核子电磁与引力形状因子的
夸克-双夸克描述

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Based on:
arXiv:2507.13484

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Content

- Motivation
- Dyson-Schwinger Equations
- EMFFs of Nucleon
- GFFs of Nucleon [*Preliminary*]
- Summary and Outlook

Motivations

➢Nucleon structure

- The nucleon magnetic moment was measured to be about $\mu_p \simeq 2.5\mu_N$ (Frisch and Stern, 1933) and $\mu_n \simeq -1.5\mu_N$ (Alvarez and Bloch, 1940);
- The first determination of the proton charge radius 0.74 ± 0.24 fm was brought by studies of elastic electron-proton scattering (McAllister and Hofstadter, 1956);
- The structure of the nucleon in DIS is described in terms of parton model (Feynman, 1969); The development of the parton model were key to establishing quantum chromodynamics.
- Nowadays: Origin of proton mass? Spin puzzle? PDFs (GPDs, TMDs)? D-term(the less well-known)? ......

Motivations

➢Form factors

✓The electromagnetic form factors (EMFFs) are important quantities for the understanding of hadron’s electromagnetic structure:

charge radius, magnetic momentum, charge and magnetisation densities

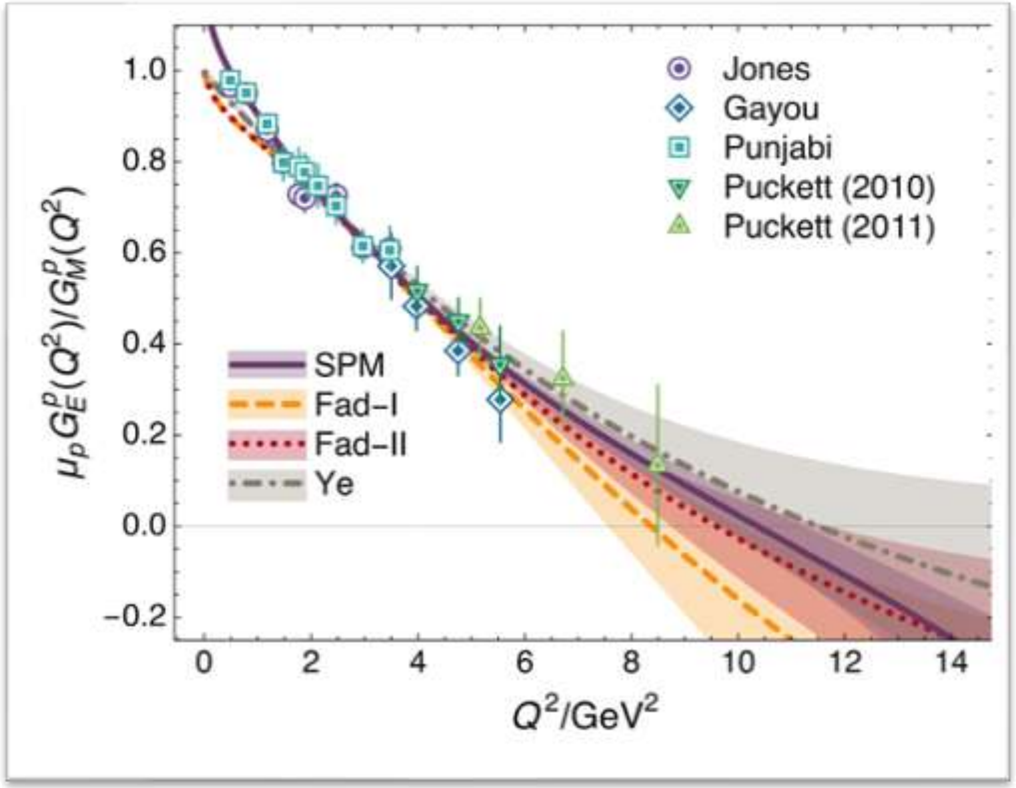
✓The gravitational form factors(GFFs) contains fundamental information on hadron’s mechanical properties:

mass, spin, D term, the distributions of energy and internal forces

✓The evolution behavior of the FFs with Q^2 can reveal the scale dependence of effective degrees of freedom.

meson-baryon, dressed quark, current quark

Motivations



D. Binosi, C. D. Roberts, Z.-Q.Yao, arXiv: 2503.05984

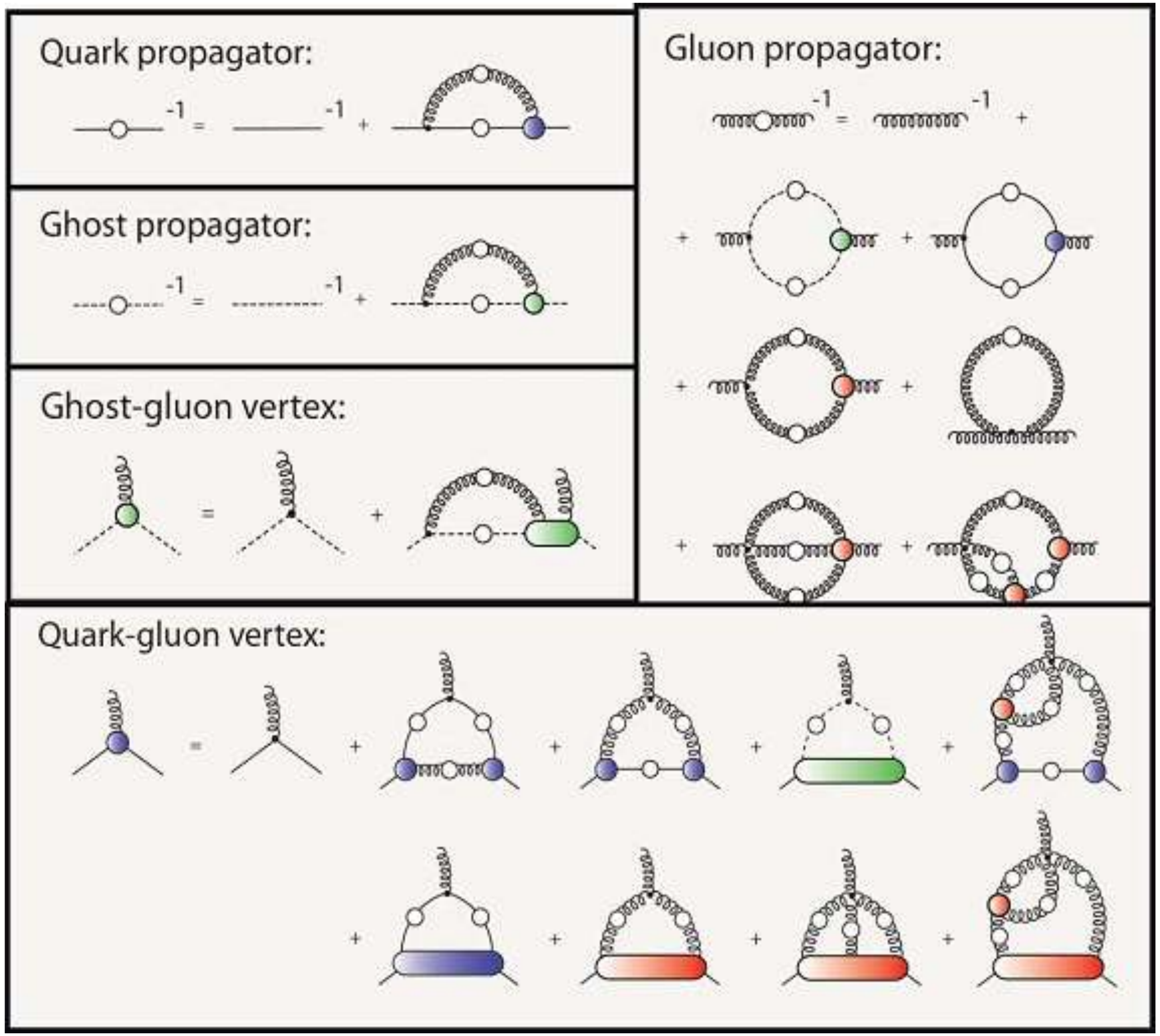
$$\mathcal{T}_a^{\mu\nu}(\vec{r}) = \int \frac{\mathrm{d}^3\Delta}{(2\pi)^3 2E} e^{-i\vec{\Delta}\cdot\vec{r}} \langle p'|T_a^{\mu\nu}|p\rangle$$

In order to obtain a more reliable distribution of mechanical properties, it is necessary to obtain the results of the form factor over a wider range of momentum Q^2.

As a continuous non-perturbative method, DSEs is a good choice!

Dyson-Shwinger Equations(DSEs)

- Continuum Schwinger function methods
- ✓ nonperturbative
- ✓ symmetry-preserving
- Owing to the infinite coupling feature, it is necessary to truncate the DSEs at a certain level for practical calculations.



C. D. Roberts and A. G. Williams, Prog. Part. Nucl. Phys. 33 (1994) 477-575.
C. D. Roberts and S. M. Schmidt, Prog. Part. Nucl. Phys. 45 (2000) S1-S103.
P. Maris and C. D. Roberts, Int. J. Mod. Phys. E 12 (2003) 297-365.

Dyson-Shwinger Equations(DSEs)

- 2n-point Green function G^n obeys Dyson's equation:

$$G^n = G_0^n + G_0^n K G^n$$

K is the n-quark scattering kernel, G_0^n is the disconnected n-quark propagator.

- A bound state of mass M with wave function ψ show up as a pole in the 2n-point function, i.e. in the vicinity of the pole, G^n becomes(P is the total momentum):

$$G^n \sim \frac{\psi(k_1, k_2, \ldots k_n)\overline{\psi}(p_1, p_2, \ldots p_n)}{P^2 + M^2}$$

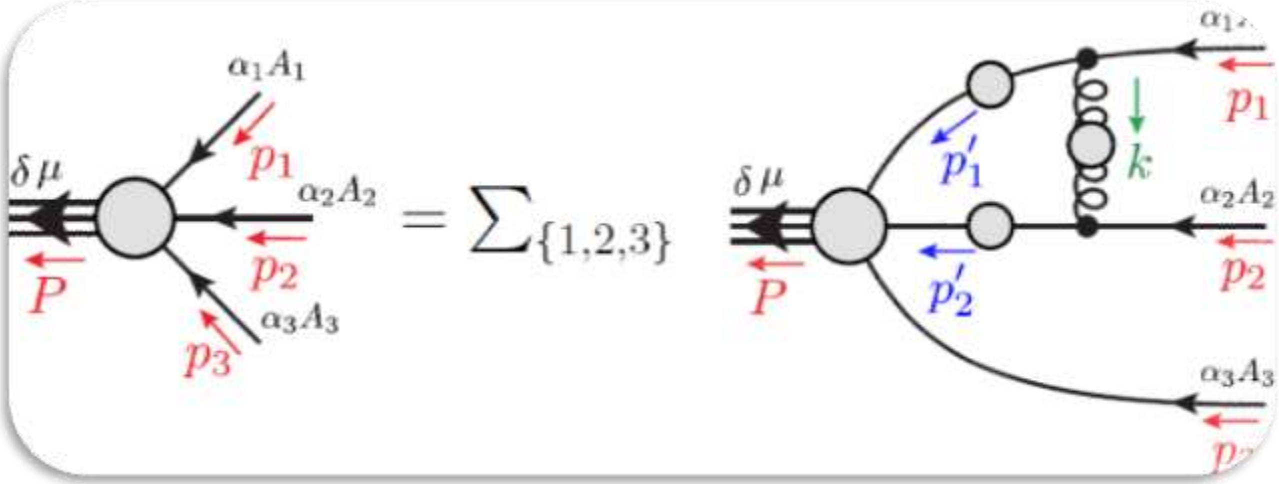
- Comparing residues, one finds the homogeneous bound state equation:

$$\psi = G_0 K \psi$$

- For the Faddeev equation of three quark system, the kernel consists of three terms:

$$K = K_1 + K_2 + K_3$$

Dyson-Shwinger Equations(DSEs)



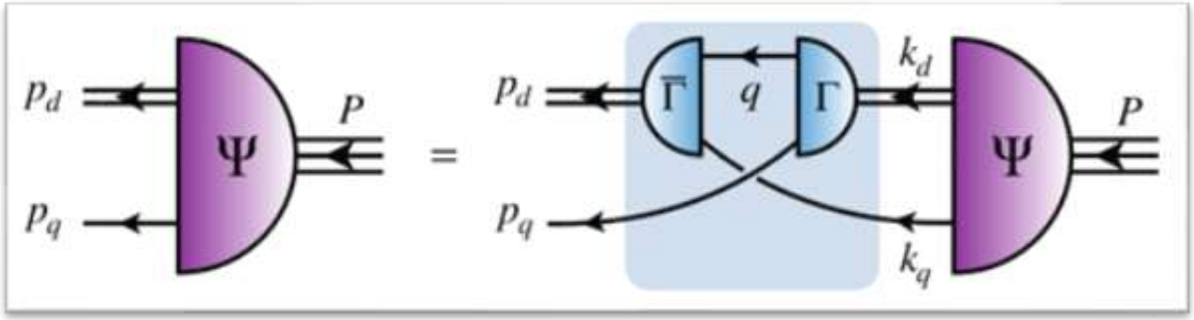
- ✓ Nucleon mass from a covariant three-quark Faddeev equation,
  G. Eichmann et al., Phys. Rev. Lett. 104 (2010) 201601
- ✓ Poincaré-covariant analysis of heavy-quark baryons,
  S.-X. Qin (秦思学) et al., Phys.Rev. D 97 (2018) 114017/1-13
- ✓ Nucleon Gravitational Form Factors,
  Z.-Q. Yao (姚照千) et al., Eur. Phys. J. A 61 (2025) 92/1-13

- Baryons appear as poles in the six-point Schwinger function, and their amplitude satisfy a homogeneous integral equation-Faddeev equation.

- Direct solution of Faddeev equation using rainbow-ladder truncation is now possible, but remains challenging problem – algorithms and numerical analysis.

Dyson-Shwinger Equations(DSEs)

- **Faddeev Equation(Quark+Diquark Framework)**
  - For many applications, diquark approximation to quark+quark scattering kernel is used
  - ***Prediction***: Owing to DCSB, *diquark correlations may exist within baryons*



Diquark correlations in hadron physics: Origin, impact and evidence
M.Yu.Barabanov, Craig D.Roberts et al. Prog.Part.Nucl.Phys. 116 (2021) 103835

- Diquark correlation
  - (I=0,J^P=0^+):isoscalar-scalar diquark
  - (I=1,J^P=1^+):isovector-axialvector diquark
  - (I=0,J^P=0^-):isoscalar-pesudoscalar diquark
  - (I=0,J^P=1^-):isoscalar-vector diquark
  - (I=1,J^P=1^-):isovector-vector diquark

✓ G. Eichmann, H. Sanchis-Alepuz, R. Williams, R. Alkofer, C. S. Fischer, Prog.Part.Nucl.Phys. 91 (2016) 1- 100

✓ ChenChen, B. El-Bennich, C. D. Roberts, S. M. Schmidt, J. Segovia, S-L. Wan, Phys.Rev. D97 (2018) no.3, 034016

EMFFs of Nucleon

- The nucleon electromagnetic interaction current:

$$J_\mu(P_f,P_i) = ie\,\Lambda_+(P_f)\,\Lambda_\mu(Q,P)\,\Lambda_+(P_i)\,,$$
$$= ie\,\Lambda_+(P_f)\,\Big[\gamma_\mu F_1(Q^2) + \frac{1}{2m_N}\,\sigma_{\mu\nu}\,Q_\nu\,F_2(Q^2)\Big]\,\Lambda_+(P_i)\,,$$

where $Q = P_f - P_i$ is the transferred photon momentum. Λ_+ is the projection operator of a positive energy nucleon, $F_{1\,2}$ are the Dirac and Pauli form factors.

- The nucleon charge and magnetization distributions ($\tau = Q^2/[4m_N^2]$):

$$G_E(Q^2) = F_1(Q^2) - \tau F_2(Q^2)\,,$$
$$G_M(Q^2) = F_1(Q^2) + F_2(Q^2)\,.$$

The $SU(2)_F$ isospin limit is used: $m_u = m_d$.

$$J_\mu(P_f,P_i) = \int \frac{d^4p}{(2\pi)^4}\frac{d^4k}{(2\pi)^4} \sum_{i=1}^{6} \bar{\Psi}(p,-P_f)\Lambda^i_\mu(p,P_f;k,P_i)\Psi(k;P_i)$$

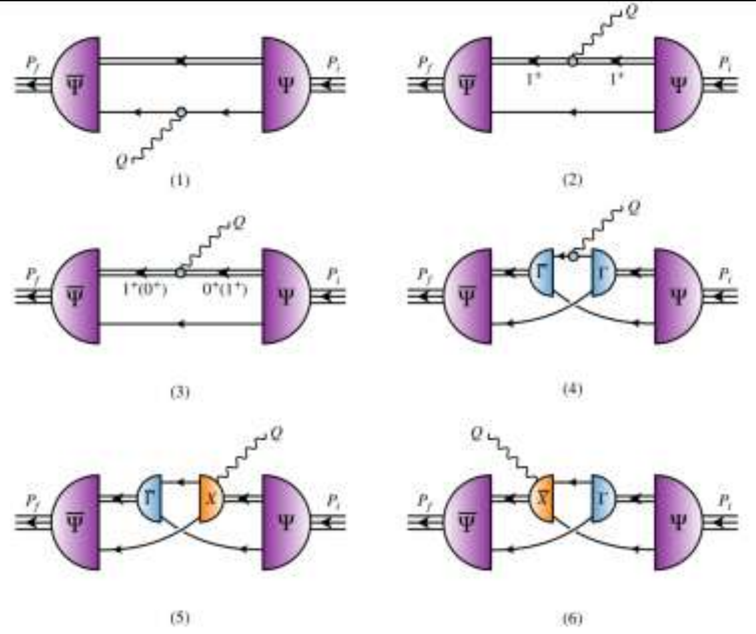
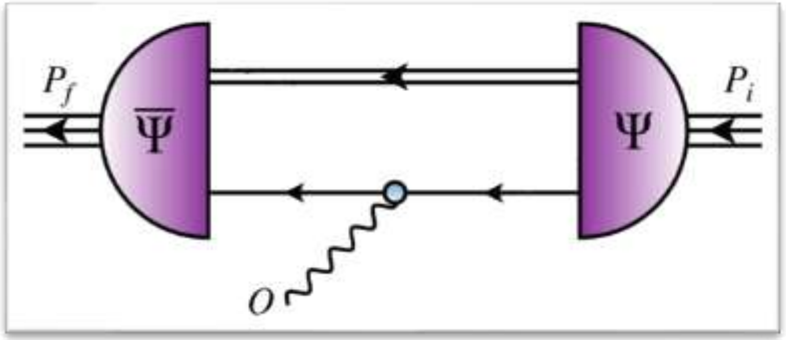


Fig. 2 The collection of electromagnetic interaction diagrams that ensures a conserved current for on-shell nucleons described by the Faddeev amplitude, Ψ, calculated as described in Sect. 2. Legend. *single line*, dressed-quark propagator; *undulating line*, electromagnetic probe; Γ, diquark correlation amplitude; *double line*, diquark propagator; and χ, seagull terms.

EMFFs of Nucleon

➢The unamputated photon-quark vertex satisfy Ward identity:

$$i(\ell_1-\ell_2)_\mu \chi_\mu(\ell_1,\ell_2) = S(\ell_2) - S(\ell_1)$$



the following Ansatz for the vertex, expressed in terms of quantities already specified in dress quark propagator:

$$\begin{aligned}\chi_\mu(\ell_1,\ell_2) =& \gamma_\mu \Sigma_{\sigma_V} + 2\ell_\mu[\gamma\cdot\ell\Delta_{\sigma_V} + i\Delta_{\sigma_S}] \\ &+ \frac{1}{2}[s_1-\bar{s}_1][\gamma\cdot Q\gamma_\mu\gamma\cdot\ell - \gamma\cdot\ell\gamma_\mu\gamma\cdot Q]\Delta_{\sigma_V} \\ &- [s_2-\bar{s}_2]\sigma_{\mu\nu}Q_\nu\Delta_{\sigma_S} + \frac{i}{2}[1+s_3]\gamma\cdot Q\sigma_{\mu\nu}Q_\nu\Delta_{\sigma_V}\end{aligned}$$

$$\Sigma_F = \frac{1}{2}[F(\ell_1^2)+F(\ell_2^2)]$$

$$\Delta_F = [F(\ell_1^2)-F(\ell_2^2)]/[\ell_1^2-\ell_2^2]$$

$$s_i = a_i + b_i \exp\left[-\frac{1}{4}\mathcal{E}(Q^2)/M_q^E\right],$$

$$\bar{s}_{1,2} = 1 - s_{1,2}$$

$$\mathcal{E}(Q^2)/M_q^E = \left(1+Q^2/[2M_q^E]^2\right)^{1/2} - 1.$$

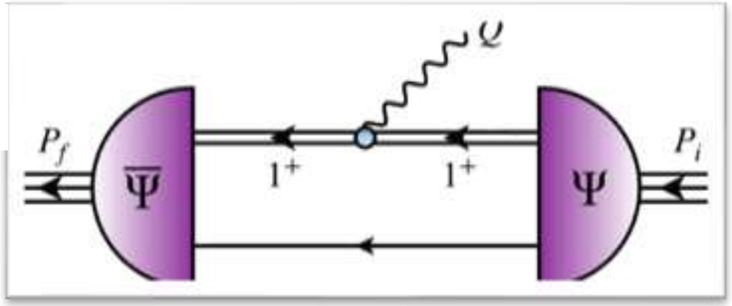
where $\ell = [\ell_1+\ell_2]/2$ and $Q = \ell_1 - \ell_2$.

M. Ding, K. Raya, A. Bashir, D. Binosi, L. Chang, M. Chen, C.D. Roberts, Phys. Rev. D 99, 014014 (2019).

EMFFs of Nucleon

- The photon-diquark vertex satisfy a Ward identity:

$$Q_\mu \chi_\mu^{0^+}(\ell_1,\ell_2) = \left[\Delta^{0^+}(\ell_2^2) - \Delta^{0^+}(\ell_1^2)\right] F_{sc}(Q^2) \quad F_{sc}(Q^2) = \frac{1}{1+\frac{1}{6}r_{sc}^2 Q^2}$$



- The photon- scalar diquark vertex:

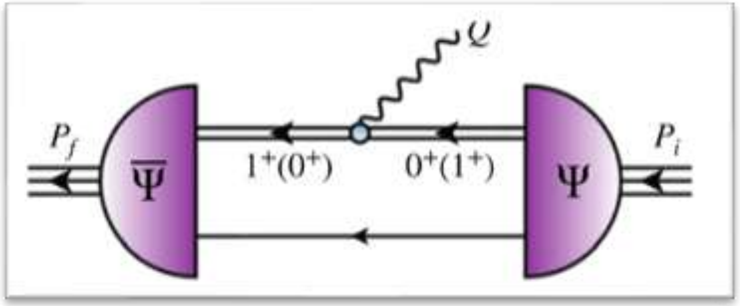
$$\chi_\mu^{0^+}(\ell_1,\ell_2) = -2k_\mu \, \Delta_{\Delta^{0+}}(\ell_1^2,\ell_2^2)\, F_{sc}(Q^2)$$

- The photon- axialvector diquark vertex:

$$\chi_{\mu\alpha\beta}^{1^+}(\ell_1,\ell_2) = -\Big[2\delta_{\alpha\beta}\ell_\mu \Delta_{\Delta^1}(\ell_1^2,\ell_2^2) + \frac{1}{m_{1^+}^2}\left(\delta_{\mu\alpha}\ell_{1\beta}\Delta^1(\ell_1^2) + \delta_{\mu\beta}\ell_{2\alpha}\Delta^1(\ell_2^2)\right)$$
$$+\frac{2}{m_{1^+}^2}\ell_{2\alpha}\ell_{1\beta}\ell_\mu \Delta_{\Delta^1}(\ell_1^2,\ell_2^2)\Big] F_{av}(Q^2) + \kappa(Q_\beta\delta_{\mu\alpha} - Q_\alpha\delta_{\mu\beta})\Delta_{\Delta^1}(\ell_1^2,\ell_2^2)$$

- The photon-scalar-axialvector diquark vertex:

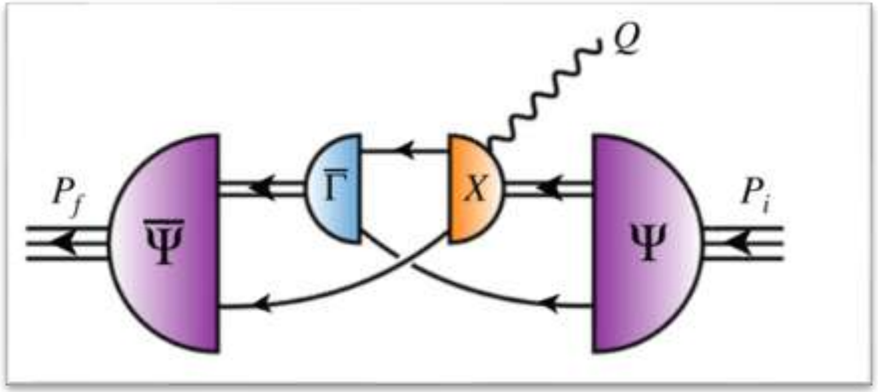
$$\Gamma_{SA}^{\gamma\alpha}(\ell_1,\ell_2) = -\Gamma_{AS}^{\gamma\alpha}(\ell_1,\ell_2) = \frac{i}{M_N}\kappa_{sa}F_{sa}(Q^2)\,\varepsilon_{\gamma\alpha\rho\lambda}\ell_{1\rho}\ell_{2\lambda}$$



EMFFs of Nucleon

➢The coupling of photon to diquark amplitude:

$$X_\mu^{J^P}(k,Q) = e_{\rm by}\frac{4k_\mu - Q_\mu}{4k\cdot Q - Q^2}\left[\Gamma^{J^P}(k-Q/2) - \Gamma^{J^P}(k)\right] + e_{\rm ex}\frac{4k_\mu + Q_\mu}{4k\cdot Q + Q^2}\left[\Gamma^{J^P}(k+Q/2) - \Gamma^{J^P}(k)\right]$$



M. Oettel, M. Pichowsky and L. von Smekal, Eur. Phys. J. A 8, 251-281 (2000)

➢The parameters are chosen by reproducing selected results from 3-body analyses of nucleon elastic electromagnetic form factors:

a_1	a_2	a_3	b_1	b_2	b_3
0.17	1.47	−0.93	1.03	−0.17	1.61
r_{sc}/fm	r_{av}/fm				
0.31	1.05				

Z.-Q. Yao, D. Binosi, Z.-F. Cui, C. D. Roberts, arXiv:2403.08088

EMFFs of Nucleon

Table 2 Calculated results for $Q^2 \simeq 0$ (static) properties of nucleon electromagnetic form factors. Also listed, for comparison, results obtained using the *ab initio* three-body approach [25] and experiment [74, PDG].

		r_E^2/fm^2	$r_E^2 M^2$	r_M^2/fm^2	$r_M^2 M^2$	μ
herein	p	0.67^2	4.02^2	0.67^2	4.02^2	2.80
	n	-0.29^2	-1.73^2	0.72^2	4.30^2	-1.86
[25]	p	0.89^2	4.23^2	0.82^2	3.91^2	2.23
	n	-0.25^2	-1.19^2	0.81^2	3.87^2	-1.33
[74, PDG]	p	0.84^2	4.00^2	0.85^2	4.05^2	2.79
	n	-0.34^2	-1.62^2	0.86^2	4.11^2	-1.91

Magnetic moments:

$$\mu_N = G_M^N(Q^2 = 0).$$

Radii:

$$\langle r_{E,\,M}^2 \rangle^N = -6 \frac{d \ln G_{E,\,M}^N(Q^2)}{dQ^2}\Big|_{Q^2=0}$$

$$\langle r_E^2 \rangle^n = -6 G_E^{n\prime}(Q^2)|_{Q^2=0}$$

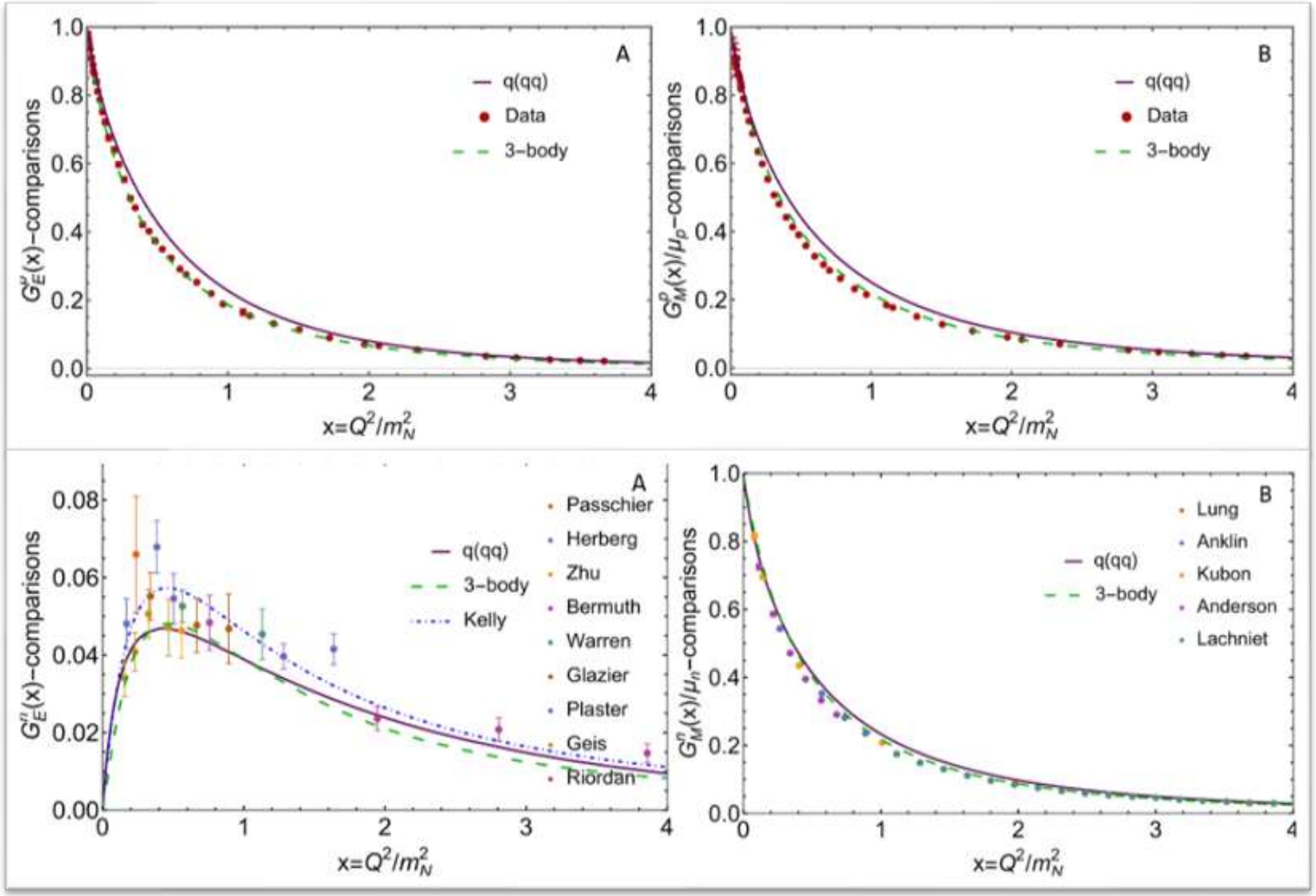
$$r_E^p \approx r_M^p$$

[25] Z.-Q. Yao, D. Binosi, Z.-F. Cui, C. D. Roberts, arXiv: 2403. 08088.

[74] S. Navas, et al., Review of particle physics, Phys. Rev. D 110 (3) (2024) 030001.

P. Cheng, et al., arXiv: 2507.13484

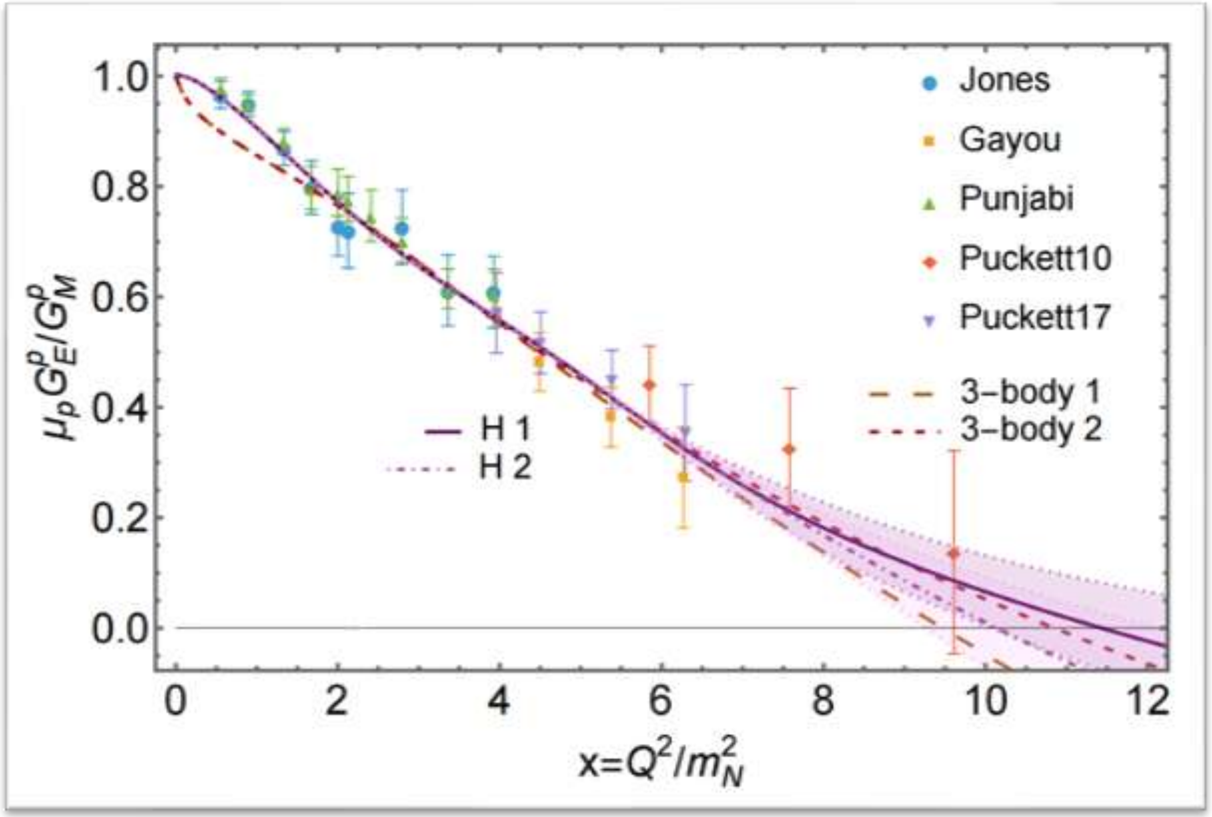
EMFFs of Nucleon



- ✓The agreement is good for $x > 2$.
- ✓For $x < 2$, the differences may stem from the contribution of the meson cloud.

P. Cheng, et al., arXiv: 2507.13484

EMFFs of Nucleon

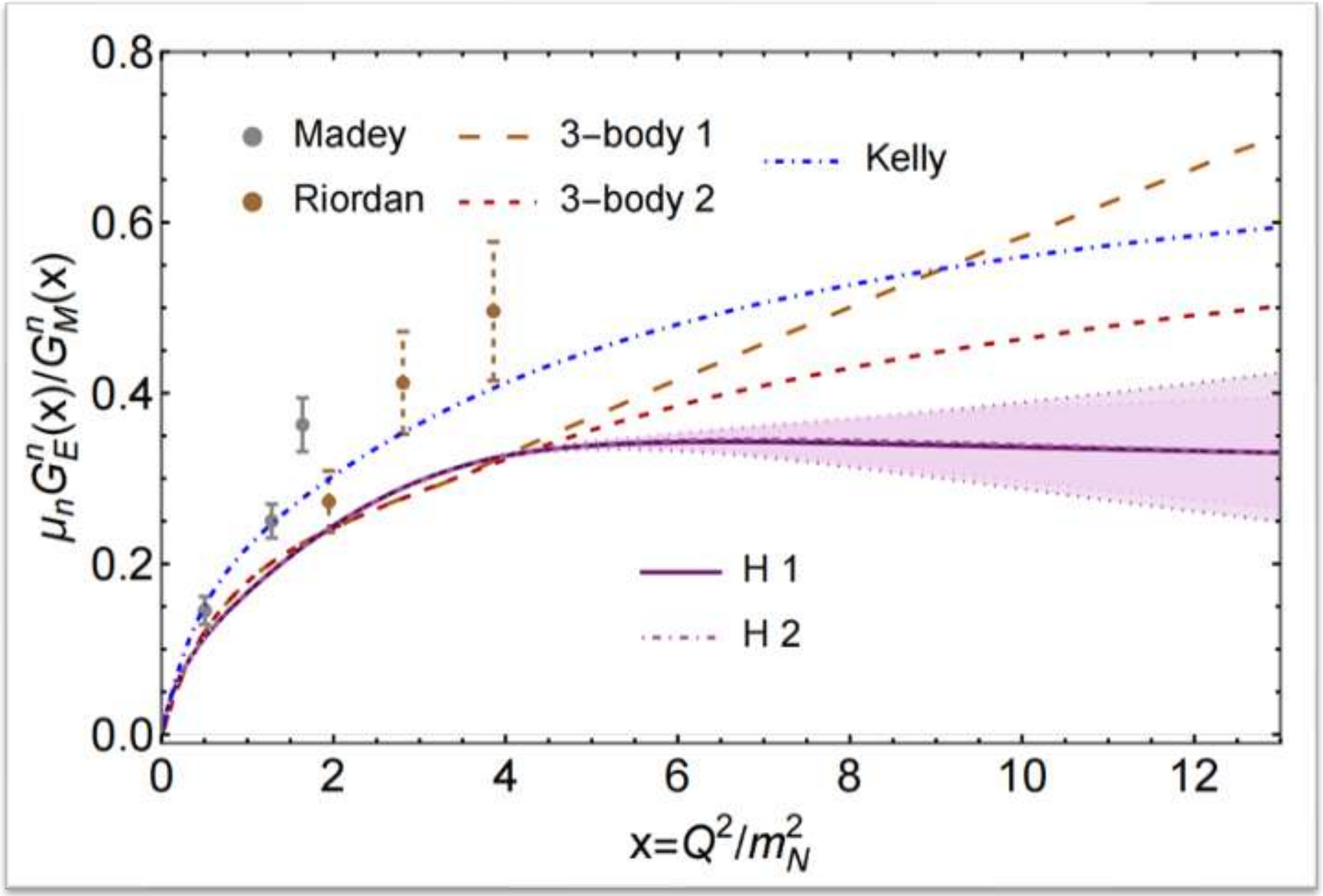


✓ A zero in G_E^p:

	$q(qq)$ herein	$3-\text{body}$
SPM 1	$11.44^{+3.35}_{-1.37}$	$9.47^{+1.90}_{-0.92}$
SPM 2	$10.14^{+1.99}_{-0.88}$	$10.85^{+2.37}_{-0.96}$

P. Cheng, et al., arXiv: 2507.13484

EMFFs of Nucleon



- ✓ The results are consistent with the trend of the experimental data.
- ✓ Regarding comparison with the 3-body analyses, deviations become evident on $x \gtrsim 5$.
- ✓ Finding no zero crossing in G_E^n on $x \lesssim 15$.

P. Cheng, et al., arXiv: 2507.13484

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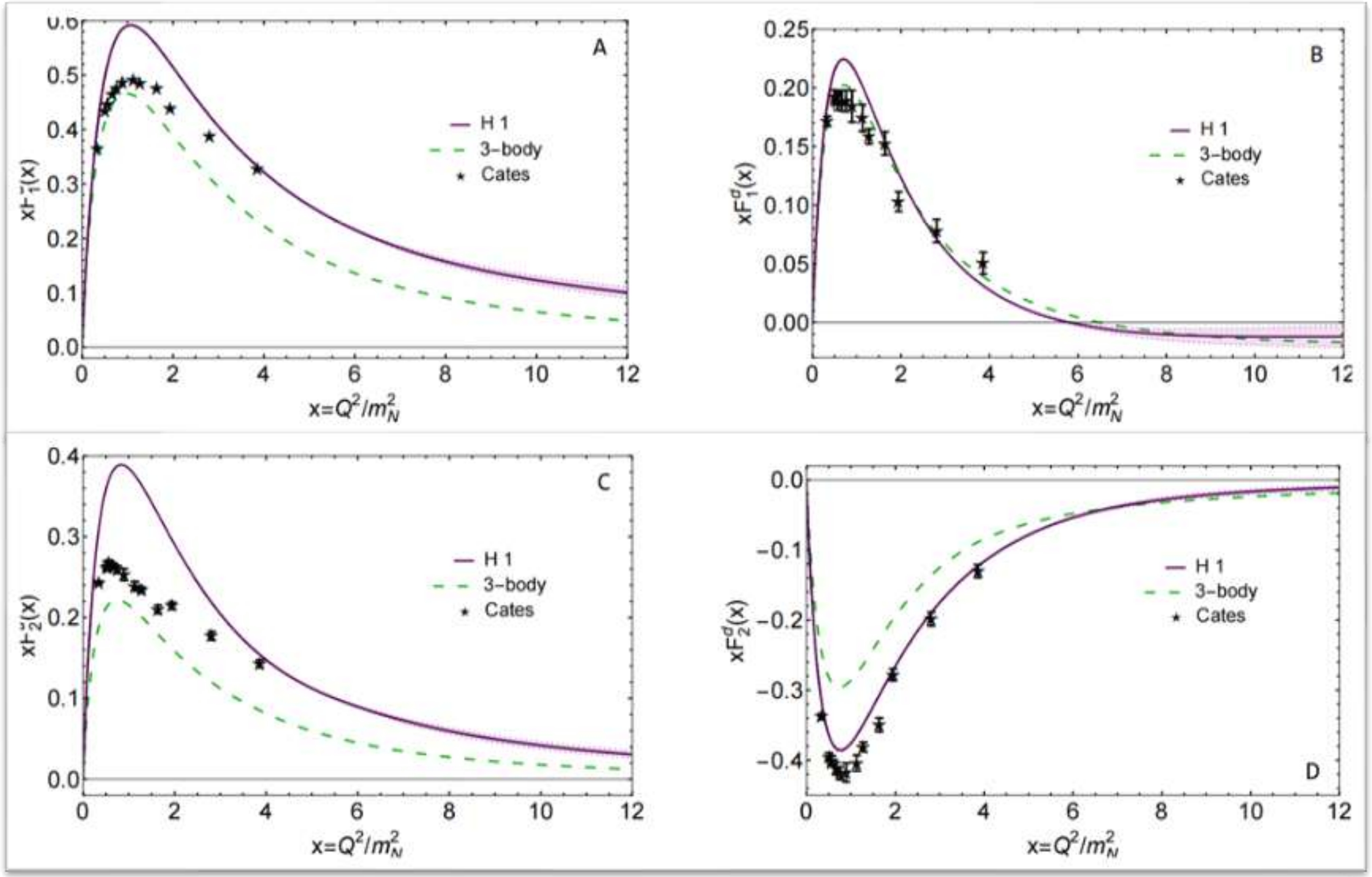
EMFFs of Nucleon



$$F_i^u = 2F_i^p + F_i^n,$$

$$F_i^d = F_i^p + 2F_i^n,$$

- ✓ The analysis predicts that F_1^d exhibits a zero:

$$x = 5.80^{+0.20}_{-0.14}$$

close to 3-body's results:

$$x \approx 6.5$$

- ✓ The analysis predicts that F_2^d doesn't exhibits a zero.

P. Cheng, et al., arXiv: 2507.13484

GFFs of Nucleon

- The total GFFs of nucleon are defined as:

$$\begin{aligned}\langle P_f | T^g_{\mu\nu} | P_i \rangle =& \Lambda^{Ng}_{\mu\nu}(P_f, P_i) \\ =& -\Lambda_+(P_f)\Big[P_\mu P_\nu A(Q^2) + iP_{\{\mu}\sigma_{\nu\}\rho}Q_\rho J(Q^2) \\ &+\frac{1}{4}(Q_\mu Q_\nu - \delta_{\mu\nu}Q^2)D(Q^2)\Big]\Lambda_+(P_i)/m_N\,,\end{aligned}$$

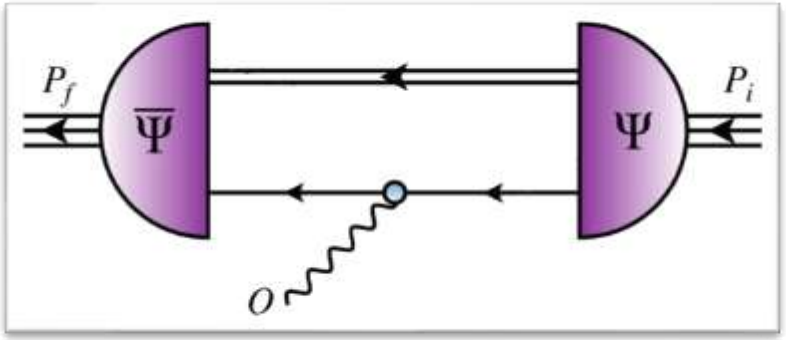
where $a_{\{\mu}b_{\nu\}} = (a_\mu b_\nu + a_\nu b_\mu)/2$, The GFFs $A(Q^2)$ is the nucleon mass distribution form factors; $J(Q^2)$ relates to the nucleon spin distribution; $D(Q^2)$ provides information on pressure and shear forces inside nucleon.

- The interaction current also has six terms:

$$\Lambda^{Ng}_{\mu\nu}(P_f, P_i) = \int \frac{d^4p}{(2\pi)^4}\frac{d^4k}{(2\pi)^4}\sum_{\hat{i}=1}^{6}\bar{\Psi}(p, -P_f)\, J^{\hat{i}}_{\mu\nu}(p, P_f; k, P_i)\,\Psi(k, P_i).$$

GFFs of Nucleon

➢The unamputated graviton-quark vertex:



$$
\begin{aligned}
i\chi^{qg}_{\mu\nu}(\ell_1,\ell_2) = \ell_\nu \Big[& i\gamma_\mu \Sigma_{\sigma V} + 2\ell_\mu \left[i\gamma\cdot\ell \Delta_{\sigma V} - \Delta_{\sigma S} \right] \\
& + \frac{i}{2}[s_1 - \bar{s}_1]\left[\gamma\cdot Q\gamma_\mu\gamma\cdot\ell - \gamma\cdot\ell\gamma_\mu\gamma\cdot Q\right]\Delta_{\sigma V} \\
& - i[s_2 - \bar{s}_2]\sigma_{\mu\rho}Q_\rho\Delta_{\sigma S} - \frac{1}{2}[1+s_3]\gamma\cdot Q\sigma_{\mu\rho}Q_\rho\Delta_{\sigma V} \Big] \\
& - \frac{\delta_{\mu\nu}}{2}\left[S(\ell_1)+S(\ell_2)\right] + i\chi^{qgT}_{\mu\nu}(\ell_1,\ell_2)
\end{aligned}
$$

where $\chi^{qgT}_{\mu\nu}$ represents all possible other transverse structures. It may be determined by solving the iBSE. In doing so, one sees the emergence of isoscalar scalar mesons in the graviton+quark vertex. Duing to the lightest scalar dominates, the following term is used:

$$
\chi^{qgT}_{\mu\nu}(\ell_1,\ell_2) = iS(\ell_1)T_{\mu\nu}(Q)S(\ell_2)P^{\mathbb{S}}_q(Q^2) \qquad P^{\mathbb{S}}_q(t) = \frac{-t r_{\mathbb{S}_q}}{t + m^2_{\mathbb{S}_q}}
$$

where the predicted: $m_{\mathbb{S}_q} = 0.55\text{GeV}$, $r_{\mathbb{S}_q} = 0.193\text{GeV}$

Y. Z. Xu, M. Ding, K. Raya, C. D. Roberts, J. Rodríguez-Quintero and S. M. Schmidt, Eur. Phys. J. C 84, 191 (2024)

GFFs of Nucleon

- The graviton- scalar diquark vertex:

$$\chi^{g,0^+}_{\mu\nu}(\ell_1,\ell_2) = \left[-2\ell_\mu\ell_\nu\,\Delta_{\Delta^{0^+}}(\ell_1^2,\ell_2^2) - \delta_{\mu\nu}\frac{\Delta^{0^+}(\ell_1^2)+\Delta^{0^+}(\ell_2^2)}{2}\right] F_{sc}(Q^2)$$

where the r_{sc} being a parameter: $r_{sc} = 0.74 r_{sc}^{em}$.

Y. Z. Xu, M. Ding, K. Raya, C. D. Roberts, J. Rodríguez-Quintero and S. M. Schmidt, Eur. Phys. J. C 84, 191 (2024)

- The graviton- axialvector diquark vertex:

$$\chi^{g,1^+}_{\mu\nu,\alpha\beta}(\ell_1,\ell_2) = \left[-\ell_\nu\left[\delta_{\alpha\beta}(\ell_1+\ell_2)_\mu\Delta_{\Delta^{1^+}}(\ell_1^2,\ell_2^2) + \frac{1}{m_{1^+}^2}\left(\delta_{\mu\alpha}\ell_{1\beta}\Delta^{1^+}(\ell_1^2) + \delta_{\mu\beta}\ell_{2\alpha}\Delta^{1^+}(\ell_2^2)\right)\right.\right.$$
$$\left.\left. + \frac{1}{m_{1^+}^2}\ell_{2\alpha}\ell_{1\beta}(\ell_1+\ell_2)_\mu\Delta_{\Delta^{1^+}}(\ell_1^2,\ell_2^2)\right] - \delta_{\mu\nu}\frac{\Delta^{1^+}_{\alpha\beta}(\ell_1)+\Delta^{1^+}_{\alpha\beta}(\ell_2)}{2}\right] F_{av}(Q^2)$$

where the r_{ax} being a parameter: $r_{ax} = 0.74 r_{ax}^{em}$.

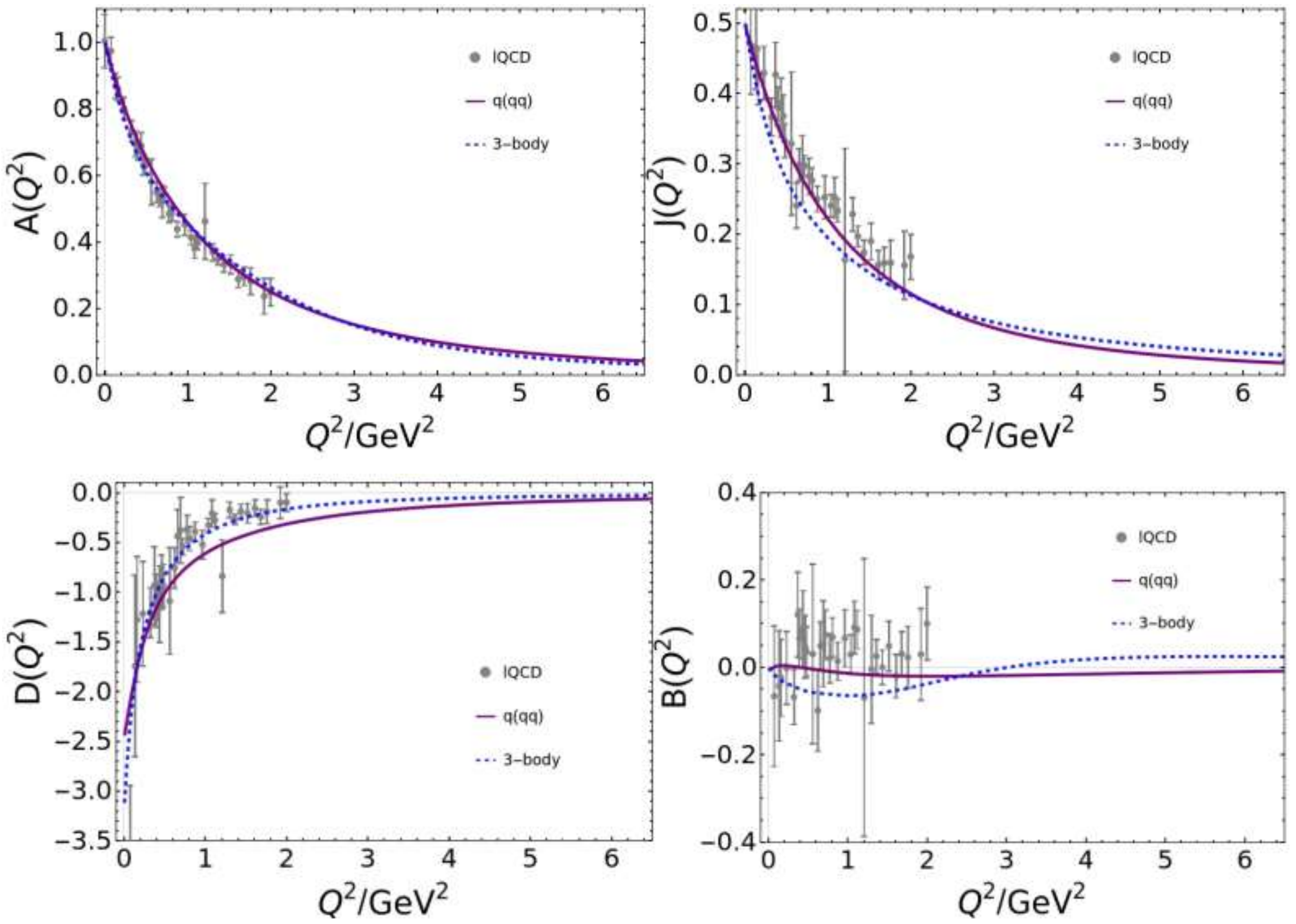
- The coupling of graviton to diquark amplitude:

$$X^{J^P}_{\mu\nu}(\ell;K) = p_{q\nu}\frac{4\ell_\mu - Q_\mu}{4\ell\cdot Q - Q^2}\left[\Gamma^{J^P}(\ell - Q/2;K) - \Gamma^{J^P}(\ell;K)\right]$$
$$+ \frac{4\ell_\mu + Q_\mu}{4\ell\cdot Q + Q^2}\left[\Gamma^{J^P}(\ell + Q/2;K) - \Gamma^{J^P}(\ell;K)\right] q_\nu + \delta_{\mu\nu}\Gamma(\ell;K),$$

M. Oettel, M. Pichowsky and L. von Smekal, Eur. Phys. J. A 8, 251-281 (2000)

where p_q:the bystander quark, q: the exchange quark.

GFFs of Nucleon



- ✓ The predictions of $A(Q^2)$ and $J(Q^2)$ agree with available lQCD results within mutual uncertainties.
- ✓ The magnitude of D term ($D(0)$) is approximately 50% smaller than the results of 3-body and lQCD.

Preliminary

GFFs of Nucleon

$$\langle r^2_{\text{mass}}\rangle = \left[-6\frac{d}{dt}A(t)\Big|_{t=0} - 3\frac{D(0)}{2m_N^2}\right]\frac{1}{A(0)}$$

$$\langle r^2_{\text{mech}}\rangle = \frac{6}{\int_0^\infty dt[D(t)/D(0)]}$$

$$\langle r^2_J\rangle = -20\frac{d}{dt}J(t)\Big|_{t=0}$$

$$\langle r^2_\Theta\rangle = -6\frac{d}{dt}\frac{A(t)}{A(0)}\Big|_{t=0} - \frac{9D(0)}{2m_N^2}$$

Table 2: D-term($D(0)$) and radii for the corresponding nucleon GFFs.(The unit of radii are fm.)

	$q(qq)$	3-body	DR	lQCD(dipole)	lQCD(z-expansion)
D-term	-2.67	$-3.11(1)$	$-3.38^{+0.34}_{-0.35}$	$-3.87(97)$	$-3.35(58)$
$\sqrt{[<r^2_{mass}>]}$	0.65	0.72(4)	$0.70^{+0.03}_{-0.04}$	-	-
$\sqrt{[<r^2_{mech}>]}$	0.51	0.64(2)	$0.72^{+0.09}_{-0.08}$	-	-
$\sqrt{[<r^2_\Theta>]}$	0.88	-	$0.97^{+0.03}_{-0.03}$	-	-
$\sqrt{[<r^2_J>]}$	0.61	-	$0.70^{+0.02}_{-0.02}$	-	-

$$r_E^p \approx r_M^p > r_{mass} > r_{mech}$$

Preliminary

Summary and Outlook

- **Developing a refined symmetry preserving current for electron + nucleon elastic scattering, our $q(qq)$ picture agreement with available data;**
- **We predict a zero in G_E^p at $x = Q^2/m_N{}^2 \approx 11$; the absence of such a zero in G_E^n; a zero at $x \approx 5.8$ in the proton's *d*-quark Dirac form factor.**
- **Within the same framework, the predicted of GFFs $A(Q^2)$ and $J(Q^2)$ agree with available lQCD results, and we predict $r_E^p \approx r_M^p > r_{mass} > r_{mech}$.**

- **We plan to extend the above analysis to nucleon resonances.**
- **Based on the above analysis, we will further consider the contribution of the meson cloud.**

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Thank you for your attention!

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