

Confronting Near-Threshold Charmonium Photoproduction with First Principles



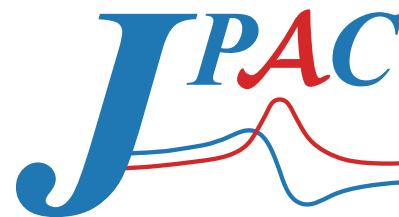
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Physics with High Luminosity Facilities

Jefferson Lab

05 October 2026



Instituto de Ciencias Nucleares **UNAM**



A physics-rich process

Gravitational form factors

Mamo & Zahed [Phys. Rev. D 101, 086003 (2020)]

Guo, Ji & Liu [Phys. Rev. D 103, 096010 (2021)]

Mass radius

Kharzeev [Phys. Rev. D 104, 054015 (2021)]

Mamo & Zahed [Phys. Rev. D 103, 094010 (2021)]

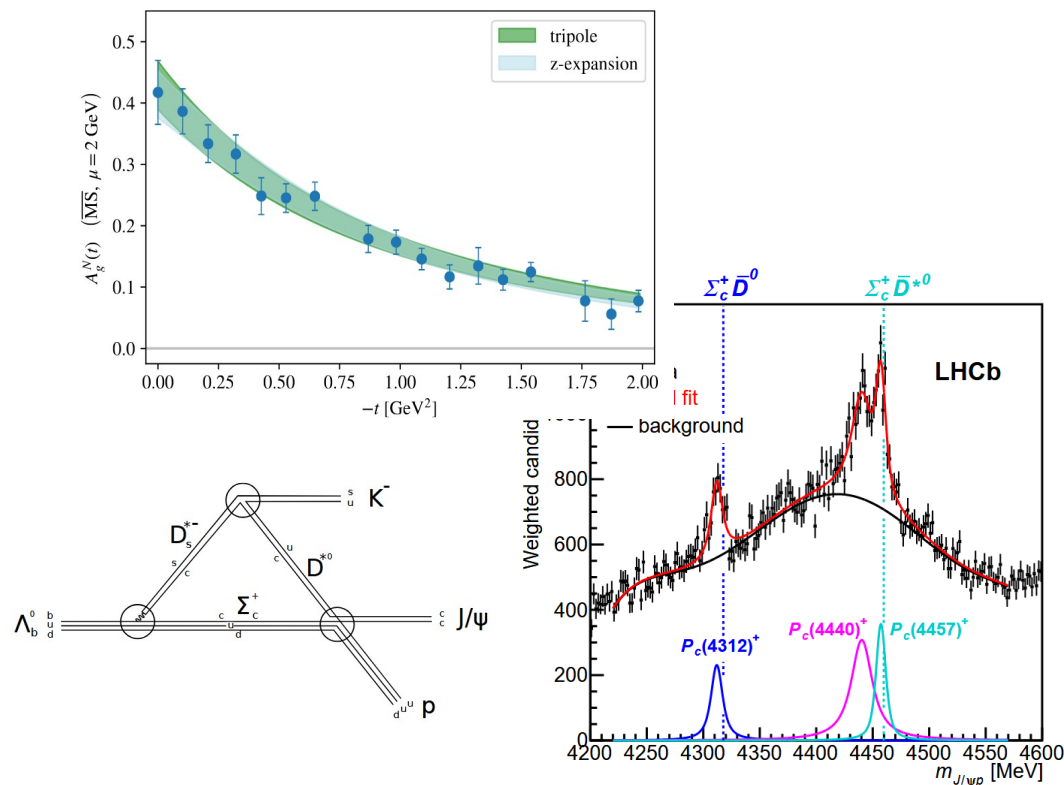
QCD Trace anomaly

Wang, Chen, & Evslin [Eur.Phys.J.C 80 (2020) 6, 507]

Hatta & Yang [Phys. Rev. D 98, 074003 (2018)]

Signal channel for the LHCb pentaquarks in exclusive final state (**avoids triangle singularities**).

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



LHCb [Phys. Rev. Lett. 122 (2019) 22, 222001]

... with many bold claims

nature

Article | Published: 29 March 2023

Determining the gluonic gravitational form factors of the proton

[B. Duran](#), [Z.-E. Meziani](#) , [S. Joosten](#), [M. K. Jones](#), [S. Prasad](#), [C. Peng](#), [W. Armstrong](#), [H. Atac](#), [E. Chudakov](#), [H. Bhatt](#), [D. Bhetuwal](#), [M. Boer](#), [A. Camsonne](#), [J.-P. Chen](#), [M. M. Dalton](#), [N. Deokar](#), [M. Diefenthaler](#), [J. Dunne](#), [L. El Fassi](#), [E. Fuchey](#), [H. Gao](#), [D. Gaskell](#), [O. Hansen](#), [F. Hauenstein](#), ... [Z. Zhao](#) [+ Show authors](#)

[Nature](#) **615**, 813–816 (2023) | [Cite this article](#)

Experimental Access to the Gluonic Origin of the Proton Mass

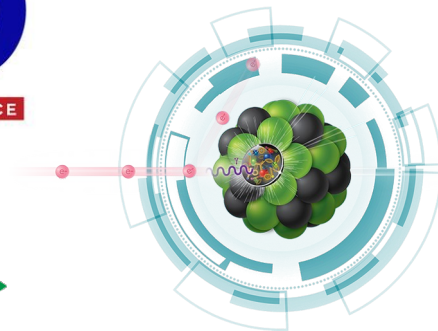
Zein-Eddine Meziani¹ and Ismail Zahed²

[arXiv:2607.07969]

Nucleon Strong-Interaction Size From Charmonium Photoproduction

Xiangdong Ji^{1,2}, Sylvester Joosten³, Zein-Eddine Meziani^{3*}, Dimitra A. Pefkou^{4,5,6}

[arXiv:2609.09318]



Flagship measurement for current
and future experiments

Things which are not first principles:

- **QCD Factorization (GPD formalism):** with no factorization theorem in this process, we cannot rigorously justify a separation of perturbative and non-perturbative dynamics.
- **QCD Holography:** no rigorous correspondence between strongly coupled, non-conformal, three-color QCD and higher dimensional gravity.
- **Heavy meson loops:** HQEFT arguments not rigorously justifiable in production kinematics.
- **Breit-Wigner Pentaquarks:** existence of pentaquarks not fully established and even if it were no reason they should be BWs on a smooth background.

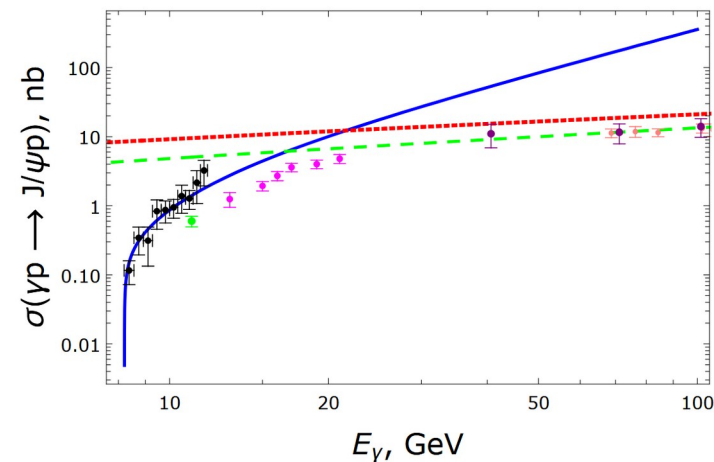
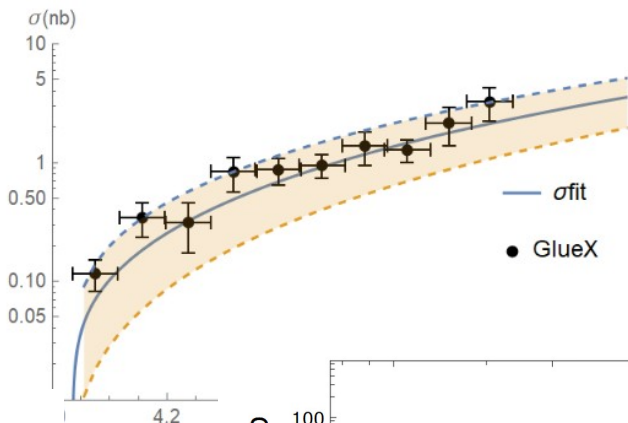
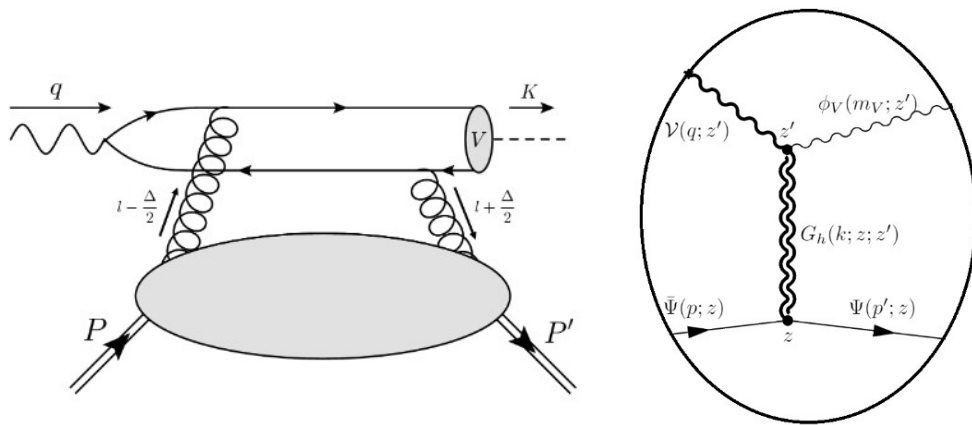
These are *models* and may still yield valuable insight into dynamics but need to be tested.

To gain meaningful understanding, our models should...

- **rely (as much as possible) on first principles.**
- **be consistent with available measurements.**
- **make non-trivial predictions (and be corroborated by future measurement).**

Status of Current Data

New measurements by JLab are well described by GPD and Holographic QCD models which claim **direct experimental access to fundamental proton structure!**



Mamo & Zahed [Phys. Rev. D 101 (2020) 8, 086003]

Status of Current Data

New measurements by JLab are well described by GPD and Holographic QCD models which claim **direct experimental access to fundamental proton structure!**

As well as models including unitarity corrections, coupled channel contributions, t-channel meson exchanges, etc. **which don't.**

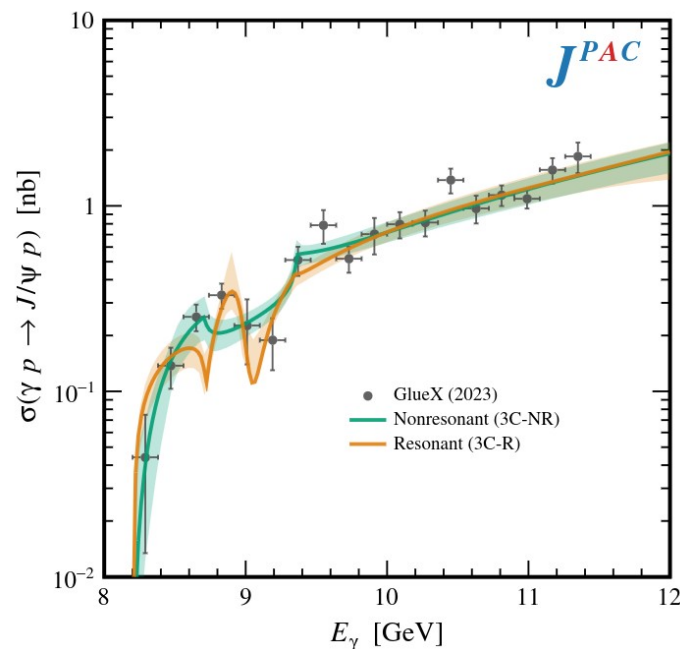
See also:

JPAC [Phys.Rev.D 100 (2019) 3, 034019]

Du et al. [Eur.Phys.J.C 80 (2020) 11, 1053]

Tang et al. [Eur.Phys.J.C 86 (2026) 3, 284]

JPAC [Phys.Rev.D 108 (2023) 5, 054018]



Zhang [Eur.Phys.J.C 85 (2025) 10, 1120]

Clymton et al. [arXiv:2606.11808]

Kim [Phys.Lett.B 868 (2025) 139725]

Duan et al. [arXiv:2409.10364]

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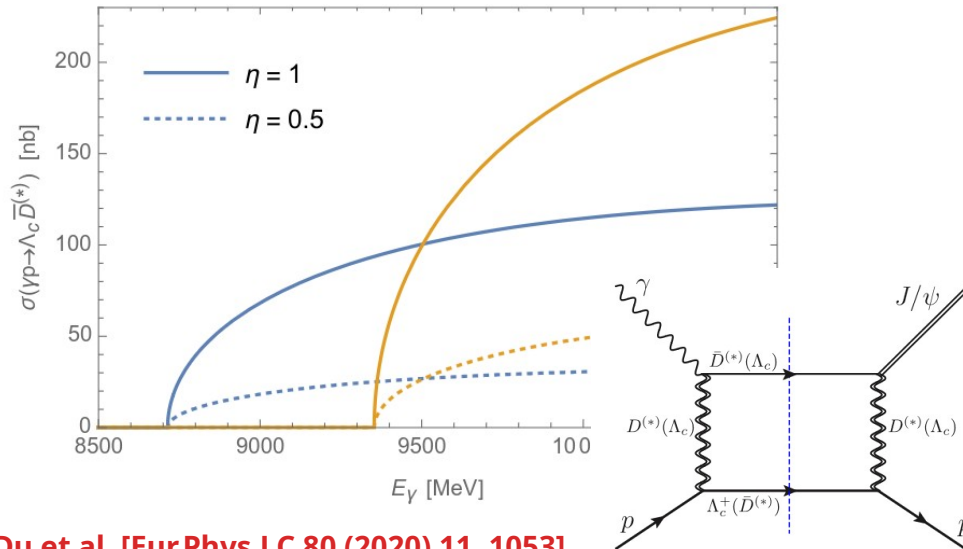
- rely (as much as possible) on first principles.
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Status of Current Predictions

From open-charm models:

Open charm production cross sections should be large and **prominent cusps**.
Experimentally challenging but upper bounds soon (?)

From GFF models:



Du et al. [Eur.Phys.J.C 80 (2020) 11, 1053]

To gain meaningful understanding, our models should...

- rely (as much as possible) on first principles.
- **be consistent with available measurements.**
- ~~make non-trivial predictions (and be corroborated by future measurement).~~

Let me help you brainstorm...

Polarization observables such as spin-density matrix elements highly constrain exchange physics and are accessible (with currently limited statistics) at GlueX.

Can be used to disentangle **t-channel exchanges**

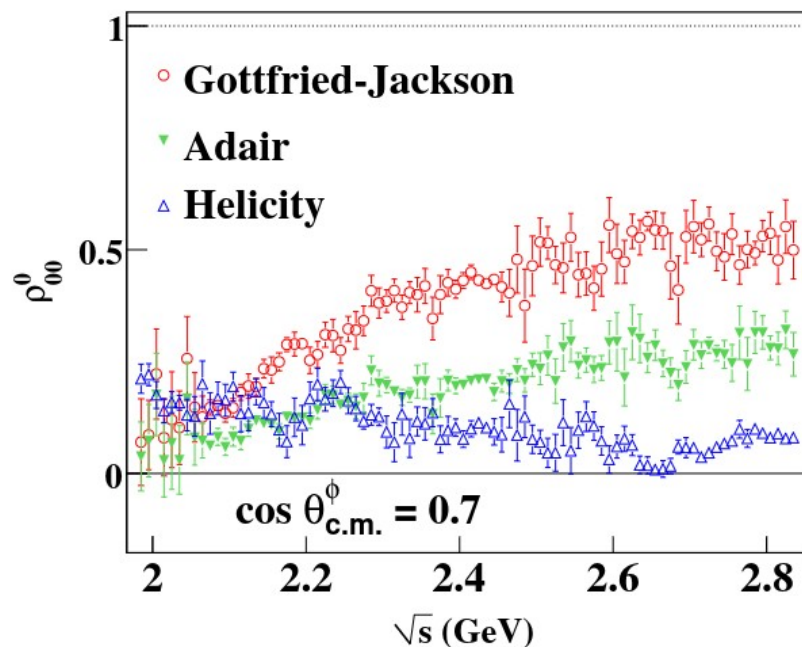
Schilling, Seyboth, & Wolf [Nucl.Phys.B 15 (1970) 397-412]

JPAC [Phys.Rev.D 97 (2018) 9, 094003]

if $F_{\gamma p \rightarrow \psi p} \propto (\epsilon_\gamma \cdot \epsilon_\psi)$ we have TCHC:

$$\rho_{\lambda\lambda'}^\alpha = 0 \quad \text{except} \quad \rho_{1-1}^1 = -\text{Im} \rho_{1-1}^2 = \frac{1}{2}$$

Huge violations of TCHC already observed in ϕ photoproduction!



CLAS [Phys.Rev.C 89 (2014) 5, 055208]

Typical dynamical assumptions

- **Vector meson dominance:**

$$F_{\gamma p \rightarrow \psi p} \propto g_{\gamma\psi} T_{\psi p \rightarrow \psi p}$$

Strakovsky et al [Phys. Rev. D 113 (2026) 11, 114023]

$$F_{\gamma p \rightarrow \psi p} \propto \phi^*(0) (\epsilon_\gamma \cdot \epsilon_V) G(t, \xi)$$

Guo et al. [Phys.Rev.D 108 (2023) 3, 034003]

- **Amplitude is real-valued:**

if amplitude isn't real, the gravitational form factors aren't either (and won't match lattice)

- **Dominated by finite number of t-channel exchanges:**

required to identify form factors with scalar or tensor gluonic currents

- **Trivial helicity dependence (TCHC and/or SCHC):**

typically assumed from factorization assumption which is taken as axiom

EHM Measurements

How does the mass of the nucleon arise?

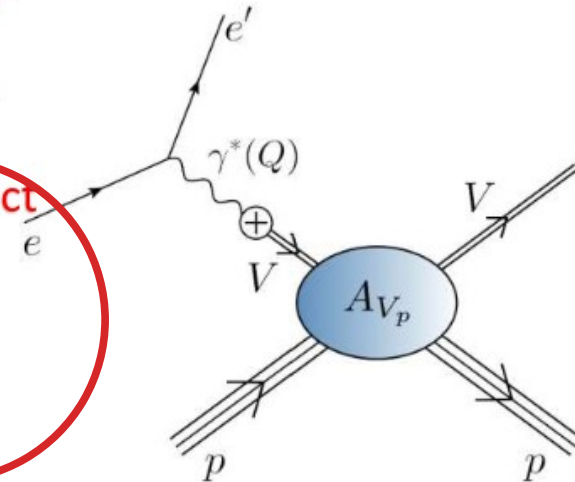
➤ Once considered viable ...

Electromagnetic process ($V = J/\psi, \Upsilon$) ... $e + p \rightarrow e' + V + p$
to access purely hadronic process ... $V + p \rightarrow V + p$

➤ But ...

- *Deciphering the mechanism of near-threshold J/ψ photoproduction*, M.-L. Du, V. Baru, F.-K. Guo *et al.*, Eur. Phys. J. C **80**, 1053 (2020)
- *Vector-meson production and vector meson dominance*, Yin-Zhen Xu, Si-Yang Chen, Zhao-Qian Yao *et al.*, Eur. Phys. J. C **81** (2021) 895/1-11
- *Near threshold heavy quarkonium photoproduction at large momentum transfer*, P. Sun, X.-B. Tong, F. Yuan, Phys. Rev. D **105** (2022) 5, 054032

- There is no objective, model-independent means by which to connect $e + p \rightarrow e' + V + p$ with $V + p \rightarrow V + p$
- Hence, vector meson photoproduction does not provide a path to the QCD trace anomaly (or anything else)



Scattering 101

Analyticity and **crossing symmetry** impose strict constraints on the structure of scattering amplitudes.

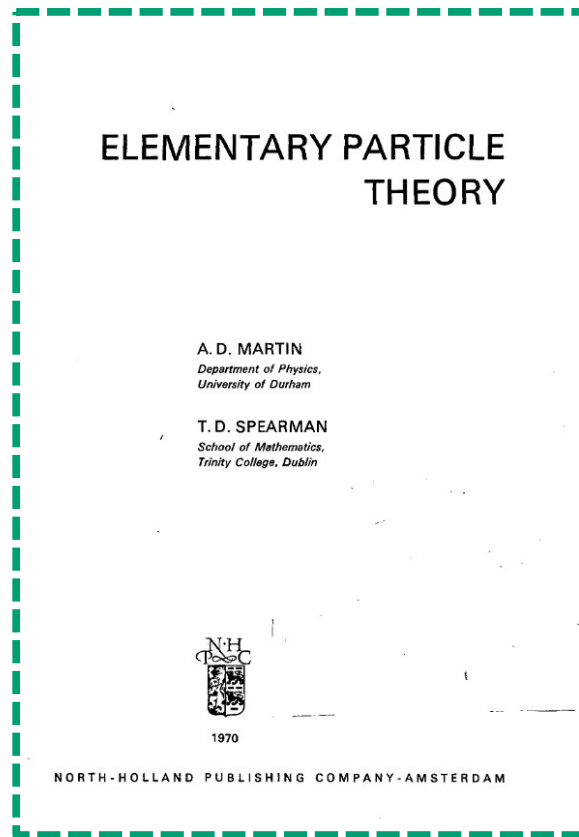
Martin & Spearman [Ch. 7 & 8]

$$\langle \lambda_\psi \lambda_f | F | \lambda_\gamma \lambda_i \rangle = \sum_{J=M_s}^{\infty} (2J+1) d_{\lambda\lambda'}^J(\theta_s) \langle \lambda_\psi \lambda_f | F_J | \lambda_\gamma \lambda_i \rangle$$

Near-threshold, the partial waves behave as:

$$\langle \lambda_\psi \lambda_f | F_J | \lambda_\gamma \lambda_i \rangle \propto q^{L_i} p^{L_f}$$

First principles justify a systematically improvable truncation of partial-wave series in the **s-channel** with **no arbitrary form factors of t** .

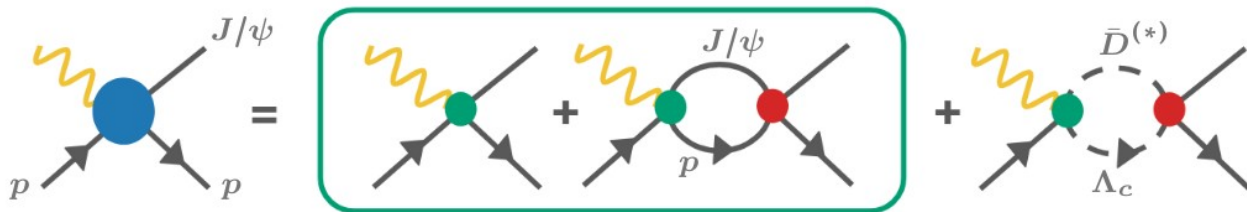


Scattering 101

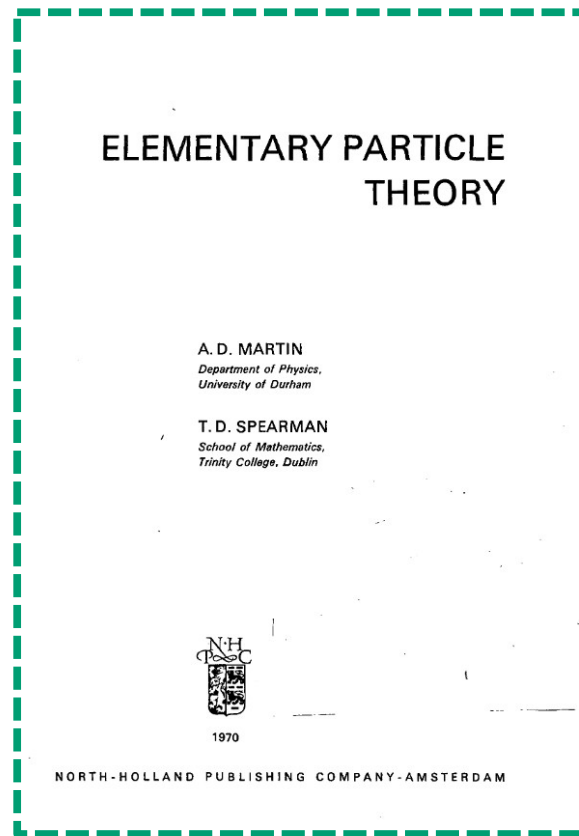
The “objective, model-independent” means by which to connect production and elastic reactions is **unitarity**

Martin & Spearman [Ch. 4.5 & 8]

$$\text{Im} \langle \lambda_\psi \lambda_f | F_J | \lambda_\gamma \lambda_i \rangle = \sum_{\lambda'_\psi \lambda'_f} \rho \langle \lambda_\psi \lambda_f | T_J^\dagger | \lambda'_\psi \lambda'_f \rangle \langle \lambda'_\psi \lambda'_f | F_J | \lambda_\gamma \lambda_i \rangle$$



Photoproduction amplitudes are **essentially complex** with an imaginary part determined by **hadronic rescattering**.



Let's test some claims!

Model claim: Amplitudes are approximately real and have a VMD-like structure.

First principles: s-channel partial wave expansion, analyticity, and unitarity

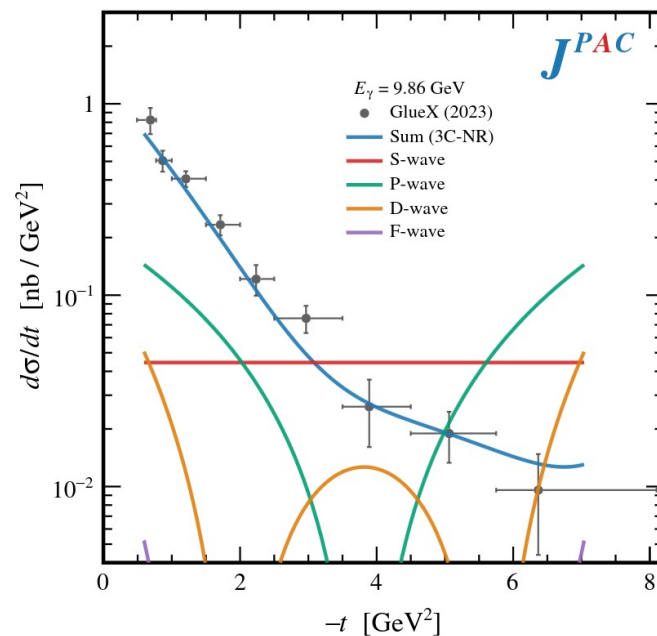
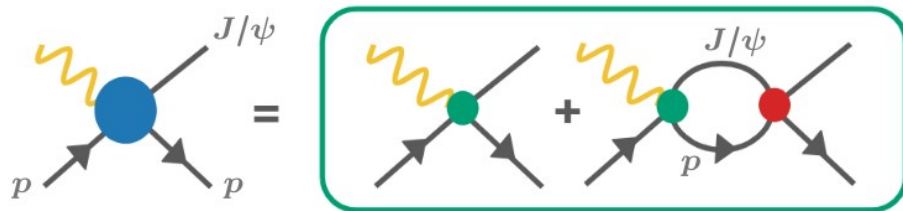
Systematically-improvable, first-principles-constrained model:

$$\mathcal{F}(s, \cos \theta_s) = \sum_{\ell=0}^{\ell_{\max}} (2\ell + 1) P_{\ell}(\cos \theta_s) F_{\ell}(s)$$

$$F_{\ell}(s) = (pq)^{\ell} n_{\ell} [1 + i\rho T_{\ell}(s)]$$

$$T_{\ell}(s) = K_{\ell} [1 - i\rho K_{\ell}]^{-1}$$

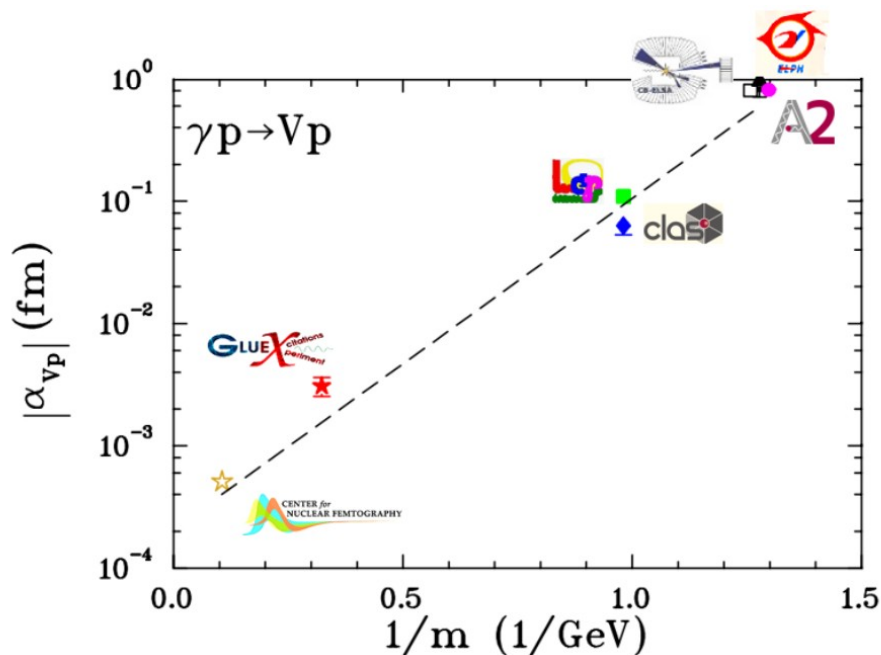
Martin & Spearman [Ch. 8.3]



J^{PAC} [Phys.Rev.D 108 (2023) 5, 054018]

Puzzle for Vector Meson Threshold Production?

Yes, why we continue to quote VMD-based “extractions” as meaningful...



Strakovsky [PoS HADRON2025 (2026) 025]

Even if coupled-channel effects are zero,

$$R_{\text{VMD}} = \left| \frac{a_{\psi p}^{\text{VMD}}}{a_{\psi p}} \right| = [1.3, 2.0] \times 10^{-2}$$

JPAC [Phys.Rev.D 108 (2023) 5, 054018]

Unitarity corrections are very important!

Amplitudes are not real functions and assuming they are accounts for **two orders of magnitude discrepancy** at 90% CL near-threshold.

A similar (or worse) discrepancy expected in the “extraction” of *real* gravitational form factors.

J/psi p total cross section

Total cross section sensitive to the size of unitarity corrections via the **optical theorem**.

$$\sigma_{\text{tot}}^{\psi p} = \frac{1}{2q\sqrt{s}} \text{Im } T_{\psi p}(s, t = 0)$$

Martin & Spearman [Ch. 4.5]

If photoproduction amplitudes are real, we should expect highly suppressed total cross section and yet...

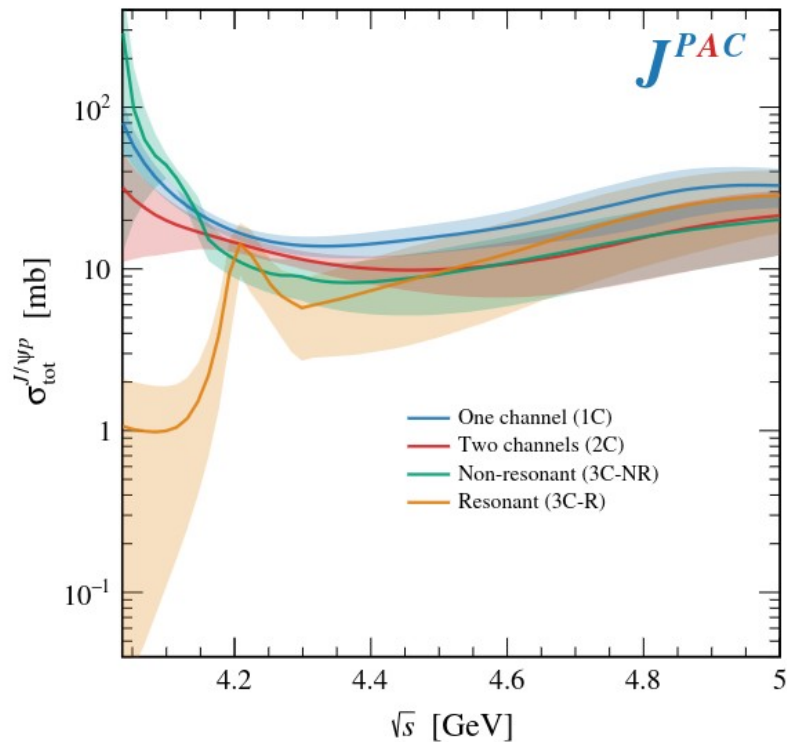
$$\sigma_{\text{tot}}^{\psi p} \simeq 3.5 \pm 0.8 \text{ mb at } \sqrt{s} \simeq 6 \text{ GeV}$$

Anderson et al. [Phys.Rev.Lett. 38 (1977) 263]

For reference:

$$\sigma_{\text{tot}}^{\pi^- p} \simeq 30 \text{ mb at } \sqrt{s} \simeq 6 \text{ GeV}$$

[PDG 2022]



JPAC [Phys.Rev.D 108 (2023) 5, 054018]

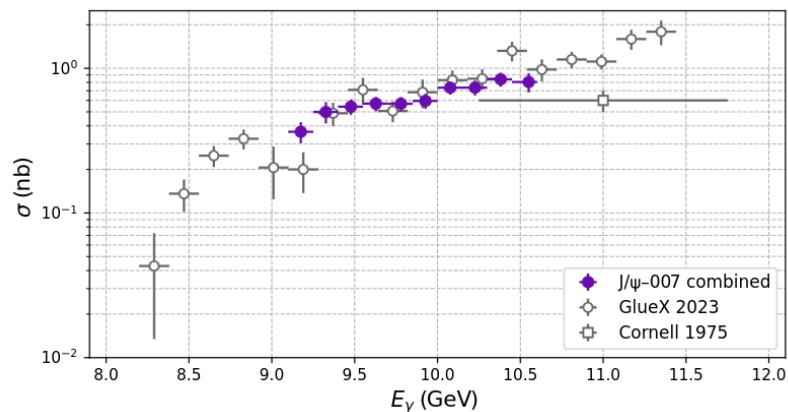
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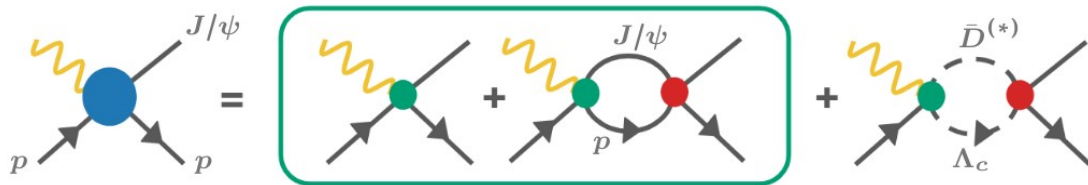
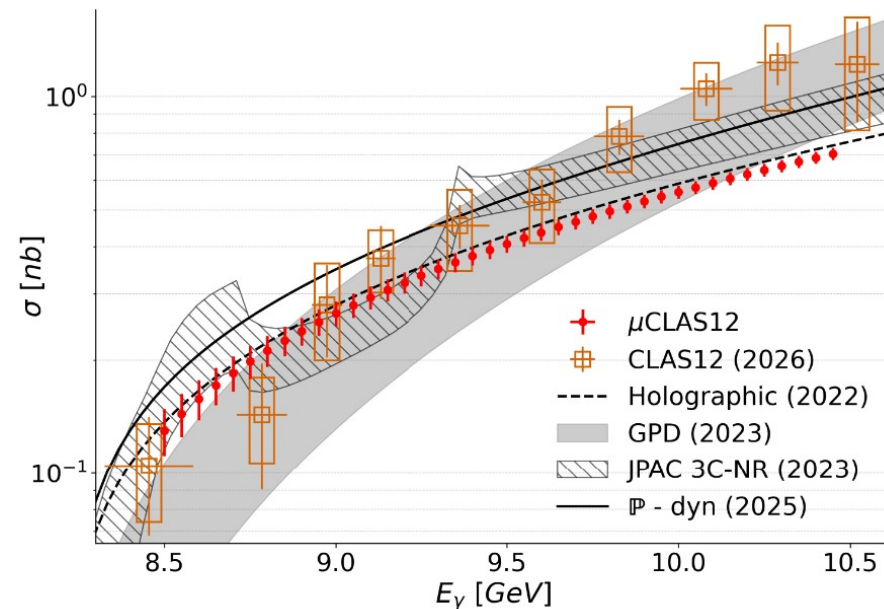
Coupled channel contributions

All current measurements still consistent with unitary model consistent with dominance of **open charm** intermediate state.

J/ψ -007 [arXiv:2602.14416]



CLAS [Eur.Phys.J.A 62 (2026) 8, 157]



In progress: more tests!

Model claim: A spin-0 and/or spin-2 exchange in t-channel is a good approximation.

First principles: s-channel partial wave expansion, analyticity, and unitarity + crossing

Under-construction systematically-improvable, first-principles-constrained model:

Reanalysis including full spin degrees of freedom to relate s-channel expansion to the t-channel.

$$\mathcal{F}_{\{\lambda\}}(s, \cos \theta_s) = \sum_{J=M_s}^{J_{\max}} (2J+1) d_{\lambda\lambda'}^J(\theta_s) F_{\{\lambda\}}^J(s)$$

$$\mathcal{G}_{\{\mu\}}(t, \cos \theta_t) = \sum_{\{\lambda\}} \mathbb{C}_{\{\mu,\lambda\}}(s,t) \mathcal{F}_{\{\lambda\}}(s, \cos \theta_s)$$

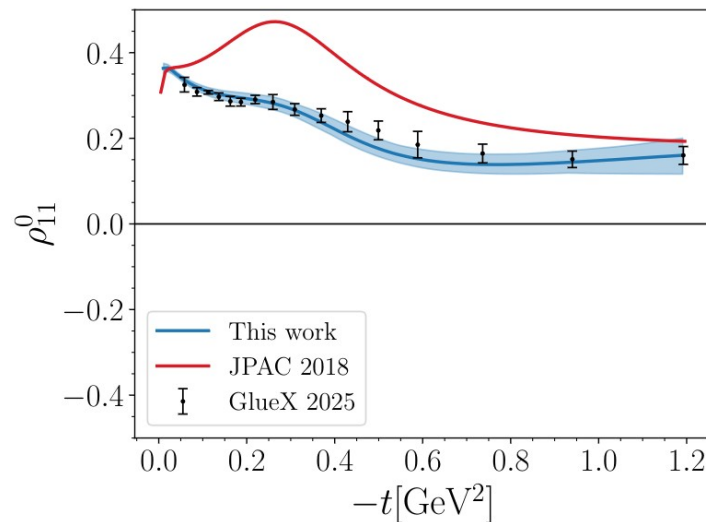
Martin & Spearman [Ch. 7.2]

Polarization observables needed for robust constraints on helicity amplitudes!

See e.g. JPAC [arXiv:2604.22719]

Also see t-channel spin re-summation analysis in holography.

Mamo, Tezgin, & Weiss [arXiv:2607.25099]



Conclusions

- Need to re-evaluate how we, as a community, discuss J/ψ **photoproduction near threshold**, especially as we plan for future experiments.
- Need thorough and measured examination of **model assumptions and uncertainties** in theory models with a focus on **non-trivial predictions** to validate claims.
- Need to identify observables and experimental measurements to differentiate and test models (feasibility of **polarization observables?**).

Thank you!

Backups

“But we’re consistent with lattice!”

Construct a model inspired by EMT but with **explicit gauge invariance**

$$\langle P' | T_g^{\mu\nu} | P \rangle = \bar{u}(P') \left[A_g(t) \gamma^{(\mu} \bar{P}^{\nu)} + C_g(t) \frac{\Delta^\mu \Delta^\nu - g^{\mu\nu} \Delta^2}{m_N} \right] u(P)$$

Subset of complete basis of covariant structures which generate 12 helicity amplitudes.

Parsons & B. Manny [Annals Phys. 80 (1973) 387-396]

Analogous to the Chew-Goldberger-Low-Nambu (CGLN) basis in pion photoproduction.

Chew et al. [Phys.Rev. 106, 1345 (1957)]

$$l_4^{\mu\nu} = g^{\mu\nu} \not{q} - q^\mu \gamma^\nu$$

$$l_2^{\mu\nu} = (q' \cdot q) g^{\mu\nu} - q^\mu q'^\nu$$

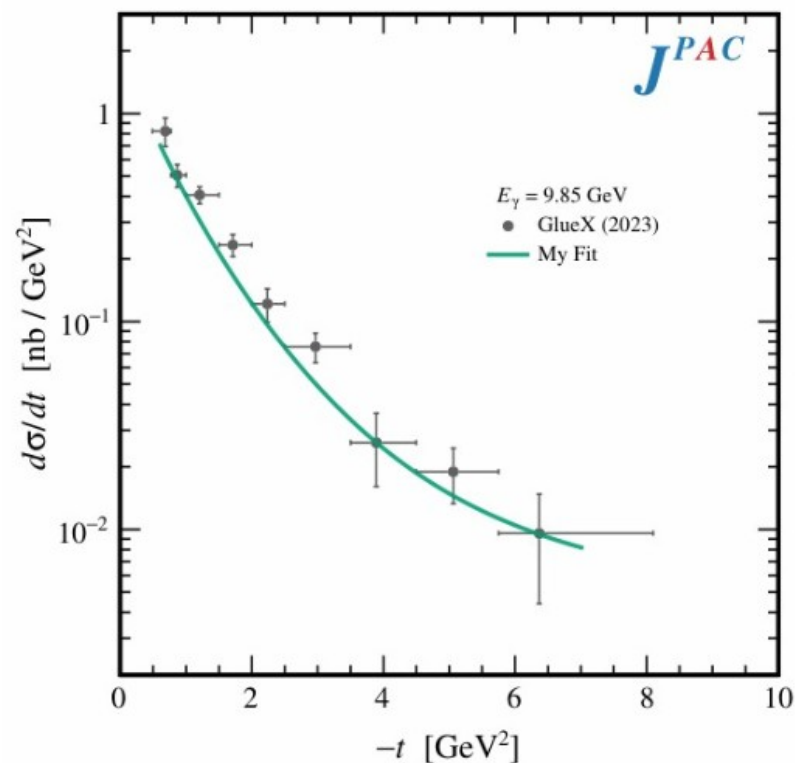
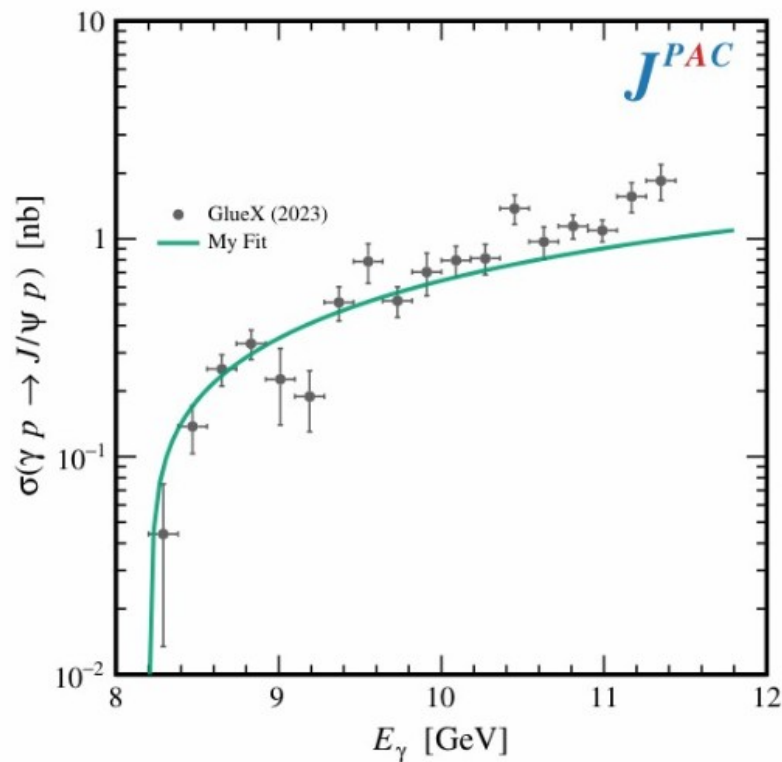
$$\mathcal{M}_{\{\lambda\}} = \bar{u}(p', \lambda_{p'}) \epsilon_\mu^*(q', \lambda_\psi) [l_4^{\mu\nu} N_A A_g(t) + l_2^{\mu\nu} N_C C_g(t)] \epsilon_\nu(q, \lambda_\gamma) u(p, \lambda_p)$$

Relative normalizations fixed by simply comparing kinematic factors to GPD model.

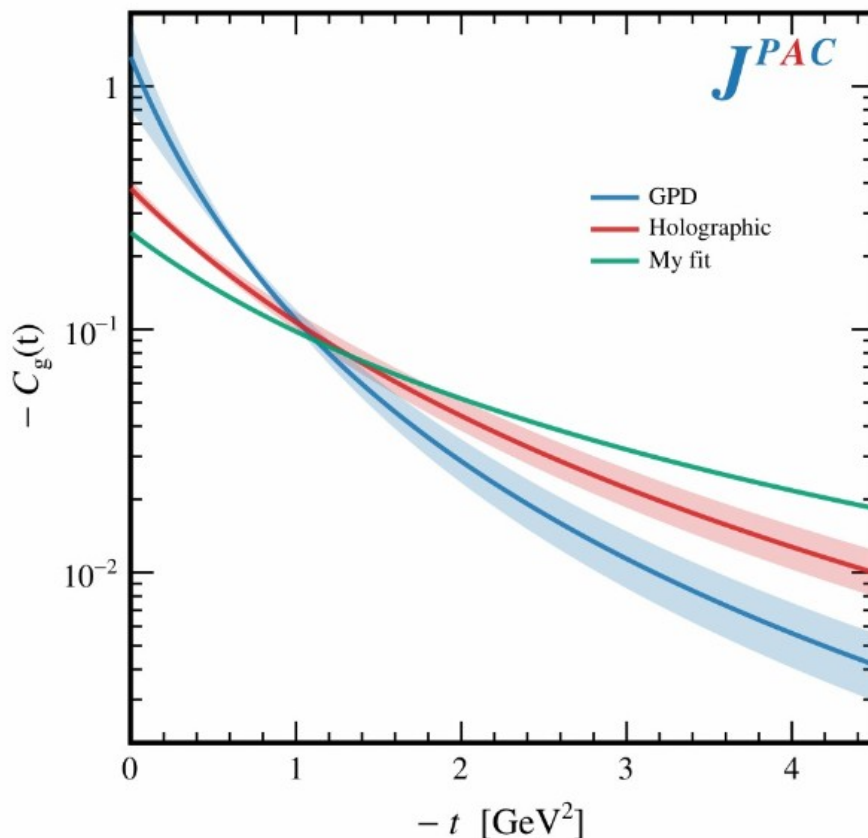
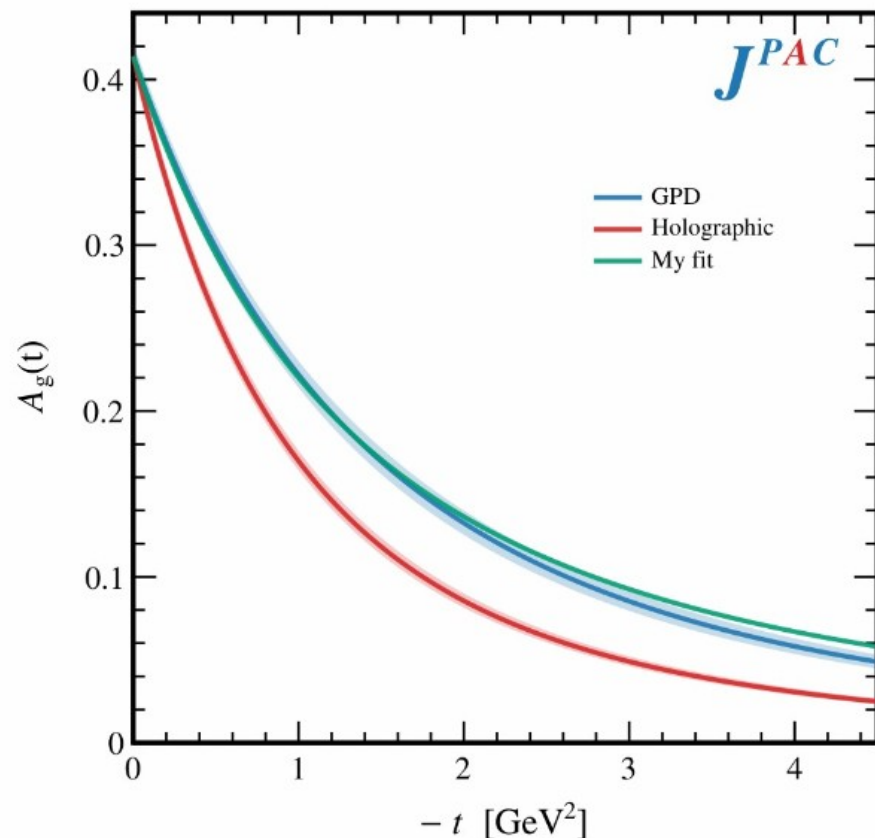
“But we’re consistent with lattice!”

Fix $A(0) = 0.414$ and fit $C(0), m_A, m_C$.

$\chi^2/\text{dof} = 2.2$



“But we’re consistent with lattice!”



Holographic and GPD fits & error bands from CLAS [Phys.Rev.C 113 (2026) 6, 6]

“But we’re consistent with lattice!”

$$\mathcal{M}_{\{\lambda\}} = \bar{u}(p', \lambda_{p'}) \epsilon_{\mu}^*(q', \lambda_{\psi}) [l_4^{\mu\nu} N_A A_g(t) + l_2^{\mu\nu} N_C C_g(t)] \epsilon_{\nu}(q, \lambda_{\gamma}) u(p, \lambda_p)$$

We can simply evaluate in the **t-channel frame** and see what spins contribute:

$$\mathcal{M}_{\{\mu\}}(t, \theta_t) = d_{\mu_{\gamma} - \mu_{\psi}, \mu_p - \mu_{p'}}^1(\theta_t) \left[K_{\{\mu\}}^A(t) N_A A_g(t) + K_{\{\mu\}}^C(t) N_C C_g(t) \right]$$

$$K_{\{\mu\}}^A(t) = \begin{cases} 2 m_N q_t & \mu_{\gamma} = \mu_{\psi}, \mu_p = \mu_{p'} \\ q_t \sqrt{t} & \mu_{\gamma} = \mu_{\psi}, \mu_p = -\mu_{p'} \\ -\sqrt{2} q_t \sqrt{t} \frac{m_N}{m_{\psi}} & \mu_{\psi} = 0, \mu_p = \mu_{p'} \\ \frac{q_t \sqrt{t}}{\sqrt{2} m_{\psi}} & \mu_{\psi} = 0, \mu_p = -\mu_{p'} \end{cases} \quad K_{\{\mu\}}^C(t) = 2 q_t p_t \sqrt{t} \delta_{\mu_{\gamma}, \mu_{\psi}} \delta_{\mu_p, \mu_{p'}}$$

This model is purely spin-1 (nothing to do with the energy-momentum tensor)!

Extraction of same form factors from entirely unrelated model demonstrates coincidence with lattice calculations is not a meaningful validation of GPD/Holographic GFFs.