Near - threshold photoproduction as a probe of the nucleon gravitational structure

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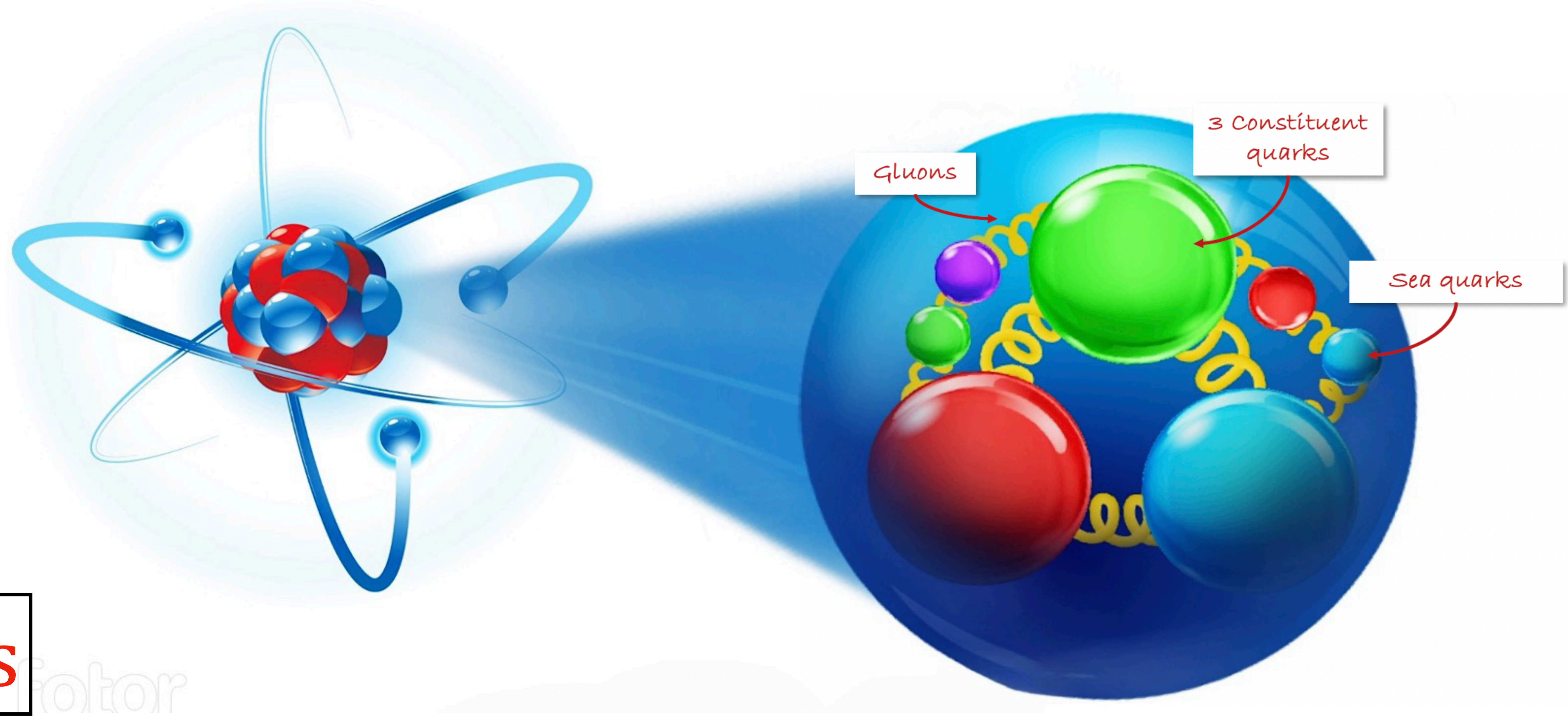
Based on : PRD 113 (2026) 5, 054041, PRD 111 (2025) 9, 094011 and 2601.19141 [hep-ph]

In collaboration with: C. Mondal, A. Sain, A. Mukherjee, D. Chakrabarti, P. Choudhary, Y. Li, X. Cao, C. Chen

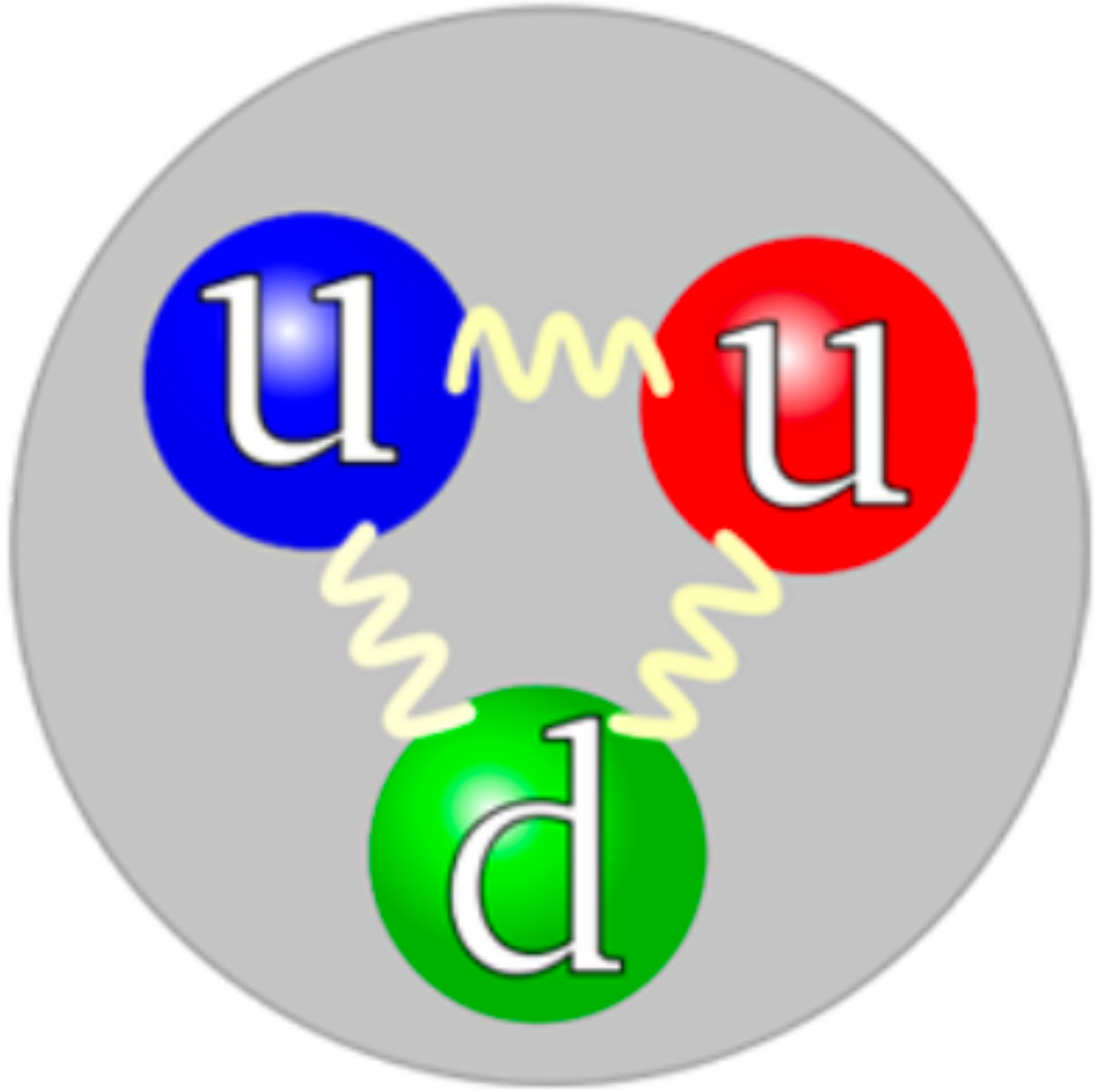
The 1st Annual Conference on EIC Physics in China @ Qingdao [April 19-22, 2026]

- Matter forms from fundamental particles through the formation of hadrons, which are composite particles made of quarks.

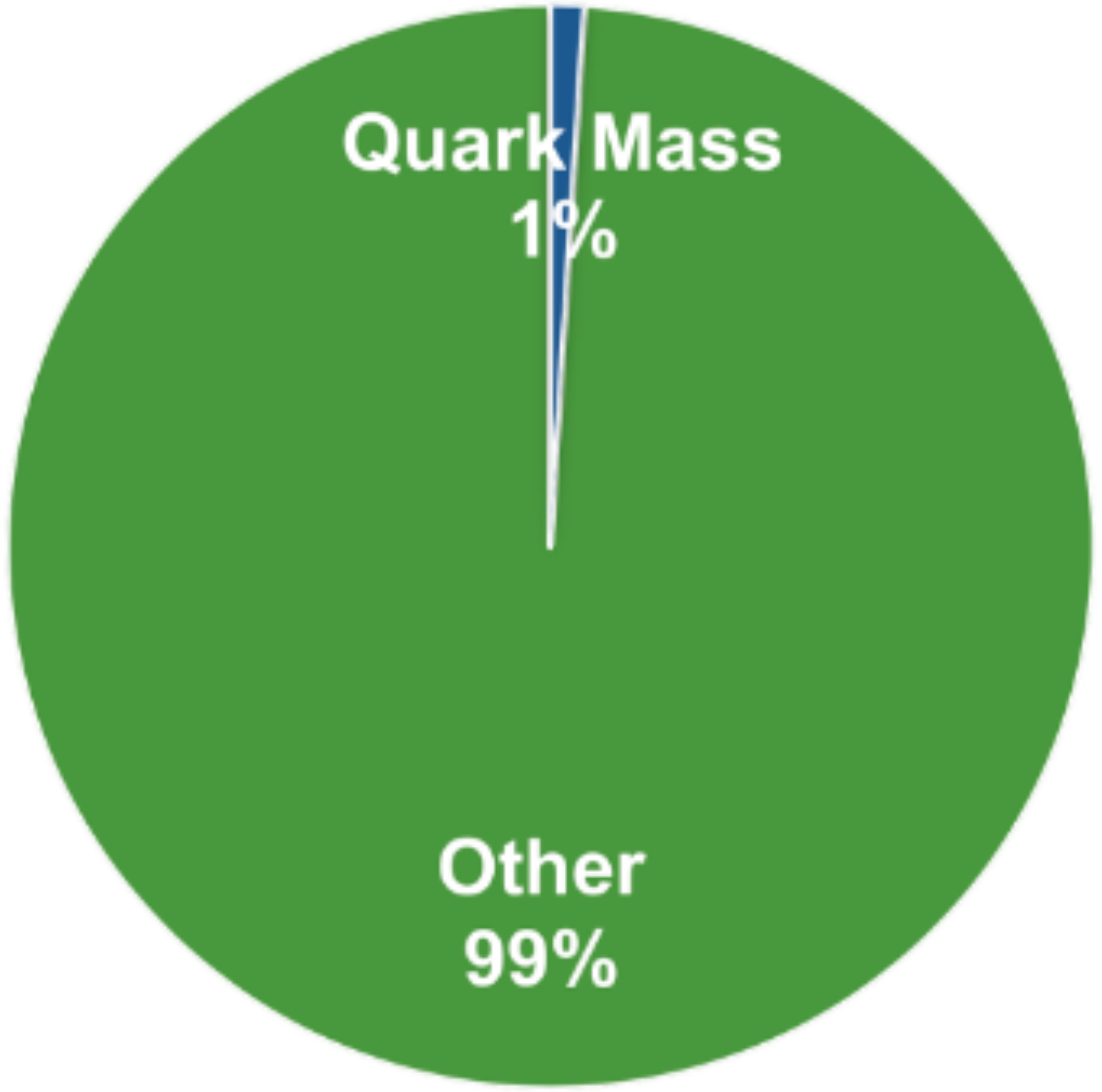


Big puzzles of the strong forces within the hadrons

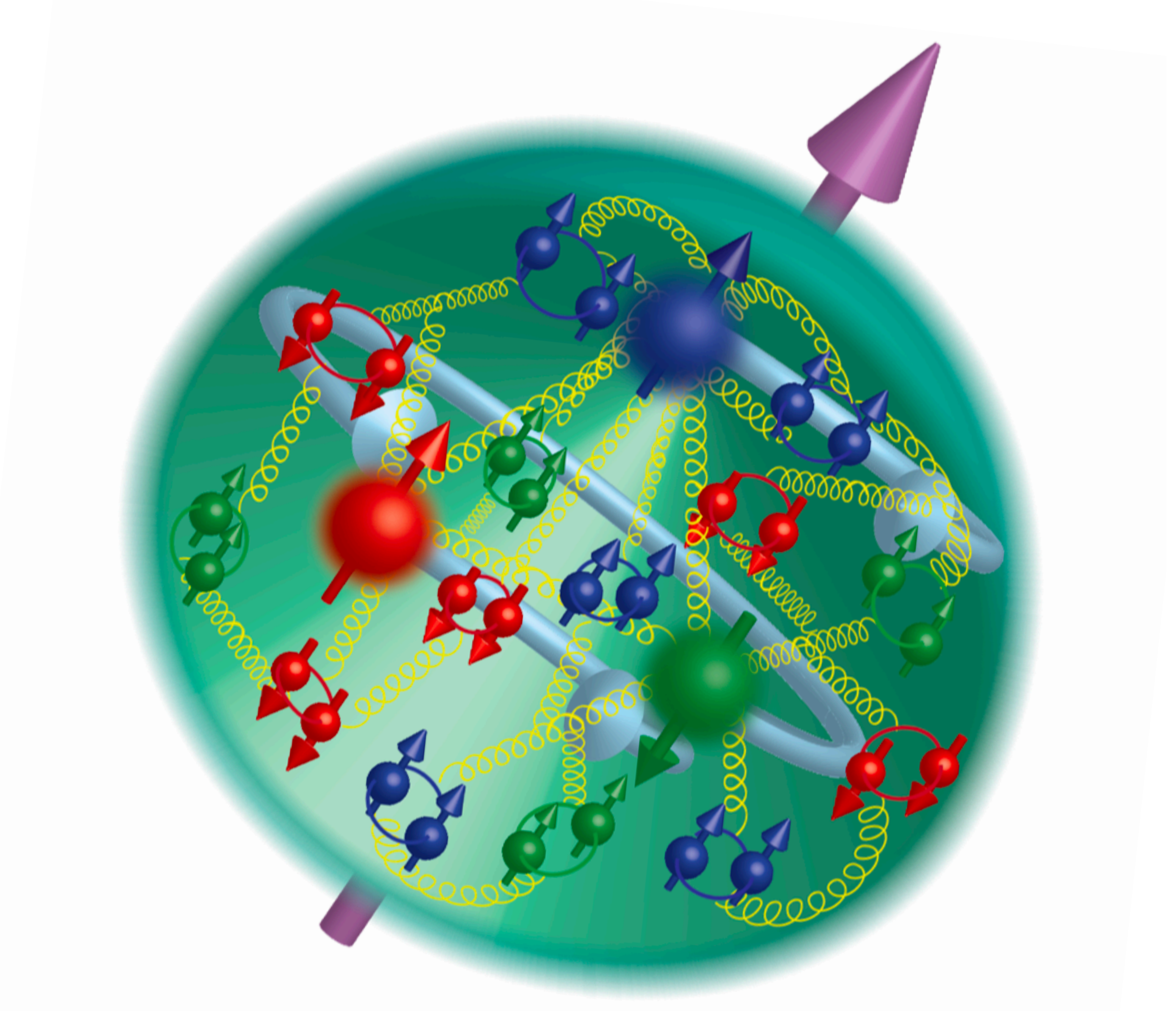
Origin of confinement ?



Origin of nucleon mass ?



Origin of nucleon spin ?



👉 To address these fundamental issues → nature of the subatomic force between quarks and gluons, and the internal landscape of hadrons.

Fundamental global properties of the proton

- The structure of strongly interacting particles can be investigated using other fundamental forces, such as the electromagnetic, weak, and (in principle) gravitational forces.

em:	$\partial_\mu J^\mu_{\text{em}} = 0$	$\langle N'\|J^\mu_{\text{em}}\|N\rangle$	$\longrightarrow$	Q_{prot}	$=$	$1.602176487(40) \times 10^{-19}\text{C}$
	vector			μ_{prot}	$=$	$2.792847356(23)\mu_N$
weak:	PCAC	$\langle N'\|J^\mu_{\text{weak}}\|N\rangle$	$\longrightarrow$	g_A	$=$	$1.2694(28)$
	axial			g_p	$=$	$8.06(0.55)$
gravity:	$\partial_\mu T^{\mu\nu}_{\text{grav}} = 0$	$\langle N'\|T^{\mu\nu}_{\text{grav}}\|N\rangle$	$\longrightarrow$	M_{prot}	$=$	$938.272013(23)\,\text{MeV}/c^2$
				J	$=$	$\frac{1}{2}$
	tensor			D	$=$	**?**

P. Schweitzer et al., arXiv:1612.0672, 2016.

The D-term is the "last unknown global property" of the nucleon

- The nucleon GFFs provide information on the **mass**, **pressure**, and **shear** distributions of partons inside the proton.

Lorce and Schweitzer (2025); Burkert, Elouadrhiri, Girod, Lorce, Schweitzer, and Shanahan (2023)

Probing basic properties of the proton

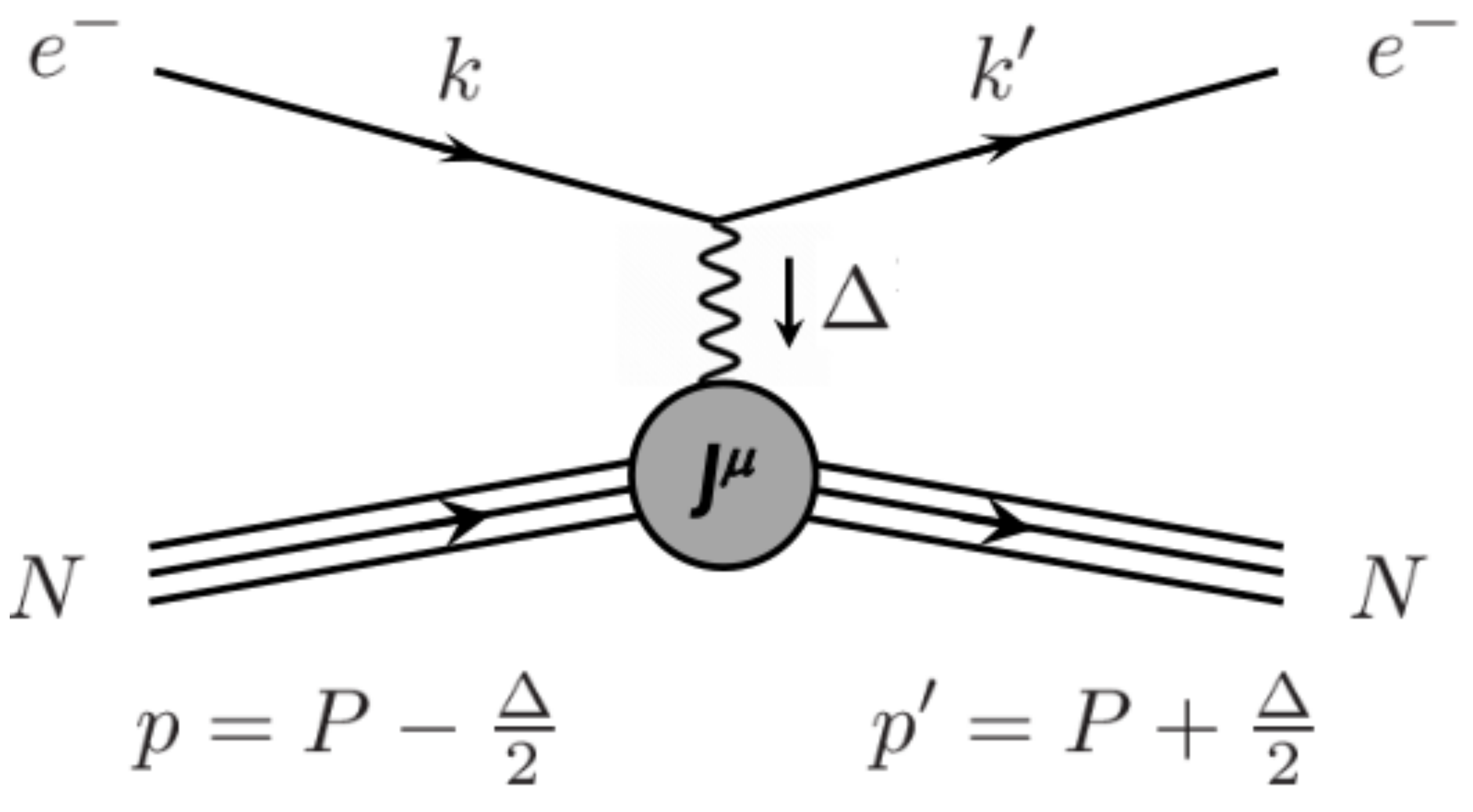
GAUGE AND HIGGS BOSONS

graviton $J = 2$

graviton MASS $< 6 \times 10^{-32}$ ev

Electromagnetic properties → Probed with photons.

Photon exchange
(~1)



Electromagnetic current

↓

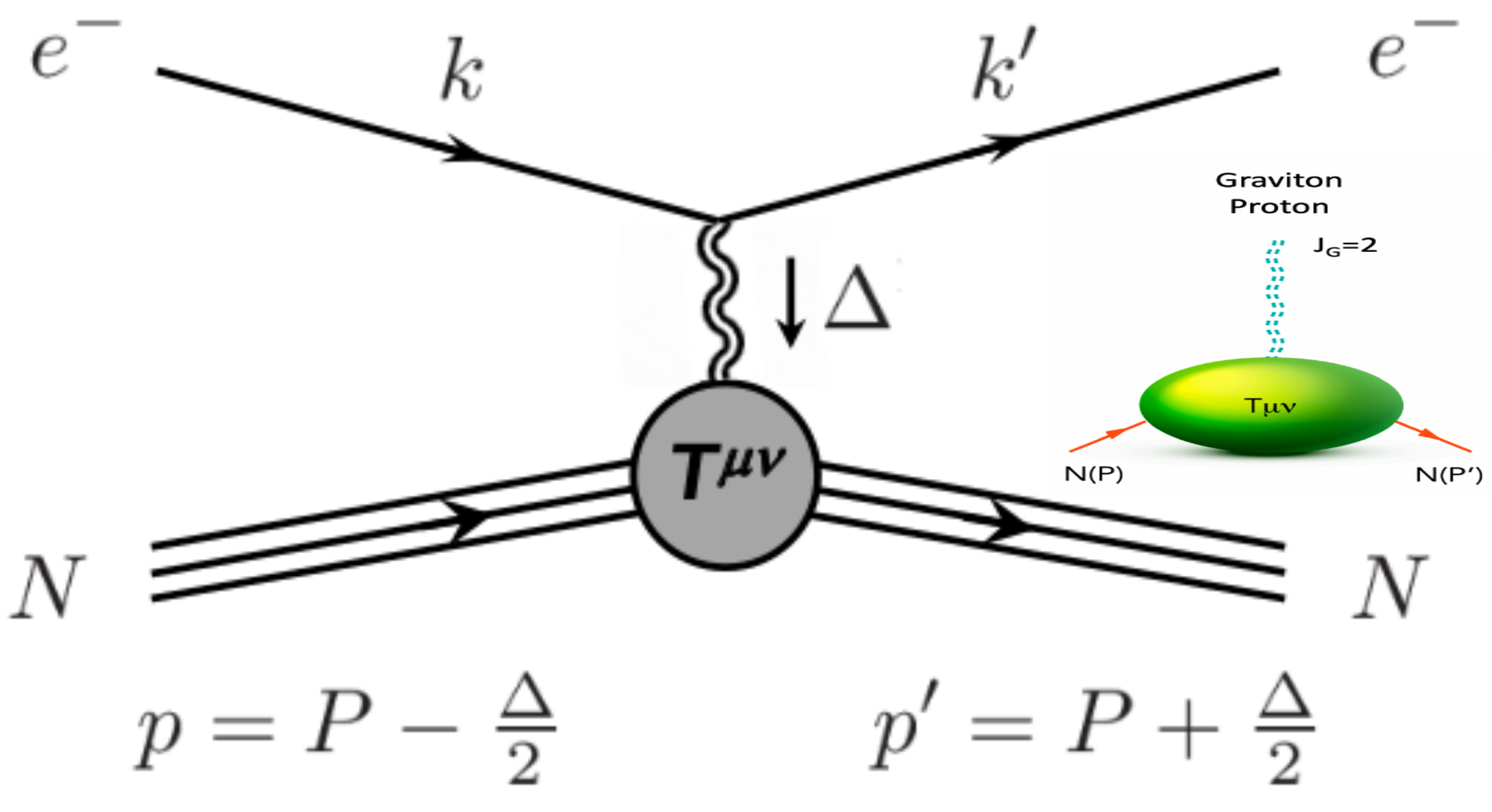
Electromagnetic form factors

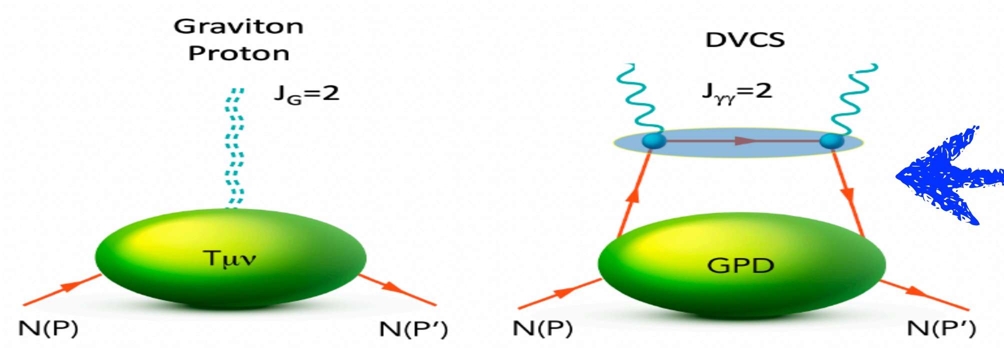
Inelastic structure functions, proton charge radius, charge and current densities

Gravitational properties → Probed with gravitons.

Graviton exchange
($\sim 10^{-36}$)

"………there is very little hope of learning anything about the detailed mechanical structure of a particle because of the extreme weakness of the gravitational interaction" —— [H. Pagels, (1966)]





Hard exclusive scattering (DVCS/DVMP)

↓

CFFs & GPDs

[Mellin ↓ moments]

GFFs

Energy-momentum tensor

↓

Gravitational form factors

Burkert, Elouadrhiri, Lorce, Schweitzer and Shanahan, RMP, 95(2023) 4, 041002

Mass: Energy and Mass densities.
Spin: Angular Momentum distribution.
D-term: Dynamical stability, Normal and Shear forces, Pressure distribution

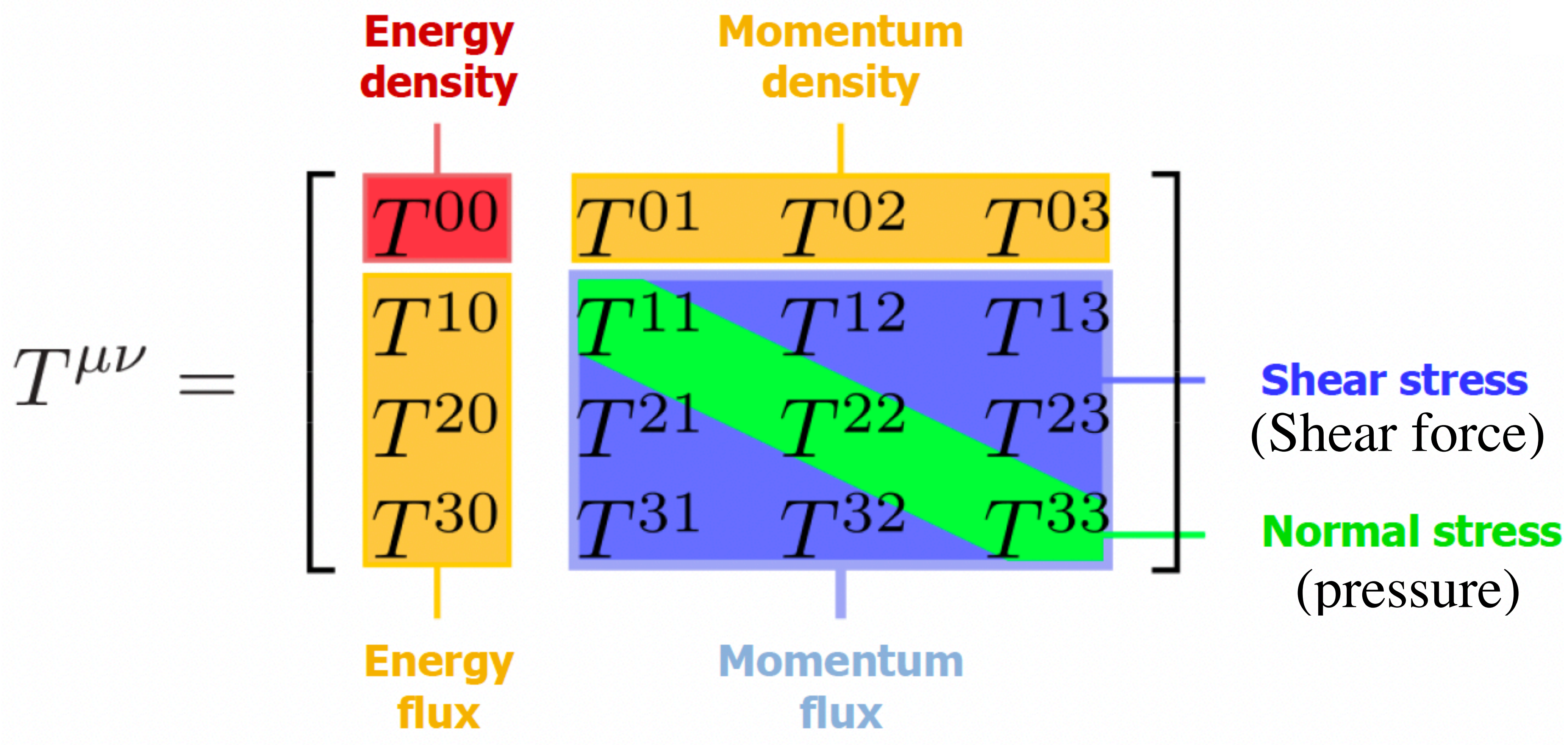
QCD Energy Momentum Tensor (EMT) and related Physical quantities

- The EMT describes how energy, momentum, pressure, and forces are distributed inside the nucleon.

The gauge-invariant, symmetric form of the QCD EMT

$$T^{\mu\nu} = \underbrace{-F_a^{\mu\alpha} F_{a,\alpha}^{\nu} + \frac{1}{4} g^{\mu\nu} F_a^{\alpha\beta} F_{a,\alpha\beta}}_{T_g^{\mu\nu}} + \underbrace{\sum_f i\bar{\psi}_f \gamma^\mu D^\nu \psi_f}_{T_q^{\mu\nu}}$$

The total EMT is conserved: $\partial_\mu T^{\mu\nu} = 0$



Parametrization of EMT matrix elements in terms of GFFs

GFFs are the hadronic matrix elements of the QCD EMT

$$\langle N' \mid T_{q,g}^{\mu,\nu} \mid N \rangle = \bar{u}(N') \left(A_{g,q}(t) \gamma^{\{\mu} P^{\nu\}} + B_{g,q}(t) \frac{i P^{\{\mu} \sigma^{\nu\}} \rho \Delta_\rho}{2M} + C_{g,q}(t) \frac{\Delta^\mu \Delta^\nu - g^{\mu\nu} \Delta^2}{M} + \bar{C}_{g,q}(t) M g^{\mu\nu} \right) u(N)$$

- $A_{g,q}(t)$: Related to quark and gluon momenta, $A_{g,q}(0) = \langle x_{q,g} \rangle$
- $J_{g,q}(t) = 1/2 \left(A_{g,q}(t) + B_{g,q}(t) \right)$: Related to angular momentum
- $D_{g,q}(t) = 4C_{g,q}(t)$: Related to pressure and shear forces
- $\bar{C}_{g,q}(t)$: Related to Trace anomaly (nucleon mass decomposition)

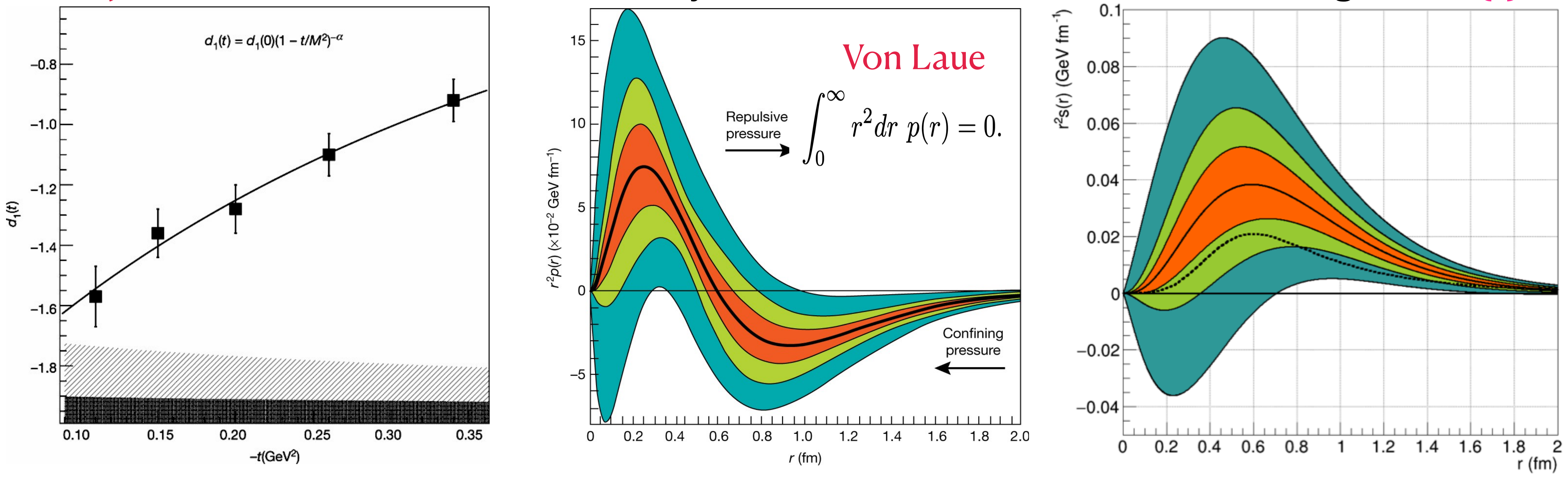
H. Pagels, Phys.Rev., 1966, Burkert, Elouadrhiri & Girod, Nature 2018; arXiv:2104.02031, Polyakov, & Schweitzer, IJMPA 2018; arXiv:2104.02031

Sum Rules for GFFs:

1. Momentum sum rule: $\sum_{i=q,g} A_i(0) = 1.$
2. Ji's spin sum rule:
$$\sum_{i=q,g} J_i(0) = \frac{1}{2}\sum_{i=q,g}[A_i(0) + B_i(0)] = \frac{1}{2} \Rightarrow \sum_{i=q,g} B_i(0) = 0.$$
3. EMT conservation: $\sum_{i=q,g} \bar{C}_i(t) = 0.$
4. Mechanical stability: $\sum_{i=q,g} C_i(t) < 0.$

Polyakov, & Schweitzer (2018); X. Ji, PRL (1996); A. Radyushkin, PLB (1996)

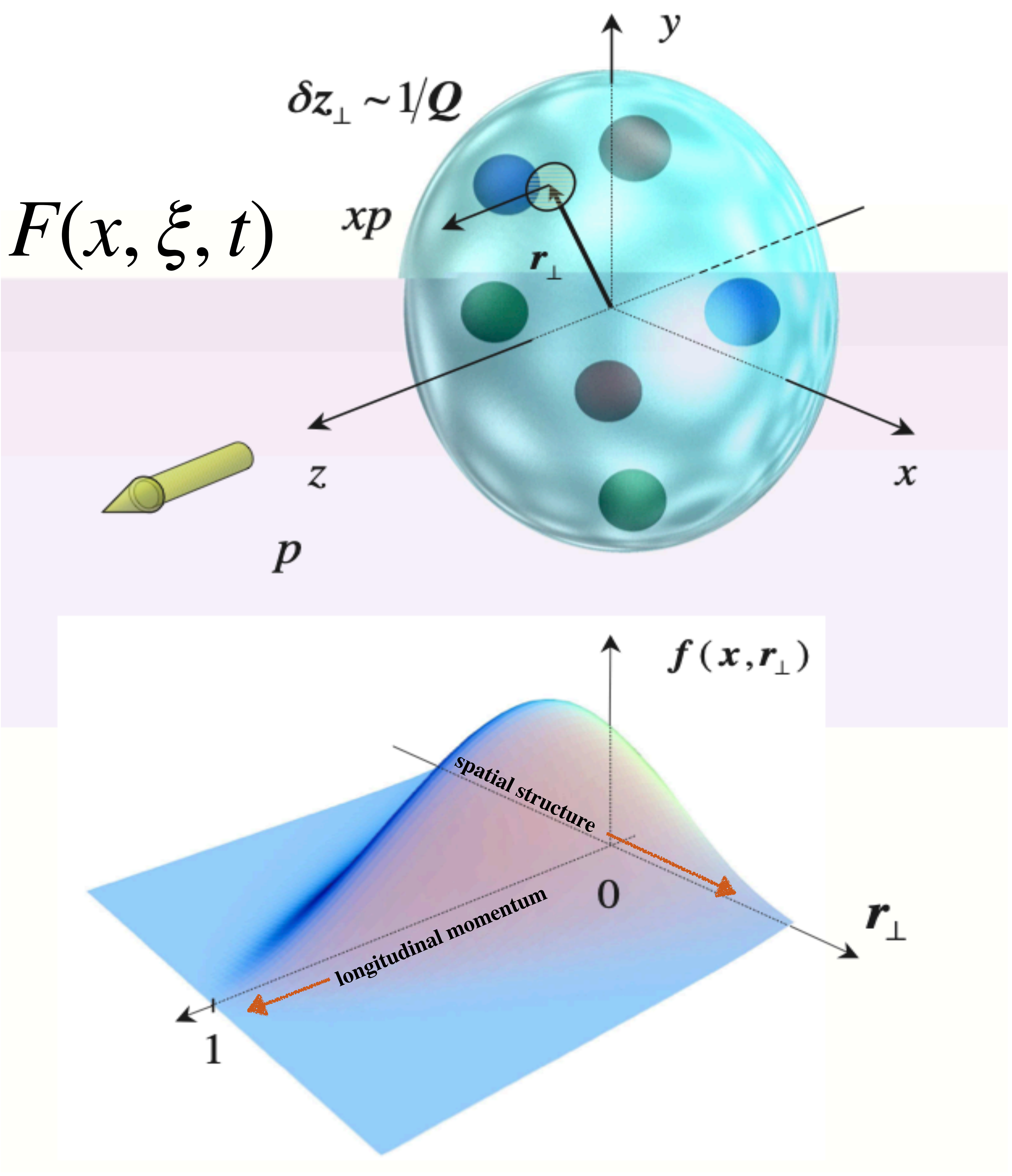
Conjecture: For the stable hadronic systems the D-term GFF should be negative D(t)<0.



Burkert, Elouadrhiri & Girod, Nature 2018; arXiv:2104.02031

Generalized Parton Distributions (GPDs)

GPDs are distributions unifying parton distributions and form factors and provide the spatial nucleon tomography.



M. Diehl (2003); A.V. Belitsky et al. (2005); X. Ji (1997)

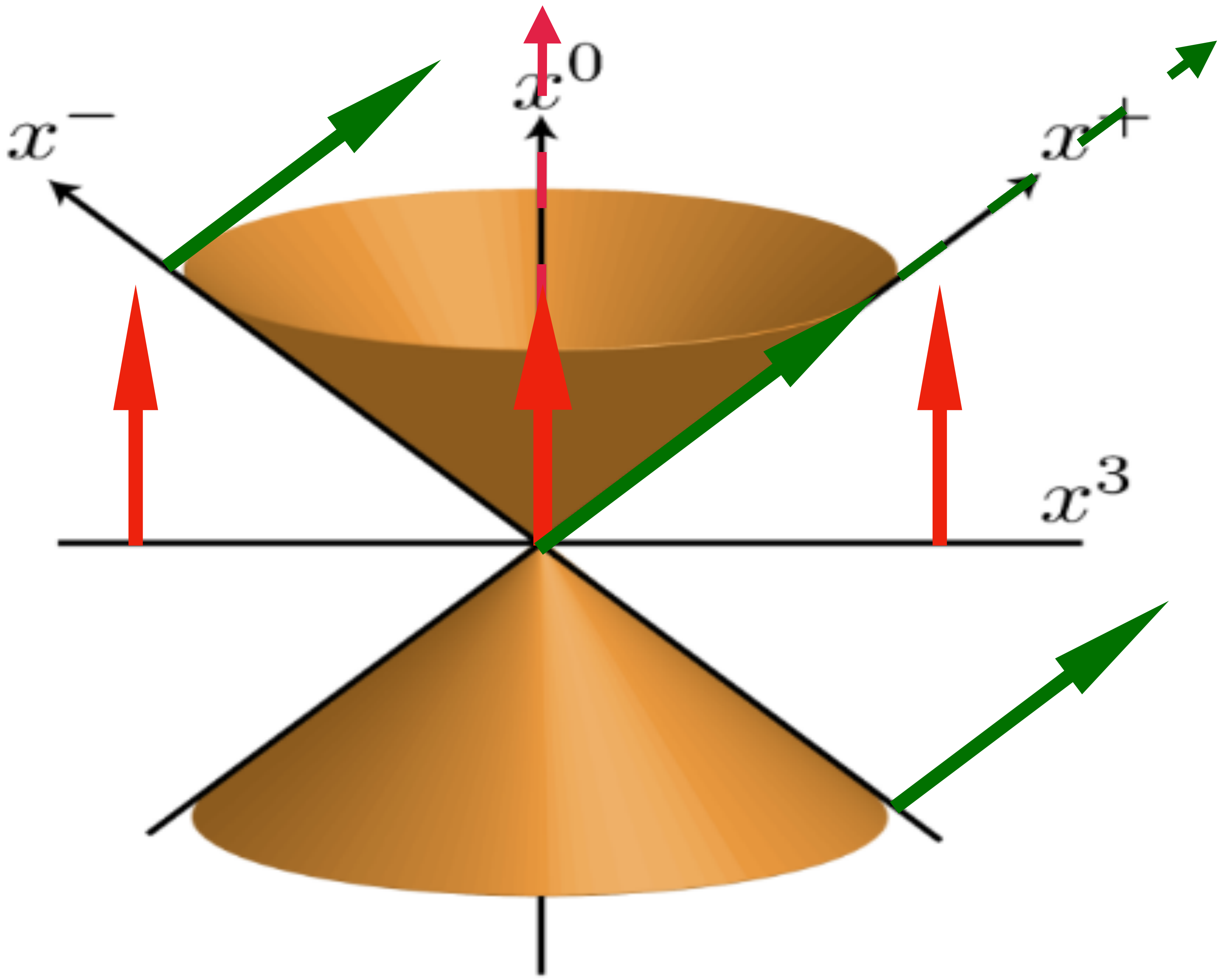
REVIEWS OF MODERN PHYSICS VOLUME 21, NUMBER 3 JULY, 1949

Forms of Relativistic Dynamics

P. A. M. DIRAC
St. John's College, Cambridge, England

Out of 10 Poincare Generators 6 are kinematical and 4 are dynamical

7 Generators are kinematical and 3 are dynamical



LIGHT CONE TIME

$$x^+ = x^0 + x^3$$

LONGITUDINAL MOMENTUM

$$p^+ = p^0 + p^3$$

LIGHT CONE SPACE

$$x^- = x^0 - x^3$$

LIGHT-FRONT ENERGY

$$p^- = p^0 - p^3$$

$$x^\perp = (x^1, x^2)$$

$$p^- = \frac{(p^\perp)^2 + m^2}{p^+}$$

light front formulation has a larger stability group

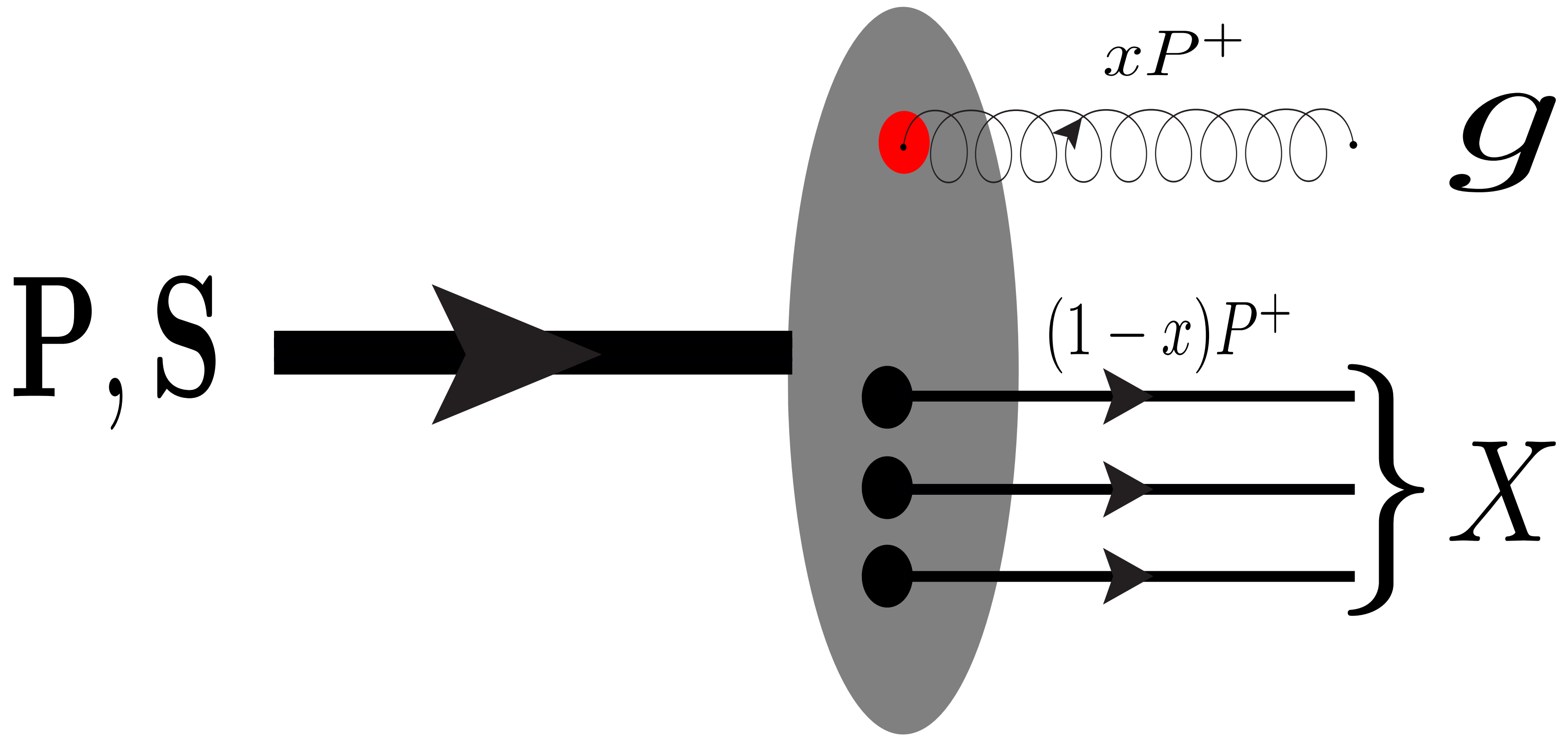
In light-front boost become simple scale transformation

The dispersion relation is quite remarkable for the several reasons

According to Dirac (1949) "... the three-dimensional surface in space-time formed by a plane wave front advancing with the velocity of light. Such a surface will be called front for brevity".

A. Harindranath, arXiv:hep-ph/9612244 (1998); P.A.M Dirac, Rev. Mod. Phys.(1949)

◆ In this model the nucleons [p=$|g(uud)\rangle$, n=$|g(udd)\rangle$] are considered as an effective two particle bound state of spin-1 active gluon and a spin-1/2 spectator cluster. [Motivated by the quantum fluctuations of an electron in QED: $|e\rangle \rightarrow |e\rangle_{\text{bare}} + |\gamma e\rangle + \cdots$]



The **two particle Fock-state expansion**

$$|P;\uparrow(\downarrow)\rangle = \int \frac{d^2\mathbf{k}_\perp dx}{16\pi^3\sqrt{x(1-x)}} \psi^{\uparrow(\downarrow)}_{\lambda_g,\lambda_X}(x,\mathbf{k}_\perp) \left|\lambda_g,\lambda_X; xP^+,\mathbf{k}_\perp\right\rangle$$

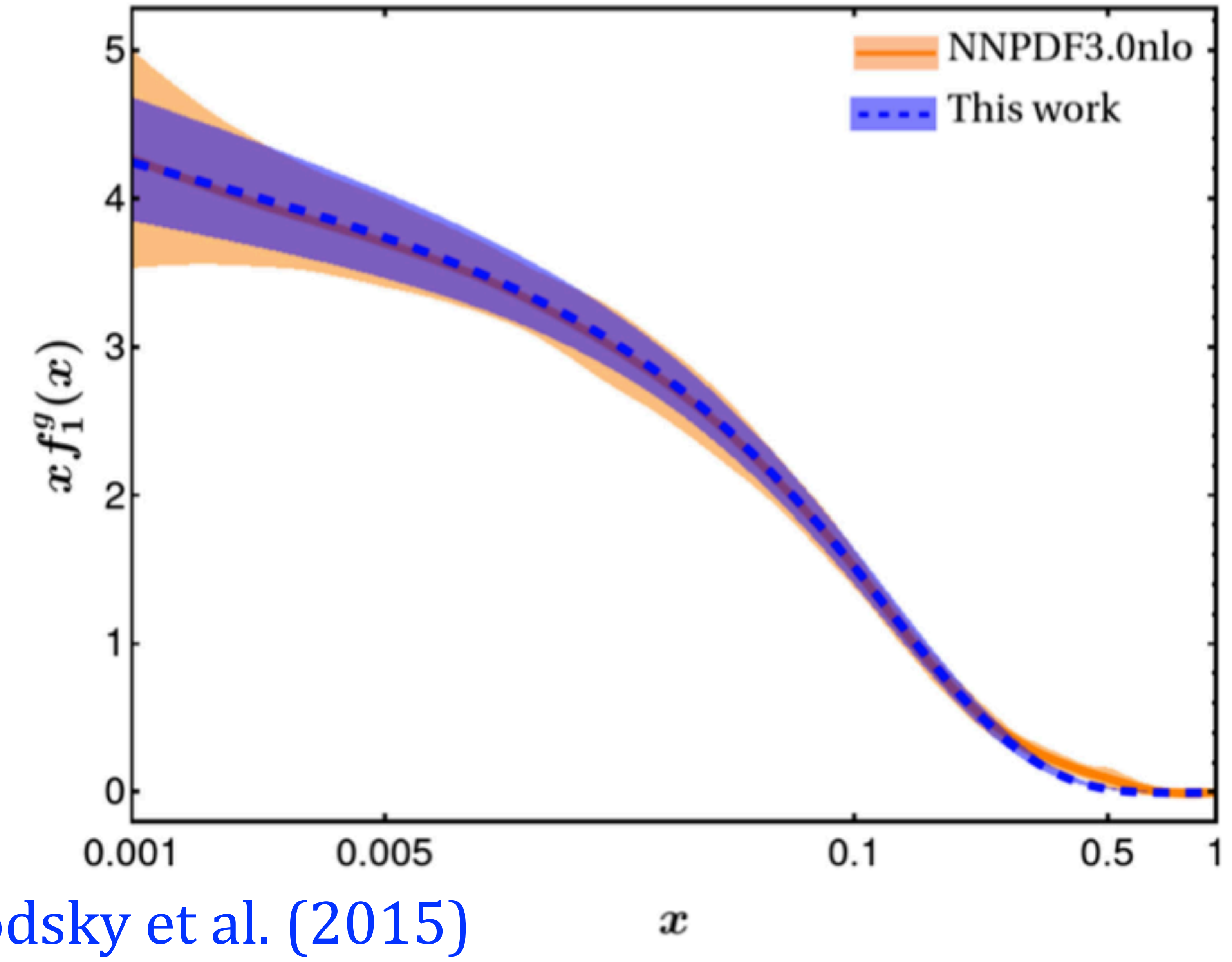
LFWFs

$$f(x,k_\perp,\lambda_g,\lambda_X) \otimes \varphi(x,k_\perp)$$

◆ The scalar function: $\varphi(x,\mathbf{k}_\perp) \rightarrow$ Contains the nonperturbative partonic dynamics and adopted form of soft-wall AdS/QCD wave function.

$$\varphi(x,\mathbf{k}_\perp^2) = N_g\sqrt{\frac{\log[1/(1-x)]}{x}}x^b(1-x)^a\exp\left[-\frac{\log[1/(1-x)]}{2\kappa^2x^2}\mathbf{k}_\perp^2\right],$$

Introduced a and b to reproduce the correct QCD endpoint behavior.



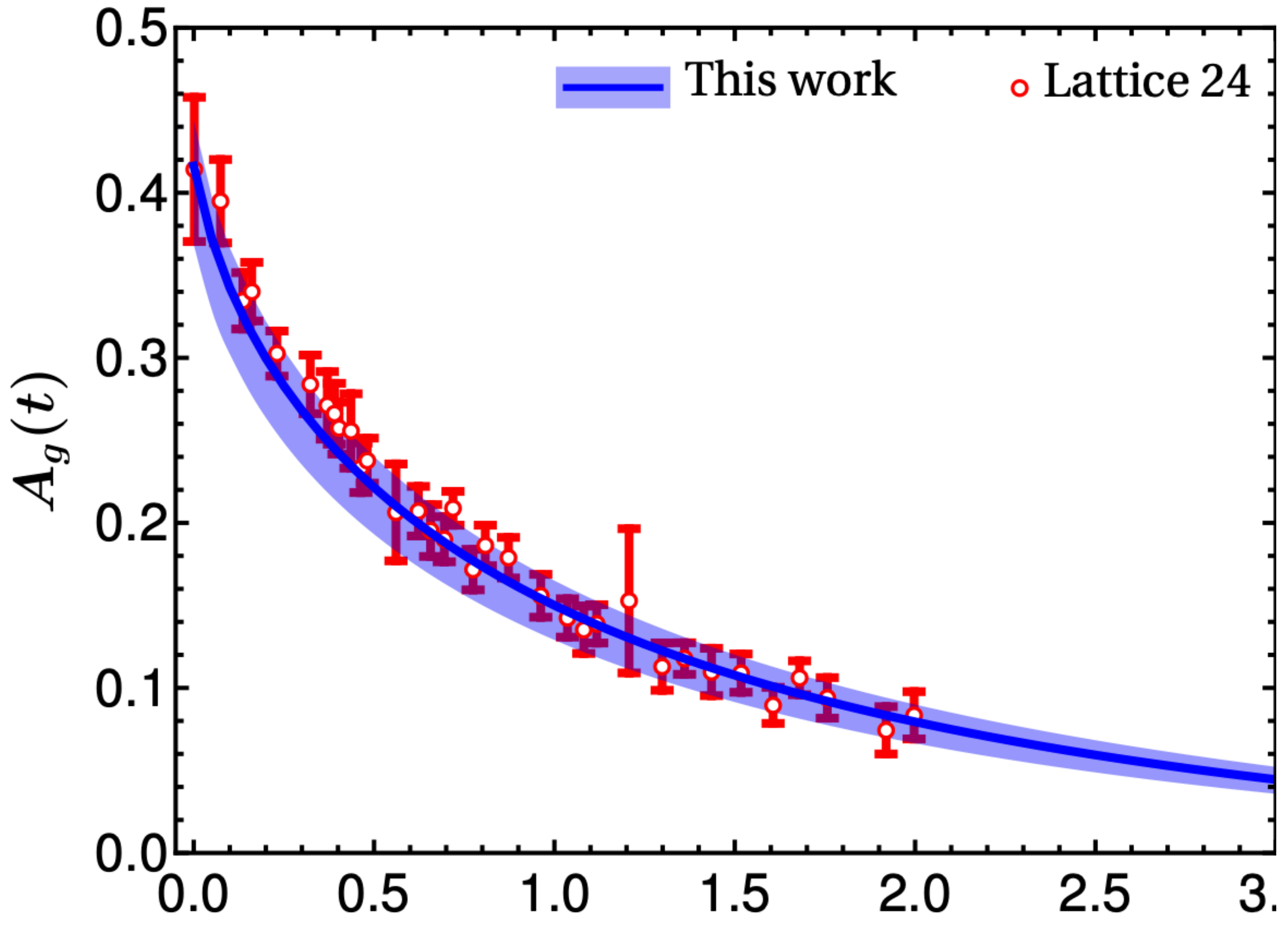
S. J. Brodsky et al. (2001); G. P. Lepage and S. J. Brodsky (1980); D. Chakrabarti et al. (2023); S.J Brodsky et al. (2015)

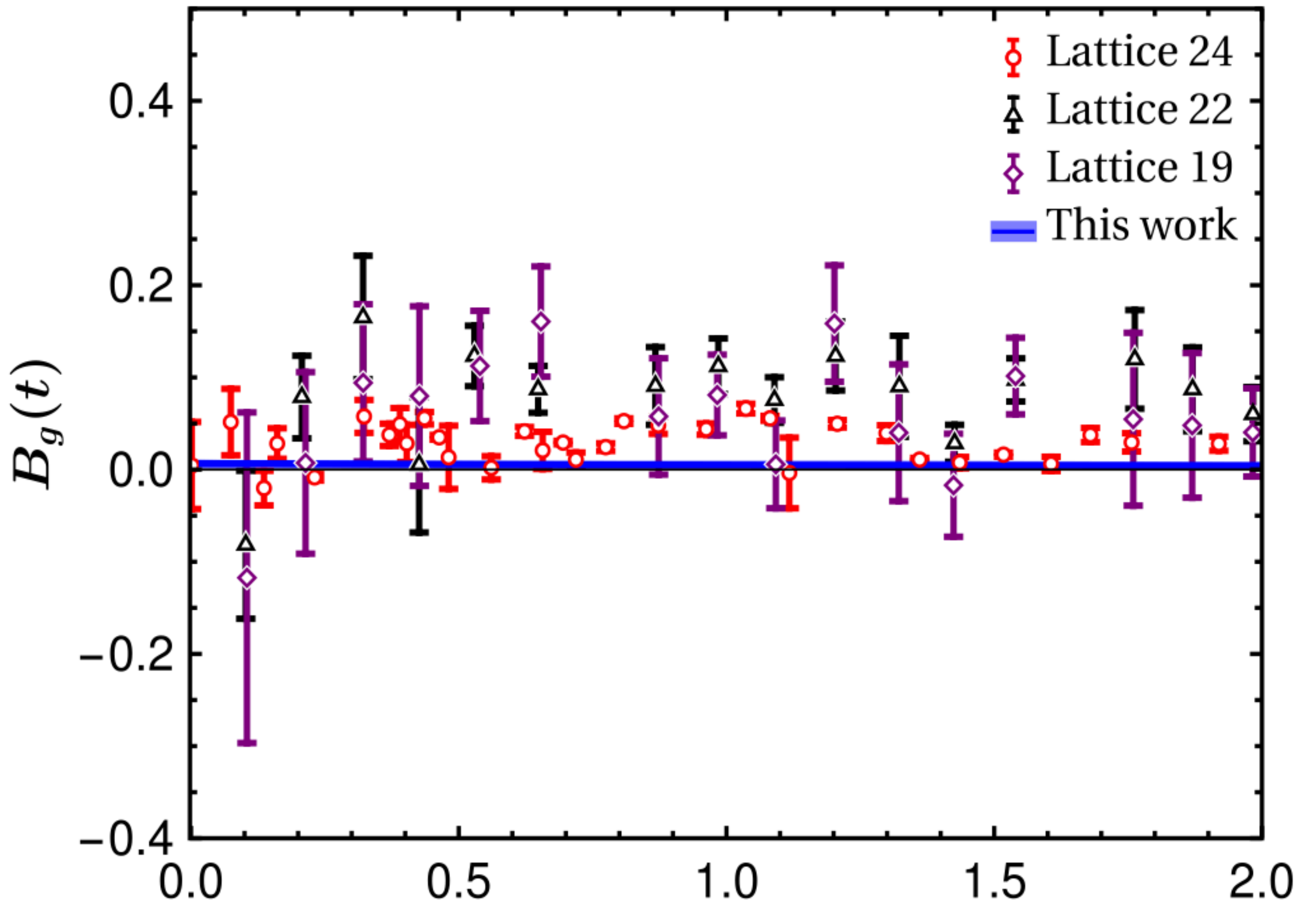
Model results for gluon GFFs

The proton spin conserving (A_i) and spin non-conserving GFF (B_i) can extracted from the "++" components of QCD EMT matrix elements:

$$\mathcal{M}^{++}_{\uparrow\uparrow} + \mathcal{M}^{++}_{\downarrow\downarrow} = 2\ (P^+)^2 A_i(t), \quad \mathcal{M}^{++}_{\uparrow\downarrow} + \mathcal{M}^{++}_{\downarrow\uparrow} = 2\ (P^+)^2 B_i(t)$$

$$\mathcal{M}^{\mu\nu}_{\lambda\lambda'} = \frac{1}{2} \langle P', \lambda' |\, T^{\mu\nu}_g(0) \,| P, \lambda \rangle$$

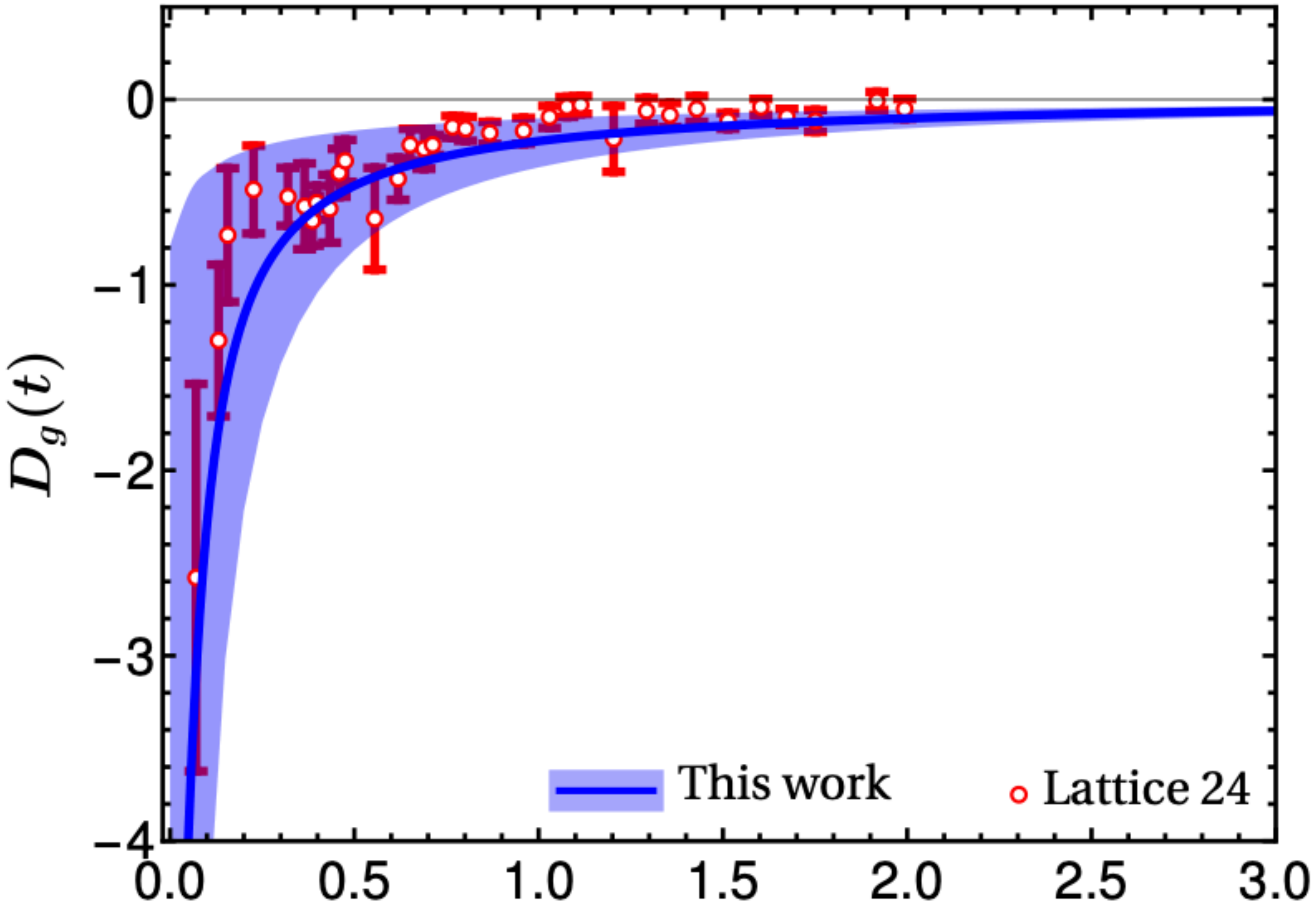




$\bar{C}_i(t)$ and $D_i(t)$ GFFs → Transverse component of the QCD EMT (T^{ij}_a)

$$\sum_{i=1,2} \mathcal{M}^{ii}_{\uparrow\downarrow} + \mathcal{M}^{ii}_{\downarrow\uparrow} = i\left[B_g(q^2)\frac{q^2}{4M} - D_g(q^2)\frac{3q^2}{4M} + \bar{C}_g(q^2)2M\right]q^{(2)}$$

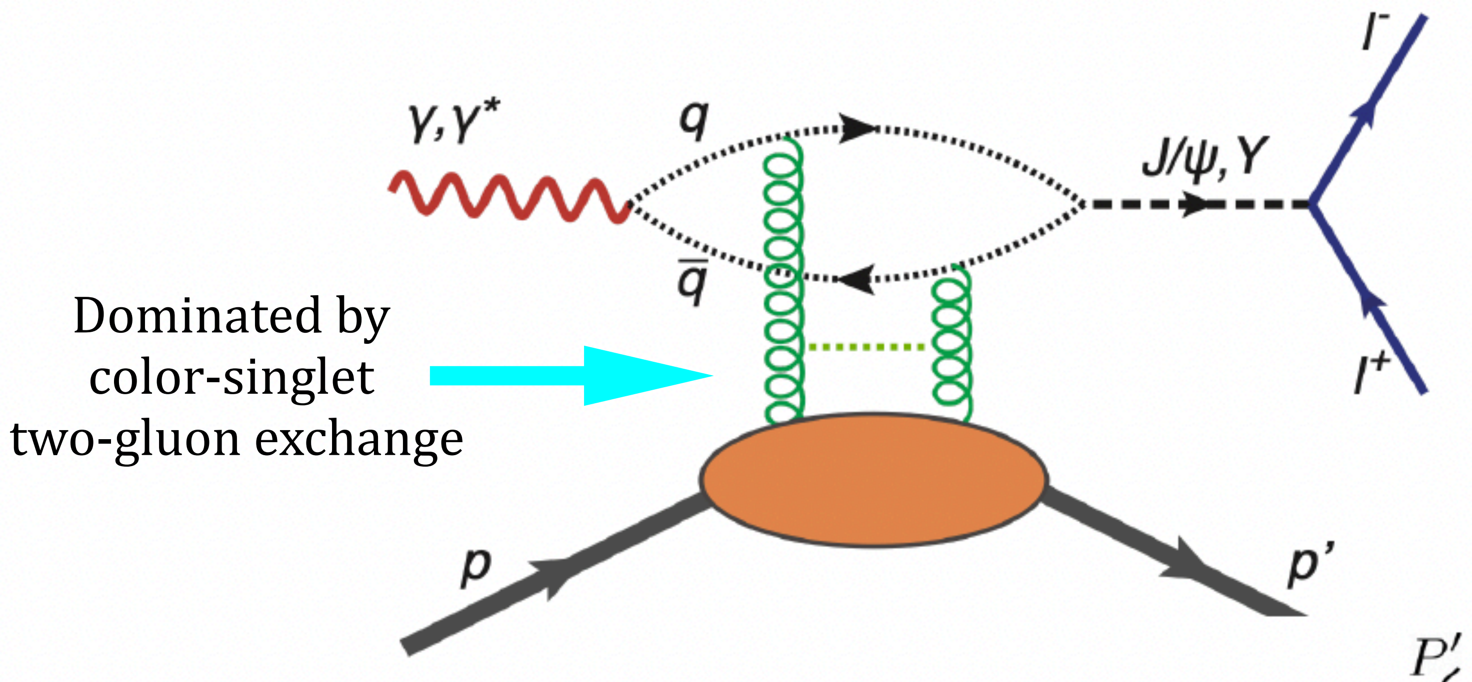
EMT conservation equation: $q_\mu \mathcal{M}^{\mu 1}_{\uparrow\downarrow} + q_\mu \mathcal{M}^{\mu 1}_{\downarrow\uparrow} = -iq^{(1)}q^{(2)}M\bar{C}_i(q^2)$



A. Sain at al. PRD 111, 094011 (2025)   E. Leader et al. Phys.Rept. 541 (2014)   C. Lorce et al., Eur.Phys.J.C 79 (2019)

LO GPD framework Near-Threshold J/ψ production

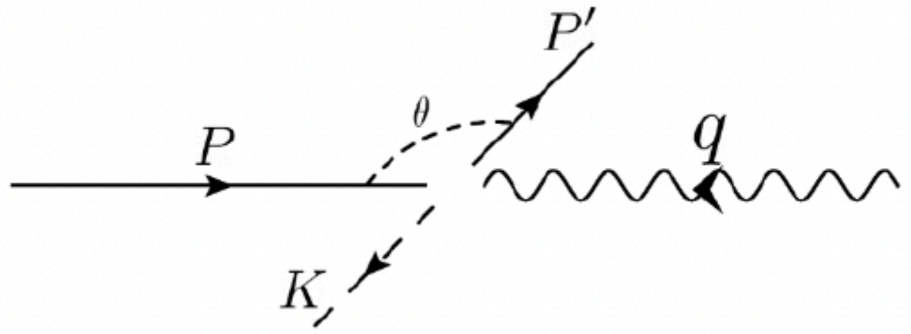
- The near-threshold J/ψ photoproduction cross sections and gluonic GFFs are strictly related only in the heavy-quark $\rightarrow m_Q \gg \Lambda_{QCD}$, large-|t| and $\xi \rightarrow 1$ limits.



Lorentz scalars

$s = W^2 = (P+q)^2$

$t = (P - P')^2 = (q - K)^2$



$$E_\gamma^{th} = \frac{(m_{J/\psi} + m_p)^2 - m_p^2}{2m_p} \approx 8.2\ \text{GeV}$$

Near-threshold heavy vector meson production cross section

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

Extracted from the **leptonic decay width** of J/Ψ $\quad |\psi_{NR}(0)|^2 = \frac{1.0952}{4\pi} (\text{GeV})^3$

$$|G(t,\xi)|^2 = (1-\xi^2)(\mathcal{H} + \mathcal{E})^2 - 2\mathcal{E}(\mathcal{H} + \mathcal{E}) + \left(1 - \frac{t}{4M_N^2}\right)\mathcal{E}^2$$

Within the LO QCD factorization framework of GPDs the CFFs ⟵ $\mathcal{H} = \sum_{i=q,g} \mathcal{H}_i$ and $\mathcal{E} = \sum_{i=q,g} \mathcal{E}_i$ Compton-like form factors (**CFFs**)

$$\mathcal{H}_{q/g}(\xi,t) \equiv \int_{-1}^{1} dx\, \mathcal{C}_{q/g}(x,\xi,\mu_f)\, H_{q/g}(x,\xi,t,\mu_f)$$

LO Wilson Coefficients

$$\mathcal{C}_g(x,\xi,\mu_f) \equiv \frac{1}{x+\xi-i0} - \frac{1}{x-\xi+i0}$$

Gluon GPD correlator

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

The dominant contribution to the production amplitude → lowest GPD moments.

$$\int_{-1}^{1} dx\, xH^a(x,\xi,t) = A^a(t) + \xi^2 D^a(t)$$

$$\int_{-1}^{1} dx\, xE^a(x,\xi,t) = B^a(t) - \xi^2 D^a(t)$$

⟶

$$\mathcal{H}(\xi,t) \approx \frac{2}{\xi^2}\left[A_g(t) + \xi^2 D_g(t)\right]$$

$$\mathcal{E}(\xi,t) \approx \frac{2}{\xi^2}\left[B_g(t) - \xi^2 D_g(t)\right]$$

Model predictions for differential cross-section

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

✦ Model results show good agreement with the **low–momentum-transfer** data from the J/ψ-007 experiment and the GlueX Collaboration.

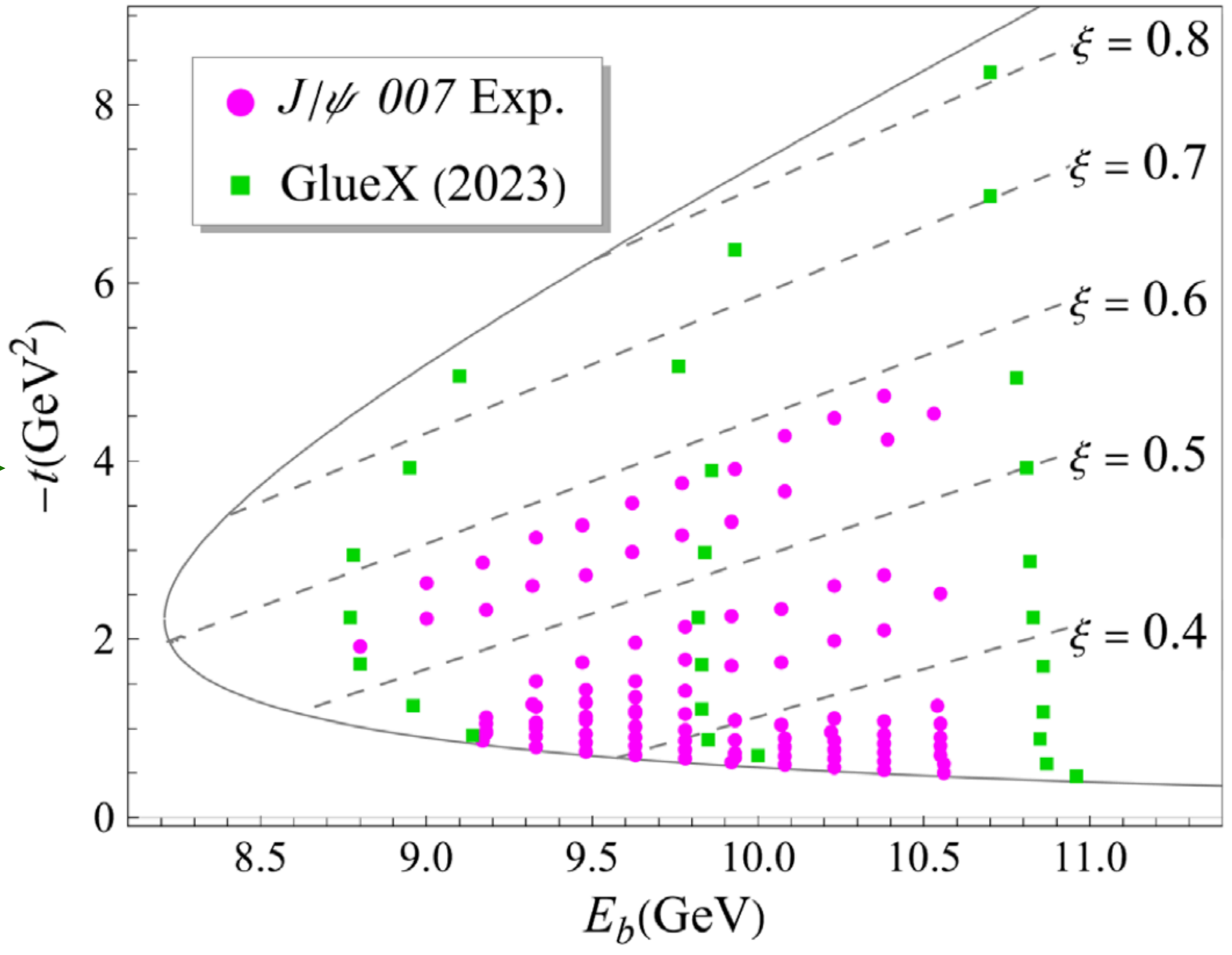
✦ The inclusion of **N**ext-to-**L**eading **O**rder (**NLO**) QCD effects is necessary to describe the data in large-momentum-transfer region.

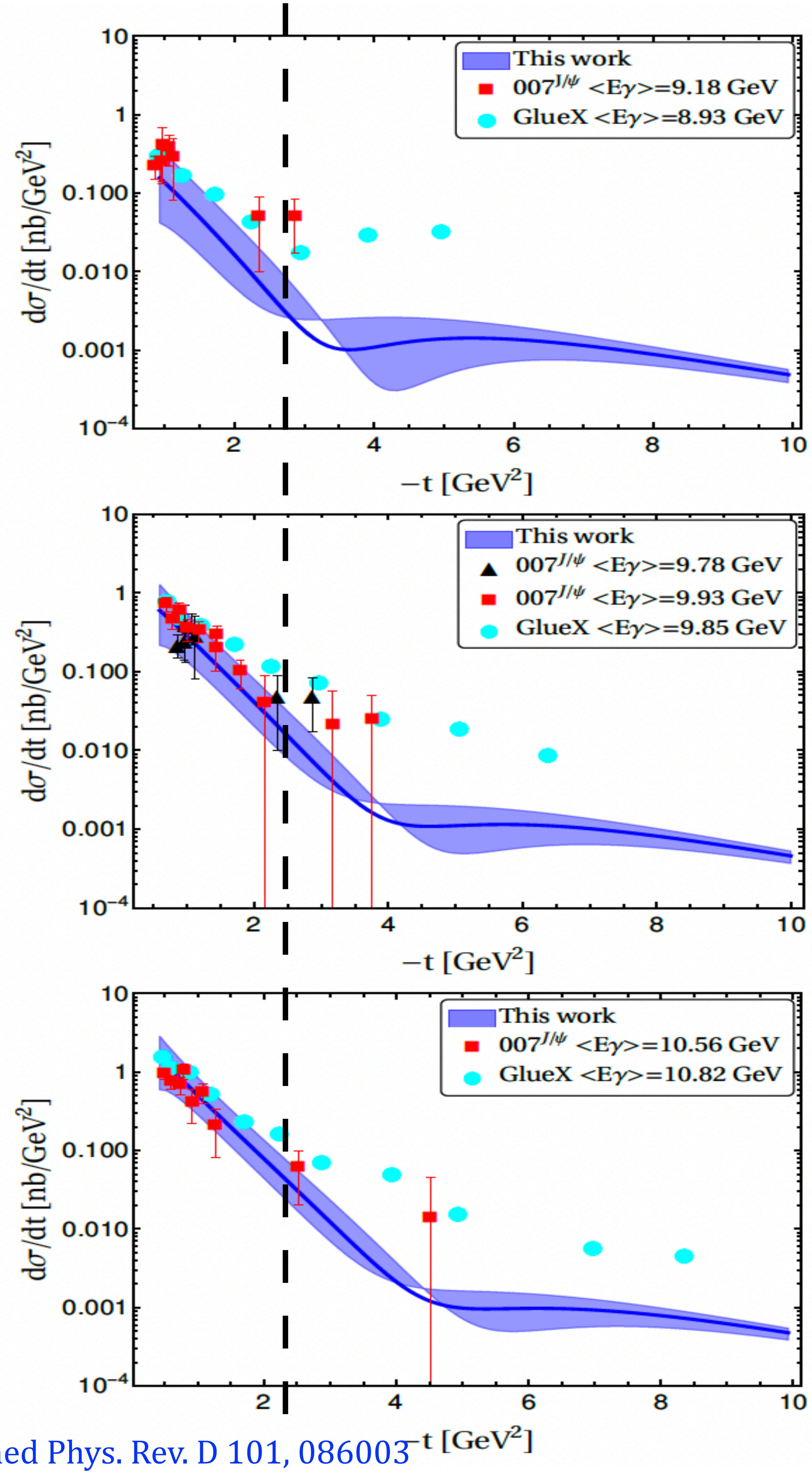
Current experimental limitation:

✓ Expt. data is available only at small $|t|$ and ξ values.

✓ **J/ψ – 007 (Hall C)** covers $\xi < 0.6$

✓ **GlueX (Hall D)** reaches larger ξ but with limited statistics



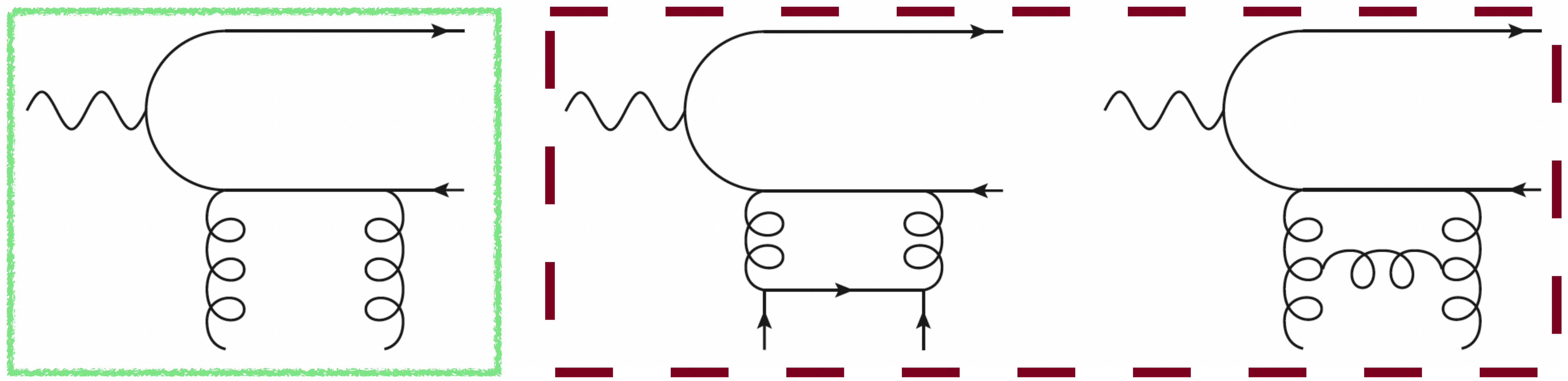


D. Kharzeev Phys. Rev. D 104, 054015; Ji et. al. Phys. Rev. D 103, 096010; Hatta et. al. Phys. Rev. D 98, 074003; Mamo & Zahed Phys. Rev. D 101, 086003

GPD framework at NLO

Y. Guo et al. Phys. Rev. Lett. 135 (2025), 111902

LO NLO



NLO Wilson coefficients

LO NLO

$$\bar{C}_g^{(1)} = \frac{5}{4} + \alpha_S \left[\bar{c}_g^1 - \frac{55}{16\pi} \log\left(\frac{m_c^2}{\mu_F^2}\right) \right] + \mathcal{O}(\alpha_S^2) \ ,$$

$$\bar{C}_q^{(1)} = 0 + \alpha_S \left[\bar{c}_q^1 + \frac{10}{9\pi} \log\left(\frac{m_c^2}{\mu_F^2}\right) \right] + \mathcal{O}(\alpha_S^2) \ ,$$

Modified CFFs

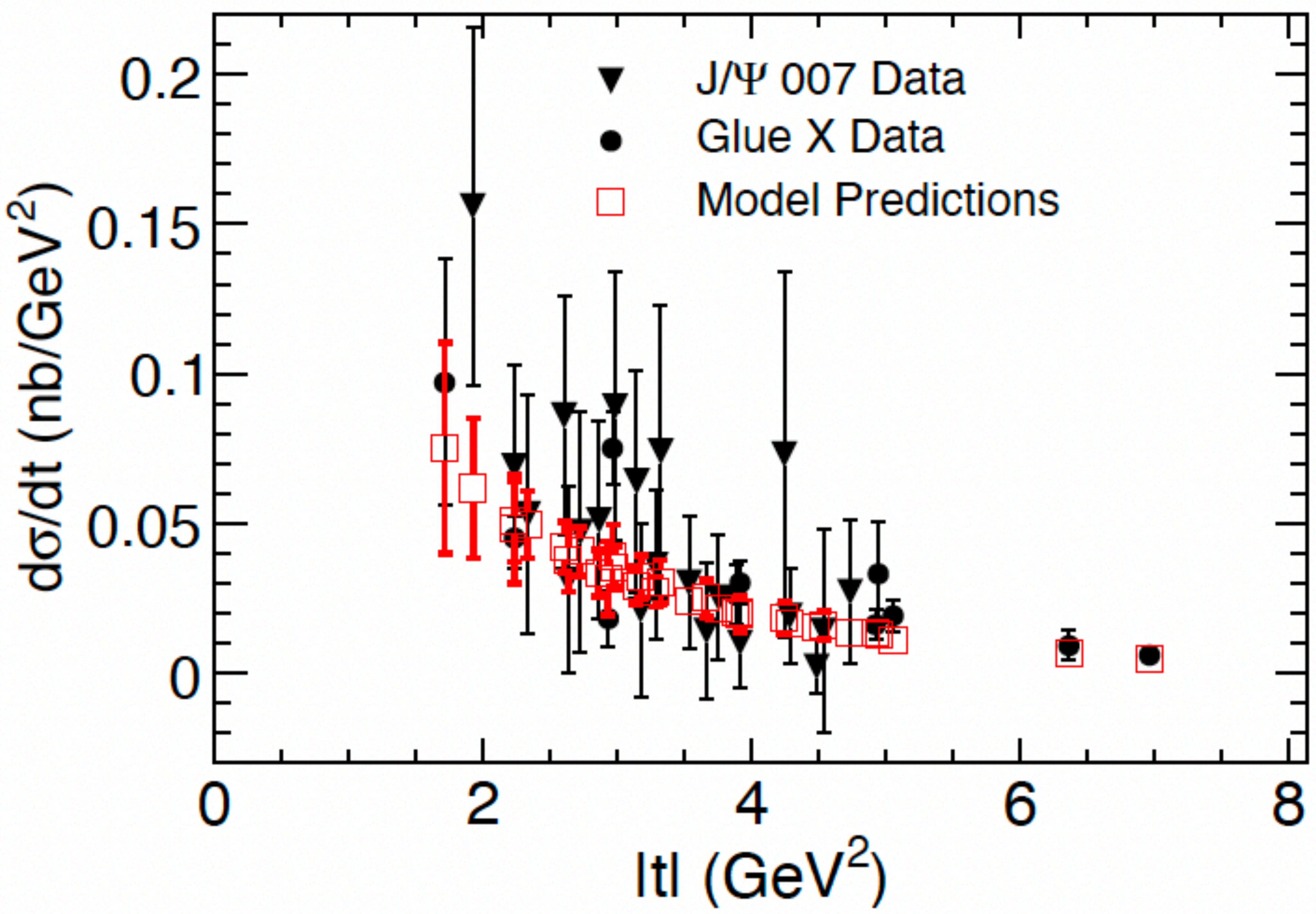
$$\mathscr{H}(\xi,t) \approx \frac{2}{\xi^2}\left[A_g(t)+\xi^2 D_g(t)\right]$$

$$\mathscr{E}(\xi,t) \approx \frac{2}{\xi^2}\left[B_g(t)-\xi^2 D_g(t)\right]$$

$\rightarrow$

$$\mathscr{H}(\xi,t) \approx \frac{2}{\xi^2}\left[\bar{c}_g^{(1)}\left(A_g(t)+\xi^2 D_g(t)\right) + \bar{c}_q^{(1)}\left(A_q(t)+\xi^2 D_q(t)\right)\right]$$

$$\mathscr{E}(\xi,t) \approx \frac{2}{\xi^2}\left[\bar{c}_g^{(1)}\left(B_g(t)-\xi^2 D_g(t)\right) + \bar{c}_q^{(1)}\left(B_q(t)-\xi^2 D_q(t)\right)\right]$$



- ✓ NLO → We can constrain both the quark and gluon GFFs.
- ✓ Current constraint on gluon GFFs ($D_g(0)$) is limited → Lack of precise large-ξ (>0.5) data.
- ✓ GlueX and J/ψ-007measurements have large uncertainties.
- ✓ EIC will provide more precise measurements.

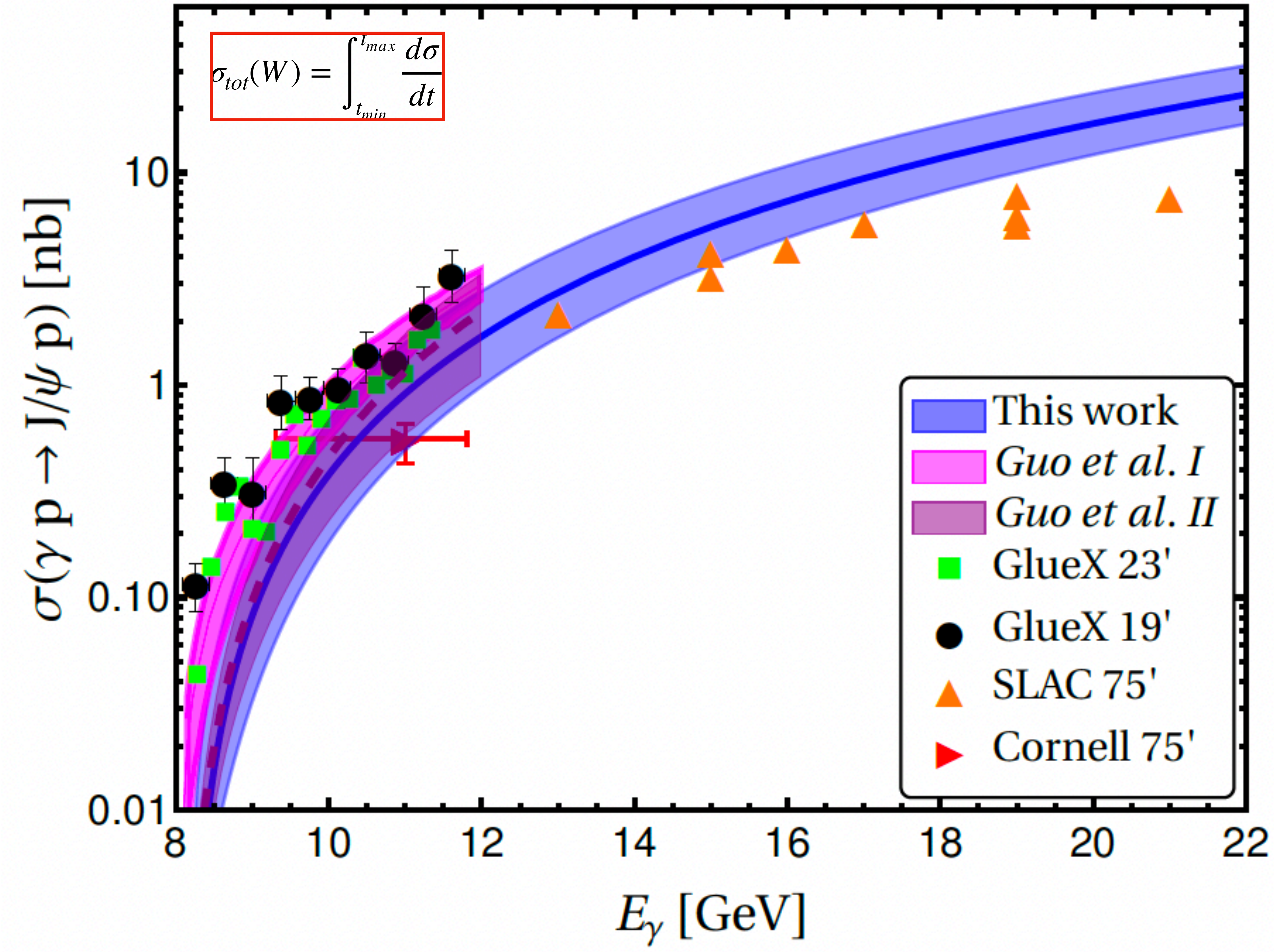
D. Y. Ivanov et al., Eur. Phys. J. C 34, 297 (2004),

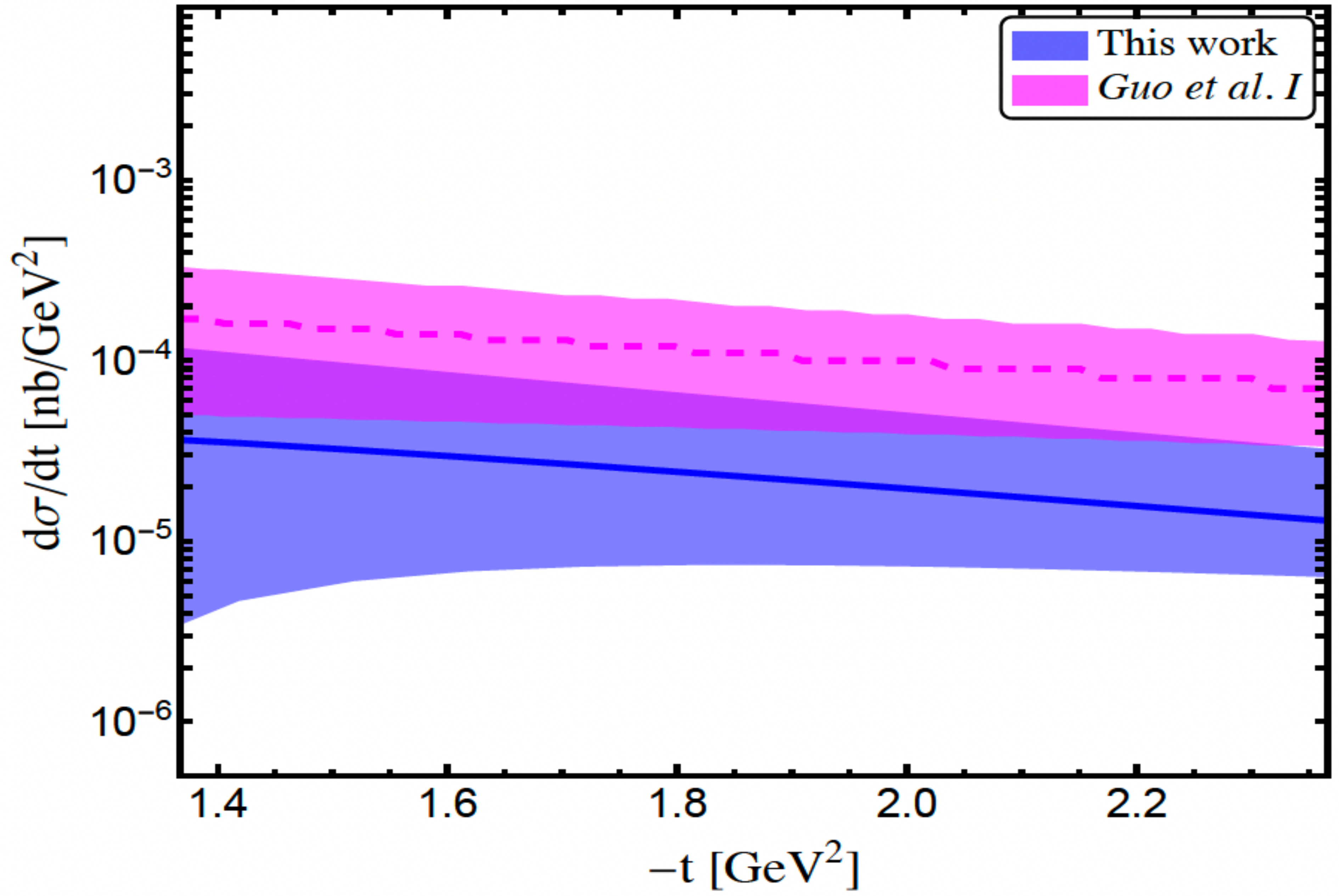
Z.-Q. Chen et al., Phys. Lett. B 797, 134816 (2019)

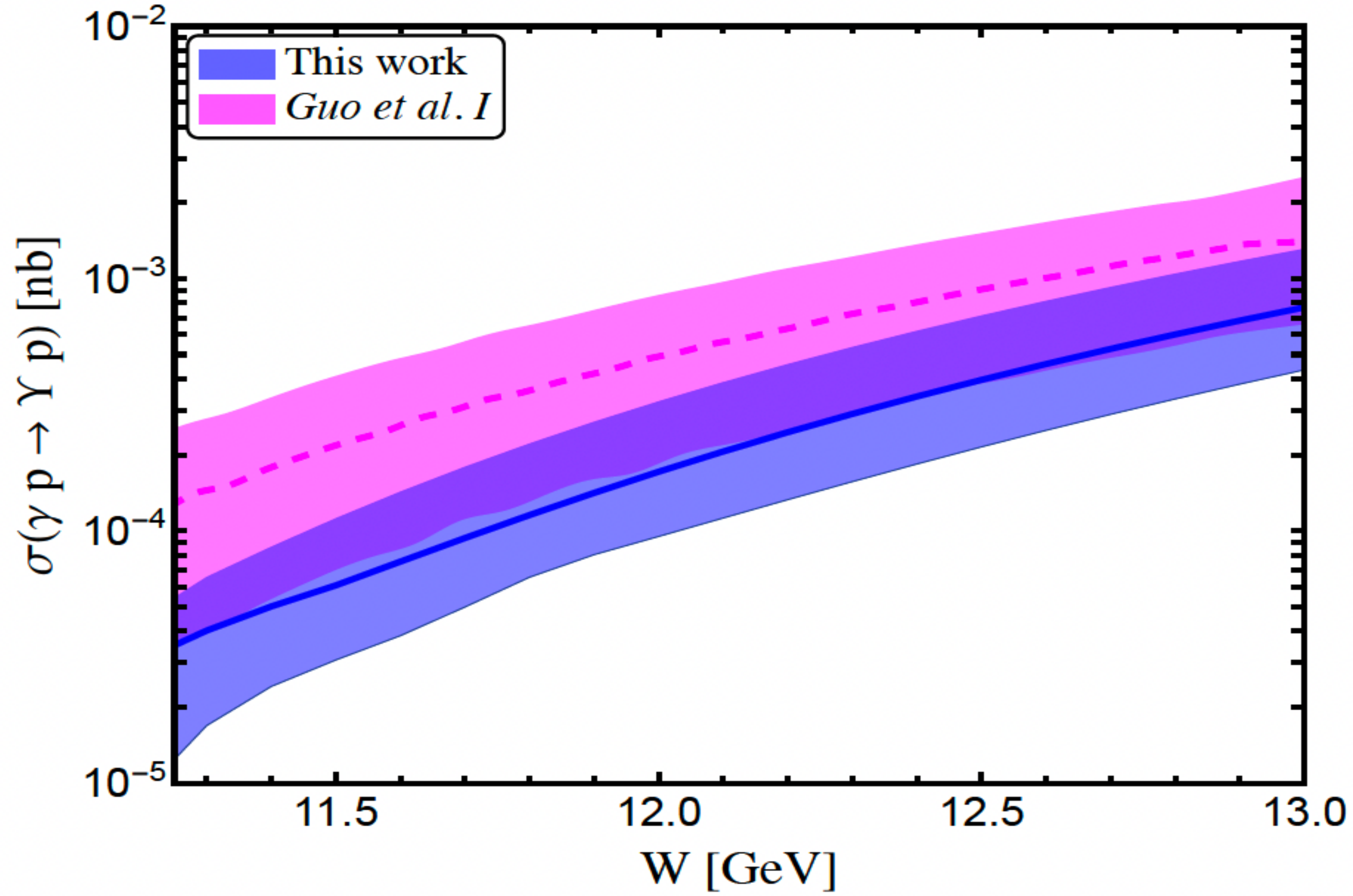
C. A. Flett et al., JHEP 08, 150 (2021)

Total cross section

Υ production is more **suppressed** due to **higher mass**







Y. Guo et al., Phys.Rev.D 108 (2023), Phys.Rev.D 103 (2021); S. Adhikari et al. (GlueX) Phys. Rev. C 108, 025201(2023); B. Gittelman et al., Phys. Rev. Lett. 35, 1616 (1975).

Conclusion & Outlook

- Heavy quarkonium production is an important tool for probing the gluonic gravitational structure of nucleons.

- Light-Front AdS-QCD is a powerful technique to study the strongly interacting hadronic systems and provides a good description of experimental data.

- The gGFFs are consistent with Lattice and Extractions but deviates with the cross-section data, requires the contributions from higher order QCD corrections.

- Sub-threshold photo production of J/ψ and Υ in γA collisions provide the independent test of the universality of the nucleon-nucleon short range correlation (SRC) in nuclear scattering processes.

Thank You for your attention !!