# CLAS N* Excitation Results from Pion and Kaon Electroproduction

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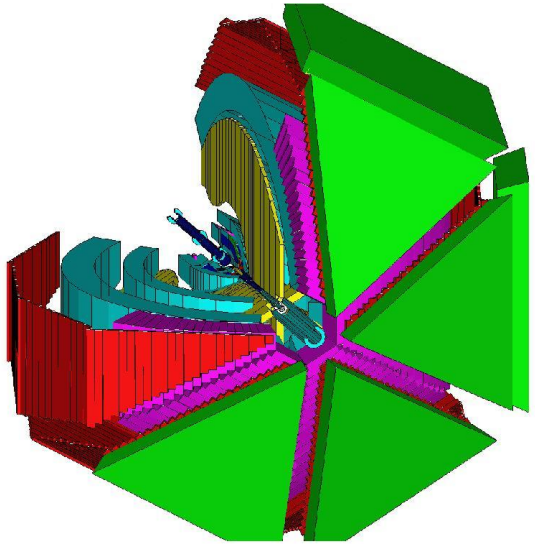
## Outline

- N* Spectrum & Structure
- CLAS $\gamma_v p \rightarrow \pi N$, KY Data
- CLAS12 N* Program
- Concluding Remarks

# CLAS N* Program

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



- CLAS was designed to measure $\gamma N$ and $\gamma_v N$ cross sections and spin observables over a broad kinematic range for exclusive reaction channels

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

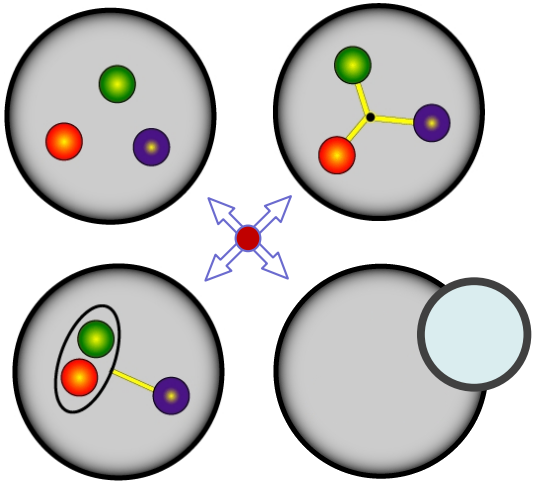
$$KY,\ K^*Y,\ KY^*$$

*- Consistent results for N* parameters from different exclusive channels with different hadronic couplings and backgrounds offers model-independent support for findings*

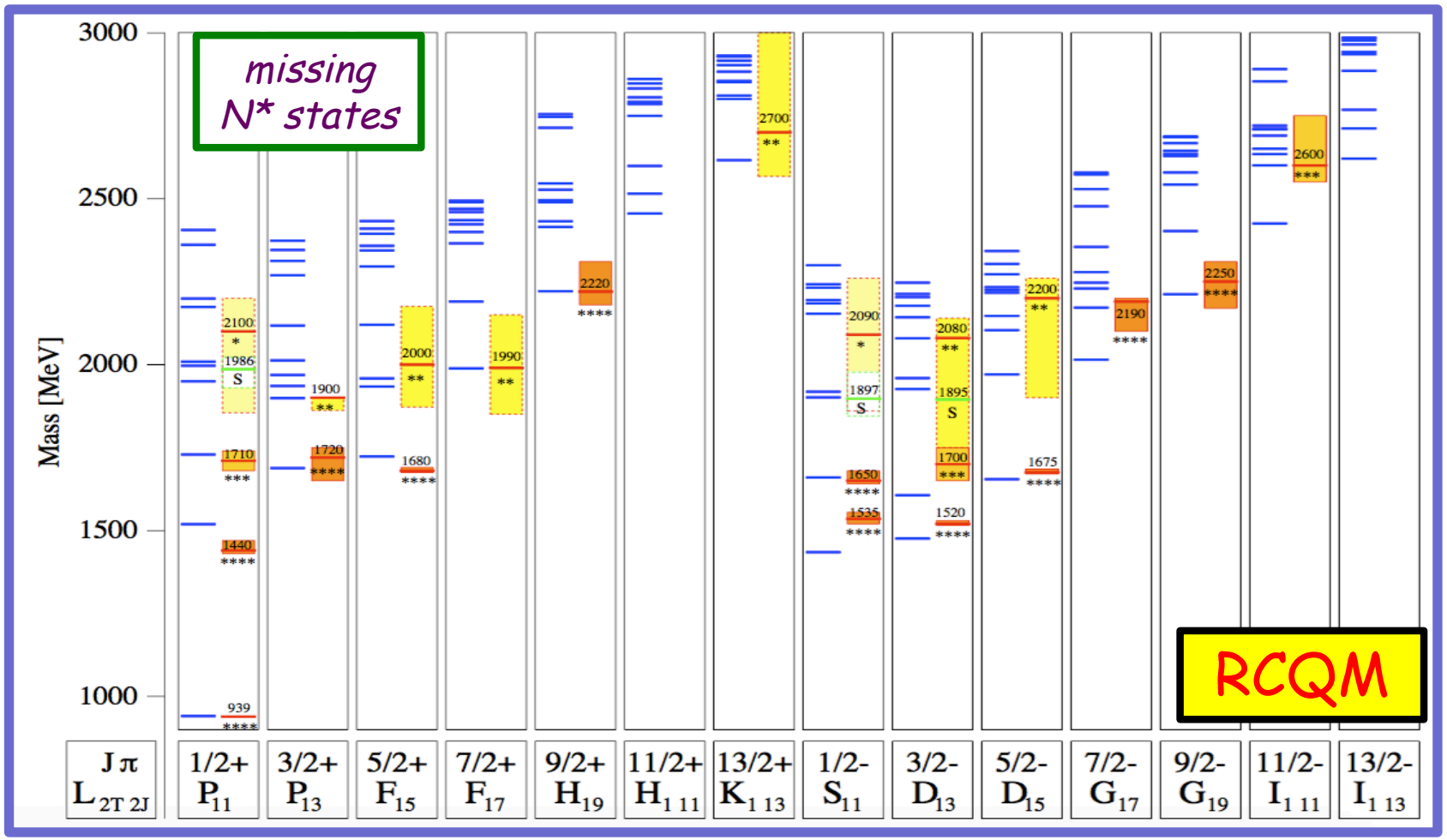
- The program goal is to probe the ***spectrum*** of states and their ***structure*** through studies of the $Q^2$ evolution of the $\gamma_v NN^*$ electrocouplings

*- Probe the underlying degrees of freedom of the nucleon*

*- Study the non-perturbative strong interaction that generates N* of different quantum numbers from quark and gluons*



# Excited Nucleon Spectrum




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

Recent LQCD predictions support CQM

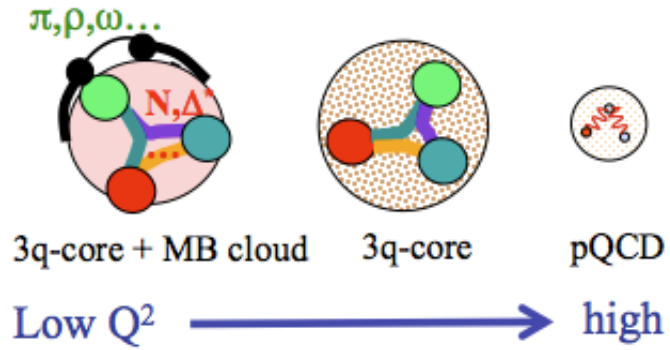
*[Dudek, Edwards, PRD 85, 054016 (2012)]*

# Excited Nucleon Structure

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

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

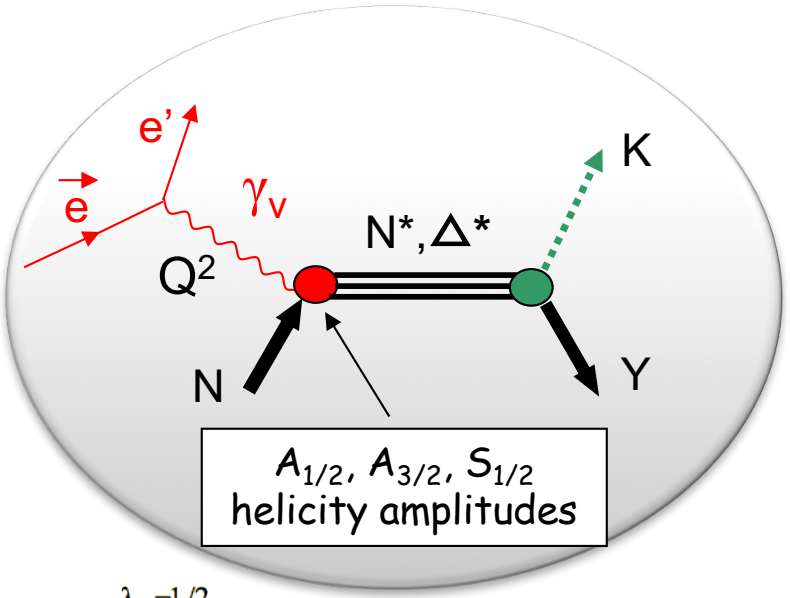
  - *High $Q^2$:* *quark core dominates; transition from confinement to pQCD regime* ($Q^2 > 5$ GeV$^2$)

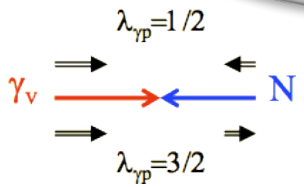



- Electroproduction studies from low to high $Q^2$ probe the detailed structure of the N* states through the $\gamma_v$NN* electrocoupling amplitudes

  - *Elucidate relevant degrees of freedom and their evolution with distance scale*

  - *Only source of information on many facets of the non-perturbative strong interaction in the generation of different N* states from quarks and gluons*




*$A_{1/2}$ , $A_{3/2}$ – transverse*

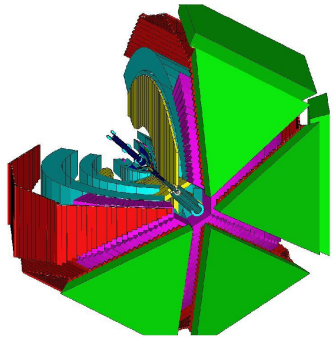
*$S_{1/2}$ - longitudinal*

# CLAS N* Program Measurement Overview

| Reaction | Observable | $Q^2$ (GeV$^2$) | W (GeV) | Reference |
|---|---|---|---|---|
| ep --> ep$\pi^+\pi^-$ | $d\sigma/dM$, $d\sigma/cos\theta$, $d\sigma/d\alpha$ | 2.0 - 5.0 | 1.4 - 2.0 | PRC, arXiv:1705.01901 |
| | | 0.25 - 0.60 | 1.34 - 1.56 | PRC 86, 035203 (2012) |
| | | 0.2 - 0.6 | 1.3 - 1.57 | PRC 79, 015204 (2009) |
| | | 0.5 - 1.5 | 1.4 - 2.1 | PRL 91, 022002 (2003) |
| ep --> ep$\pi^0$ | $A_t$, $A_{et}$ | 1.0 - 6.0 | 1.1 - 3.0 | PRC 95, 035207 (2017) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$ | 1.0 - 4.6 | 2.0 - 3.0 | PRC 90, 025205 (2014) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$ | 2.0 - 4.5 | 1.08 - 1.16 | PRC 87, 045205 (2013) |
| | $d\sigma/dt$ | 1.0 - 4.6 | | PRL 109, 112001 (2012) |
| | $d\sigma/d\Omega$ | 3.0 - 6.0 | 1.1 - 1.4 | PRL 97, 112003 (2006) |
| | $A_t$, $A_{et}$ | 0.187 - 0.77 | 1.1 - 1.7 | PRC 78, 045204 (2008) |
| | $\sigma_{LT'}$ | 0.4 - 0.65 | 1.34 - 1.46 | PRC 72, 058202 (2005) |
| | $A_t$, $A_{et}$ | 0.5 - 1.5 | 1.1 - 1.3 | PRC 68, 035202 (2003) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$ | 0.4 - 1.8 | 1.1 - 1.4 | PRL 88, 122001 (2002) |
| ep --> en$\pi^+$ | $A_t$, $A_{et}$ | 1.0 - 6.0 | 1.1 - 3.0 | PRC 95, 035206 (2017) |
| | $A_t$, $A_{et}$ | 0.05 - 5.0 | 1.1 - 2.6 | PRC 94, 05520 (2016) |
| | $A_t$, $A_{et}$ | 0.0065 - 0.35 | 1.1 - 2.0 | PRC 94, 045207 (2016) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$ | 1.8 - 4.5 | 1.6 - 2.0 | PRC 91, 045203 (2015) |
| | $d\sigma/dt$ | 1.6 - 4.5 | 2.0 - 3.0 | EPJA 49, 16 (2013) |
| | $\sigma_{LT'}$ | 0.4 - 0.65 | 1.1 - 1.3 | PRC 85, 035208 (2012) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$, $\sigma_{LT'}$ | 1.7 - 4.5 | 1.15 - 1.7 | PRC 77, 015208 (2008) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$ | 0.25 - 0.65 | 1.1 - 1.6 | PRC 73, 025204 (2006) |
| | $\sigma_{LT'}$ | 0.4 - 0.65 | 1.34 - 1.46 | PRC 72, 058202 (2005) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$ | 2.12 - 4.16 | 1.11 - 1.15 | PRC 70, 042201 (2004) |
| | $A_{et}$ | 0.35 - 1.5 | 1.12 - 1.72 | PRL 88, 082001 (2002) |

| Reaction | Observable | $Q^2$ (GeV$^2$) | W (GeV) | Reference |
|---|---|---|---|---|
| en --> ep$\pi^-$ | $A_t$, $A_{et}$ | 0.05 - 5.0 | 1.1 - 2.6 | PRC 94, 05520 (2016) |
| ep --> ep$\eta$ | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$ | 1.6 - 4.6 | 2.0 - 3.0 | PRC 95, 035202 (2017) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$ | 0.13 - 3.3 | 1.5 - 2.3 | PRC 76, 015204 (2007) |
| | $d\sigma/d\Omega$ | 0.25 -1.50 | 1.5 - 1.86 | PRL 86, 1702 (2001) |
| ep --> eK$^+\Lambda$ | $P^0$ | 0.8 - 3.2 | 1.6 - 2.7 | PRC 90, 035202 (2014) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$, $\sigma_{LT'}$ | 1.4 - 3.9 | 1.6 - 2.6 | PRC 87, 025204 (2013) |
| | $P'_x$, $P'_z$ | 0.7 - 5.4 | 1.6 - 2.6 | PRC 79, 065205 (2009) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$, $\sigma_{LT'}$ | 0.5 - 2.8 | 1.6 - 2.4 | PRC 75, 045203 (2007) |
| | $P'_x$, $P'_z$ | 0.3 - 1.5 | 1.6 - 2.15 | PRL 90, 131804 (2003) |
| ep --> eK$^+\Sigma^0$ | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$, $\sigma_{LT'}$ | 1.4 - 3.9 | 1.6 - 2.6 | PRC 87, 025204 (2013) |
| | $P'_x$, $P'_z$ | 0.7 - 5.4 | 1.6 - 2.6 | PRC 79, 065205 (2009) |
| | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$, $\sigma_{LT'}$ | 0.5 - 2.8 | 1.6 - 2.4 | PRC 75, 045203 (2007) |
| ep --> ep$\omega$ | $\sigma_U$, $\sigma_{LT}$, $\sigma_{TT}$ | 1.725 - 4.85 | 1.85 - 2.77 | EPJA 24, 445 (2005) |
| ep --> ep$\rho^0$ | $\sigma_U$ | 1.6 - 5.6 | 1.8 - 2.8 | EPJA 39, 5 (2009) |
| | $\sigma_L/\sigma_T$ | 1.5 - 3.0 | 1.85 - 2.2 | PLB 605, 256 (2005) |
| ep --> ep$\phi$ | $d\sigma/dt$ | 1.4 - 3.8 | 2.0 - 3.0 | PRC 78, 025210 (2008) |
| | $d\sigma/dt'$ | 0.7 - 2.2 | 2.0 - 2.6 | PRC 63, 059901 (2001) |

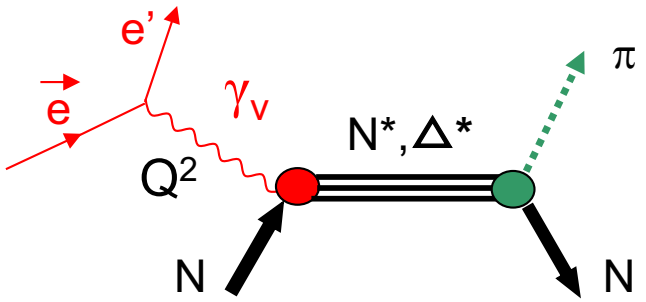
*CLAS: 1997 - 2012*



*CLAS Physics Data Base http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi*

# Extraction of Electrocouplings

| Reaction Channel | N*, Δ* States | $Q^2$ ranges of $\gamma_v NN^*$ Electrocouplings ($GeV^2$) |
|---|---|---|
| $\pi^0 p$, $\pi^+ n$ | $\Delta(1232)3/2^+$<br>$N(1440)1/2^+$, $N(1520)3/2^-$, $N(1535)1/2^-$ | 0.16 – 6.0<br>0.30 – 4.16 |
| $\pi^+ n$ | $N(1675)5/2$, $N(1680)5/2^+$, $N(1710)1/2^+$ | 1.6 – 4.5 |
| $\eta p$ | $N(1535)1/2^-$ | 0.2 – 2.9 |
| $\pi^+\pi^- p$ | $N(1440)1/2^+$, $N(1520)3/2^-$<br>$\Delta(1620)1/2^-$, $N(1650)1/2^-$, $N(1680)5/2^+$, $\Delta(1700)3/2^-$, $N(1720)3/2^+$, $N'(1720)3/2^+$ | 0.25 – 1.5<br>0.5 – 1.5 |
| http://userweb.jlab.org/~mokeev/resonance_electrocouplings | | |




Analysis codes for single and double PS meson production:

- Unitary Isobar Model (UIM)
- Fixed-t dispersion relations (DR)

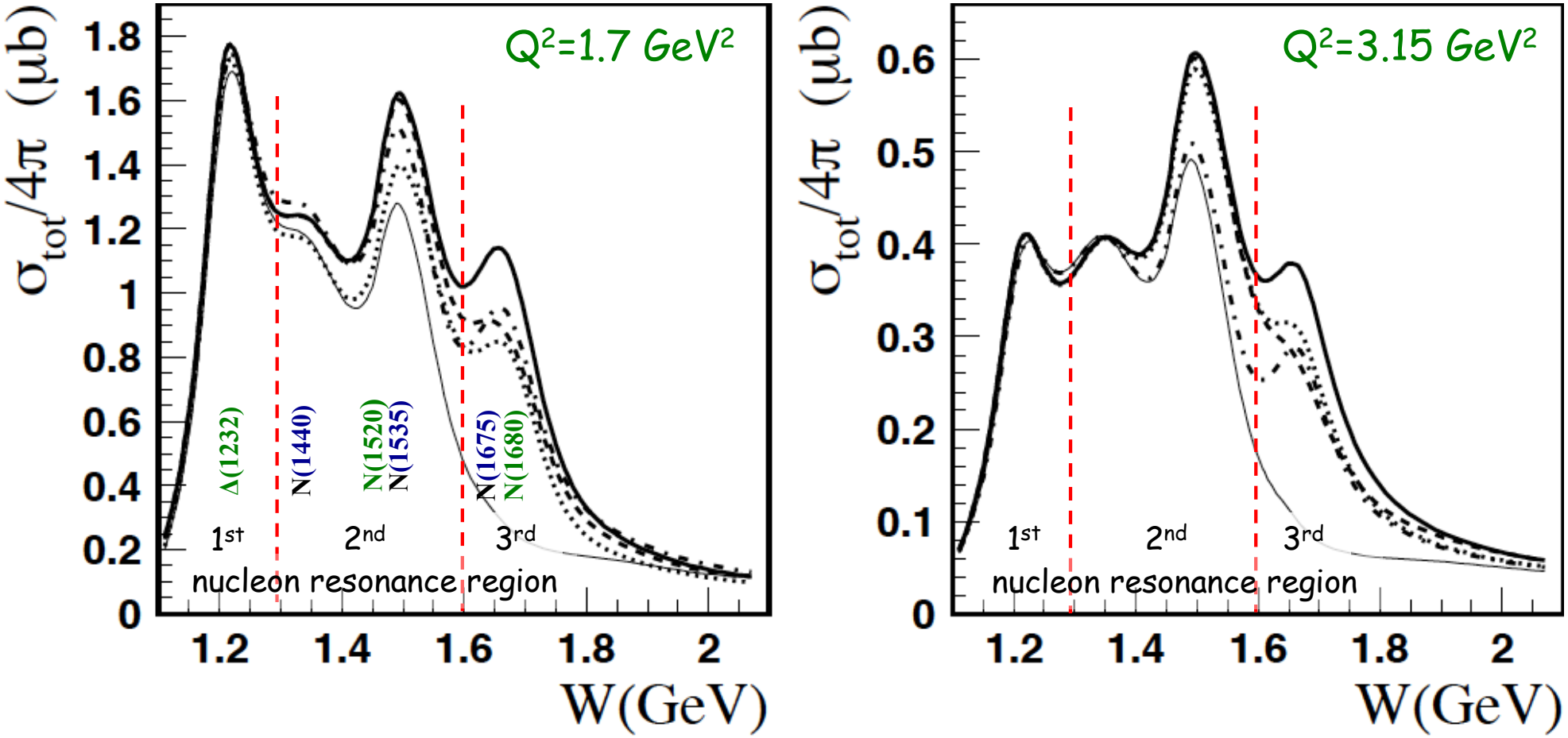
} for πN and ηN

- Data-driven reaction model for $\pi^+\pi^-$N (JM09, JM16)

*[Aznauryan et al., Int. J. Mod. Phys. E 22, 1330015 (2013)]*
*[Mokeev, FBS 57, 909 (2016)]*

# Total Cross Sections

$\gamma^* p \rightarrow \pi^+ n$

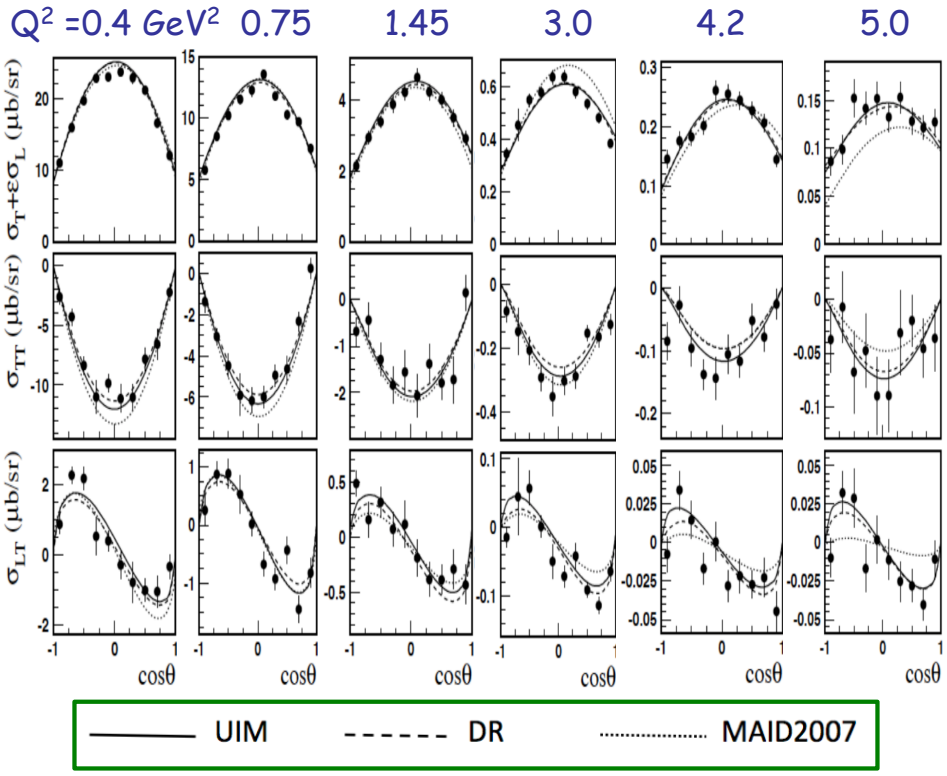


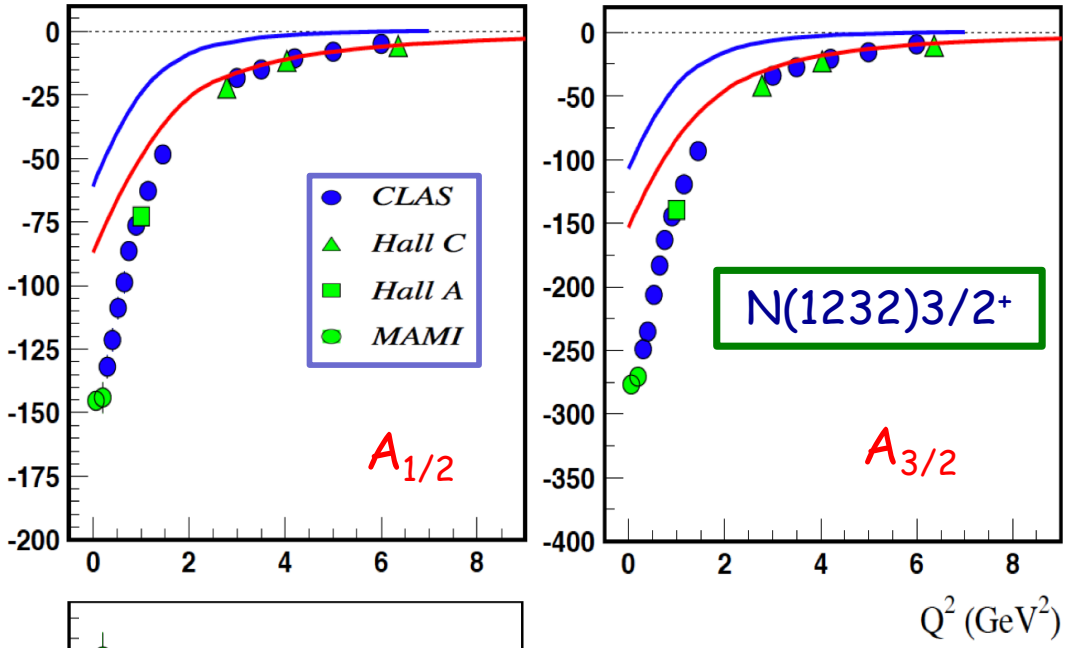

*[Park et al., PRC 77, 015208 (2008), PRC 91, 045203 (2015)]*

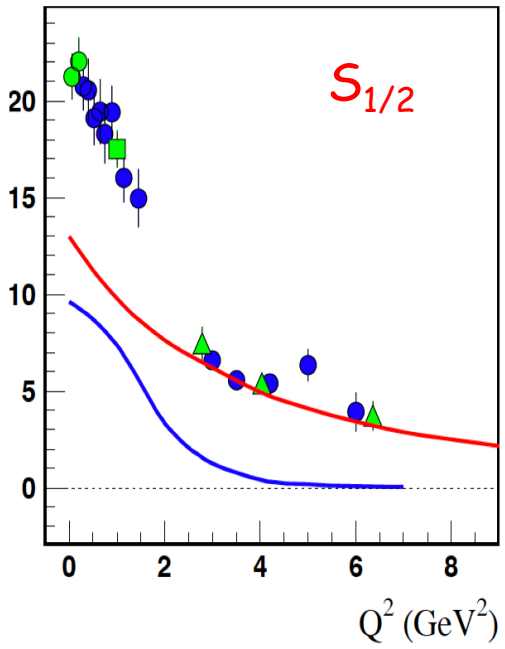
# First Resonance Region

$\gamma^* p \rightarrow \pi^0 p$

W = 1.232 GeV




LC RQM

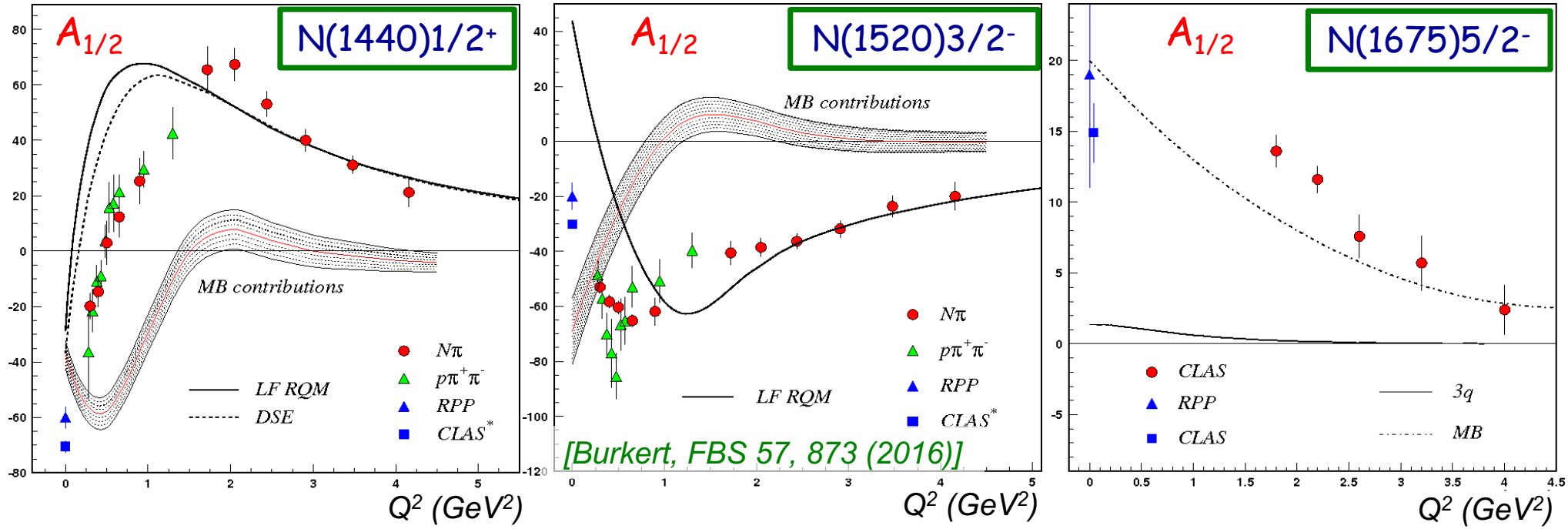
MB (inferred)

The MB contributions are significant for $Q^2 \lesssim 3$ GeV²

- Good agreement between UIM and DR approaches

*[Aznauryan et al., PRC 80, 055203 (2009)]*

# Low-Lying N* States




- Electrocouplings reveal different interplay between quark core and M-B cloud
  - *Important to study different N* states vs. distance scale*
- Good agreement of the extracted N* electrocouplings from Nπ and Nππ
  - *Compelling evidence for the reliability of the results*
  - *Channels have very different mechanisms for the non-resonant background*

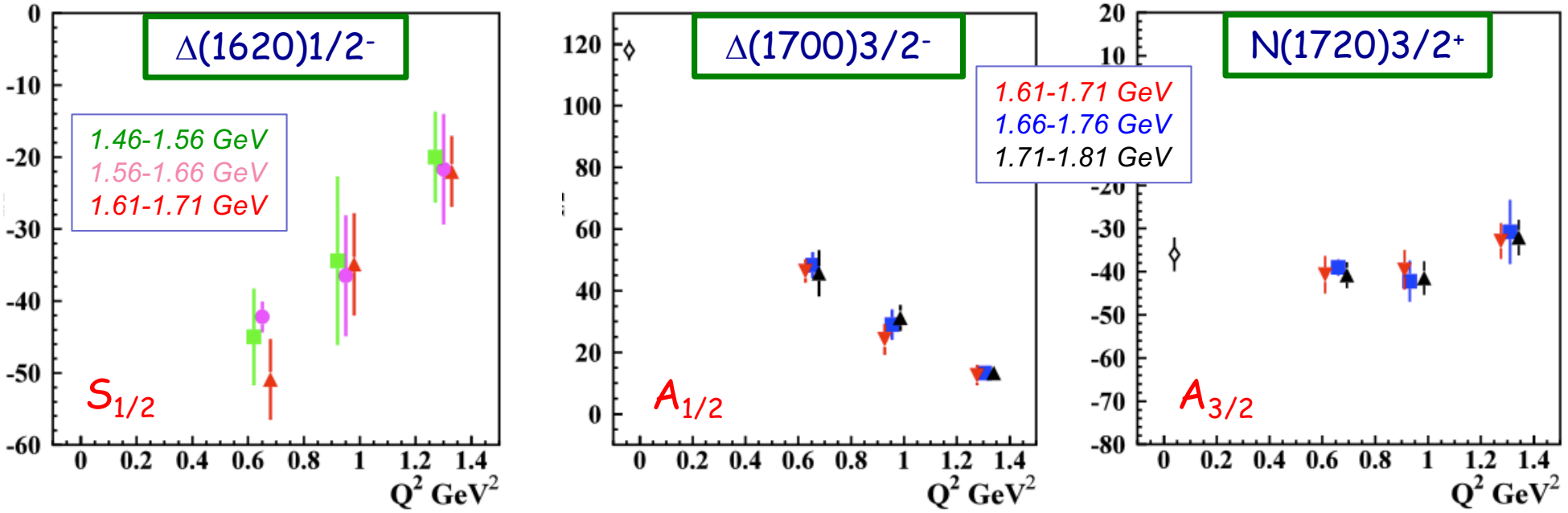
Structure studies of low-lying N* states have advanced due to agreement of results from independent analyses of the Nπ and Nππ final states

# Higher-Lying N* States

- Nππ channel gave first electrocoupling results on higher-lying states up to 1.7 GeV:

*Δ(1620)1/2⁻, N(1650)1/2⁻, Δ(1700)3/2⁻, N(1720)3/2⁺*

*Note: Most high-lying N* states (M > 1.6 GeV) decay mainly to Nππ with much smaller strength to Nπ*




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

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

# N*,Δ* → KY Landscape

Old

| 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) | ** | - |

[Beringer et al. (PDG), PRD 86, 010001 (2012)]

New

| 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) | ** | - | - | | | |

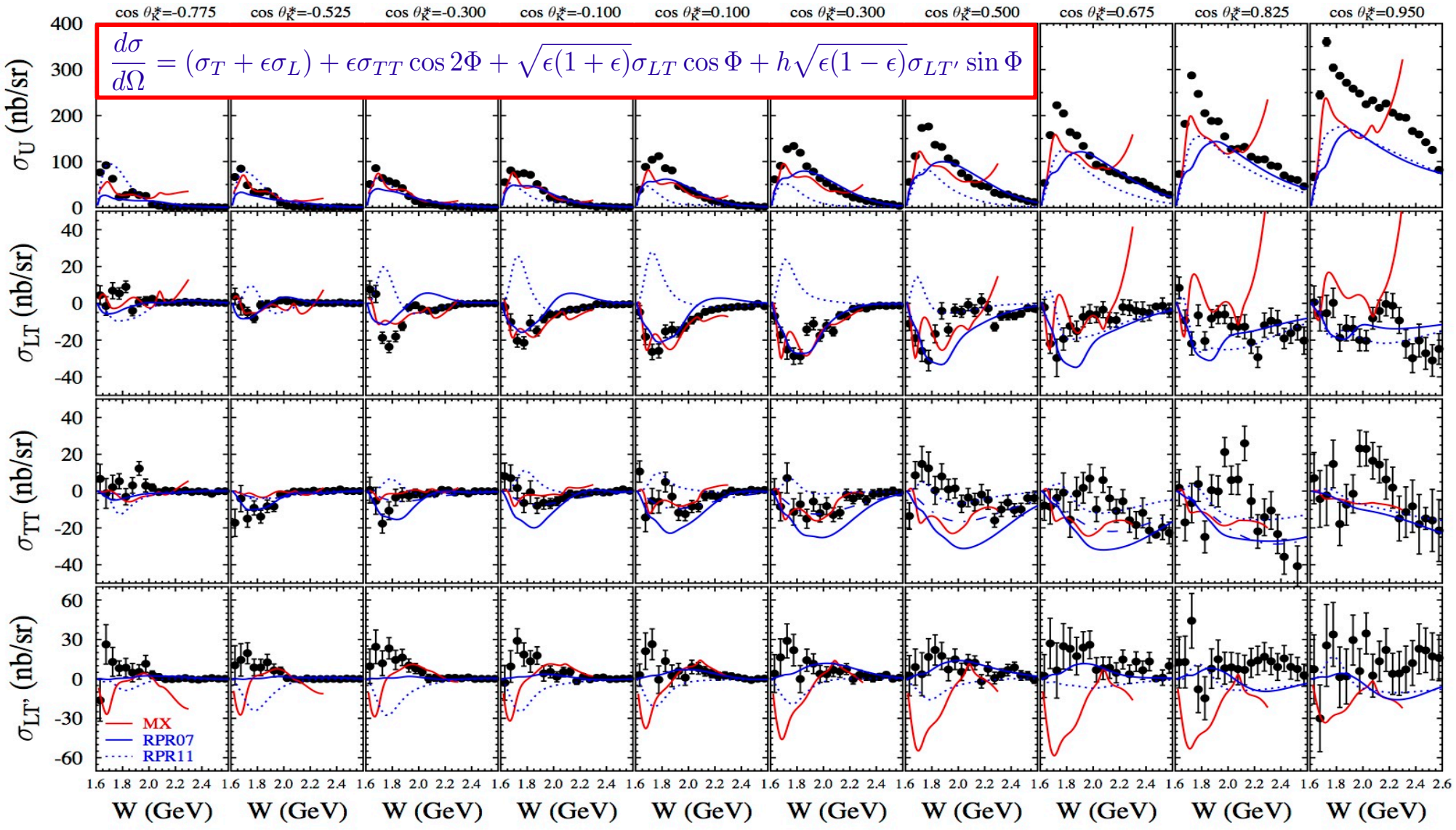
[Anisovich et al., EPJ A 48, 15 (2012)]

# Evidence for New N* in KY Final States

| State N(mass)$J^P$ | PDG pre-2010 | PDG 2016 | KΛ | KΣ | Nγ |
|---|---|---|---|---|---|
| N(1710)$1/2^+$ | *** | **** | **** | ** | **** |
| N(1880)$1/2^+$ | | ** | ** | | ** |
| N(1895)$1/2^-$ | | ** | ** | * | ** |
| N(1900)$3/2^+$ | ** | *** | *** | ** | *** |
| N(1875)$3/2^-$ | | *** | *** | ** | *** |
| N(2150)$3/2^-$ | | ** | ** | | ** |
| N(2000)$5/2^+$ | * | ** | ** | * | ** |
| N(2060)$5/2^-$ | | ** | | ** | ** |

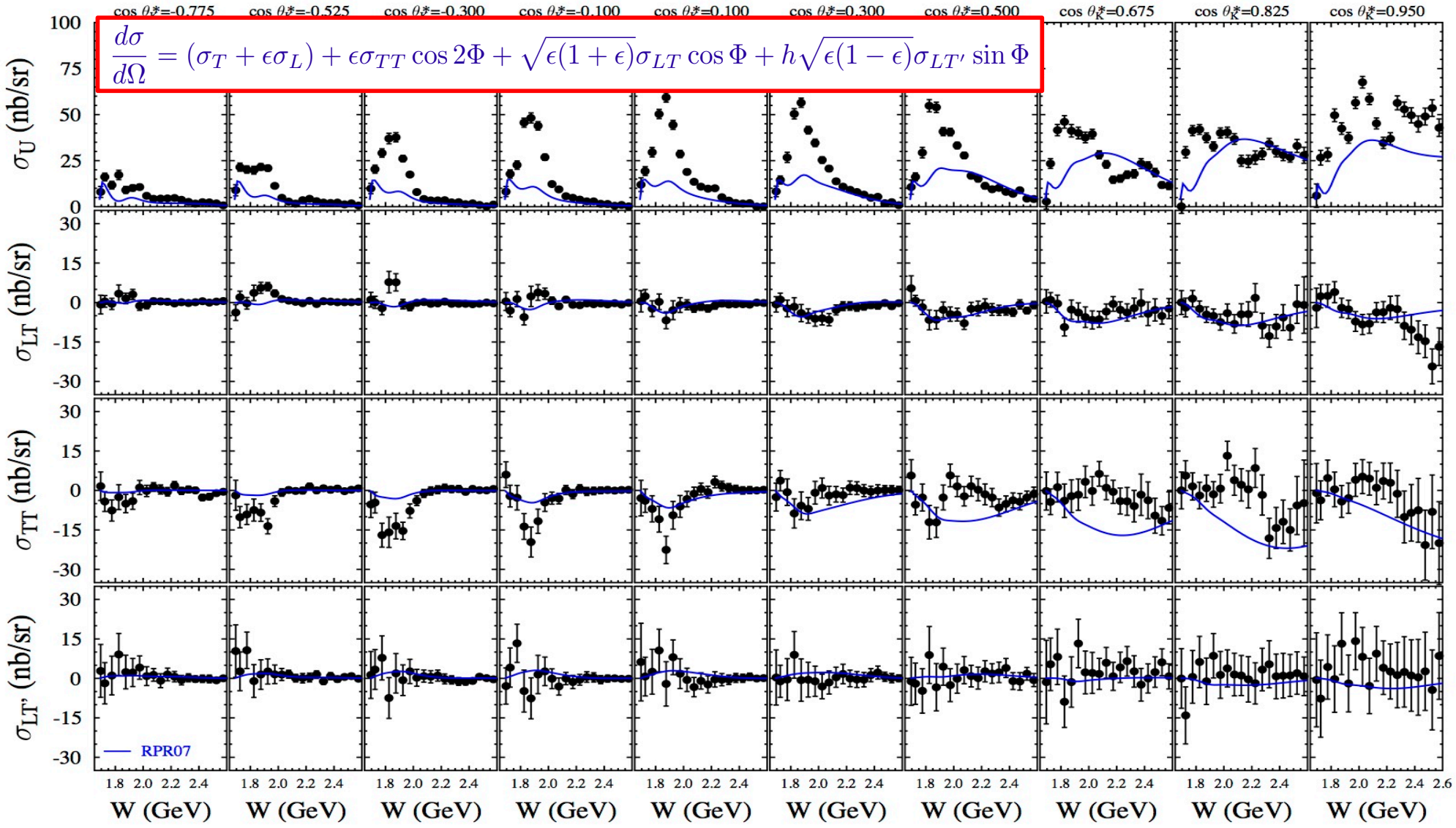
Extend these studies to electroproduction and to higher masses

# $K^+\Lambda$ Structure Functions



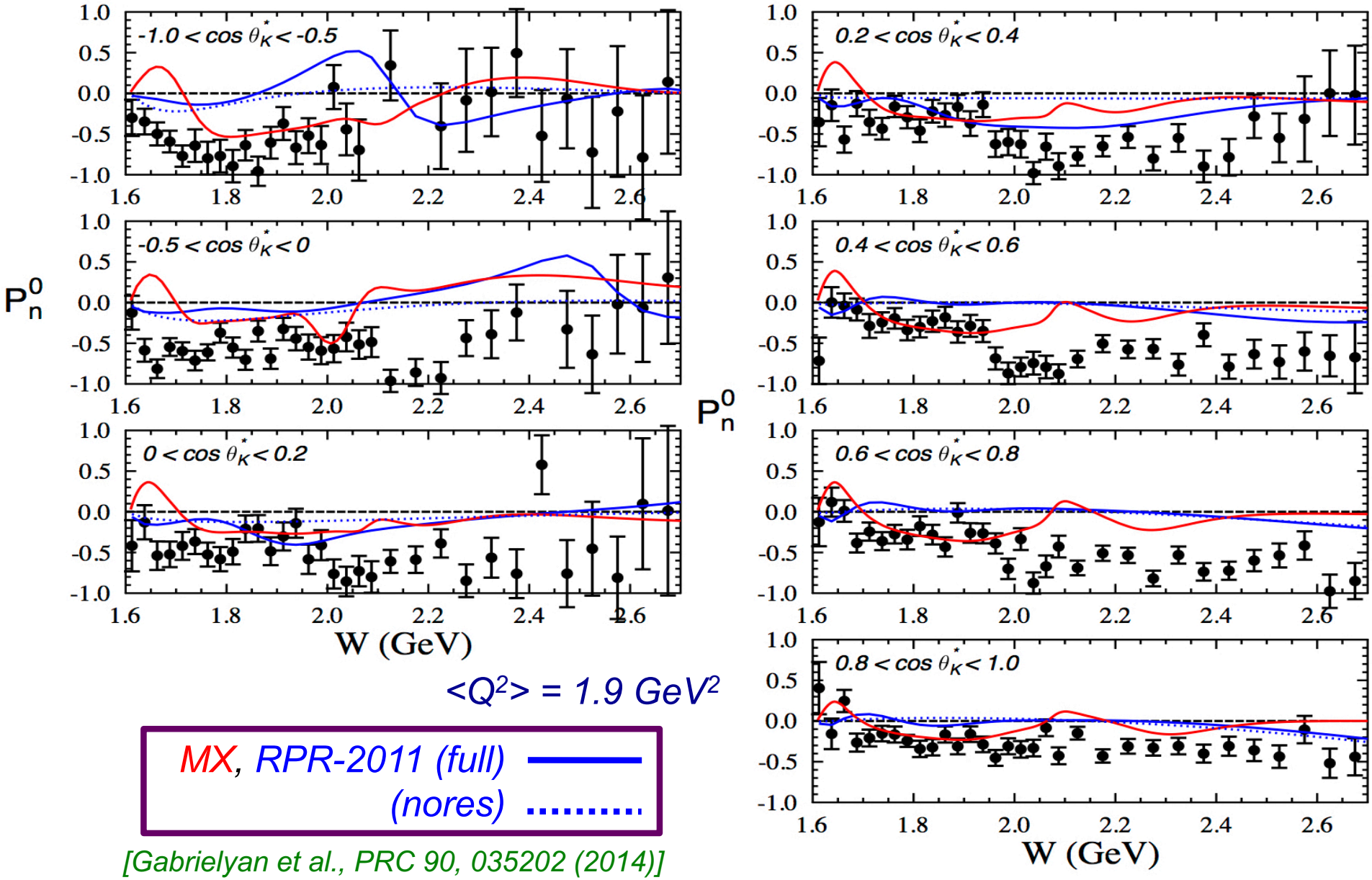

*E = 5.5 GeV, W: thr – 2.6 GeV, $Q^2$ = 1.80, 2.60, 3.45 $GeV^2$* *[Carman et al., PRC 87, 025204 (2013)]*

# $K^+\Sigma^0$ 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 $ep \rightarrow e'K^+\vec{\Lambda}$



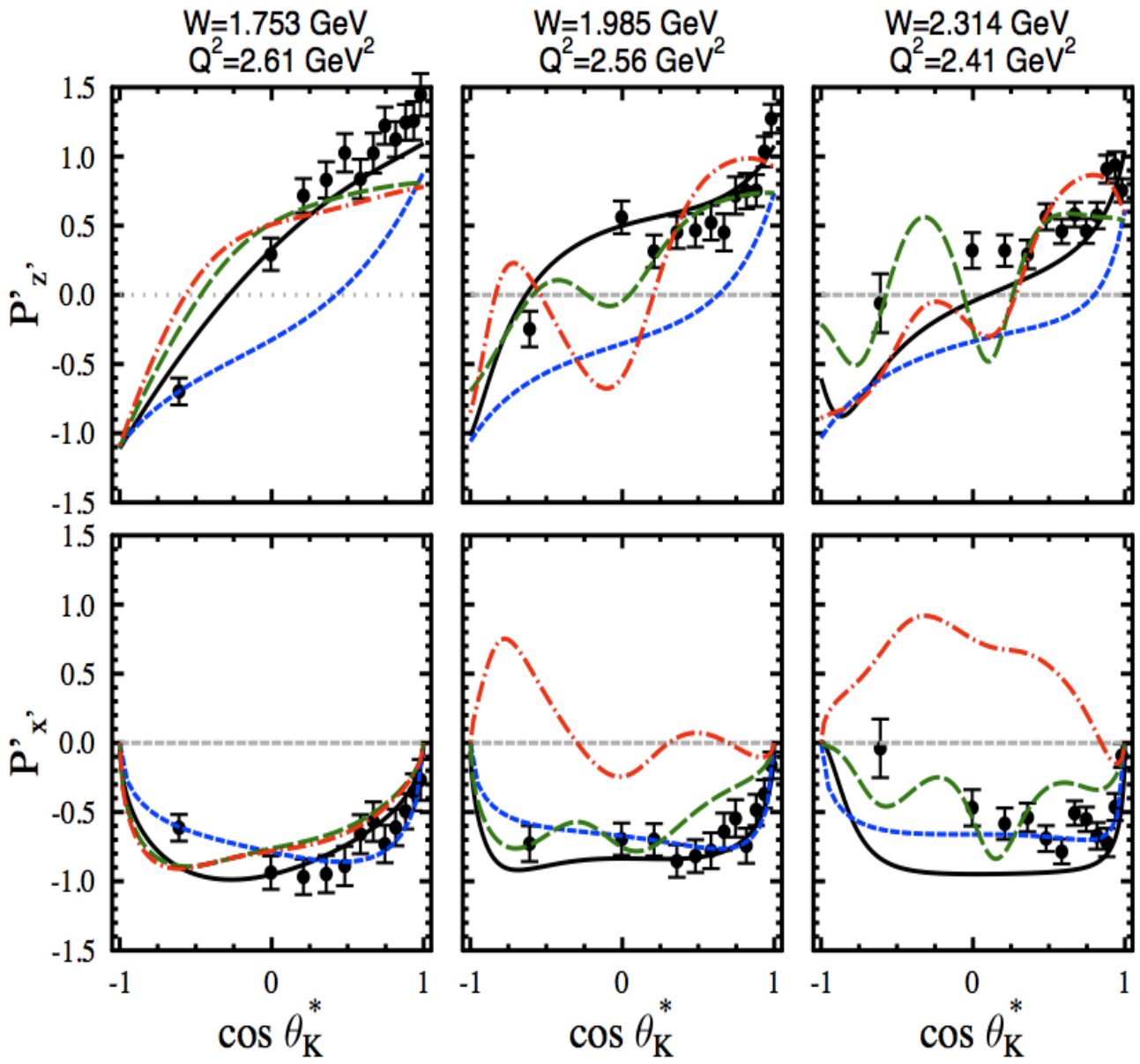

$\langle Q^2 \rangle = 1.9\ GeV^2$

MX, RPR-2011 (full) ——

(nores) .....

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

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



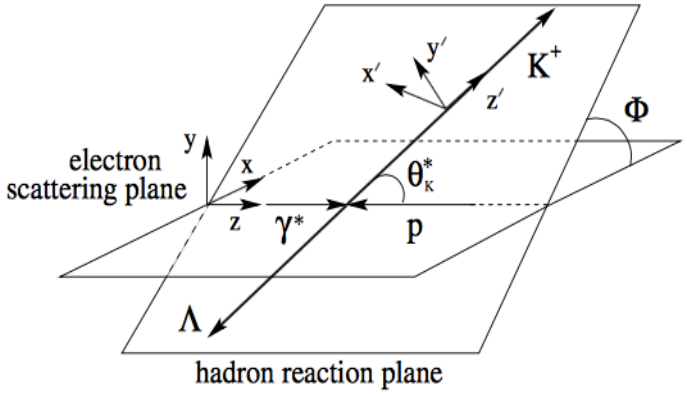

5.754 GeV
Summed over $Q^2$, $\Phi$

*Isobar Model - Mart*

*Regge Model - GLV*

*RPR07 w $P_{11}(1900)$*

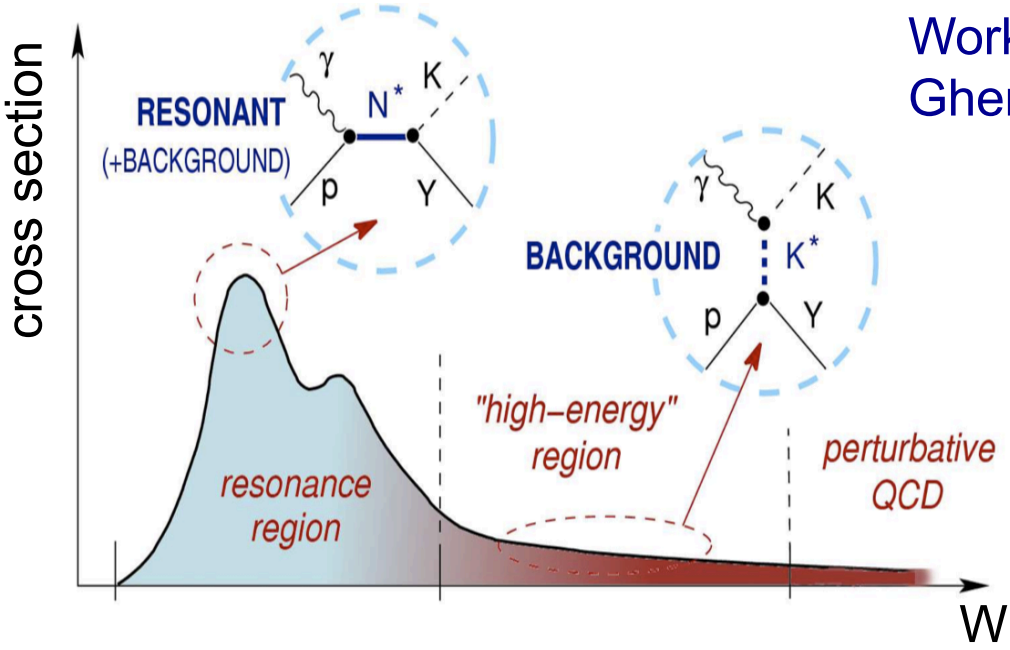
*RPR07 w $D_{13}(1900)$*




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

# KY Reaction Model

There is an ***urgent*** need for KY reaction models - first for lower $Q^2$ data from CLAS and then for higher $Q^2$ data from CLAS12




Work is underway to further develop the Ghent Regge plus Resonance (RPR) model:

- Update RPR electrocoupling parameters
- Refit model to CLAS $\gamma p$ and $\gamma_v p$ data:

  *$W \rightarrow 2.6$ GeV, $Q^2 \rightarrow 4$ GeV$^2$*
- Extend model to CLAS12 kinematics:

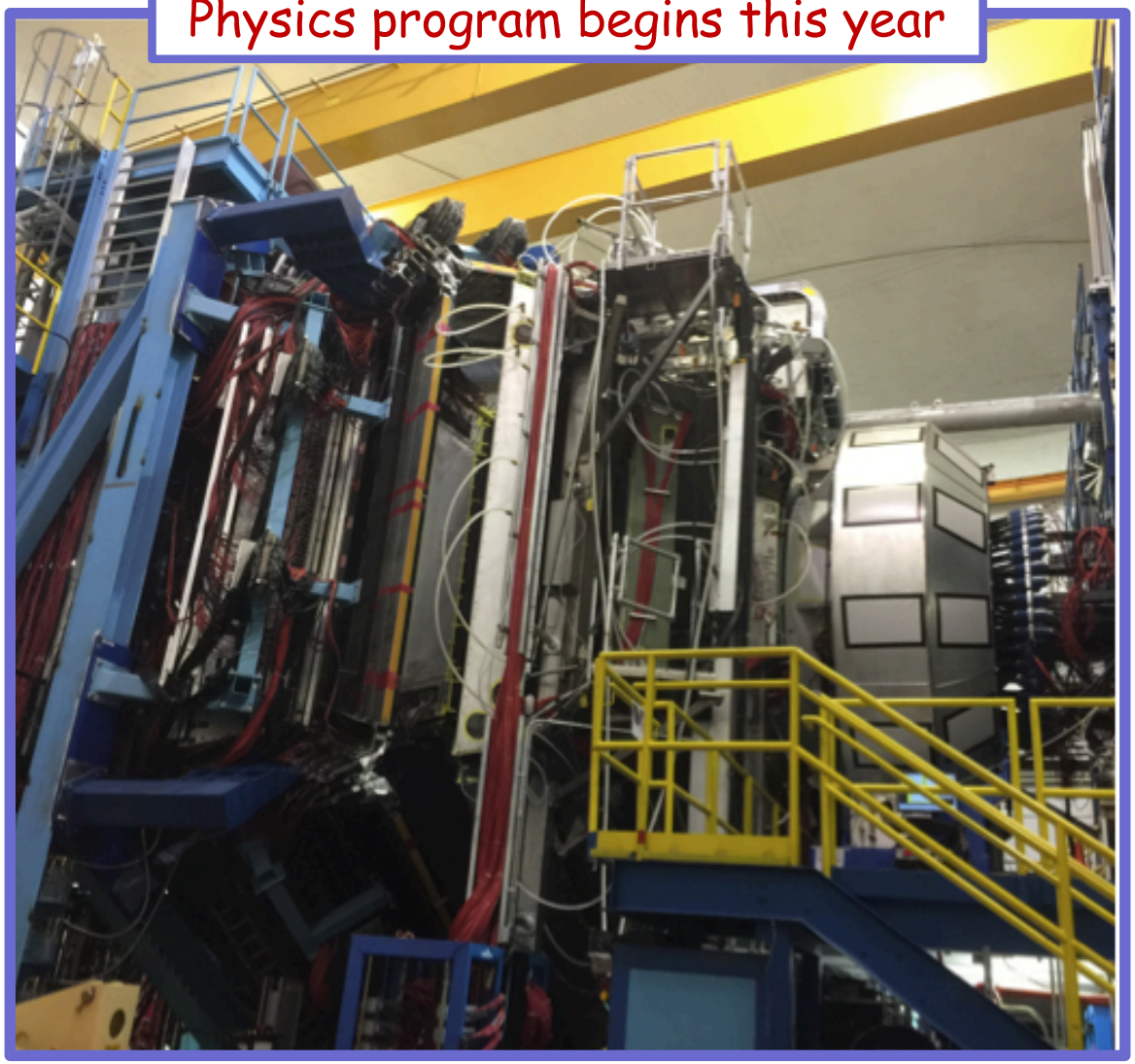
  *$W \rightarrow 3$ GeV, $Q^2 \rightarrow 12$ GeV$^2$*

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

Ultimately need analysis within global multi-channel electroproduction model *(e.g. ANL-Osaka, Bonn-Gatchina, JPAC@JLab)* - getting underway now

# CLAS12 Spectrometer

Physics program begins this year



## CLAS12 Specifications

| | Forward | Central |
|---|---|---|
| Angular coverage | $5^o$ – $35^o$ | $35^o$ – $135^o$ |
| Momentum resolution | $\delta p/p < 1\%$ | $\delta p/p < 5\%$ |
| $\theta$ resolution | 1 mrad | 5 – 10 mrad |
| $\phi$ resolution | 1 mrad/sin$\theta$ | 5 mrad/sin$\theta$ |
| **PID:** | | |
| $\pi$/K | 4$\sigma$ to 2.8 GeV | 3$\sigma$ to 0.6 GeV |
| K/p | 4$\sigma$ to 4.8 GeV | 3$\sigma$ to 1.0 GeV |
| $\pi$/p | 4$\sigma$ to 5.4 GeV | 3$\sigma$ to 1.2 GeV |
| Calorimeter resolution | $\sigma_E \sim 0.1\sqrt{E}$ | |
| Luminosity | $10^{35}$ cm$^{-2}$s$^{-1}$ | |

# CLAS12 N* Program

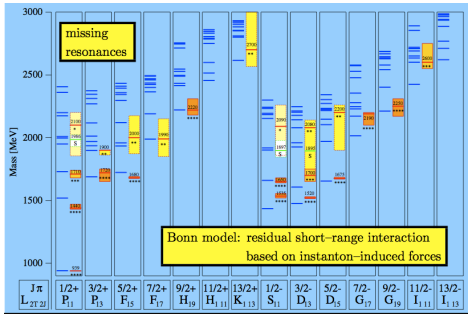
| | |
|---|---|
| E12-09-003 | Nucleon Resonance Studies with CLAS12 |
| E12-06-108A | KY Electroproduction with CLAS12 |
| E12-16-010A | N* Studies Via KY Electroproduction at 6.6 and 8.8 GeV |

- Measure exclusive electroproduction of $N\pi$, $N\eta$, $N\pi\pi$, KY final states from an unpolarized proton target with longitudinally polarized electron beam

$E_b$ = 6.6, 8.8, 11 GeV, $Q^2$ = 2 → 12 GeV$^2$, $W$ → 3.0 GeV, cos $\theta_m^*$ = [-1:1]

- *Study spectrum and structure of all prominent N* states vs. $Q^2$*
  - *A unique opportunity to explore the nature of confinement that is responsible for the dominant part of N* masses and the emergence of N* states from QCD*
- *The independent analysis of $N\pi$, $N\eta$, $N\pi\pi$, and KY allows for "model independent" extraction of the electrocoupling amplitudes*
  - *At moderate $Q^2$ (1 – 5 GeV$^2$), the new CLAS12 electroproduction data will be of comparable statistical quality as existing CLAS photoproduction data*

# N* Spectrum and Structure

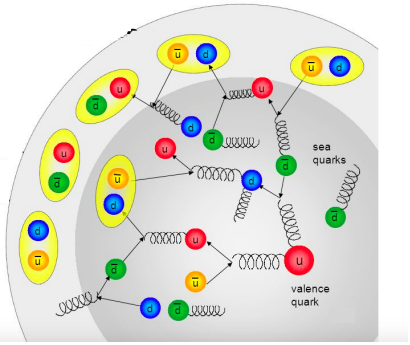


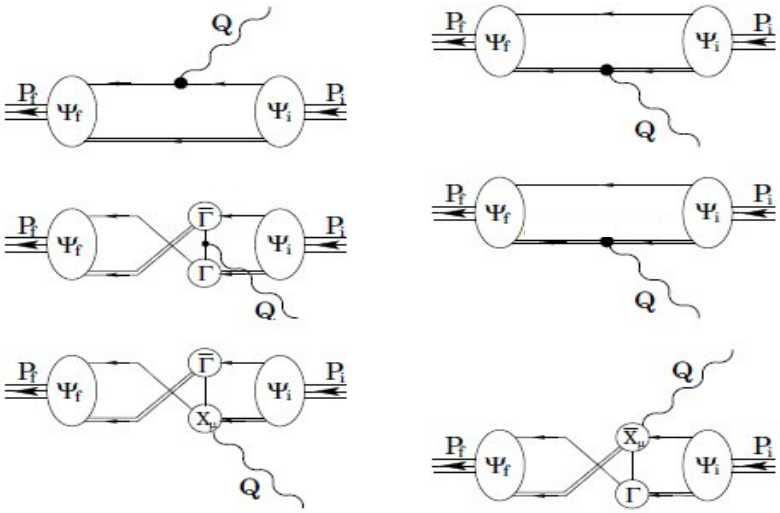

## Study higher-lying states in N* spectrum:

- *important precision tests to confirm signals of new baryon states observed in KY photoproduction*
- *require consistency between photo- and electroproduction data*

## Understand the effect of N* structure from M-B cloud:

- *use transition regime to explore the emergence of the external M-B cloud from the core of confined quarks and gluons*
- *check the theoretical expectations on the M-B cloud generation from the confinement regime*



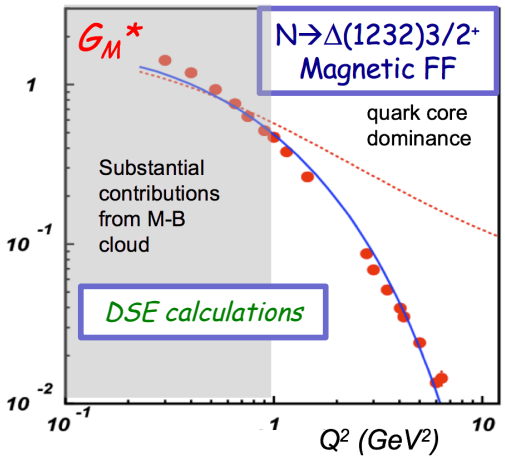



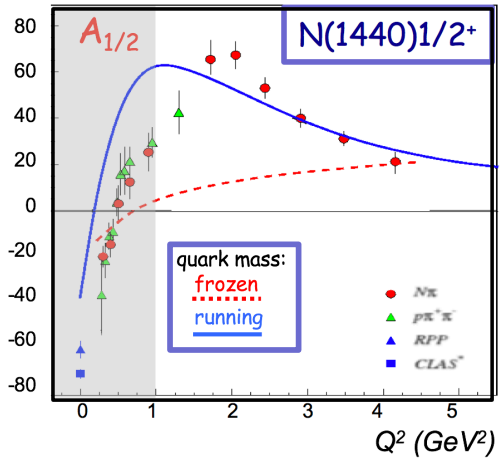

non-point-like diquarks

## Access di-quark correlations in N* structure:

- *important part of N* structure and $\gamma_v NN^*$ transition amplitudes*
- *determined by dressed quark mass function through DCSB*
- *dependent on N* quantum numbers*
- *sizable for $Q^2 < 5$ GeV$^2$; reduced contributions from M-B cloud in range from $Q^2 = 2 \rightarrow 5$ GeV$^2$*

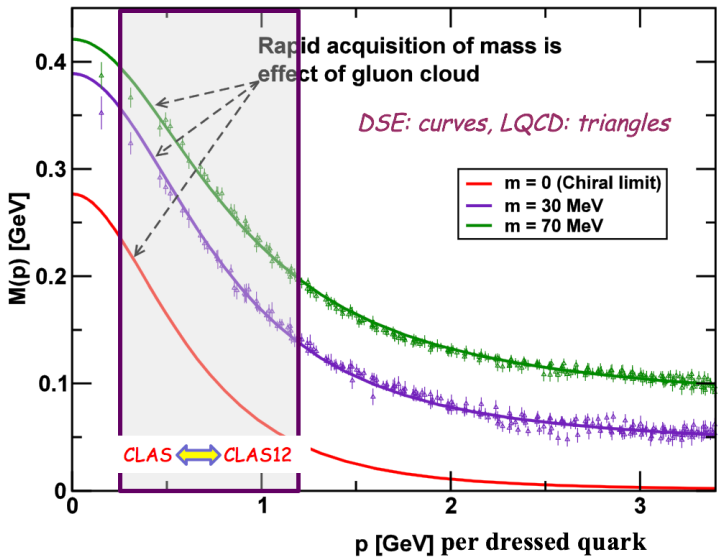
# Exploring Hadron Mass Generation




## Dressed quark mass function:

- *DSE calculations of FFs for N* states can test the relevance of dressed quarks with dynamically generated masses*
- *The mass function can be "measured" as it influences and determines the electrocoupling amplitudes*




## Open questions in Standard Model:

- *Data spanning the transition region from low to high $Q^2$ can help to map out the momentum-dependent dressed quark mass*
- *These dynamical contributions account for more than 98% of the dressed quark mass*
- *Help to address the essence of confinement, mass generation, and its distribution within hadrons*

# Concluding Remarks

- The study of N* states is one of the key foundations of the Hall B physics program with CLAS:
  - CLAS has provided a huge amount of precision data (cross sections and pol. observables) for the $N\pi$, $N\eta$, KY, and $N\pi\pi$ channels $Q^2$ from 0 to 4.5 $GeV^2$
  - Electrocouplings of most N* states < 1.7 GeV have been extracted from these data for the first time for the non-strange M-B final states
  - Analysis tools to extract the structure information from the KY experimental observables are sorely needed
- The CLAS12 N* program will extend these studies for $2 < Q^2 < 12$ $GeV^2$:
  - These studies will allow for insight into the strong interaction dynamics of dressed quarks and their confinement in baryons over a broad $Q^2$ range
  - These data will address the most challenging problems of the SM on the nature of hadron mass, confinement, and the emergence of N* states