Near-threshold quarkonium production and the nucleon gravitational form factors

Yoshitaka Hatta

BNL/RIKEN BNL

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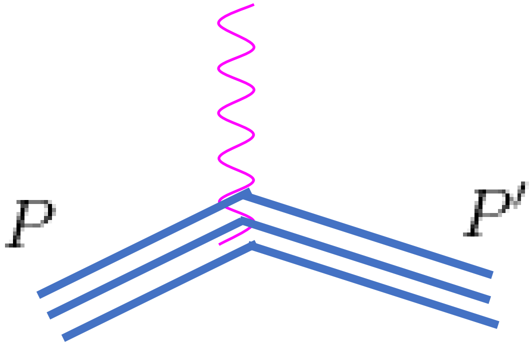
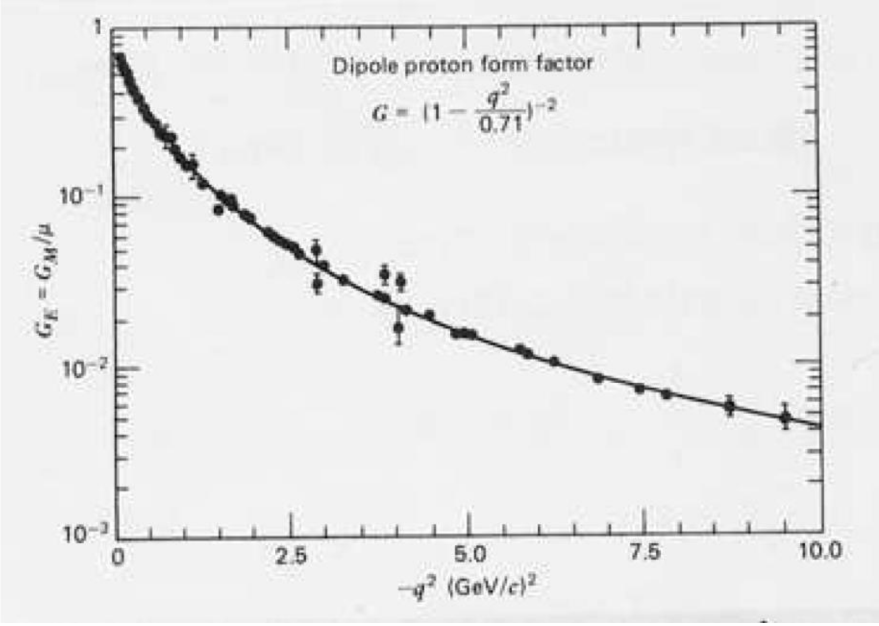
- Quark GFF from DVCS
- Gluon GFF from near-threshold quarkonium production

Proton electromagnetic form factors

$$\langle p', \sigma' | J^\mu | p, \sigma \rangle = \bar{u}_{p',\sigma'} \left[F_1(Q^2)\gamma^\mu + F_2(Q^2)\frac{i\sigma^{\mu\nu}q_\nu}{2m_N} - F_3(Q^2)\frac{\gamma_5\sigma^{\mu\nu}q_\nu}{2m_N} \right] u_{p,\sigma}$$



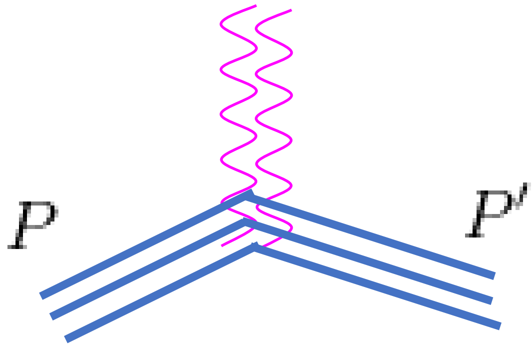


PRad (2019)

$$r_p = 0.831 \pm 0.007_{\rm stat} \pm 0.012_{\rm syst}$$

Over 70 years of experimental study.
Charge radius known to percent-level accuracy!

Nucleon gravitational form factors



Off-forward matrix element of the QCD energy momentum tensor

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

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

Form factors associated with scattering off a graviton
Width of GFF→ mass radius of proton

Can we measure these form factors in experiments?

D-term: the last global unknown

$D(t=0)$ is a fundamental conserved charge of the proton

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

Spatial components of the energy momentum tensor
→ May be interpreted as radial `pressure' exerted by quarks and gluons

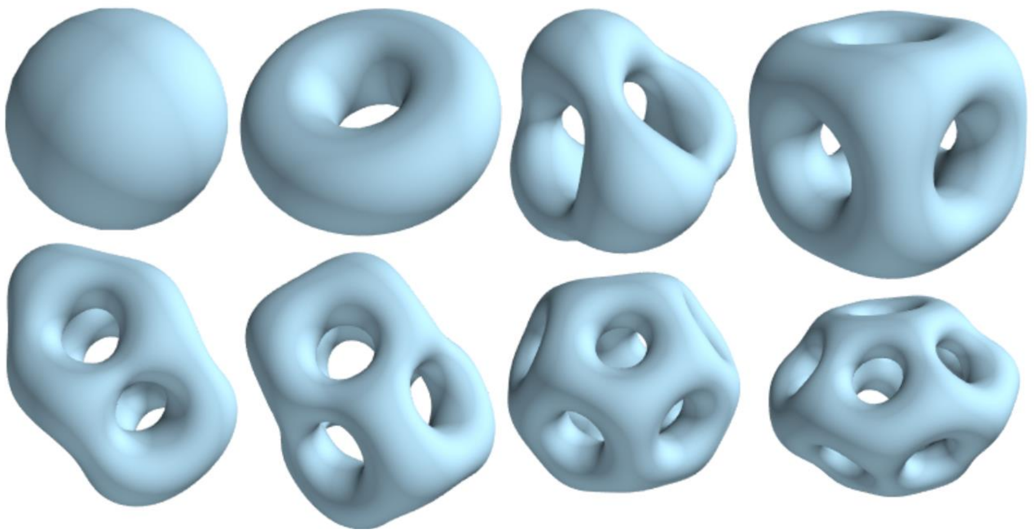
$$T^{ij}(\boldsymbol{r}) = \left(\frac{r^i r^j}{r^2} - \frac{1}{3}\delta^{ij}\right) s(r) + \delta^{ij}\, p(r) \qquad D = M\int d^3r\, r^2 p(r)$$

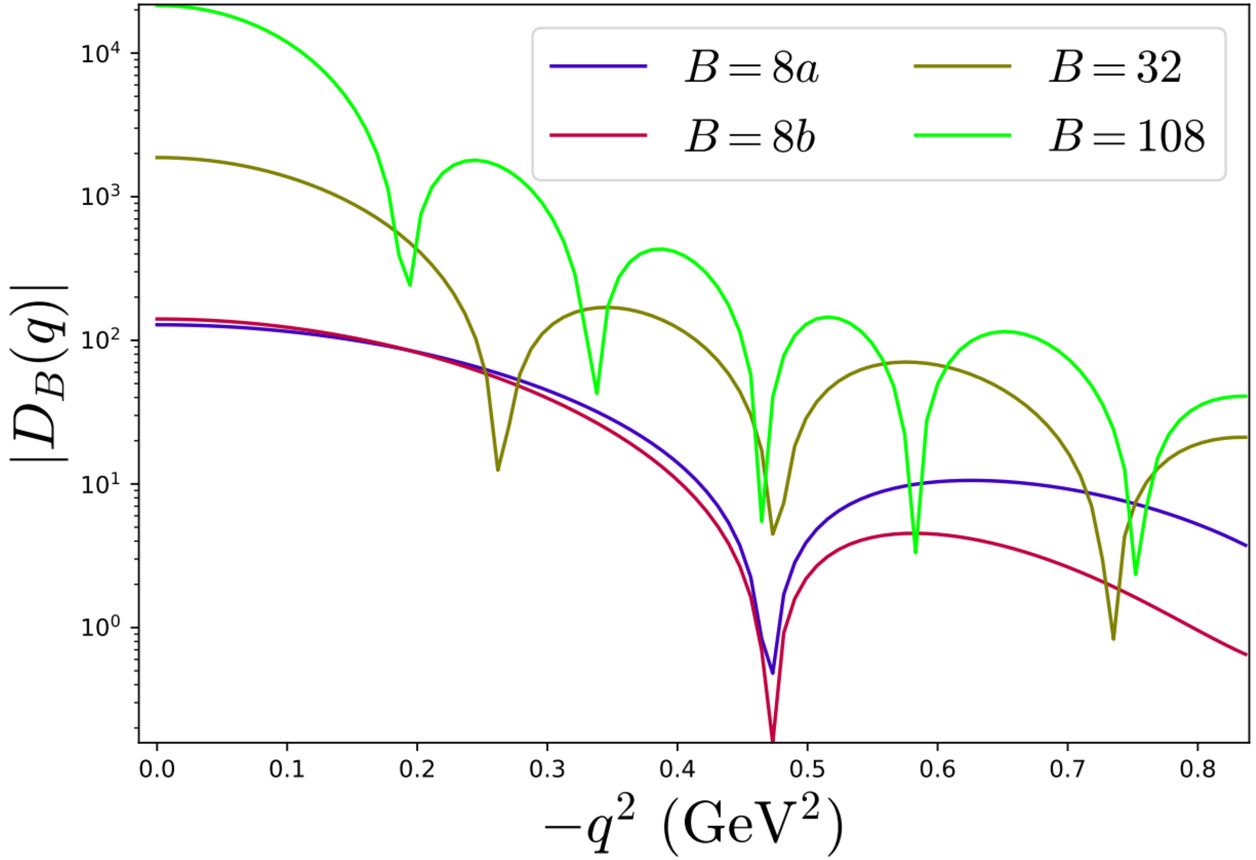
Conjecture: Stable hadrons must have a negative D-term $D(t=0) < 0$

D-term of nuclei in the Skyrme model

Martin-Caro, Huidobro, YH, 2304.05994 (preprint today)

Skyrmion solutions known up to B=108



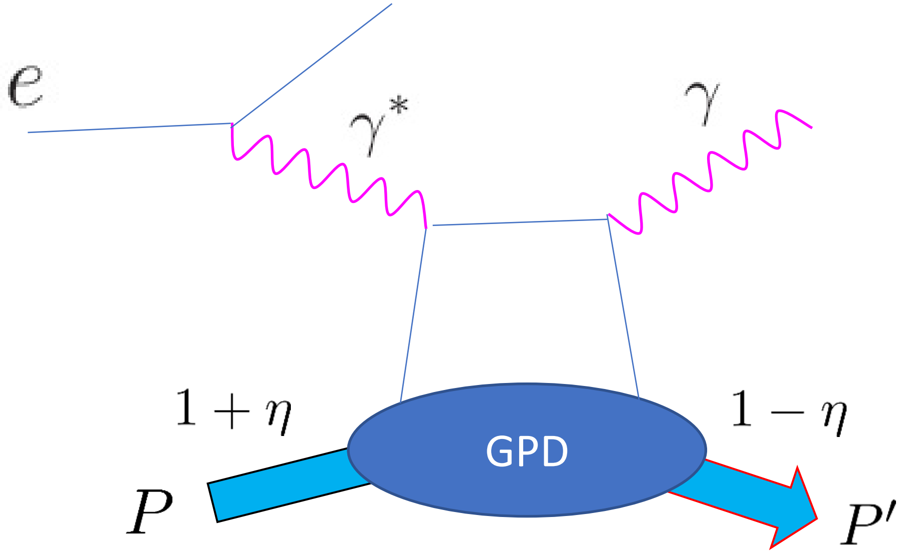


Giant D-term for massive nuclei

Form factor resembles the diffractive pattern in elastic scattering

Deeply Virtual Compton Scattering (DVCS)

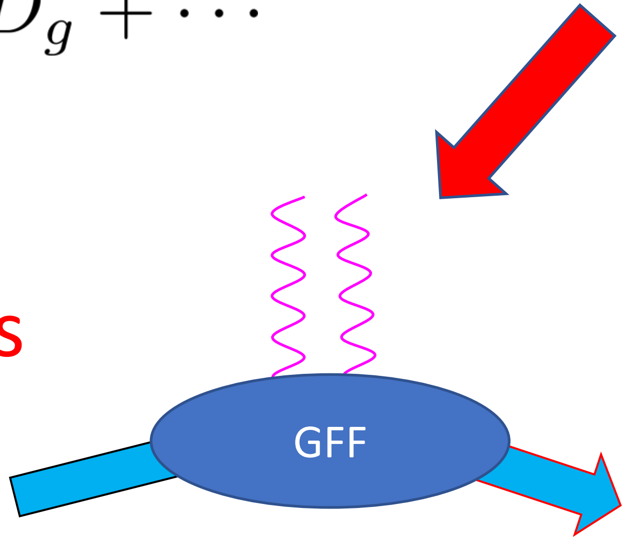
Experimental access to GPDs

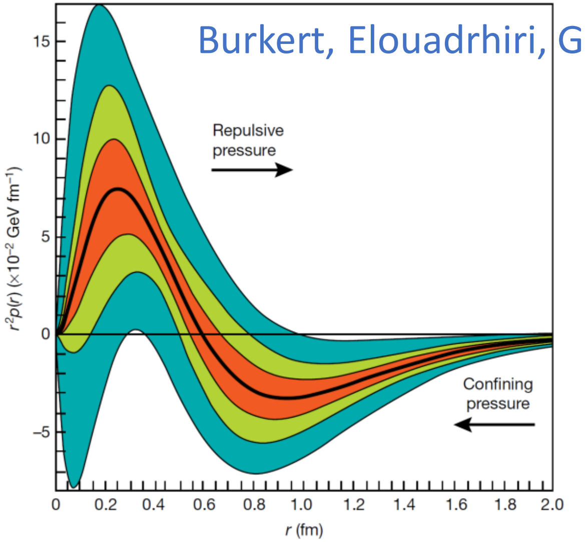


Moments of GPDs → GFFs
Can access the quark D-term?

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

1 graviton ≈ 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)

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

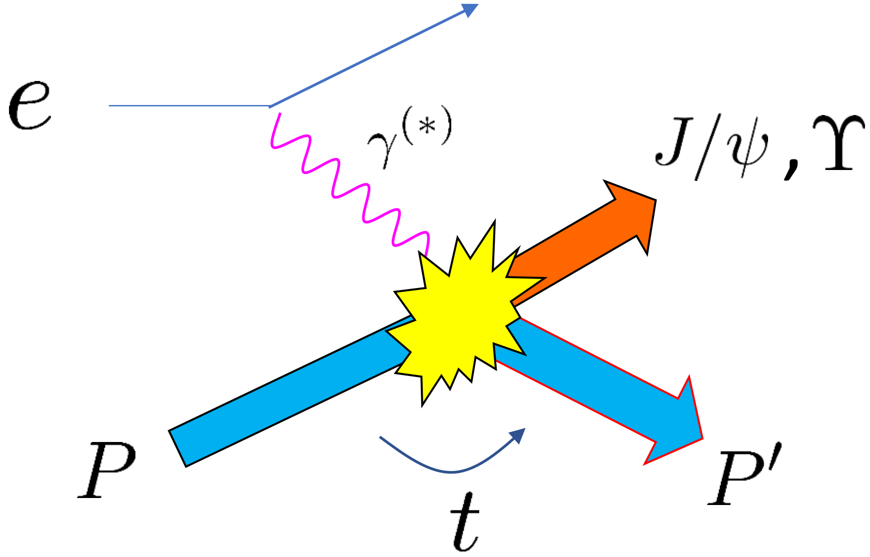
HOWEVER, this is not directly proportional to what we want $\int_{-1}^{1} dz z D_q(z,t) = D_q(t)$

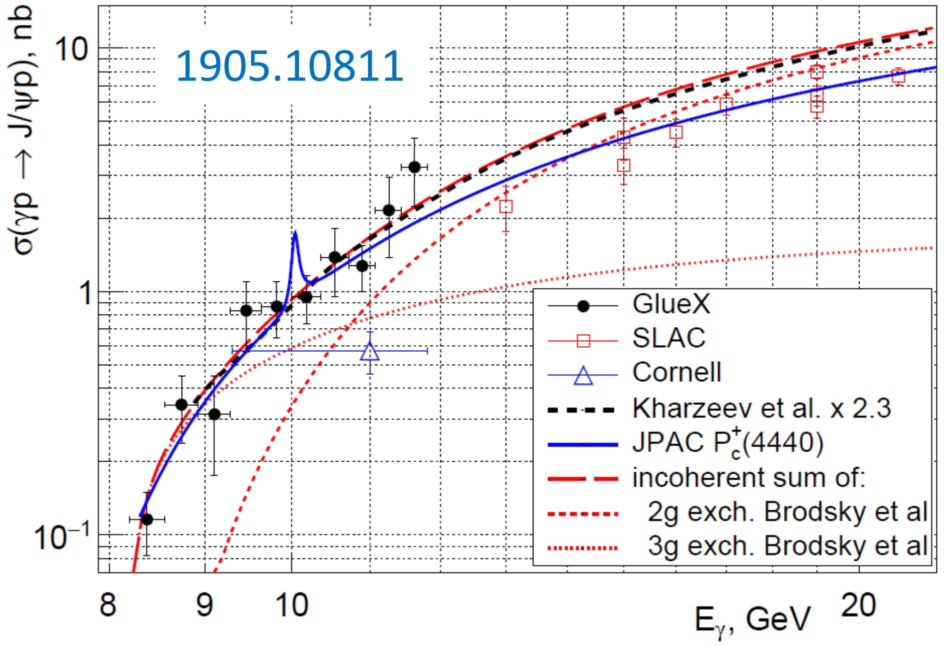
The difference is due to twist-2, higher-spin ($j>2$) operators $\bar{q}\gamma^+(\overleftrightarrow{D}^+)^{j-1}q$

Two-photon state couples to not just the energy momentum tensor, but infinitely many higher spin operators.

There is no controlled parameter to suppress higher spin contributions.

Quarkonium photo-production near threshold

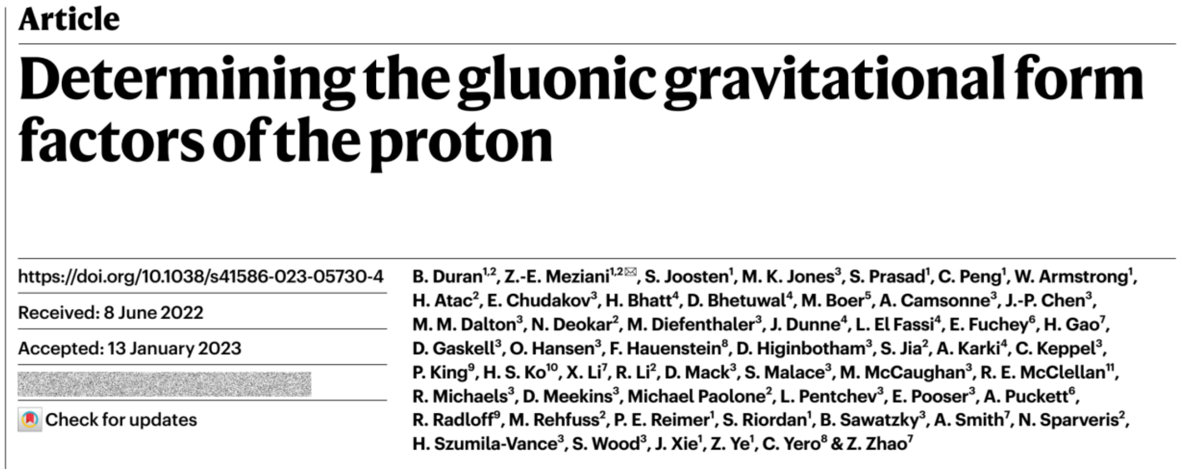




Ongoing experiments at Jlab,
future measurement at EIC, RHIC?

Original motivation:
Insight into the origin of proton mass
Kharzeev, et at.(1997)

The process is also sensitive to GFFs, in particular, the gluon D-term   YH, Yang (2018)


Article

Determining the gluonic gravitational form factors of the proton

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Check for updates

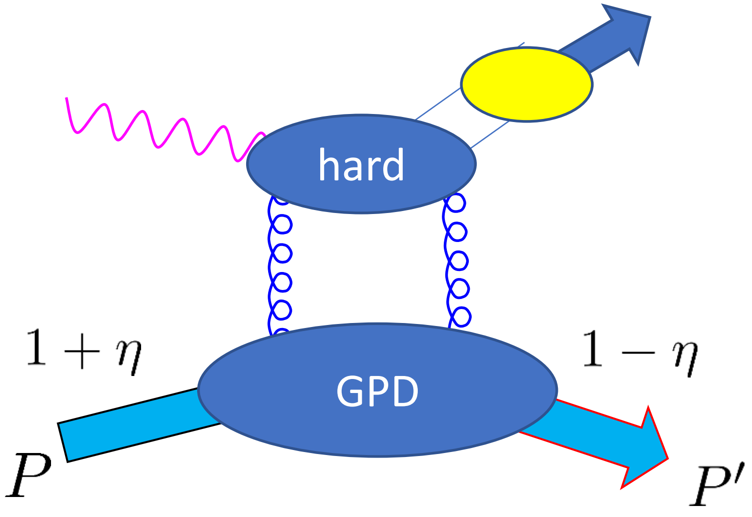
B. Duran[1,2], Z.-E. Meziani[1,2]✉, S. Joosten[1], M. K. Jones[3], S. Prasad[1], C. Peng[1], W. Armstrong[1], H. Atac[2], E. Chudakov[3], H. Bhatt[4], D. Bhetuwal[4], M. Boer[5], A. Camsonne[3], J.-P. Chen[3], M. M. Dalton[3], N. Deokar[2], M. Diefenthaler[3], J. Dunne[4], L. El Fassi[4], E. Fuchey[6], H. Gao[7], D. Gaskell[3], O. Hansen[3], F. Hauenstein[8], D. Higinbotham[3], S. Jia[2], A. Karki[4], C. Keppel[3], P. King[9], H. S. Ko[10], X. Li[7], R. Li[2], D. Mack[3], S. Malace[3], M. McCaughan[3], R. E. McClellan[11], R. Michaels[3], D. Meekins[3], Michael Paolone[2], L. Pentchev[3], E. Pooser[3], A. Puckett[6], R. Radloff[9], M. Rehfuss[2], P. E. Reimer[1], S. Riordan[1], B. Sawatzky[3], A. Smith[7], N. Sparveris[2], H. Szumila-Vance[3], S. Wood[3], J. Xie[1], Z. Ye[1], C. Yero[8] & Z. Zhao[7]

GPD 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)

Assume factorization is valid near the threshold (OK to leading order Guo, Ji, Liu (2021))



Amplitude proportional to Compton form factor

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

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

Gluon GPD

Connection to GFF?

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.

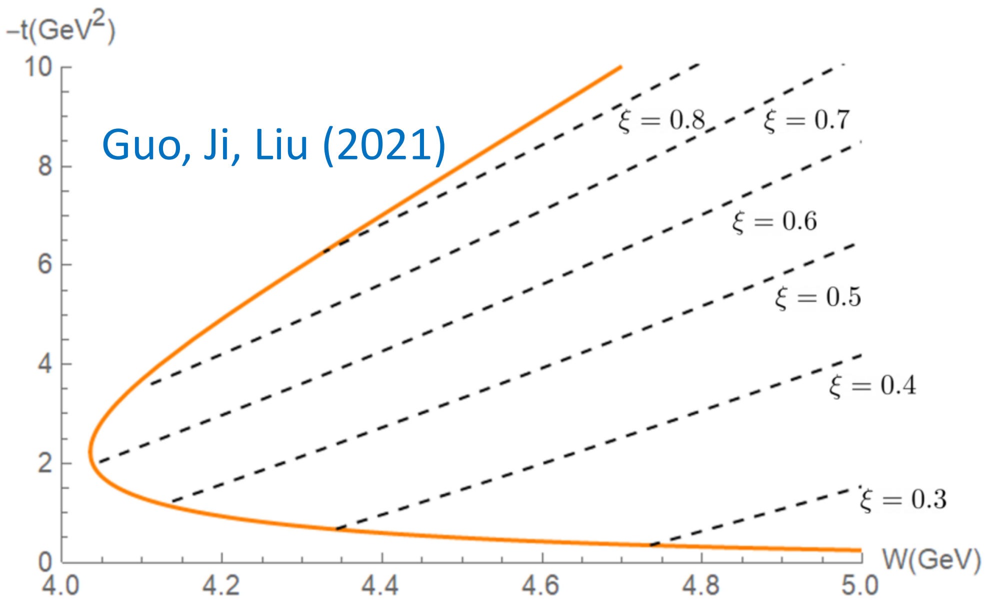
Connection to GFFs unclear. Cogent criticism by Sun, Tong, Yuan (2021)

> Clearly, from the above GPD formalism, one can only link to the gluonic gravitational form factors by making approximations of no x-dependence in the pre-factor $\frac{1}{(x+\xi-i\varepsilon)(x-\xi+i\varepsilon)}$ [26, 29]. This is the same as we discussed

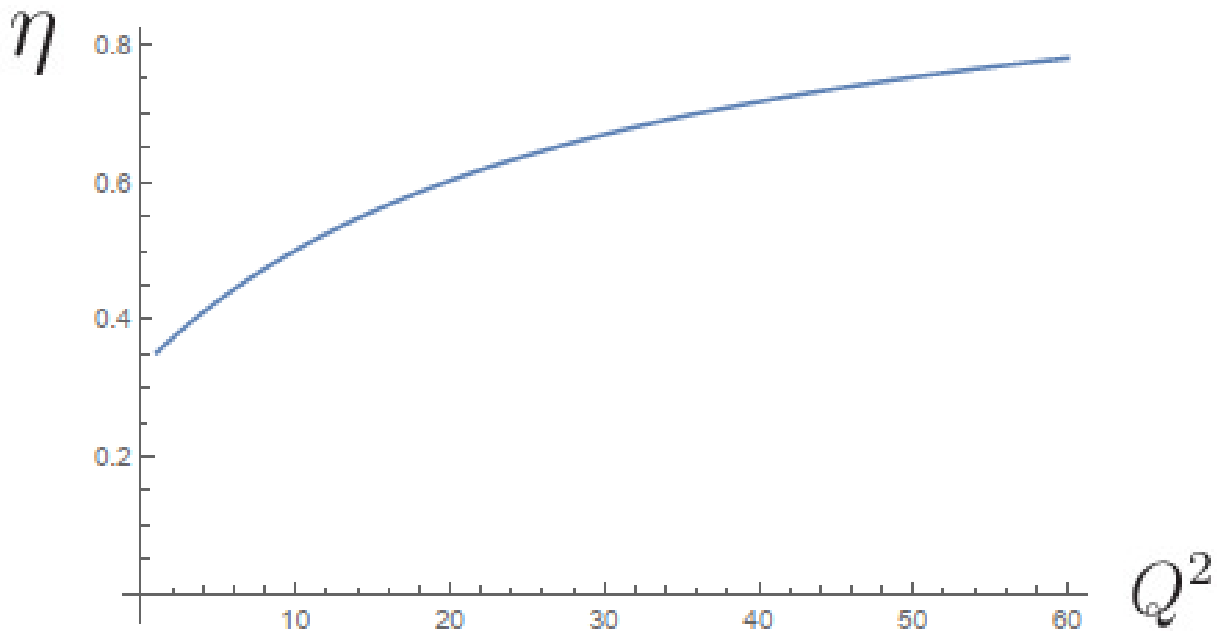
Essentially the same criticism applies to the extraction of the quark D-term in DVCS.

Skewness

J/ψ Photoproduction



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



Threshold production is characterized by large values of skewness

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

Energy momentum tensor strikes back

YH, Strikman (2021)
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 $$\int dx \frac{H_g(x,\eta=1,t)}{1-x^2} \sim \int_0^1 dx \frac{(1-x^2)^2}{1-x^2} = \frac{2}{3}$$

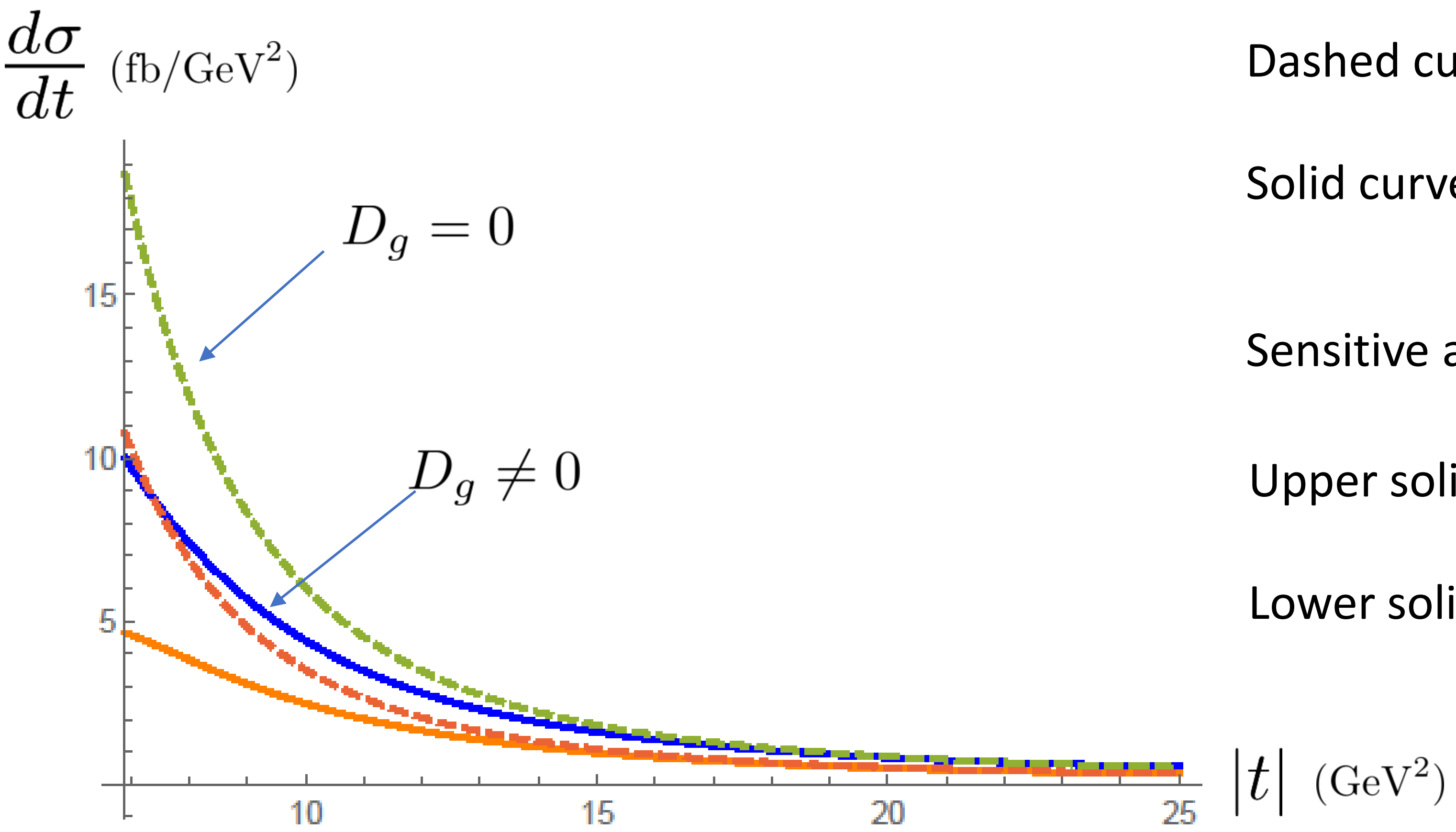
spin-2 only $$\int_0^1 dx (1-x^2)^2 = \frac{8}{15}$$ ← 80% of the total

Energy momentum tensor dominates over all the other twist-2 operators combined!

Prediction for the Electron-Ion Collider (EIC)

Boussarie, YH (2020)

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



Dashed curves: without gluon D-term

Solid curves: with gluon D-term

Sensitive also to the gluon condensate

Upper solid $b = 1$

Lower solid $b = 0$

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

Summary

Gravitational form factors and mechanical properties of the proton
→ One of the largely unexplored frontiers of nucleon science,
fits perfectly with the scope of EIC

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.

Make skewness larger by measuring

Υ photo-production,
J/ψ (maybe ϕ) electro-production at high Q^2