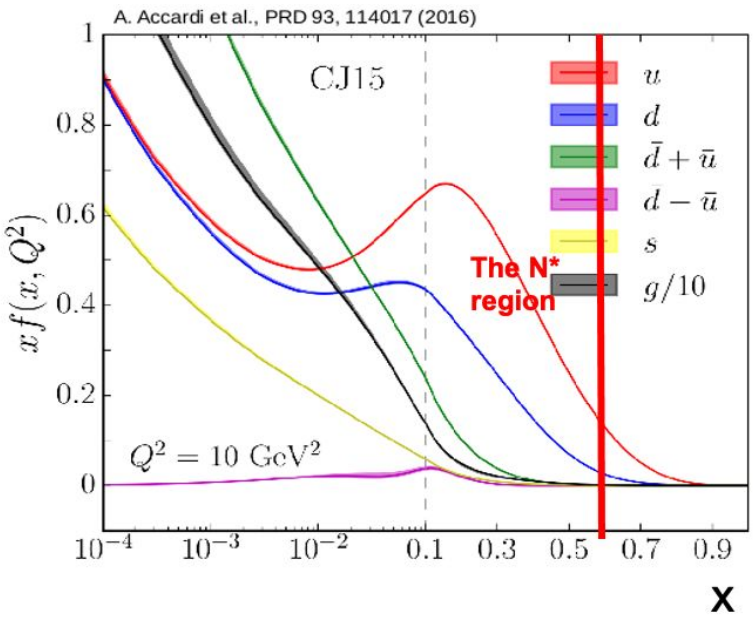
Resonance contributions to polarized structure functions in inclusive electron scattering

Speaker: Bogdan Fadeenko
Physics Department at Moscow State U.(MSU)
In collaboration with: Evgeny L. Isupov and Anna A. Rusova, MSU
Victor I. Mokeev, Hall B at JLab & USC
Wally Melnitchouk, JLab Theory Center
Cezar Fernandez-Ramirez, JPAC
Sebastian Kuhn, CLAS DPW
Darren Upton, CLAS DPW

Extending Knowledge of the Nucleon PDF in the Resonance Region



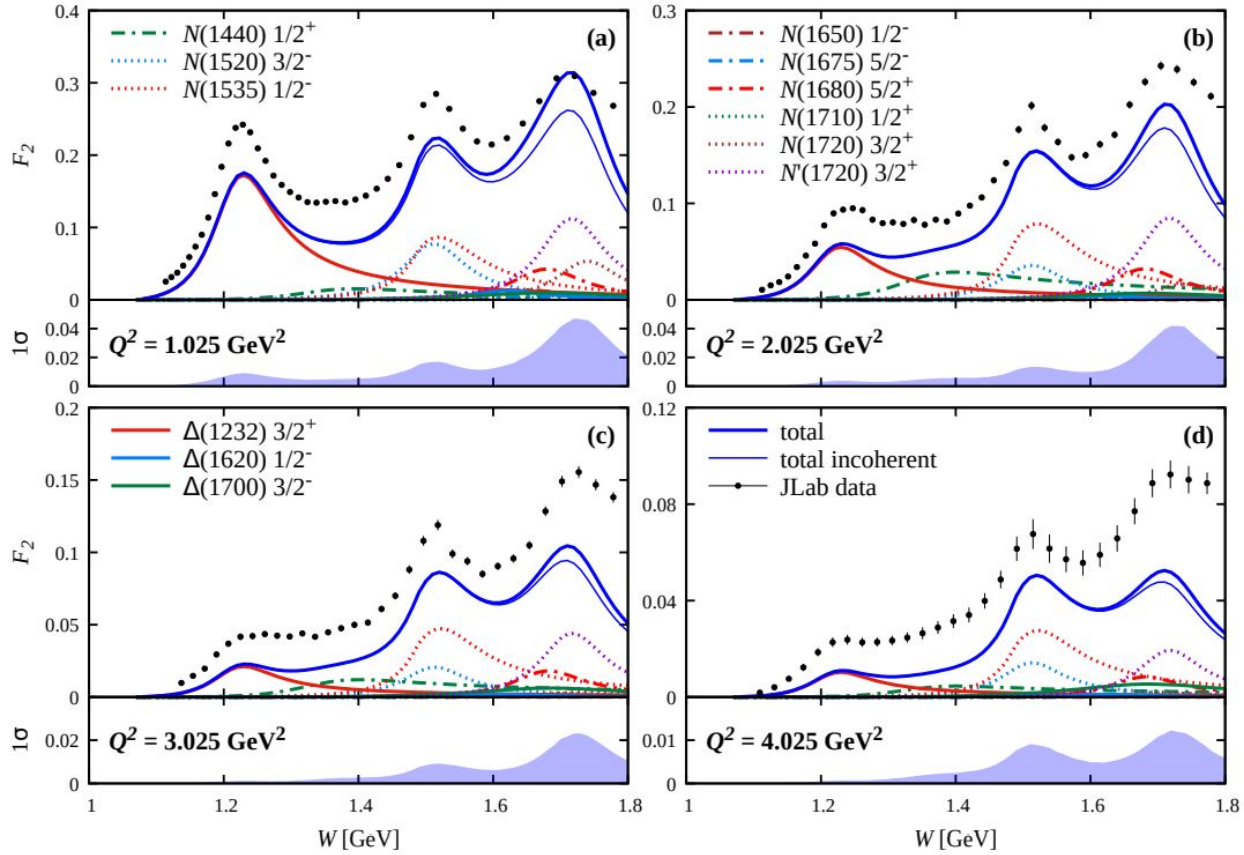
- The global QCD-driven analyses have provided detailed information on the nucleon quark and gluon PDFs in a wide range of fractional parton momenta x from 10^{-4} to above 0.9 and at photon virtualities Q^2 from 1 - 10^4 GeV^2 .

- Advances in QCD-connected hadron structure theory make it possible to predict PDFs directly from the QCD Lagrangian. Comparing these theoretical predictions with PDFs extracted from global analyses of experimental data provides insight into the emergence of the non-perturbative strong interaction.

.

- CLAS measurements of $\gamma_v pN^*$ electrocouplings for W < 1.8 GeV and Q^2 < 5.0 GeV^2 make it possible, for the first time, to evaluate the resonant contributions to inclusive structure functions and their moments from experimental results on N* electroexcitation.

Introduction



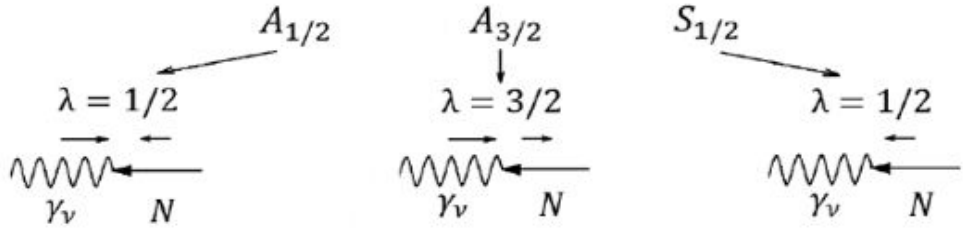
A. N. Hiller Blin et al., Phys. Rev. C 104 025201 (2021)

- Peaks in the W-evolution of the unpolarized structure function F_2 are generated by the resonant contributions.
- Pronounced differences in their Q^2 evolution are related to different evolution of $\gamma_v pN^*$electrocouplings with Q^2 for N* of markedly different structure located in the first, second, and third resonance regions.
- Evaluation of the resonant contributions across the full resonant region of W<2.0 GeV requires information on the evolution of N* electrocouplings of all contributing resonances across full range of Q^2 covered by inclusive data analyses.

Objectives of current work:

- **evaluate resonant contributions to polarized g_1 and g_2 structure functions and their truncated moments**

N^* electrocoupling amplitudes



$$\Gamma_\gamma^T(W = M_r, Q^2) = \frac{q_{\gamma,r}^2(Q^2)}{\pi} \frac{2M_N}{(2J_r+1)M_r} \left(|A_{1/2}(Q^2)|^2 + |A_{3/2}(Q^2)|^2\right),$$

$$\Gamma_\gamma^L(W = M_r, Q^2) = 2\frac{q_{\gamma,r}^2(Q^2)}{\pi} \frac{2M_N}{(2J_r+1)M_r} |S_{1/2}(Q^2)|^2,$$

$$q_\gamma = \sqrt{Q^2 + E_\gamma^2}, \quad E_\gamma = \frac{W^2 - Q^2 - M_N^2}{2W}$$

Q^2 - photon virtuality

W - invariant mass of the photon-proton system

q_γ - virtual photon momentum

M_r - resonance mass

J_r - nucleon resonance spin

Resonance helicity contributions

$$G_m^R(Q^2) = \frac{1}{2M}\left\langle R(\lambda_R)\left|\epsilon^{\mu}_{(m)}\cdot J_\mu(0)\right|N(\lambda=1/2)\right\rangle$$

$$G_+^R = C\frac{\sqrt{M_R\Gamma_R(W)}}{M_R^2-W^2-i\Gamma_R(W)M_R}A_{1/2}^R(Q^2),$$

$$G_-^R = C\frac{\sqrt{M_R\Gamma_R(W)}}{M_R^2-W^2-i\Gamma_R(W)M_R}P\,A_{3/2}^R(Q^2),$$

$$G_0^R = C\frac{\sqrt{M_R\Gamma_R(W)}}{M_R^2-W^2-i\Gamma_R(W)M_R}P\,S_{1/2}^R(Q^2),$$

$$C=\frac{1}{2\pi}\sqrt{\frac{W^2-M^2}{\alpha M}}\frac{q_{\gamma,R}}{q_\gamma},\quad P=\eta\,(-1)^{J-1/2}$$

η - parity

α - fine-structure constant

Structure functions

$$\left(1+\frac{Q^2}{\nu^2}\right) g_1^{\rm res} = M^2 \sum_{IJ\eta} \left\{ \left| \sum_{R^{IJ\eta}} G_+^{R^{IJ\eta}} \right|^2 - \left| \sum_{R^{IJ\eta}} G_-^{R^{IJ\eta}} \right|^2 + \frac{\sqrt{2Q^2}}{\nu} \Re\left[\left(\sum_{R^{IJ\eta}} G_0^{R^{IJ\eta}} \right) \left(\sum_{R^{IJ\eta}} (-1)^{J_{R^{IJ\eta}} - \frac{1}{2}} \eta_{R^{IJ\eta}} G_+^{R^{IJ\eta}} \right)^* \right] \right\},$$

$$\left(1+\frac{Q^2}{\nu^2}\right) g_2^{\rm res} = -M^2 \sum_{IJ\eta} \left\{ \left| \sum_{R^{IJ\eta}} G_+^{R^{IJ\eta}} \right|^2 - \left| \sum_{R^{IJ\eta}} G_-^{R^{IJ\eta}} \right|^2 - \frac{\nu\sqrt{2}}{\sqrt{Q^2}} \Re\left[\left(\sum_{R^{IJ\eta}} G_0^{R^{IJ\eta}} \right) \left(\sum_{R^{IJ\eta}} (-1)^{J_{R^{IJ\eta}} - \frac{1}{2}} \eta_{R^{IJ\eta}} G_+^{R^{IJ\eta}} \right)^* \right] \right\},$$

$$F_1^{\rm res} = M \sum_{IJ\eta} \left\{ \left| \sum_{R^{IJ\eta}} G_+^{R^{IJ\eta}} \right|^2 + \left| \sum_{R^{IJ\eta}} G_-^{R^{IJ\eta}} \right|^2 \right\},$$

$$\left(1+\frac{\nu^2}{Q^2}\right) F_2^{\rm res} = M\nu \sum_{IJ\eta} \left\{ \left| \sum_{R^{IJ\eta}} G_+^{R^{IJ\eta}} \right|^2 + \left| \sum_{R^{IJ\eta}} G_-^{R^{IJ\eta}} \right|^2 + 2 \left| \sum_{R^{IJ\eta}} G_0^{R^{IJ\eta}} \right|^2 \right\},$$

v - energy transfer to the proton in the lab frame

Input for N* contributions:

γ_vpN* electrocouplings from exclusive meson electroproduction data measured with CLAS

Q^2, Gev^2	$A_{1/2}$*1000, GeV$^{-1/2}$	$S_{1/2}$*1000, GeV$^{-1/2}$
0.	-65±15.	
0.	-56.4±1.7	
0.275	-36.3±17.0	37.8±6.3
0.300	-19.8±4.8	34.7±3.8
0.325	-21.5±7.7	35.8±4.7
0.375	-10.9±5.9	32.7±5.3
0.400	-14.6±5.6	32.5±3.4
0.425	-8.8±5.4	33.8±3.8
0.475	3.7±5.9	37.4±5.9
0.500	3.0.±8.0	33.8±4.0
0.525	15.8±9.1	26.8±3.5
0.575	17.2±10.4	22.2±6.8
0.625	12.4±7.5	31.4±4.6
0.650	21.4±6.2	25.7±5.9
0.900	25.3±8.3	33.4±5.5
0.950	29.9±6.5	25.6±6.2

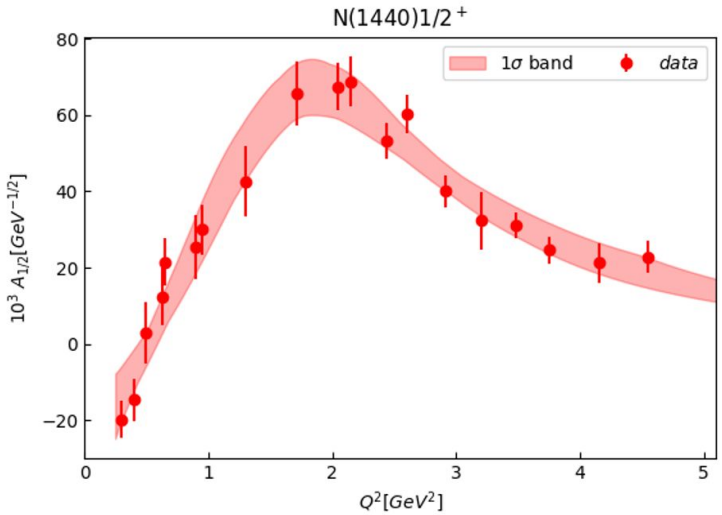
https://userweb.jlab.org/~mokeev/resonance_electrocouplings23/

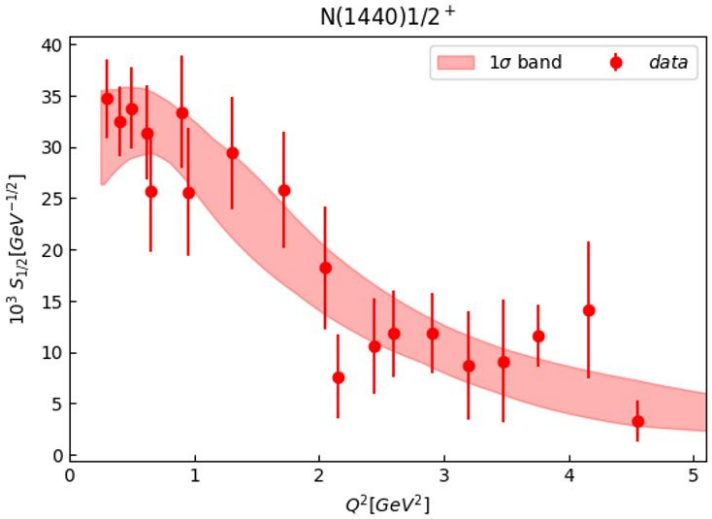
Experimental data on g1 structure function:

Determination of the proton spin structure functions for $0.05 < Q^2 < 5$ GeV^2 using CLAS

R.G. Fersch,[45,7] N. Guler,[31,37] P. Bosted,[39,45] A. Deur,[39] K. Griffioen,[45] C. Keith,[39] S.E. Kuhn,[31] R. Minehart,[44] Y. Prok,[31] K.P. Adhikari,[26] S. Adhikari,[11] Z. Akbar,[12] M.J. Amaryan,[31] S. Anefalos Pereira,[18] G. Asryan,[46] H. Avakian,[39,18] J. Ball,[6] I. Balossino,[17] N.A. Baltzell,[39] M. Battaglieri,[19] I. Bedlinskiy,[23] A.S. Biselli,[9,4] W.J. Briscoe,[14] W.K. Brooks,[40,39] S. Bültmann,[31] V.D. Burkert,[39] Frank Thanh Cao,[8] D.S. Carman,[39] S. Careccia,[15,31] A. Celentano,[19] S. Chandavar,[30] G. Charles,[31] T. Chetry,[30] G. Ciullo,[17,10] L. Clark,[42] L. Colaneri,[8] P.L. Cole,[16,39] N. Compton,[30] M. Contalbrigo,[17] O. Cortes,[16] V. Crede,[12] A. D'Angelo,[20,34] N. Dashyan,[46] R. De Vita,[19] E. De Sanctis,[18] C. Djalali,[36] G.E. Dodge,[31] R. Dupre,[22] H. Egiyan,[39,45] A. El Alaoui,[40] L. El Fassi,[26] L. Elouadrhiri,[39] P. Eugenio,[12] E. Fanchini,[19] G. Fedotov,[36,35] A. Filippi,[21] J.A. Fleming,[41] T.A. Forest,[16] M. Garçon,[6] G. Gavalian,[39,27] Y. Ghandilyan,[46] G.P. Gilfoyle,[33] K.L. Giovanetti,[24] F.X. Girod,[39,6] C. Gleason,[36] E. Golovatch,[35] R.W. Gothe,[36] M. Guidal,[22] L. Guo,[11,39] K. Hafidi,[1] H. Hakobyan,[40,46] C. Hanretty,[39] N. Harrison,[39] M. Hattawy,[1] D. Heddle,[7,39] K. Hicks,[30] M. Holtrop,[27] S.M. Hughes,[41] Y. Ilieva,[36,14] D.G. Ireland,[42] B.S. Ishkhanov,[35] E.L. Isupov,[35] D. Jenkins,[43] K. Joo,[8] D. Keller,[44] G. Khachatryan,[46] M. Khachatryan,[31] M. Khandaker,[28,*] A. Kim,[8] W. Kim,[25] A. Klein,[31] F.J. Klein,[5] V. Kubarovsky,[39,32] V.G. Lagerquist,[31] L. Lanza,[20] P. Lenisa,[17] K. Livingston,[42] H.Y. Lu,[36] B. McKinnon,[42] C.A. Meyer,[4] M. Mirazita,[18] V. Mokeev,[39,35] R.A. Montgomery,[42] A Movsisyan,[17] C. Munoz Camacho,[22] G. Murdoch,[42] P. Nadel-Turonski,[39] S. Niccolai,[22] G. Niculescu,[24] I. Niculescu,[24] M. Osipenko,[19] A.I. Ostrovidov,[12] M. Paolone,[38] R. Paremuzyan,[27] K. Park,[39,25] E. Pasyuk,[39,2] W. Phelps,[11] J. Pierce,[44,29] S. Pisano,[18] O. Pogorelko,[23] J.W. Price,[3] D. Protopopescu,[27,†] B.A. Raue,[11,39] M. Ripani,[19] D. Riser,[8] A. Rizzo,[20,34] G. Rosner,[42] P. Rossi,[39,18] P. Roy,[12] F. Sabatié,[6] C. Salgado,[28] R.A. Schumacher,[4] Y.G. Sharabian,[39] A. Simonyan,[46] Iu. Skorodumina,[36,35] G.D. Smith,[41] D. Sokhan,[42] N. Sparveris,[38] I. Stankovic,[41] S. Stepanyan,[39] I.I. Strakovsky,[14] S. Strauch,[36] M. Taiuti,[13,‡] Ye Tian,[36] B. Torayev,[31] M. Ungaro,[39,32] H. Voskanyan,[46] E. Voutier,[22] N.K. Walford,[5] D.P. Watts,[41] X. Wei,[39] L.B. Weinstein,[31] N. Zachariou,[41] and J. Zhang[39,31]
(The CLAS Collaboration)

R. Fersch et al., (CLAS Collaboration) Phys. Rev. C96 065208 (2017).

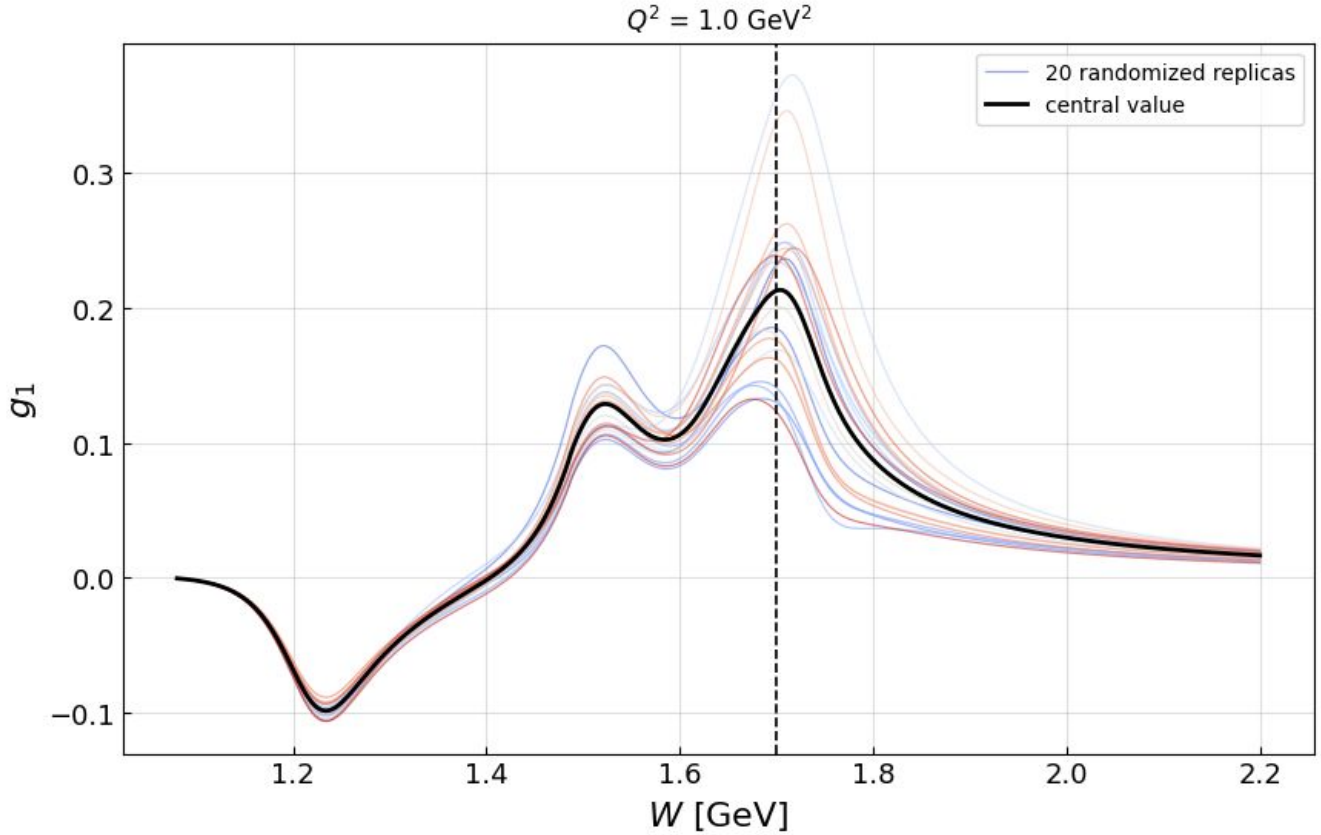




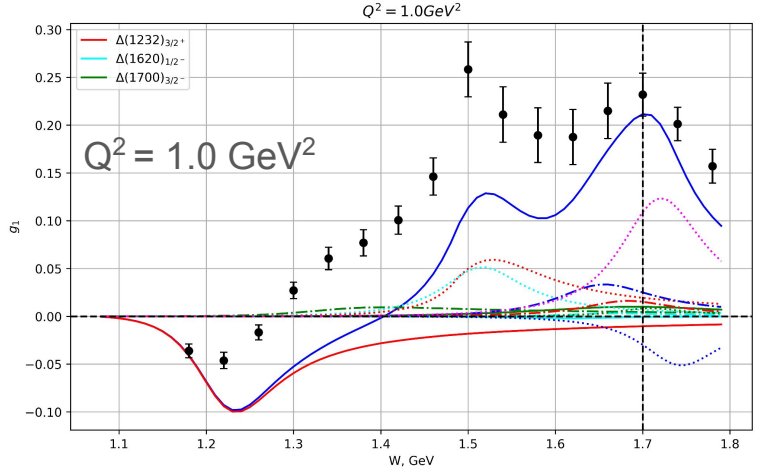
N* electrocoupling parameterization

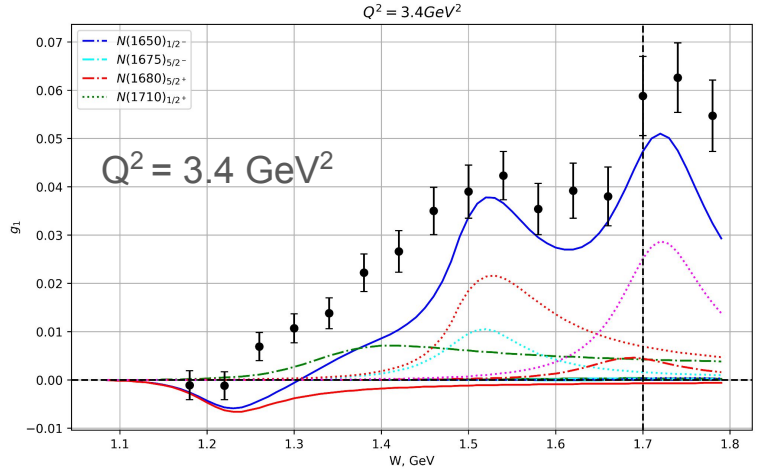
- New interpolations of the experimental N* electrocoupling data were obtained by imposing analyticity constraints.
- The data is consistent with the imposed analyticity constraints.
- To interpolate the N* electrocoupling amplitudes, a sample of 10,000 datasets were randomized within the error bars and each dataset fit to the data producing interpolating curves. The mean values and standard deviations are evaluated across the ensembles of interpolating curves.

Structure function evaluation

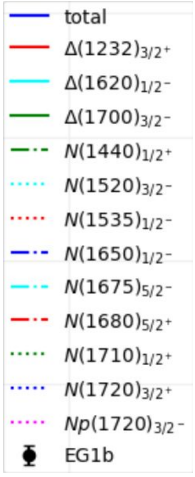


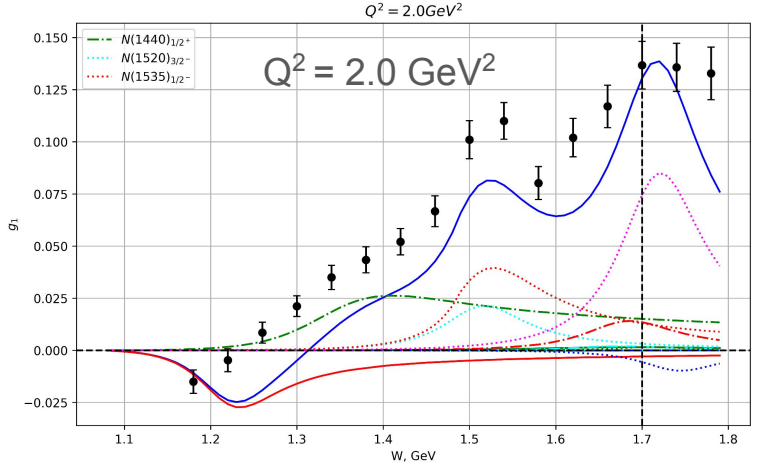
g_1 : CLAS data and the resonant contributions

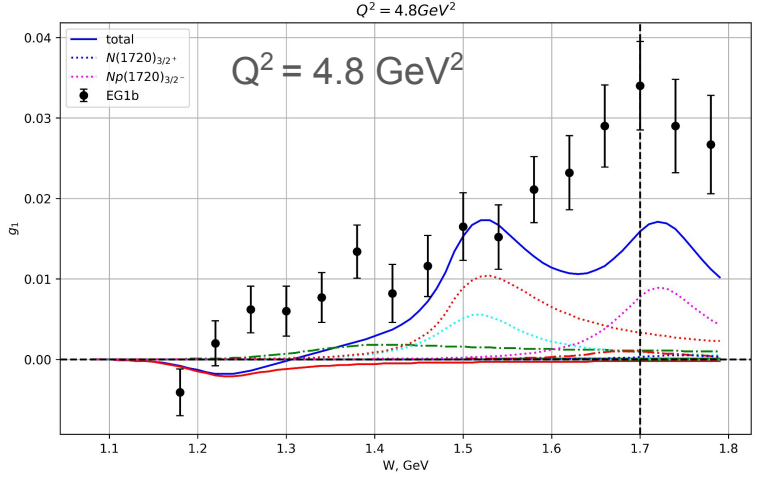




Driving N* contributions:
in the first region-$\Delta(1232)3/2^+$;
in the second region-$N(1520)3/2^-$; $N(1535)1/2^-$;
In the third region:
the biggest from $N'(1720)\ 3/2^+$ new state from CLAS data and $N(1440)1/2^+$,$N(1535)1/2^-$ tails

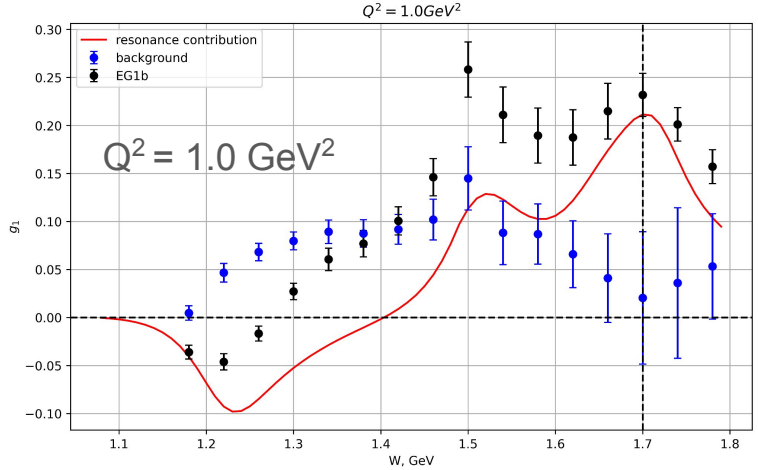


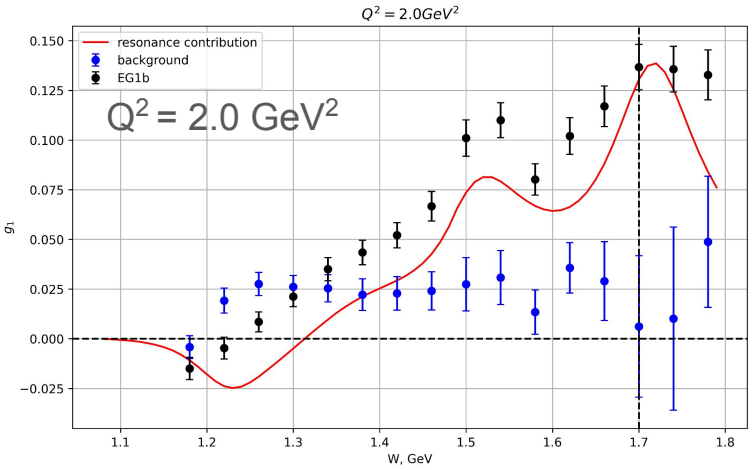




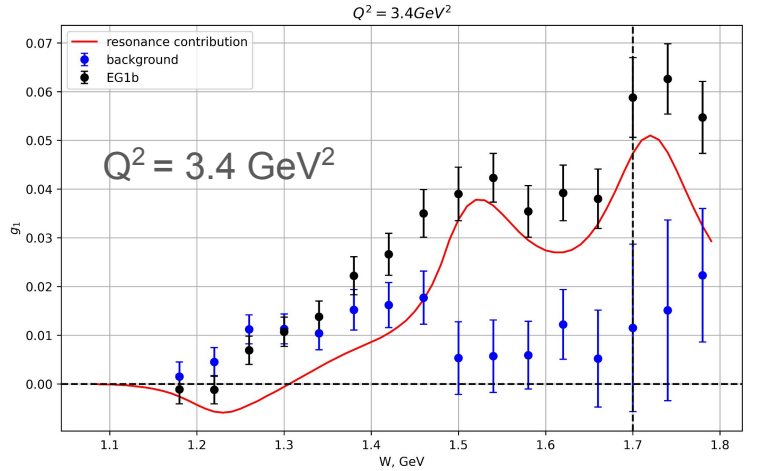
g_1: resonant contributions, EG1b data and background

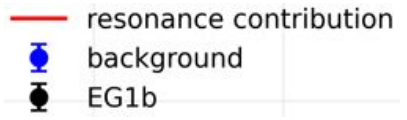
Background=(g_1_data - resonant contributions)

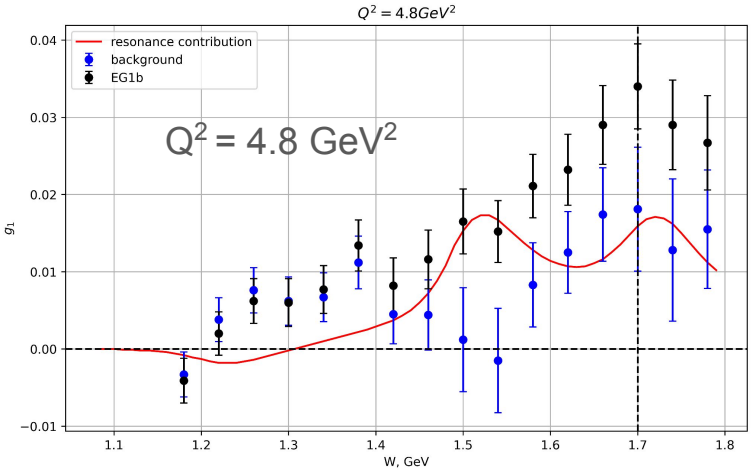




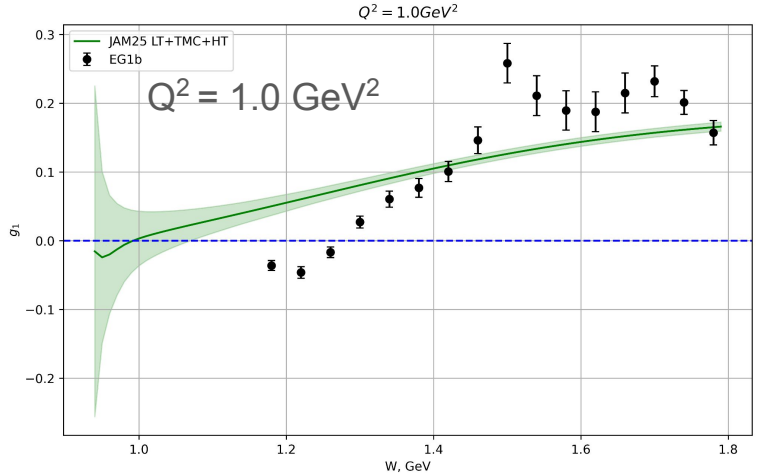
Across the most of (W, Q^2) area, the resonant contributions are either the biggest or comparable to the background



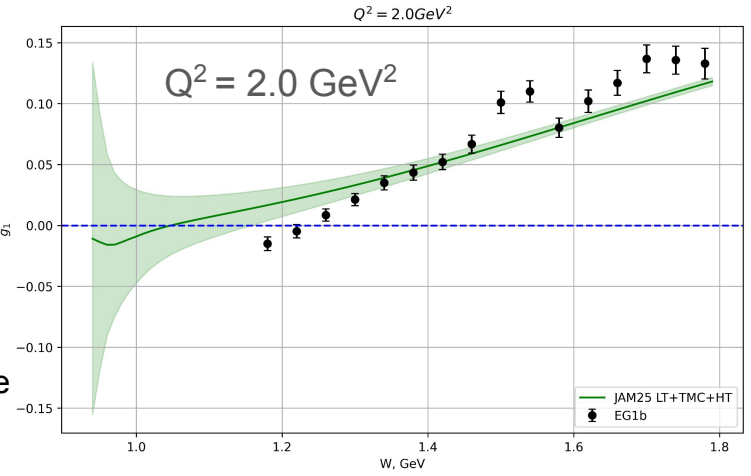


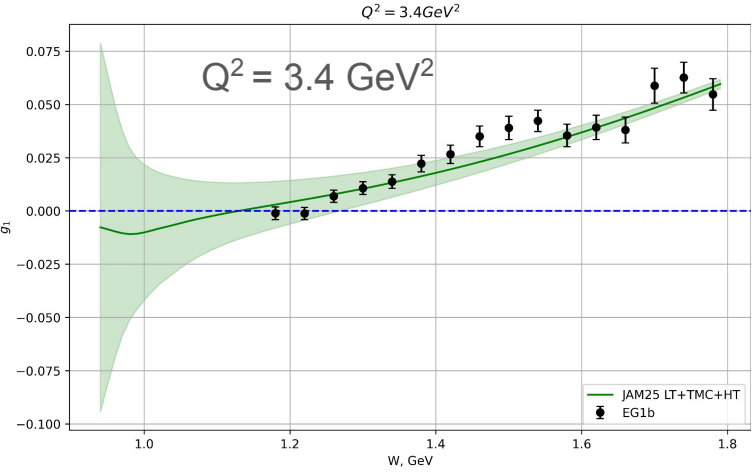


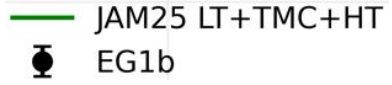
EG1b data and expectations from JAM25 PDF

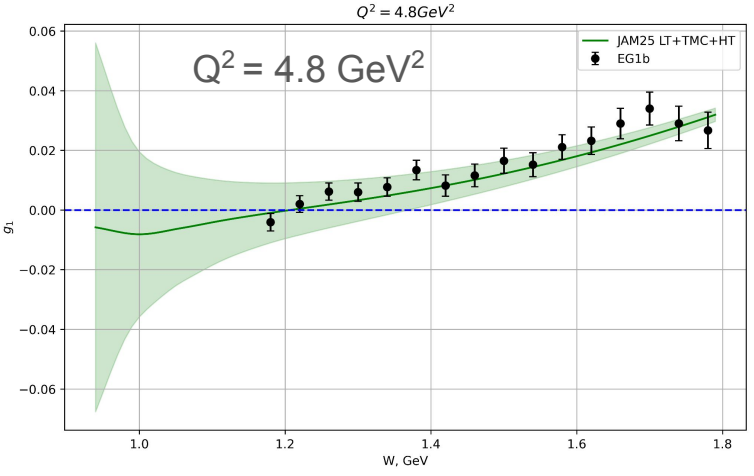


Comparison between W-dependencies of g_1 from the CLAS data and the expectations from JAM25 PDF fit to the world data in the DIS region is suggestive of duality set-up across Q^2>2.0 GeV^2

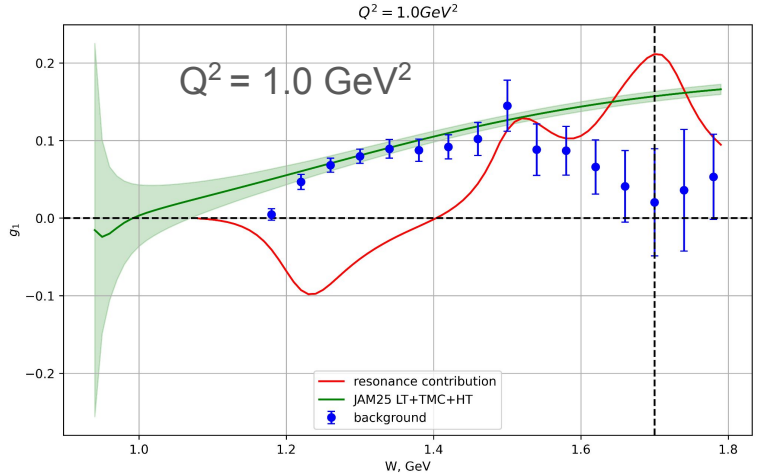




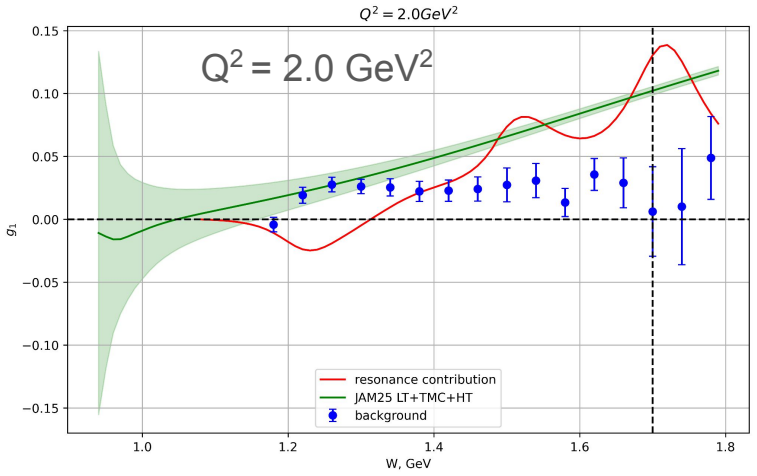


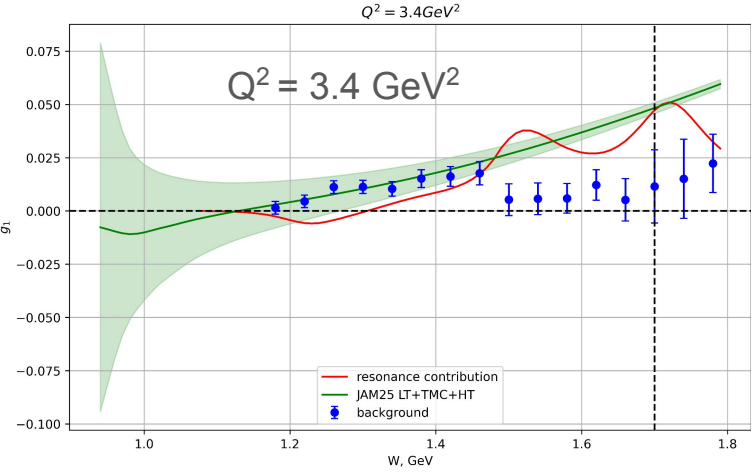


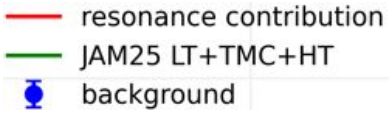
g_1 : resonant contributions, background, and expectations from JAM25 PDF

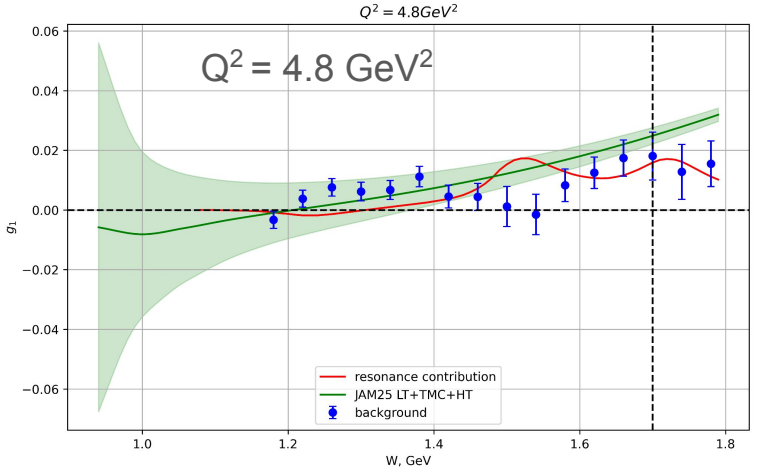


Resonant contributions (abs. values) are comparable with expectations from the JAM25 PDF and suggestive of a duality set-up for Q^2>3.0 GeV^2









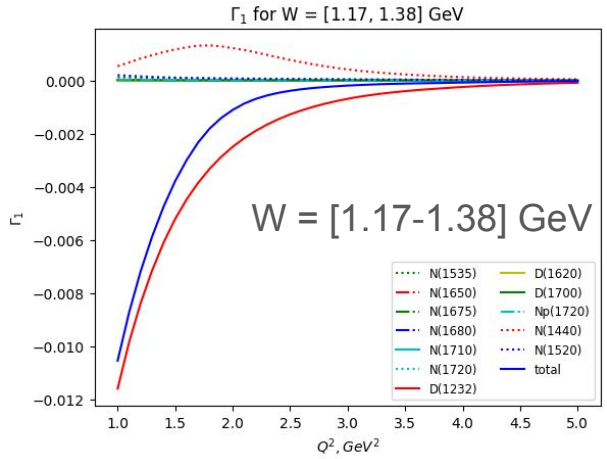
The moments analysis

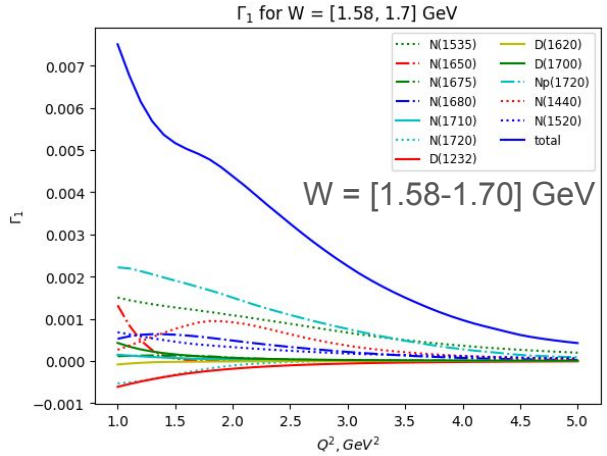
$$\Gamma_1(\Delta x; Q^2) = \int_{\Delta x} dx g_1(x, Q^2)$$

$$\Gamma_2(\Delta x; Q^2) = \int_{\Delta x} dx g_2(x, Q^2)$$

- Truncated moments average over resonance peaks, which makes data, N* contributions and the JAM25 PDF predictions directly comparable.
- Region-by-region moments allow testing of local duality while the full W range tests global duality.

Γ_1 moments: resonant contributions





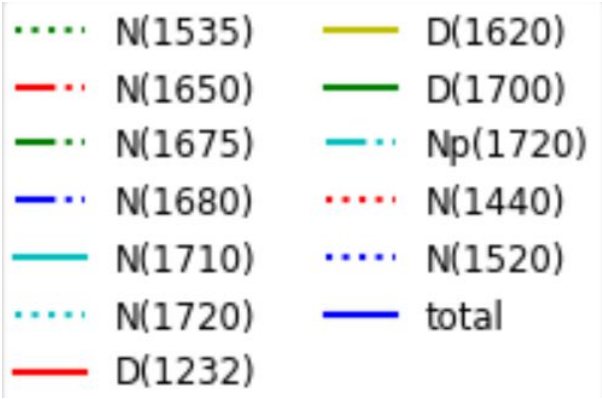
Driving N* contributions:

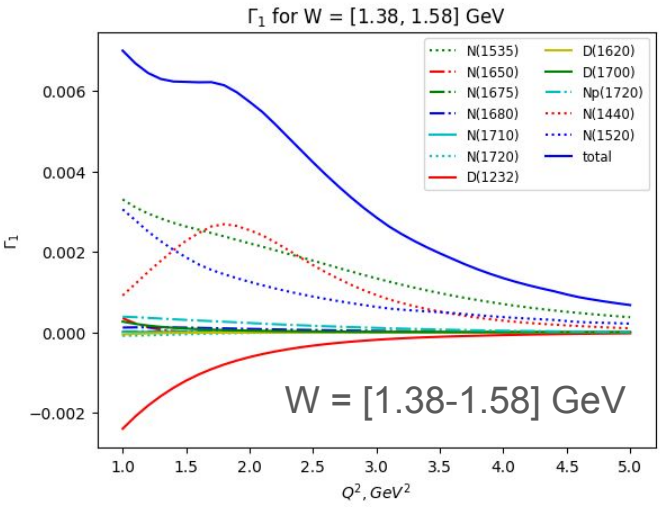
the first region: $\Delta(1232)3/2^+$

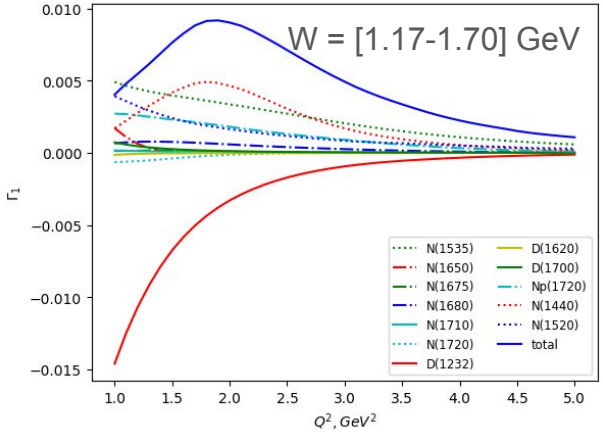
in the second region: $N(1440)1/2^+$, $N(1520)3/2^-$, $N(1535)1/2^-$

in the third region: $N'(1720)3/2^+$

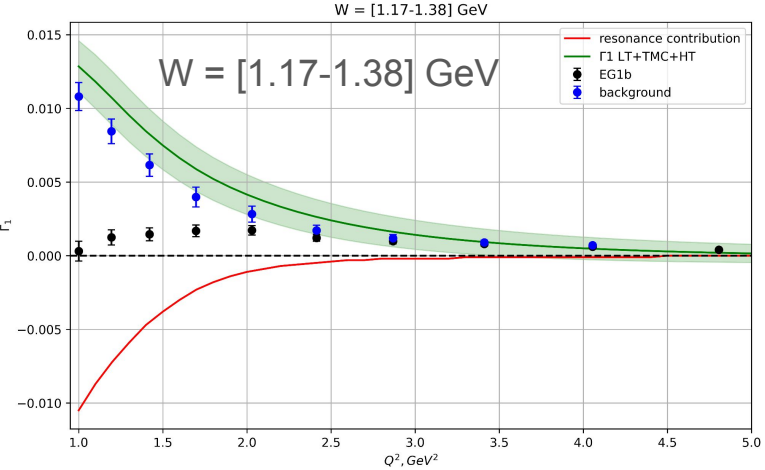
W=[1.08-1.75] GeV: $N(1440)1/2^+$ and $\Delta(1232)3/2^+$

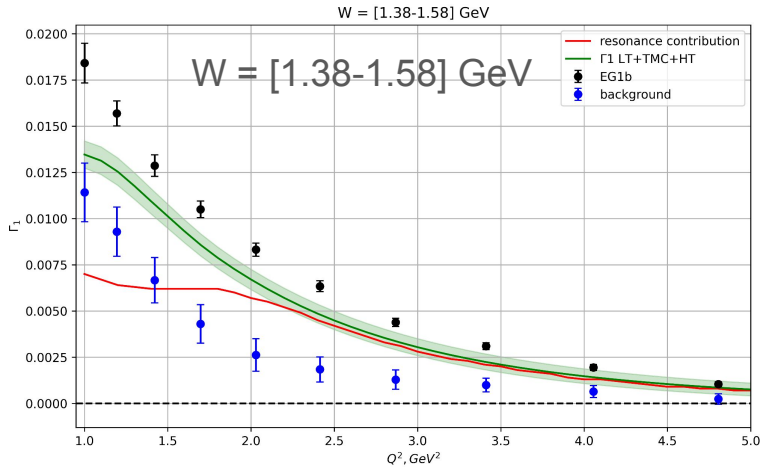


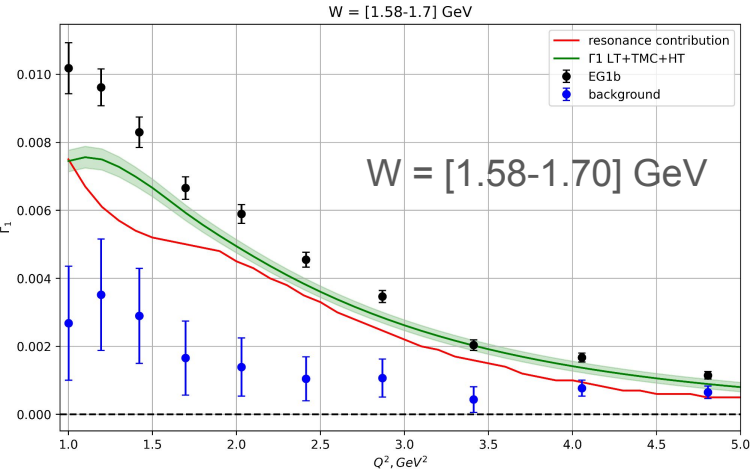


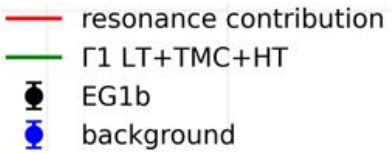


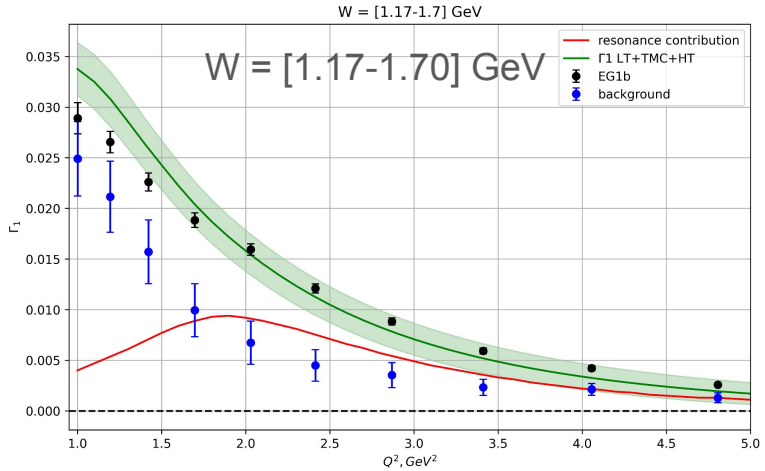
Γ_1 moments: EG1b data, expectations from JAM25 PDF, resonant and background contributions











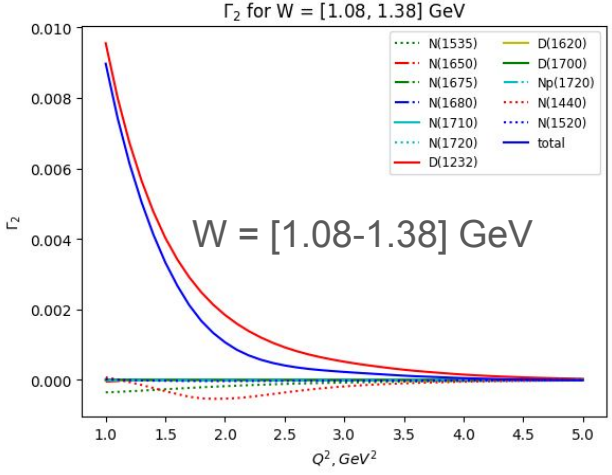
Novel Features of the Duality Concept Revealed by Comparing Γ_1 Moments with JAM25 PDF Predictions and Their Resonant and Background Contributions

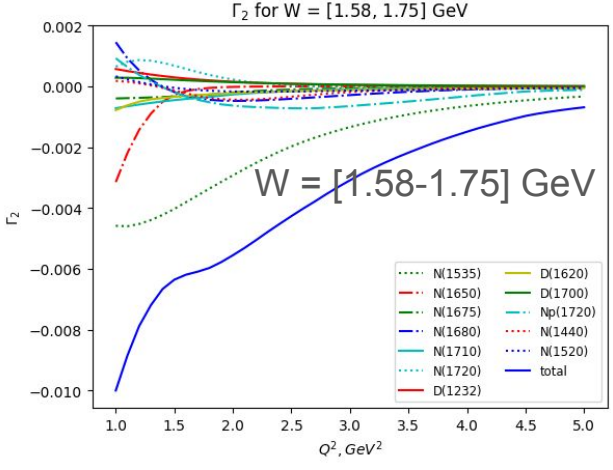
- The truncated Γ_1 moments in the second and third resonance regions, as well as over the combined range W = 1.17–1.70 GeV, demonstrate duality among the JAM25 PDF predictions, CLAS experimental results, and resonant contributions for $Q^2 > 2.5$ GeV^2.

- Thus, the manifestation of duality in the Q^2 evolution of Γ_1 moments, evaluated from the measured g_1 structure functions and compared with PDF expectations, which was previously interpreted as signaling the transition to the dominance of partonic degrees of freedom, does not imply the disappearance of N* contributions. Our analysis demonstrates, for the first time, that resonant contributions remain essential throughout the range $Q^2 < 5.0$ GeV^2.

- The observed duality between the resonant contributions and JAM25 PDF expectations suggests a connection between the Q^2 evolution of $\gamma_v pN^*$ electrocouplings and the evolution of PDFs in the resonance region. Uncovering the nature of this connection represents a challenging problem for hadron structure theory.

Γ_2 moments: resonant contribution





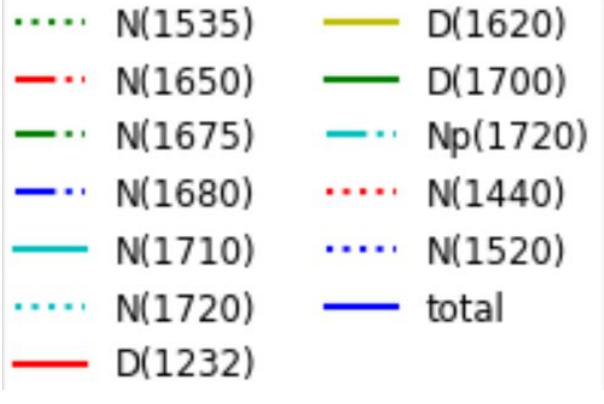
Driving N* contributions:

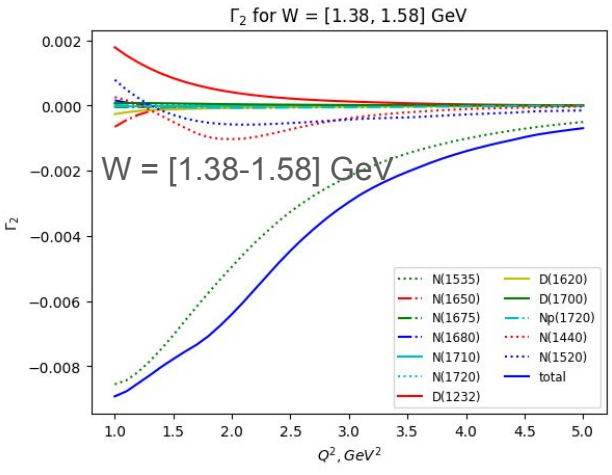
the first region: $\Delta(1232)3/2^+$

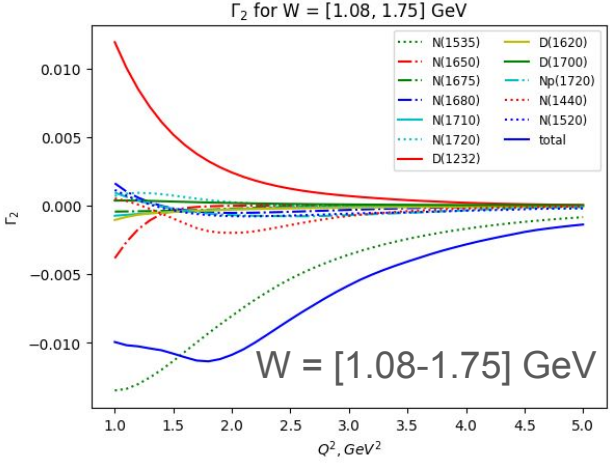
in the second region: $N(1535)1/2^-$

in the third region: $N(1535)1/2^-$

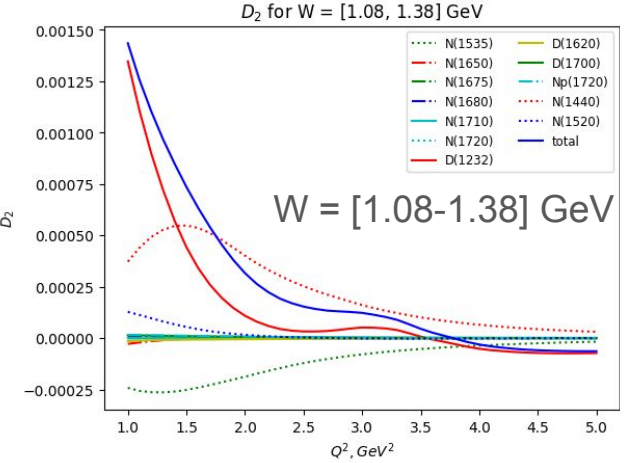
W=[1.08-1.75] GeV: $N(1535)1/2^-$ and $\Delta(1232)3/2^+$

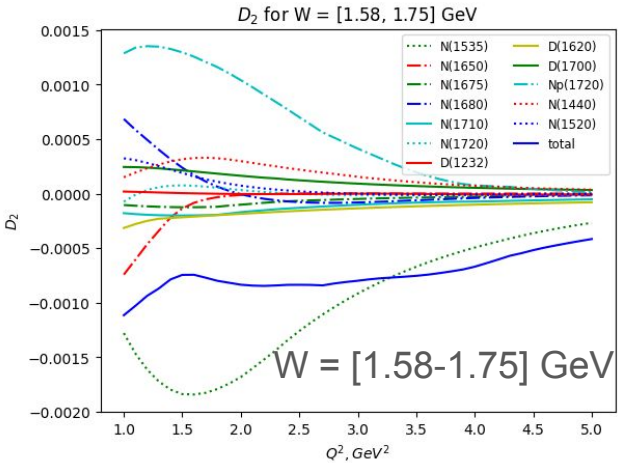






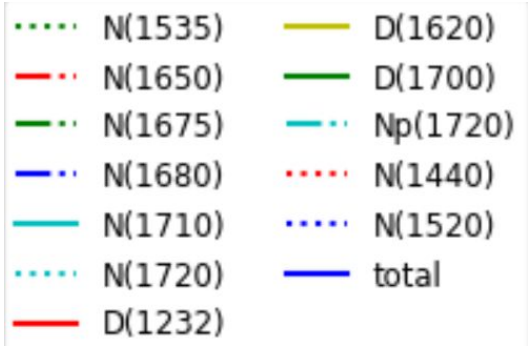
d_2 resonant contribution

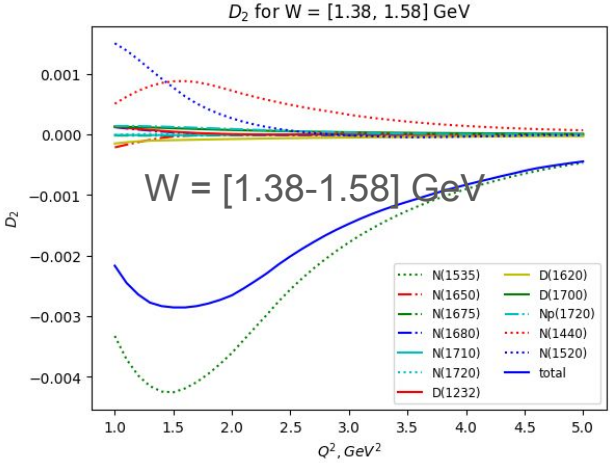


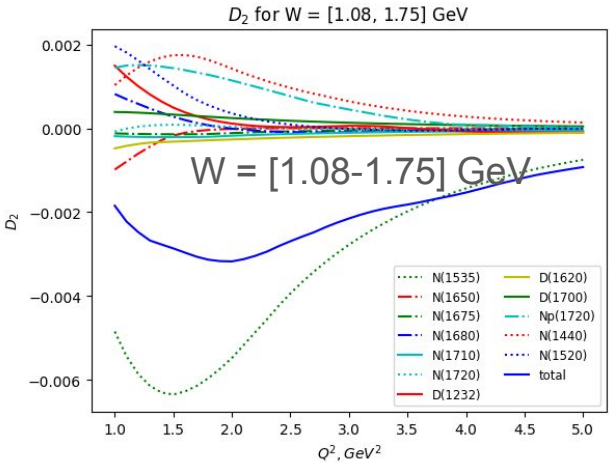


Several resonances contribute to the evolution of d_2 truncated moments across the first, the second, and the third resonance regions, and for W=[1.08-1.75] GeV

$$d_2 = \int_{\Delta x} x^2(2g_1 + 3g_2)dx$$







Conclusion and Outlook

- For the first time, the resonant contributions to the inclusive polarized structure functions $g_1(W,Q^2)$ and $g_2(W,Q^2)$ have been evaluated over the kinematic range $W < 1.7$ GeV and $Q^2 = 2.0–5.0$ GeV^2, using the Q^2 evolution of $\gamma_v pN^*$ electrocouplings extracted from CLAS exclusive meson electroproduction data. Nucleon resonance contributions remain significant throughout the studied resonance region ($W < 1.75$ GeV) over the entire Q^2 range covered by the present analysis ($Q^2 < 5.0$ GeV^2).

- The resonant and non-resonant contributions to the truncated $\Gamma_1(Q^2)$ moments, along with the resonant contributions to the $\Gamma_2(Q^2)$ and $d_2(Q^2)$ moments, have been evaluated for $W < 1.75$ GeV, both over the full kinematic range and separately in the first, second, and third resonance regions.

- Comparison of the measured g_1 structure functions and their Γ_1 moments with JAM25 PDF predictions demonstrates duality between the experimental results and PDF expectations for $Q^2 > 2.0$ GeV^2.

- We also observe duality between the resonant contributions alone and the corresponding PDF expectations. Thus, contrary to earlier conjectures, duality is exhibited not only by the full experimental g_1 structure functions and Γ_1 moments but also by their resonant contributions alone.

- The expected CLAS12 results on the Q^2 evolution of $\gamma_v pN^*$ electrocouplings over the range $Q^2 = 5–10$ GeV^2 will enable us to investigate the evolution of resonant contributions to inclusive structure functions across distance scales spanning the anticipated transition from the strongly coupled to the perturbative QCD regime.

Back Up

Γ_1 resonant contribution

