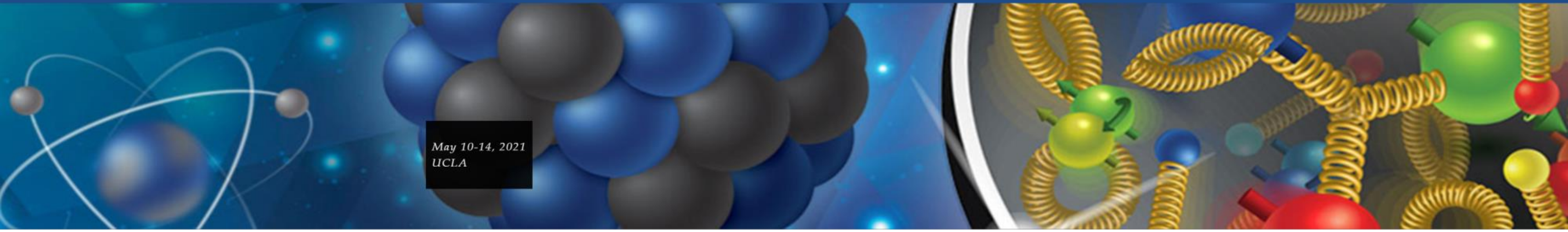
UCLA QCD Evolution Workshop 2021



Near-Threshold Production of Heavy Quarkonium

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Based on 2103.11506 in collaboration with Xiangdong Ji and Yizhuang Liu.

Outline

- Introduction
- Gravitational form factors
- QCD interaction of a color dipole
- Photoproduction of J/ψ
- Polarization and spin asymmetry
- Conclusions and outlook

Introduction to proton mass

-mass without mass

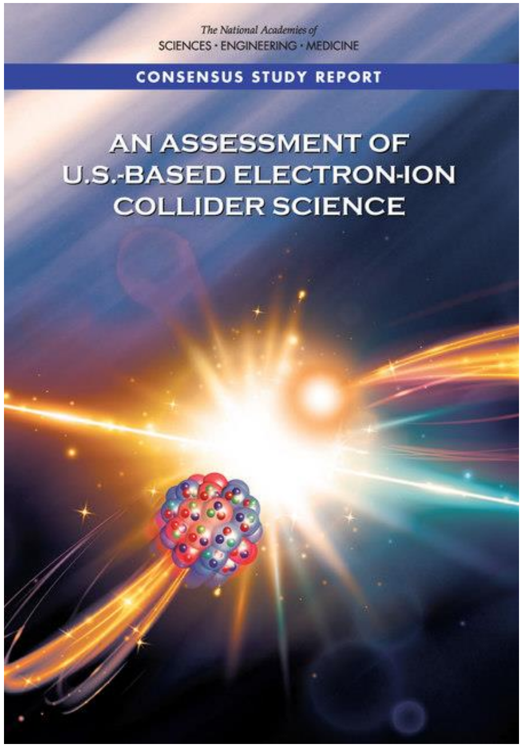
$m_u \approx 2.2$ MeV
$m_d \approx 4.7$ MeV
$m_g = 0$

$m_p \approx 938$ MeV

Most of the proton mass comes from dynamical energy!

Introduction to proton mass

-importance scientific goal of EIC



Finding 1:

An EIC can uniquely address three profound questions about nucleons--neutrons and protons--and how they are assembled to form the nuclei of atoms:

- How does the mass of the nucleon arise?
- How does the spin of the nucleon arise?
- What are the emergent properties of dense systems of gluons?

Introduction to proton mass

-previous works on heavy quarkonium production

- Vector dominance model

  D. Kharzeev (1996),
  D. Kharzeev et. al. (1999),

- Dispersive analysis

  O. Gryniuk and M. Vanderhaeghen (2016)
  O. Gryniuk et. al. (2020)

- Holographic QCD

  Y. Hatta and D.-L. Yang (2018)
  Y. Hatta, A. Rajan and D.-L. Yang (2019)
  K. A. Mamo and I. Zahed (2020,2021)

- pQCD analysis at large momentum transfer

  P. Sun, X.-B. Tong and F. Yuan (2021)

Two important questions

- Quantum anomalous energy (QAE) X. Ji (1995), X. Ji, Y. Liu and A. Schafer (2021)

$$H_{\mathrm{QCD}} = \int \mathrm{d}^3\boldsymbol{x} T^{00}(0,\boldsymbol{x}) = H_q + H_m + H_g + H_a$$

Quark energy, Quark mass, Gluon energy, QAE

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

- Mass radius D. Kharzeev (2021), X. Ji (2021)

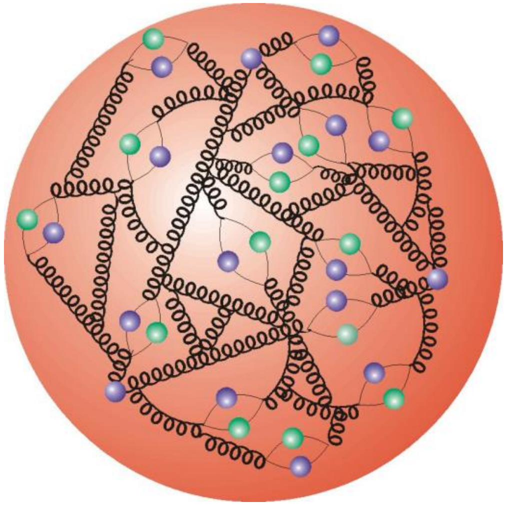
mass $M = \int \mathrm{d}^3\boldsymbol{x} \langle \boldsymbol{P}=0 | T^{00}(0,\boldsymbol{x}) | \boldsymbol{P}=0 \rangle$

mass form factors $G_m(Q^2)$ $\langle P' | T^{00} | P \rangle = \bar{u}(P') G_m(-\Delta^2) u(P)$ (Breit frame)

mass radius $\langle r^2 \rangle_m = -6 \frac{dG_m(Q^2)/M_N}{dQ^2}\Big|_{Q^2=0}$

Gravitational form factors

Matrix element of EMT can be written into gravitation form factors. X. Ji (1996)



$$\langle P' \left| T^{\mu\nu}_{q,g} \right| P \rangle = \bar{u}(P') \left[A_{q,g}(t)\gamma^{(\mu}\bar{P}^{\nu)} + B_{q,g}(t)\frac{\bar{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha}{2M_N} + C_{q,g}(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{M_N} + \bar{C}_{q,g}(t)M_N g^{\mu\nu} \right] u(P) \; .$$

Importance to mass structure

QAE $H_a = \langle P \left| T^{\mu}_{\mu} \right| P \rangle = \frac{1}{4}(A_q(0) + A_g(0))M_N$

Mass form factors $G_m(Q^2) = M_N A(Q^2) - B(Q^2)\frac{Q^2}{4M_N} + C(Q^2)\frac{Q^2}{M_N}$

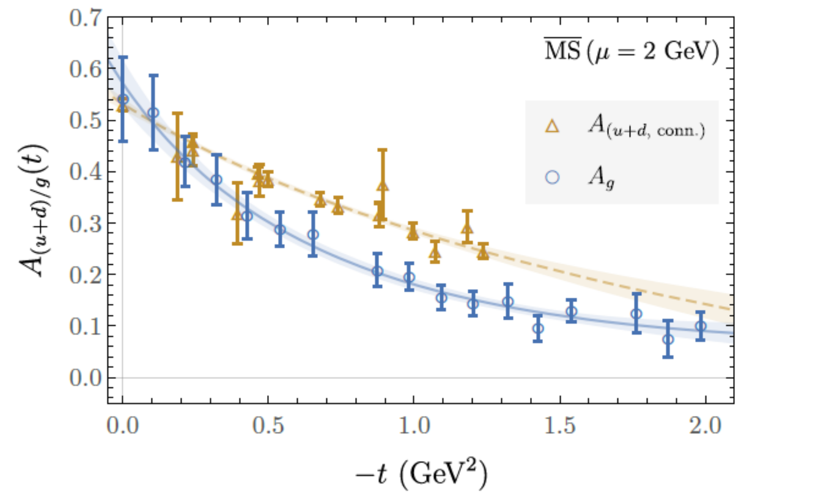
Lattice calculation

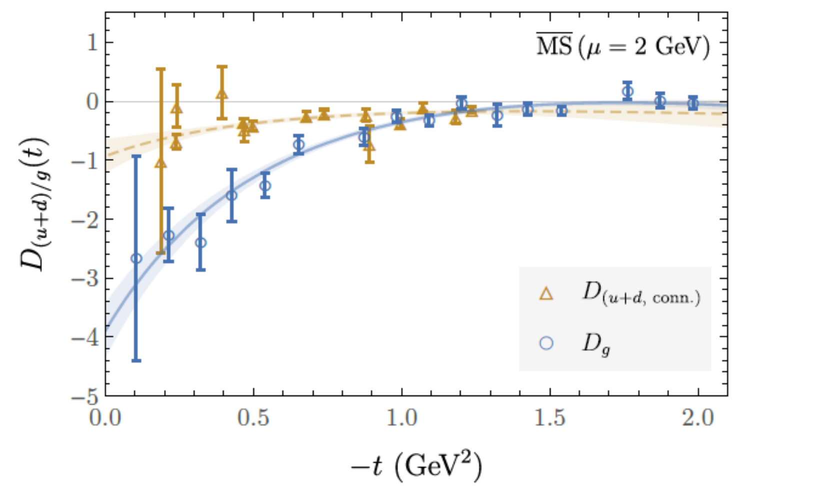
Hagler et. al. (2008), Shanahan et. al. (2018)

Gravitational form factors calculated with lattice QCD.

$$\langle r^2 \rangle_m \sim (0.74 \text{ fm})^2$$

Dominated by gluon contribution

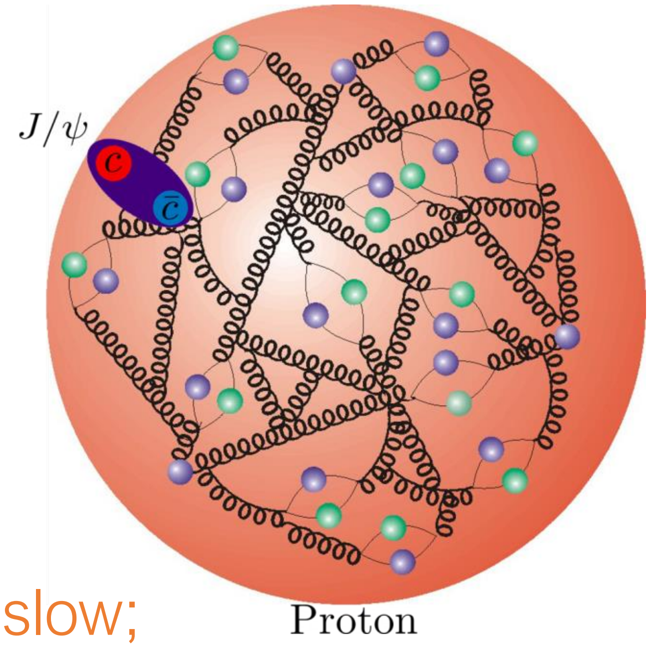




Color dipole as a probe

D. Kharzeev (1996),
M.B. Voloshin (1979)

$$\mathcal{H}_{\text{int}} = -\xi^a \boldsymbol{r} \cdot \boldsymbol{E}^a \quad \text{with} \quad \xi^a = t_1^a - t_2^a$$

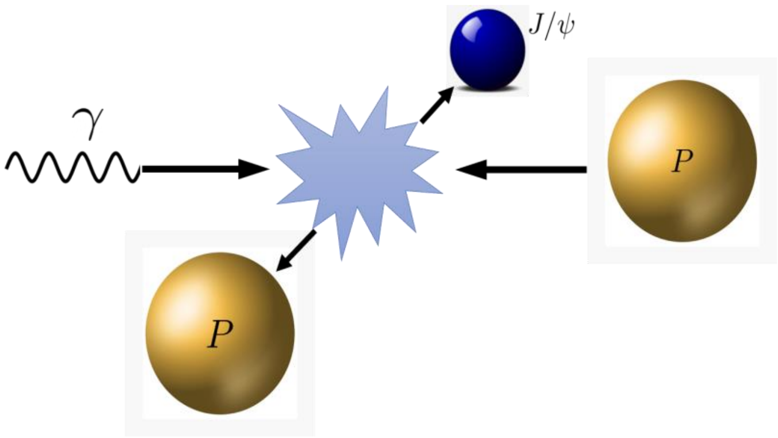


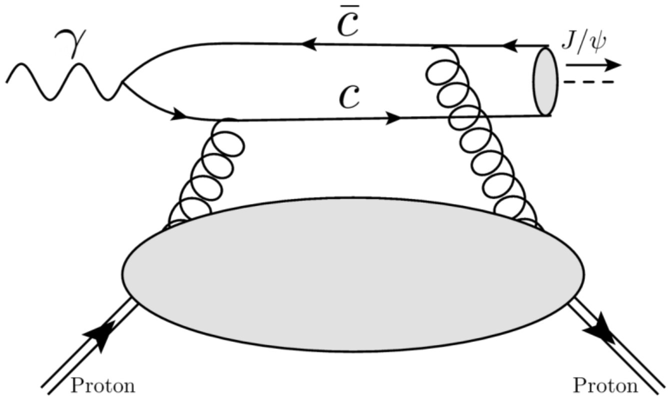
Quadratic Stark effect in QCD –
measures the color electric field $\boldsymbol{E}^2$

The quarkonium needs to be small;
The relative motion in the quarkonium is slow;
Perturbatively calculable;

Heavy quarkonium is needed!

Heavy quarkonium production





Near threshold, J/ψ slowly goes through the proton and measures the $\boldsymbol{E}^2$ distribution inside.

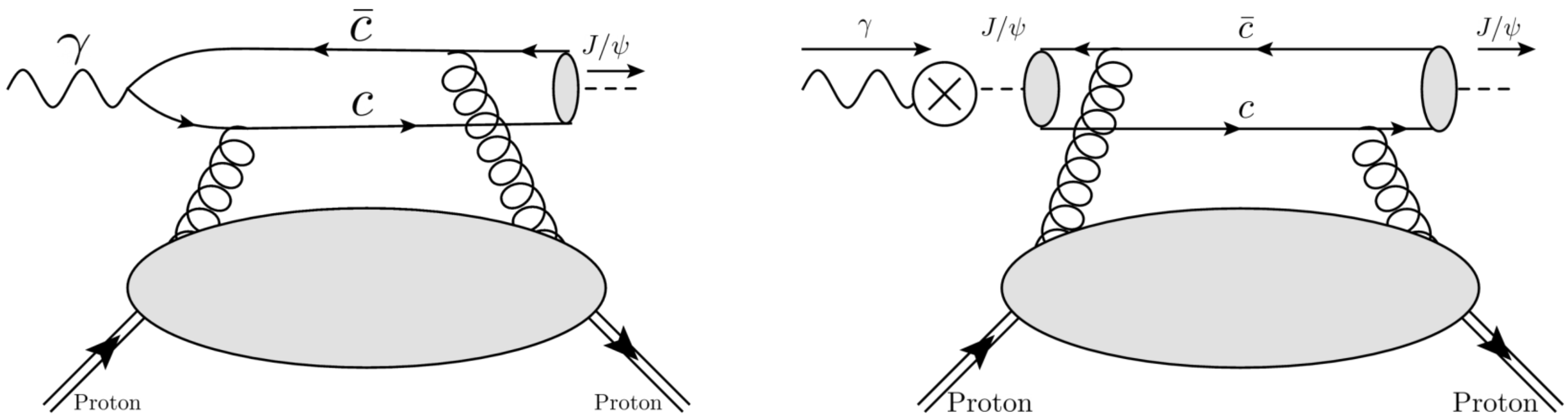
$M_P = 938$ MeV,
$M_{J/\psi} = 3097$ MeV,

$W_{th} = 4.035$ GeV → 4.8 GeV (JLab)
$E_{th}^{\gamma} = 8.210$ GeV → 10.8 GeV (JLab)

Vector dominance model

V. Barger et. al. (1975),
D. Kharzeev et. al. (1999)

In VDM, the photoproduction σ is extrapolated to t=0, and matched to J/ψ-proton forward scattering σ.



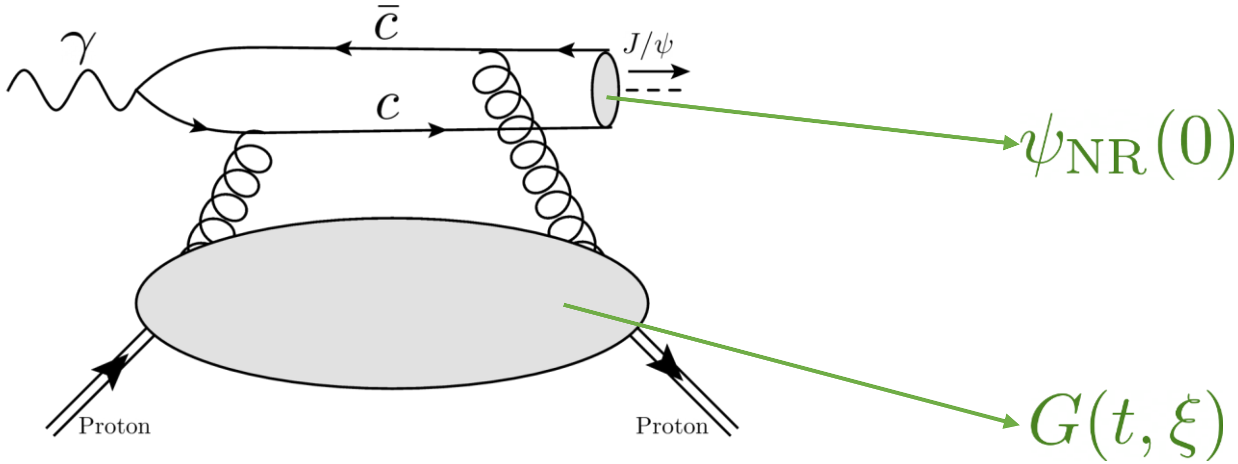
$$\frac{d\,\sigma_{\gamma\,N\to\psi\,N}}{d\,t}(s,t=0)=\frac{3\Gamma(\psi\to e^+e^-)}{\alpha m_\psi}\left(\frac{k_{\psi N}}{k_{\gamma N}}\right)^2\frac{d\,\sigma_{\psi\,N\to\psi\,N}}{d\,t}(s,t=0)$$

$\boldsymbol{E}^2$ Distribution (OPE)

QCD factorization

YG, X. Ji and Y. Liu (2021)

The cross section can be analyzed using QCD factorization in the heavy quark limit near the threshold.



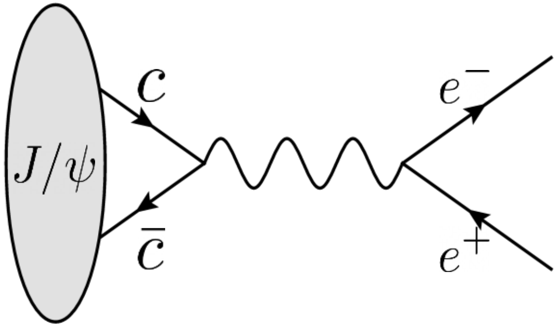
$$\frac{d\sigma}{dt} = \frac{e^2 e_Q^2}{16\pi\left(W^2 - M_N^2\right)^2}\frac{1}{2}\sum_{\rm polarization}\left|\mathcal{M}(\varepsilon_V, \varepsilon)\right|^2 ,$$

$$= \frac{\alpha_{\rm EM} e_Q^2}{4\left(W^2 - M_N^2\right)^2}\frac{(16\pi\alpha_S)^2}{3M_V^3}|\psi_{\rm NR}(0)|^2|G(t,\xi)|^2 ,$$

Distribution amplitude

$\psi_{\rm NR}(0)$: Non-relativistic distribution amplitude of J/ψ

To the leading order of α_S, J/ψ can be estimated as hydrogen like system.

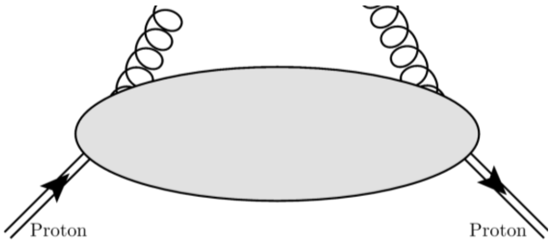


$$\Gamma\left(V \to e^+e^-\right) = \frac{16\pi\alpha_{\rm EM}^2 e_Q^2 |\psi_{\rm NR}(0)|^2}{M_V^2}\left(1 - \frac{16\alpha_s}{3\pi}\right)$$

Higher order terms can be analyzed with NRQCD.

R. Van Royen and V. F. Weisskopf(1967)
B. Gittelman et. al. (1975)
G. T. Bodwin et. al. (2006)

Hadronic matrix element



$G(t,\xi)$:Hadronic matrix element

$$G(t,\xi)=\frac{1}{2\xi}\int_{-1}^{1}\mathrm{d}x\mathcal{A}(x,\xi)F_g(x,\xi,t)\ .$$

Hard Kernel: $\mathcal{A}(x,\xi)\equiv\frac{1}{x+\xi-i0}-\frac{1}{x-\xi+i0}\ .$

Gluon GPD: $F_g(x,\xi,t)\equiv\frac{1}{(\bar{P}^{+})^2}\int\frac{\mathrm{d}\lambda}{2\pi}e^{i\lambda x}\left\langle P'\middle|\mathrm{Tr}\left\{F^{+i}\left(-\frac{\lambda n}{2}\right)F_i^{+}\left(\frac{\lambda n}{2}\right)\right\}\middle|P\right\rangle,$

Consistent with leading twist deeply virtual meson production result

J. Koempel et. al. (2011)

Kinematics near threshold

t and ξ are large near threshold.

$$\mathcal{A}(x,\xi) \equiv \frac{1}{x+\xi-i0} - \frac{1}{x-\xi+i0} \,.$$

$$\Downarrow$$

$$\frac{1}{2\xi}$$

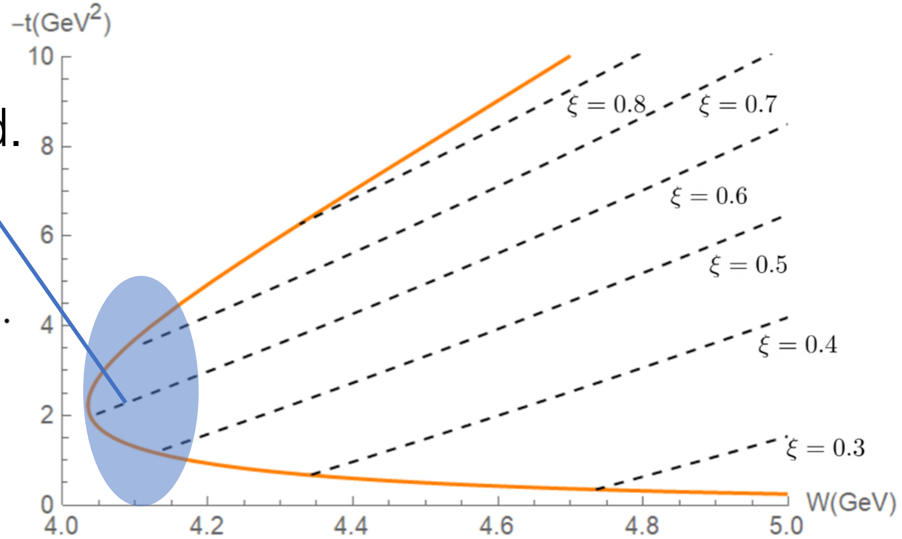


FIG. 2: ξ on the $(W,-t)$ plane in the kinematically allowed region with $M_{J/\psi} = 3.097$ GeV.

Taking the leading moment of x,

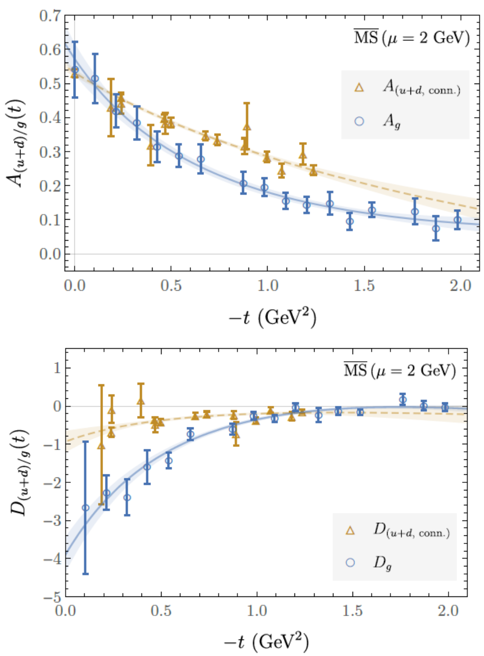
$$G(t,\xi) = \frac{1}{2\xi^2(\bar{P}^+)^2} \left\langle P' \left| T_g^{++} \right| P \right\rangle \;,$$

Measurement of the gravitational form factors.

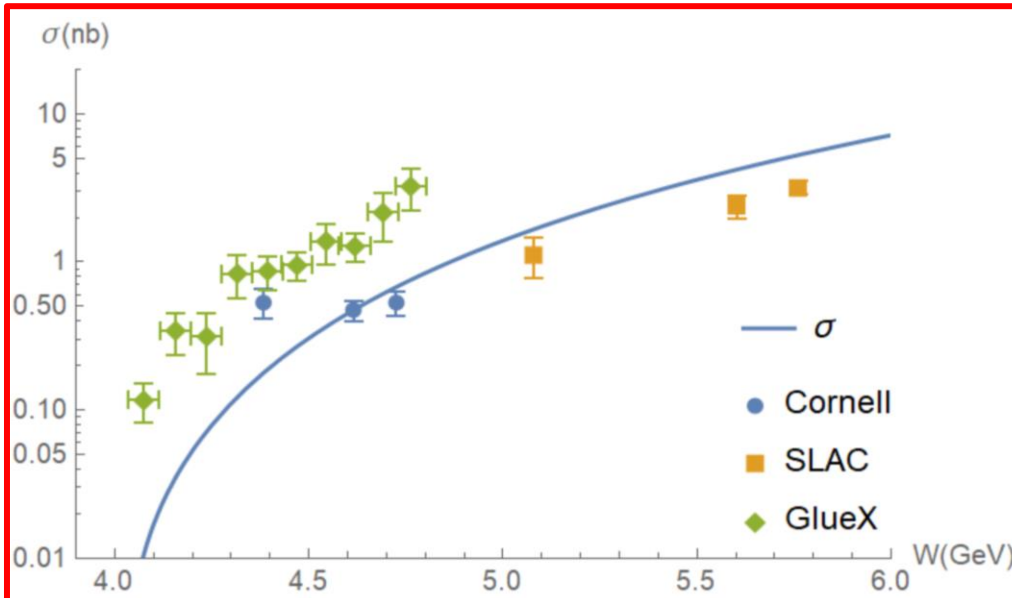
Connect lattice results with exp.

$$\langle P' \left| T_g^{++} \right| P \rangle \sim G(t, \xi)$$

Lattice calculated form factors



cross section $\frac{d\sigma}{dt}$



QCD works quite well!

Fitting gravitational form factors

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

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

$A_g(0) = 0.58$
$m_C = 0.48$ GeV

Fixed

$C_g(0) = -0.84 \pm 0.82$
$m_A = 1.64 \pm 0.11$ GeV

Fit

$$\langle r^2 \rangle_m \approx (0.68 \text{ fm})^2$$

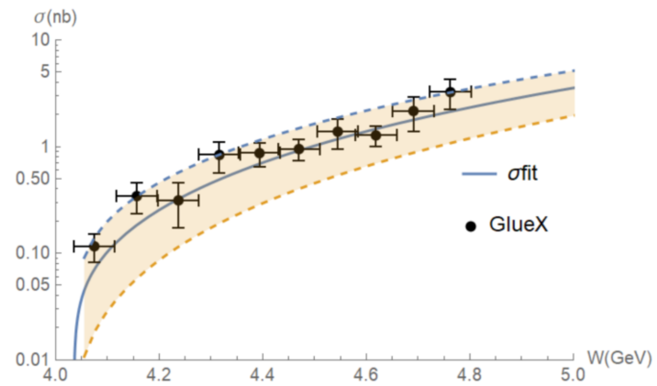


FIG. 6: Fit total cross section for J/ψ production compared with the total cross section measured at GlueX [36]. The 95% confidence band is shown as the shaded region hereafter.

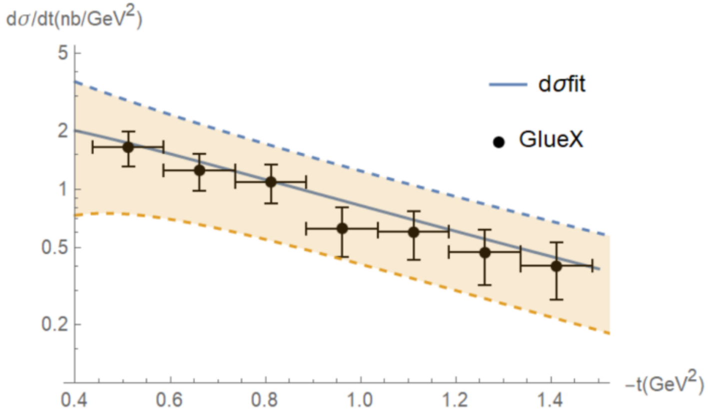


FIG. 7: Fit differential cross section for J/ψ production compared with the differential cross section at $W = 4.58$ GeV measured at GlueX [36].

More J/ψ data at JLab

Z.-E. Meziani

	GlueX HALL D	HMS+SHMS HALL C	CLAS 12 upgrade I HALL B	SoLID HALL A
J/ψ counts (photo-prod.)	~469 published, 10k phase I+II	4k	14k	804k
J/ψ Rate (electro-prod.)			1k	21k
Photon-proton luminosity				
Acceptance	$\sim 2\pi$	$< 3\text{x}10^{-4}$	$< 2\pi$	$\sim 2\pi$
When?	Finished	Finished	Proposed	~8 years?

More data at JLab will allow much more precise measurements of gravitational form factors.

Polarization measurement

The leading amplitude before summing over polarizations reads

$$\mathcal{M}(\varepsilon_V, \varepsilon) = \frac{8\sqrt{2}\pi\alpha_S(M_V)}{M_V^2}\phi^*(0)G(t,\xi)(\varepsilon_V^* \cdot \varepsilon) \; .$$

- Photon polarization ε^μ and vector meson polarization ε_V^μ are factored out.

- The proton polarizations are contained in the hadronic matrix element $G(t,\xi)$ -- polarization measurements provide more information on the gravitational form factors.

Conclusions

- Factorization formula to the leading order in the heavy quark limit.
- Measurements of the gluonic gravitational form factors .
- Proton polarization measurements can be helpful.

Outlook

- Higher order correction in $\mathcal{O}\left(\frac{M_N}{M_V}\right)$ and $\mathcal{O}(\alpha_S)$
- Higher twist effects including three-gluon exchange
- Factorization theorem to higher/all order