Towards a proton structure map from low to large x

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November 3, 2021

Outline

1. The broader context
2. A brief excursion to exotic baryon resonances

3. Proton structure: inclusive electron scattering
4. Information from exclusive meson production channels
5. Inclusive and exclusive data: an information interplay

6. An excursion to existing data so far
7. What we hope to see in future experiments

1. What’s new about the proton?

Probing protons with lepton/photon beams

- The properties of the proton have been the subject of scrutiny for decades.
  There are many open questions!

- Mass, radius, quark and gluon distributions,… All are far from already being well understood.

- Lepton-nucleon/nucleus collisions are great laboratories:
  cleaner than hadronic collisions, richer than e^+e^- annihilation.

- High luminosity experiments will allow for multi-differential exploration of kinematic regimes:
  Promising in the electron-ion collider era and timely in the existing JLab experiments.

Towards unveiling proton properties

- Emergence of proton mass: **current quark masses** make up only fraction of the total proton mass.
  In addition, one needs to consider the **kinetic/potential energy** of quarks and gluons,
  and the **considerable trace anomaly contribution** from QCD energy-momentum tensor (EMT).

  $$M_N = M_m + M_q + M_g + M_a$$

  Tightly connected with the gluon content and distributions/form factors within the proton!

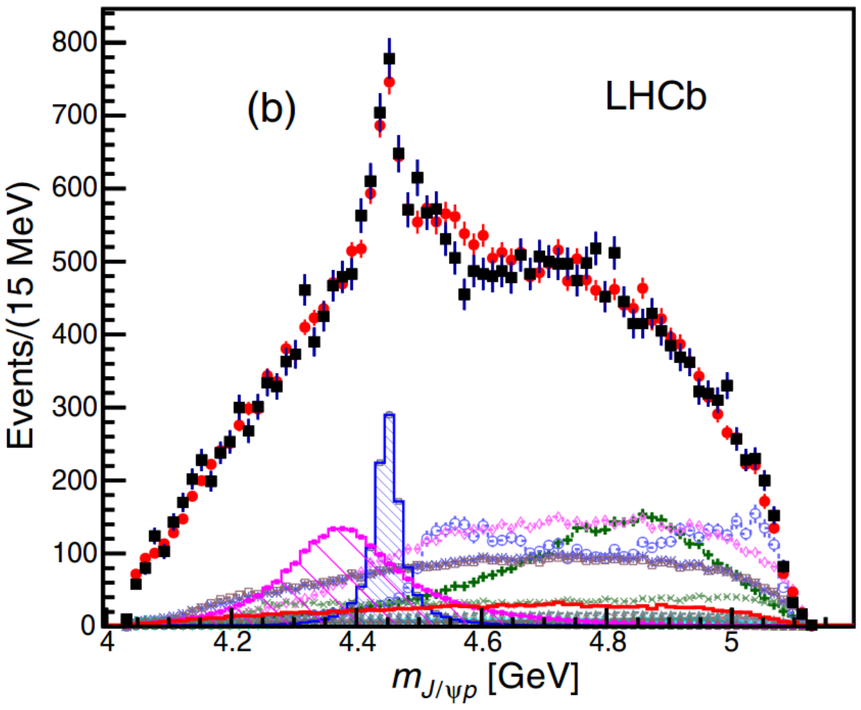
- **Color van der Waals** forces arise between protons and heavy quarkonia
  (even when no valence quarks are shared):
  visible in quarkonium production close to threshold (small relative momentum in the final state).
  The attractive force might lead to proton/nucleus-quarkonium **bound states**.

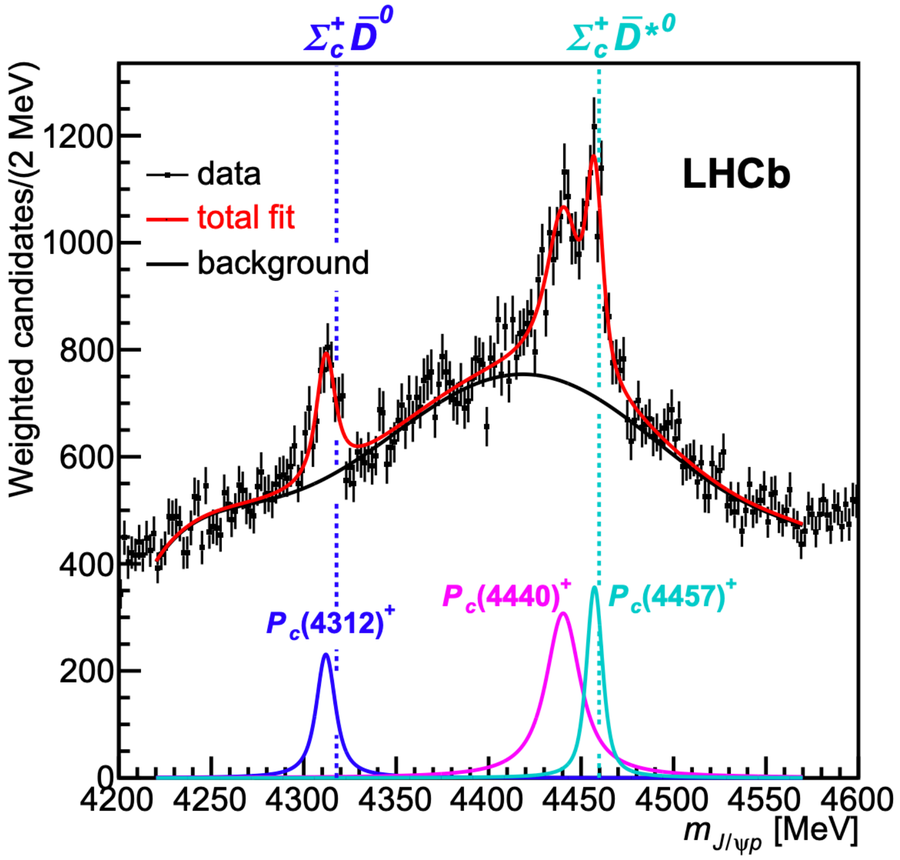
- The proton shows a rich N^* and Δ **resonance excitation spectrum**.
  Do the quarkonium-nucleon interactions enable the appearance of **exotic pentaquark resonances?**
  Can we confirm their resonant nature in photoproduction experiments?

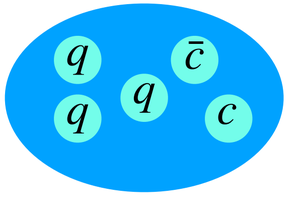
2. Pentaquarks briefly

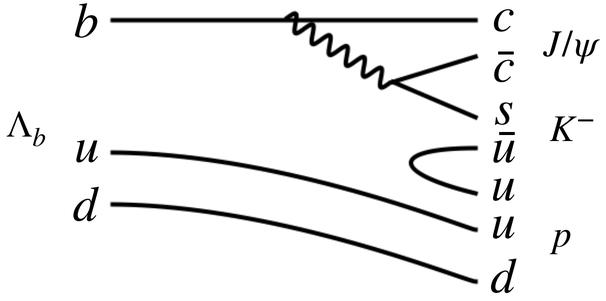
A brief excursion to exotic baryons

- In 2015, exotic-like structures in the $J/\psi\, p$ channel were found.
  [Aaij et al. [LHCb], PRL 115 (2015) 072001; Aaij et al. [LHCb], PRL 122 (2019) 222001]





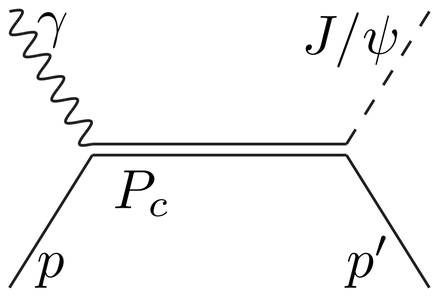


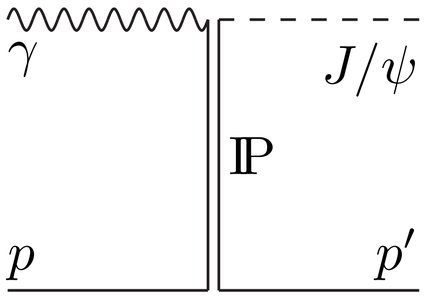


$P_c \equiv c\bar{c}uud$

Possible interpretations

- Compact 5-quark states.
- Weakly-bound $\bar{D}^*\Sigma_c^{(*)}$ molecule.
- Kinematic final-state rescattering effects (triangle singularities).
- **Confirm resonant nature with photo-/electroproduction.**





[Wang et al., PRD 92 (2015) 034022;
ANHB et al., Phys. Rev. D 94 (2016) 034002;
Huang et al., Chin.Phys.C 40 (2016) 124104;
LoI12-18-001 (PAC 46);
Wang et al., PRD 99 (2019) 114007;
Winney et al., PRD 100 (2019) 034019;
Wu et al., PRC 100 (2019) 035206;
Cao and Dai, PRD 100 (2019) 054033;
Cao et al., PRD 101 (2020) 074010]

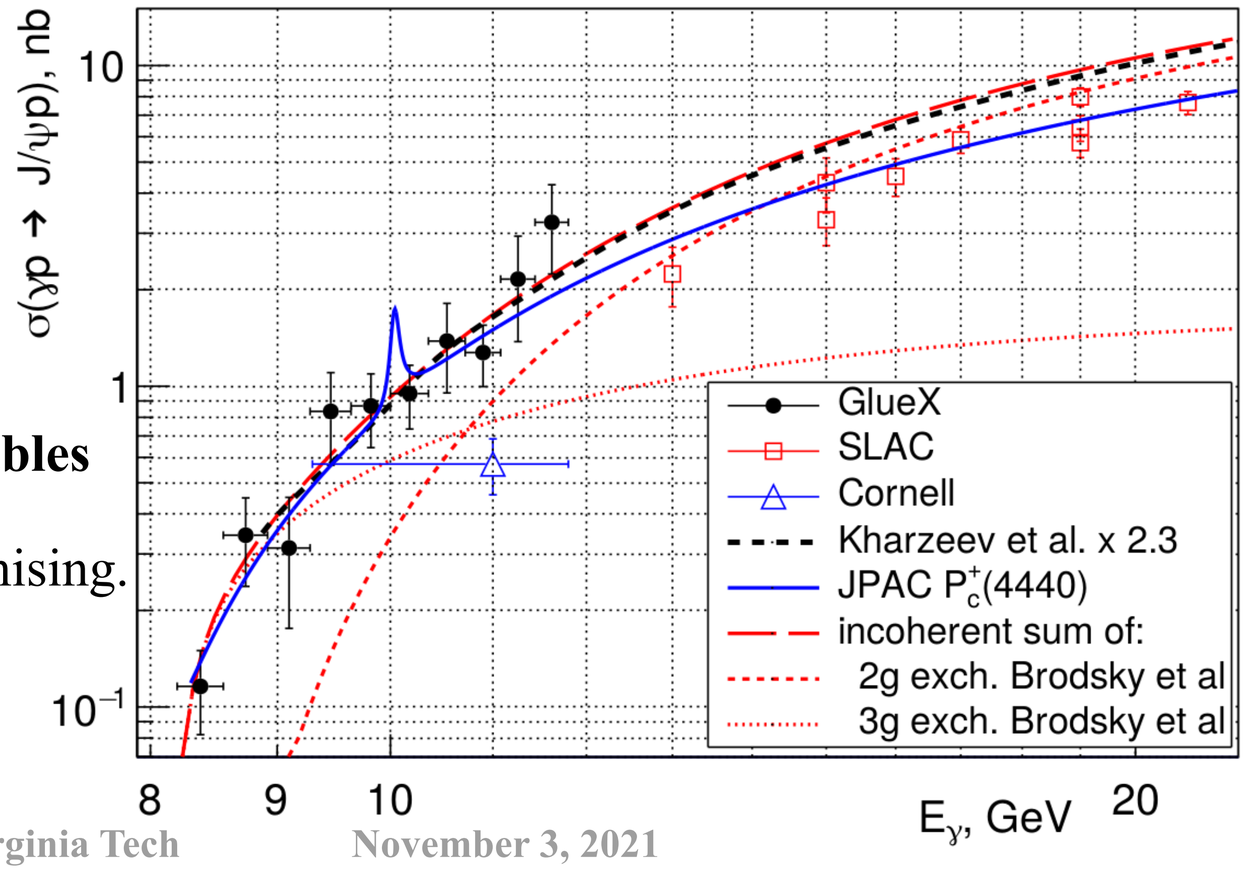
Photoproduction data so far

- GlueX set upper limits to $\sigma(\gamma p \to P_c) \times \mathscr{B}(P_c \to J/\psi\, p)$, model-dependent limits to $\mathscr{B}(P_c \to J/\psi\, p) < 2.0\,\%$.
  [Ali et al., PRL 123 (2019) 072001; ANHB et al., PRD 94 (2016) 034002; Winney et al., PRD 100 (2019) 034019]
  Challenges several theory models,
  but still allows for many others.

- **New results expected based on 2200 J/ψ events.**

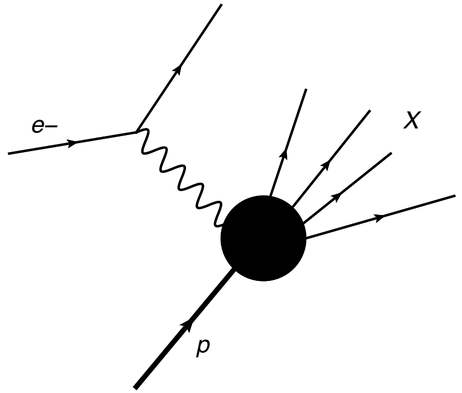
- New J/ψ-007 (Hall C) results have been presented and order of magnitude more stringent limits.
  [See S. Joosten's talk at DNP2021]

- Moving forward, measurement of **polarization observables** (sensitive even to broader and overlapping signals), **open-charm** production, and P_b searches might be promising.
  [LoI12-18-001 (PAC 46); Cao and Dai, PRD 100 (2019) 054033]



3. Proton structure functions

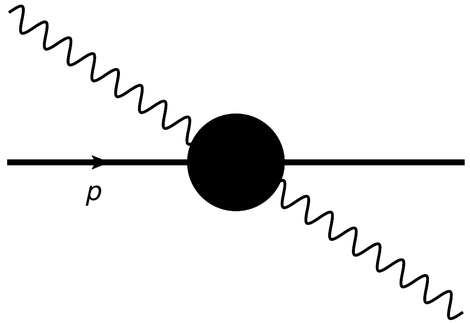
Back to the proton structure



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

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

$$\sigma_U(W, Q^2) = \sigma_T(W, Q^2) + \epsilon_T \sigma_L(W, Q^2)$$

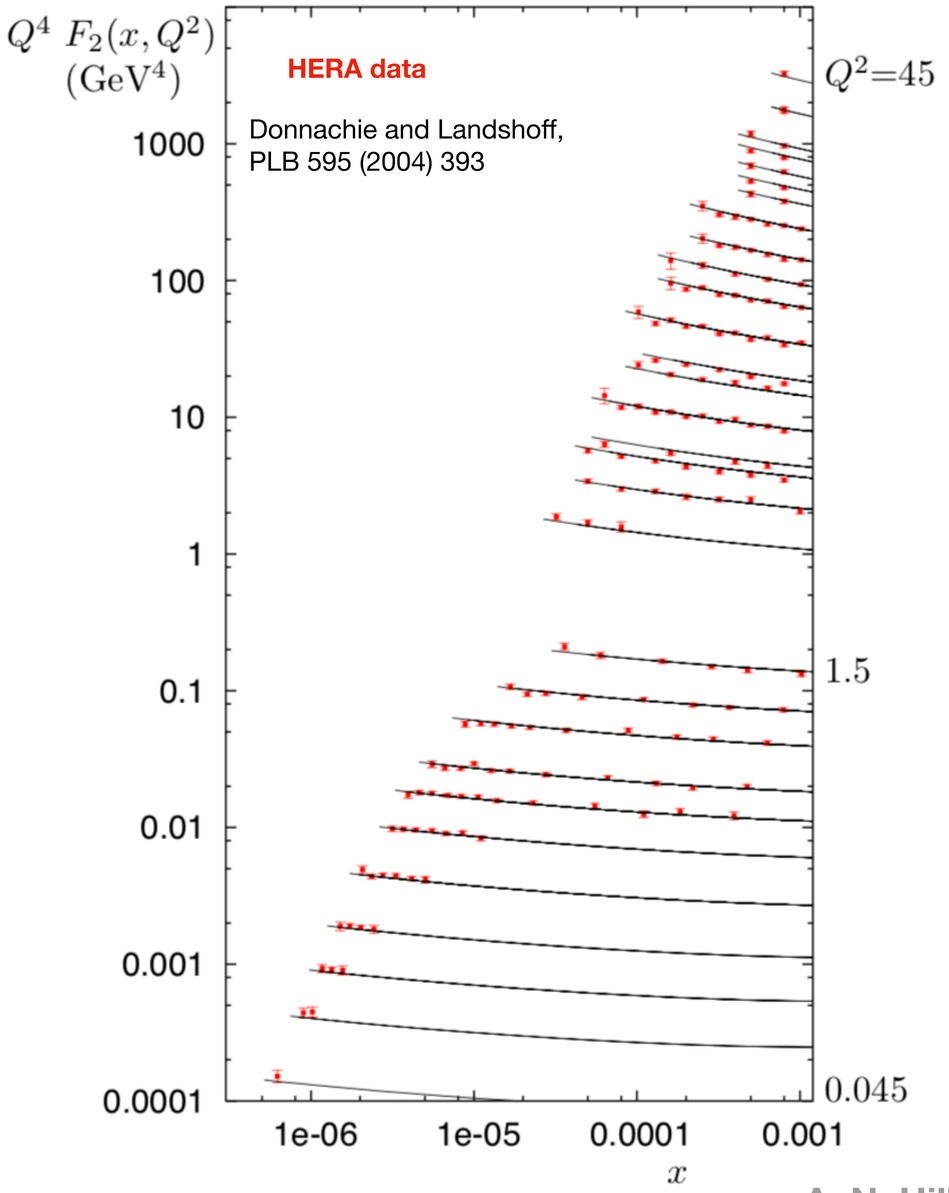


$$\Im T_1(W, Q^2) = \frac{\pi\alpha}{M} F_1(W, Q^2)$$

$$\Im T_2(W, Q^2) = \frac{\pi\alpha}{\nu} F_2(W, Q^2)$$

- Inclusive electron scattering gives access to structure functions F_i .
  Related to forward virtual Compton scattering (VVCS) amplitudes T_i .
- **Precise CLAS(12) data make studies of resonance region very timely:**
  to reach $0.05\ \text{GeV}^2 < Q^2 < 12\ \text{GeV}^2$, $W \approx 4$ GeV.
- Goal: combining high and low-energy descriptions in one framework.
- Important for tests on quark-hadron duality and integrated observables:
  Cottingham formula, Lamb shift, parton distribution functions (PDFs), …

Low and high energies: towards a connection



$$F_2(x,Q^2) = f_h(Q^2)x^{-\alpha_h+1} + f_s(Q^2)x^{-\alpha_s+1} + f_r(Q^2)x^{-\alpha_r+1}$$

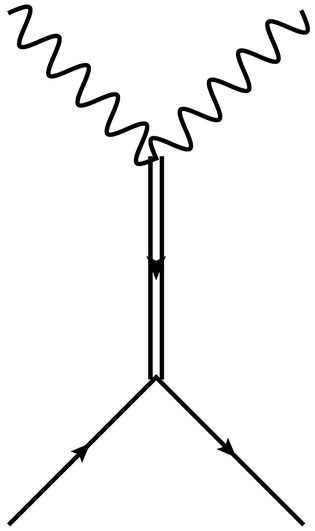
Hard pomeron
$\alpha_h = 1.452$

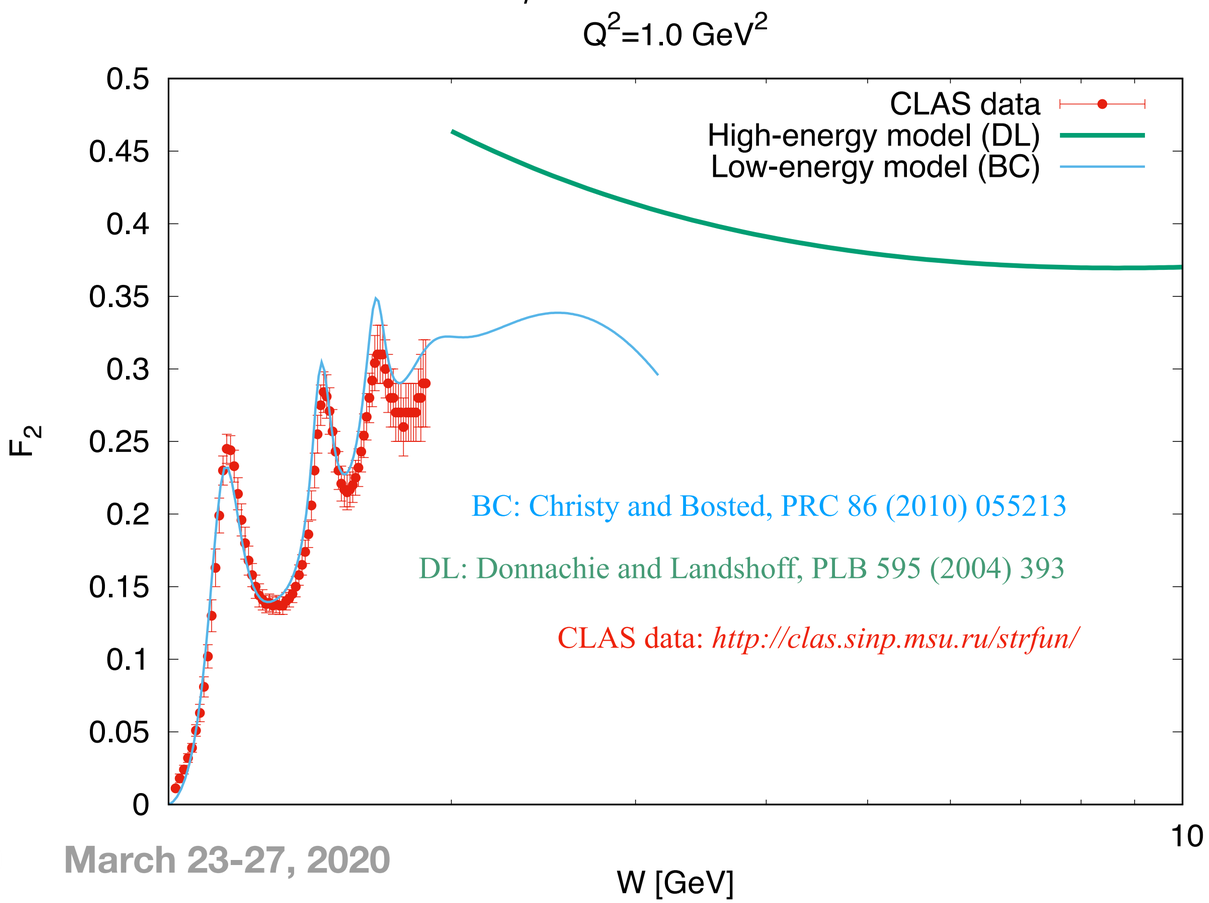
Soft pomeron
$\alpha_s = 1.0667$

Reggeon exchange
$\alpha_r = 0.524$

$$x = \frac{Q^2}{2M_N\nu}$$

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

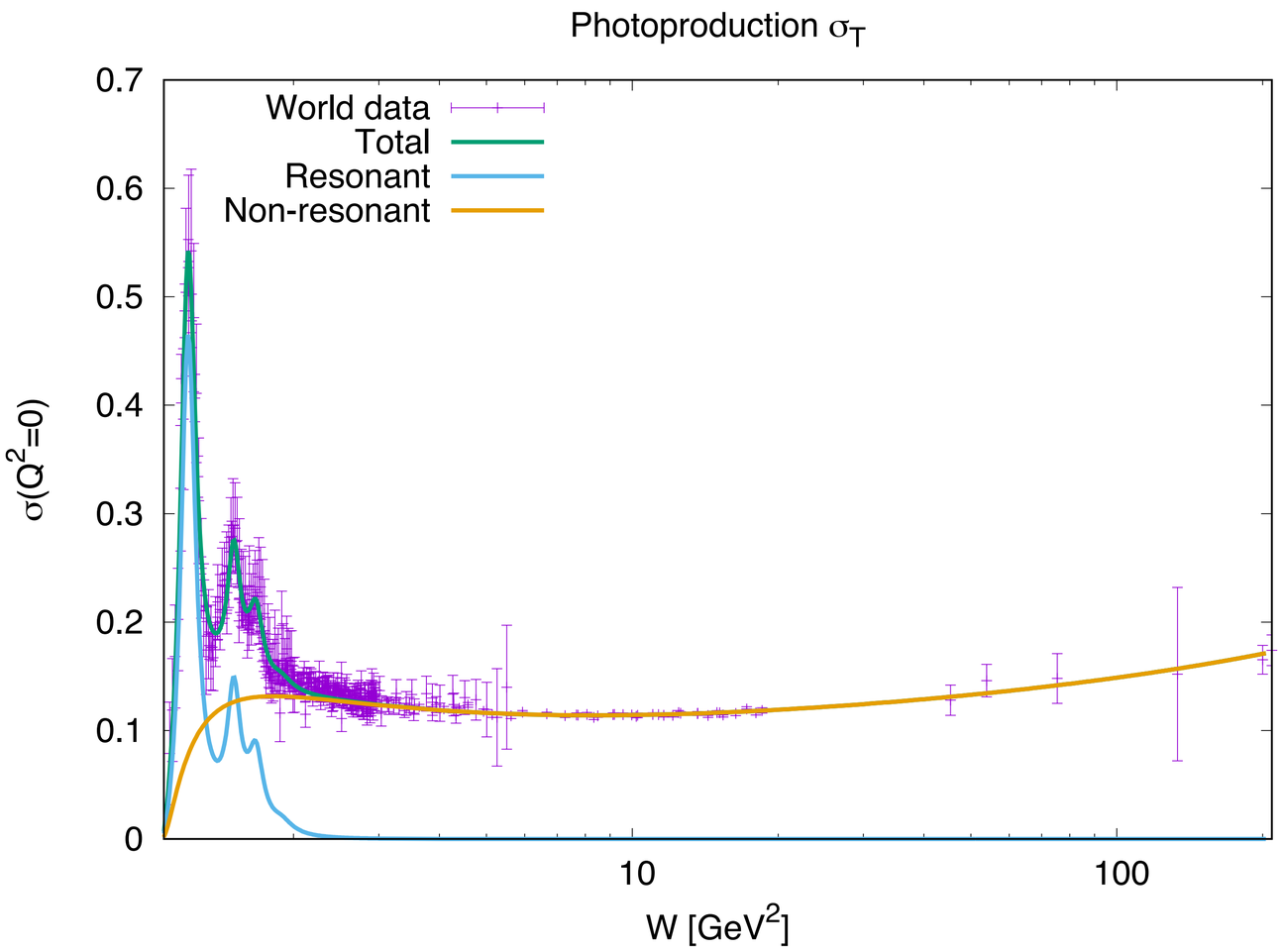




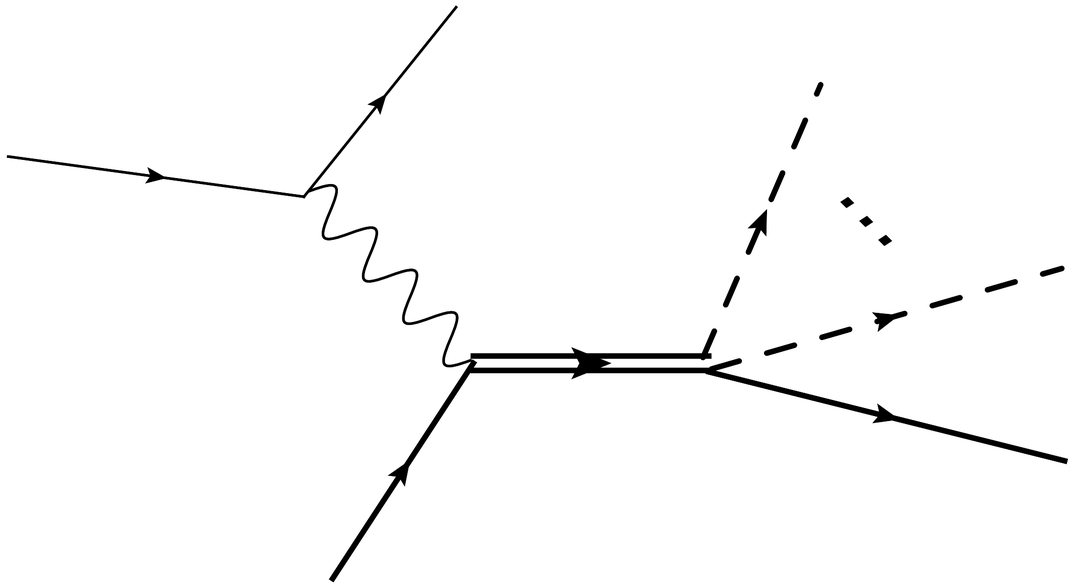
Proposal for updated parametrization

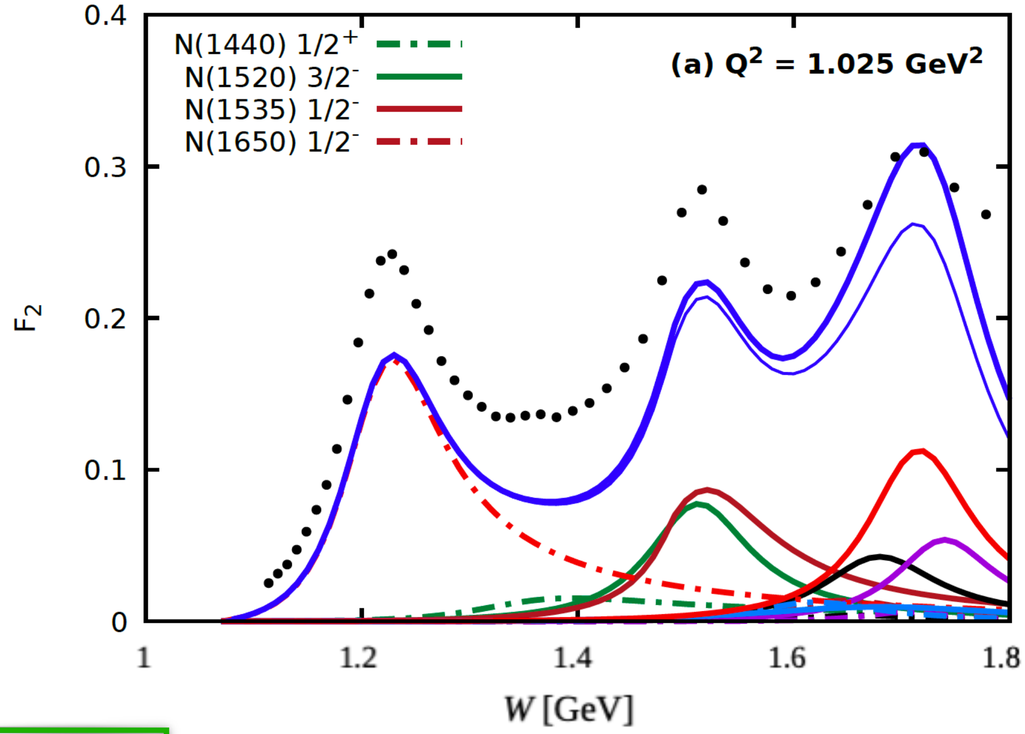
$$F_1(\nu, Q^2) = F_1^{\text{res}}(\nu, Q^2) + \sum_{i=0}^{2} \gamma_{\alpha_i}(Q^2)(\nu - \nu_{\text{thr}})^{\alpha_i} \left(1 - \frac{\nu_{\text{thr}}}{\nu}\right)^{a_i(Q^2)} \left(1 + \frac{\nu_{\text{thr}}}{\nu}\right)^{b_i(Q^2)}$$

- Recovers Regge behavior at high energies.
- Implements threshold behavior.
- Obeys dispersion relations.
- Allows to describe the rich resonance region.



Resonant part of inclusive cross sections





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

Breit-Wigner resonance model: coherent sum!

Mokeev et al., PRC 86 (2012) 035203

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

3. Resonance electrocouplings

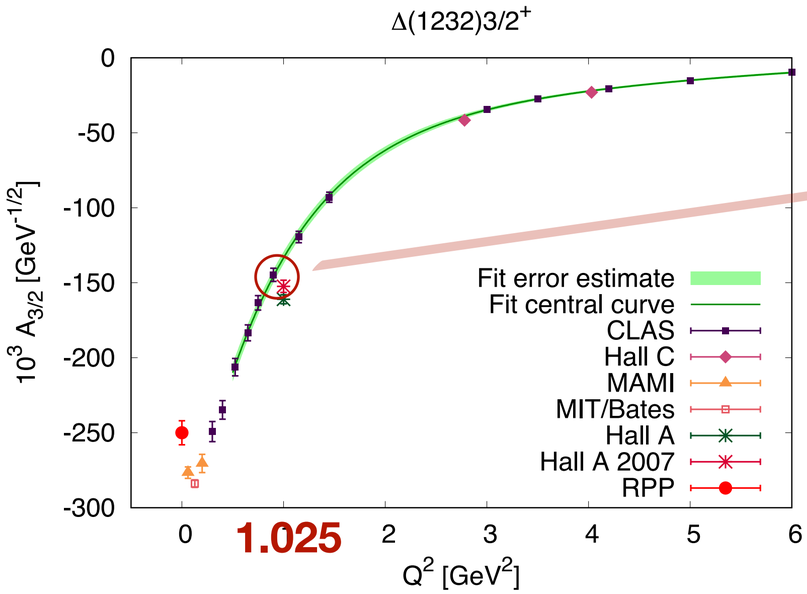
From exclusive to inclusive electron scattering

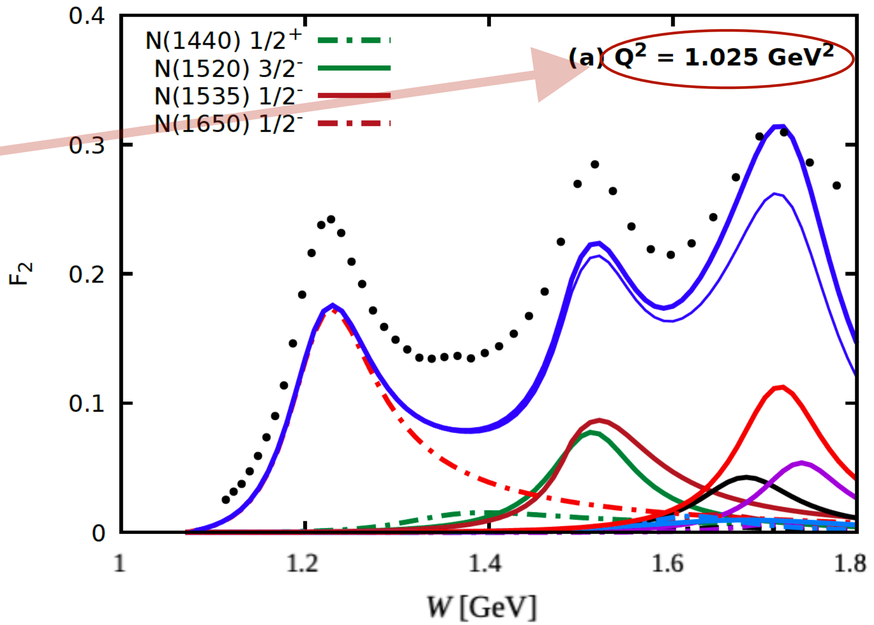
https://userweb.jlab.org/~mokeev/resonance_electrocouplings/
https://userweb.jlab.org/~isupov/couplings/

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

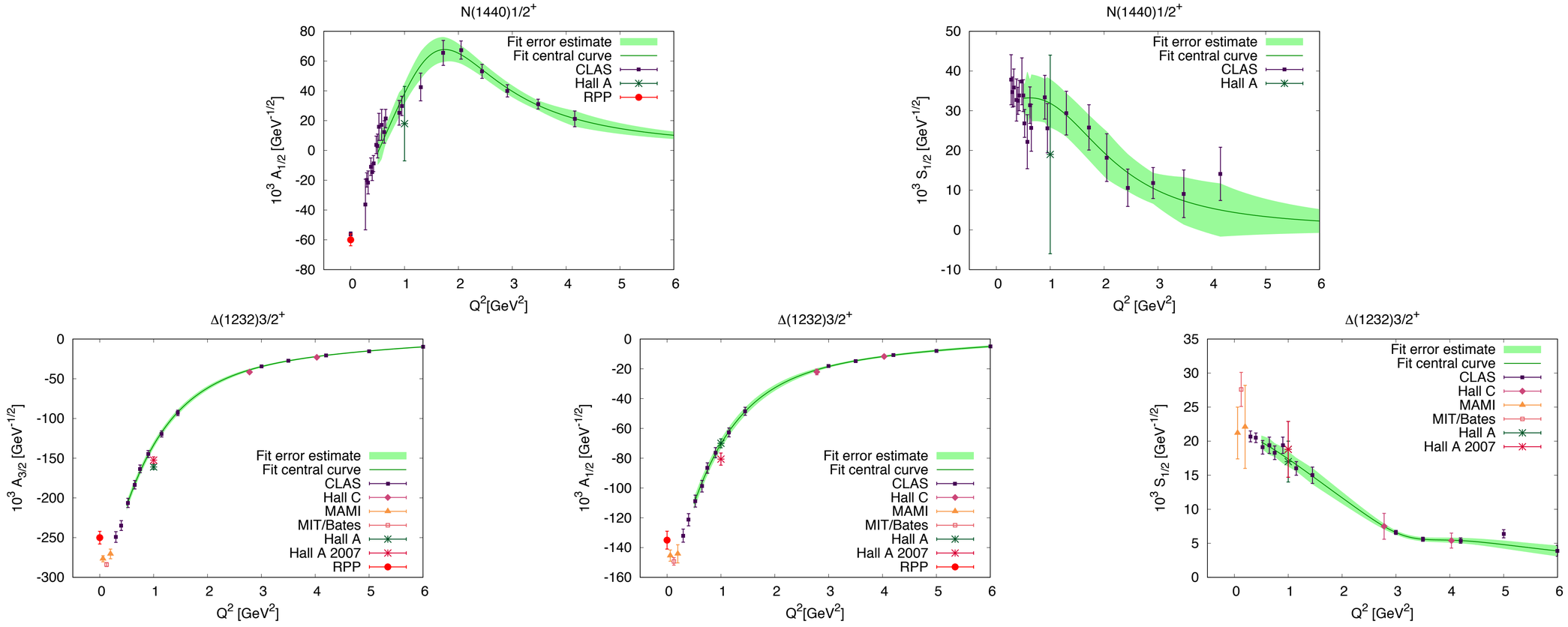
$$\Gamma^{T}_{\gamma}(M_r,Q^2) \sim \left|A_{1/2}(Q^2)\right|^2 + \left|A_{3/2}(Q^2)\right|^2$$
$$\Gamma^{L}_{\gamma}(M_r,Q^2) \sim \left|S_{1/2}(Q^2)\right|^2$$

Data on longitudinal and transverse **electrocouplings**: determine each resonant contribution separately!



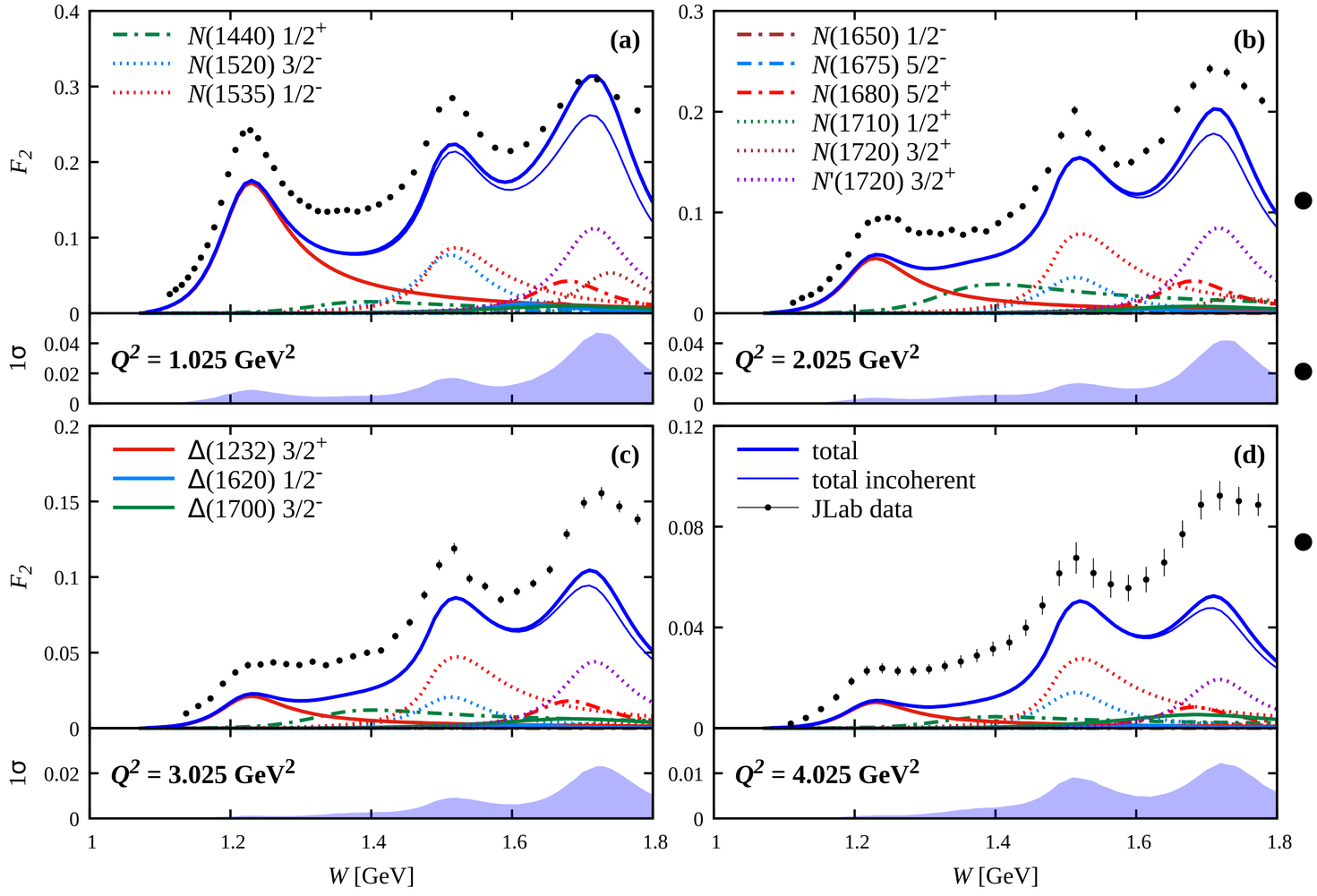


Exclusive electroproduction channels



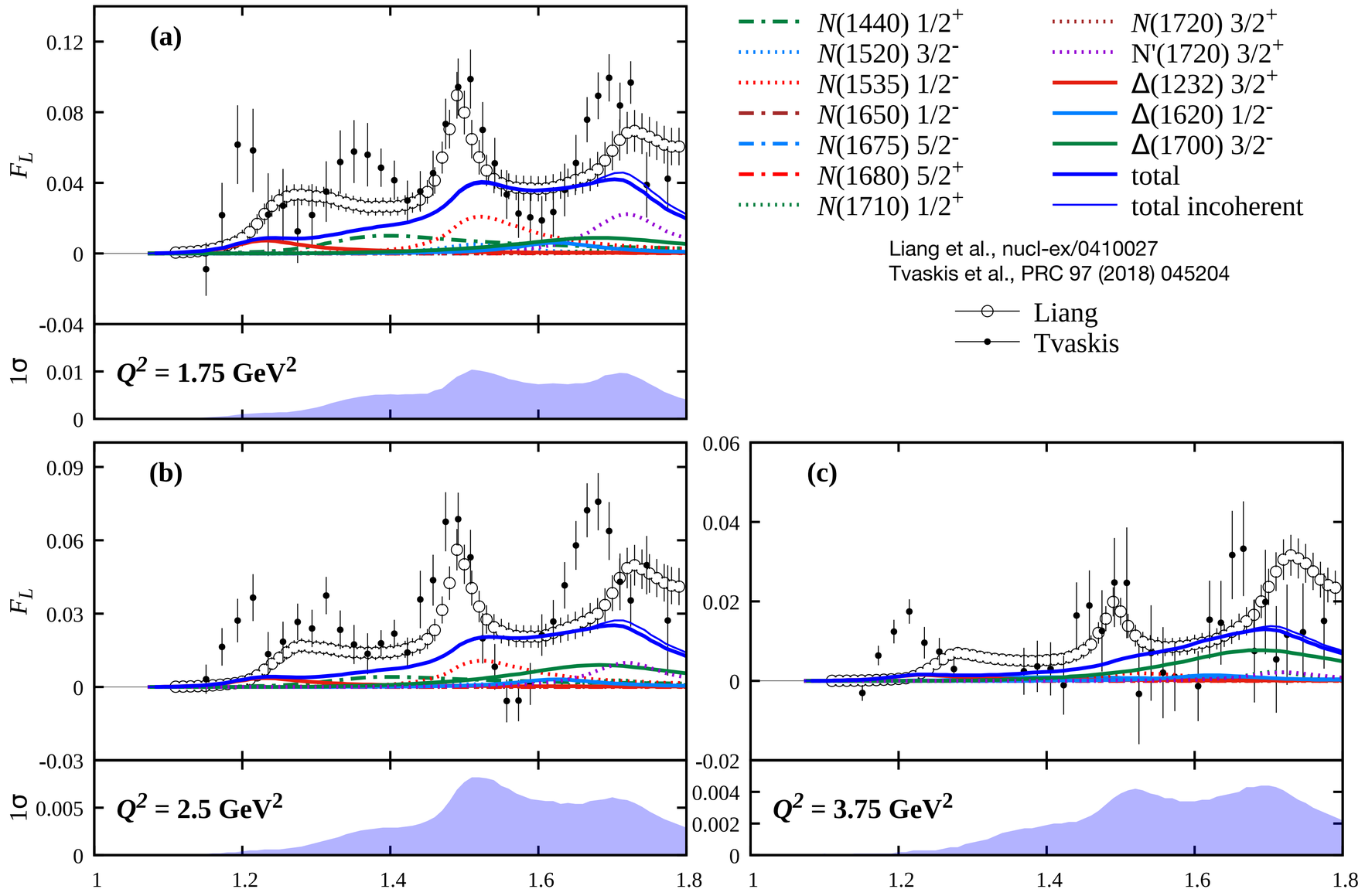
- Interpolation/extrapolation functions:
  good agreement with world data and preliminary CLAS12 results at higher Q^2.
- Error bands estimated from data uncertainties and scaled with coupling size in extrapolation region.

Resonant contributions at different Q^2

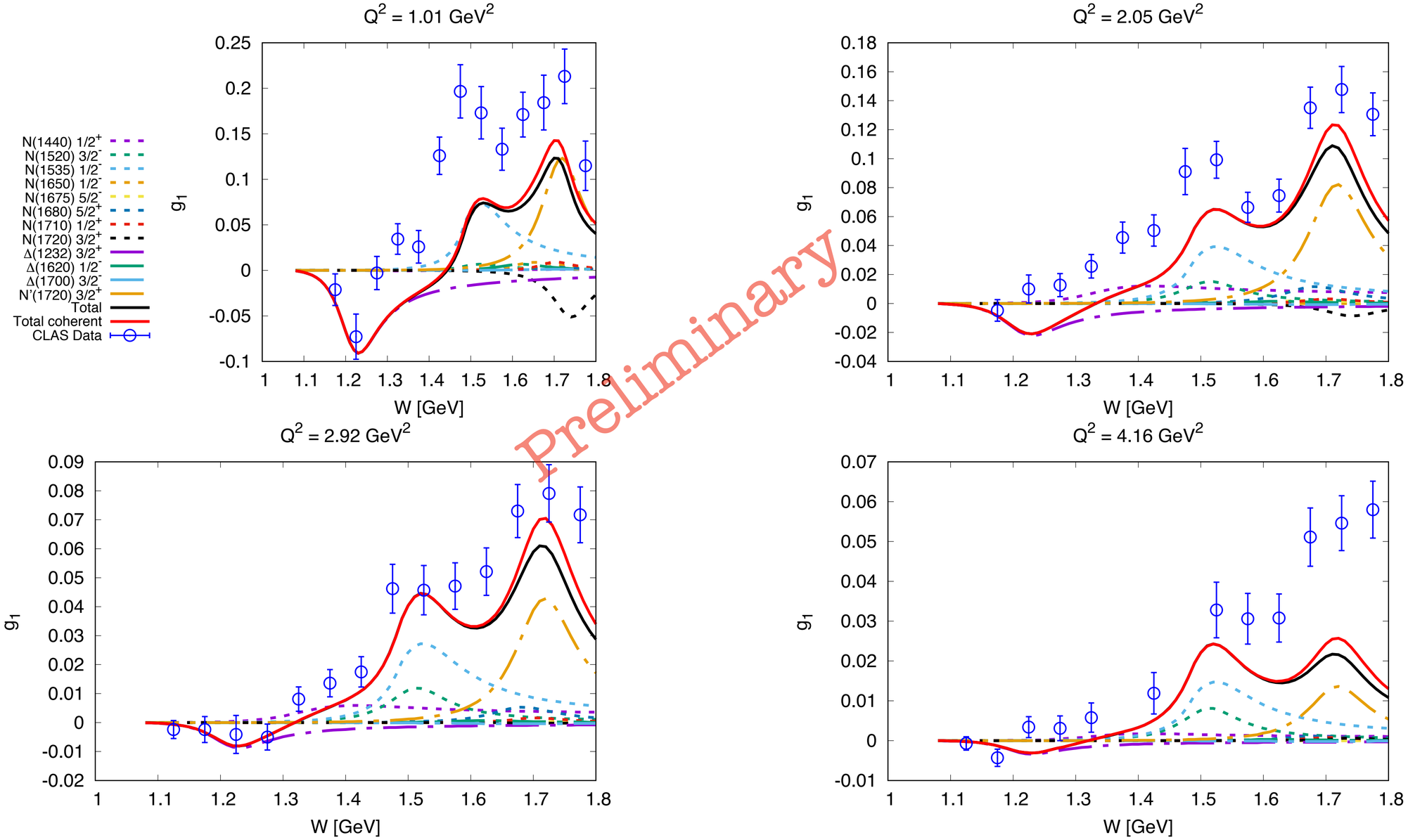


- Resonance tails contribute substantially to neighboring resonance peaks.
- 2nd resonance region decreases less with Q^2: intricate differences in electrocoupling evolution.
- 2nd and 3rd regions remain strong at all Q^2: **the studies of respective electrocouplings at larger Q^2 with CLAS12 is very promising!**

The longitudinal structure function

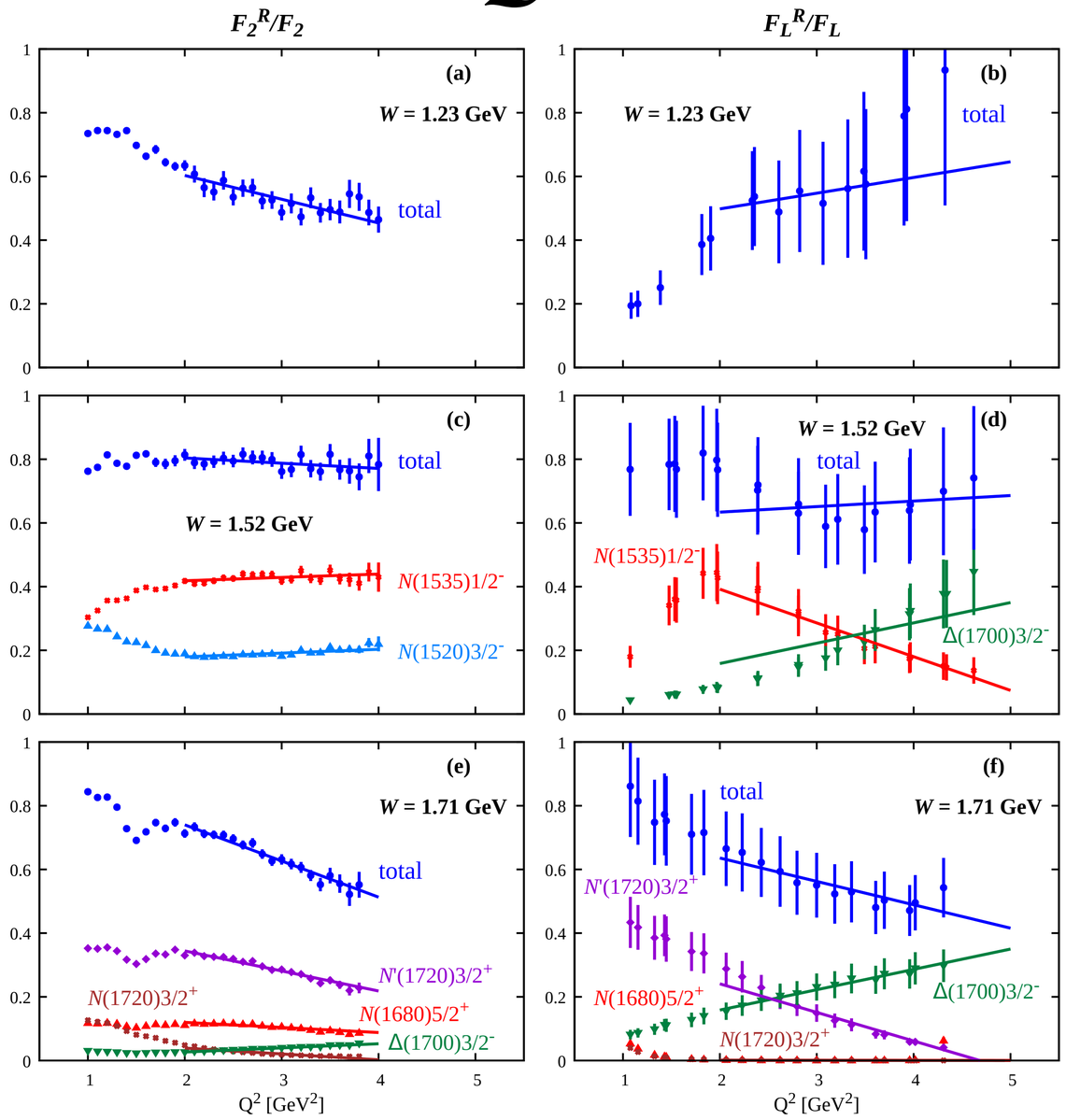


Polarized structure functions



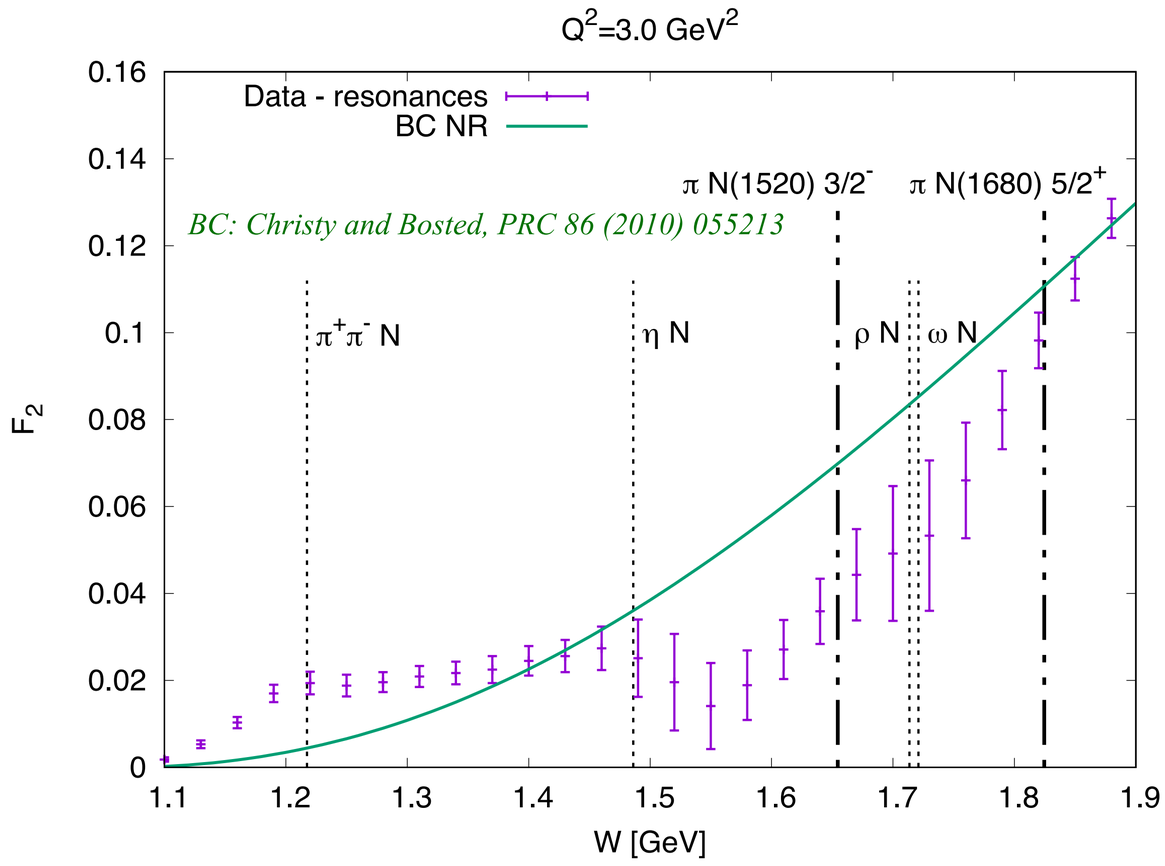
4. Combining the information

Q^2 evolution of ratio resonance/total



- Resonance contributions decrease with Q^2, but so do the total contributions.
- $\Delta(1232)$: even at 4 GeV^2, ~50% significance; 2nd region: nearly flat ratio.
- Behavior points to non-vanishing resonances!

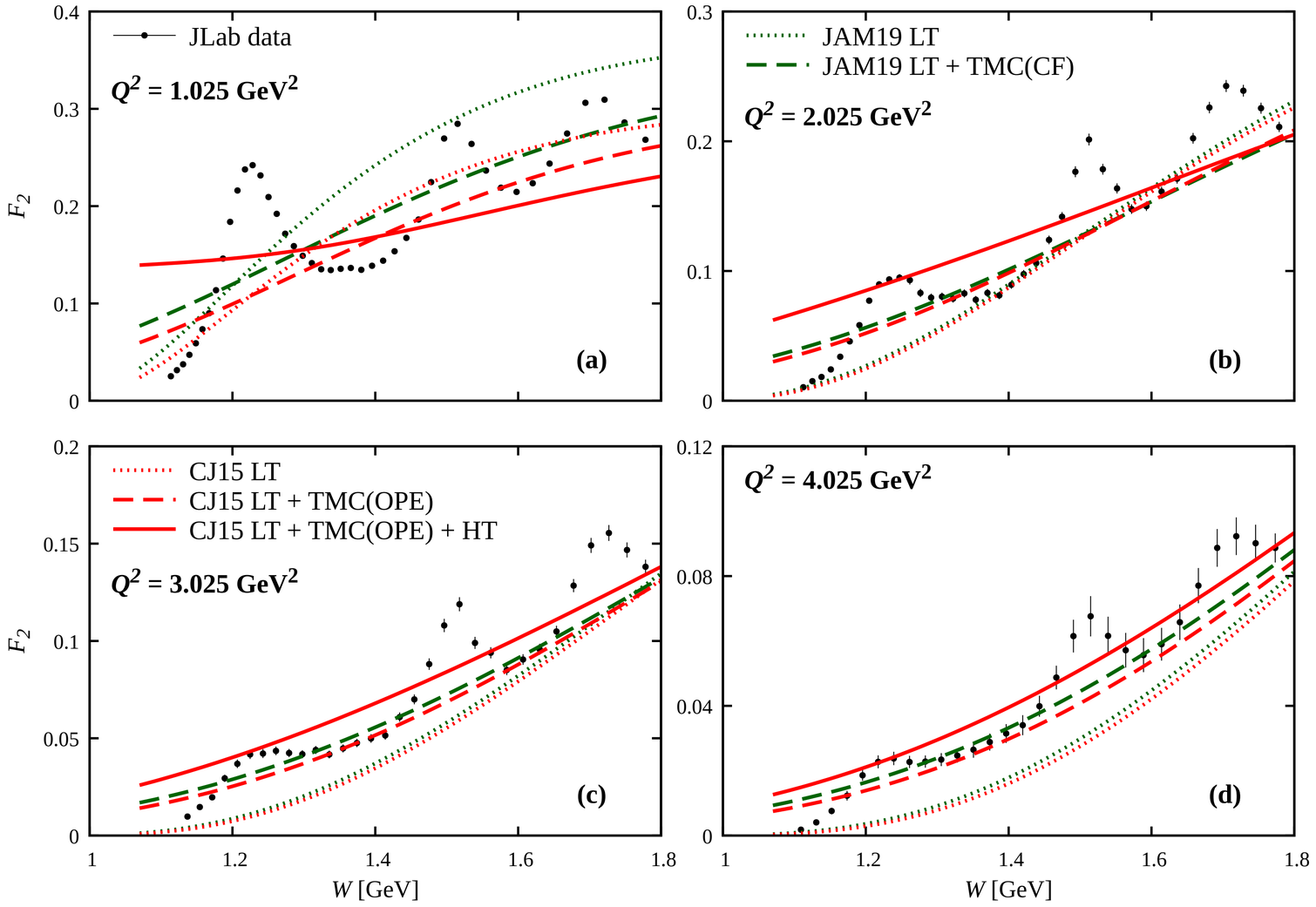
First estimates of non-resonant contributions



- When "removing" the resonances from the data, something rather smooth as a background remains.
- How do we interpret it?

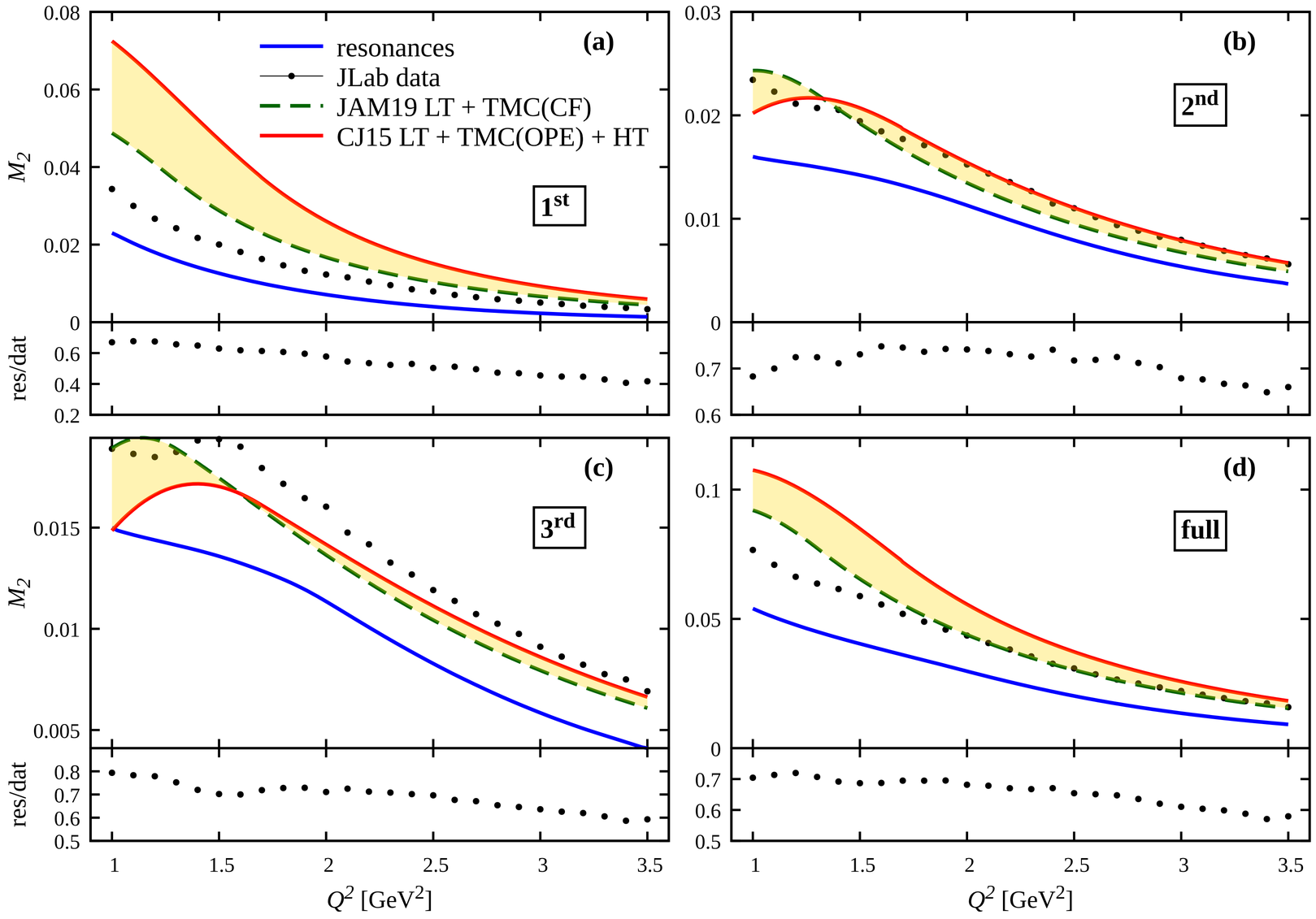
5. Reaching across energy scales

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 **resonance region:** global duality onset at $Q^2 > 2.0$ GeV^2, especially with target mass corrections and higher-twist contributions.

Outlook

Results point to promising prospects of combined fits to DIS and resonance regions.
To do so, we have already:

- Computed coherent sum of **resonant contributions to structure functions**.
  CLAS electrocouplings allowed mapping of this highly non-trivial behavior for first time.
- **Found that resonances** compared to full data **do not seem to vanish** at larger Q^2:
  promising prospects for CLAS12!
- Gained more insight into PDFs at large x and quantified duality behavior in truncated moments.

Furthermore, we wish to:

- Extend to polarized structure functions.
- Perform fit which recovers high-energy behavior while implementing threshold and resonances.
- Probe applications of ML for Rosenbluth separation and electrocoupling extraction.