

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

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Based on : [PRD 113, 054041 \(2026\)](#), [PRD 113, L071503 \(2026\)](#), and [PRD 111, 094011 \(2025\)](#)

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

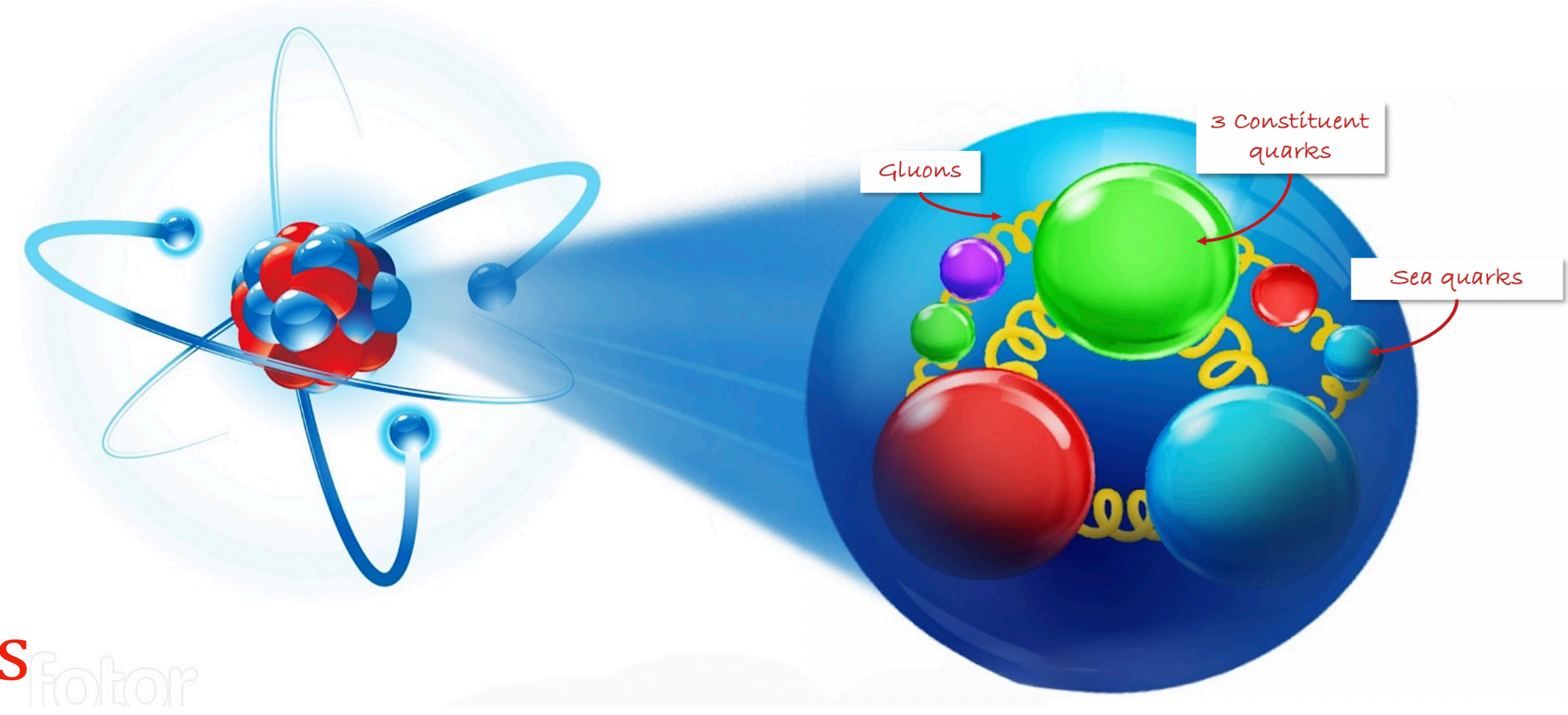
Date : April 30, 2026

EIC-Asia Workshop on QCD and Hadron Structure, April 29-May 1st, 2026 @ Institute of Physics,
Academia Sinica Taipei, Taiwan

Outline

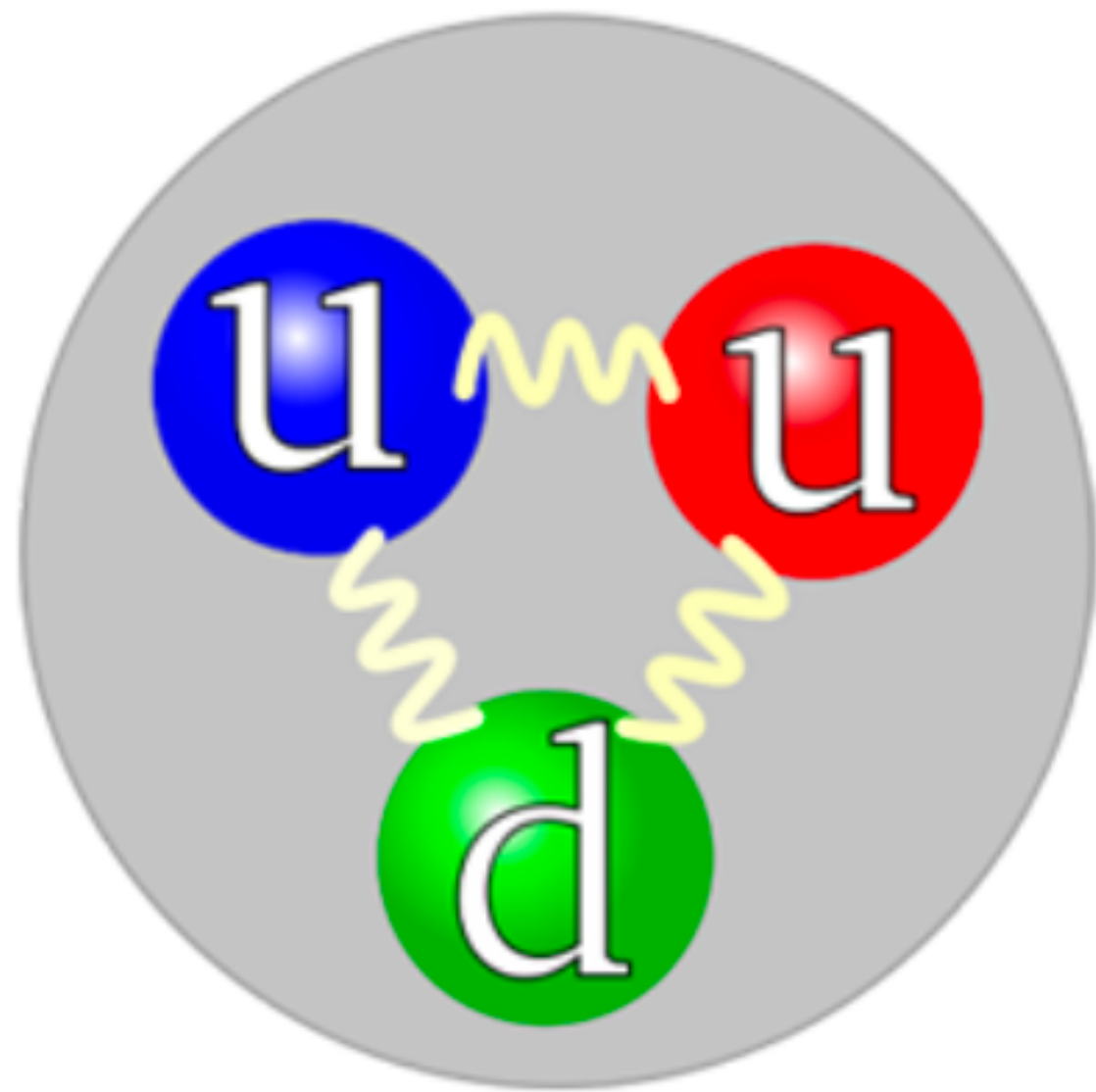
- ◆ Fundamental properties of nucleons: Mass, spin and mechanical properties
- ◆ Light-Front QCD and the spectator model
- ◆ Hadronic energy-momentum tensor and extractions of GFFs
- ◆ GPD framework to access the GFFs near-threshold kinematics
- ◆ Conclusion and outlooks

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

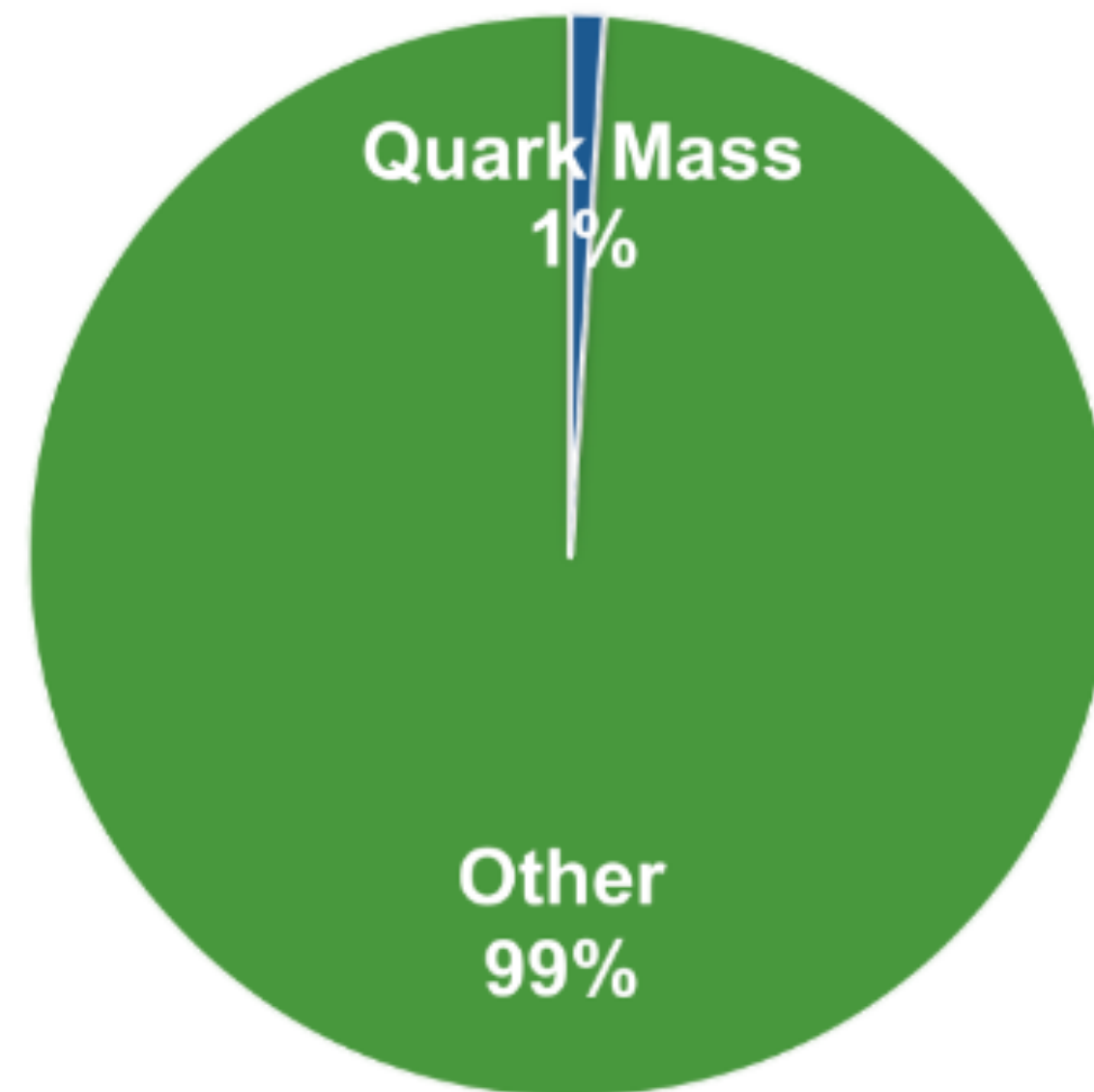


Big puzzles of the strong forces within the hadrons

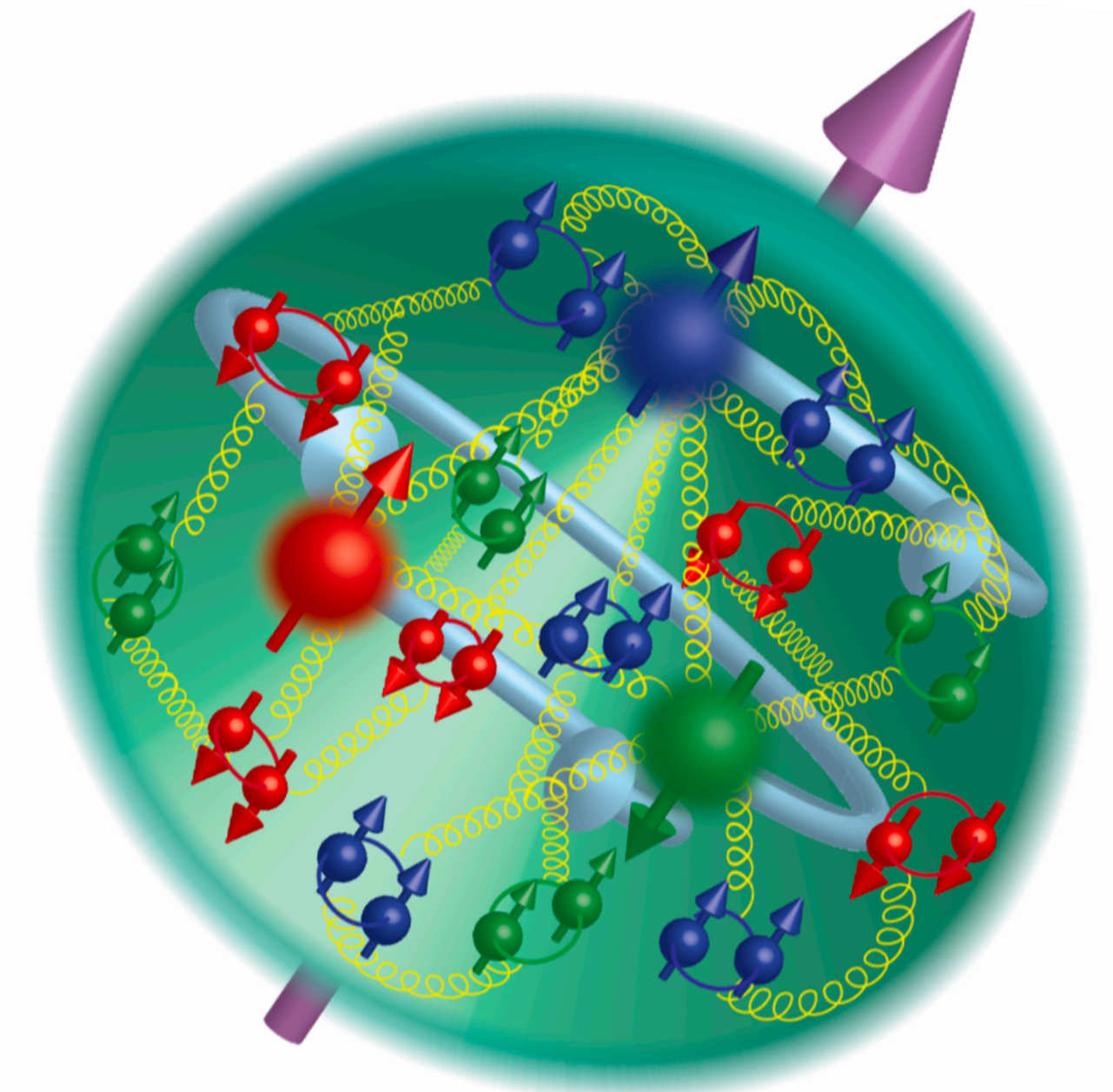
Origin of confinement ?



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:	$\partial_\mu J_{\text{em}}^\mu = 0$	$\langle N' J_{\text{em}}^\mu N \rangle$	\longrightarrow	$Q_{\text{prot}} = 1.602176487(40) \times 10^{-19} \text{C}$
	<i>vector</i>			$\mu_{\text{prot}} = 2.792847356(23) \mu_N$
weak:	PCAC	$\langle N' J_{\text{weak}}^\mu N \rangle$	\longrightarrow	$g_A = 1.2694(28)$
	<i>axial</i>			$g_p = 8.06(0.55)$
gravity:	$\partial_\mu T_{\text{grav}}^{\mu\nu} = 0$	$\langle N' T_{\text{grav}}^{\mu\nu} N \rangle$	\longrightarrow	$M_{\text{prot}} = 938.272013(23) \text{MeV}/c^2$
	<i>tensor</i>			$J = \frac{1}{2}$
				$D = ?$

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.

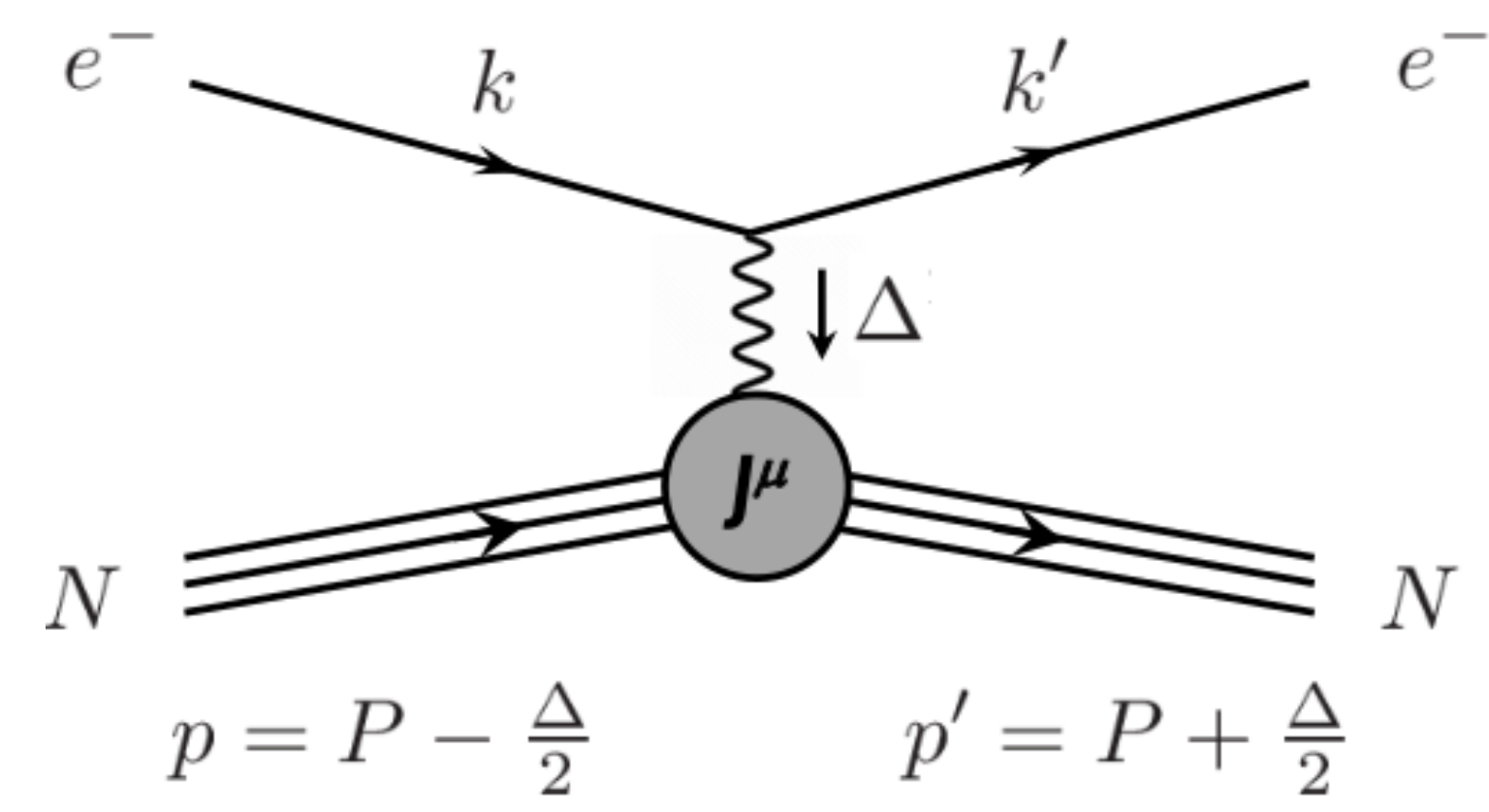
Probing basic properties of the proton

Electromagnetic properties \rightarrow
Probed with **photons**.

Gravitational properties \rightarrow Probed with **gravitons**.

Photon exchange

(~ 1)



Electromagnetic current

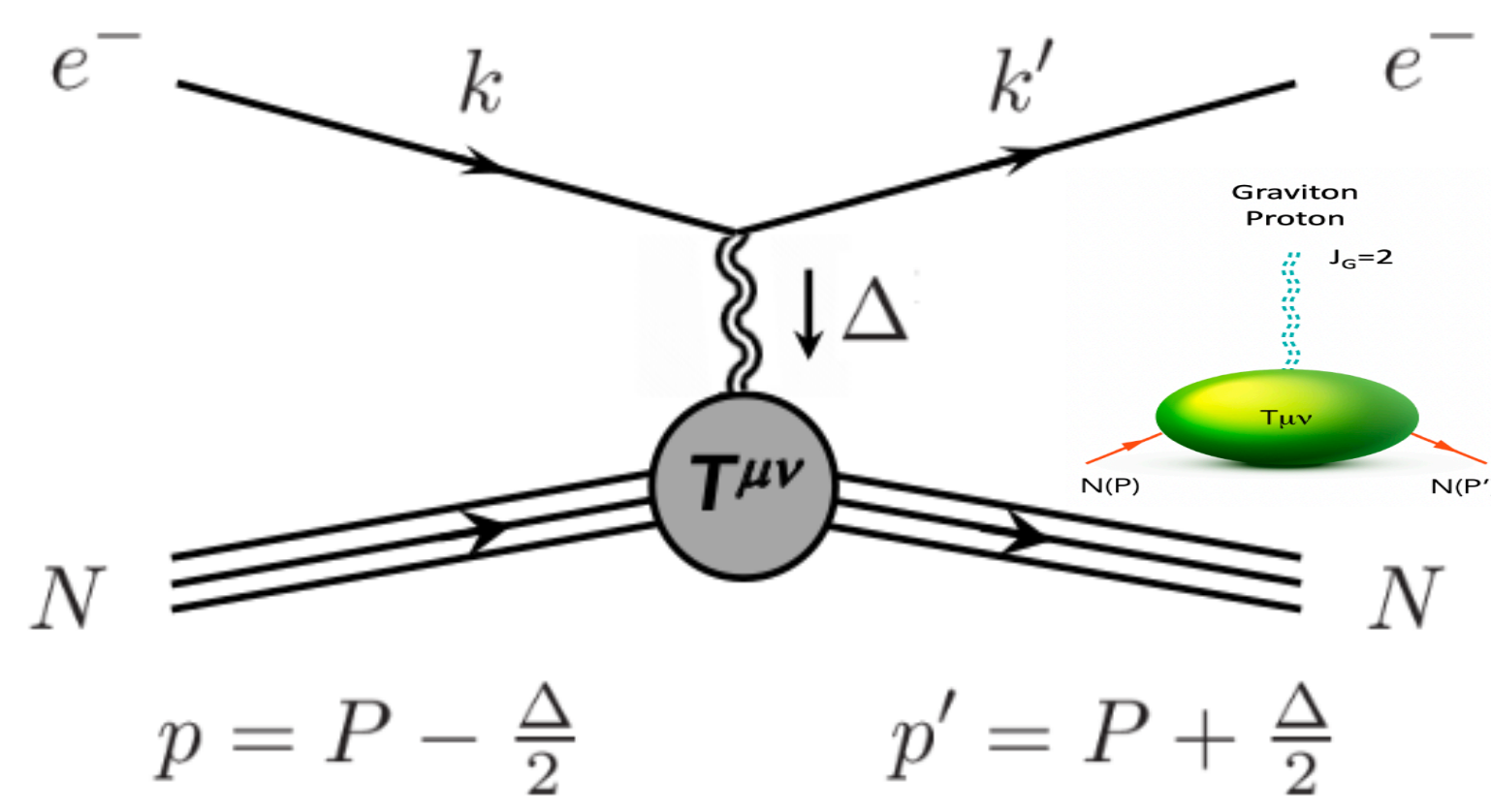


Electromagnetic form factors

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

Graviton exchange

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



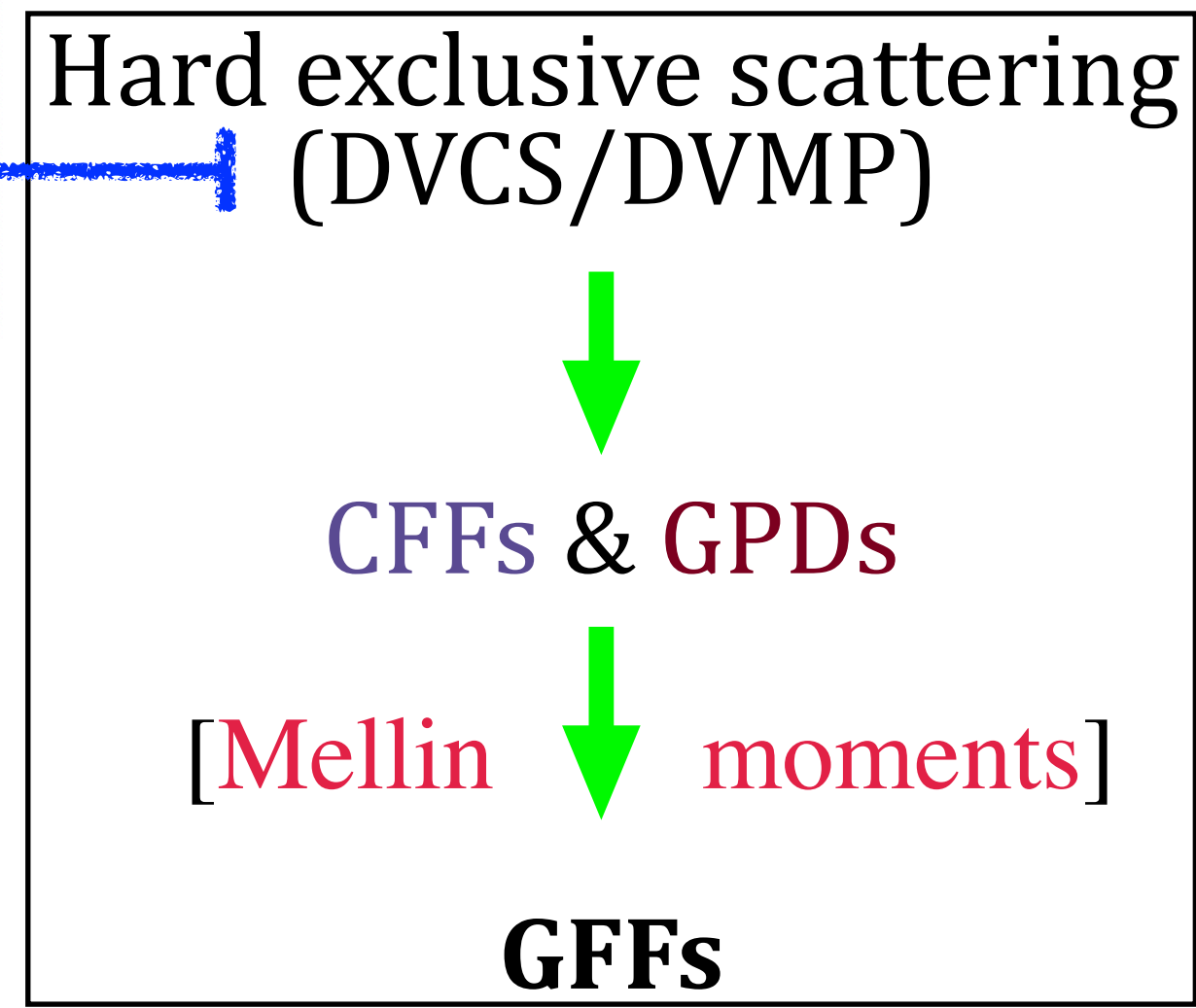
Energy-momentum tensor



Gravitational form factors

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

“.....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)]



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

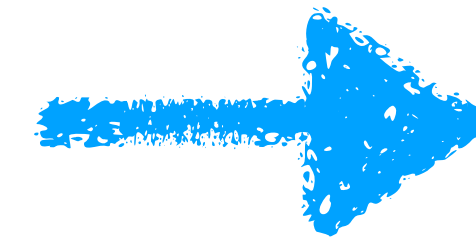
QCD Energy Momentum Tensor (EMT) and related Physical quantities

◆ 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: $\partial_\mu T^{\mu\nu} = 0$



$$T^{\mu\nu} = \begin{bmatrix} \text{Energy density} & & & \\ T_{00} & T_{01} & T_{02} & T_{03} \\ T_{10} & T_{11} & T_{12} & T_{13} \\ T_{20} & T_{21} & T_{22} & T_{23} \\ T_{30} & T_{31} & T_{32} & T_{33} \\ \text{Energy flux} & \text{Momentum flux} & & \end{bmatrix}$$

Shear stress (Shear force)
Normal stress (pressure)

Parametrization of EMT matrix elements in terms of GFFs

GFFs are the hadronic matrix elements of the QCD EMT

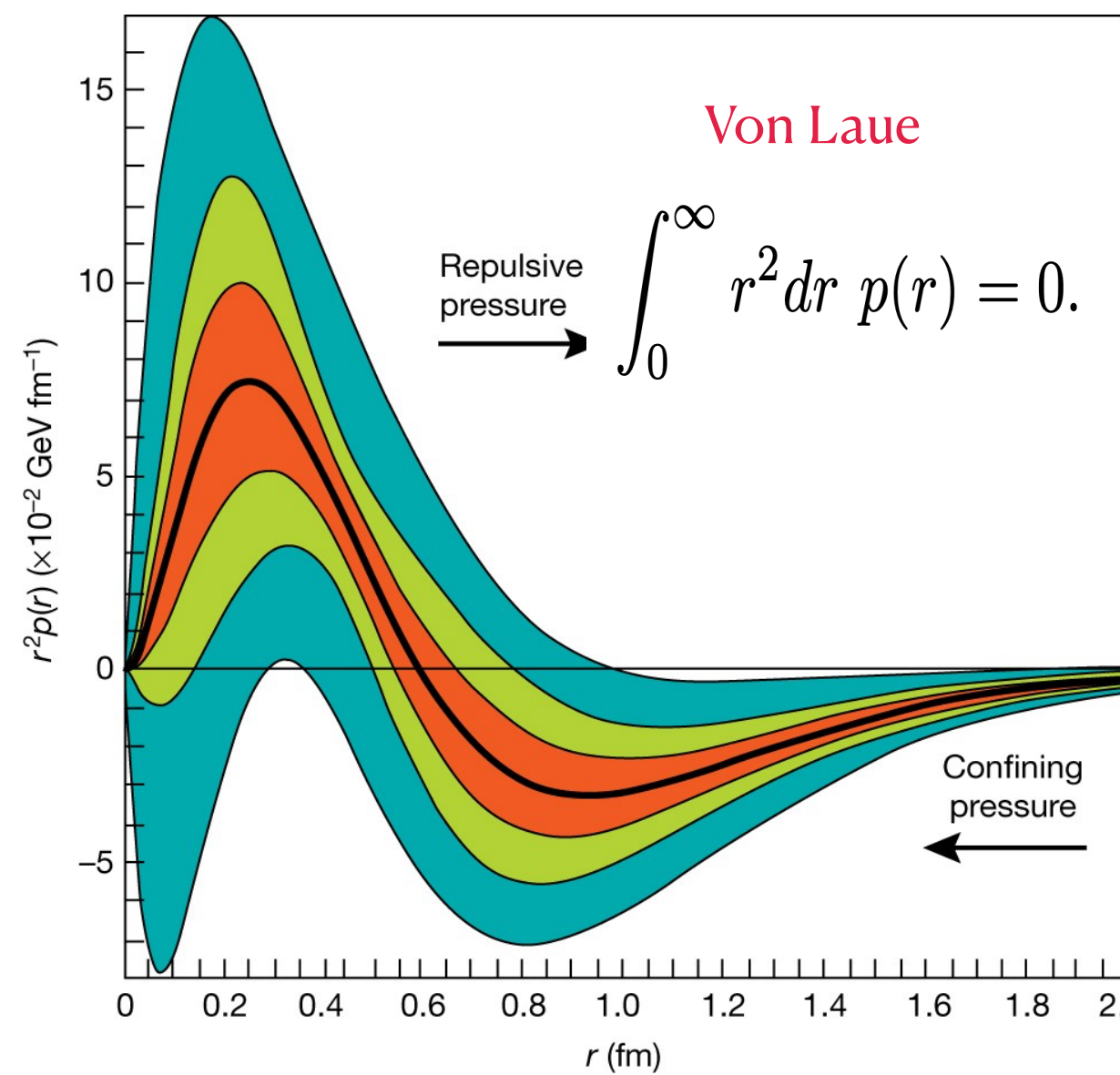
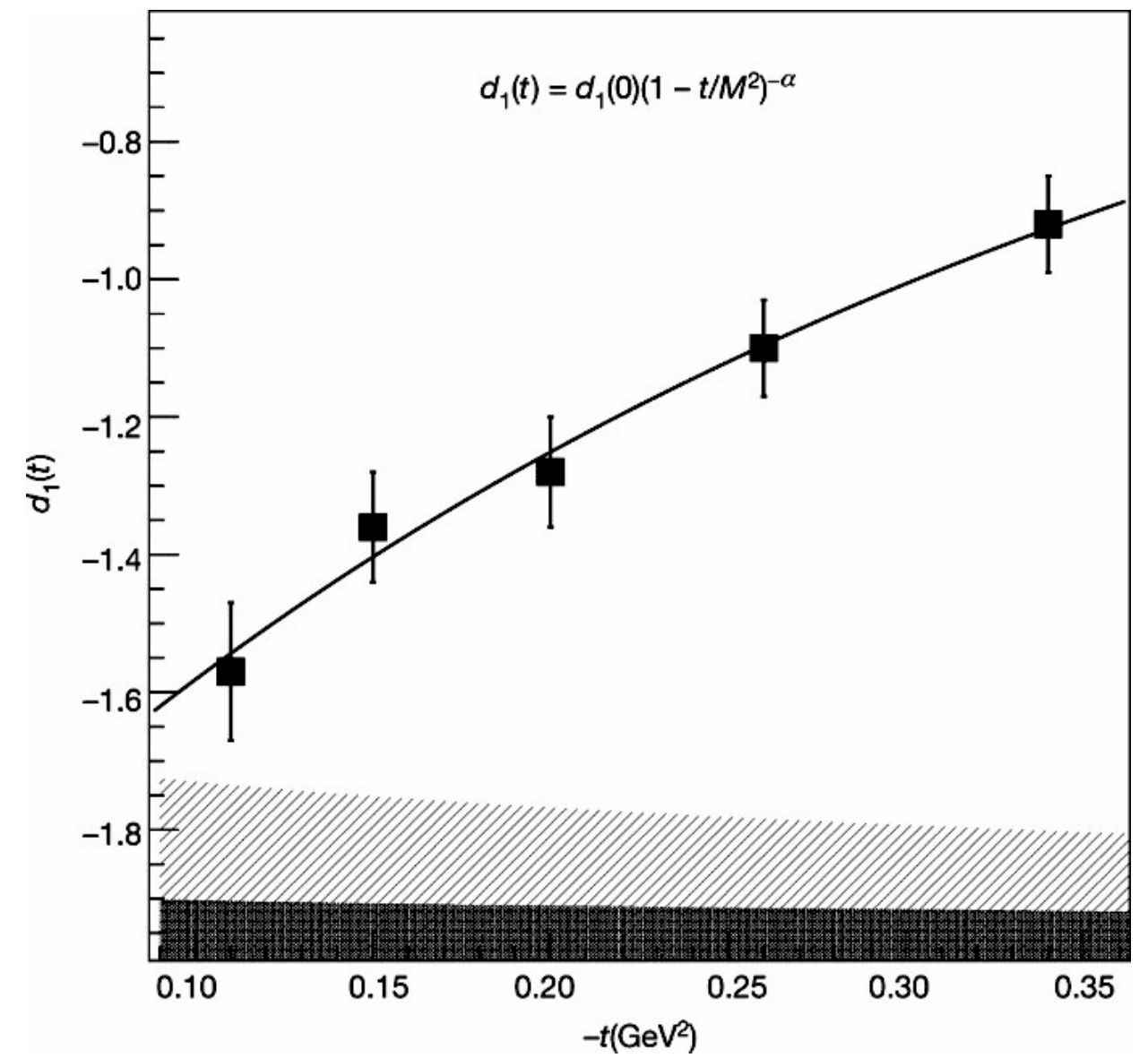
$$\langle N' | T_{q,g}^{\mu,\nu} | N \rangle = \bar{u}(N') \left(A_{g,q}(t) \gamma^{\{\mu} P^{\nu\}} + B_{g,q}(t) \frac{iP^{\{\mu} \sigma^{\nu\}} \rho \Delta_\rho}{2M} + C_{g,q}(t) \frac{\Delta^\mu \Delta^\nu - g^{\mu\nu} \Delta^2}{M} + \bar{C}_{g,q}(t) M g^{\mu\nu} \right) u(N)$$

- $A_{g,q}(t)$: Related to quark and gluon momenta, $A_{g,q}(0) = \langle x_{q,g} \rangle$
- $J_{g,q}(t) = 1/2 (A_{g,q}(t) + B_{g,q}(t))$: 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)

Sum Rules for GFFs:

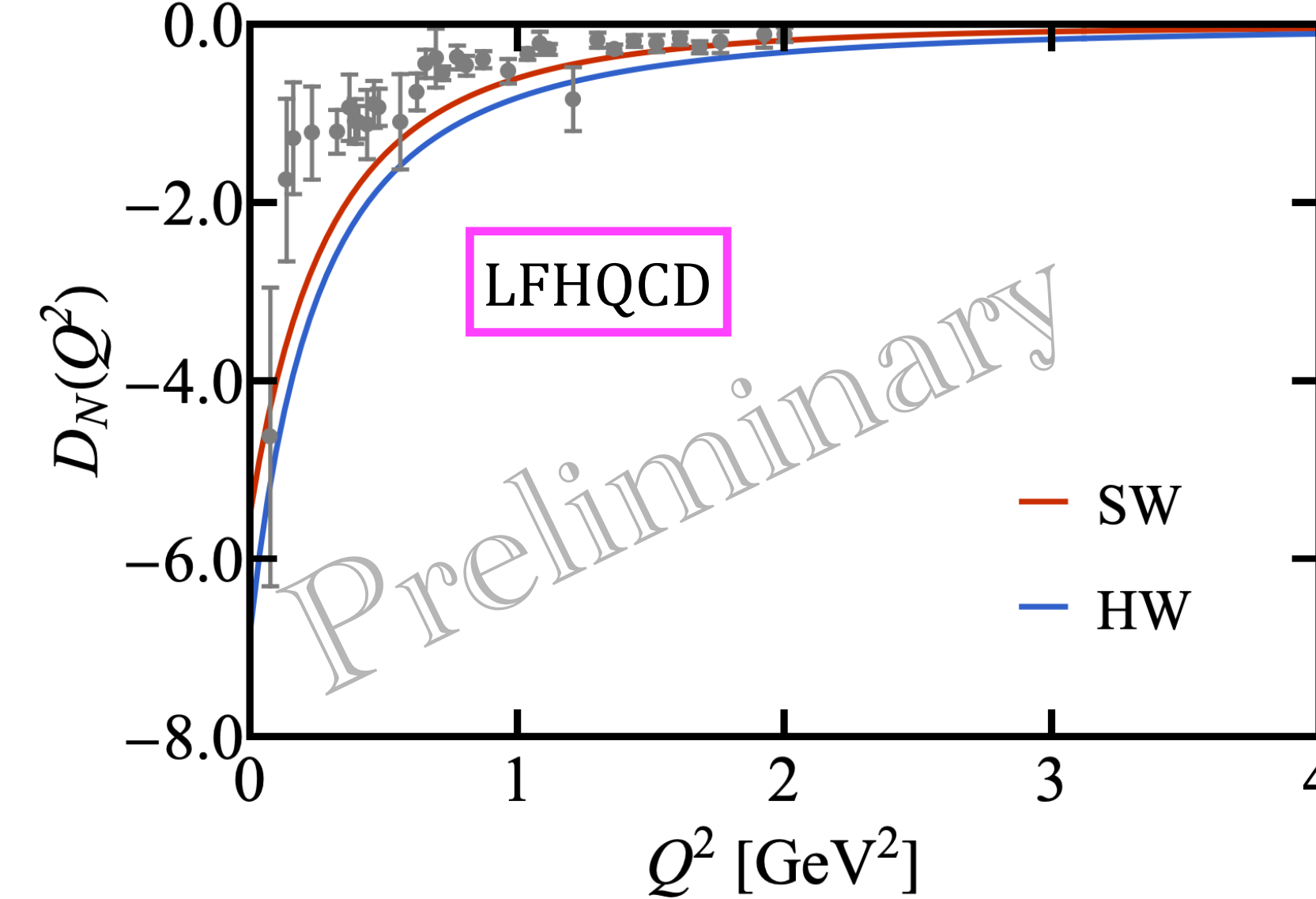
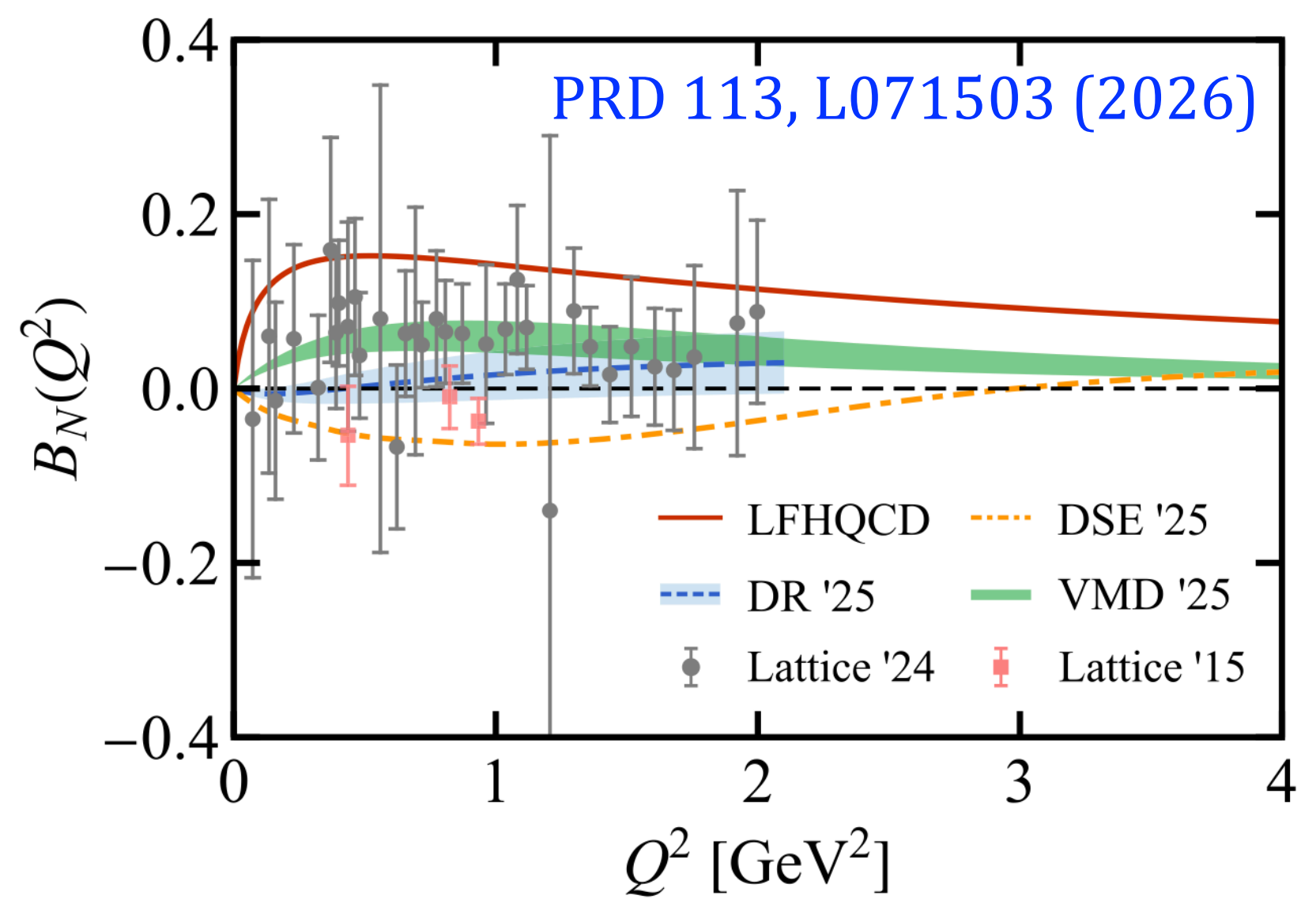
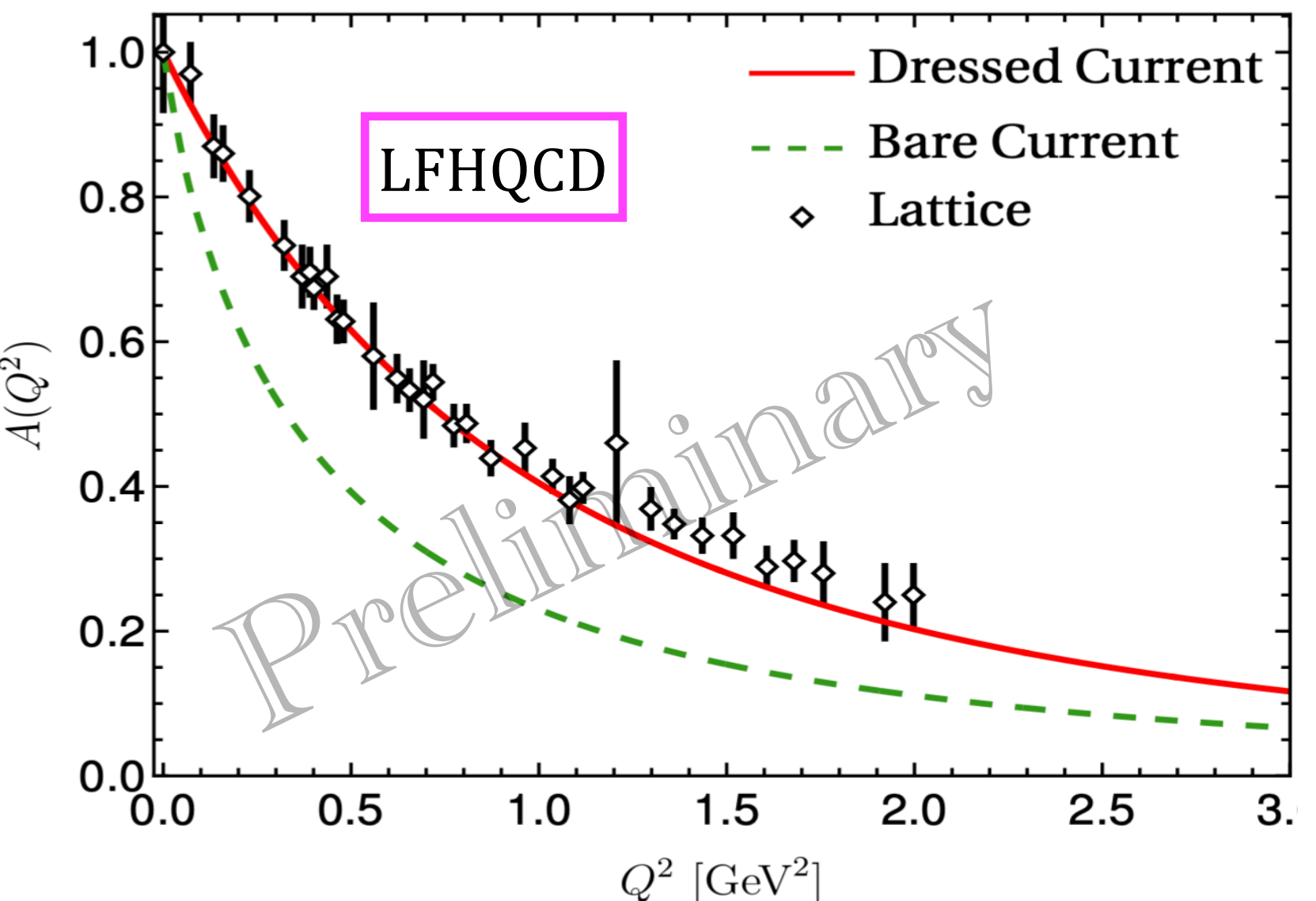
1. Momentum sum rule: $\sum_{i=q,g} A_i(0) = 1.$
2. Ji's spin sum rule: $\sum_{i=q,g} J_i(0) = \frac{1}{2} \sum_{i=q,g} [A_i(0) + B_i(0)] = \frac{1}{2} \Rightarrow \sum_{i=q,g} B_i(0) = 0.$
3. EMT conservation: $\partial_\mu T^{\mu\nu} = 0 \Rightarrow \sum_{i=q,g} \bar{C}_i(t) = 0.$
4. Mechanical stability: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

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



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

In preparation with: Y. Li, J. Vary, X. Cao and C. Mondal



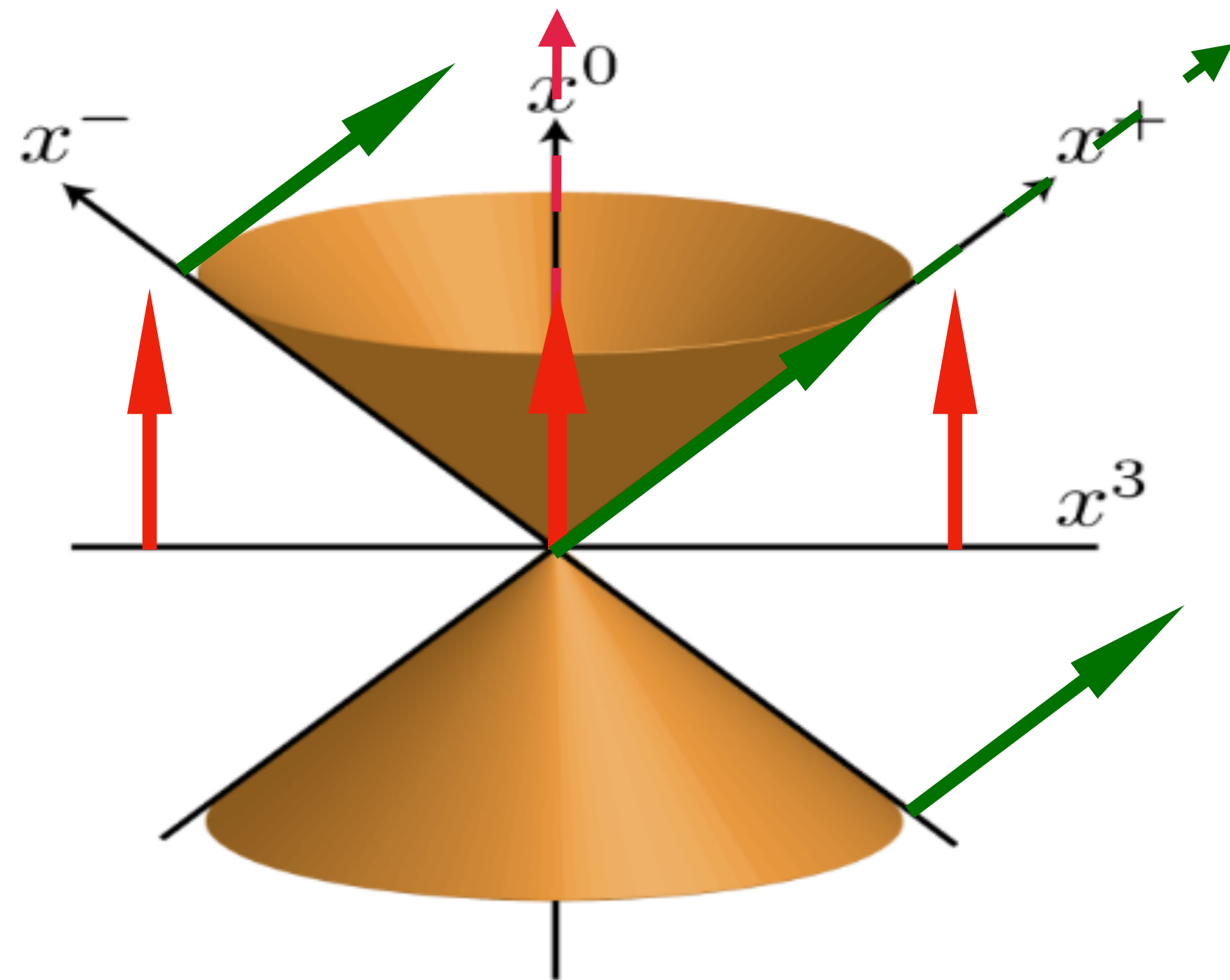
Forms of Relativistic Dynamics

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

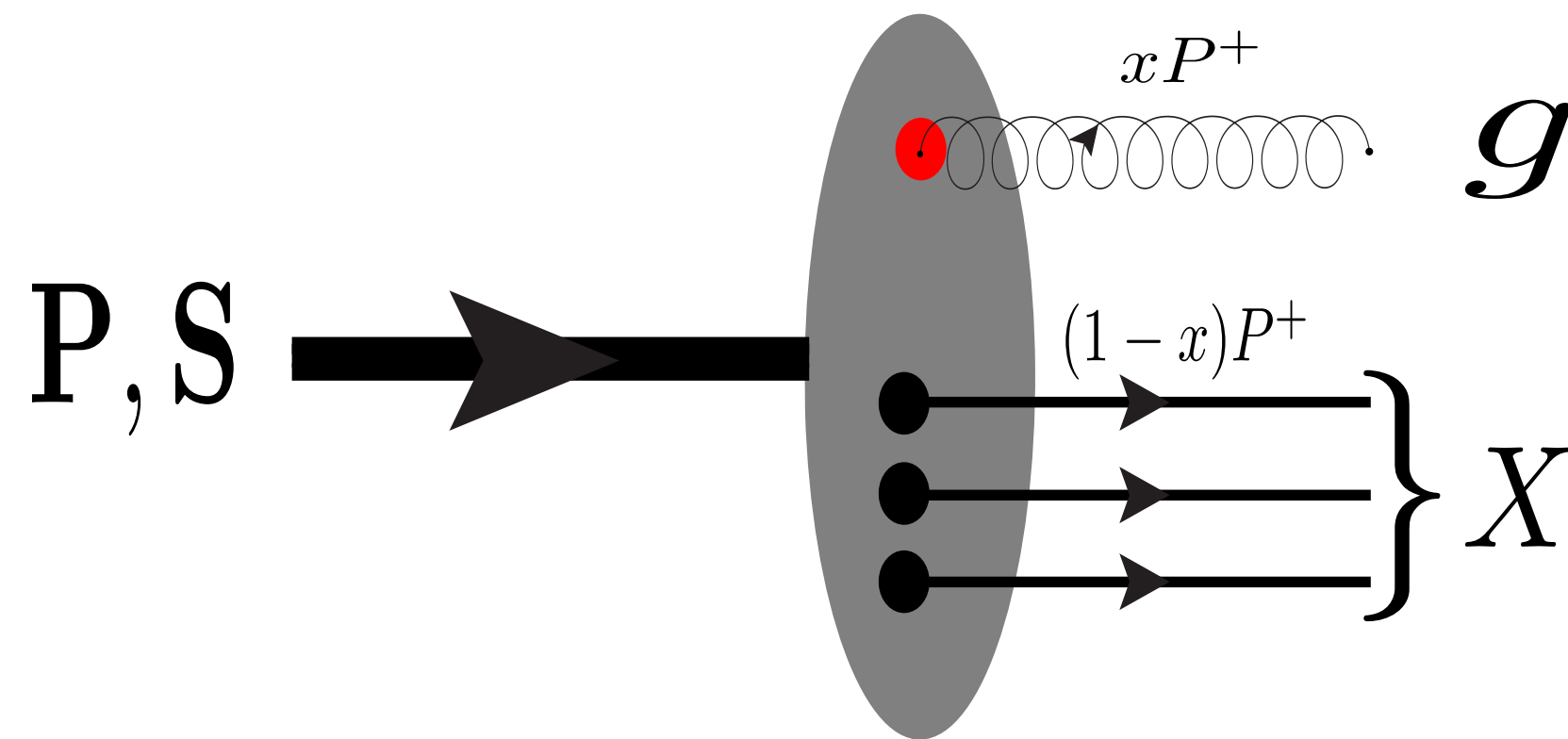
The dispersion relation is quite remarkable for the several reasons

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: $|e\rangle \rightarrow |e\rangle_{\text{bare}} + |\gamma e\rangle + \dots$]



The two particle Fock-state expansion

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

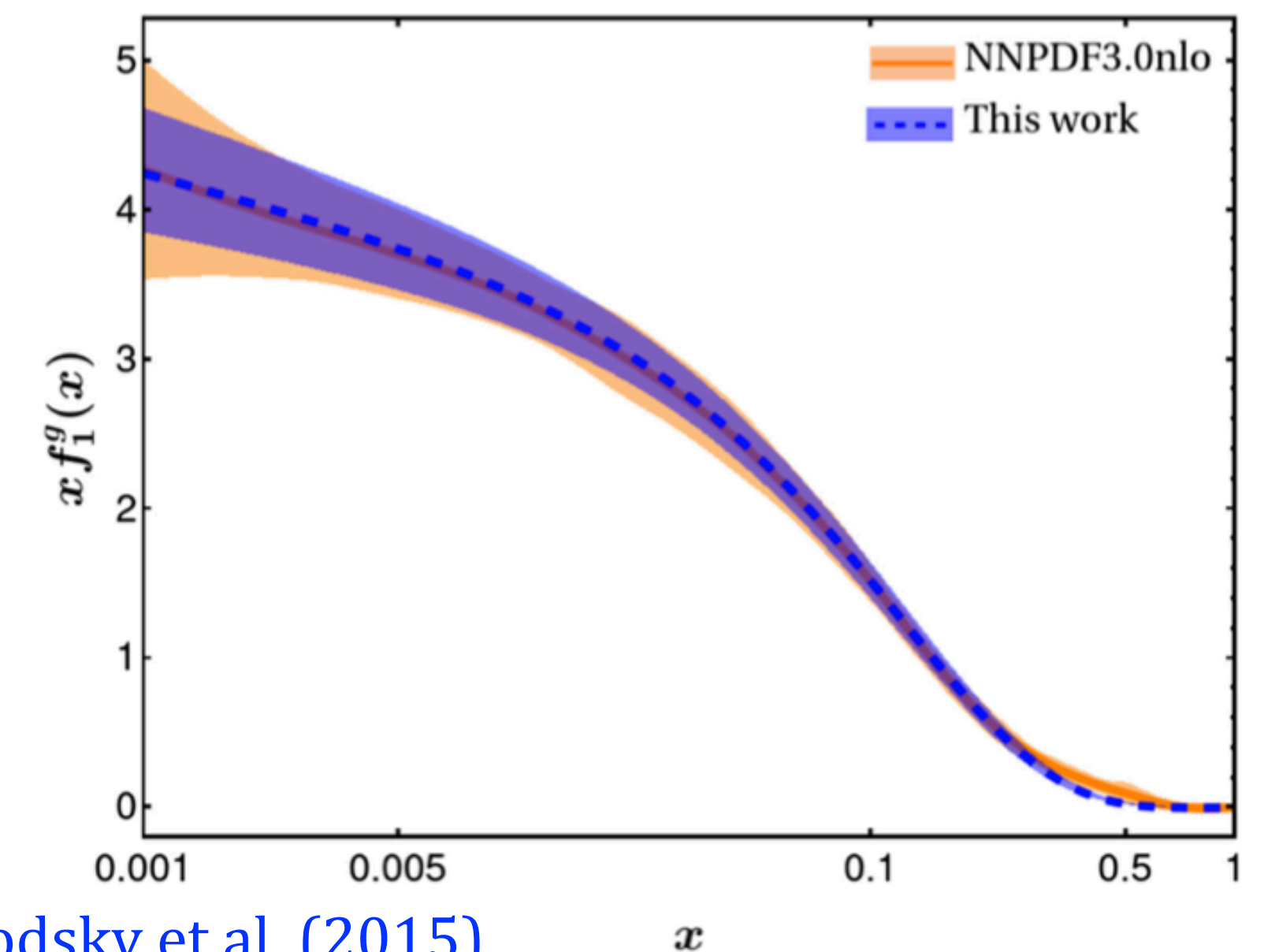
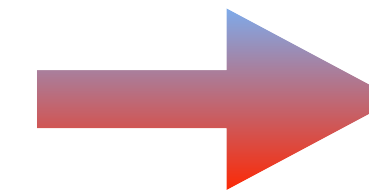
LFWFs ↓

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

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

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

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

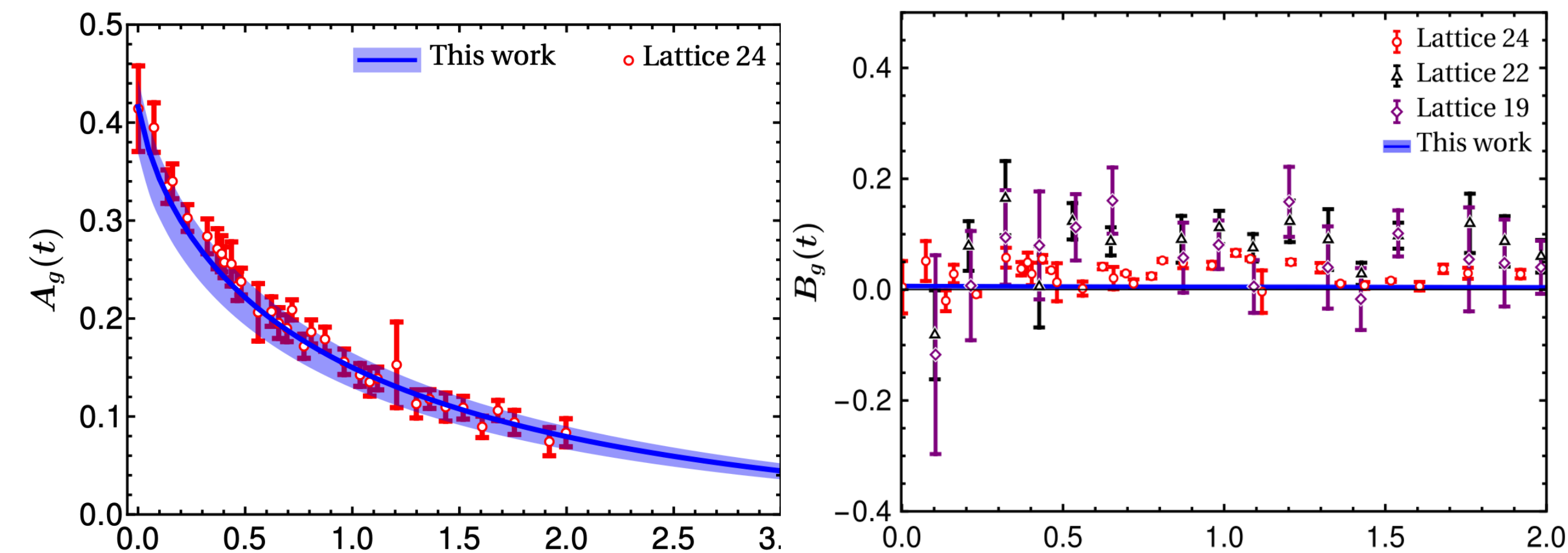


Model results for gluon GFFs

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

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

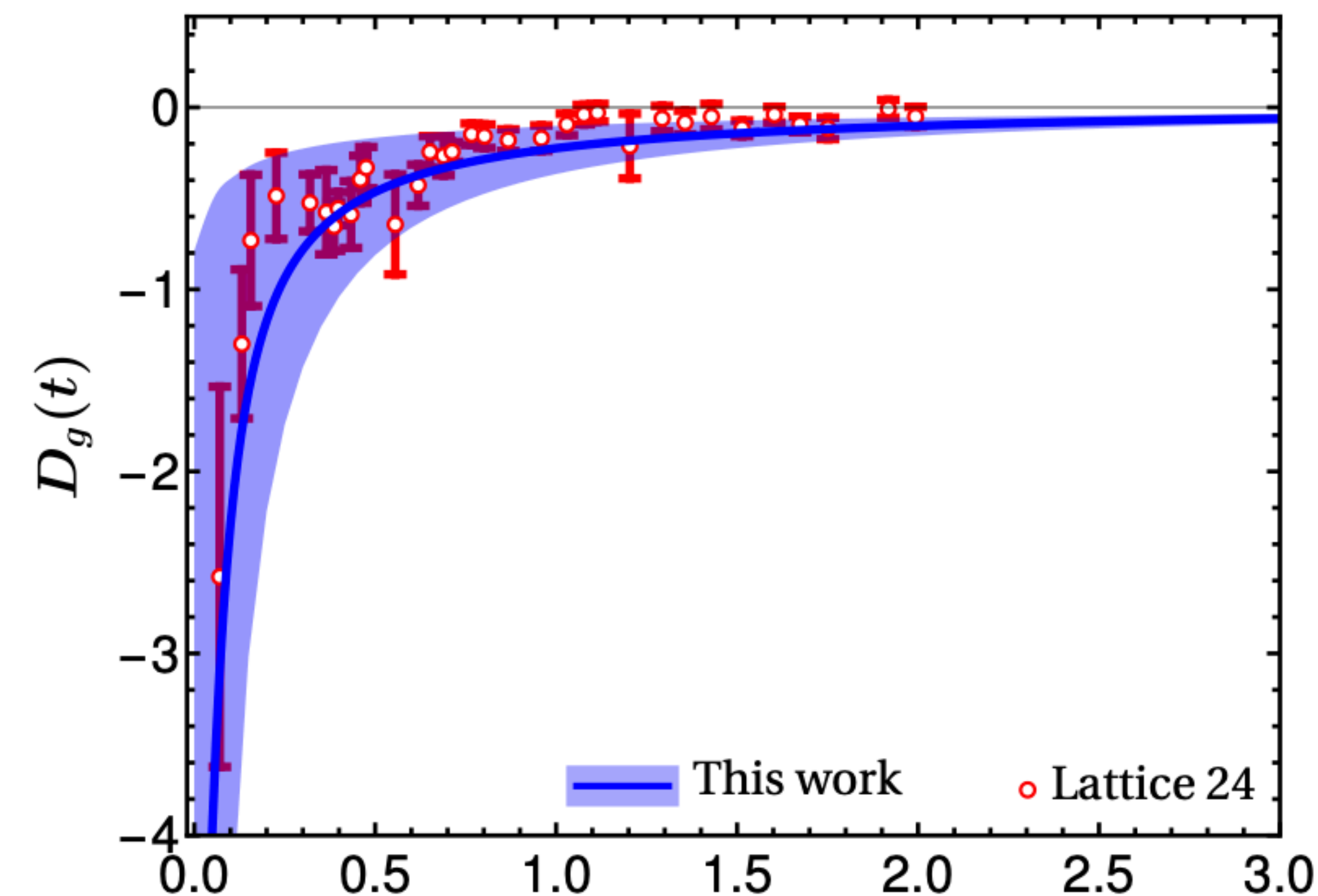
$$\mathcal{M}_{\lambda\lambda'}^{\mu\nu} = \frac{1}{2} \langle P', \lambda' | T_g^{\mu\nu}(0) | P, \lambda \rangle$$



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

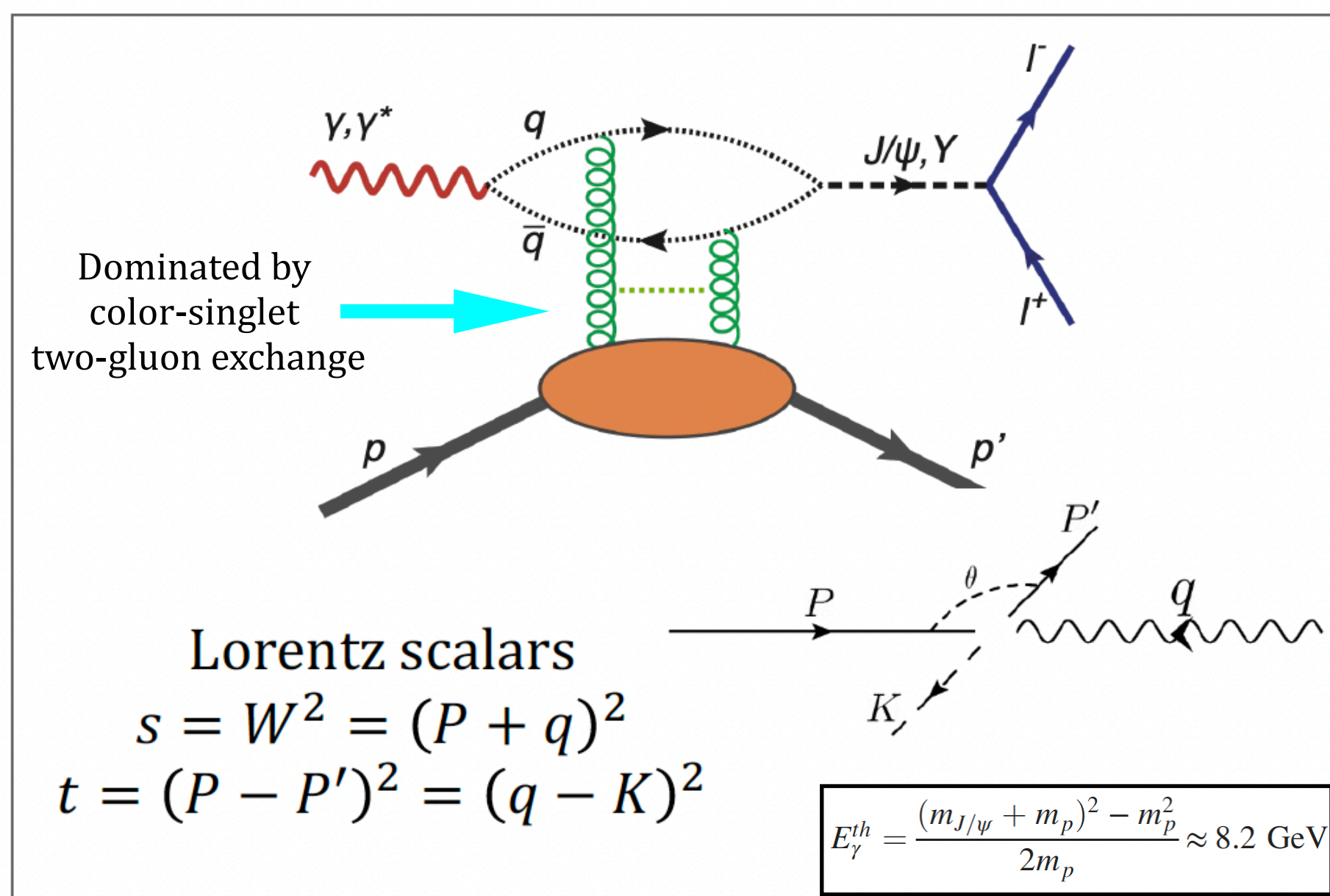
$$\sum_{i=1,2} \mathcal{M}_{\uparrow\downarrow}^{ii} + \mathcal{M}_{\downarrow\uparrow}^{ii} = i \left[B_g(q^2) \frac{q^2}{4M} - D_g(q^2) \frac{3q^2}{4M} + \bar{C}_g(q^2) 2M \right] q^{(2)}$$

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



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** $\rightarrow m_Q \gg \Lambda_{\text{QCD}}$, **large- $|t|$** and $\xi \rightarrow 1$ limits.



Near-threshold heavy vector meson production cross section

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

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

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

Within the LO **QCD factorization** framework of **GPDs** the CFFs $\leftarrow \mathcal{H} = \sum_{i=q,g} \mathcal{H}_i$ 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

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

The dominant contribution to the production amplitude \rightarrow lowest GPD moments.

$$\int_{-1}^1 dx x H^a(x, \xi, t) = A^a(t) + \xi^2 D^a(t) \quad \mathcal{H}(\xi, t) \approx \left(\frac{2}{\xi^2}\right) [A_g(t) + \xi^2 D_g(t)]$$

$$\int_{-1}^1 dx x E^a(x, \xi, t) = B^a(t) - \xi^2 D^a(t) \quad \mathcal{E}(\xi, t) \approx \left(\frac{2}{\xi^2}\right) [B_g(t) - \xi^2 D_g(t)]$$

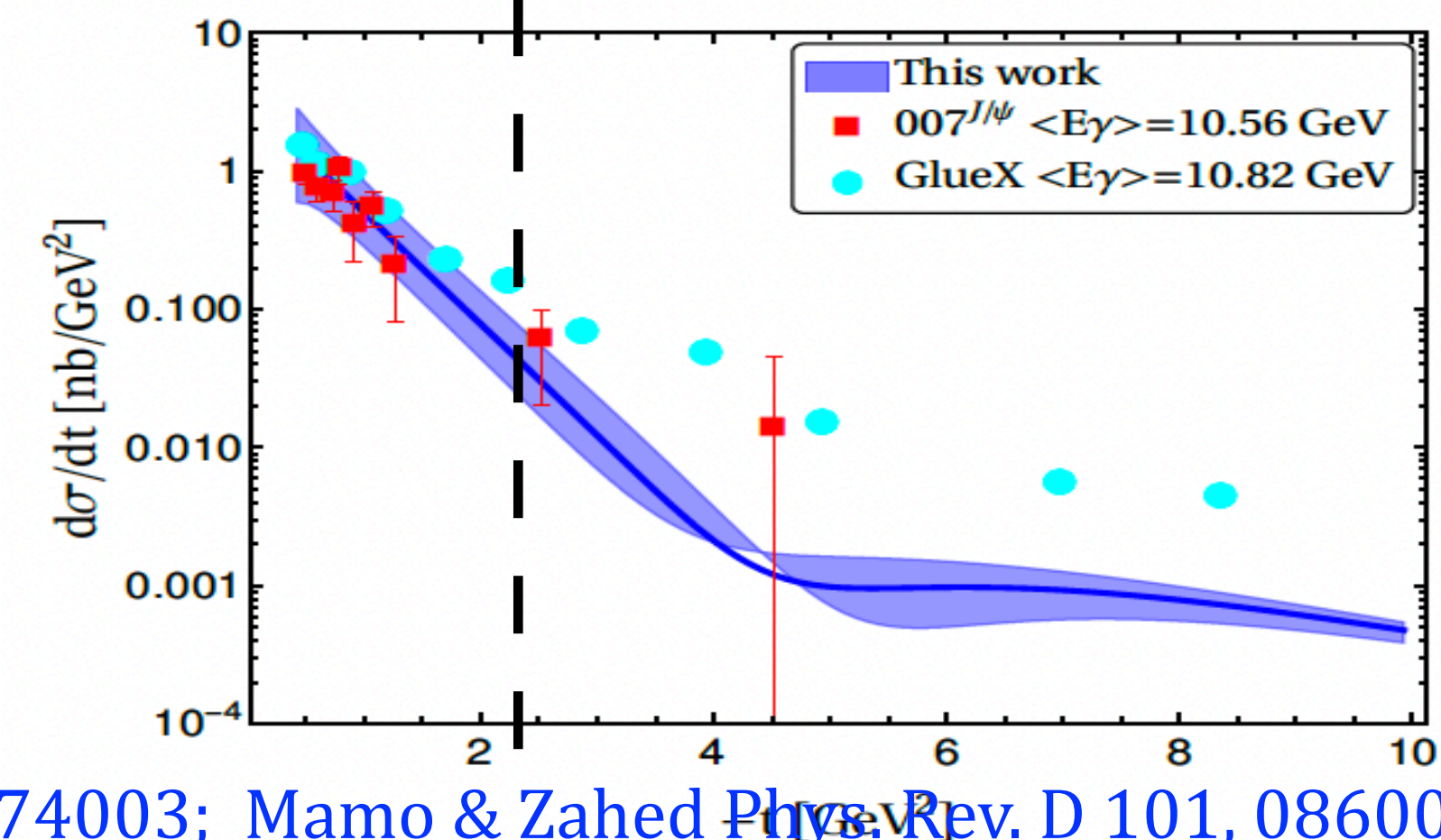
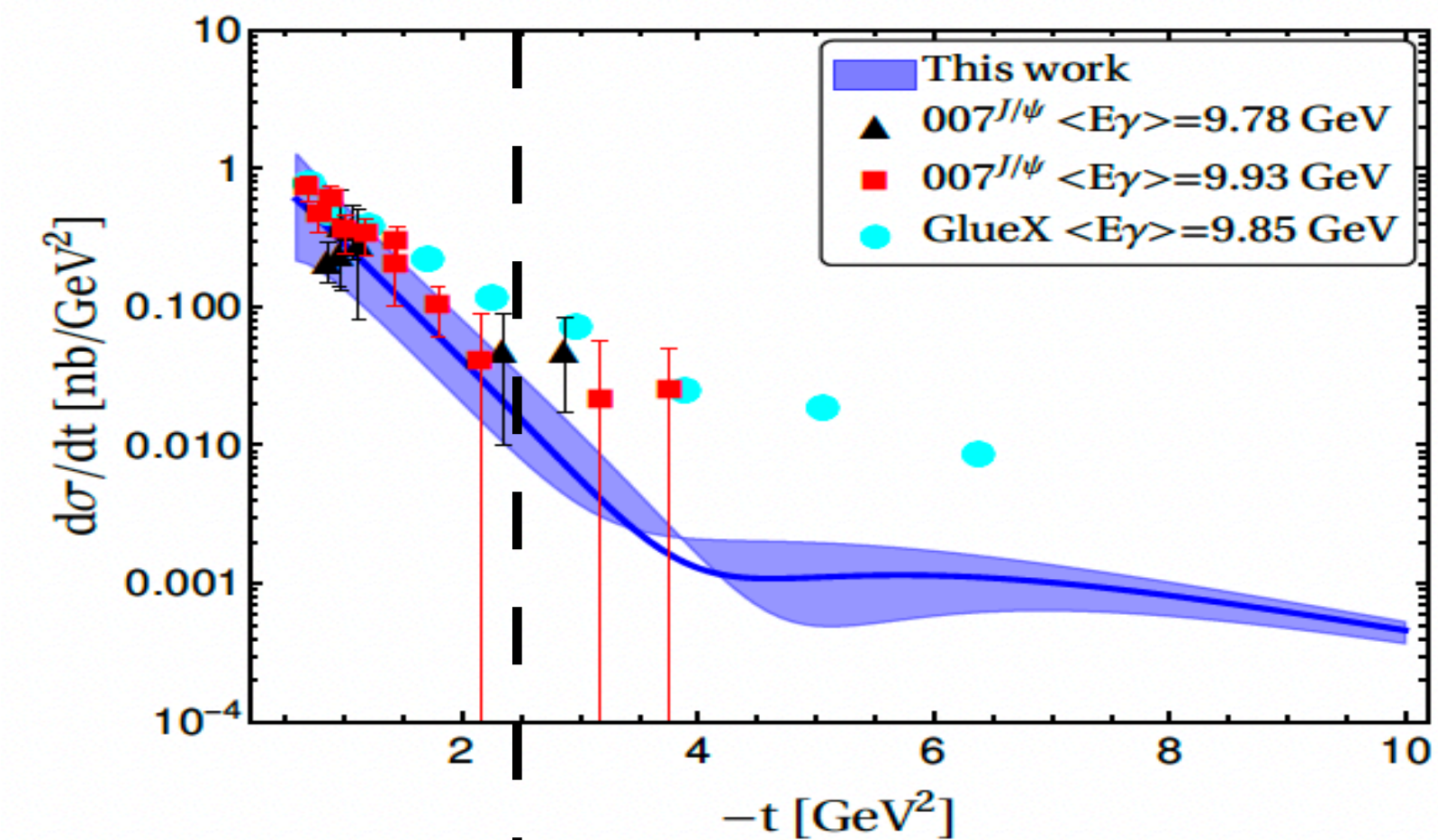
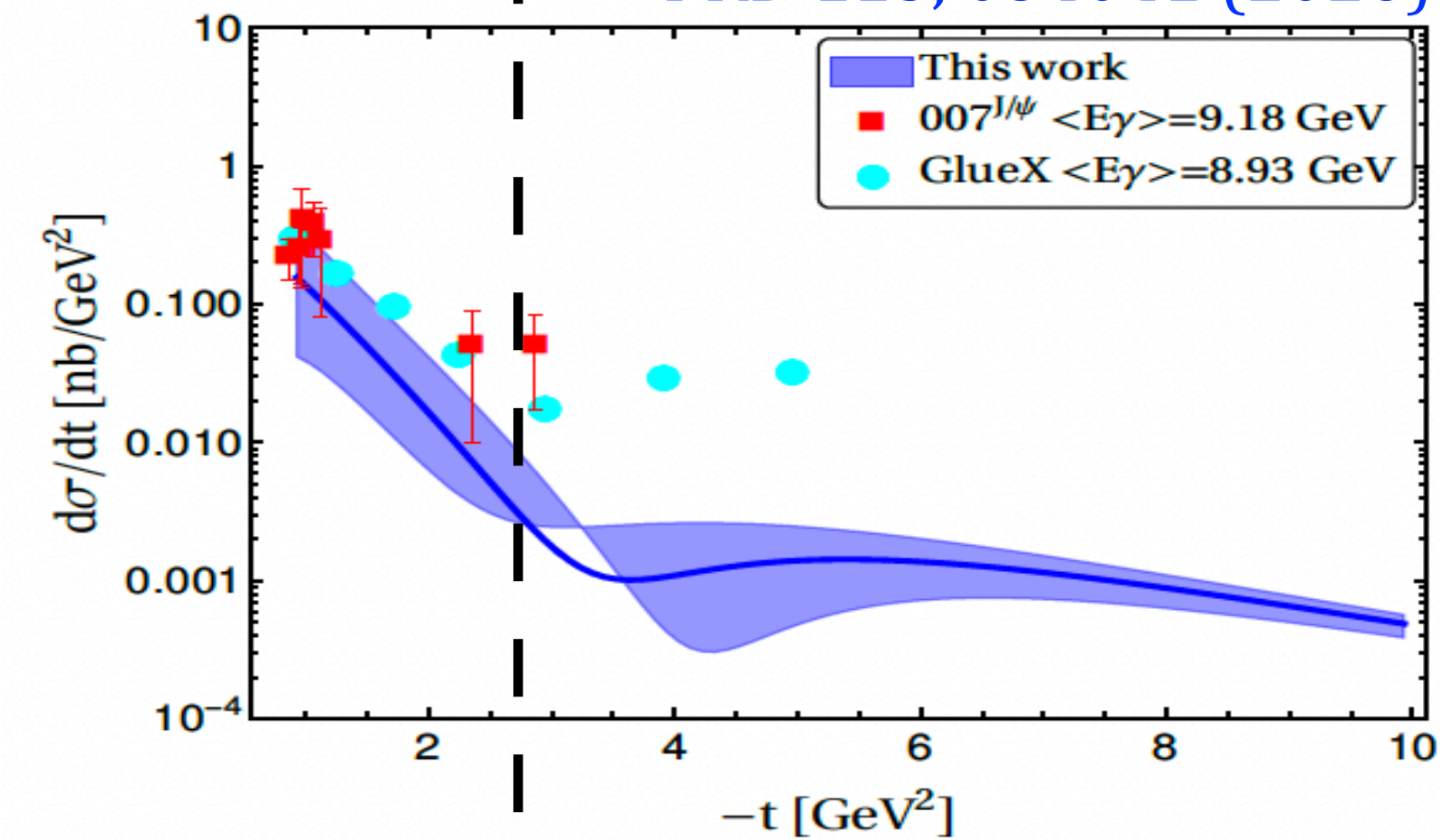
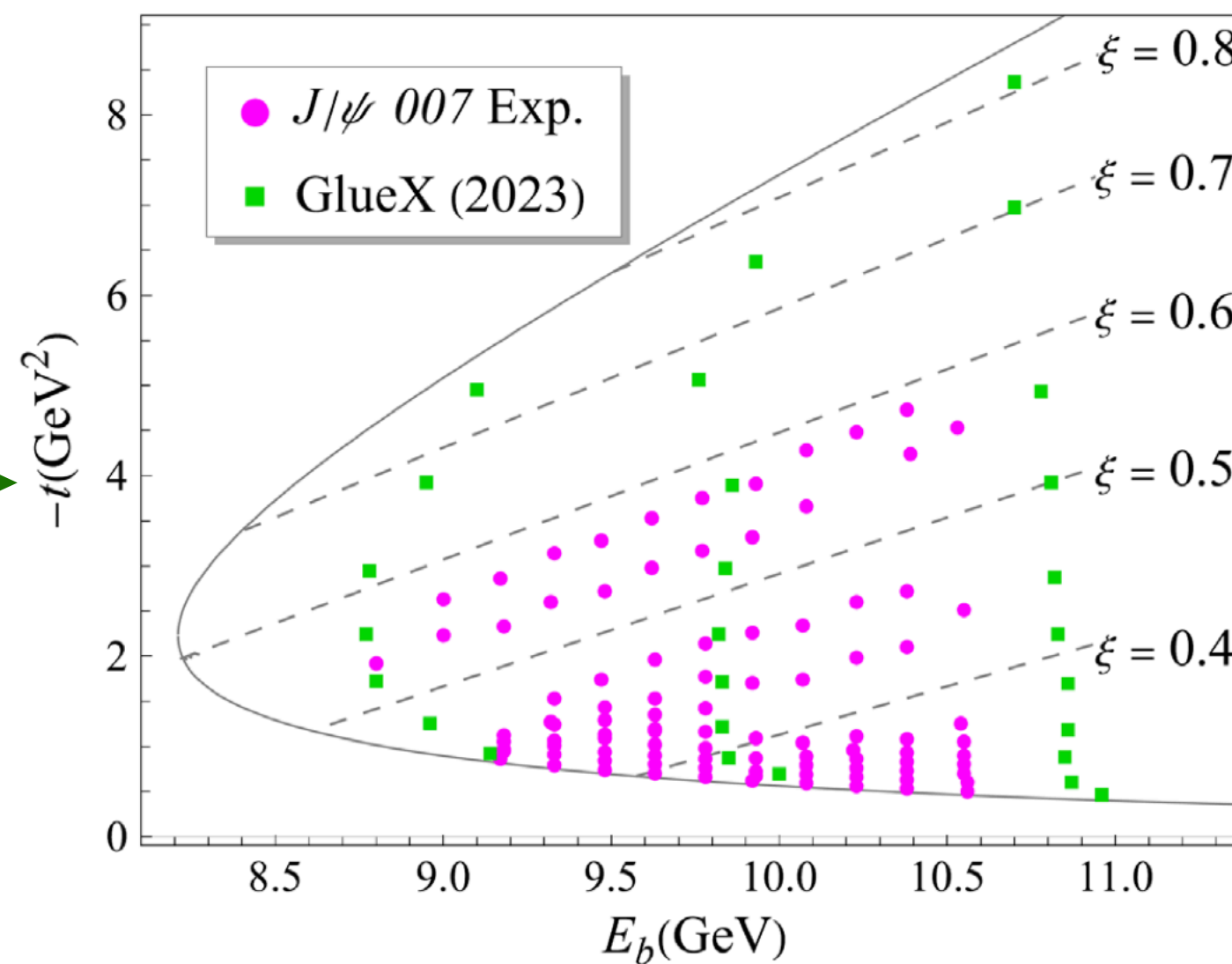
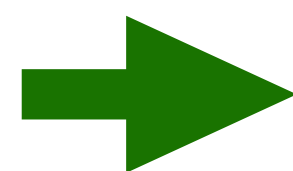
Model predictions for differential cross-section

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

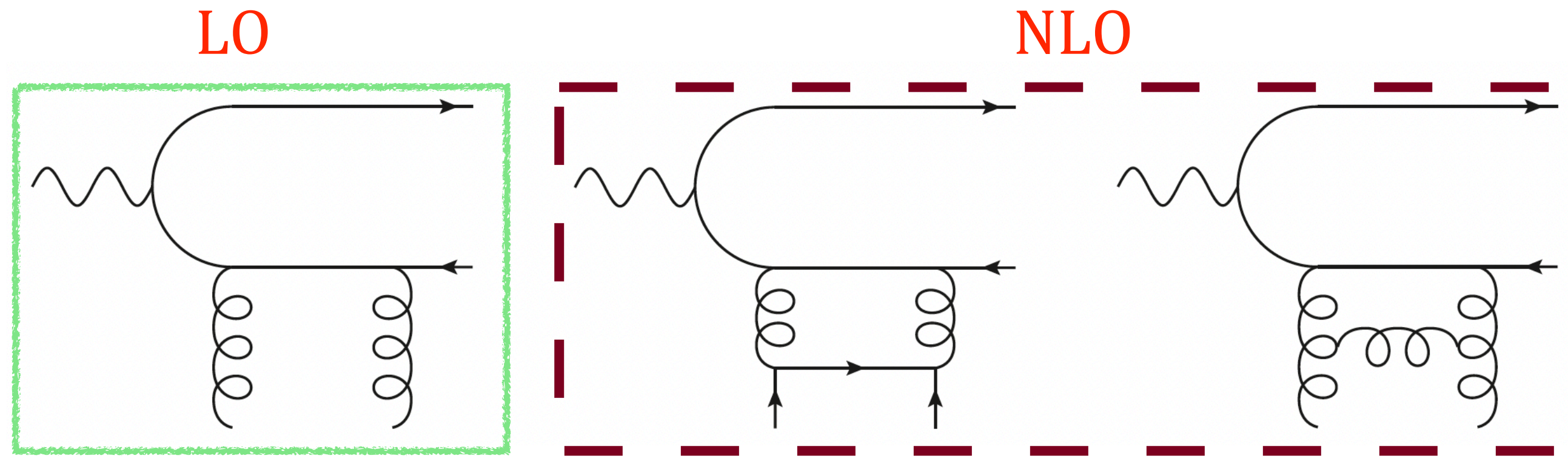
- Model results show good agreement with the **low-momentum-transfer** data from the **J/ψ-007** experiment and the **GlueX** Collaboration.
- The inclusion of **Next-to-Leading Order (NLO)** QCD effects is necessary to describe the data in **large-momentum-transfer** region.

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



GPD framework at NLO



NLO Wilson coefficients

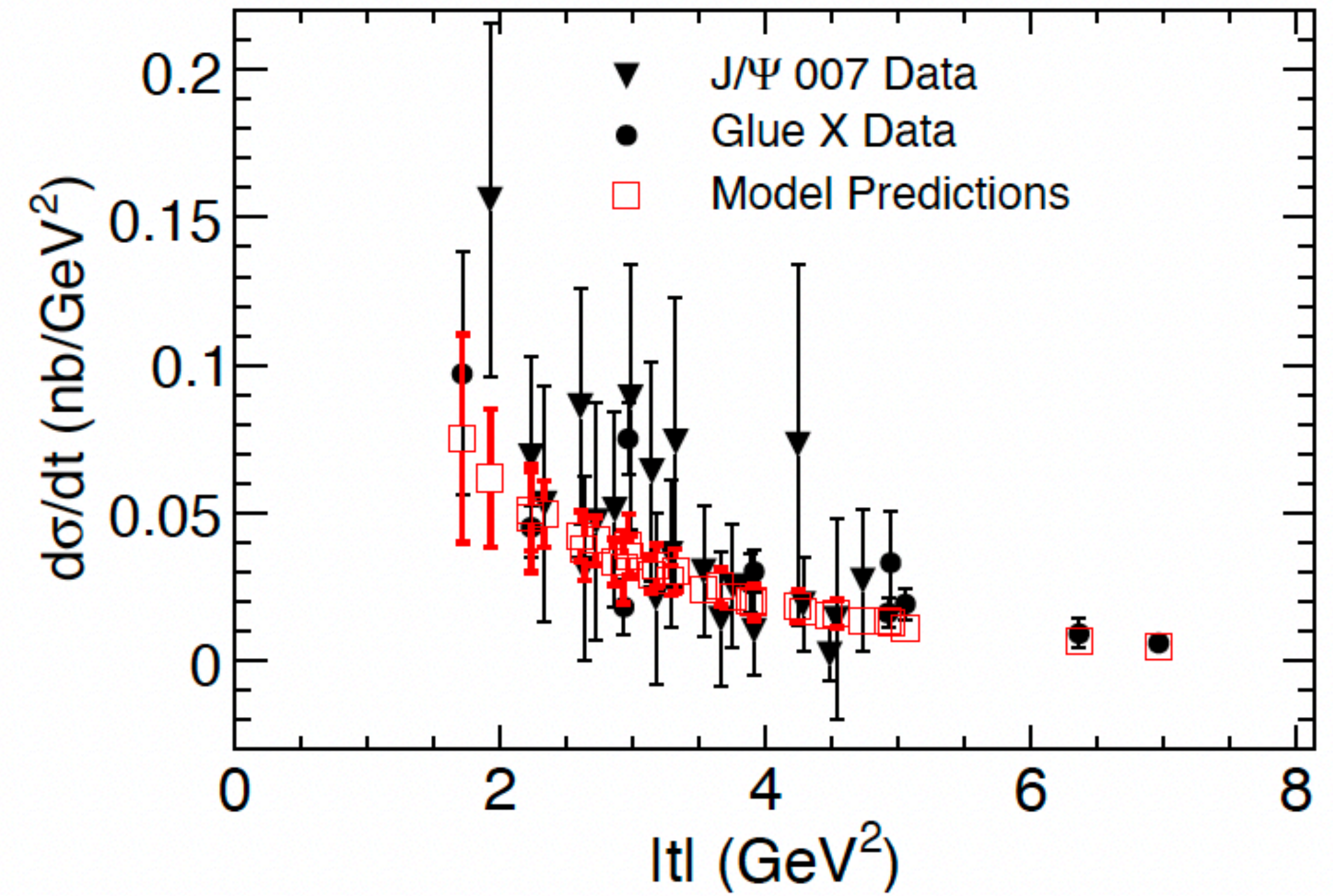
$$\bar{C}_g^{(1)} = \frac{5}{4} + \alpha_S \left[\bar{c}_g^1 - \frac{55}{16\pi} \log \left(\frac{m_c^2}{\mu_F^2} \right) \right] + \mathcal{O}(\alpha_S^2),$$

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

Modified CFFs

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

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

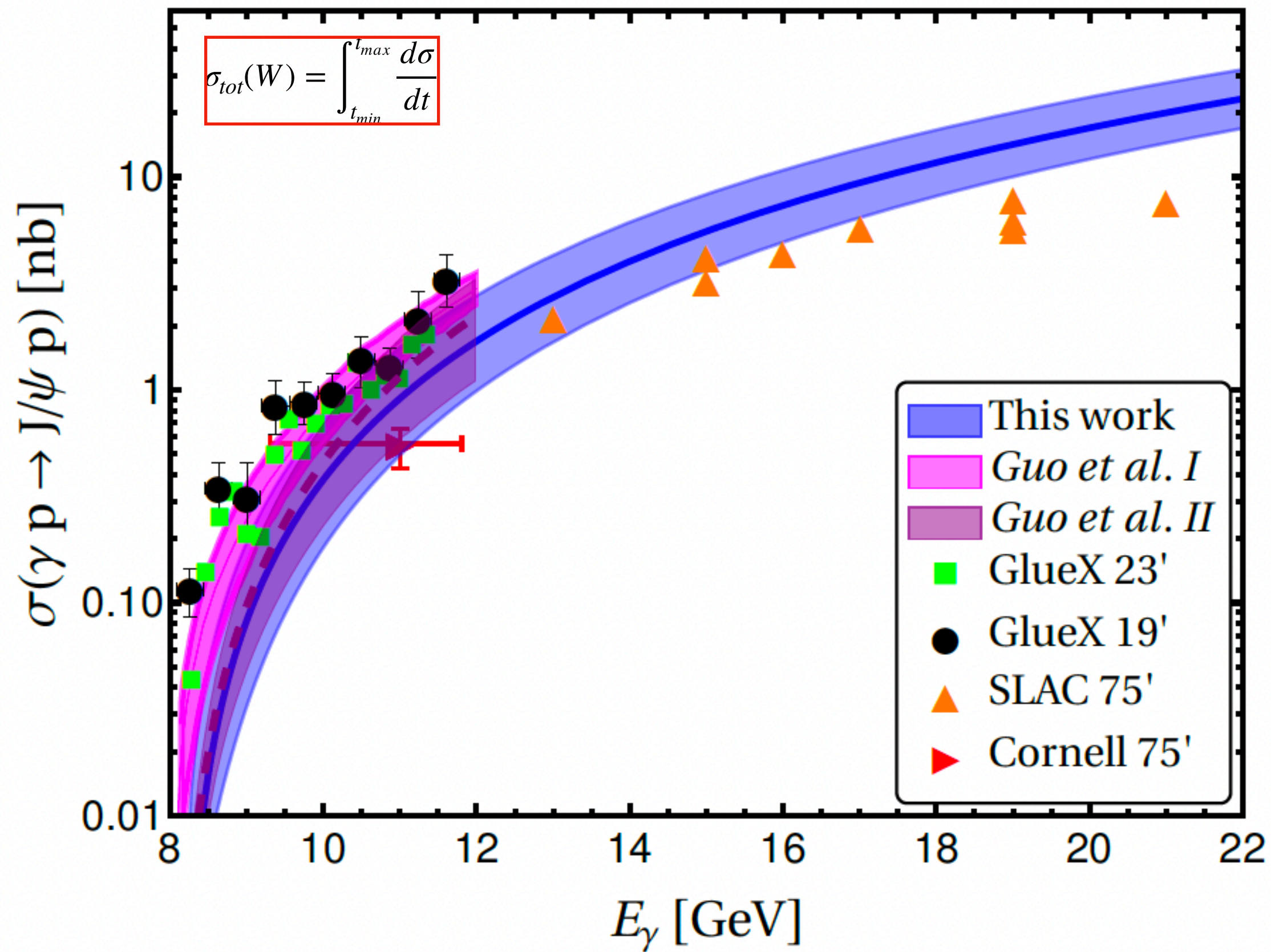


- ✓ NLO → We can constrain both the quark and gluon GFFs.
- ✓ Current constraint on gluon GFFs ($D_g(0)$) is limited → Lack of precise large- ξ (>0.5) data.
- ✓ GlueX and J/ψ-007 measurements have large uncertainties.
- ✓ EIC will provide more precise measurements.

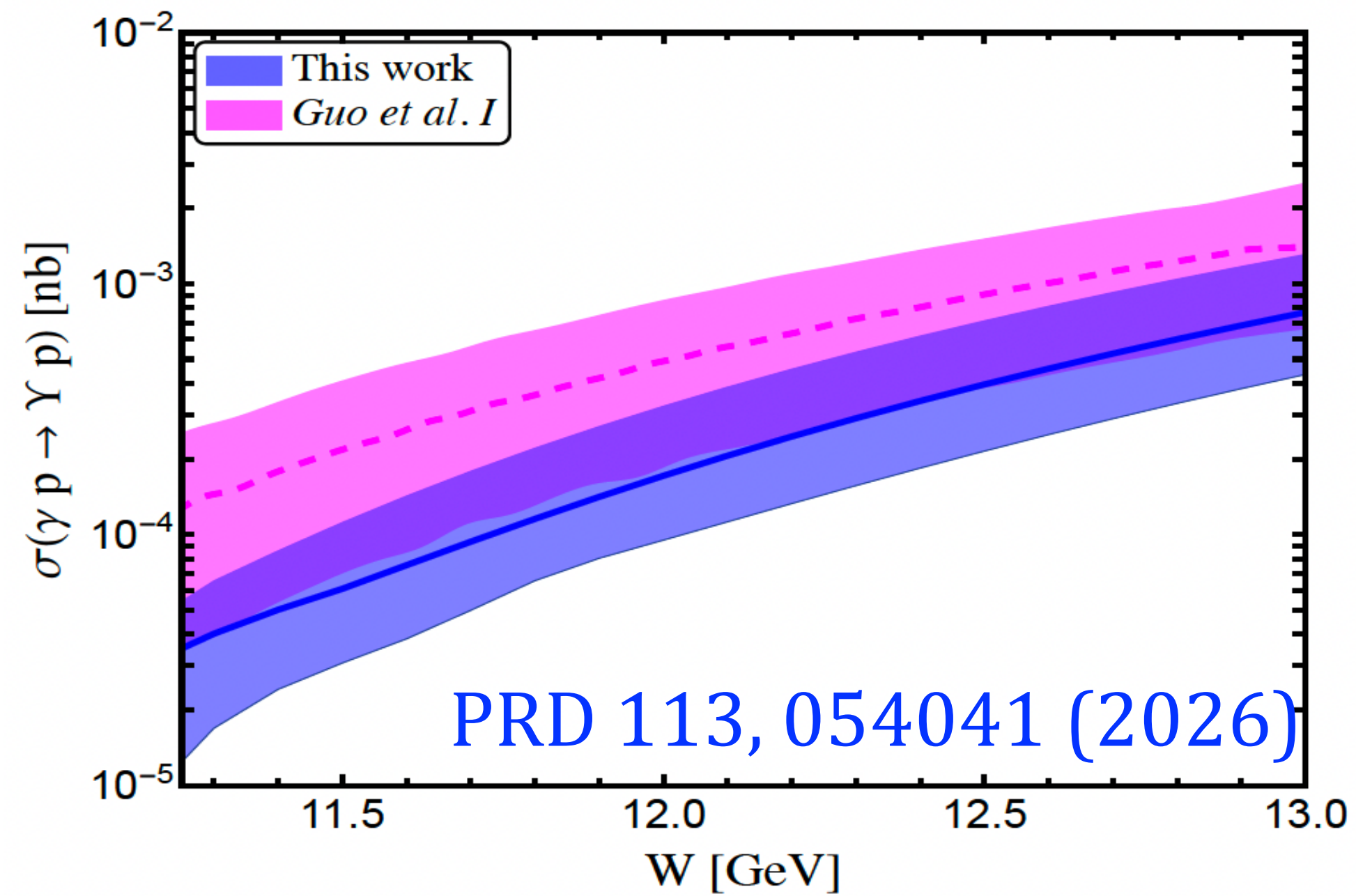
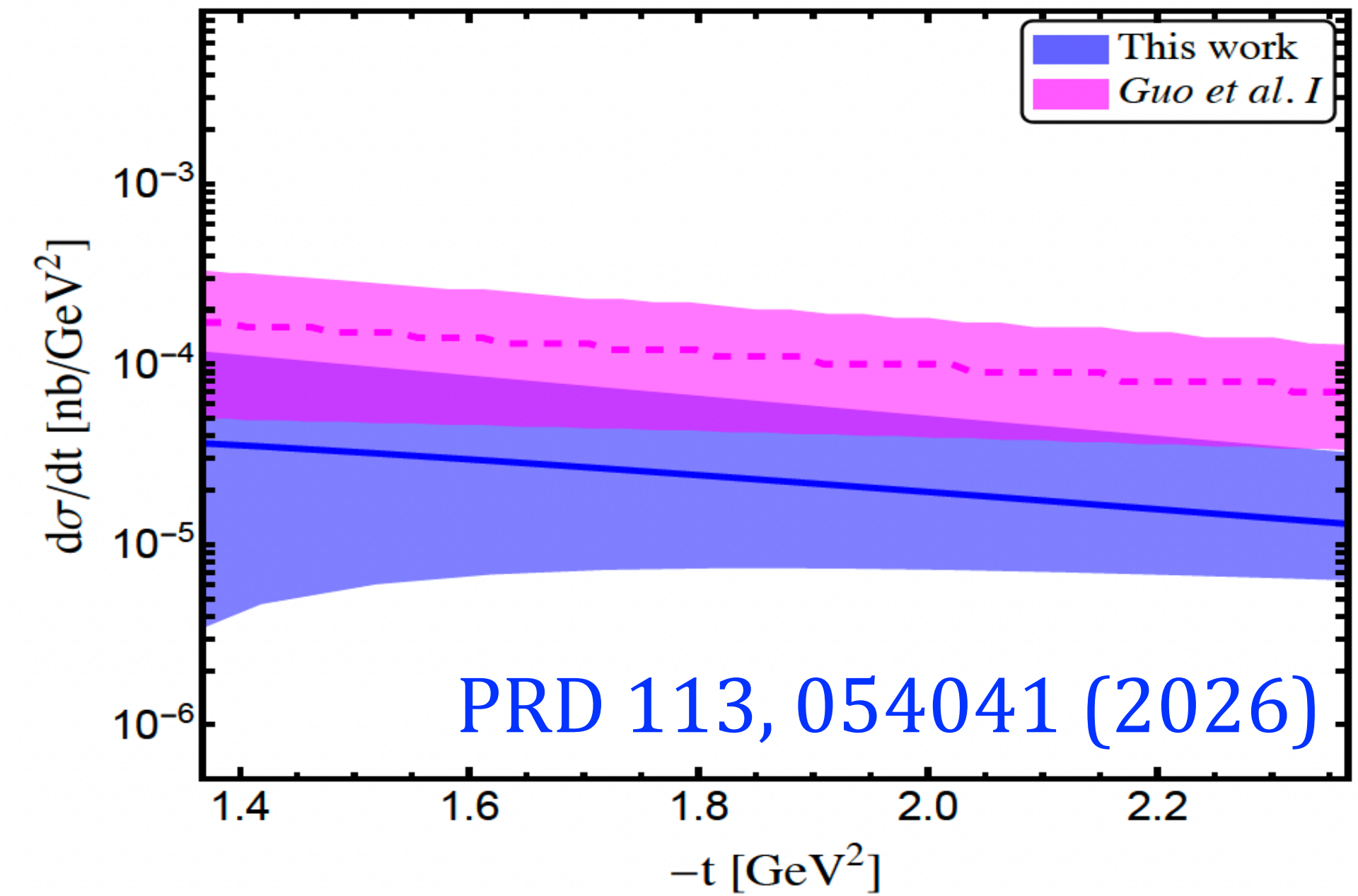
D. Y. Ivanov et al., Eur. Phys. J. C 34, 297 (2004),
 Z.-Q. Chen et al., Phys. Lett. B 797, 134816 (2019)
 C. A. Flett et al., JHEP 08, 150 (2021)

Total cross section

PRD 113, 054041 (2026)



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 an effective 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 for **larger $|t|$** → requires the contributions from **higher order QCD** corrections.
- ◆ Near-threshold photo production in collisions offers an independent test of the universality of nucleon–nucleon **short-range correlations** (SRC) in nuclear scattering through Sub-threshold photo production.

Thank you for your attention !!