Brookhaven National Laboratory

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Near-threshold quarkonium photo/leptoproduction

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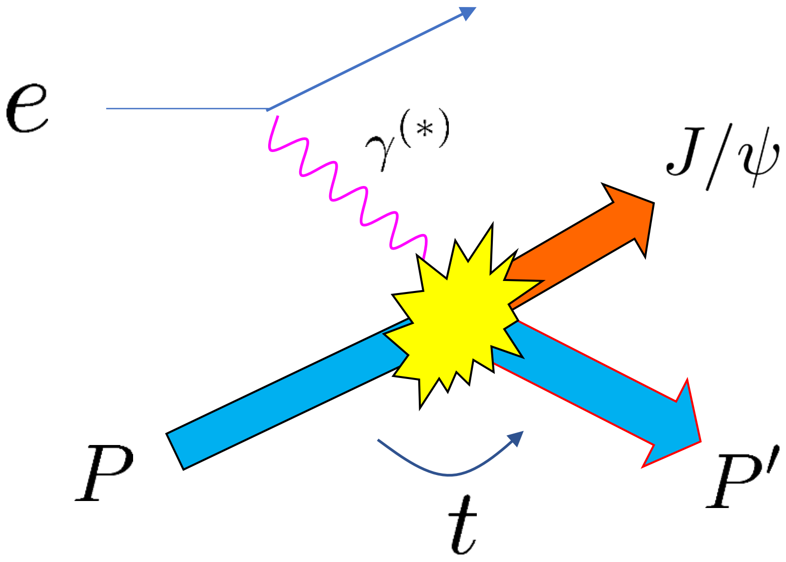
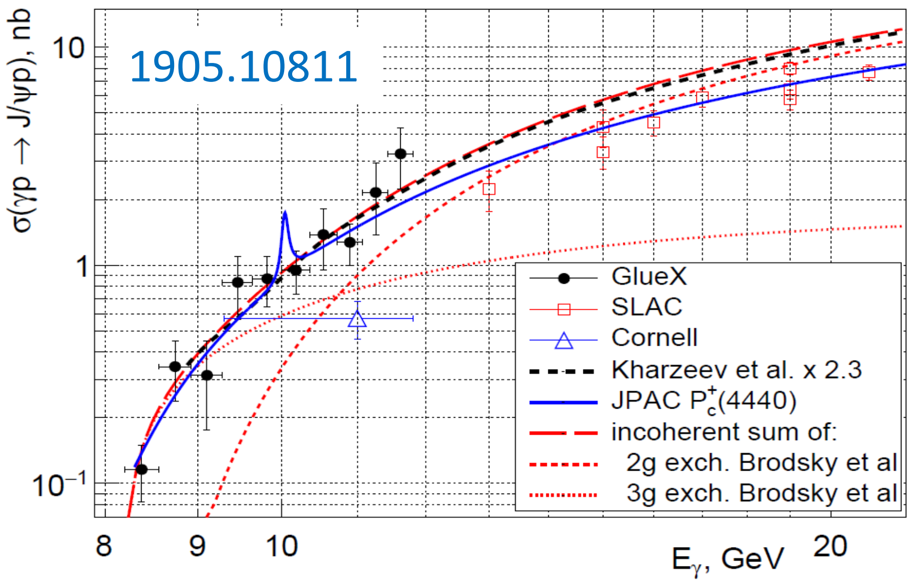
Jlab workshop J/Psi and beyond, August 16-17, 2022

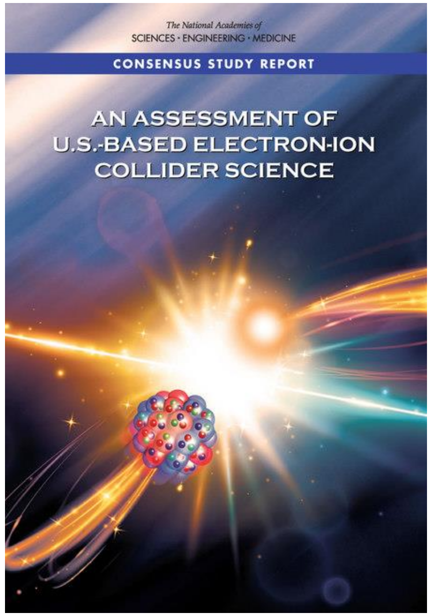
Photo-production of J/ψ near threshold





Ongoing experiments at Jlab, future measurement at EIC, and Jlab24GeV?

One of the main motivations: Insight into the origin of proton mass

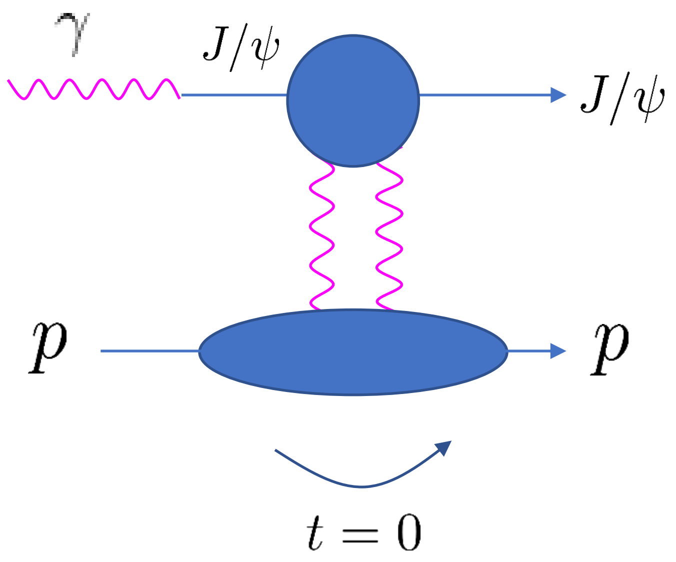


Is the connection clear?
What else can one learn from this process?
Is lepto-production $Q^2 \neq 0$ also useful? What about Υ ?

Theory approach 1: Vector meson dominance + heavy quark OPE

Kharzeev, Satz, Syamtomov, Zinovjev (1998)

Use VMD to reduce $\gamma p \to J/\psi p$ to forward $J/\psi p \to J/\psi p$
$(t=0)$



Interaction between J/ψ and proton via local gluonic operators in the limit $m_c \to \infty$

Peskin (1979), Luke, Manohar, Savage (1992)

$$\mathcal{L}_{\rm int} = \sum_v \frac{1}{\Lambda_Q^3} \left(P_v^\dagger P_v - V_{\mu v}^\dagger V_v^\mu\right)\left(c_E \mathcal{O}_E + c_B \mathcal{O}_B\right)$$

$$\mathcal{O}_E = T^{\mu\nu}_{\rm gluon} v_\mu v_\nu + \frac{2\pi}{b_Q \alpha_s(\Lambda_Q)} T^\alpha_\alpha ,$$

$$\mathcal{O}_B = T^{\mu\nu}_{\rm gluon} v_\mu v_\nu - \frac{2\pi}{b_Q \alpha_s(\Lambda_Q)} T^\alpha_\alpha .$$

In the weak coupling limit $\alpha_s \ll 1$, the scalar (trace anomaly) term dominates

Experimental access to $\langle P|F^2|P\rangle$

Theory approach 2: Gluonic form factors

Near the threshold, $|t|$ can be large.

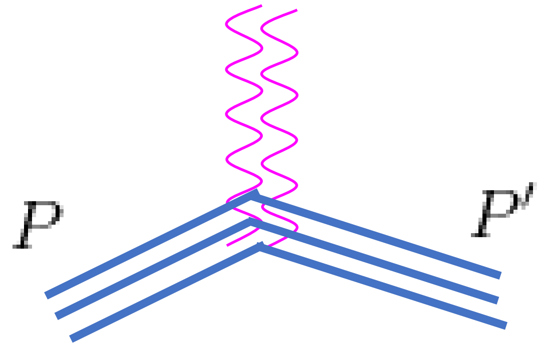
In the heavy-quark limit, the interaction should be governed by local gluonic operators.

Amplitude proportional to `2-gluon form factors’ Frankfurt, Strikman (2002)

$$\frac{d\sigma}{dt} \sim A^2(t) \sim \frac{1}{(1-t/m^2)^4}$$

In 2018, Di-lun Yang and I pointed out that these are the gravitational form factors including the gluon D-term.

Nucleon gravitational form factors



Off-forward matrix element of the QCD energy momentum tensor (EMT)

$$T^{\mu\nu} = -F^{\mu\alpha}F^{\nu}{}_{\alpha} + \frac{\eta^{\mu\nu}}{4}F^{\alpha\beta}F_{\alpha\beta} + \bar{\psi}i\gamma^{(\mu}D^{\nu)}\psi$$

$$\langle P'|T^{\mu\nu}|P\rangle = \bar{u}(P')\left[A(t)\gamma^{(\mu}\bar{P}^{\nu)} + B(t)\frac{\bar{P}^{(\mu}i\sigma^{\nu)\alpha}\Delta_\alpha}{2M} + D(t)\frac{\Delta^\mu\Delta^\nu - g^{\mu\nu}\Delta^2}{4M}\right]u(P)$$

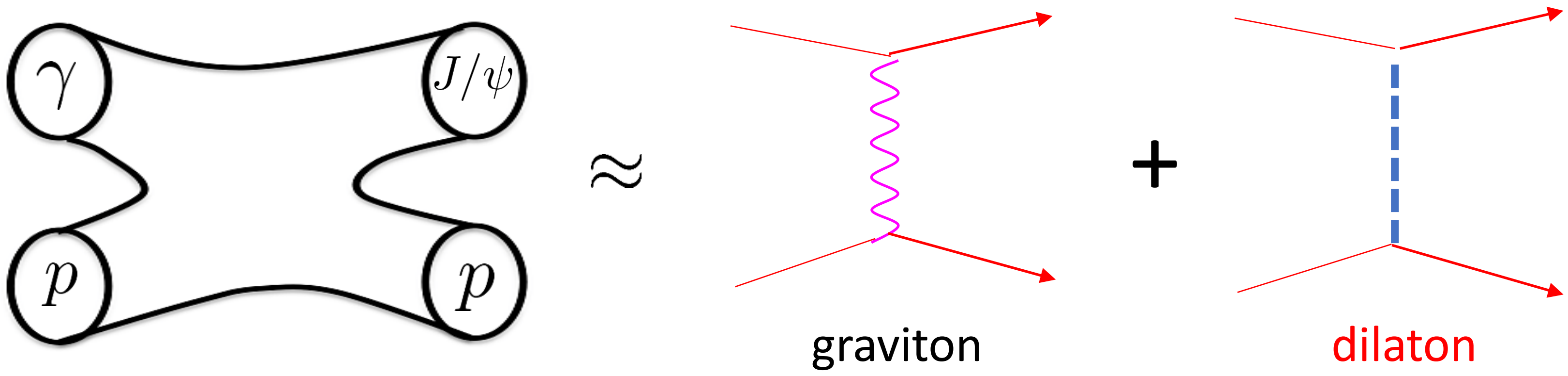
A, B relevant to Ji sum rule.

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

The value, even the sign, is unknown at the moment. No entry in the Particle Data Group.

Holographic approach

YH, Yang (2018); YH, Rajan, Yang (2019)
Mamo and Zahed (2019~), next talk by Kiminad

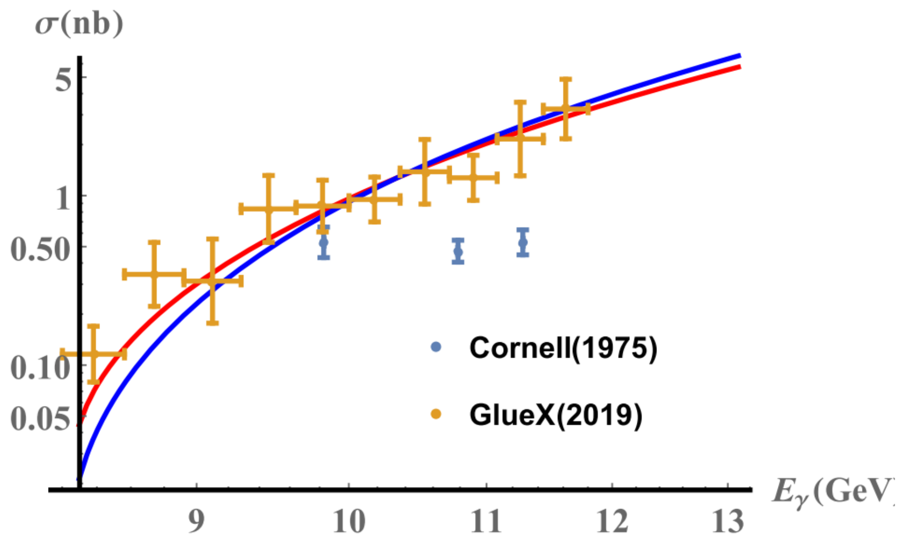


dual to $T^{\mu\nu}$

dual to F^2

In a field theory language, at strong coupling, only $T^{\mu\nu}$ and $F^{\mu\nu}F_{\mu\nu}$ survive in the OPE.

Other operators (higher spin, higher twist) have a large anomalous dimension and get suppressed.

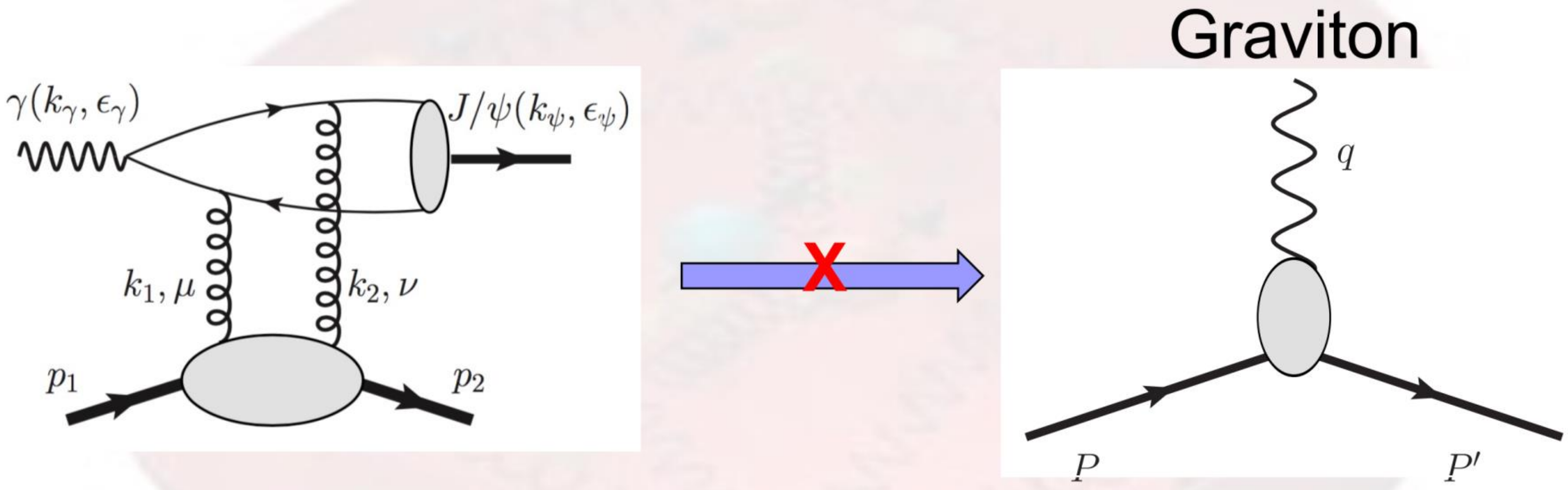


Theory approach 3: perturbative gluon exchange at large-$|t|$

Sun, Tong, Yuan (2021)
F. Yuan, talk at a workshop @ Virginia Tech (July 2022)

There is no direct connection to the gluonic gravitational form factors

It is a long stretch to make this connection

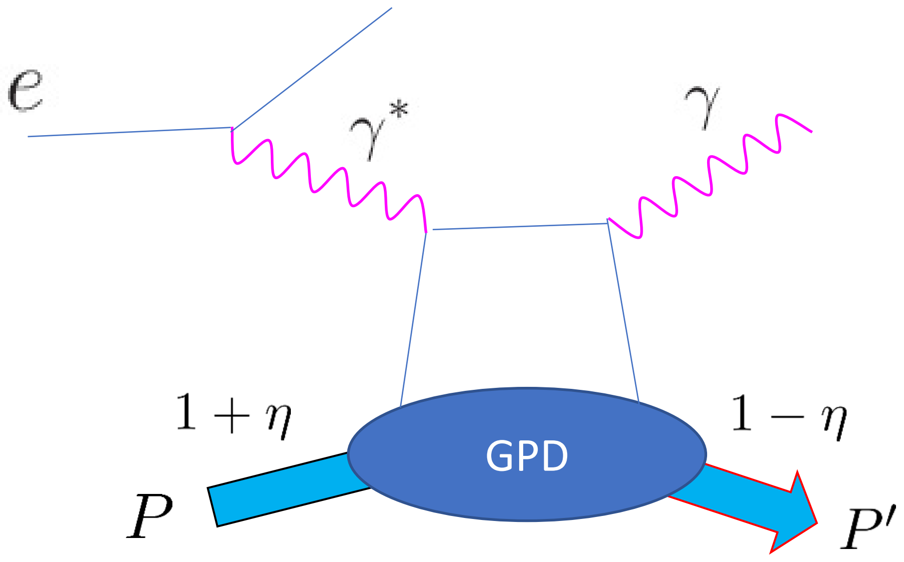


- There are other approaches to threshold production (Du, et al., Kharzeev, Wang et al.,…). Theory not converging.

- In this talk, I try to clarify under what assumptions and in what sense threshold quarkonium production is sensitive to GFFs.

Deeply Virtual Compton Scattering (DVCS)

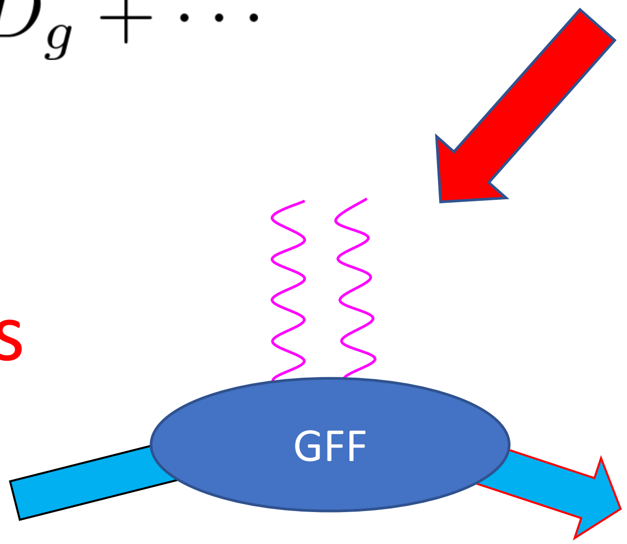
Experimental access to GPDs

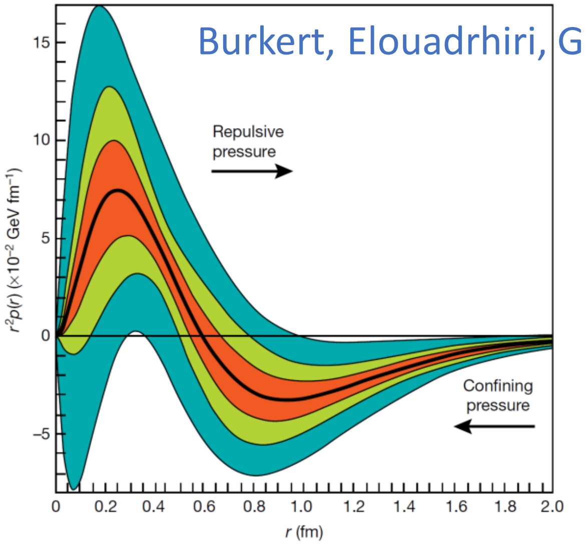


Maybe we can also access GFFs, in particular the quark D-term!?

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

1 graviton $\approx$ 2 photons





Burkert, Elouadrhiri, Girod (2018)

Extraction of (quark) D-term from DVCS

$D_{u,d}$ related to the subtraction constant in the dispersion relation for the Compton form factor

Teryaev (2005)

$$\mathrm{Re}\mathcal{H}_q(\xi,t) = \frac{1}{\pi}\int_{-1}^{1} dx \mathrm{P}\frac{\mathrm{Im}\mathcal{H}_q(x,t)}{\xi - x} + 2\int_{-1}^{1} dz \frac{D_q(z,t)}{1-z}$$

HOWEVER, this is not directly proportional to what we want $\int_{-1}^{1} dz z D_q(z,t) = D_q(t)$

The difference is due to twist-2, higher-spin ($j > 2$) operators $\bar{q}\gamma^+(\overleftrightarrow{D}^+)^{j-1}q$

Two-photon state probes not just EMT ($j = 2$), but infinitely many higher spin operators.

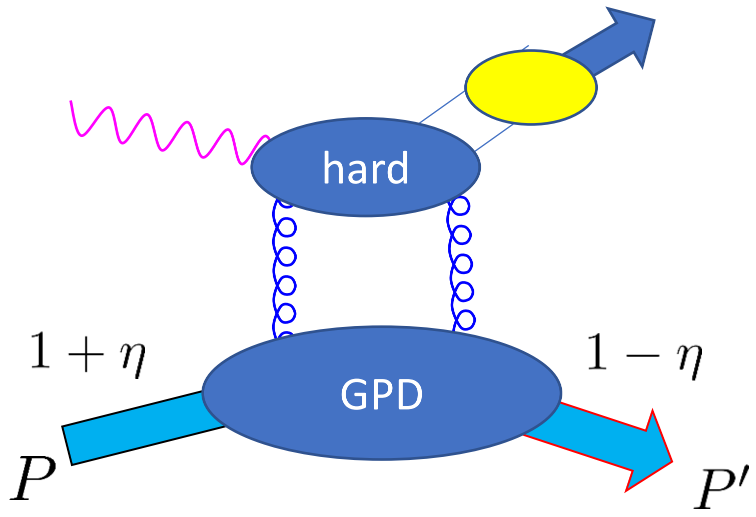
In other words, there is no direct connection to the gravitational form factors.

Theory approach 4: QCD factorization

Light-cone dominance when $Q^2 \to \infty$ or $M_{QQ} \to \infty$

GPD factorization at high energy Collins, Frankfurt, Strikman (1996)
Ivanov, Schafer, Szymanowski, Krasnikov (2004)

Let's assume factorization is valid and see what happens.



Amplitude proportional to Compton form factor

$$\int_{-1}^{1} \frac{dx}{x} \left(\frac{1}{\eta - x - i\epsilon} - \frac{1}{\eta + x - i\epsilon} \right) H_g(x,\eta,t)$$

Gluon GPD

Skewness $\eta = \frac{P^+ - P'^+}{P'^+ + P^+}$

1 graviton $\approx$ 2 gluons ??

- We are in a dilemma. GPD factorization allows us to study this reaction from first principles. But it also means that we are dealing with infinitely many twist-2 operators.

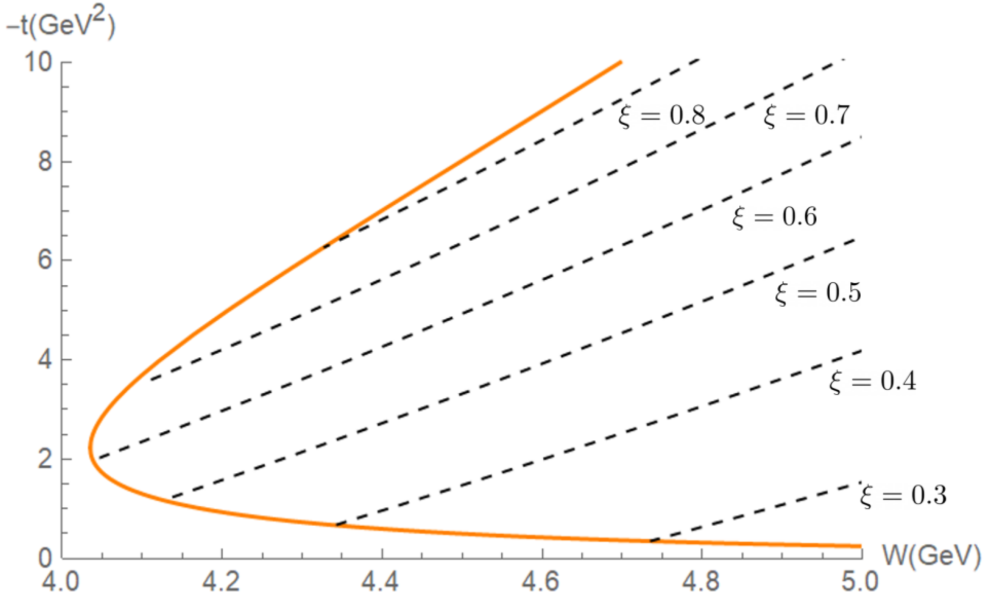
- The role of EMT is unclear, exactly the same problem as in the extraction of the quark D-term from DVCS. Cf. Sun, Tong, Yuan (2021)

- This is not what we wanted!

- However, a surprise is coming…

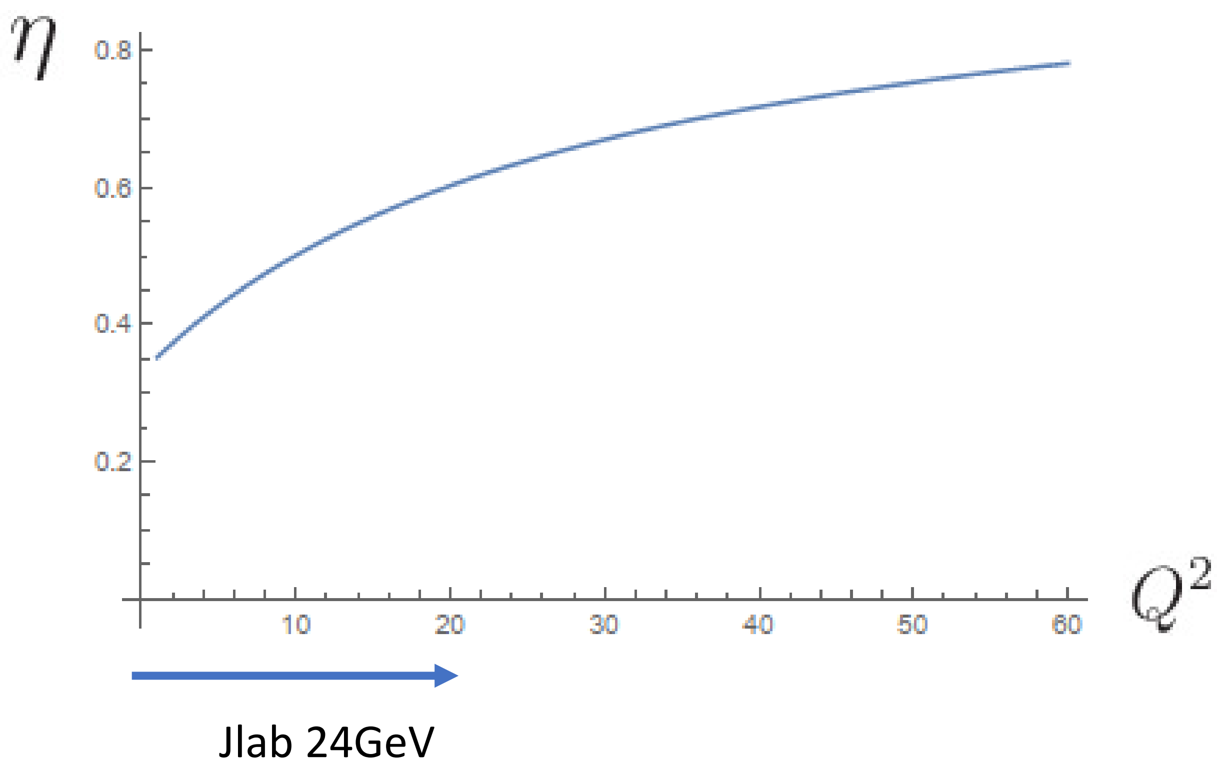
Skewness

J/ψ Photoproduction



Guo, Ji, Liu (2021)

Electro-production $|t| \ll Q^2$ $W = 4.5\,\mathrm{GeV}$



In the ideal limits $Q^2 \to \infty$ or $m_V \to \infty$ $\eta \approx 1$

Energy momentum tensor strikes back

YH, Strikman (2021) (appendix)
Guo, Ji, Liu (2021)

If (and only if) $\eta \approx 1$, one can Taylor expand.

$$\frac{1}{1-x} = 1 + x + x^2 + \cdots$$

spin=2 (energy momentum tensor)

$$\int_{-1}^{1} \frac{dx}{x}\left(\frac{1}{\eta - x - i\epsilon} - \frac{1}{\eta + x - i\epsilon}\right) H_g(x,\eta,t) \approx 2\int dx(1+x^2+x^4+\cdots)H_g(x,\eta,t)$$

spin=4 spin=6

Asymptotic form $H_g(x,\eta=1) \approx (1-x^2)^2$

all spins $\displaystyle \int dx \frac{H_g(x,\eta=1,t)}{1-x^2} \sim \int_0^1 dx \frac{(1-x^2)^2}{1-x^2} = \frac{2}{3}$

spin-2 only $\displaystyle \int_0^1 dx (1-x^2)^2 = \frac{8}{15}$ ← 80% of the total (100% in AdS/CFT)

EMT dominates over all the other twist-2 operators combined!

- At least in the limit of $Q^2 \to \infty$ or $m_V \to \infty$, threshold quarkonium production is dominated by the energy-momentum tensor

  → connection to gluon GFFs.

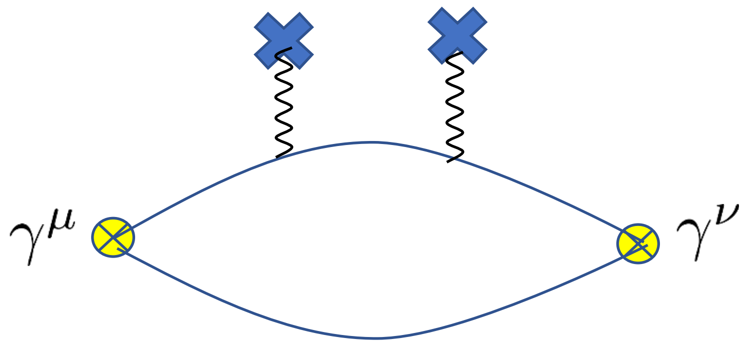
- We are not as fortunate in the case of quark GFFs in DVCS (40% instead of 80% YH, Strikman (2021))

- We should aim at either Υ photoproduction or J/ψ (or maybe ϕ) leptoproduction at high Q^2 to make η larger. Neither is possible at the current Jlab energy.

Including the trace anomaly

Boussarie, YH (2020)

In the GPD approach, only the component T_g^{++} is kept.
Why not keep all components of $T_g^{\mu\nu}$?



Local OPE between photon and J/ψ interpolating operators

$$
\begin{aligned}
& i \int d^4 r e^{ir\cdot q} \bar{c}\gamma^\mu c(0) \bar{c}\gamma^\nu c(-r) \\
& \approx -\frac{\alpha_s(\mu_R)}{3\pi q^2}\left[2\ln(-q^2/\mu_R^2)\left\{\left(g^{\mu\alpha}-\frac{q^\mu q^\alpha}{q^2}\right)\left(g^{\nu\beta}-\frac{q^\nu q^\beta}{q^2}\right)+\frac{q^\alpha q^\beta}{q^2}\left(g^{\mu\nu}-\frac{q^\mu q^\nu}{q^2}\right)\right\}\hat{T}^g_{\alpha\beta}(0)\right. \\
& \left. -2\frac{q^\alpha q^\beta}{q^2}\left(g^{\mu\nu}-\frac{q^\mu q^\nu}{q^2}\right)\hat{T}^g_{\alpha\beta}(0)+3\frac{q_\alpha q_\beta}{q^2}F^{\mu\alpha}F^{\nu\beta}(0)\right],
\end{aligned}
$$

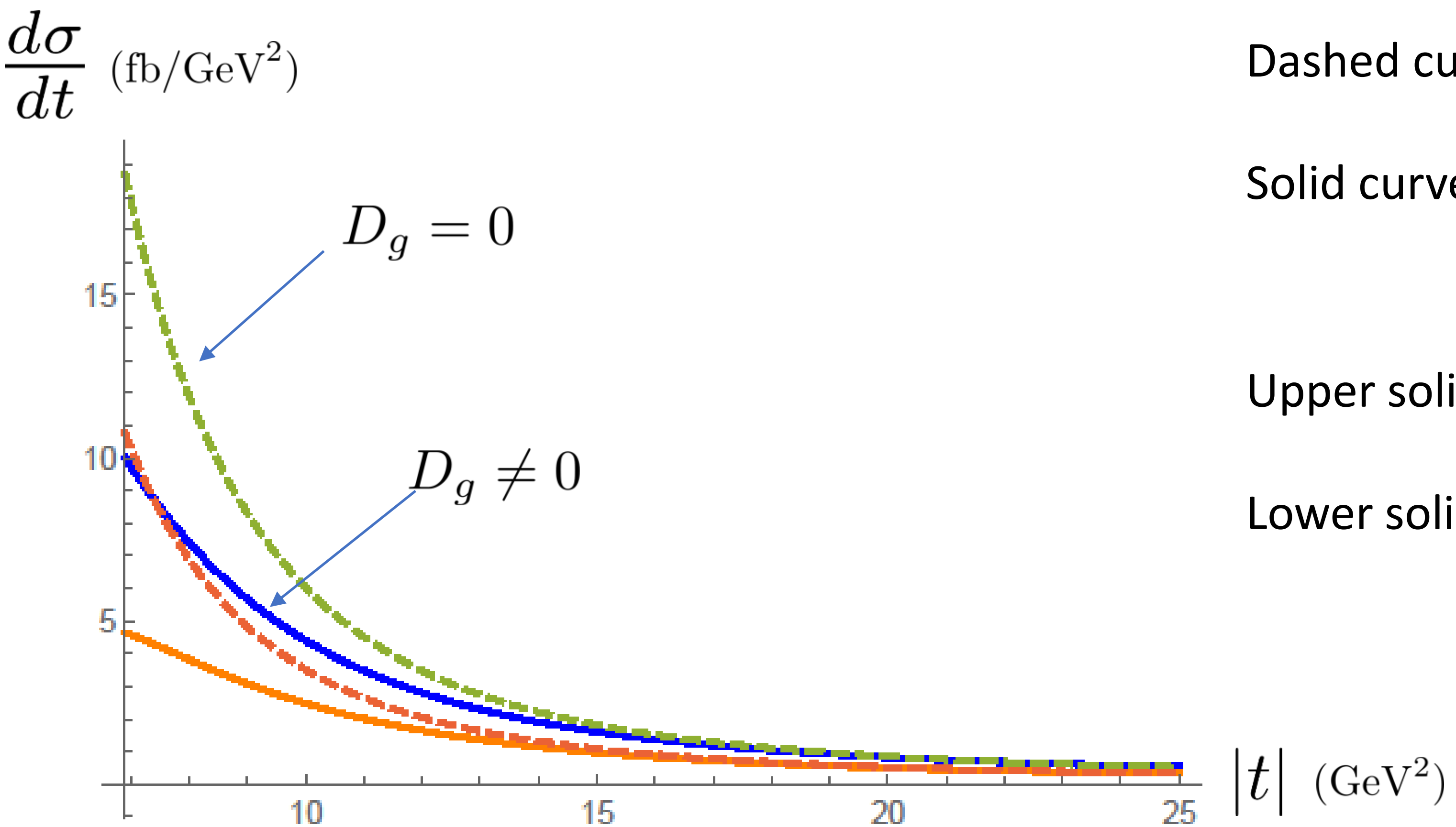
gluon EMT (traceless part)

sensitive to the gluon condensate $F^{\mu\nu}F_{\mu\nu} \sim \frac{1}{\alpha_s} T^\mu_\mu$

Prediction for the Electron-Ion Collider (EIC)

Boussarie, YH (2020)

$J/\psi \quad Q^2 = 64\,\mathrm{GeV}^2 \quad \sqrt{S_{ep}} = 20\,\mathrm{GeV} \qquad W = 4.4\,\mathrm{GeV}$



Dashed curves: without gluon D-term

Solid curves: with gluon D-term

Upper solid $b = 1$

Lower solid $b = 0$

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

Conclusion

Quarkonium threshold production at large Q or M_{QQ} is characterized by

1. gluon dominance
2. large skewness

This unique combination allows us to access the gluon gravitational form factors.

Connection to glueballs, trace anomaly, proton mass, pressure,...
tackling the most challenging problems of QCD

$$D(|\vec{k}|) \sim \sum_{n=1}^{\infty} \frac{c_n^{\mathrm{T}}(|\vec{k}|)}{\vec{k}^2 + (m_n^{\mathrm{T}})^2} + \sum_{n=1}^{\infty} \frac{c_n^{\mathrm{S}}(|\vec{k}|)}{\vec{k}^2 + (m_n^{\mathrm{S}})^2}$$

\`Glueball dominance'

Fujita, YH, Sugimoto, Ueda, arXiv:2206:06578