

# Effective field theories and phenomenology for electron and neutrino-induced processes

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Universität Regensburg

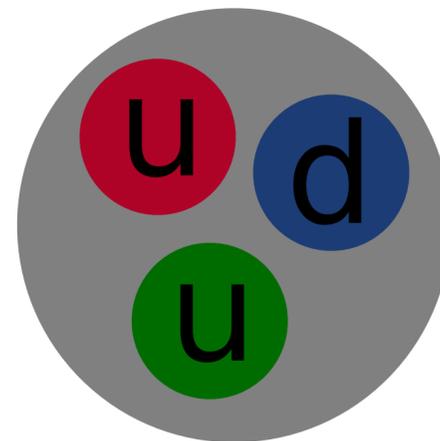
Eberhard Karls Universität Tübingen



Baryons, Sevilla  
November 8, 2022

# Baryons and their mysteries

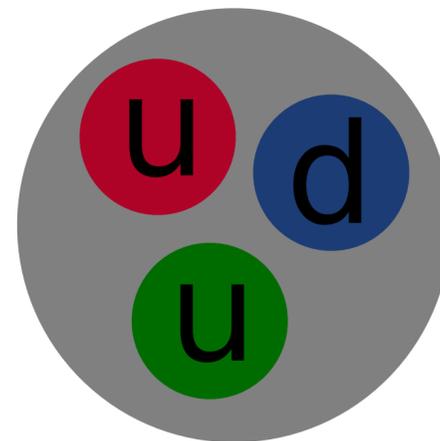
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QCD describes the strong force binding the constituents,  
**but it behaves remarkably differently at high and low energies.**

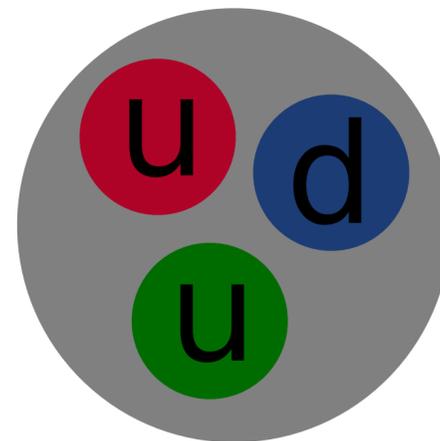


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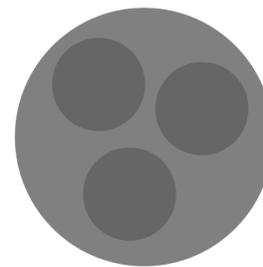
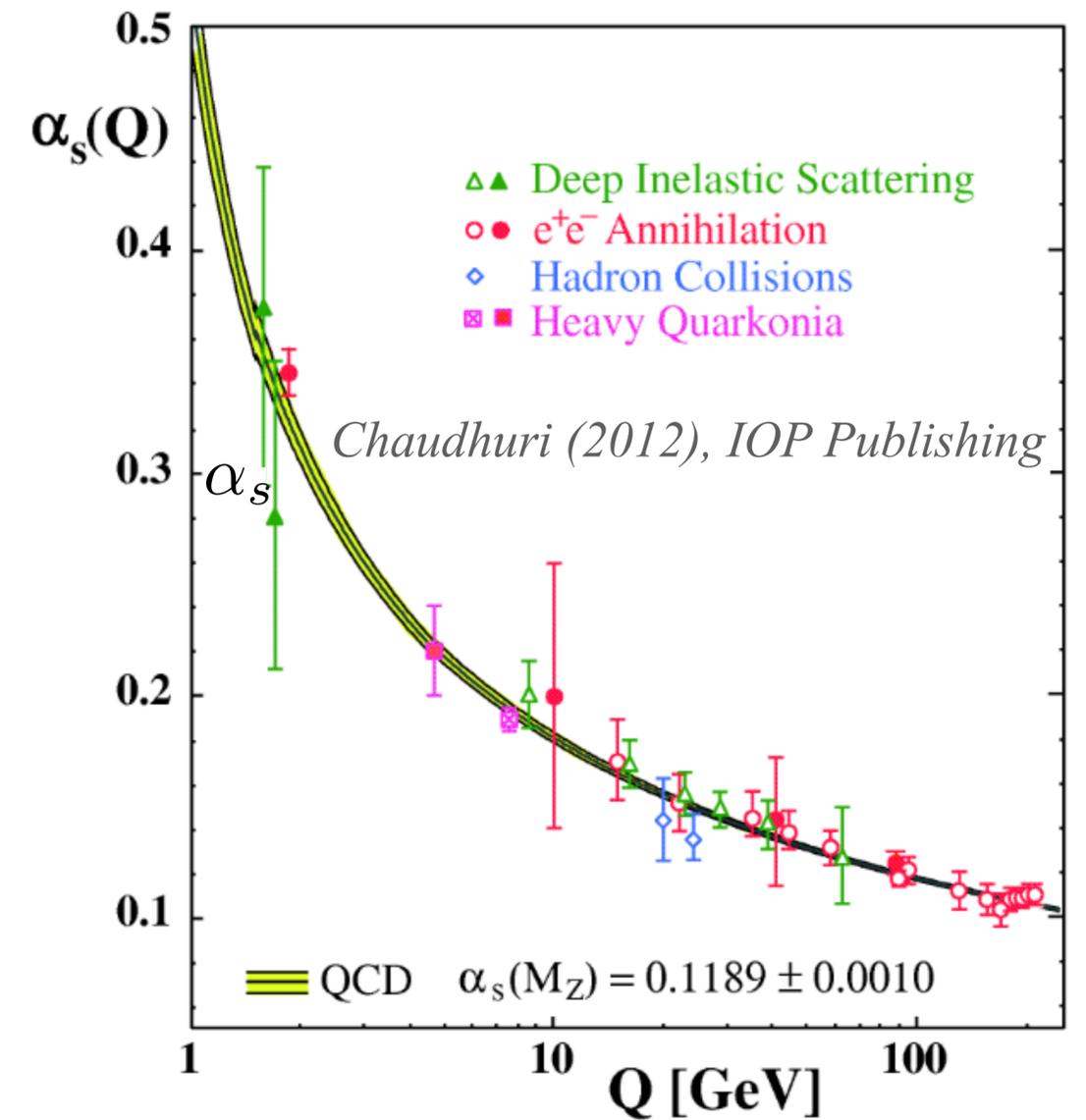
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**but it behaves remarkably differently at high and low energies.**

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



# Low energies — large distances

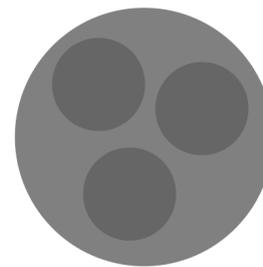
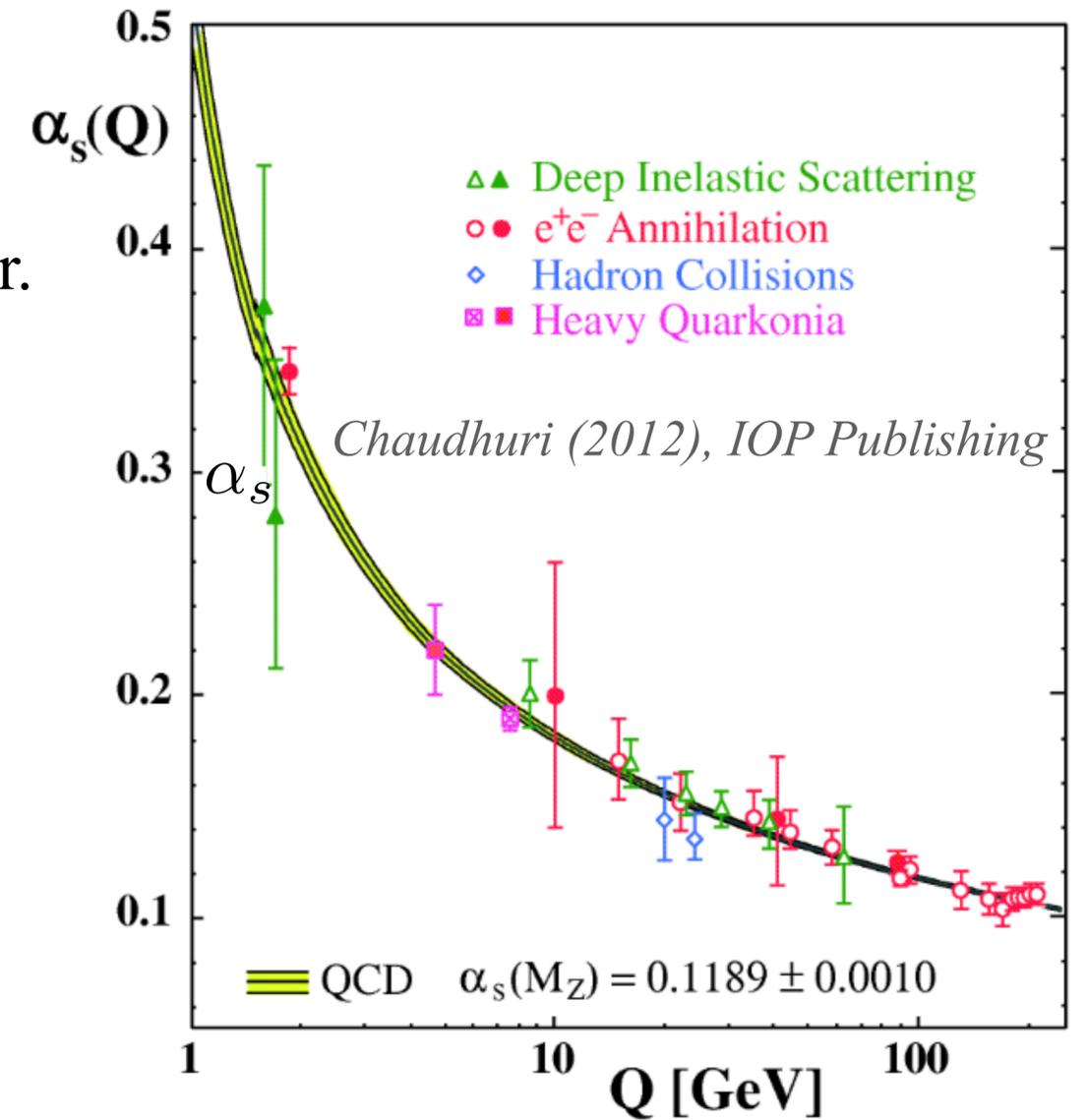
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$\alpha_s$  becomes too large to be a valid perturbative expansion parameter.



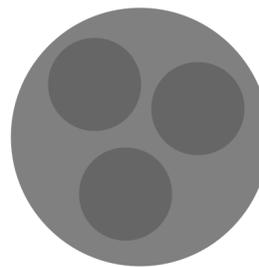
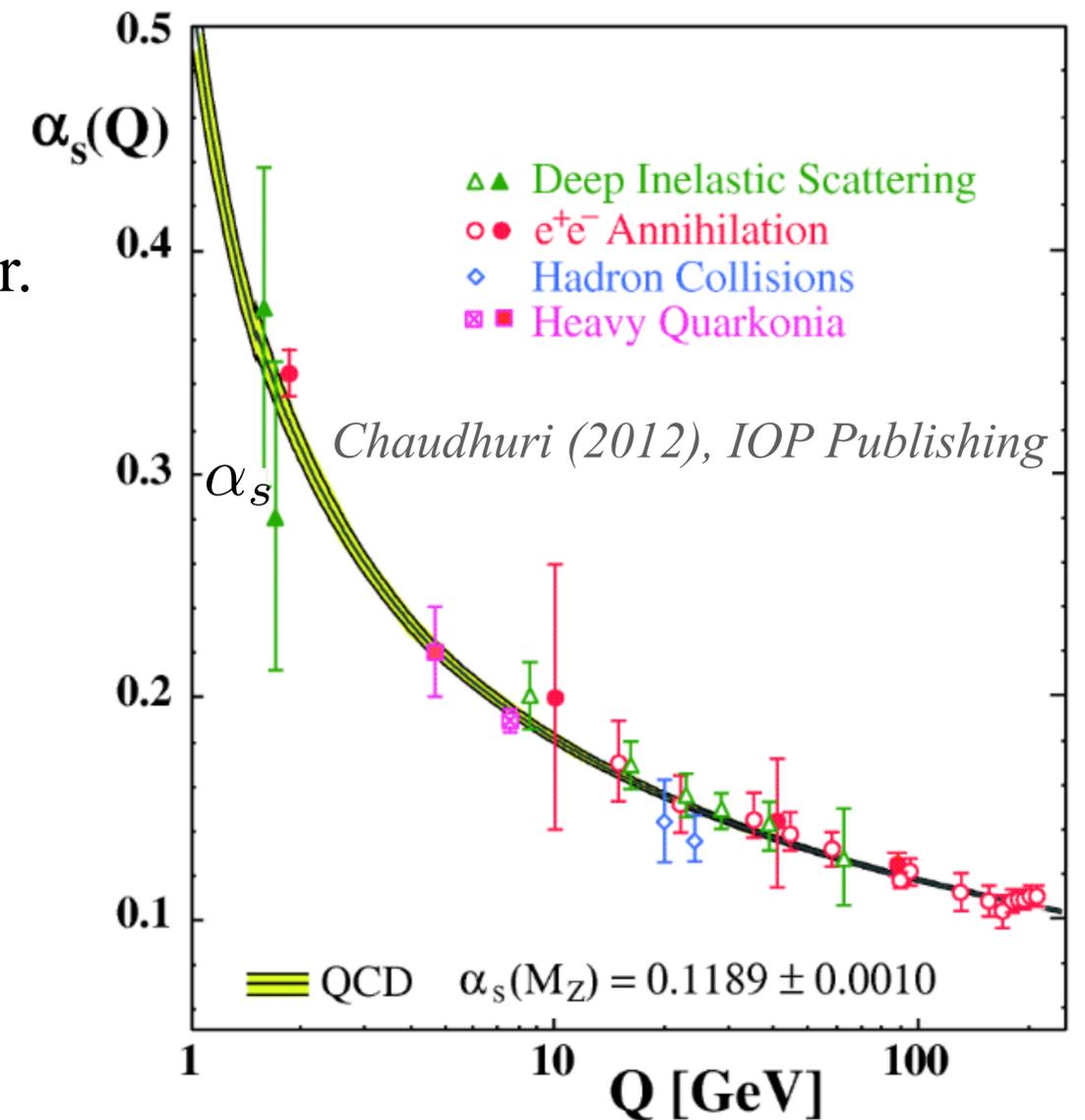
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Perturbative QCD breaks down —  
**effective field theories (EFTs)** are called for.  
E.g. chiral perturbation theory obeys all QCD symmetries  
and one can have a perturbative expansion again.

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



*See also the ChPT talks in this session:*

Electroweak nucleon properties – **Fernando Alvarado**

Neutron beta decays – **Oleksandr Tomalak**

# Outline

Electroweak interactions: structure and spectroscopy

Exotic resonances

Transition from low to high energies

Ongoing and future goals

# Outline

## Electroweak interactions: structure and spectroscopy

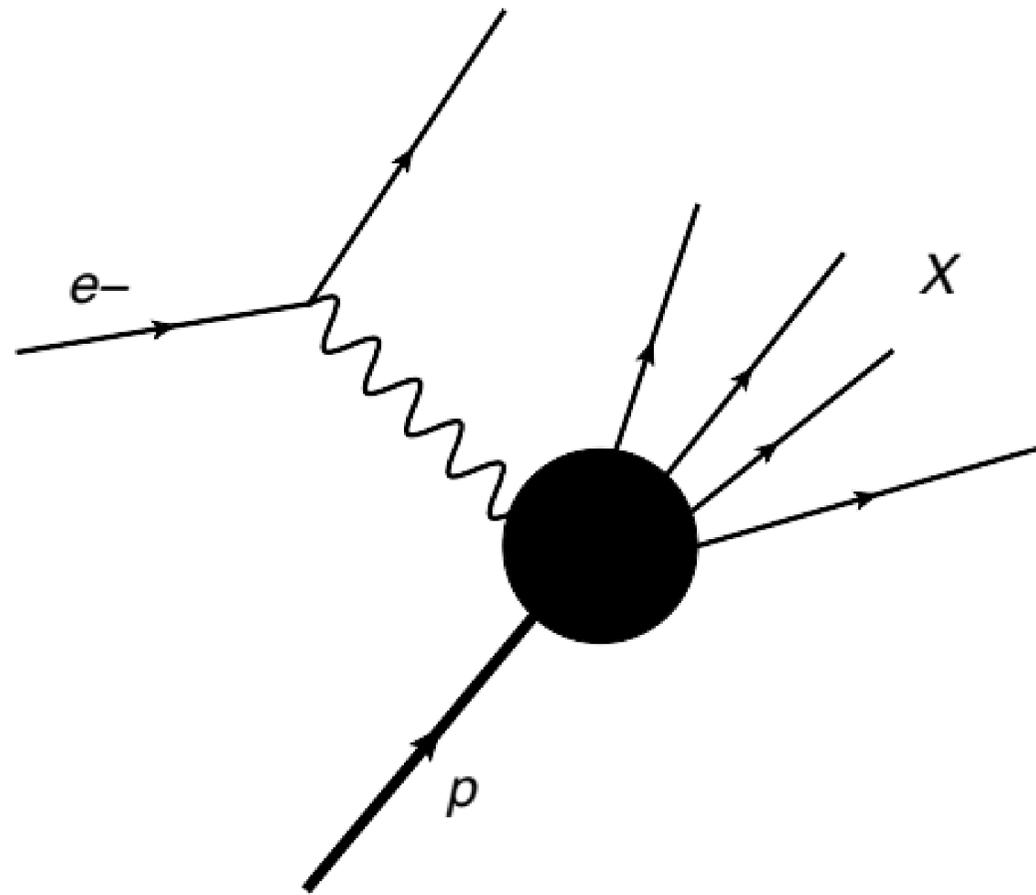
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# Probing hadrons with electron beams

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.



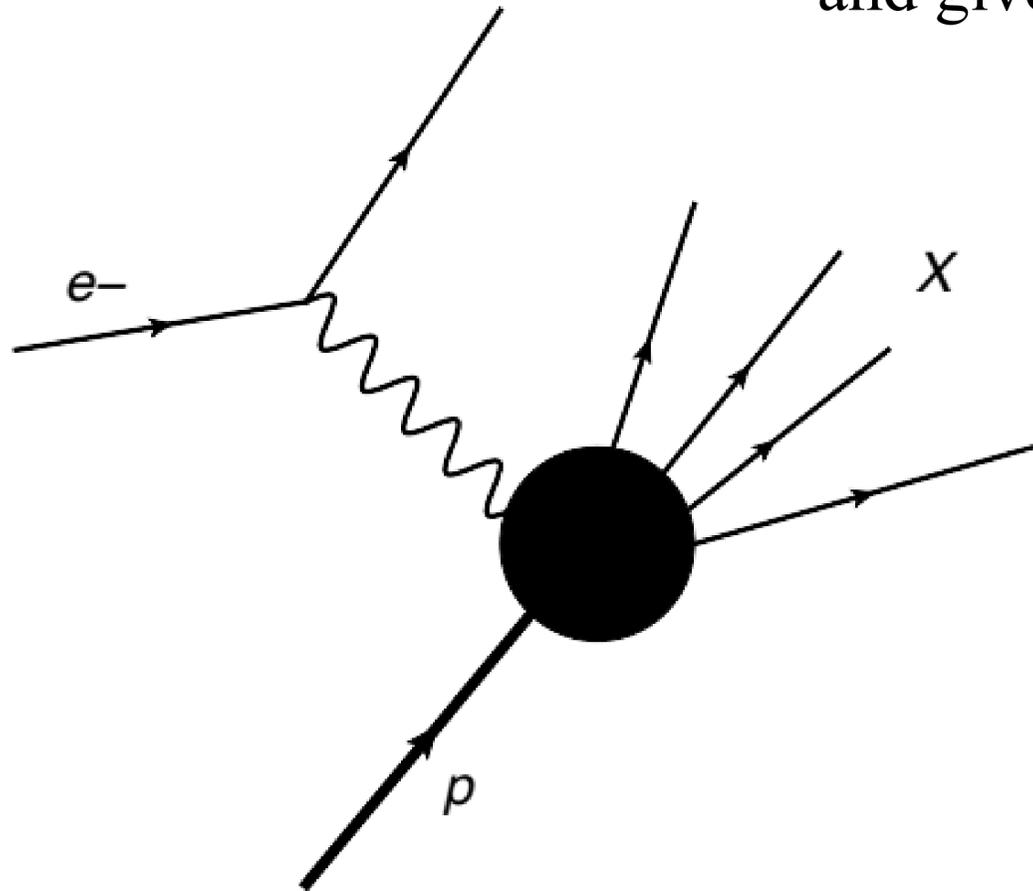
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**Inclusive** reactions probe **all possible final states** and give access to the structure functions.

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

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



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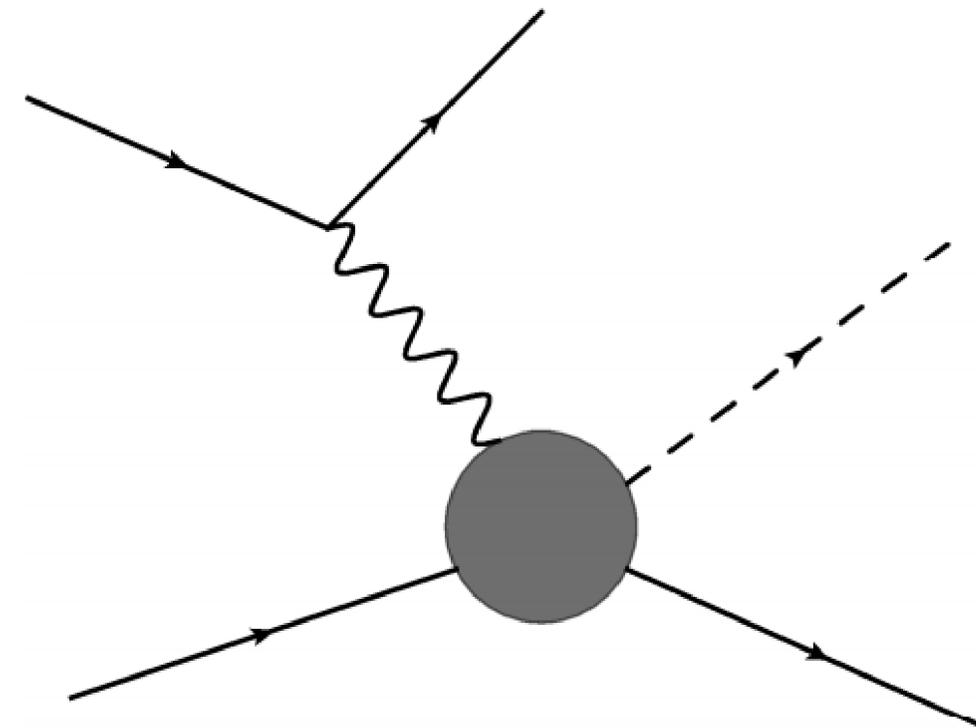
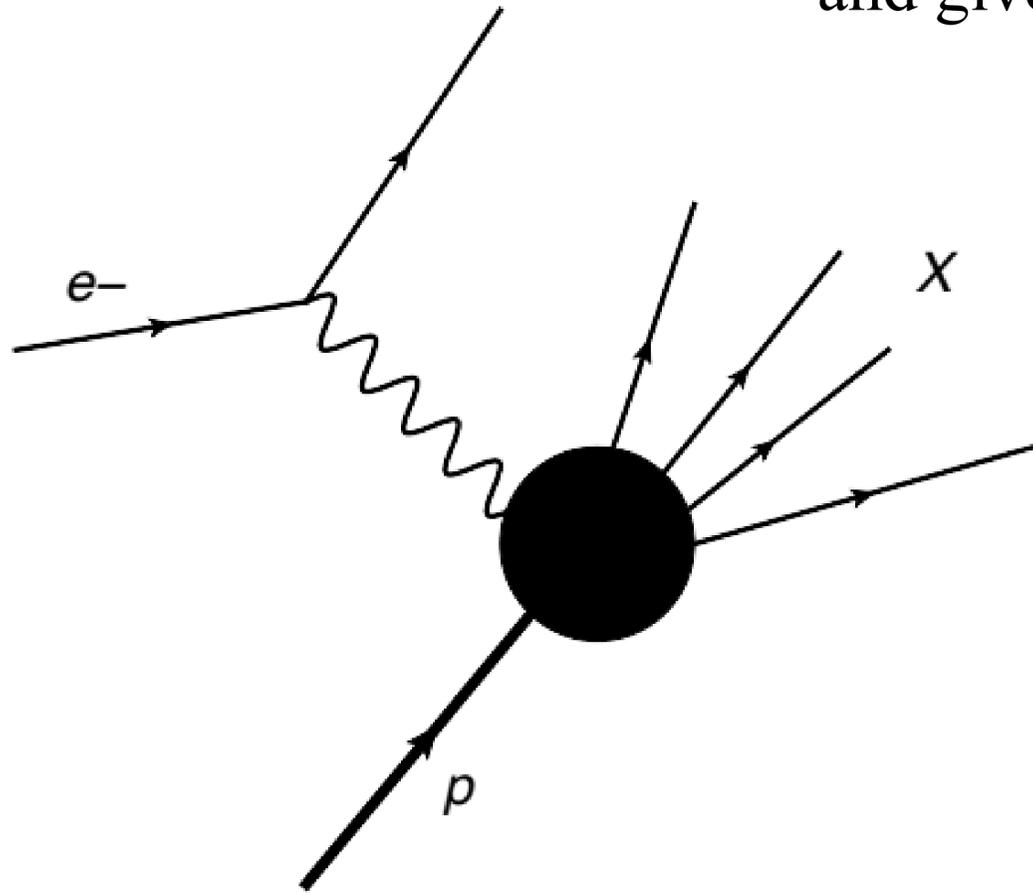
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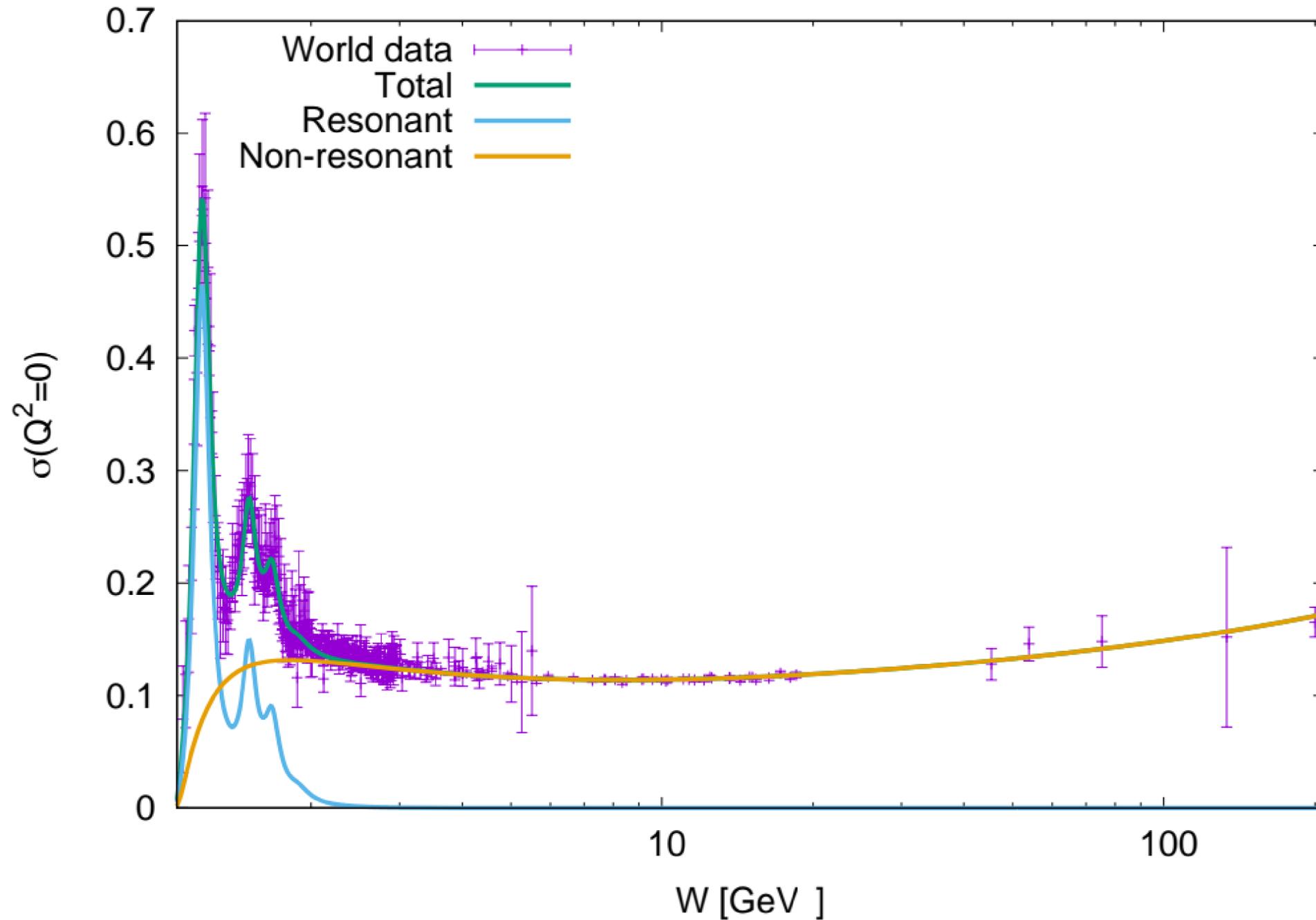
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**Exclusive** reactions probe **specific production channels**. Smaller cross-section yield, but cleaner analysis.



# Goals of inclusive and exclusive reactions

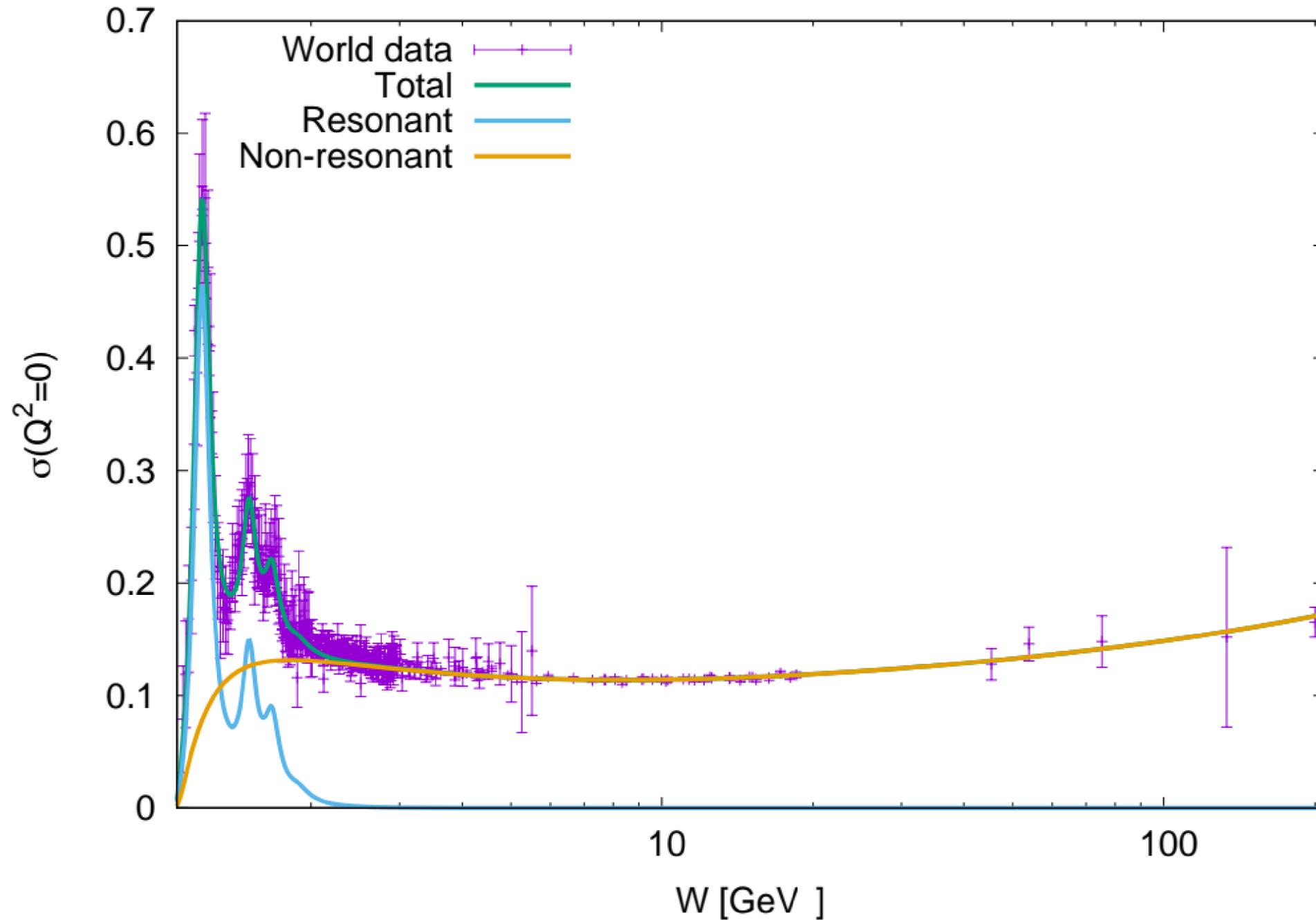
Inclusive photoproduction cross section



Insight into targets' inner **structure**:  
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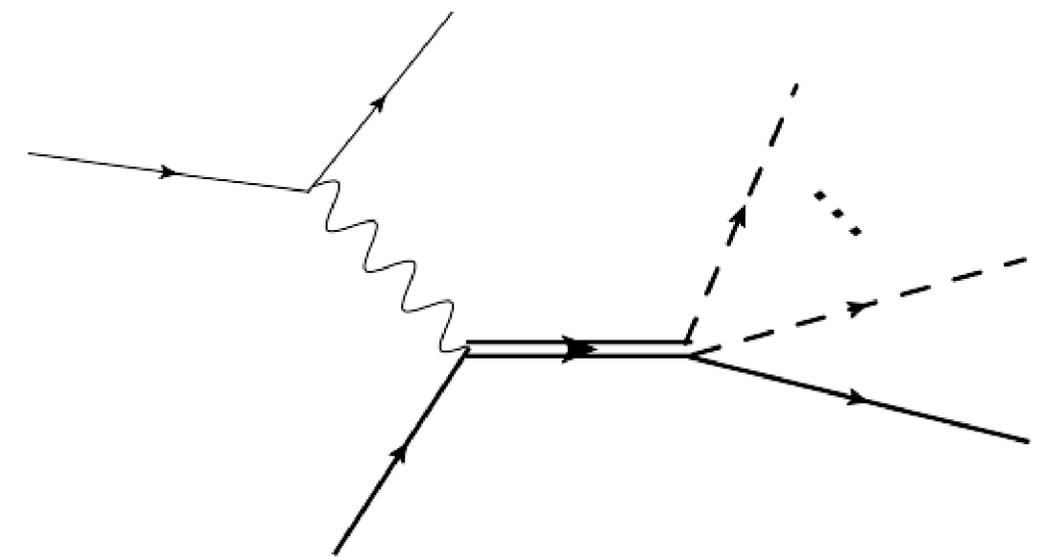
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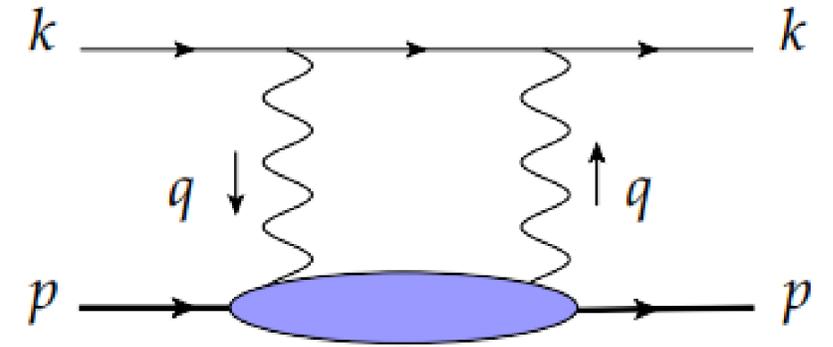
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Hadron spectroscopy.



# Precision in integrated observables

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



# Precision in integrated observables

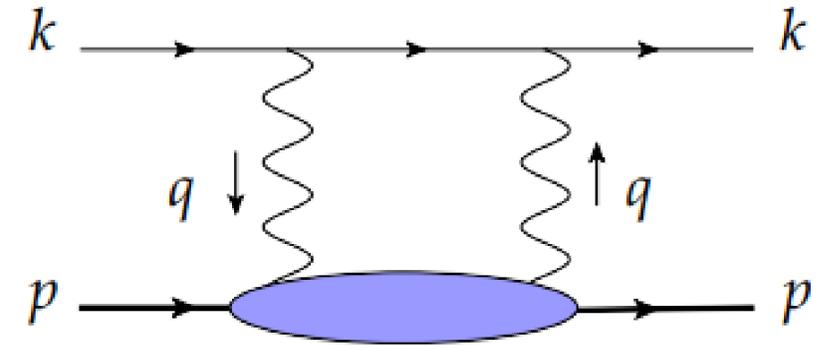
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**Atomic physics:** hadronic contributions to the **Lamb shift** in muonic hydrogen.

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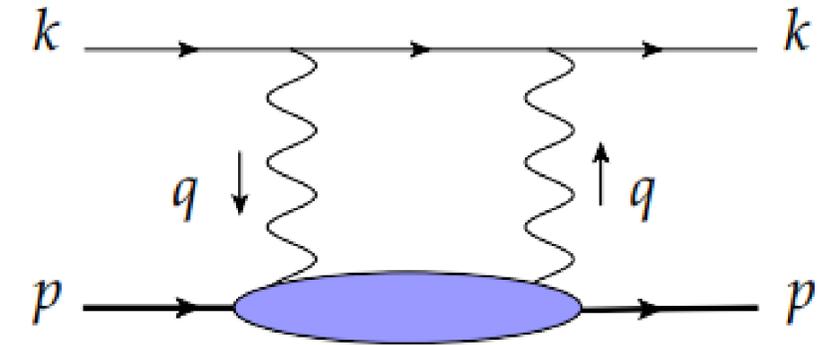
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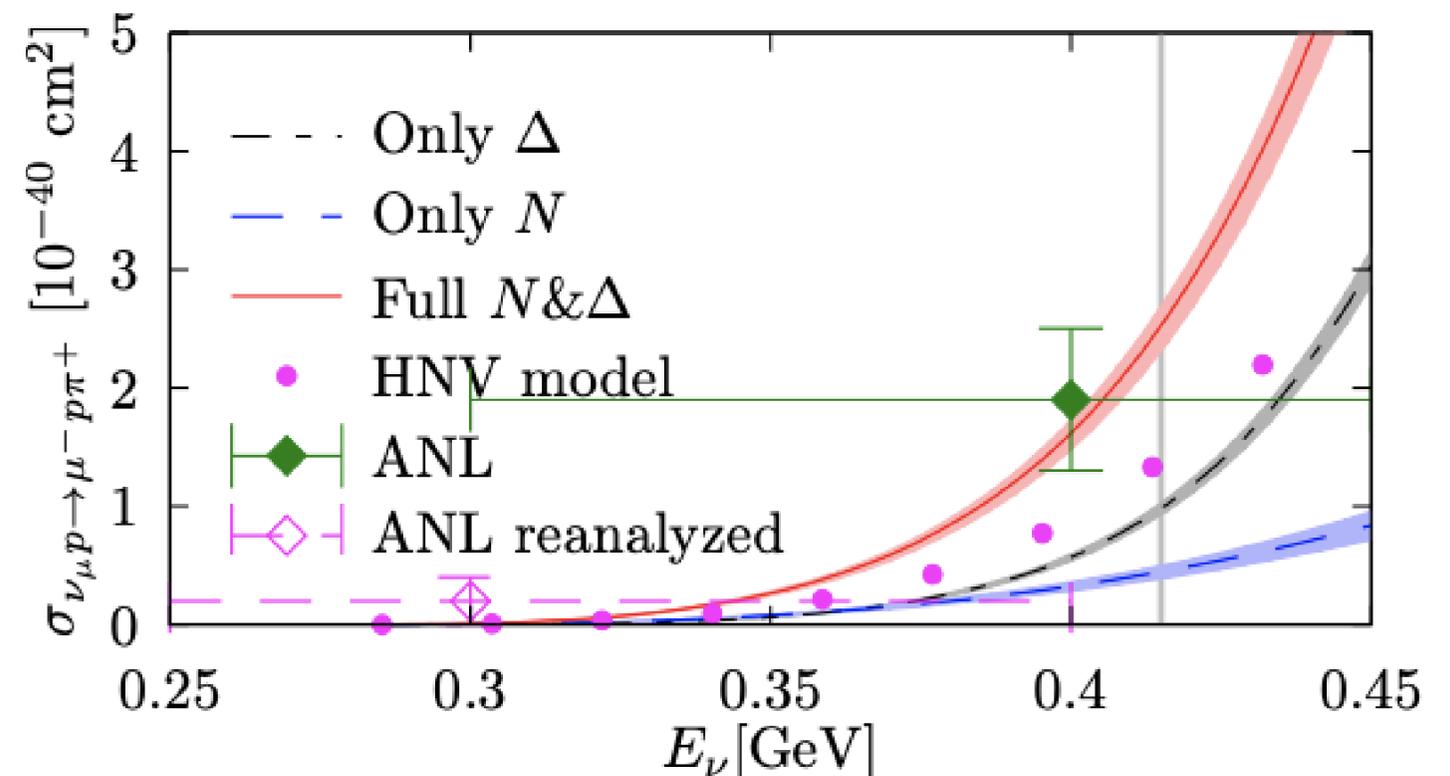


**Particle physics:** precision in **neutrino oscillation** studies –

$\nu N$  cross sections integrated over large energy bins.

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Neutrino-induced pion production – **Misha Gorshtein**



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

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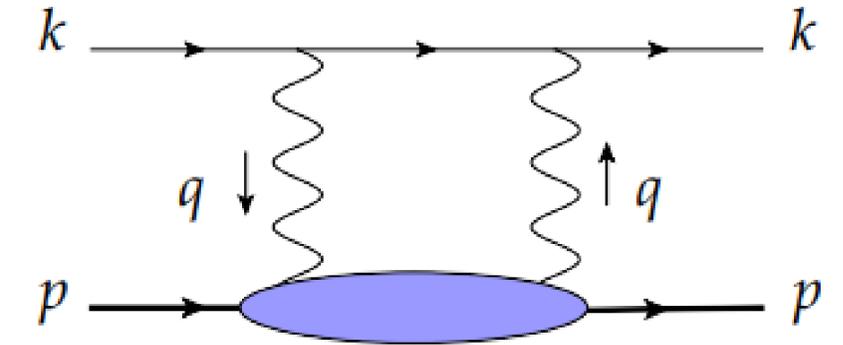
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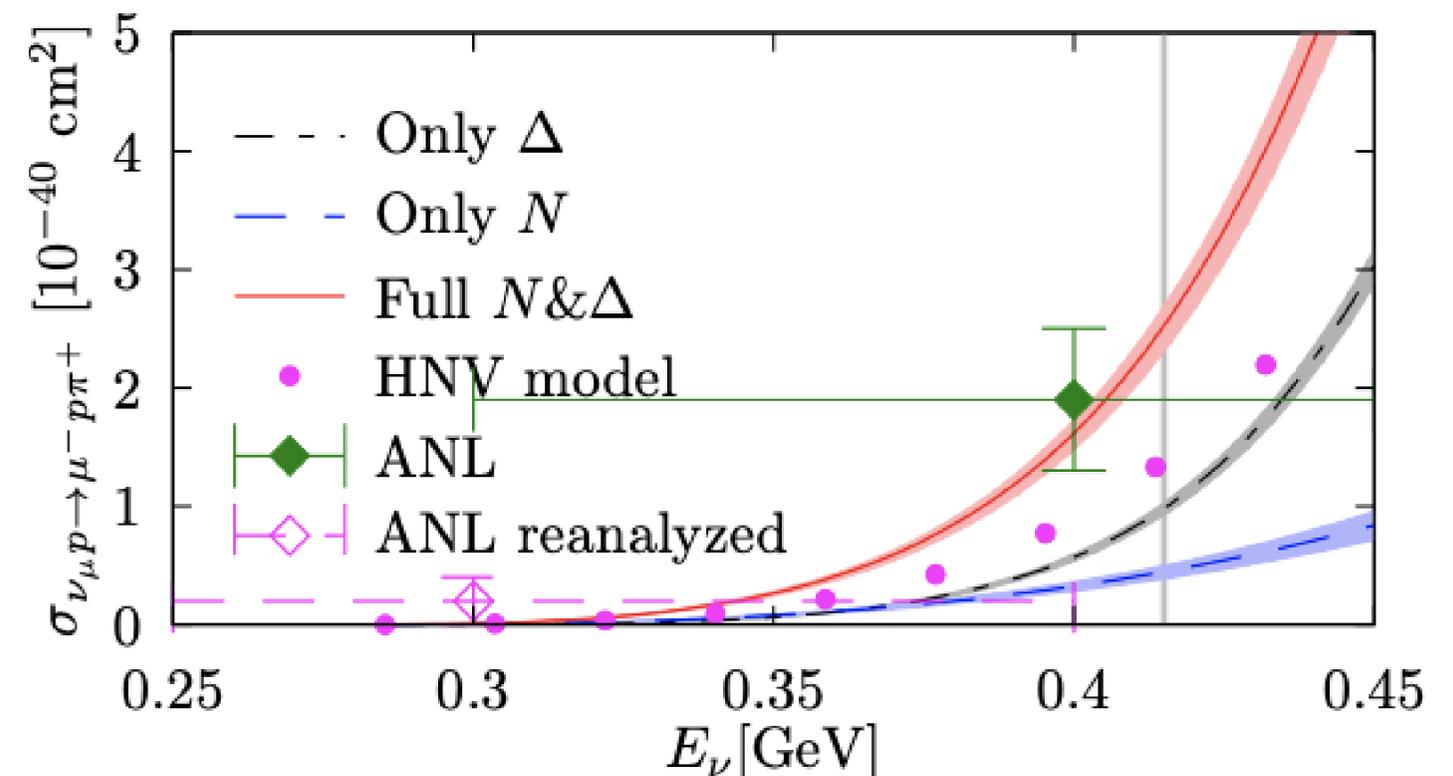
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Tests on **quark-hadron duality**.



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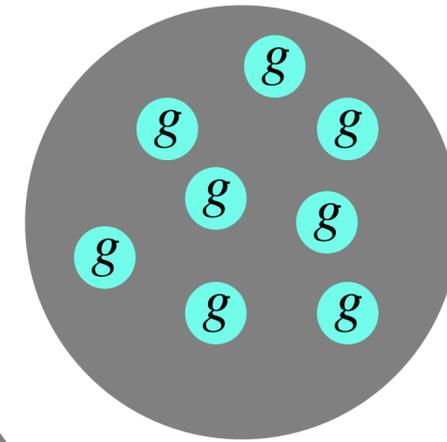
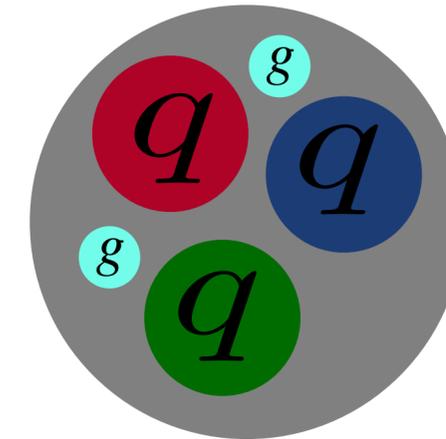
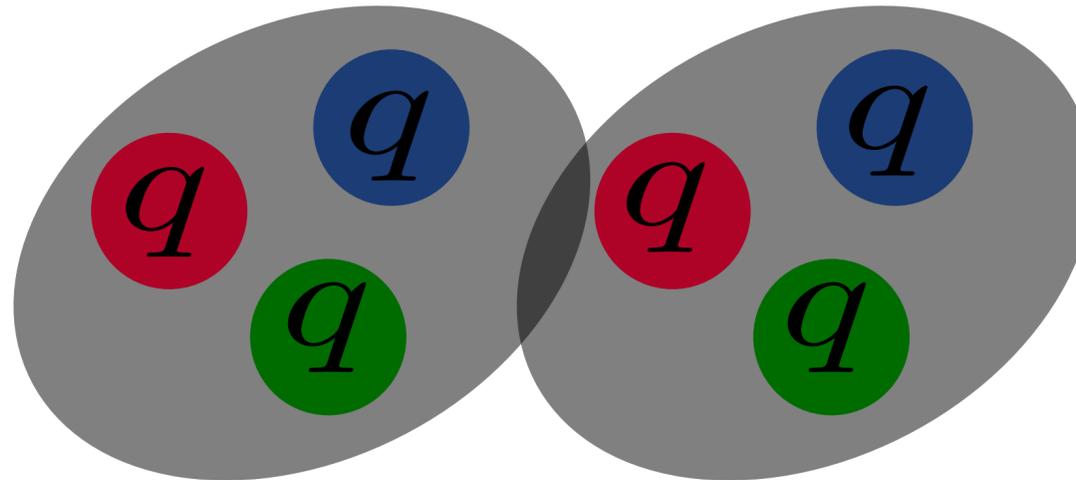
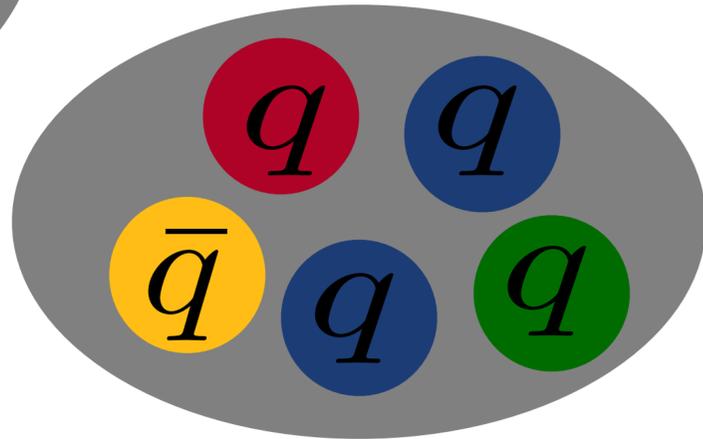
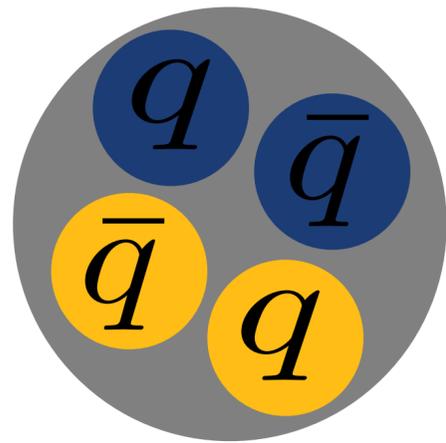
## **Exotic resonances**

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Ongoing and future goals

# Exotic resonances

Many resonances do not fall into the conventional 2- or 3-quark picture.



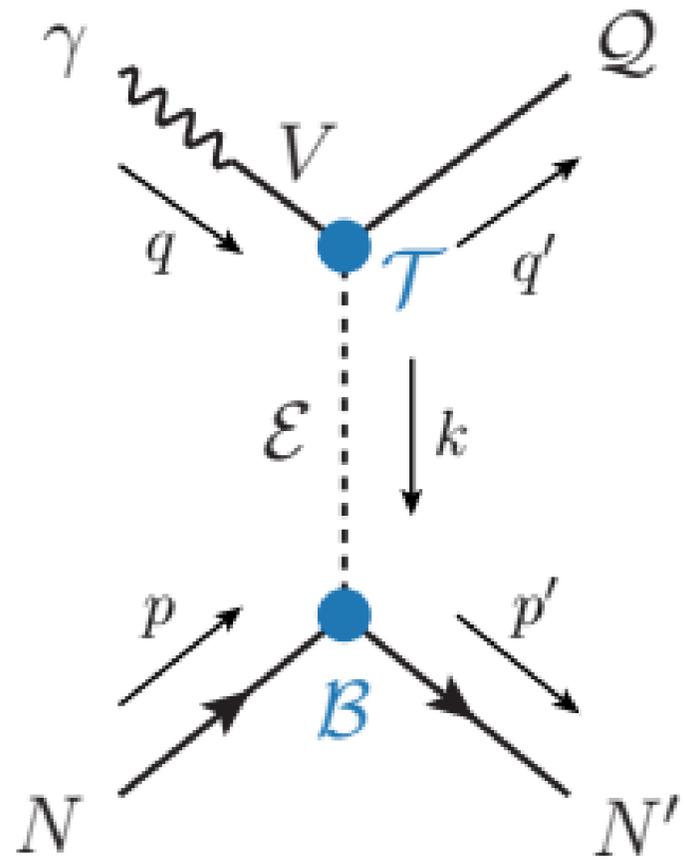
Tetraquarks and pentaquarks.

Hadron molecules.

Hybrids.

Glueballs.

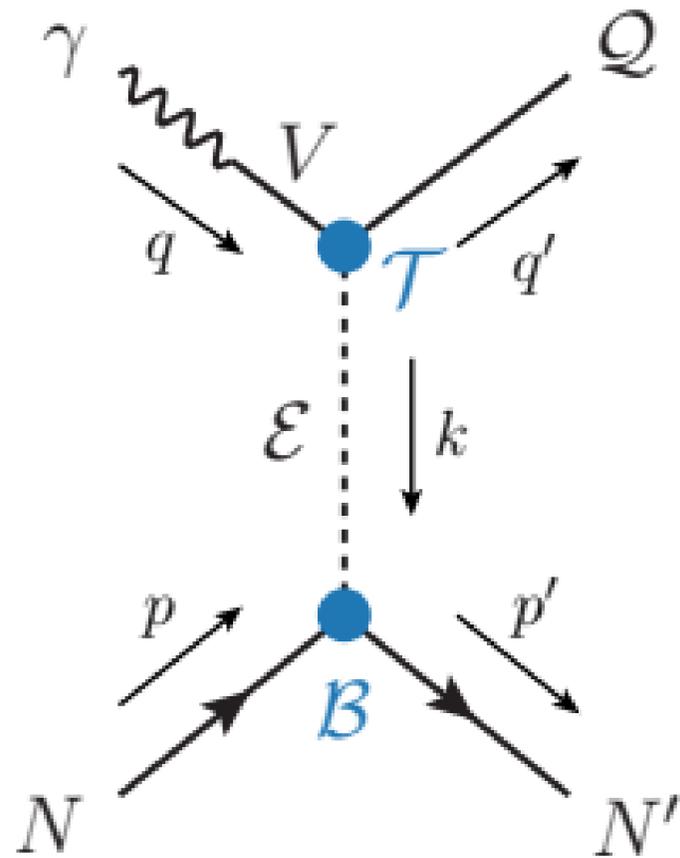
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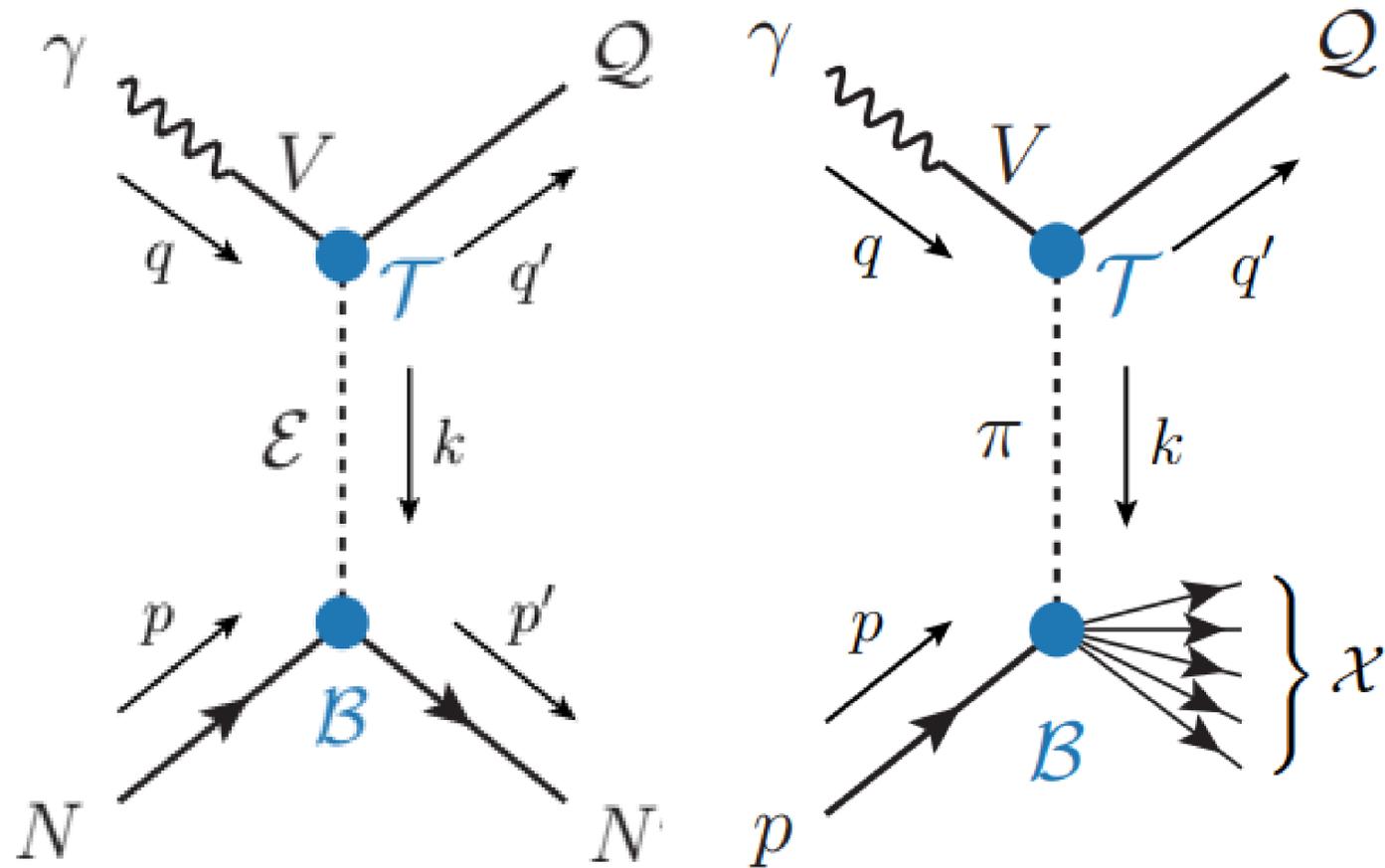
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**Reggeized version of pion exchange:**  
effective exchange of tower of particles with increasing spin.

# Charged Z photoproduction

**Smoking guns in exotic searches:**

hidden-charm content, but also charged – at the minimum, **tetraquark** content!

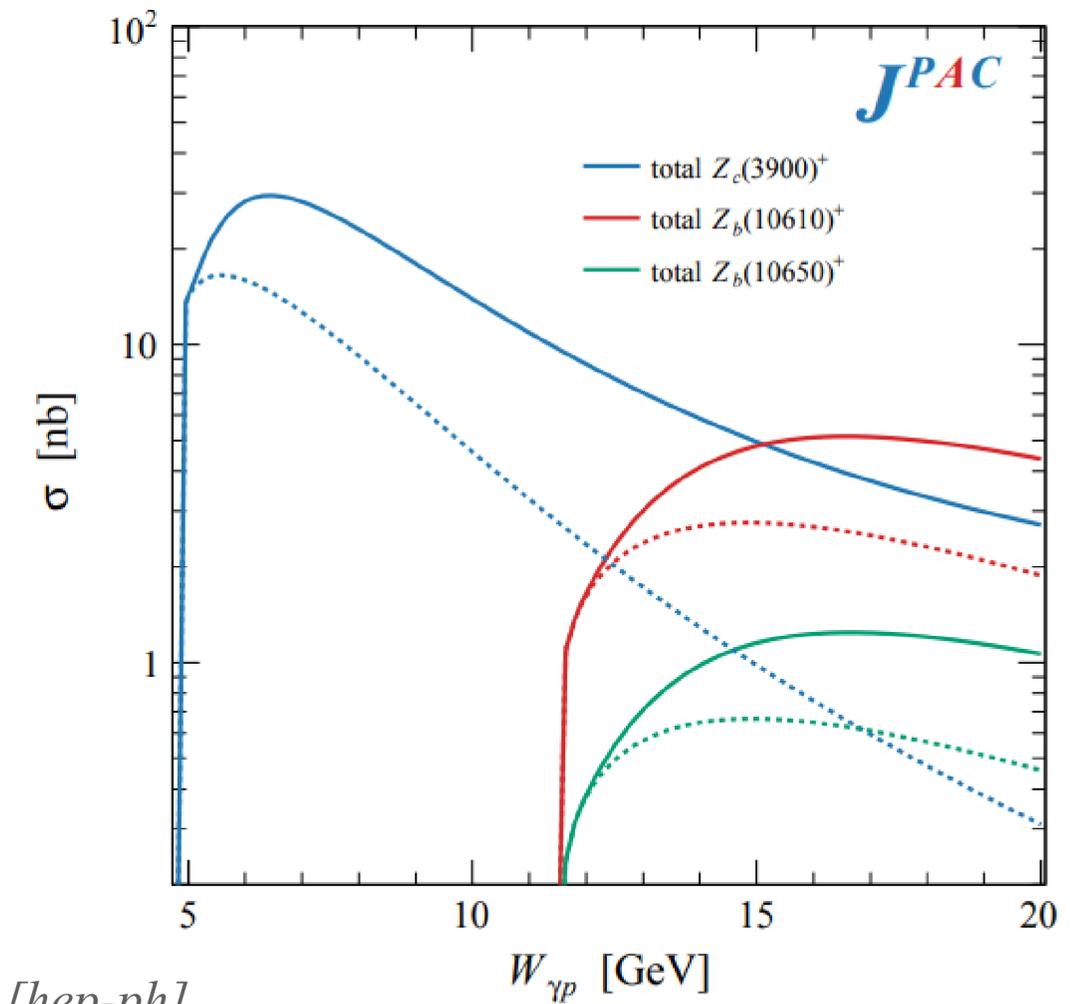
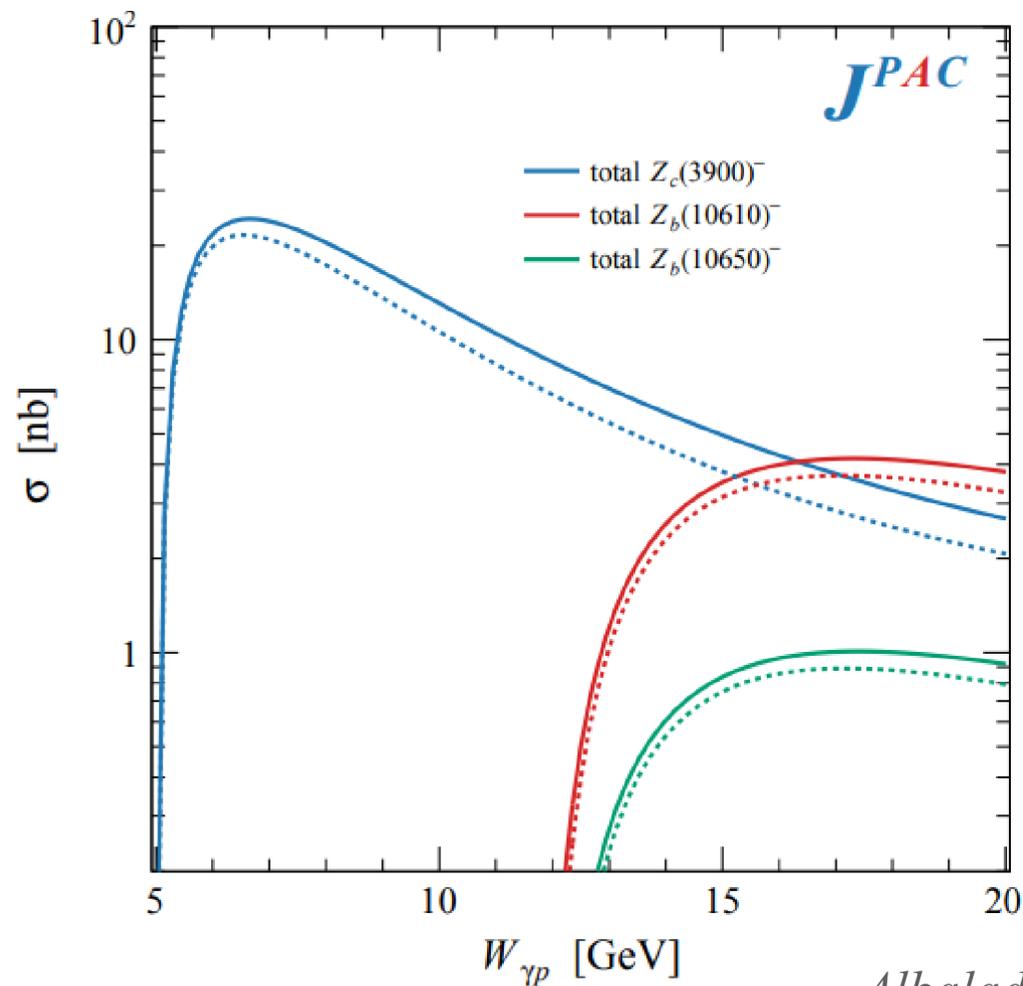
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**inclusive overall larger  
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(Dashed lines exclusive.)



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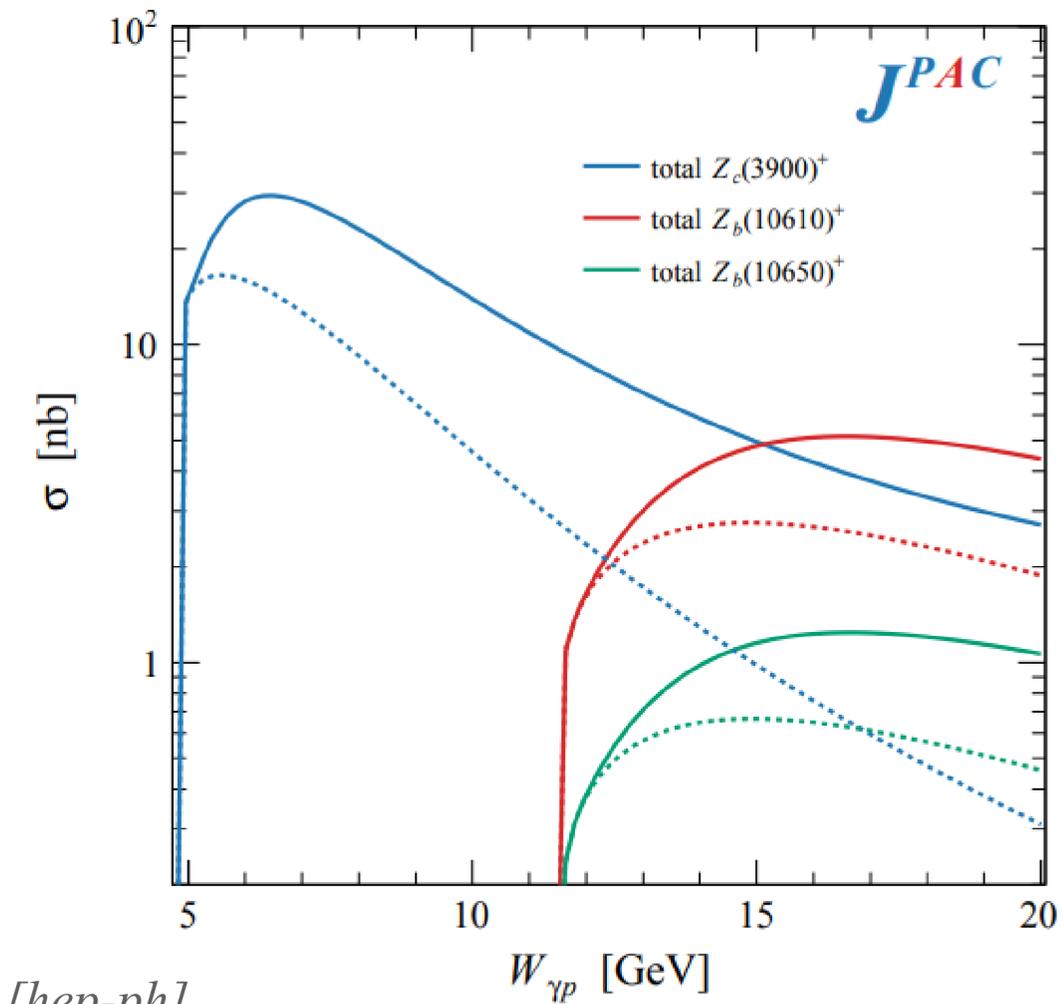
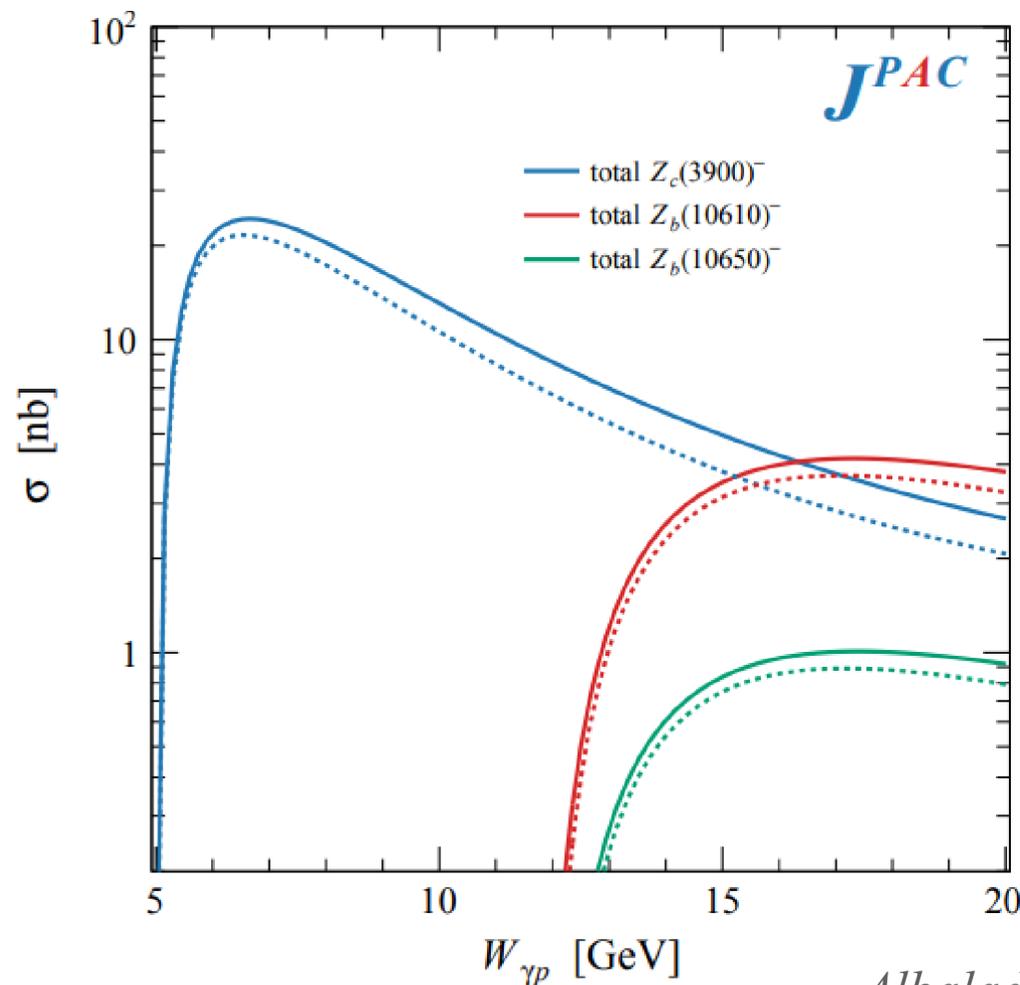
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**Conservative lower bound:**  
model reliable at large x,  
vanishes towards smaller x!

Large contribution from intermediate  
**Delta resonance:**  
promising to work towards exclusive  
Delta production experiments.



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# LHCb pentaquark confirmation: photoproduction

GlueX set upper limits to branching fractions.

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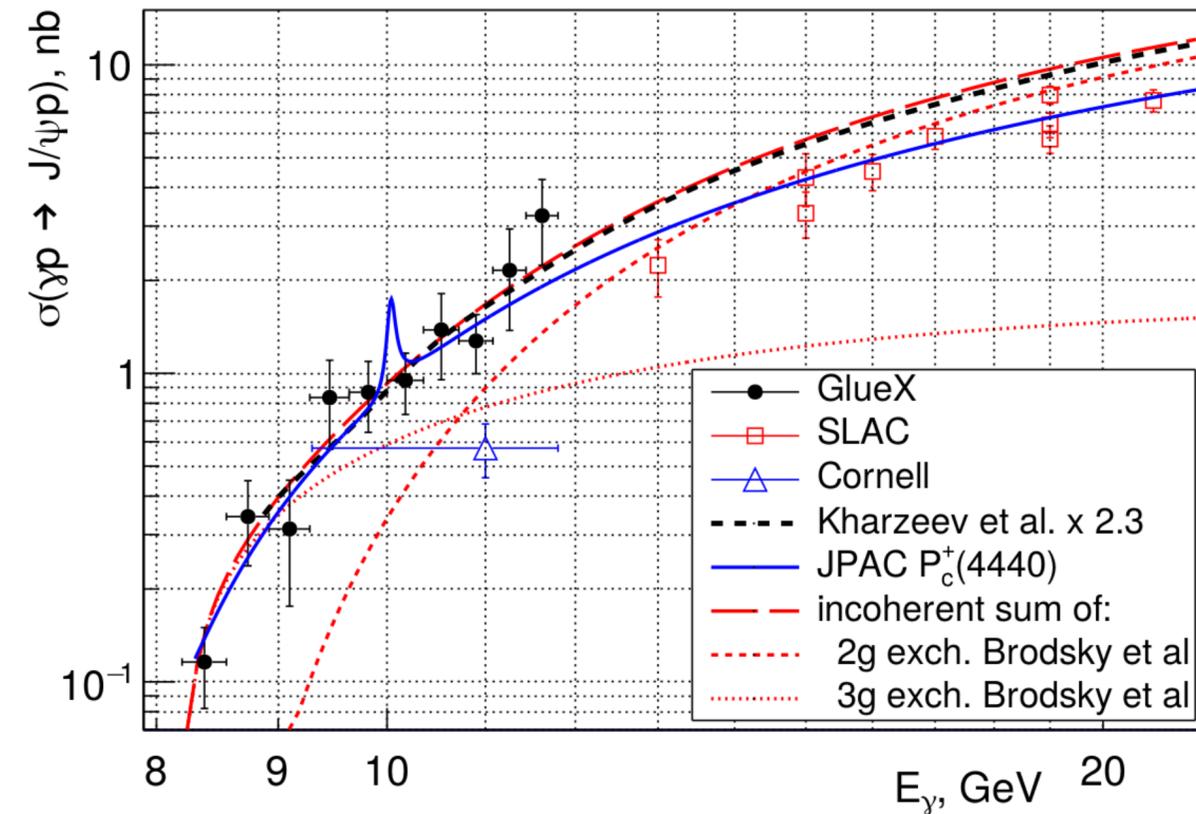
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**Differential cross sections soon, 2200 events.**

Hall C results have been presented –  
order of magnitude more stringent limits.

**Challenges several resonance theory models,  
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[See S. Joosten's talk at DNP2021]



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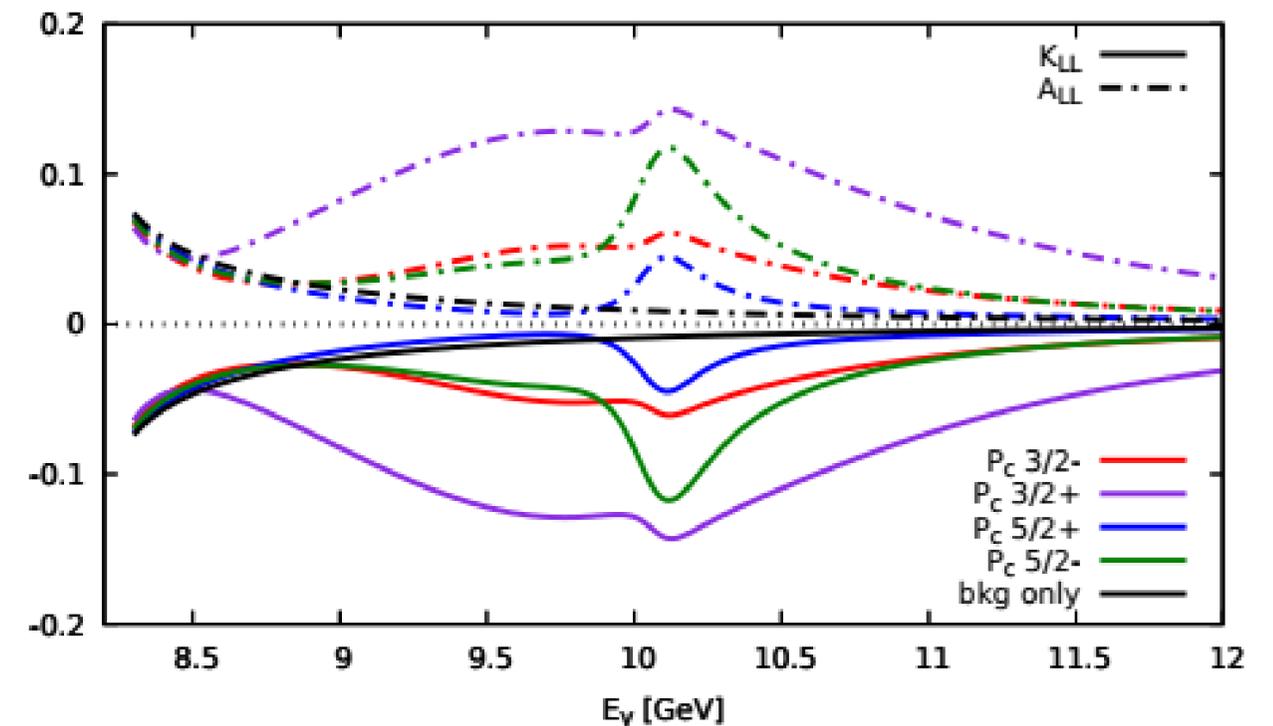
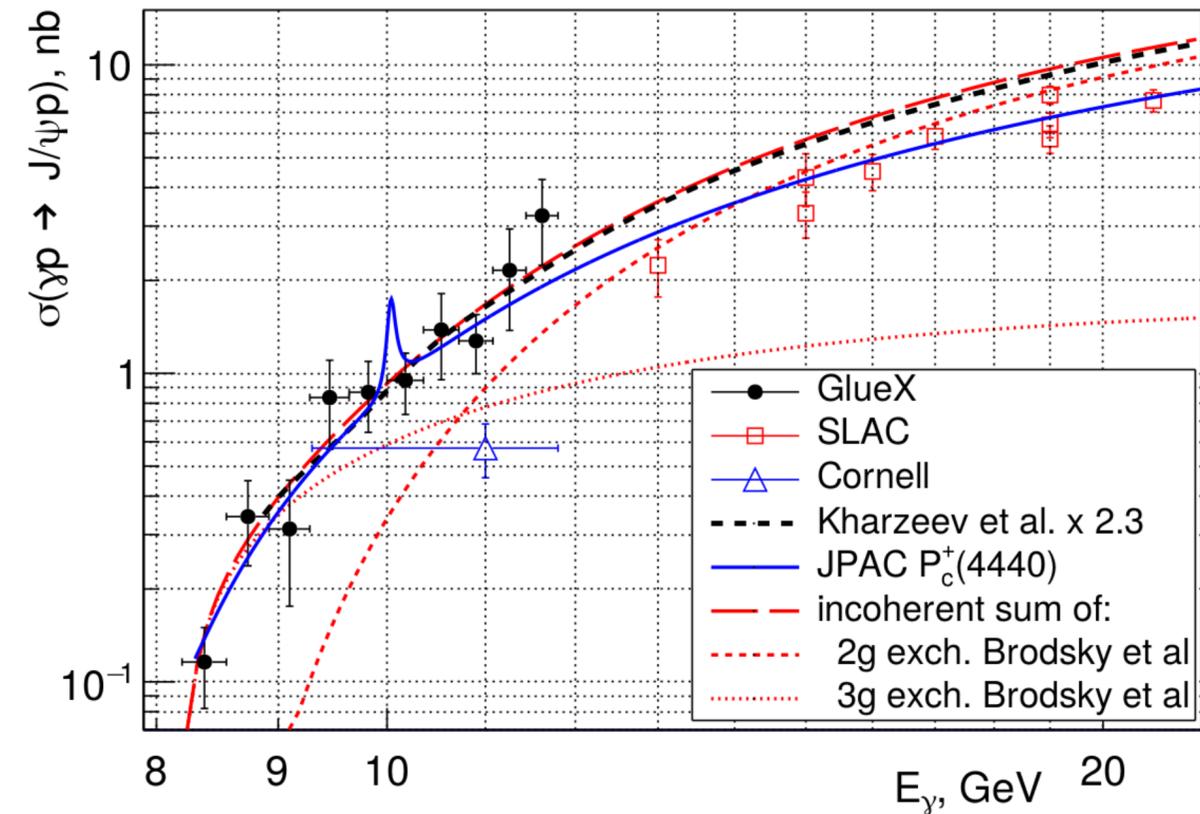
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Moving forward, measurement of **polarization observables**  
(sensitive even to broader and overlapping signals),

**open-charm** production,  
and hidden-bottom **searches** are promising.

[LoI12-18-001 (PAC 46);

Cao and Dai, PRD 100 (2019) 054033]



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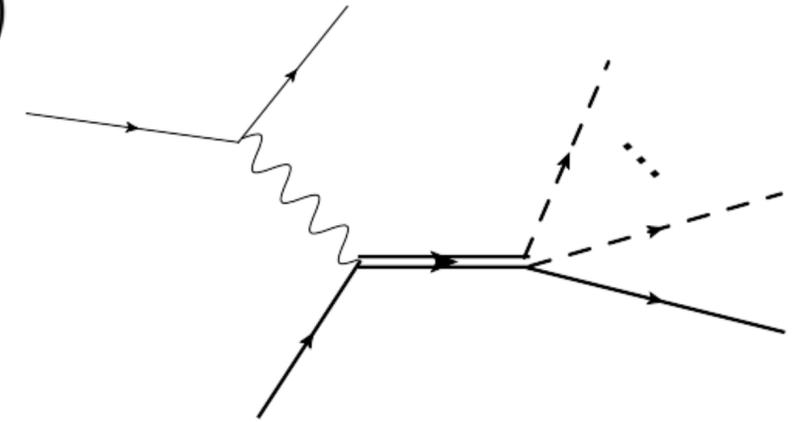
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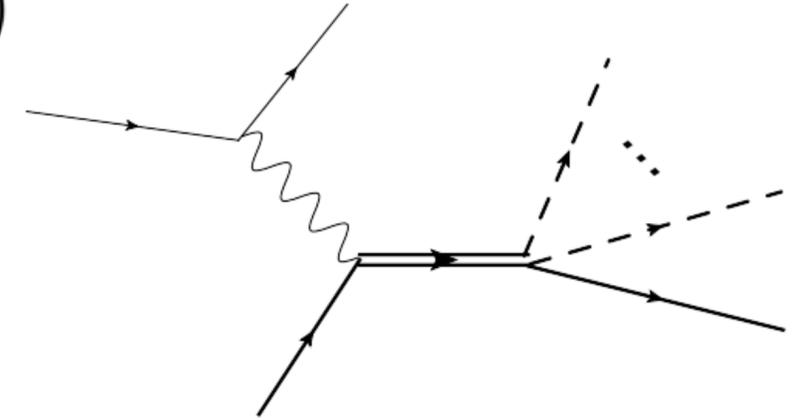


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Breit-Wigner resonance model:  
coherent sum of resonances.



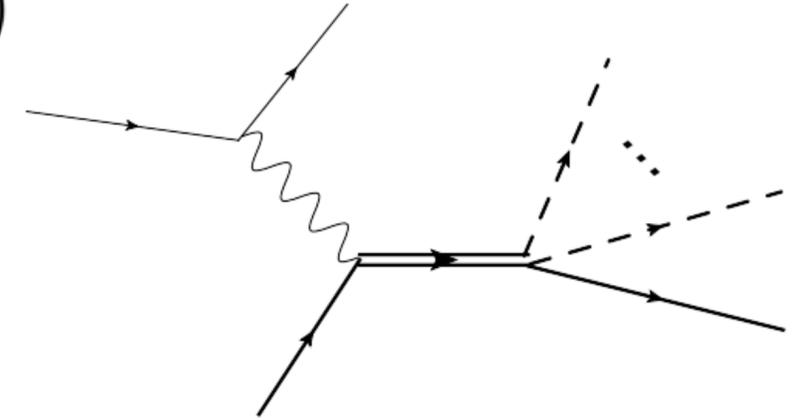
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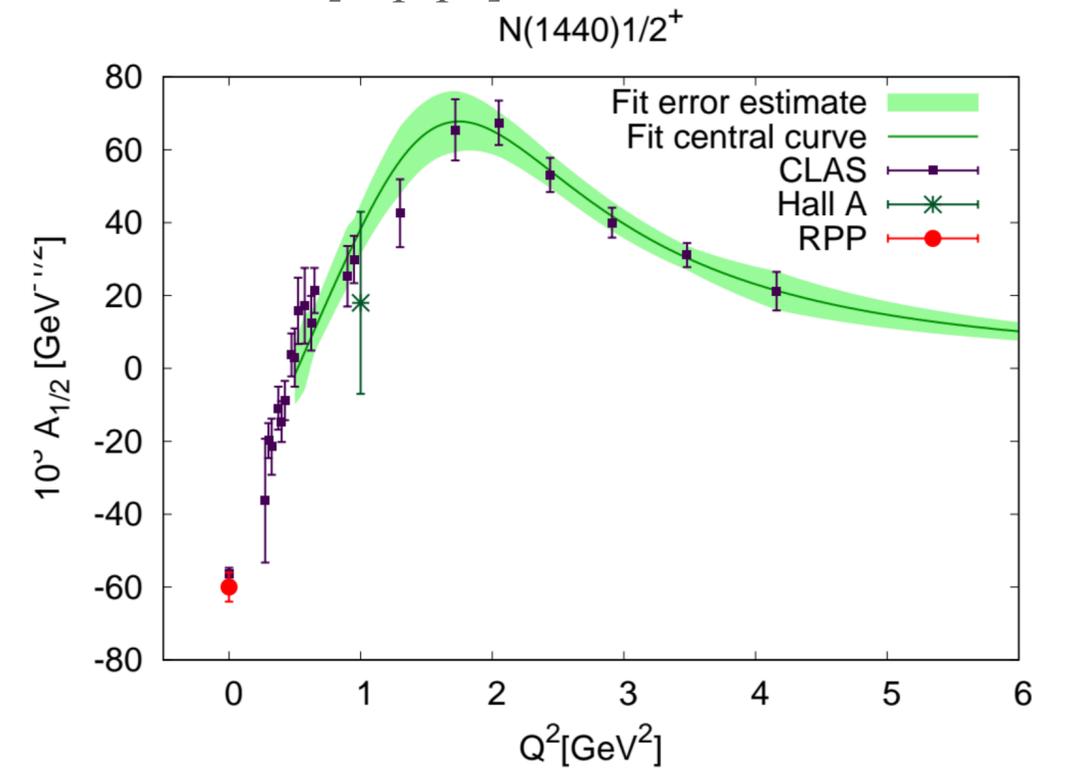
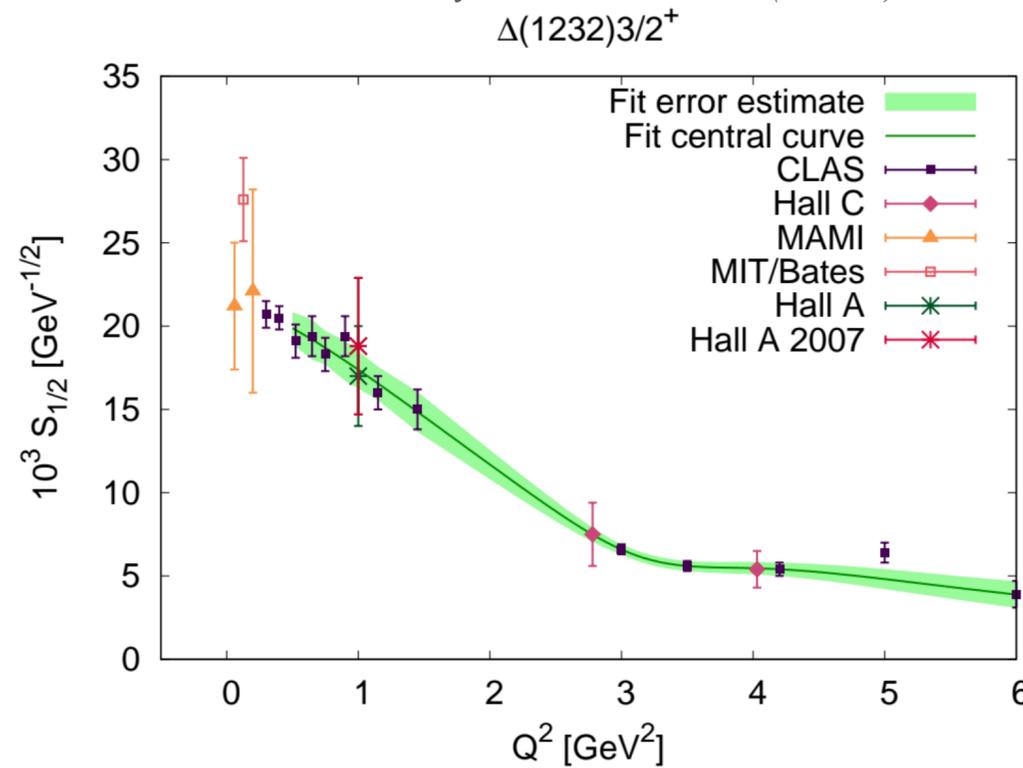
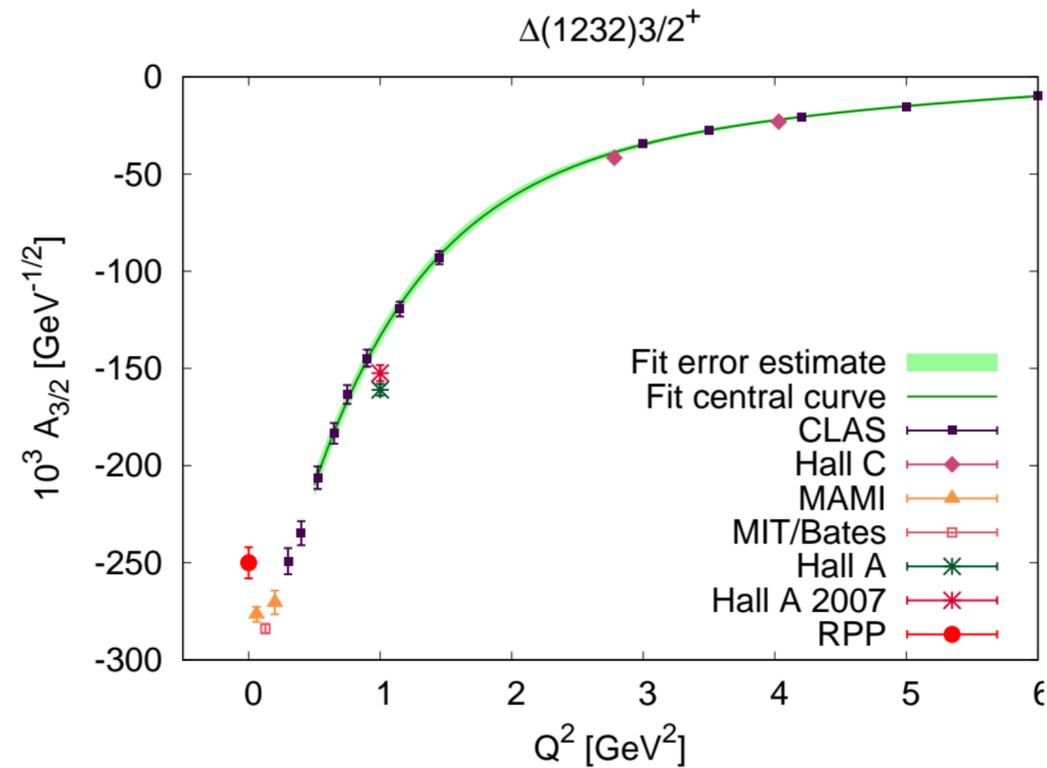
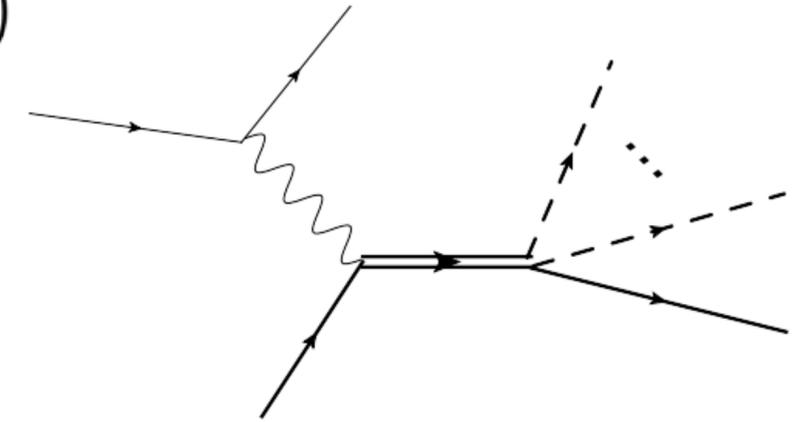
From exclusive data: electrocouplings.

<https://userweb.jlab.org/~isupov/couplings/>

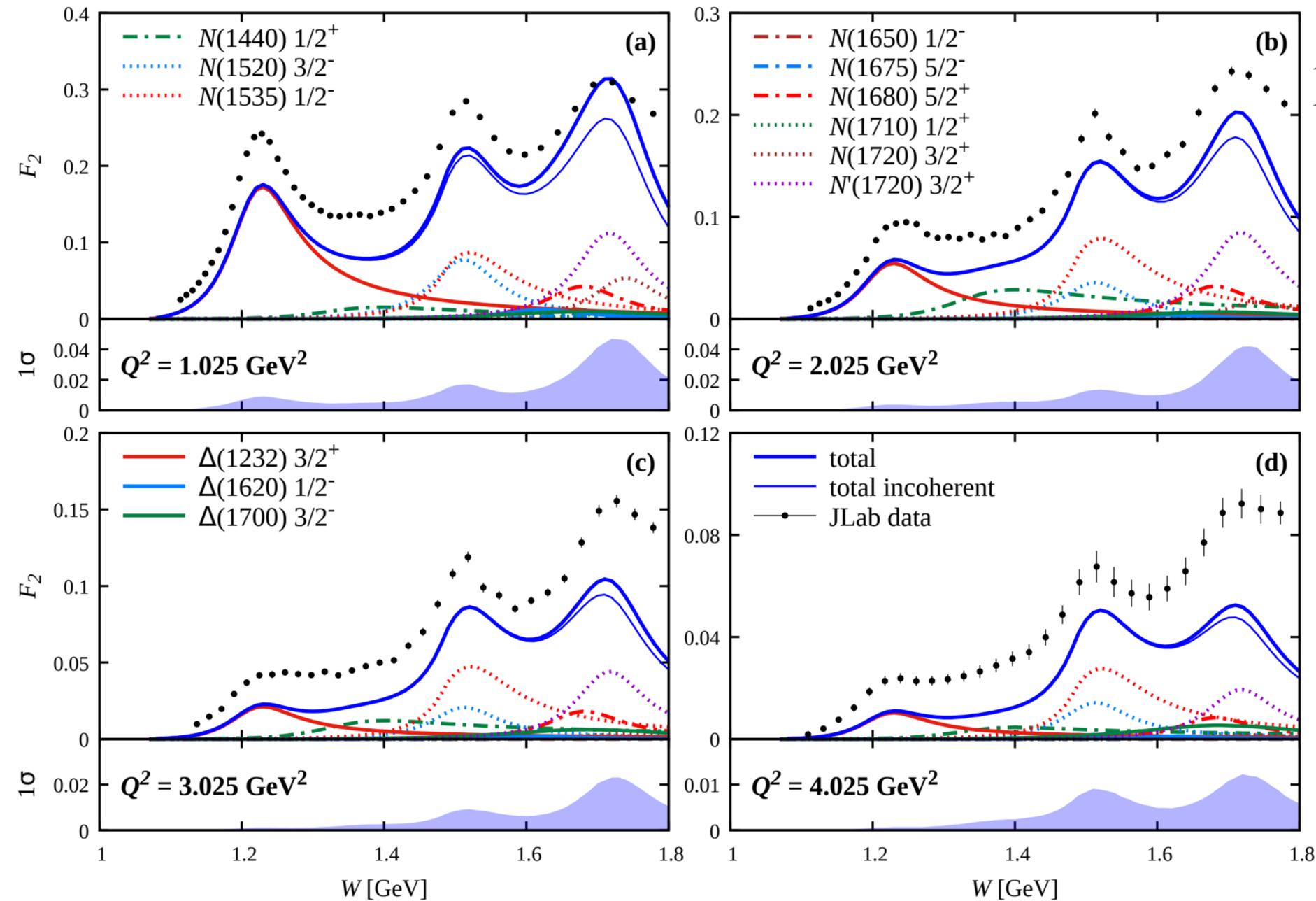
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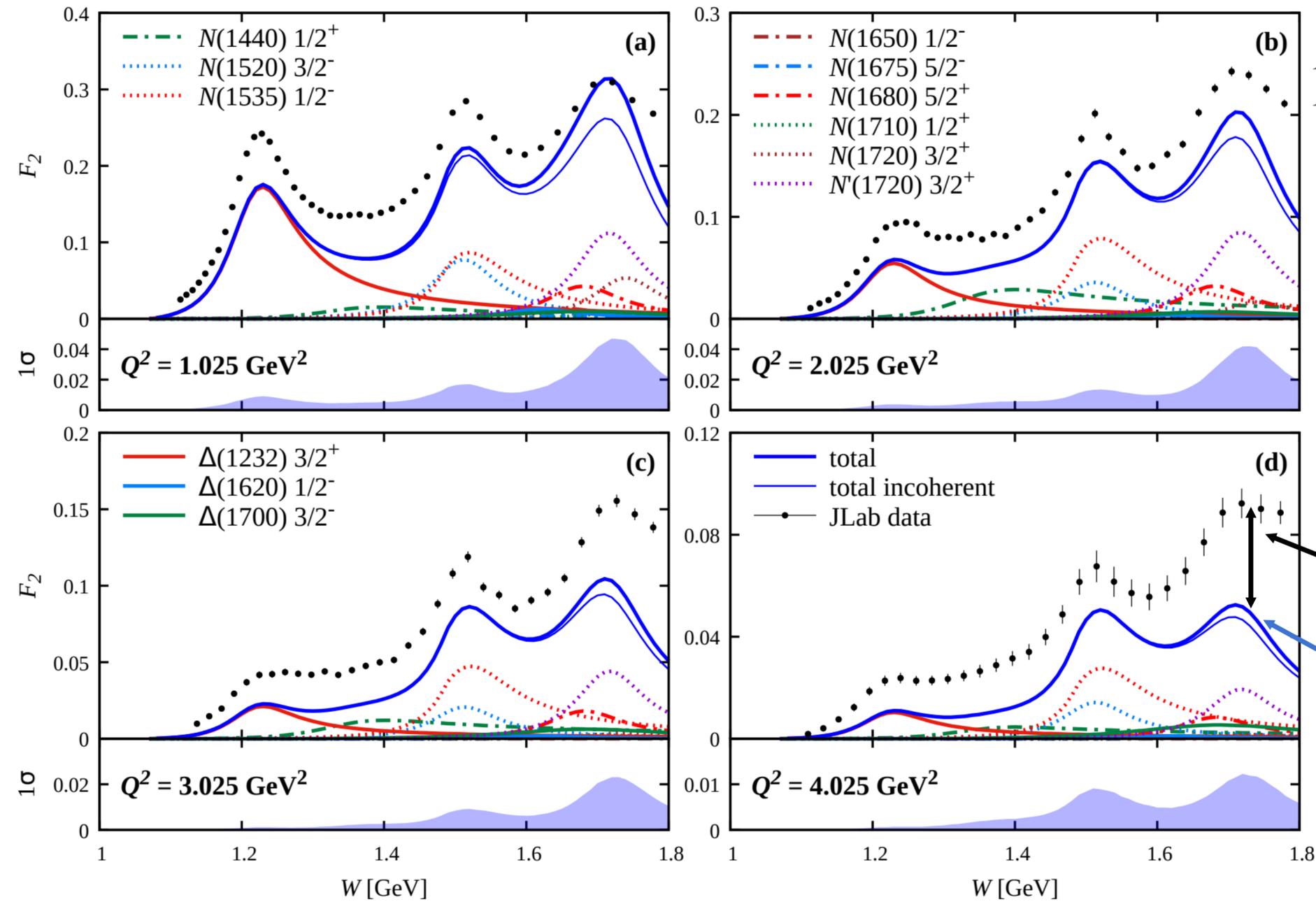


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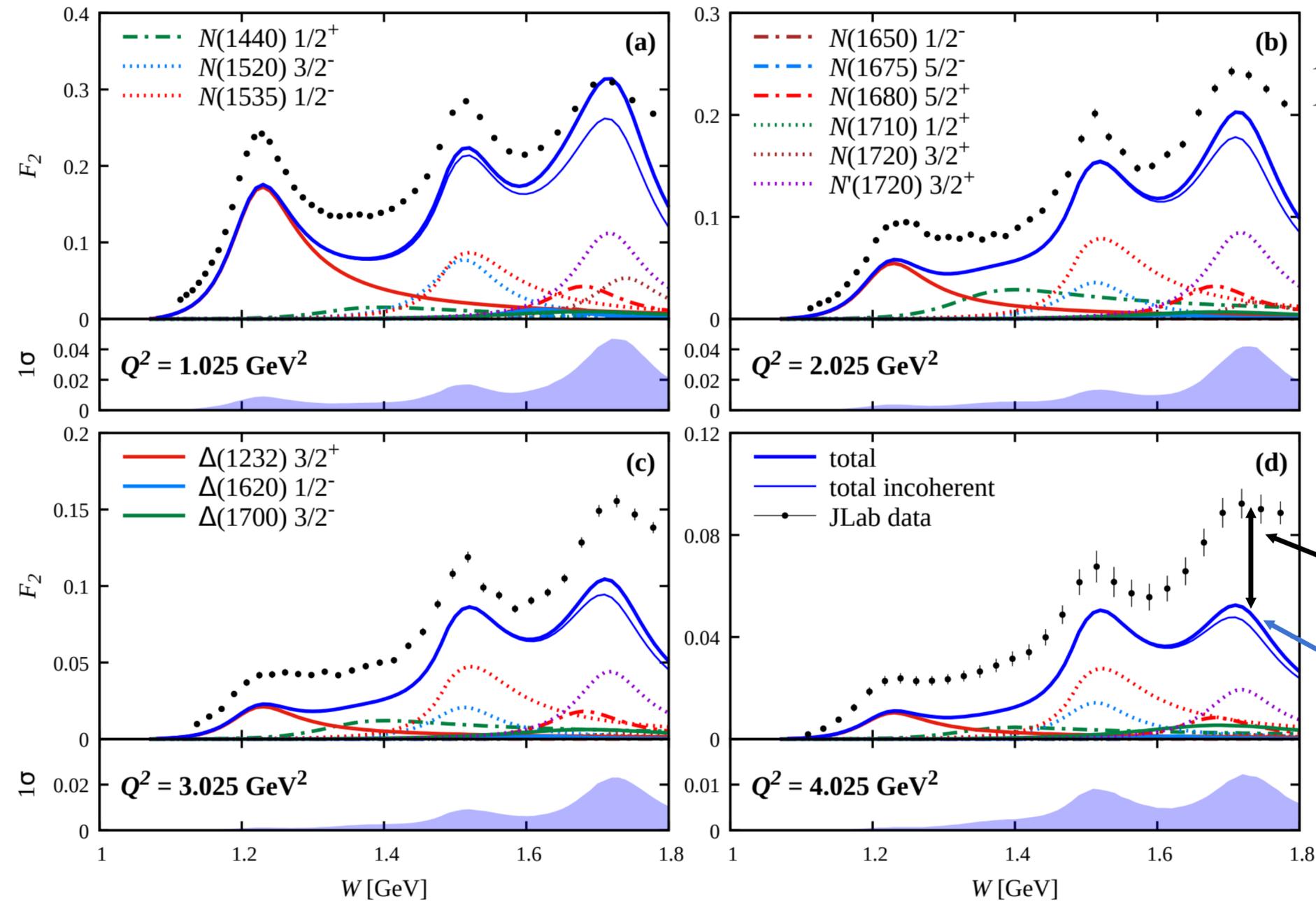
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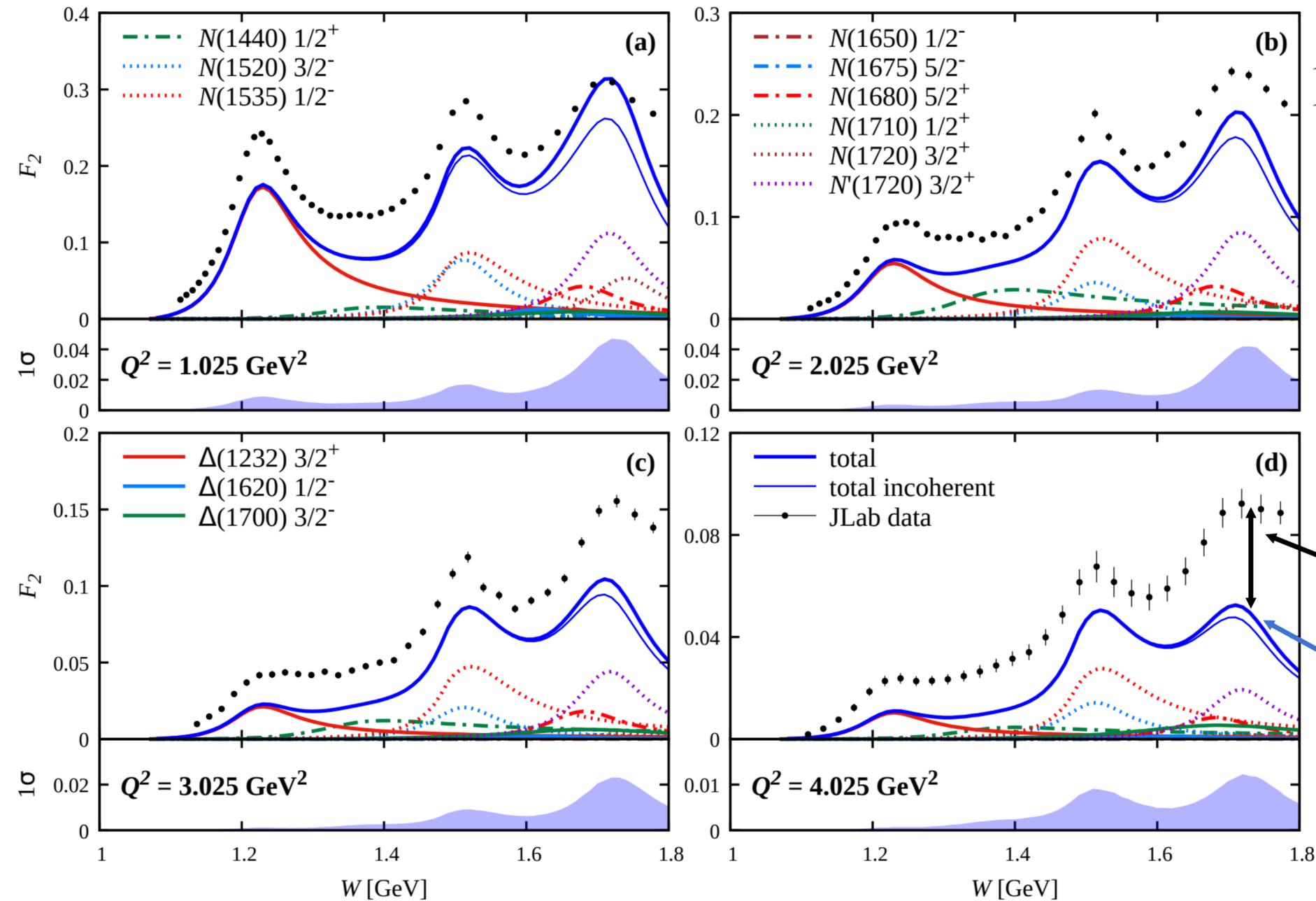


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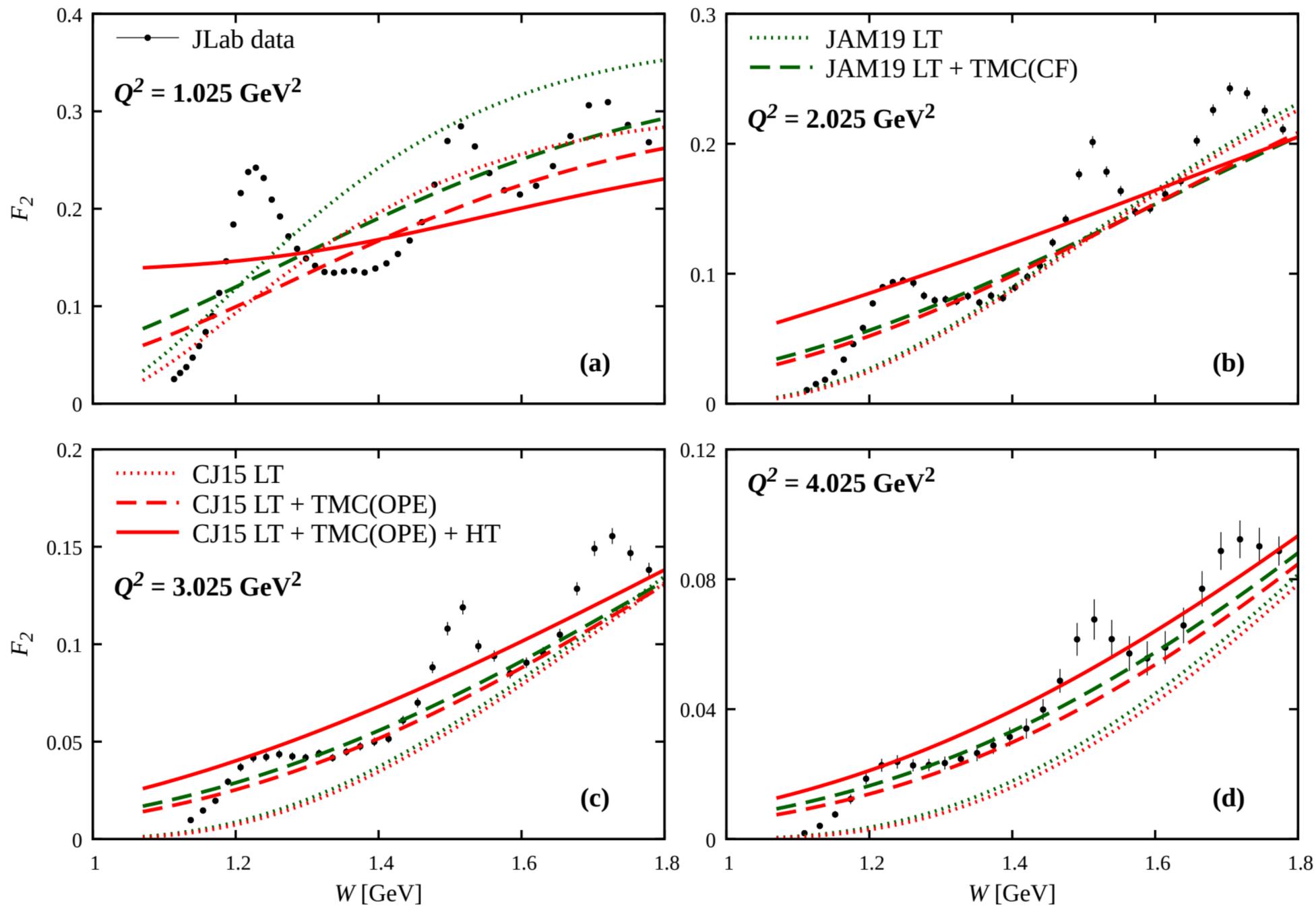
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*ANHB et al., Phys. Rev. C 104 (2021) 025201, 2105.05834 [hep-ph]*

Intricate differences in evolution of peaks with  $Q^2$ .

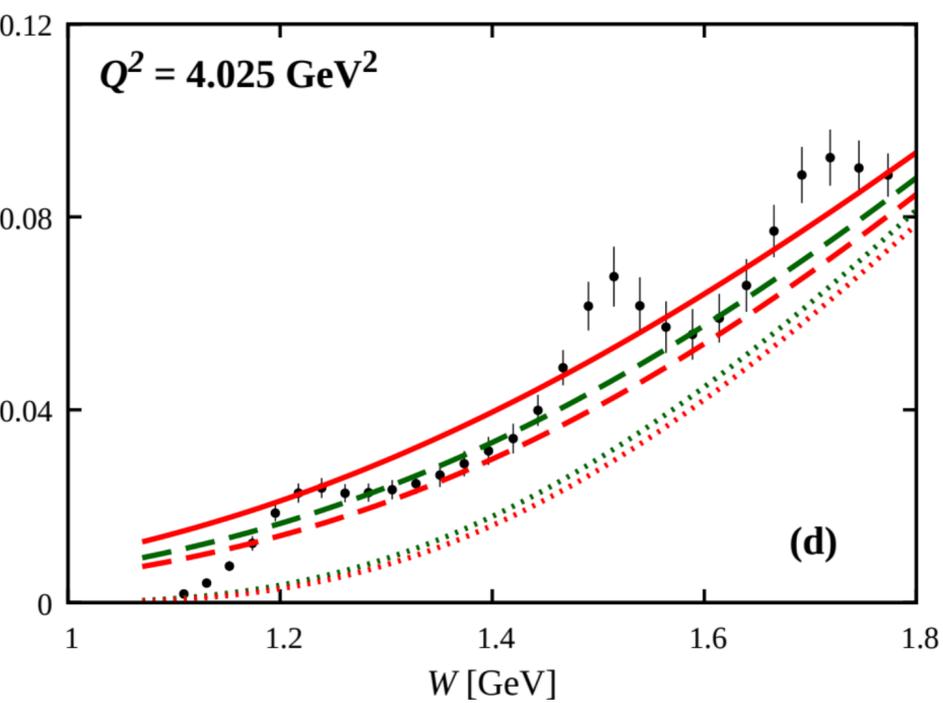
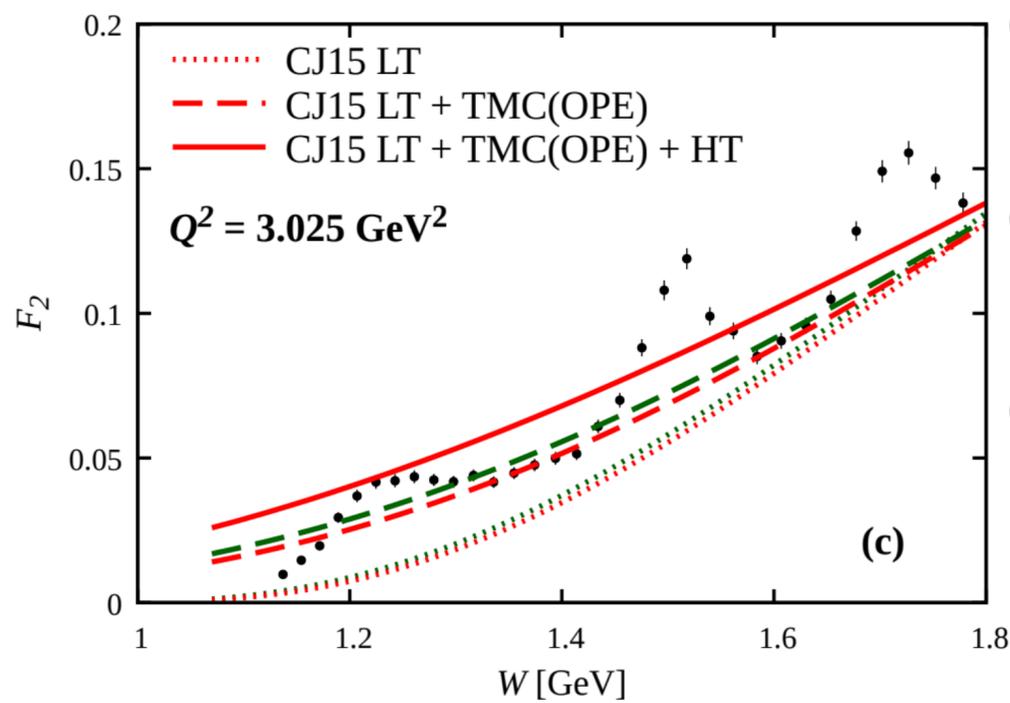
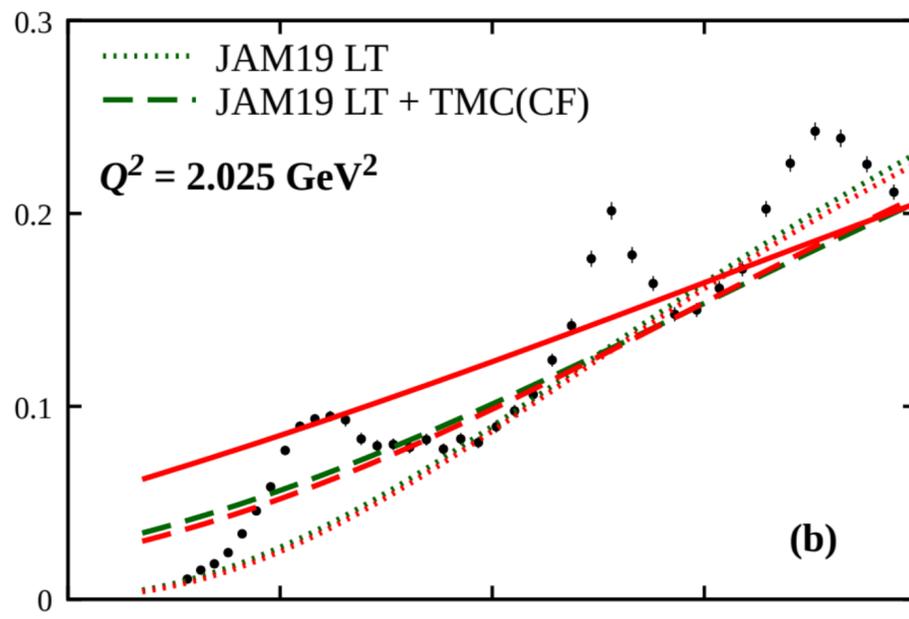
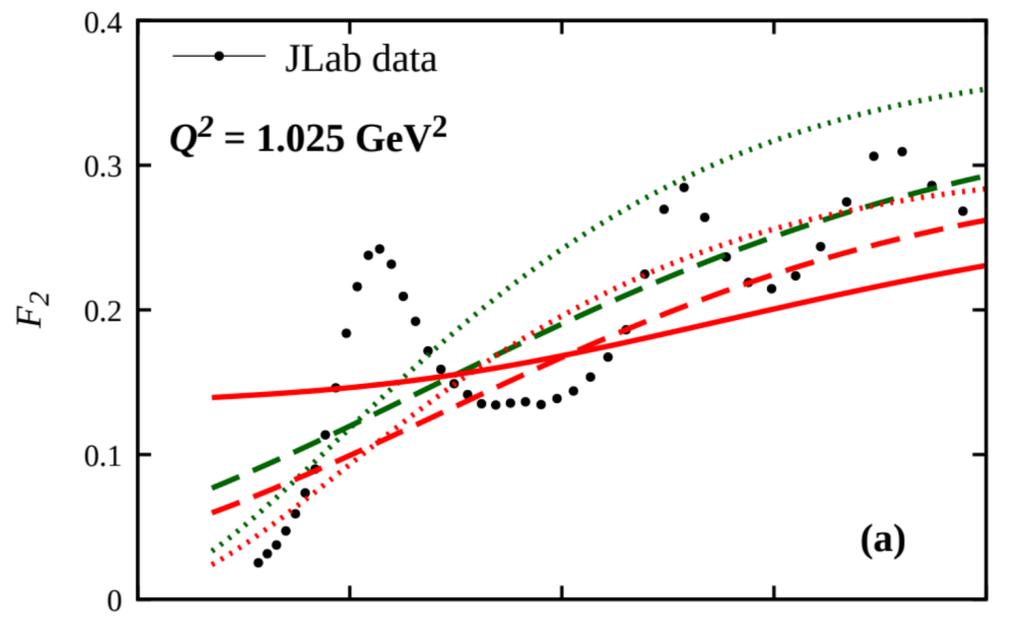
Resonance contributions remain strong at all  $Q^2$ ,  
**supporting future studies of electrocouplings.**

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

# Fits to high energies extrapolated to low energies

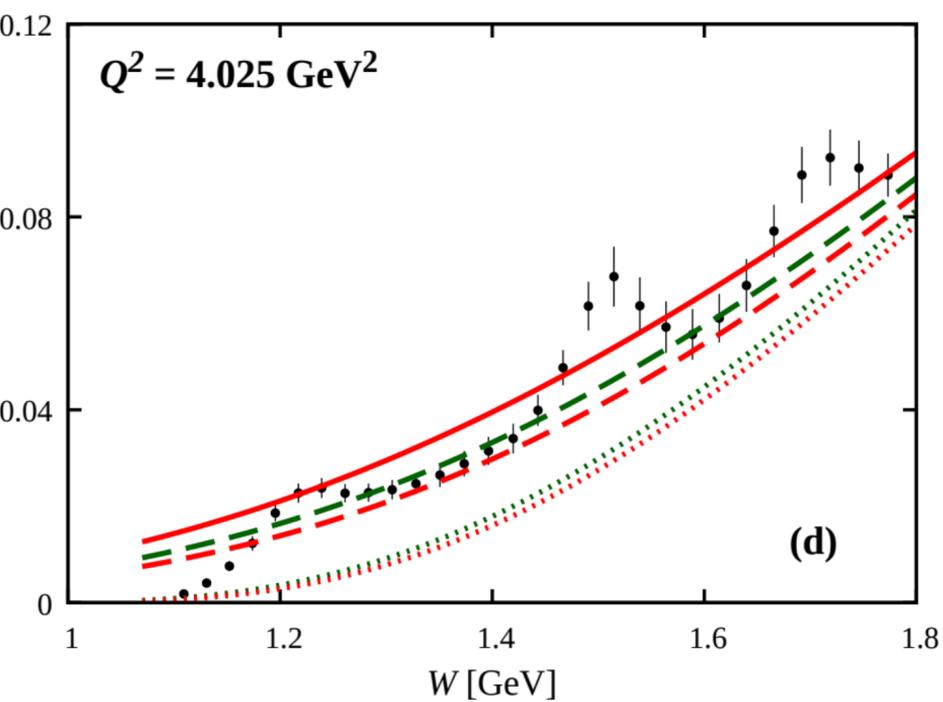
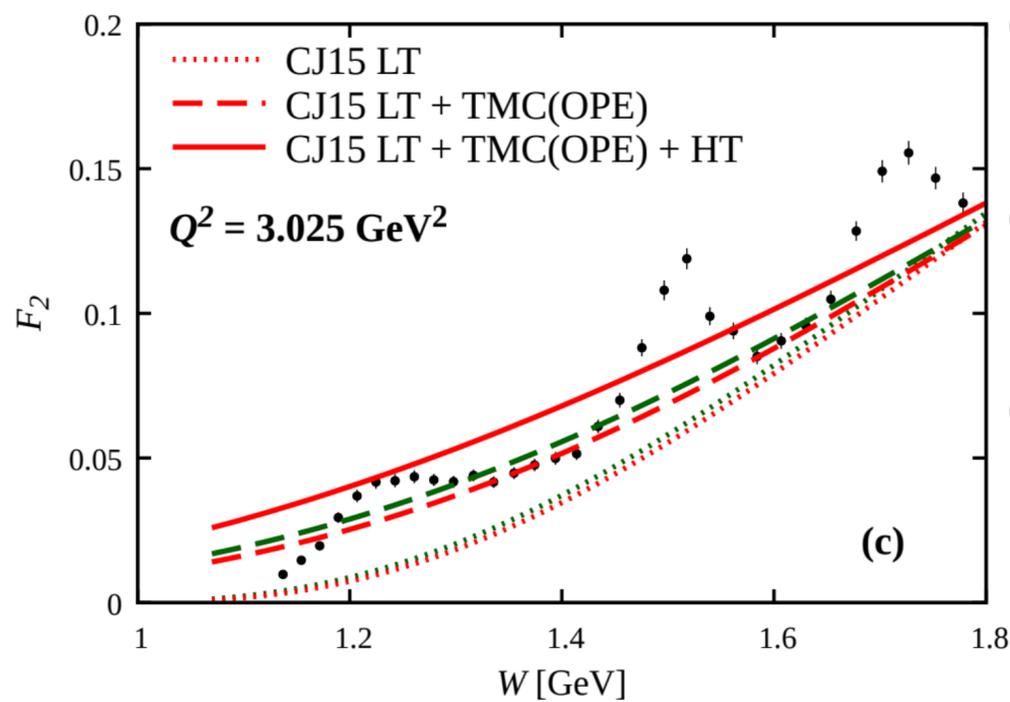
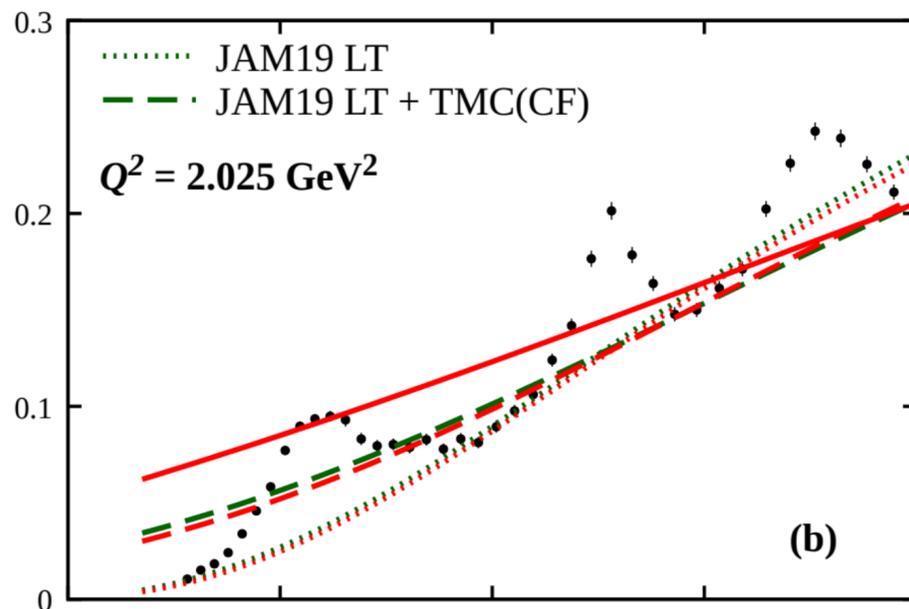
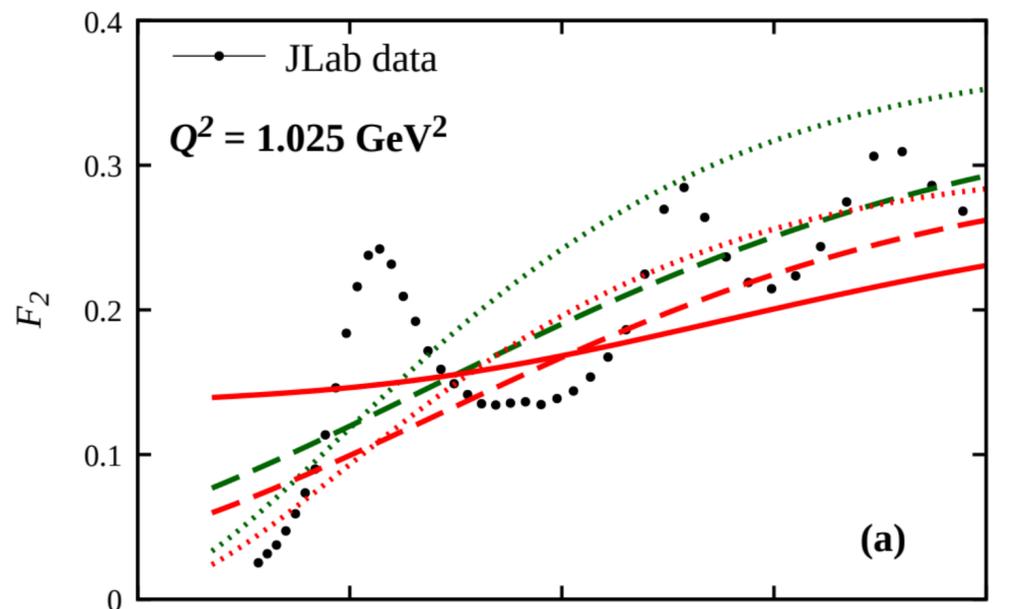


# Fits to high energies extrapolated to low energies



High-energy fits compatible with averaged data in the resonance region:

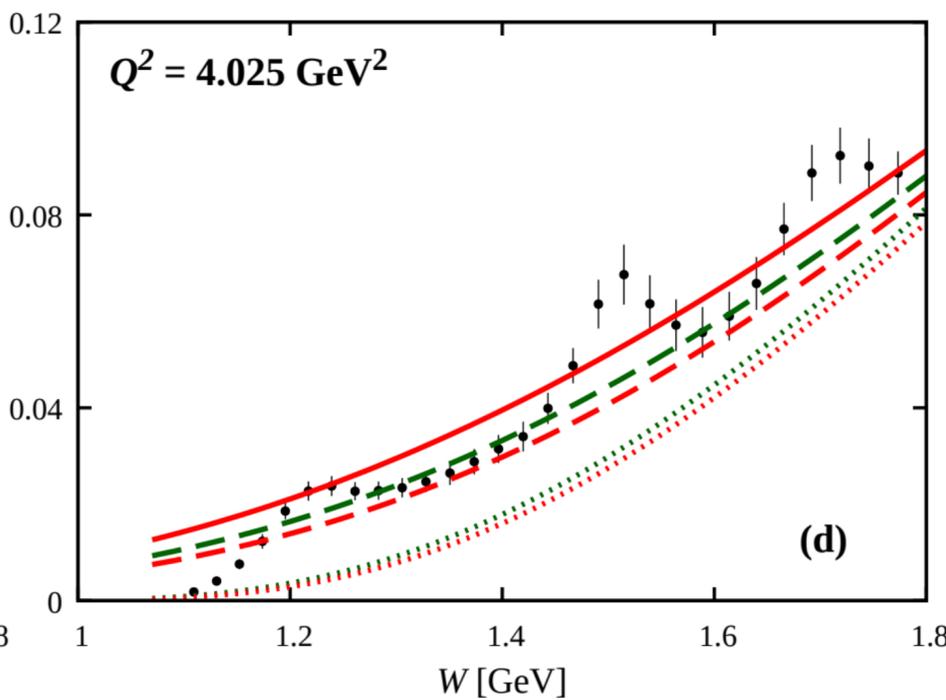
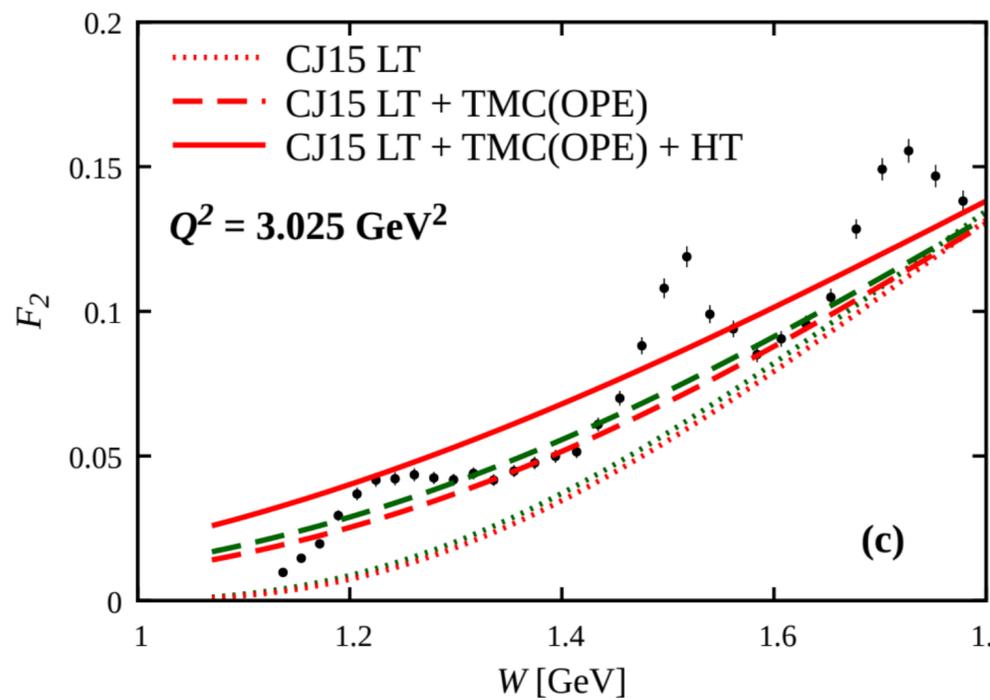
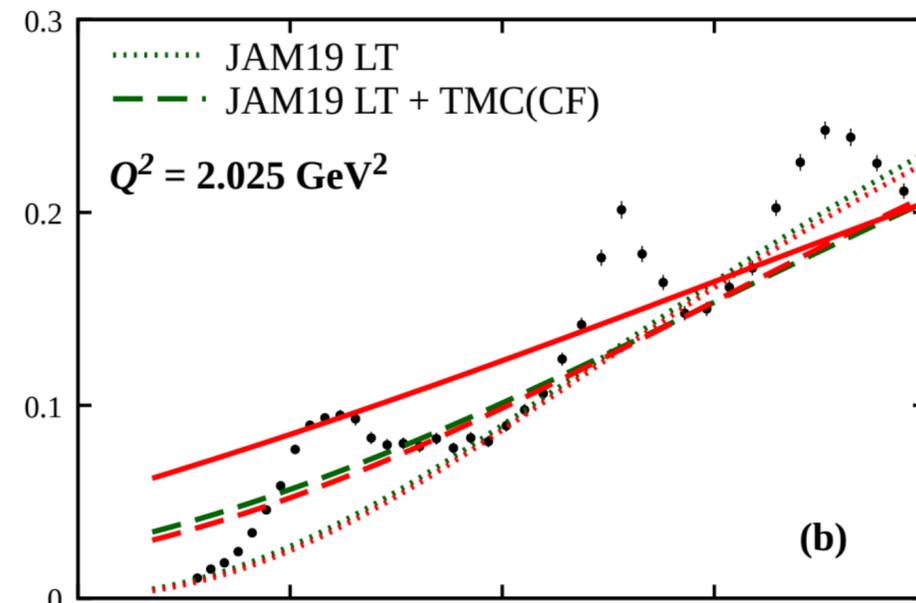
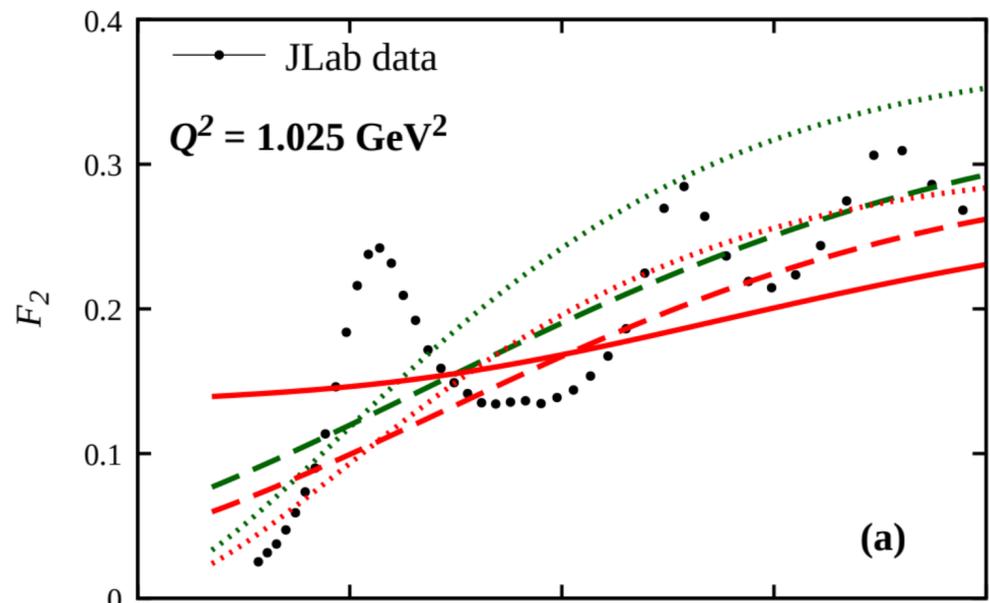
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High-energy fits compatible with averaged data in the resonance region:

**global duality onset!**

# Fits to high energies extrapolated to low energies



High-energy fits compatible with averaged data in the resonance region:

**global duality onset!**

Opportunities for studies of **parton distribution functions at large x.**

# Outline

Electroweak interactions: structure and spectroscopy

Exotic resonances

Transition from low to high energies

**Ongoing and future goals**

# Summary and outlook

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

**hadron spectroscopy** — insight into spectrum of hadron (exotic!) resonances;

**nucleon structure** — describing analytically transition from perturbative QCD to low-energy regime.

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yield predictions of **pentaquark and XYZ photoproduction**;

a sturdy **separation between resonant and non-resonant** contributions to the proton structure.

These benchmarks allow to, in future:

study yields and asymmetries for **photo- and electroproduction experiments**;

**analytically connect** unpolarized and spin structure functions in the **transition** from low to high energies;

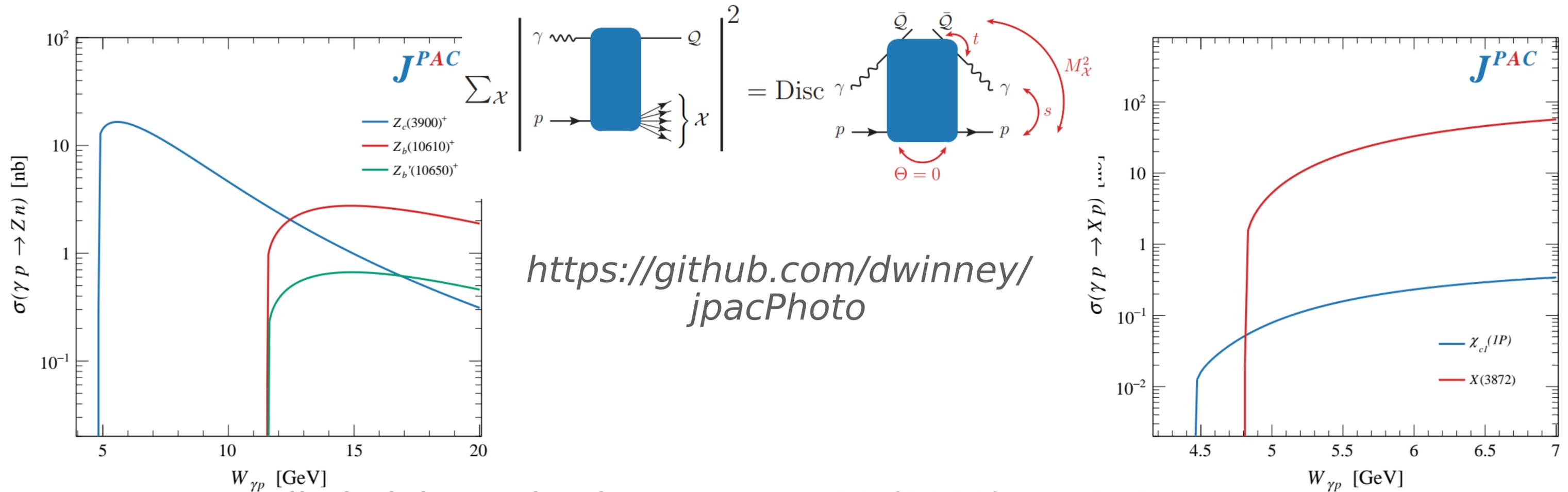
**extract integrated precision observables** in unpolarized and spin observables.

# tetraquark and

The are smoking-gun exotics, as they have content, but are charged!

The nature of the is still debated, but it intrigues with its apparent isospin-breaking decays.

Both have most sizable cross sections close to threshold: experiments should search at low energies!



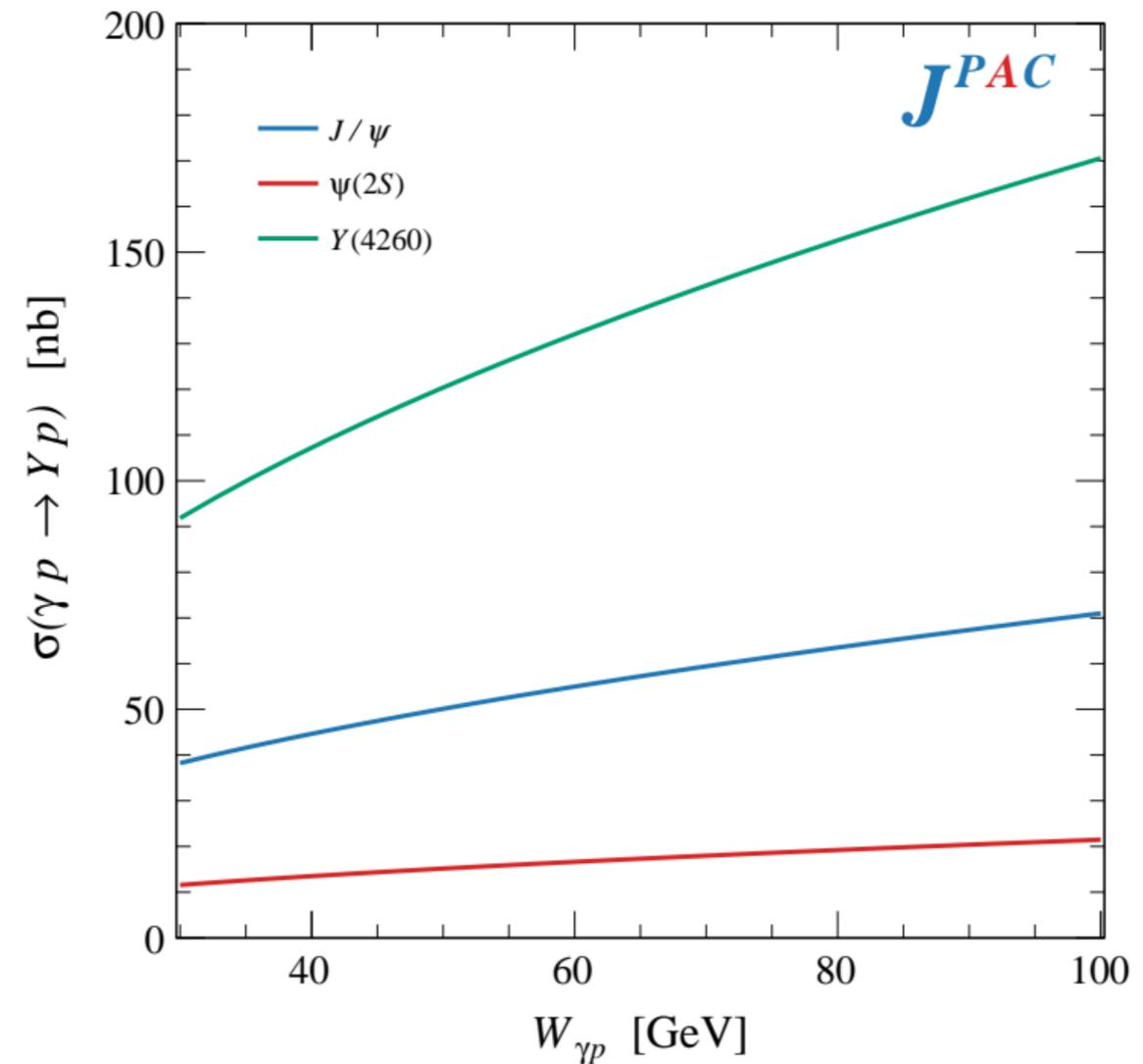
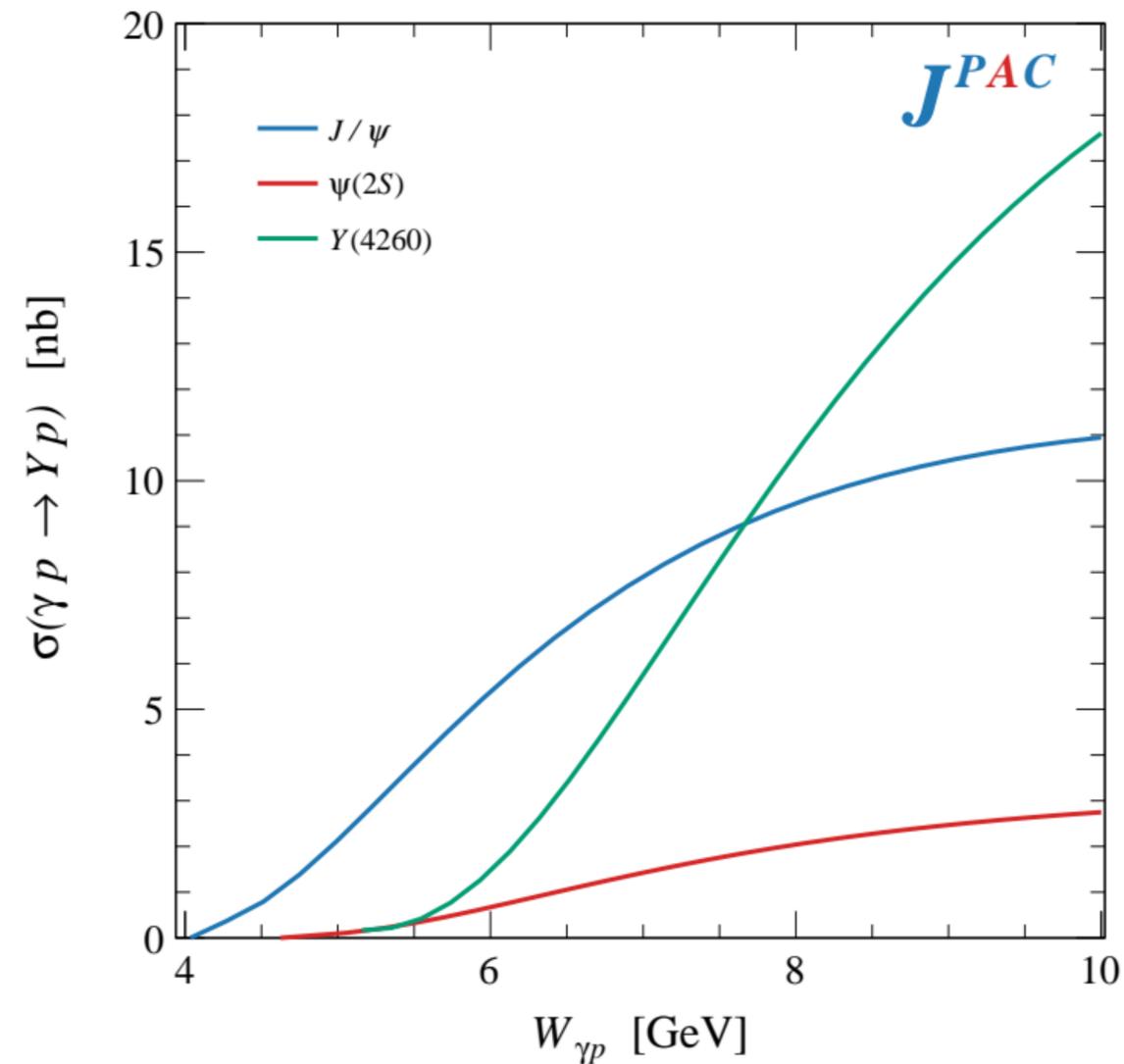
<https://github.com/dwinney/jpacPhoto>

Albaladejo et al., Phys. Rev. D 102 (2020) 114010, 2008.01001 [hep-ph]

# The hybrid (?) mesons with vector quantum numbers

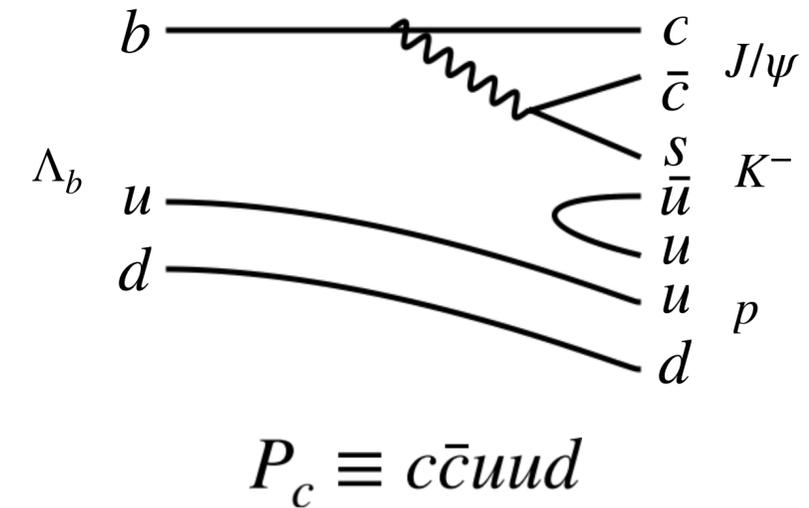
Known to be well described by diffractive exchange.

Good candidates for future EIC: diffractive production increases with energy!



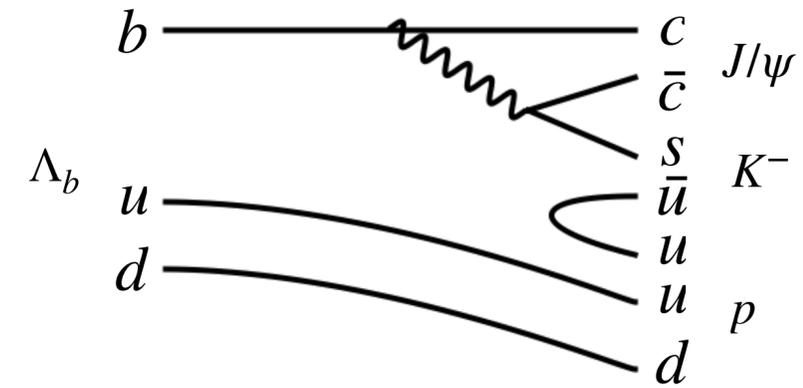
# Hidden-charm pentaquark searches

In 2015, exotic-like structures were found.  
[Aaij et al. [LHCb], PRL 115 (2015) 072001;  
Aaij et al. [LHCb], PRL 122 (2019) 222001]

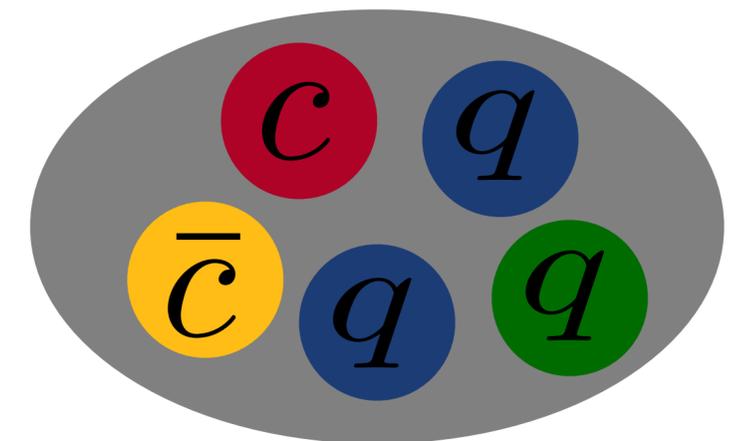
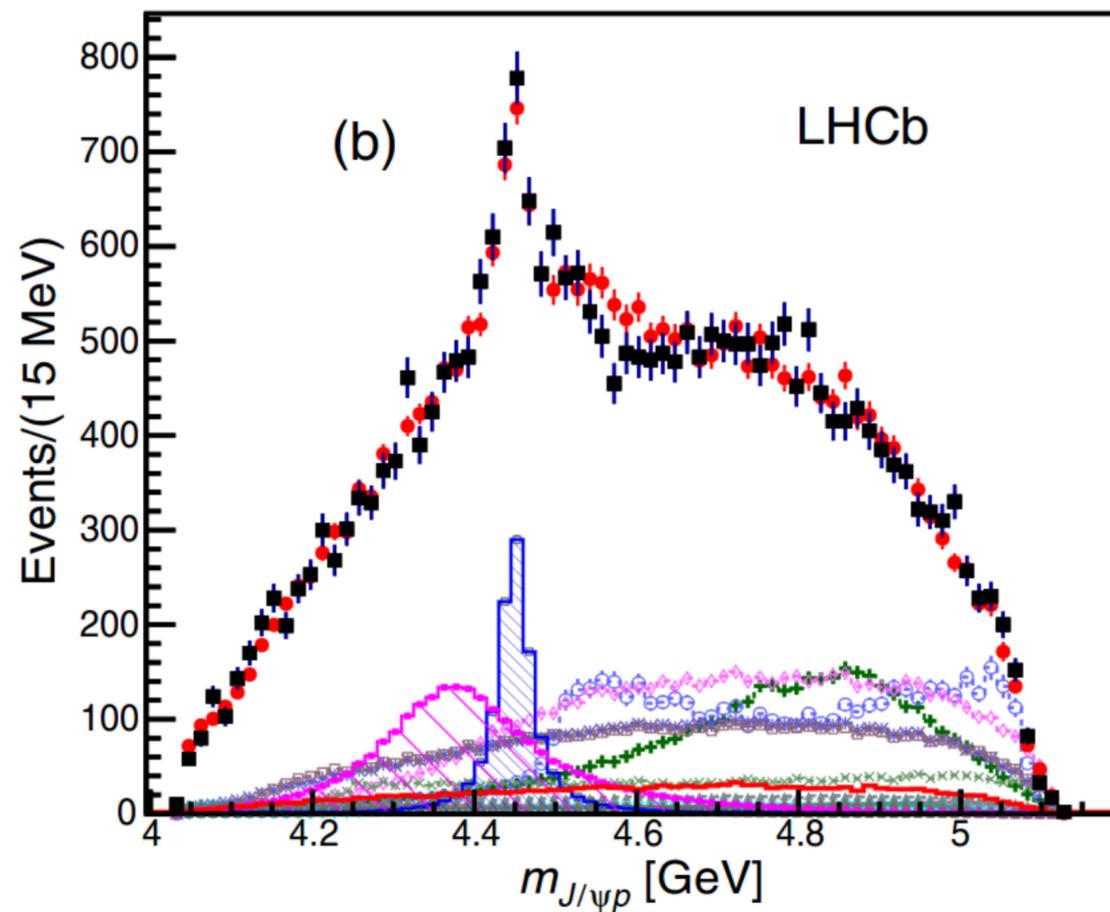


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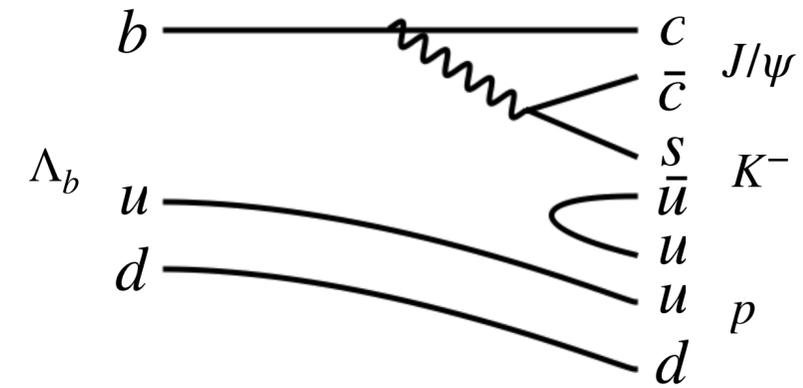


$$P_c \equiv c\bar{c}uud$$

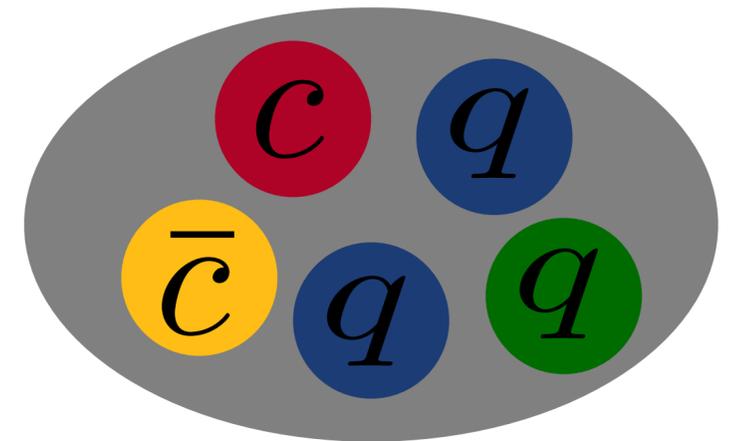
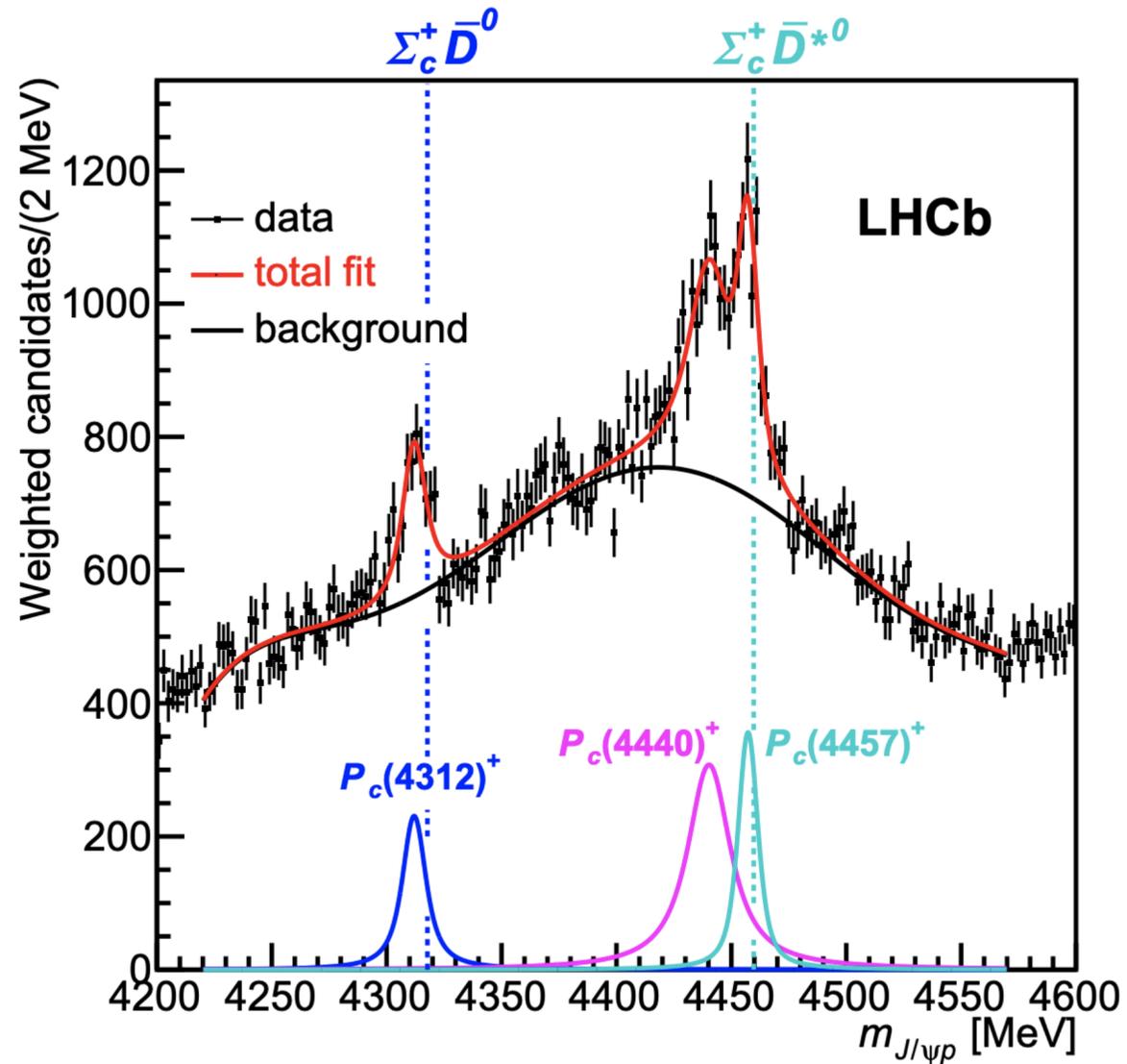
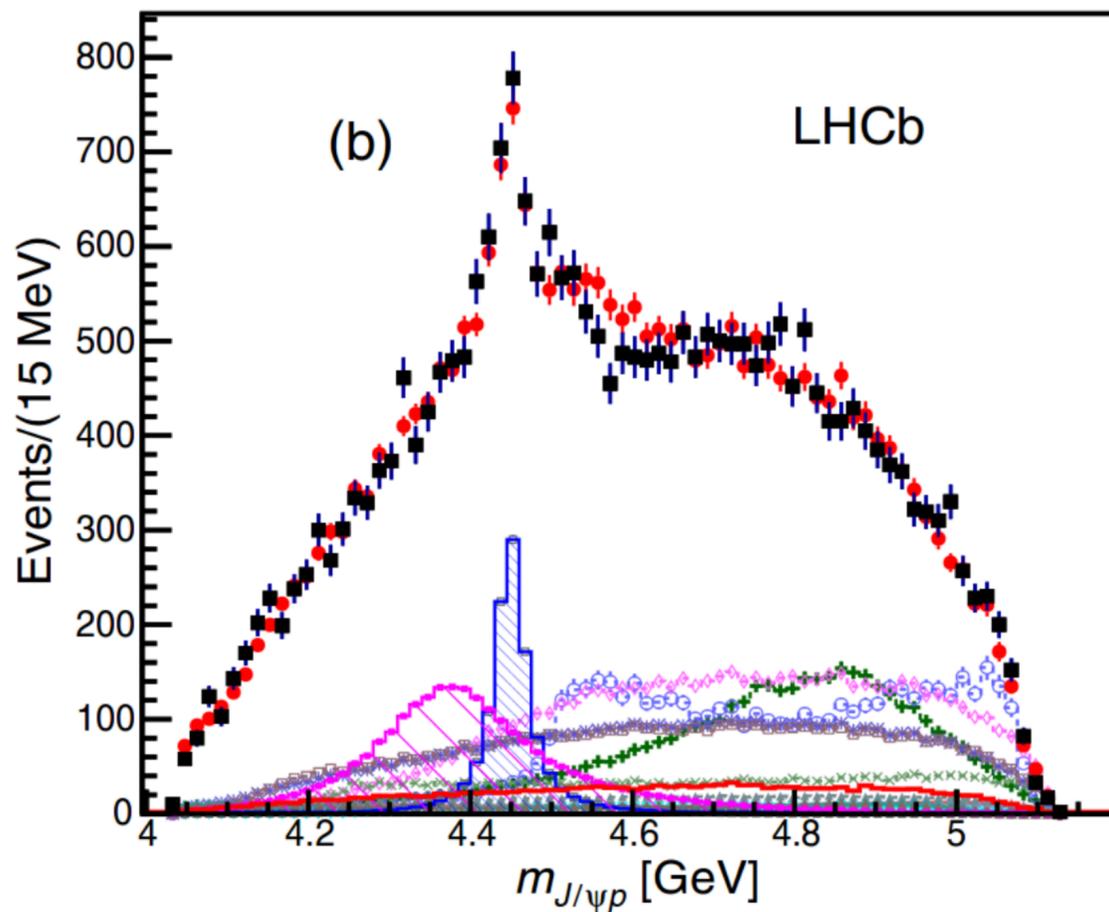


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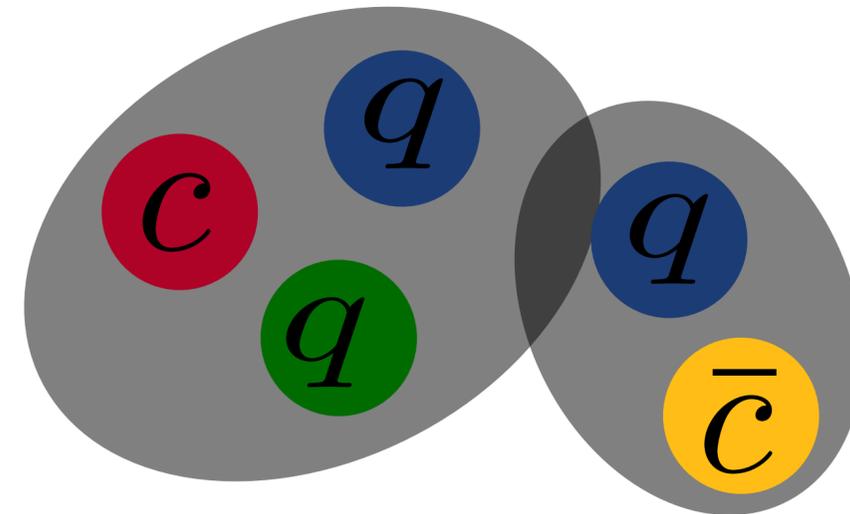
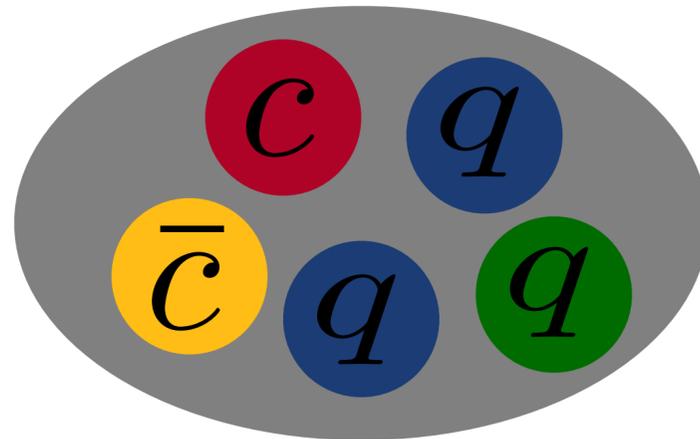


# Possible interpretations

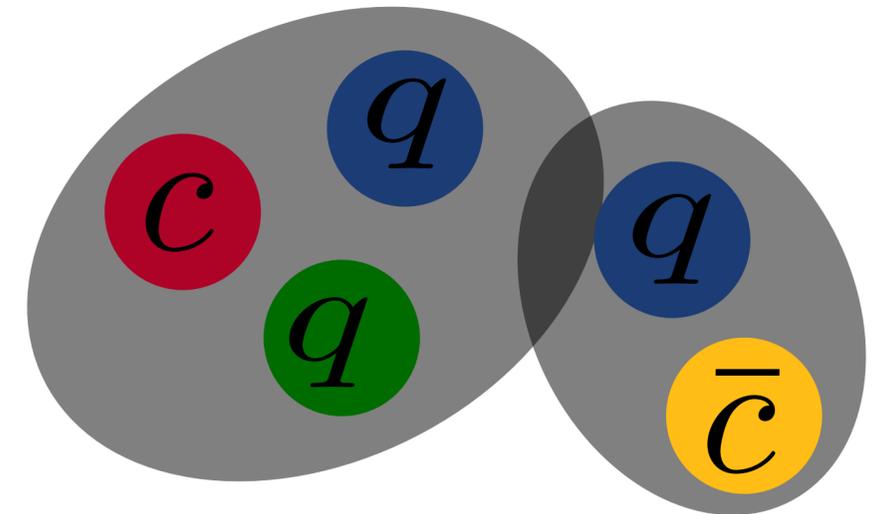
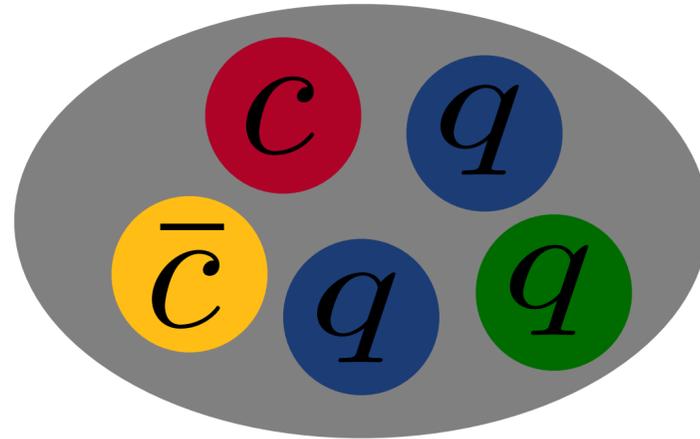
Compact 5-quark states.

Weakly-bound molecule.

Kinematic final-state rescattering effects (triangle singularities).



# Possible interpretations



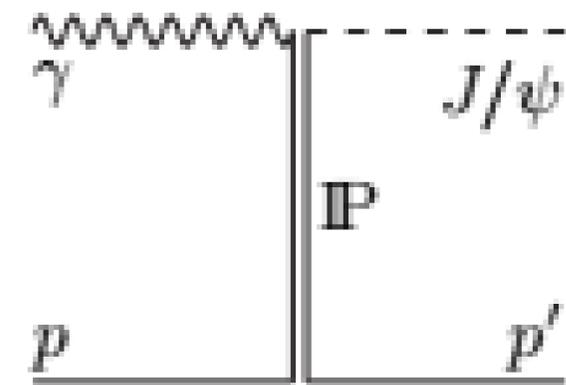
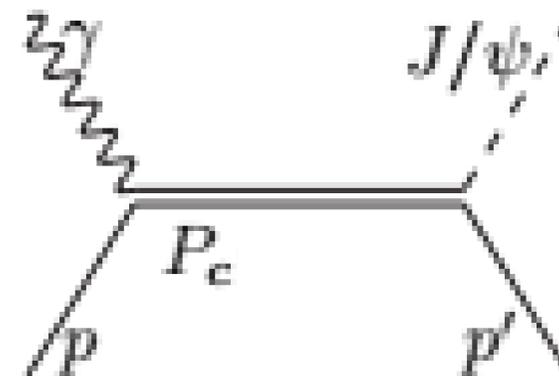
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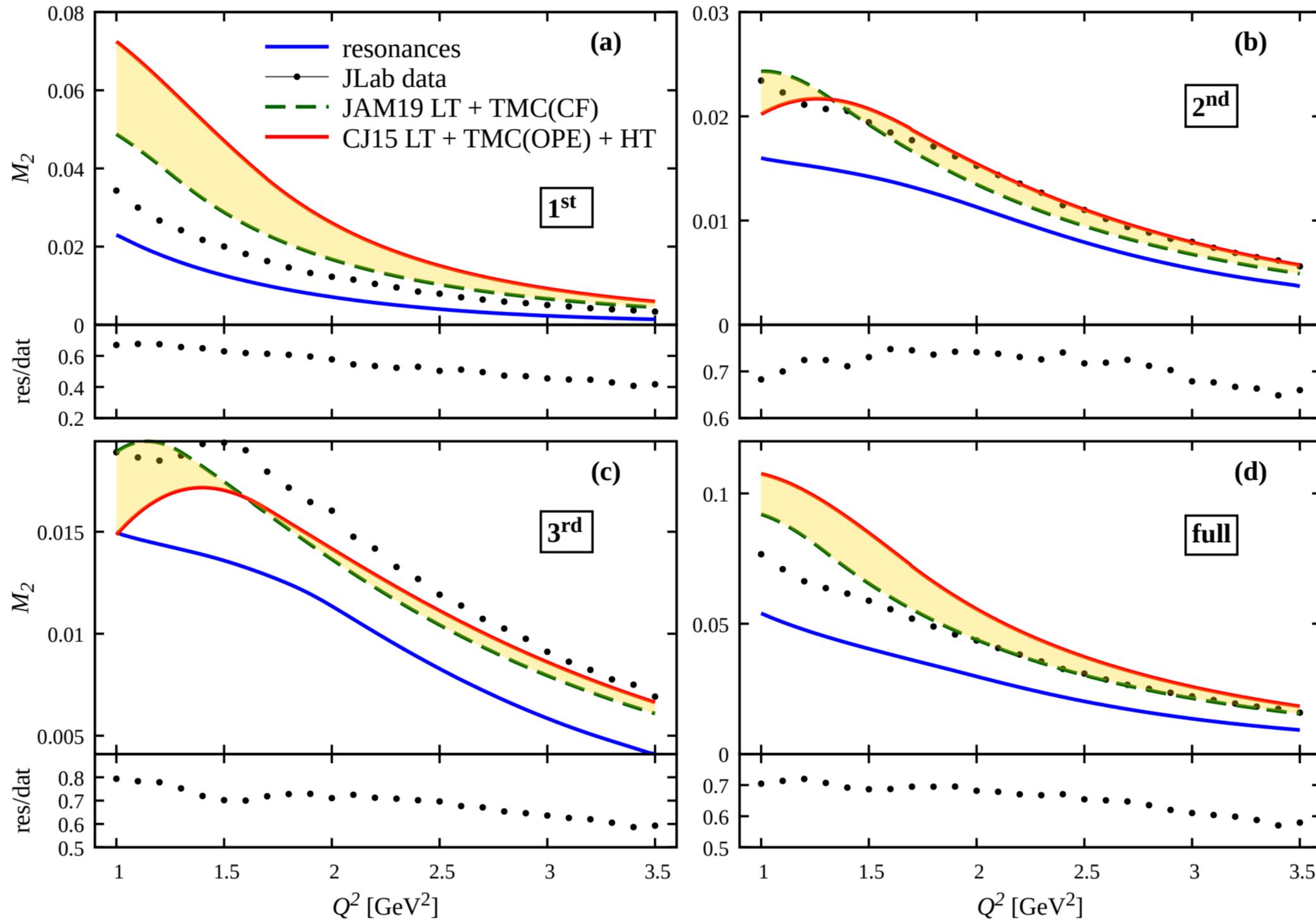
Kinematic final-state rescattering effects (triangle singularities).

## 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]

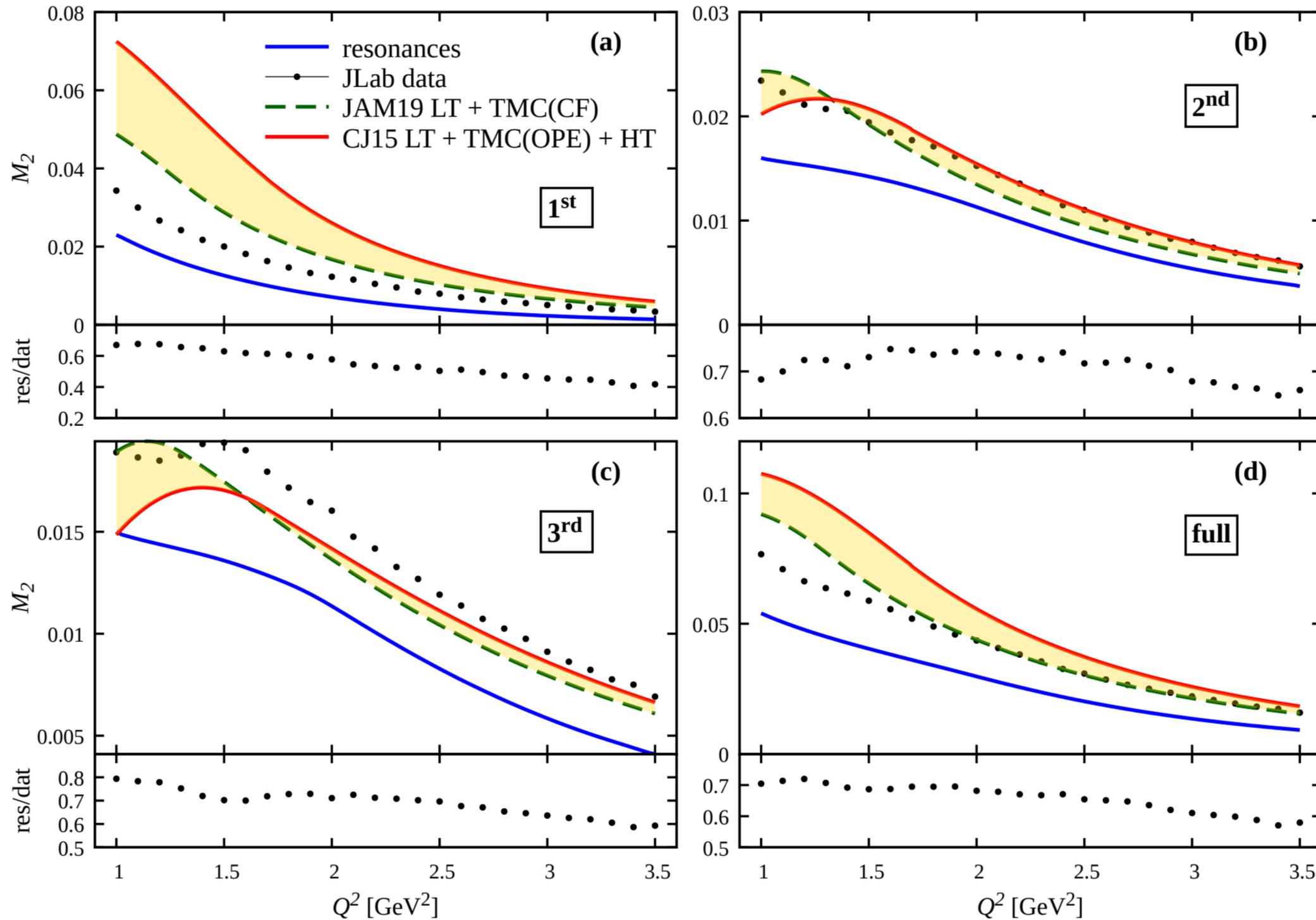


# Truncated moments



Integration over energies to **quantify duality** between averaged **resonances** and smooth **DIS** behavior.

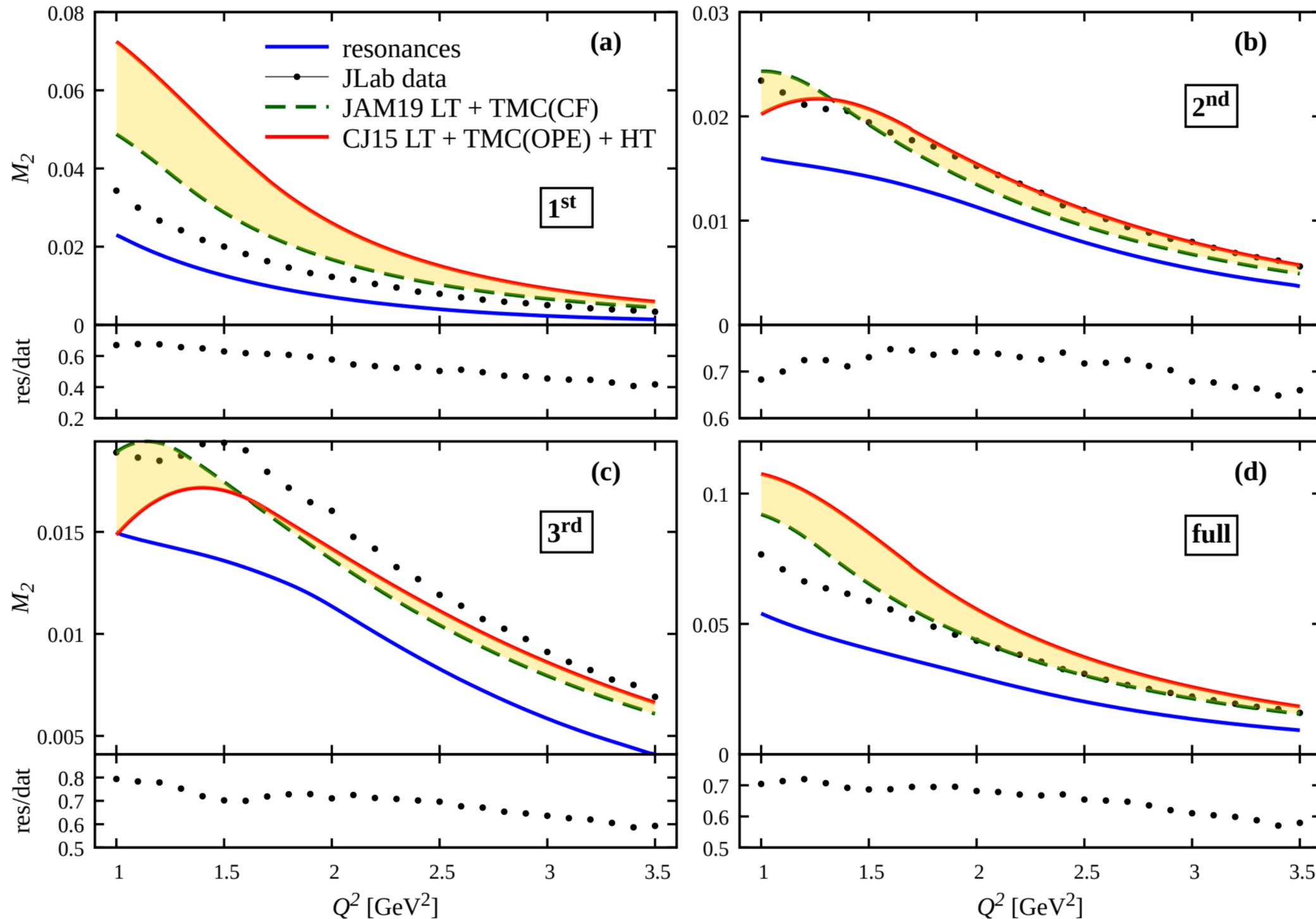
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PDF fits in the **DIS region extrapolated** and compared to the **resonance region**.

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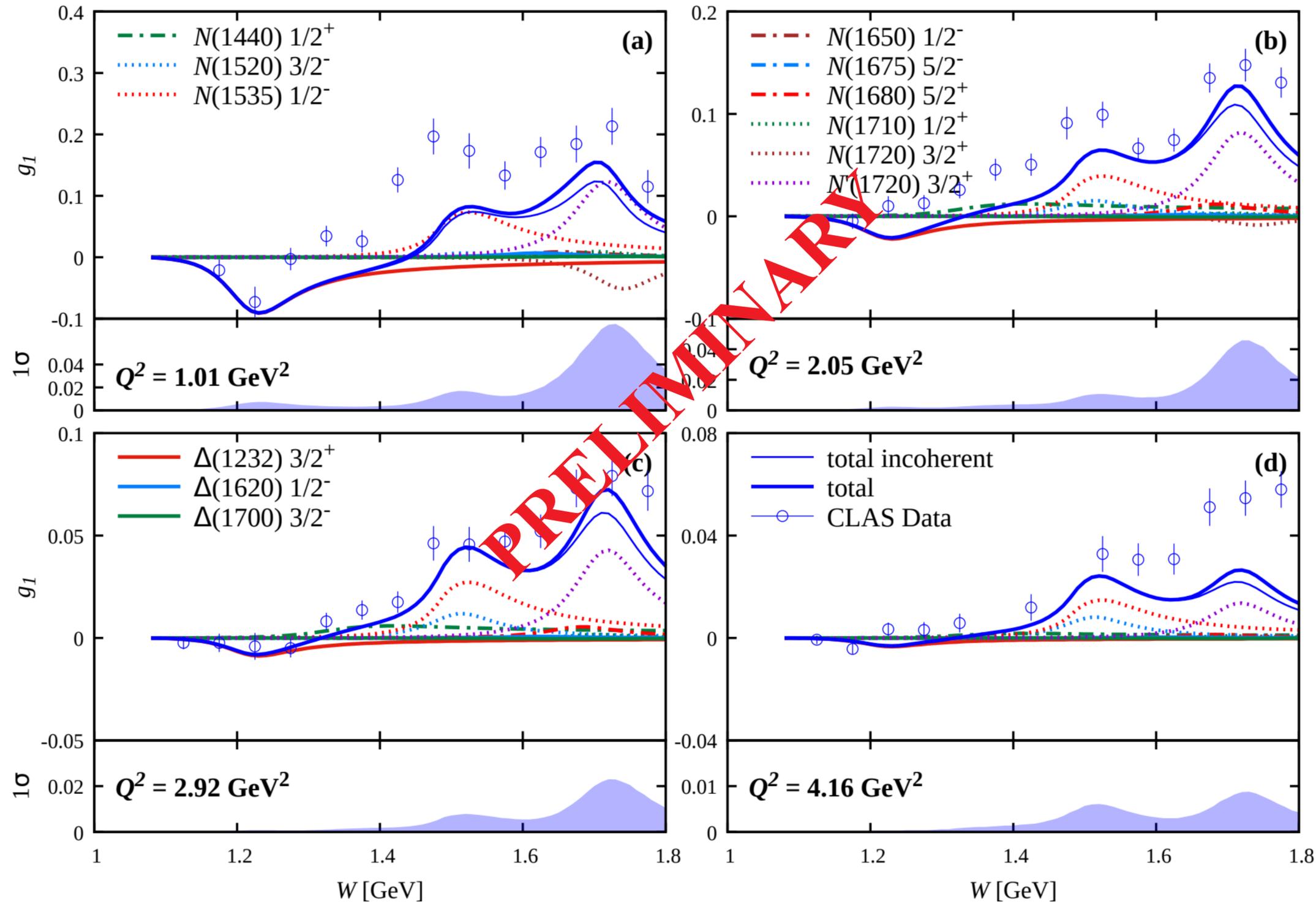


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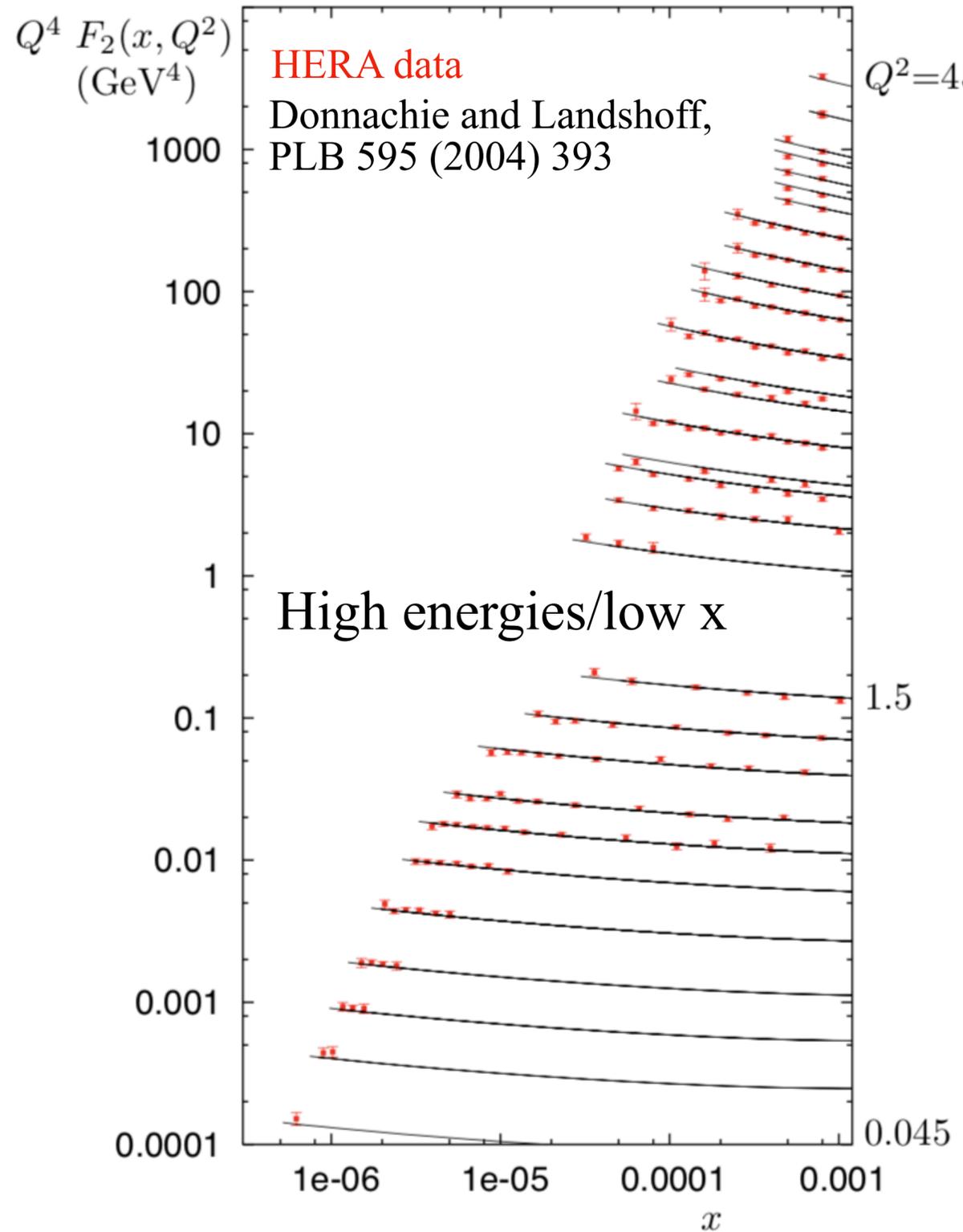
Global duality onset, especially when considering target mass corrections and higher-twist contributions.

# Polarized structure functions



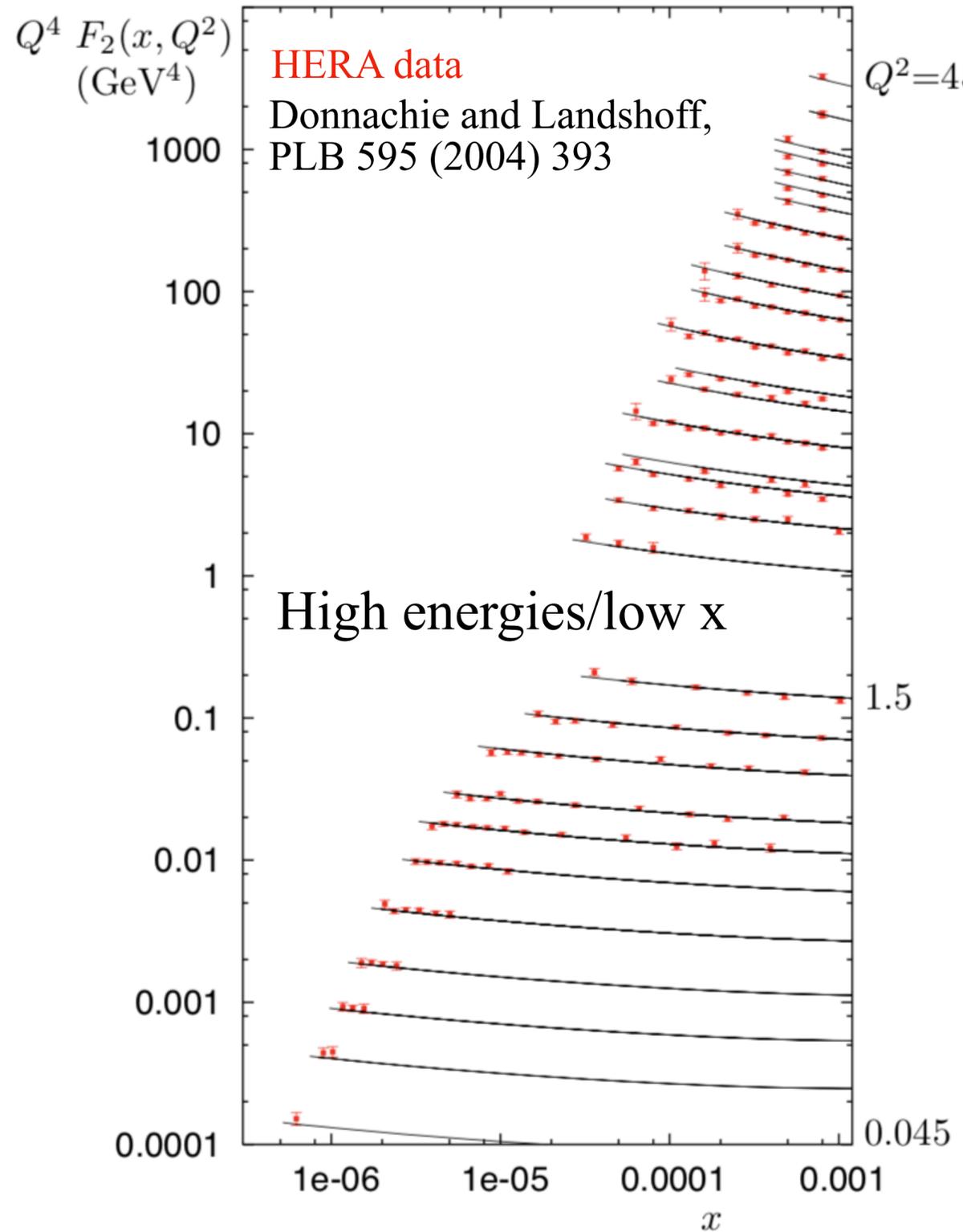
Currently extending to polarized structure functions (polarized beam and target).

# Low and high energies: towards a connection

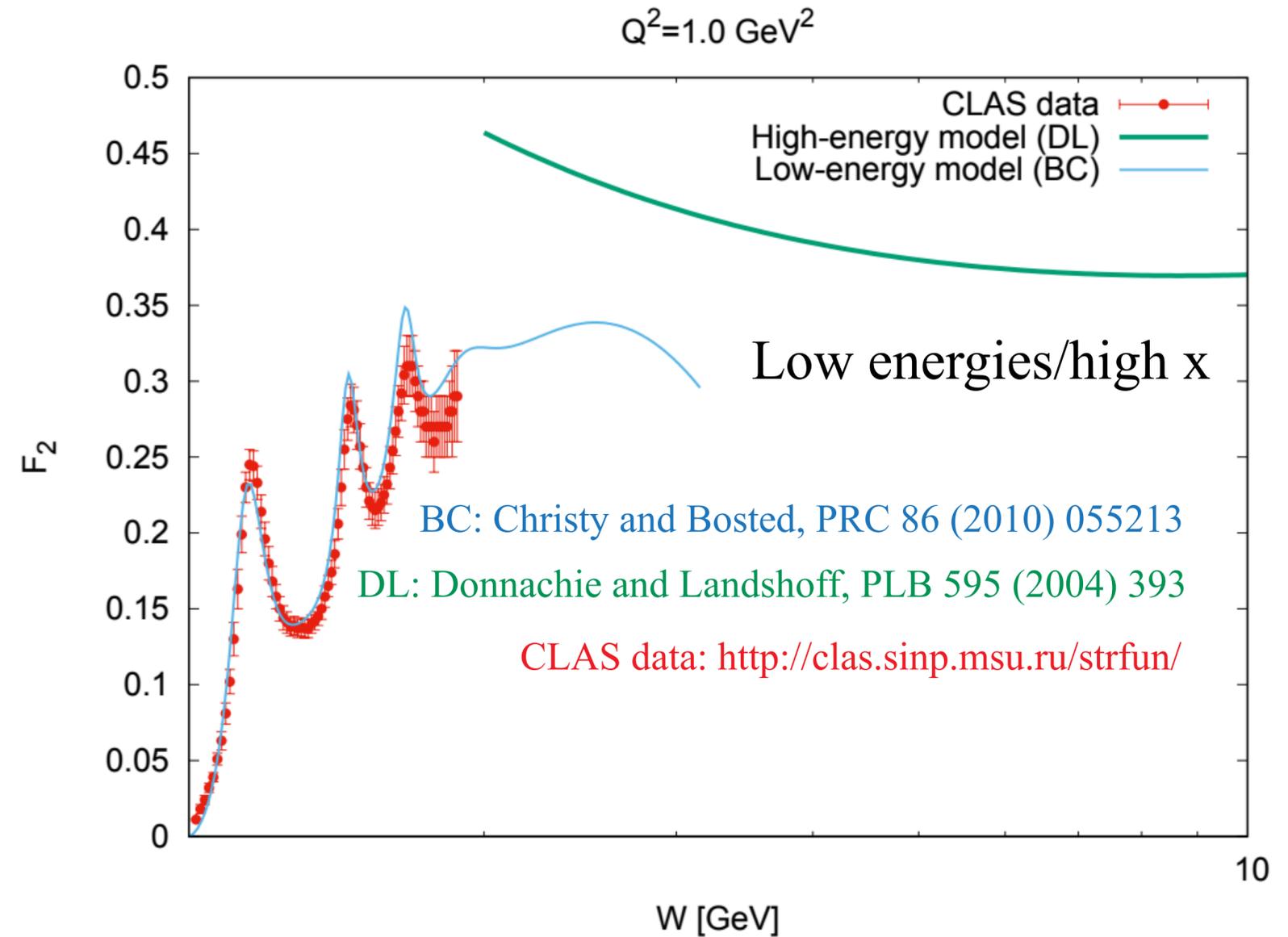


$$x = \frac{Q^2}{2M_N \nu} \quad \nu = \frac{W^2 - M_N^2 + Q^2}{2M_N}$$

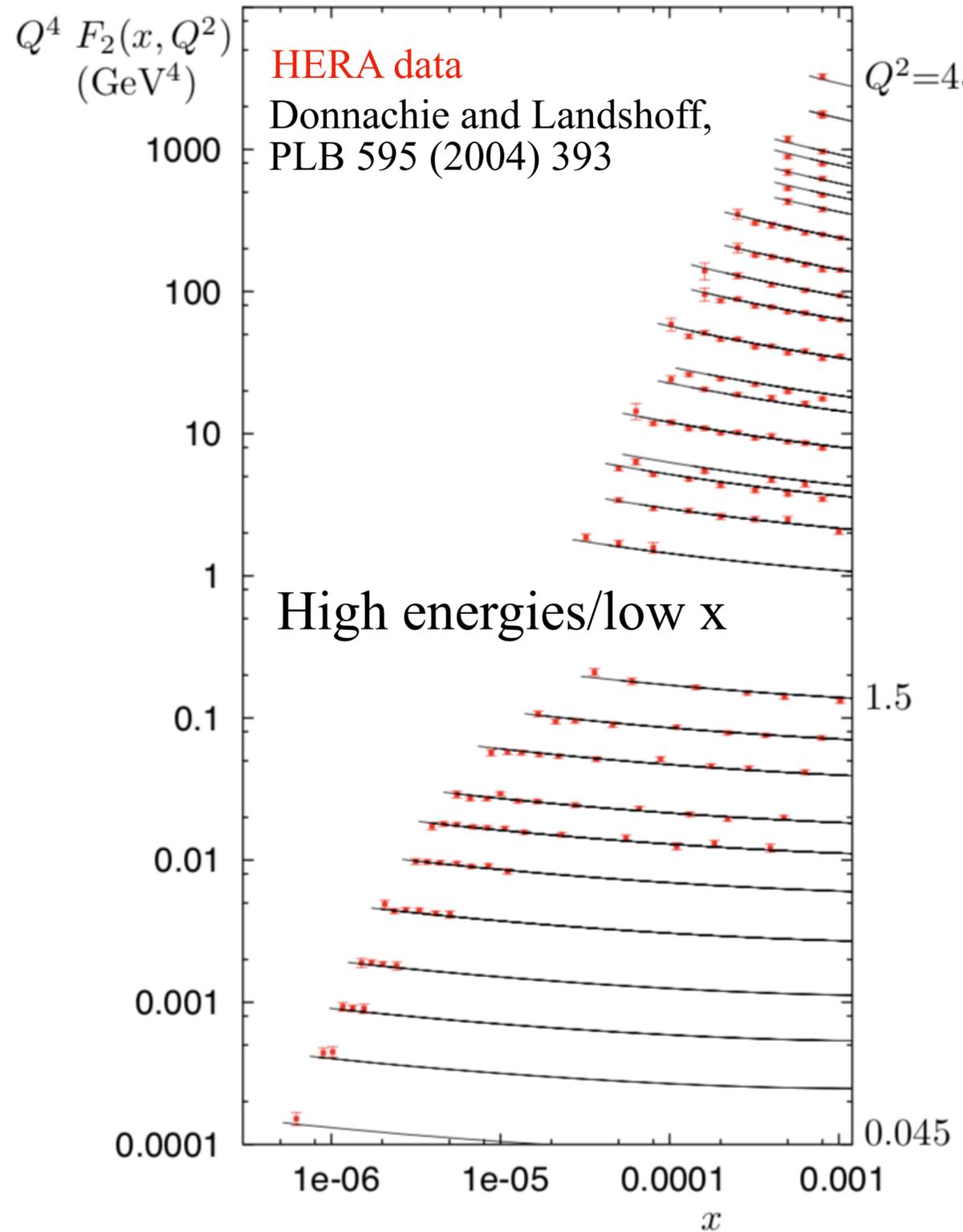
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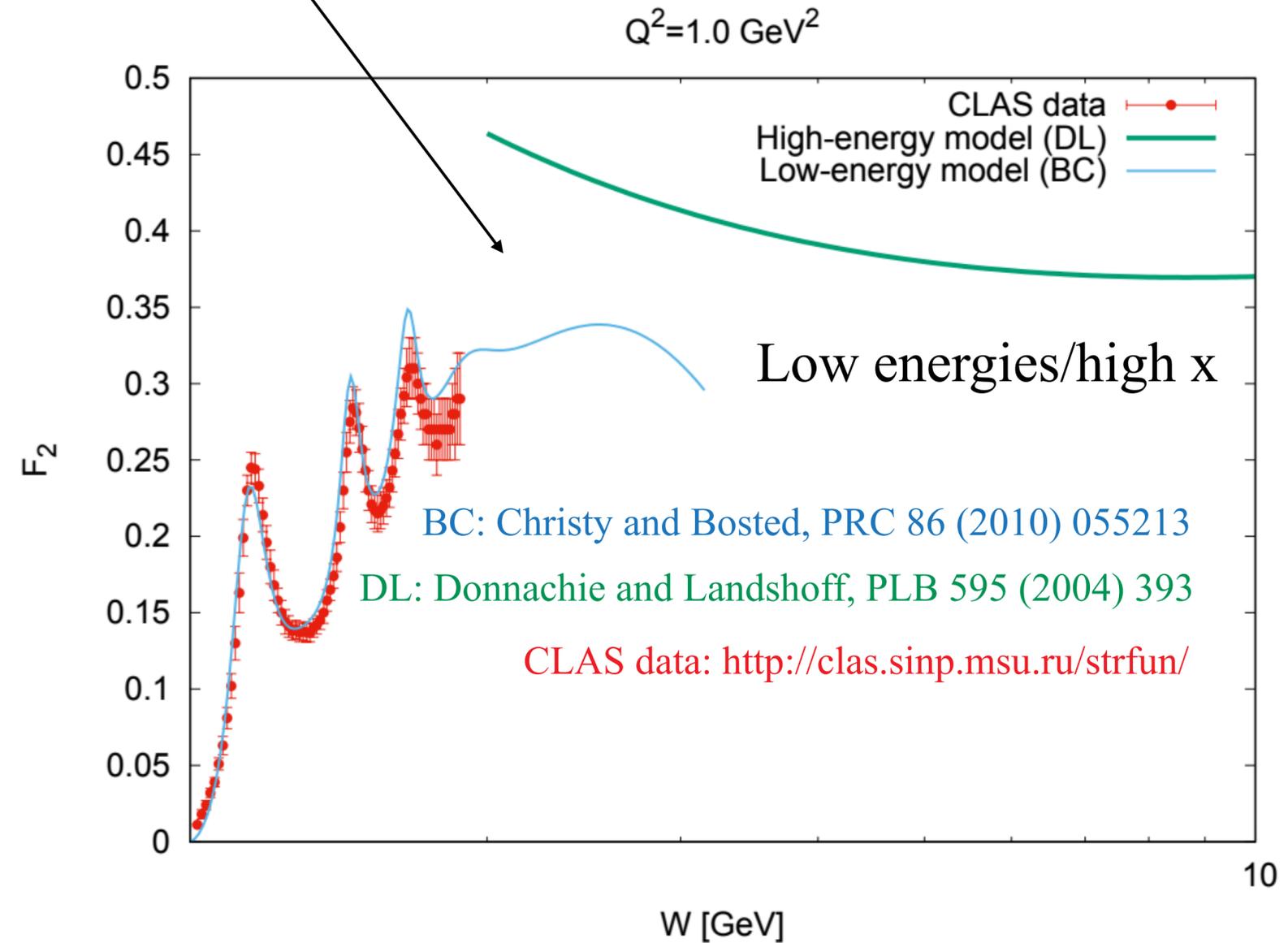


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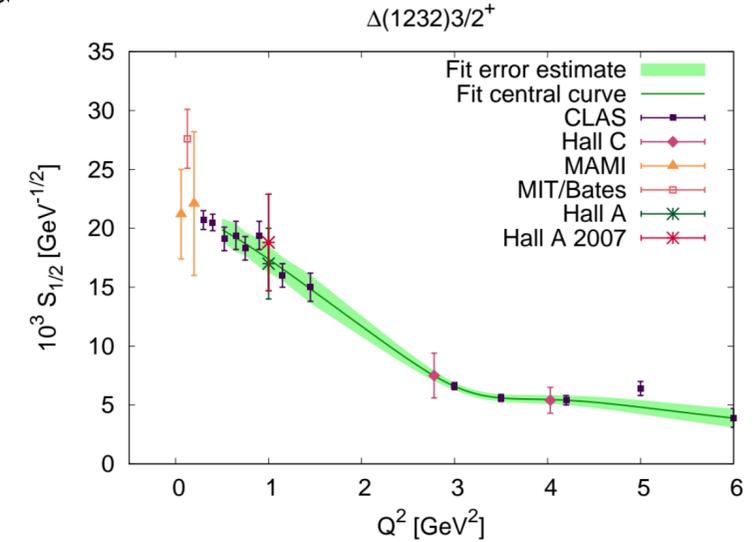
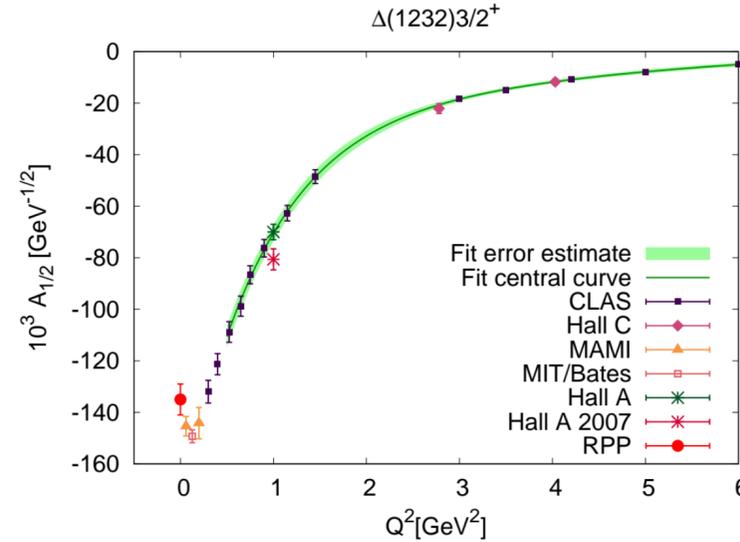
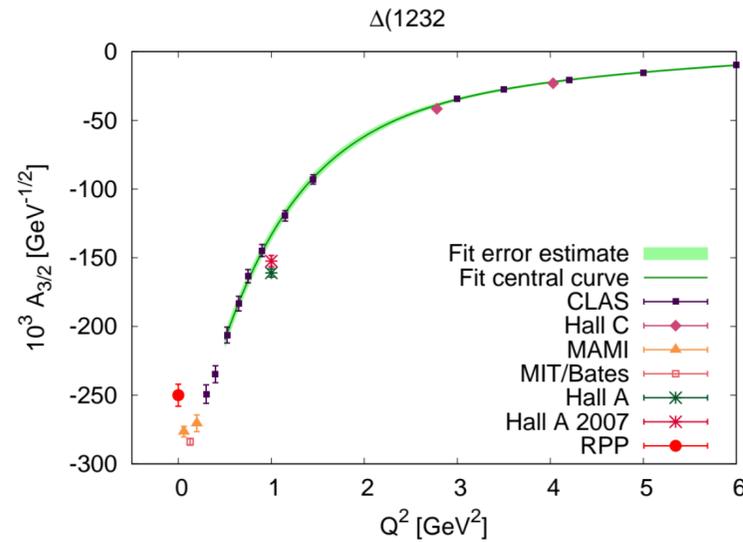
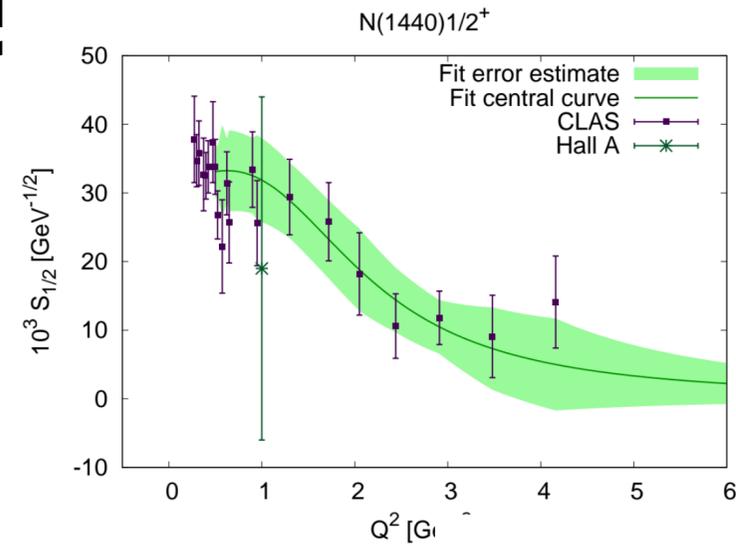
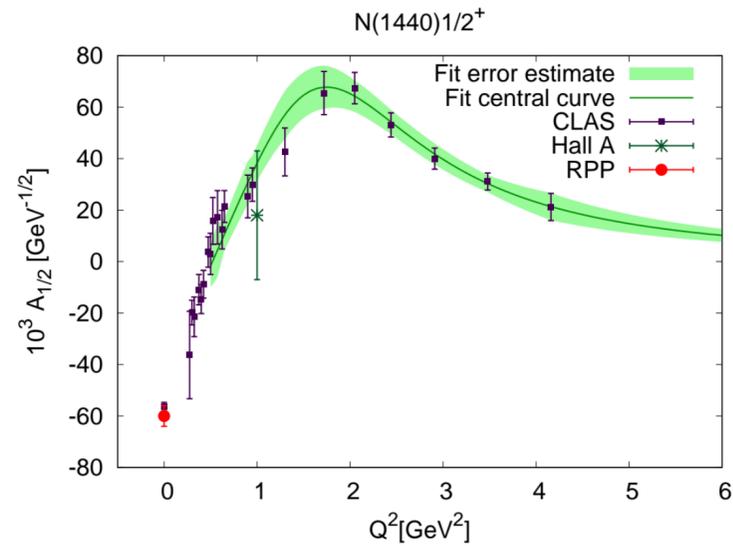
$$x = \frac{Q^2}{2M_N \nu} \quad \nu = \frac{W^2 - M_N^2 + Q^2}{2M_N}$$

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



# Exclusive electroproduction

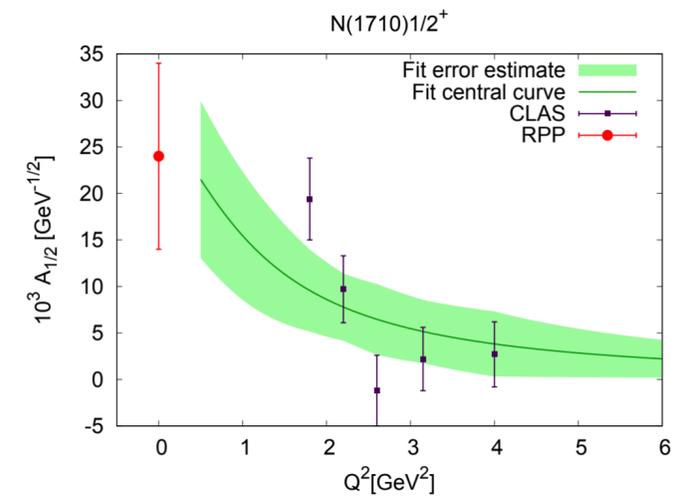
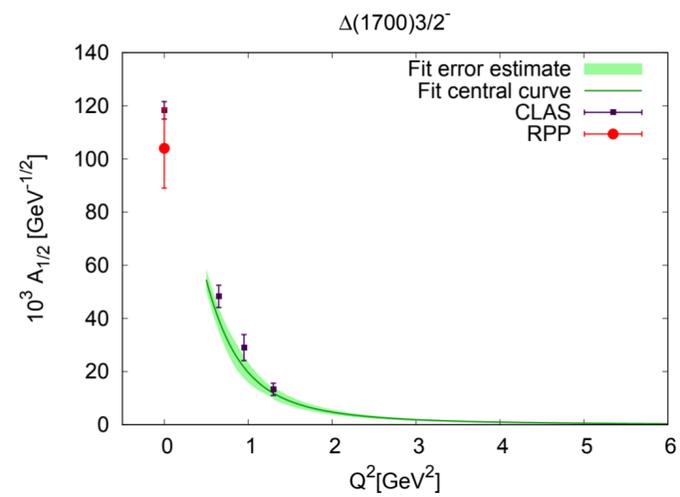
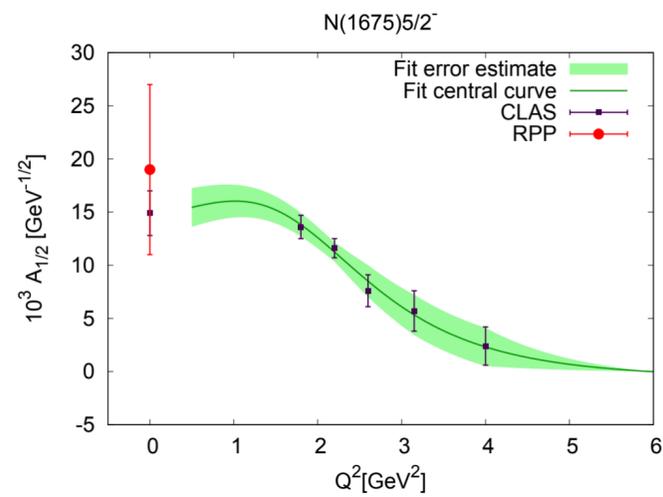
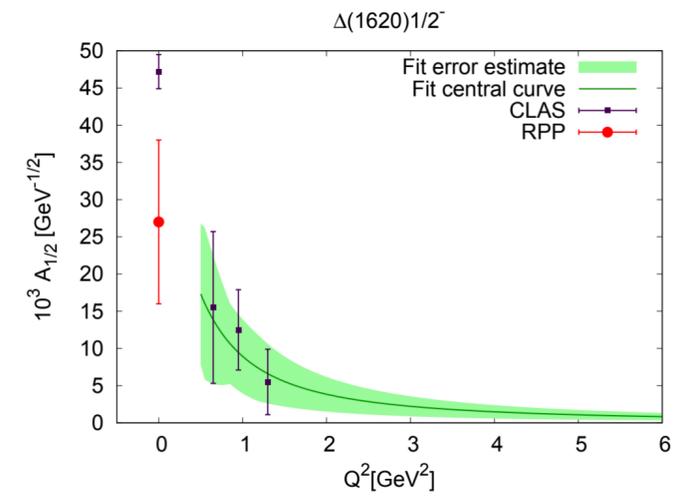
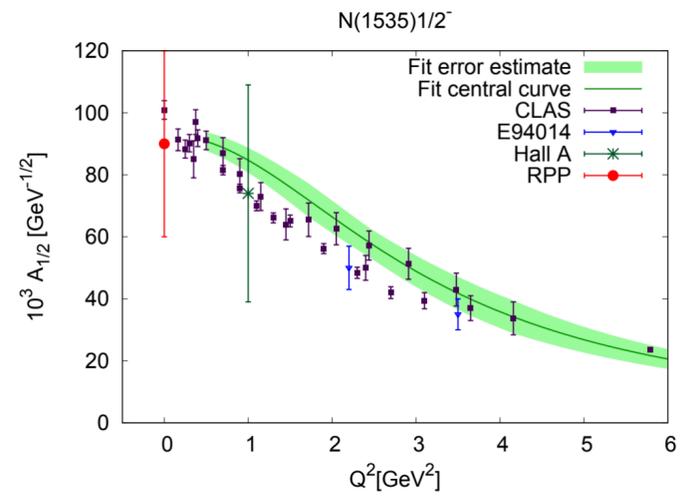
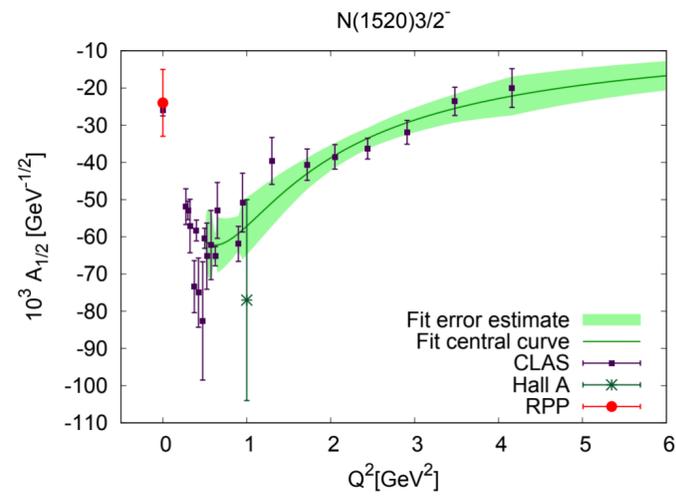
## Yvanne

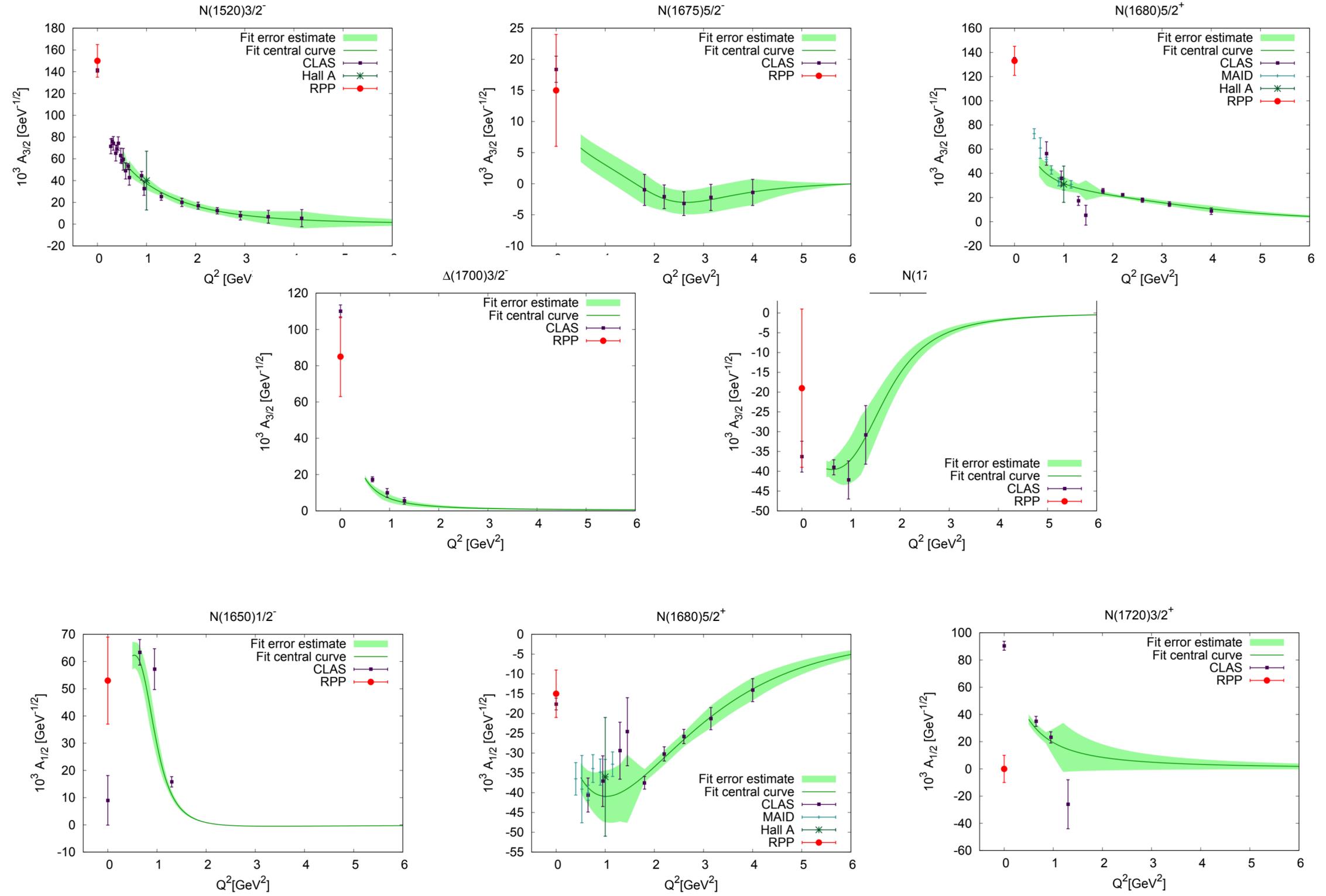


Interpolation/extrapolation functions: good agreement with world data and preliminary CLAS12 results at higher  $Q^2$ .

Error bands estimated from data uncertainties and scaled with coupling size in extrapolation region.

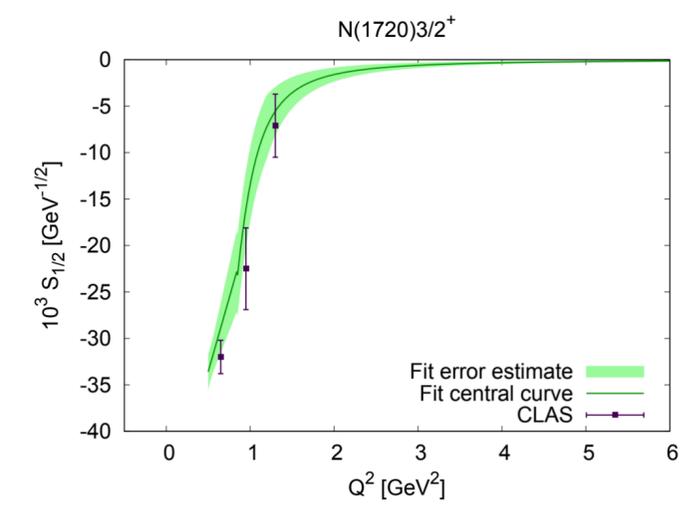
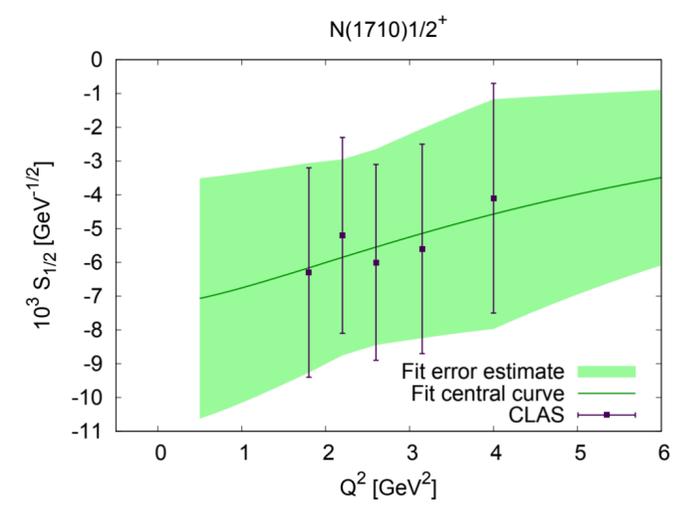
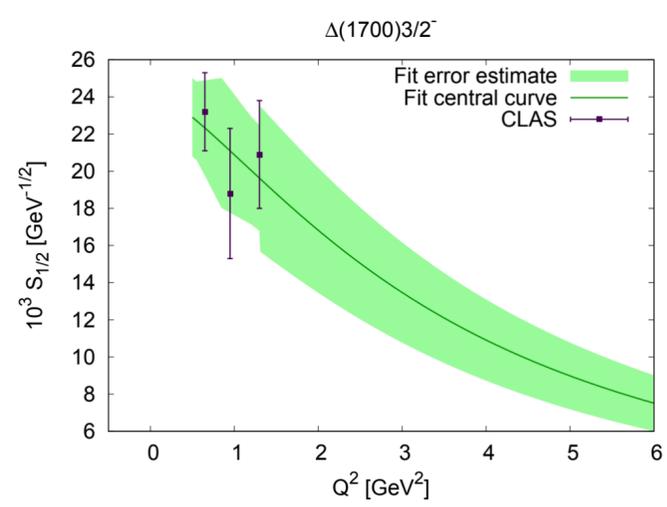
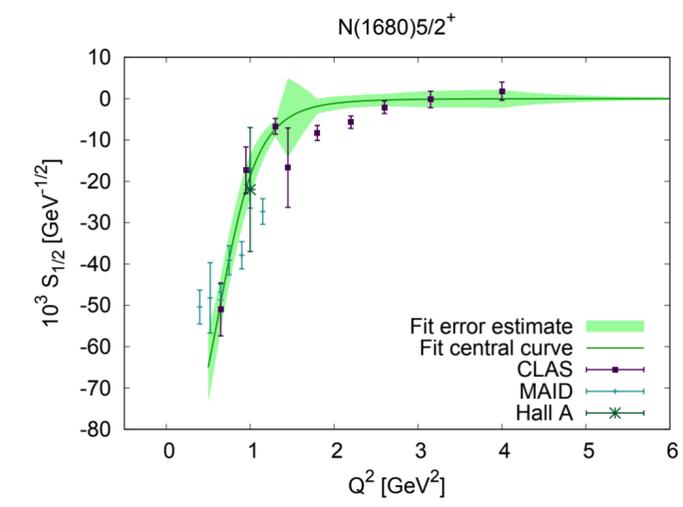
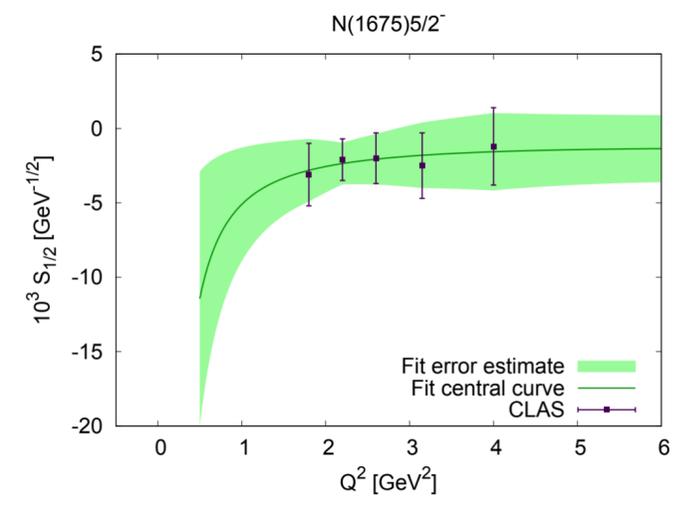
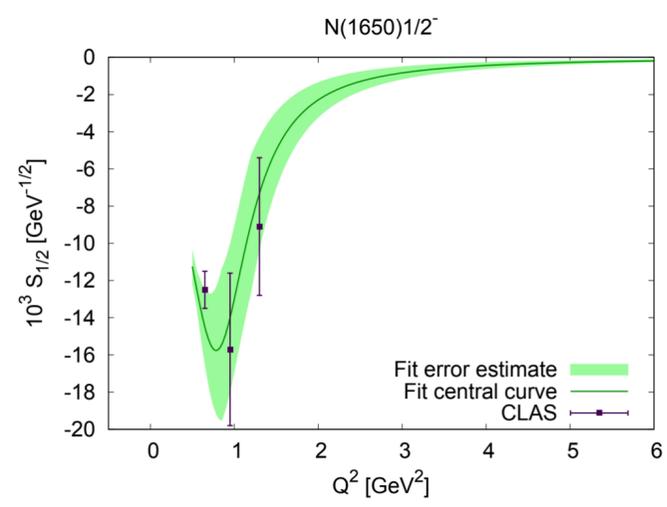
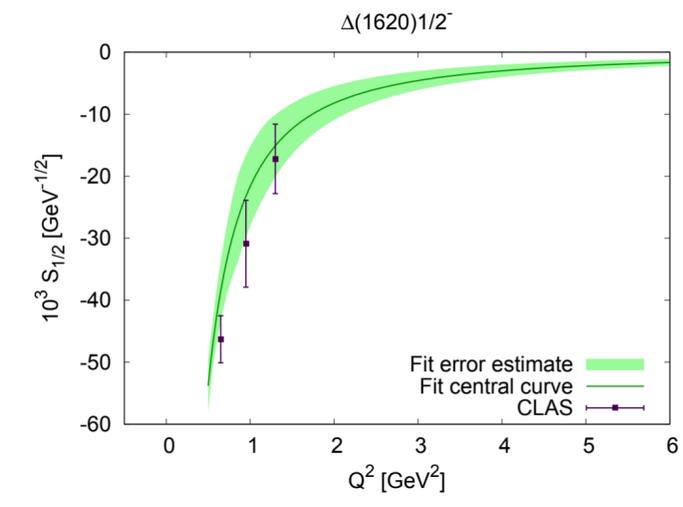
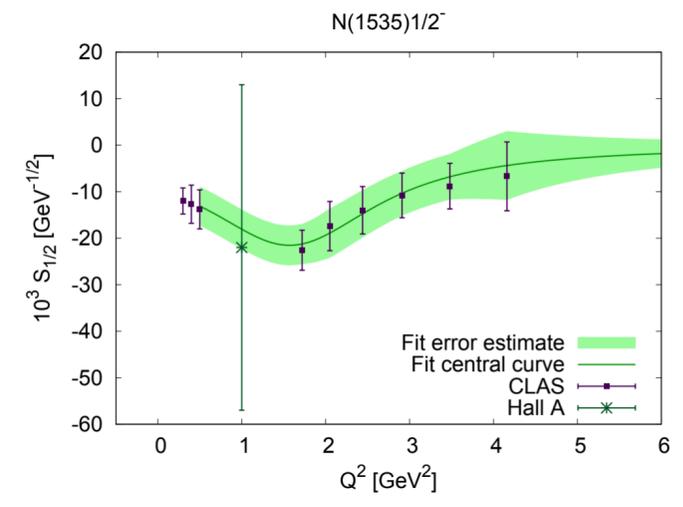
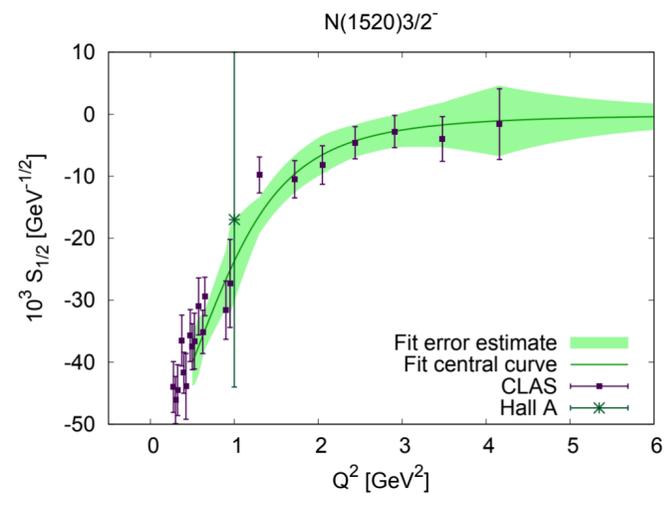
# Further electrocoupling data examples





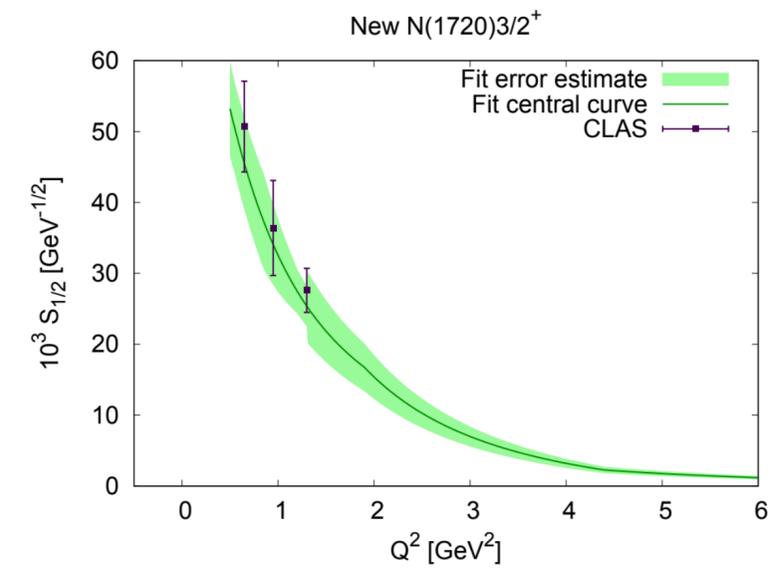
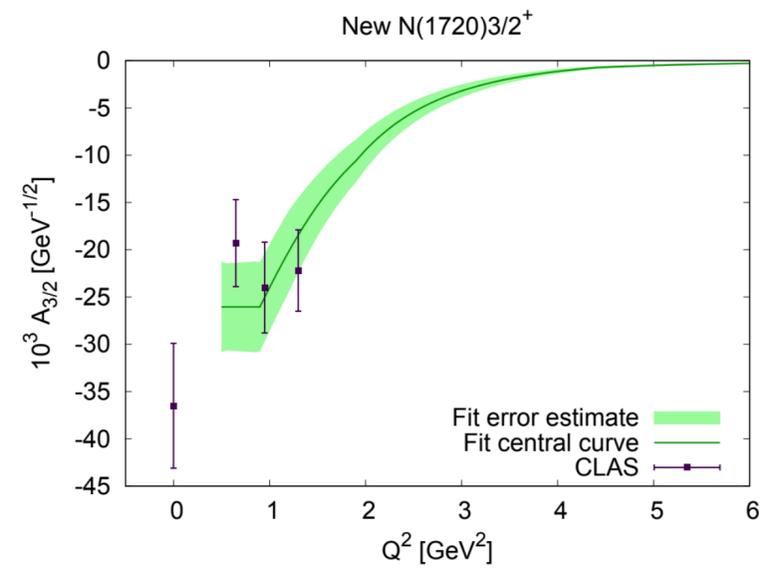
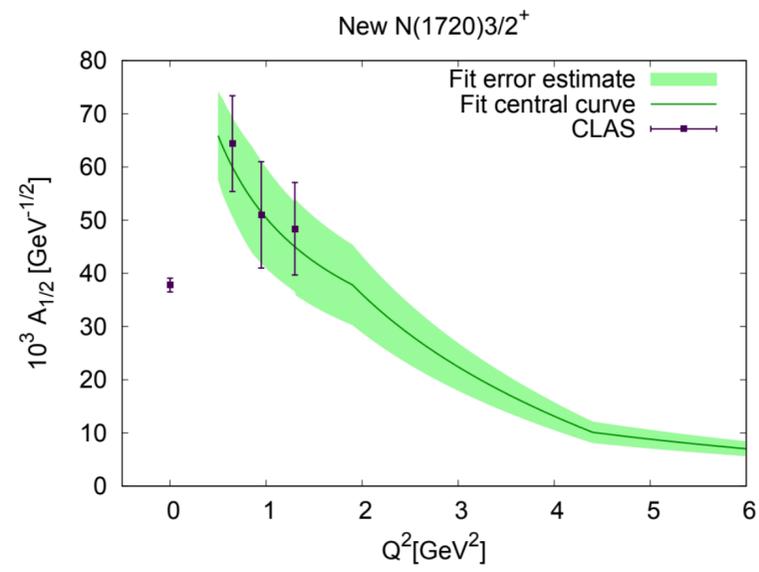
$A_{3/2}$

$A_{1/2}$



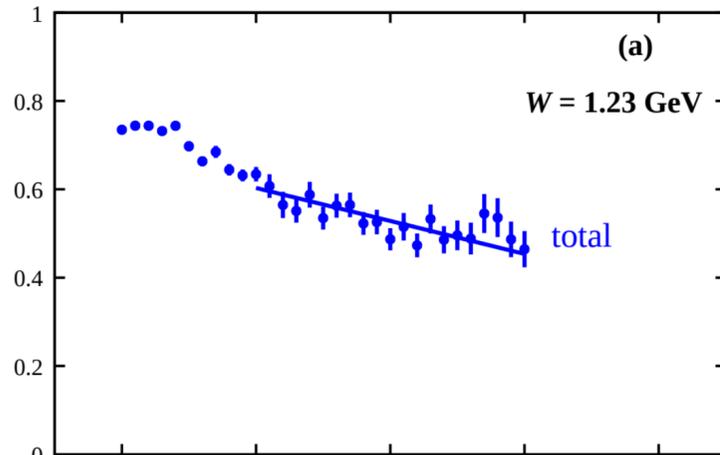
**$S_{1/2}$**

# $N'(1720)$

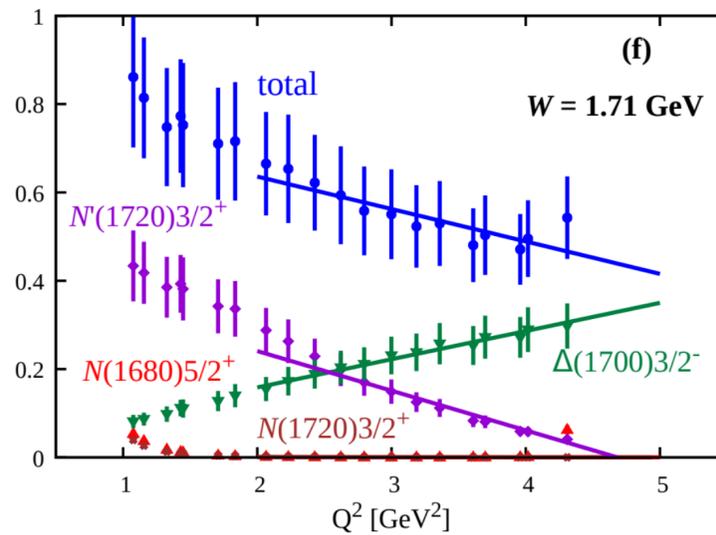
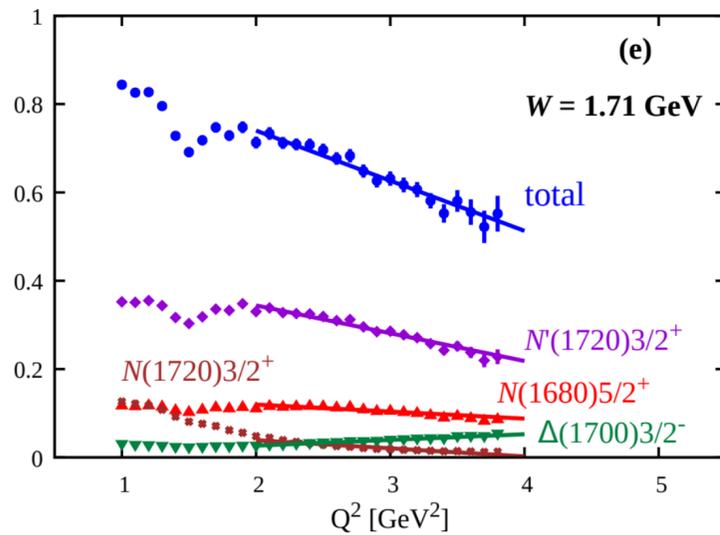
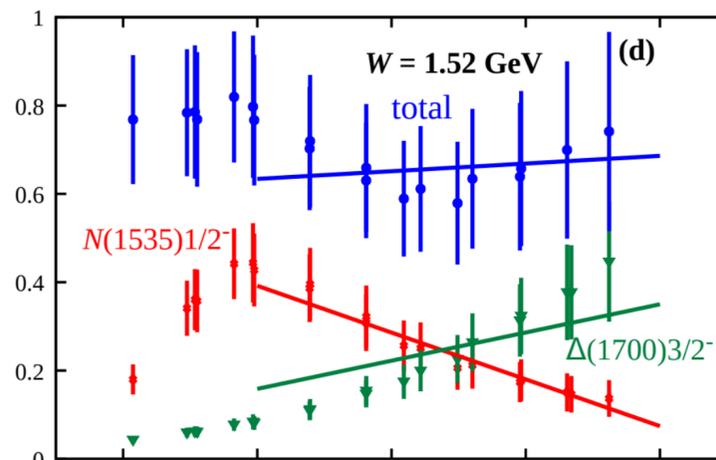
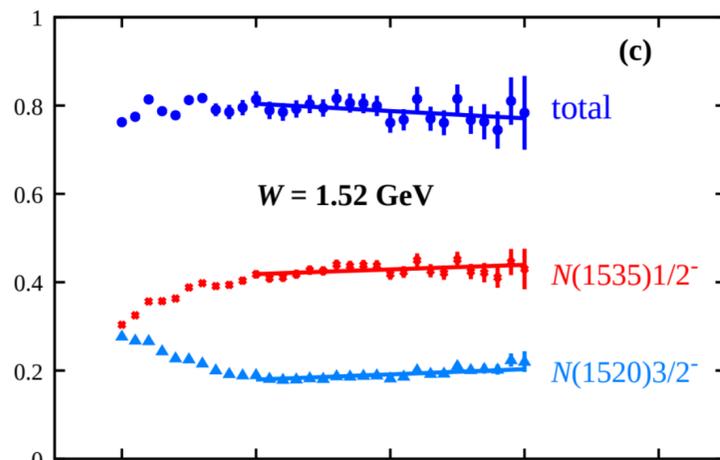
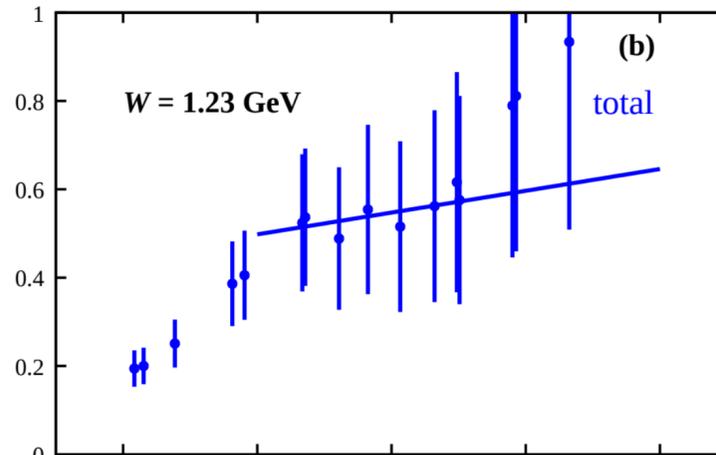


# $Q^2$ evolution of ratio resonance/total

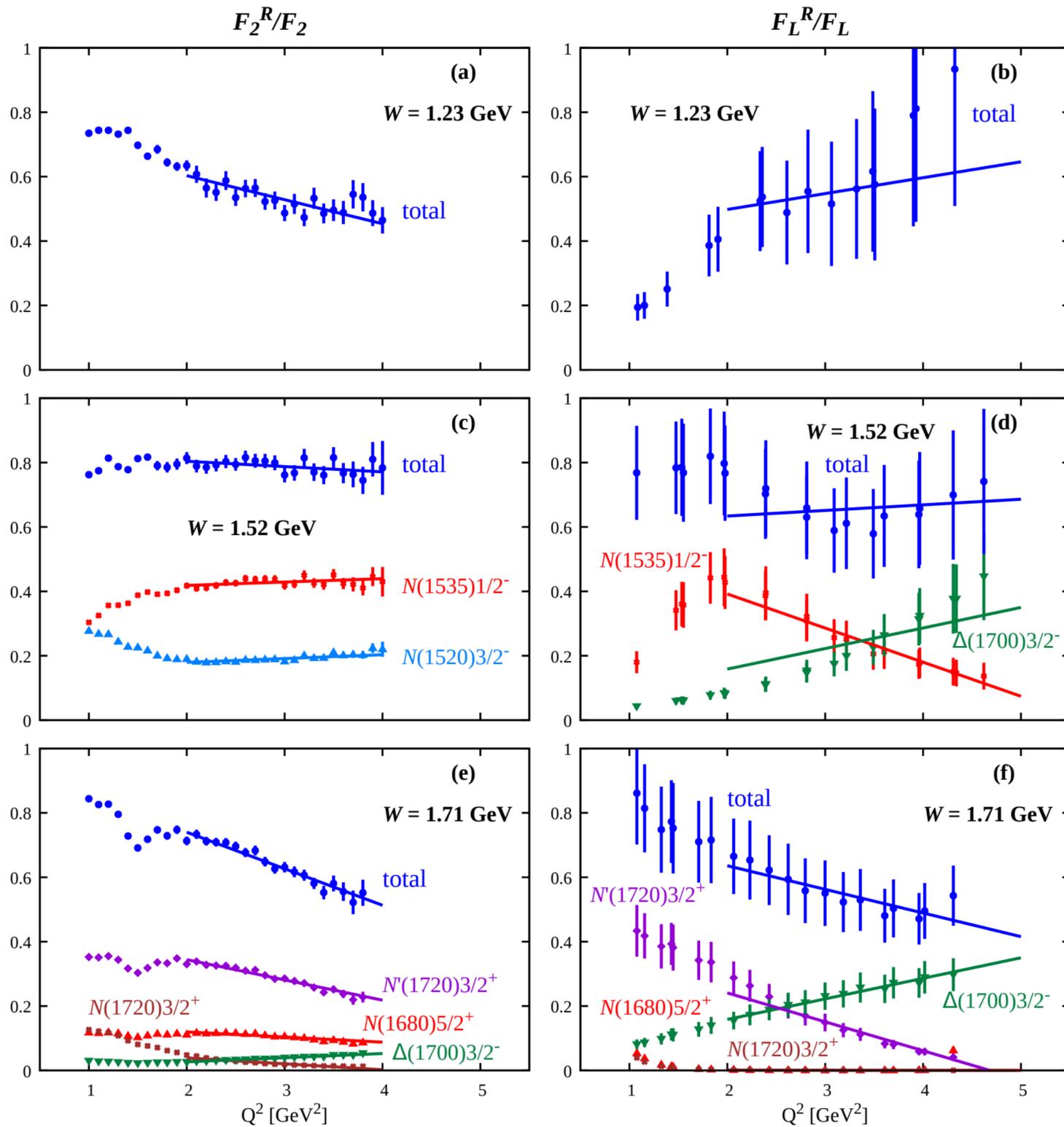
$F_2^R/F_2$



$F_L^R/F_L$

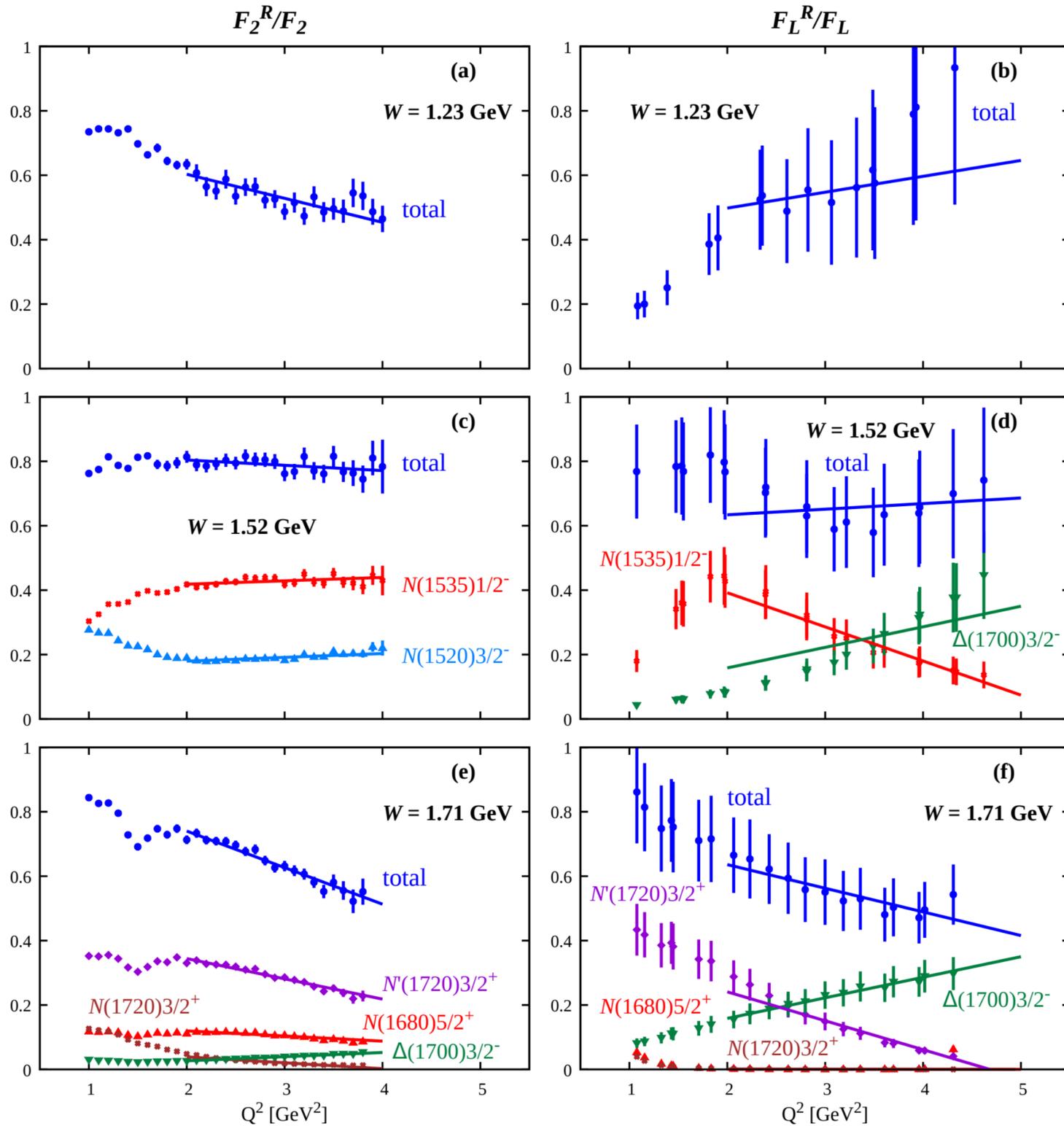


# $Q^2$ evolution of ratio resonance/total



Resonance contributions decrease with  $Q^2$ ,  
but so do the total contributions.

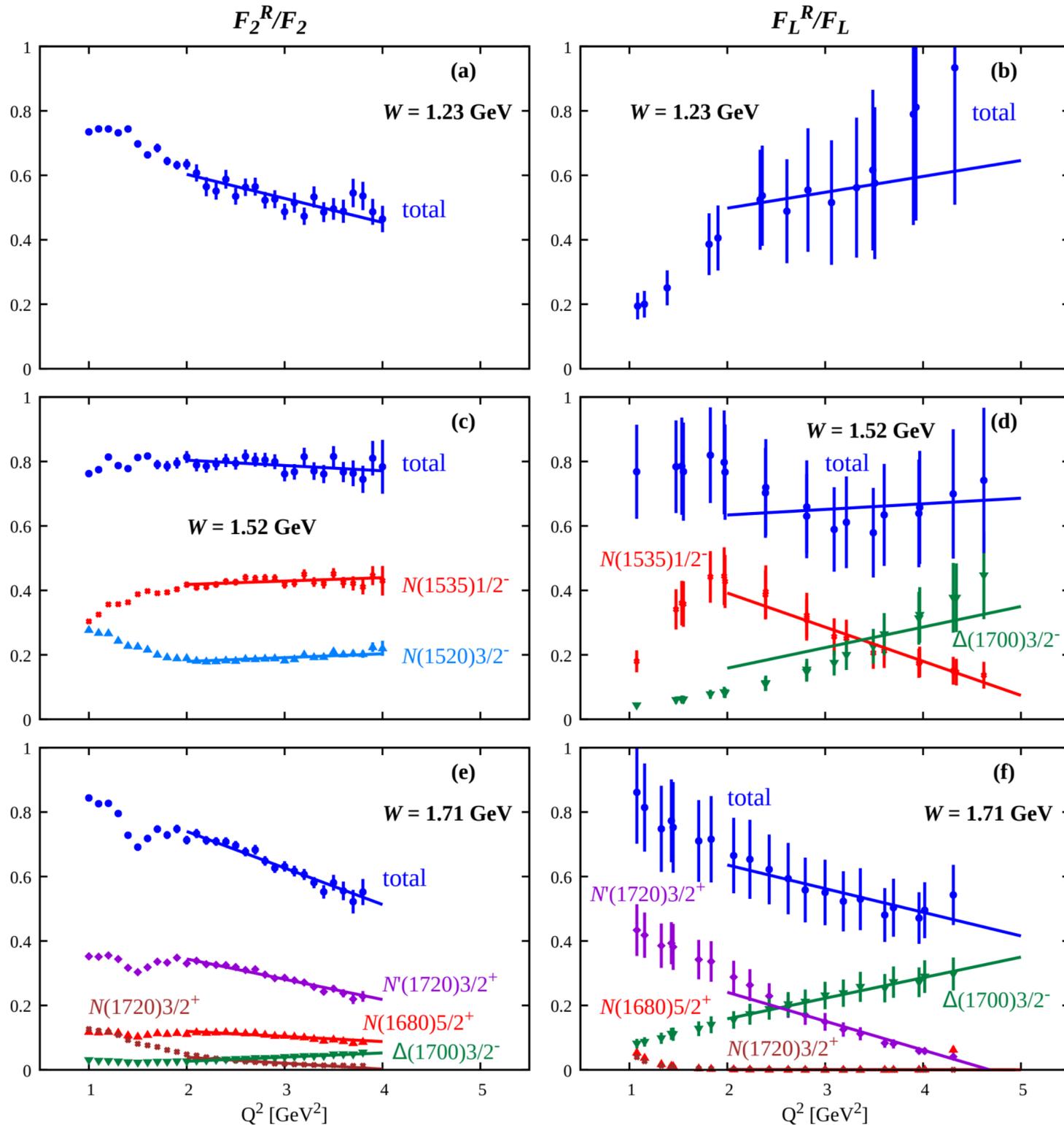
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$\Delta(1232)$ : even at  $4 \text{ GeV}^2$ ,  $\sim 50\%$  significance;  
2nd peak: nearly flat ratio.

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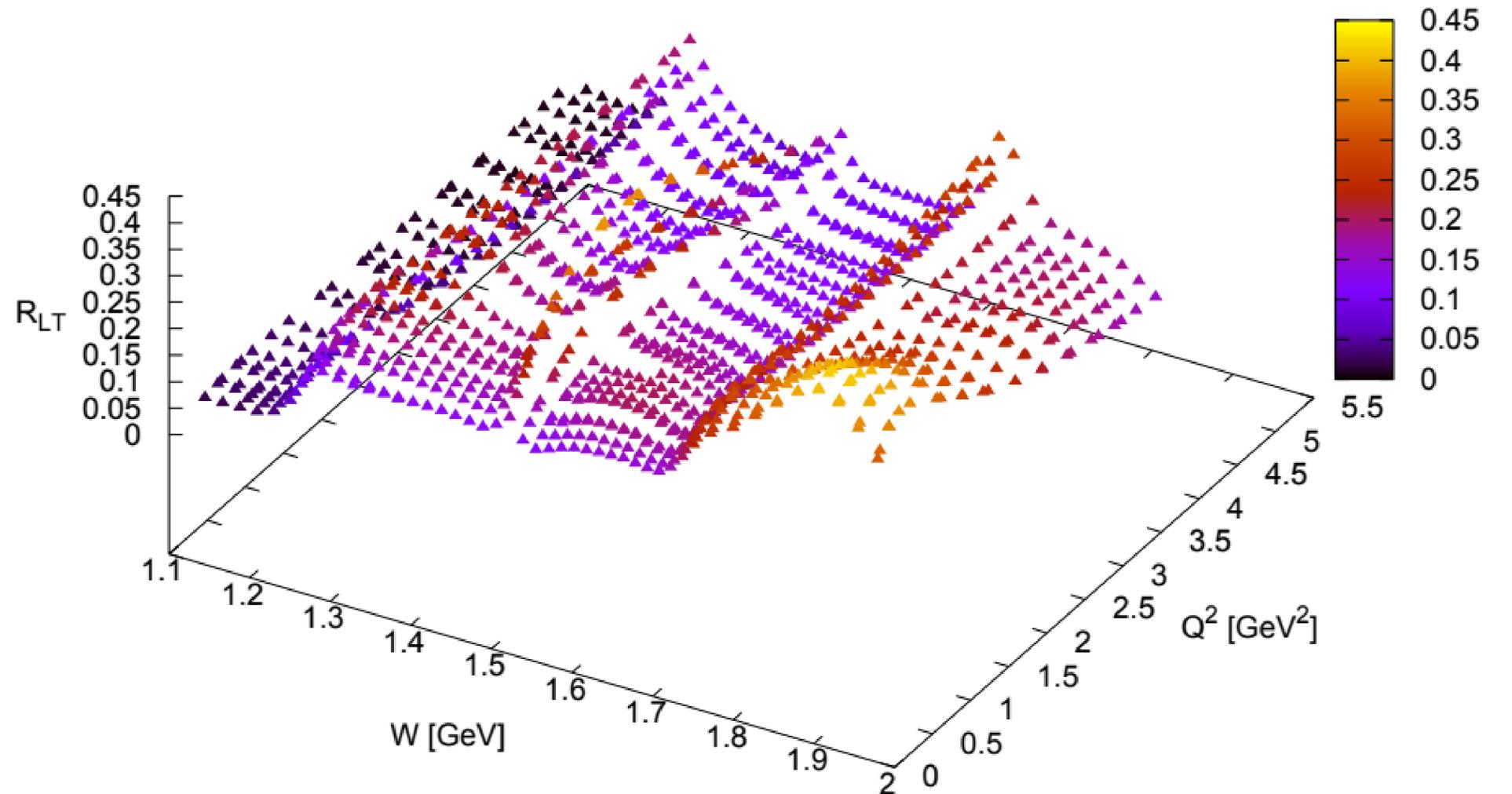
Resonance contributions decrease with  $Q^2$ , but so do the total contributions.

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Behavior points to non-vanishing resonances!

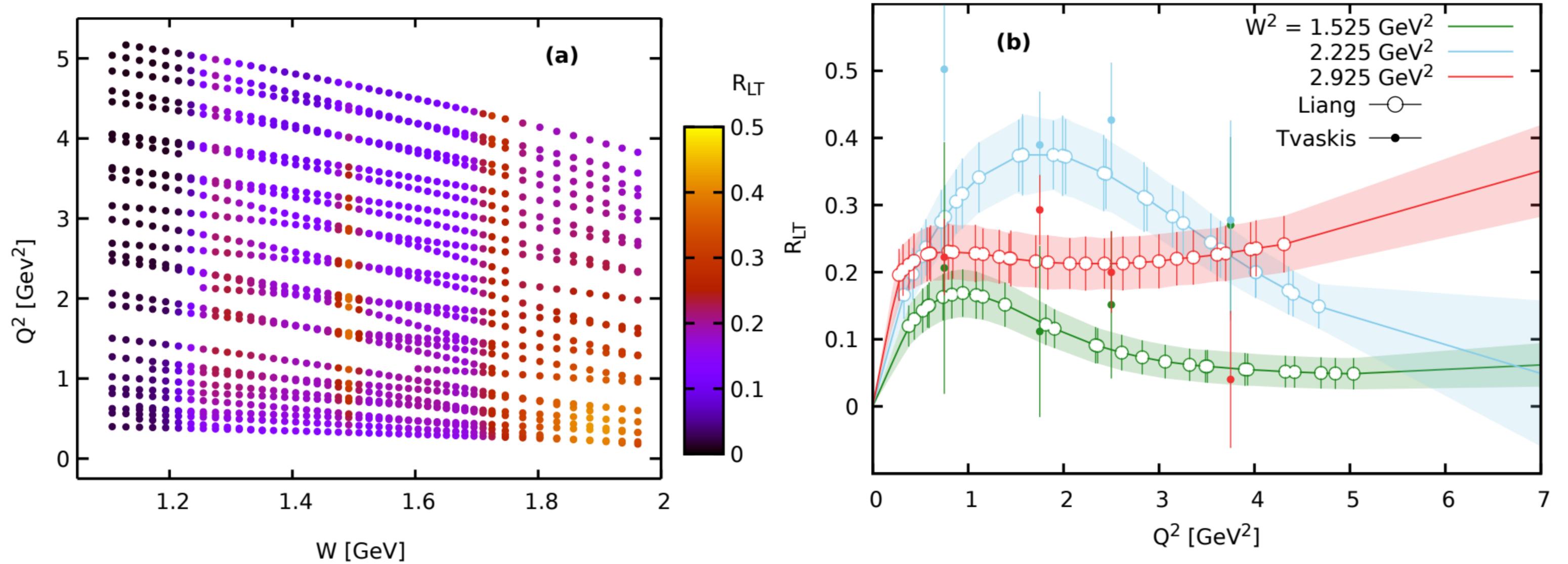
# Longitudinal vs. transverse separation

*Tvaskis et al., PRC 97 (2018) 045204*  
*Liang et al., nucl-ex/0410027*

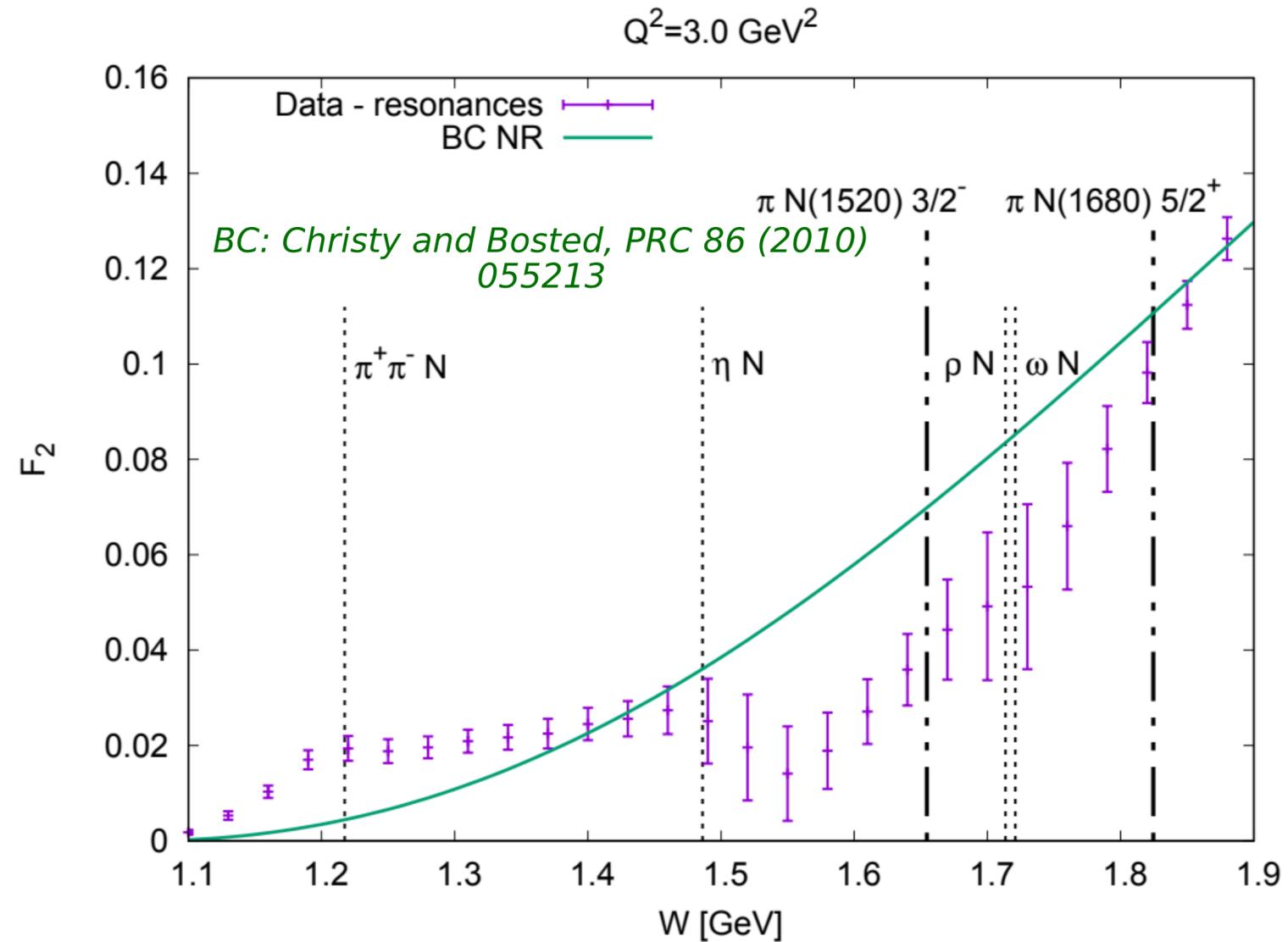


The Hall C L/T separated data cover the resonance region: can be used to separate out  $F_1$ ,  $F_2$ ,  $F_L$  from CLAS cross sections.

# Longitudinal vs. transverse separation



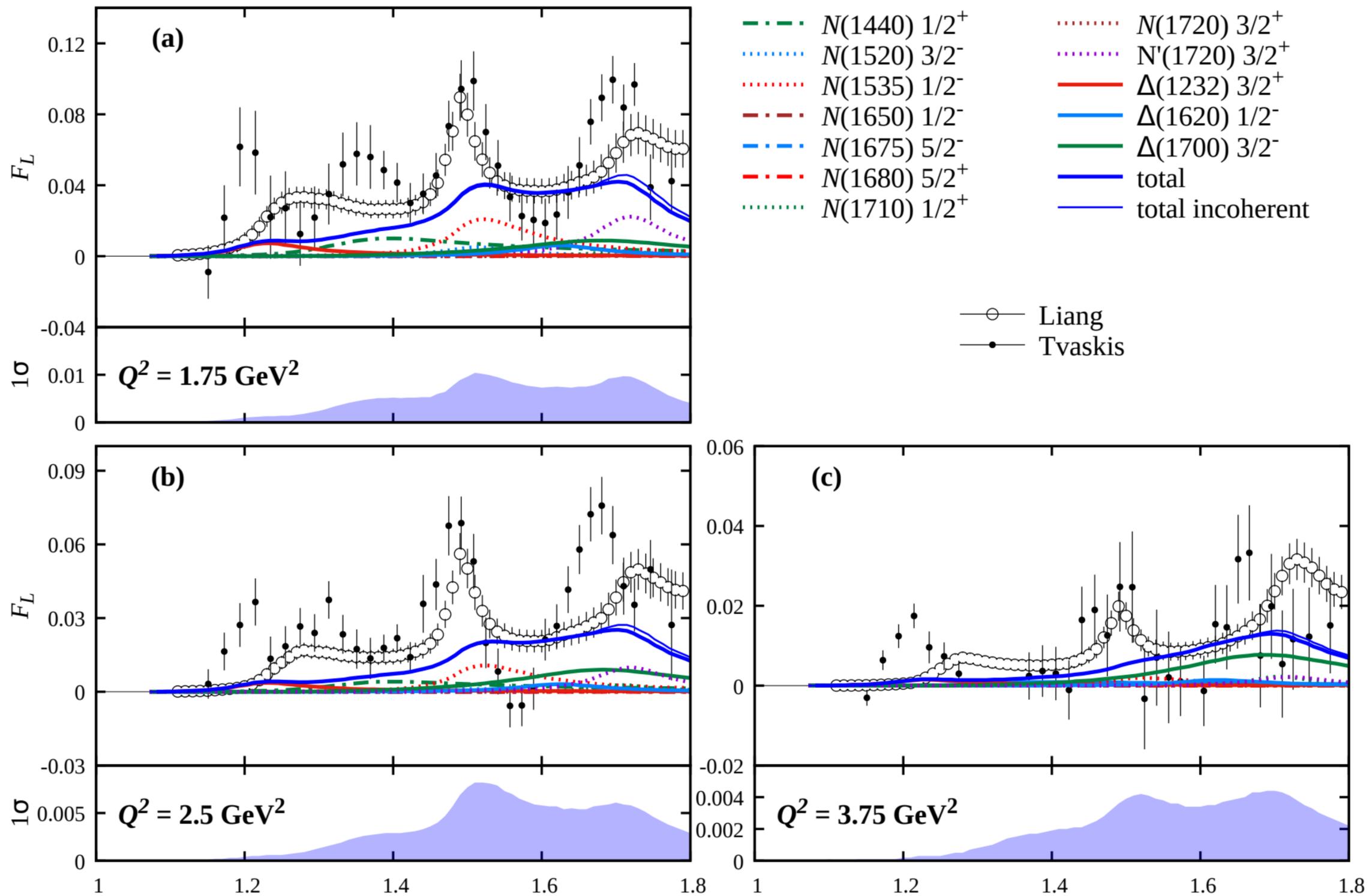
# First estimates of non-resonant contributions



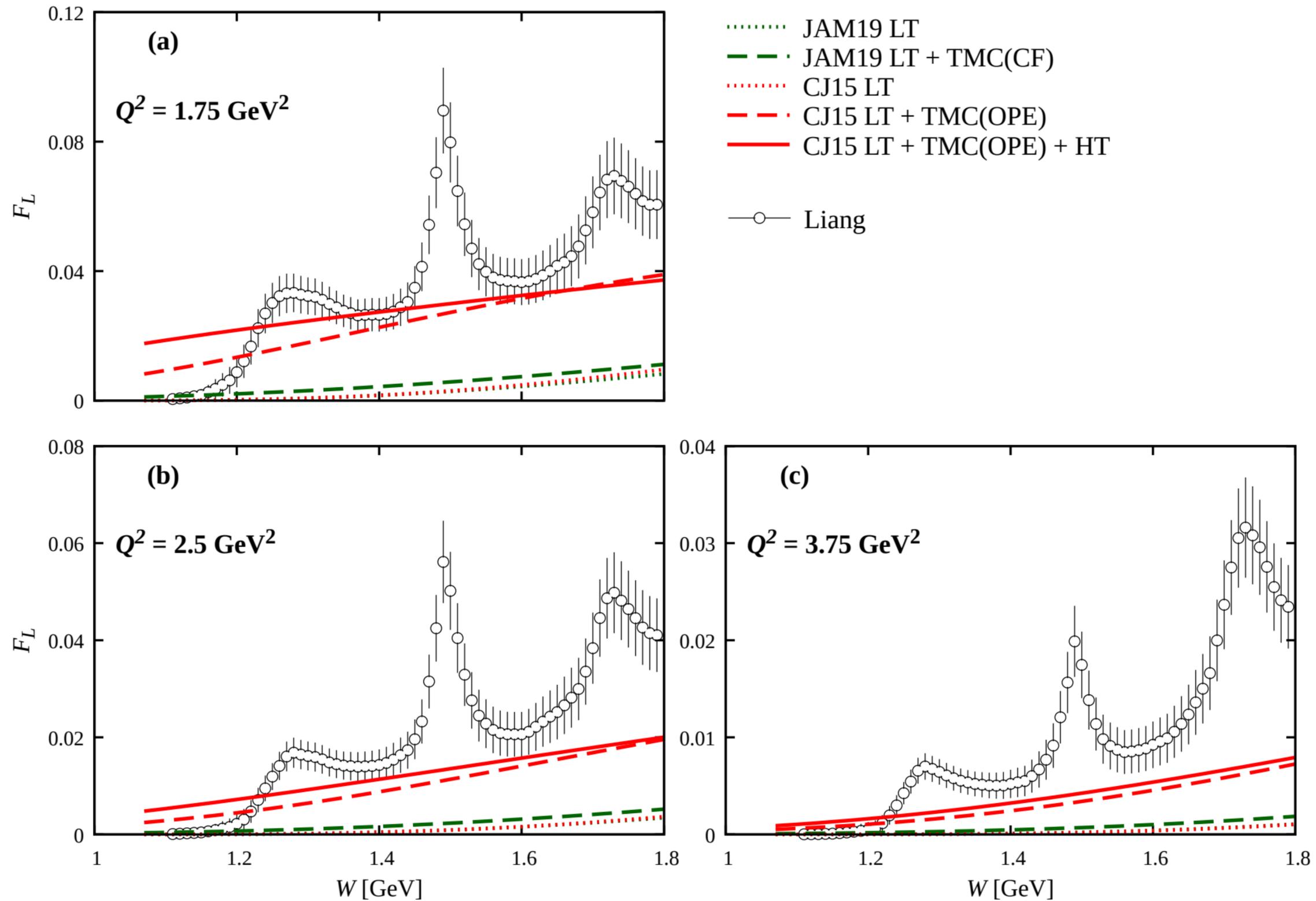
When “removing” the resonances from the data, something rather smooth as a background remains.

How do we interpret it?

# The longitudinal structure function



# And the longitudinal piece



# Truncated moments - longitudinal piece

