Probing the Nucleon's Gravitational structure through near-threshold heavy quarkonium photoproduction at JLab

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Based on : PRD 113, 054041 (2026), PRD 113, L071503 (2026), and PRD 111, 094011 (2025)

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Date : June 23, 2026

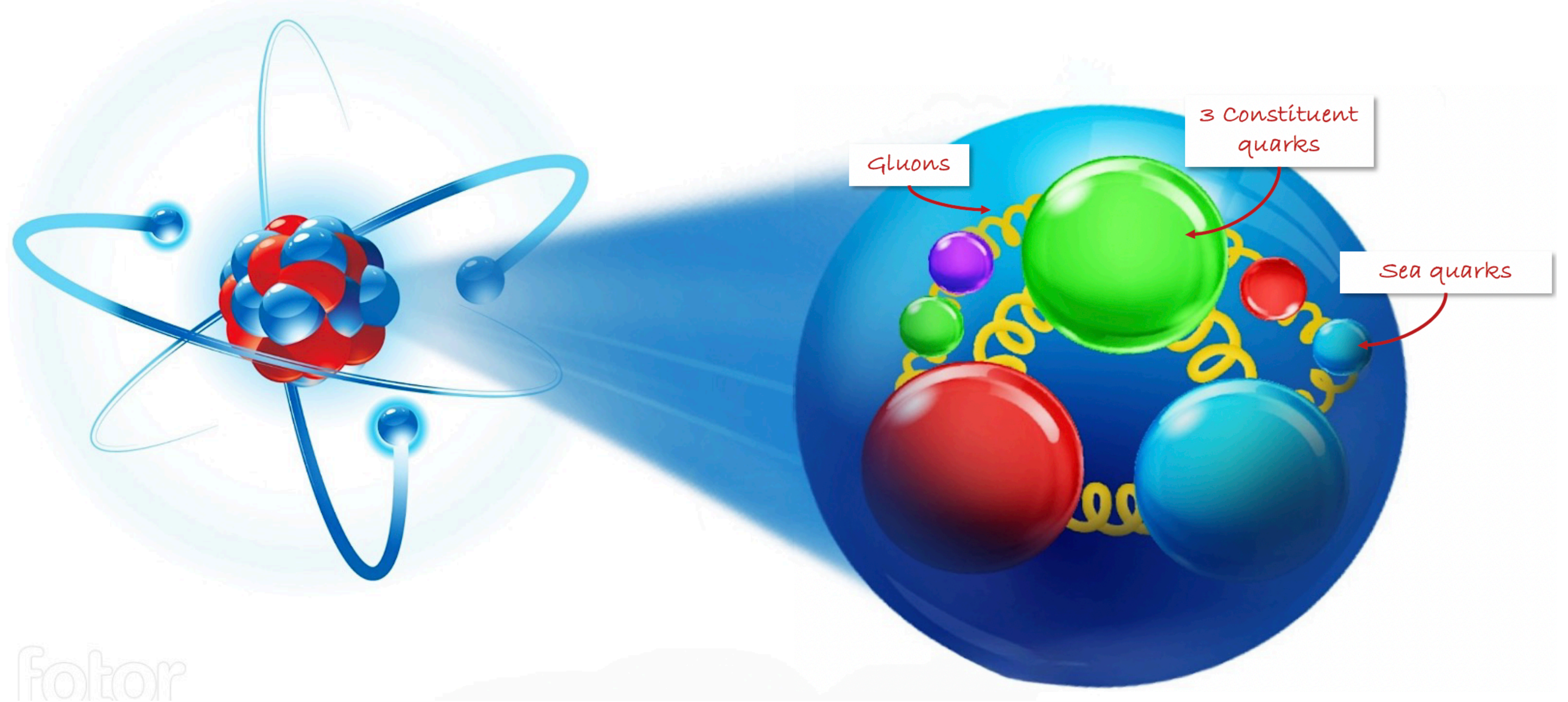
Light-Cone 2026: Applications at EIC era (LC2026), June 22-26, 2026 @ Stony Brook University

Outline

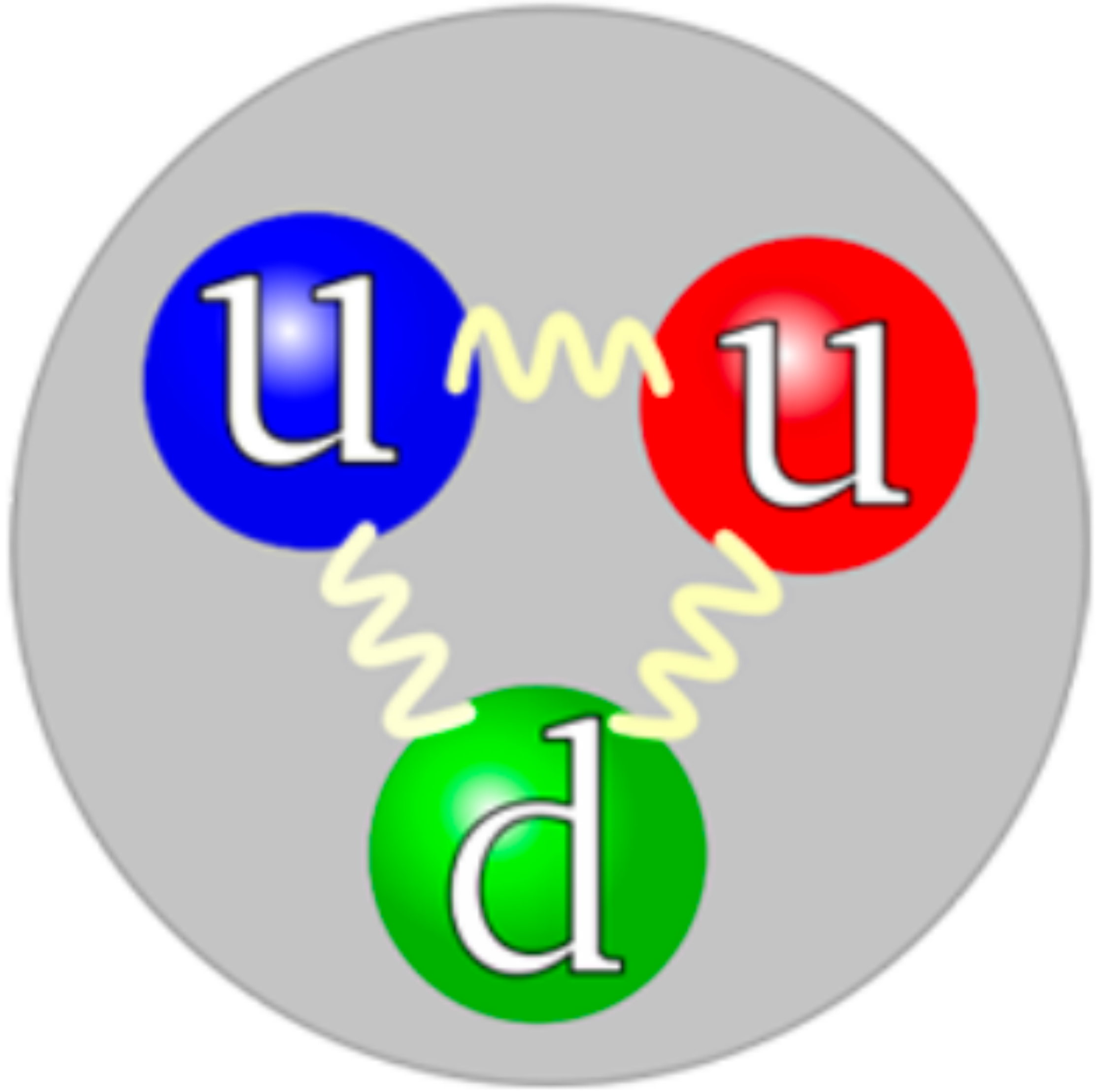
- Fundamental properties of nucleons: mass, spin, and mechanical properties
- Light-Front QCD and the spectator model
- Hadronic energy momentum tensor and GFFs
- GPD framework to access the GFFs near-threshold kinematics
- Conclusion and outlooks

Fundamental problems in Hadronic Physics

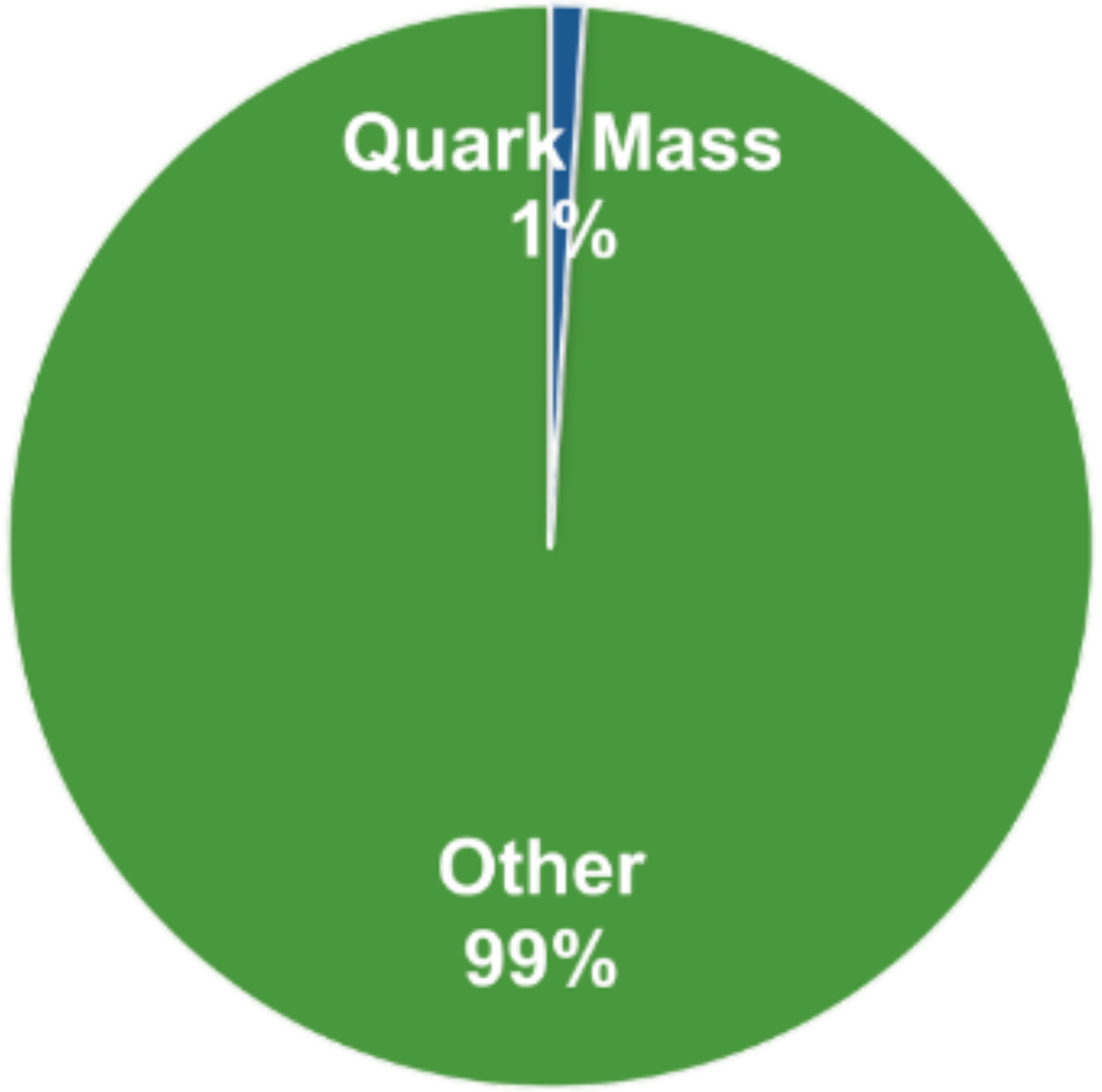
◆ Matter forms from fundamental particles through the formation of hadrons, which are composite particles made of quarks.



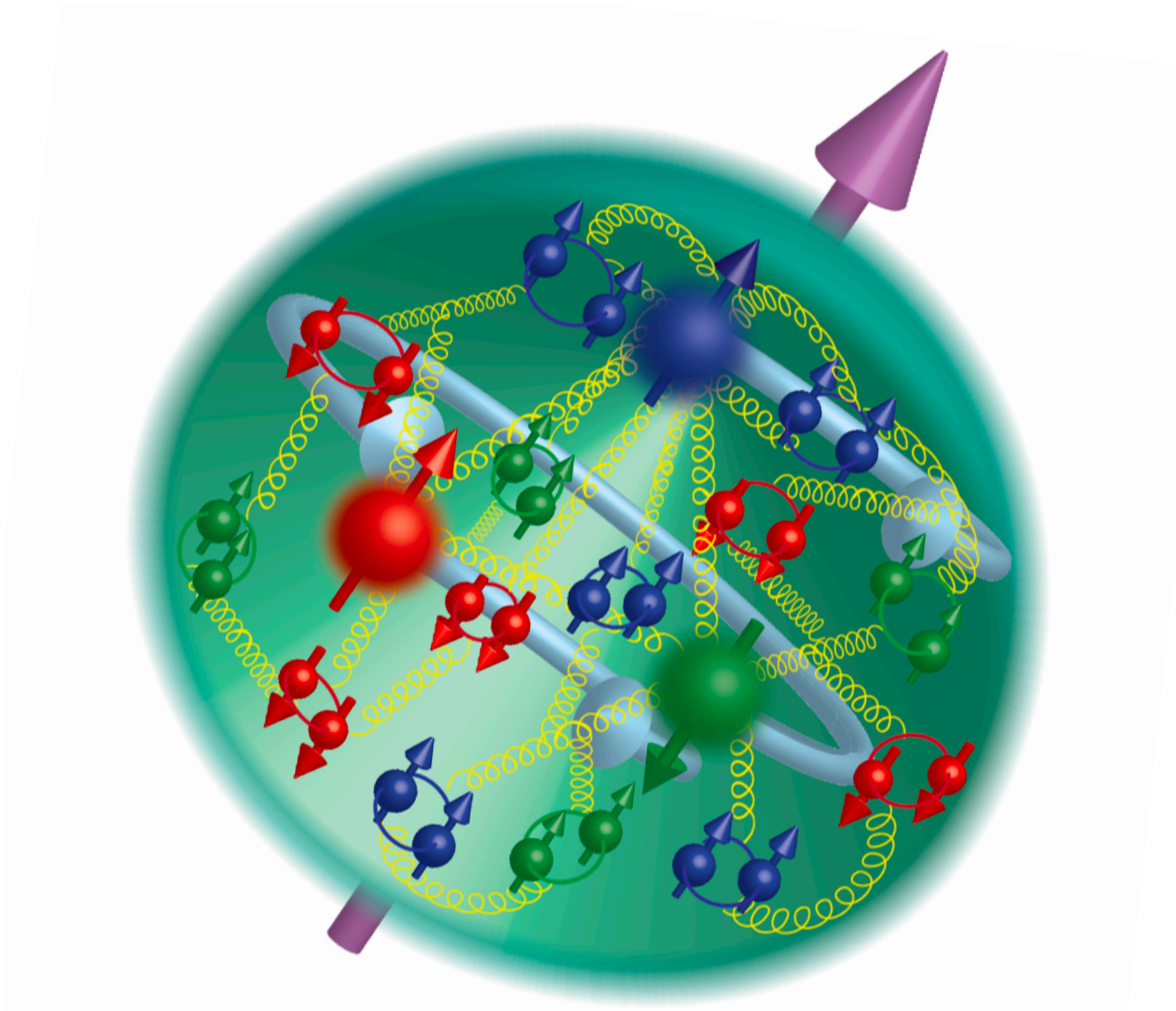
Origin of confinement ?



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

[Lorce:2025oot,Burkert:2022hjz]

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

Probing basic properties of the proton

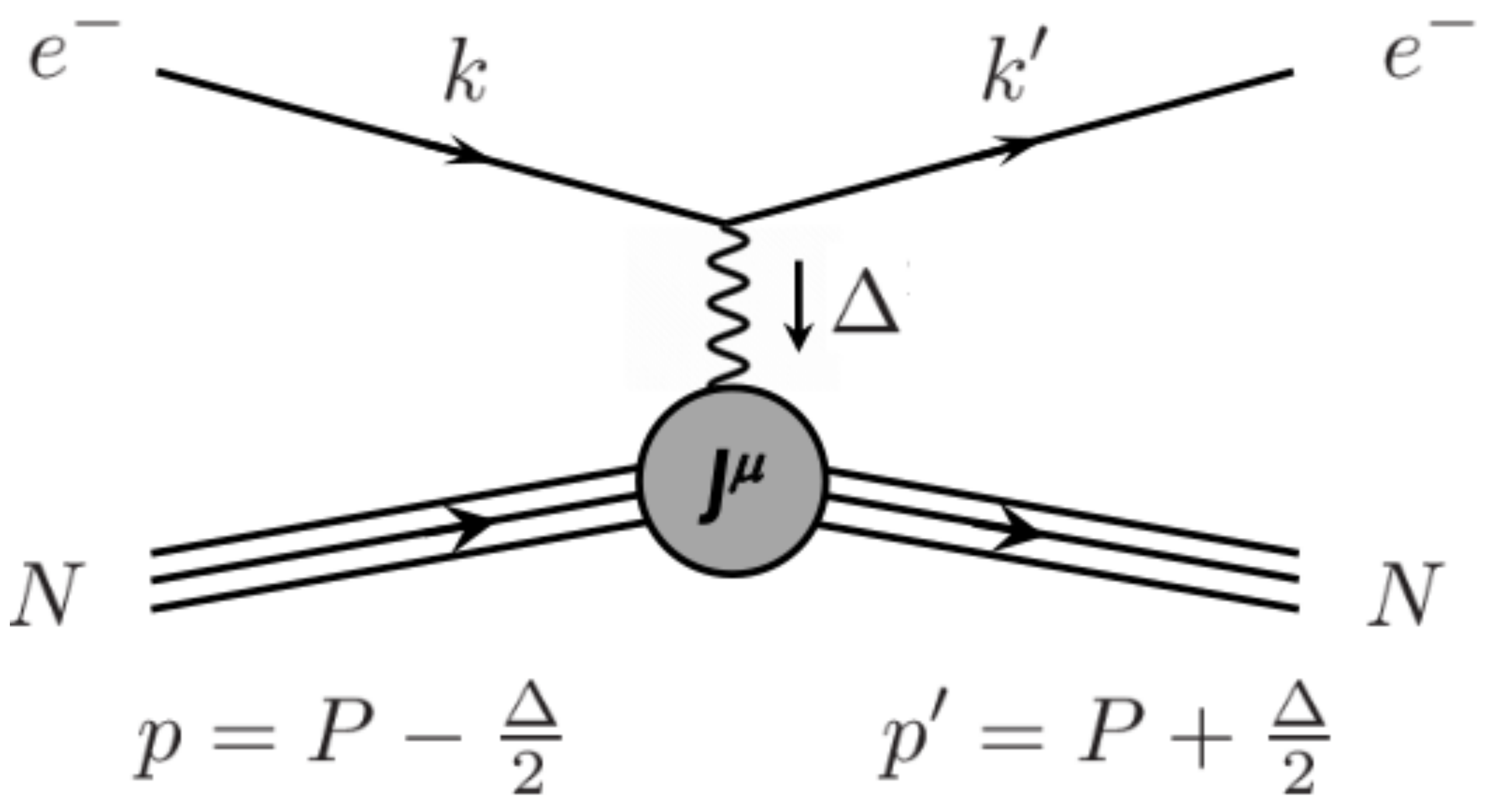
GAUGE AND HIGGS BOSONS

graviton $J = 2$

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

Electromagnetic properties → Probed with photons.

Photon exchange
(~1)



Electromagnetic current

↓

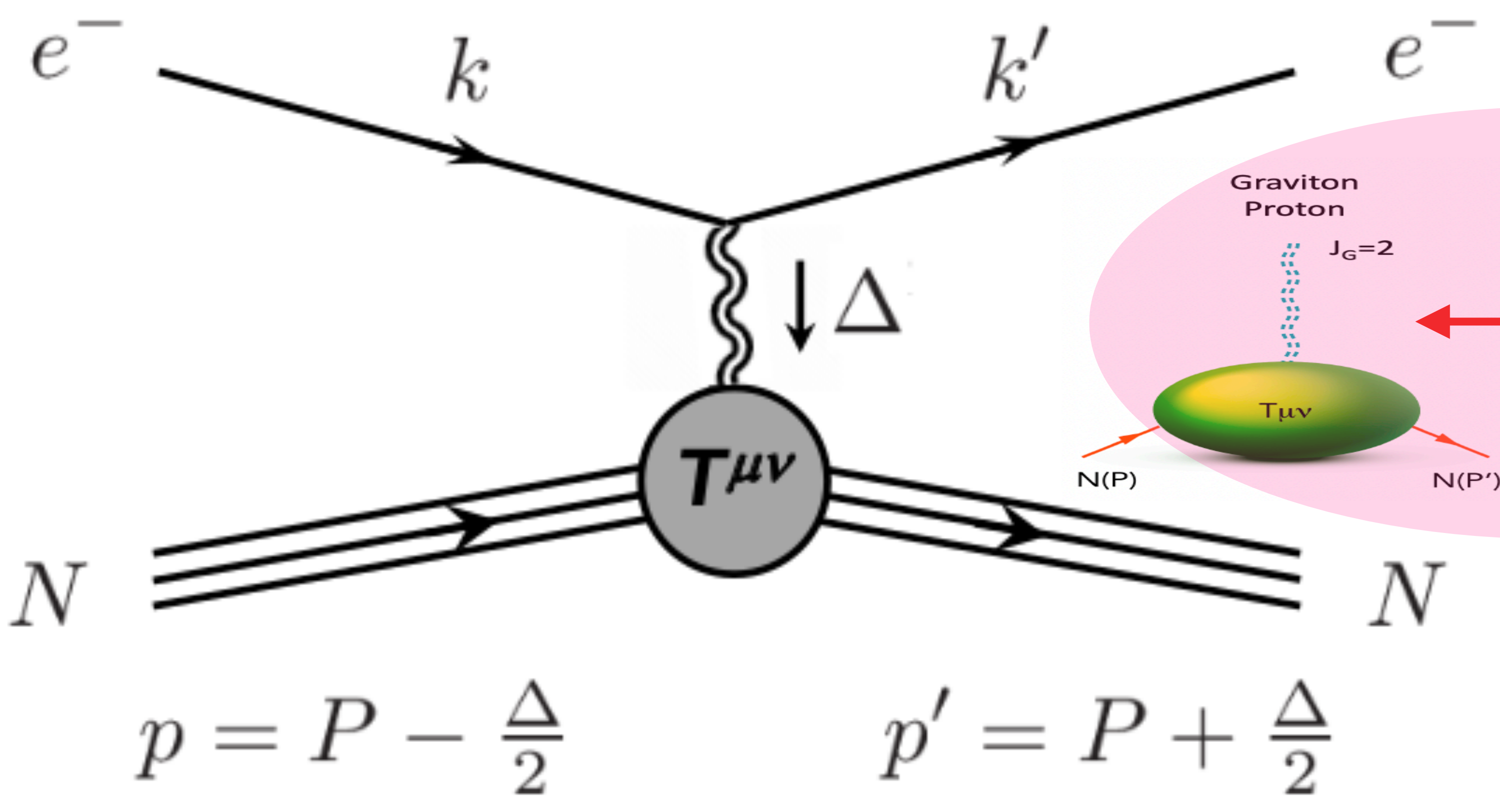
Electromagnetic form factors

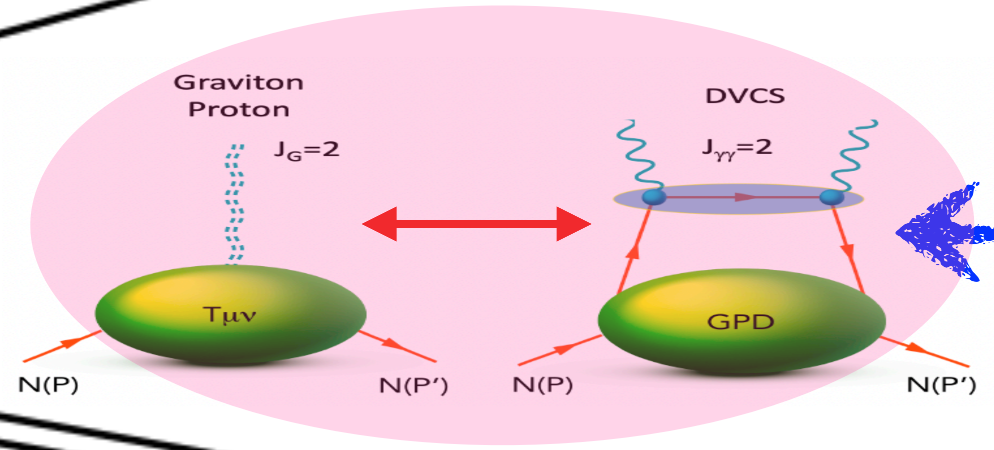
Inelastic structure functions, proton charge radius, charge and current densities

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)

[Ji:1996nm]

↓

CFFs & GPDs

[Mellin ↓ moments]

GFFs

↓

Energy-momentum tensor

↓

Gravitational form factors

[Burkert:2023wzr]

→

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

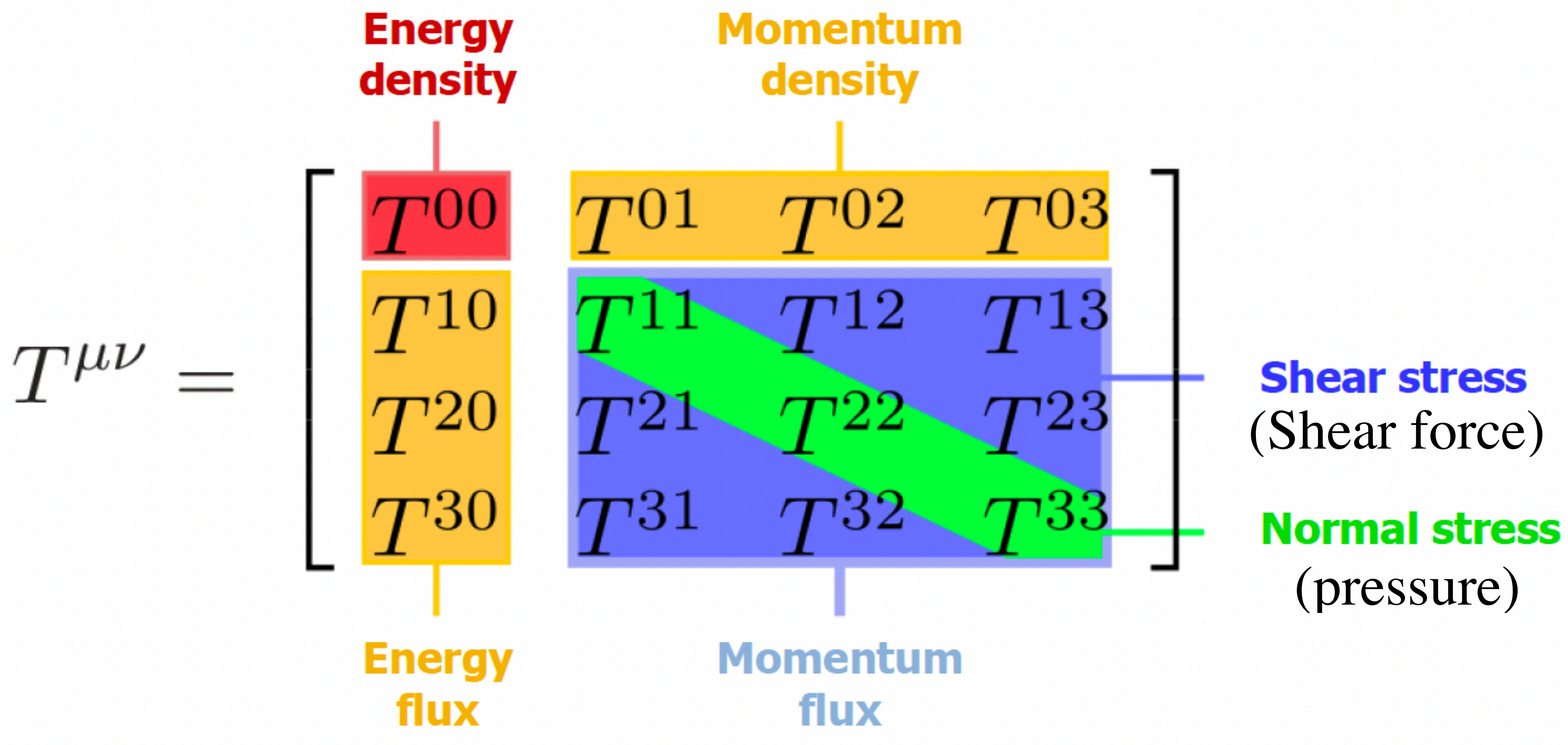
QCD Energy Momentum Tensor and related Physical quantities

◆ 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 QCD EMT → GFFs [Ji:1996ek]

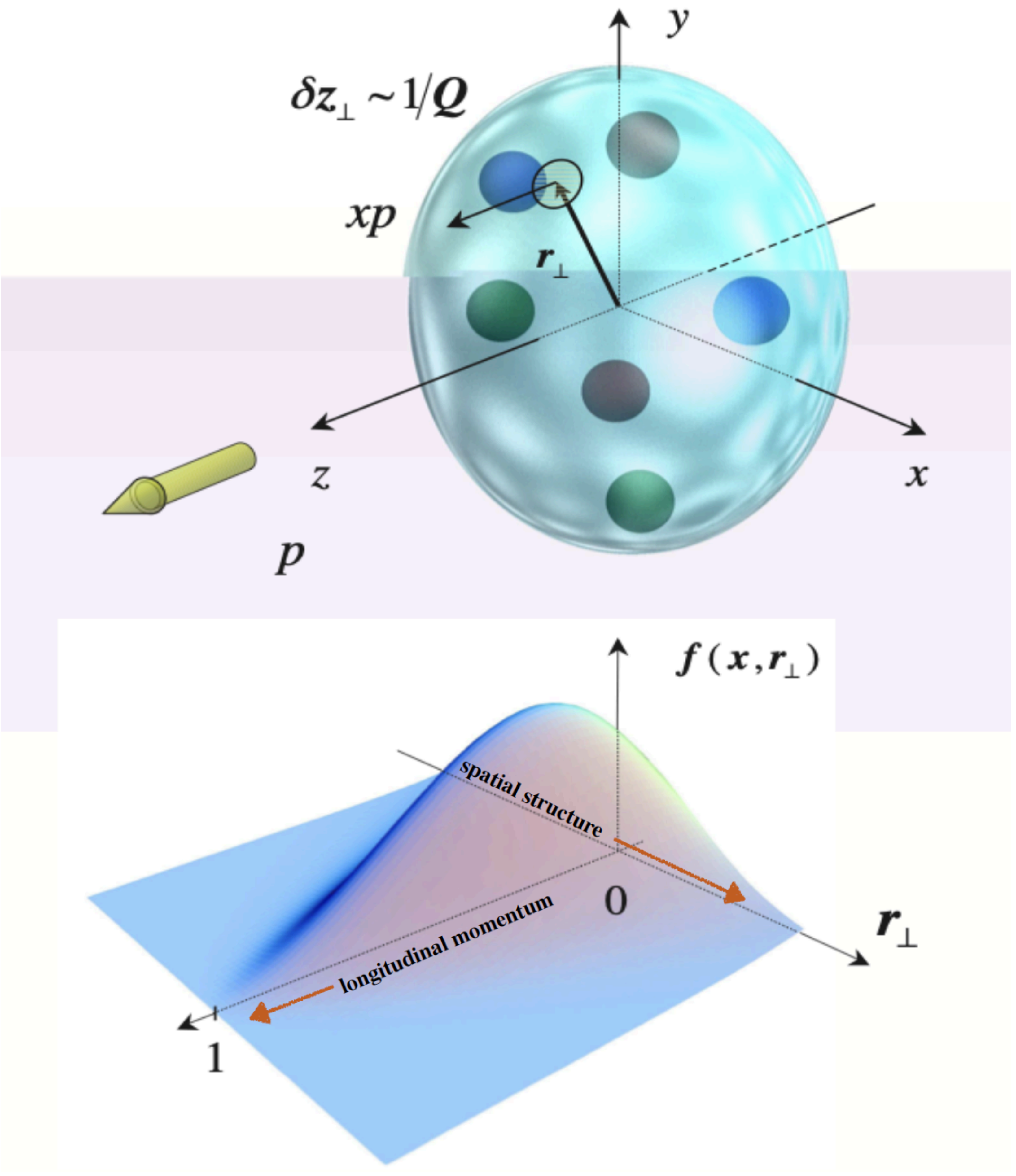
$$\langle P', s' | T_i^{\mu\nu}(0) | P, s \rangle = \bar{u}_{s'}(P') \Bigg[A_i(t) \gamma^{(\mu} \bar{P}^{\nu)} + B_i(t) \frac{i\bar{P}^{(\mu}\sigma^{\nu)\rho}\Delta_\rho}{2m_N} + C_i(t) \frac{\Delta^\mu \Delta^\nu - g^{\mu\nu}\Delta^2}{m_N} + \bar{C}_i(t) m_N g^{\mu\nu} \Bigg] u_s(P),$$

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: $\partial_\mu T^{\mu\nu} = 0 \Rightarrow \sum_{i=q,g} \bar{C}_i(t) = 0.$
4. Mechanical stability: $\sum_{i=q,g} D_i(t) < 0.$

[Pagels:1966zza, Burkert:2018bqq, Burkert:2021ith, Polyakov:2018zvc]

Generalized Parton Distribution and hadron structure

$$F^g(x,\Delta;\lambda,\lambda') = \frac{1}{2P^+}\bar{u}(p',\lambda')\left(\gamma^+ H^g(x,\xi,t) + \frac{i\sigma^{+\mu}\Delta_\mu}{2M} E^g(x,\xi,t)\right)u(p,\lambda)$$

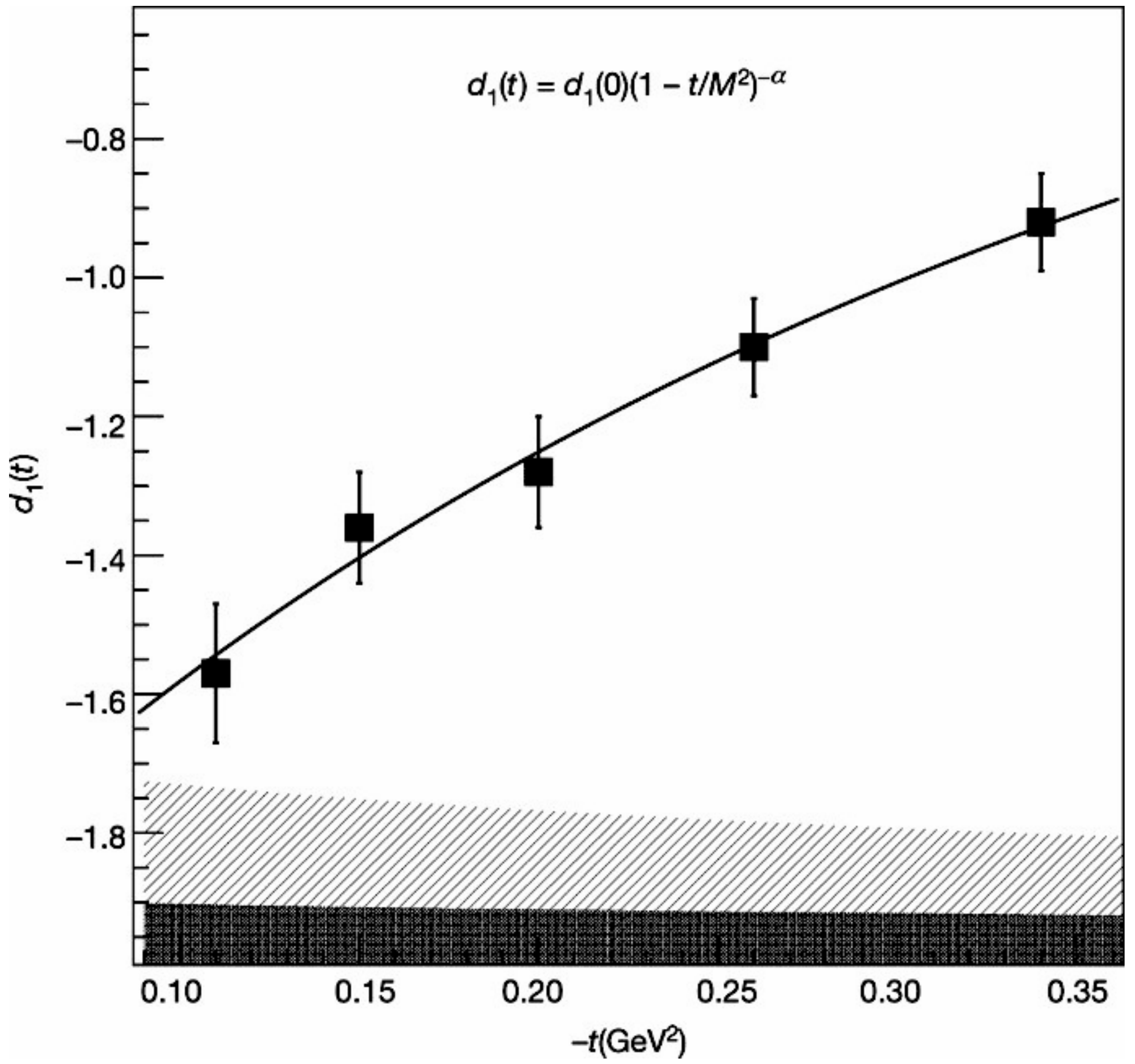


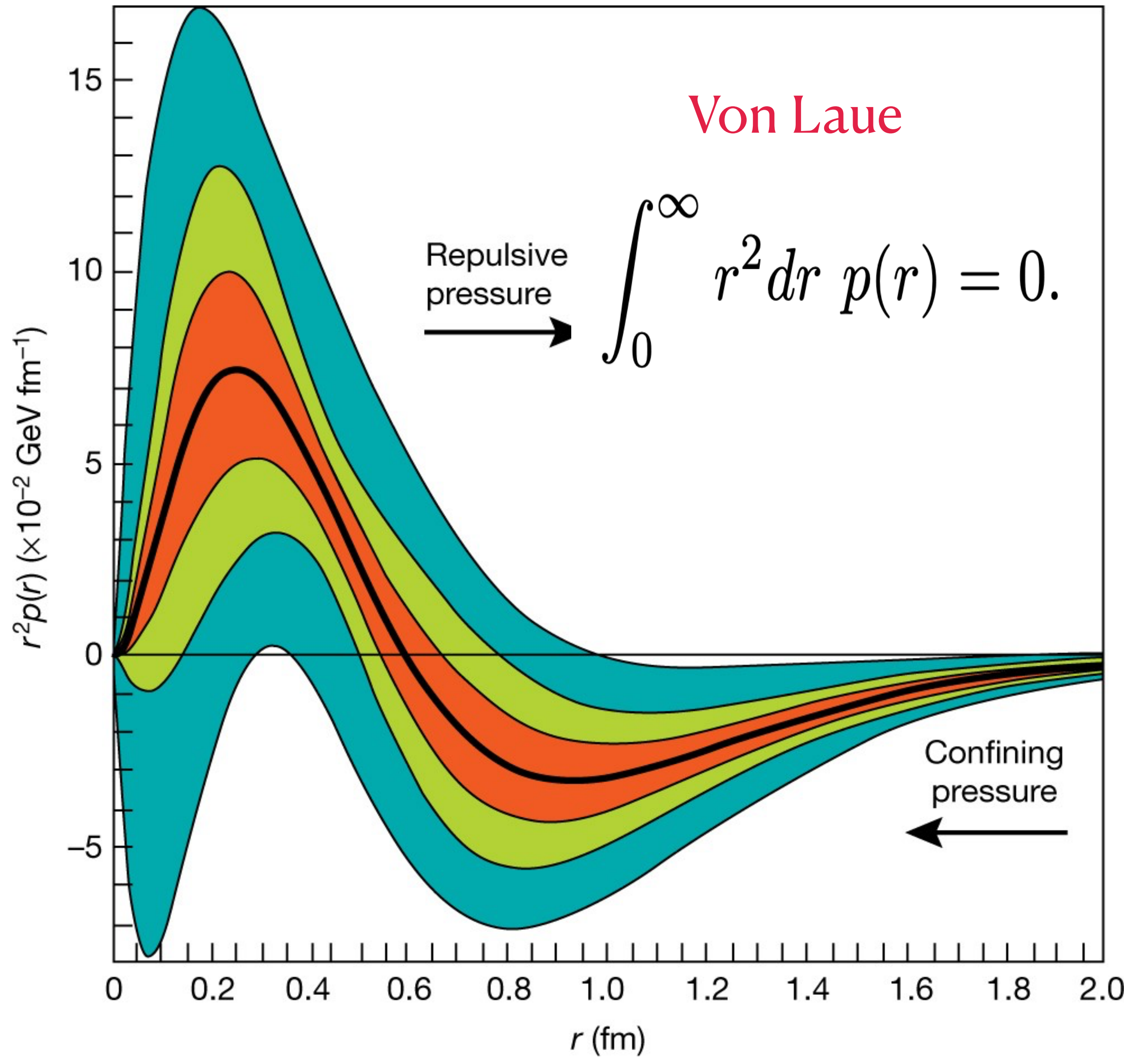
➢GPDs in impact parameter space: $\mathcal{X}(x,b) = \frac{1}{2\pi}\int d^2\Delta e^{-i\Delta^\perp\cdot b^\perp}\mathcal{X}(x,t).$

The x-moments of GPDs

$$\int_{-1}^{1} dx\ H^a(x,\xi,t) = F_1^a(t) \qquad \int_{-1}^{1} dx\ xH^a(x,\xi,t) = A^a(t) + \xi^2 D^a(t)$$

$$\int_{-1}^{1} dx\ E^q(x,\xi,t) = F_2^a(t) \qquad \int_{-1}^{1} dx\ xE^a(x,\xi,t) = B^a(t) - \xi^2 D^a(t)$$





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

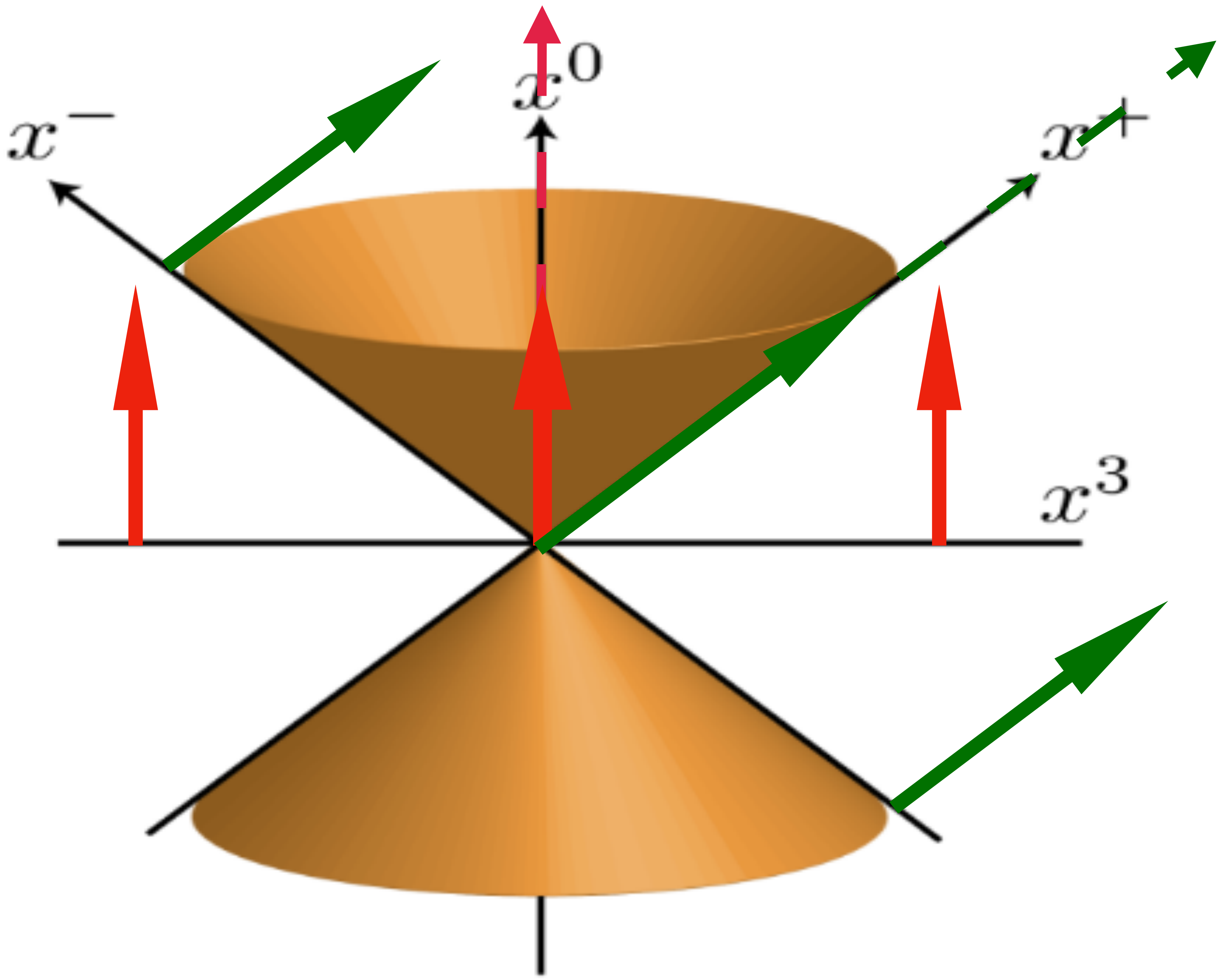
REVIEWS OF MODERN PHYSICS VOLUME 21, NUMBER 3 JULY, 1949

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

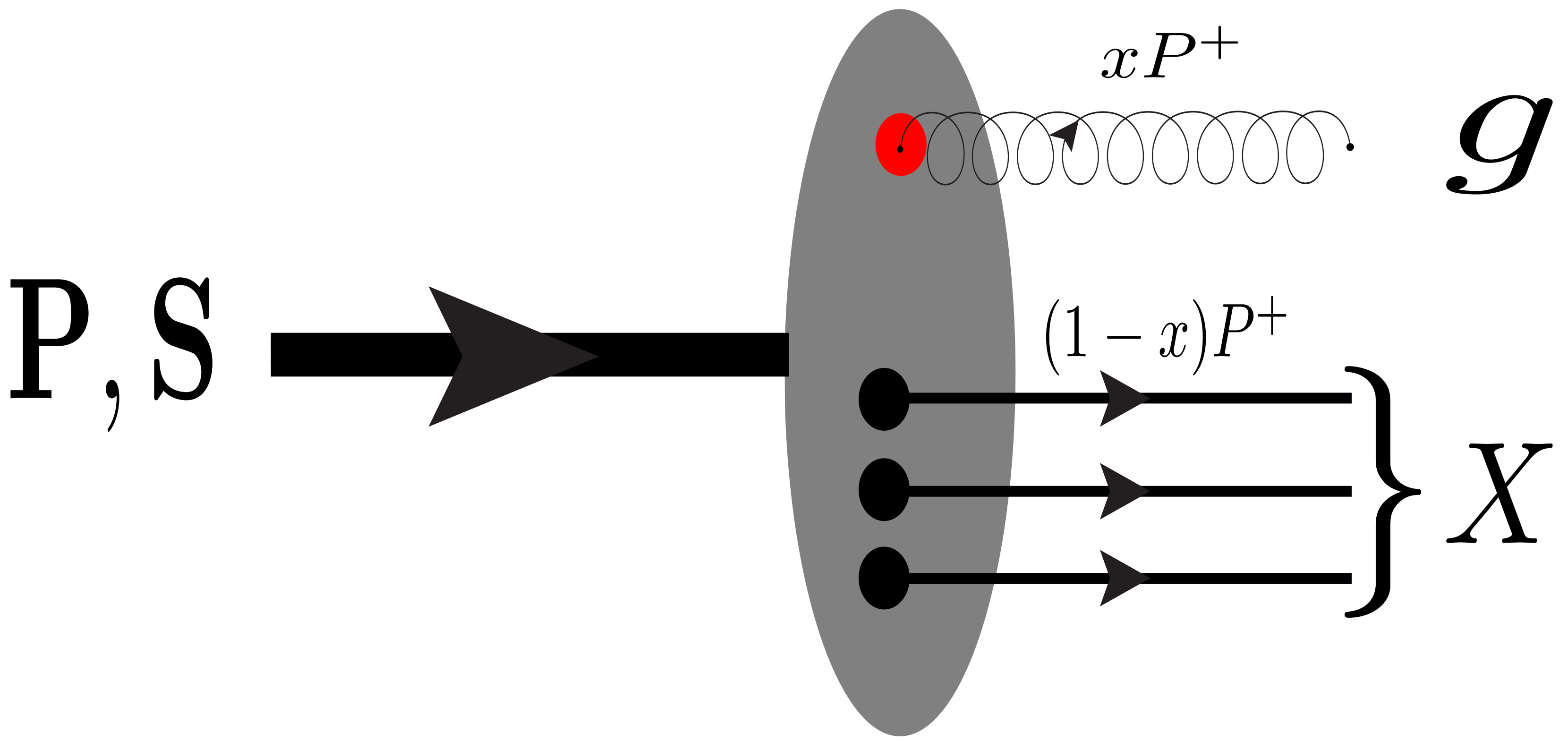
In light-front boost become simple scale transformation

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".

[Harindranath:1996hq; Dirac:1949cp]

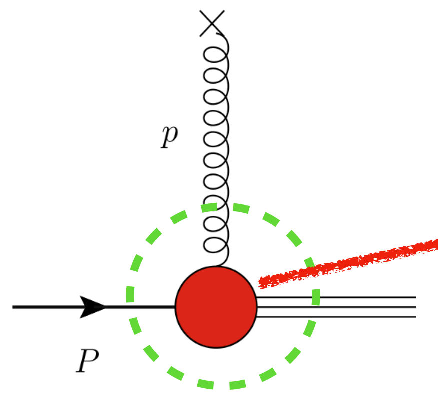
◆ In this model the nucleons [p=|g(uud)⟩, n=|g(udd)⟩] are considered as an effective two particle bound state of spin-1 active gluon and a spin-1/2 spectator cluster. [Motivated by the quantum fluctuations of an electron in QED: $|e\rangle \to |e\rangle_{\text{bare}} + |\gamma e\rangle + \cdots$]



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

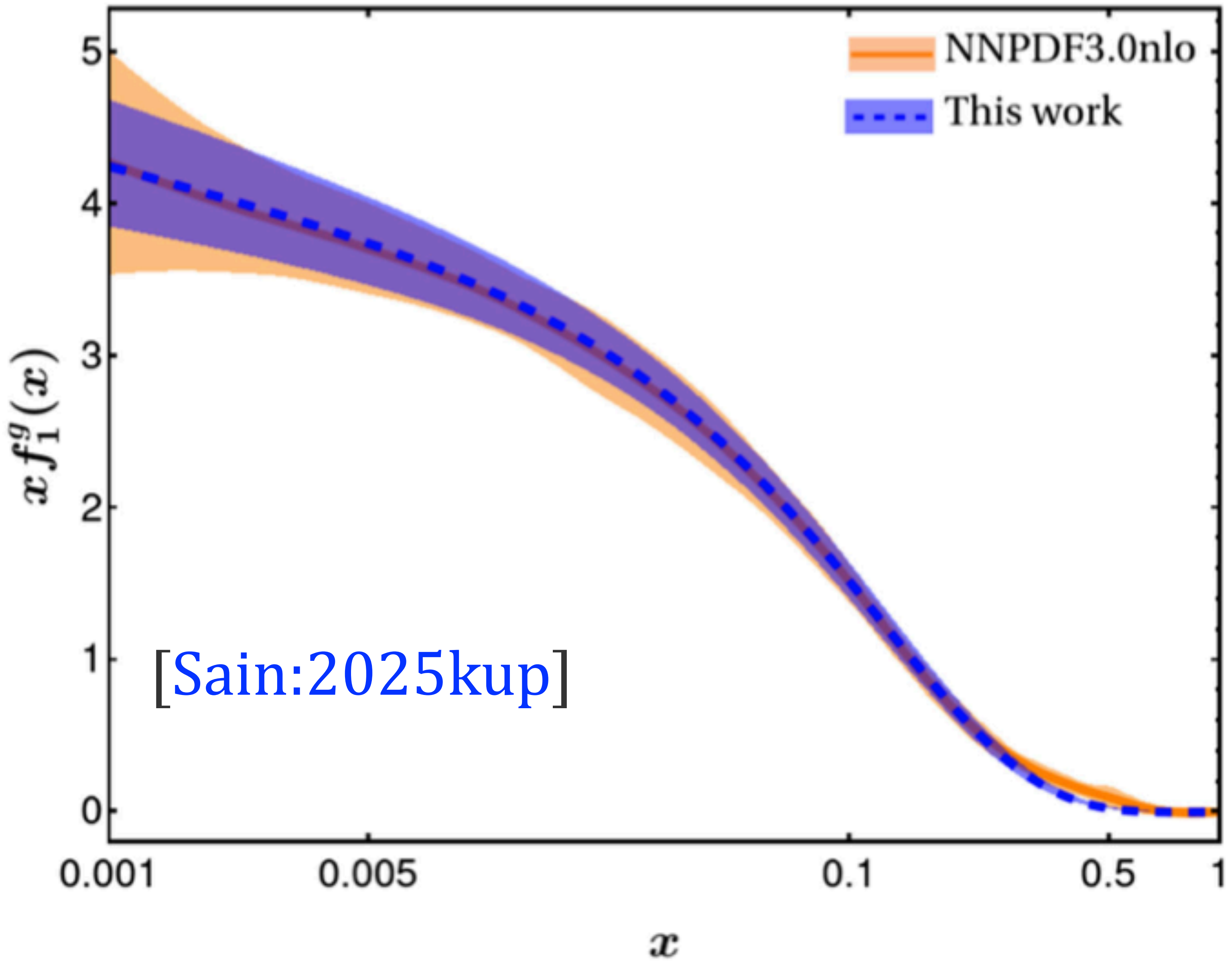


$$f(x,k_\perp,\lambda_g,\lambda_X) \otimes \varphi(x,k_\perp)$$

◆ The scalar function: $\varphi(x,\mathbf{k}_\perp)$ → 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.



[Brodsky:2000ii, Lepage:1980fj, Chakrabarti:2023djs, Brodsky:2014yha]

Model predictions for gluonic GFFs

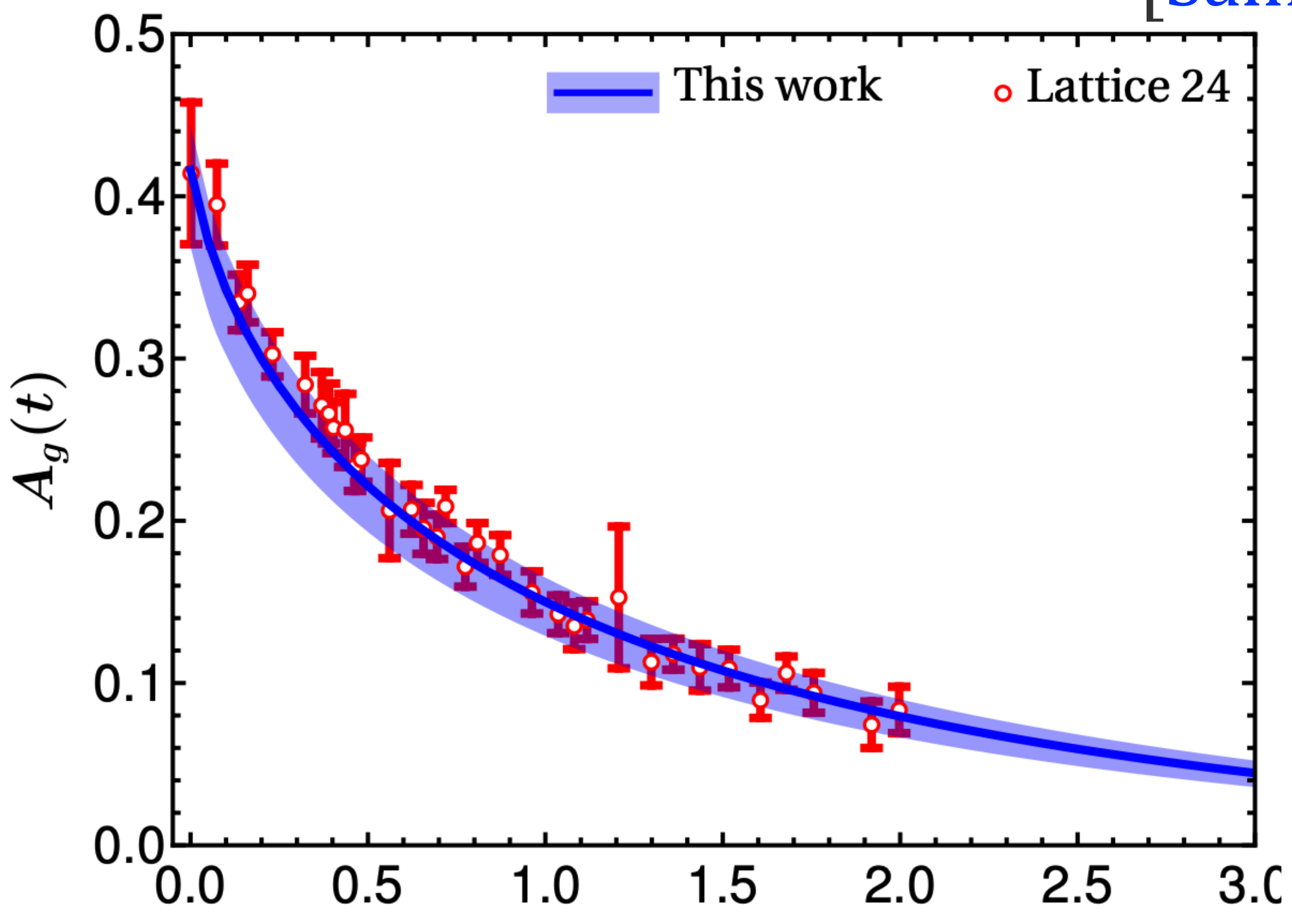
The proton spin conserving (A_i) and spin non-conserving GFF (B_i) can extracted from the "++" components of QCD EMT matrix elements:

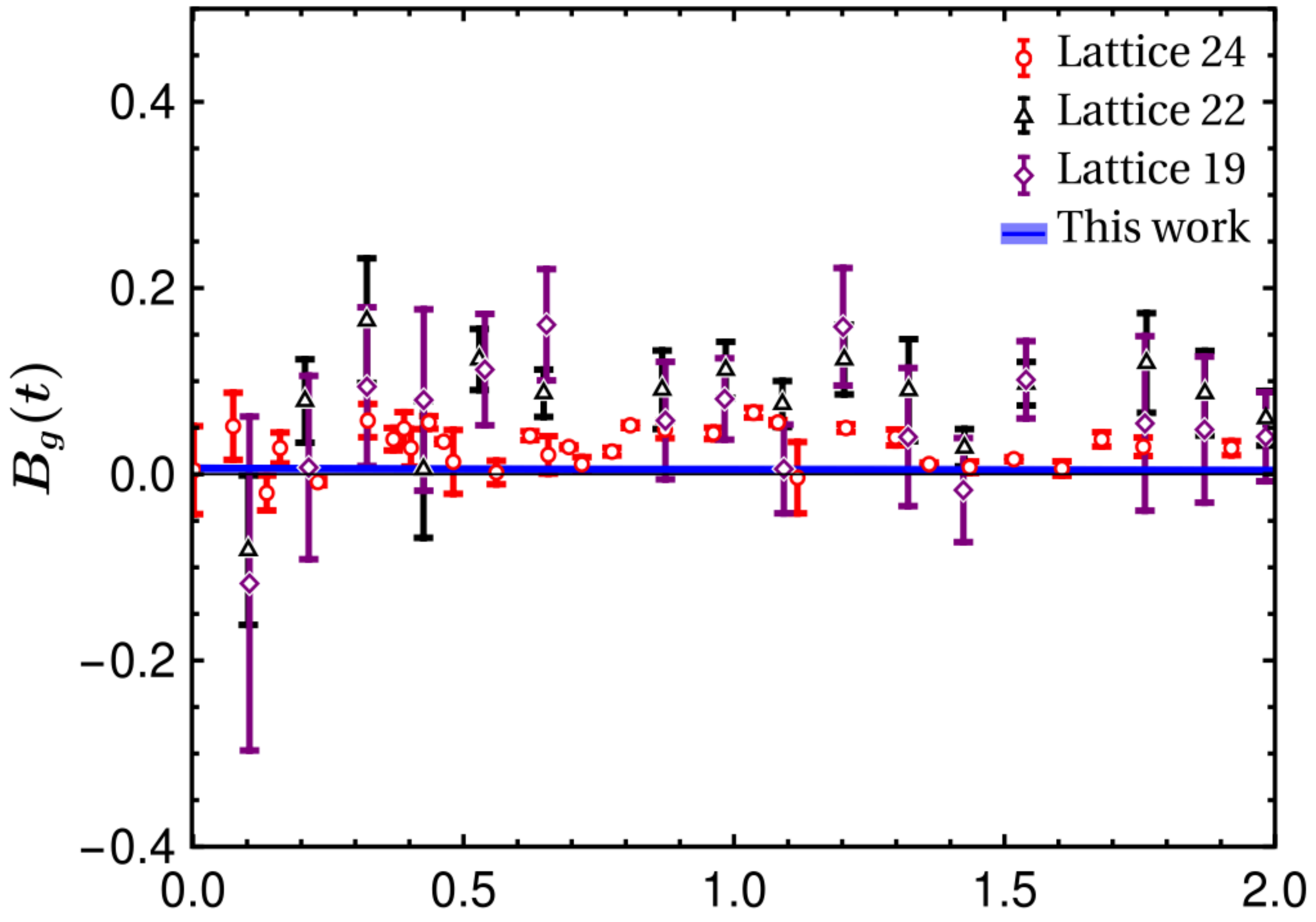
$$\mathscr{M}^{++}_{\uparrow\uparrow} + \mathscr{M}^{++}_{\downarrow\downarrow} = 2\ (P^+)^2 A_i(t), \quad \mathscr{M}^{++}_{\uparrow\downarrow} + \mathscr{M}^{++}_{\downarrow\uparrow} = 2\ (P^+)^2 B_i(t)$$

Hadronic Matrix elements of QCD EMT →

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

[Sain:2025kup]



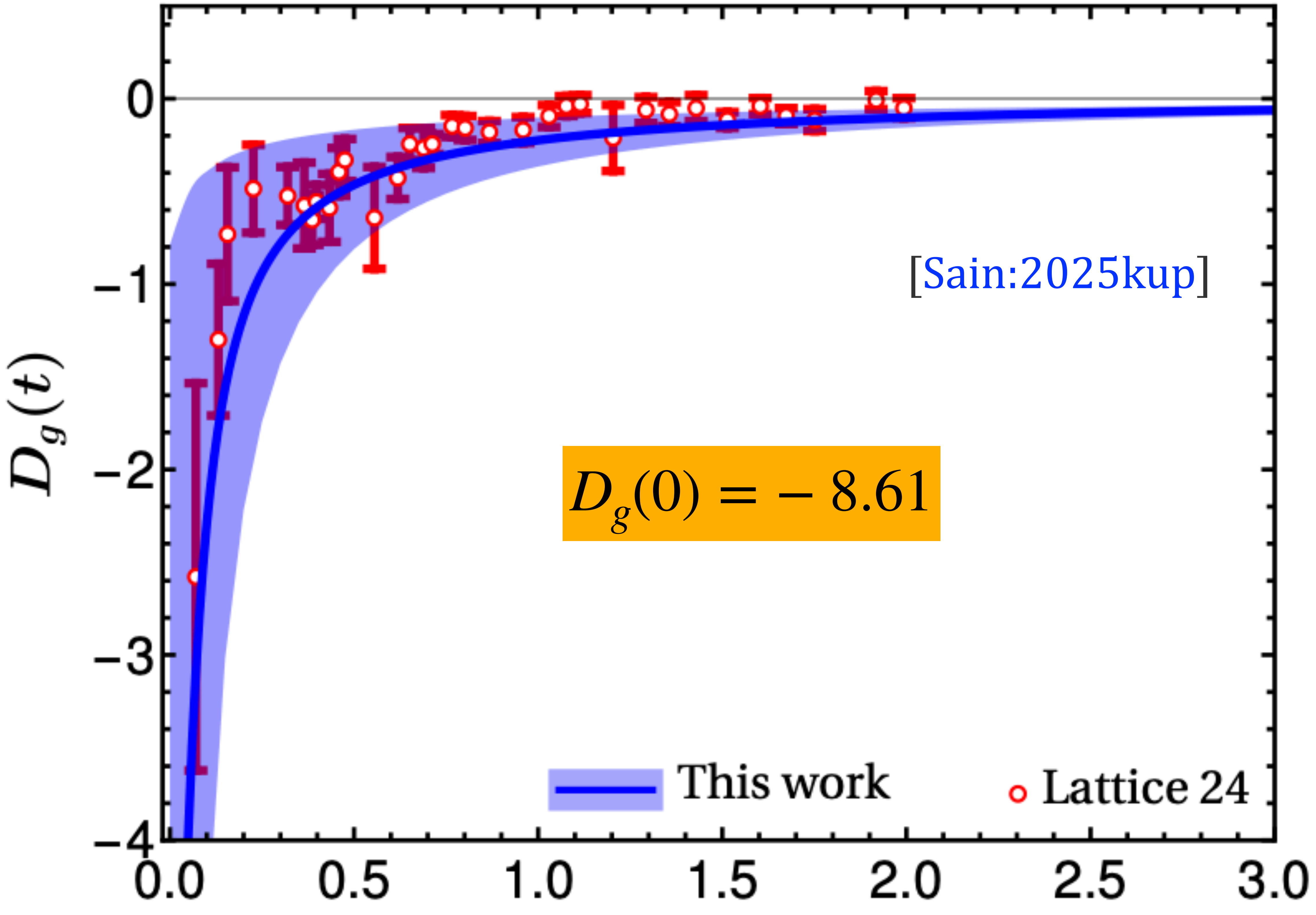


[Sain:2025kup, Leader:2013jra, Cosyn:2019aio, Hackett:2023rif]

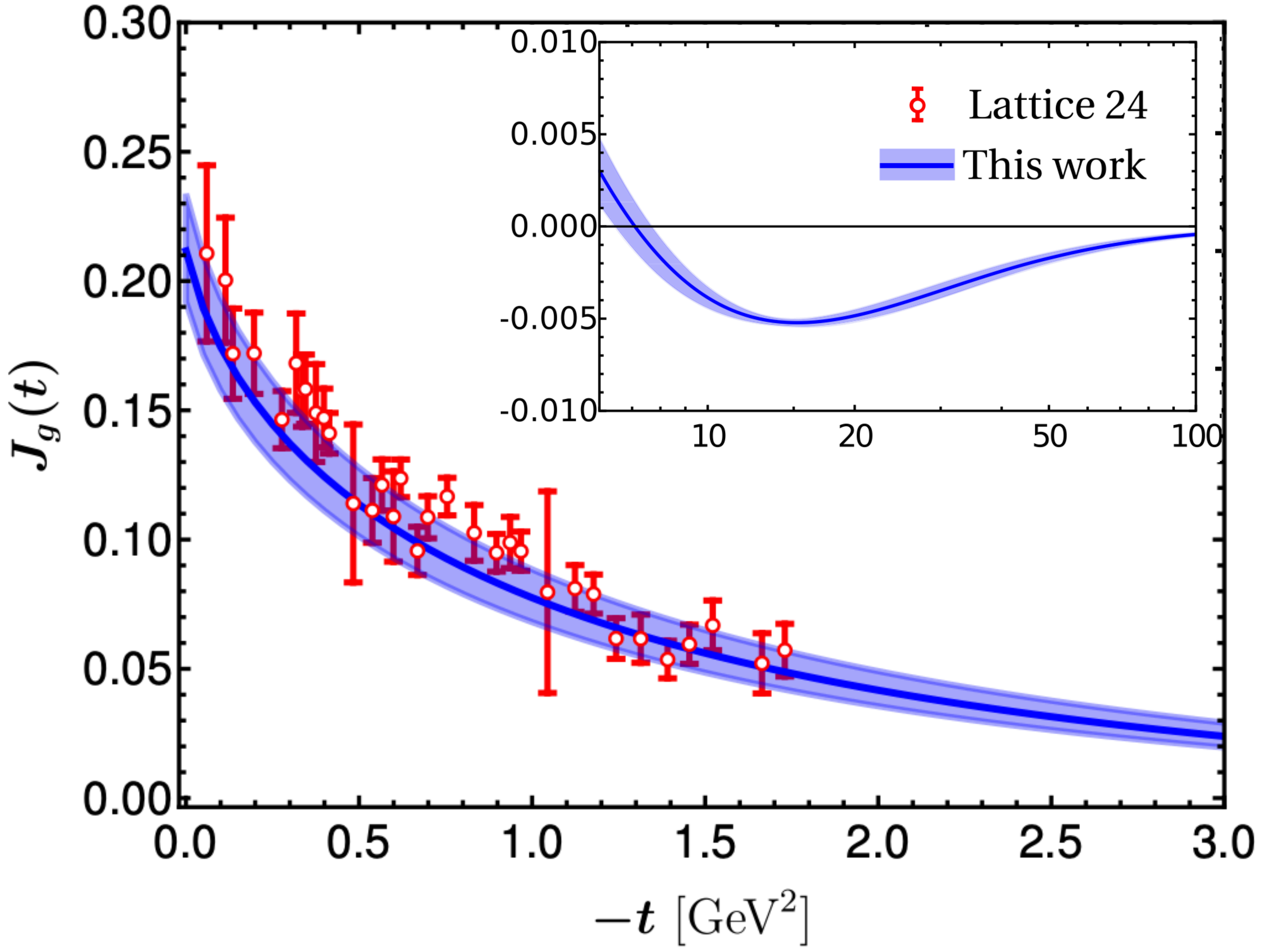
$\bar{C}_i(t)$ and $D_i(t)$ GFFs → Transverse component of the QCD EMT (T^{ij}_a)

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

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



Angular momentum GFF: Ji spin sum rule $\Rightarrow J(t) = \frac{1}{2}\left[A(t) + B(t)\right]$



We obtain $J_g = 0.206 \pm 0.013$ within uncertainties in model parameters a and b, and find a reasonable agreement with recent lattice QCD calculations: $J_g = 0.231(11)(22)$ [130], $J_g = 0.187(46)$ [85], and $J_g = 0.255(13)$ [81]. Additionally, our result is consistent with the Bethe-Salpeter approach, which gives $J_g = 0.208 \pm 0.06$ [92].

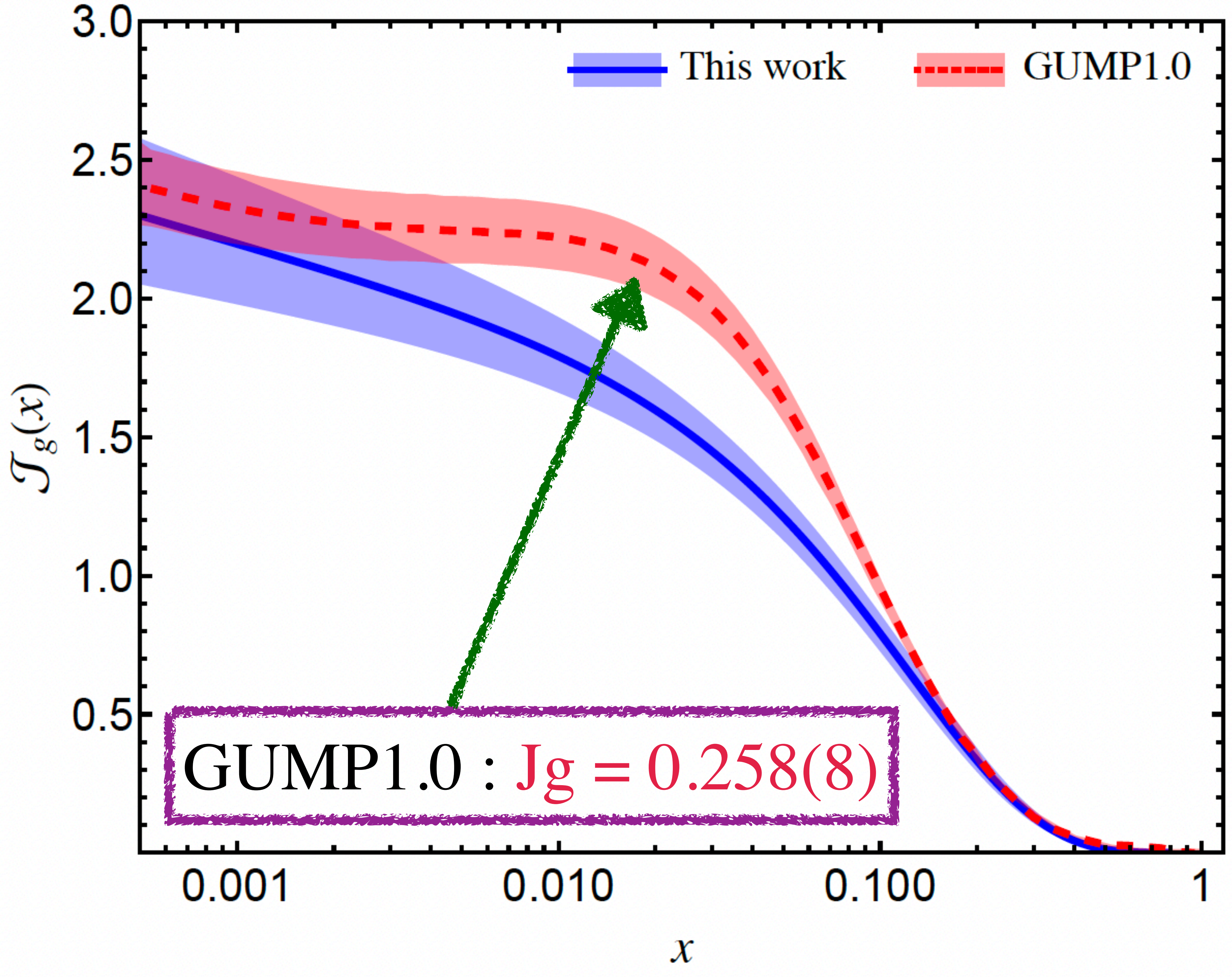
[Sain:2026ran]

$$J_g(0) = \int \mathrm{d}x \mathscr{J}_g(x)$$

Experimentally Accessible via DVCS and DVMP @ JLab and EICs

[Ji:1996ek]

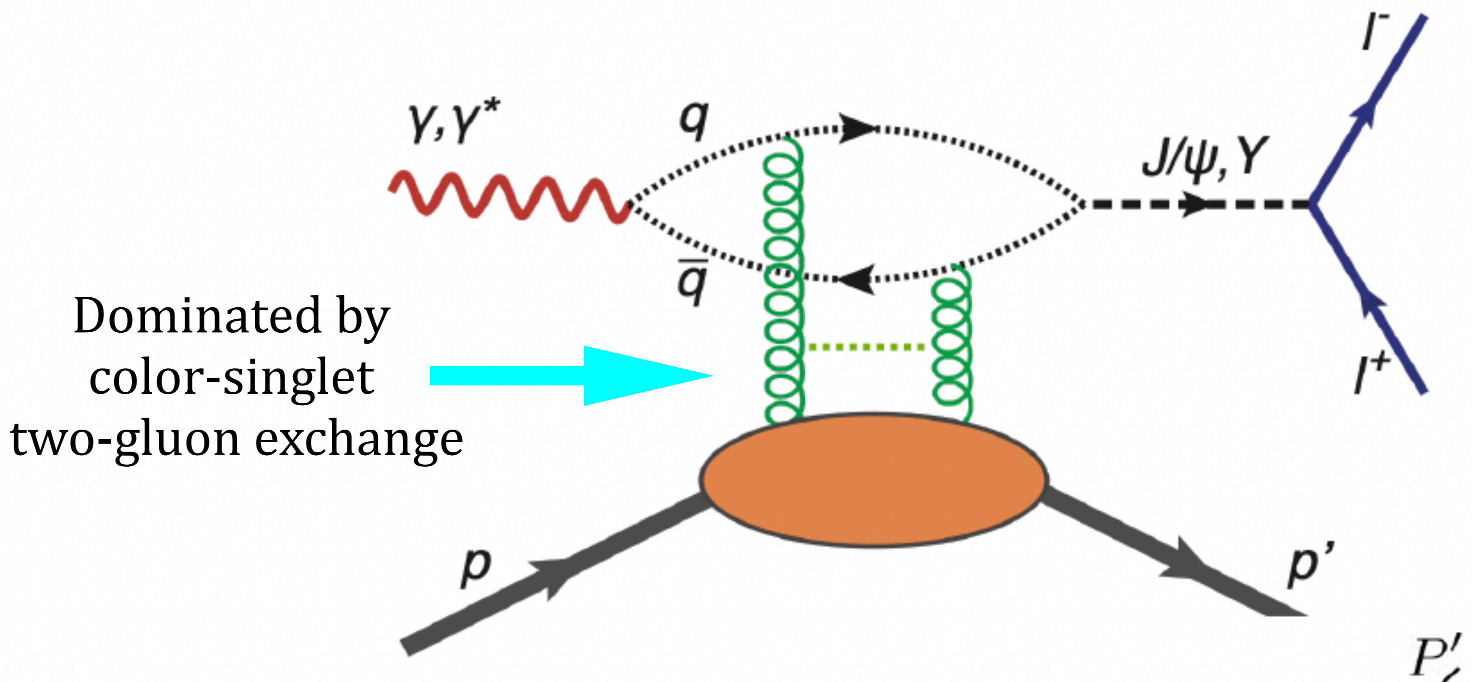
GUMP1.0 → The first global GPD extraction from DVCS and ρ-meson production data from **JLab** and **HERA** with global fits of PDFs, charge form factors, and lattice QCD results.

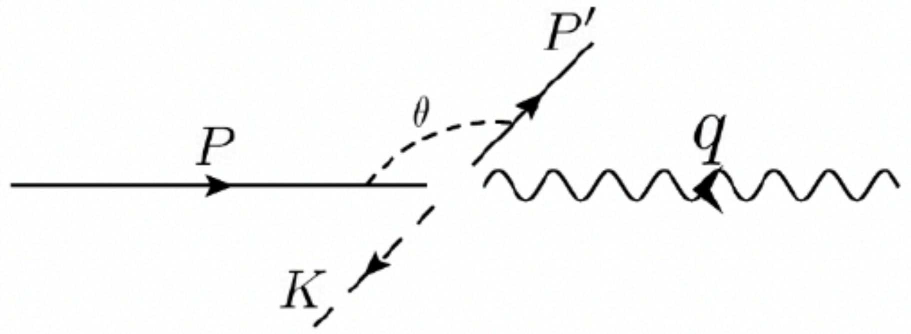


[Guo:2025muf]

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 $\quad |\psi_{NR}(0)|^2 = \frac{1.0952}{4\pi}(\text{GeV})^3$

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

$$\mathcal{H} = \sum_{i=q,g} \mathcal{H}_i \text{ and } \mathcal{E} = \sum_{i=q,g} \mathcal{E}_i$$

Compton-like form factors (**CFFs**)

Within the LO QCD factorization framework of GPDs the CFFs

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

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.

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

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

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

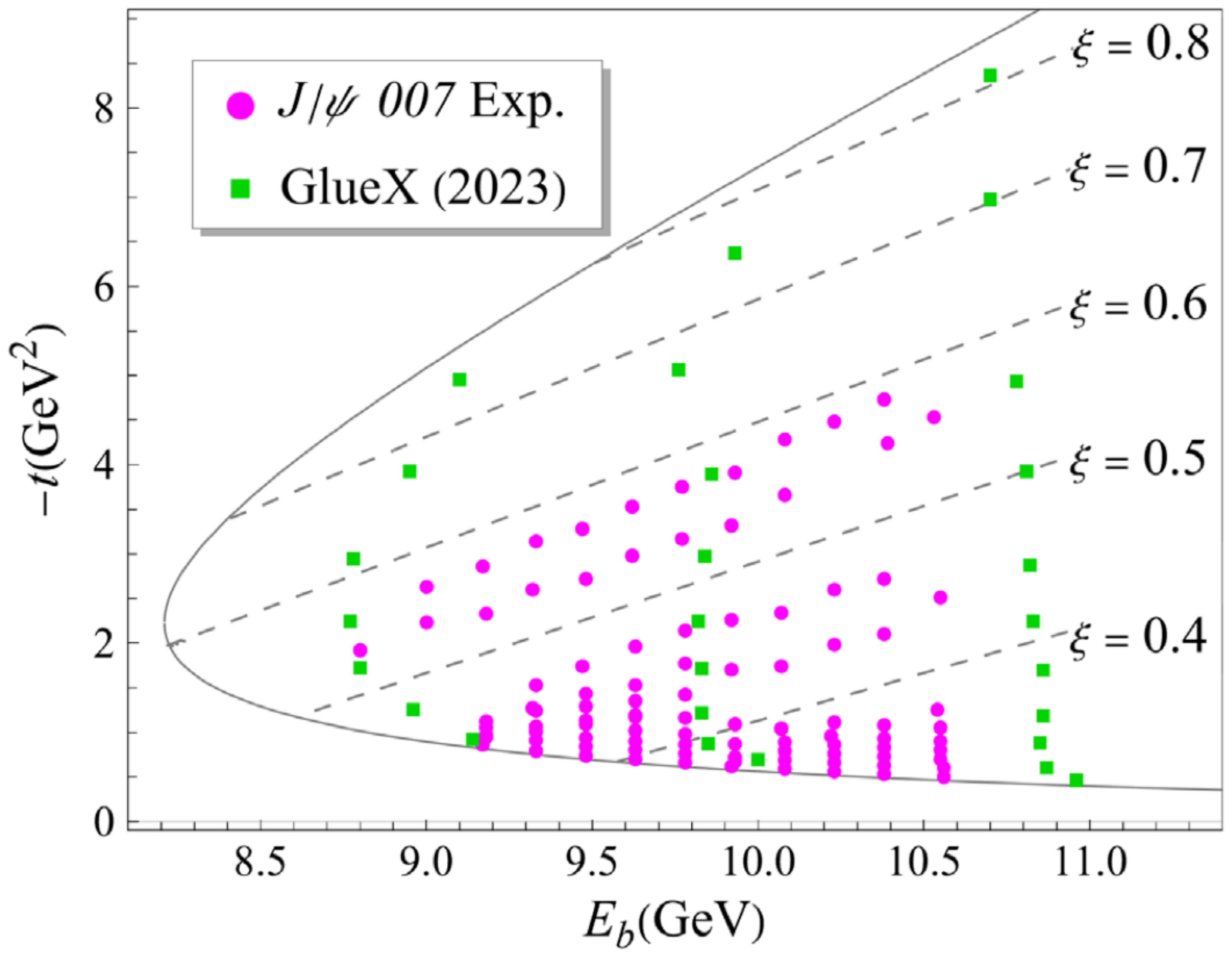
$$\mathcal{E}(\xi,t) \approx \frac{2}{\xi^2}\left[B_g(t) - \xi^2 D_g(t)\right]$$

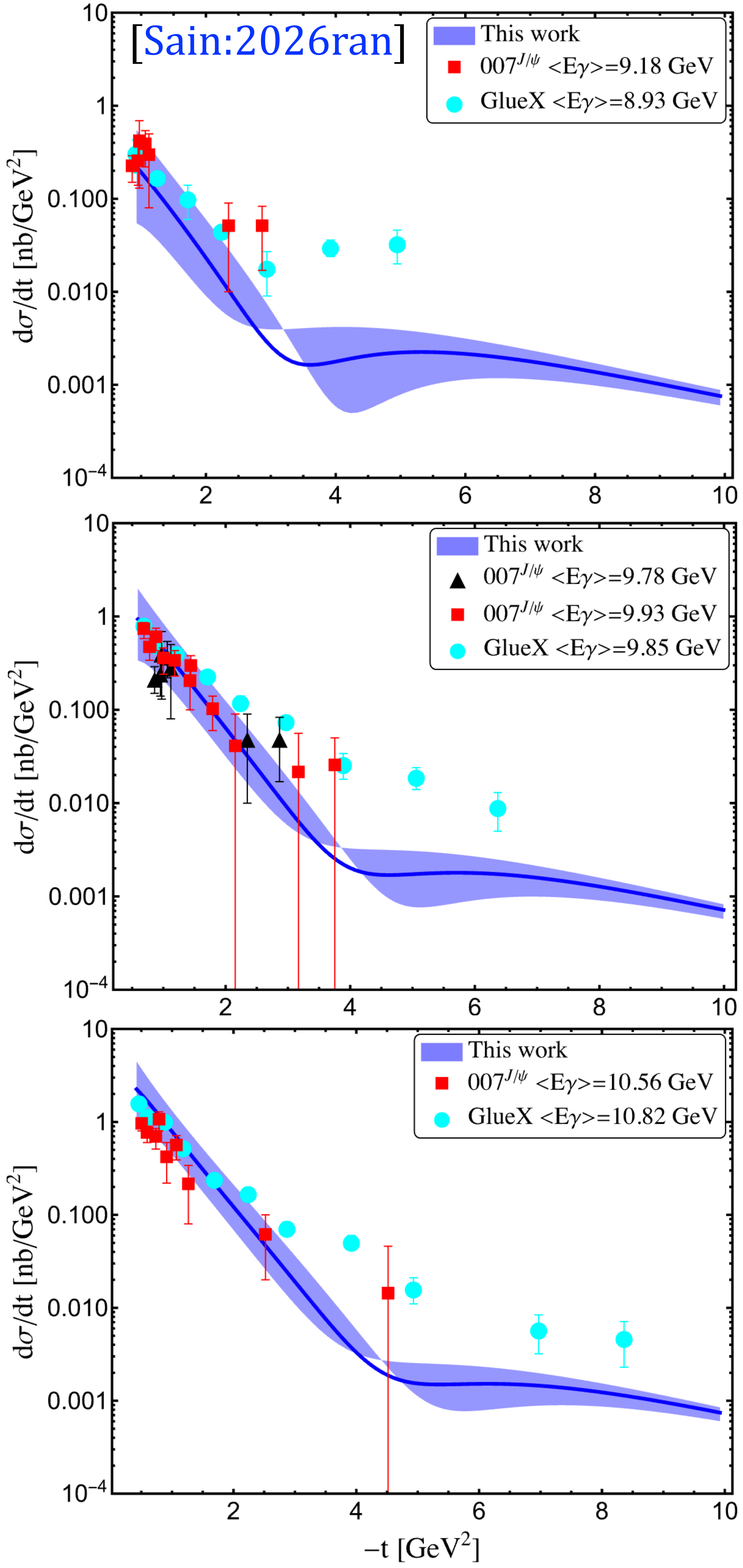
Model predictions for differential cross-section

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

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



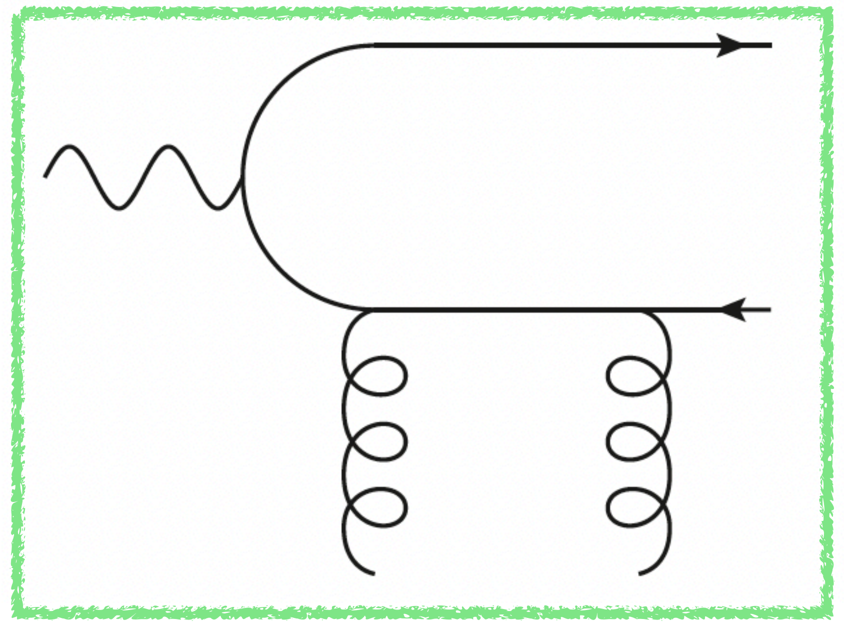


➡ The inclusion of **N**ext-to-**L**eading **O**rder (**NLO**) QCD effects is necessary to describe the data in large-momentum-transfer region.

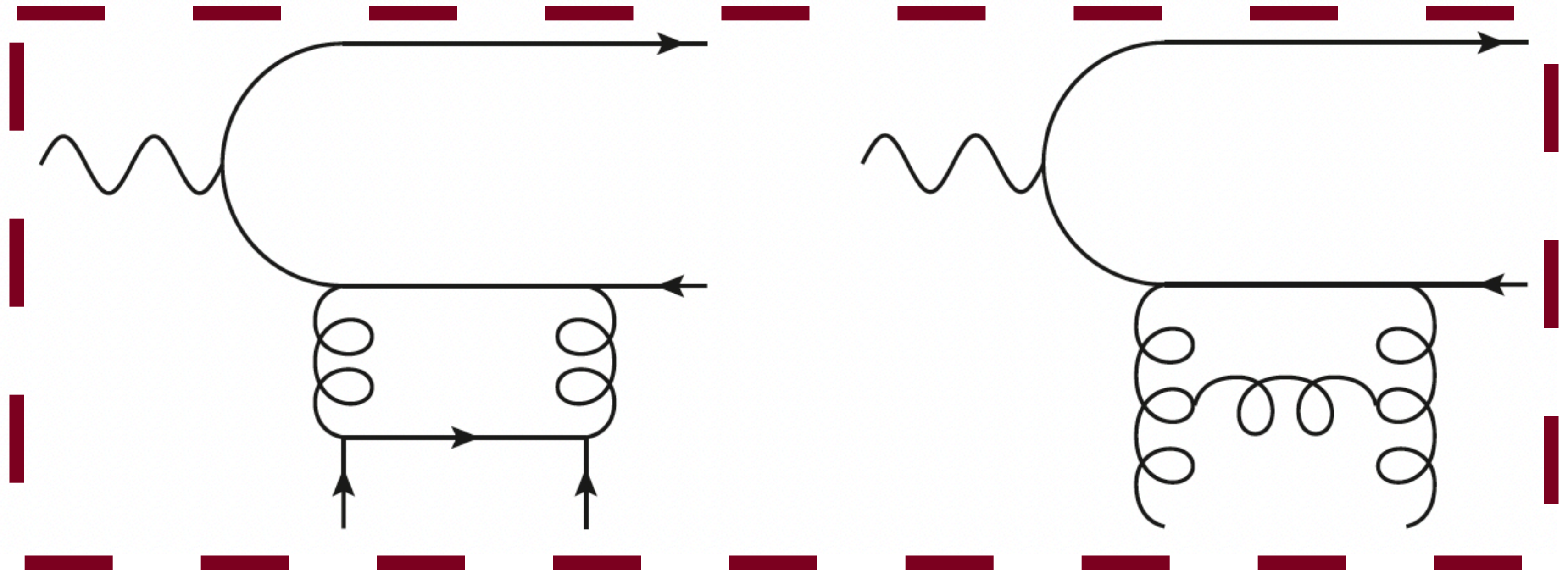
[Kharzeev:2021qkd, Guo:2021ibg, Hatta:2019lxo, Mamo:2019mka, GlueX:2023pev]

GPD framework at NLO

LO



NLO



The Wilson coefficients

LO

NLO

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

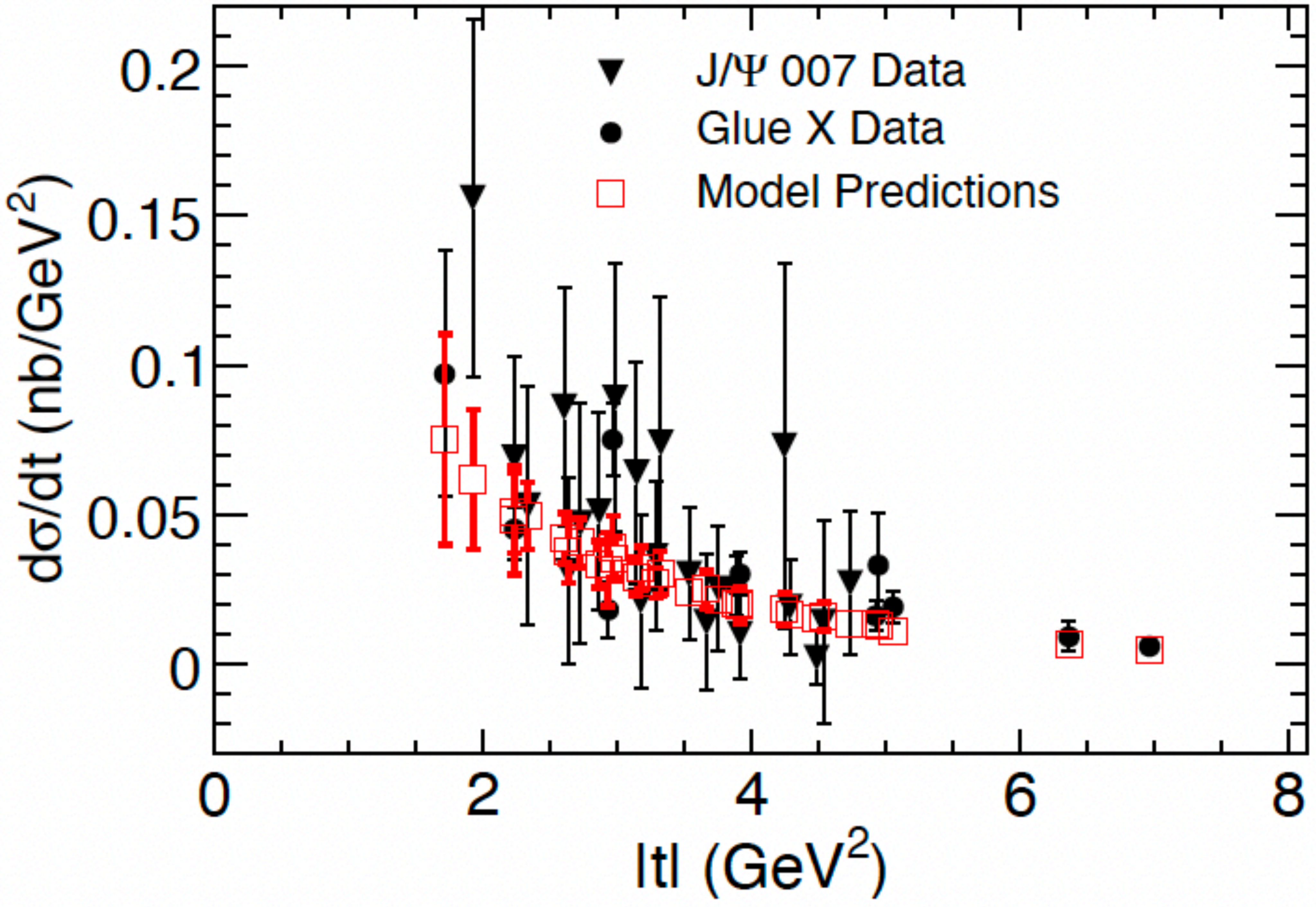
$$\bar{C}_q^{(1)} = 0 + \alpha_S \left[\bar{c}_q^1 + \frac{10}{9\pi} \log\left(\frac{m_c^2}{\mu_F^2}\right)\right] + \mathcal{O}(\alpha_S^2) \ ,$$

Modified CFFs

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

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

[Guo:2025jiz]



- ➡ 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.

[Ivanov:2004vd, Chen:2019uit]

Total cross section

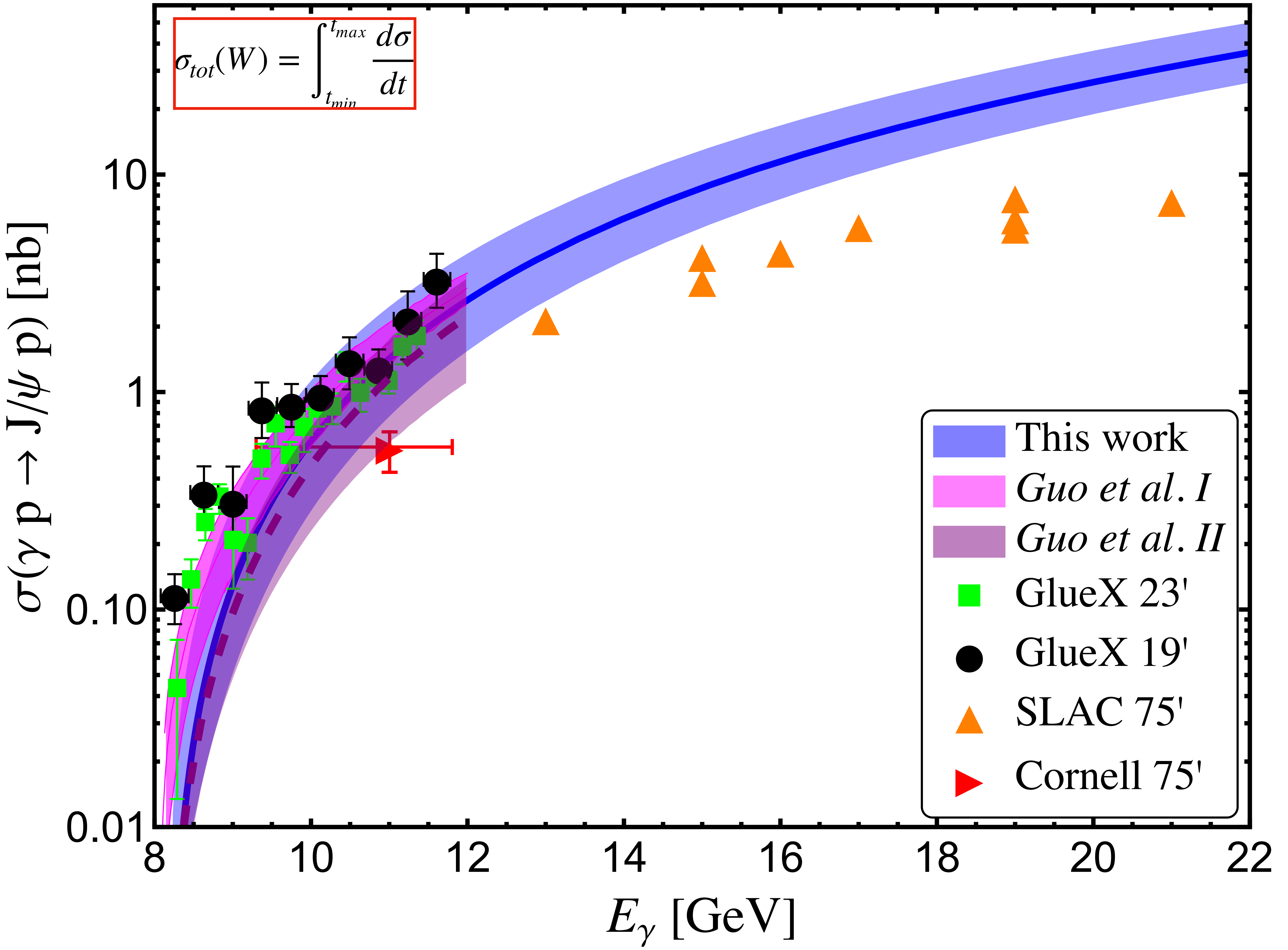
Forward scattering: $\theta = 0$

$$-t_{\rm min} = -\left(\frac{Q^2 + M_V^2}{2W}\right)^2 + (p_{\rm cm} - k_{\rm cm})^2,$$

$$-t_{\rm max} = -\left(\frac{Q^2 + M_V^2}{2W}\right)^2 + (p_{\rm cm} + k_{\rm cm})^2.$$

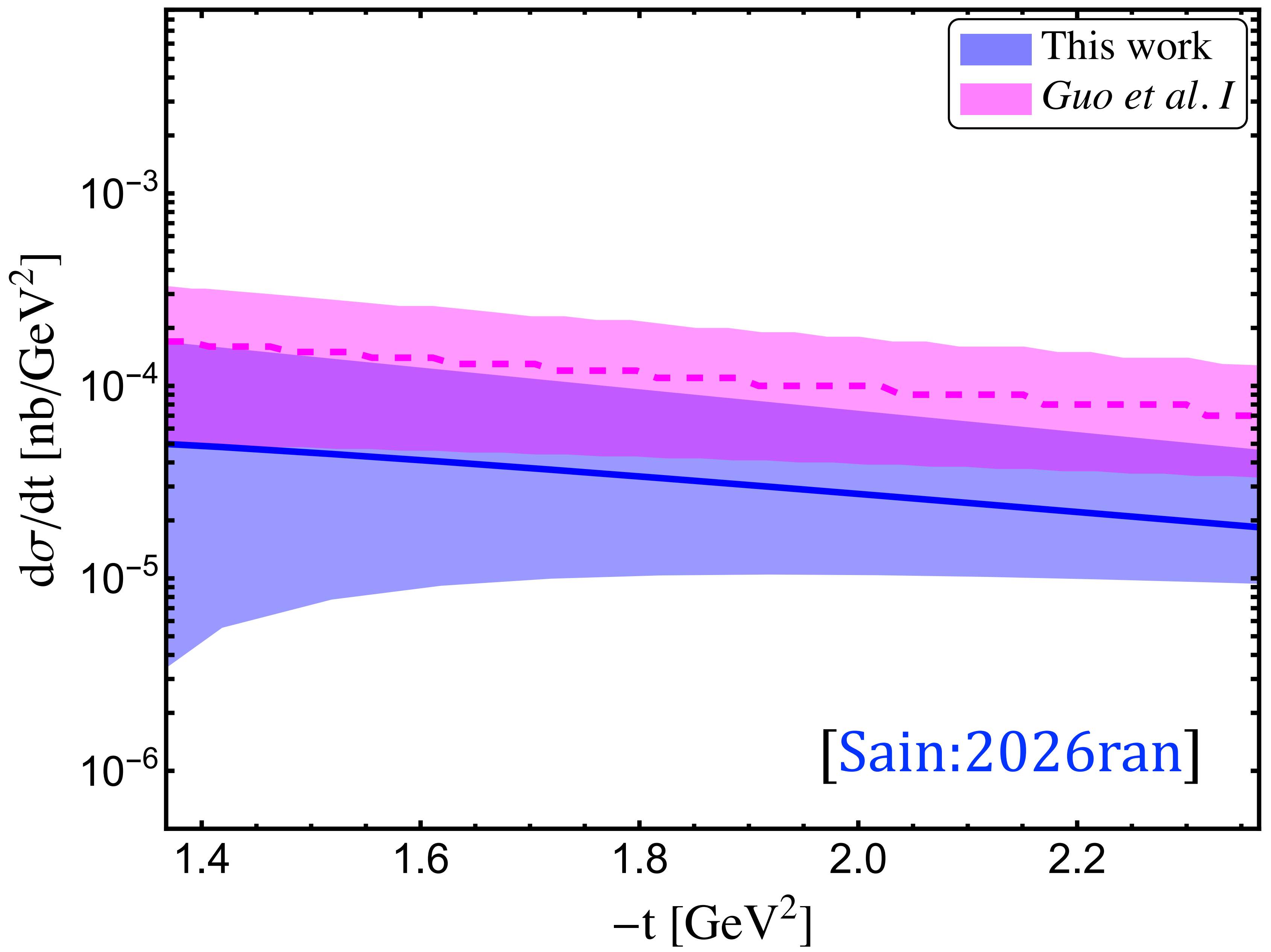
Backward scattering: $\theta = \pi$

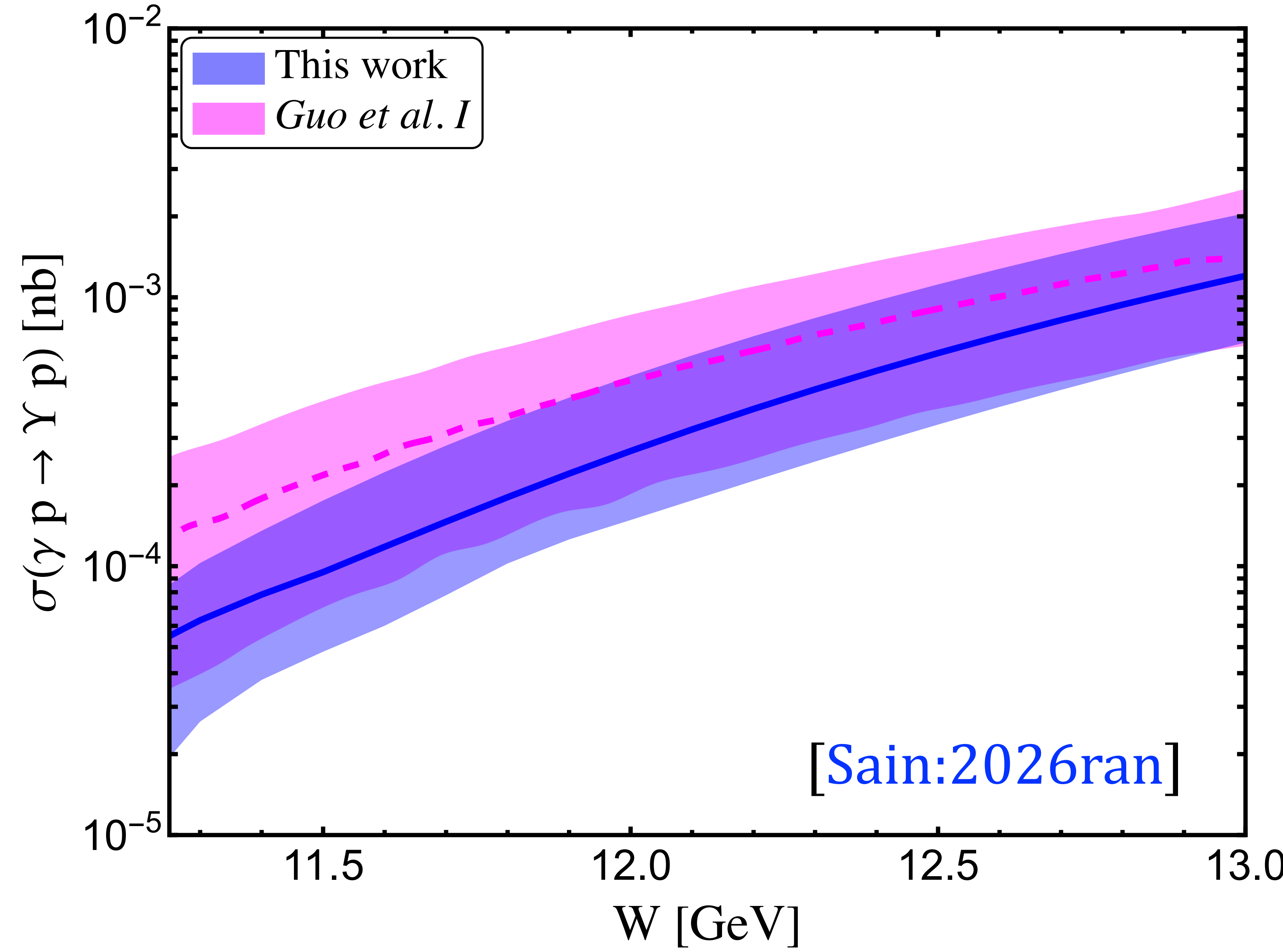
[Sain:2026ran]



[Guo:2023pqw, Guo:2021ibg, GlueX:2023pev, Gittelman:1975ix]

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





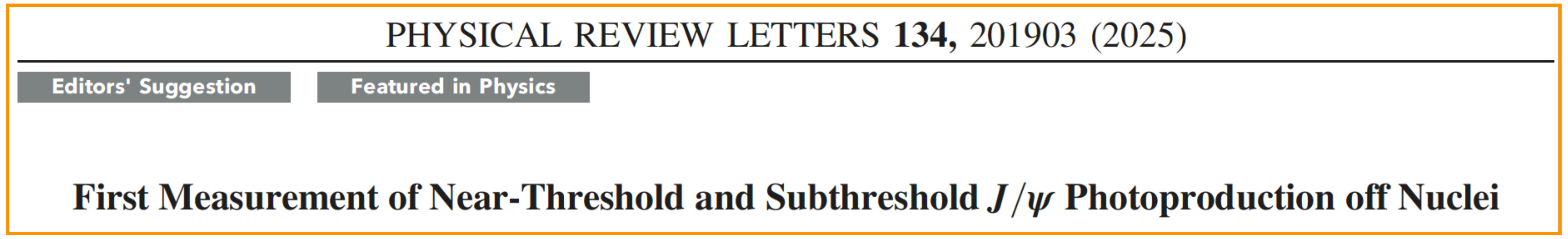
Conclusion & Outlook

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

- **Light-Front AdS-QCD** is very useful approach to study the strongly interacting hadronic systems and provides a good description of experimental data.

- The gGFFs are consistent with Lattice and experimental extractions but the cross-section predictions deviates with data for **larger |t|** → requires the contributions from **higher order QCD** corrections.

- Near-threshold photo production also offers an independent test of the universality of nucleon–nucleon **s**hort-**r**ange **c**orrelations (**SRCs**) in nuclear scattering through subthreshold photo production.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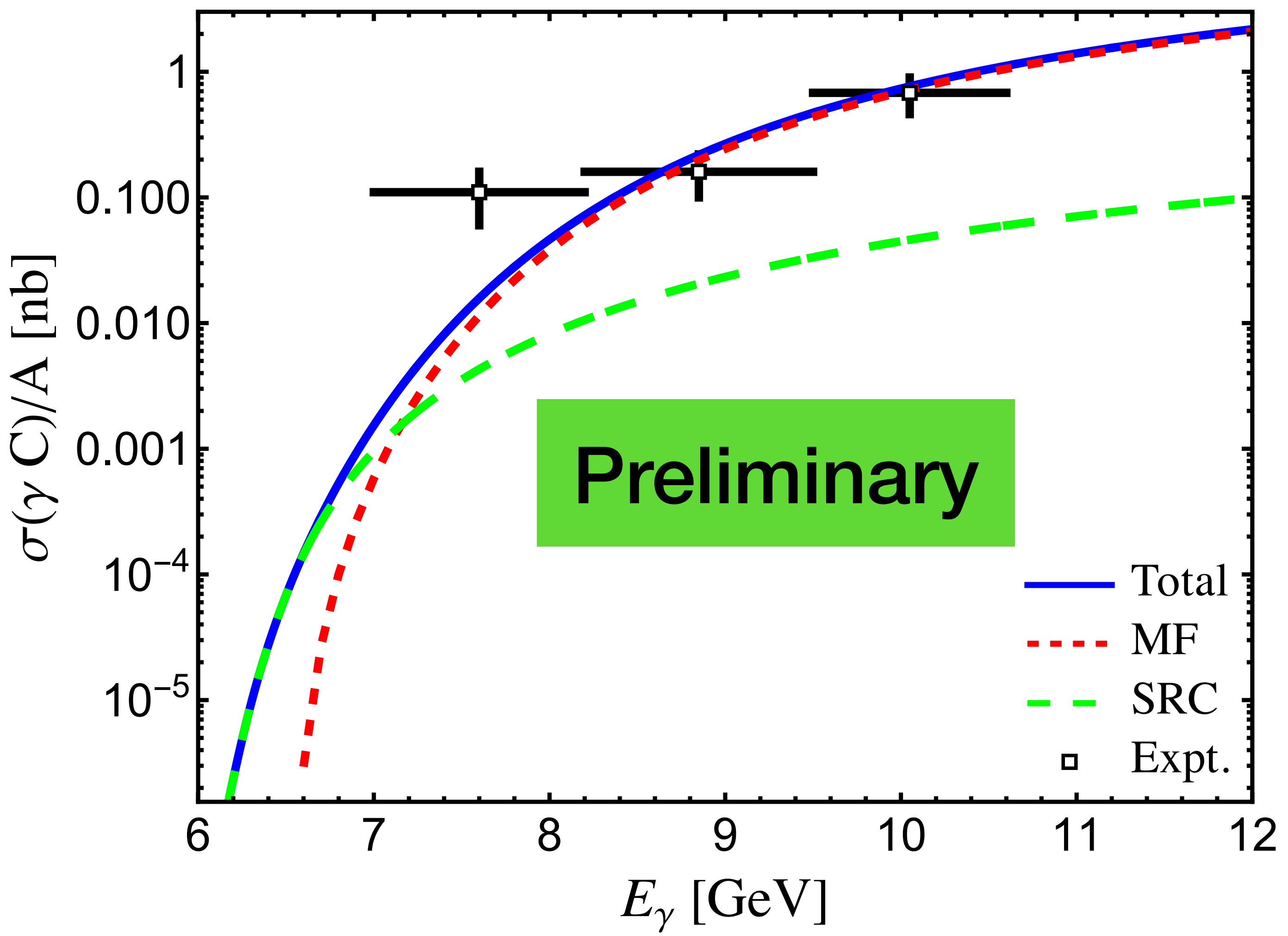
Editors' Suggestion | Featured in Physics

First Measurement of Near-Threshold and Subthreshold J/ψ Photoproduction off Nuclei



Thank you for your attention !!