# Exclusive KY Electroproduction

## N* Studies with CLAS and CLAS12


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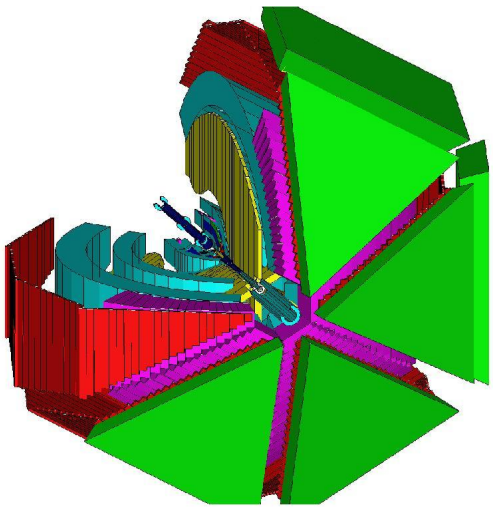
### Outline

- N* Spectrum & Structure
- Relevance of $\gamma^*p \rightarrow KY$ Data
- CLAS $\gamma^*p \rightarrow KY$ Data
- New CLAS12 KY Experiment
- Summary & Conclusions

# Introduction

The *N** program is one of the key physics foundations of Hall B



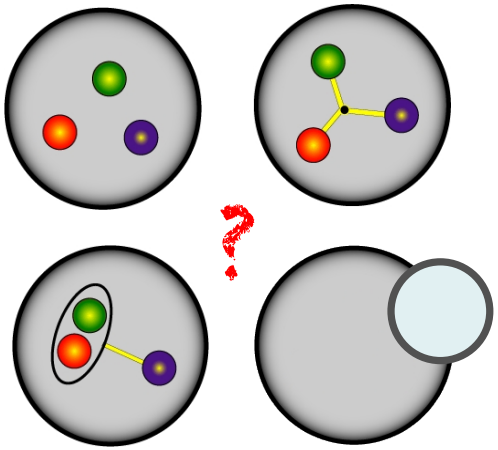
- CLAS was designed to measure γN and γ*N cross sections and spin observables over a broad kinematic range for exclusive reaction channels.

$\pi N$, $\omega N$, $\phi N$, $\eta N$, $\eta' N$, $\pi\pi N$

$KY$, $K^*Y$, $KY^*$

*- Different final states provide complementarity via different couplings and mix of resonant/non-resonant processes*

- The program goal is to study the spectrum of states and their associated structure vs. distance scale.
  - *Probe the relevant degrees of freedom and strong interaction mechanisms that generate excited nucleon states*
  - *N* studies dominated by pionic ($N\pi$, $N\pi\pi$) channels*
  - *KY final states are valuable to study high-lying N* states*

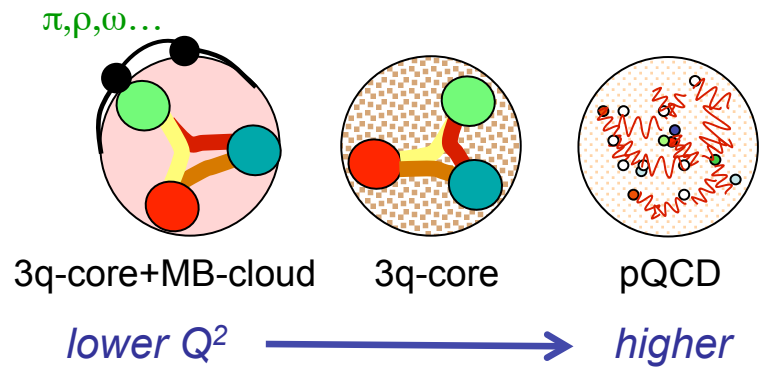


# Nucleon Structure - I

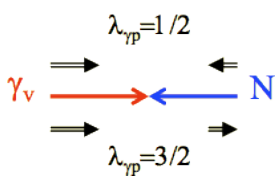
- Nucleon structure is more complex than what can be described accounting for quark degrees of freedom only.

  - *Lower $Q^2$:* *structure well described by adding an external MB cloud to inner quark core* ($Q^2 < 5$ GeV$^2$)

  - *Higher $Q^2$:* *quark core dominates; transition from confinement to pQCD regime* ($Q^2 > 5$ GeV$^2$)

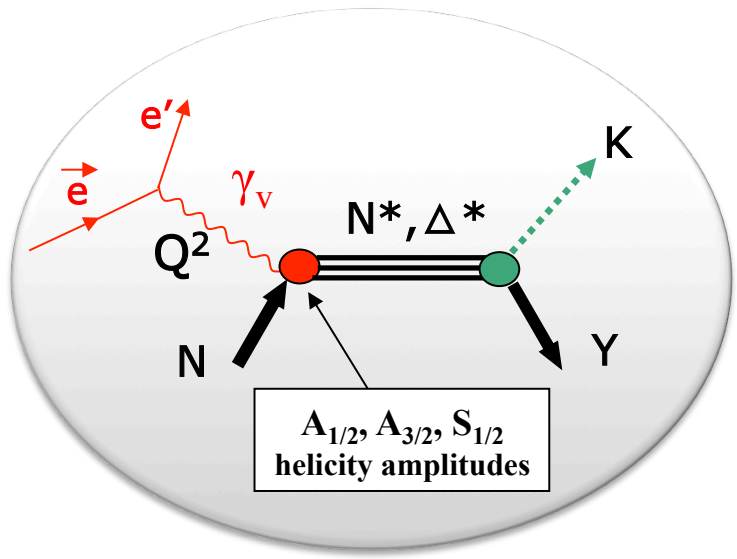



- Electroproduction at high $Q^2$ probes the quark core of the excited N* resonances through the $\gamma_v NN^*$ electrocoupling amplitudes.



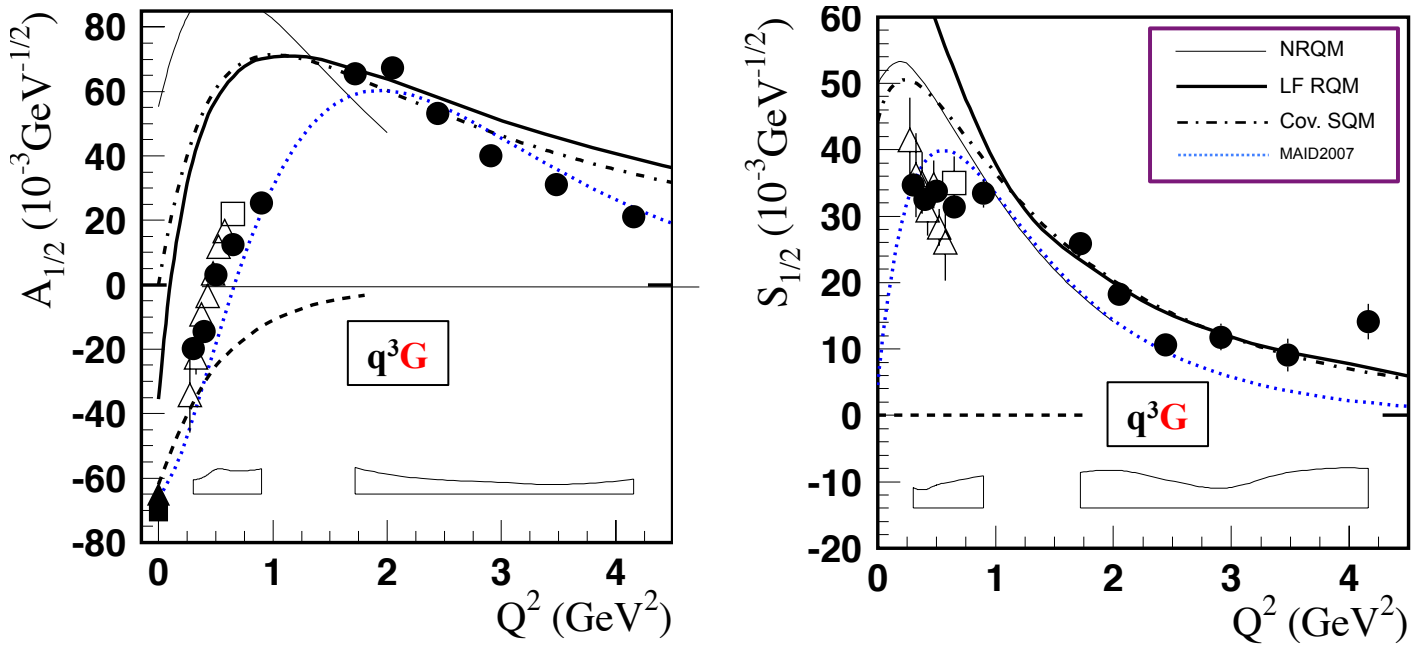

*$A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$ - transverse*

*$S_{1/2}(Q^2)$ - longitudinal*




- Comparison of theory predictions to data test our understanding of the strong interaction dynamics.

# Nucleon Structure - II




Lower $Q^2$

Roper

$P_{11}(1440)$

*3q state + MB cloud*

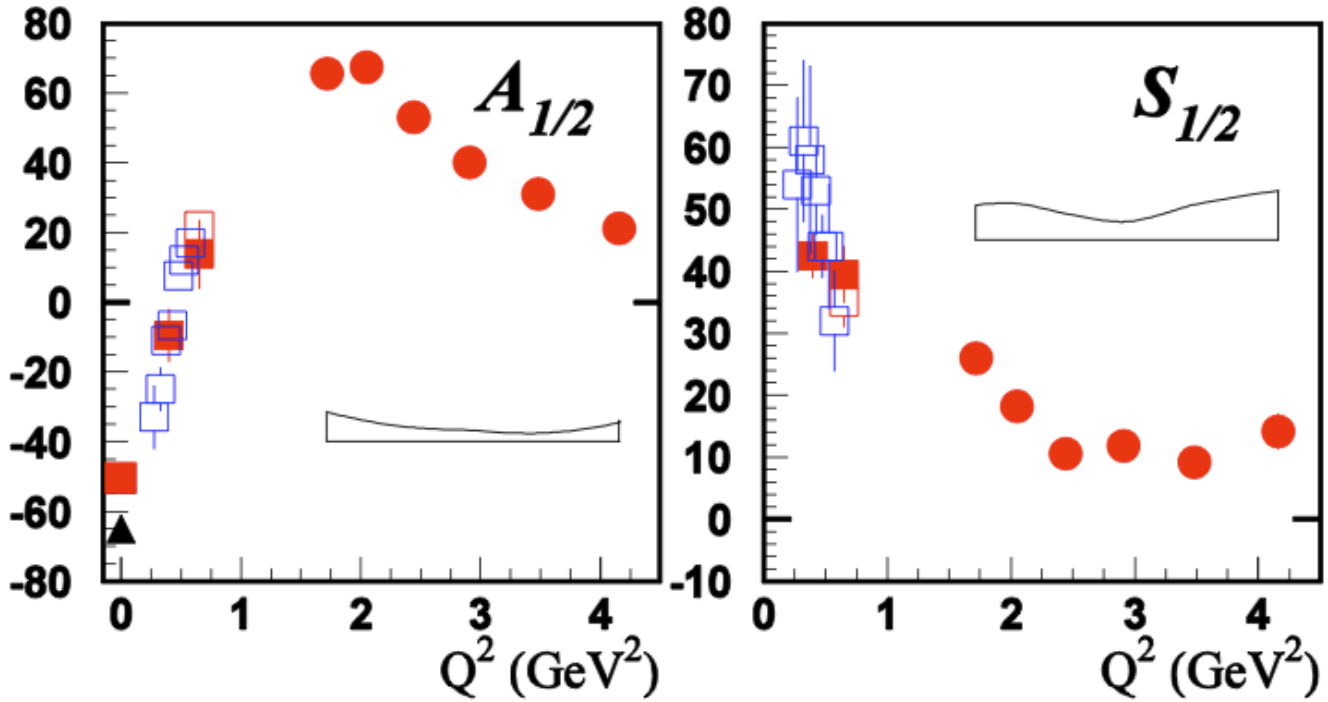
*[Aznauryan and Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012)]*

Higher $Q^2$

- For $Q^2 > 5$ GeV$^2$ the quark d.o.f will be (more) directly accessible from experiment with only small contributions from the MB cloud.
- Extracting the electrocoupling amplitudes gives information on the mass and structure of dressed quarks in the transition from the quark-gluon confinement to pQCD regimes.

# Electrocouplings – $P_{11}(1440)$

$P_{11}(1440)$

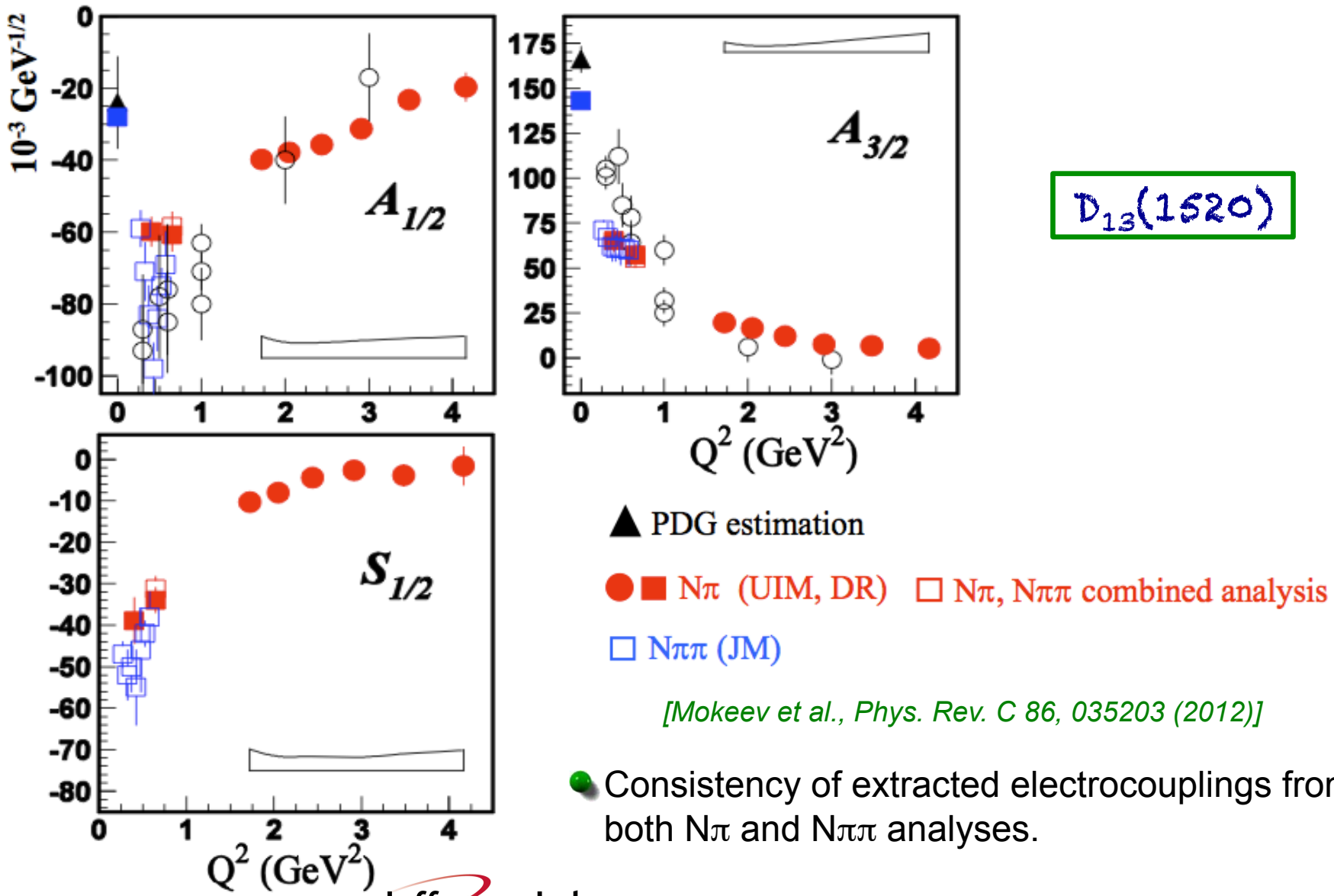



▲ PDG estimation ●■ Nπ (UIM, DR) □ Nπ, Nππ combined analysis □ Nππ (JM)

*[Mokeev et al., Phys. Rev. C 86, 035203 (2012)]*

- The good agreement of the extracted N* electrocouplings between the two exclusive channels (Nπ, Nππ) – *having fundamentally different mechanisms for the non-resonant background* – provides compelling evidence for the reliability of these results.

# Electrocouplings – $D_{13}(1520)$



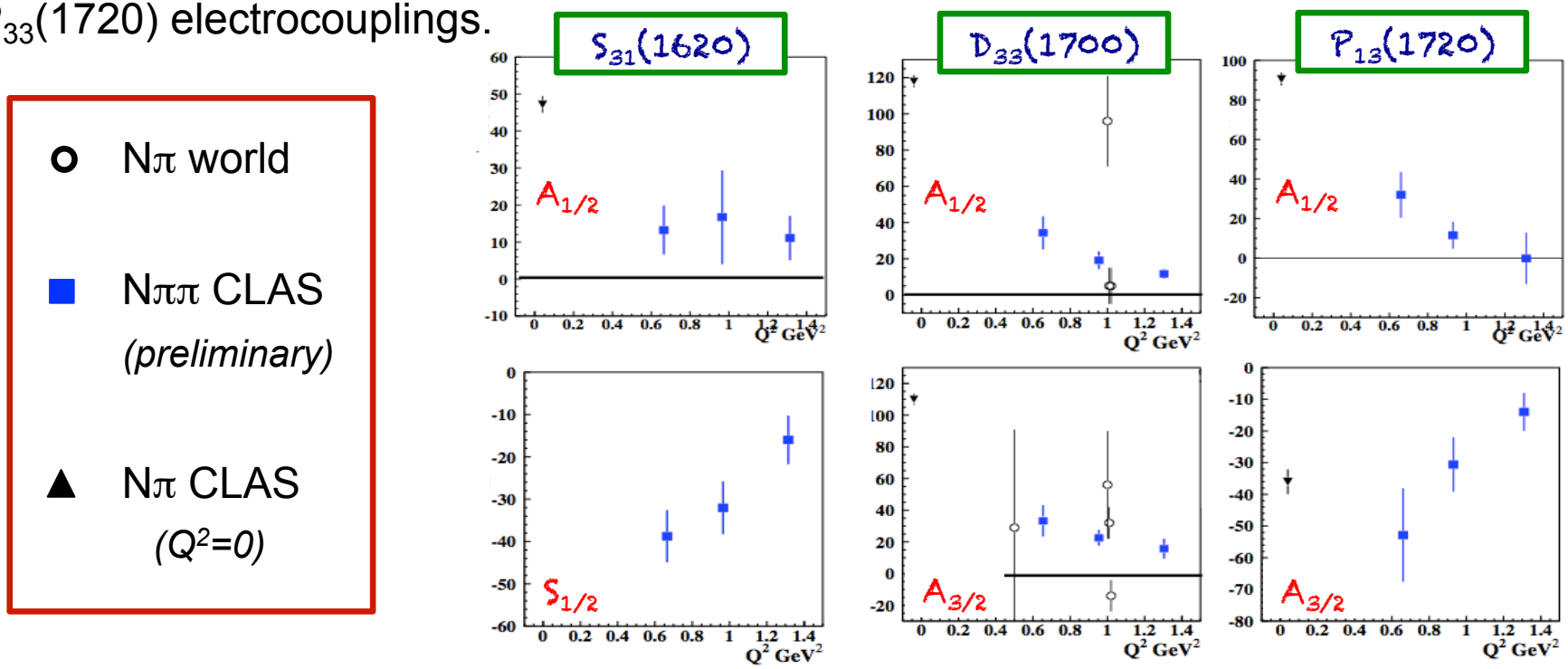

$D_{13}(1520)$

*[Mokeev et al., Phys. Rev. C 86, 035203 (2012)]*

- Consistency of extracted electrocouplings from both Nπ and Nππ analyses.

# Higher-Lying N* States

- $N\pi\pi$ channel provided the first results on $S_{31}(1620)$, $S_{11}(1650)$, $F_{15}(1685)$, $D_{33}(1700)$, $P_{33}(1720)$ electrocouplings.

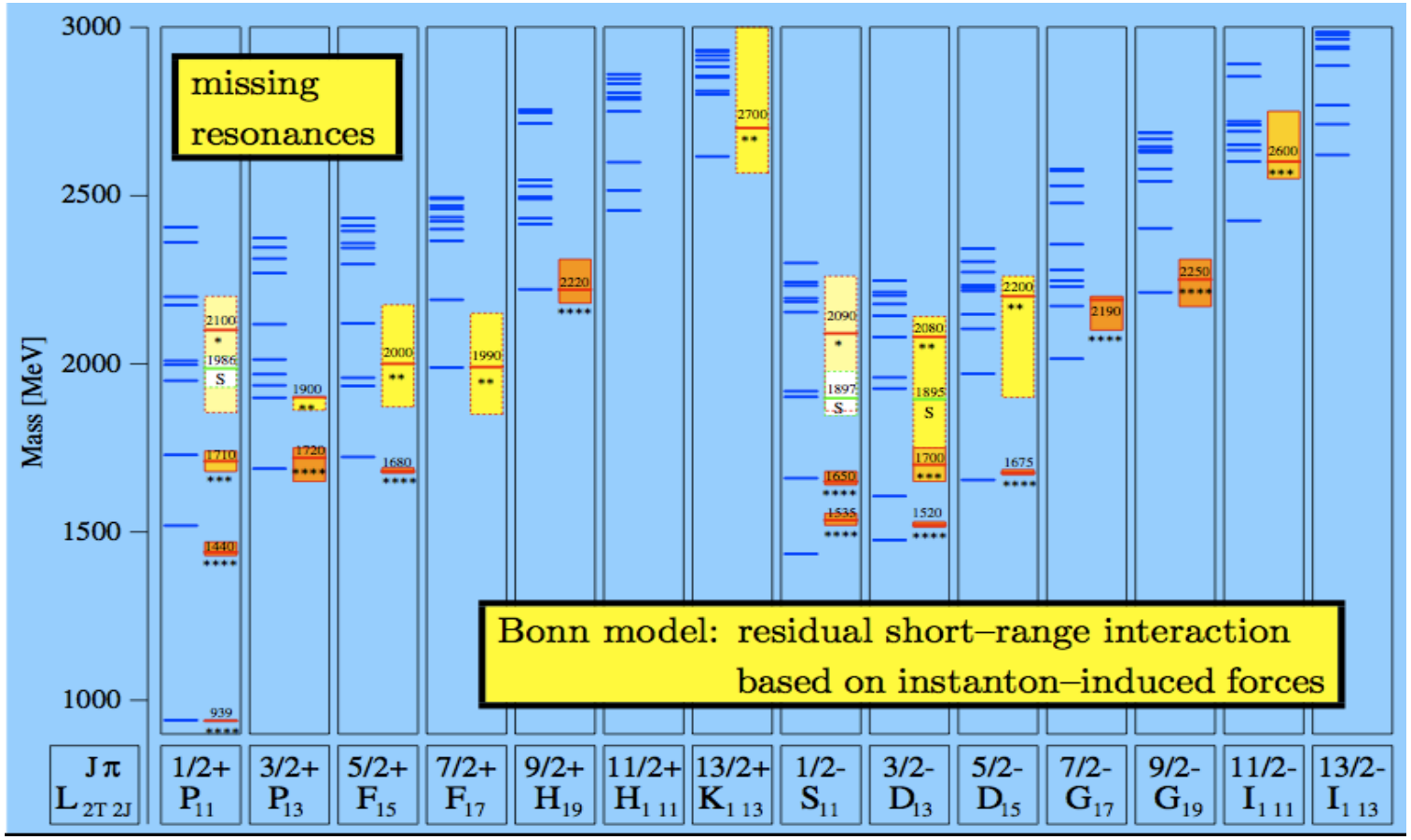



*[Mokeev, Aznauryan, Int. J. Mod. Phys. Conf. Ser. 26, 1460080 (2014)]*

- High-lying N* states (M > 1.6 GeV) decay mainly to $N\pi\pi$ with minimal strength to $N\pi$.

**Data from the KY channels is critical to provide an independent extraction of the electrocoupling amplitudes for the high-lying N* states**

# Baryon Spectrum in RCQM




N*

*[Löhring, Metsch, Petry, Eur. Phys. J. A 10, 395 (2001)]*

- Missing quark model states prevalent above 1.7 GeV

*Recent LQCD predictions justify CQM* *[Dudek, Edwards, PRD 85, 054016 (2012)]*

# N*,Δ* → KY Landscape

PDG

| N* → KY | | | | Δ* → KΣ | | |
|---|---|---|---|---|---|---|
| State | Rating | BR % (KΛ) | BR % (KΣ) | State | Rating | BR % (KΣ) |
| N*(1650) | **** | 3–11 | - | Δ*(1700) | **** | - |
| N*(1675) | **** | < 1 | - | Δ*(1750) | * | - |
| N*(1680) | **** | - | - | Δ*(1900) | ** | - |
| N*(1700) | *** | < 3 | - | Δ*(1905) | **** | - |
| N*(1710) | *** | 5–25 | - | Δ*(1910) | **** | 9 |
| N*(1720) | *** | 1–15 | - | Δ*(1920) | *** | 2.1 |
| N*(1875) | *** | - | - | Δ*(1930) | *** | - |
| N*(1900) | *** | 0-10 | 5 | Δ*(1940) | ** | - |
| N*(1990) | ** | - | - | Δ*(1950) | **** | - |
| N*(2000) | ** | - | - | Δ*(2000) | ** | - |

*[Olive et al. (PDG), Chin. Phys. C38, 090001 (2014)]*

Update?

| N* → KY | | | | Δ* → KΣ | | |
|---|---|---|---|---|---|---|
| State | Rating | BR % (KΛ) | BR % (KΣ) | State | Rating | BR % (KΣ) |
| N*(1650) | **** | 10±5 | - | Δ*(1620) | **** | - |
| N*(1675) | **** | - | - | Δ*(1700) | **** | - |
| N*(1680) | **** | - | - | Δ*(1750) | * | - |
| N*(1700) | *** | - | - | Δ*(1900) | ** | 5±3 |
| N*(1710) | *** | 23±7 | - | Δ*(1905) | **** | - |
| N*(1720) | **** | - | - | Δ*(1910) | **** | 9±5 |
| N*(1875) | *** | 4±2 | 15±8 | Δ*(1920) | *** | 4±2 |
| N*(1880) | ** | 2±1 | 17±7 | Δ*(1930) | *** | - |
| N*(1895) | ** | 18±5 | 13±7 | Δ*(1940) | *** | - |
| N*(1900) | ** | 16±5 | 5±2 | Δ*(1950) | **** | 0.4±0.1 |
| N*(1990) | ** | - | - | Δ*(2000) | ** | - |
| N*(2000) | ** | - | - | | | |

*[Anisovich et al., EPJ A 48, 15 (2012)]*

***Bonn-Gatchina coupled-channels fits***

# CLAS Strangeness Program

- The initial thrust of the CLAS measurement program focused on exclusive production of ground-state $\Lambda$ and $\Sigma$ hyperons.

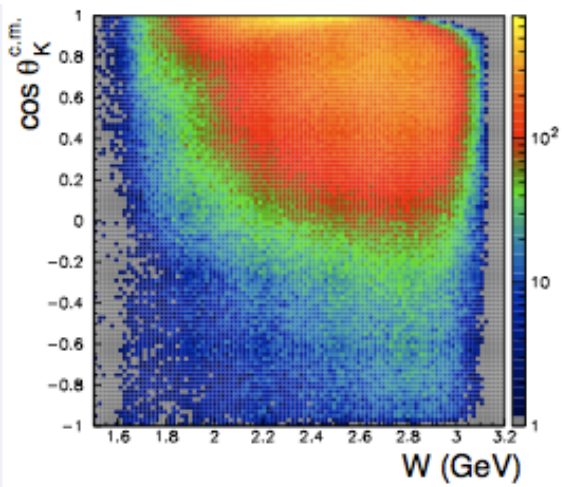



**Photo- and electroproduction experiments**

*W: 1.6 – 3.0 GeV* *cos $\theta_K^{c.m.}$: [-1: 1]*

*$Q^2$: 0 – 4.5 GeV$^2$* *$E_b$: up to 6 GeV*

- *Provide extensive database of cross sections for model fits.*

- Measurement of hyperon polarizations: *recoil, transferred*
  - *$\Lambda$ polarization "self-analyzing" via decay frame angular distribution.*

- Program has grown to include studies of:
  - *Vector meson production (K*Y)*
  - *Excited hyperon production (KY*)*
  - *Semi-inclusive hyperon processes (YX)*
  - *"Complete" experiments ($\gamma$p and $\gamma$n) in photoproduction (FROST, HD-Ice)*

# Electroproduction Data

- Electroproduction data is the only source of information on the structure of excited nucleon states:

$$\frac{d\sigma}{d\Omega} = (\sigma_T + \epsilon\sigma_L) + \epsilon\sigma_{TT}\cos 2\Phi + \sqrt{\epsilon(1+\epsilon)}\sigma_{LT}\cos\Phi + h\sqrt{\epsilon(1-\epsilon)}\sigma_{LT'}\sin\Phi$$

  - Studies of electroproduction processes are sensitive to both L and T amplitudes
  - The LT and TT structure functions provide signatures of interfering partial wave strengths that can differentiate among production mechanisms
  - The structure functions are particularly useful to gain control over the parameterization of the background diagrams
  - Polarized virtual photons provide information on the interference of electroproduction amplitudes of different helicities.
  - The $Q^2$ dependence of the data gives access to the $\gamma^*NN^*$ transition FFs, our source of information on N* structure

**Electroproduction provides constraints on the production amplitudes beyond the photoproduction data**

**Photoproduction allows us to identify new states but tells us little about their nature**

# CLAS ep Data Set Overview

| # | Period | $E_b$ (GeV) | # Trig. |
|---|---|---|---|
| 1 | e1c | 2.567 | 900M |
| 2 | e1c | 4.056 | 370M |
| 3 | e1c | 4.247 | 620M |
| 4 | e1c | 4.462 | 420M |
| 5 | e1-6 | 5.754 | 4500M |
| 6 | e1f | 5.499 | 5000M |

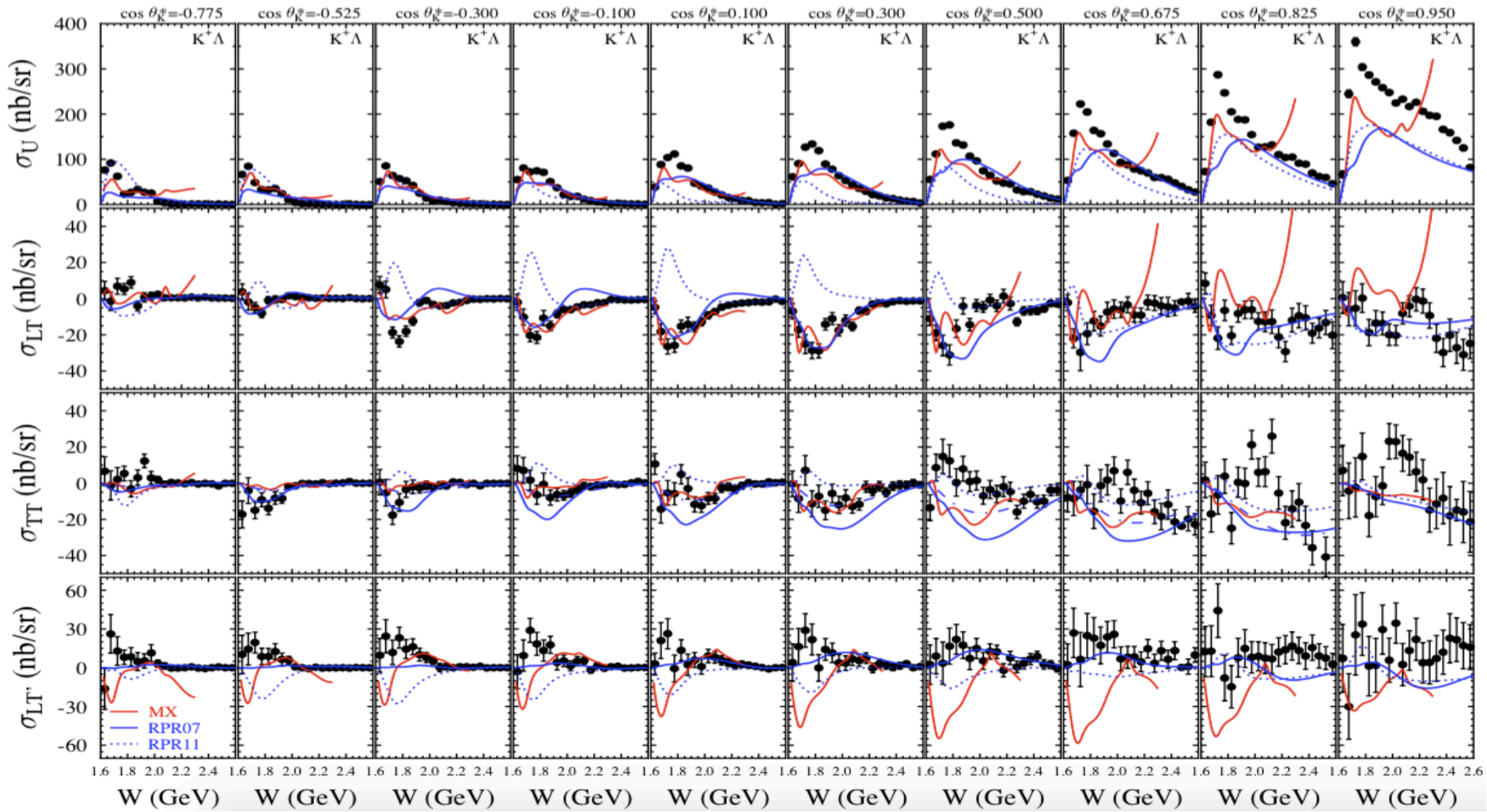
- $K^+\Lambda$ fifth structure function $\sigma_{LT'}$
  - *W=1.6-2.1 GeV, $Q^2$=0.65-1.0 GeV$^2$*
    *[Nasseripour et al., PRC 77, 065208 (2008)]*
- $K^+\Lambda$ recoil pol.
  - *W=1.6-2.7 GeV, $\langle Q^2 \rangle$=1.9 GeV$^2$*
    *[Gabrielyan et al., PRC 90, 035202 (2014)]*

## CLAS $\gamma^*p \rightarrow$ KY Publications:

- $K^+\Lambda$, $K^+\Sigma^0$ beam-recoil pol. transfer
  - *W=1.6-2.15 GeV, $Q^2$=0.3-1.5 GeV$^2$*
    *[Carman et al., PRL 90, 131804 (2003)]*
  - *W=thr-2.6 GeV, $Q^2$=1.6-2.6 GeV$^2$*
    *[Carman et al., PRC 79, 065205 (2009)]*
- $K^+\Lambda$ $\sigma_L/\sigma_T$ ratio from pol. transfer data
  - *W=1.72-1.98 GeV, $Q^2$~0.7 GeV$^2$*
    *[Raue & Carman, PRC 71, 065209 (2005)]*
- $K^+\Lambda$, $K^+\Sigma^0$ separated structure functions
  - *W=thr-2.4 GeV, $Q^2$=0.5-2.8 GeV$^2$*
    $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$, $\sigma_L$, $\sigma_T$ - $K^+\Lambda$, $K^+\Sigma^0$
    *[ Ambrozewicz et al., PRC 75, 045203 (2007)]*
  - *W=thr-2.6 GeV, $Q^2$=1.4-3.9 GeV$^2$*
    $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$, $\sigma_{LT'}$ – $K^+\Lambda$ , $K^+\Sigma^0$
    *[Carman et al., PRC 87, 025204 (2013)]*

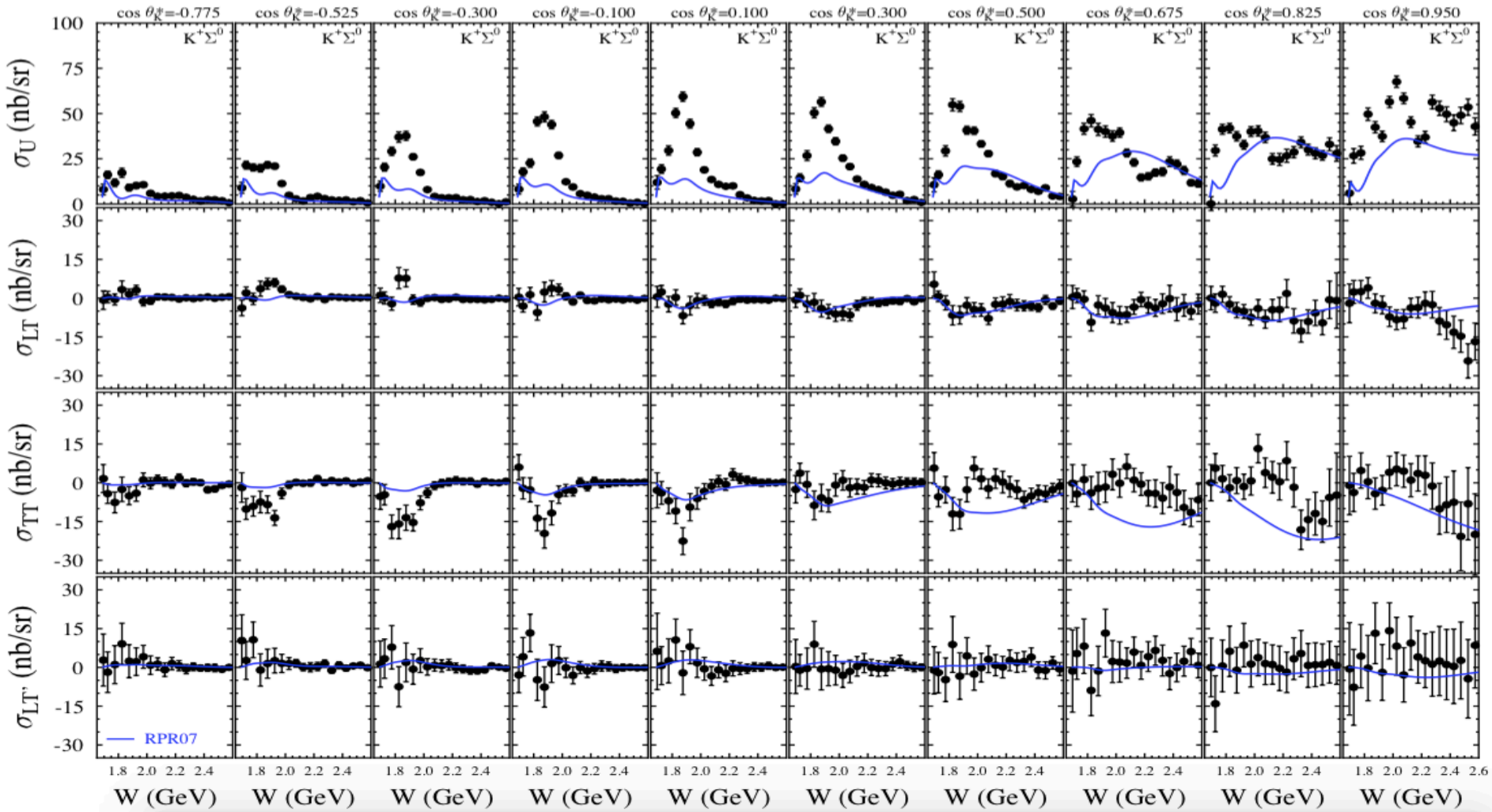
CLAS KY data dominates world's database

# $K^+\Lambda$ Structure Functions



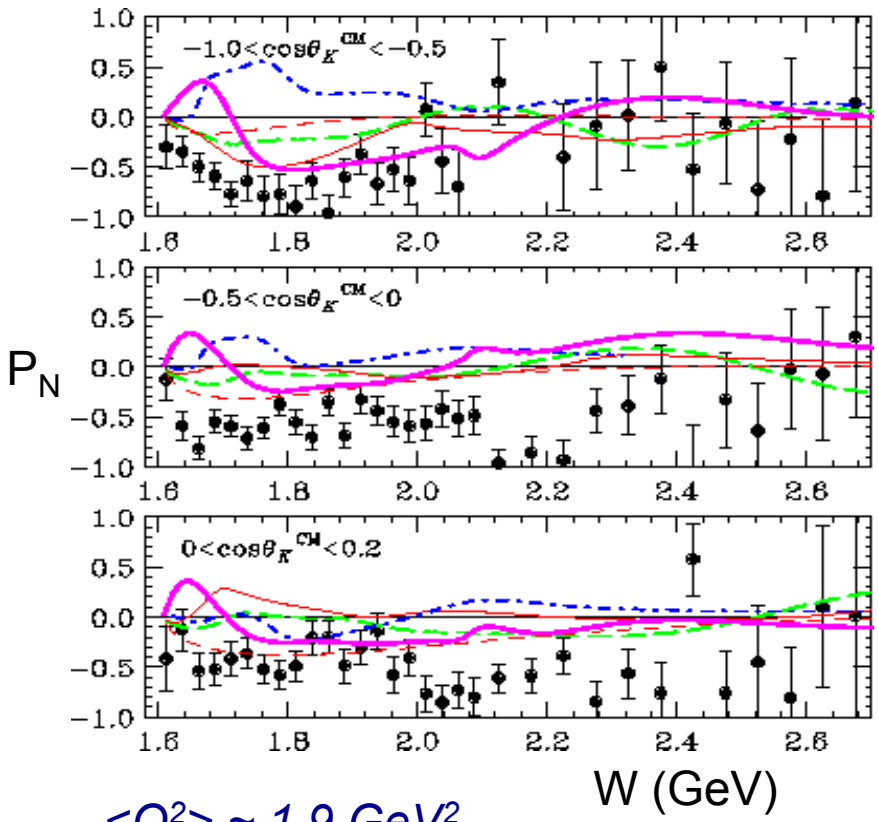

*E = 5.5 GeV, W: thr – 2.6 GeV, $Q^2$ = 1.80, 2.60, 3.45 $GeV^2$* *[Carman et al., PRC 87, 025204 (2013)]*

# $K^+\Sigma^0$ Structure Functions

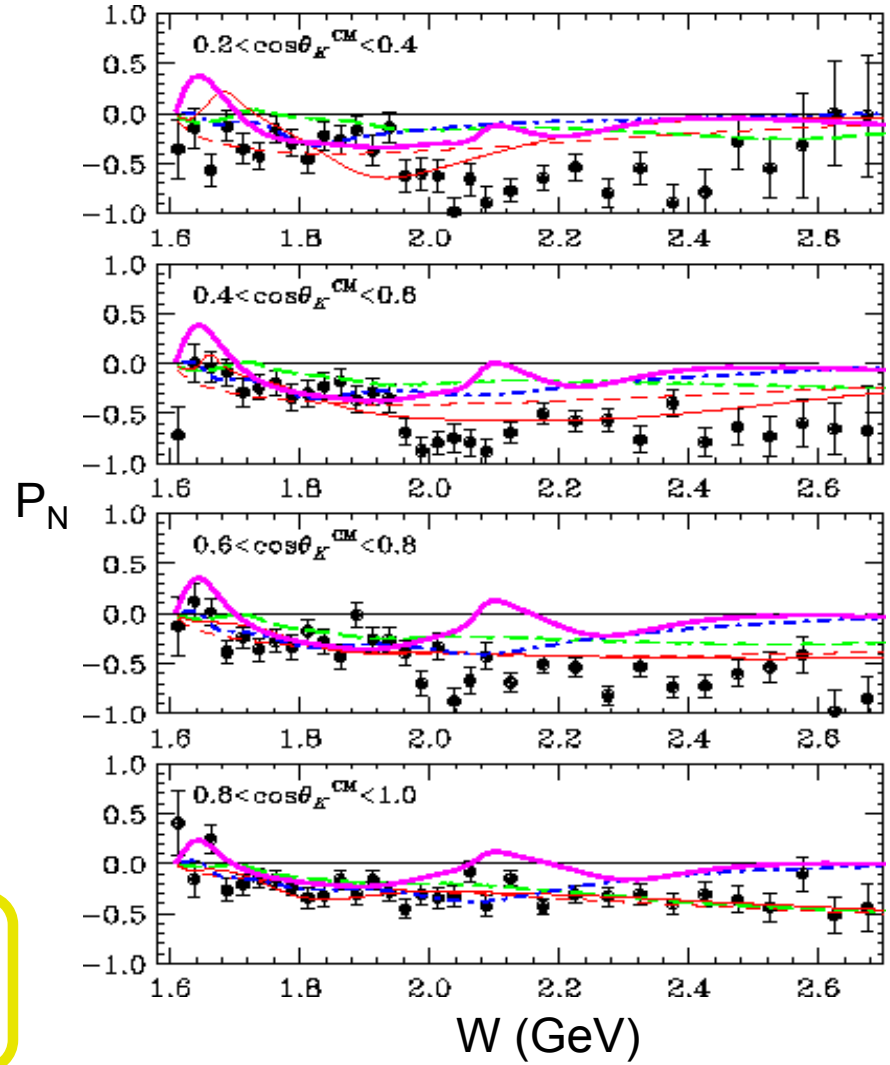



*E = 5.5 GeV, W: thr – 2.6 GeV, $Q^2$ = 1.80, 2.60, 3.45 $GeV^2$* *[Carman et al., PRC 87, 025204 (2013)]*

# Recoil Polarization $ep \rightarrow e'K^+\vec{\Lambda}$




$\langle Q^2 \rangle \sim 1.9\ GeV^2$



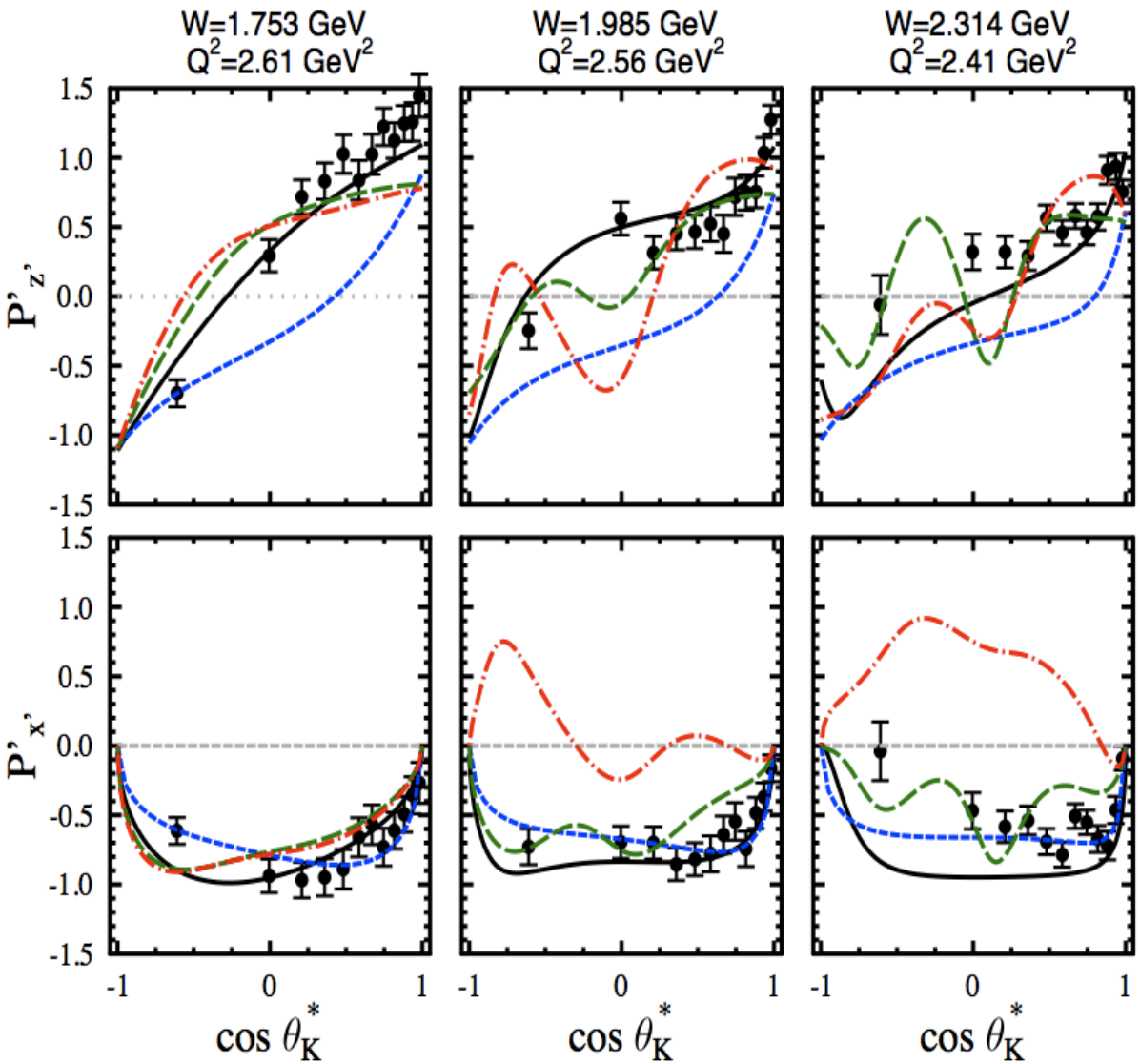

*Kaon-Maid* *Maxwell* *RPR-2007*

*RPR-2011 (solid-full, dash-NR)*

*[Gabrielyan et al., PRC 90, 035202 (2014)]*

# Transferred Polarization

$\vec{e}p \rightarrow e'K^+\vec{\Lambda}$




5.754 GeV
Summed over $Q^2$, $\Phi$

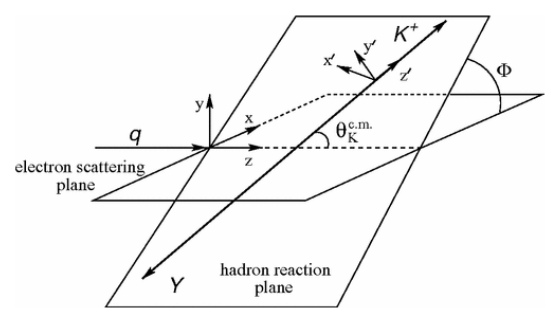
*Isobar Model – Mart*

*Regge Model – GLV*

*RPR w $P_{11}(1900)$ - Ghent*

*RPR w $D_{13}(1900)$ - Ghent*

RPR background + $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$, $P_{13}(1900)$




*[Carman et al., PRC 79, 065205 (2009)]*

# Dominant Couplings: $N^* \rightarrow K^+\Lambda$

- PDG status for 30 years: Core set of states: *$S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1720)$*
  Recent emergence of: *$P_{13}(1900)$* *(from $\gamma p$ fits)*

- Coupled-Channel Model (Bonn-Gatchina): *[Anisovich et al., EPJA 48, 15 (2012)]*
  *Most relevant: $S_{11}(1650)$, $P_{11}(1710)$, $D_{13}(1895)$, $P_{13}(1900)$*
  *Other required states: $F_{15}(1680)$, $P_{13}(1720)$, $P_{11}(1880)$, $S_{11}(1895)$, $F_{15}(2000)$, $D_{13}(2150)$*

- Coupled-Channel Model (EBAC/AO): *[Kamano et al., PRC 88, 035209 (2013)]*
  *Most relevant: $S_{11}(1650)$, $P_{11}(1710)$, $P_{13}(1900)$*
  *Other required states: $D_{15}(1675)$, $F_{15}(1680)$, $D_{13}(1700)$, $P_{13}(1720)$*

- Isobar Model (Mart): *[Mart and Kholili, PRC 86, 022201 (2012)]*
  *Most relevant: $S_{11}(1650)$, $P_{13}(1720)$, $P_{11}(1880)$, $P_{13}(1900)$, $D_{13}(2080)$*

- Fits including electroproduction data are critical to better constrain model fits.
  *- Consistent hadronic couplings in all $Q^2$ bins is a necessary condition for convergence*

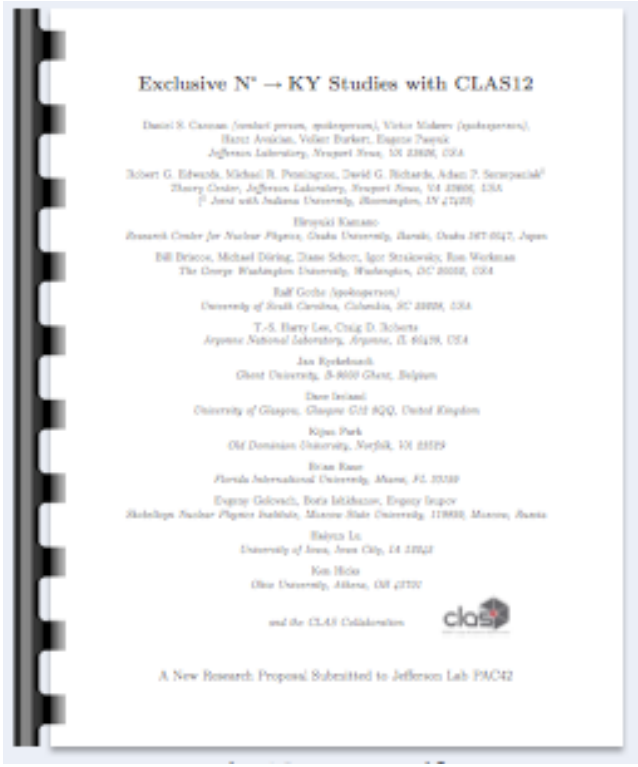
# New KY Proposal for CLAS12

- Measure exclusive $K^+\Lambda$ and $K^+\Sigma^0$ electroproduction cross sections from an unpolarized proton target with polarized electron beam.

*$E_b$ = 11 GeV, $Q^2$ = 3 – 12 GeV$^2$, W = 1.6 – 3.0 GeV, cos $\theta_K$* = [-1:1]*

*Part of run group assigned 80 days of running*

- Key Motivations:
  - *Study spectrum and structure of high-lying baryon states at high $Q^2$.*
  - *Search for new baryon states and their couplings to KY.*
  - *KY data needed to provide independent information for studies of high-mass N* states inaccessible with N$\pi$ final states.*


Exclusive N* → KY Studies with CLAS12

A New Research Proposal Submitted to Jefferson Lab PAC42

*Spokespersons: D.S. Carman, R. Gothe, V. Mokeev*

E12-06-108A

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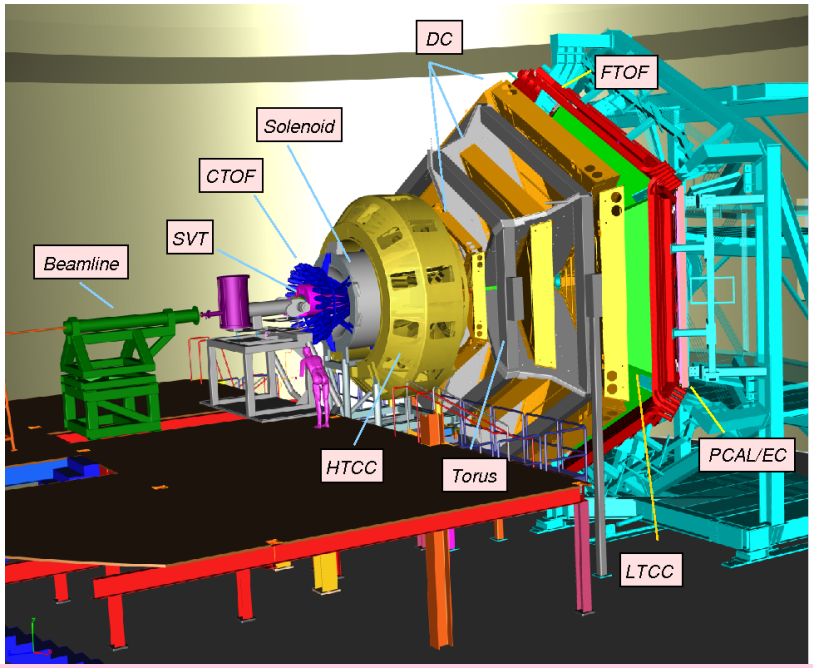


*Experimental program to begin 2017*

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- Measure exclusive $K^+\Lambda$ and $K^+\Sigma^0$ electroproduction cross sections from an unpolarized proton target with polarized electron beam.

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*Spokespersons: D.S. Carman, R. Gothe, V. Mokeev*

**Note:**

A dedicated experiment to study N* structure in the electroproduction of exclusive non-strange final states with CLAS12 has already been approved.

E12-09-003 (Gothe, Mokeev, Burkert)

*Focus on $N\pi$, $N\pi\pi$ final states*

This new KY proposal extends our physics reach on N* structure studies and represents the formation of a more complete and far-reaching N* program with CLAS12.

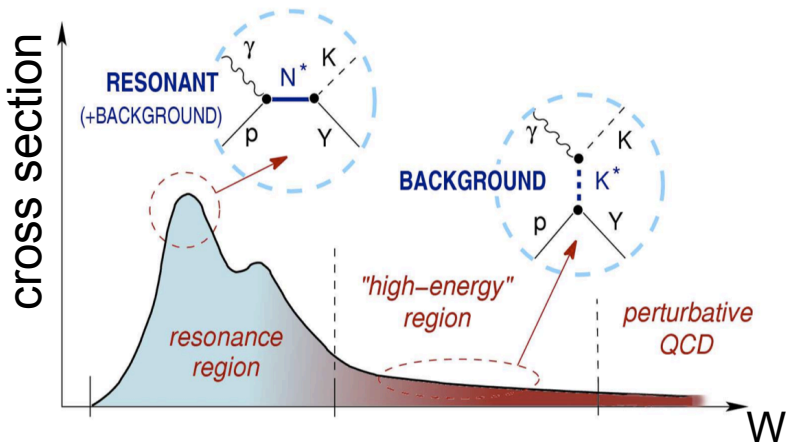
# KY Reaction Model

- At present there is no reaction model that describes the KY electroproduction data

*This is essential in order to extract the electrocoupling parameters from the existing CLAS data and from the expected CLAS12 data*

**Regge + Resonance Model**

*[DeCruz et al., PRC 86, 015212 (2012)]*




Model not constrained by any $\gamma^*p$ data

**Resonances:**

- *Standard isobar model formulation*
- *11 s-channel states (J=1/2, 3/2, 5/2) with W < 2 GeV*
- *EM form factors from Bonn CQM*
- *Model parameters from fit to world $\gamma p$ data*

**Background:**

- *K(494) and K*(892) Regge trajectories in t-channel*
- *Parameterized by 3 coupling strengths and 2 phases*
- *Background tuned to high-energy data and CLAS data in resonance region*

# Development of Reaction Model

- Phase #1: Update the RPR model parameters
  - *Provide consistency with electrocoupling parameters from fits to CLAS $N\pi$ and $N\pi\pi$ data*
  - *Finalize set of s-channel resonant states for $K^+\Lambda$ and $K^+\Sigma^0$ for W up to ~2 GeV*
  - *Perform new fits to re-establish the RPR model resonant and non-resonant parameters*
- Phase #2: Develop a true extraction model from the current RPR model
  - *Refit to CLAS $\gamma p$ and $\gamma^* p$ data for W → 2.6 GeV and $Q^2$ → 4 $GeV^2$ with known parameters constrained to within their measured uncertainties*
  - *Extract the electrocoupling parameters and KY decay widths for all prominent N* states that couple to $K^+\Lambda$ and $K^+\Sigma^0$*
  - *Study stability of fit results and sensitivities to the different fit assumptions*
- Phase #3: Extend the RPR model to include the new CLAS12 KY data
  - *Model should be valid for kinematics W → ~3 GeV and $Q^2$ → 10 – 12 $GeV^2$*

*Work in collaboration with J. Ryckebusch (Ghent), D. Ireland (Glasgow), V. Mokeev (JLab/MSU)*

# Summary/Conclusions

- **The CLAS strangeness physics program:**
  - Designed to measure cross sections and all combinations of beam, target, and recoil polarization states.

    *- Precision data – broad kinematic coverage*
  - CLAS data dominates the world's strangeness physics database for both photo- and electroproduction cross sections and spin observables.

- **A new CLAS12 experiment will extend this program to $Q^2$ up to 12 $GeV^2$:**
  - This new experiment aims to extract the electrocouplings for the prominent high-lying $N^*/\Delta^*$ states vs. $Q^2$ that couple to KY final states:

    *See the full proposal: https://userweb.jlab.org/~carman/ky12.html*
  - These studies are a needed part of efforts to explore the dynamics of the strong interaction in the transition from quark-gluon confinement to the pQCD regime.
  - These studies are an important source of information on the mechanisms that are responsible for the formation of N* states of different quantum numbers from quarks and gluons – important complement to the $N\pi$ and $N\pi\pi$ analyses.

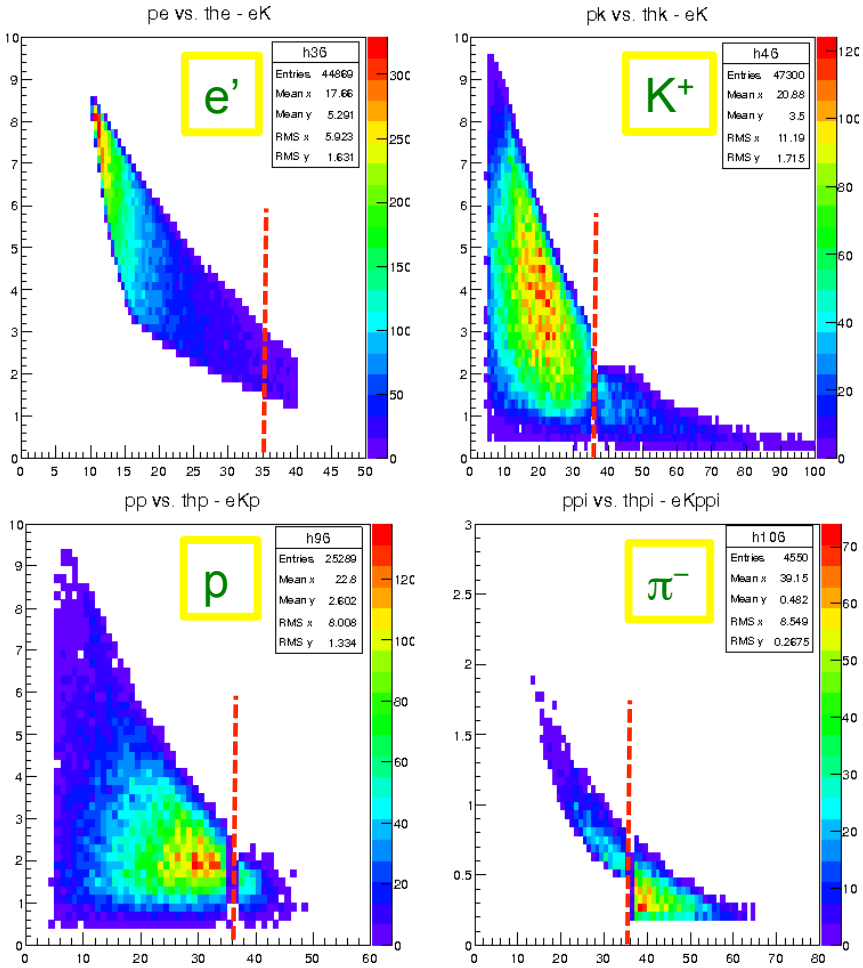
# BACKUP SLIDES

# CLAS12 KY Reconstruction

$$e + p \rightarrow e' + K^+ + Y \quad @\ 11\ \text{GeV}$$

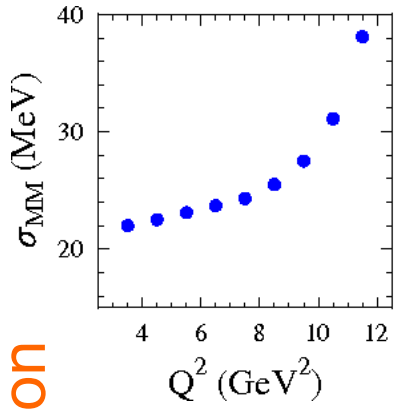
*fastMC*

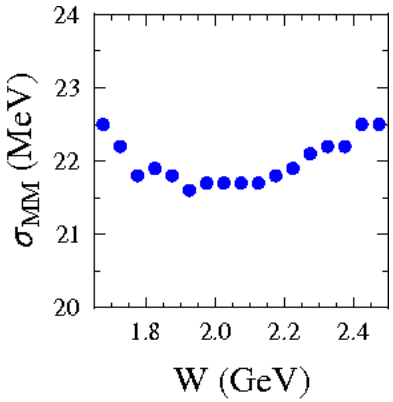
p vs. θ

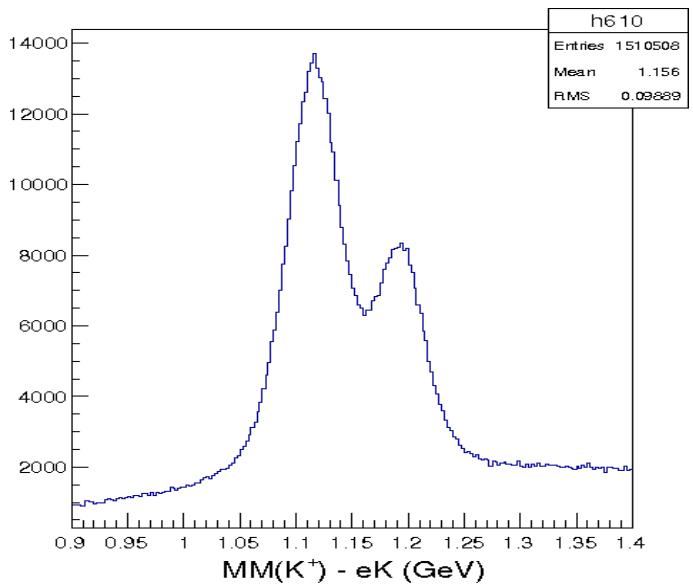



*FTOF primary system for PID*

MM reconstruction



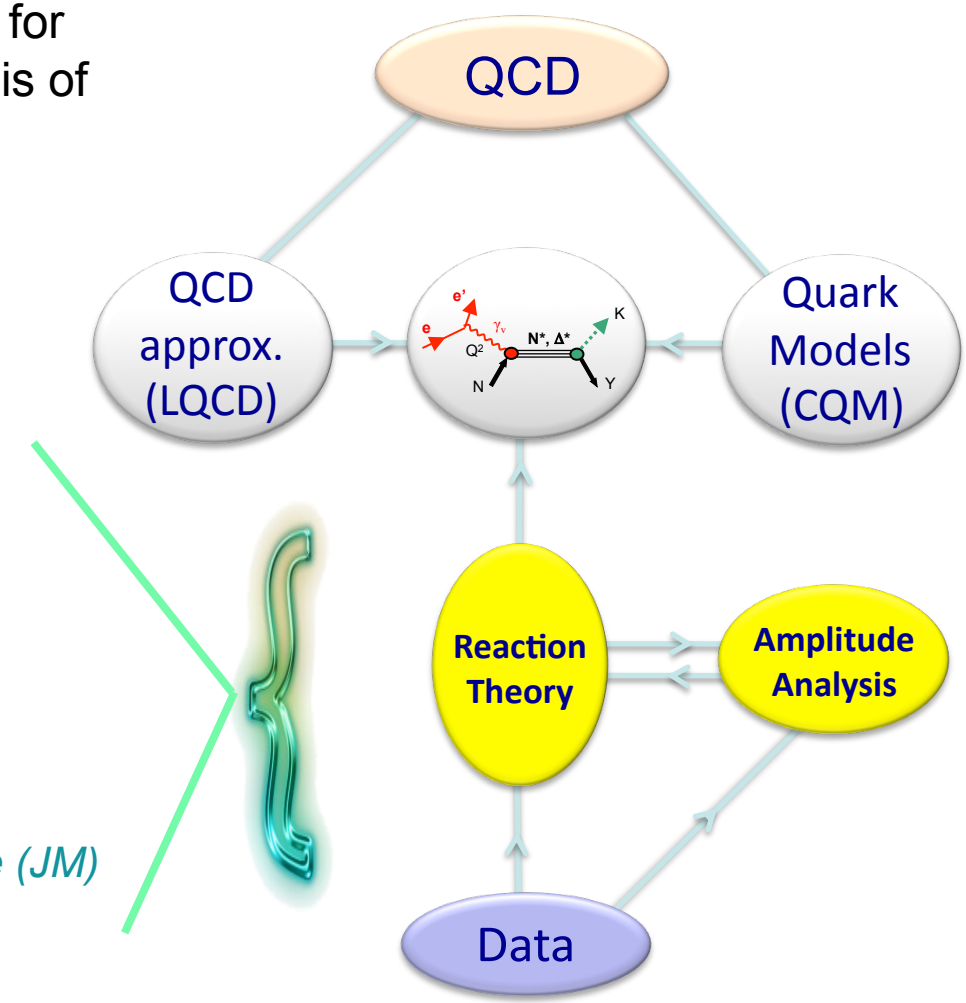
# Phenomenological Analysis

- Comparisons of theoretical predictions for these amplitudes to the data is the basis of progress toward understanding non-perturbative QCD.

- Analyses of pion electroproduction channels carried out independently:
  - $\pi^+n$ and $\pi^0p$ Channels:
    - *Unitary Isobar Model (UIM) for single pseudoscalar meson production*
    - *Fixed-t Dispersion Relations (DR)*
  - $\pi^+\pi^-p$ Channel:
    - *Unitary Isobar Model for $N\pi\pi$ final state (JM)*

- Recent review:

*Aznauryan et al., Int. J. Mod. Phys. E 22, 1330015, 1 (2013)*




Hadronic production EM production

# The Role of N*→ KY Studies

- Structure studies of low-lying N* states (M < 1.6 GeV):

  *e.g. $P_{33}(1232)$, $P_{11}(1440)$, $D_{13}(1520)$, $S_{11}(1535)$,*

  have advanced significantly in recent years due to agreement of results from independent analysis of the Nπ and Nππ final states.

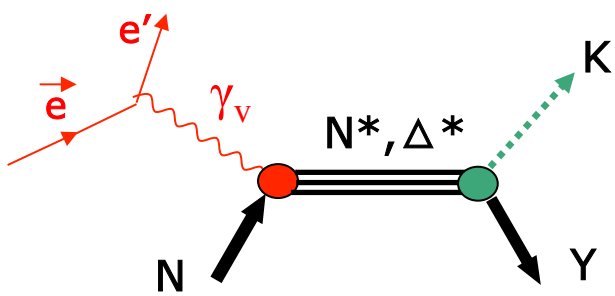
- However, most of the high-lying N* states (M > 1.6 GeV) decay preferentially through the Nππ channel instead of the Nπ channel.

- At the current time, the only detailed structure information regarding high-lying N* states:

  *e.g. $S_{31}(1620)$, $S_{11}(1650)$, $F_{15}(1685)$, $D_{33}(1720)$, $P_{13}(1720)$,*

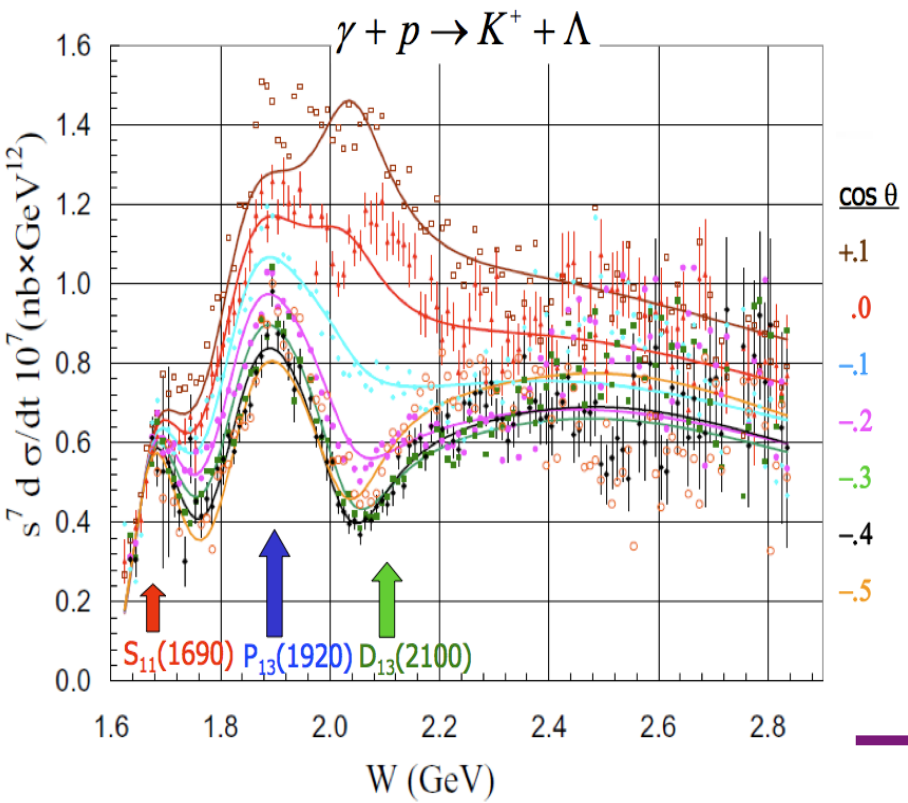
  is available from analysis of Nππ data alone.

- Data from the KY channels is critical to provide an independent extraction of the electrocoupling amplitudes for the high-lying N* states.



# N* → K⁺Λ Amplitude Analysis

*[Schumacher & Sargsian, PRC 83, 025207 (2011)]*




- Compute coherent total amplitude:

$$|A(m,\cos\theta_K^*)|^2 = |\Psi_S(\frac{1}{2},\frac{1}{2}) + \Psi_P(\frac{3}{2},\frac{1}{2}) + \Psi_P(\frac{3}{2},\frac{3}{2}) + \Psi_D(\frac{3}{2},\frac{1}{2}) + \Psi_D(\frac{3}{2},\frac{3}{2})|^2$$

- Fit to observed angular distributions:

$$s^7\left(\frac{d\sigma}{dt} = \frac{(hc)^2}{64\pi}\frac{1}{s}\frac{1}{k^2}|A|^2\right)$$

- Test various resonance sets vs. mass
- Free parameters: mass, width, couplings

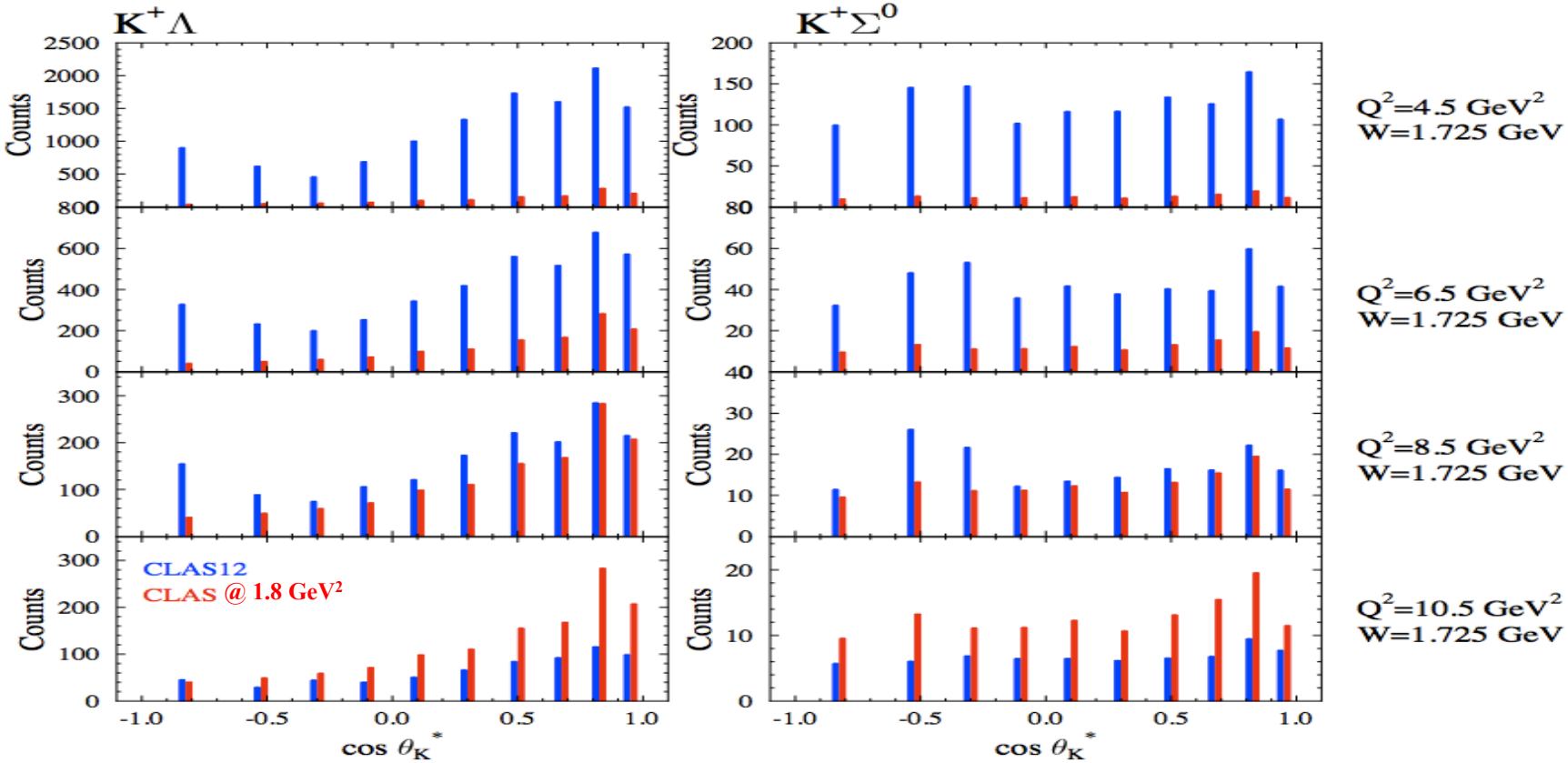
- Reasonable correspondence with Bonn-Gatchina/EBAC fits:
  - *cross section fits reveal dominant N* states*
  - *confirm P-wave character for state at 1.9 GeV*
  - *other contributions could be investigated including spin observables*

# Count Rate Estimates

$$\frac{d\sigma}{d\Omega} = \frac{1}{\mathcal{L}} \cdot \frac{N}{ACC \cdot (\Delta Q^2 \Delta W \Delta \cos\theta_K^* \Delta\Phi)} \cdot \frac{1}{\Gamma_v} \cdot \frac{1}{t}$$

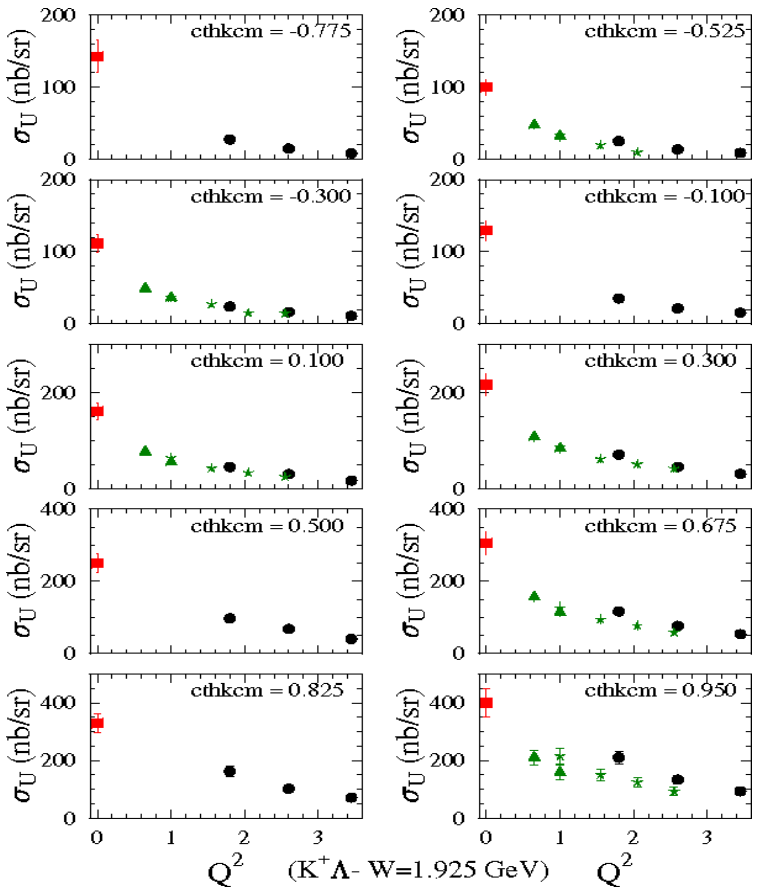
$\mathcal{L} = 1 \times 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}, t = 80$ days, ACC from fastMC, full field

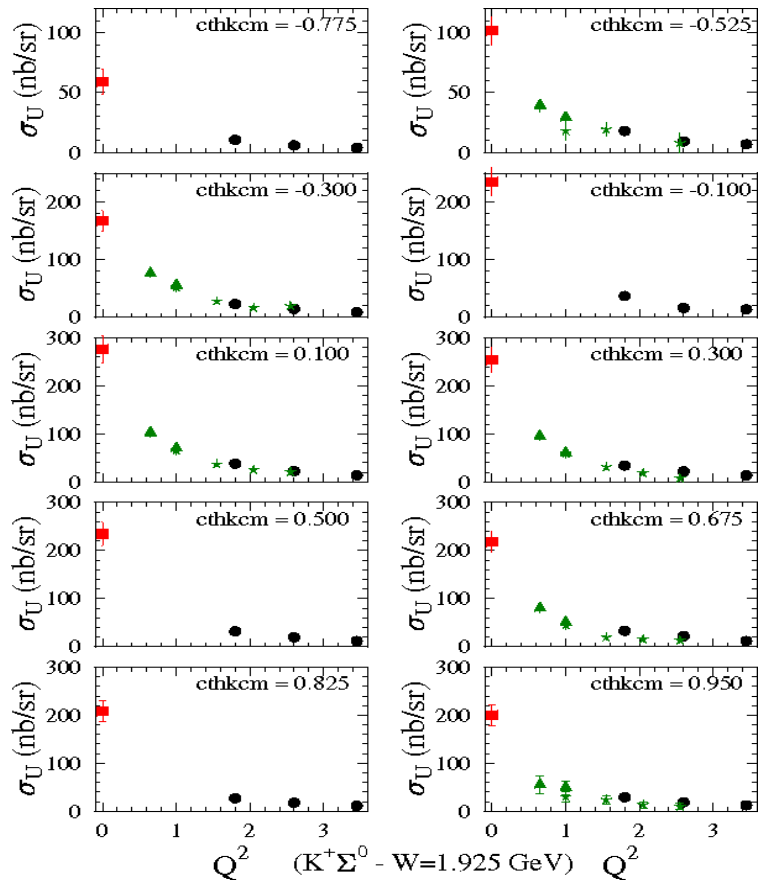
$\Delta Q^2 \Delta W \Delta \cos\theta_K^* \Delta\Phi = 1.0\ \mathrm{GeV}^2 \cdot 50\ \mathrm{MeV} \cdot 0.2 \cdot 45°$



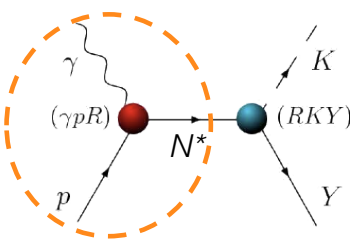
# γ*NN* Transition Form Factors – $K^+Y$

$K^+\Lambda$



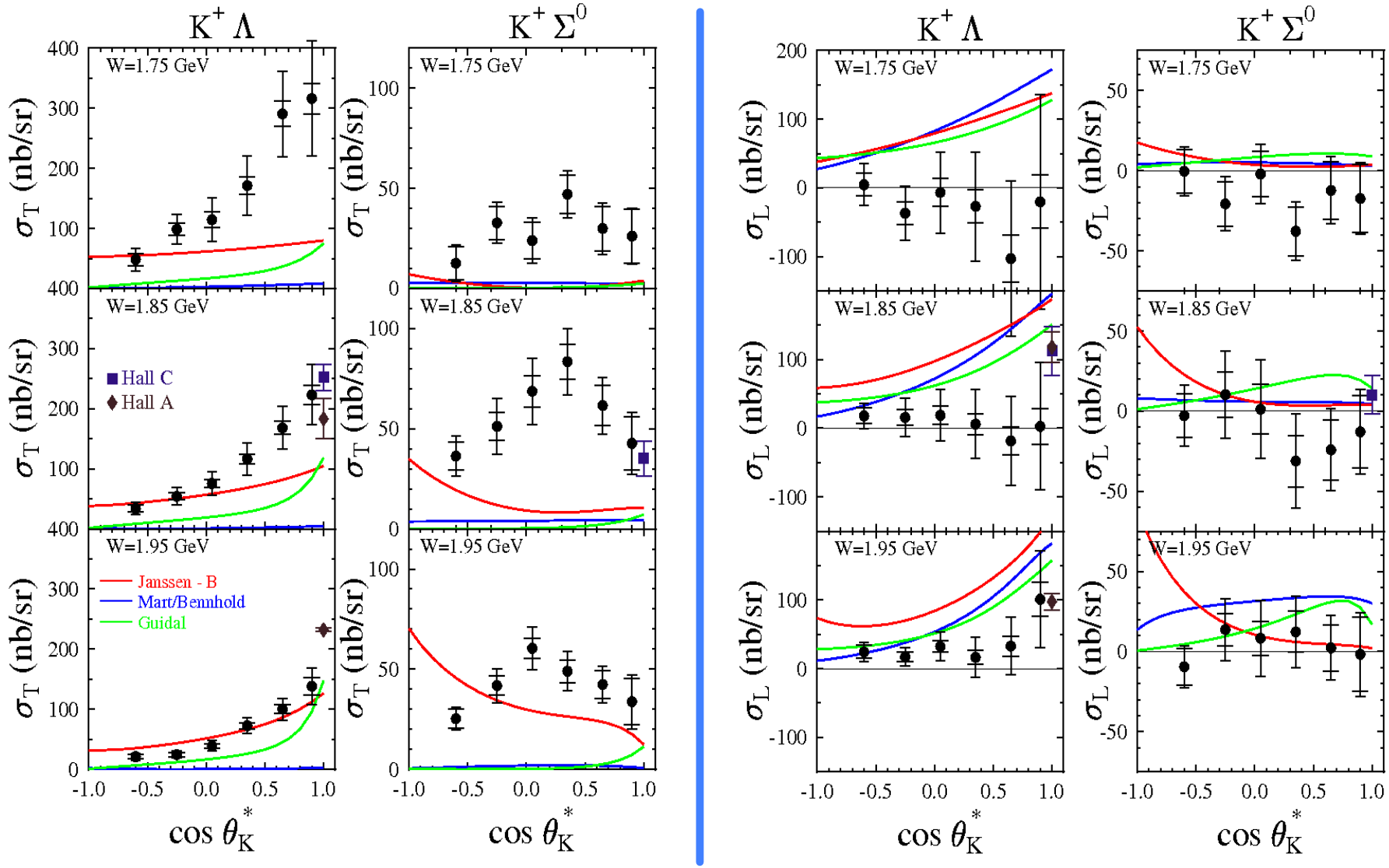




$K^+\Sigma^0$




- Study of $Q^2$ dependence gives sensitivity to γ*NN* transition form factors.
  - *$Q^2$ < ~ 1 $GeV^2$ dominated by meson-baryon d.o.f.*
  - *$Q^2$ > ~ 5 $GeV^2$ dominated by quark-gluon d.o.f.*

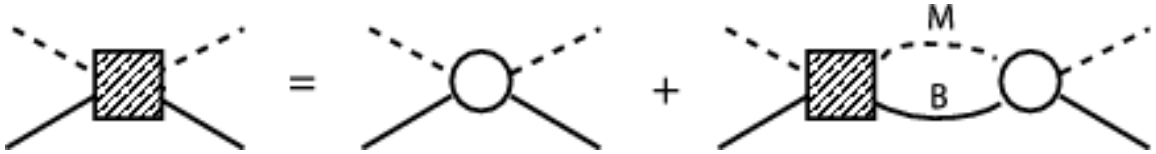
# L/T Separation




[Ambrozewicz et al., PRC 75, 045203 (2007)]

# Model Types

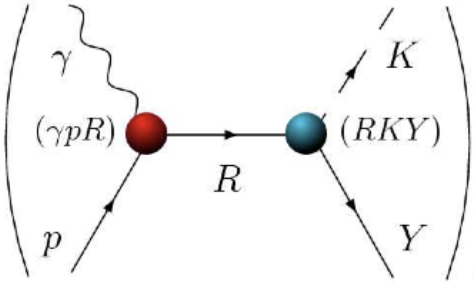
- Coupled-Channels:




$$\pi N \oplus \eta N \oplus \pi\Delta \oplus \rho N \oplus \sigma N \oplus KY$$

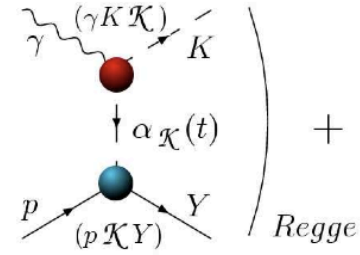
*Developed by several groups: Giessen, EBAC, KVI, Bonn-Julich*

- Isobar: $\mathcal{M} = \sum_R$

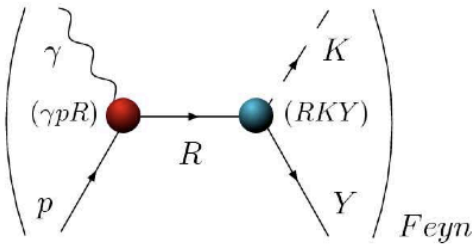



*"hand-select" s-channel resonant contributions for amplitude*

- Regge + Resonance: $\mathcal{M}_{RPR} = \sum_{\mathcal{K}}$

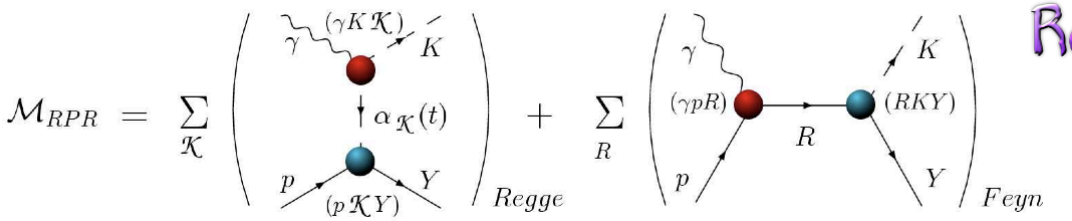



$+ \sum_R$



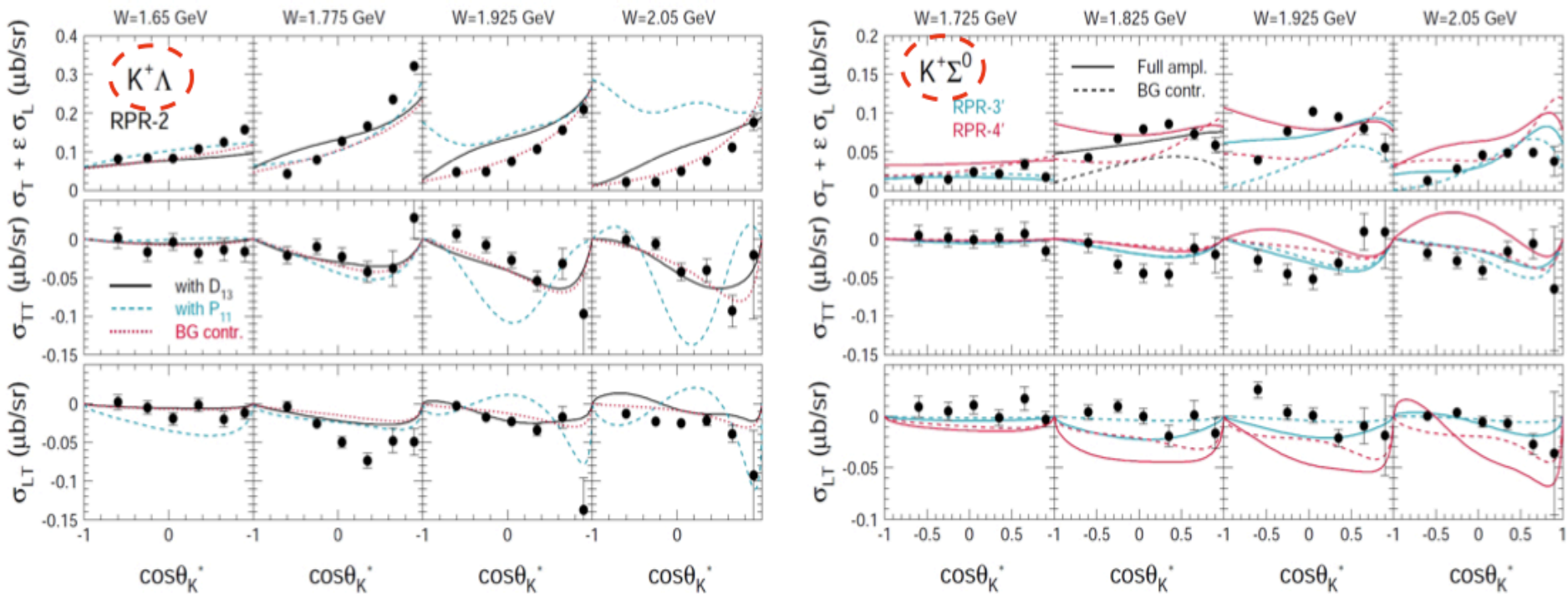

background resonance

# Electroproduction Predictions




## Regge + Resonance Model

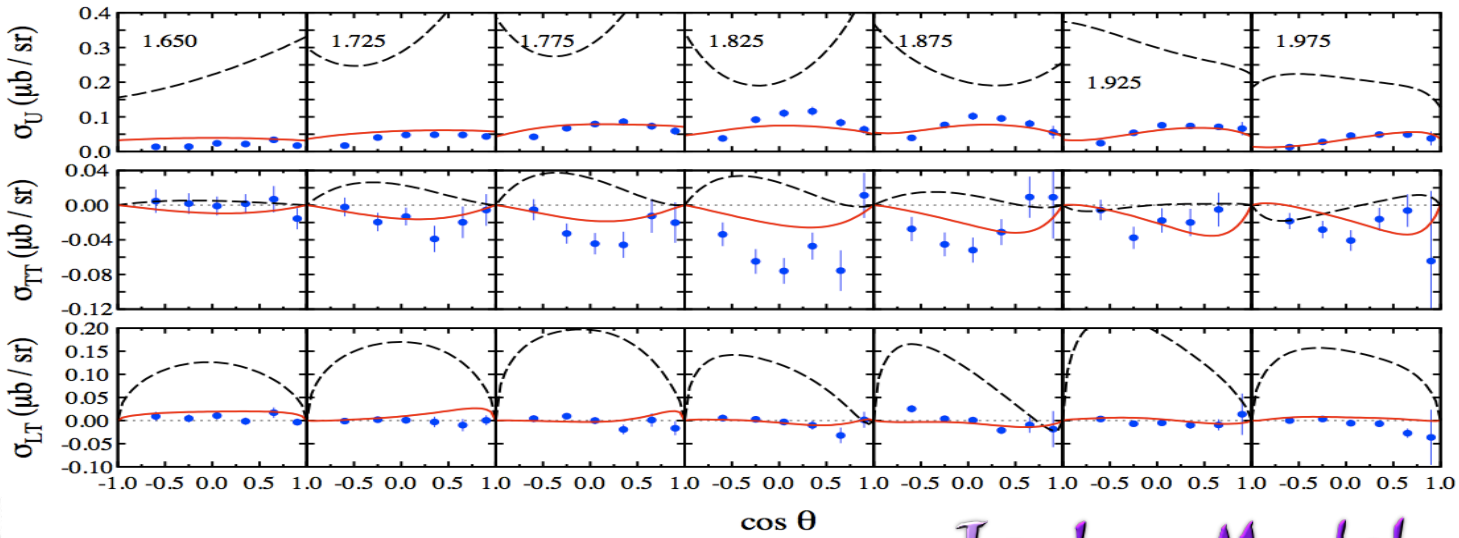
*[Corthals et al., PLB 656, 185 (2007)]*

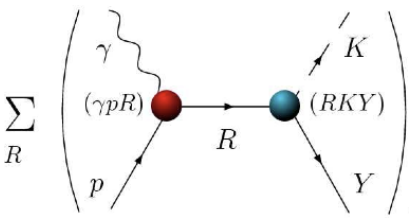



- Rule out $P_{11}$ and $D_{13}$ assignments for N* state at 1900 MeV

# Structure Function Fits

$K^+\Lambda$

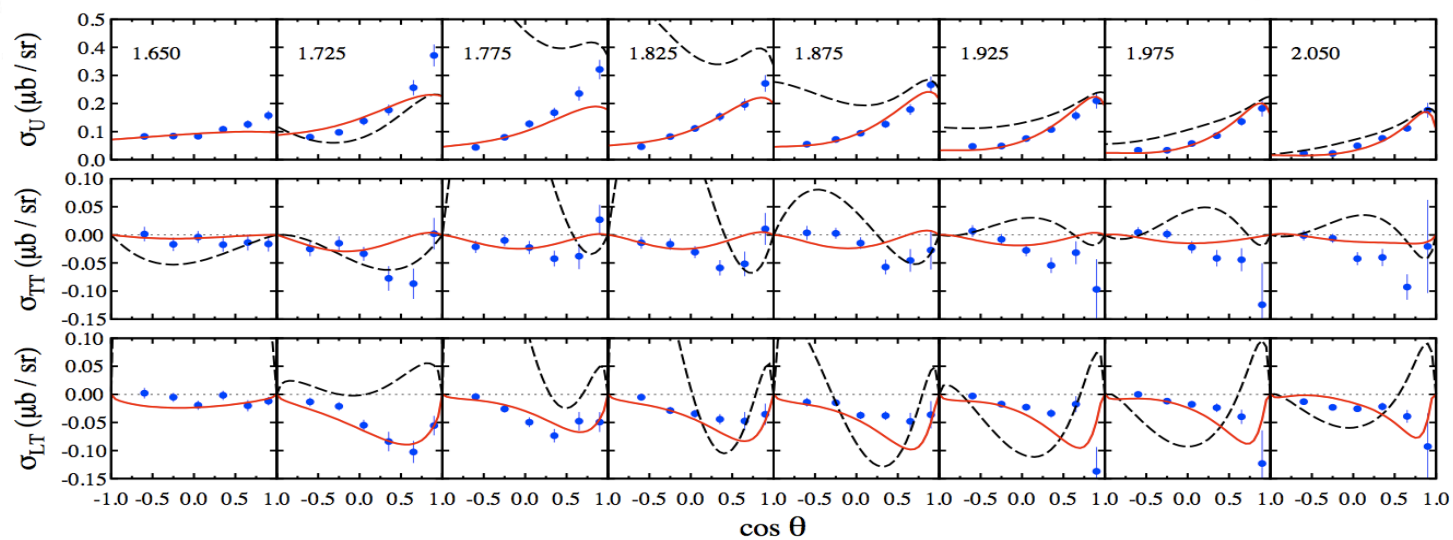



*[Mart, EPJ Web Conf. 3, 07002 (2010)]*

Isobar Model

$K^+\Sigma^0$



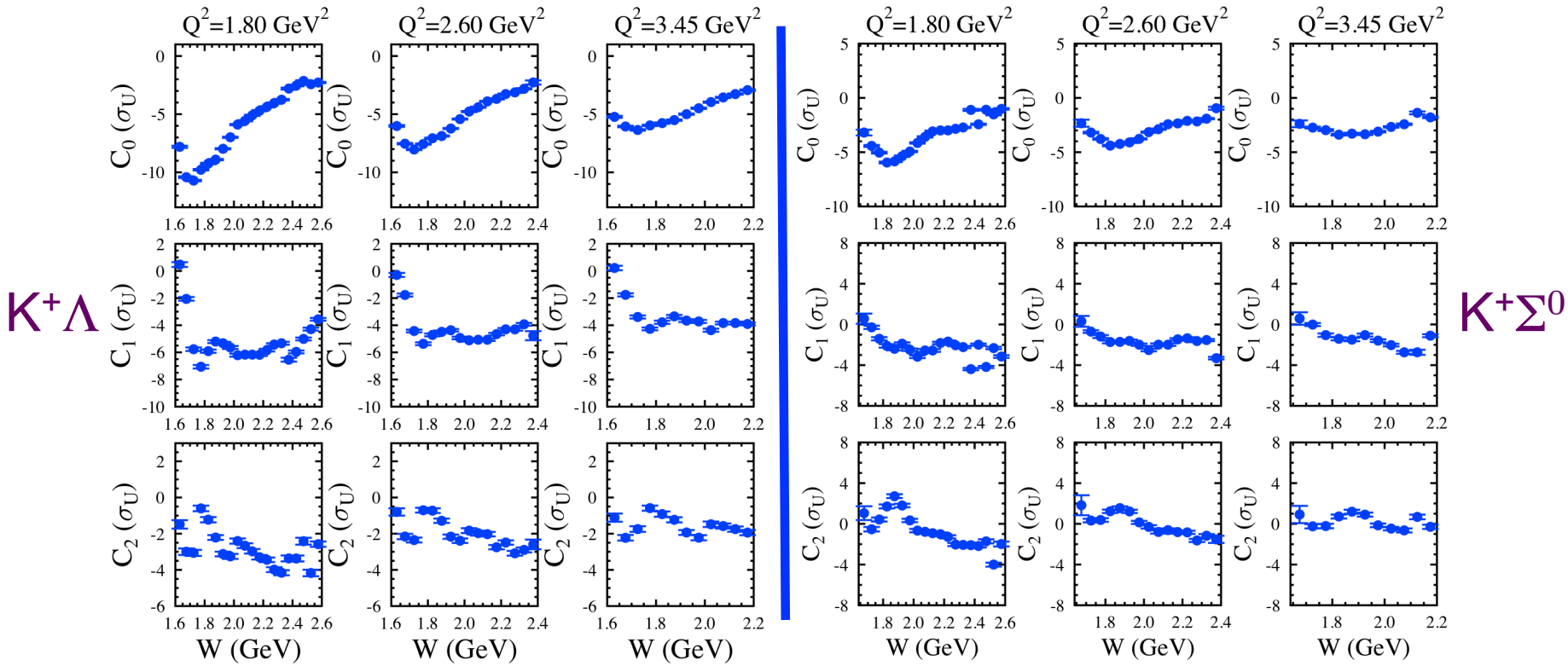

*KAON-MAID*
*New fits*

*(includes only PDG states)*

# Legendre Analysis

Coherent Legendre fit:

$$\frac{d\sigma}{d\Omega_K^*} = \left[\sum_{L=0}^{2} C_L(Q^2, W) P_L(\cos\theta_K^*)\right]^2 + C_x^2$$



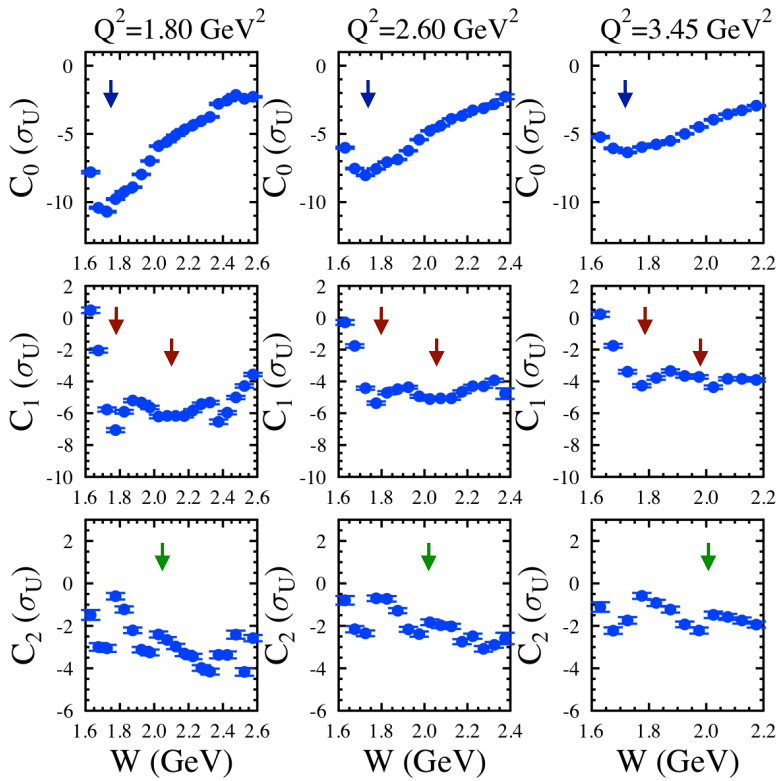

- Structures in *W* dependence of $C_L$ moments at the same *W* in all $Q^2$ bins are consistent with *s*-channel resonance contributions. *[Carman et al., PRC 87, 025204 (2013)]*
- Reaction model is needed for the extraction of the *N** parameters.

# Legendre Analysis

Coherent Legendre fit:

$$\frac{d\sigma}{d\Omega_K^*} = \left[\sum_{L=0}^{2} C_L(Q^2, W) P_L(\cos\theta_K^*)\right]^2 + C_x^2$$

$K^+\Lambda$




S-wave state at 1650 MeV

P-wave states at 1700, 1900 MeV

D-wave state at 2000 MeV

- Consistency with coupled channel models for dominant couplings

*… again a complete reaction model is needed for a proper analysis*