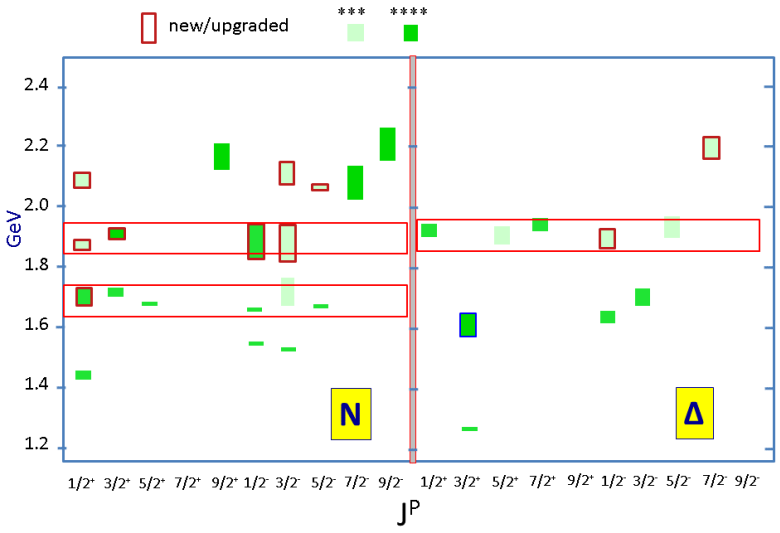
New Baryon States from Exclusive Meson Photo- and Electroproduction

New states from exclusive meson photoproduction off protons



Additional new state N'(1720)3/2$^+$ from $\pi^+\pi^-$p photo- and electroproduction off protons

Resonances at W ~ 1.7 GeV	Mass, GeV	Total width, MeV
N'(1720)3/2$^+$	1.715-1.735	120±6
N(1720)3/2$^+$	1.743-1.753	112±8

Resonances	BF($\pi\Delta$), %	B(ρp), %
N'(1720)3/2$^+$	47-64	3-10
N(1720)3/2$^+$	39-55	23-49

V.I. Mokeev
Jefferson Laboratory

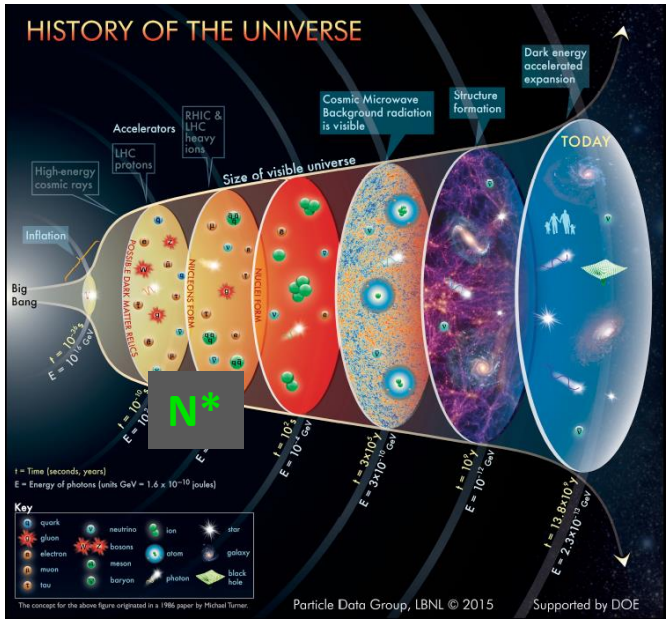
Talk Outline:

- N* spectrum and insight into strong QCD
- New N* states from exclusive meson photoproduction off protons
- Evidence for new N'(1720)3/2$^+$ baryon state
- Insight into the structure of new baryon states

Office of Science

CLAS Collaboration Meeting, March 5-8, 2019 Newport News, VA

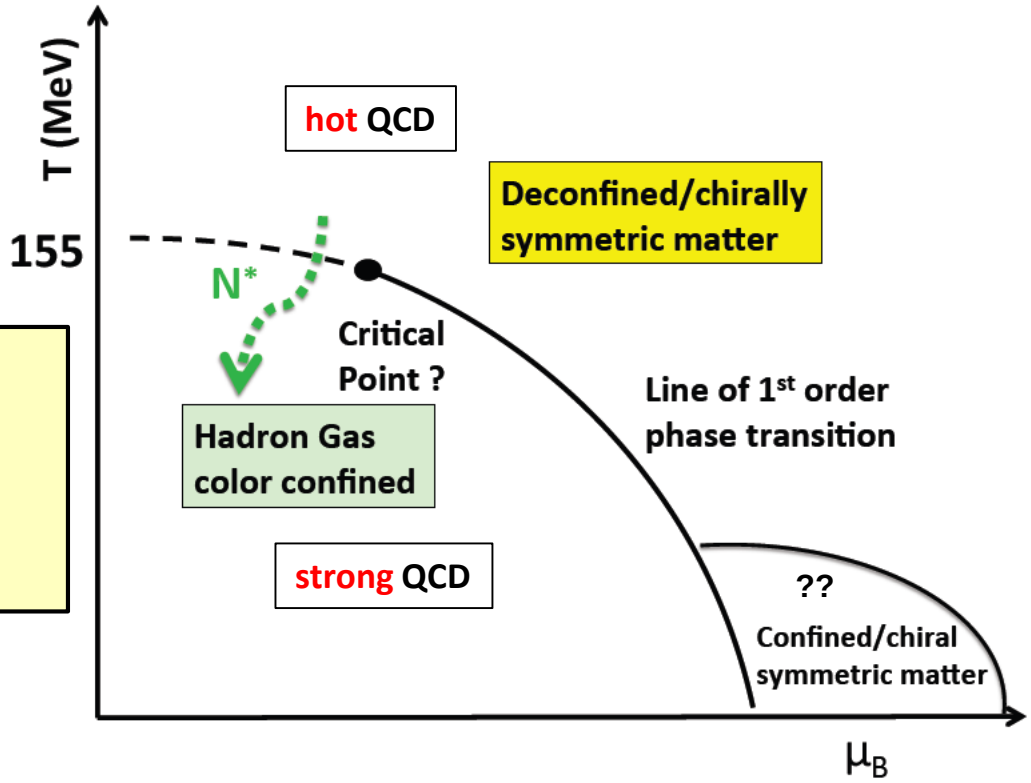
Nucleon Resonances in the Emergence of Hadron Matter and Strong QCD



Dramatic events occurred in the micro-second old universe during the transition from the deconfined quark and gluon phase to the hadron phase

- Quark-gluon confinement emerges
- Chiral symmetry of QCD is broken
- Quarks and gluons acquire mass
- Baryon resonances occur

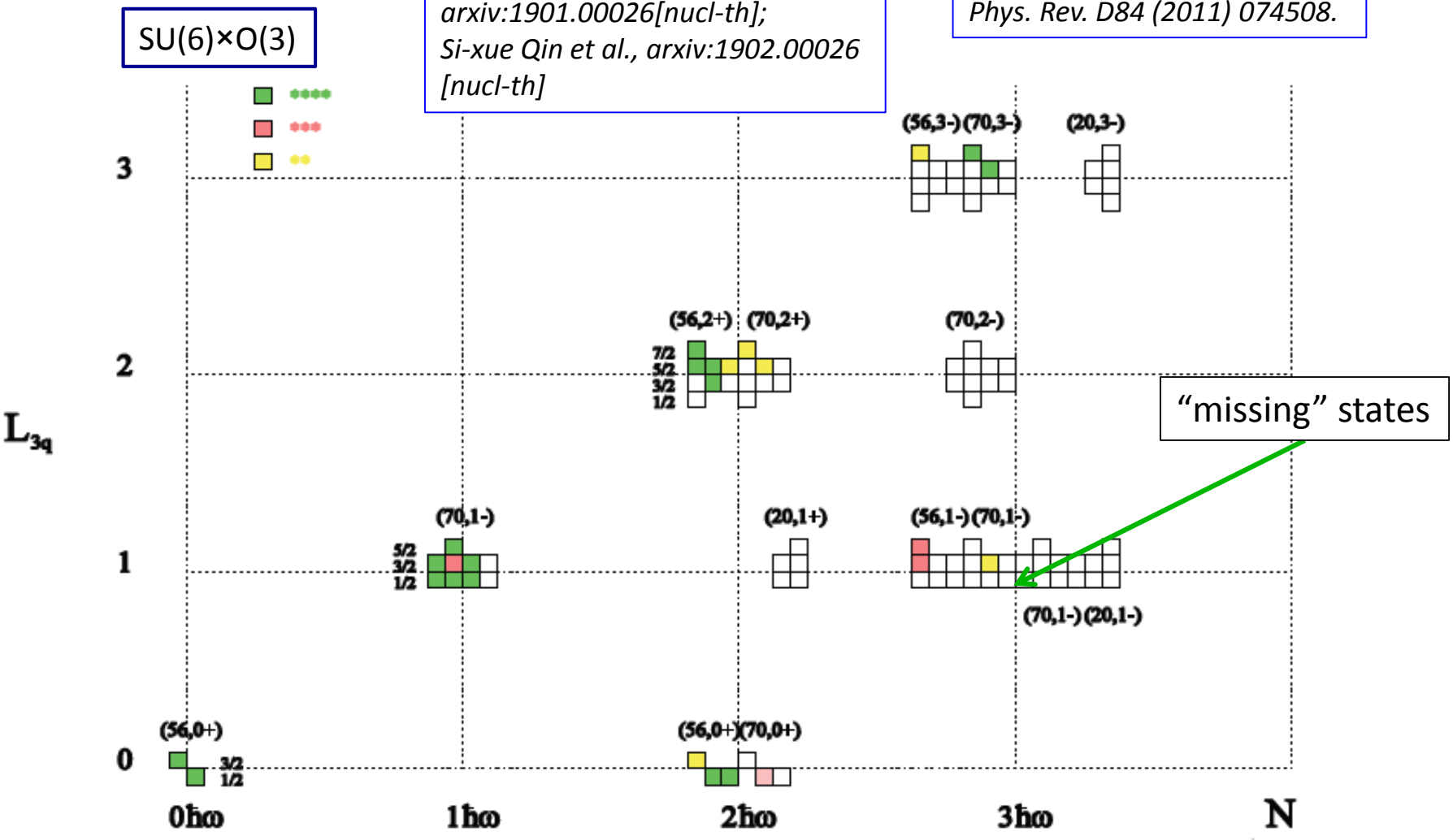
This transition was shaped by the full baryon spectrum



SU(6)xO(3) Spin-Flavor Symmetry and ``Missing" Resonances

Continuum QCD: Chen Chen et al., arxiv:1901.00026[nucl-th]; Si-xue Qin et al., arxiv:1902.00026 [nucl-th]

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



Studies of the N*-spectrum were driven by a guess for the ``missing" baryon states expected from the underlying SU(6)xO(3) symmetry and supported by lattice/continuum QCD exploratory results on the N* spectrum

N* Spectrum and Symmetries of Strong QCD

- Studies of the excited nucleon state spectrum offers access to the approximate symmetries underlying the generation of N* states in the strong QCD regime

- They allow us to explore whether almost exact at ~GeV mass scale chiral symmetry of QCD evolves into approximate O(3)xSU(6) symmetry, when the orbital momentum conservation imposed by O(3)-symmetry breaks the chiral symmetry, making the existence of the parity-doublet states, as required by chiral symmetry, impossible

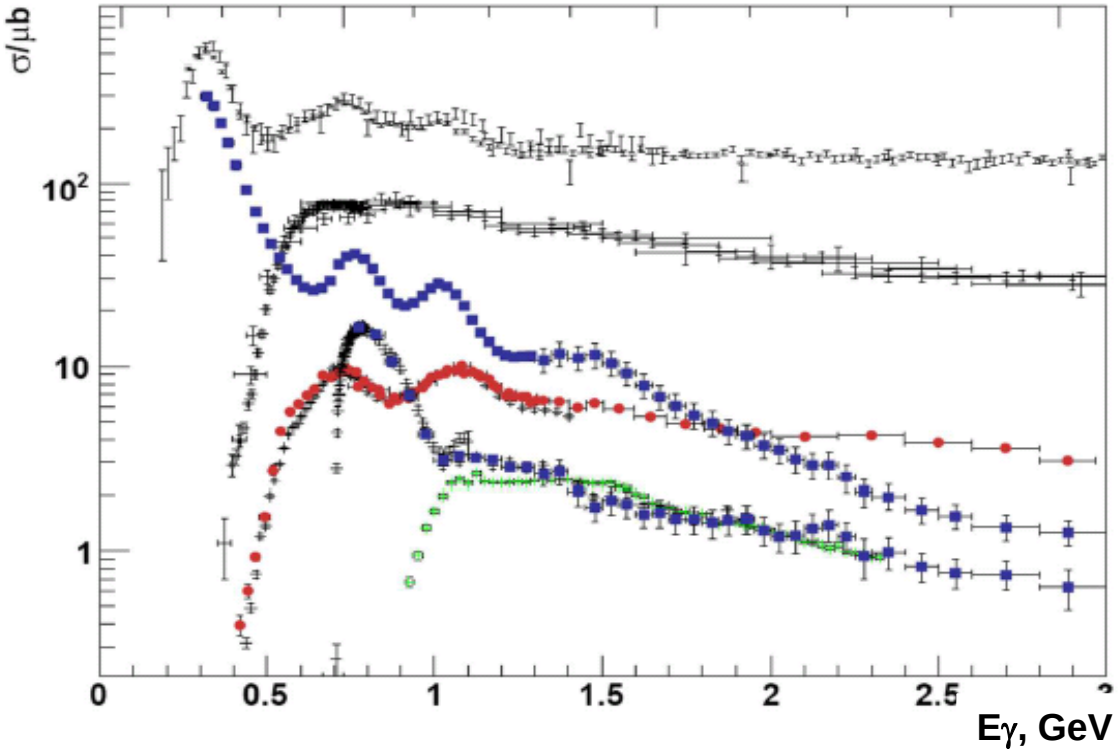
- If it is the case, then we have to observe more excited nucleon states than have been reported in the PDG 2016 listing

Exclusive Photoproduction in the Nucleon Resonance Region

Common effort at ELSA, JLab and MAMI.

Combination of continuous electron beams and detectors of ~4π acceptance allows us to determine types of all final state particles and their 4-momenta in each reaction

Most exclusive photoproduction channels in the resonance region were studied



2-Body Photoproduction off Protons: Data and Analysis Approaches

✓ - *data acquired* ✓ - *analyzed/published*

Observable	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
$p\pi^0$	✓	✓	✓		✓	✓	✓	✓								
$n\pi^+$	✓	✓	✓		✓	✓	✓	✓								
$p\eta$	✓	✓	✓		✓	✓	✓	✓								
$p\eta'$	✓	✓	✓		✓	✓	✓	✓								
$K^+\Lambda$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^+\Sigma^0$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^{+*}\Lambda$	✓			✓					SDME							
$K^{0*}\Sigma^+$	✓	✓									✓	✓	SDME			

clas

$\gamma p \rightarrow X$

Coupled-channel approaches for N* parameter extraction from exclusive meson photoproduction data off the proton

Bonn-Gatchina **A.V. Anisovich et al., Eur. Phys. J. A53, 242 (2017).**
A.V. Anisovich et al., Eur. Phys. J. A50, 129 (2014).
A.V. Anisovich et al., Eur. Phys. J. A48, 15 (2012).

Argonne-Osaka **H. Kamano et al., Phys. Rev. C94, 015201 (2016).**
H. Kamano et al., Phys. Rev. C88, 035209 (2013).

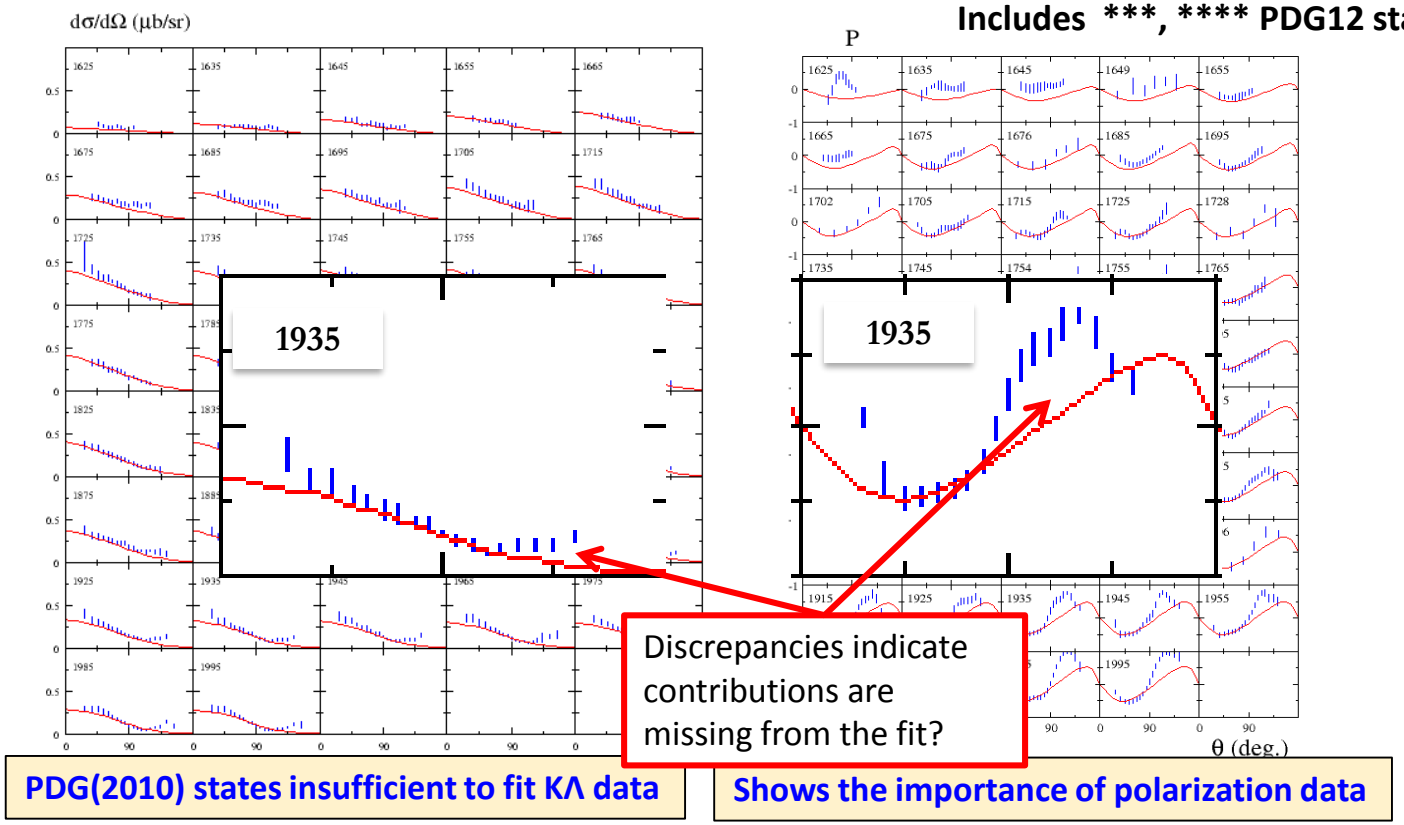
GWU-Julich D. Rönchen et al., Eur. Phys. J. A51, 70 (2015).
D. Rönchen et al., Eur. Phys. J. A50, 101 (2014).

Establishing the N* Spectrum

Hyperon photoproduction $\gamma p \rightarrow K^+\Lambda \rightarrow K^+ p\pi^-$ from CLAS

ANL-Osaka 8 coupled-channel analysis

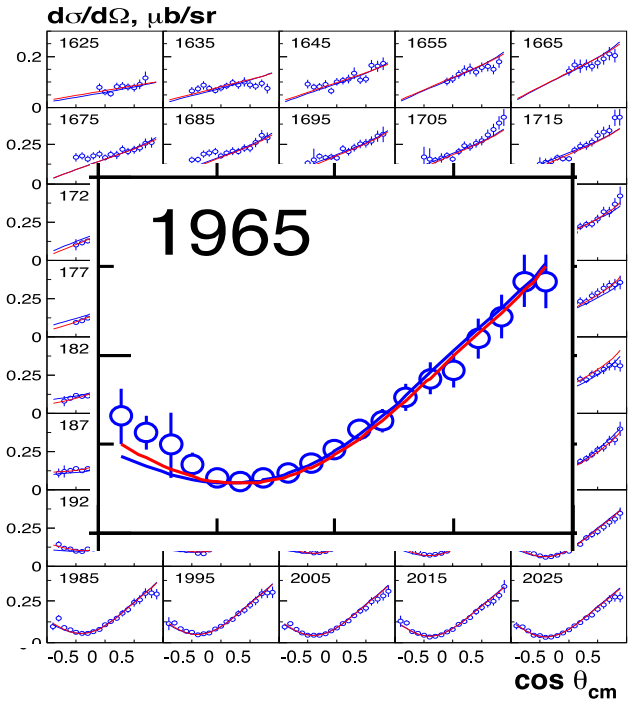
Includes *, **** PDG12 states**



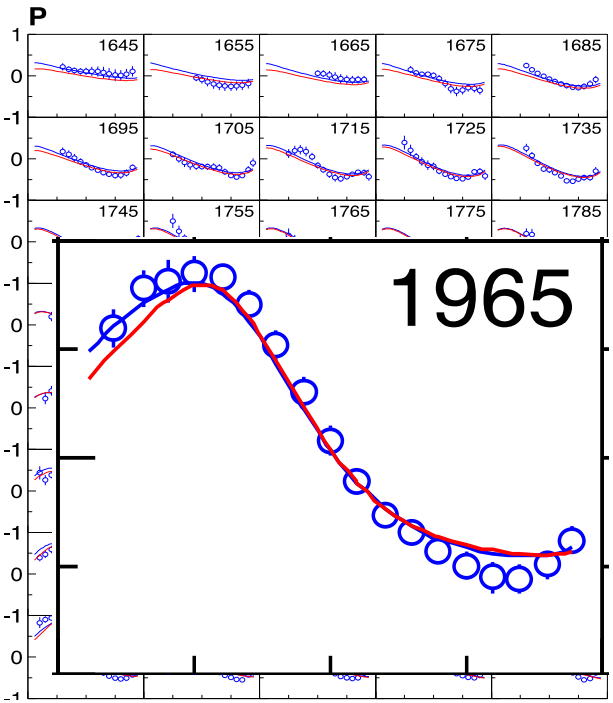
Establishing the N* Spectrum, cont'd

Hyperon photoproduction $\gamma p \rightarrow K^+ \Lambda \rightarrow K^+ p \pi^-$ from CLAS

Bonn-Gatchina multichannel analysis:
9 new resonances were included



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



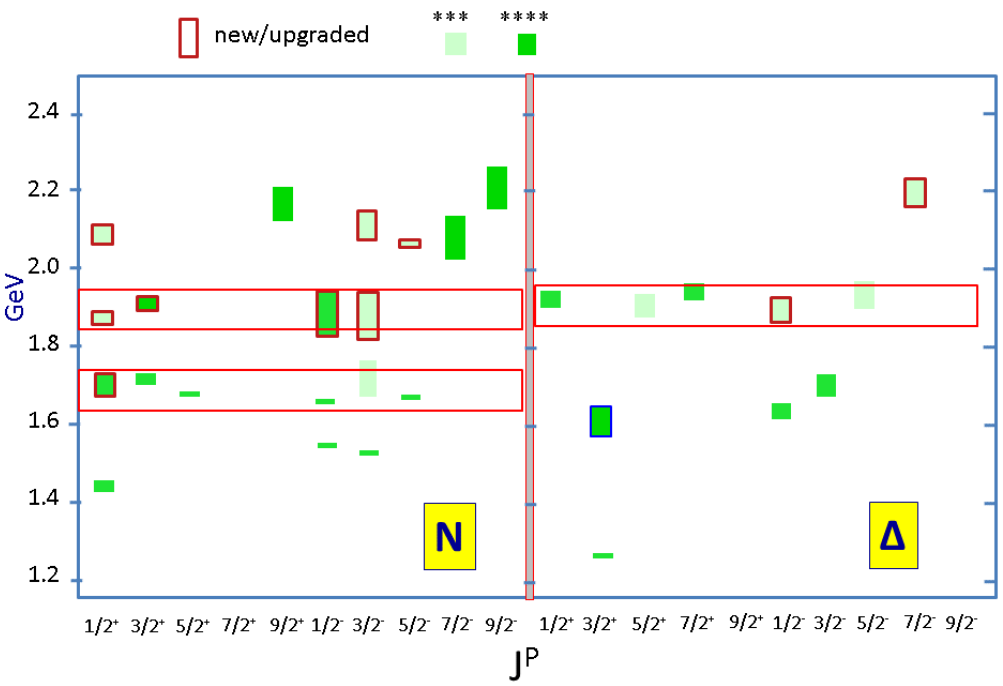
A.V. Anisovich et al, EPJ A48, 15 (2012)

Advances in Exploration of the N*-Spectrum

Several new nucleon resonances were established in a global multi-channel analysis of exclusive photoproduction data

Challenging milestone on ``missing" resonance discovery has been achieved !

N^*/Δ^* Spectrum 2018



Nucleon resonances listed in Particle Data Group (PDG) tables

State $N(mass)J^P$	PDG pre 2012	PDG 2018*
$N(1710)1/2^+$	***	****
$N(1880)1/2^+$		***
$N(1895)1/2^-$		****
$N(1900)3/2^+$	**	****
$N(1875)3/2^-$		***
$N(2100)1/2^+$	*	***
$N(2120)3/2^-$		***
$N(2000)5/2^+$	*	**
$N(2060)5/2^-$		***
$\Delta(1600)3/2^+$	***	****
$\Delta(1900)1/2^-$	**	***
$\Delta(2200)7/2^-$	*	***

Description of the exclusive electroproduction data off the proton with the same masses and hadronic decay widths as in photoproduction will validate the existence of new baryon states.

Combined studies of the $\pi^+\pi^-p$ photo-/electroproduction off proton CLAS data revealed evidence for the existence of a new $N'(1720)3/2^+$ baryon state in addition to those listed above.

Interpretation of the Structure at W~1.7 GeV in $\pi^+\pi^-$p Electroproduction

M. Ripani et al., CLAS Collaboration
Phys. Rev. Lett. 91, 022002 (2003)

..... *conventional states only, consistent with PDG 02*

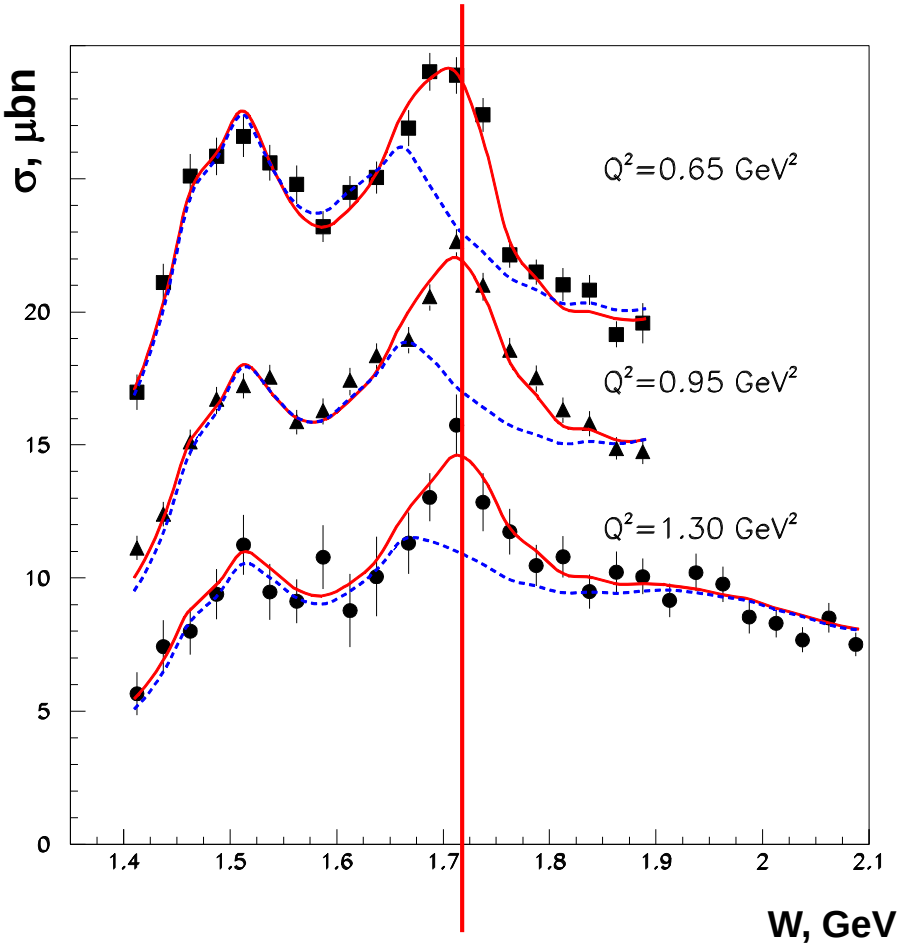
——— *implementing N'(1720)3/2⁺ candidate or conventional states only with different N(1720)3/2⁺ Nππ decays than in PDG 02*

Two equally successful ways for the data description:
different than in PDG 02' N(1720)3/2⁺ Nππ hadronic decay widths:

	$\Gamma_{tot,}$ MeV	BF(πΔ) %	BF(ρp) %
N(1720)3/2⁺ decays fit to the CLAS Nππ data	**126±14**	**64-100**	**<5**
N(1720)3/2⁺ PDG 02'	**150-300**	**<20**	**70-85**

new N'(1720)3/2⁺ state and consistent with PDG 02' Nππ hadronic decays of the regular N(1720)3/2⁺:

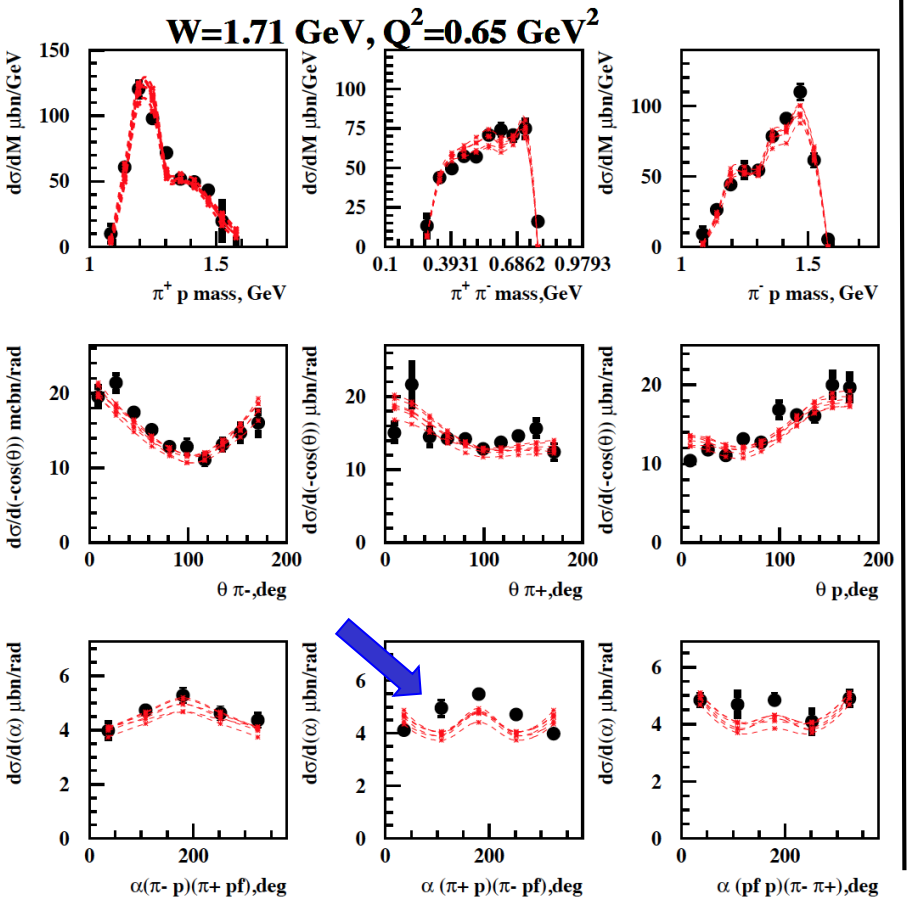
	$\Gamma_{tot,}$ MeV	BF(πΔ) %	BF(ρp) %
N'(1720)3/2⁺ New	**119±6**	**47-64**	**3-10.**
N(1720)3/2⁺ Conventional	**112±8**	**39-55**	**23-49**



Analysis of the ep→ $\pi^+\pi^-$p CLAS data at W~1.7 GeV in the JM model

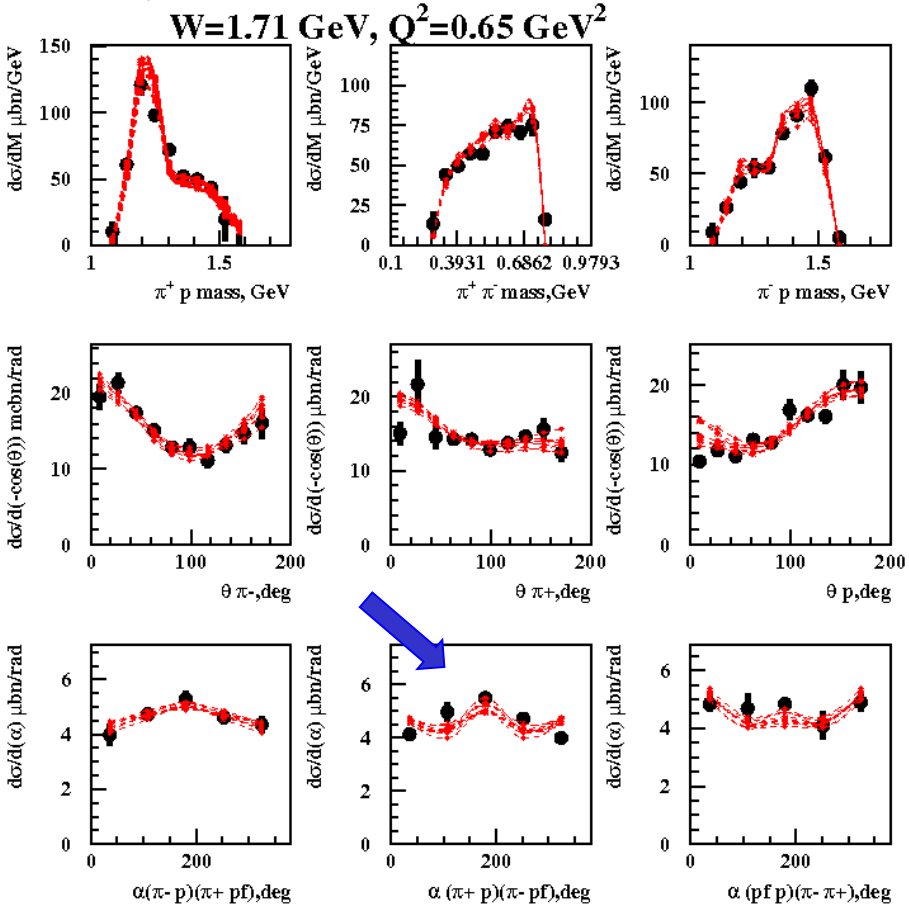
conventional N*-states with $\pi\Delta$, ρp couplings fit to the data

$2.85<\chi^2/d.p.<3.03$ (1.66 GeV<W<1.76 GeV)



N'(1720)3/2$^+$ candidate state is included in the fit

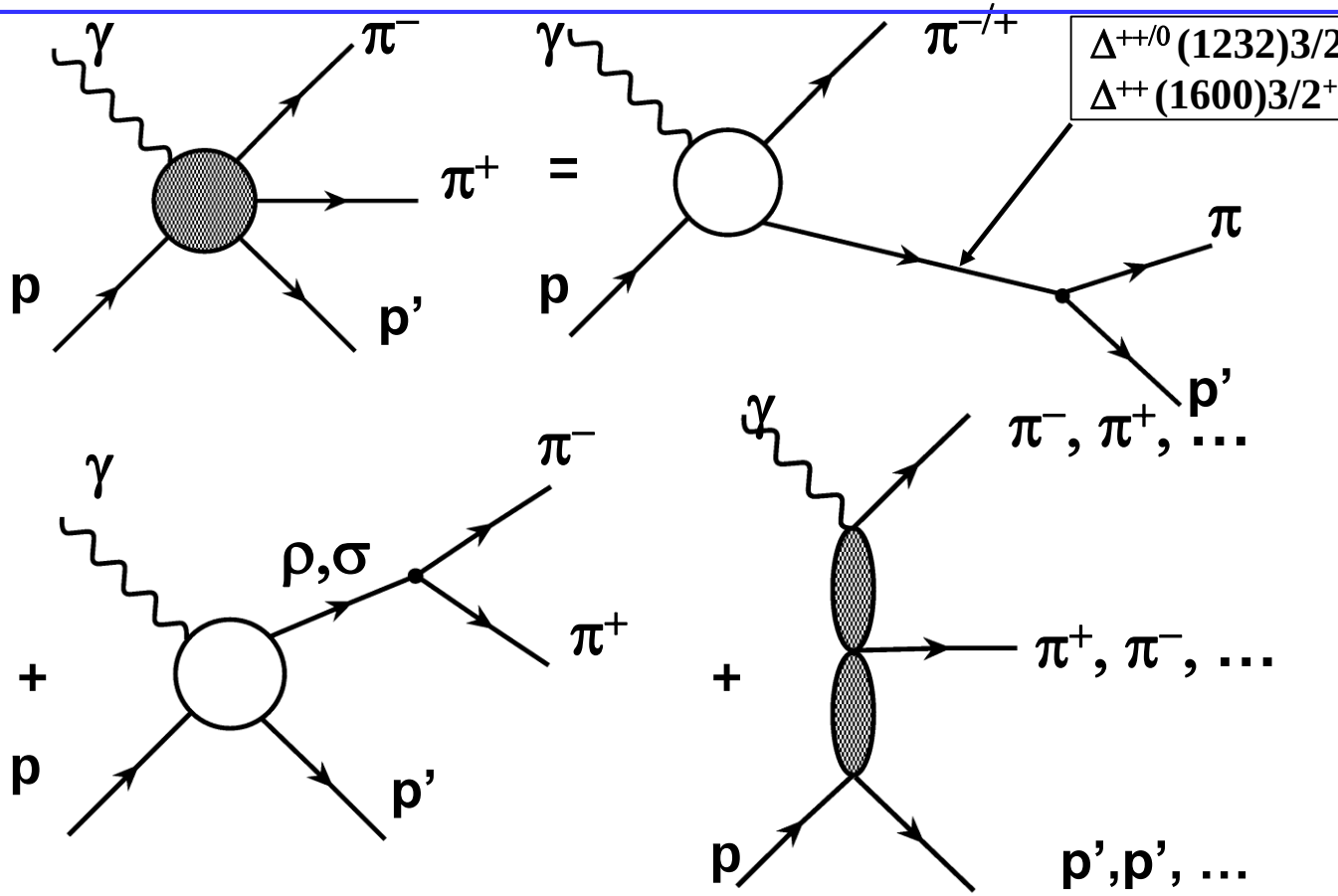
$2.56<\chi^2/d.p.<2.80$ (1.66 GeV<W<1.76 GeV)



- Fit of $\theta_{\pi-}$, $\theta_{\pi+}$, θ_p angular distributions requires essential contribution(s) from the resonance(s) of $J^\pi=3/2^+$.
- Single state of $J^\pi=3/2^+$ should have major $\pi\Delta$ (>60%) and minor ρp (<5%) decays in order to reproduce pronounced Δ–peaks in π^+p and to avoid ρ-peak formation in the $\pi^+\pi^-$ mass distributions.

JM Model for Analysis of $\pi^+\pi^-$p Photo-/Electroproduction

Major objectives: extraction of $\gamma_{r,v}$pN* photo-/electrocouplings and $\pi\Delta$, ρp decay widths



- five channels with unstable intermediate meson/baryon and direct $\pi^+\pi^-$p production;
- N* contribute to $\pi\Delta$ and ρp channels only;
- unitarized Breit-Wigner ansatz for resonant amplitudes;
- phenomenological parameterization of the other meson-baryon channel amplitudes (see Ref. 2)

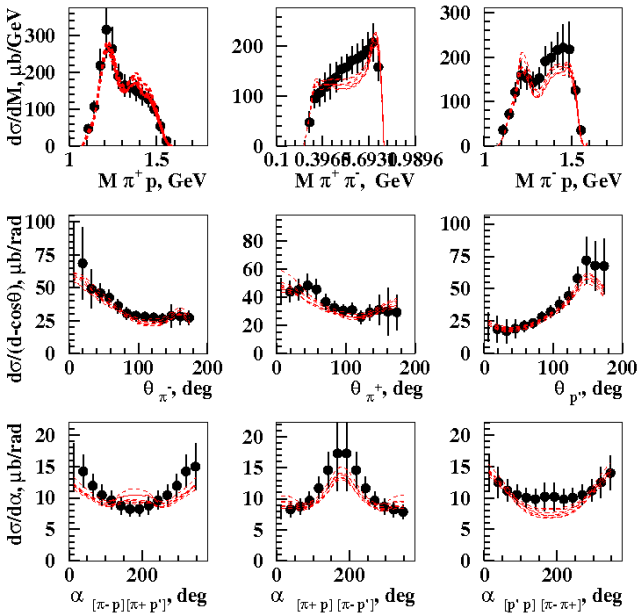
1. V.I. Mokeev, V.D. Burkert et al., (CLAS Collaboration) Phys. Rev. C86, 035203 (2012).
2. V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C80, 045212 (2009).
3. V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C93, 025206 (2016).

Good description of $\pi^+\pi^-$p photo-/electroproduction off protons cross sections at 1.4 GeV<W<2.0 GeV and 0.2 GeV^2<Q^2<5.0 GeV^2

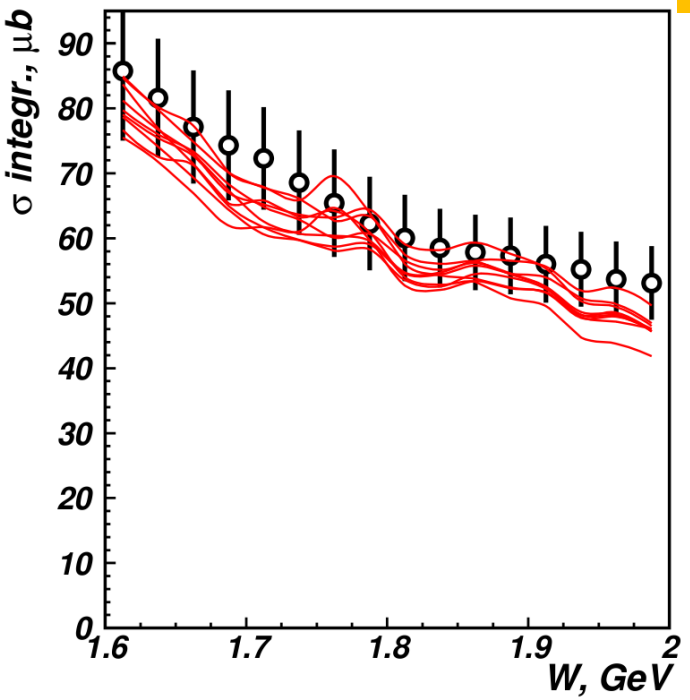
Description of the CLAS $\pi^+\pi^-$p Photoproduction off Protons Data with/without the New State N'(1720)3/2$^+$

One-fold differential cross sections

W=1.71 GeV



Fully integrated cross sections



E.N. Golovach et al., CLAS Collaboration, Phys. Lett. B 788, 371 (2019).

Almost the same quality of the photoproduction data fit was achieved with and without N'(1720)3/2$^+$ new state:

N(1720)3/2$^+$ and N'(1720)3/2$^+$ ⟶ 1.19 < χ^2/dp. < 1.28

N(1720)3/2$^+$ only ⟶ 1.08 < χ^2/dp. < 1.26

Would it be possible to describe photo- and electroproduction data with Q^2-independent resonance masses, the total and partial hadron decay width?

Evidence for the Existence of the New State N'(1720)3/2$^+$ from Combined $\pi^+\pi^-$p Analyses in both Photo- and Electroproduction

N(1720)3/2$^+$ hadronic decays from the CLAS data fit with conventional resonances only

	BF($\pi\Delta$), %	BF(ρp), %
electroproduction	64-100	<5
photoproduction	14-60	19-69

The contradictory BF values for N(1720)3/2$^+$ decays to the $\pi\Delta$ and ρp final states deduced from photo- and electroproduction data make it impossible to describe the data with conventional states only.

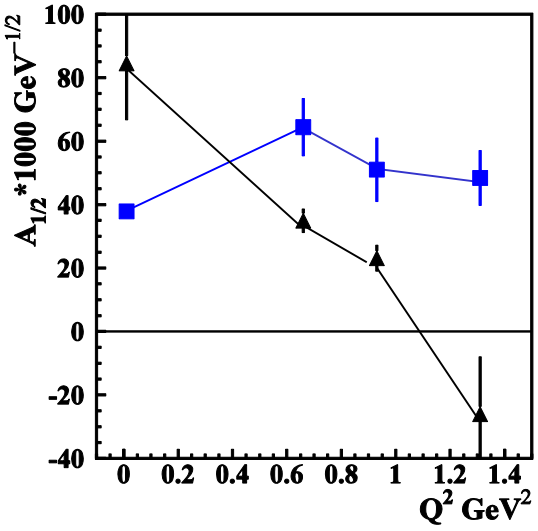
N* hadronic decays from the data fit that incorporates the new N'(1720)3/2$^+$ state

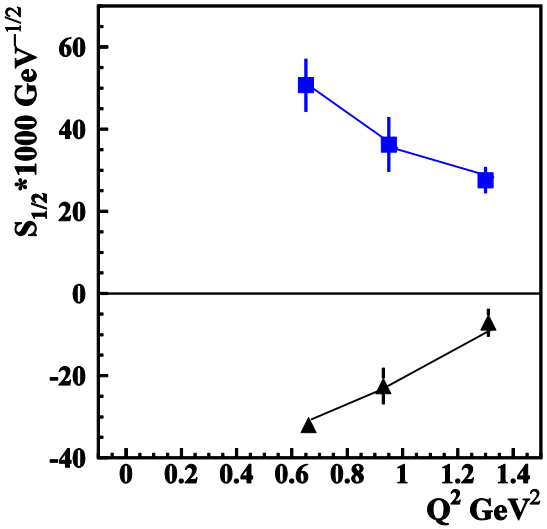
Resonance	BF($\pi\Delta$), %	BF(ρp), %
N'(1720)3/2$^+$ electroproduction photoproduction	 47-64 46-62	 3-10 4-13
N(1720)3/2$^+$ electroproduction photoproduction	 39-55 38-53	 23-49 31-46
Δ(1700)3/2$^-$ electroproduction photoproduction	 77-95 78-93	 3-5 3-6

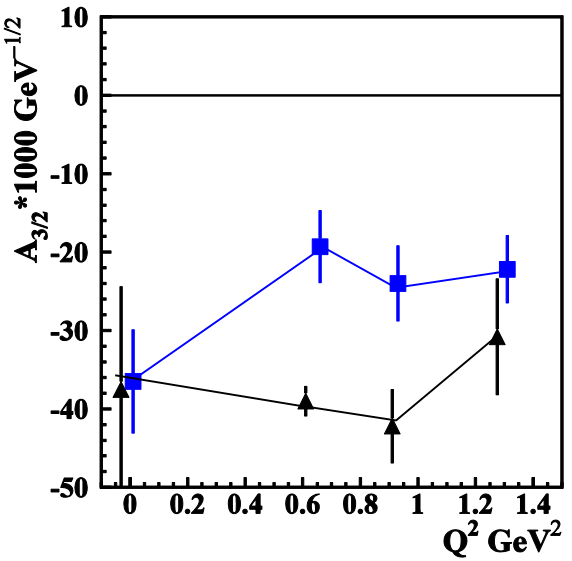
Successful description of $\pi^+\pi^-$p photo- and electroproduction data achieved by implementing new N'(1720)3/2$^+$ state with Q^2-independent hadronic decay widths of all resonances contributing at W~1.7 GeV provides strong evidence for the existence of new N'(1720)3/2$^+$ state.

The Parameters of New N'(1720)3/2$^+$ State from the CLAS Data Fit

The photo-/electrocouplings of N'(1720)3/2$^+$ and conventional N(1720)3/2$^+$ states:







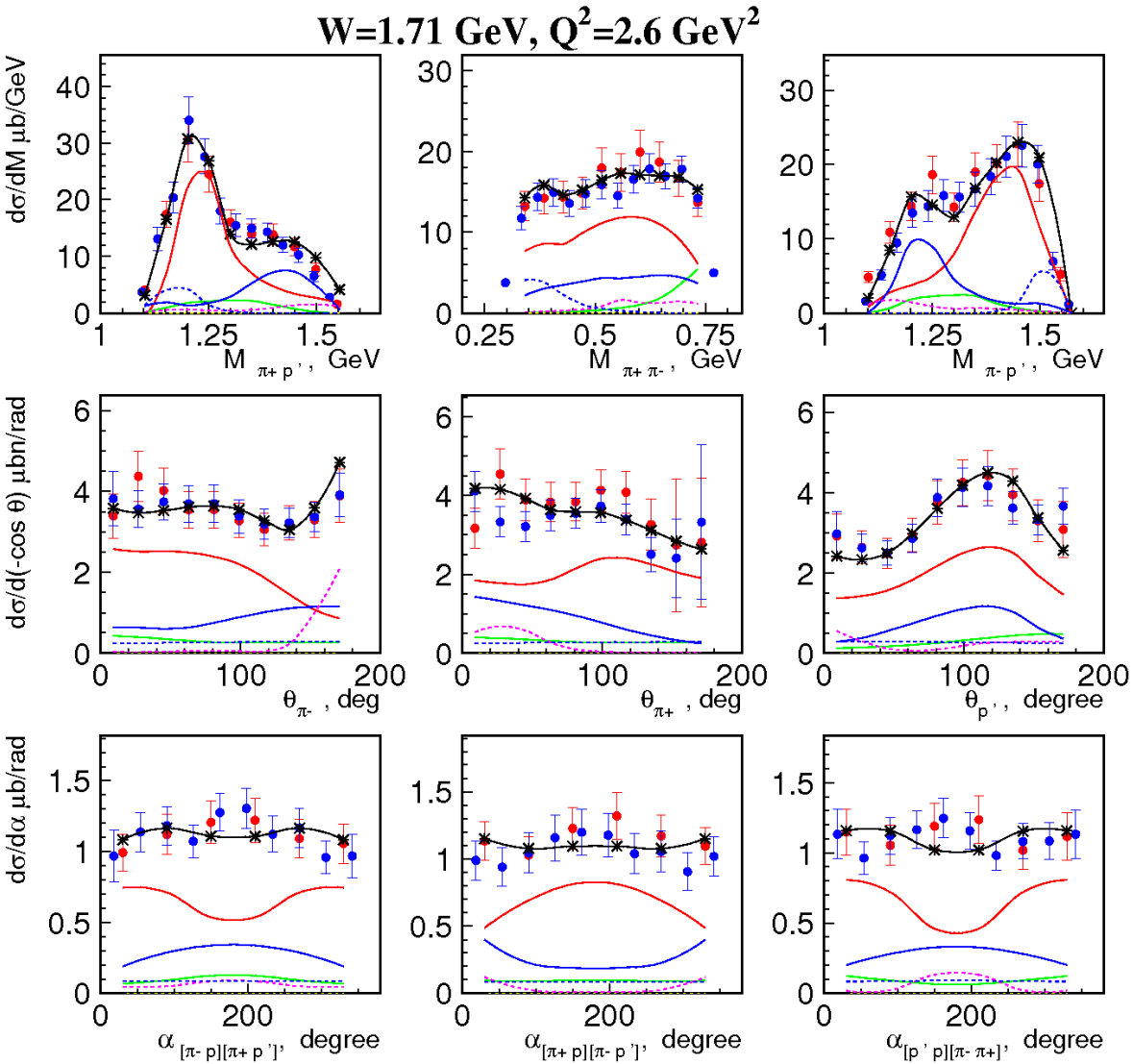
N'(1720)3/2$^+$

N(1720)3/2$^+$

Resonance	Mass, GeV	Total width, MeV
N'(1720)3/2$^+$	1.715-1.735	120±6
N(1720)3/2$^+$	1.743-1.753	112±8

Search for the N'(1720)3/2$^+$ in $\pi N \to \pi\pi N$ reactions in KEK/J-PARC-2012-3 experiment will further check the new state existence from independent results with the hadronic probe.

Extending the Kinematical Coverage of $\pi^+\pi^-$p Electroproduction off Proton Data



Two data sets at
1.40 GeV <W<2.0 GeV and
2.0 GeV² < Q² < 5.0 GeV² :

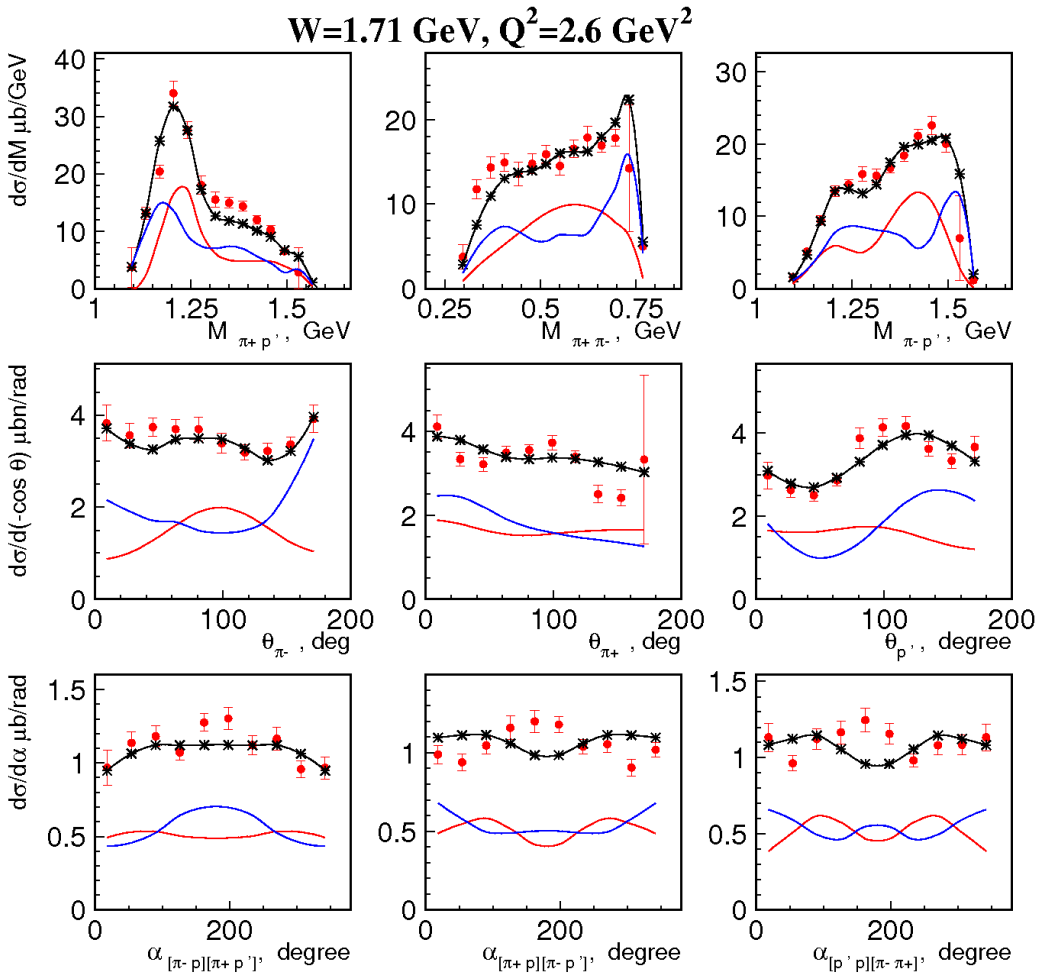
red - E. Isupov et al., CLAS Collaboration, Phys. Rev. C96, 025209 (2017) (MSU/Ohio U.).
blue - preliminary, A.Trivedi, R.W. Gothe (USC).

JM18 results:

- full JM
- ρp
- $\pi^-\Delta^{++}$
- $\pi^+\Delta^0$
- π^+ N(1520)3/2⁻
- π^+ N(1680)5/2⁺

The JM18 model offers a good description of both $\pi^+\pi^-$p electroproduction off protons data sets

Future Extension of the Results on N'(1720)3/2$^+$ Electrocouplings



JM18 model version adjusted to the preliminary A.Trivedi & R.W. Gothe analysis results

Resonant contributions

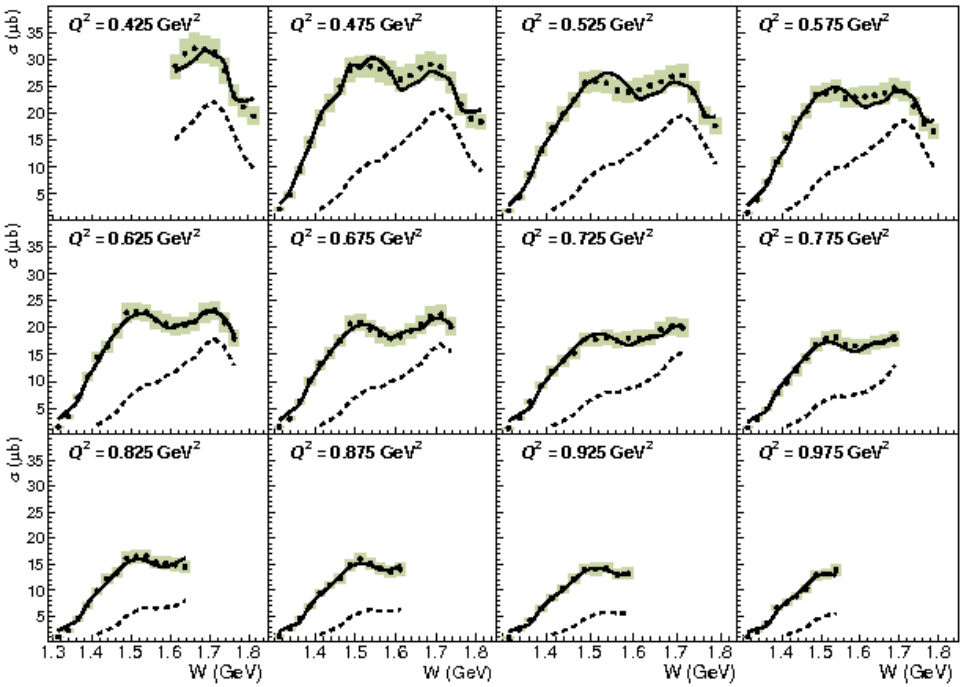
Non-resonant contributions

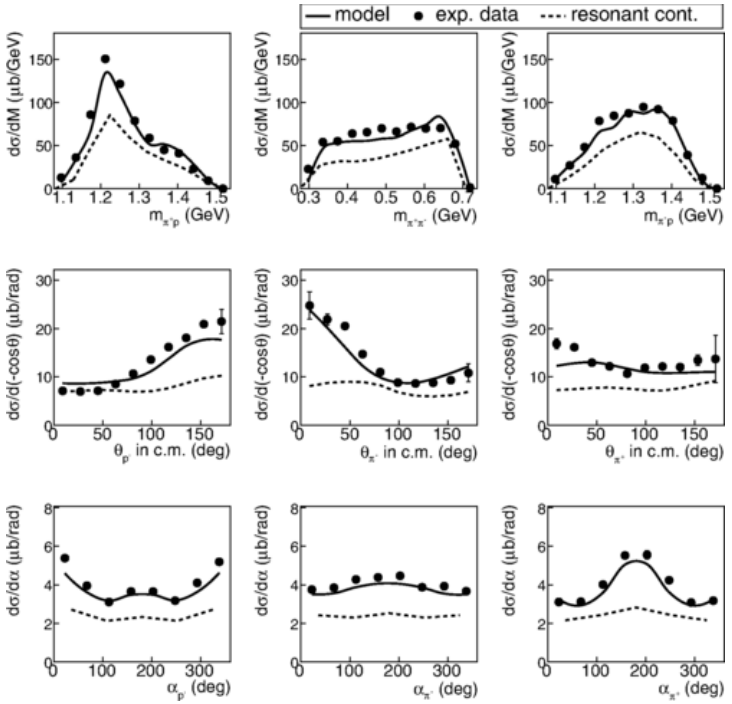
Significant resonant contributions and pronounced differences in behavior of the resonant /non-resonant contributions seen in all nine one-fold differential cross sections.

In the near term future electrocouplings of new baryon state N'(1720)3/2$^+$ will become available in 5 Q^2-bins at 2.0 GeV^2<Q^2<5.0 GeV^2

Recent CLAS Data on $\pi^+\pi^-p$ Electroproduction off Protons at $0.4<Q^2<1.0$ GeV^2

G.V. Fedotov, Iu.A. Skorodumina et al., CLAS Collaboration Phys. Rev. C98, 025203 (2018). (USC/Ohio U.)





9 one-fold differential cross sections at W<1.8 GeV and 0.4 GeV^2 <Q^2 <1.0 GeV^2 of the best statistical and systematical accuracy obtained with minimal bin size over Q^2 ever achieved ΔQ^2= 0.05 GeV^2

JM model/TWOPEG EG analysis:

– – – – resonant contribution

——— full cross section

- **Promising prospects to improve knowledge on Q^2-evolution of N'(1720)3/2$^+$ electrocouplings from the recent CLAS $\pi^+\pi^-p$ electroproduction off proton data in the range of 0.4 GeV^2 < Q^2< 0.8 GeV^2.**

Accessing the Nature of New N'(1720)3/2$^+$ State

- **In the mass range of W<1.8 GeV all N* states expected from quark models were already established suggesting peculiar features for the structure of the new N'(1720)3/2$^+$ state.**
- **N'(1720)3/2$^+$ is the only candidate state for which the results on Q^2-evolution of transition electro-couplings have become available offering the insight into the structure of the new baryon state.**
- **CQM evaluation of N(1720)3/2$^+$ and N'(1720)3/2$^+$ electrocouplings assuming [56,2+] and [20,1+] SU(6)-supermultiplet assignments for these states, respectively. If electrocoupling computations under the aforementioned state assignments will be supported by the CLAS data, then the N'(1720)3/2$^+$ state represents the resonance with orbital excitations over both ρ- and λ-coordinates observed for the first time.**
- **Continuum QCD DSE evaluation of the spectrum of the excited nucleon states with spin-parities J^p=3/2$^+$ under a traceable connection to the QCD Lagrangian either will confirm the emergence of both N(1720)3/2+ and N'(1720)3/2+ quark cores from QCD or will establish the limits of applicability for the currently used Faddeev kernel in description of the baryon spectrum and structure.**
- **Observation of N'(1720)3/2$^+$ may pave a way for extension of Faddeev kernel (di-quark radial excitations, adding dressed gluon or dressed qq-bar pair, or….)**

Conclusions and Outlook

- **The knowledge of the spectrum of excited nucleons was extended considerably from the studies of the CLAS data on exclusive meson photo- and electroproduction.**

- **The new N(1895)1/2$^-$ and N(1900)3/2$^+$ resonances with the four-star PDG ratings were established in the global multi-channel analysis of the exclusive photo- and hadroproduction channels with a major impact from the CLAS KΛ, KΣ photoproduction data. Challenging milestone on ``missing" resonance discovery has been achieved !**

- **Combined studies of exclusive $\pi^+\pi^-$p photo-/electroproduction off proton data revealed convincing evidence for existence of new N'(1720)3/2$^+$ resonance and offer insight on the state structure from the data on the resonance electroexcitation amplitudes in a wide range of photon virtualities available for the first time.**

- **New data on $\pi^+\pi^-$p electroproduction from CLAS (see ## 16-18) and hadroproduction from experiments at JPARC will solidify the N'(1720)3/2$^+$ resonance observation.**

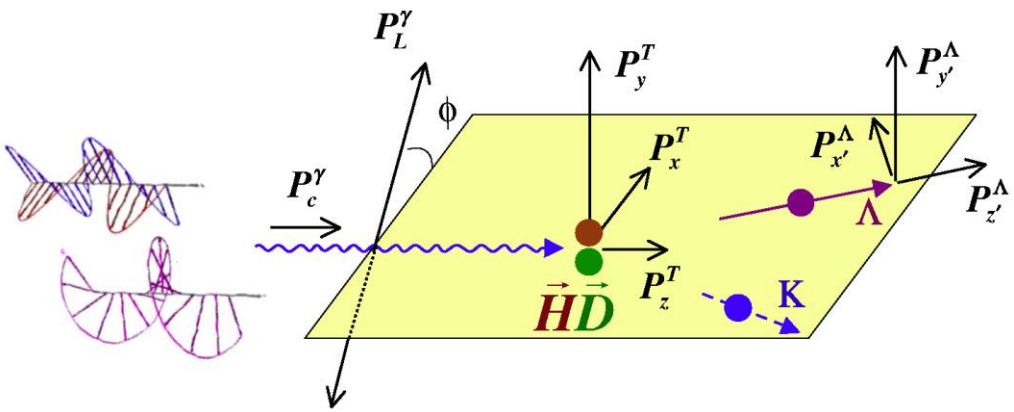
- **Evaluation of the resonance spectrum in the partial wave J^P=3/2$^+$ and the resonance electroexcitation amplitudes within constituent quark models and continuum QCD approaches will elucidate the nature of N'(1720)3/2$^+$.**

Back Up

Polarization Observables in Meson-Baryon Photoproduction Channels

[SHKL, J Phys G**38** (11) 053001]

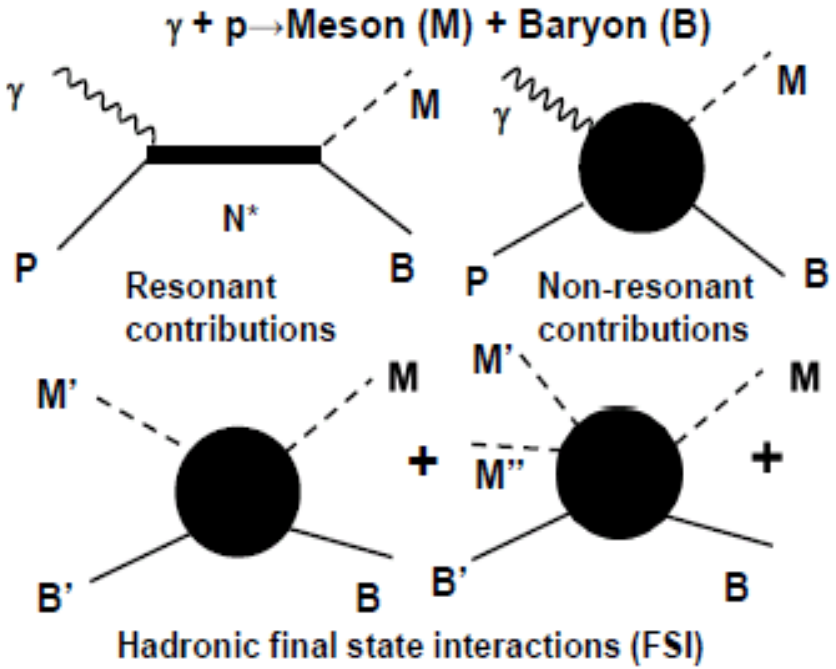
Photon beam		***Target***			***Recoil***			***Target - Recoil***								
					x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
		x	y	z				x	y	z	x	y	z	x	y	z
unpolarized	σ_0		T			P		$T_{x'}$		$L_{x'}$		Σ		$T_{z'}$		$L_{z'}$
$P_L^\gamma \sin(2\phi_\gamma)$		H		G	$O_{x'}$		$O_{z'}$		$C_{z'}$		E		F		$-C_{x'}$	
$P_L^\gamma \cos(2\phi_\gamma)$	$-\Sigma$		$-P$			$-T$		$-L_{z'}$		$T_{z'}$		$-\sigma_0$		$L_{x'}$		$-T_{x'}$
circular P_c^γ		F		$-E$	$C_{x'}$		$C_{z'}$		$-O_{z'}$		G		$-H$		$O_{x'}$	



16 different observables

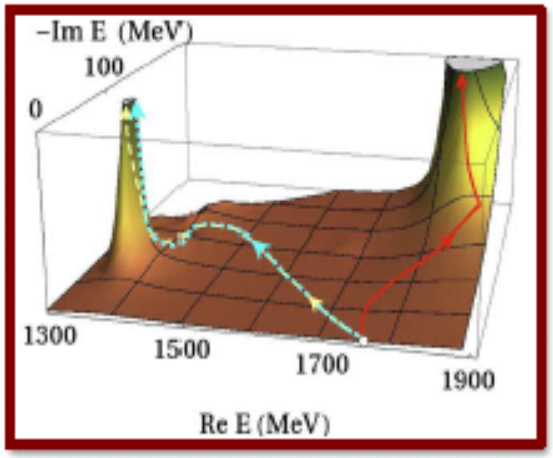
- ***They are described by different bi-linear combinations of amplitudes***
- ***Combined fit of all observables offers rigorous constraints on the reaction amplitude at the real energy axis***

Connecting Nucleon Resonance Properties to the Photoproduction Observables



Breit-Wigner parameterization and the amplitude poles:

$$T_{res} = \frac{T(R \to MB)\,T(\gamma p \to R)}{M_{N^*}^2 - W^2 - i\Gamma_{N^*}(W)\,M_{N^*}}$$



- Constrain exclusive photoproduction amplitudes by fitting them to the differential cross sections and polarization asymmetries.
- Incorporate the FSI effects→ Global multi-channel analyses of all exclusive photo-/hadro-production channels.
- Make analytical continuation of reaction amplitudes into the complex energy plane and:

  a) locate poles ⇒ Resonance masses (M_{N^*}) and total widths (Γ_{N^*}) ;

  b) determine residues ⇒ Resonance photocouplings and partial hadronic decay widths.