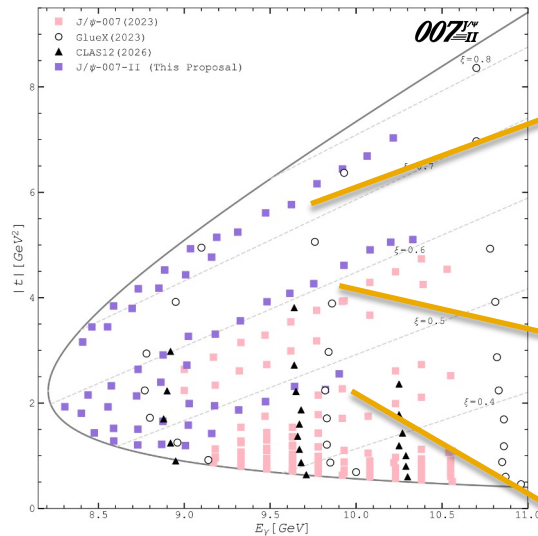
007^{J/ ψ} _{II}

Chatagnon et al (CLAS12), PRC (2026), arXiv:2602.22128

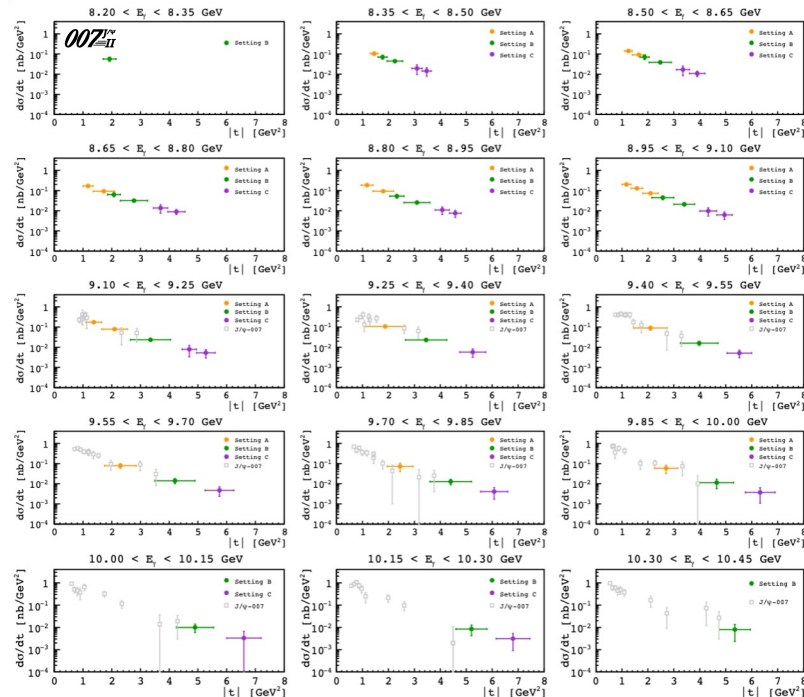


J/ψ-007-II in Hall C

007^{J/ψ}_{II}



- Same J/ψ-007 setup: 11 GeV, 50 μA, 9% Cu radiator, 15 cm LH₂ for 27 days
- Leverages the high luminosity in Hall C to zoom in on a hard-to-measure kinematic region

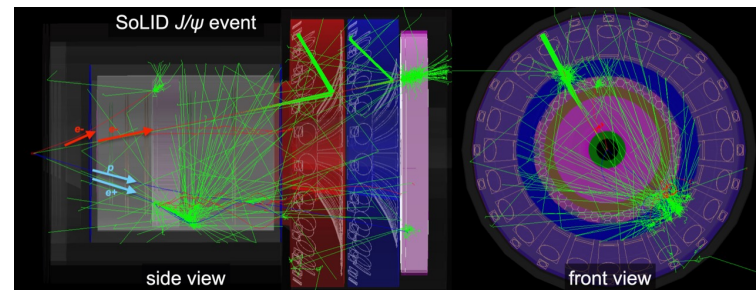
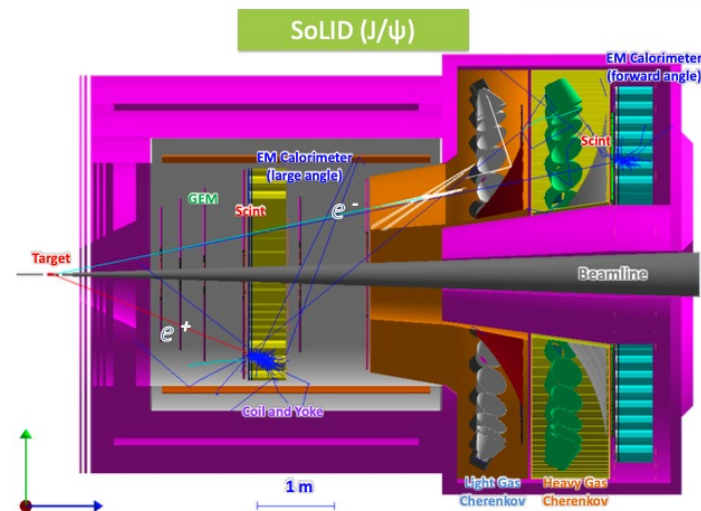


Approved by PAC54 with A-

SoLID—J/ ψ in Hall A

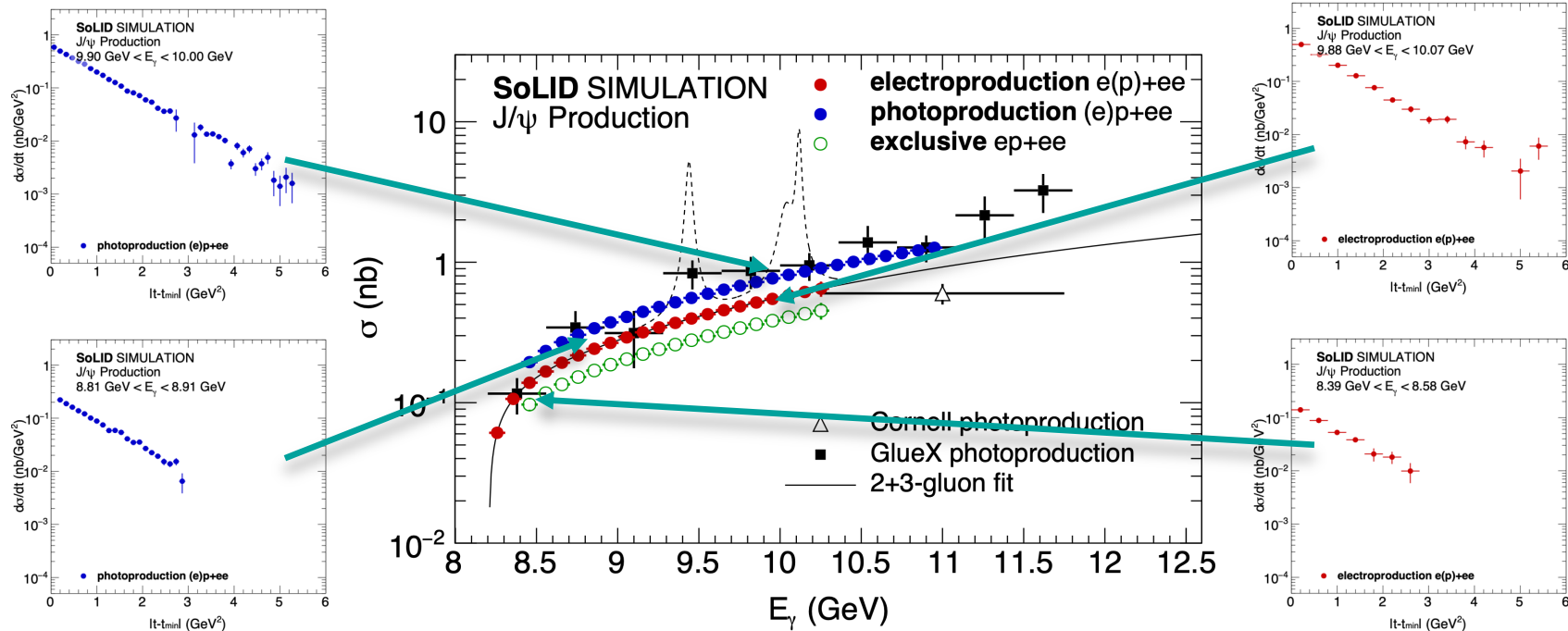
Ultimate factory for near-threshold J/ ψ

- General purpose large-acceptance spectrometer
- 50+10 days of 3 μA beam on a 15 cm long LH2 target ($10^{37}/\text{cm}^2/\text{s}$)
- **Ultra-high luminosity:** 43.2 ab^{-1}
- **Open 2-particle trigger**, covering J/ ψ production in four channels:
Electroproduction (e, e^-e^+), photoproduction (p, e^-e^+),
inclusive (e^-e^+), exclusive (ep, e^-e^+)
- The electroproduction channel provides for a modest lever-arm in Q^2 near threshold



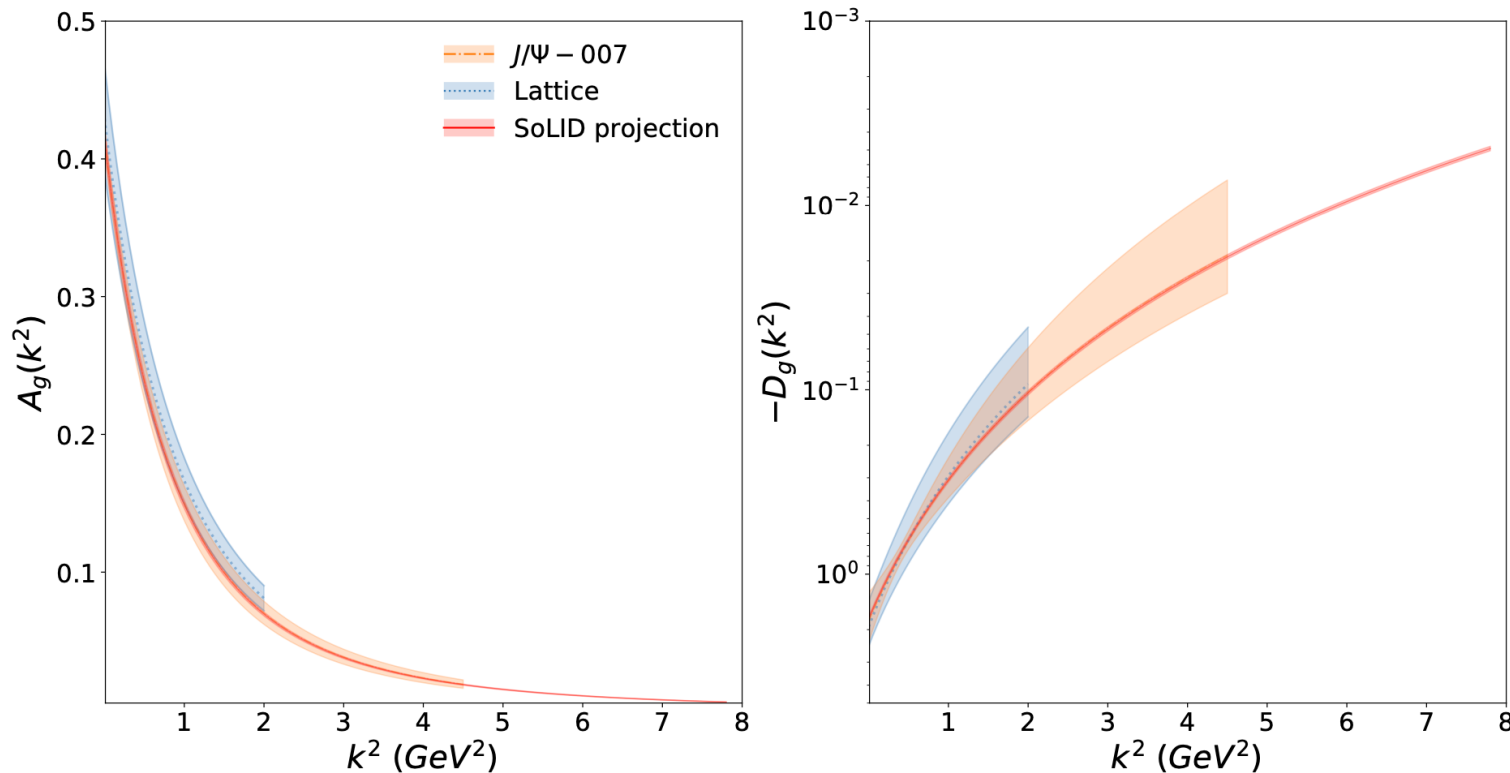
Future: SoLID-J/ ψ in Hall A

High-precision 2-D cross section crucial to really connect GFFs to data



SoLID Projected Impact on gluon GFFs

Comparison with J/ψ-007 (Holographic QCD approach) and Lattice



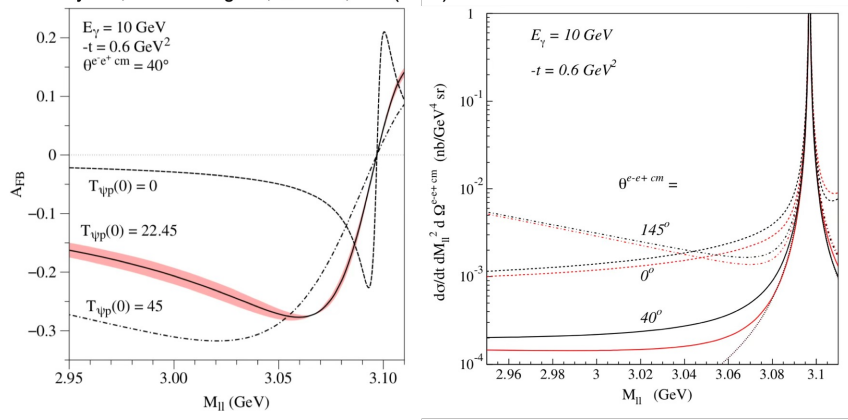
B. Duran, et al., proton, *Nature* **615**, no.7954, 813-816 (2023)

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

Other J/ψ Observables with SoLID?

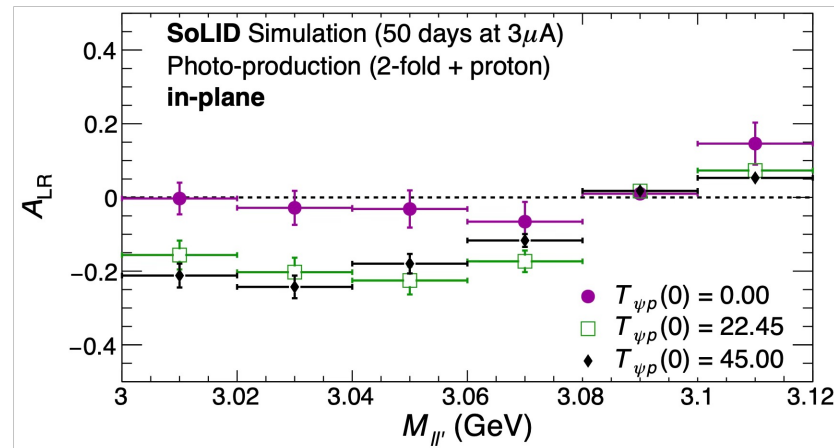
Gryniuk, Vanderhaeghen, PRD 94, 105 (2016)



- Node at J/ψ peak: need to be outside of peak
- Cross section very low within typical experimental acceptance

$$A_{FB} \equiv \frac{d\sigma(\theta^{e^-e^+cm}) - d\sigma(\theta^{e^-e^+cm} - 180^\circ)}{d\sigma(\theta^{e^-e^+cm}) + d\sigma(\theta^{e^-e^+cm} - 180^\circ)}$$

- e.g.: SoLID sensitive to interference with Bethe Heitler pair production near the J/ψ peak
- Should further develop other observables, e.g., polarization observables, that can help further develop our theoretical understanding.

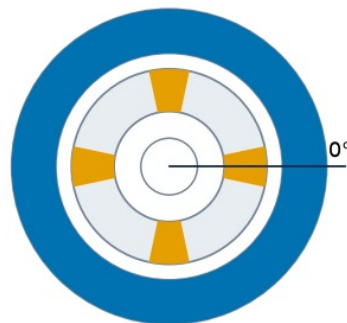


- Translates into left-right asymmetry that is experimentally better defined

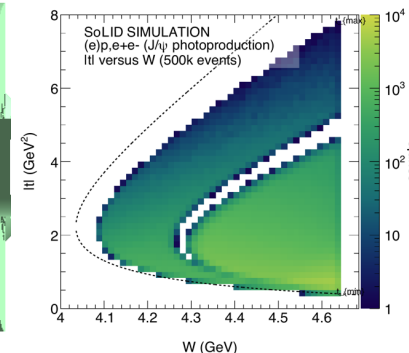
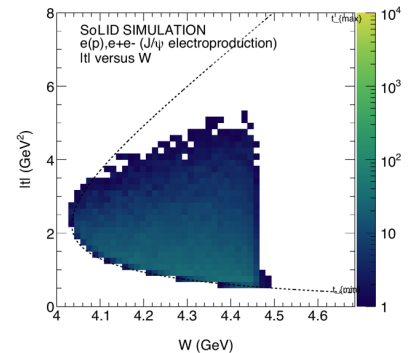
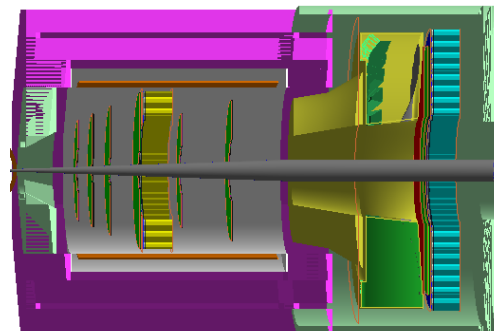
“SoLID–Lite”

What could we do with a partial SoLID-like setup?

- A “SoLID–Lite” detector can use a simplified SoLID-like design to deliver on the flagship J/ψ photoproduction results
- Example:
 - 4 x 24 degree sectors in the forward direction with single Cherenkov and calorimeter
 - Full wide-angle detector (with recycled ECAL)
 - Double luminosity (possible with lower total number of channels)
 - 50+10 days of 6 μ A beam on a 15cm long LH2 target ($2 \times 10^{37}/\text{cm}^2/\text{s}$)
 - Ultra-high luminosity: 86.4 ab^{-1}
- Proof-of-concept: Other configurations and optimizations still being explored



WA full ϕ | FA $4 \times 24^\circ$



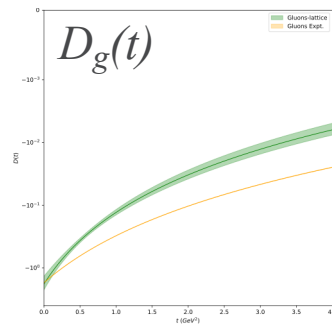
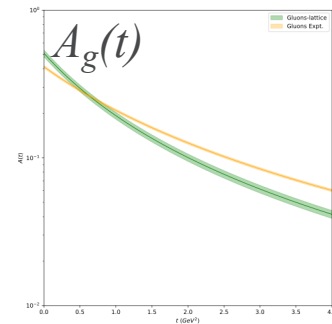
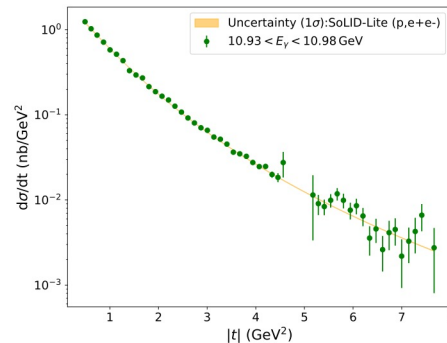
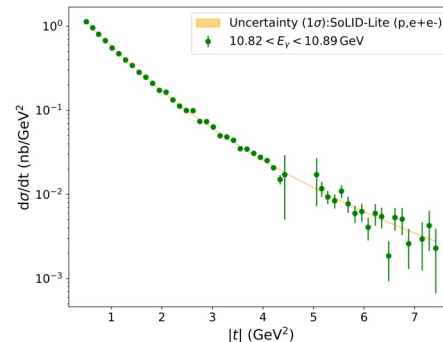
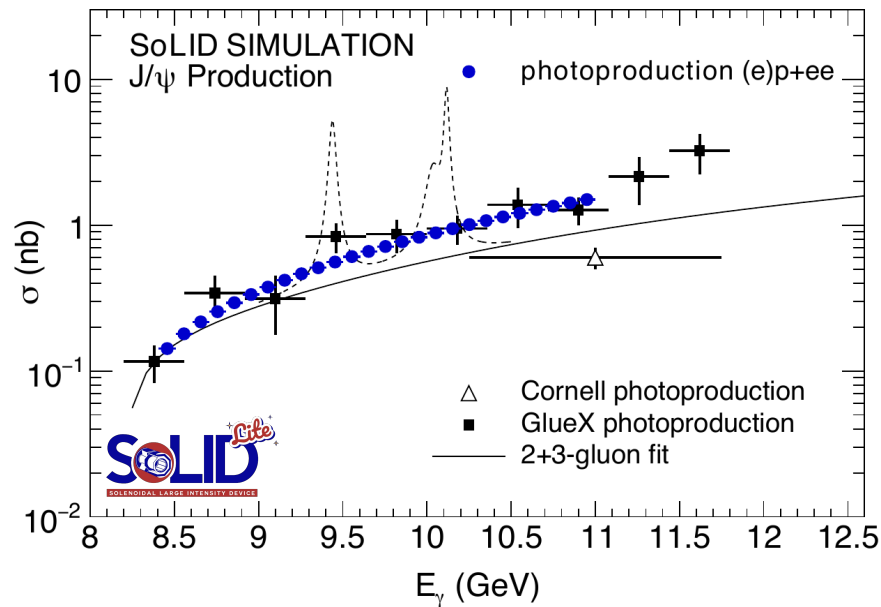
"SoLID-Lite"

J/ ψ photoproduction



Simultaneous 2D fit to all t-spectra

Projected GFF precision

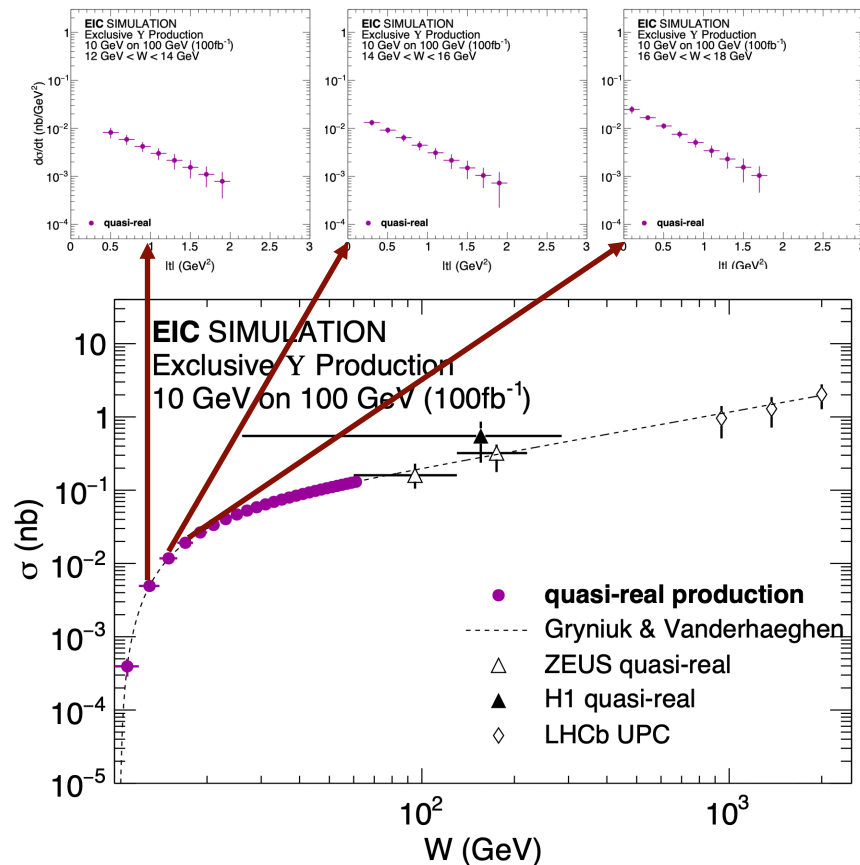


Can recover almost full SoLID
precision for J/ ψ photoproduction
(but we lose electroproduction!)

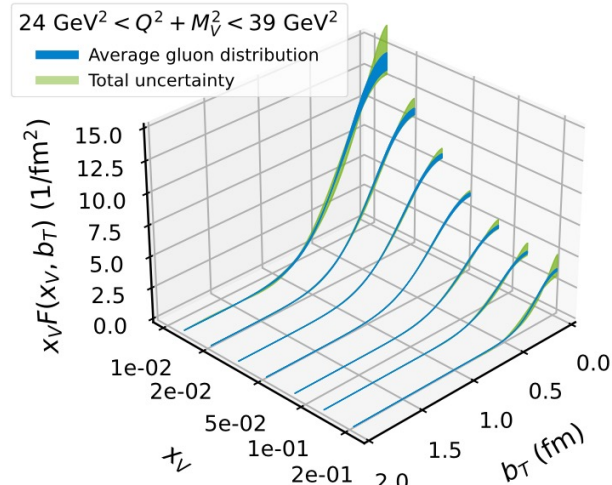
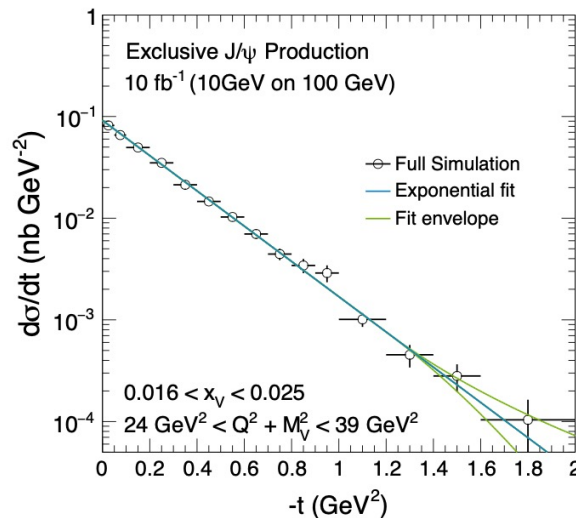
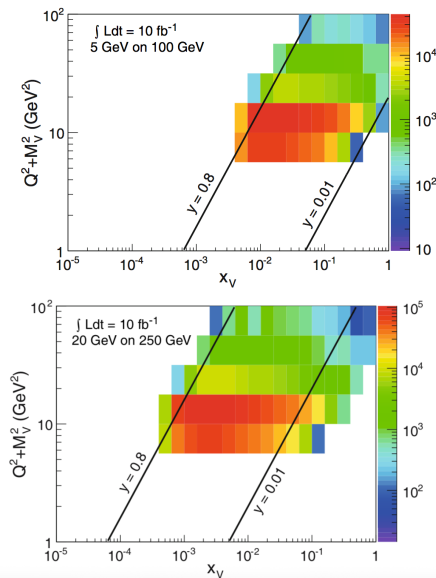
Complimentary: near-threshold $Y(1S)$ at EIC

Near-threshold quarkonium at EIC

- $Y(1S)$ 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



Complimentary: EIC Gluon Tomography



Only possible at an EIC:
from the valence region
deep into the sea!

t -spectra for each x_V - Q^2 bin

**Normalized average gluon
density**

Conclusion

J/ Ψ -007 in Hall C has already delivered high-impact results on near-threshold J/ ψ

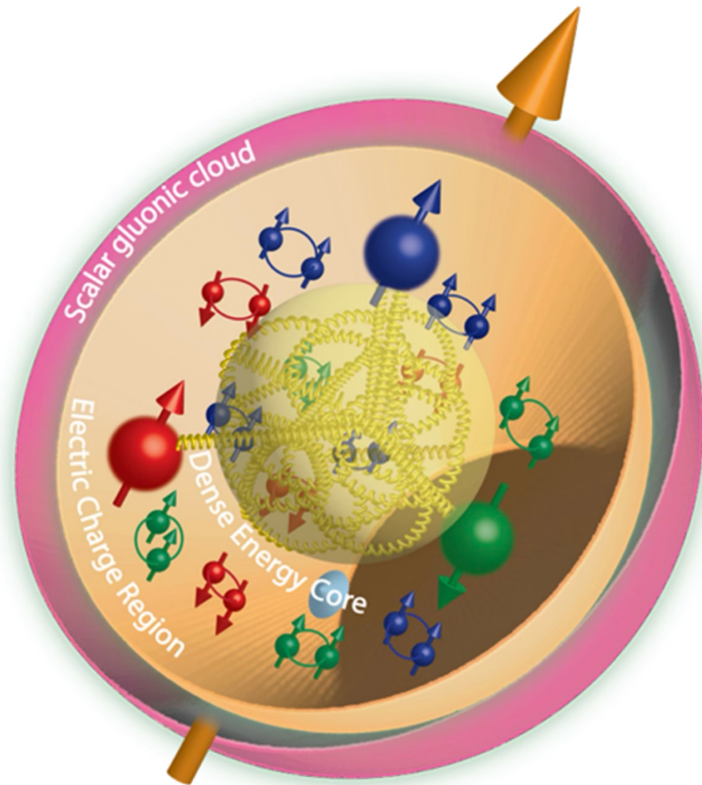
- A new window on the gluonic structure of the proton

J/ Ψ -007-II will leverage the high luminosity in Hall C to focus on the hard-to-measure high $|t|$ and $\xi > 0.5$ region

- Impacts theoretical understanding of process, GFF extractions, and sensitive to open charm and u-channel

SoLID or a SoLID-like program would take near-threshold J/ ψ into an era of precision

- A large-acceptance high-luminosity experiment can reach observables that cannot be achieved anywhere else
- A minimal SoLID-like program ("SoLID-Lite") can deliver on most of the photoproduction observables of SoLID
- Can use theory input for other high-lumi observables



High-lumi experiments at Jlab will transform our understanding J/ ψ near threshold.

QUESTIONS?



Model Assumptions and Caveats

First model-dependent attempt to determine the GFFs from experiment

Assumptions

Neglect $B(t)$ - in concordance with both models and lattice QCD

Neglect $\bar{C}_g$ when evaluating the cross section and radii (*)

Assume tripole shape for $A(t)$ and $C(t)$ (**)

Fix $A(0)$ to the average gluon PDF from CT18

Both models fit the data well ($\chi^2 \sim 1$)

(*) This is appropriate for the holographic model but not the GPD model. See Hatta *et al.* JHEP 12 (2018) 008 & Tanaka, K. JHEP 03 (2023) 013 for a calculation of $\bar{C}_g = -\bar{C}_q$

(**) Doing the same extraction with a dipole shape does not meaningfully impact our results

Holographic Model

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

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

$\mathcal{N}$ is normalized to the previous World Data (not given by the model)

GPD Model

Y. Guo, X. Ji, Y. Liu, PRD 103, 096010 (2021)

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

Assume $\xi \sim 1$ (it is less than 0.5 for most of the experimental data)

Quarkonium Photoproduction Near Threshold

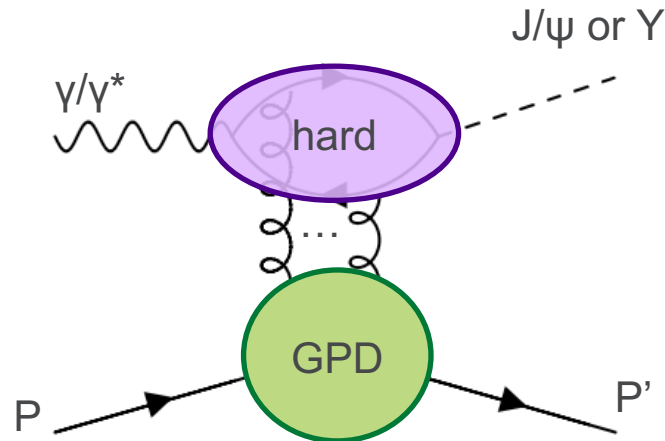
More Formally (GPD/pQCD approach)

What we measure

$$\int_{-1}^1 \frac{dx}{x} \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) \mathcal{H}_g(x, \xi, t)$$

What we need

$$\int_{-1}^1 dx \mathcal{H}_g(x, \xi, t) = A_g(t) + 4\xi^2 C_g(t)$$



- This is the same “problem” as the case for linking DVCS to the D -term?
- Important difference: skewness parameter ξ is tunable (large near threshold!)
- Conformal partial wave expansion is a **good approximation** for $\xi \rightarrow 1$ for gluon and strangeness GPDs (but not light quarks), has been shown in LO and NLO!

Hatta, Strikman PLB (2021) [2102.12631](#)Guo et al., PRD (2021) [2103.11506](#)Guo et al., PRD (2024) [2308.13006](#)Guo et al. PRL (2025) [2501.10532](#)Hatta, et al., PTEB (2025), [2501.12343](#)Hatta, Schoenleber, PRL (2025) [2502.12061](#)

- Alternative non-perturbative approach through Holographic QCD

Mamo, Zahed PRD (2021) [2103.03186](#)Mamo, Zahed PRD (2022) [2204.08857](#)

From GFFs to Mass Structure

- Mass (energy) form factor is related to the (0,0) component of the EMT:

$$\langle P' | T^{00} | P \rangle \sim G_m(t)$$

$$G_m(t) = M \left[A(t) + \frac{t}{4M^2} B(t) - \frac{t}{M^2} C(t) \right]$$

- In the Breit frame, its Fourier Transform gives an energy density. The RMS for zero momentum transfer ($t = 0$) is the mass radius $\sqrt{\langle r_m^2 \rangle}$ of the proton.

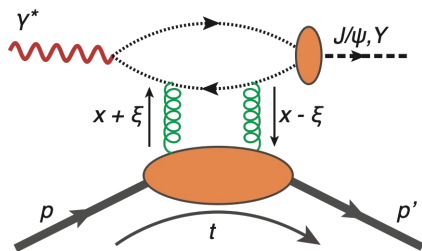
$$\langle r_m^2 \rangle \equiv \frac{\int d\vec{x} x^2 G_m(\vec{x})}{\int d\vec{x} G_m(\vec{x})}$$

$$= 6 \frac{dA(t)}{dt} \Big|_{t=0} - 6 \frac{C(0)}{M_N^2}$$

Depends on slope
and intercept of the
GFFs at $t = 0$

Future: Deeply-Virtual Quarkonium Production

Accessing the 3-D gluon structure



Hard scale: $Q^2 + M_V^2$

Modified Bjorken-x: $x_V = \frac{Q^2 + M_V^2}{2p \cdot q}$

average unpolarized gluon GPD related to t -dependent cross section (LO)

$$|\langle \mathcal{H}_g \rangle|(t) \propto \sqrt{\frac{d\sigma}{dt}(t) / \frac{d\sigma}{dt}(t=0)}$$



Fourier transform:
3-D transverse gluonic density

$$\rho(|\vec{b}_T|, x_V) = \int \frac{d^2 \vec{\Delta}_T}{(2\pi)^2} e^{i\vec{\Delta}_T \vec{b}_T} |\langle H_g \rangle|(t = -\vec{\Delta}_T^2)$$

3D GPDs can be related to 2D Gravitational Form Factors