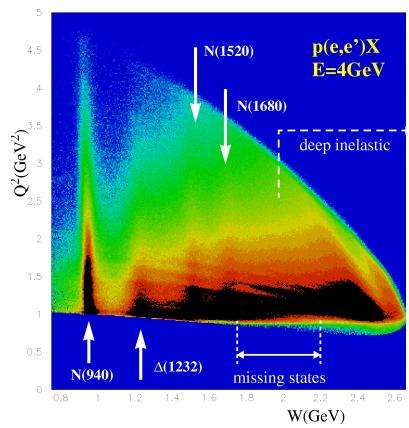


N* Experiments and their Impact on Strong QCD Physics

Volker D. Burkert

Jefferson Laboratory



The 12th International Workshop on the
Physics of Excited Nucleons
10-14 June 2019 Bonn



The time frame – 2030 ?

Why N^ 's are important*

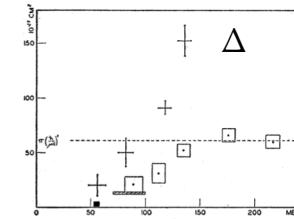
*Nathan Isgur, N^*2000*



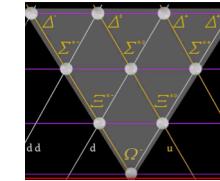
“I am convinced that completing this chapter in the history of science will be one of the most interesting and fruitful areas of physics for at least the next thirty years”

Some historical markers

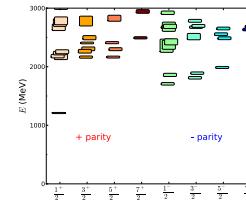
1952: First glimpse of the $\Delta(1232)$ in πp scattering indicates internal structure of the proton



1964: Baryons essential in establishing the quark model and color degrees of freedom



1989: Broad experimental effort proposed to address the “missing” baryons puzzle

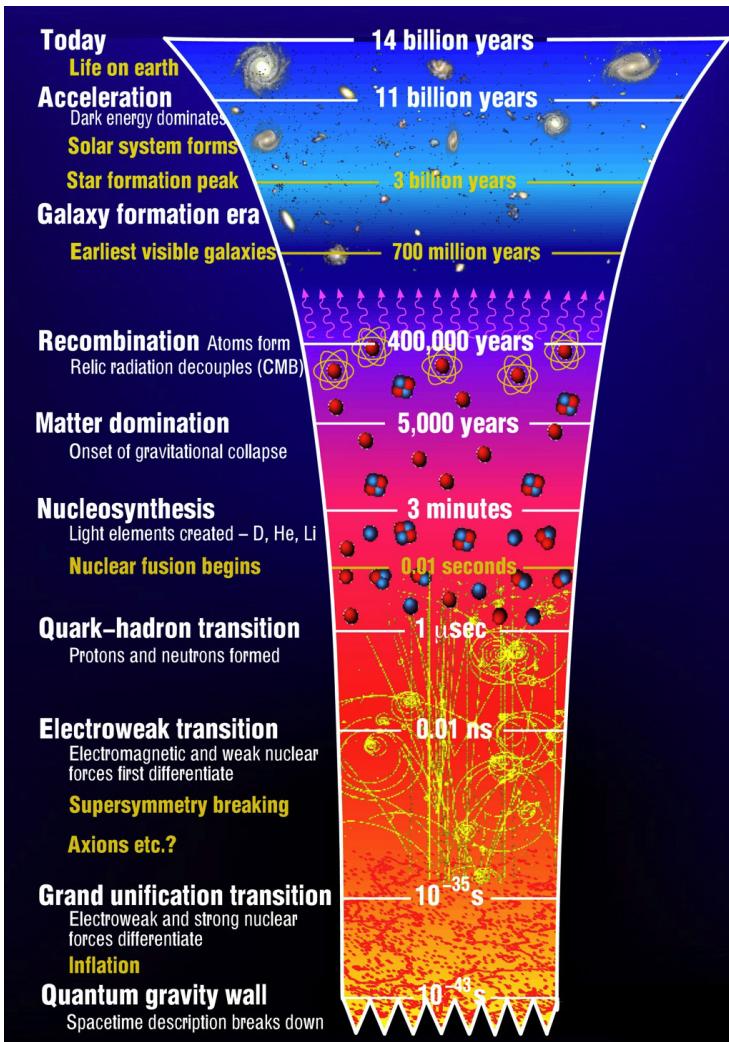


2010: First prediction of the nucleon spectrum in LQCD

State	PDG 2018 evidence	Mass (Pole)
$N(1710)1/2^+$	***	1700
$N(1880)1/2^+$	***	1860
$N(2190)1/2^-$	***	2100
$N(1895)1/2^-$	***	1910
$N(1900)3/2^-$	***	1920
$N(1875)3/2^-$	***	1900
$N(2120)3/2^-$	***	2100
$N(2060)5/2^-$	***	2070
$A(2200)7/2^-$	***	2150

2018: Advanced understanding of the nucleon excitation spectrum and of the structure of several states with traceable links to QCD

Strong QCD is born $\sim 1\mu\text{sec}$ after the Big Bang



Time after the Big Bang

$T \sim 700,000,000 \text{ yrs}$: galaxies

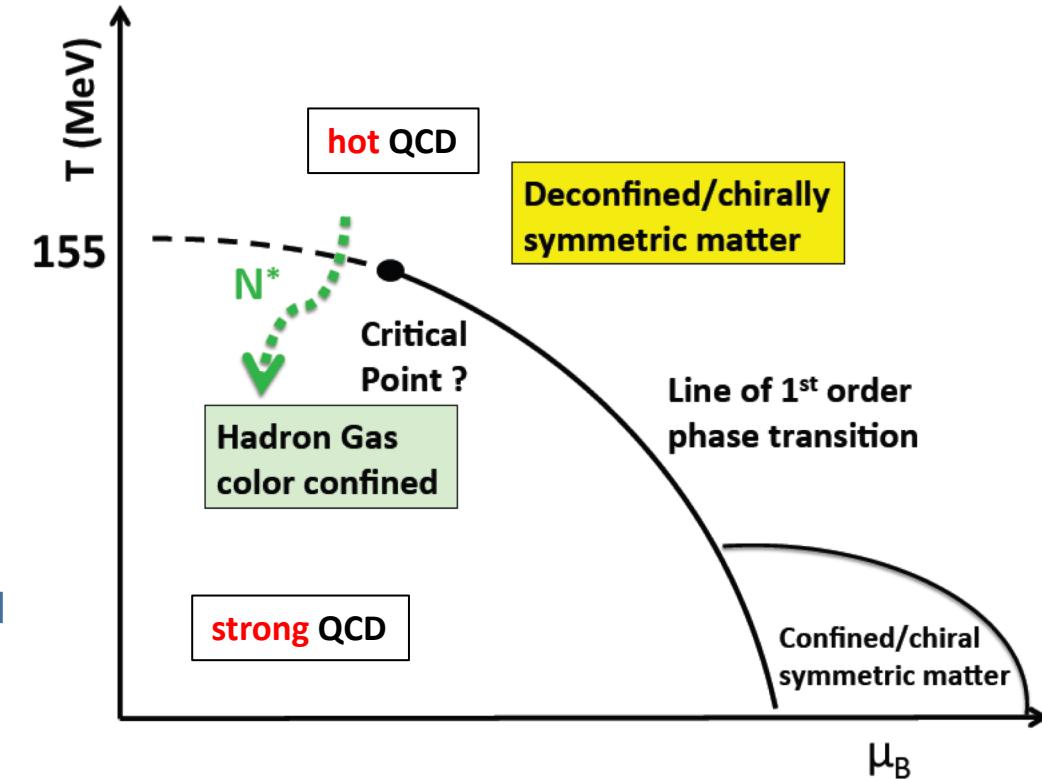
$T \sim 400,000 \text{ yrs}$: atoms

$T \sim 10^2 \text{ s}$: nuclei

$T \sim 10^{-6} \text{ s}$: Nucleons

$T \sim 10^{-9} \text{ s}$: QGP

$T \sim 10^{-6} \text{ s}$: Transition from the QGP to Nucleons



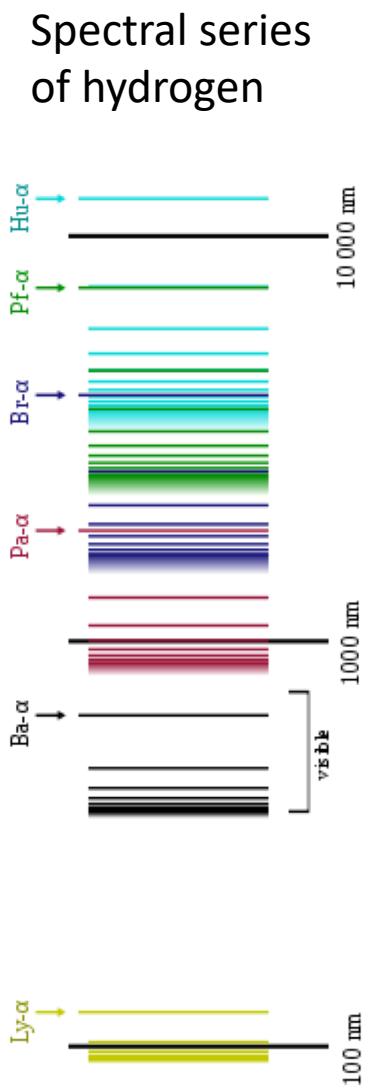
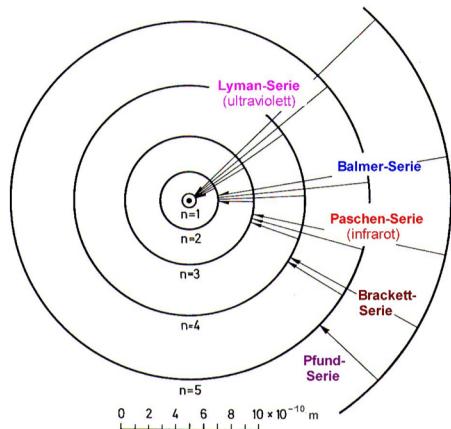
- chiral symmetry is broken
- light quarks acquire mass dynamically
- color confinement manifest

With existing accelerators we explore these events in (relative) isolation

From the H spectrum to the N* spectrum



Niels Bohr, model of the hydrogen atom, 1913.



Analogy QCD & QED => path to discoveries ?

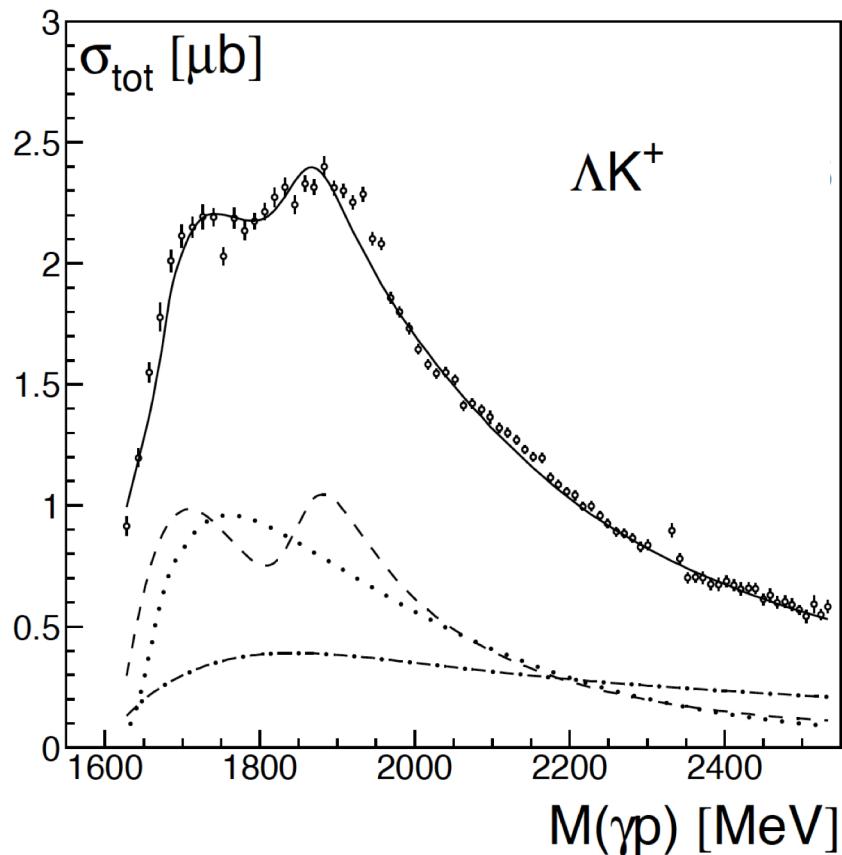
- Understanding the hydrogen atom requires understanding its spectrum of *sharp energy levels*
 - > From the *Bohr model* to **QED**
 - > Lamb shift, ...
- **Understanding the proton requires understanding its energy spectrum of *broad energy levels***
 - > From the *quark model* to **strong QCD**
 - > Accuracy of predictions should be commensurate with experiments, i.e. O(10 MeV).

How do we learn from N*'s about sQCD?

- Measure the N* spectrum more completely and more accurately (experiments & analysis)
 - Probe the running quark mass function $m(q)$
 - Study confinement of light quark flavors
 - determine the effective degrees of freedoms
 - measure the internal forces on quarks
 - Find non-quark contributions and clarify their nature
 - meson-baryon contributions to N*'s
 - gluonic excitations
 - dynamically generated states
 - molecule type states
- Vigorous experimental program in search for new states and the measurement of the transition amplitudes and form factors



The N(1900)3/2⁺ state



- First baryon resonance observed and fully established with multiple confirmations in electromagnetic meson production.
- State confirmed in an effective Langrangian resonance model analysis of $\gamma p \rightarrow K^+ \Lambda$.
O. V. Maxwell, PRC85, 034611, 2012
- State confirmed in a covariant isobar model single channel analysis of $\gamma p \rightarrow K^+ \Lambda$.

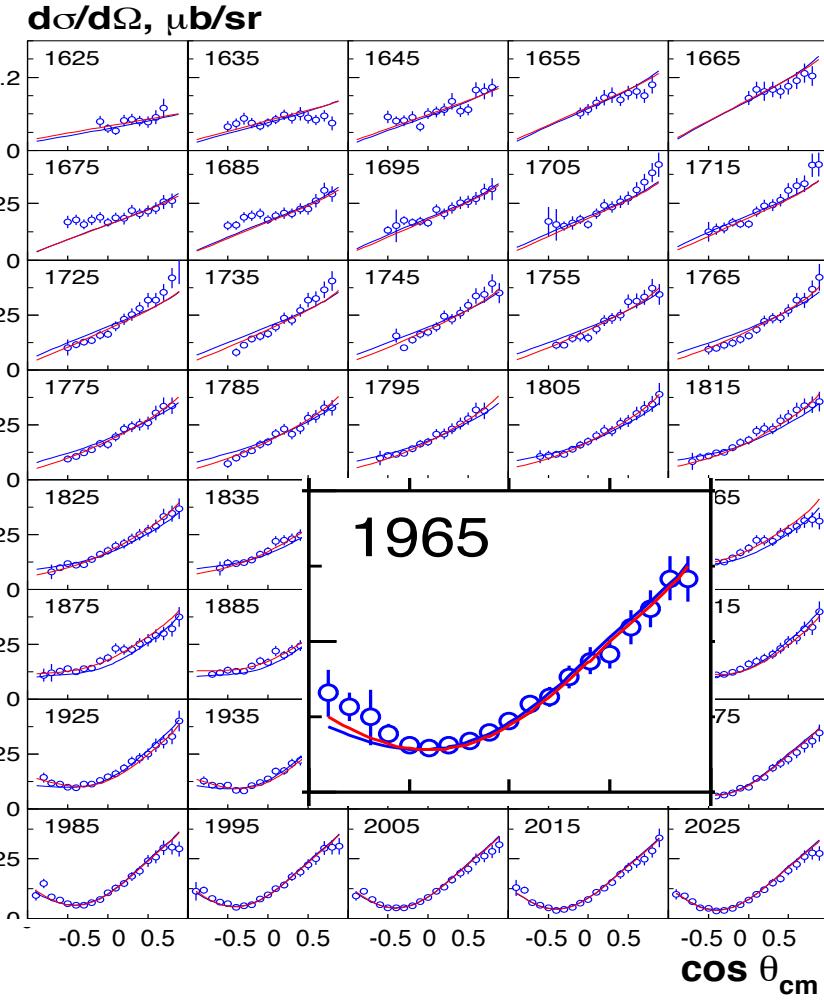
T. Mart, M. J. Kholili , PRC86, 022201, 2012

Precise data require precise analysis

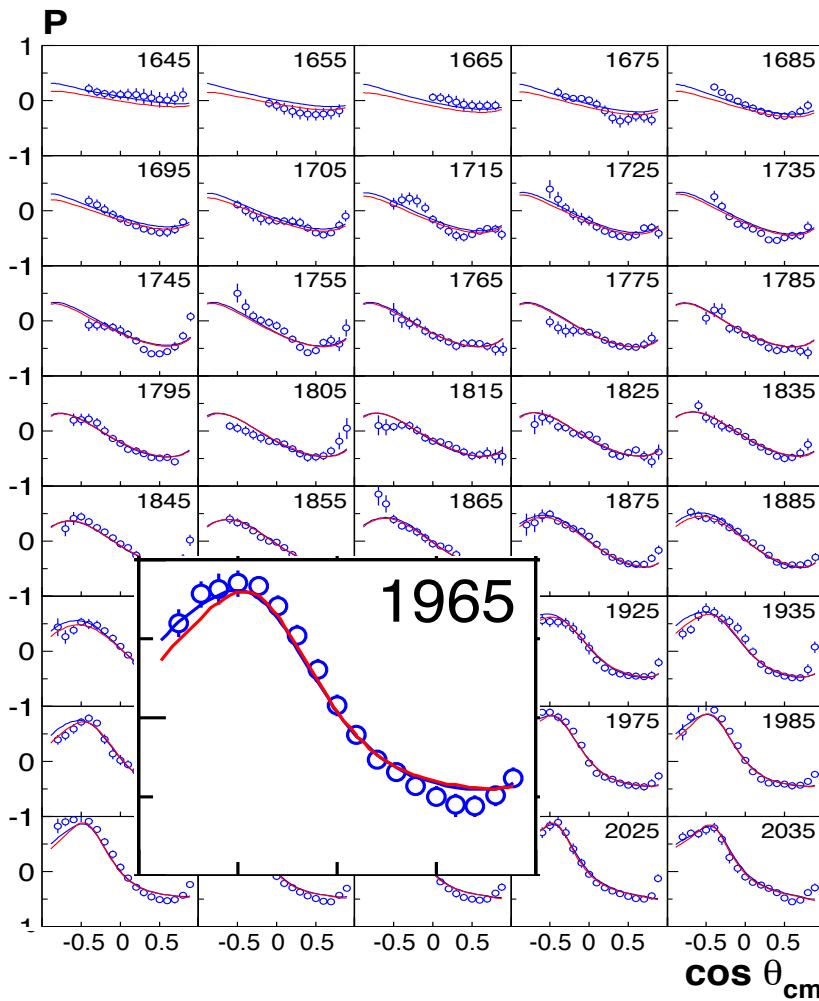
Establishing the N* spectrum

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

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

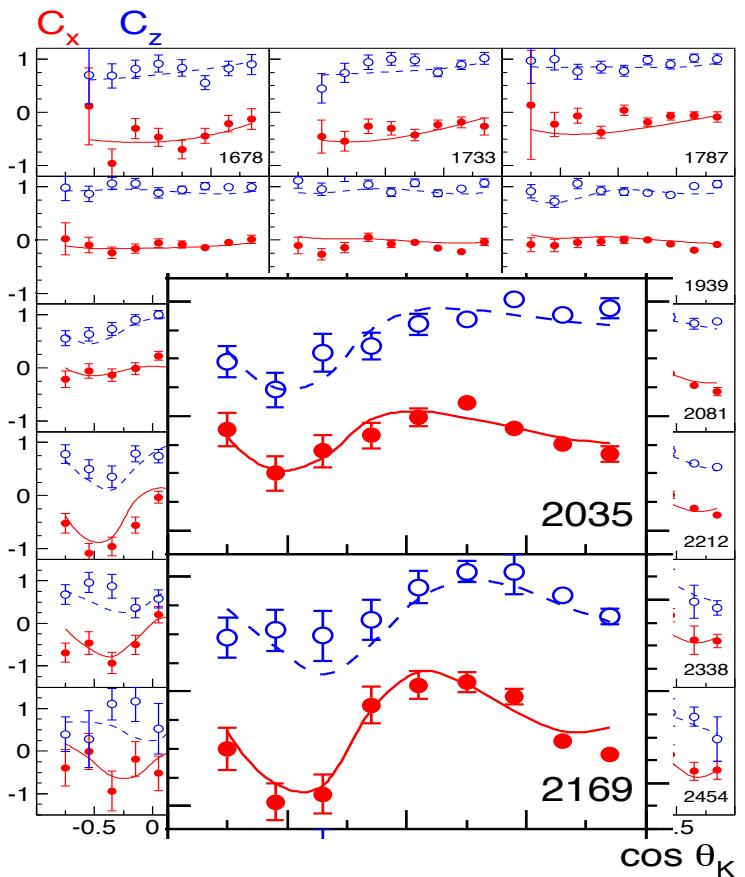


M. McCracken et al.(CLAS), Phys.RevC81,025201,2010



8

$\gamma \rightarrow \Lambda$ Polarization transfer



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

Establishing the N* spectrum

PWA ANL-Osaka (2012)

Includes ***, ****

PDG states

ANL-Osaka (AO)

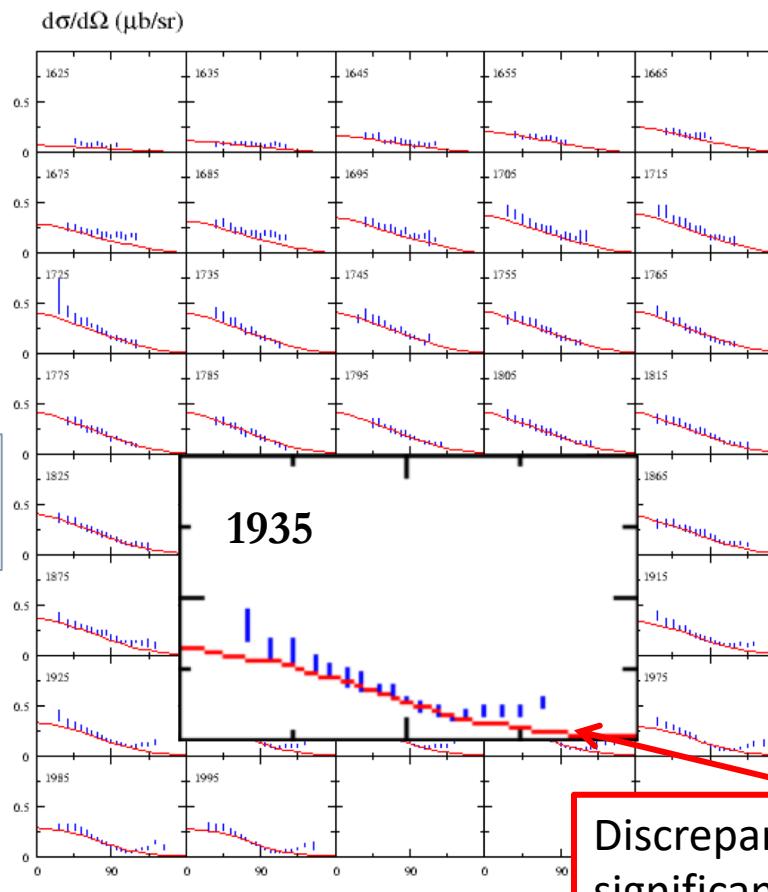
DCC Analysis

H. Kamano et al., Phys.
Rev. C88 (2013) 3, 035209

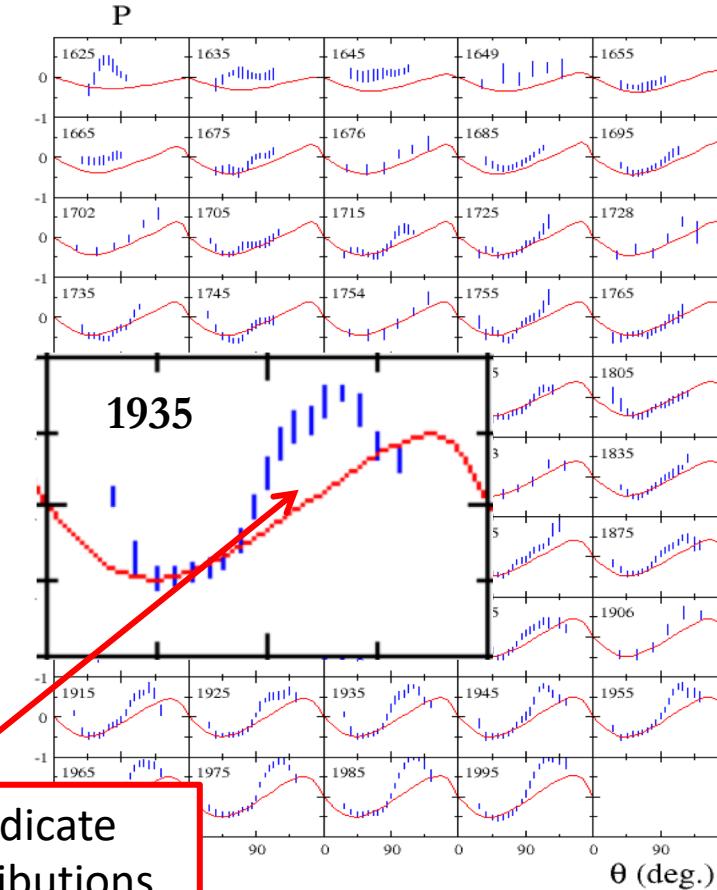
AO claims that $N(1900)3/2^+$
is not needed in their fit.

The fit quality at large W is
not sufficient to support
such conclusions. It shows
missing strength around
1900 MeV and higher.

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



Discrepancies indicate
significant contributions
are missing from the fit



PDG(2010) states insufficient to fit $K\Lambda$ data

Shows the importance of polarization data

Polarization observables in $K\Lambda/K\Sigma$ production

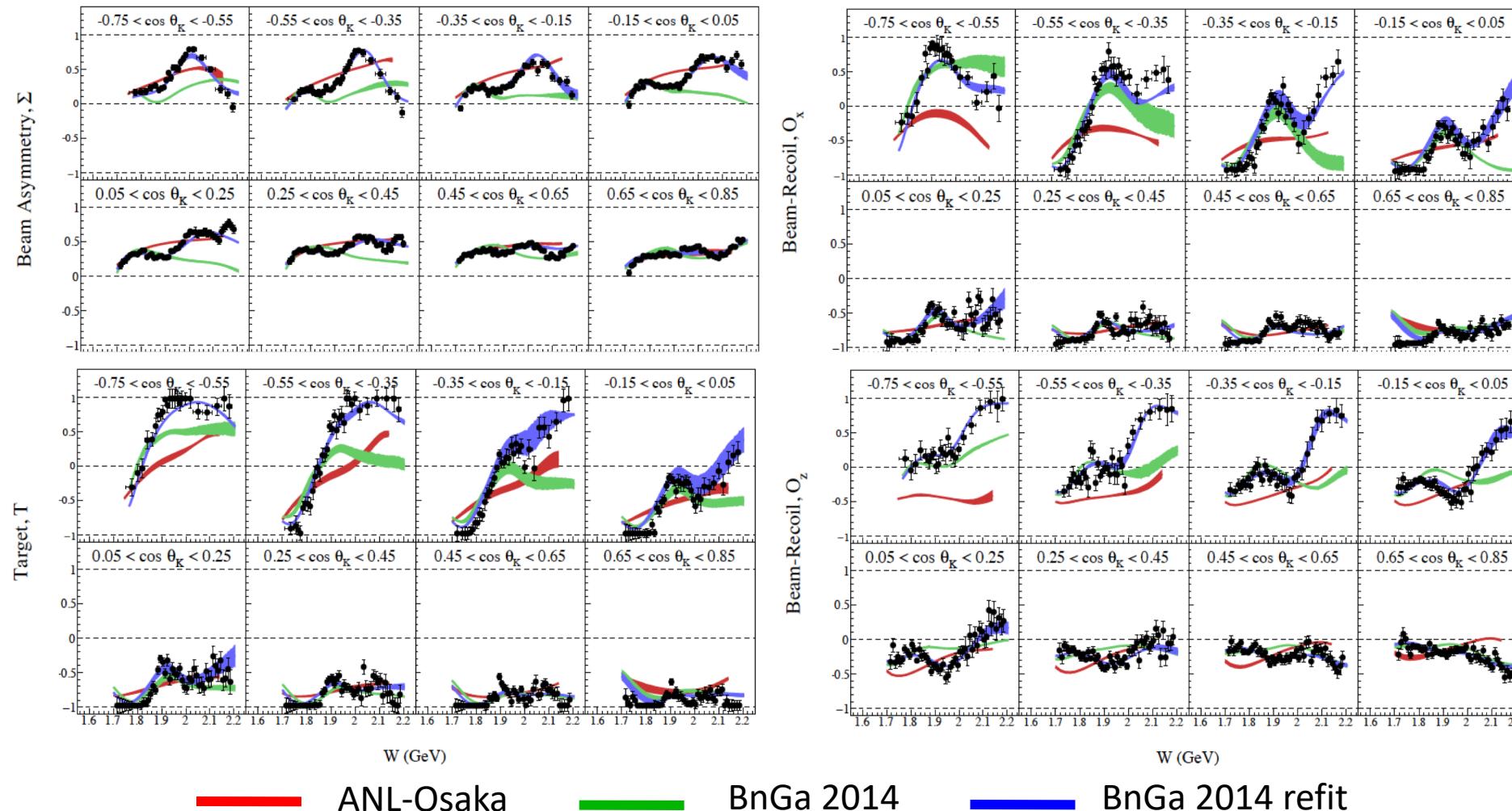
By including additional polarization observables can we find new states?

Experiment	Final State	W range (GeV)	Σ	P	C_x	C_z	T	O_x	O_z
CLAS g11	$K\Lambda$	1.62–2.84		★					
	$K\Sigma^0$	1.69–2.84		★					
CLAS g1c	$K\Lambda$	1.68–2.74		★	★	★			
	$K\Sigma^0$	1.79–2.74		★	★	★			
LEPS	$K\Lambda$	1.94–2.30	★						
	$K\Sigma^0$	1.94–2.30	★						
GRAAL	$K\Lambda$	1.64–1.92	★	★			★	★	★
	$K\Sigma^0$	1.74–1.92	★	★					
CLAS g8	$K\Lambda$	1.71–2.19	★	★			★	★	★
	$K\Sigma^0$	1.75–2.19	★	★			★	★	★

More N*'s from polarized $K^+\Lambda$ production?



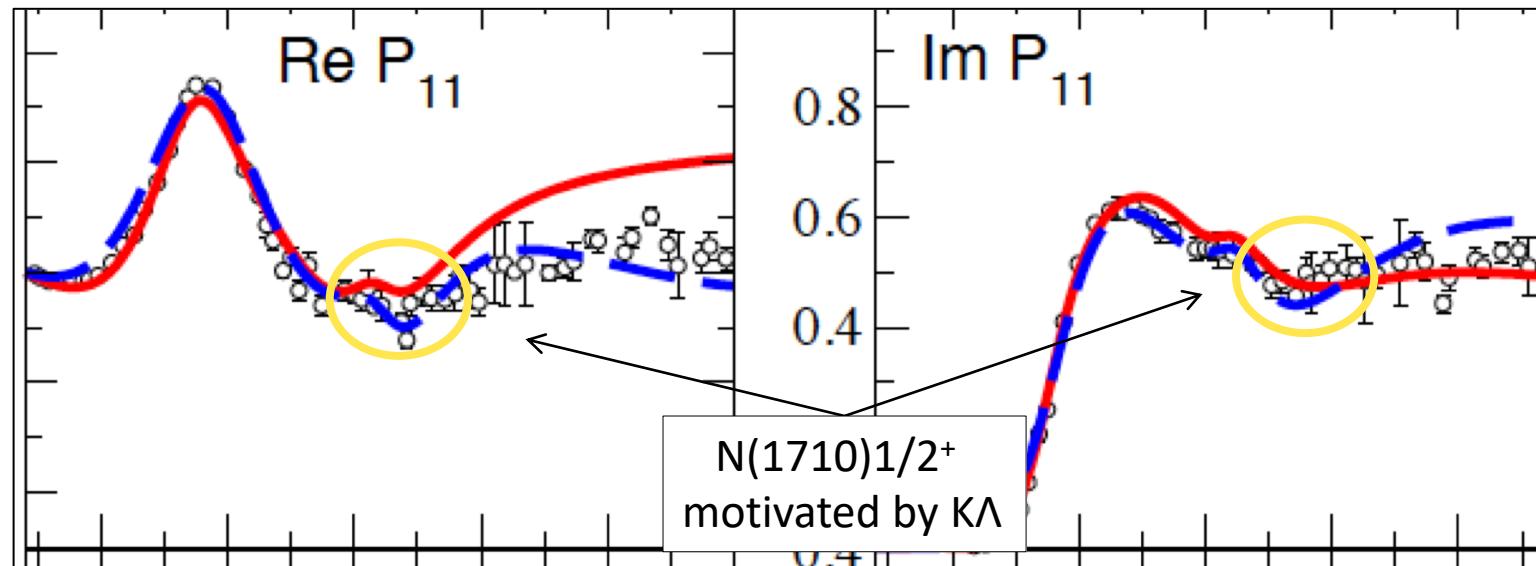
C.A. Paterson et al., PRC93 (2016) 065201



The N(1710) $1/2^+$ state ***

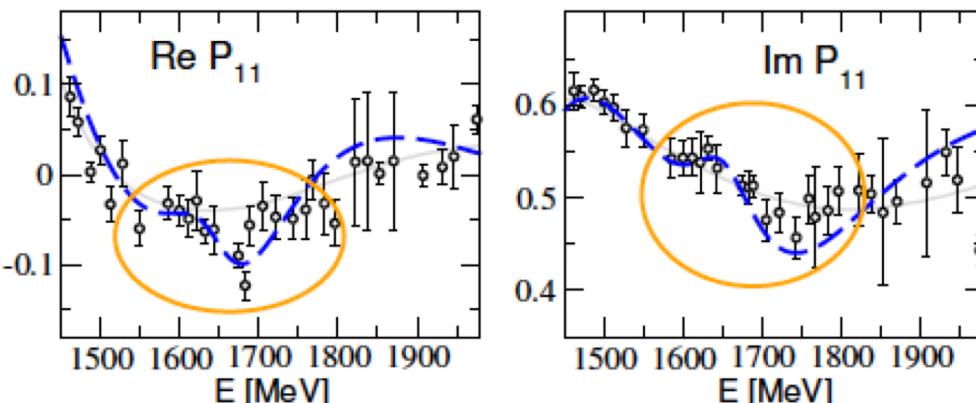
Jülich $\pi N \rightarrow \pi N$ analysis

D. Rönchen, M. Döring, et al., EPJA 50: 101(2014)



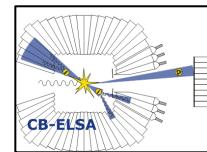
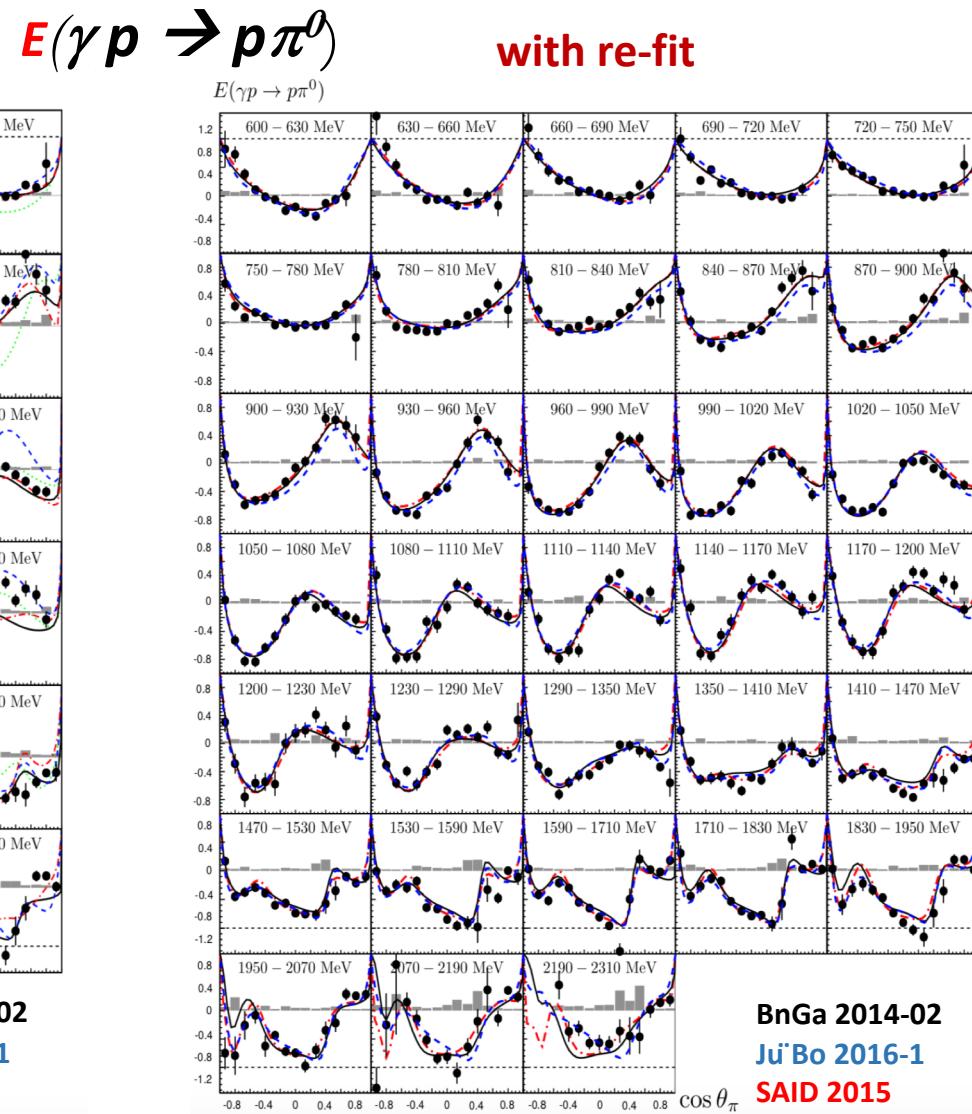
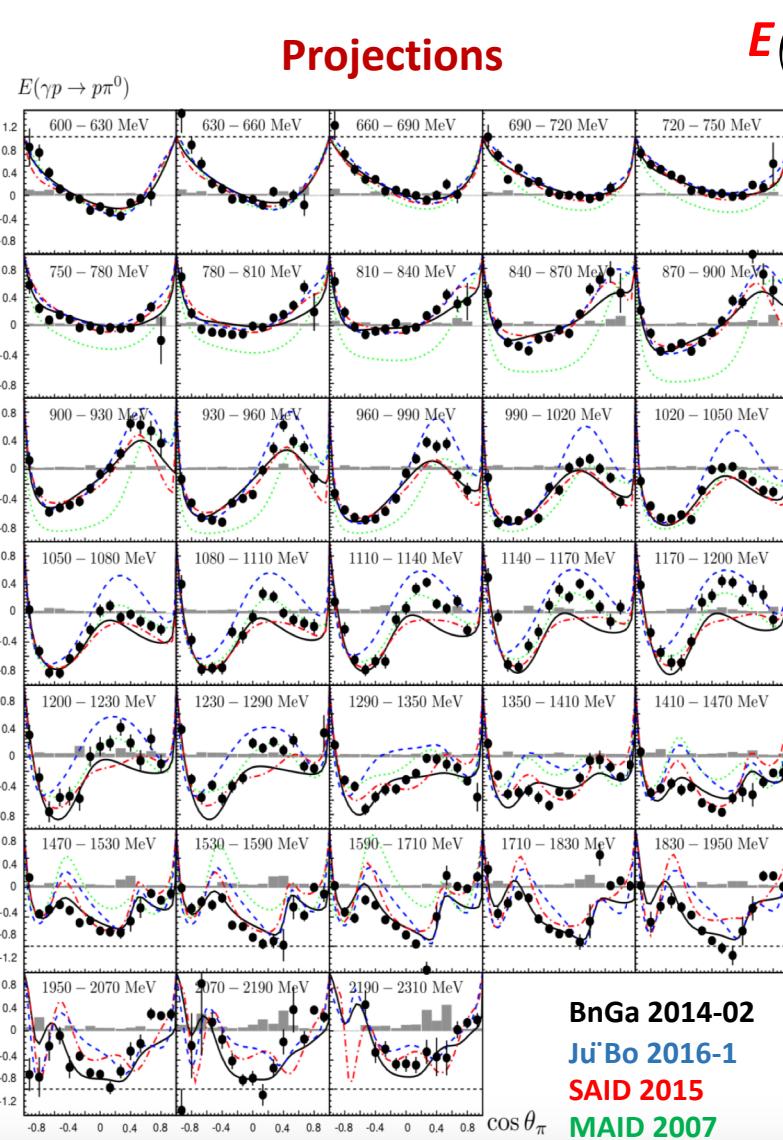
State also needed in:

- S. Ceci, Svarc, B. Zauner,
 $\pi N \rightarrow \eta N$ analysis, PRL 97 (2006)
062002
- A.V. Anisovich et al. (BnGa), EPJA 48
(2012) 15



Compute χ^2 in
limited mass range

N* spectrum – $\Delta(2200)7/2^-$



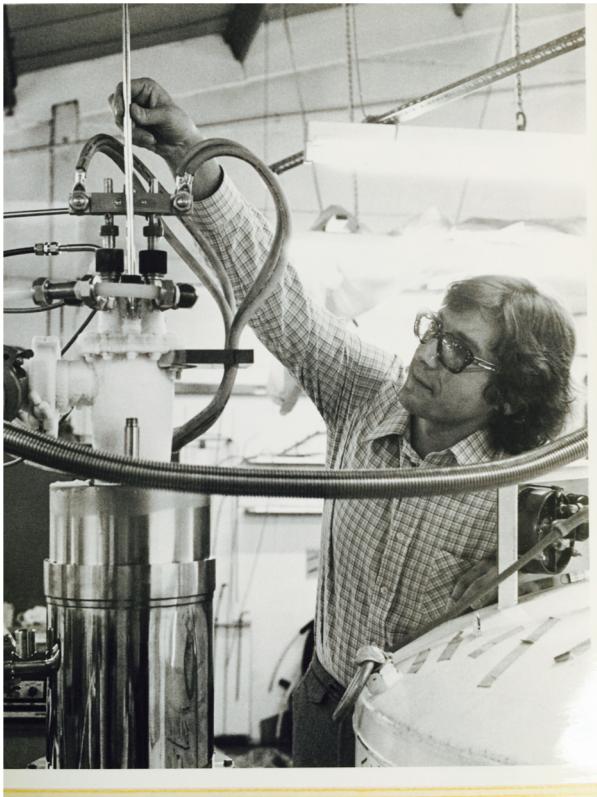
M. Gottschall et al.,
arXiv:1904.12560 (2019)

To measure E requires circular polarized photons from bremsstrahlung of longitudinally polarized electrons.

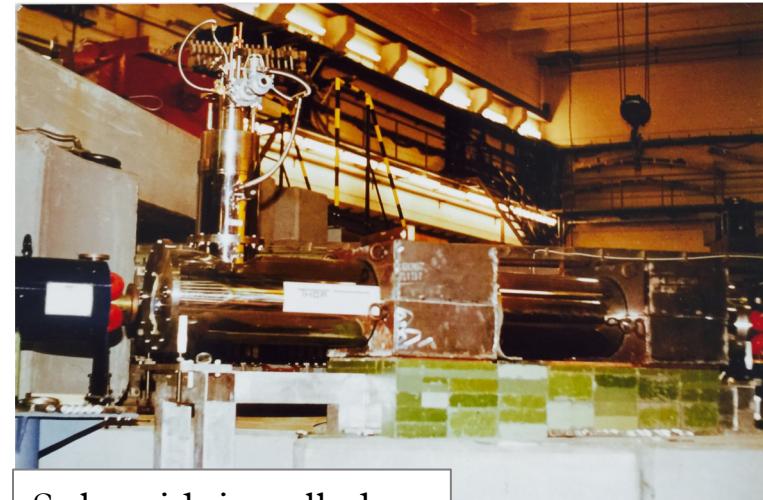
How to get long. spin-polarized electrons in experiment after they are accelerated in a synchrotron with transverse magnetic fields? Use spin rotator.

Spin precession SOLENOID at Bonn University

at THOR CRYOGENICS LTD



13 Tesla-meter SOLENOID
during Acceptance tests at
THOR, Oxford, England,
ca. 1978.



Solenoid installed
in the beamline of
the 2.5GeV electron
synchrotron, 1978.
(long before ELSA)

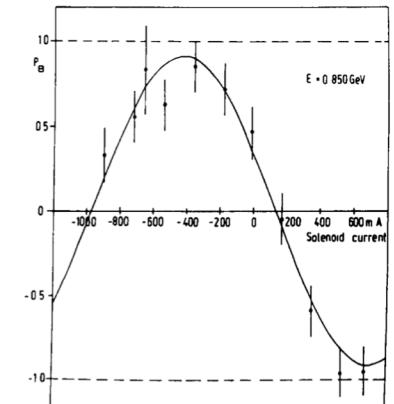
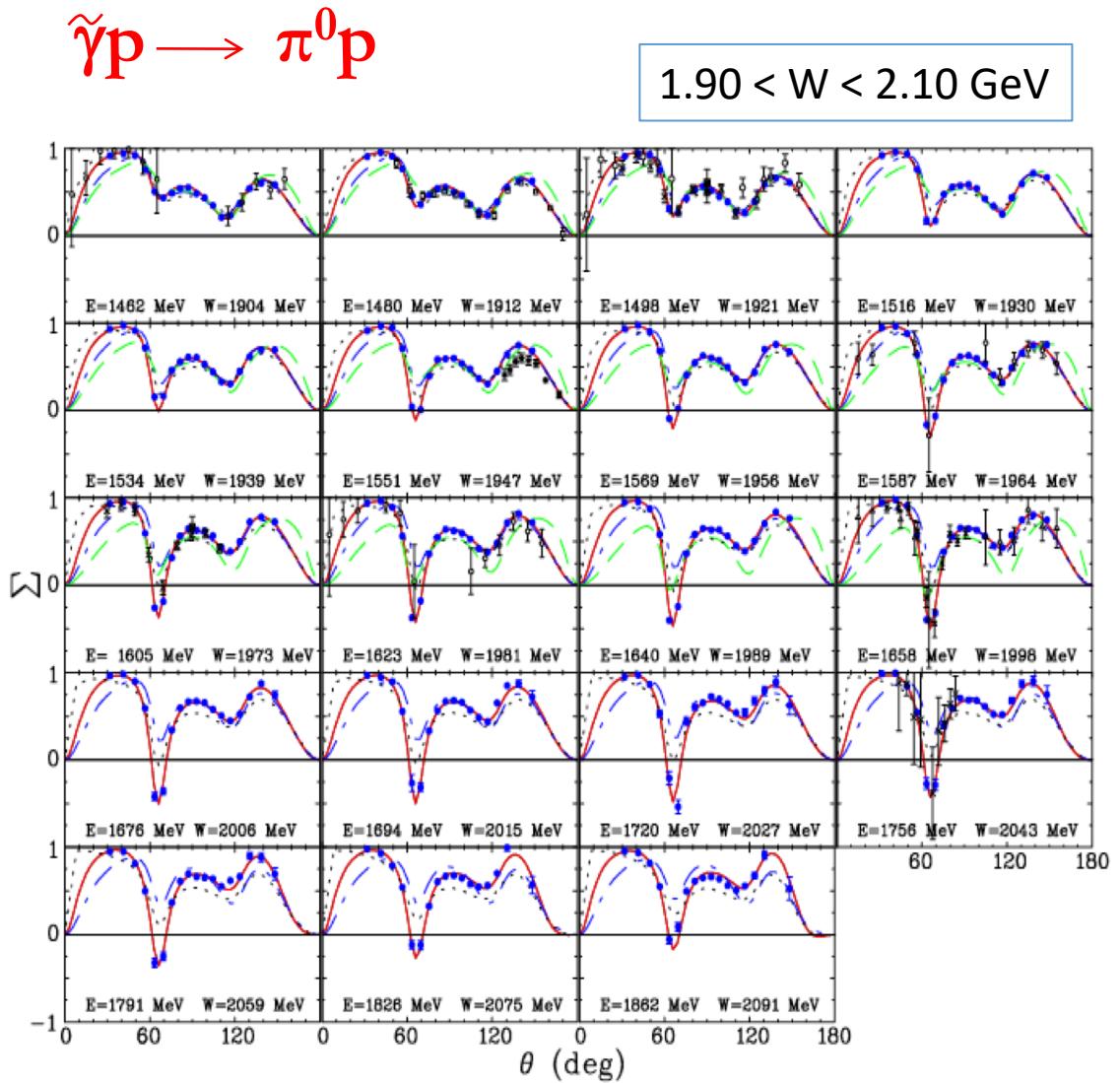
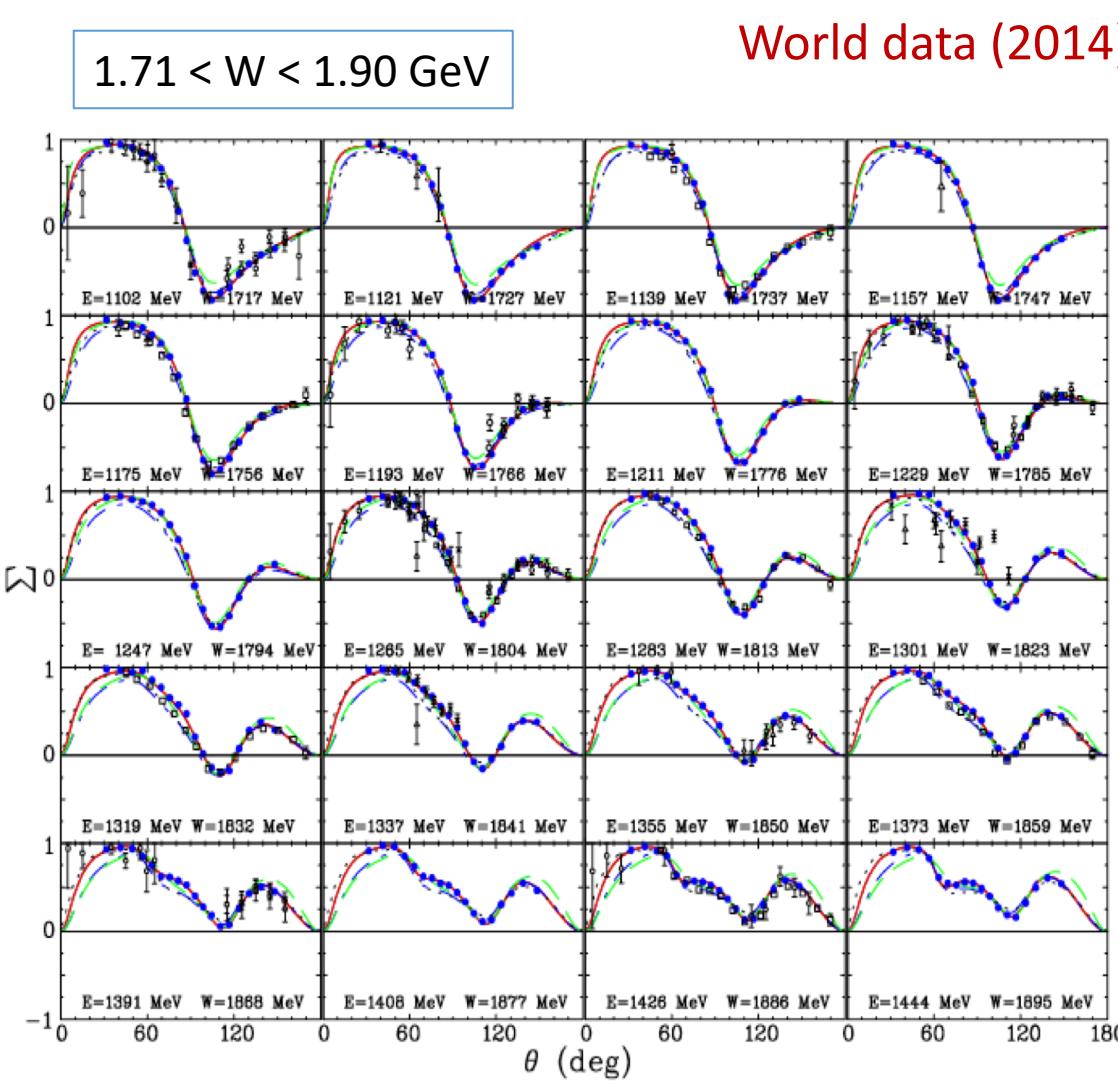


Fig. 6. Polarization degree, measured at 850 Mev as a function of the solenoid current. The measured points show the expected sine-like behaviour.

N* spectrum, cont'd - $\Delta(2200)7/2^-$



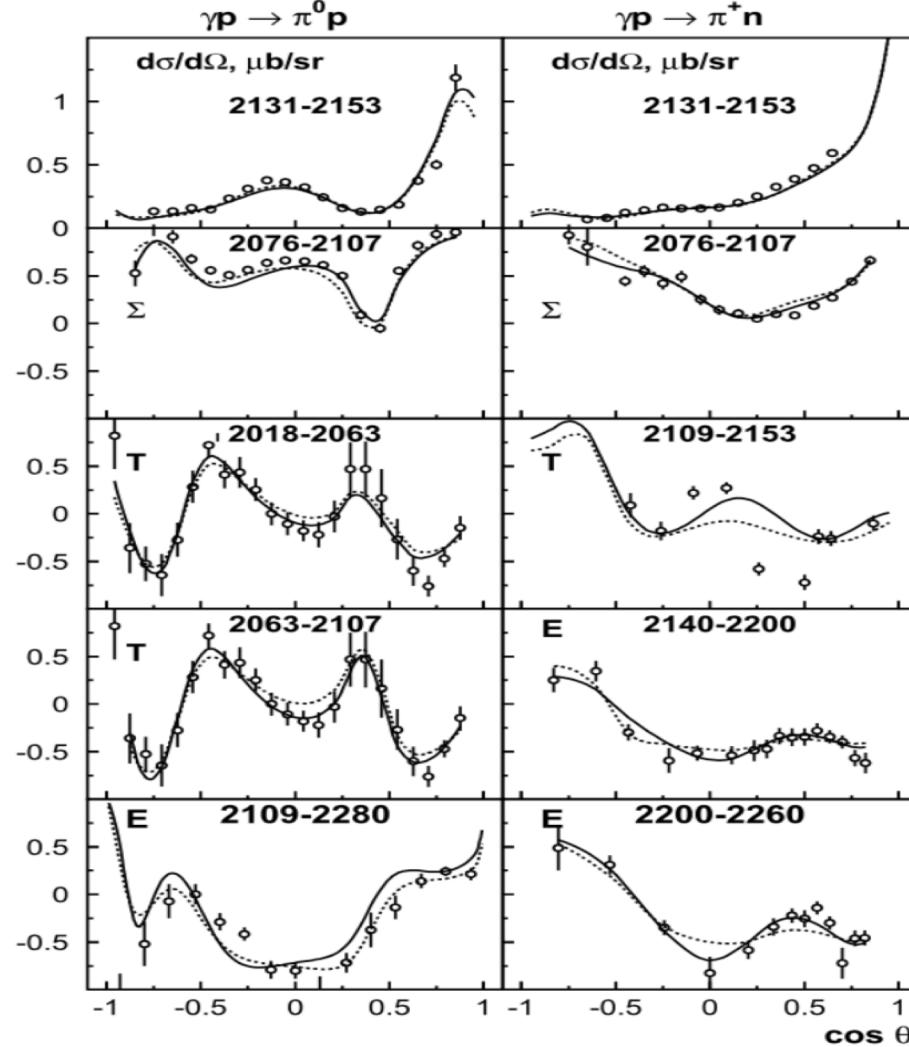
N^* Spectrum cont'd - $\Delta(2200)7/2^-$

$$\gamma N \rightarrow \pi N$$

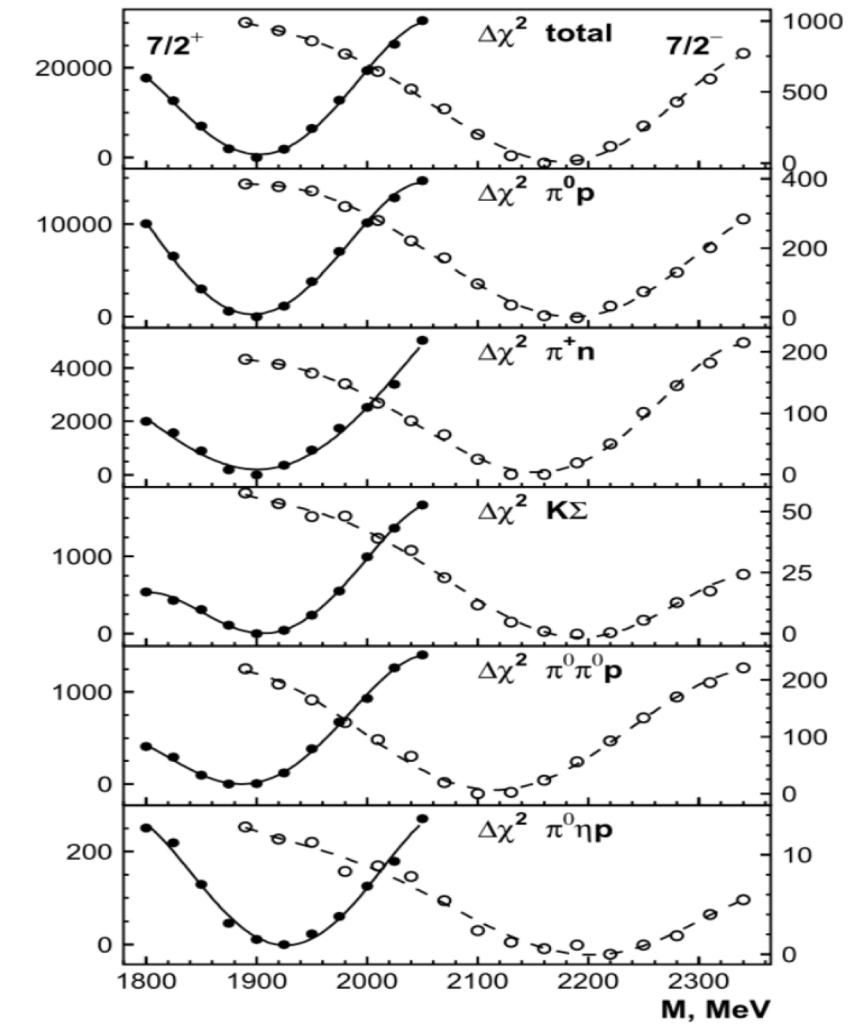
Use all available $p\pi^0$, $n\pi^+$,
data σ , and single and double
polarization data on T , Σ , E .

Analysis verifies the strong 4^*
 $\Delta(1950)7/2^+$ state and finds
evidence for $\Delta(2200)7/2^-$

$$\begin{aligned} M &= 2176 (40) \text{ MeV} \\ \Gamma &= 210 (70) \text{ MeV} \\ \text{BR}(N\pi) &= 3.5(1.5)\% \end{aligned}$$



A.V. Anisovich et al., Phys.Lett. B766 (2017) 357-361



The Quest for Excited Nucleons

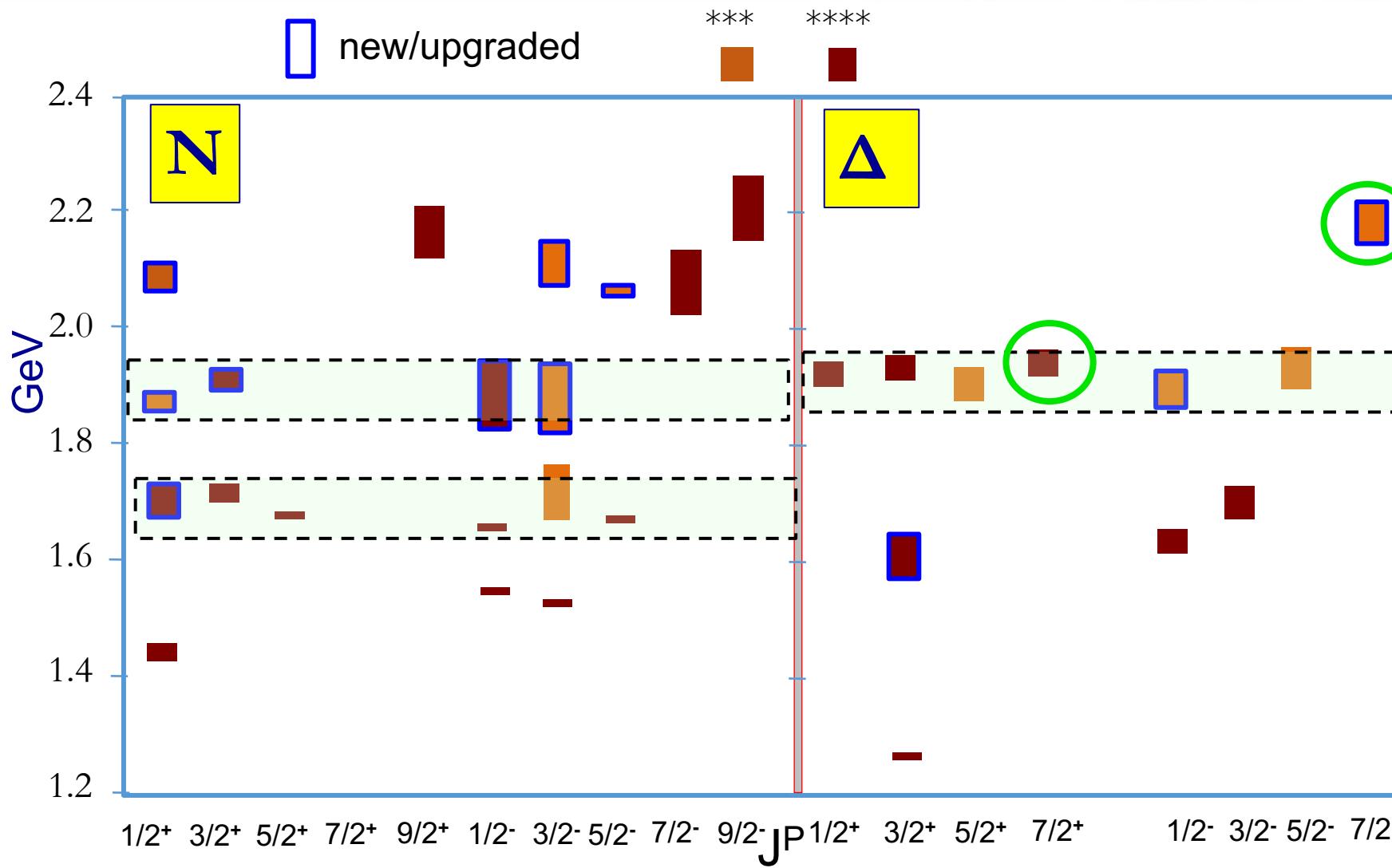
Precision meson photo-production data led to the discovery of several new states and the full establishment of poorly known states, in the mass range up to 2200 MeV.

State $N((\text{mass})J^P)$	PDG 2010	PDG 2018
$N(1710)1/2^+$	***	****
$N(1880)1/2^+$		***
$N(2100)1/2^+$	*	***
$N(1895)1/2^-$		****
$N(1900)3/2^+$	**	****
$N(1875)3/2^-$		***
$N(2120)3/2^-$		***
$N(2060)5/2^-$		***
$\Delta(1600)3/2^+$	***	****
$\Delta(1900)1/2^-$	**	***
$\Delta(2200)7/2^-$	*	***

- **** - existence is certain
- *** - existence is likely
- ** - evidence of existence is fair
- * - evidence of existence is poor

<http://pdg.lbl.gov/2019/reviews/rpp2018-rev-n-delta-resonances.pdf>

The N/ Δ Spectrum 2018 (PDG)



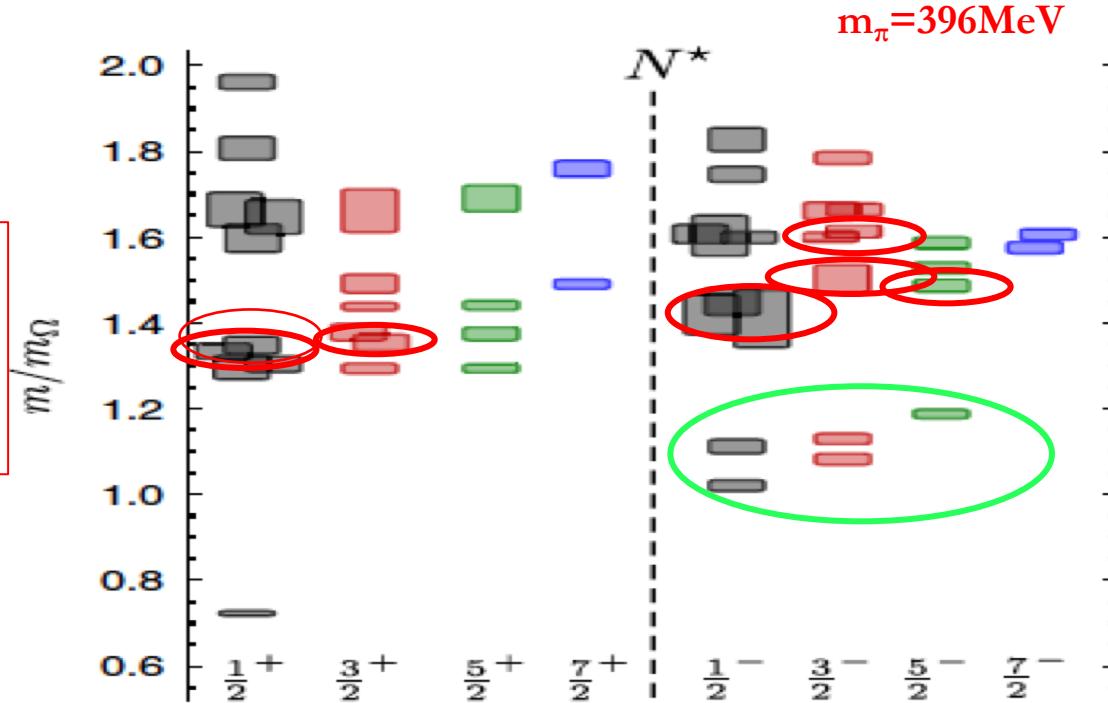
The parity partners $\Delta(1950)7/2^+$ and $\Delta(2200)7/2^-$ show no mass degeneracy.

Do new states correlate with LQCD states?

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

$m_\Omega = 1672 \text{ MeV}$

Fit needed
N(1900)3/2⁺
N(2100)1/2⁺
N(1880)1/2⁺



Fit needed
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⁻

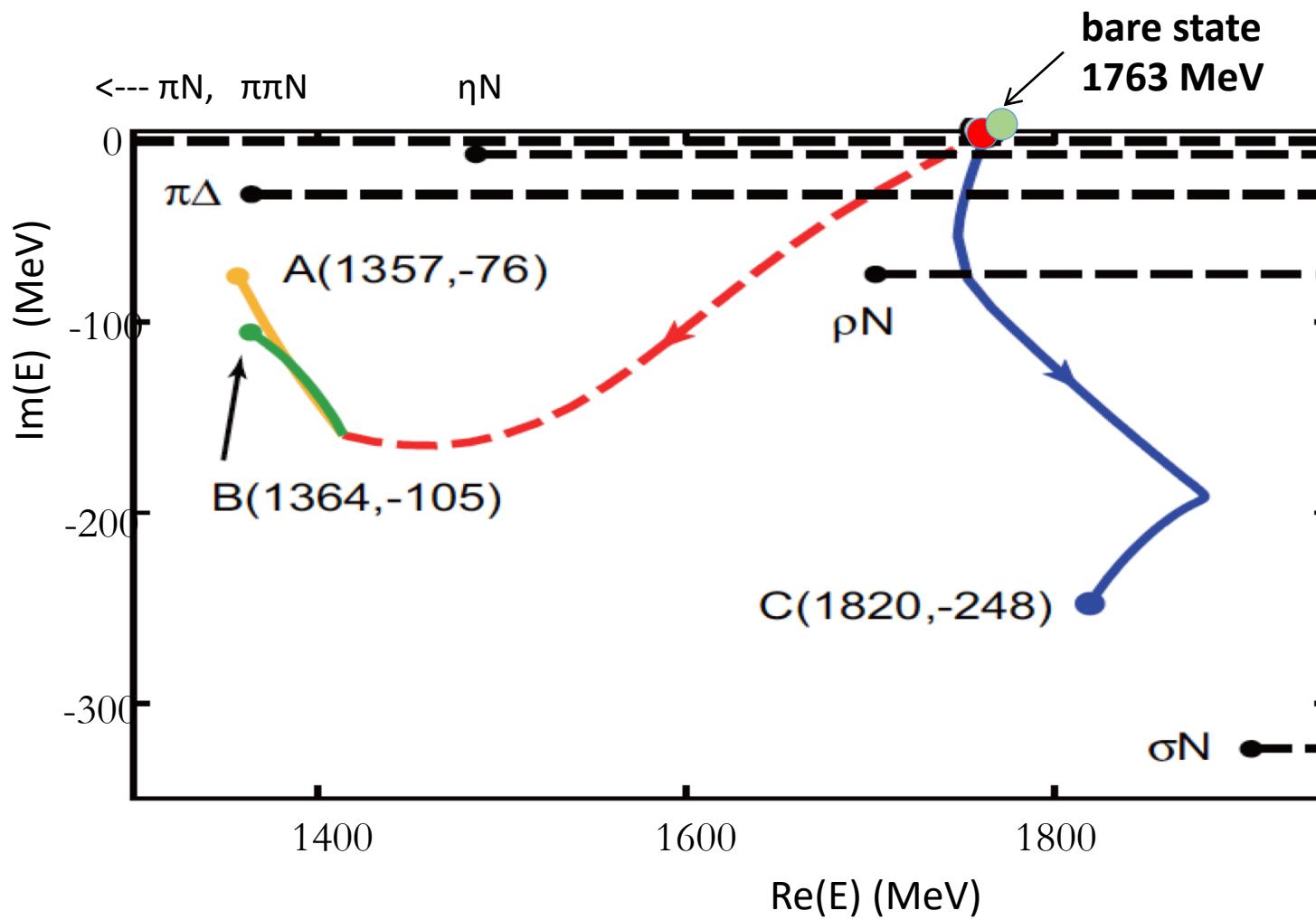
Lowest J⁺ states 500 -700 MeV high

Lowest J⁻ states 200-300 MeV high

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

We need LQCD projections at or near the physical pion mass

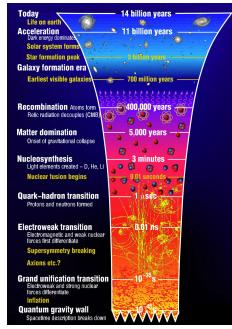
Dynamics of the Roper N(1440) resonance



Resonance masses (poles) can change significantly when the coupling to inelastic channels is included dynamically.
For the Roper state by 400MeV.

N. Suzuki, B. Julia-Diaz, H. Kamano, T.-S. H. Lee, A. Matsuyama, T. Sato, Phys.Rev.Lett.104:042302,2010

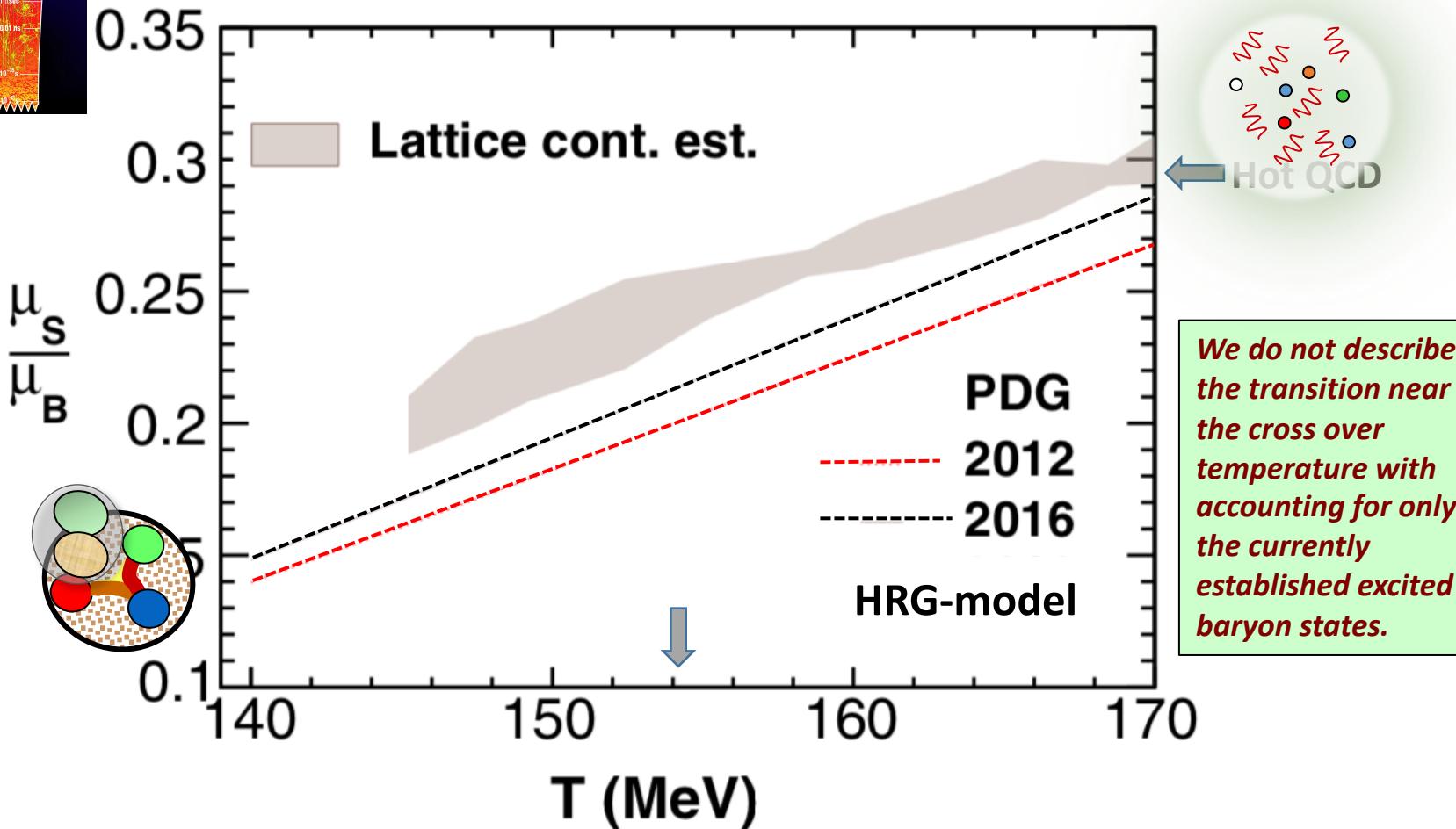
The quest for missing excited baryons



Understanding the history of our universe

strangeness / baryon chemical potential

Sandeep Chatterjee [et al](#);
PRC 96, 054907 (2017)



not included

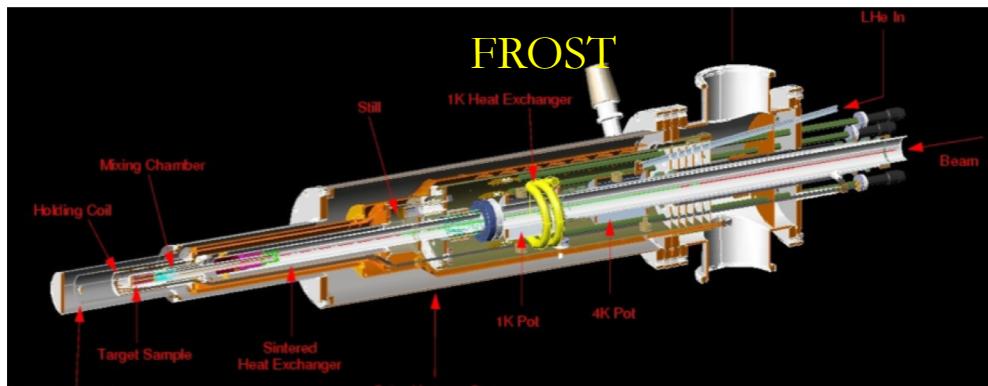
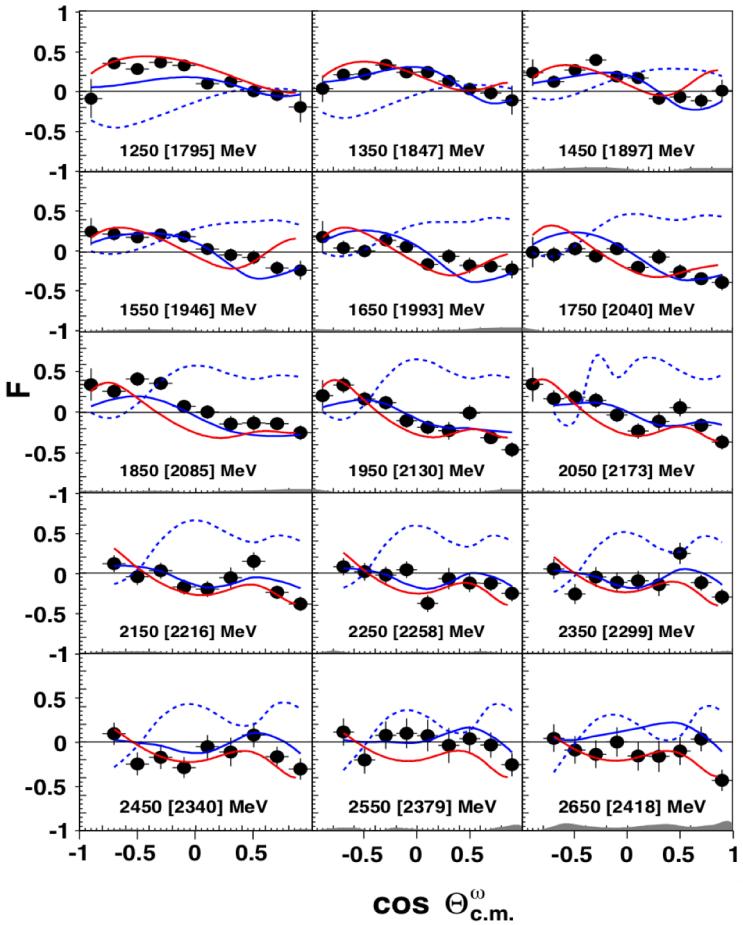
PDG 2016 with *, **

$N(1860)$	$N(1880)$
$N(1895)$	
$N(2000)$	$N(2040)$
$N(2060)$	$N(2100)$
$N(2120)$	$N(2300)$
$N(2570)$	$N(2700)$
$\Delta(1750)$	$\Delta(1900)$
$\Delta(1940)$	$\Delta(2000)$
$\Delta(2150)$	$\Delta(2200)$
$\Delta(2300)$	$\Delta(2350)$
$\Delta(2390)$	$\Delta(2400)$
$\Delta(2750)$	$\Delta(2950)$
$N(1875)$	

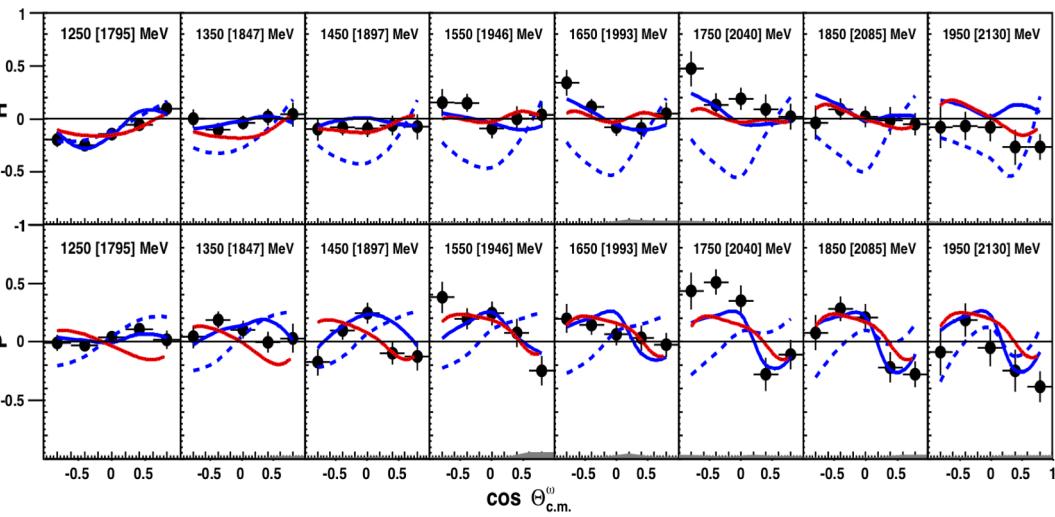
PDG 2018 with
, *

Beam-target asymmetries $\gamma \vec{p} \rightarrow p\omega$

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega} \{ (1 - \delta_l \Sigma \cos 2\beta) \\ + \Lambda \cos \alpha (-\delta_l H \sin 2\beta + \delta_\odot F) \\ - \Lambda \sin \alpha (-T + \delta_l P \cos 2\beta) \},$$



P. Roy et al. (CLAS), Phys. Rev. Lett. 122 (2019) 162301



PWA: BnGa, Wei

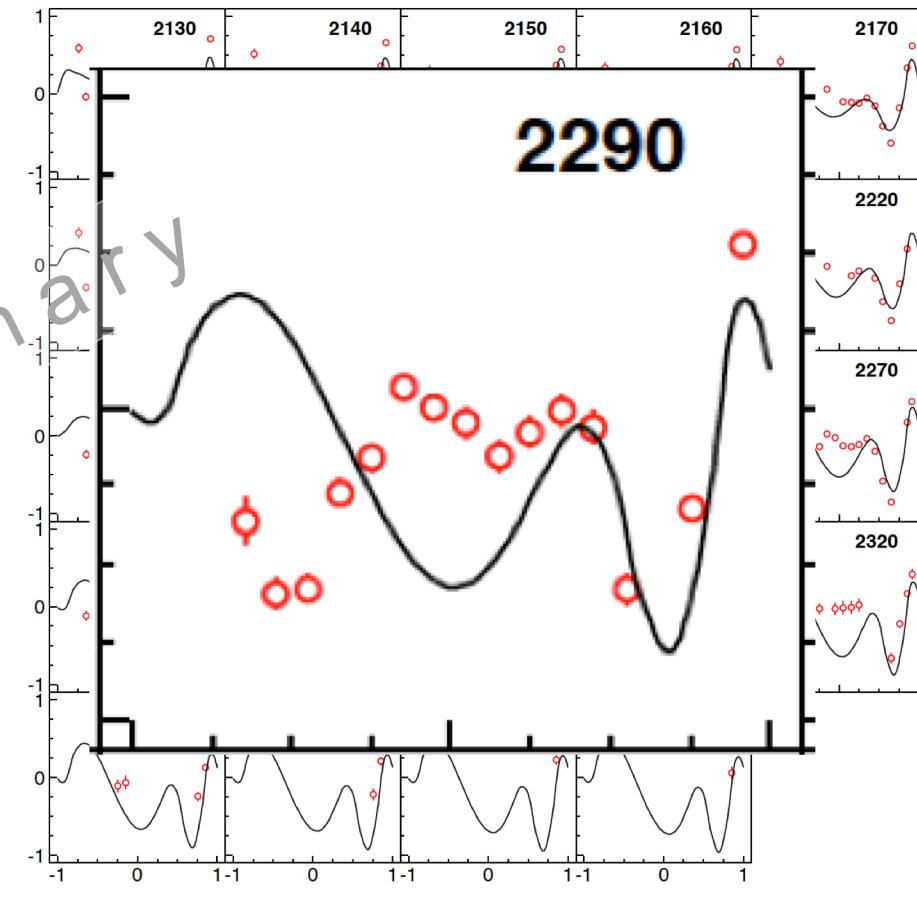
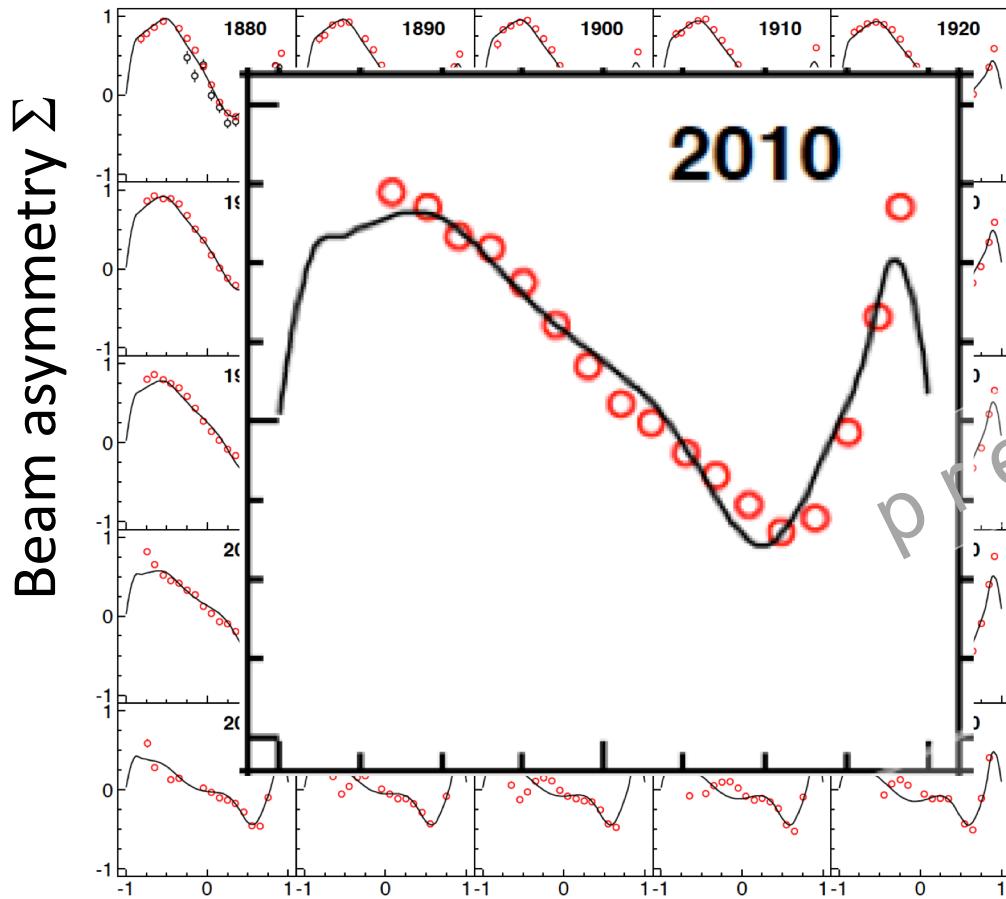
Both PWA need newly discovered nucleon resonances: N(1880)1/2⁺, N(1895)1/2⁻, N(1875)3/2⁻, N(2120)3/2⁻. Also strong evidence is found for N(2000)5/2⁺ (previously also seen in unpolarized CLAS ω data)

Search for Neutron States



$\Sigma (\gamma n \rightarrow \pi^- p)$

Fit: Bonn-Gatchina, 2018



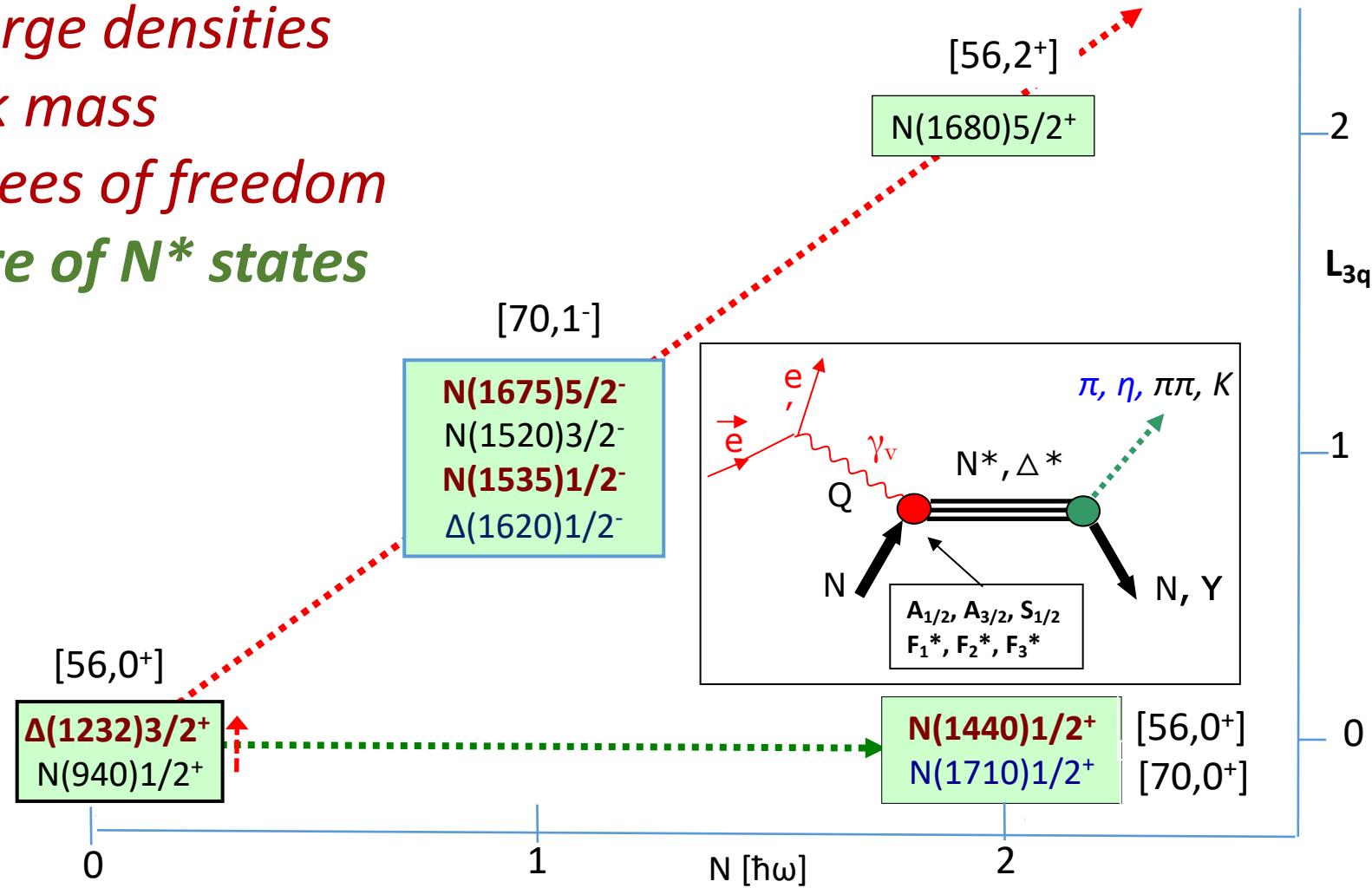
Fit requires additional new resonances above 2100 MeV

Internal structure of excited states

- Meson photoproduction very effective in searching for and identifying new resonances.
- To probe the internal structure and relevant degrees of freedom versus distance scale, a hard scale is needed, which is provided in electron scattering.

Structure of excited baryons

- *transition charge densities*
 - *running quark mass*
 - *effective degrees of freedom*
- => *reveal nature of N^* states*



<http://pdg.lbl.gov/2019/reviews/rpp2018-rev-n-delta-resonances.pdf>

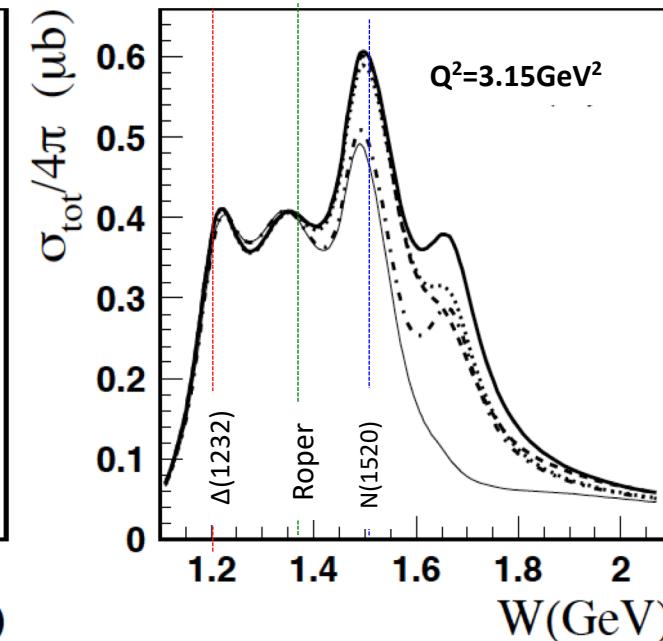
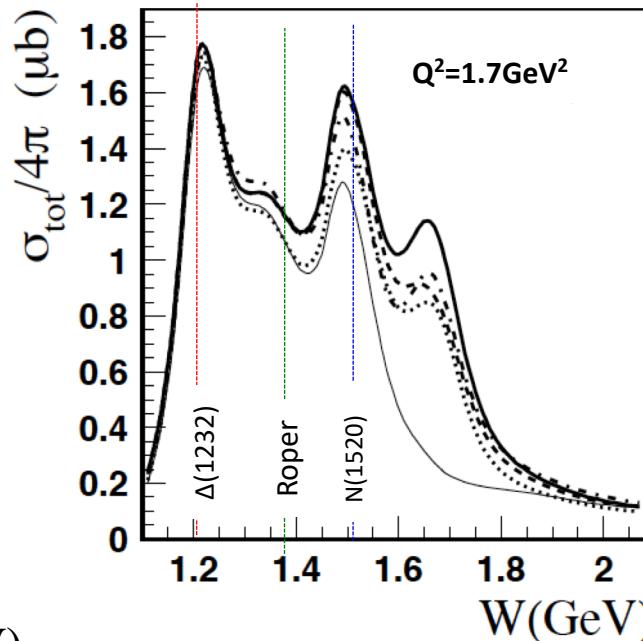
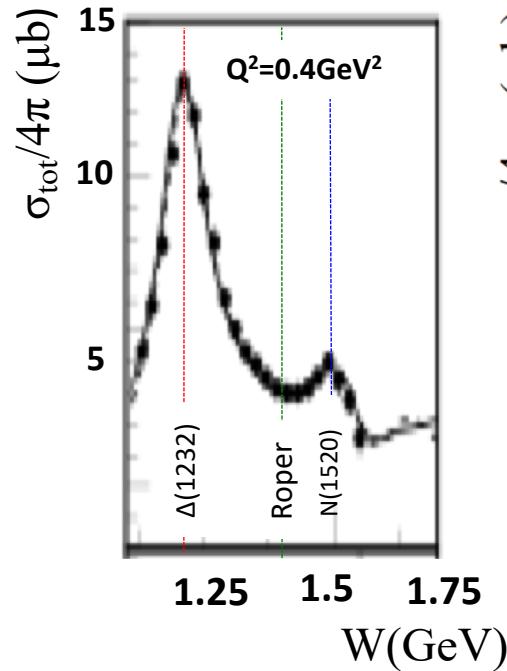
Integrated cross section at W<2GeV

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

K. Park et al., PR C77 (2008)
015208; PR C91 (2015) 045203



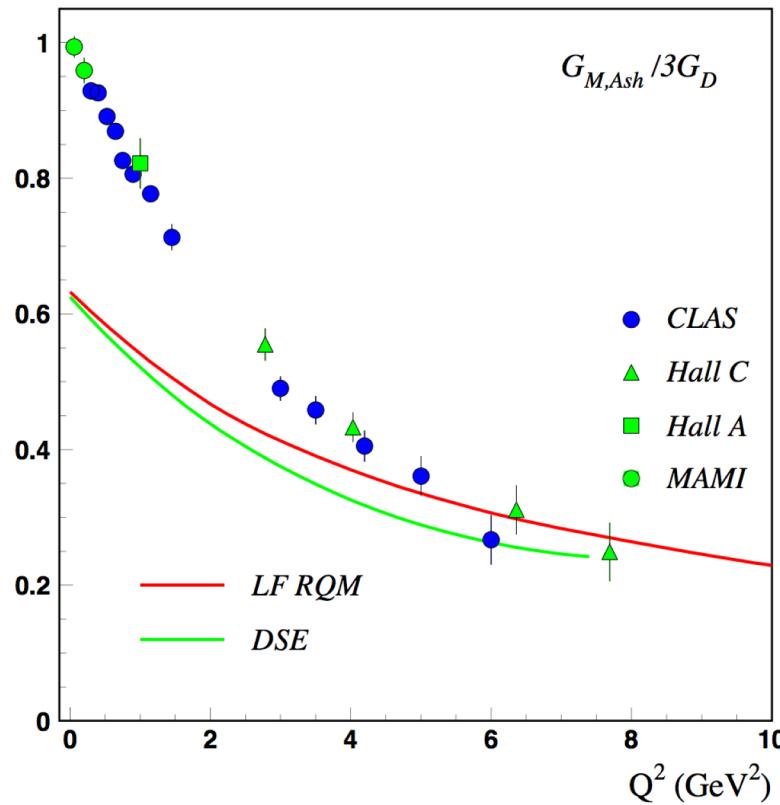
Why measure form factors of more than one resonance, aren't they all the same?



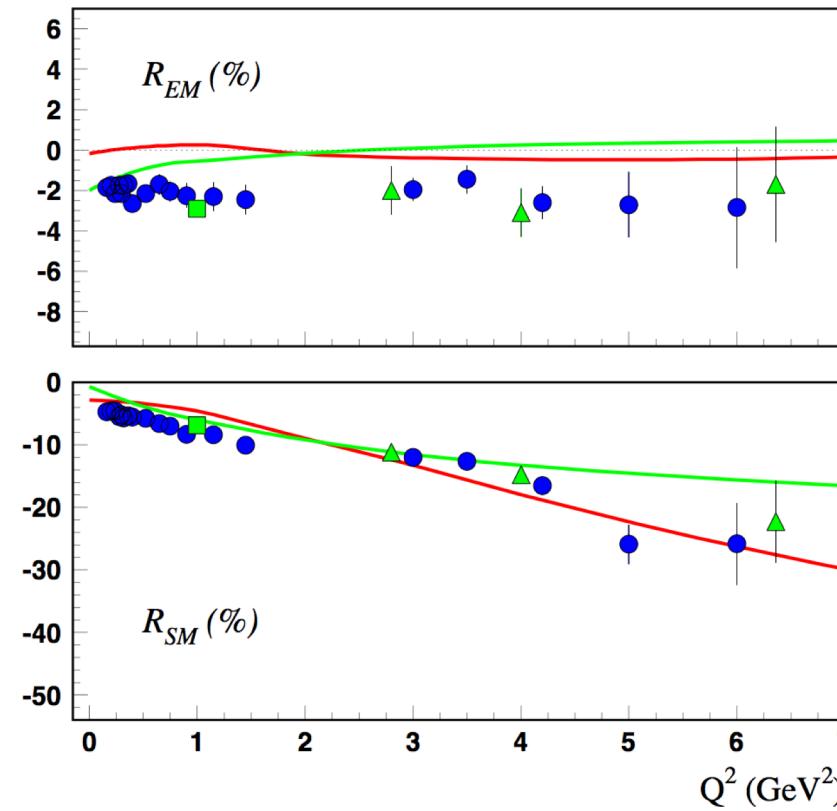
→ Different states respond differently to changes in Q^2 .

$N\Delta(1232)3/2^+$ transition form factors

LF RQM: I. Aznauryan, V.B. arXiv:1603.06692

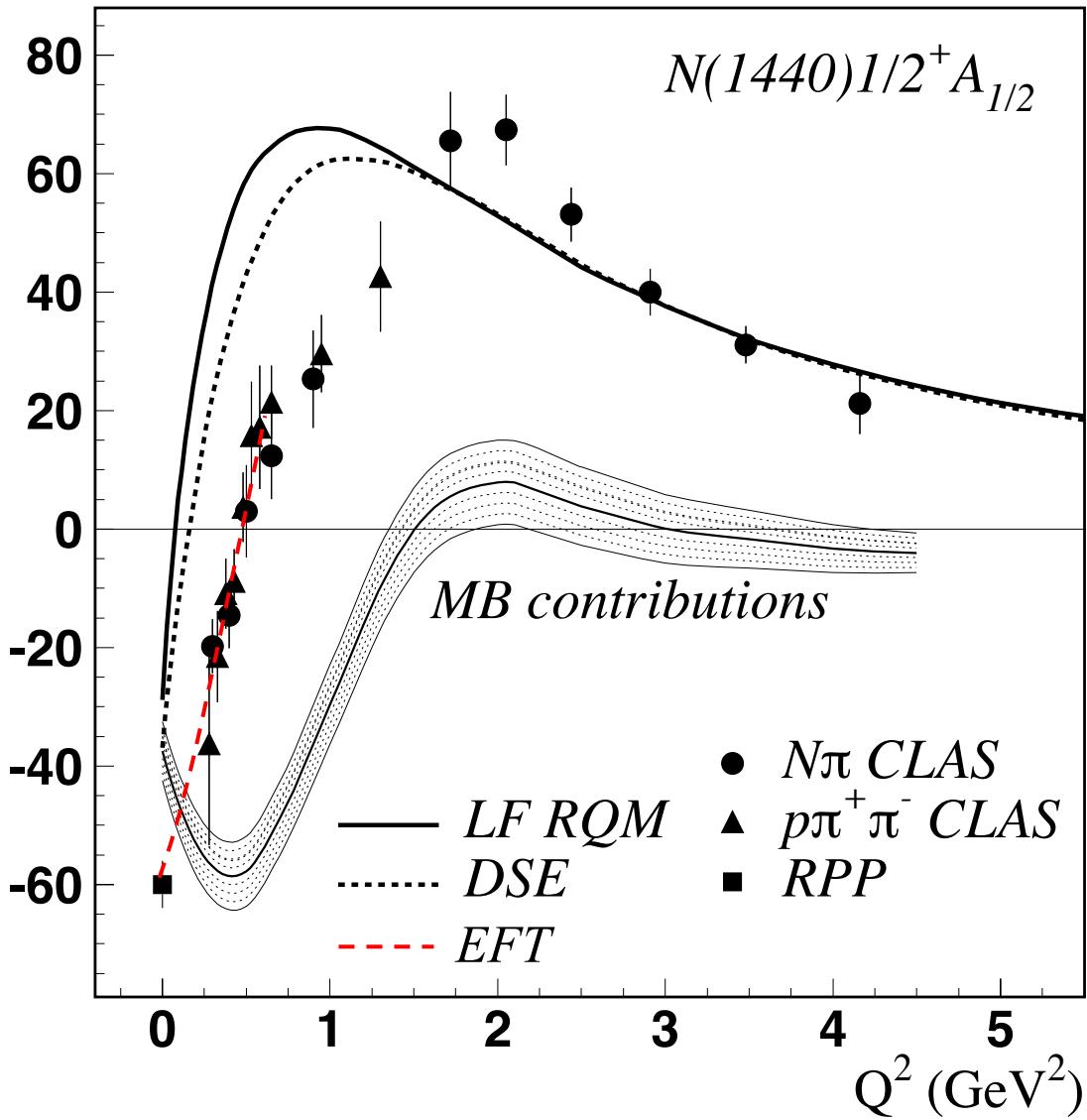


DSE: J. Segovia, C.D. Roberts et al., PRC94 (2016) 042201



- G_M shows dominance of q^3 contribution at $Q^2 > 3$ GeV 2
- $R_{EM} = -2\%$ consistent with MB, no trend towards asymptotic behavior ($R_{EM} \rightarrow +100\%$)
- $R_{SM} \sim$ consistent with q^3 dominance, $R_{SM} \rightarrow -100\%$; DSE has different trend at high Q^2

Roper - 1st nucleon radial excitation?



V.B., C. Roberts, *Rev.Mod.Phys.* 91 (2019) no.1, 011003

LF RQM: I. Aznauryan, V.B. arXiv:1603.06692

DSE: J. Segovia, C.D. Roberts et al., *PRC*94 (2016) 042201

EFT: T. Bauer, S. Scherer, L. Tiator, *PRC*90 (2014) 015201

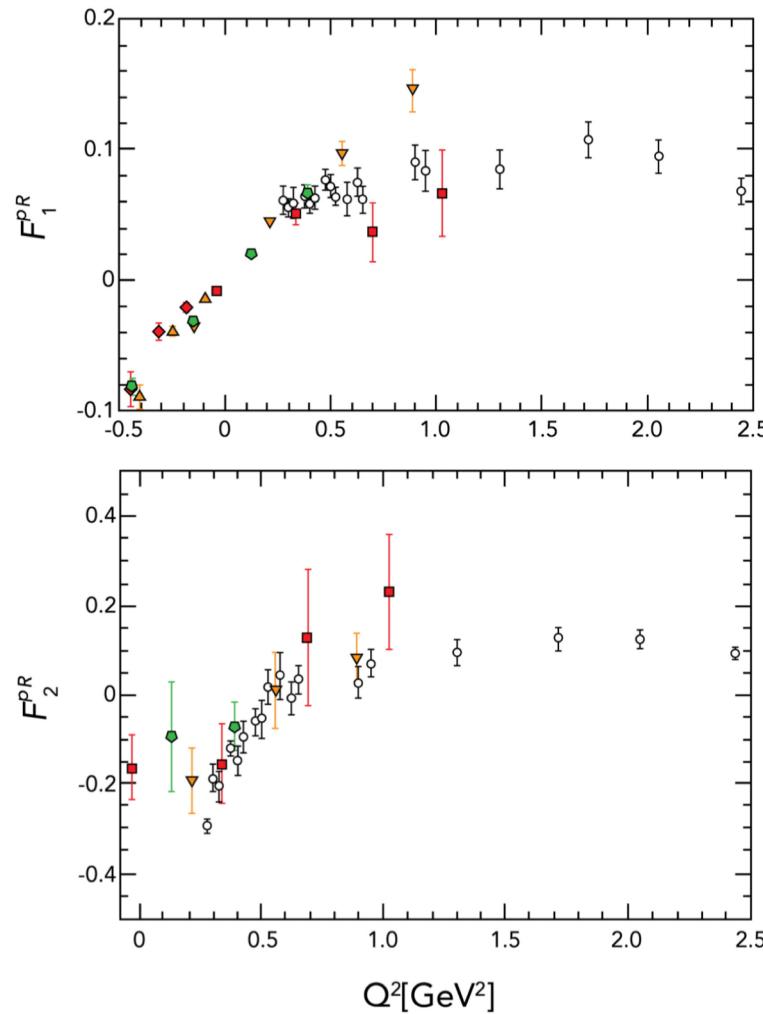
→ Non-quark contributions are significant at $Q^2 < 2.0 \text{ GeV}^2$. The behavior at $Q^2 < 0.5$ can be modeled in EFT.

→ The 1st radial excitation of the q^3 core emerges as the probe penetrates the MB cloud

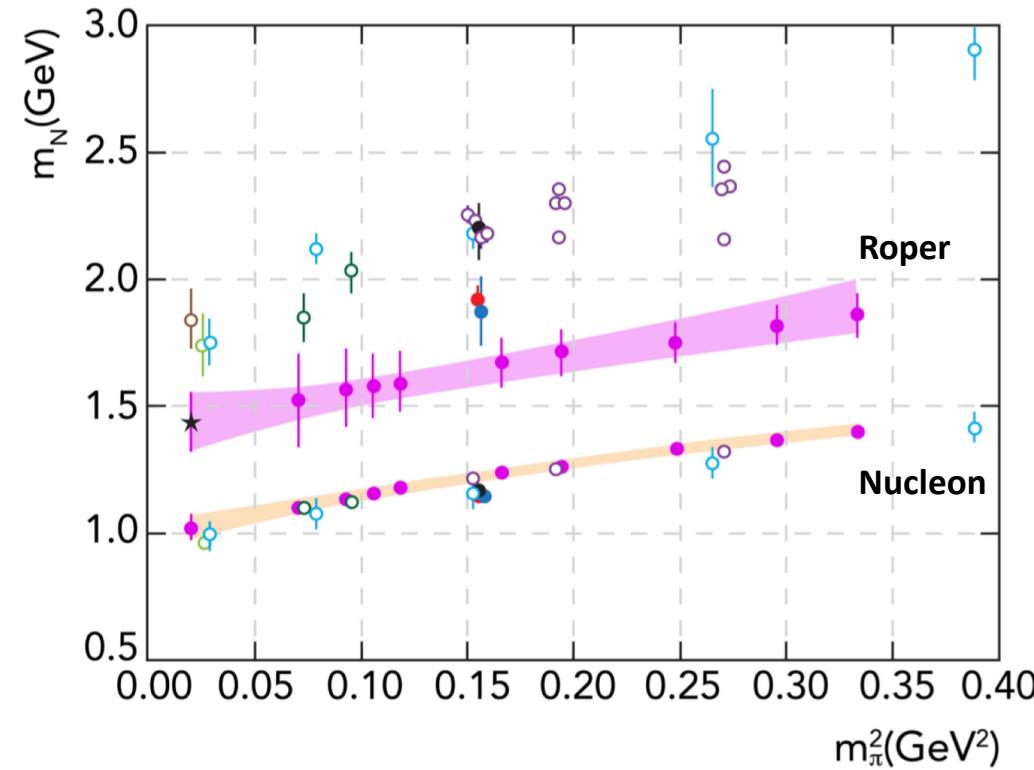
“Nature” of the Roper – is consistent with the 1st radial excitation of its quark core surrounded by a meson-baryon “cloud”.

Roper resonance from LQCD

H.-W. Lin, S. D. Cohen, 2012



Roper mass in LQCD

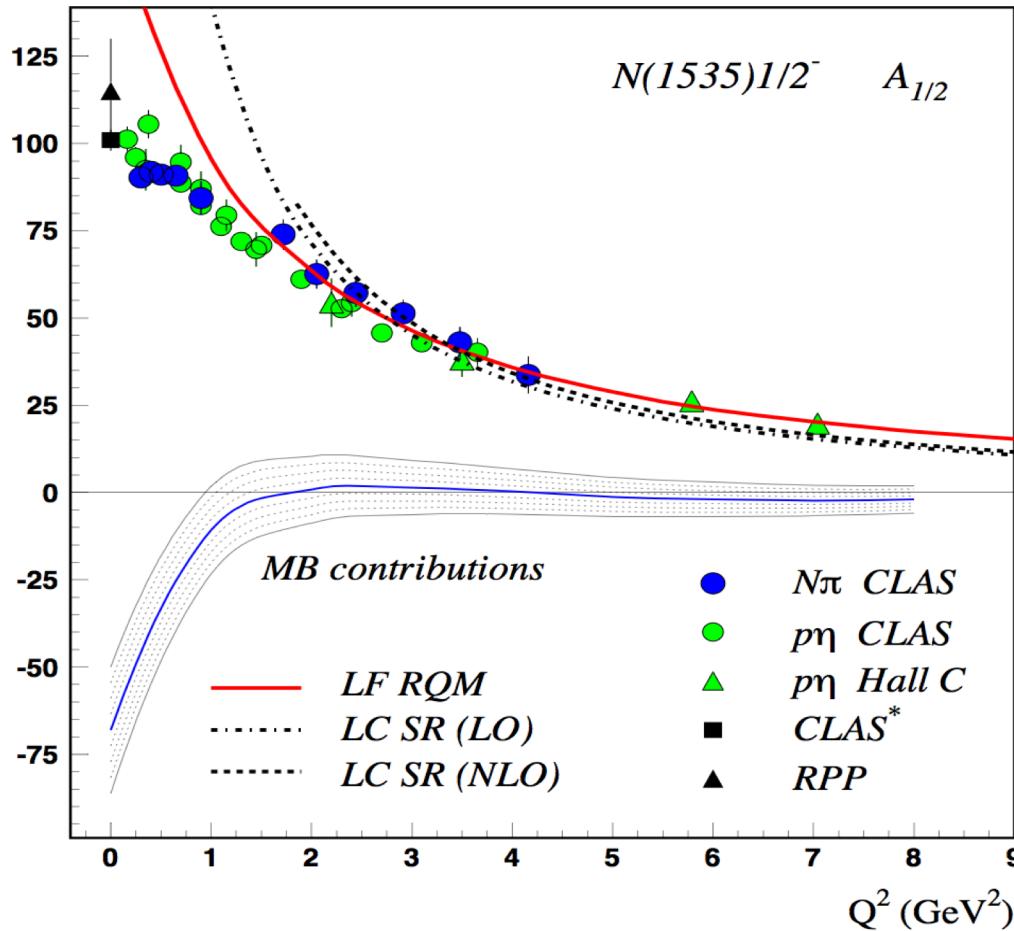


In the Q^2 region where data and calculations overlap $0.3 < Q^2 < 1 \text{ GeV}^2$ is good agreement.

$N(1535)1/2^-$ – Parity partner of the nucleon

LC SR: I. Anikin, V. Braun, N. Offen,
PRD92 (2015) 014018

LF RQM: I. Aznauryan, V.B. arXiv:1603.06692



- LF RQM describes data at $Q^2 > 1.0 \text{ GeV}^2$
- LC SR with direct link to sQCD describe transition at $Q^2 > 1.5 \text{ GeV}^2$
- Non-quark contributions concentrated at $Q^2 < 1.0 \text{ GeV}^2$
- **$N(1535)1/2^-$ quark core excitation is consistent with the 1st orbital excitation of the nucleon.**

Light Front γpN^* transition charge densities

L. Tiator, M. Vanderhaeghen
Phys.Lett. B672 (2009) 344-348

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

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

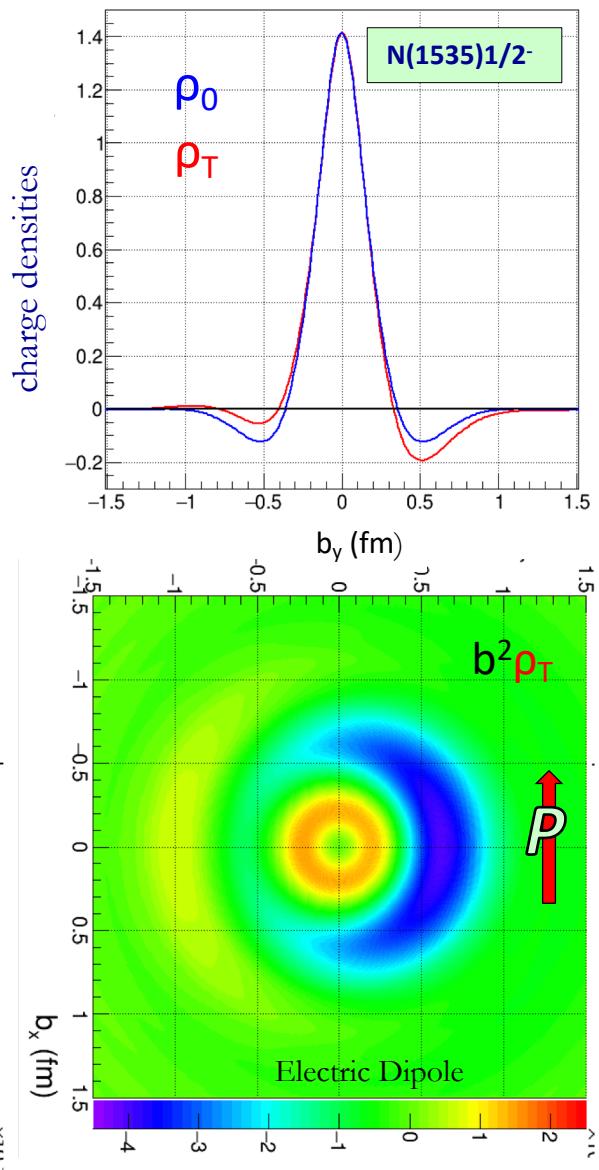
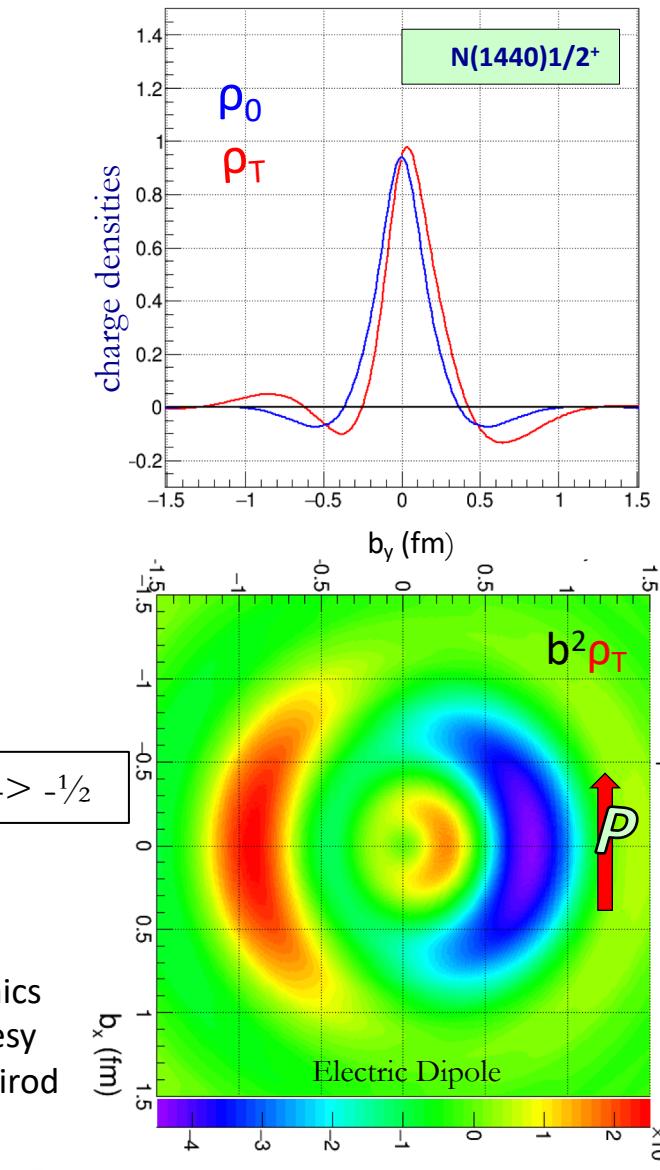
Exp: $0 < Q^2 < 4.5-7 \text{ GeV}^2$

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

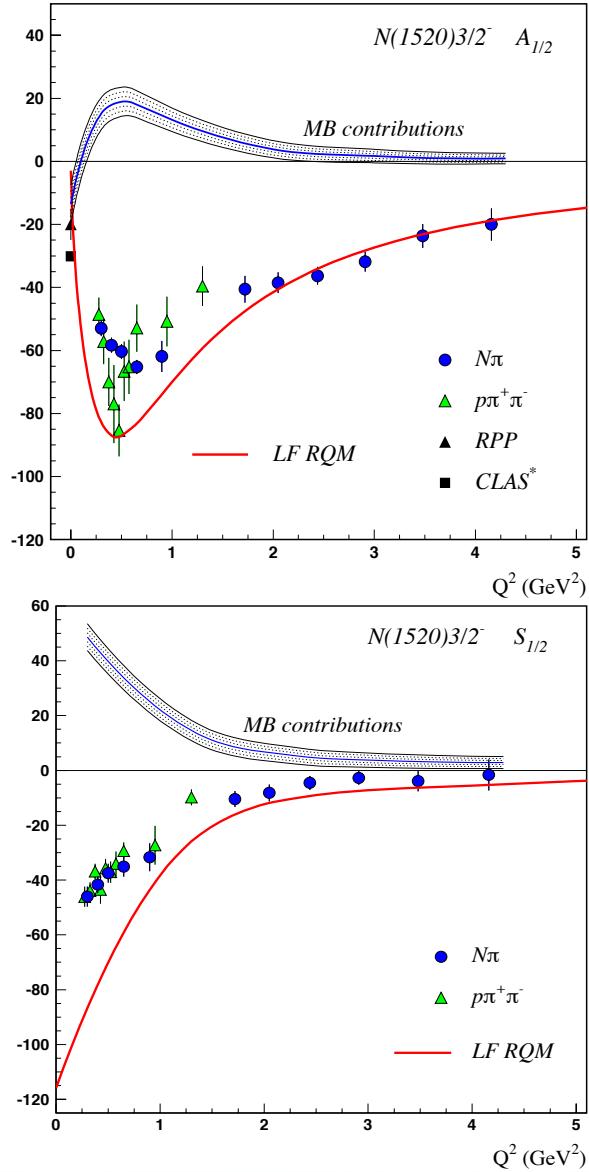
$$\rho_T^{NN^*}(\vec{b}) = \rho_0^{NN^*}(b) + \sin(\phi_b - \phi_S) \int_0^\infty \frac{dQ}{2\pi} \frac{Q^2}{(M^* + M_N)} J_1(bQ) F_2^{NN^*}(Q^2)$$

N(1440) exhibits a somewhat softer core and a more complex meson cloud contribution than N(1535) which has a harder core and smaller cloud.

graphics
courtesy
F.X. Girod

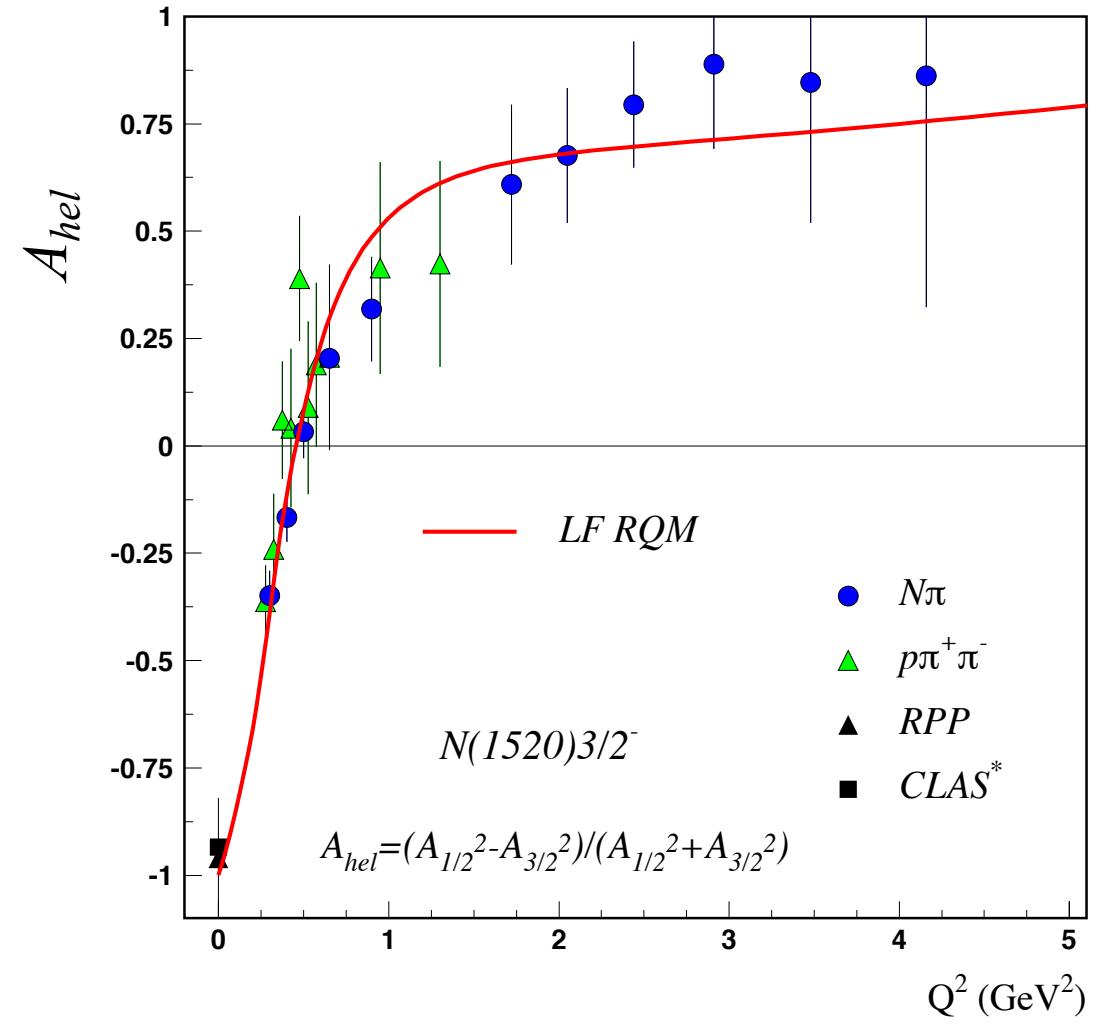


Electrocoupling amplitudes $N^+(1520)3/2^-$



=> $A_{1/2}$ amplitude
dominant at $Q^2 > 1$ GeV 2

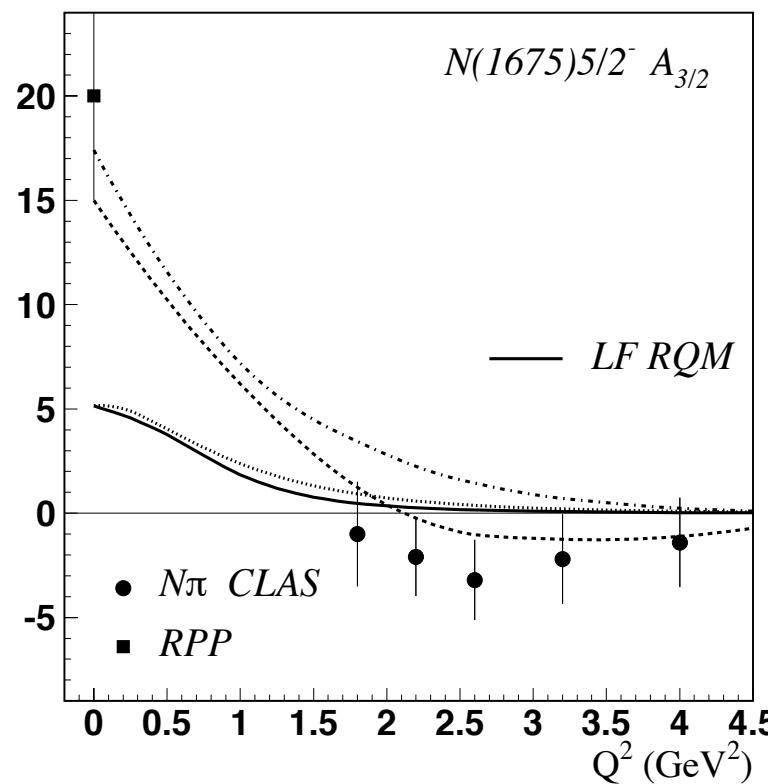
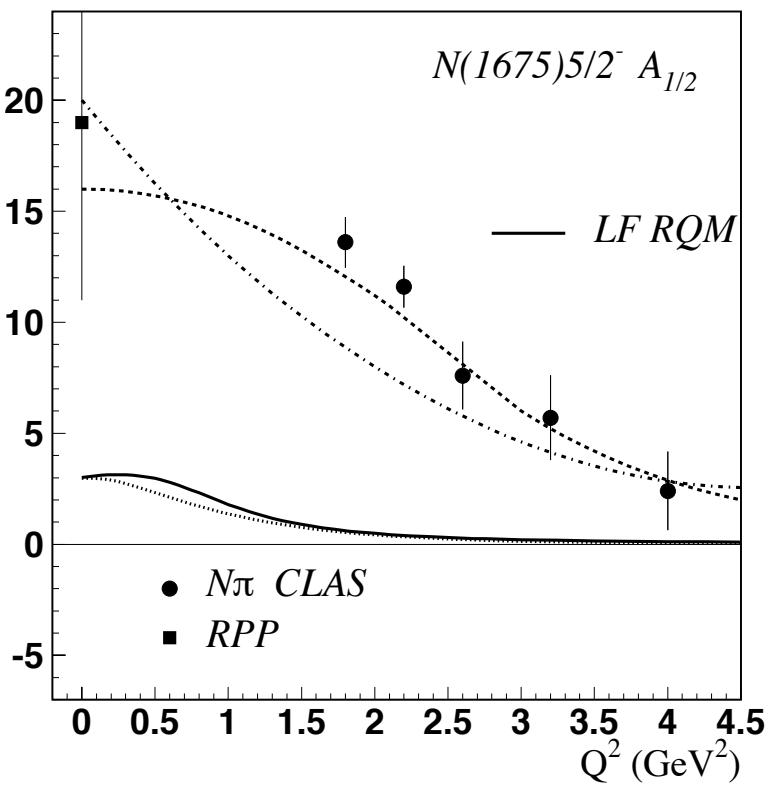
=> $A_{1/2}$ is only significant
contributor at $Q^2 > 3$ GeV 2



$N^+(1675)5/2^-$ photo/electrocoupling amplitudes

On **proton** target the q^3 transverse amplitudes are suppressed due to a selection rule.
=> Expect MB contributions to dominate at all Q^2

K. Park et al.; PR C91 (2015) 045203

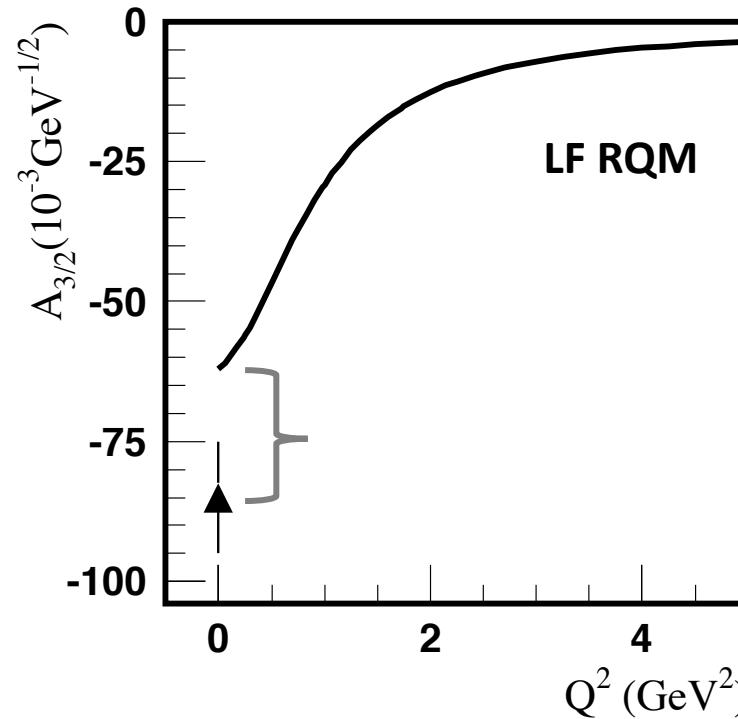
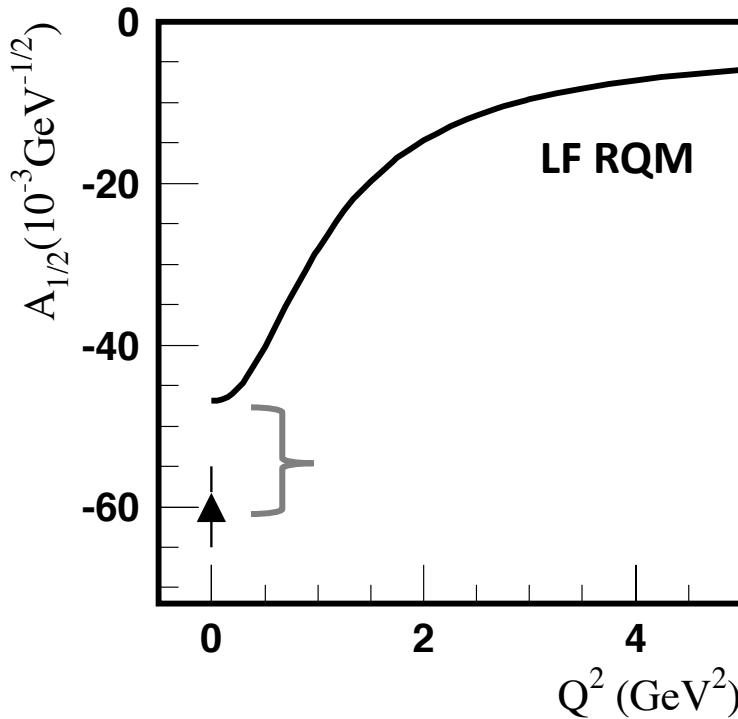


- ⇒ Meson-baryon contributions significant.
- ⇒ State is not a MB resonance.
- ⇒ CQM predicts large amplitudes on neutrons – seen in data.

$N^0(1675)5/2^-$ photo/electrocoupling amplitudes

On **neutron** target the q^3 transverse amplitudes are not suppressed.

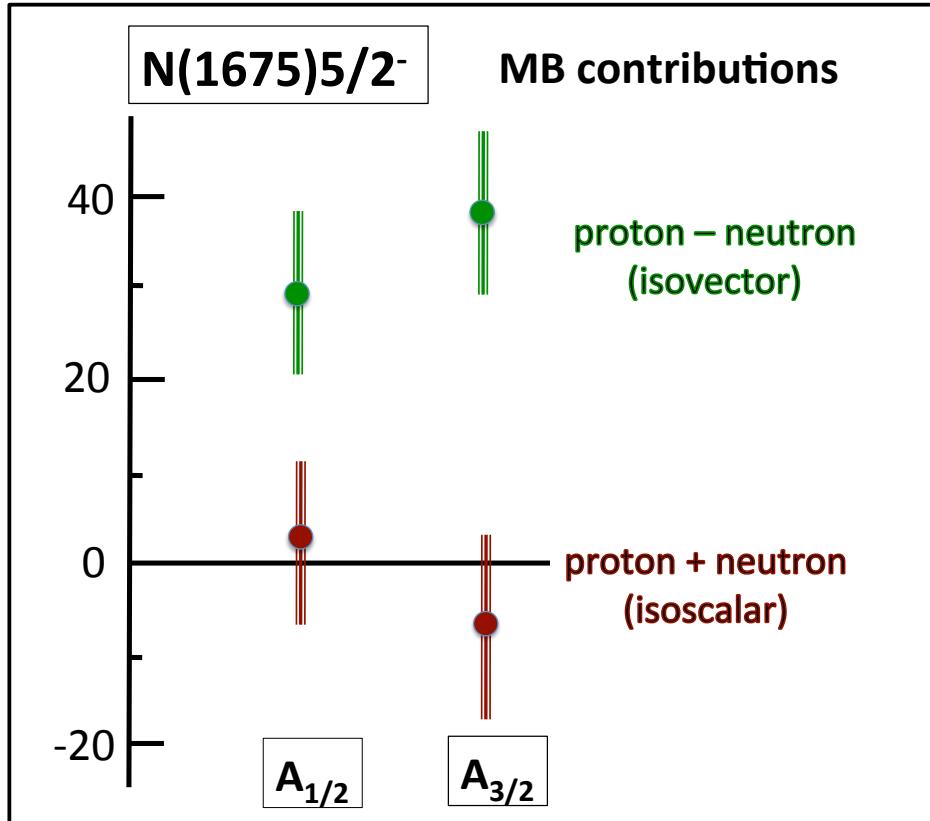
=> Expect q^3 contributions to dominate at all Q^2



- ⇒ LF RQM predicts large amplitudes on neutrons – seen at the photon point
- ⇒ Meson-baryon contributions significant, not dominant ($\sim 25\%$).

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

Resonance	$A_{1/2}$	$A_{3/2}$	$A_{1/2}$	$A_{3/2}$
	exp. [15]		exp – LF RQM	
$N(1440)\frac{1}{2}^{+}$			proton	
	-60 ± 4			-31 ± 4
$N(1520)\frac{3}{2}^{-}$	-20 ± 5	140 ± 10	-17 ± 5	-174 ± 10
$N(1535)\frac{1}{2}^{-}$	115 ± 15			-54 ± 15
$N(1675)\frac{5}{2}^{-}$	19 ± 8	20 ± 5	16 ± 8	15 ± 5
	neutron			
$N(1440)\frac{1}{2}^{+}$	40 ± 10		12 ± 10	
$N(1520)\frac{3}{2}^{-}$	-50 ± 10	-115 ± 10	20 ± 10	131 ± 10
$N(1535)\frac{1}{2}^{-}$	-75 ± 20		87 ± 20	
$N(1675)\frac{5}{2}^{-}$	-60 ± 5	-85 ± 10	-13 ± 5	-23 ± 10

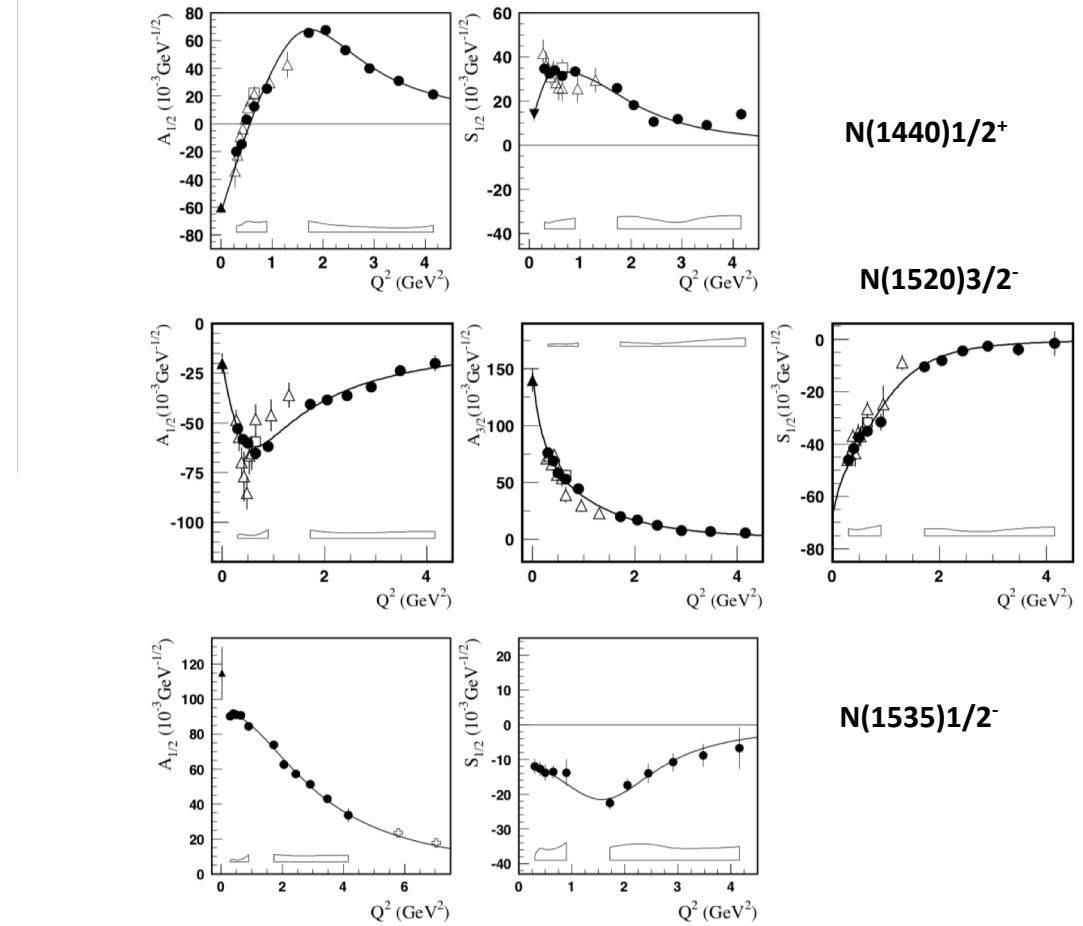
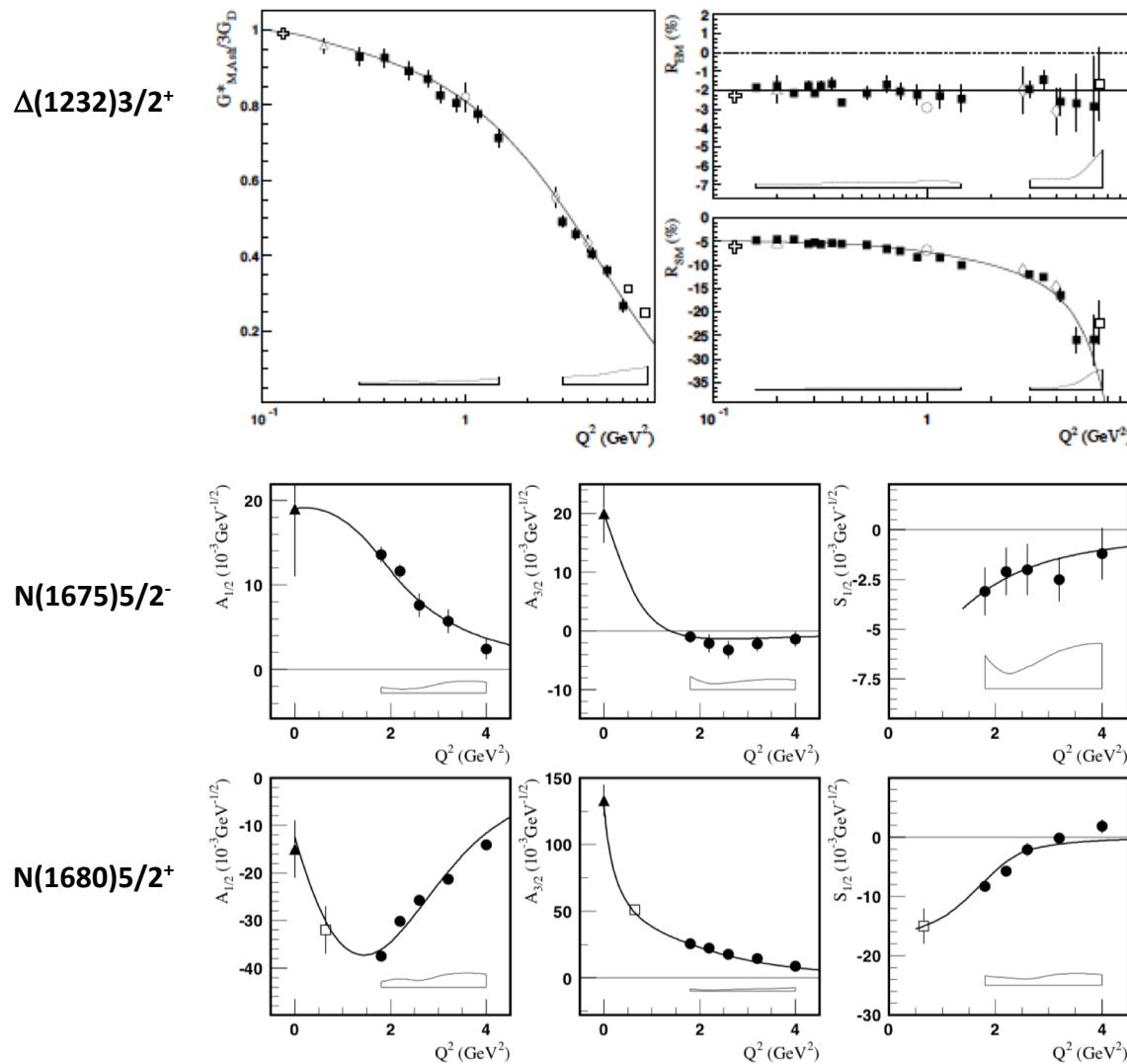


Using the quark selection rule and the LF RQM and hCQM we obtain insight into the isospin components of the MB contributions to the $\gamma p N^+(1675)5/2^-$ and $\gamma n N^0(1675)5/2^-$ transitions.

MB at $Q^2=0$ are dominated by isovector amplitudes.

<http://pdg.lbl.gov/2019/reviews/rpp2018-rev-n-delta-resonances.pdf>

Resonance Electrocouplings in RPP 2019



PDG Online 2019

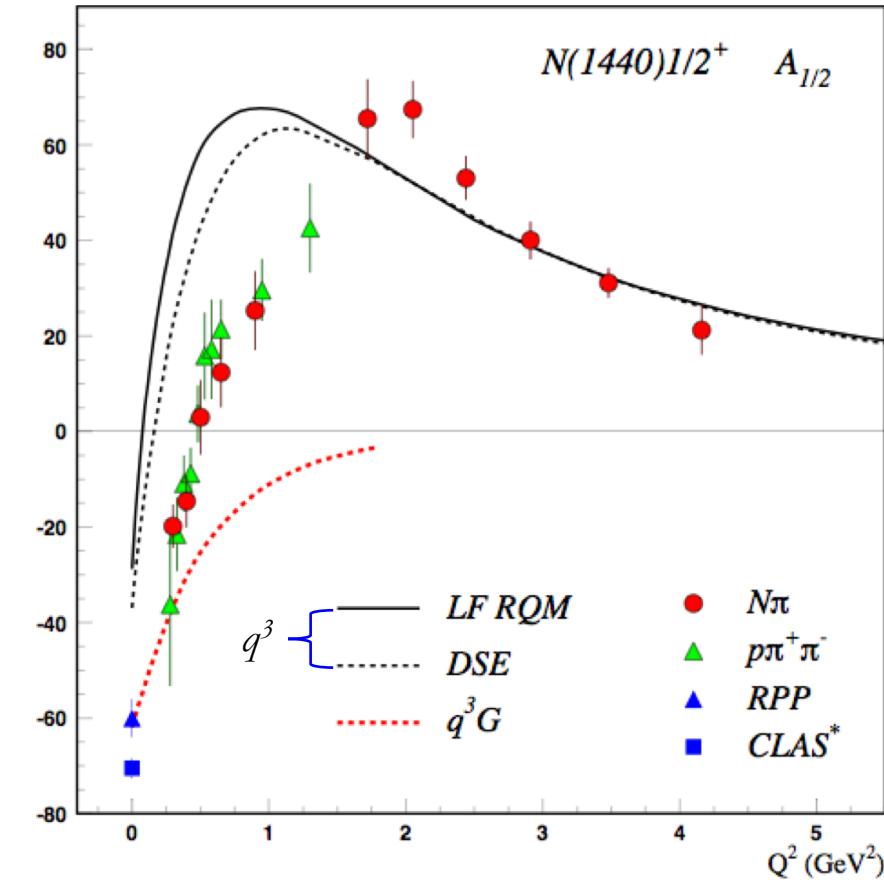
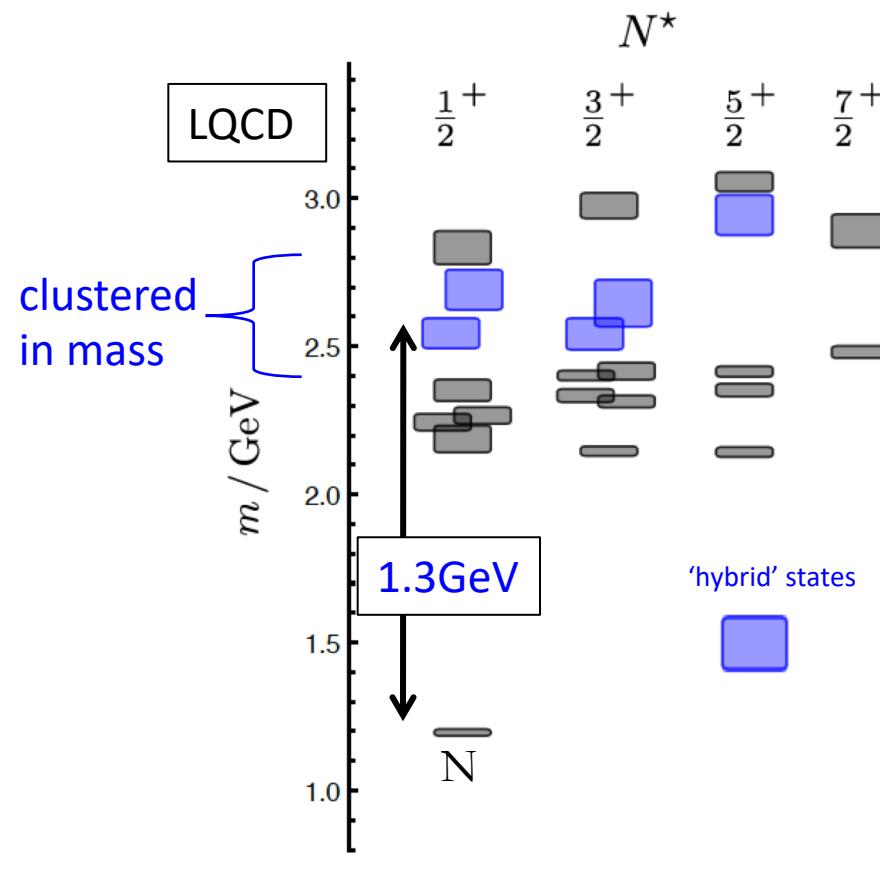
<http://pdg.lbl.gov/2019/reviews/rpp2018-rev-n-delta-resonances.pdf>

The N* program continues

- The search for new N* states continues with the precision data from CBELSA, MAMI, JLAB, LEPS, J-PARC, ..
- Multi-channel analyses have been critical components in the search for new states and should be further developed to include vector mesons, multiple mesons, ...
- We need to search for the missing strangeness states in new experimental programs, e.g. J-PARCe. K_L-Facility at JLab/Hall D,.. ..
- We need to address experimentally how nearly massless quarks become massive as predicted in LQCD and DSE
- We need to search for gluonic baryons predicted by LQCD and models

Hybrid Baryons q^3G

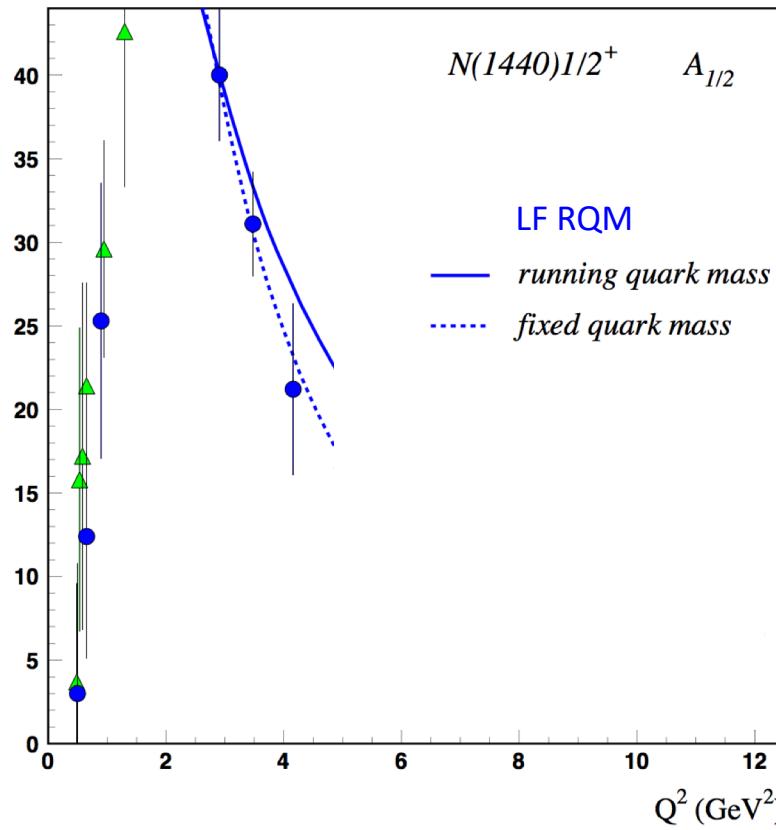
J.J. Dudek and R.G. Edwards, PRD 85 (2012) 054016



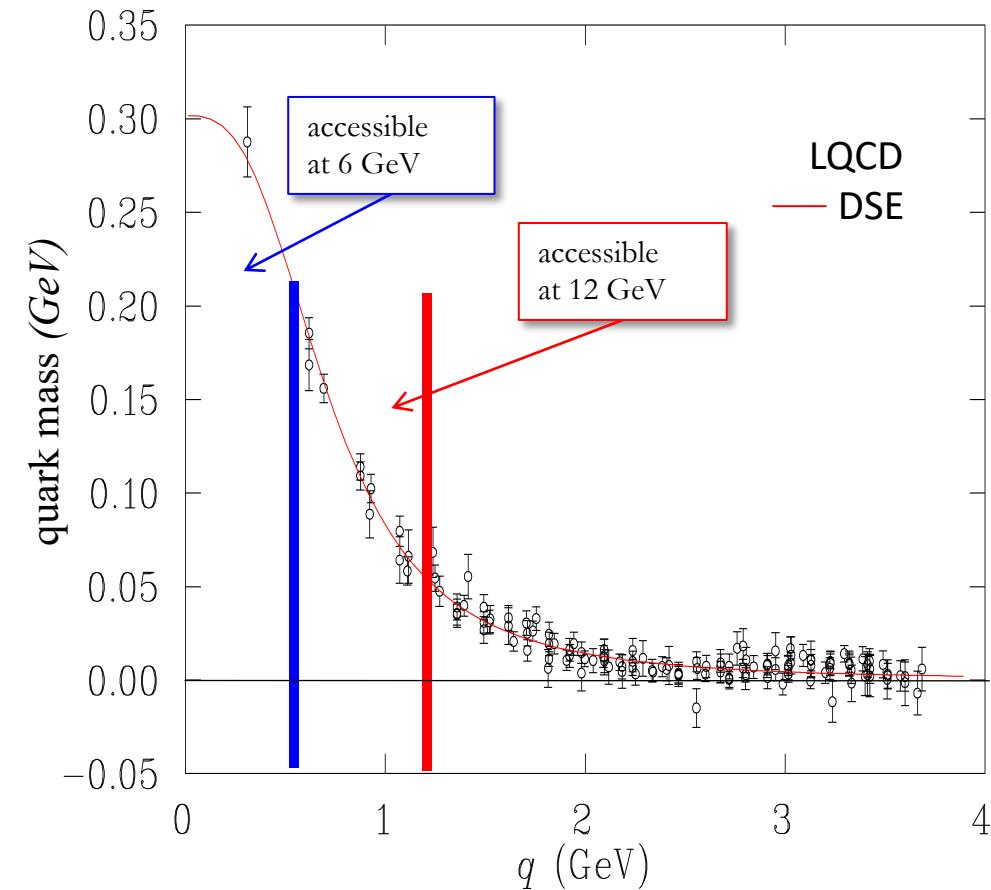
Cover low Q^2 range with very high statistics using the CLAS12 detector

Probing the running quark mass at JLab12

Roper resonance



Running quark mass



- Probe the transition from interaction on dressed quarks to elementary quarks.

So where are the connection of N*'s to sQCD?

- Strong QCD was born in the transition from the QGP to hadrons, a period when N*'s filled the microsecond old Universe.

→N*'s are the embodiment of sQCD

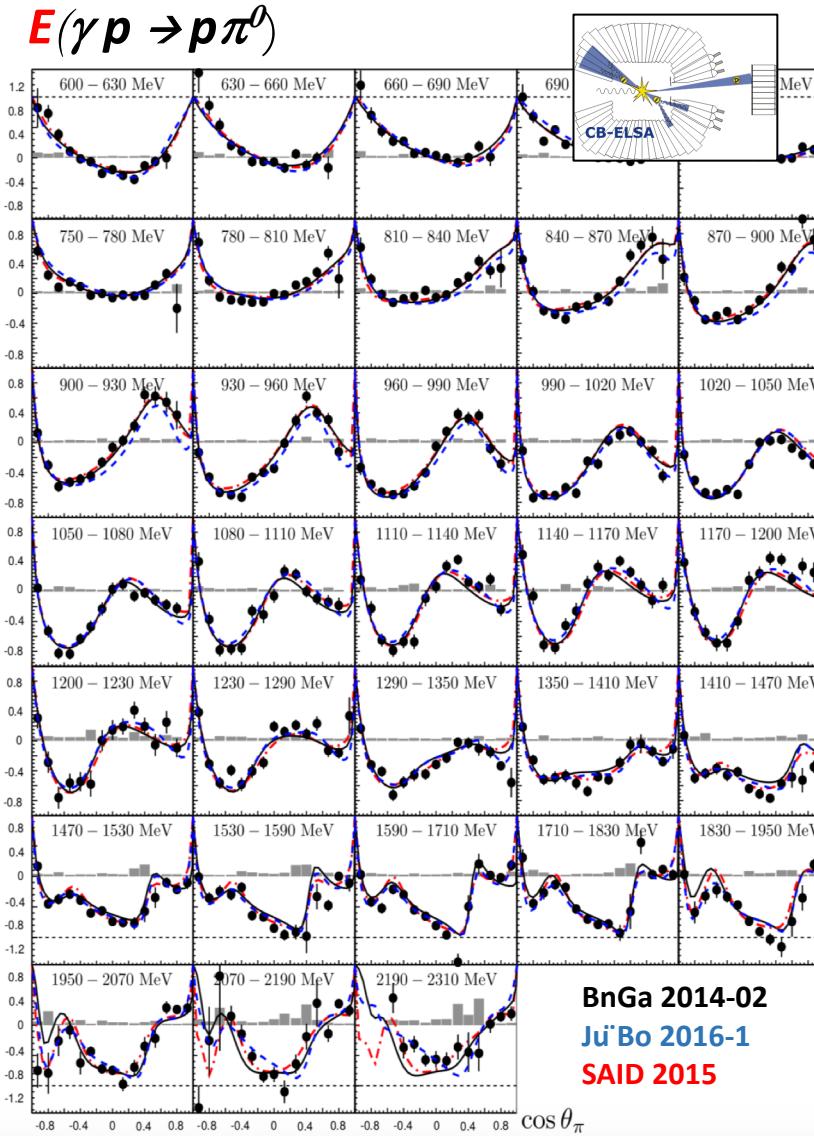
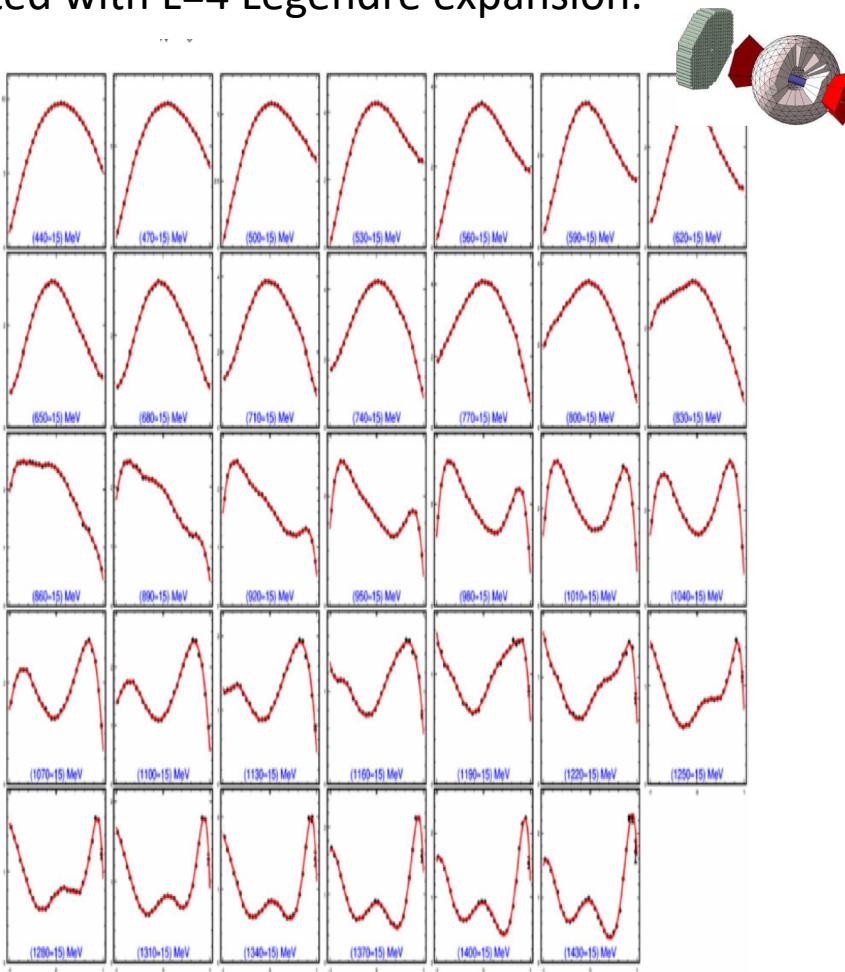
- Since 2011 we have predictions of the N* spectrum from sQCD on a Lattice with ~400 MeV pions
- High precision data and multi-channel analyses were essential in the discovery of new N*'s (that fit into the spectrum of sQCD), but masses cannot be compared yet.
- sQCD has been applied in the description of several N* transitions, and domains where dressed quarks are the active degrees of freedom have been identified.
- The description of transition form factors at small Q^2 remains elusive, but needs to be solved within sQCD. Meson cloud effects may be crucial in solving the confinement challenge.
- Advanced LF RQM, LC SR, hQCD, EFT, and others continue to provide insights where sQCD has not been solved.
- Hope to see more sQCD calculations of N* transition form factors.

The N*2019 Workshop keeps the momentum going

Additional slides

Establishing the N* spectrum – $\Delta(2200)7/2^-$

Differential $p\pi^0$ cross section at MAMI-CB
fitted with L=4 Legendre expansion.



M. Gottschall et al.,
arXiv:1904.12560 (2019)

To measure E requires circular polarized photons from bremsstrahlung of longitudinally polarized electrons.

How to get long. spin-polarized electrons in experiment after they are accelerated in a synchrotron with transverse magnetic fields? Use spin rotator.