Quarkonium photo- and lepto-production near threshold

Yoshitaka Hatta

Brookhaven

3rd Proton mass workshop; origin and perspective, Argonne National Lab, Jan. 14-16, 2021

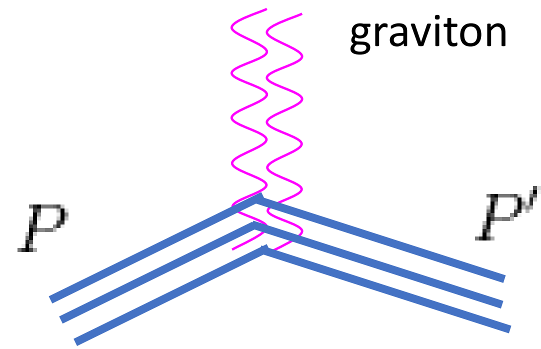
Outline

- Nucleon gravitational form factors
- Near-threshold quarkonium production in γp and $\gamma^* p$

YH, Dilun Yang, 1808.02163
YH, Abha Rajan, Kazuhiro Tanaka, 1810.05116
YH, Rajan, Yang, 1906.00894
Renaud Boussarie, YH, 2004.12715

Nucleon gravitational form factors

$$\langle P'|T^{\mu\nu}_{q,g}|P\rangle = \bar{u}(P')\Bigg[A_{q,g}\gamma^{(\mu}\bar{P}^{\nu)} + B_{q,g}\frac{\bar{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha}{2M} + D_{q,g}\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{4M} + \bar{C}_{q,g}Mg^{\mu\nu}\Bigg]u(P)$$



$$\Delta = P' - P$$

All the form factors are interesting and measurable!

$A_{q,g}$ Momentum fraction

$B_{q,g}$ Ji sum rule

$$\frac{1}{2} = J_q + J_g$$

$$J_{q,g} = \frac{1}{2}(A_{q,g} + B_{q,g})$$

$D_{q,g}$ pressure inside proton

$\bar{C}_{q,g}$ Mass, pressure

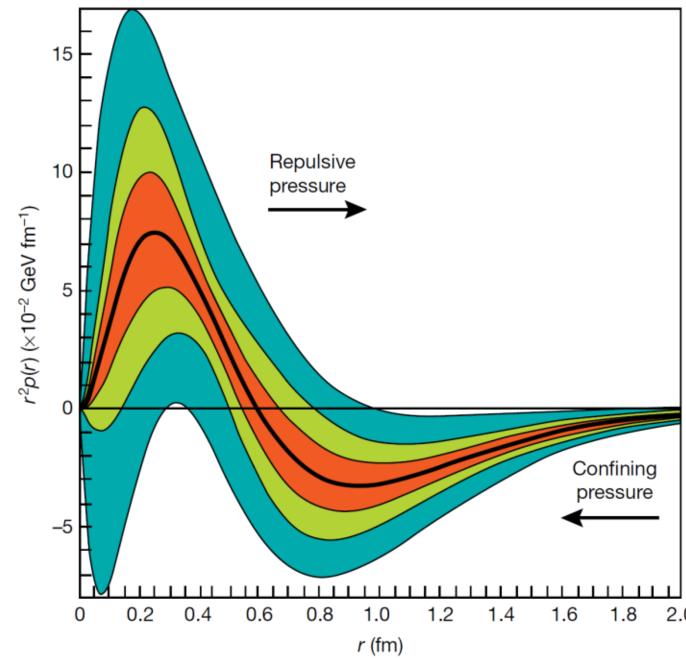
D-term: the last global unknown

$D(t=0)$ is a conserved charge
of the nucleon, just like mass and spin!

Related to the radial pressure (force) distribution
inside a nucleon

$$D = D_u + D_d + D_s + D_g + \cdots$$

Burkert, Elouadrhiri, Girod (2018)



u,d-quark D-term can be extracted from Deeply Virtual Compton Scattering (DVCS)
First results from Jlab data, large model dependence.
Need significant lever-arm in Q^2 to disentangle various moments

EIC

What about gluon D-term?
What about strangeness D-term?

Physics of $\bar{C}_{q,g}$

- Non-conservation of the quark/gluon parts

$$\langle \partial_\mu T^{\mu\nu}_{q,g} \rangle \sim \Delta^\nu \bar{C}_{q,g} \qquad \bar{C}_q + \bar{C}_g = 0$$ because the total EMT is conserved.

- Pressure inside the proton from quark and gluon subsystems   Polyakov, Schweitzer,...

$$p_{q,g}(r) = \frac{1}{6Mr^2}\frac{d}{dr}r^2\frac{d}{dr}D_{q,g}(r) - M\bar{C}_{q,g}(r)$$

- Related to the quark and gluon parts of the trace anomaly
  intimate connection to the proton mass decomposition.

$$T^\mu_\mu = (T_q)^\mu_\mu + (T_g)^\mu_\mu = \frac{\beta}{2g}F^2 + m(1+\gamma_m)\bar{\psi}\psi$$

$$\langle P|(T_{q,g})^\mu_\mu|P\rangle = 2M^2(A_{q,g} + 4\bar{C}_{q,g})$$

Beware, $\bar{C}_{q,g}$ is scheme and scale dependent.

$\bar{C}_{q,g}$ in $\overline{\mathrm{MS}}$ scheme, 2-loop result

YH, Rajan, Tanaka (2018)

$$\bar{C}_q^R(\mu) = -\frac{1}{4}\left(\frac{n_f}{4C_F+n_f}+\frac{2n_f}{3\beta_0}\right)+\frac{1}{4}\left(\frac{2n_f}{3\beta_0}+1\right)\frac{\langle P|\left(m\bar{\psi}\psi\right)_R|P\rangle}{2M^2}$$
$$-\frac{4C_F A_q^R(\mu_0)+n_f\left(A_q^R(\mu_0)-1\right)}{4(4C_F+n_f)}\left(\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\right)^{\frac{8C_F+2n_f}{3\beta_0}}$$
$$+\frac{\alpha_s(\mu)}{4\pi}\left[\frac{n_f\left(-\frac{34C_A}{27}-\frac{49C_F}{27}\right)}{4\beta_0}+\frac{\beta_1 n_f}{6\beta_0^2}\right.$$
$$\left.+\frac{1}{4}\left(\frac{n_f\left(\frac{34C_A}{27}+\frac{157C_F}{27}\right)}{\beta_0}+\frac{4C_F}{3}-\frac{2\beta_1 n_f}{3\beta_0^2}\right)\frac{\langle P|\left(m\bar{\psi}\psi\right)_R|P\rangle}{2M^2}\right]+\cdots,$$

nucleon sigma-term

$$\simeq -0.146 - 0.25\left(A_q^R(\mu_0)-0.36\right)\left(\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)}\right)^{\frac{50}{81}} - 0.01\alpha_s(\mu)$$
$$+\left(0.306+0.08\alpha_s(\mu)\right)\frac{\langle P|\left(m\bar{\psi}\psi\right)_R|P\rangle}{2M^2},$$

Asymptotic value in the chiral limit

$(n_f = 3)$

3-loop result available Tanaka (2018)

Lorentz invariant hadron mass decomposition

YH, Rajan, Tanaka (2018)

$$M^2 = M_q^2 + M_g^2 \qquad M_{q,g}^2 \equiv \frac{1}{2}\langle P|(T_{q,g})^\mu_\mu|P\rangle$$

three-loop result in $\overline{\mathrm{MS}}$

$$\eta_{\lambda\nu}\left(T_g^{\lambda\nu}\right)_R\Big|_{\mu=1\ \mathrm{GeV}} = -0.285452\left(F^2\right)_R\big|_{\mu=1\ \mathrm{GeV}} + 0.500593\left(m\bar{\psi}\psi\right)_R ,$$

$$\eta_{\lambda\nu}\left(T_q^{\lambda\nu}\right)_R\Big|_{\mu=1\ \mathrm{GeV}} = 0.0531842\left(F^2\right)_R\big|_{\mu=1\ \mathrm{GeV}} + 1.05832\left(m\bar{\psi}\psi\right)_R .$$

$$m_\pi^2 = 0.521 m_\pi^2 + 0.479 m_\pi^2$$

Tanaka (2018)

from $(T_g)^\mu_\mu$ from $(T_q)^\mu_\mu$

For the proton, the quark contribution is negative in $\overline{\mathrm{MS}}$!

$$m_p^2 \approx 1.1 m_p^2 - 0.1 m_p^2$$

from $(T_g)^\mu_\mu$ from $(T_q)^\mu_\mu$

See Metz, Pasquini, Rodini (2020) for an alternative scheme.

Can we measure the gluon condensate $\langle P|F^{\mu\nu}F_{\mu\nu}|P\rangle$?

The operator $F^{\mu\nu}F_{\mu\nu}$ is twist-four,
highly suppressed in high energy scattering.

Purely gluonic operator, very difficult to compute in lattice QCD
(but there are ongoing efforts)

Instead, we should look at low-energy scattering.

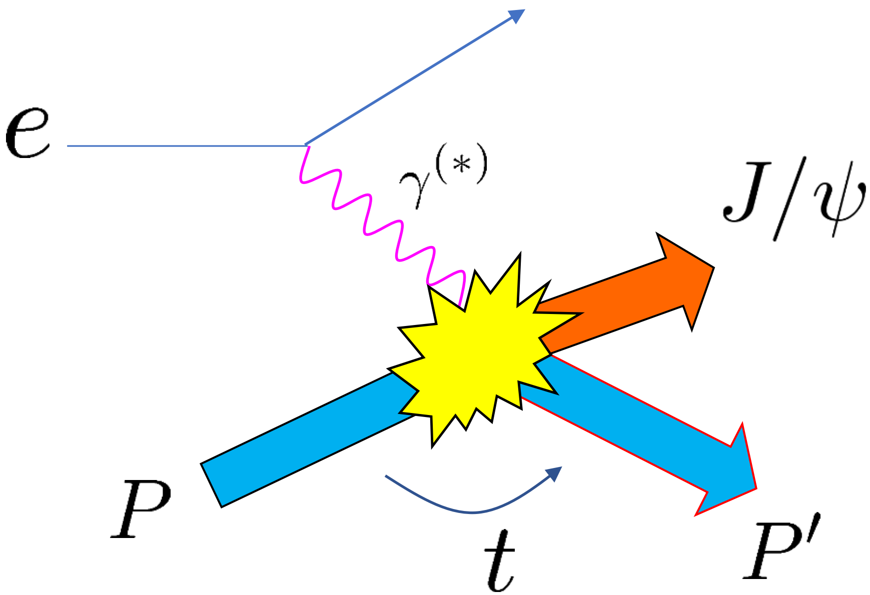
Purely gluonic operator. Use quarkonium as a probe.

→ J/ψ photo-production near threshold.

Kharzeev, Satz, Syamtomov, Zinovjev (1998)

Photo-production of J/ψ near threshold

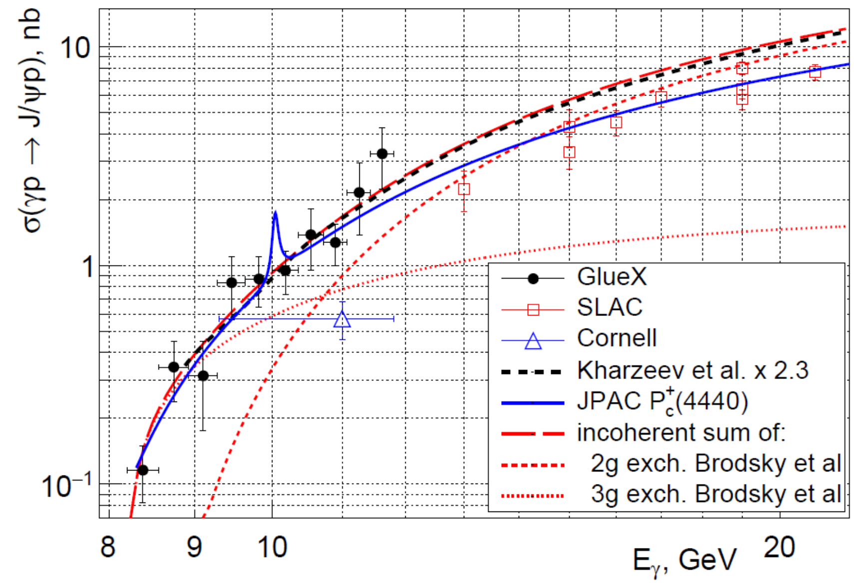
Sensitive to the non-forward matrix element $\langle P'|F^{\mu\nu}F_{\mu\nu}|P\rangle$

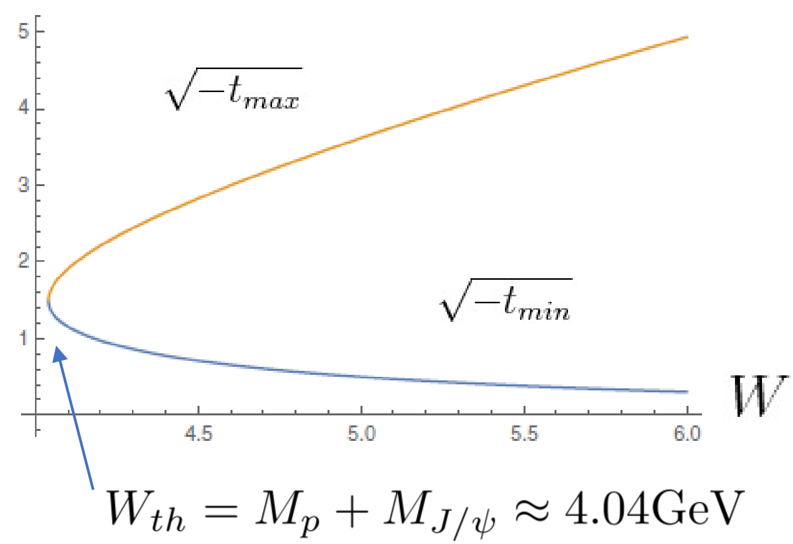


Ongoing experiments at Jlab (Glue-X)
Future measurement at EIC, EIcC?

Difficult to compute from first principles

1905.10811





Near-threshold photo-production: theory approaches

Kharzeev, Satz, Syamtomov, Zinovjev (1998); Gryniuk, Vanderhaeghen (2016)…

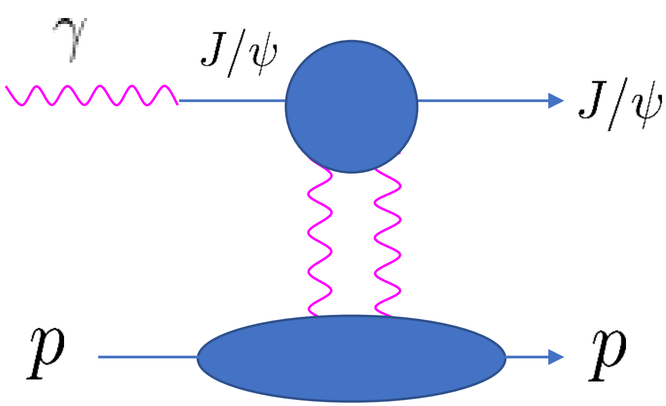
Assume vector meson dominance to relate $\gamma p \to J/\psi p$ to forward $J/\psi p \to J/\psi p$

Compute $\mathrm{Im} T^{J/\psi p}(t=0) \sim \sigma_{tot}^{J/\psi p}$

Reconstruct $\mathrm{Re} T^{J/\psi p}(t=0)$ via dispersion relation. $\langle P|F^2|P\rangle$ enters as a subtraction constant.

Brodsky, Chudakov, Hoyer, Laget (2001)

Two-gluon, three-gluon exchanges
Amplitude from quark counting rule



Frankfurt, Strikman (2002)

t-dependence not exponential but power-law,
that of 2-gluon form factors (Which form factors?)

Du, Baru, Guo, Hanhart, Meissner (2020)

D-meson loop, nothing to do with trace anomaly

An observation regarding t-dependence

thanks to Lubomir Pentchev

t-dependence → \`2-gluon' form factor → gravitational form factors $A_g(t), D_g(t)$

Frankfurt, Strikman (2002) YH, Yang (2018)

$$\frac{d\sigma}{dt} \sim (A_g(t))^2 \sim \left(\frac{1}{(1-t/m^2)^2}\right)^2 \quad ?$$

Experimental result from GlueX 1905.10811

For the t-dependence of the differential cross section (see Supplemental Material) for beam energies of 10.00 – 11.80 GeV with an average of 10.72 GeV, we obtain an exponential t-slope of 1.67 ± 0.35 (stat.) ± 0.18 (syst.) GeV^{-2}. This can be compared with the Cornell result at $E_\gamma \approx 11$ GeV of 1.25 ± 0.20 GeV^{-2} [15] and the SLAC result at $E_\gamma = 19$ GeV of 2.9 ± 0.3 GeV^{-2} [16]. All these results are consistent [27] with the hypothesis in Ref. [12] of the dipole t-dependence for the differential cross section assuming a mass scale of 1.14 GeV, as given in Eq. (1).

Compare this with a lattice calculation by Shanahan, Detmold (2018)

$$X_{\text{dipole}}(t) = \frac{\alpha}{(1-t/m^2)^2},$$

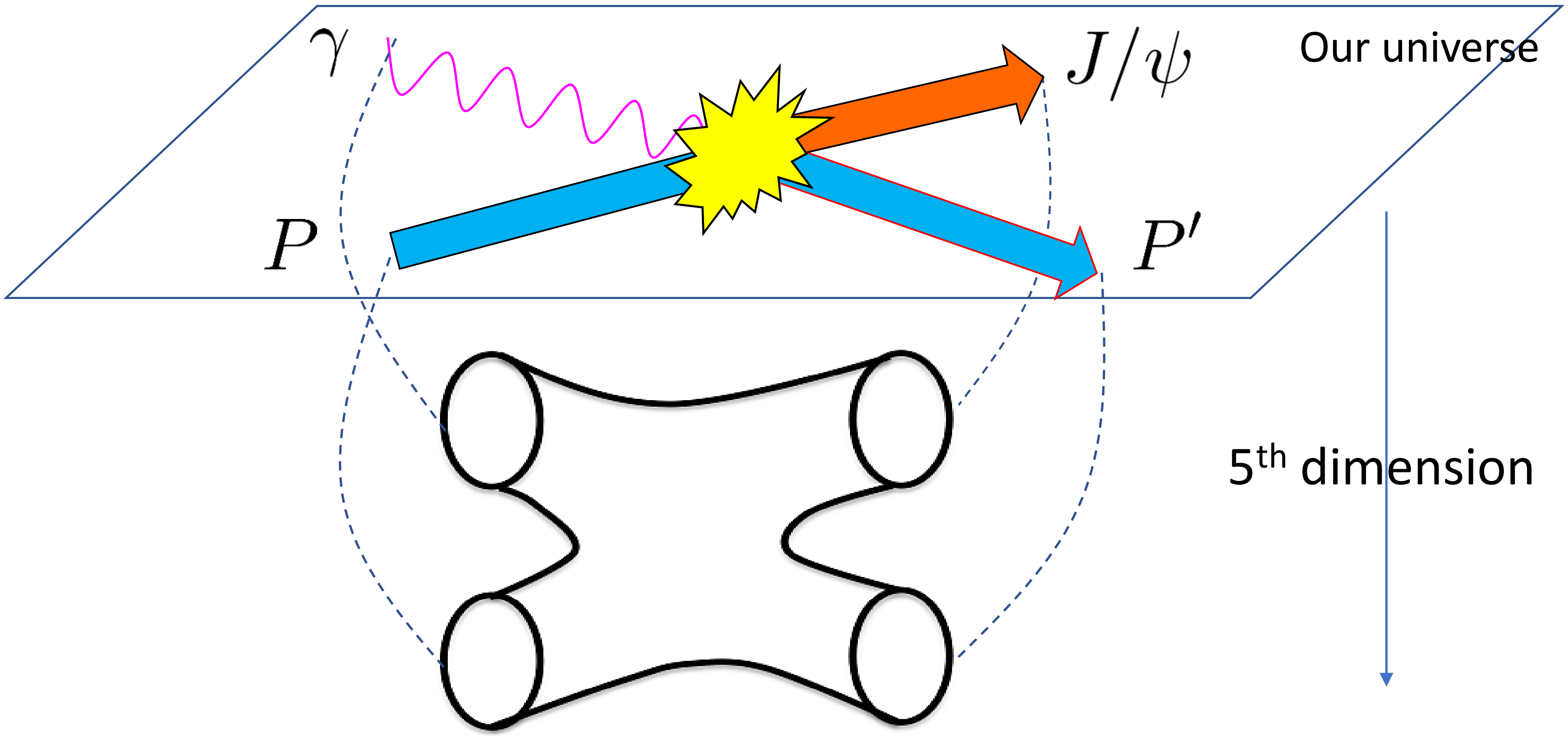
	m (GeV)	α
A_g	1.13(6)	0.58(5)
D_g	0.48(5)	-10(3)
$A_g^{(\pi)}$	2.1(2)	0.56(3)
$D_g^{(\pi)}$	1.24(7)	-1.2(1)

Holographic approach

YH, Yang (2018)
Mamo, Zahed (2019)

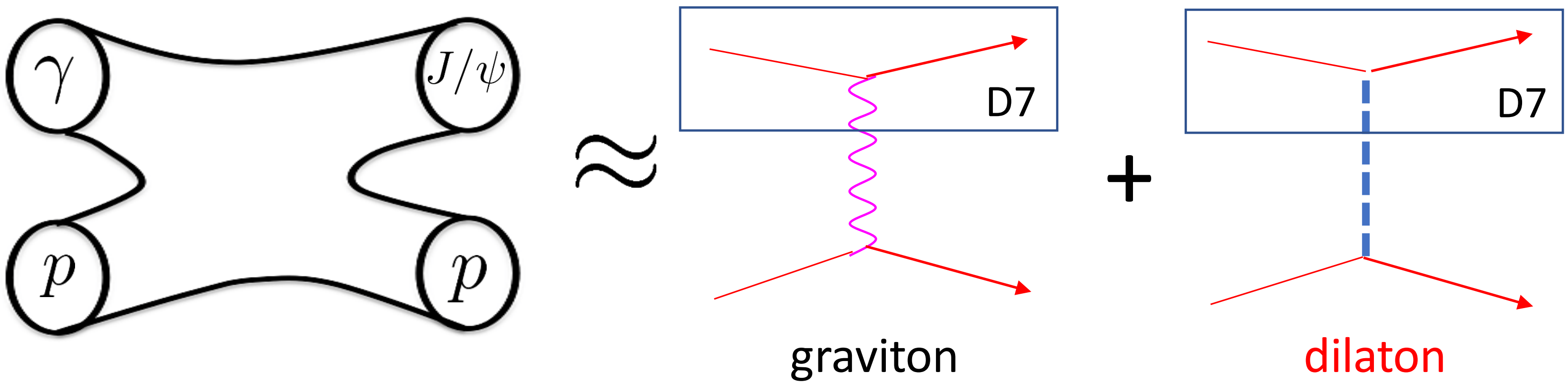
Strongly coupled gauge theories $\overset{\text{dual}}{\Longleftrightarrow}$ string theory in curved spaces.

QCD amplitude $\approx$ string amplitude in asymptotically AdS_5.



The dilaton

The operator $F^{\mu\nu}F_{\mu\nu}$ is dual to a massless string called dilaton



Suppressed compared to graviton exchange at high energy, but not at very low energy!

$$\langle P|\epsilon \cdot J(0)|P'k\rangle \approx -\frac{2\kappa^2}{f_\psi R^3}\int_0^{z_m} dz \frac{\delta S_{D7}(q,k,z)}{\delta g_{\mu\nu}}\frac{z^2R^2}{4}\langle P|T^{gTT}_{\mu\nu}|P'\rangle + \frac{2\kappa^2}{f_\psi R^3}\frac{3}{8}\int_0^{z_m} dz \frac{\delta S_{D7}(q,k,z)}{\delta \phi}\frac{z^4}{4}\underline{\langle P|\frac{1}{4}F^{\mu\nu}_a F^a_{\mu\nu}|P'\rangle}$$

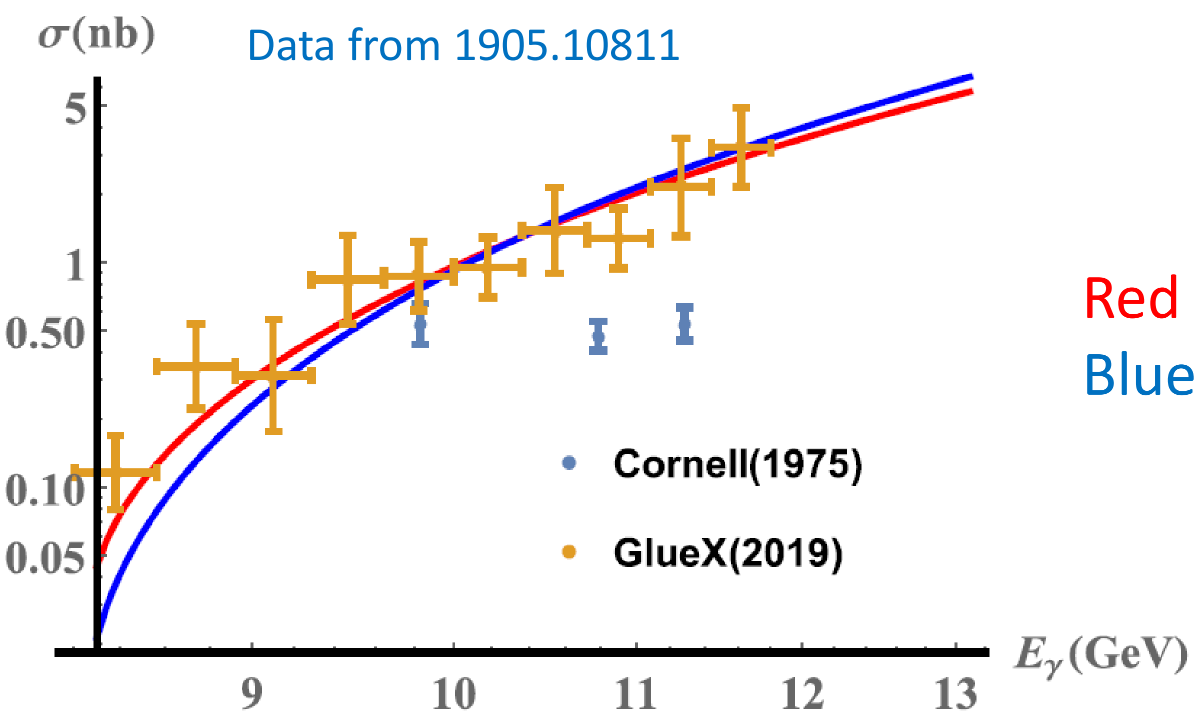
Gluon condensate (nonforward version)

Cross section sensitive to the gluon D-term.

Fitting the GlueX data

YH, Rajan, Yang (2019)

$$M_m = \frac{1}{4}\frac{\langle P|m(1+\gamma_m)\bar{\psi}\psi|P\rangle}{2M} \equiv \frac{b}{4}M \qquad M_a = \frac{1}{4}\frac{\langle P|\frac{\beta}{2g}F^2|P\rangle}{2M} \equiv \frac{1-b}{4}M$$



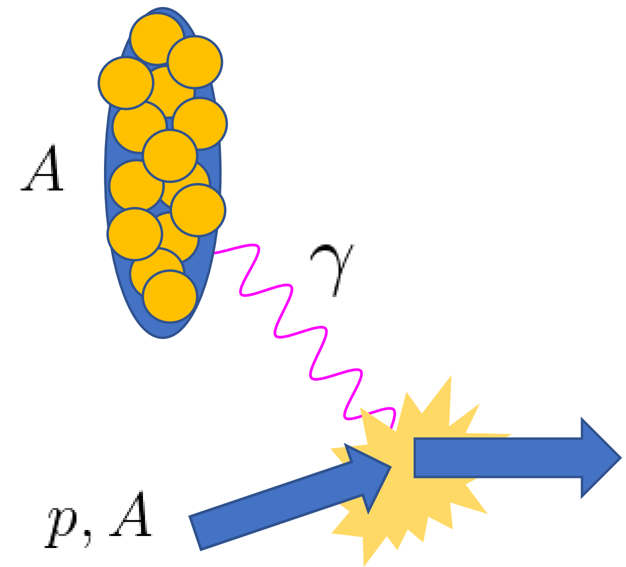
Red $b=0$

Blue $b=1$

Threshold photo-production at RHIC?

YH, Rajan, Yang (2019)

RHIC, ultra-peripheral pA collisions (UPC)



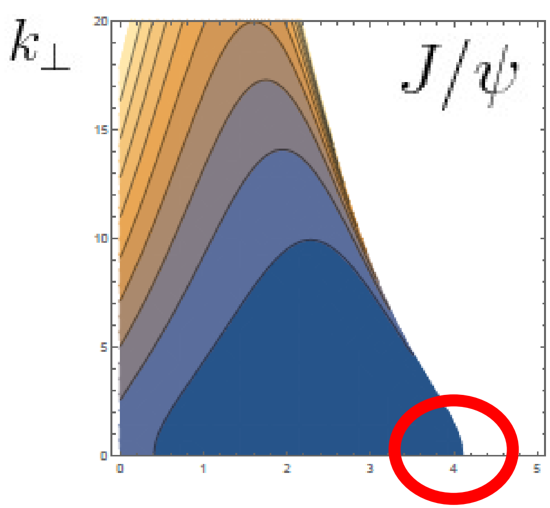
Cross section enhanced by $Z^2 = 6241$

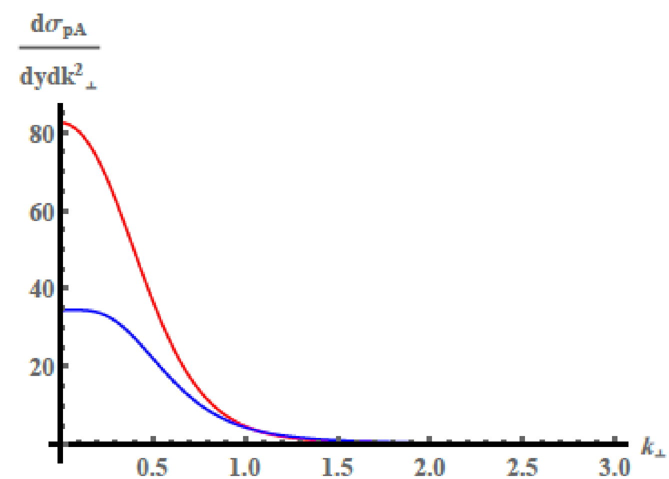
Typical γp energy at 200 GeV runs

$$\sqrt{(P+q)^2} \sim 28\,\mathrm{GeV}$$

enough to produce Υ, but they are produced in the forward rapidity region

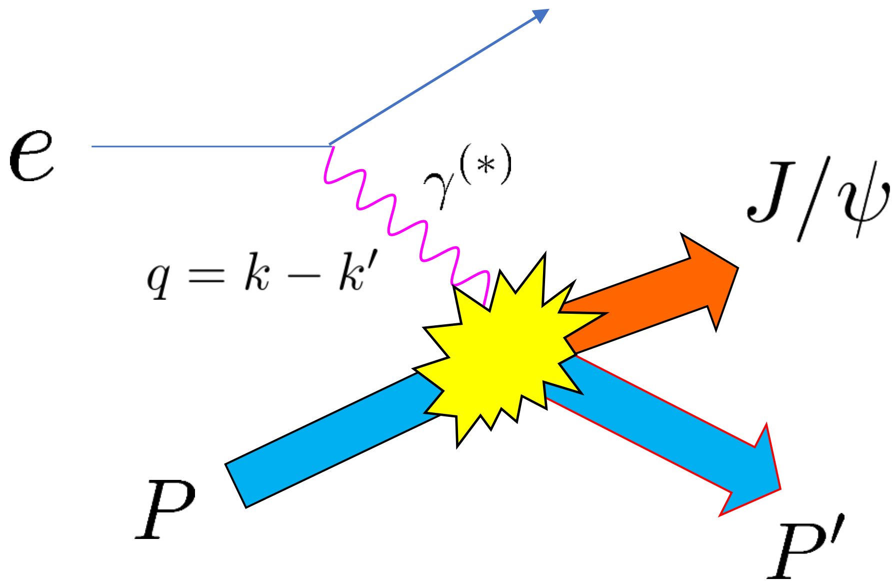
Measurable after the completion of STAR forward upgrades?





Threshold leptoproduction at high-Q^2

Boussarie, YH, 2004.12715



Larger $Q^2 = -(k-k')^2$, better chance to use perturbative approaches

$Q^2 < 10\mathrm{GeV}^2$ at Jlab.

ideal for EIC (or EIcC) low energy runs.

Even if ep center-of-mass energy $S_{ep} = (k+p)^2$ is large,
γp center-of-mass energy $W^2 = (p+q)^2$ can be adjusted close to the threshold.

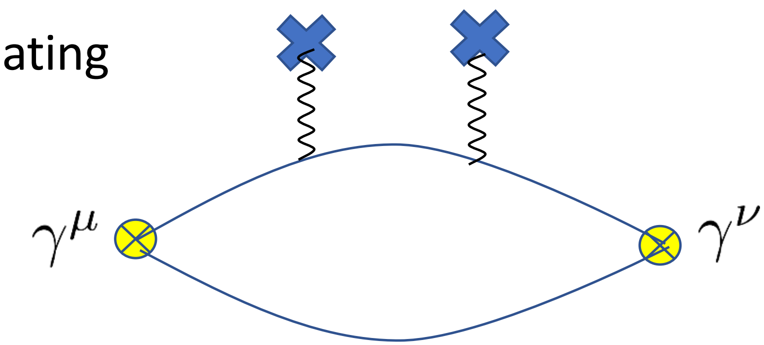
$$W^2 = y(S_{ep} - m_N^2) + m_N^2 - Q^2$$

Operator product expansion

$$\langle p'k|J^{\nu}_{em}(0)|p\rangle \quad \sim \quad i\int d^4x d^4y e^{ik\cdot x - iq\cdot y}\langle p'|\mathrm{T}\{\bar{c}\gamma^{\mu}c(x)J^{\nu}_{em}(y)\}|p\rangle$$

OPE between the elemag current and an interpolating operator of J/ψ in the regime

$$Q^2 \gg M_V^2 \gg m_N^2 \qquad Q^2 \gg |t|$$



$$i\int d^4r e^{ir\cdot q}\bar{c}\gamma^{\mu}c(0)\bar{c}\gamma^{\nu}c(-r)$$

$$\approx -\frac{\alpha_s(\mu_R)}{3\pi q^2}\left[2\ln(-q^2/\mu_R^2)\left\{\left(g^{\mu\alpha}-\frac{q^{\mu}q^{\alpha}}{q^2}\right)\left(g^{\nu\beta}-\frac{q^{\nu}q^{\beta}}{q^2}\right)+\frac{q^{\alpha}q^{\beta}}{q^2}\left(g^{\mu\nu}-\frac{q^{\mu}q^{\nu}}{q^2}\right)\right\}\hat{T}^{g}_{\alpha\beta}(0)\right.$$
$$\left. -2\frac{q^{\alpha}q^{\beta}}{q^2}\left(g^{\mu\nu}-\frac{q^{\mu}q^{\nu}}{q^2}\right)\hat{T}^{g}_{\alpha\beta}(0)+3\frac{q_{\alpha}q_{\beta}}{q^2}F^{\mu\alpha}F^{\nu\beta}(0)\right],$$

gluon EMT (traceless part)

sensitive to the trace anomaly

Numerical results

Assume dipole form factor for $A_g, \bar{C}_g$, tripole for D_g

$$A_g(t) = \frac{A_g(0)}{(1-t/m_A^2)^2}, \qquad A_q(t) = \frac{1-A_g(0)}{(1-t/m_A^2)^2},$$

$$D_g(t) = \frac{D_g(0)}{(1-t/m_C^2)^3}, \qquad \bar{C}_g(t) = \frac{\bar{C}_g(0)}{(1-t/m_A^2)^2}.$$

$A_g(0)$ momentum fraction carried by gluons

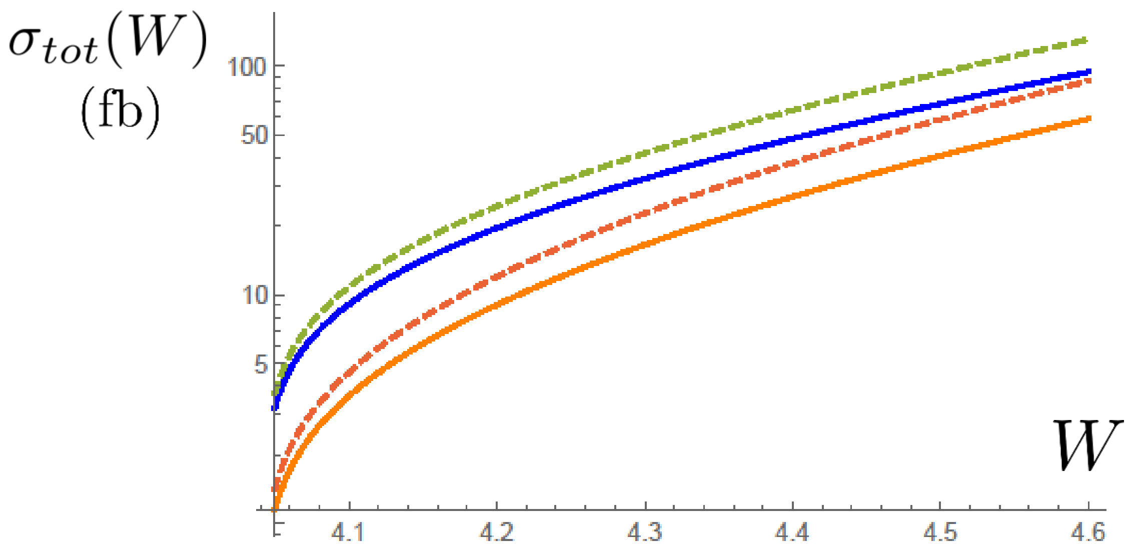
$D_g(0)$ from Shanahan, Detmold (2019)

Use the asymptotic value

$$\langle P|\frac{\beta}{2g}F^2|P\rangle = 2M^2(1-b)$$

$$\bar{C}_g(0) \approx \frac{1}{4}\left(\frac{n_f}{4C_F+n_f}+\frac{2n_f}{3\beta_0}\right) - \frac{1}{4}\left(\frac{2n_f}{3\beta_0}+1\right)\frac{b}{1+\gamma_m},$$

J/ψ $\quad Q^2 = 64\,\mathrm{GeV}^2 \quad \sqrt{S_{ep}} = 20\,\mathrm{GeV}$ (plots revised from 2004.12715)



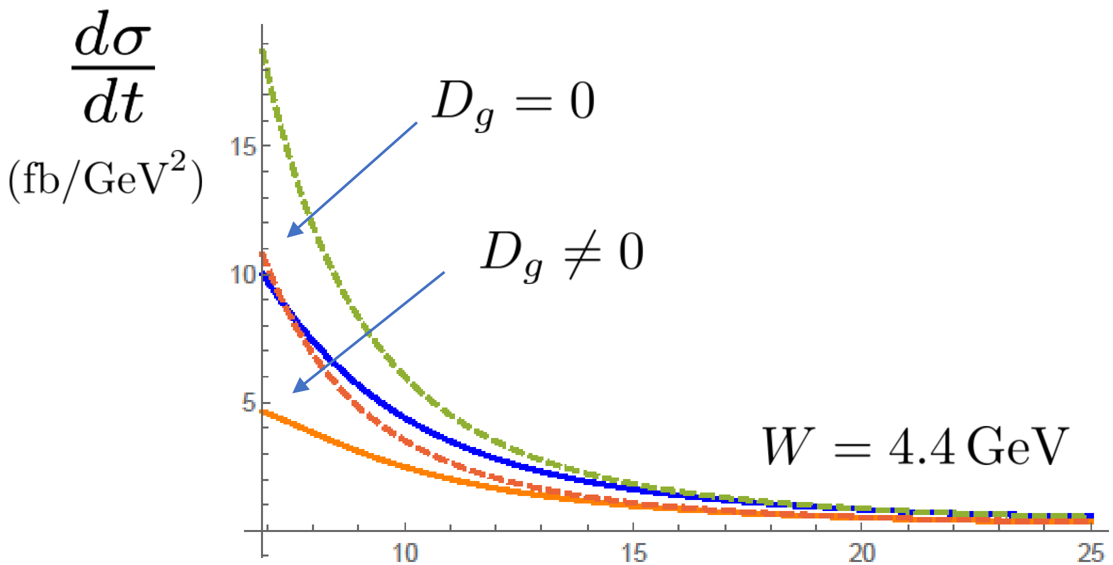
Dashed curves:
without gluon D-term

Solid curves: with gluon D-term

Upper solid $\quad b = 1$

Lower solid $\quad b = 0$

$$\langle P | \frac{\beta}{2g} F^2 | P \rangle = 2M^2(1-b)$$



Conclusions

Quark and gluon parts of the trace anomaly

$$T^\mu_\mu = (T_q)^\mu_\mu + (T_g)^\mu_\mu$$ → scheme dependent, definition of $\bar{C}_{q,g}$

Not only of conceptual interest. Needed to establish connection between the scattering amplitude and the parameter b in the $\overline{\mathrm{MS}}$ scheme.

Near-threshold quarkonium photo- and lepto-production
→ gluon condensate, gluon D-term. (In VMD approaches, connection to D-term is lost.)

Υ theoretically cleaner, but cross section smaller $\mathcal{O}(10^{-2})$
In practice, lepto-production viable only for J/ψ? Can be done at EIC, EIcC?

Sub-threshold production in γA also interesting,
probe the short range correlation (SRC) in the nucleus. YH, Strikman, Xu, Yuan (2019)