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Quark–Hadron Duality in Inclusive Electron–Proton Scattering at High Q^2

Structure functions and truncated moments from CLAS12

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Seville · 7–11 September 2026 arXiv:2606.29690 CLAS12 RG-A data: V. Klimenko et al., Phys. Rev. C 112, 025201 (2025)

Quark–hadron duality: one nucleon, two descriptions

The empirical observation (Bloom–Gilman, 1970)

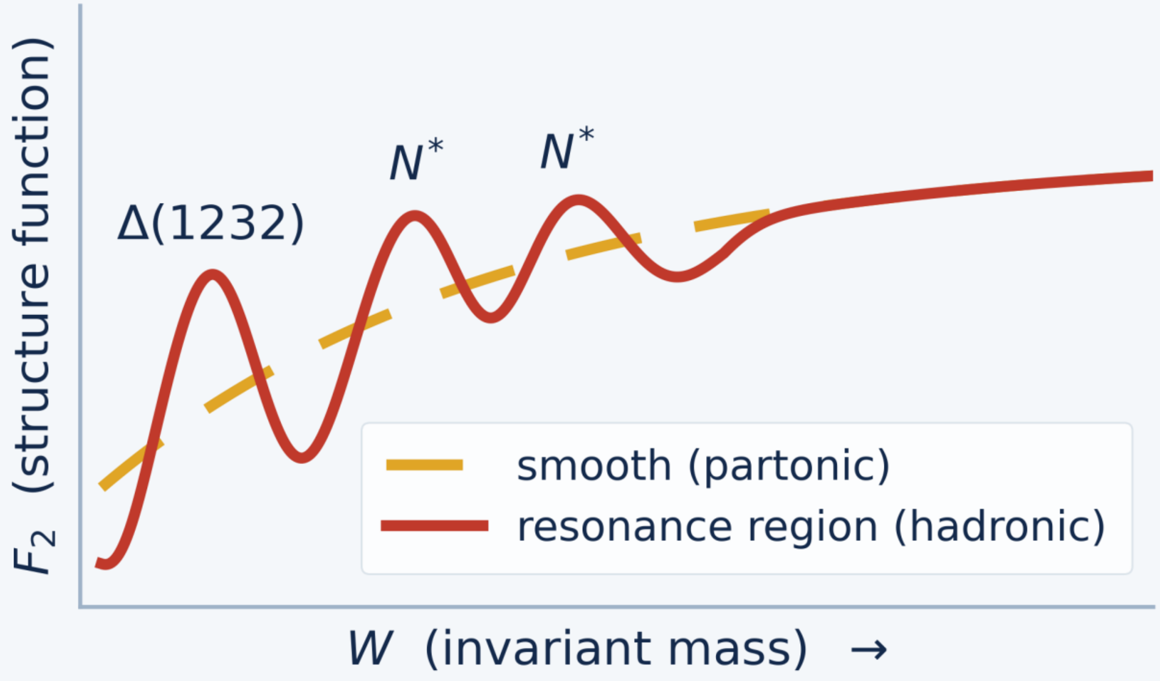
Resonance-region structure functions, averaged over W, reproduce the smooth DIS scaling curve.

Local vs. global

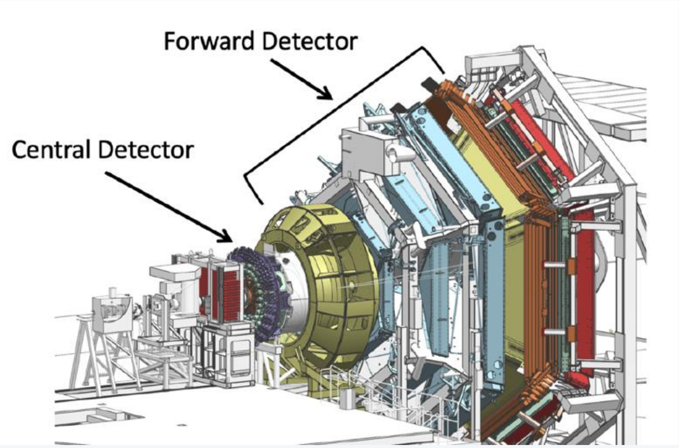
Local: averaging works within a single resonance region. Global: works over the whole resonance region.

What we measure & show

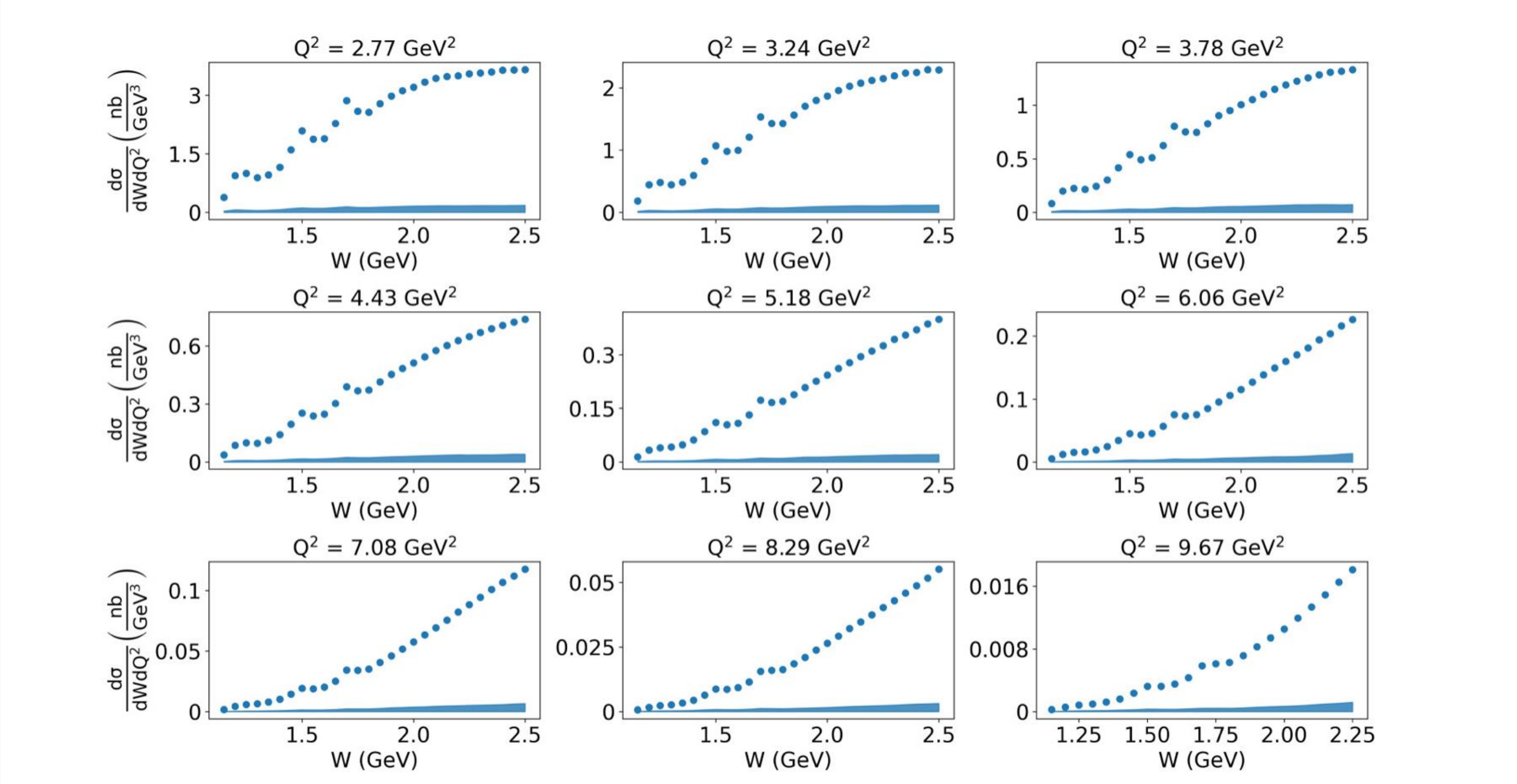
From the CLAS12 inclusive cross sections we extract F_2 and its W-truncated moments, and test duality — local and global — by comparing the hadronic and partonic descriptions.



CLAS12 covers the full resonance region at every Q^2, out to 10 GeV^2



The CLAS12 spectrometer in Hall B



Inclusive $d^2\sigma/dWdQ^2$ in all nine Q^2 bins, 2.77 – 9.67 GeV^2

What the measurement already establishes

- 10.6 GeV beam, nine Q^2 bins from 2.55 to 10.4 GeV^2, full resonance region to $W = 2.5$ GeV at every Q^2 — resonance-like structures persist throughout.
- Statistical uncertainties are below 1 %, bin-by-bin systematics average 5.8 %, and the overall scale uncertainty is 3.7 %.
- The three resonance regions evolve differently with Q^2, following the electrocouplings of the contributing N^* and Δ^*.
- Non-resonant contributions must be studied carefully throughout the resonance region.

STRATEGY

Two descriptions evaluated on the same footing

HADRONIC

ANL–Osaka coupled channels

- Dynamical coupled-channels (DCC) model — resonances + non-resonant background.
- Inclusive strength built from πN, ηN, KΛ, KΣ and ππN channels (incl. πΔ, ρN, σN).
- Provides explicit hadronic degrees of freedom with correct thresholds.
- **ANL–Osaka describes the resonance region up to $Q^2 \sim 3$ GeV^2.**

See Sato's talk

PARTONIC

CJ15 NLO global QCD analysis

- Leading-twist PDFs from a global fit (LHAPDF 6.5.4).
- **CJ15NLO + LT — leading-twist baseline.**
- **CJ15NLO + TMC + HT — adds target-mass + higher-twist corrections.**
- The +TMC+HT curve is the smooth reference duality should reproduce.

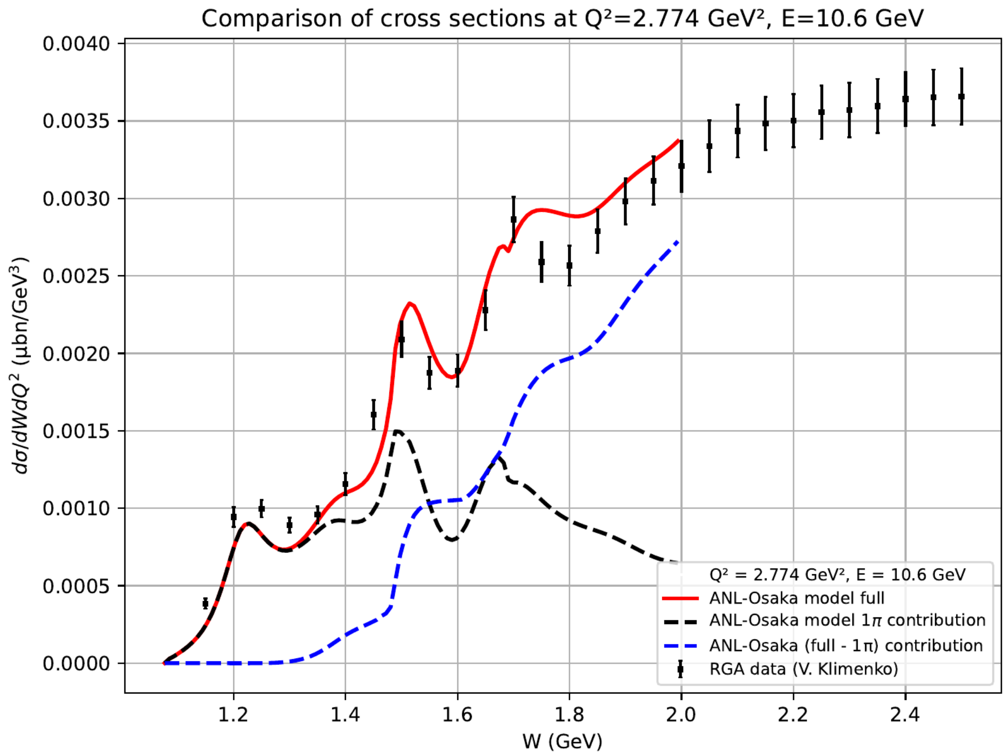
Comparison between data and the hadronic description

What the decomposition shows

- Full ANL–Osaka (red) reproduces the Δ, 2nd and 3rd resonance peaks within errors.
- The single-pion 1π channel (black) dominates only at low W.
- Above W ≈ 1.5 GeV, multi-meson channels (blue) carry most of the strength.

What this implies

- **High-mass N* with sizeable πΔ, ρN and σN branchings are required — duality above the Δ cannot be realized from 1π alone.**



ANALYSIS CHAIN

From the measured cross sections to a duality test

1 Measured σ

Absolute $d^2\sigma/dWdQ^2$, nine Q^2 bins from 2.55 to 10.4 GeV^2, covering the entire resonance region.

→

2 Hadronic basis

Anchor at $Q_0^2 = 2.774\ \mathrm{GeV}^2$, where ANL–Osaka describes the data, and extend phenomenologically to higher Q^2.

→

3 Fit 1 — extend

Evolve the 1π and 2π pieces from the anchor to reach higher Q^2 — the Ansatz describes the data to 10 GeV^2.

4 Fit 2 — apply

Same Ansatz, now on the L/T axis: σ_T and σ_L evolved separately from the anchor, $R_{LT} = \sigma_L/\sigma_T$ constrained to the ANL–Osaka value with 30% tolerance.

→

5 Structure function

$F_2 = K\nu(\sigma_T + \sigma_L) / [4\pi^2\alpha_{em}(1 + \nu^2/Q^2)]$, evaluated bin by bin.

→

6 Duality test

Truncated moments M_2 over four contiguous W windows, compared with CJ15+LT and CJ15+TMC+HT.

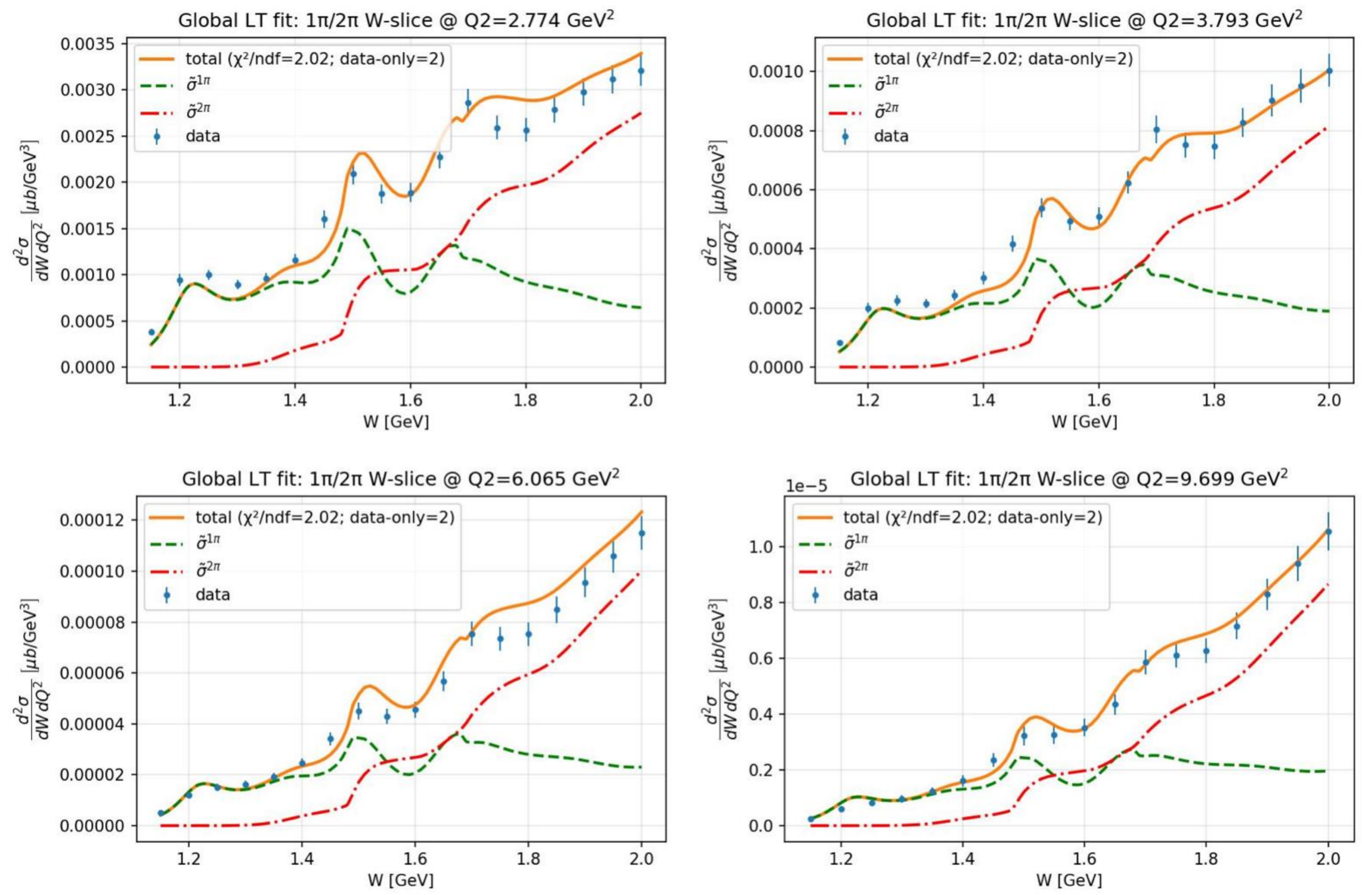
Fit 1: single-pion and multi-pion content across Q^2

Good description

- Single global fit, data-only $\chi^2/\mathrm{ndf} \approx 2$ at every Q^2.

Physics of the split

- 1π (green) governs low-W and the $\Delta(1232)$.
- 2π (red) grows with W and carries the high-W strength.
- The 1π share of the total is about 70% at the second resonance region and about 35% near W = 1.8 GeV.



Fit 2: the same Ansatz applied to the L/T separation

Anchored evolution of the transverse and longitudinal pieces

$$\sigma^{\text{tot.}}_{\text{AO}}\,(Q^2, W, E_e) = c_{\text{units}}\left[\tilde{\sigma}^{\text{AO}}_{T} + \varepsilon\,\tilde{\sigma}^{\text{AO}}_{L}\right]\Gamma_{\text{Hand}}\,\mathcal{J}$$

$$\tilde{\sigma}_T = e^{\alpha(Q^2 - Q_0^2)}\,\frac{G(\omega'[Q^2, W];\, c_i)}{G(\omega'[Q_0^2, W];\, c_i)}\,\sigma^{\text{input}}_T(Q_0^2, W)$$

$$\tilde{\sigma}_L = e^{\beta(Q^2 - Q_0^2)}\,\frac{G(\omega'[Q^2, W];\, c'_i)}{G(\omega'[Q_0^2, W];\, c'_i)}\,\sigma^{\text{input}}_L(Q_0^2, W)$$

$$\omega'(Q^2, W) = 1 + \frac{W^2}{Q^2}$$

ω' is the scaling variable. $G(\omega'; c_i)$ is a dimensionless Breidenbach–Kuti shape function, unrelated to the structure function F_2.

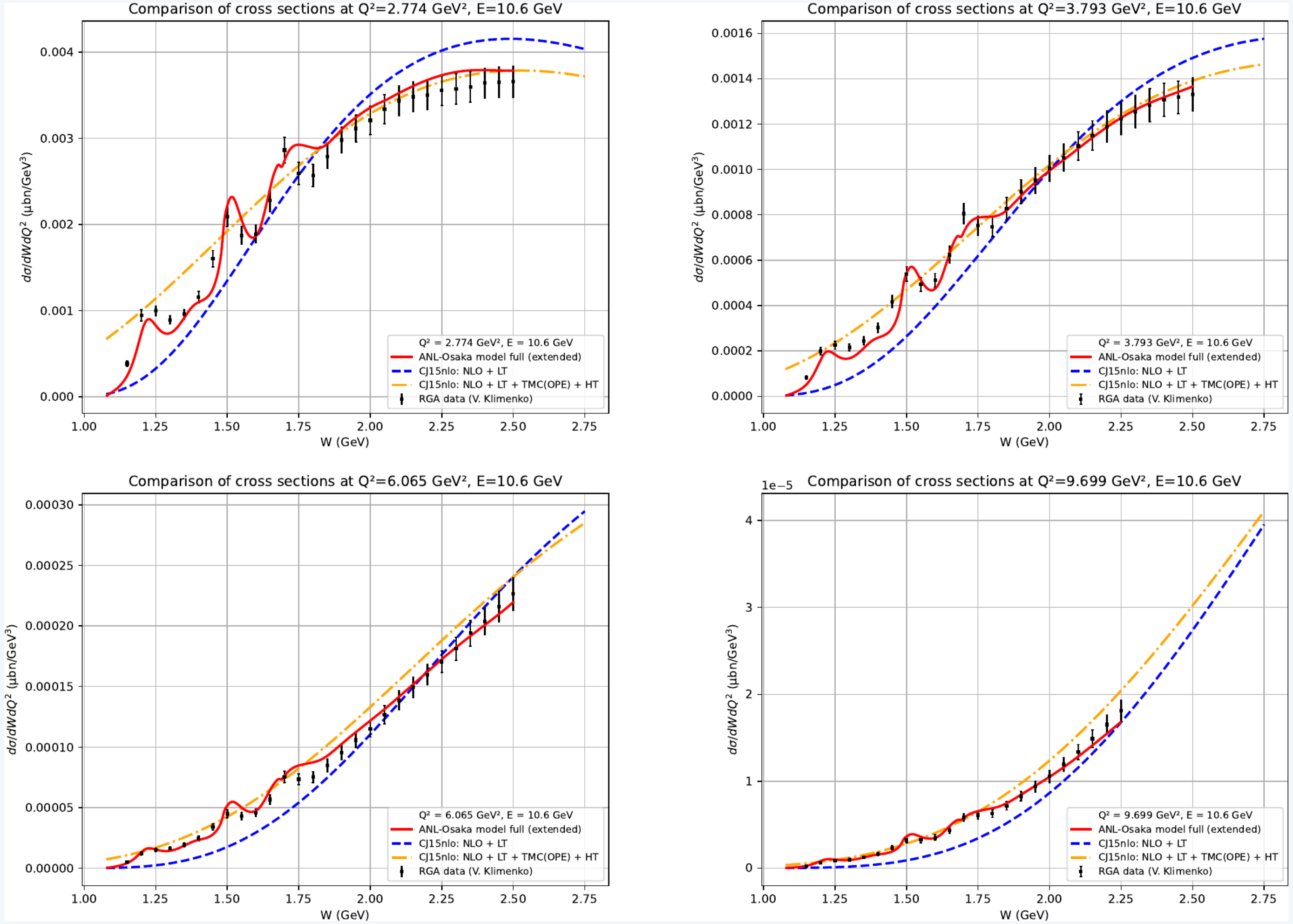
Guard-rails on the extrapolation

- Anchored to the data at Q_0^2 — no new resonances, no change to the underlying dynamics.
- Global minimum from a two-stage Monte Carlo search (5000 starts); uncertainties from a parametric bootstrap.
- We repeated the fit using the R_{LT} prior from CJ15 instead of ANL–Osaka. The extracted F_2 and M_2 changed very little.

Comparison between data, hadronic and partonic descriptions

Three observations

- The three-resonance structure persists at every Q^2 and is reproduced by the ANL–Osaka-anchored extension (red).
- CJ15+LT (blue) undershoots at low W — the higher-twist deficit; +TMC+HT (orange) restores agreement above W ≈ 1.7 GeV.
- **But CJ15+LT+TMC+HT does not vanish at the πN threshold (data and ANL–Osaka do): at low W it overshoots, biasing the 1st and 2nd resonance regions.**



Extracting F_2: local duality made visible

The oscillation picture

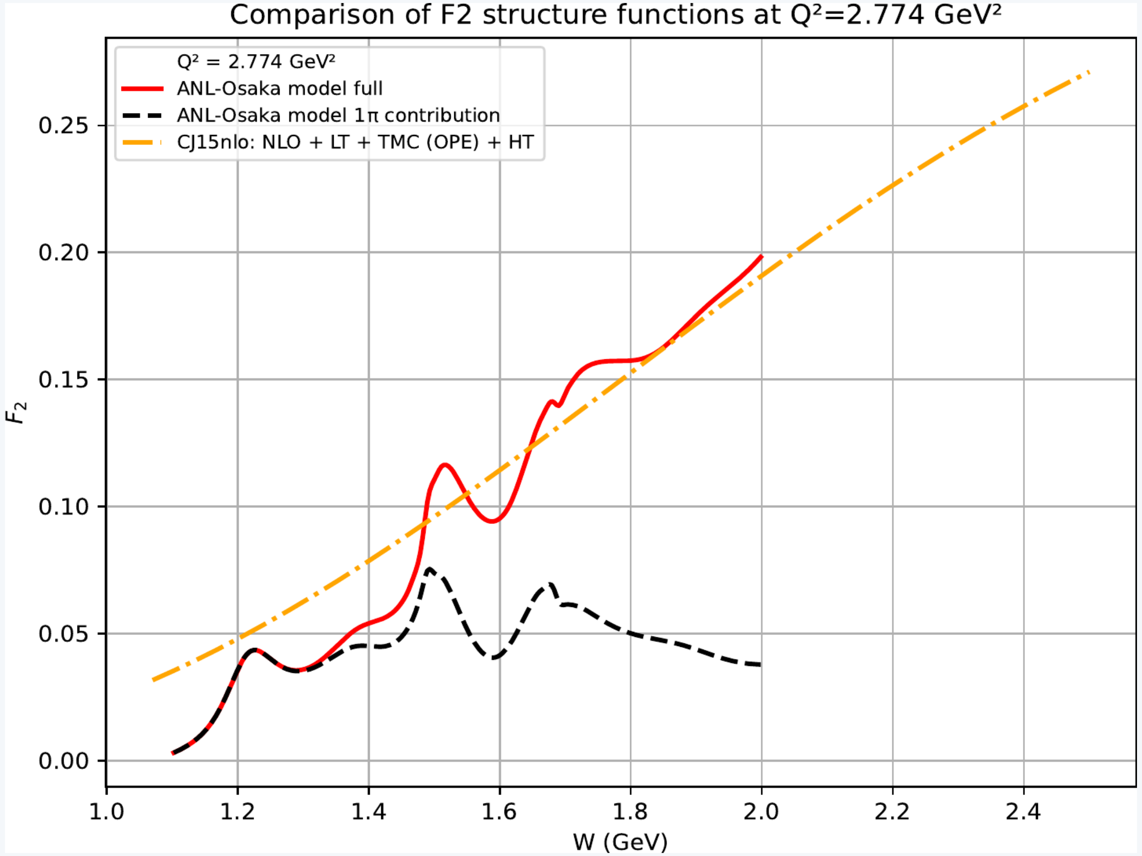
- Full ANL–Osaka F_2 (red) oscillates around the smooth CJ15+TMC+HT curve (orange).
- Crossings sit near the dips between resonances — the signature of local duality.

Multi-meson again

- **1π alone (black) sits systematically below the smooth curve above the Δ.**
- Smooth partonic strength is recovered only once multi-meson channels are included.

Near threshold

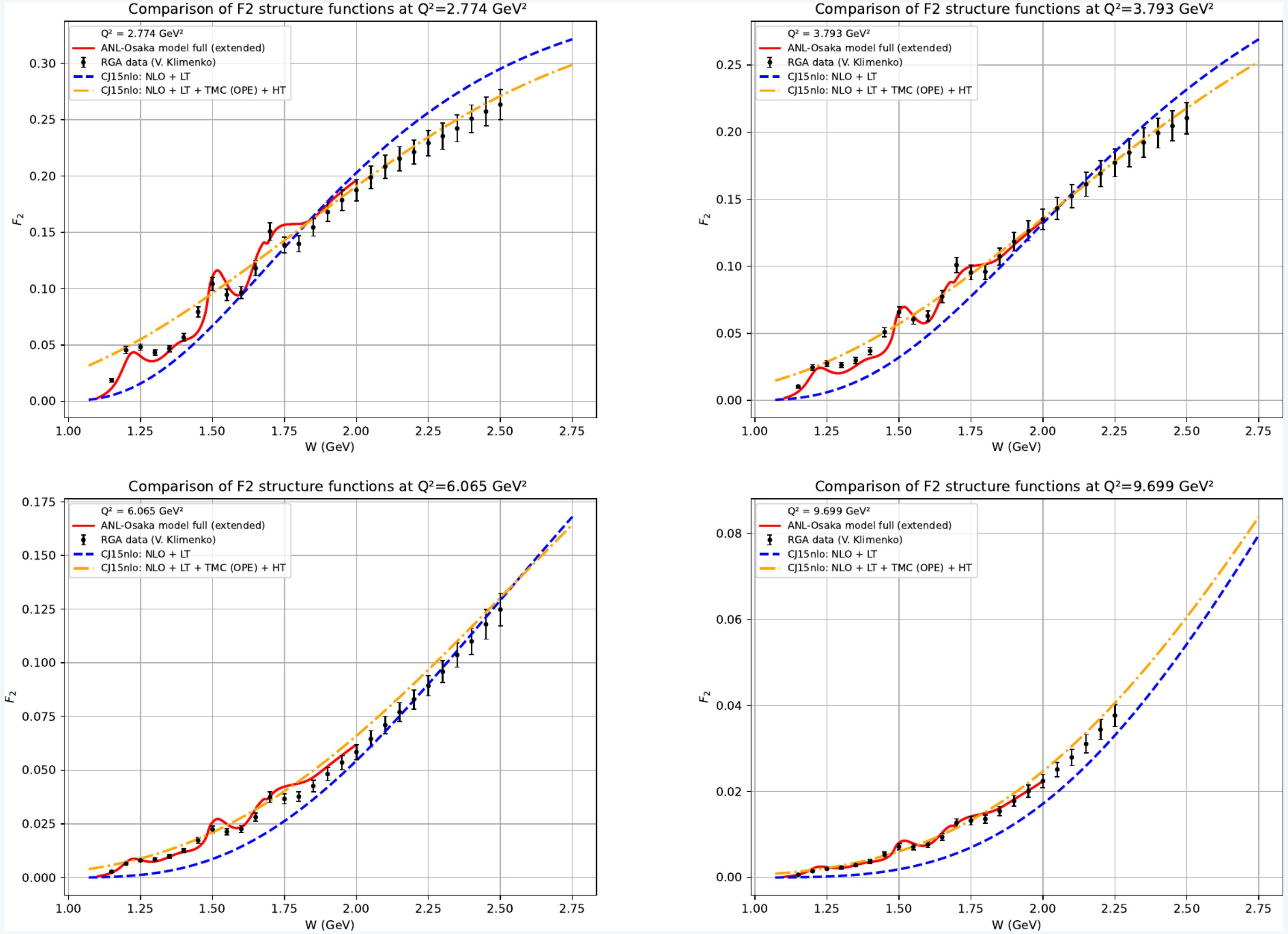
- **CJ15+LT+TMC+HT (orange) stays nonzero at the πN threshold while the extracted F_2 vanishes — a low-W distortion that later biases the 1st–2nd region moments.**



Local duality persists out to $Q^2 \approx 10\ \mathrm{GeV}^2$

Across the full range

- Extracted F_2 keeps its resonance structure and oscillates about CJ15+TMC+HT at every Q^2.
- CJ15+LT (blue) undershoots at low W; the gap closes as Q^2 grows — just as the OPE predicts for higher-twist suppression.
- **Near threshold, CJ15+LT+TMC+HT stays nonzero (unlike F_2 and CJ15+LT) — the low-W distortion behind the 1st–2nd region overshoot.**
- **Consistent with local duality within present uncertainties.**



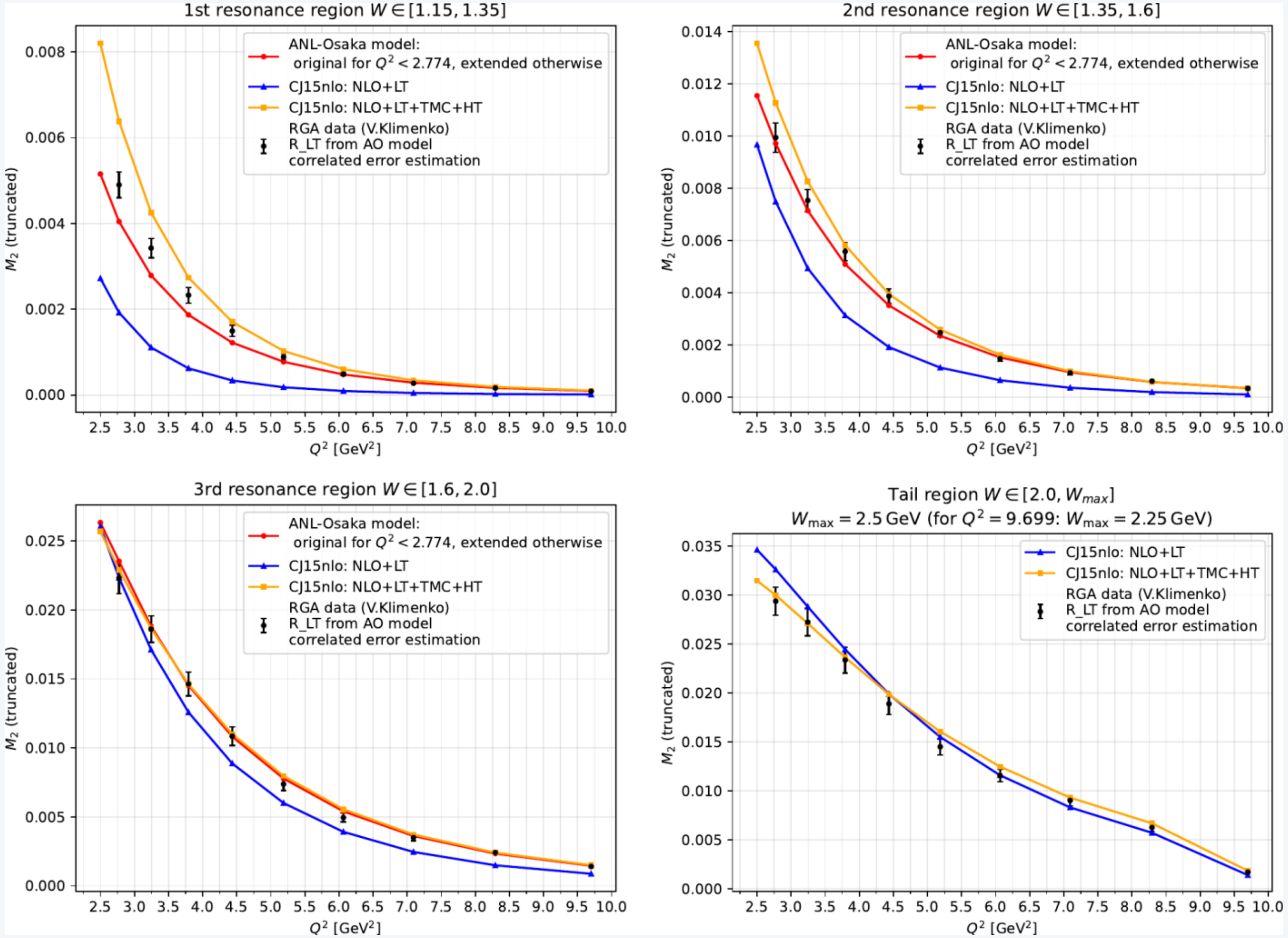
Truncated Cornwall–Norton moments $M_2(Q^2)$

Integrate F_2 over each W window

- TMC+HT overshoots the data — largest in the 1st region, smaller in the 2nd, gone by the 3rd & high-W — the ordering tracks its threshold violation.
- 3rd & high-W regions agree with CJ15+LT+TMC+HT for $Q^2 \gtrsim 2.5$ GeV².

Local → global

- **Contiguous windows ⇒ region-by-region agreement sums to global duality.**



Duality holds, simultaneously, at three levels up to $Q^2 \approx 10$ GeV^2

- Cross sections: the ANL–Osaka-anchored extension reproduces the three-resonance structure at every Q^2 and merges smoothly into CJ15+TMC+HT.

- Structure function F_2: the extracted F_2 oscillates about the smooth partonic curve across the full range — local duality, with multi-meson channels essential.

- Truncated moments M_2: good agreement in the 3rd-resonance and high-W regions; the low-W discrepancy is associated with the threshold effect.

Where this leads next

- Higher moments M_4 and M_6 would constrain higher-twist matrix elements directly through the OPE.
- Threshold-constrained global analyses — enforcing $F_2 \to 0$ at W_{thr} — would remove the first-region excess.
- Forthcoming exclusive CLAS12 data, p(e,e′π)N and p(e,e′ππ)N, will test the 1π/2π content and inform a high-Q^2 $\gamma N \to N^*$ form-factor extension.
- A JLab 22 GeV upgrade would extend the duality study to $Q^2 = 12$–$18\ \mathrm{GeV}^2$.
- The extracted F_2 can feed new global PDF analyses of the large-x proton.

Submitted to Physical Review C, currently under review — preprint arXiv:2606.29690.

The modified Breidenbach–Kuti shape function

$$G(\omega'; c_1, c_2, c_3, c_4) = \sum_{i=1}^{4} c_i\left(1-\tfrac{1}{\omega'}\right)^{2+i} = c_1\left(1-\tfrac{1}{\omega'}\right)^3 + c_2\left(1-\tfrac{1}{\omega'}\right)^4 + c_3\left(1-\tfrac{1}{\omega'}\right)^5 + c_4\left(1-\tfrac{1}{\omega'}\right)^6$$

$\omega'[Q^2, W] = 1 + W^2/Q^2$. The $i = 4$ term is the addition to the original three-term Breidenbach–Kuti form, capturing the curvature change seen in the high-W data as Q^2 increases. The same functional form, with its own coefficients $c'_1 \ldots c'_4$, is used for σ_1.

Why eight parameters, not ten

$$\alpha,\ \beta\ +\ \{c_1..c_4\}\ +\ \{c'_1..c'_4\}\ =\ 10\quad\longrightarrow\quad \alpha,\ \beta,\ r_1, r_2, r_3,\ r'_1, r'_2, r'_3\ =\ 8$$

Each G enters only as a ratio, so the overall normalizations c_1 and c'_1 cancel: $r_i = c_{i+1}/c_1$ and $r'_i = c'_{i+1}/c'_1$.

Adopted fit (ANL–Osaka R_{lt} prior): $\alpha = -0.069 \pm 0.011$, $\beta = -0.063 \pm 0.011$, $r_1 = -1.76$, $r_2 = 4.50$, $r_3 = -3.21$, $r'_1 = 4.86$, $r'_2 = -16.96$, $r'_3 = 19.00$

$\chi^2/\mathrm{ndf} = 2.02$ total, 2.00 data-only, 0.02 penalty.