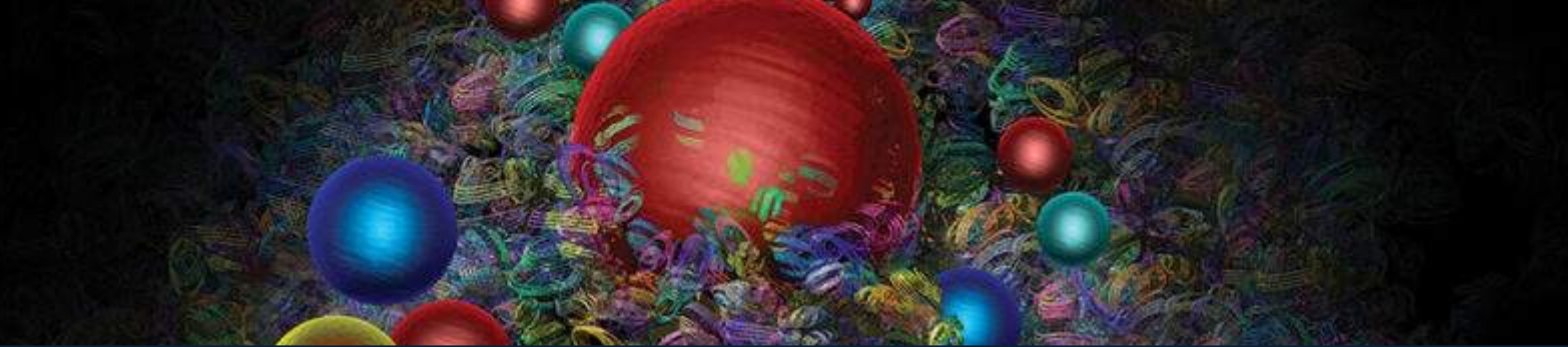

Probing the gravitational form factors of the nucleon from near-threshold heavy quarkonium photo-production

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[2308.13006]

Workshop on GPD for Nucleon Tomography in the EIC Era

Brookhaven National Laboratory, NY

Jan. 17 – 19 th, 2024

BERKELEY LAB

Brookhaven National Laboratory

RBRC RIKEN BNL Research Center

Outline

» Intro – Nucleon structure and gravitational form factors

» Quarkonium production and gluonic structure

» Approach the GFFs with Compton form factors

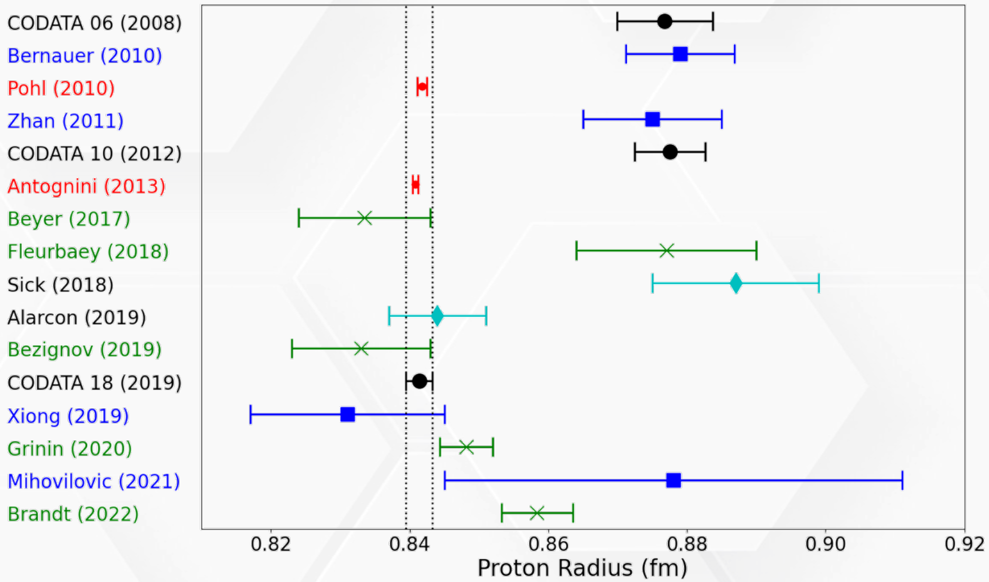
» Threshold J/psi production and proton GFFs

» Summary and outlook

Mass structure of the nucleon

Even though we can get the nucleon mass itself easily and precisely, counter-intuitively, the **mass structures** of microscopic particles are hard to access.

More than 100 years after we know the proton **charge**, we are still puzzled by its charge radius.



Plot by E. J. Downie at SPIN 2023 at Duke

We are doing worse on the proton **mass** structure, as gravitational scattering are much harder, if possible at all.

WE NEED THIS!

Energy-momentum tensor form factors

The energy-momentum tensor (EMT) is the tool to study the mechanical properties of the nucleon. Its nucleon matrix element can be written as:

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

X. Ji Phys. Rev. Lett. 78, 610 (1997)

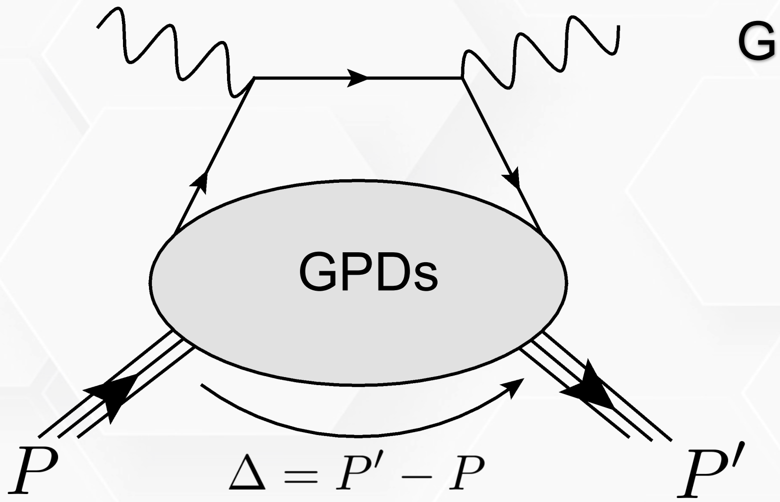
Momentum form factors: $A_{q,g}(t)$

Angular momentum form factors: $J_{q,g}(t) = \frac{1}{2}\left(A_{q,g}(t) + B_{q,g}(t)\right)$

Stress tensor form factors: $C_{q,g}(t)$

Generalized parton distributions (GPDs)

Instead of measuring the whole nucleon, we just knock out one parton at a time.



D. Muller et. al. Fortsch.Phys. 42 101 (1994)
X. Ji Phys. Rev. Lett. 78, 610 (1997)

GPDs are distributions unifying parton distributions and form factors

$$F(x, \Delta^\mu) = F(x, \xi, t)$$

x : average parton momentum fraction

ξ : skewness – longitudinal momentum transfer $\xi \equiv -n \cdot \Delta/2$

t : total momentum transfer squared $t \equiv \Delta^2$

GPDs are partonic form factors? — at zero skewness

Quarkonium Production

Color dipole probing the gluonic structure

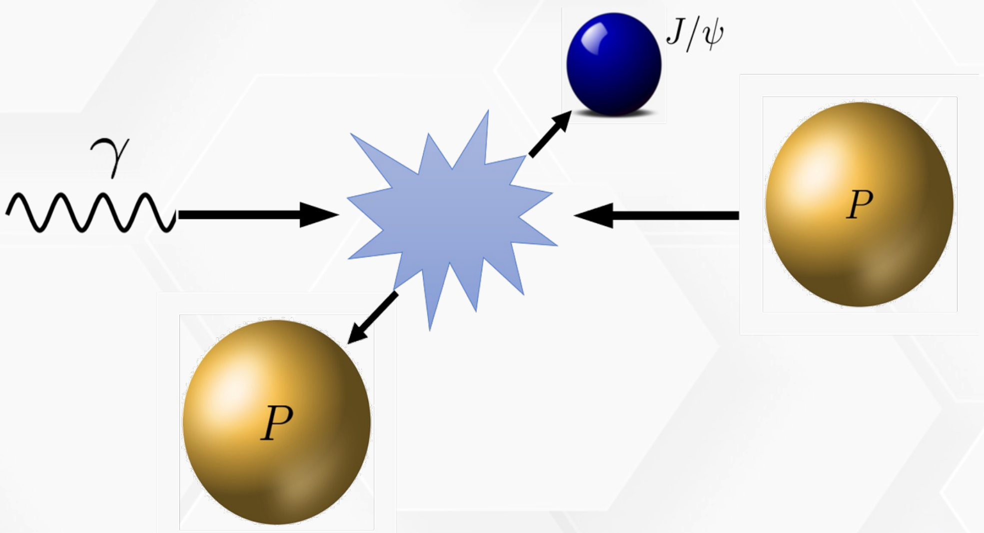
Quadratic Stark effect in QCD – measures the color electric field:

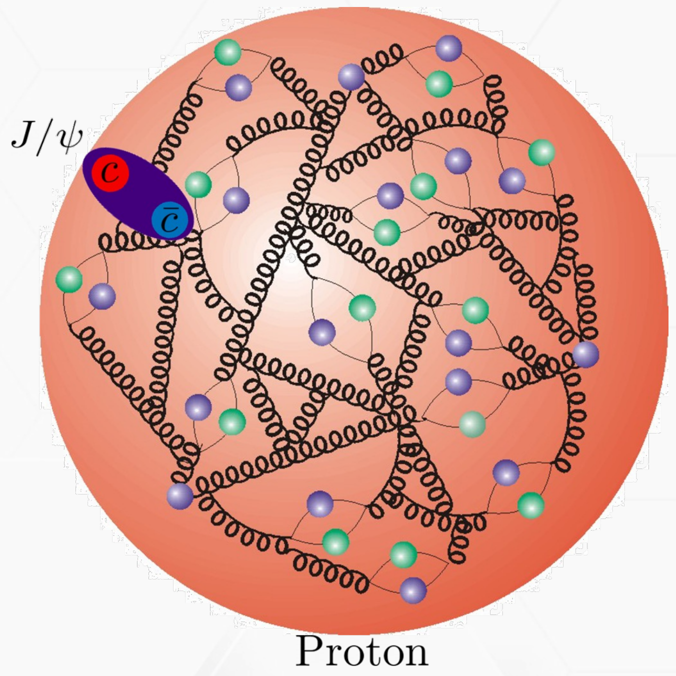
$$\mathcal{H}_{\text{Int}} = \mathbf{E}^a \cdot \left(\mathbf{r}_c t^a_c - \mathbf{r}_{\bar{c}} t^a_{\bar{c}}\right)$$

M. B. Voloshin Nucl. Phys. B 154 365-380 (1979)
M. Luke et al. Phys. Lett. B 288 355-359 (1992)
D. Kharzeev et al., Eur. Phys. J. C 9 459-462 (1999)

Elastic scattering of J/psi off the nucleon would be ideal.

In real life we have photo-/electro- production instead

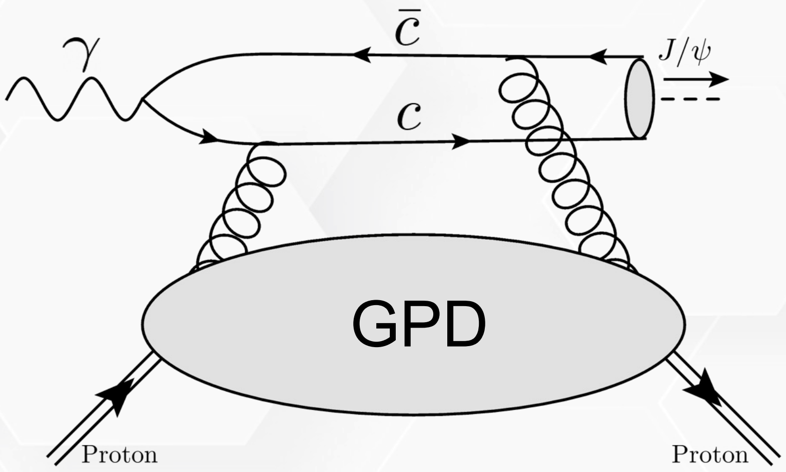




Heavy meson corresponds to small color dipole --- local gluonic distribution.

GPD framework for threshold production

Near-threshold exclusive heavy vector meson production in the GPD framework.



Y. Guo et. al. Phys. Rev. D 103 9, 096010 (2021)

- ❑ **Leading order factorization with GPDs**
- ❑ **The same amplitude as the collinear case but with different kinematics;**
- ❑ **Large momentum transfer/skewness in the heavy quark limit;**

$$\frac{d\sigma}{dt} \propto \left[\left(1-\xi^2\right)\left|\mathcal{H}_{gC}\right|^2 - 2\xi^2 \mathrm{Re}\left[\mathcal{H}^*_{gC}\mathcal{E}_{gC}\right] - \left(\xi^2+\frac{t}{4M_p^2}\right)\left|\mathcal{E}_{gC}\right|^2\right] ,$$

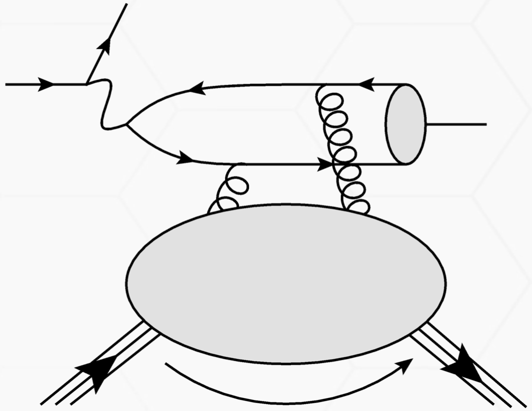
Will be sensitive to the so-called gluonic Compton form factors (gCFFs)

Inverse problem in exclusive productions

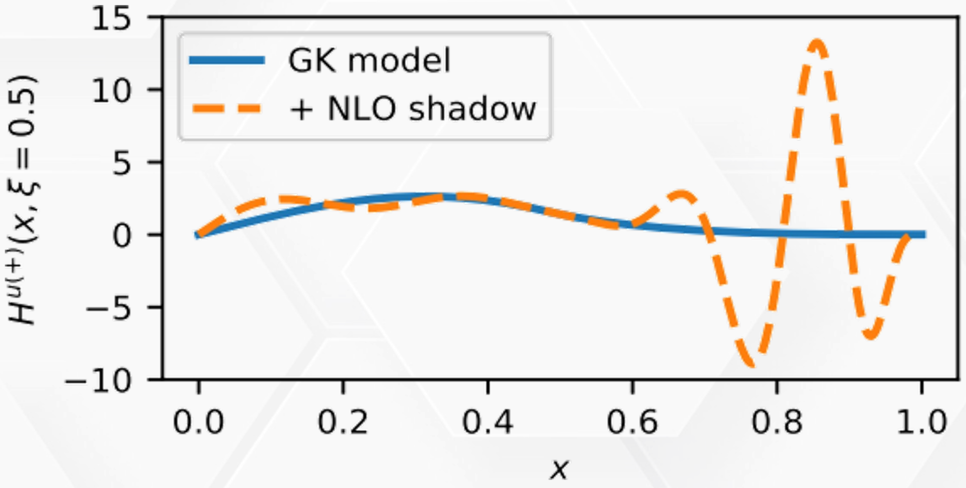
To keep the proton intact in the final state for an exclusive production,

the parton will not be explicitly probed / knocked out.

$$\mathcal{H}_{gC}(\xi,t)=\frac{1}{2\xi}\int_{-1}^{1}\mathrm{d}x\left(\frac{1}{x+\xi-i\epsilon}-\frac{1}{x-\xi+i\epsilon}\right)H_g(x,\xi,t)$$

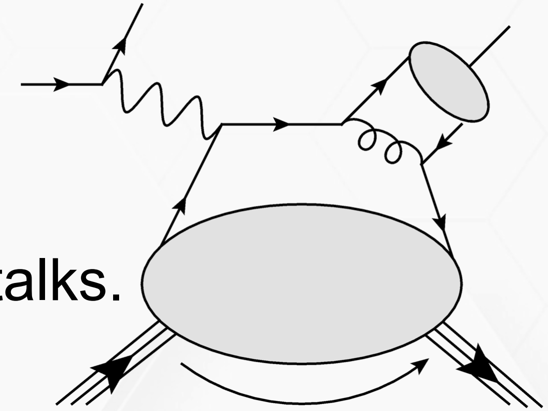


The amplitude is not sensitive to the parton momentum *x*

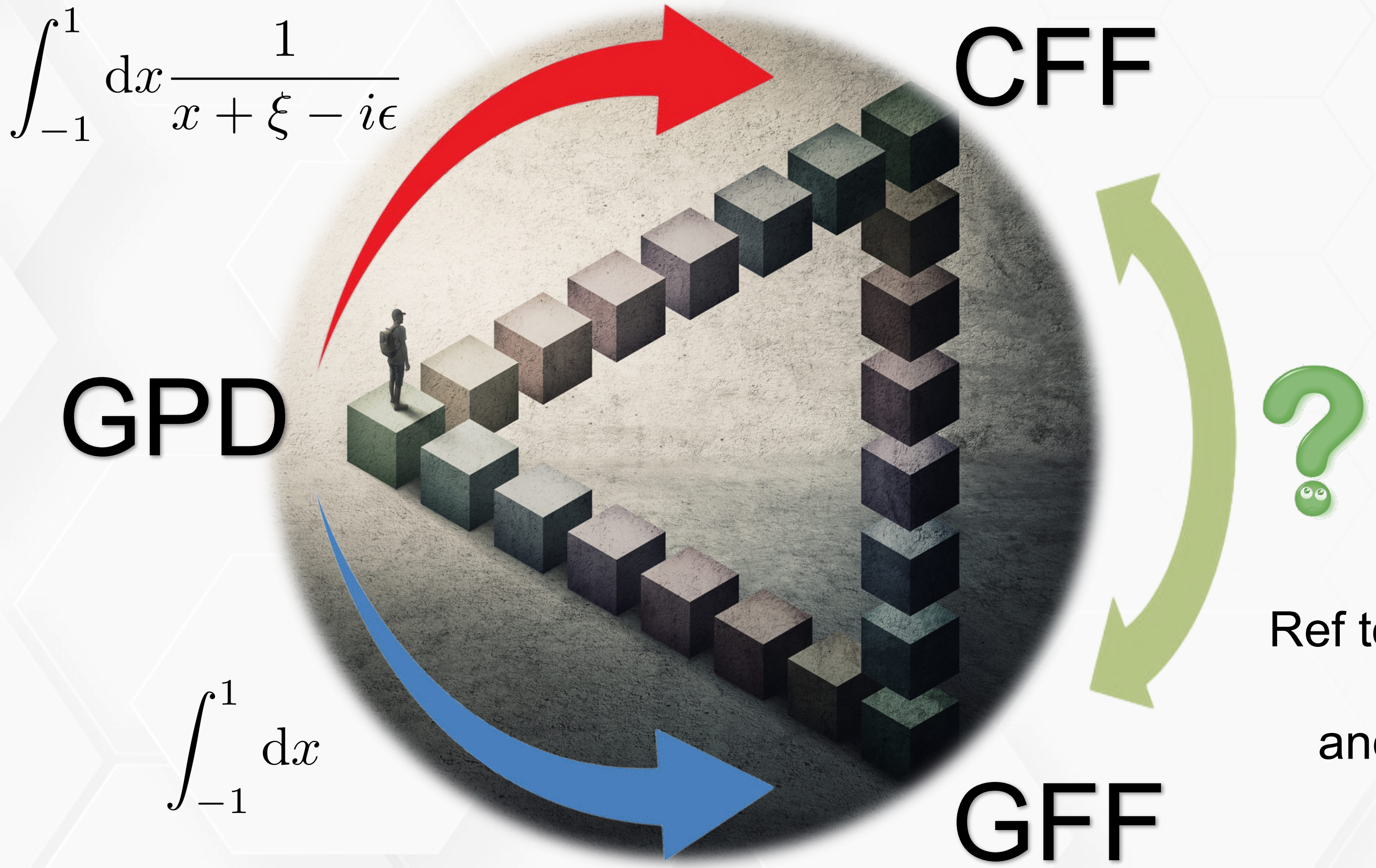


V. Bertone et. al. SciPost Phys.Proc. 8 (2022) 107

Ref. to the Most of talks.



GFFs and CFFs



Ref to P. Sznajder's Talk

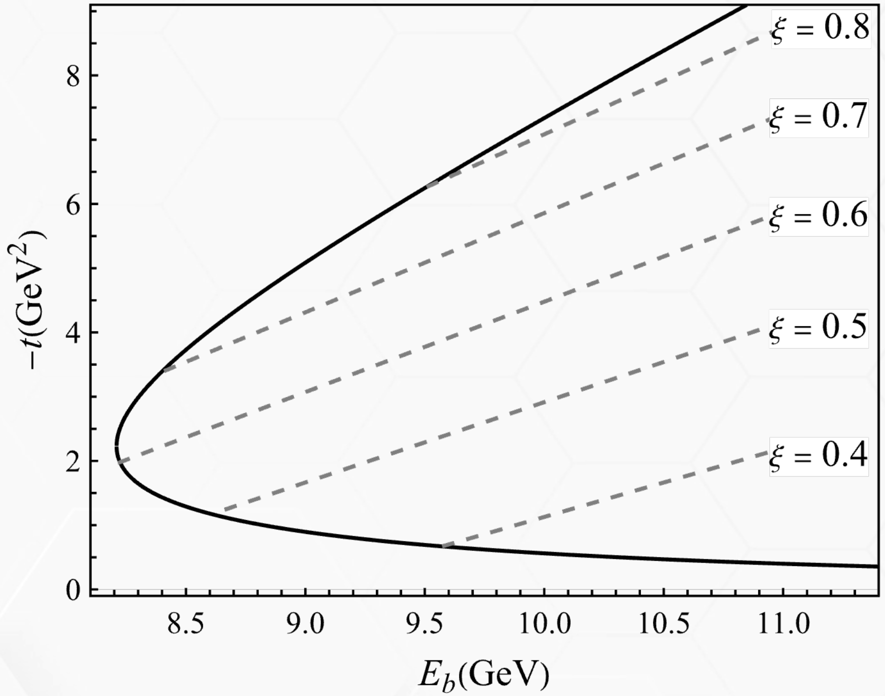
and B. Pasquini's Talk

From CFFs to GFFs

Large skewness near the threshold

When a heavy quarkonium is produced from a massless real photon near threshold, the momentum transfer must be large. Then consider a Taylor expansion:

$$\mathrm{Re}\left[\frac{1}{2\xi}\left(\frac{1}{x+\xi-i\epsilon}-\frac{1}{x-\xi+i\epsilon}\right)\right]=\sum_{n=0}^{\infty}\frac{x^{2n}}{\xi^{2+2n}}$$



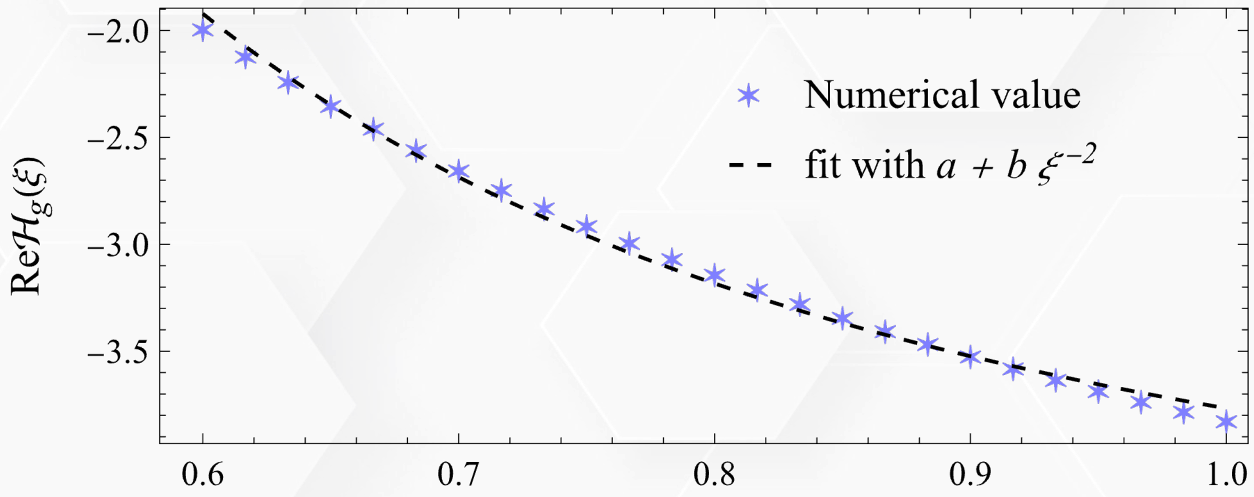
The real part of the CFF can then be written as:

$$\mathrm{Re}\mathcal{H}_{gC}(\xi,t)=\frac{2}{\xi^2}\sum_{n=0}^{\infty}\int_0^1 \mathrm{d}x\left(\frac{x}{\xi}\right)^{2n} H_g(x,\xi,t)$$

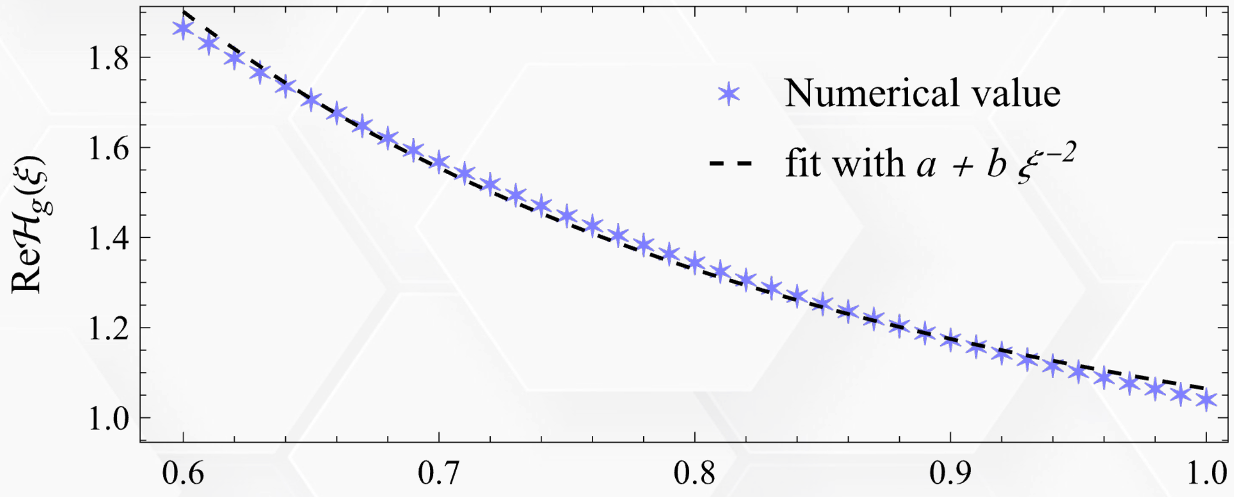
These x-integrals lead to generalized form factors

$$\mathrm{Re}\mathcal{H}_{gC}(\xi,t)=\mathcal{C}_g(t)+\sum_{n=1}^{\infty}\xi^{-2n}\mathcal{A}_g^{(2n)}(t)\overset{?}{\approx}\mathcal{C}_g(t)+\xi^{-2}\mathcal{A}_g^{(2)}(t)$$

Skewness-scaling in the CFFs



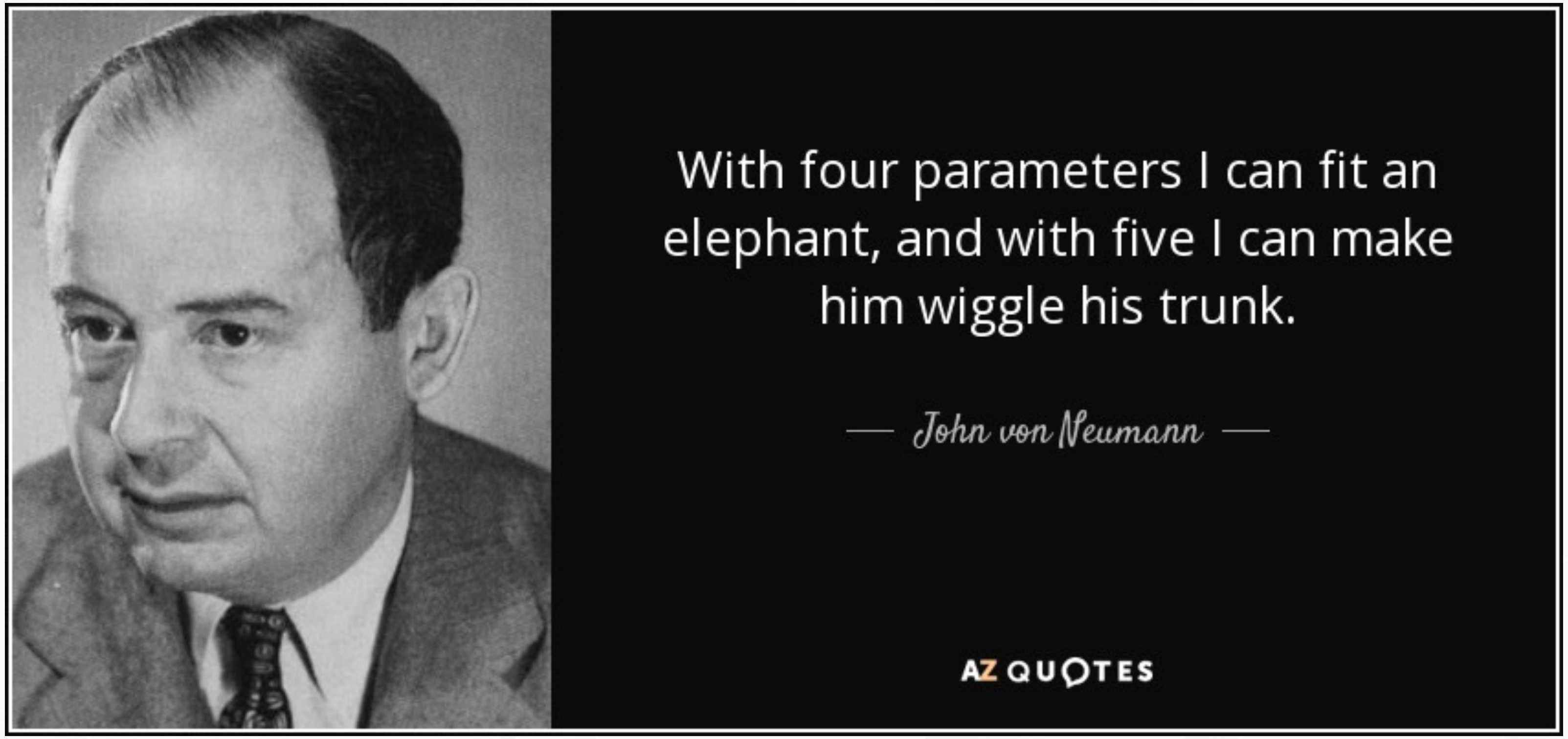
Double distribution model

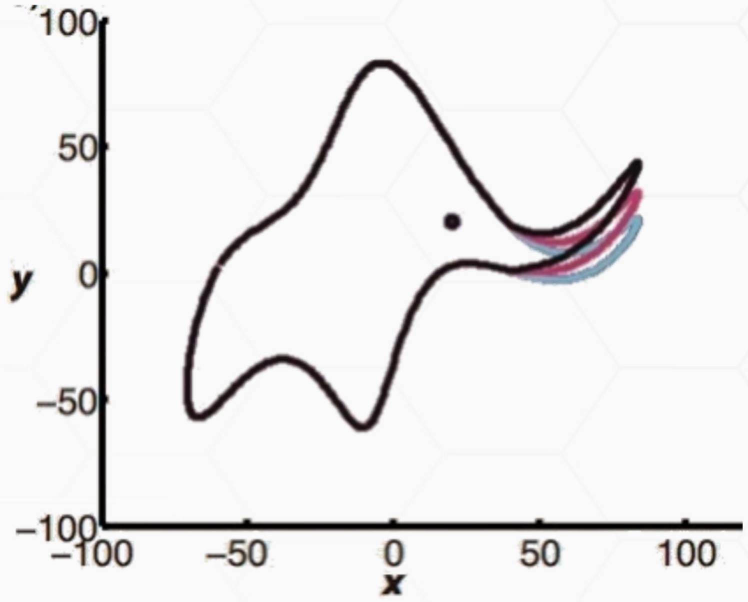


Conformal moment model

Y. Guo et. al. arxiv: 2308. 13006

Fit is meaningless if not physical





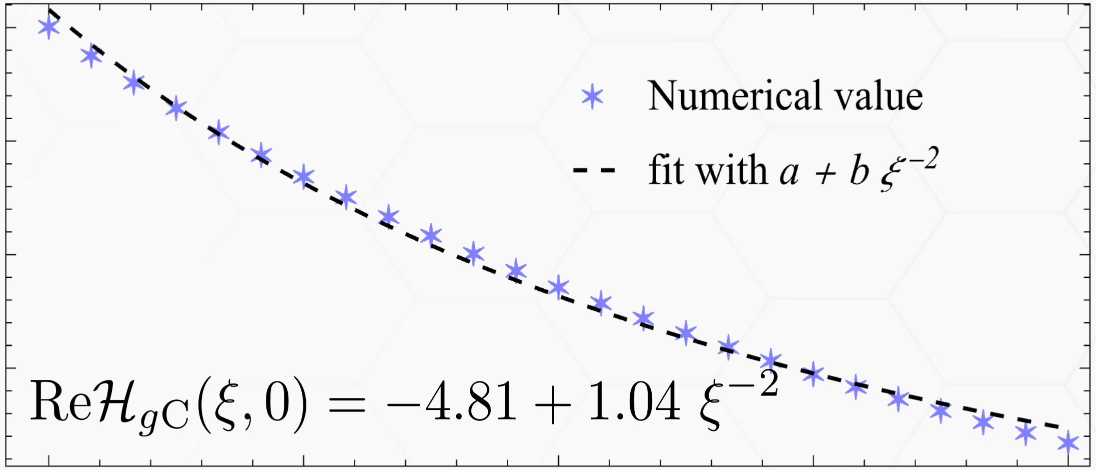
GFFs from CFFs

Let's see if the CFF is related to the GFFs.

With the approximation, the CFF will be

$$\mathrm{Re}\mathcal{H}_{g\mathrm{C}}(\xi,t) \approx \mathcal{C}_g(t) + \xi^{-2}\mathcal{A}_g^{(2)}(t)$$

$$\mathcal{A}_g^{(2)}(t) \approx 2A_g(t)\ ,\mathcal{C}_g(t) \approx 8C_g(t)\ ,$$



Y. Guo et. al. arxiv: 2308. 13006

The input gluon moments are:

$$A_g(0) \approx 0.385\ ,C_g(0) \approx -0.48$$

The extracted values are:

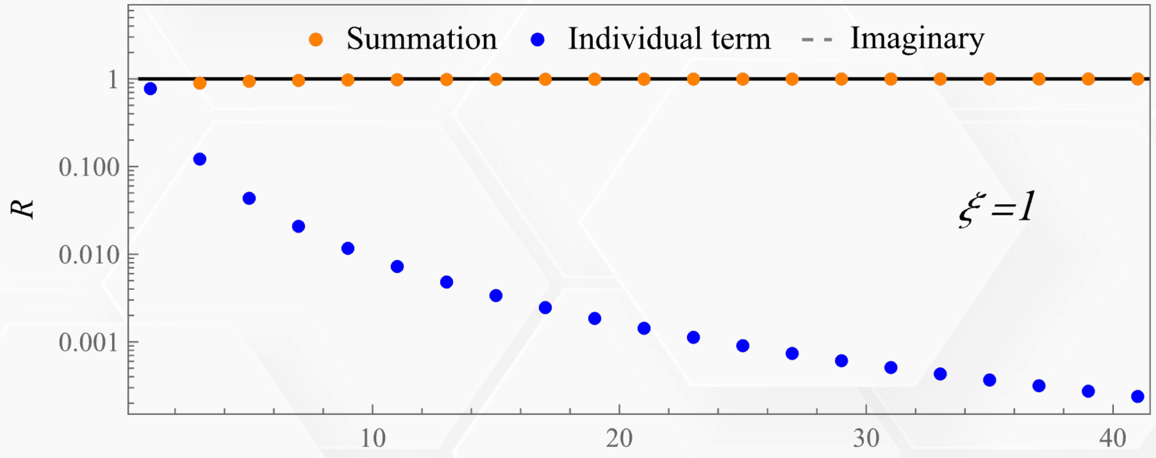
$$\frac{1}{2}\mathcal{A}_{\mathbf{g}}^{(2)}(\mathbf{0}) \approx \mathbf{0.52}\ ,\frac{1}{8}\mathcal{C}_{\mathbf{g}}(\mathbf{0}) \approx -\mathbf{0.60}$$

The extractions have 25% excess due to the higher-moment contamination.

Asymptotic expansion

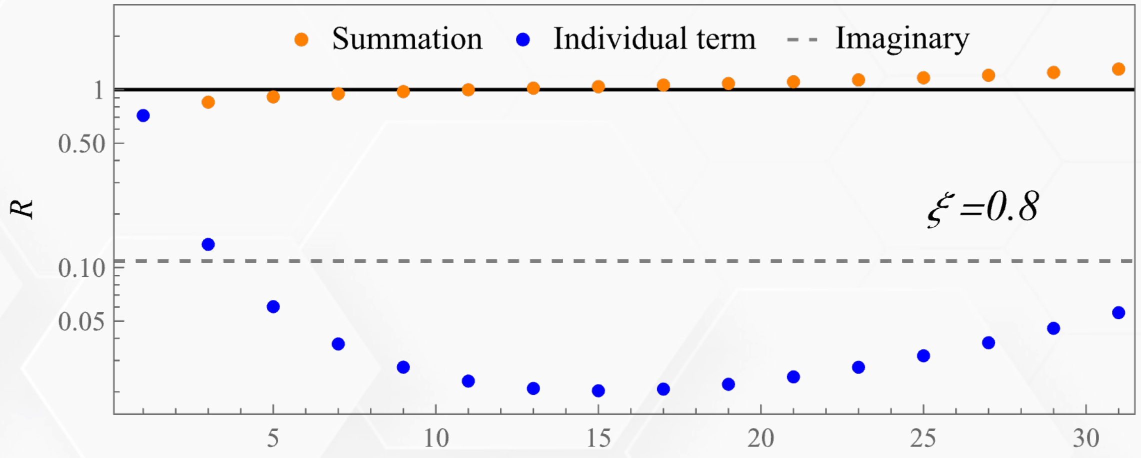
Convergent series

- Individual term decreases and vanishes
- Partial sum eventually approach the analytical result



Asymptotic series

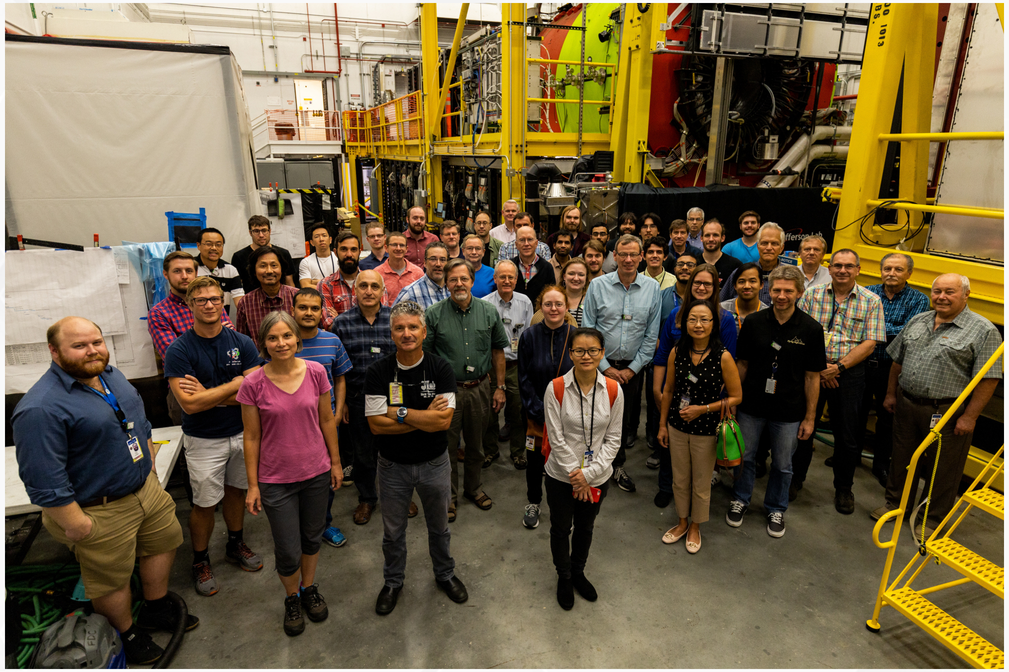
- Individual term decreases **then increases**
- Partial sum eventually diverges
- Truncation at minimal terms approximated the analytical results well



Proton GFFs from J/Psi production

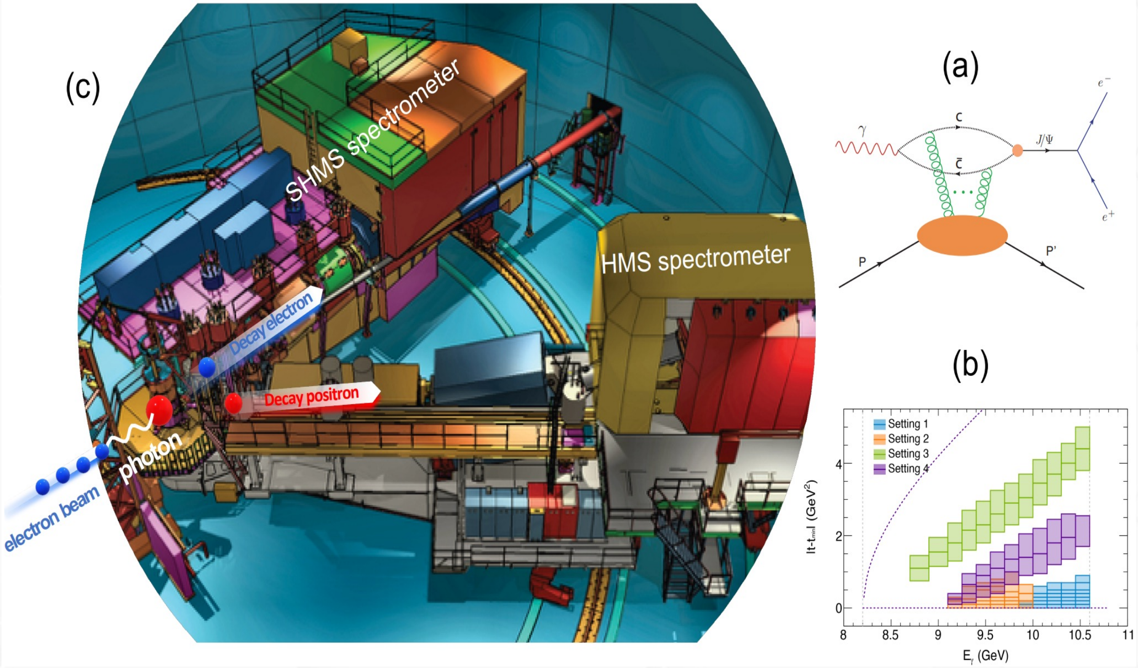
Near-threshold J/psi photoproduction

First measurement of near-threshold exclusive J/ψ photoproduction off the proton by GlueX



GlueX Collaboration Phys. Rev. Lett. 123, 072001 (2019)
GlueX Collaboration Phys. Rev. C 108 2, 025201 (2023)

Another recent measurement by the J/psi 007 experiment at JLab Hall C



B. Duran et. al. Nature 615 7954, 813-816 (2023)

General framework

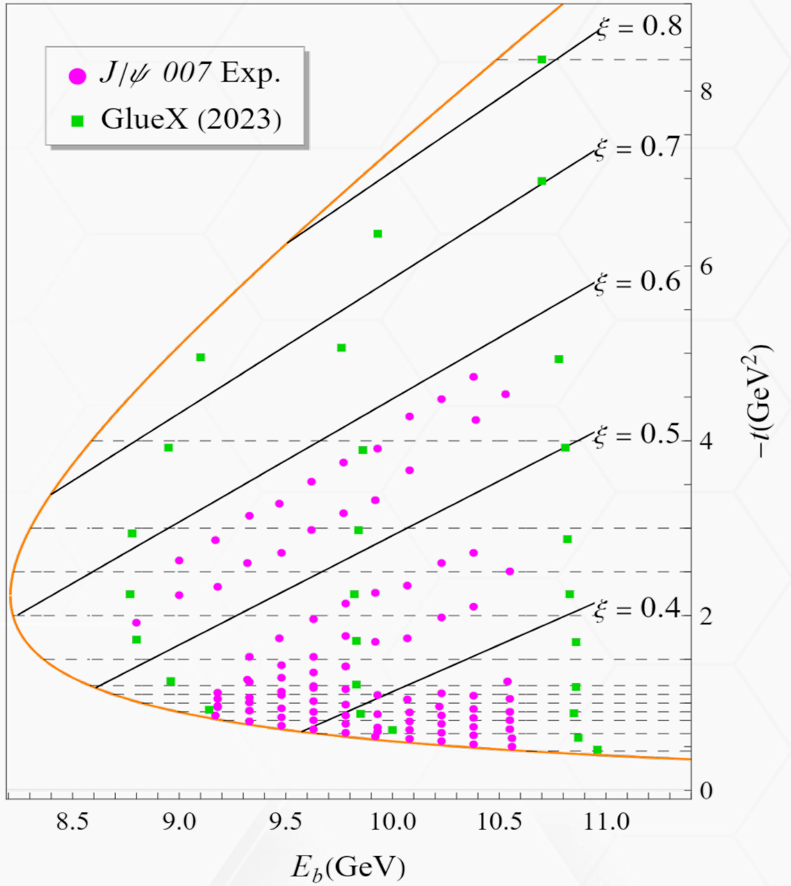
Under the approximation of **large skewness expansion** AND **higher-moment suppression**, one has:

$$\mathcal{H}_{g\mathrm{C}}(\xi,t) \approx \mathcal{C}_g(t) + \xi^{-2}\mathcal{A}_g^{(2)}(t)$$

$$\mathcal{E}_{g\mathrm{C}}(\xi,t) \approx -\mathcal{C}_g(t) + \xi^{-2}\mathcal{B}_g^{(2)}(t)$$

We can then extract the GFFs from the gCFFs, utilizing the large skewness kinematics in the near-threshold region in the heavy quark limit.

Unfortunately, much more data in the lower ξ region

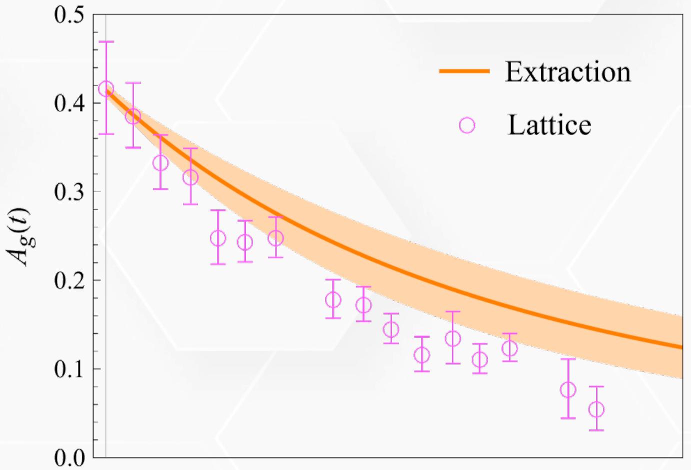


Y. Guo et. al. Phys. Rev. D 108, 034003 (2023)

Extraction of the nucleon GFFs

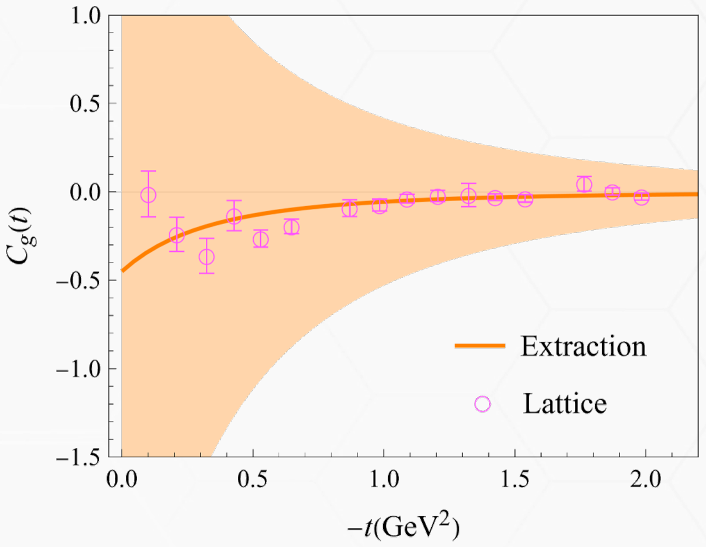
GFFs can be constrained noting the higher-moment contaminations as well as other corrections.

With $\xi > 0.5$ data



Y. Guo et. al. Phys. Rev. D 108, 034003 (2023)

D. Pefkou et. al. Phys. Rev. D 105 5, 054509 (2022)



Not a completely independent extraction:

- The lower-t region is not constrained well by the data.
- The gluonic momentum fraction from PDF is used as input
- The coverage in ξ is rather limited.

Utilizing the skewness dependence

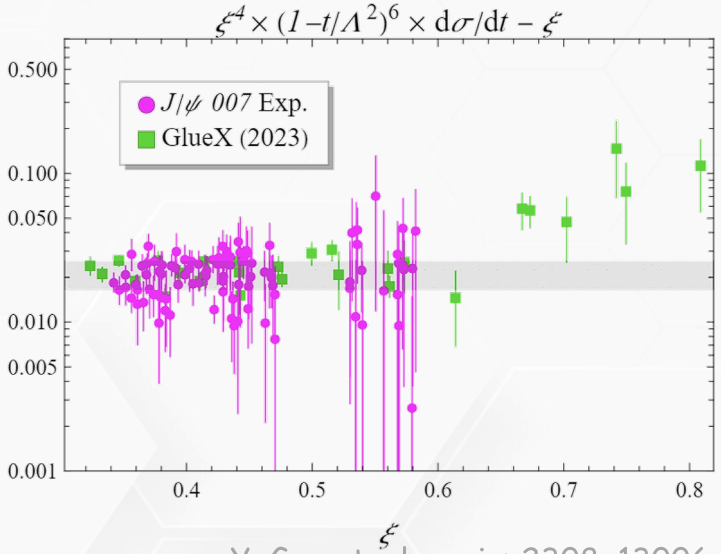
How to test the large-skewness framework and quality of the extraction?

$$|G(\xi,t)|^2 = \left[(1-\xi^2)\,|\mathcal{H}_{gC}|^2 - 2\xi^2 \mathrm{Re}\left[\mathcal{H}^*_{gC}\mathcal{E}_{gC}\right] - \left(\xi^2 + \frac{t}{4M_p^2}\right)|\mathcal{E}_{gC}|^2\right]$$

$$= \xi^{-4}\left[G_0(t) + \xi^2 G_2(t) + \xi^4 G_4(t)\right] + \cdots$$

The ξ-scaling of the cross-section has non-trivial behaviors at large ξ.

- ❑ The overall ξ-scaling are consistent with ξ^{-4}
- ❑ Extra ξ-scaling crucial for the separation of A and C form factors
- ❑ More complicated when consider t-dependence



Y. Guo et. al. arxiv: 2308. 13006

What can we do with CFF

Compton-like amplitudes basically measure GPDs at x=ξ

- Imaginary parts given by GPDs at x=ξ

$$\mathrm{Im}\mathcal{H}_{g\mathrm{C}}(\xi,t)=\frac{\pi}{\xi}H_g(\xi,\xi,t)$$

- Real parts given by dispersion relation

$$\mathrm{Re}\mathcal{H}_{g\mathrm{C}}(\xi,t)=\frac{1}{\pi}\int_0^{\xi_{\mathrm{th}}}\mathrm{d}\xi'\frac{2\xi'\mathrm{Im}\mathcal{H}_{g\mathrm{C}}(\xi,t)}{(\xi-\xi')(\xi+\xi')}+\mathcal{C}_g(t)$$

- Real parts can be formally written as

$$\mathrm{Re}\mathcal{H}_{g\mathrm{C}}(\xi,t)=\mathcal{C}_g(t)+\sum_{n=1}^{\infty}\xi^{-2n}\mathcal{A}_g^{(2n)}(t)$$

- Imaginary parts – inverse Mellin transform:

$$\mathrm{Im}\mathcal{H}_{g\mathrm{C}}(\xi,t)\propto\frac{1}{2\pi i}\int_{c-i\infty}^{c+i\infty}\xi^{-s}\mathcal{A}_g^{(s+2)}(t)\mathrm{d}s$$

The two statements are mathematically equivalent!

The different applicable regions (near forward/ large skewness) distinguish them

Summary and outlook

Summary

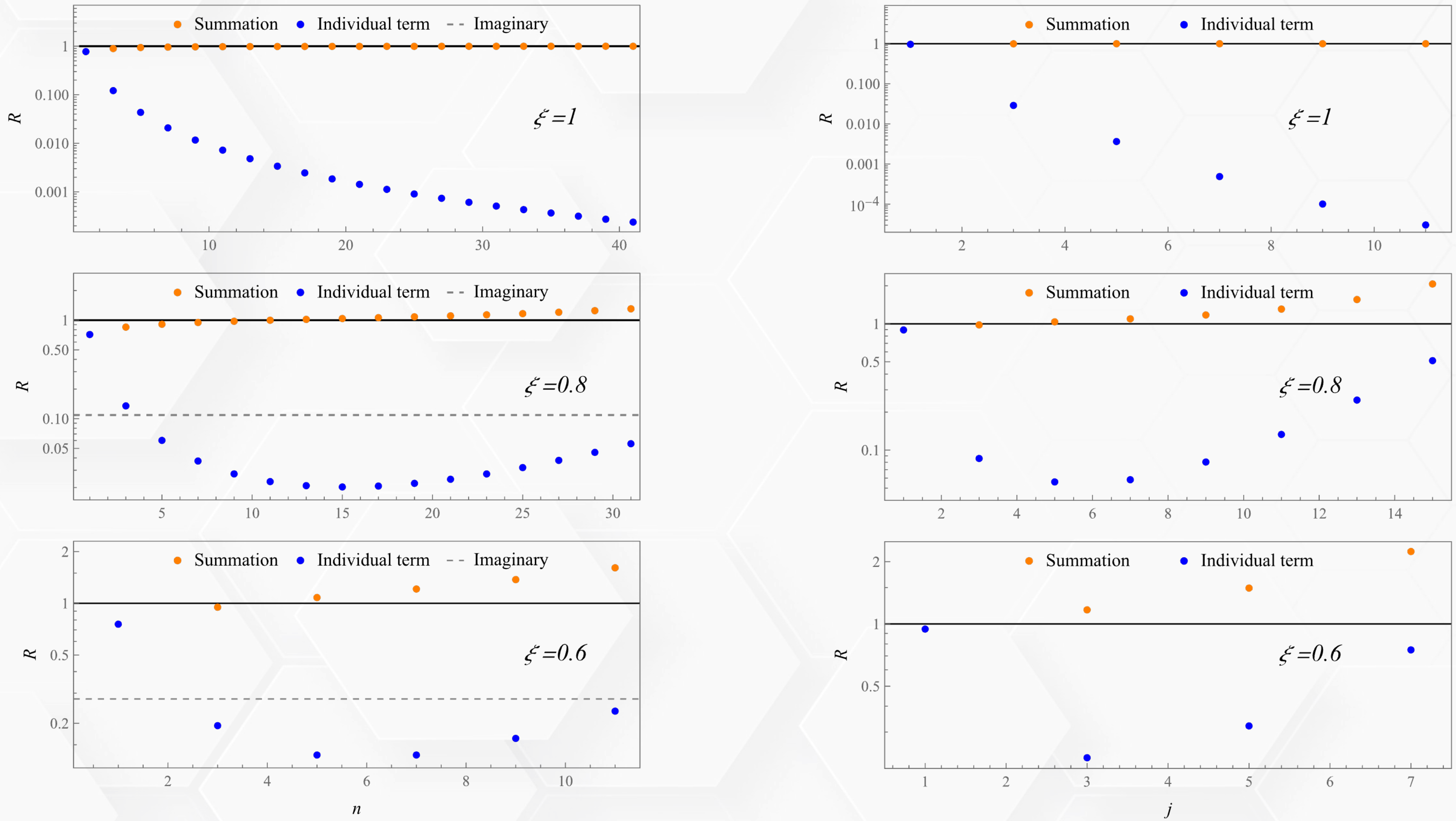
- Exclusive heavy quarkonium production as probe of gluonic structures
- Large skewness behavior of gCFFs in near-threshold heavy quarkonium production
- (Potential) extraction of gluonic GFFs in the nucleon with such framework

Outlook

- Next-to-leading order effects in strong coupling and non-relativistic corrections
- Extension to quark GPDs, e.g., time-like Compton scattering for the quark case
- Relations to the other frameworks – collinear NRQCD factorization

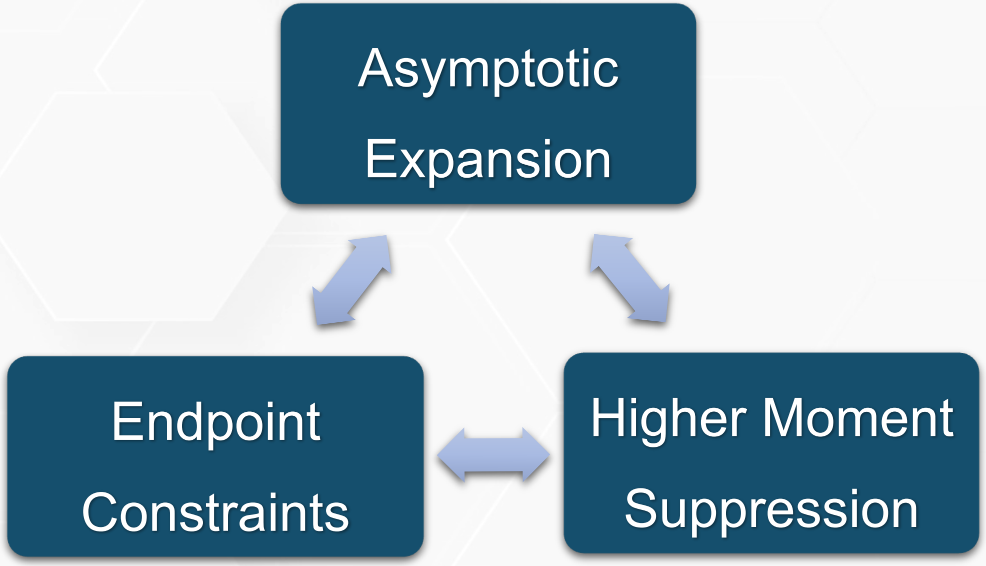
Thank you!

Conformal moment expansion



Two more comments

The asymptotic expansion is closely related to the endpoint constraints



The 25% excess from higher moments contamination relate to the conformal ratio?

$$\mathcal{A}_j^{\rm conf} = \frac{2^{j+2}\Gamma\left(5/2+j\right)}{\Gamma\left(3/2\right)\Gamma\left(4+j\right)} \qquad \mathcal{A}_1^{\rm conf} = \frac{5}{4}$$

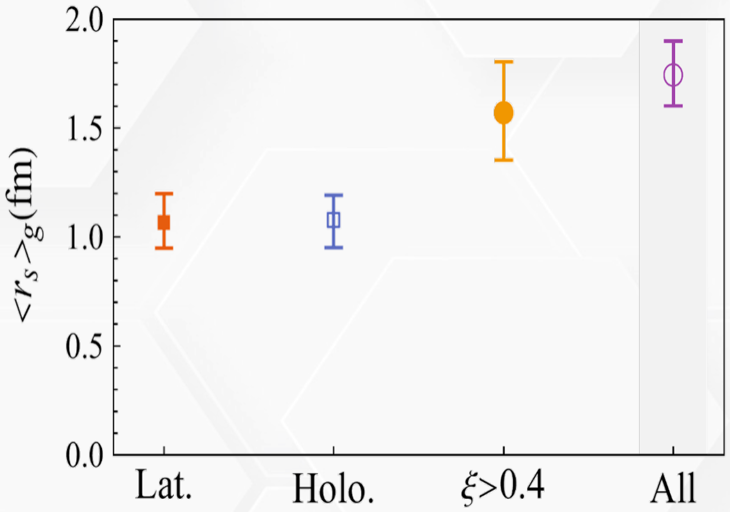
Y. Guo et. al. arxiv: 2308. 13006

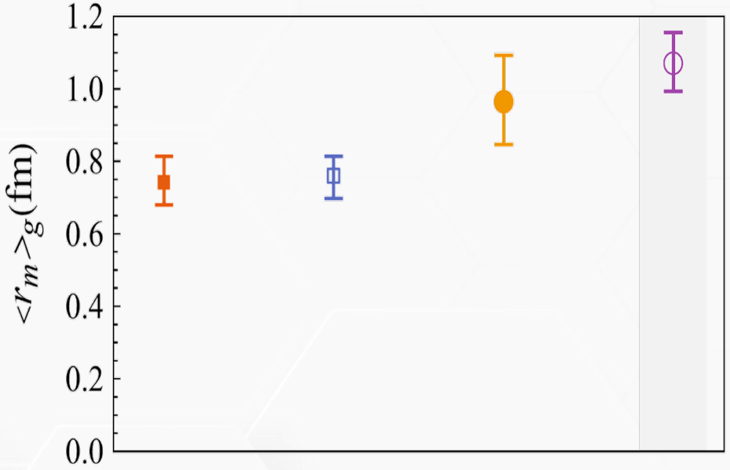
Proton mass radius extraction

Proton mass and scalar radii are closely related to the form factors at t = 0

$$\langle r_m^2 \rangle = \left[6 \frac{dA(t)}{dt}\bigg|_{t=0} - 6 \frac{C(0)}{M_N^2} \right] , \qquad \langle r_s^2 \rangle = \left[6 \frac{dA(t)}{dt}\bigg|_{t=0} - 18 \frac{C(0)}{M_N^2} \right] ,$$

Inclusion of lower-ξ data shows better statistics but introduces massive systematical uncertainties.





Y. Guo et. al. Phys. Rev. D 108, 034003 (2023)

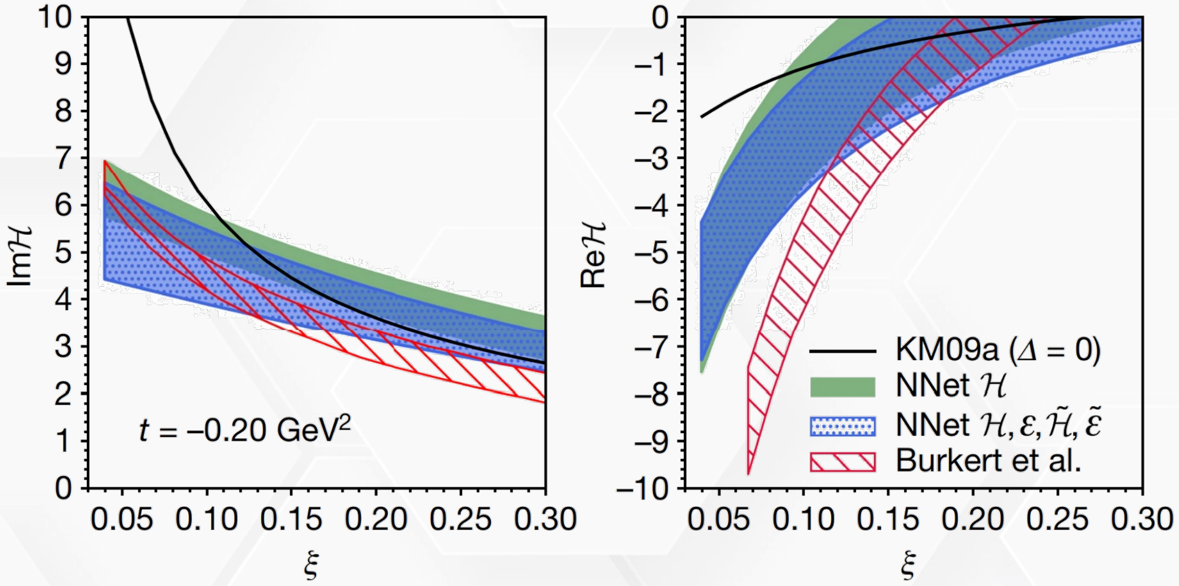
Due to the large-ξ/t nature of this framework, the extraction of proton radii with controlled precision will need more efforts.

One interesting quark analogy

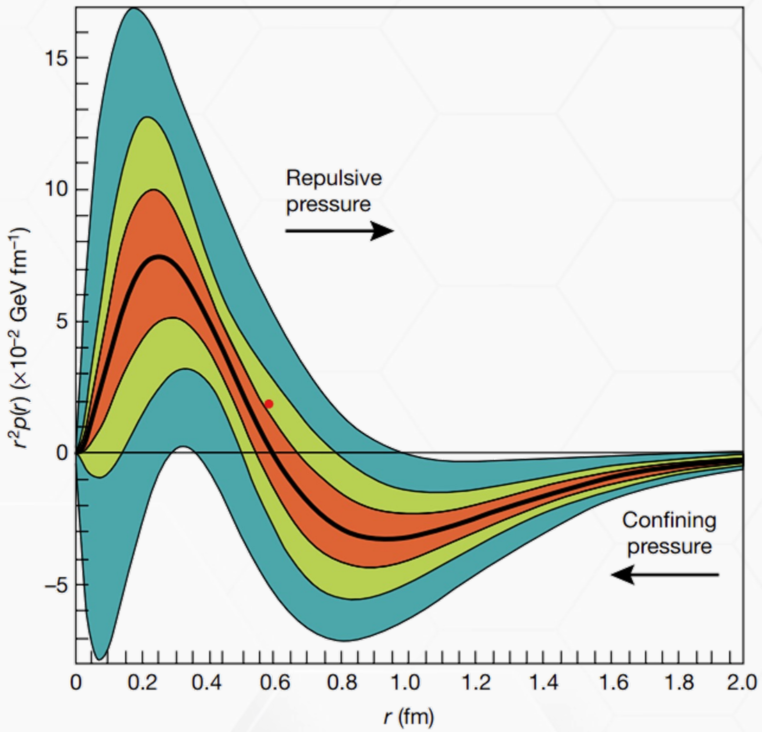
The C form factor can be extracted through the dispersion relation as well:

$$\mathcal{C}_g(t) = \mathrm{Re}\mathcal{H}_{g\mathrm{C}}(\xi,t) - \frac{1}{\pi}\int_0^{\xi_{\mathrm{th}}} \mathrm{d}\xi' \frac{2\xi' \mathrm{Im}\mathcal{H}_{g\mathrm{C}}(\xi,t)}{(\xi-\xi')(\xi+\xi')}$$

The extraction seems to be more consistent with increasing ξ:



K. Kumericki., Nature 570 (2019) 7759, E1-E2



V. D. Burkert et. al., Nature 557 7705, 396-399 (2018)