Towards a combined description of **proton structure functions** from the resonant to the perturbative regime

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Precision QCD predictions for ep Physics at the EIC
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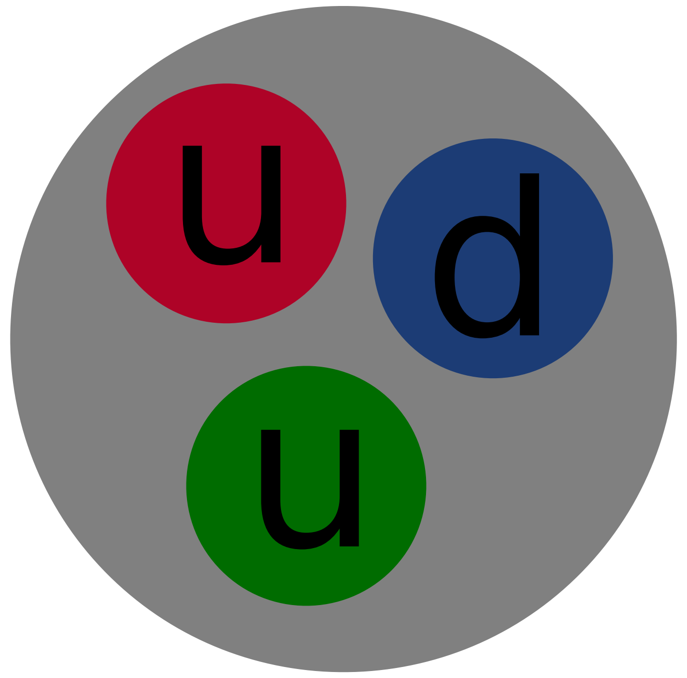
Protons and their mysteries

Protons have been the subject of scrutiny for decades,
the quark substructure was already measured in 1968 at SLAC.
But they are still far from being understood.

QCD describes the strong force binding the constituents,
but it behaves remarkably differently at high and low energies.

At high energies perturbative QCD allows for an expansion in α_s
with controlled series truncation uncertainty.
The quarks and gluons are **asymptotically free**.



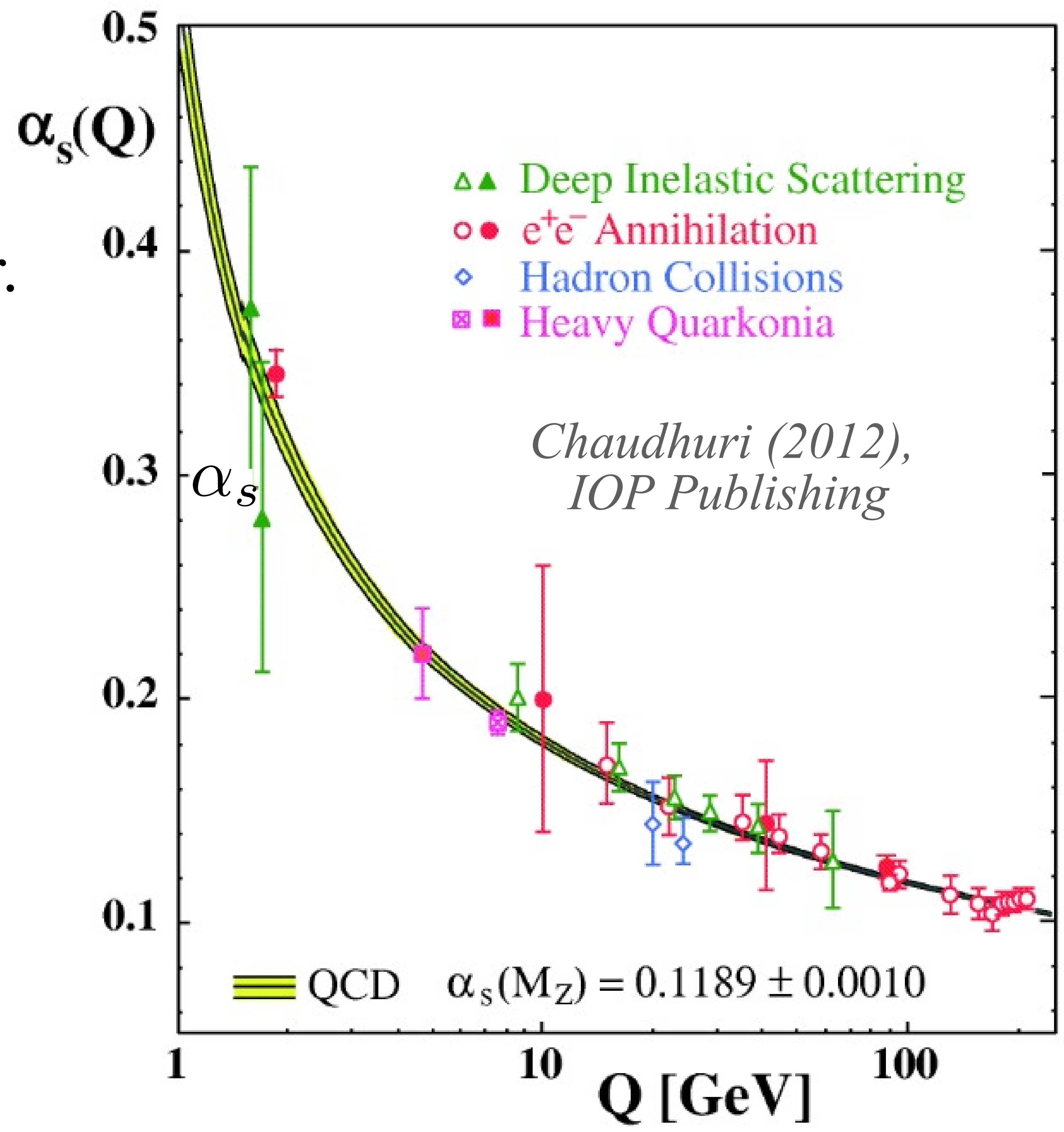
Low energies — large distances

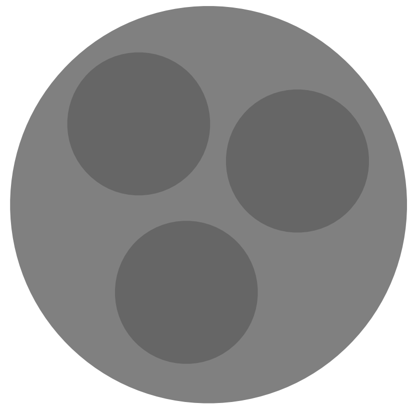
At low energies, the physics of the constituents is obscured.

α_s becomes too large to be a valid perturbative expansion parameter.

Perturbative QCD breaks down —
effective field theories (EFTs) are called for.
E.g. chiral perturbation theory obeys all QCD symmetries
and one can have a perturbative expansion again.

The quarks and gluons are **confined** —
hadrons themselves become the new degrees of freedom.





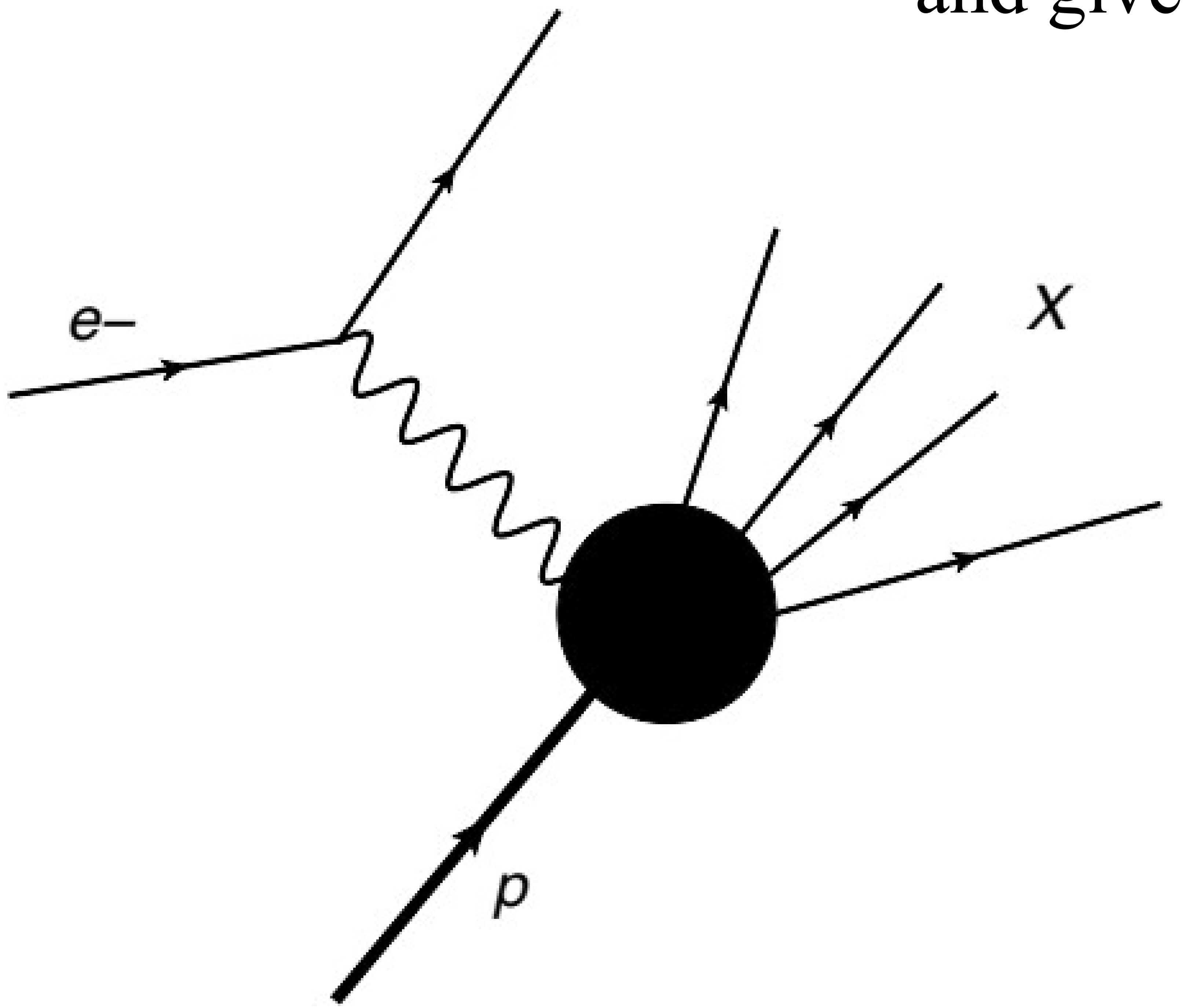
Probing protons with electron beams

Electron beams have historically been the main tool to scrutinize the proton inner structure.
Reactions with electrons and photons can yield cleaner probes than hadron colliders.

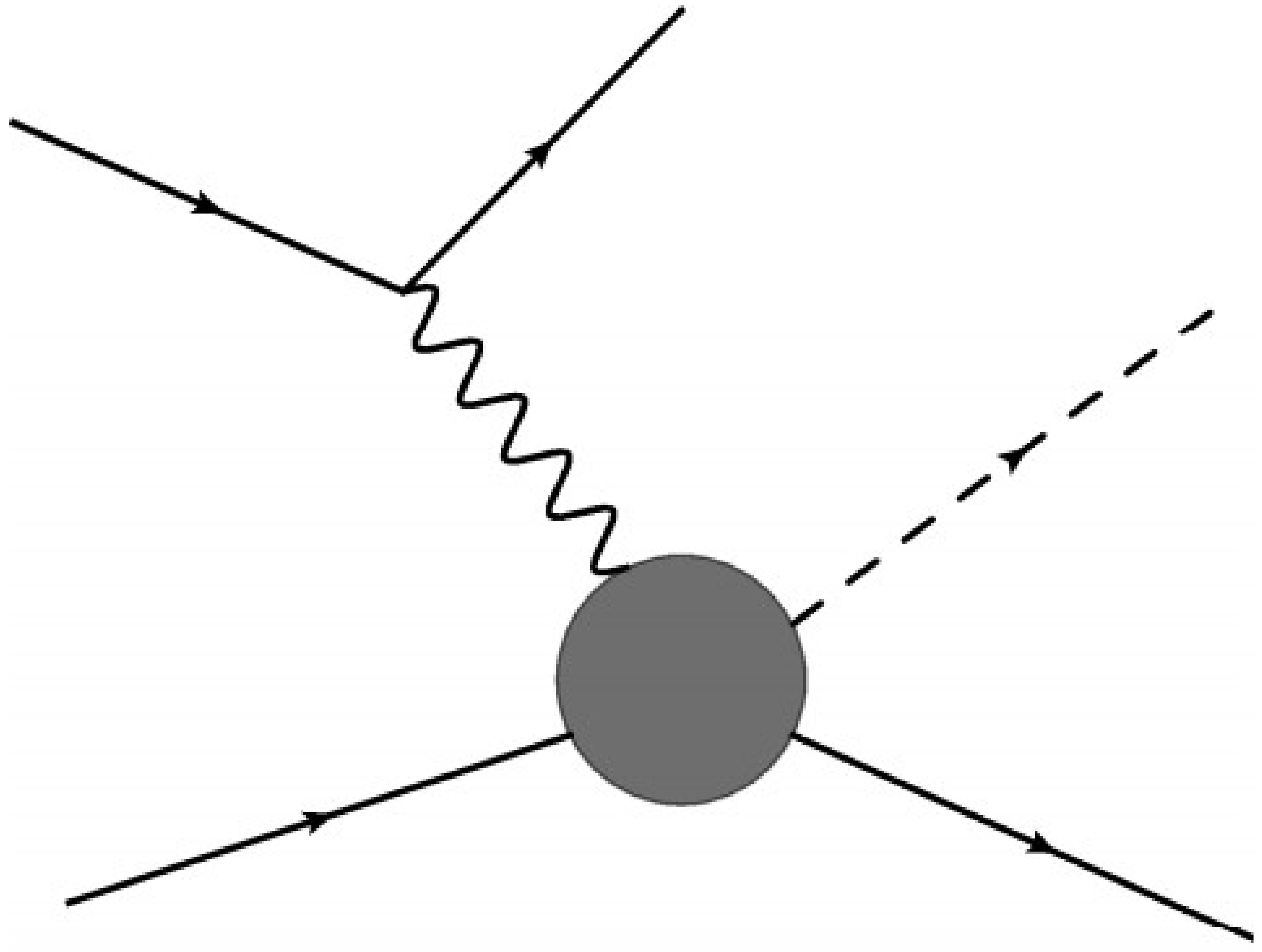
Inclusive reactions probe **all possible final states** and give access to the structure functions.

$$F_1 \propto \sigma_T(W, Q^2)$$

$$F_2 \propto \sigma_T(W, Q^2) + \sigma_L(W, Q^2)$$

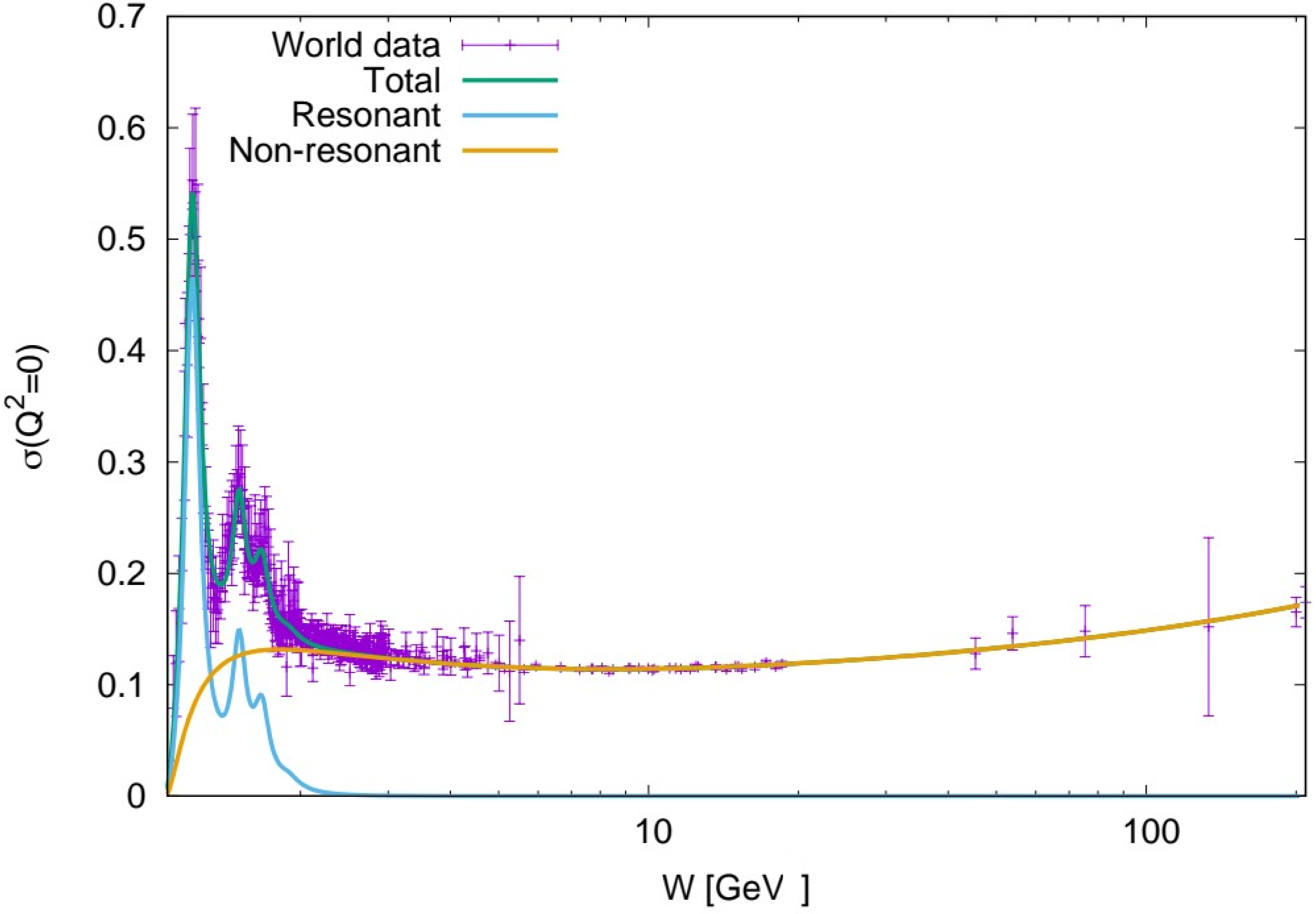


Exclusive reactions probe **specific production channels.**
Smaller cross-section yield, but cleaner analysis.



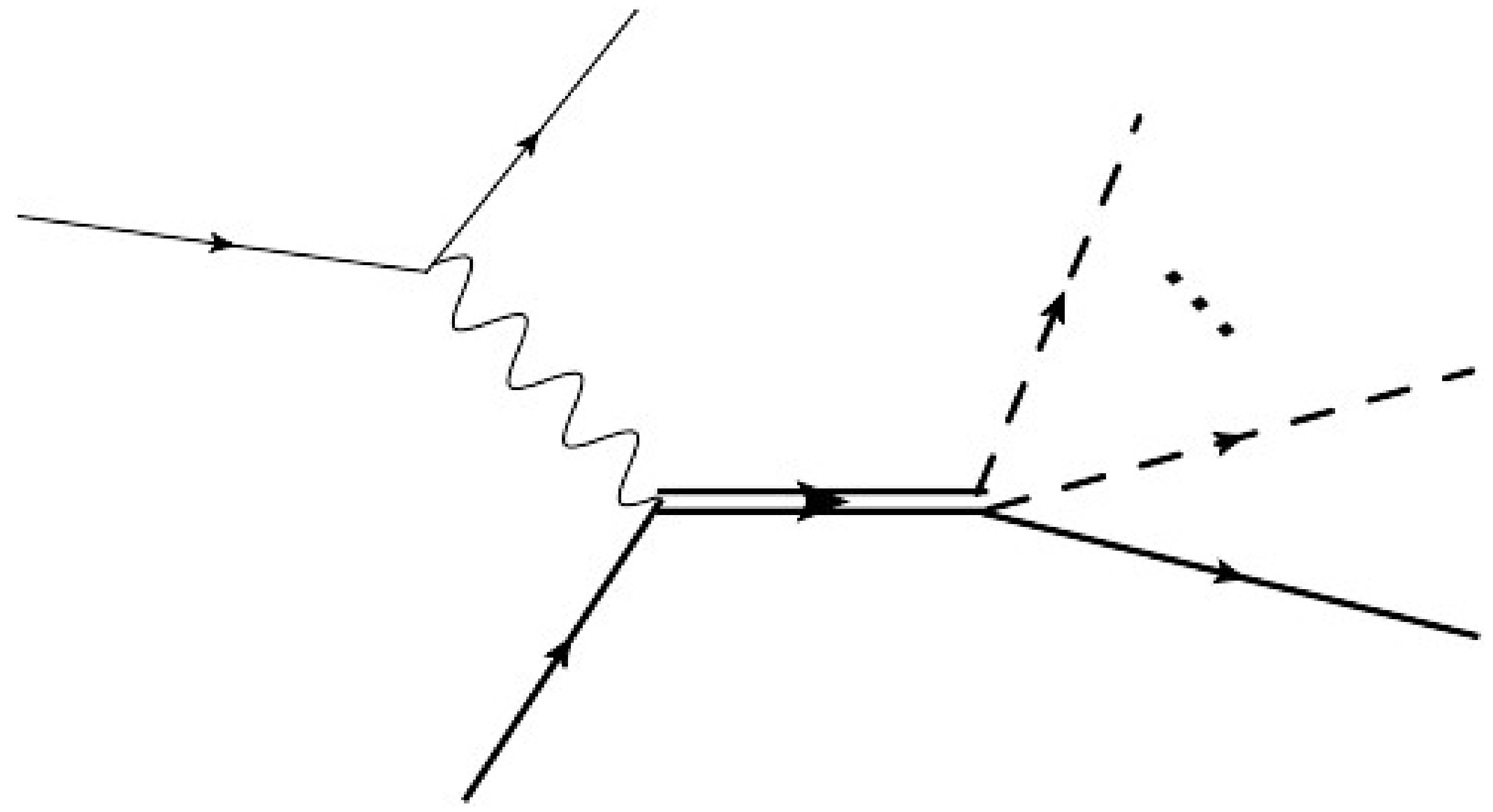
Goals of inclusive and exclusive reactions

Inclusive photoproduction cross section

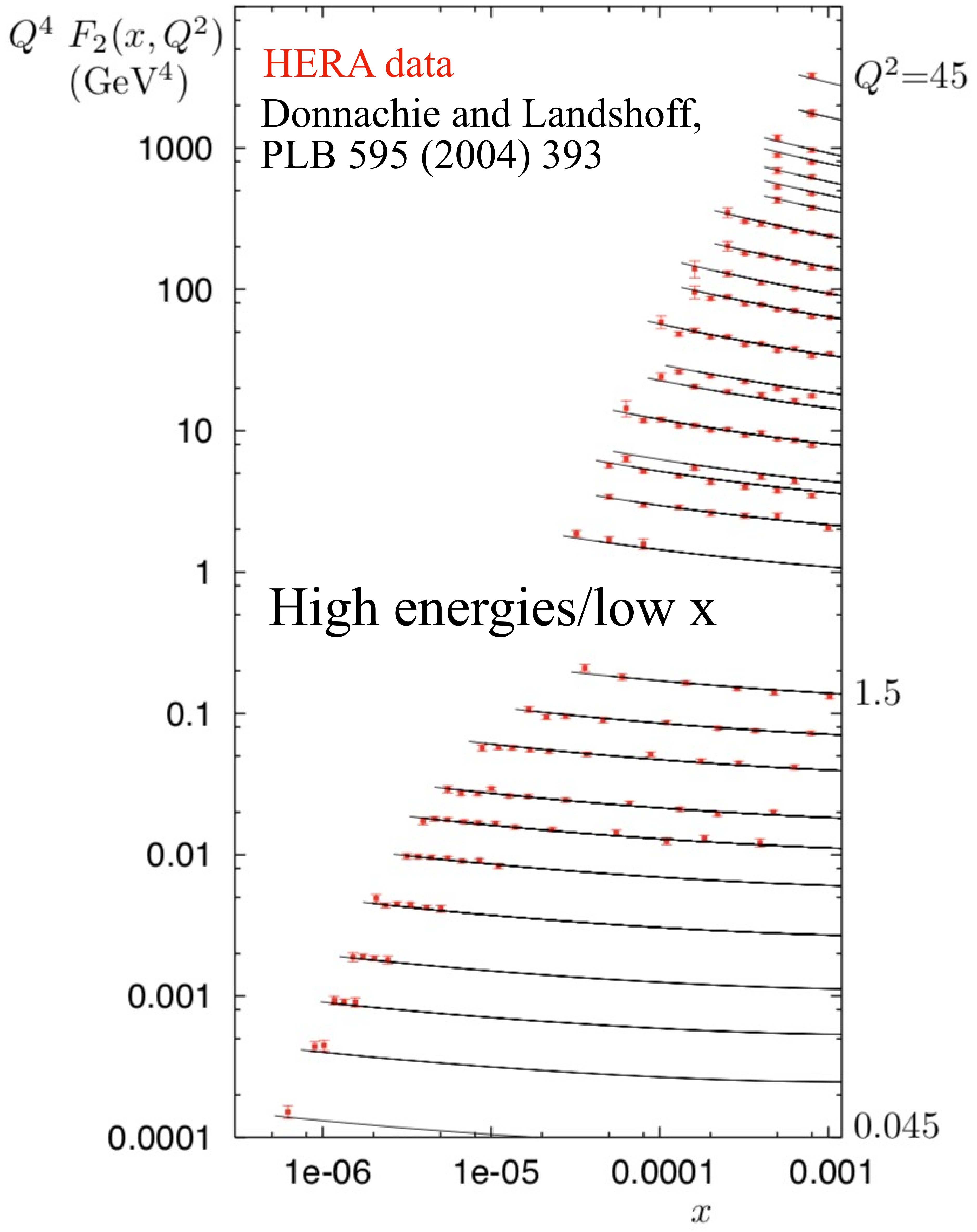


Insight into targets' inner **structure: can we describe the transition from low to high energies?**

Hadron **spectroscopy.**

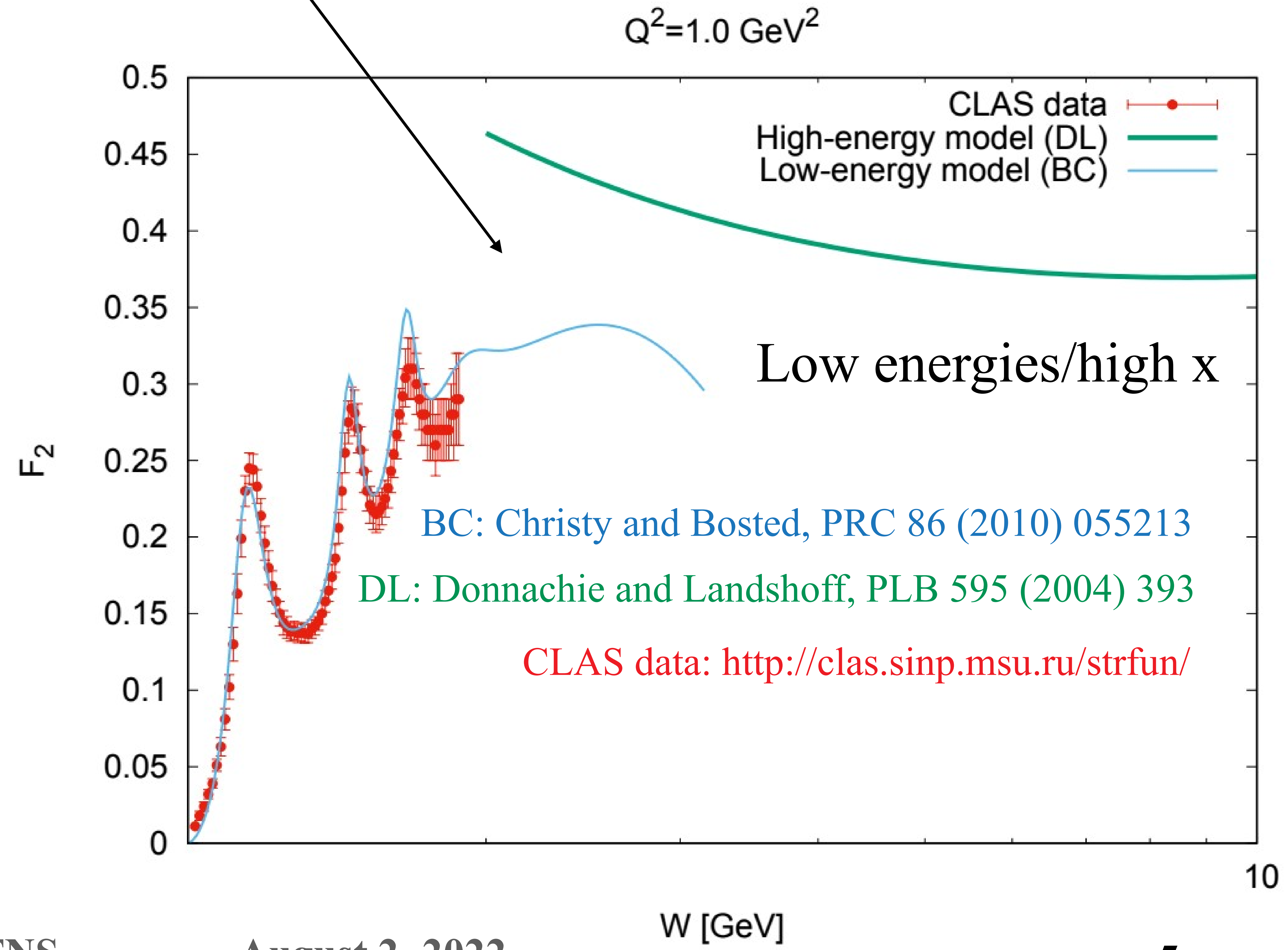


Low and high energies: towards a connection



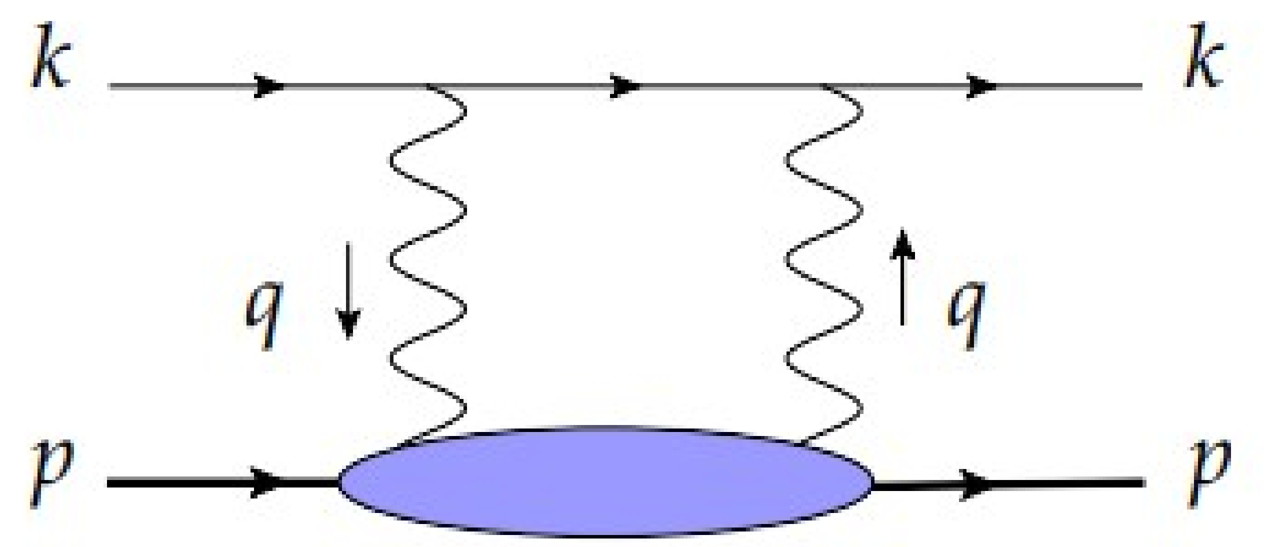
$$x = \frac{Q^2}{2M_N\nu} \quad \nu = \frac{W^2 - M_N^2 + Q^2}{2M_N}$$

Closing the gap will allow for **precision** in observables that rely on **integration across energies.**



Precision in integrated observables

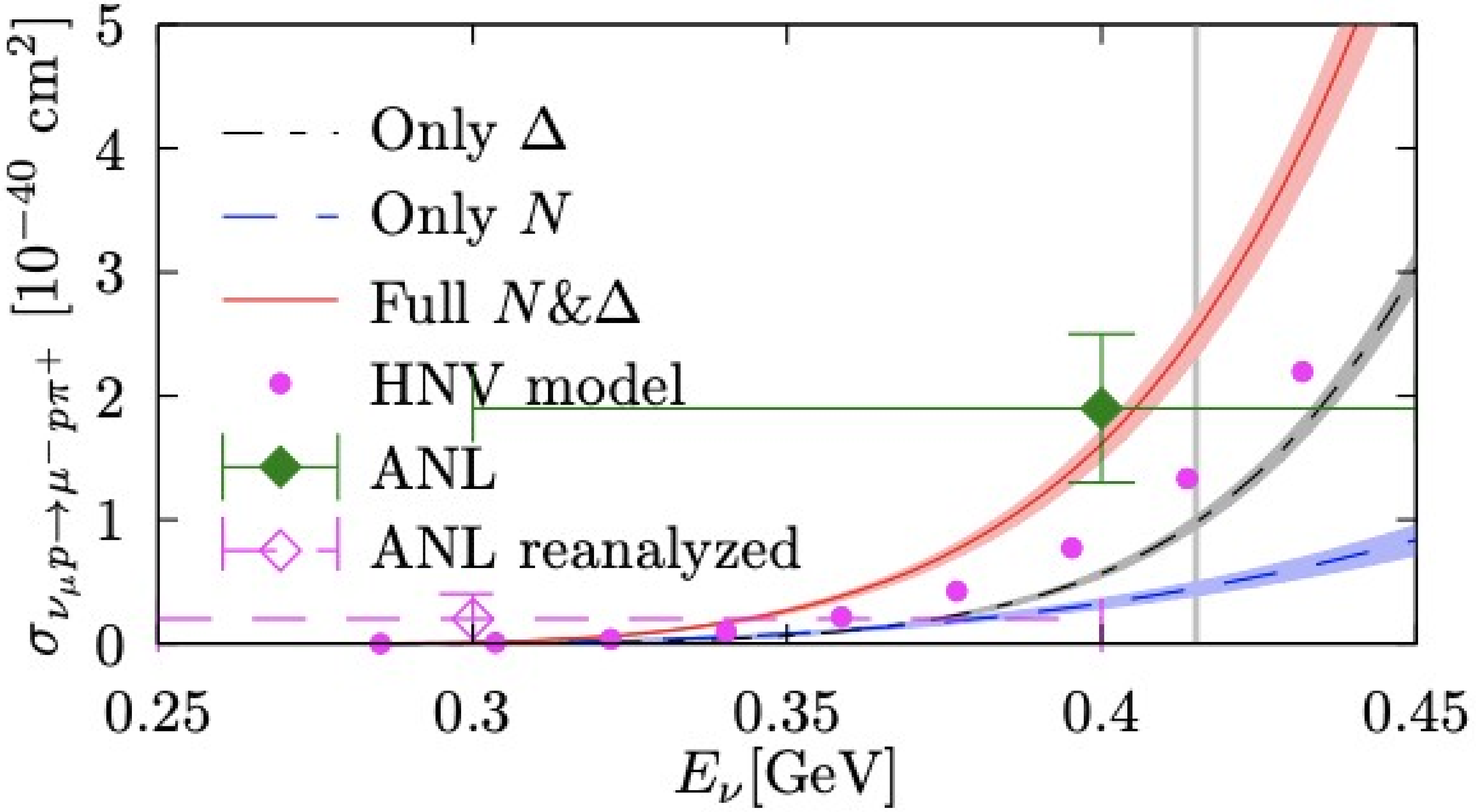
Atomic physics: hadronic contributions to the **Lamb shift** in muonic hydrogen.



$$\mathrm{Im}T_2(\nu, Q^2) = \frac{1}{4\nu} F_2(\nu, Q^2)$$

$$\mathrm{Re}T_2(q_0, Q^2) = \mathrm{Re}T_2^{pole}(q_0, Q^2) + \frac{1}{2\pi} \int_{\nu_{thr}}^{\infty} \frac{d\nu F_2(\nu, Q^2)}{\nu^2 - q_0^2}$$

Particle physics: precision in **neutrino oscillation** studies – νN cross sections integrated over large energy bins.



Yao, ANHB et al., Phys. Rev. D 98 (2018) 076004, 1806.09364 [hep-ph]

Direct connection to **parton distribution functions.**

$$F_2(x, Q^2) = \sum_i \int_x^1 \mathrm{d}\xi \, \widehat{\mathcal{F}}_2^i(x/\xi, Q^2) \, f_i(\xi)$$

Tests on **quark-hadron duality.**

A proposal for a combined parametrization

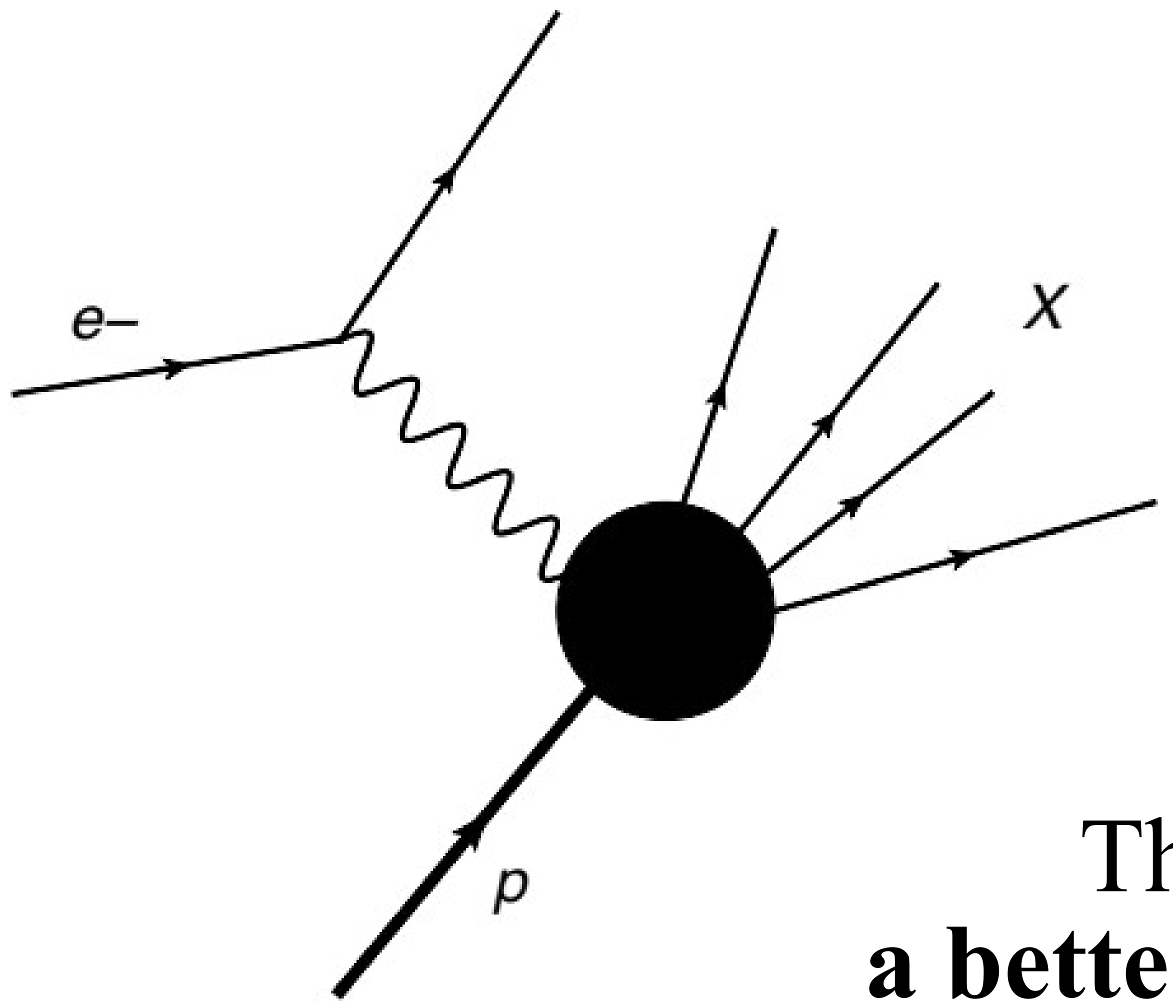
Should recover the high-energy behavior.

Implements the threshold and resonance behavior.

Has physics constraints, obeying analiticity and dispersion relations.

Experimental prospects

Precise **Jefferson Lab** CLAS(12) data make studies of **resonance region** very timely.



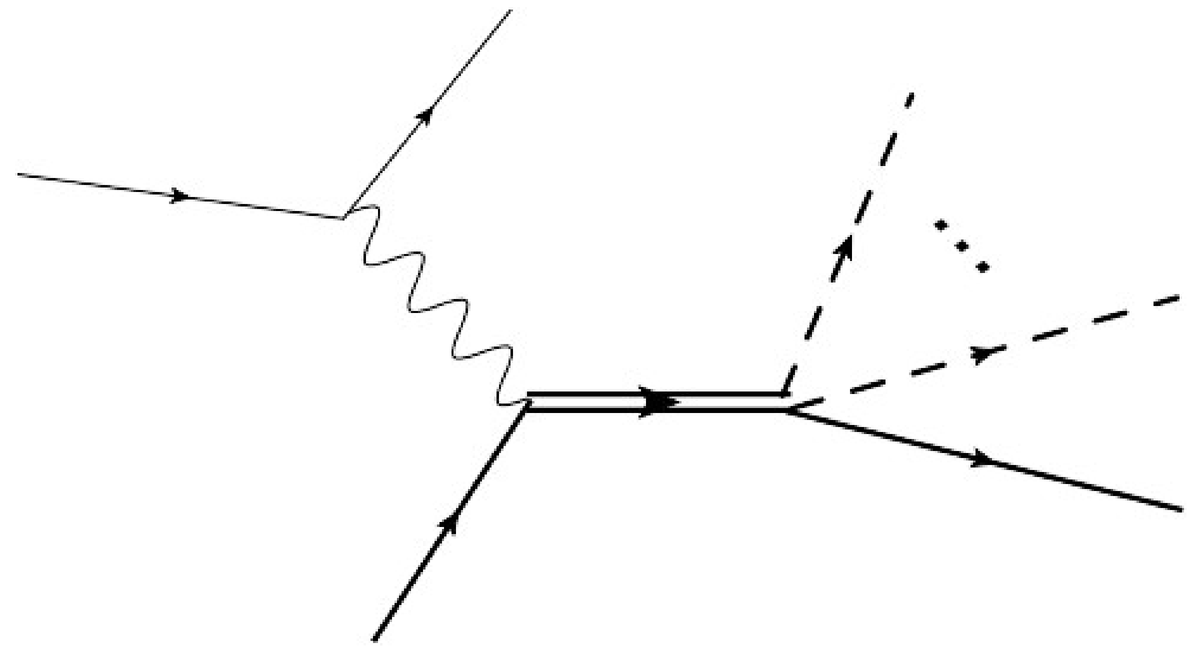
The **EIC** allows to scrutinize similar physics as electron accelerators — instead of fixed proton targets, the protons are accelerated (lightest ion).

The focus is on high luminosity at intermediate/high energies – path towards **a better understanding of the transition between chiral and perturbative regimes!**

Promising decades of insights into proton structure, quark confinement, proton spin puzzle, heavy and exotic hadron production and nature, …

From exclusive to inclusive electron scattering

$$\sigma_{T,L}(W,Q^2) = \sigma^R_{T,L}(W,Q^2) + \sigma^{NR}_{T,L}(W,Q^2)$$



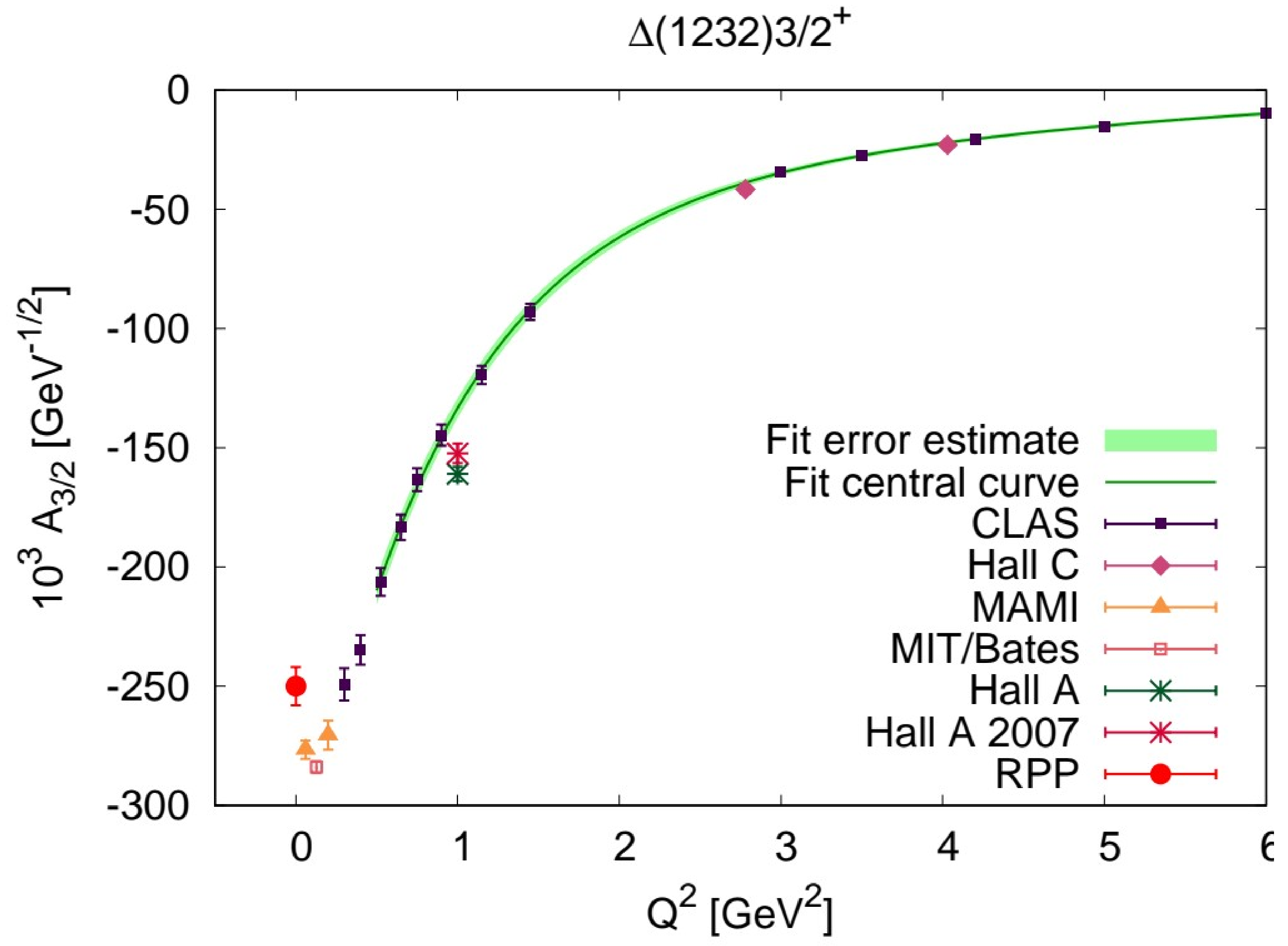
$$\sigma^R_{T,L}(W,Q^2) \propto \Gamma^{T,L}_\gamma(M_r,Q^2)$$

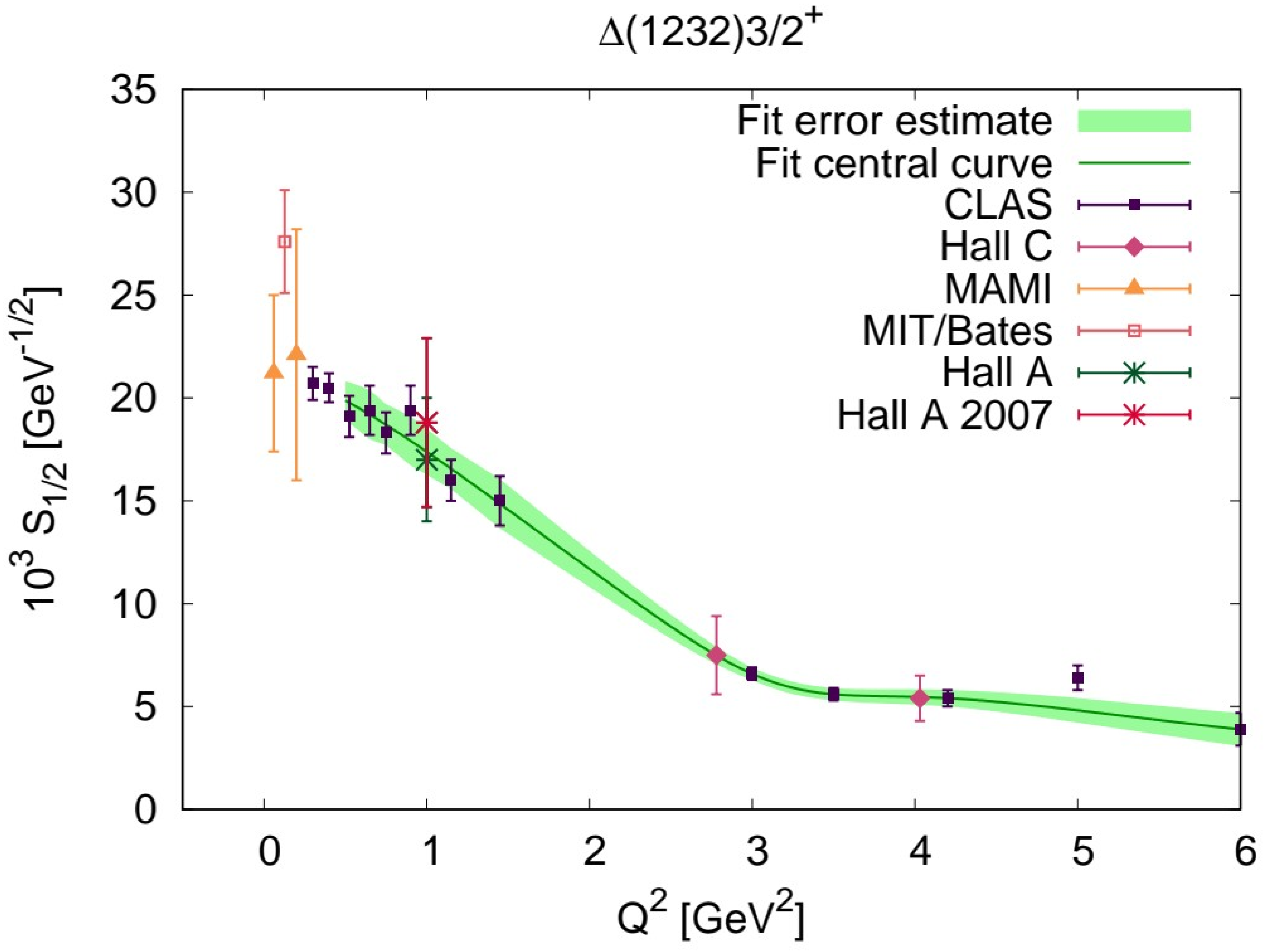
$$\Gamma^T_\gamma(M_r,Q^2) \sim \left|A_{1/2}(Q^2)\right|^2 + \left|A_{3/2}(Q^2)\right|^2$$
$$\Gamma^L_\gamma(M_r,Q^2) \sim \left|S_{1/2}(Q^2)\right|^2$$

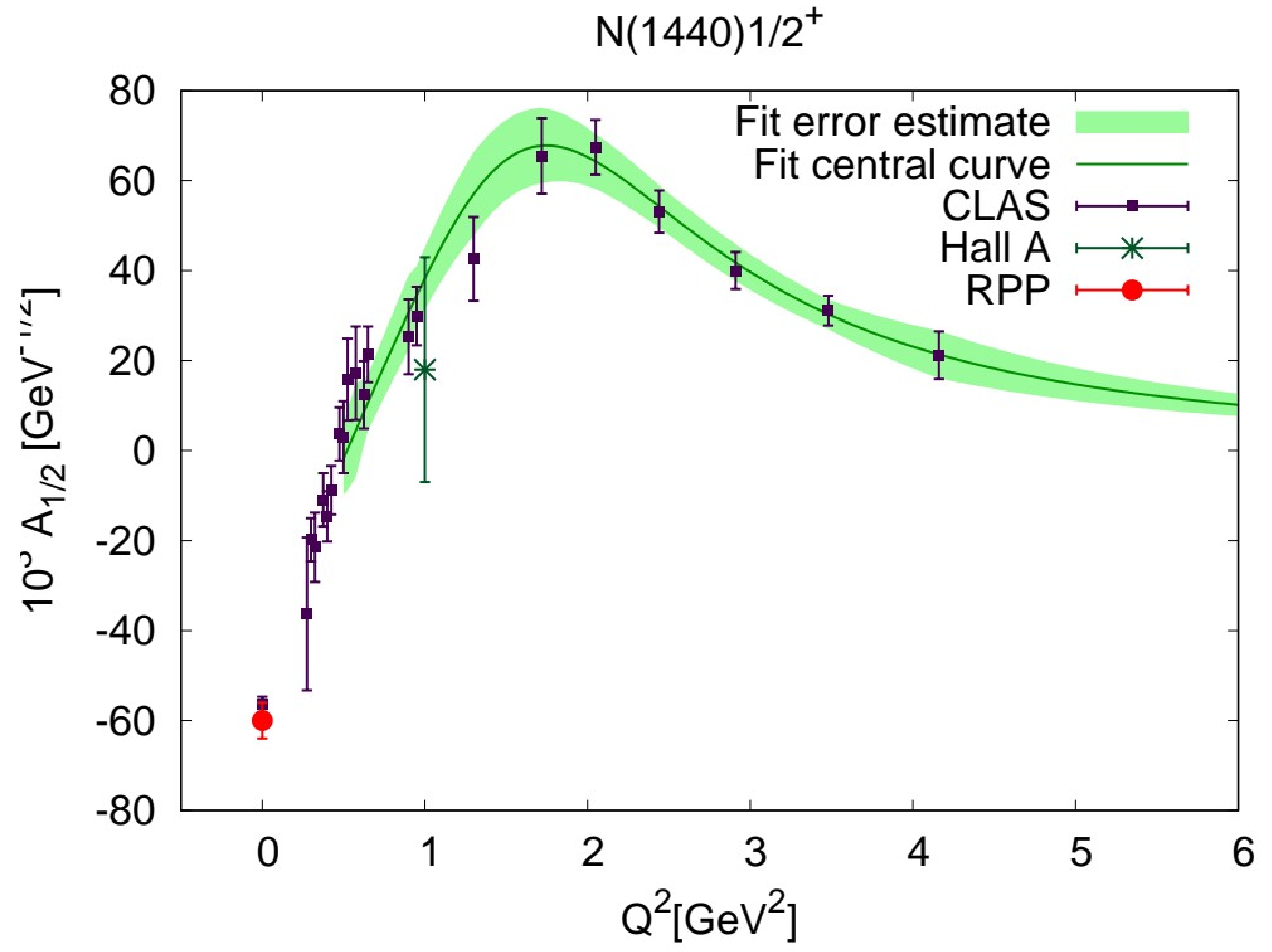
Breit-Wigner resonance model:
coherent sum of resonances.

From exclusive data: electrocouplings.

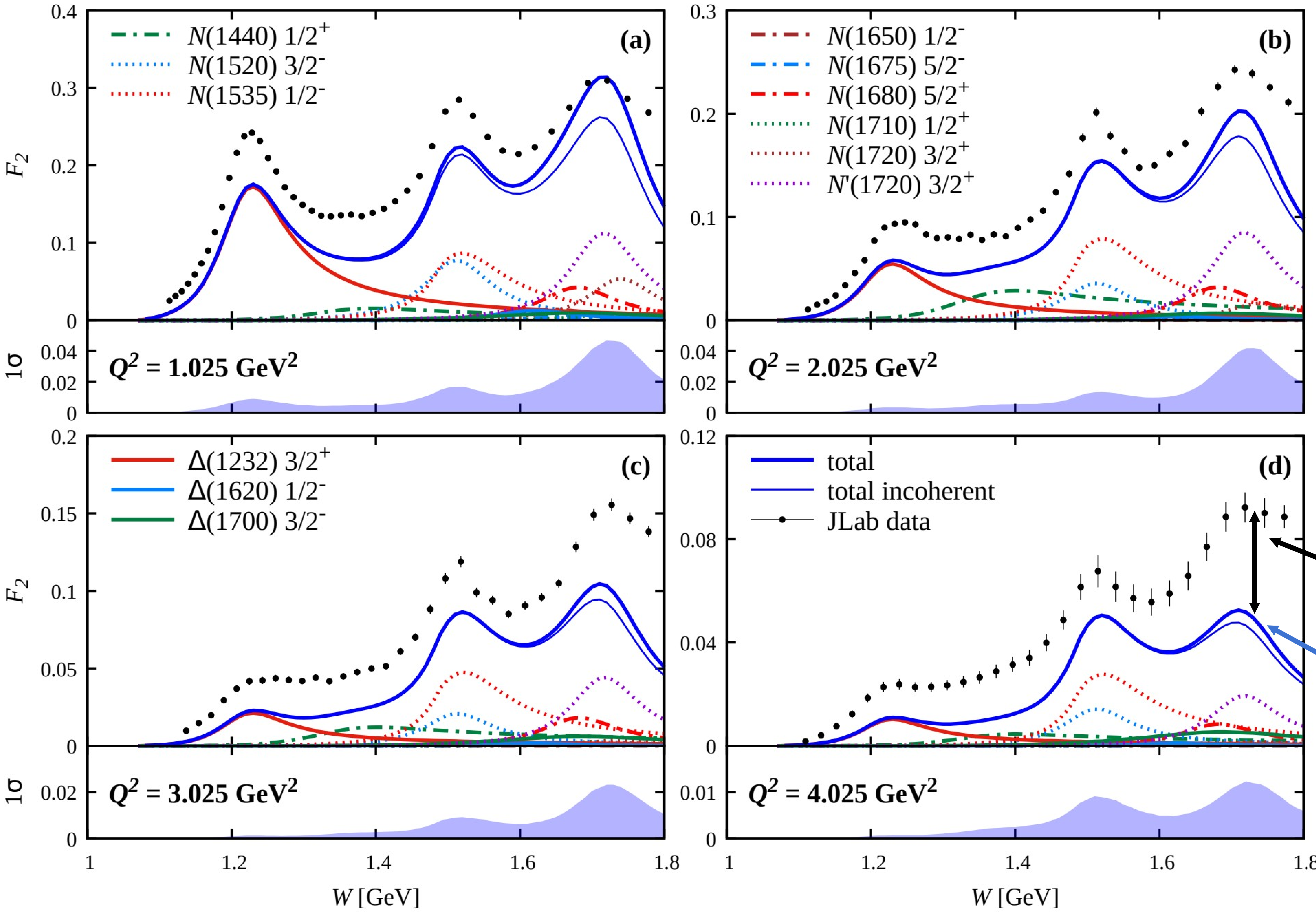
https://userweb.jlab.org/∼isupov/couplings/
https://userweb.jlab.org/~mokeev/resonance_electrocouplings/
ANHB et al., Phys. Rev. C 100 (2019) 035201, 1904.08016 [hep-ph]
ANHB et al., Phys. Rev. C 104 (2021) 025201, 2105.05834 [hep-ph]







Resonant contributions at different Q^2



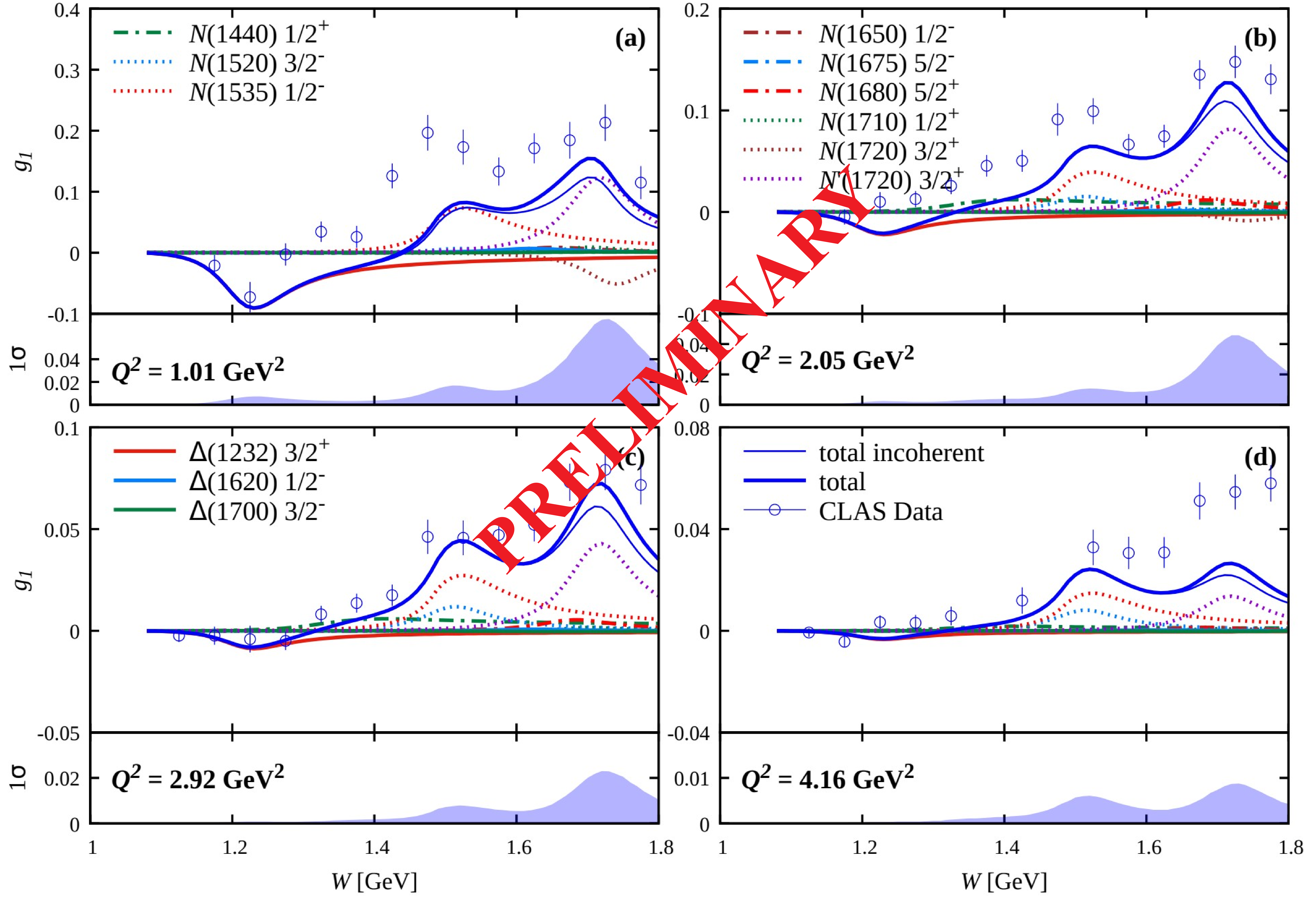
ANHB et al., Phys. Rev. C 100 (2019) 035201, 1904.08016 [hep-ph]
ANHB et al., Phys. Rev. C 104 (2021) 025201, 2105.05834 [hep-ph]

Intricate differences in evolution of peaks with Q^2.

Resonance contributions remain strong at all Q^2, **supporting future studies of electrocouplings.**

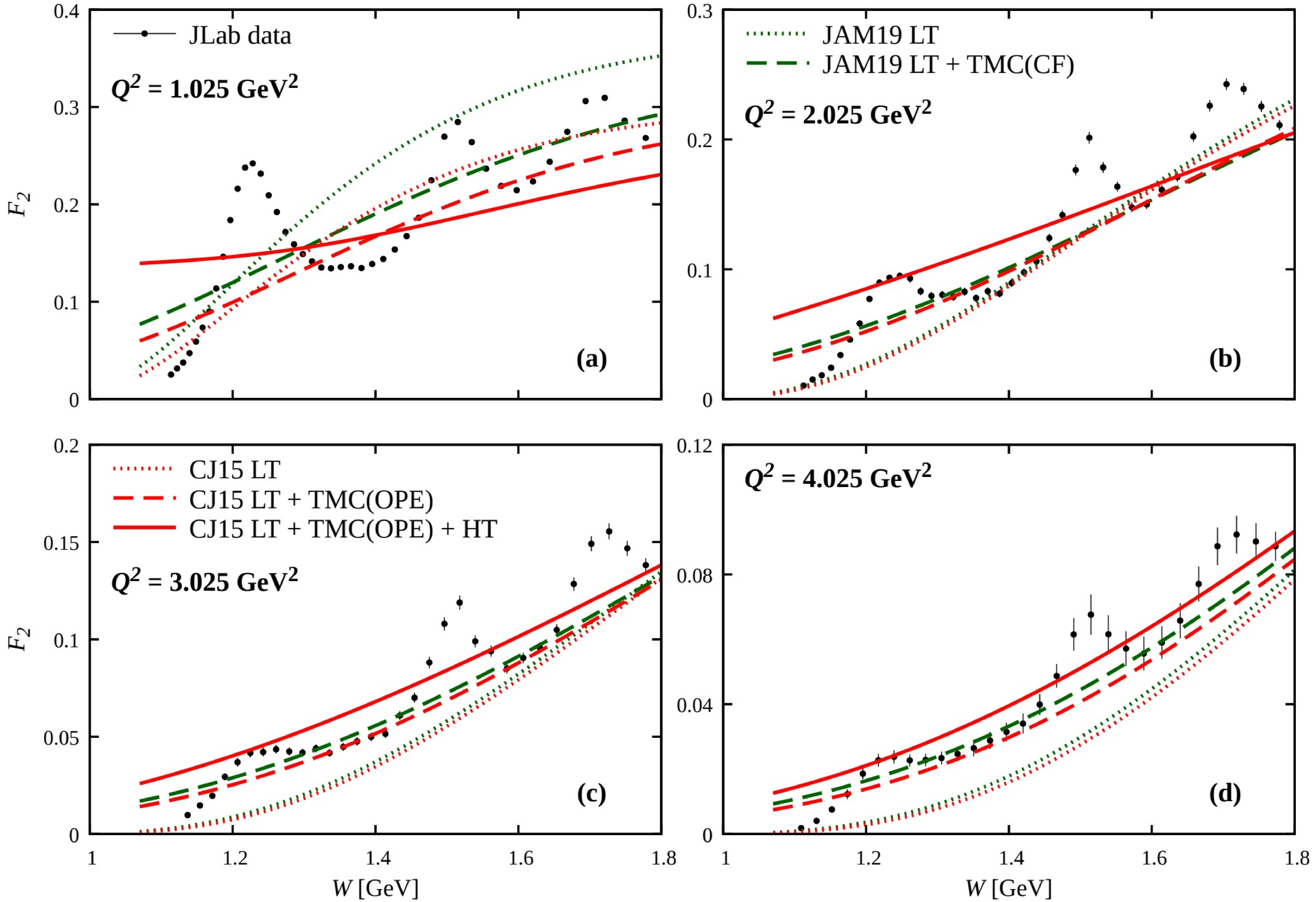
$$F_2^R + F_2^{NR} = F_2$$

Polarized structure functions



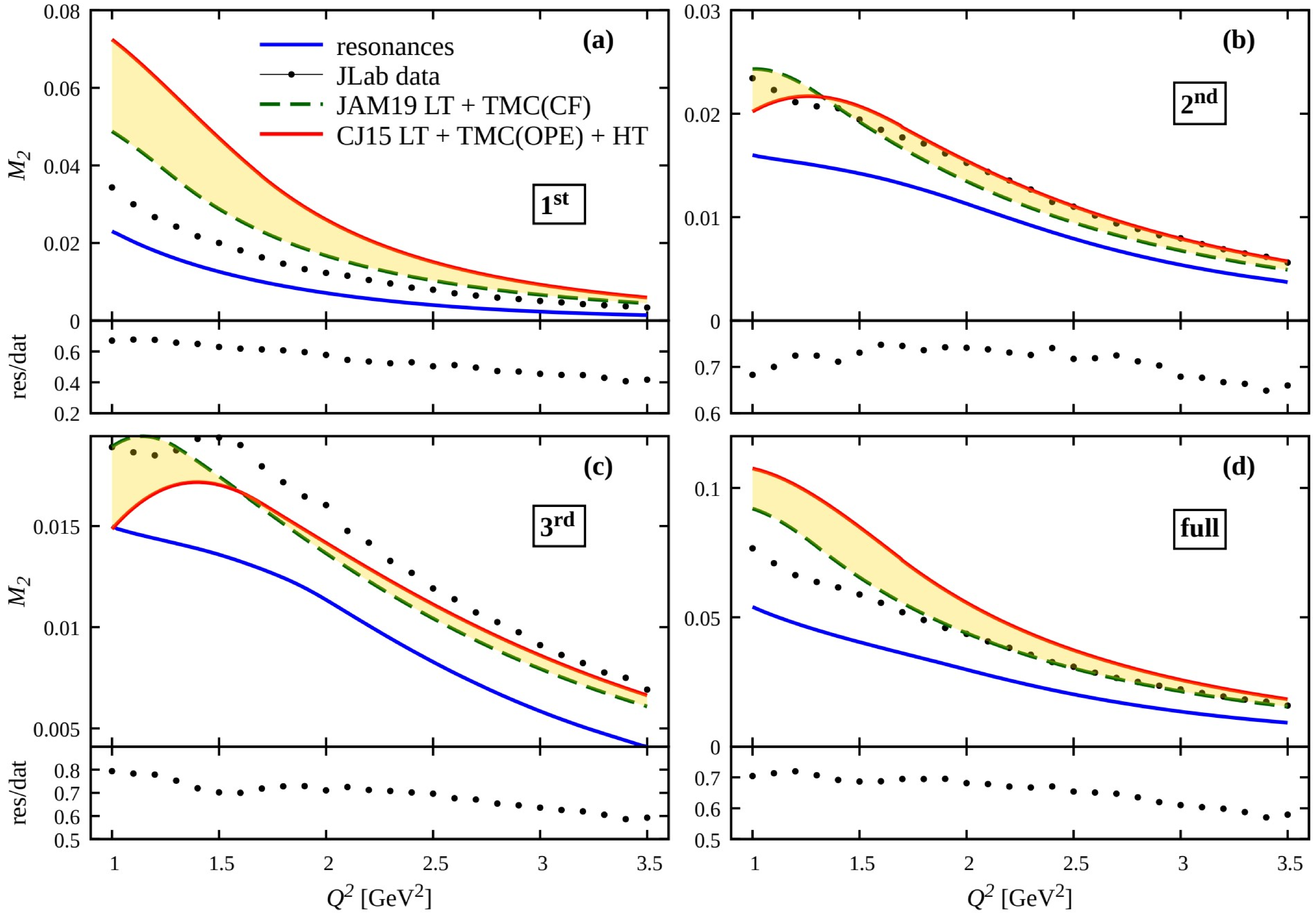
Currently extending to polarized structure functions.

Comparison with PDF fits to DIS region



The **PDF fits** with target-mass corrections and higher-twist contributions are **compatible with averaged data** in the resonance region: opportunities for studies of PDFs at large x.

Truncated moments



Integration over energies.

PDF fits in the **DIS region extrapolated** and compared to the **resonance region.**

Global duality onset, especially when considering target mass corrections and higher-twist contributions.

Summary and outlook

Scrutinizing inclusive and exclusive reactions off proton targets is useful for:

hadron spectroscopy — insight into spectrum of hadron resonances;
nucleon structure — describing the transition from perturbative QCD to the chiral regime.

The description of the transition from high to low energies:

– allows a better access to **integrated (precision) observables;**
– requires a sturdy description of the **threshold** behavior and separate **resonance** contributions;
– will profit highly from the **EIC data-taking era** at intermediate/high energies and **ML-based analysis**.

Our data-driven calculations have already provided first steps towards:

– a better understanding of the **nucleon resonance spectrum** from electrocoupling data;
– recognizing an onset of quark-hadron duality (resonance vs DIS regions) in truncated moments.