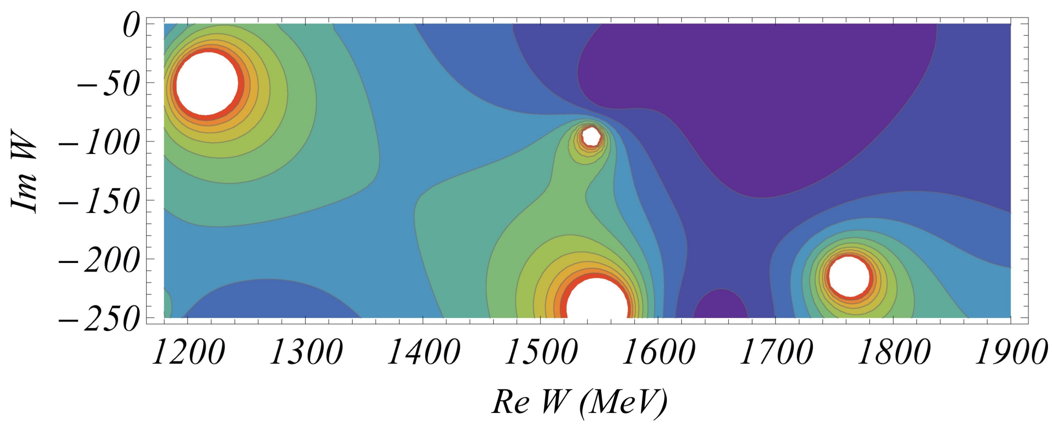
Light-quark baryon spectroscopy and nucleon structure

Volker D. Burkert

Jefferson Lab

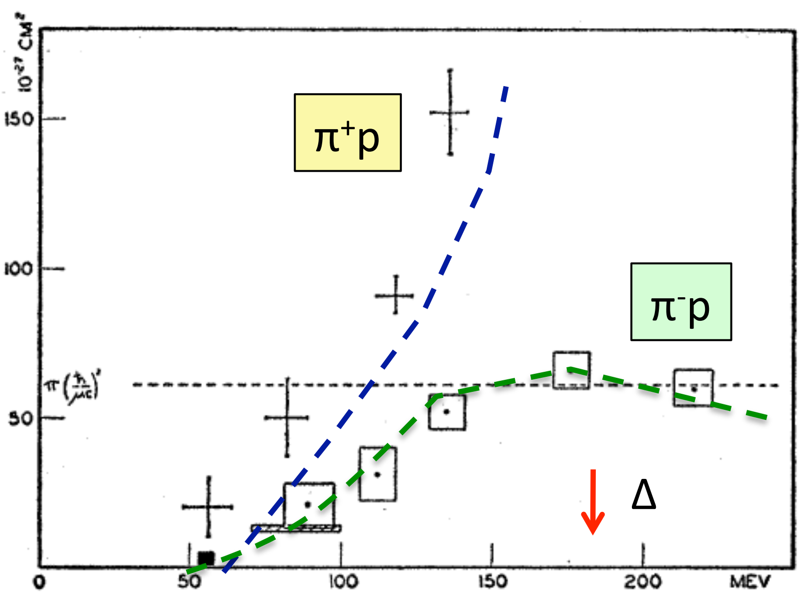
- Motivation
- Establishing the N* spectrum
- Electroproduction and N* Structure
- Gluonic (bybrid) baryons
- Conclusions

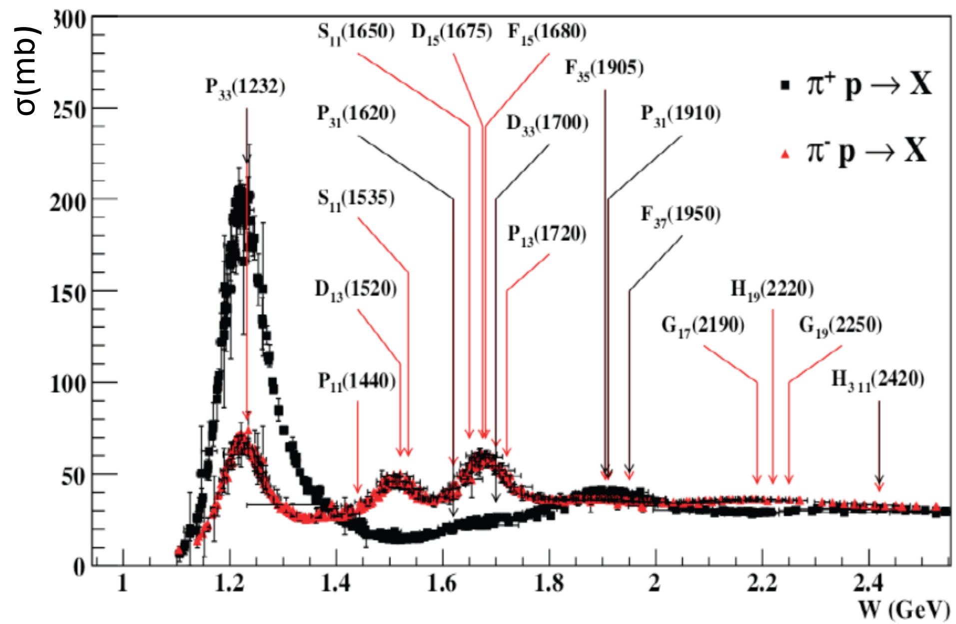


First baryon resonance and beyond

Total Cross Sections of Positive Pions in Hydrogen*

H. L. ANDERSON, E. FERMI, E. A. LONG,† AND D. E. NAGLE
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois
(Received January 21, 1952)





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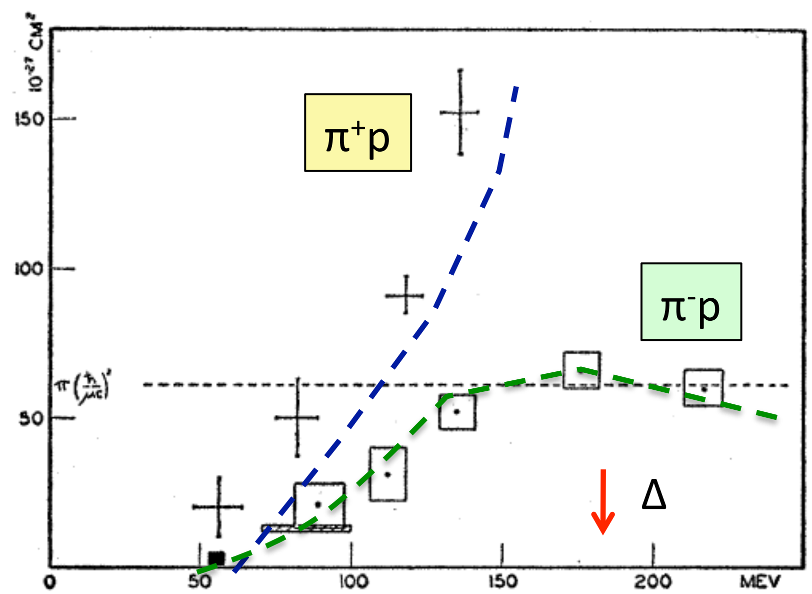
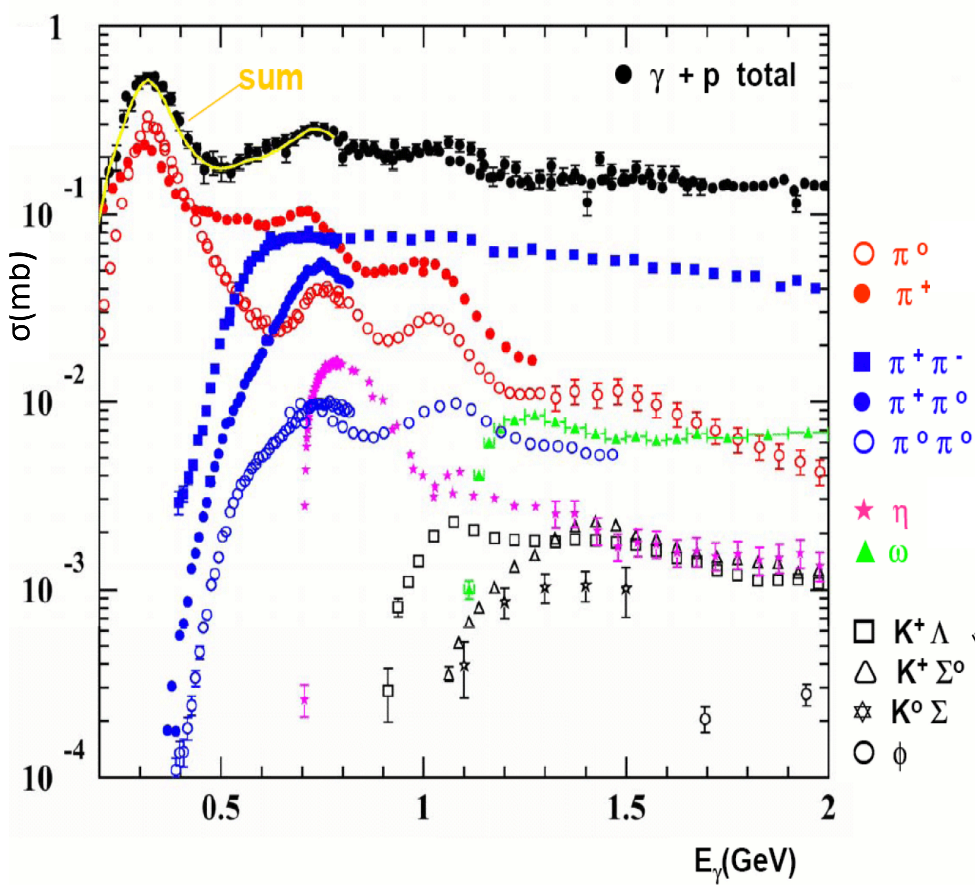
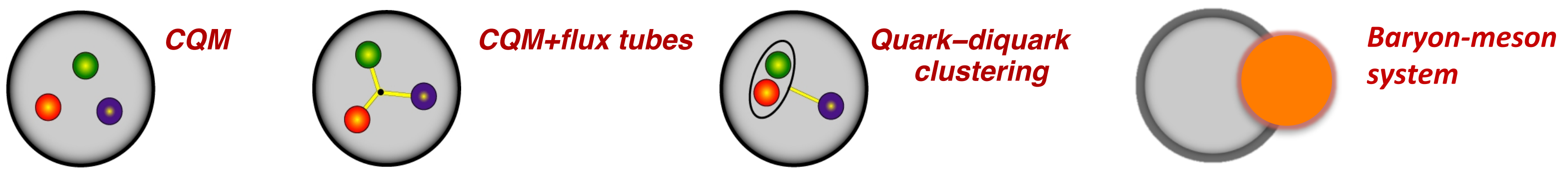




(courtesy R.Beck)

What do we expect to learn?

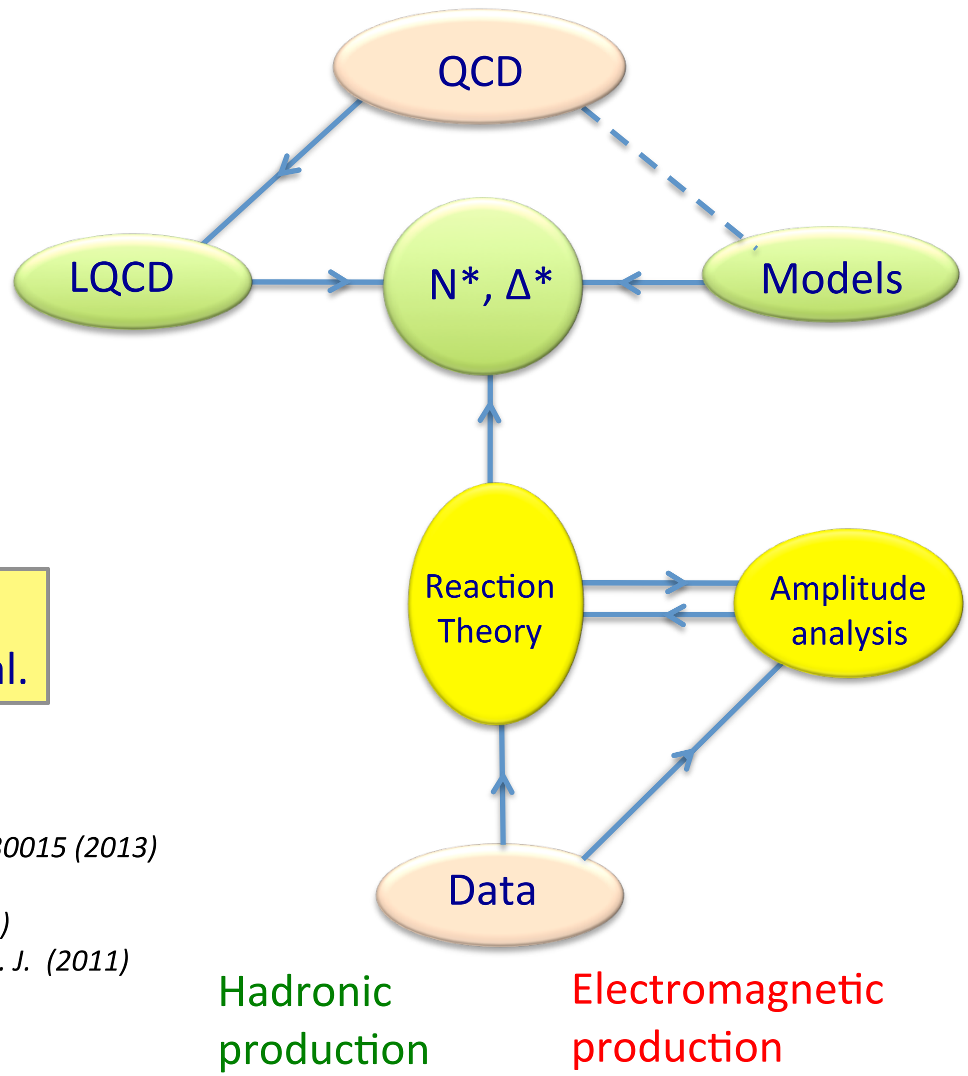
- Understand the effective degrees-of-freedom underlying the N* spectrum and quantify the effective forces between them.



- Is chiral symmetry restored for high mass states? Parity doublets?
- Vigorous experimental program needed along two avenues
  - Search for undiscovered states in meson photoproduction to characterize the systematic of the spectrum (JLab, GRAAL, CBELSA, MAMI, BESIII)
  - Measure the strength of resonance excitations for prominent states versus distance scale in meson electroproduction (JLab/JLab12)
- Developments in theory connecting experiment to QCD

Modern tools for N* and Δ* studies

- Large acceptance for precision measurements of e.m. induced 2-body processes in wide kinematics
- Polarized beams, targets, recoil baryons
- Measure more complex reactions to access high mass states, e.g Nω/ϕ, Nππ, Nπη



Engagement of groups to extract physics in theoretically sound analyses is essential.

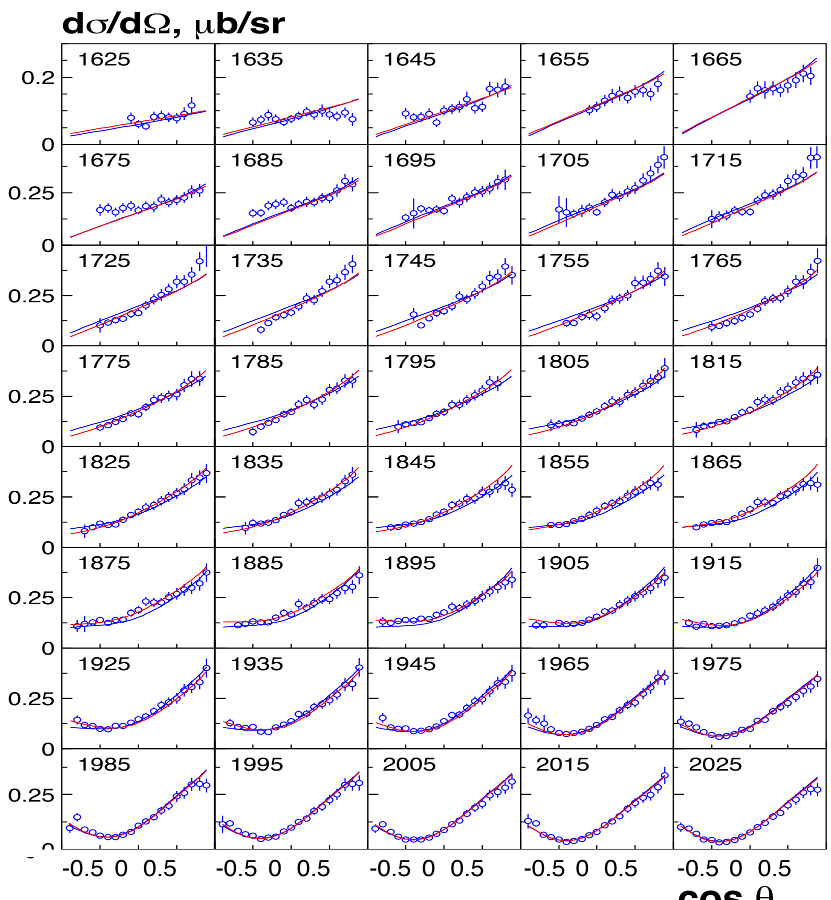
Recent reviews:

- *I.G. Aznauryan, et al. (White Paper), Int. J. Mod. Phys. E, 22, 1330015 (2013)*
- *V. Crede, W. Roberts, Rept. Prog. Phys. 76 (2013)*
- *I.G. Aznauryan, V. D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012)*
- *L. Tiator, D. Drechsel, S. Kamalov, M. Vanderhaeghen, Eur. Phys. J. (2011)*
- *E. Klempt, J.M. Richard, Rev. Mod. Phys. 82, 1095 (2010)*

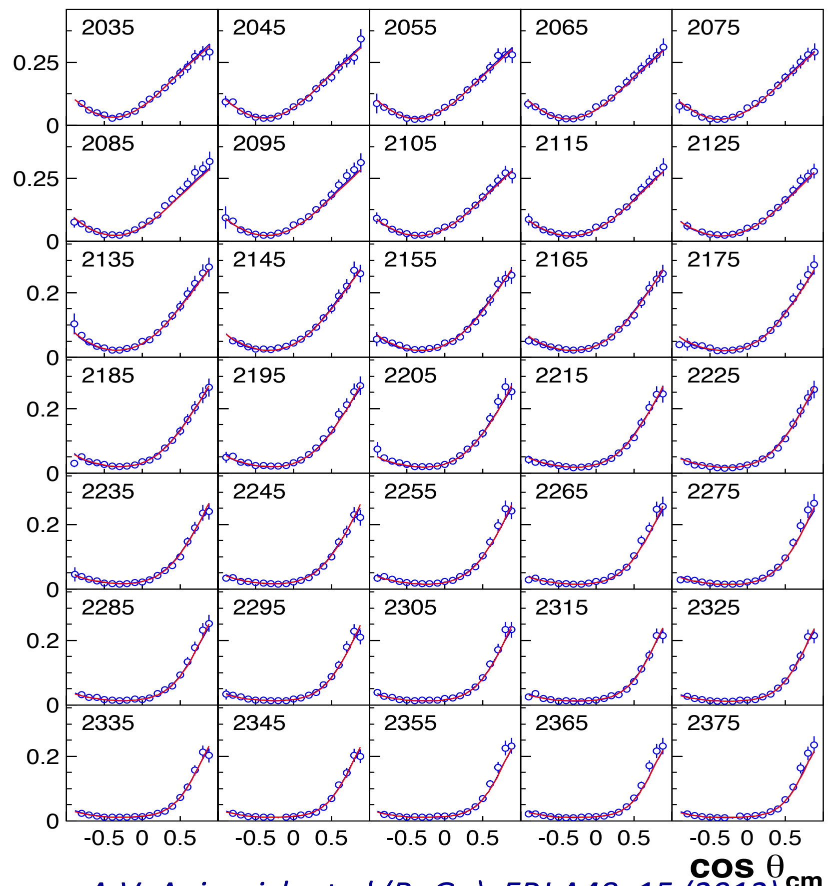
Establishing the nucleon spectrum

From elastic πN scattering to γN reactions.

Essential new data on hyperon production **$\gamma p \rightarrow K^+\Lambda \rightarrow K^+ p\pi^-$**



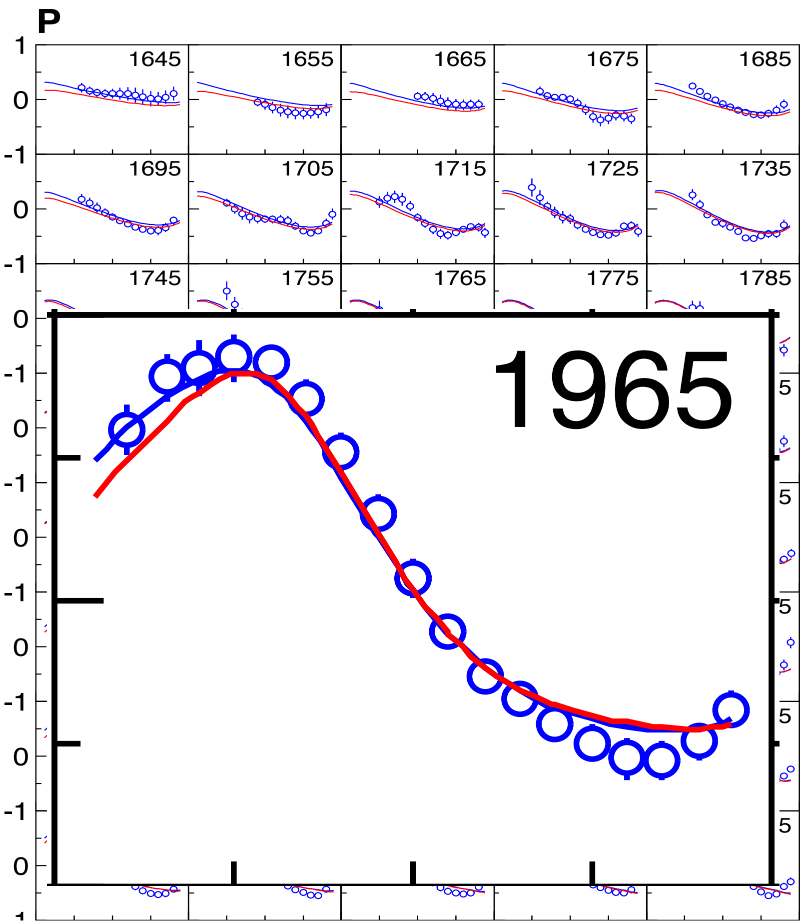
M. Mc Cracken et al.(CLAS), Phys.RevC81,025201,2010



A.V. Anisovich et al (BnGa), EPJ A48, 15 (2012)

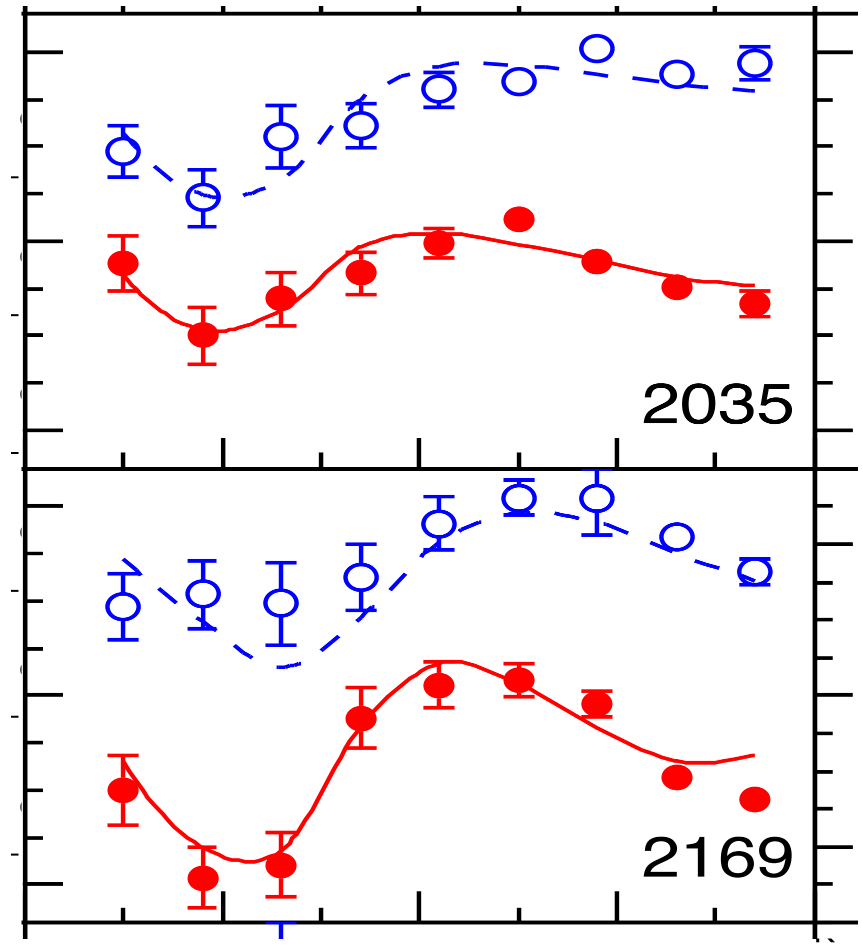
Strangeness production $\vec{\gamma}p \rightarrow K^+\vec{\Lambda} \rightarrow K^+p\pi^-$

Λ Recoil polarization



M. Mc Cracken et al. (CLAS), Phys. Rev. C 81, 025201, 2010

γ->Λ Polarization transfer



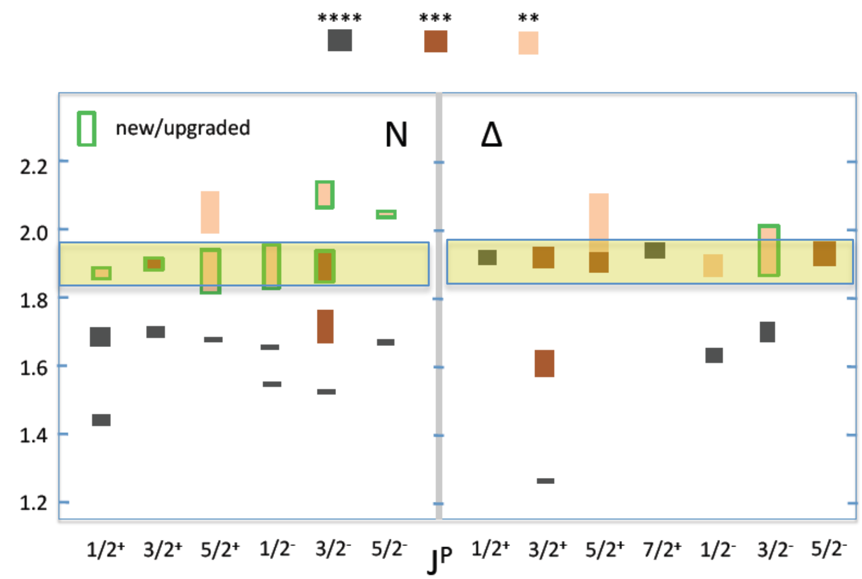
D. Bradford et al. (CLAS), Phys.Rev. C75, 035205, 2007

A.V. Anisovich et al (BnGa), EPJ A48, 15 (2012)

N/Δ spectrum in RPP 2012

N^*	J^P $(L_{2I,2J})$	2010	2012	Δ	J^P $(L_{2I,2J})$	2010	2012
p	$1/2^+$ (P_{11})	****	****	Δ(1232)	$3/2^+$ (P_{33})	****	****
n	$1/2^+$ (P_{11})	****	****	Δ(1600)	$3/2^+$ (P_{33})	***	***
N(1440)	$1/2^+$ (P_{11})	****	****	Δ(1620)	$1/2^-$ (S_{31})	****	****
N(1520)	$3/2^-$ (D_{13})	****	****	Δ(1700)	$3/2^-$ (D_{33})	****	****
N(1535)	$1/2^-$ (S_{11})	****	****	Δ(1750)	$1/2^+$ (P_{31})	*	*
N(1650)	$1/2^-$ (S_{11})	****	****	Δ(1900)	$1/2^-$ (S_{31})	**	**
N(1675)	$5/2^-$ (D_{15})	****	****	Δ(1905)	$5/2^+$ (F_{35})	****	****
N(1680)	$5/2^+$ (F_{15})	****	****	Δ(1910)	$1/2^+$ (P_{31})	****	****
N(1685)			*				
N(1700)	$3/2^-$ (D_{13})	***	***	Δ(1920)	$3/2^+$ (P_{33})	***	***
N(1710)	$1/2^+$ (P_{11})	***	***	Δ(1930)	$5/2^-$ (D_{35})	***	***
N(1720)	$3/2^+$ (P_{13})	****	****	Δ(1940)	$3/2^-$ (D_{33})	*	**
N(1860)	$5/2^+$		**				
N(1875)	$3/2^-$		***				
N(1880)	$1/2^+$		**				
N(1895)	$1/2^-$		**				
N(1900)	$3/2^+$ (P_{13})	**	***	Δ(1950)	$7/2^+$ (F_{37})	****	****
N(1990)	$7/2^+$ (F_{17})	**	**	Δ(2000)	$5/2^+$ (F_{35})	**	**
N(2000)	$5/2^+$ (F_{15})	**	**	Δ(2150)	$1/2^-$ (S_{31})	*	*
~~N(2080)~~	D_{13}	**		Δ(2200)	$7/2^-$ (G_{37})	*	*
~~N(2090)~~	S_{11}	*		Δ(2300)	$9/2^+$ (H_{39})	**	**
N(2040)	$3/2^+$		*				
N(2060)	$5/2^-$		**				
N(2100)	$1/2^+$ (P_{11})	*	*	Δ(2350)	$5/2^-$ (D_{35})	*	*
N(2120)	$3/2^-$		**				
N(2190)	$7/2^-$ (G_{17})	****	****	Δ(2390)	$7/2^+$ (F_{37})	*	*
~~N(2200)~~	D_{15}	**		Δ(2400)	$9/2^-$ (G_{39})	**	**
N(2220)	$9/2^+$ (H_{19})	****	****	Δ(2420)	$11/2^+$ $(H_{3,11})$	****	****
N(2250)	$9/2^-$ (G_{19})	****	****	Δ(2750)	$13/2^-$ $(I_{3,13})$	**	**
N(2600)	$11/2^-$ $(I_{1,11})$	***	***	Δ(2950)	$15/2^+$ $(K_{3,15})$	**	**
N(2700)	$13/2^+$ $(K_{1,13})$	**	**				

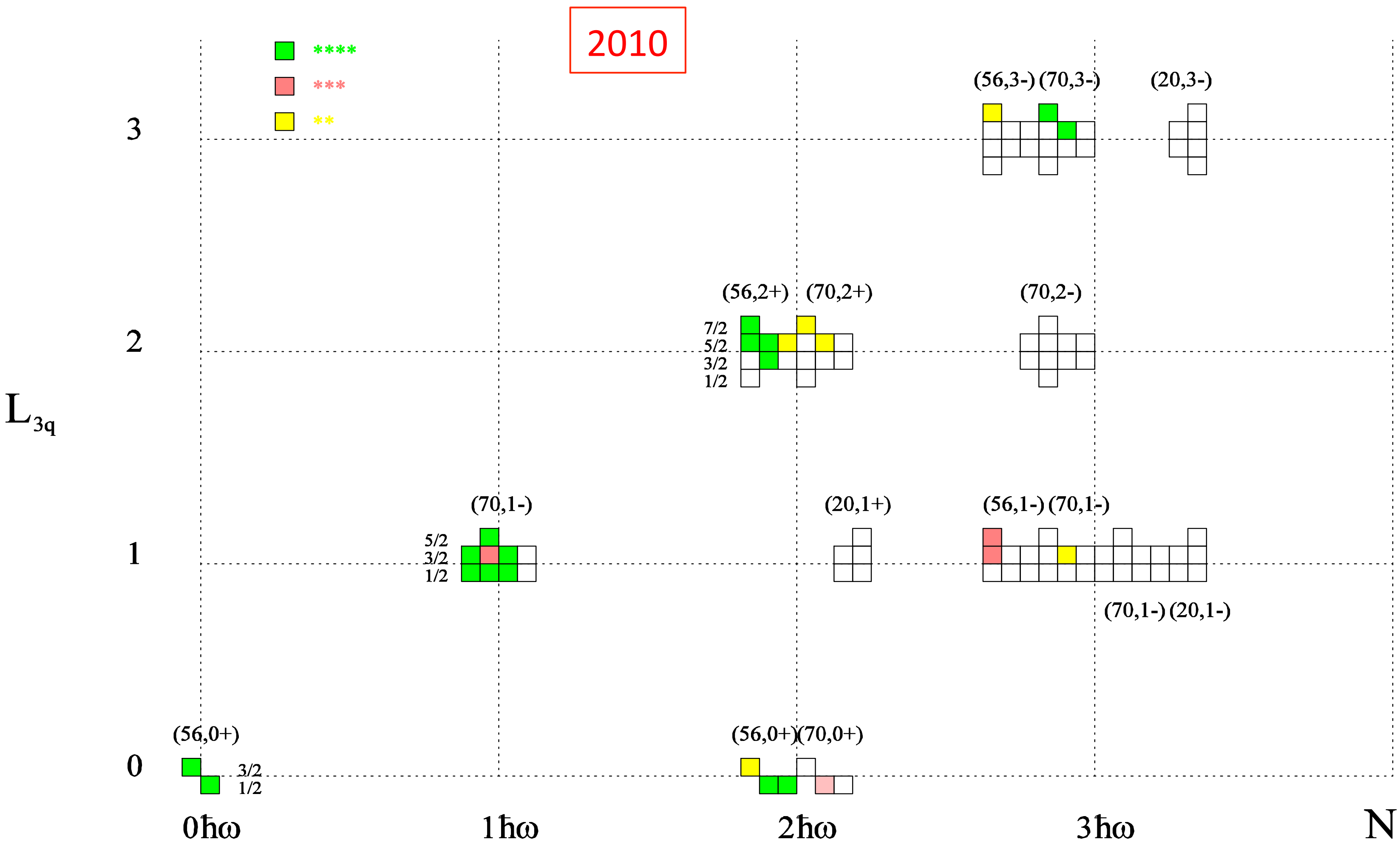
Photoproduction data from JLAB, CBELSA, GRAAL, LEPS



Are we observing spin multiplets or parity doublets with the new states?

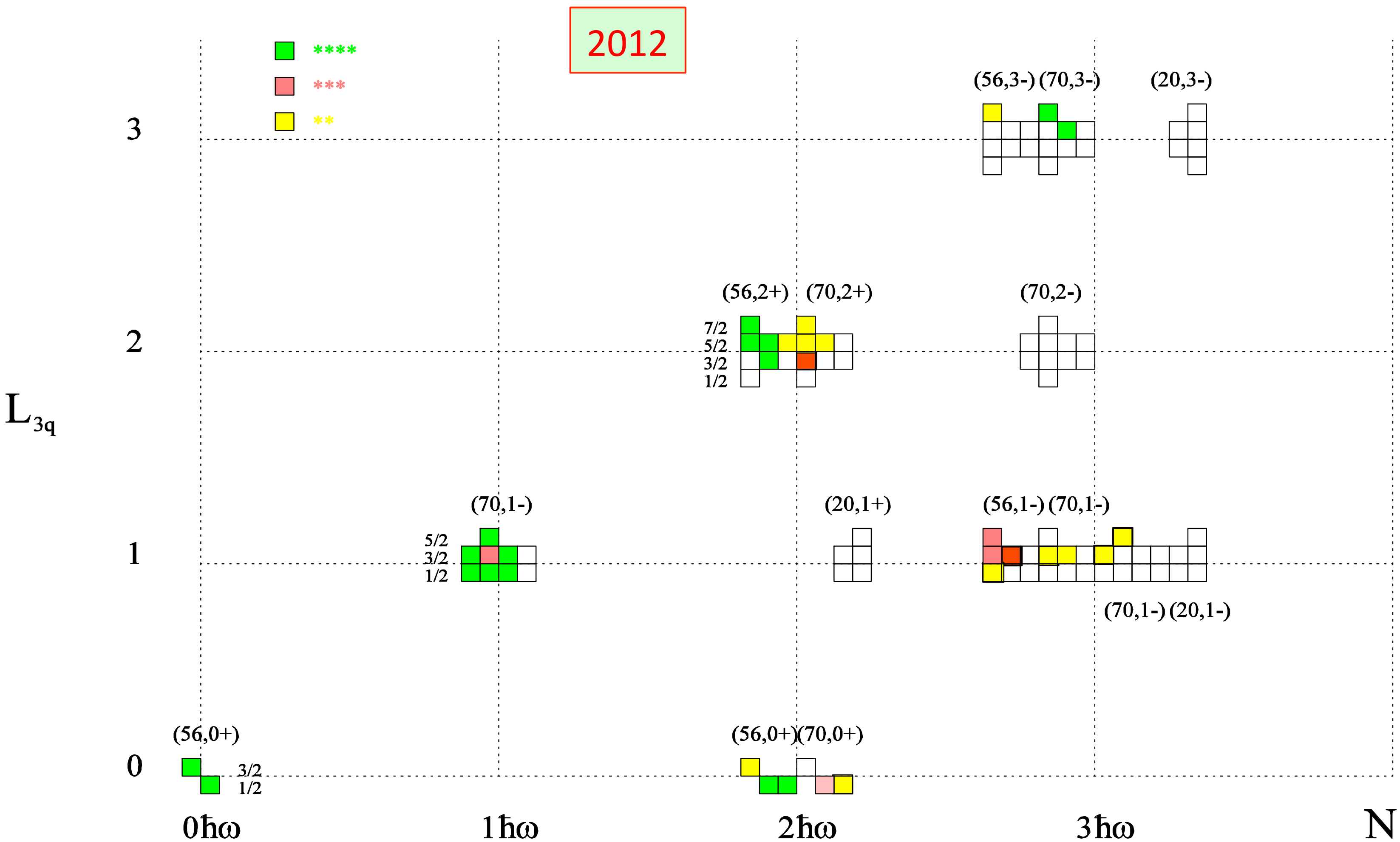
We need to verify candidate states and establish higher mass states.

SU(6)xO(3) Classification of Baryons

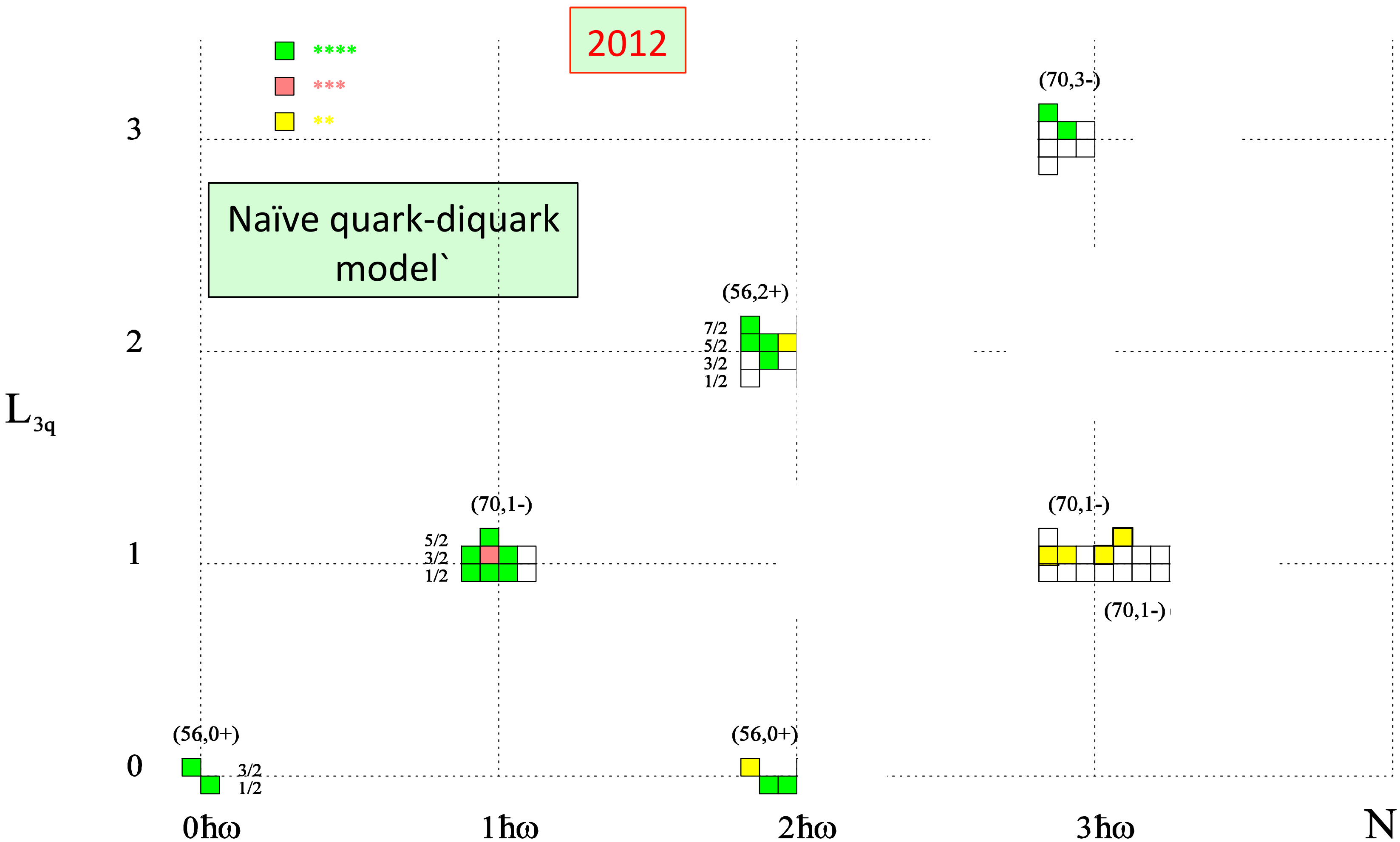


Do the new candidate states fit in projected Lattice QCD spectrum?

SU(6)xO(3) Classification of Baryons



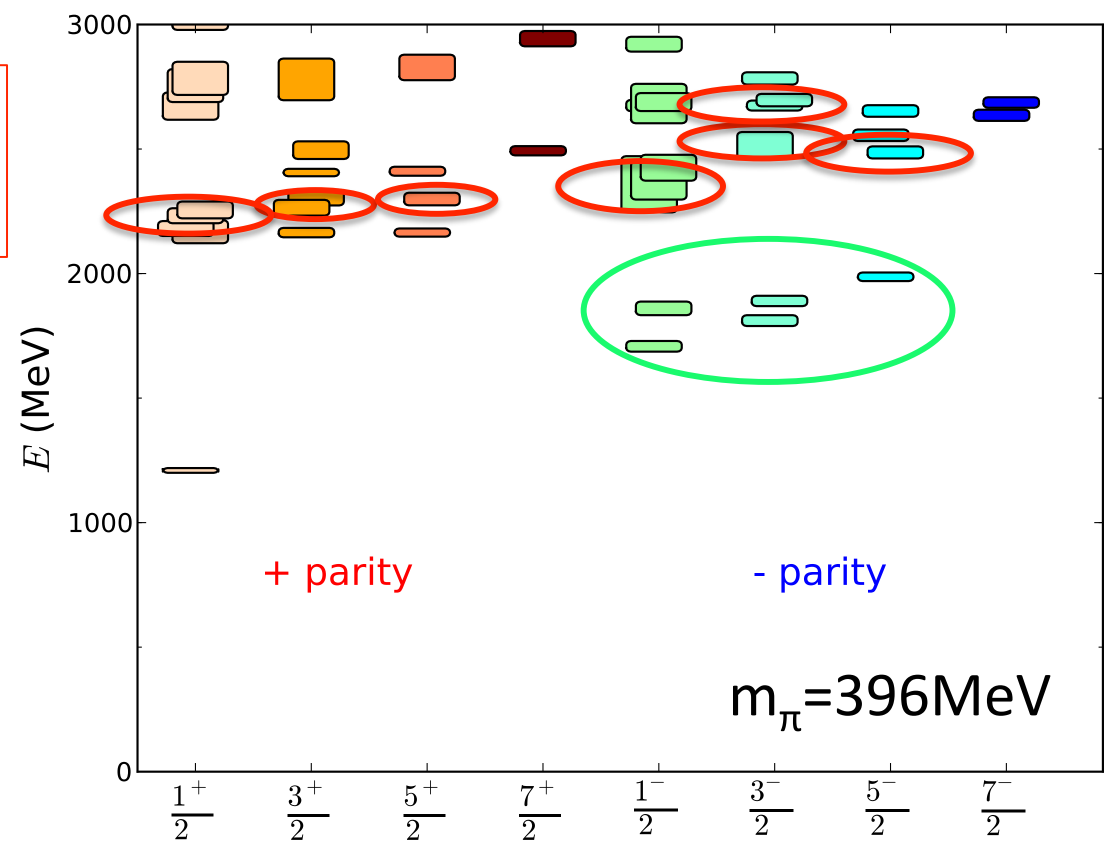
SU(6)xO(3) Classification of Baryons



N* spectrum in LQCD

R. Edwards et al., Phys.Rev. D84 (2011) 074508

N(1860)5/2+
N(1900)3/2+
N(1880)1/2+



N(2060)5/2-
N(2120)3/2-
N(1875)3/2-
N(1895)1/2-

N(1675)5/2-
N(1700)3/2-
N(1520)3/2-
N(1650)1/2-
N(1535)1/2-

Ignoring the mass scale, new candidate states fit with the J^P values predicted from LQCD.

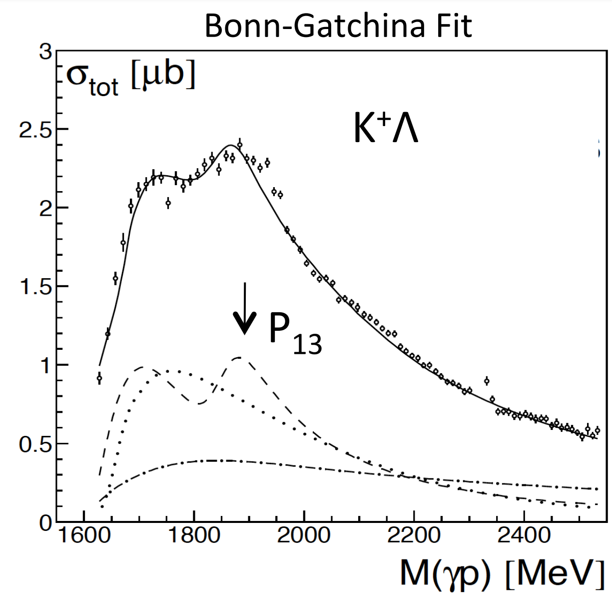
The N(1900)3/2$^+$ State

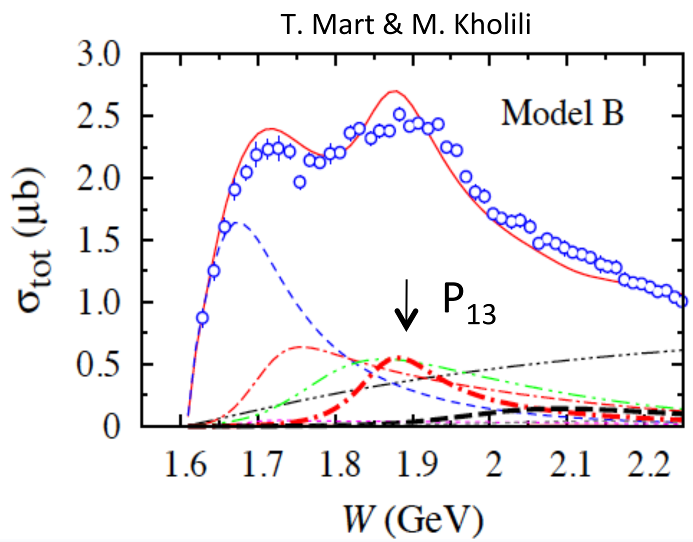
- State now solidly established in coupled-channel analysis making use of very precise KΛ crs and polarization data, let to the *** assignment in PDG2012.

- State was confirmed in covariant isobar model single channel analysis $\gamma p \rightarrow K^+\Lambda$ (*T. Mart & M. J. Kholili , PRC86 (2012) 022201*)

- Confirmed in an effective Langrangian resonance model analysis (*O. V. Maxwell, PRC85,034611, 2012)* in $\gamma p \rightarrow K^+\Lambda$ data.

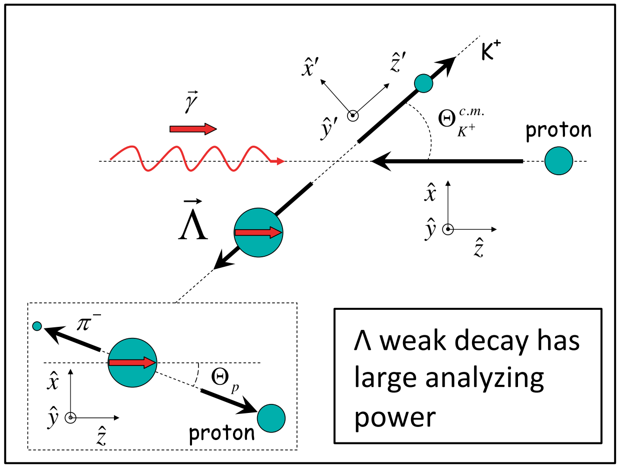
- State fulfills criteria for elevation to **** status. First baryon resonance observed and confirmed in electromagnetic meson production.





Complete photoproduction experiments

$\gamma + p \longrightarrow K^{+} + \Lambda\ (p\pi^{-})$



- Process described by 4 complex amplitudes
- 8 well-chosen measurements are needed to determine amplitude.
- Up to **16** observables measured directly
- 3 inferred from double polarization observables
- **13** inferred from triple polarization observables

Beam (P^γ)		Target (P^T)			Recoil (P^R)			Target (P^T) + Recoil (P^R)								
					x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
		x	y	z				x	y	z	x	y	z	x	y	z
unpolarized	$d\sigma_0$		$\hat{T}$			$\hat{P}$		$\hat{T}_{x'}$		$\hat{L}_{x'}$		$\underline{\hat{\Sigma}}$		$\hat{T}_{z'}$		$\hat{L}_{z'}$
$P_L^\gamma \sin(2\phi_\gamma)$		$\hat{H}$		$\hat{G}$	$\hat{O}_{x'}$		$\hat{O}_{z'}$		$\hat{\mathbf{C}}_{\mathbf{z'}}$		$\hat{\mathbf{E}}$		$\hat{\mathbf{F}}$		$-\hat{\mathbf{C}}_{\mathbf{x'}}$	
$P_L^\gamma \cos(2\phi_\gamma)$	$-\hat{\Sigma}$		$\underline{-\hat{P}}$			$\underline{-\hat{T}}$		$-\hat{\mathbf{L}}_{\mathbf{z'}}$		$\hat{\mathbf{T}}_{\mathbf{z'}}$		$-\mathbf{d\sigma_0}$		$\hat{\mathbf{L}}_{\mathbf{x'}}$		$-\hat{\mathbf{T}}_{\mathbf{x'}}$
circular P_c^γ		$\hat{F}$		$-\hat{E}$	$\hat{C}_{x'}$		$\hat{C}_{z'}$		$-\hat{\mathbf{O}}_{\mathbf{z'}}$		$\hat{\mathbf{G}}$		$-\hat{\mathbf{H}}$		$\hat{\mathbf{O}}_{\mathbf{x'}}$	

A. Sandorfi, S. Hoblit, H. Kamano, T.-S.H. Lee, J.Phys. 38 (2011) 053001

Towards “complete” experiments with CLAS

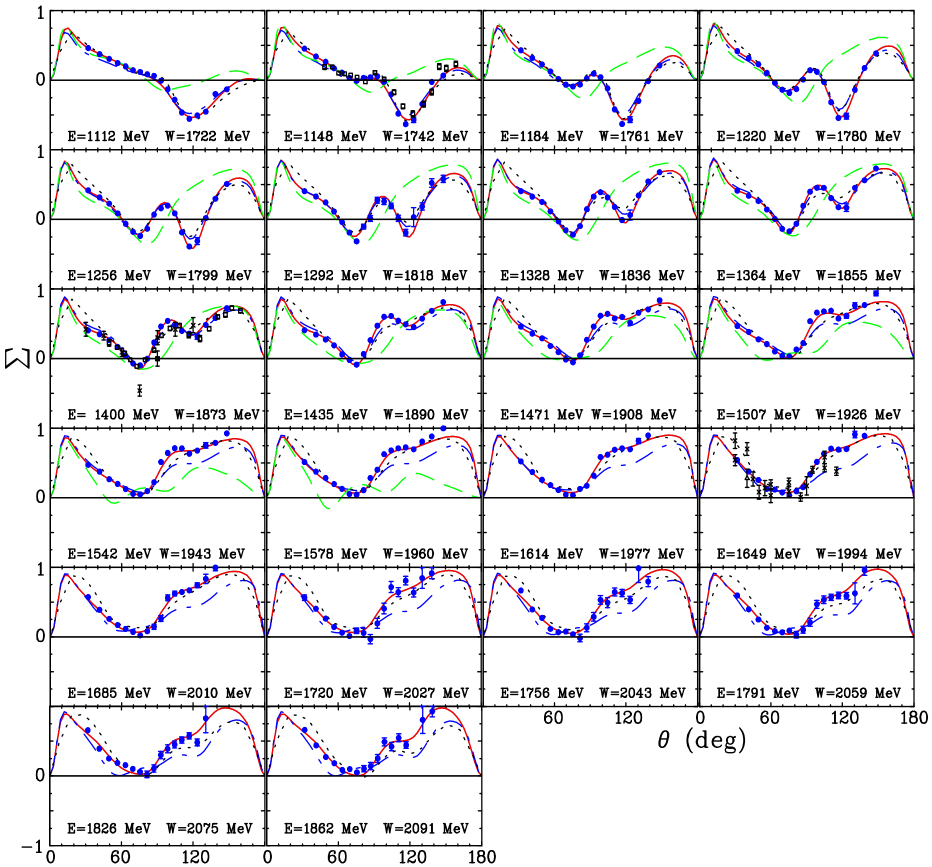
Observables	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
✔ published	✓ acquired or under analysis															
$p\pi^0$	✔	✔	✓	(✓)	✓	✓	✓	✓								
$n\pi^+$	✔	✔	✓	(✓)	✓	✓	✓	✓	Proton targets							
$p\eta$	✔	✓	✓	(✓)	✓	✓	✓	✓								
$p\eta'$	✔	✓	✓	(✓)	✓	✓	✓	✓								
$p\omega/\phi$	✔	✓	✓	(✓)	✓	✓	✓	✓	**Tensor polarization, SDME**							
$K^+\Lambda$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^+\Sigma^0$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^{0*}\Sigma^+$	✔	✓									✓	✓				
$p\pi^-$	✔	✓		(✓)	✓	✓	✓									
$p\rho^-$	✓	✓		(✓)	✓	✓	✓		Neutron targets							
$K^-\Sigma^+$	✓	✓		(✓)	✓	✓	✓									
$K^0\Lambda$	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓									✓	✓				

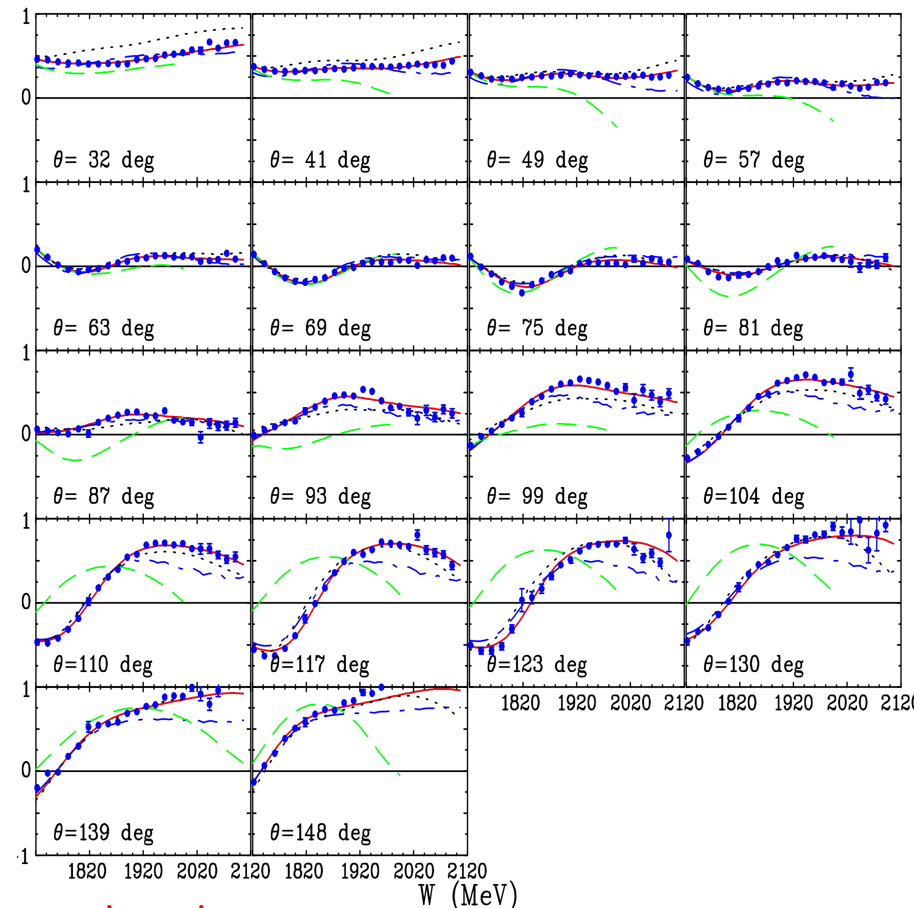
Polarized photon beam asymmetry Σ

World data $\tilde{\gamma} p \longrightarrow \pi^+ n$

M. Dugger et al. (CLAS), PRC 88, 065203 (2013)

1.72 < W < 2.10 GeV





Not yet included in multi-channel analyses

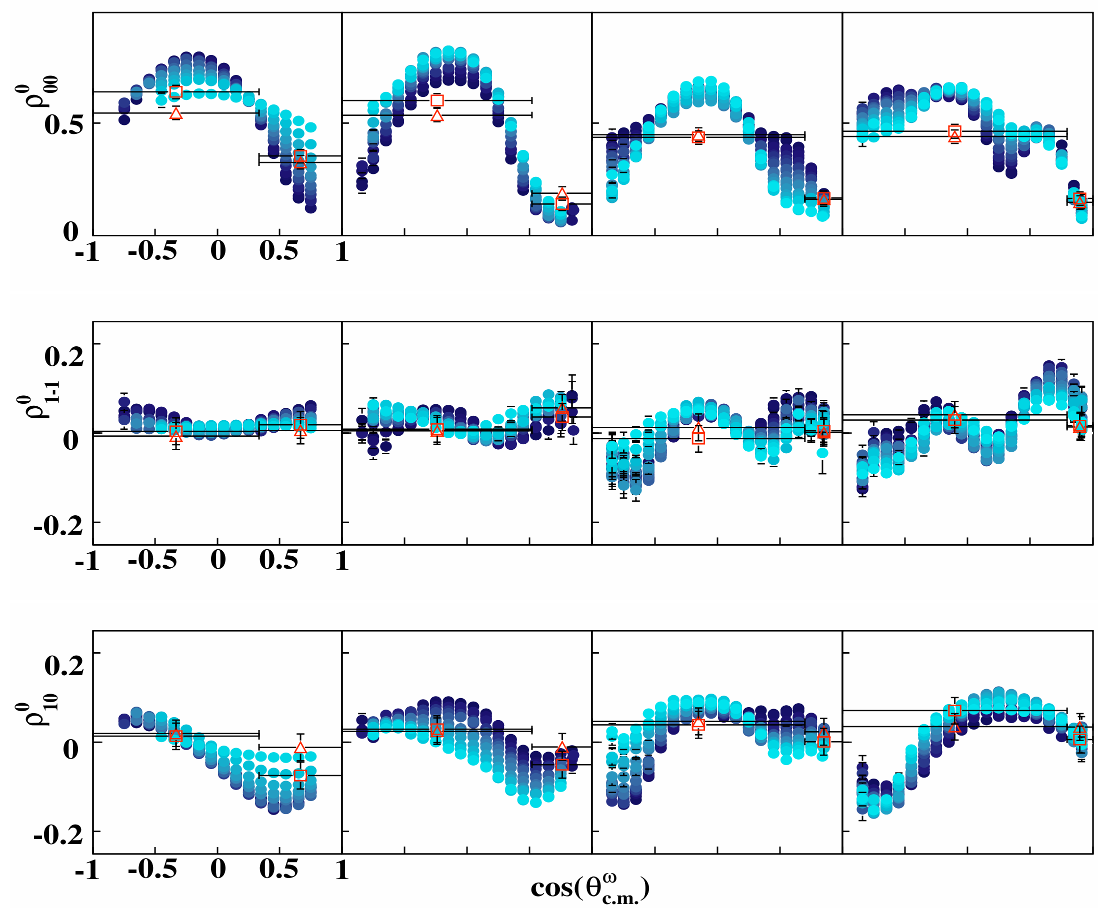
N* states in $\gamma p \to p\omega \to p\pi^+\pi^-\pi^0$?

$$\mathcal{I}(\sqrt{s}, \cos\theta^{\phi}_{\mathrm{c.m.}}) \sim \frac{1}{2}(1-\rho^0_{00}) + \frac{1}{2}(3\rho^0_{00}-1)\cos^2\zeta - \sqrt{2}Re\rho^0_{10}\sin 2\zeta\cos\varphi - \rho^0_{1-1}\cos 2\varphi,$$

- Very precise cross sections in W, $\cos\theta_\omega$. From ω decays => SDME ρ^0_{00}, ρ^0_{1-1}, ρ^0_{10}, shown in blue - blue shades.

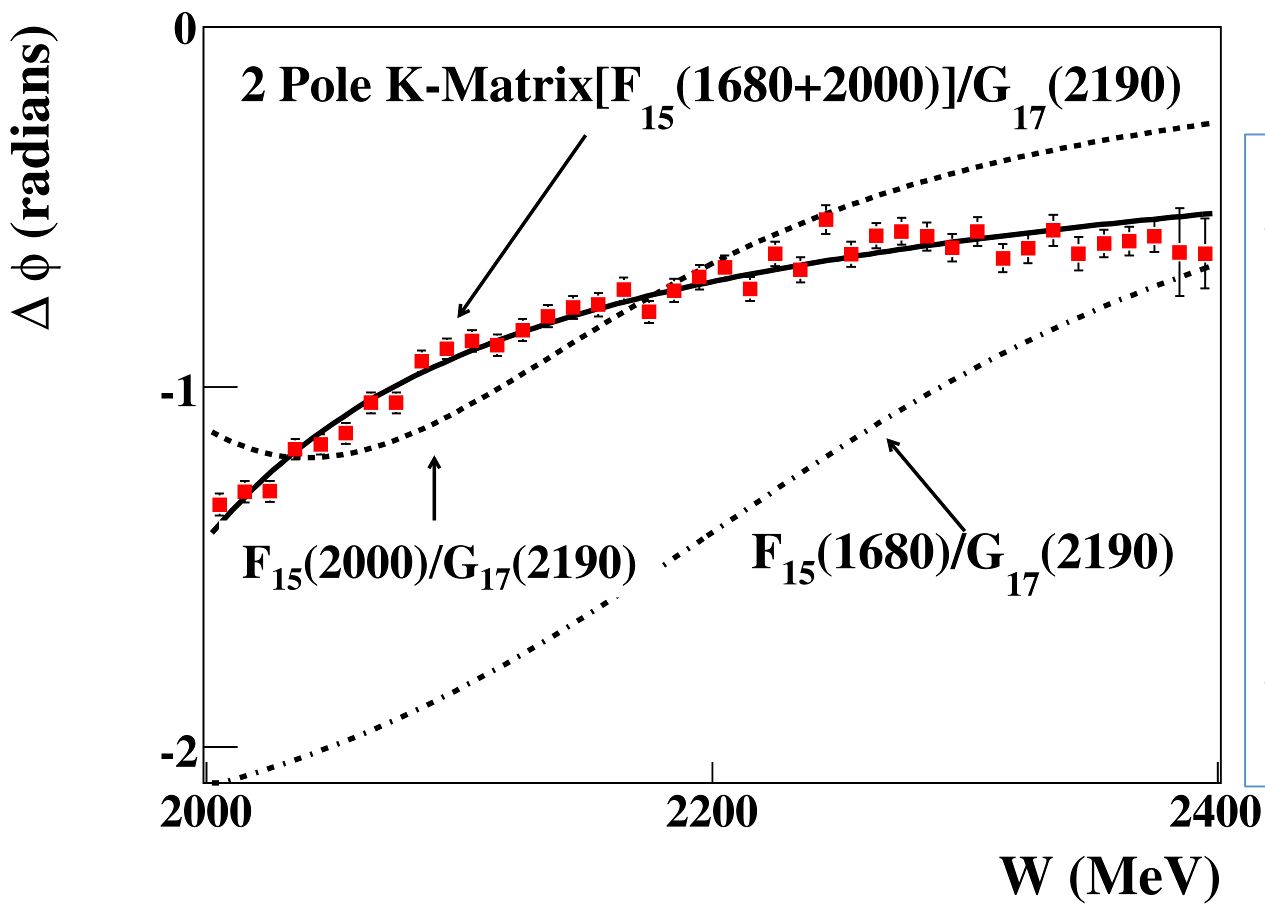
(ω data not yet included in coupled-channel amplitude analyses, in preparation by BG and other groups.)

W=1.7 – 2.4 GeV, ΔW=10 MeV bins



M. Williams, et al. (CLAS), Phys. Rev. C80:065209, 2009

N* states in $\gamma p \rightarrow p\omega \rightarrow p\pi^+\pi^-\pi^0$



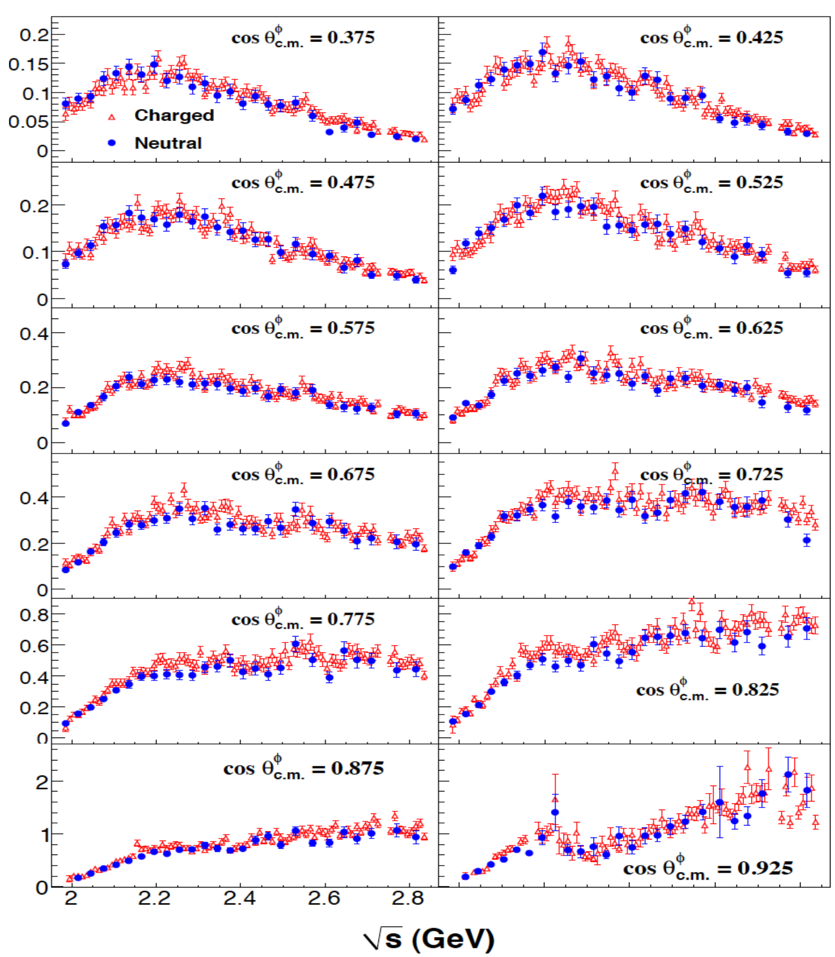
M. Williams, et al. (CLAS) , Phys.Rev. C80 (2009) 065208

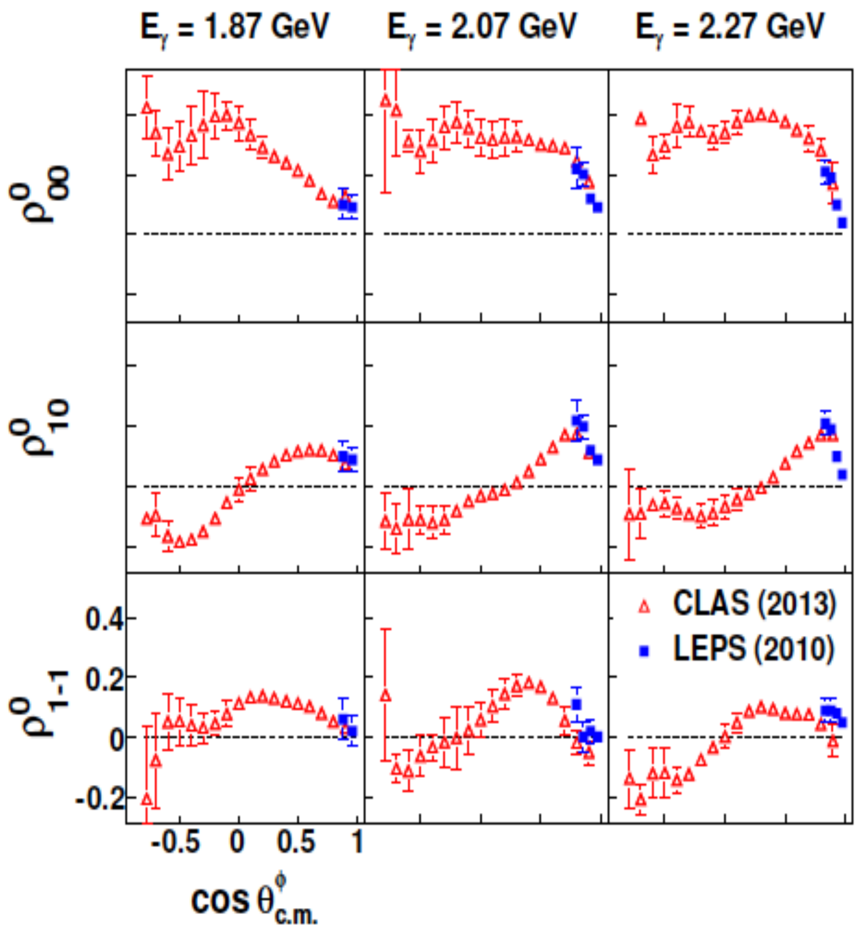
- The data are used as input to a single channel event-based, energy independent partial wave analysis (the first ever for baryons).
- **ω** photoproduction is dominated by the well known **F_{15}(1680) and G_{17}(2190)**, and the "missing" ** **F_{15}(2000)**
  new PDG: N(2000)5/2$^+$

Differential cross sections $\gamma p \rightarrow p\phi \rightarrow pKK$

First precision measurement in 80 energy bins at W=10 MeV, and nearly full angle range (CLAS).

$\phi \rightarrow K^+K^-$ $\phi \rightarrow K^0_s K^0_l$

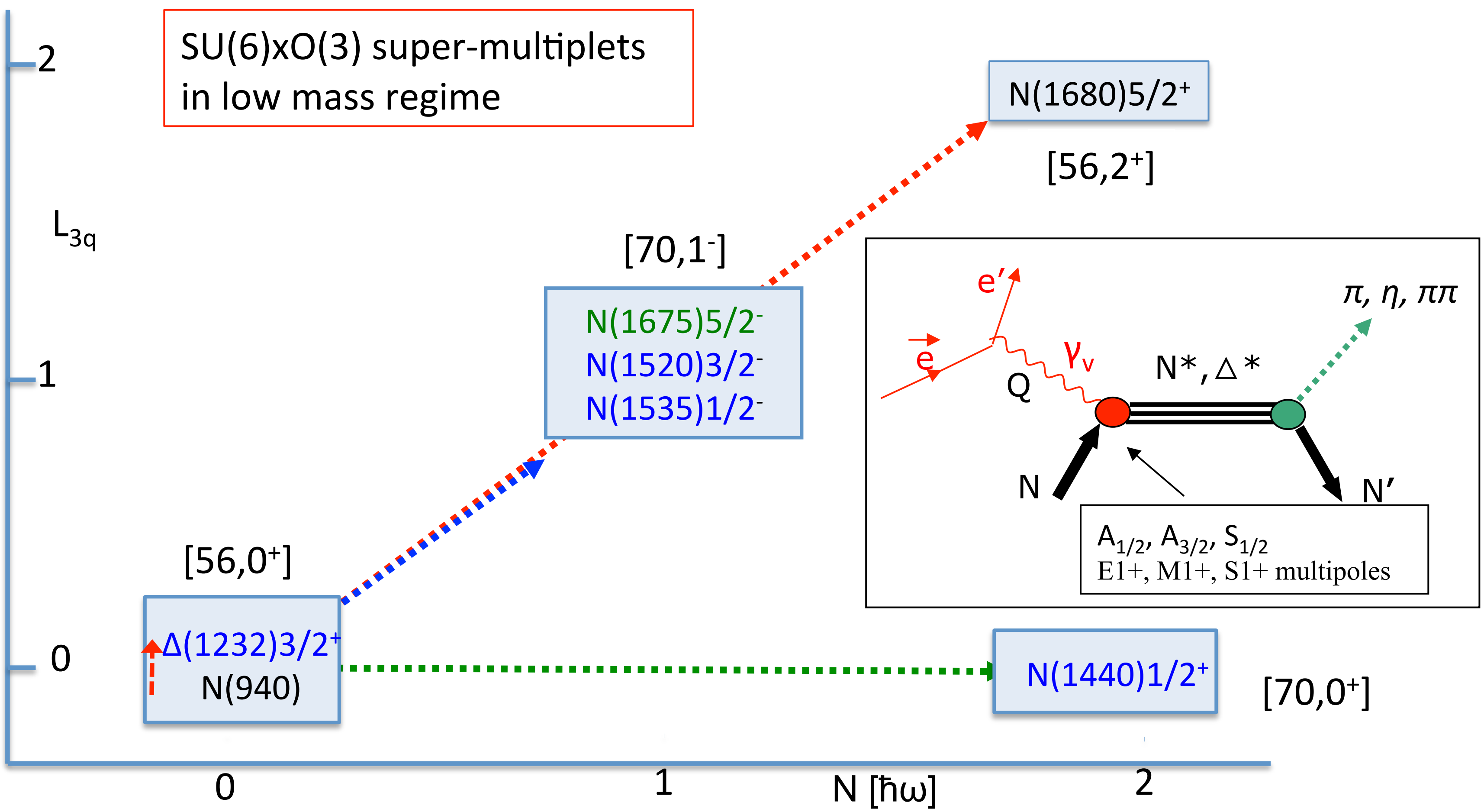




- SDME from ϕ decay angular distributions.

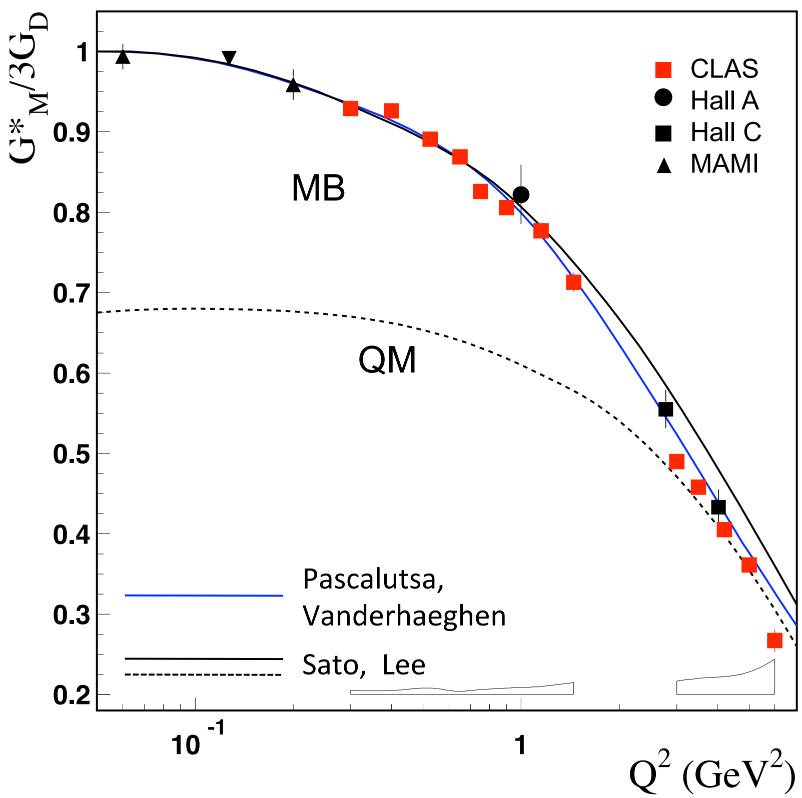
Electroexcitation of N/Δ resonances

- Virtual photon probes resonance strength vs distance

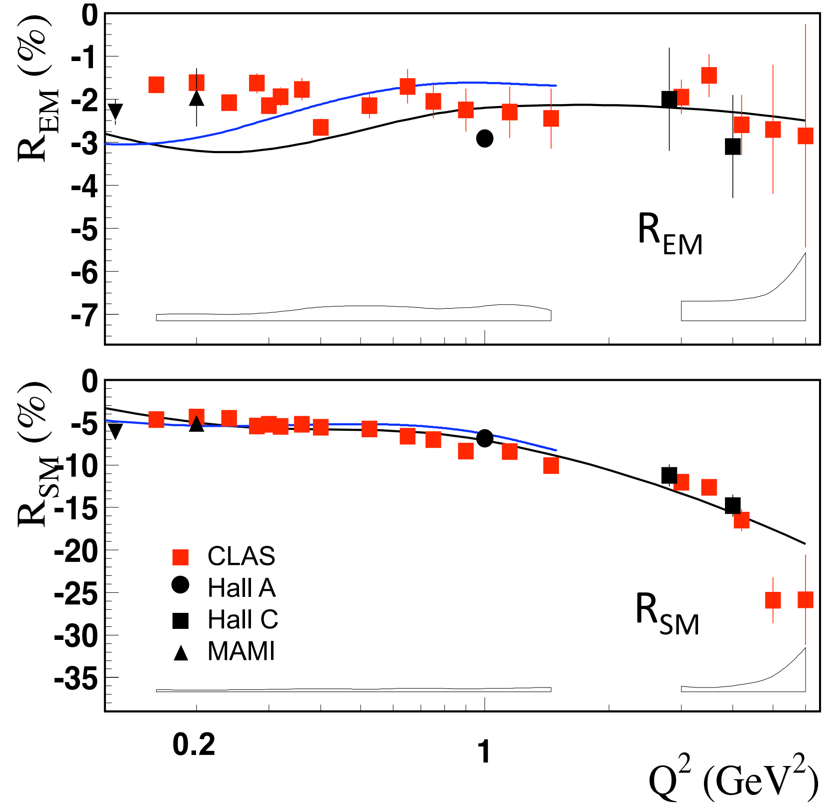


The NΔ(1232) Transition

Magnetic Dipole Form Factor



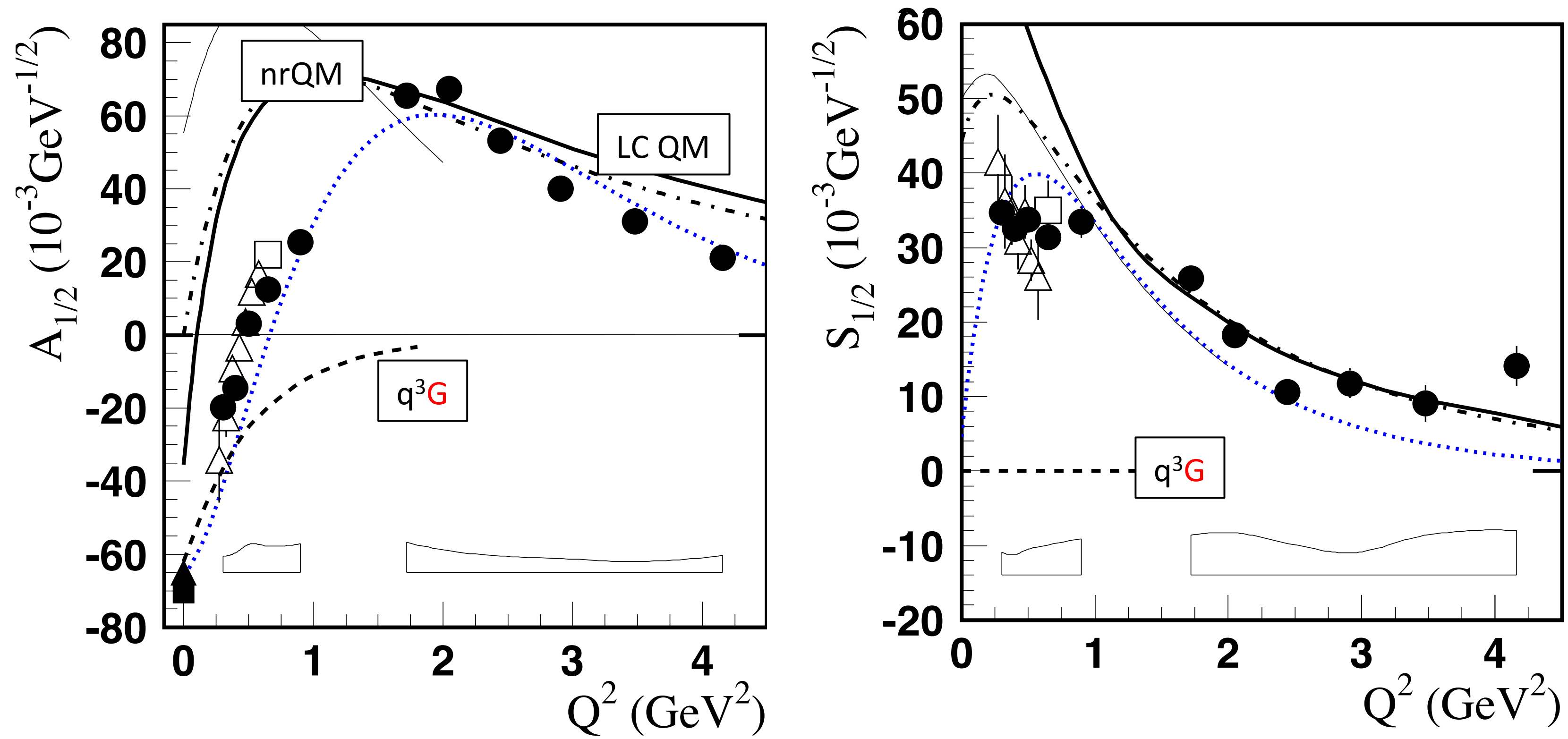
Quadrupole Ratios



- Large MB contributions (1/3) needed to describe magnetic dipole transition at $Q^2=0$
- For G^*_M the MB contribution are decreasing with increasing Q^2
- R_{EM} and R_{SM} well described with MB contributions only
- No approach to asymptotic behavior R_{EM} => +100%

Electrocouplings of 'Roper' N(1440)1/2+

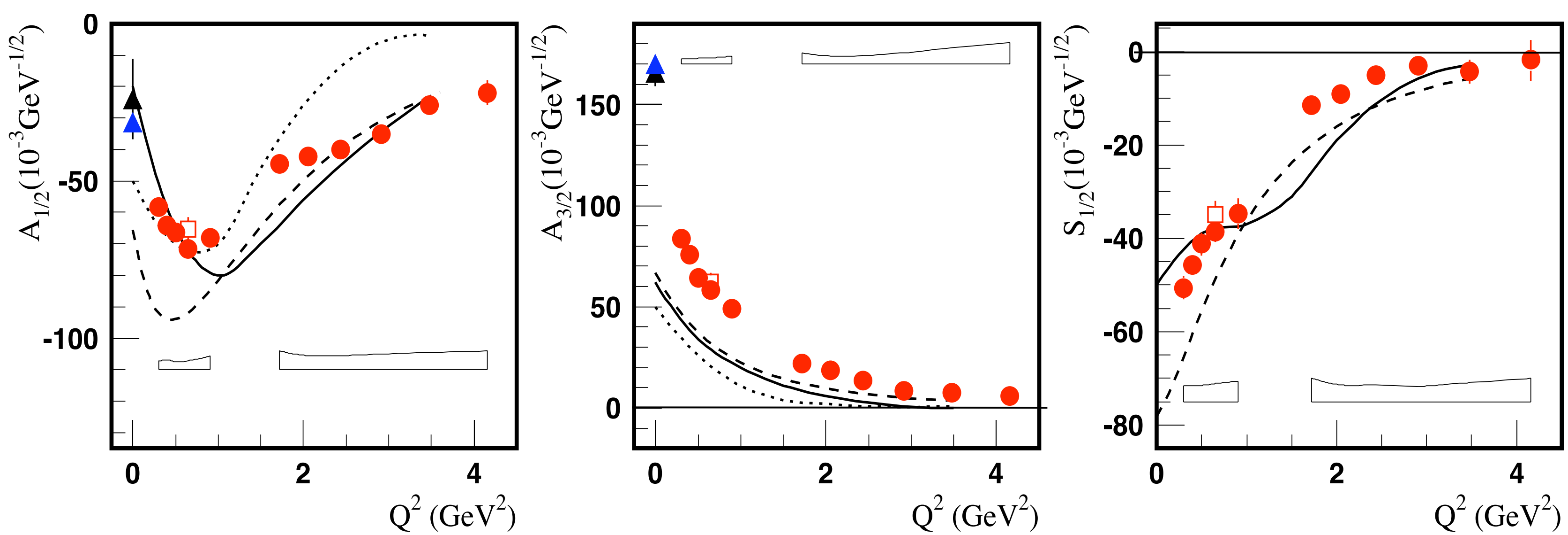
Aznauryan et al. (CLAS), PRC80, 055203 (2009), V. Mokeev et al. (CLAS), PRC86, 035203 (2012)

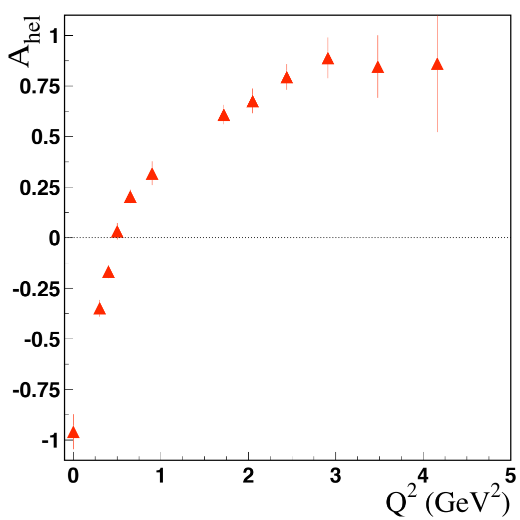


- nrQM assign it to the 1st radial excitation of the nucleon, but fails in $A_{1/2}$
- $A_{1/2}$ dominant amplitude at high Q^2 indicates radial q^3 excitation but fails at low Q^2
- Significant meson-baryon coupling needed to describe small Q^2 behavior

- $A_{1/2}(Q^2)$ and $S_{1/2}(Q^2)$ are inconsistent with gluonic excitation

Electrocouplings of N(1520)3/2$^-$





- First data set that enabled the determination of $S_{1/2}(Q^2)$
- Firmly established helicity switch from $A_{3/2}$ dominance at Q^2=0 to $A_{1/2}$ dominance at high Q^2
  => Stringent prediction of the CQM.

$$A_{hel} = \frac{(A_{1/2})^2 - (A_{3/2})^2}{(A_{1/2})^2 + (A_{3/2})^2}$$

From Q^2 dependence to charge densities

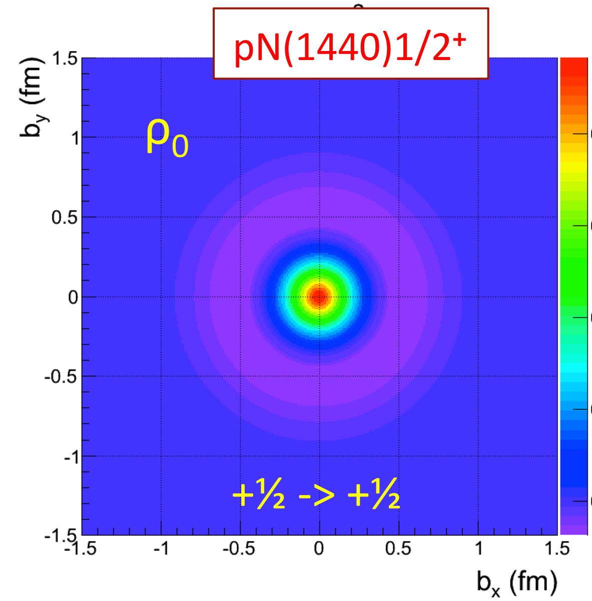
$$A_{1/2} = e\,\frac{Q_-}{\sqrt{K}\,(4M_N M^*)^{1/2}}\left\{F_1^{NN^*} + F_2^{NN^*}\right\},$$

$$S_{1/2} = e\,\frac{Q_-}{\sqrt{2K}\,(4M_N M^*)^{1/2}}\left(\frac{Q_+Q_-}{2M^*}\right)\frac{(M^*+M_N)}{Q^2}\left\{F_1^{NN^*} - \frac{Q^2}{(M^*+M_N)^2}F_2^{NN^*}\right\}$$

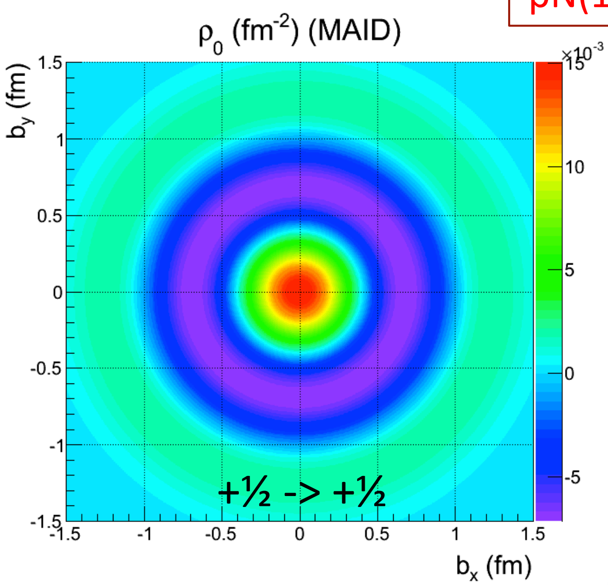
L. Tiator, M. Vanderhaeghen, PLB 672 (2009) 344

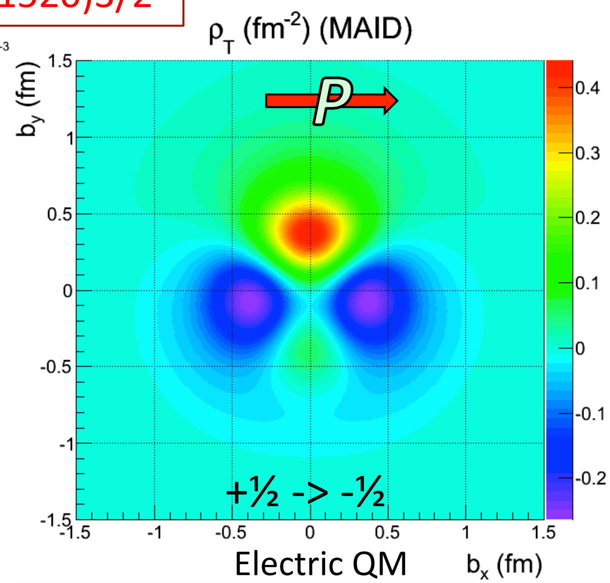
$$\rho_0^{NN^*}(\vec{b}) = \int_0^\infty \frac{dQ}{2\pi} Q\, J_0(b\,Q) F_1^{NN^*}(Q^2)$$

$$\rho_T^{NN^*}(\vec{b}) = \rho_0^{NN^*}(b) + \sin(\phi_b - \phi_S) \int_0^\infty \frac{dQ}{2\pi}\frac{Q^2}{(M^*+M_N)} J_1(b\,Q) F_2^{NN^*}(Q^2)$$

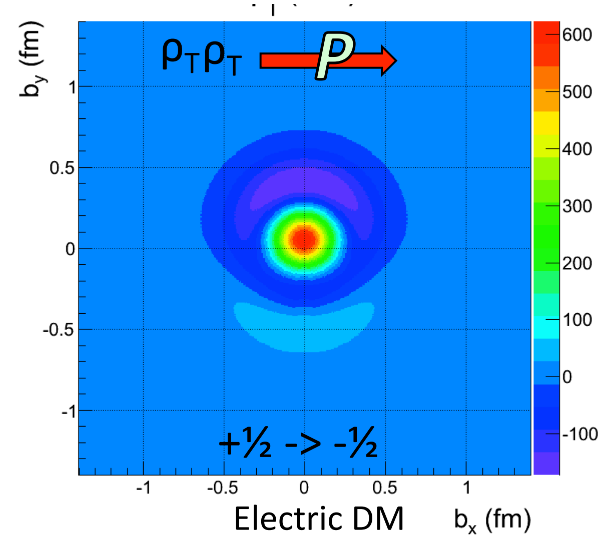


pN(1520)3/2-



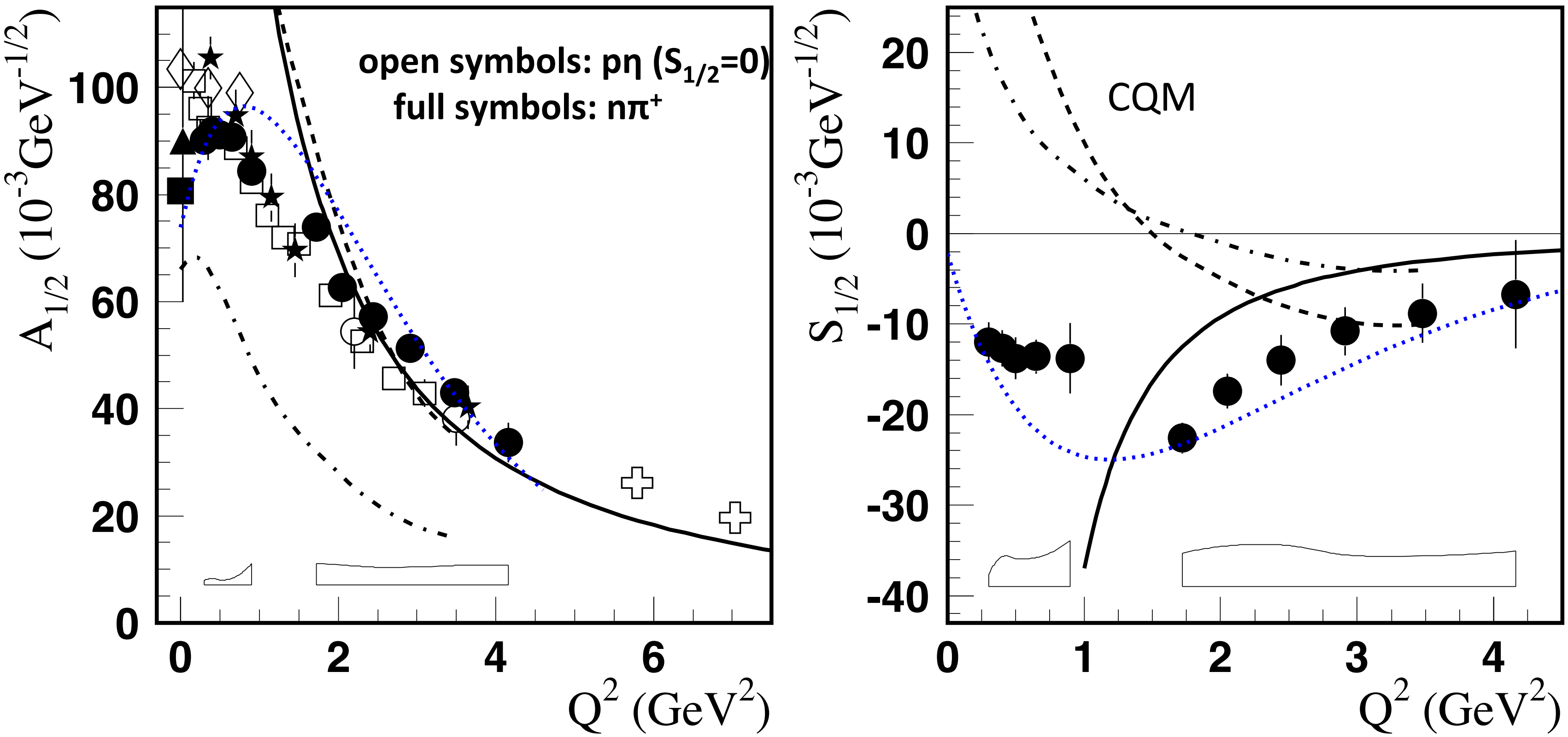


Electric QM



Electric DM

Electrocouplings of the N(1535)1/2^{-}



- Dynamical model analyses show the state may have a significant coupling to KΛ and pϕ which could indicate sizeable qqqs-sbar component in the w.f.
- Could explain the mass ordering, the large pη branching ratio, and sign of $S_{1/2}$ at low Q^2.

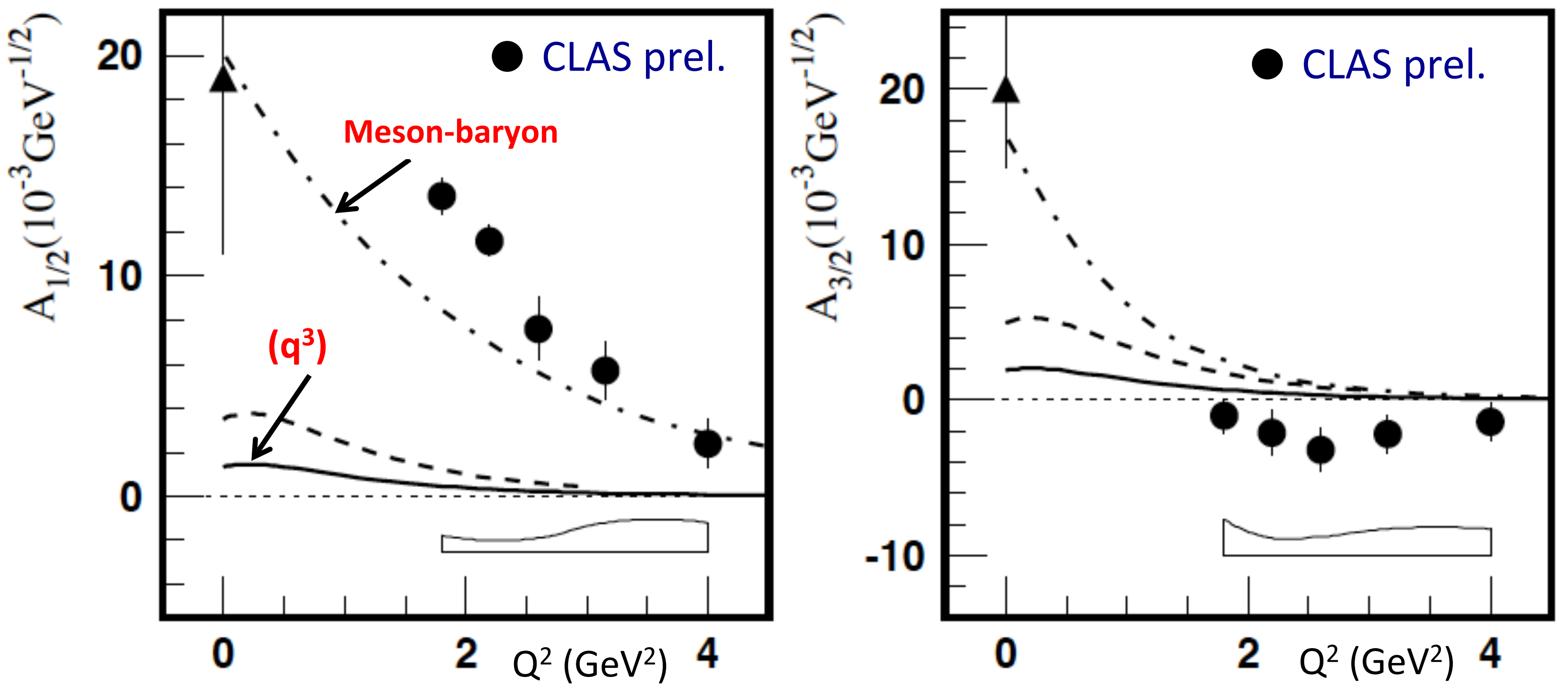
- **Are there N* states with significant N*-> pϕ coupling, similar to N(1535)1/2^{-} -> Nη ?**

  => Include high statistics γp-> pϕ data in coupled-channel PWA.

Meson-Baryon contributions to N(1675)5/2⁻

Quark components to the helicity amplitudes of the N(1675)5/2⁻ are strongly suppressed for proton target.

Single Quark Transition:
$A^p_{1/2} = A^p_{3/2} = 0$



- Measures the meson-baryon contribution to γ*pN(1675)5/2⁻ directly
- Calibrate the dynamical coupled-channel model input

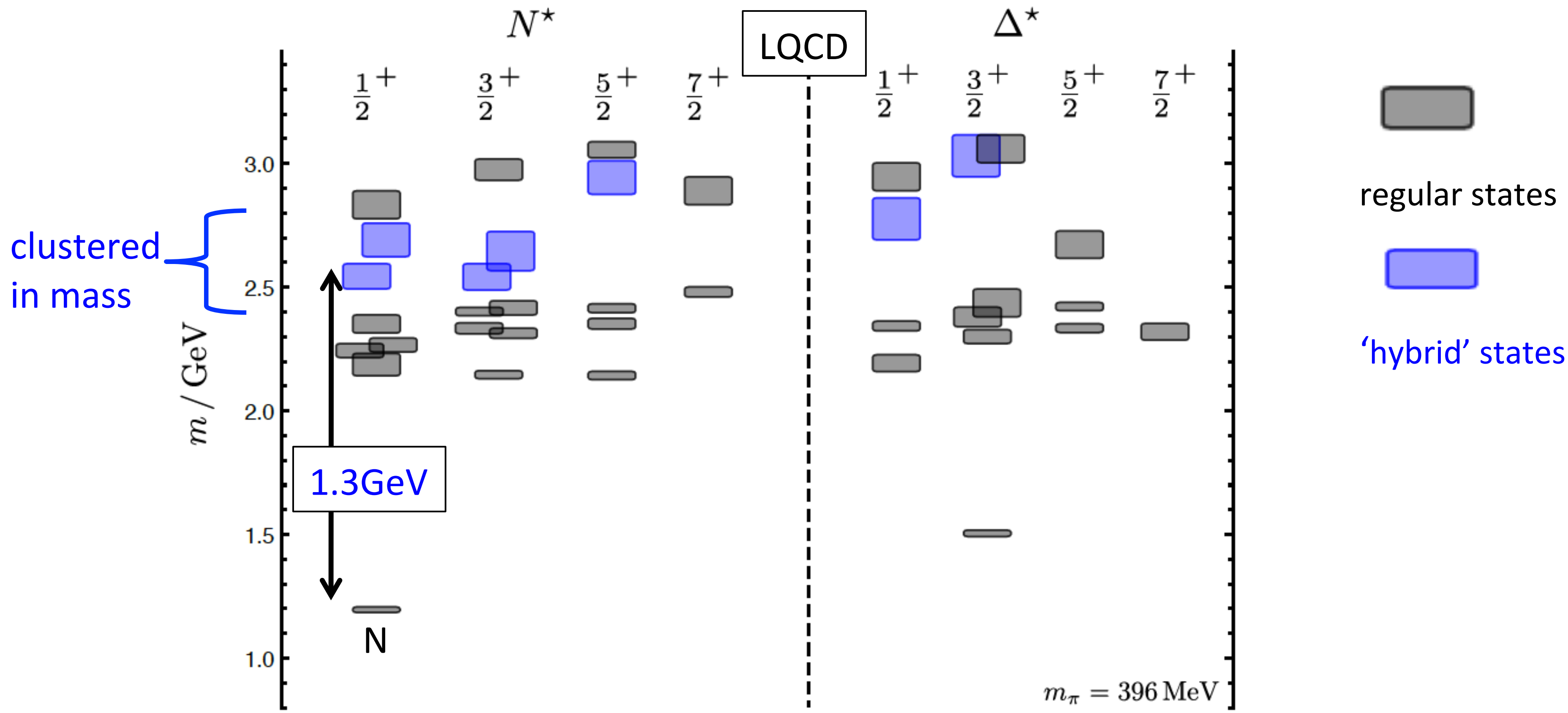
——— *E. Santopinto and M. M. Giannini, PRC 86, 065202 (2012)*

— · — · *B. Juliá-Díaz, T.-S.H. Lee, et al., PR C 77, 045205 (2008)*

Gluonic Baryons q^3G

J.J. Dudek and R.G. Edwards, PRD85 (2012) 054016

T. Barnes and F.E. Close, PLB128, 277 (1983)



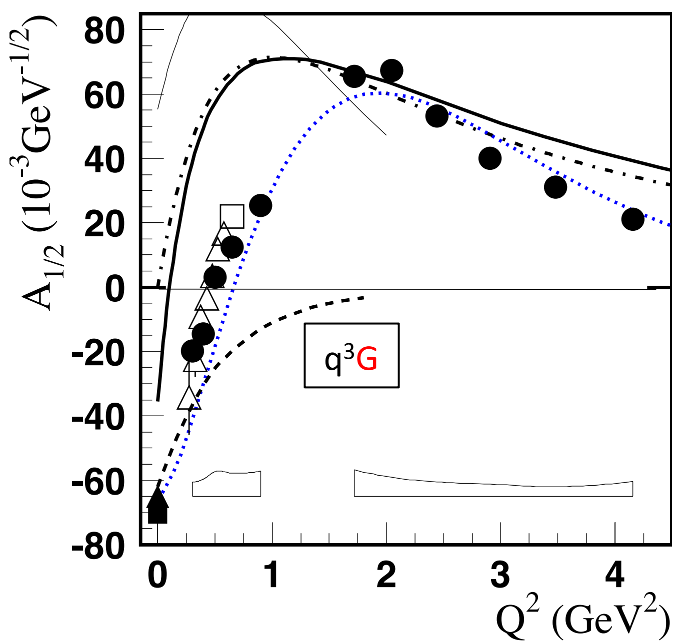
Hybrid states have same J^P values as q^3 baryons. How to identify them?

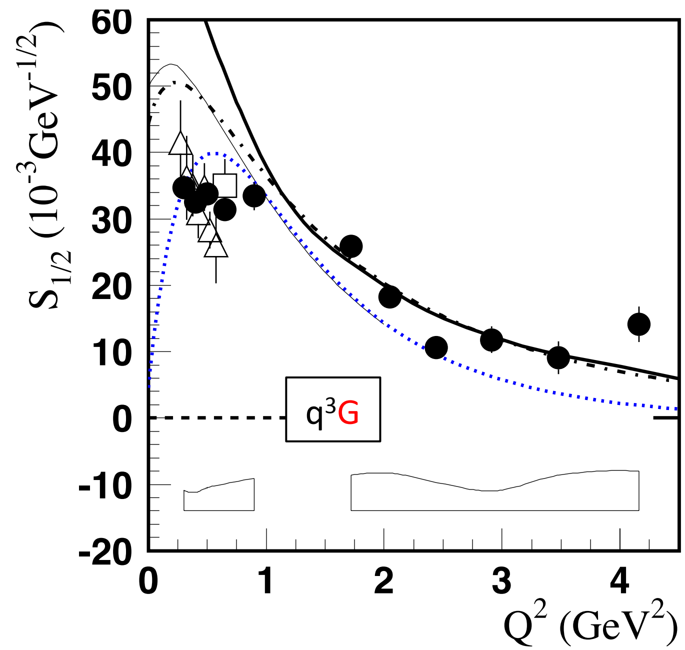
- Overpopulation of $N1/2^+$ and $N3/2^+$ states compared to QM projections?
- Transition form factors in electroproduction?

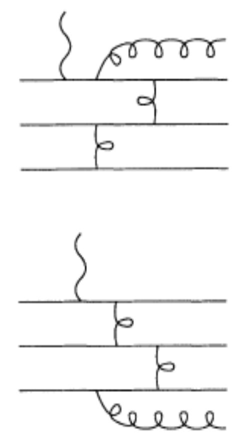
Separating q^3G from q^3 states?

Z.P. Li, V. Burkert, Zh. Li, PRD 46, 70, 1992; C.E. Carlson, N. Mukhopadhyay, PRL 67, 3745, 1991

Lowest mass $|q^3G>$ with $J^P=1/2^+$ behave like the Δ(1232)







For higher mass gluonic "Roper" $A_{1/2}(Q^2)$ expected to drop very fast with Q^2, and $S_{1/2}(Q^2) = 0$

Conclusions

- Evidence for many new states revealed in coupled-channel analysis involving high precision $K\Lambda$ and $K\Sigma$ photoproduction reactions.
- Meson photoproduction is reaching the "holy grail" of complete measurements, allowing major advances in the search for new states.
- For access to high mass excited nucleon states precision vector meson production data need to be incorporated in coupled-channel analyses.
- Meson electroproduction reveals strength of quark and meson-baryon degrees of freedom in N* transitions and could be essential to identify hybrid baryons.
- Transverse transition densities reveal complex charge distributions. High Q^2 data are needed to access the short distance behavior that is most uncertain.