Excited Nucleons Spectrum and Structure

Volker D. Burkert
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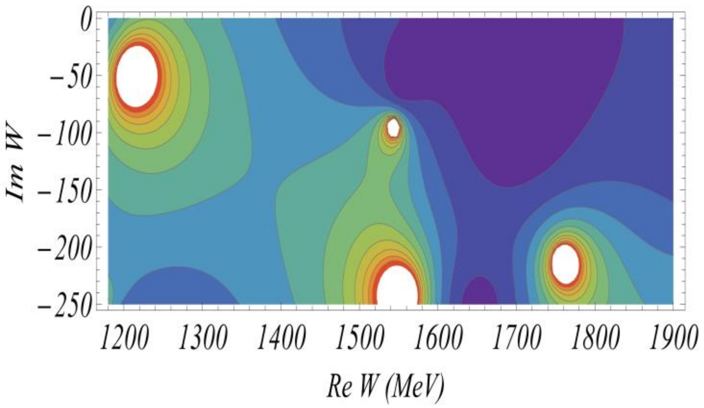
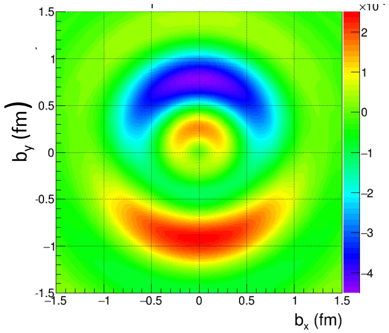


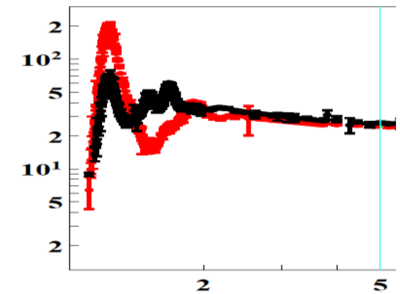


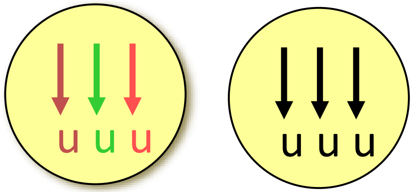
Jefferson Lab
Thomas Jefferson National Accelerator Facility

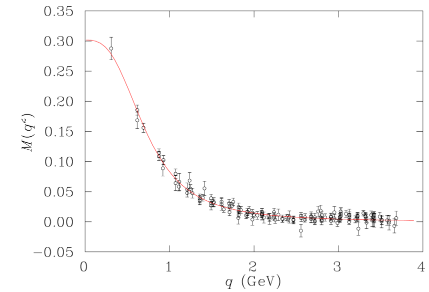
clas
CEBAF Large Acceptance Spectrometer

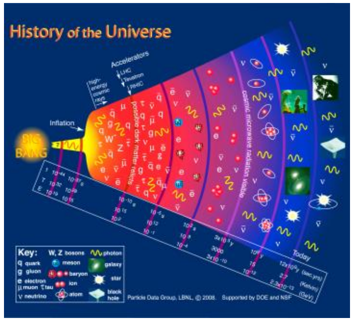
Excited nucleons – some markers

- ✓ **1952**: First glimpse of the Δ(1232) in πp scattering
- ✓ **1964:** Excited baryons are essential in establishing the quark model and the color degrees of freedom. The Δ^{++} state is not allowed in a quark model without color.
- ✓ **1990**: A broad effort to verify the quark model predictions of the spectrum and to understand the relevant degrees of freedom (missing resonances).
- ✓ **2010:** Research in DSE/QCD and LF RQM show, when nucleon resonances are excited at different distance scales (Q^2), their transition form factors probe the dynamical quark mass function $m_q(q)$.
- ✓ **2015:** Baryon resonances play a critical role in the interpretation of the evolution of the universe during the first microseconds.

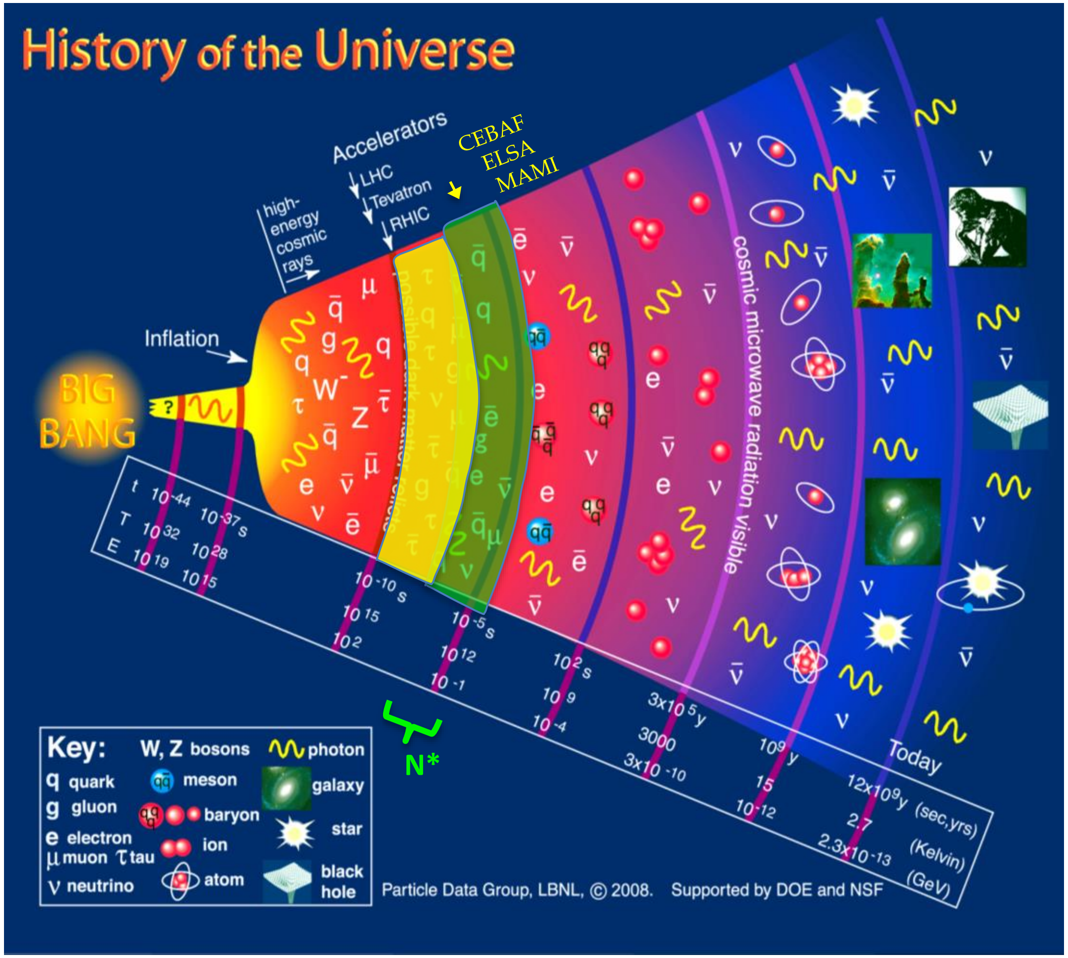


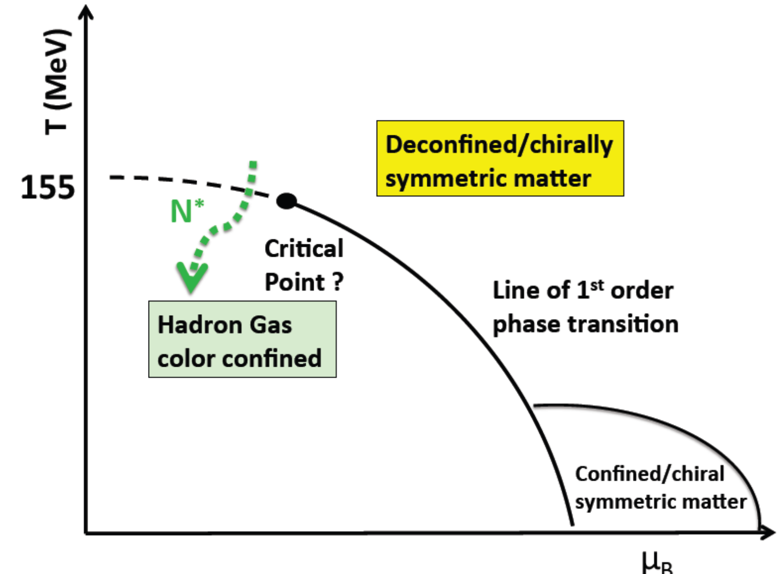






History of the Universe and N*'s





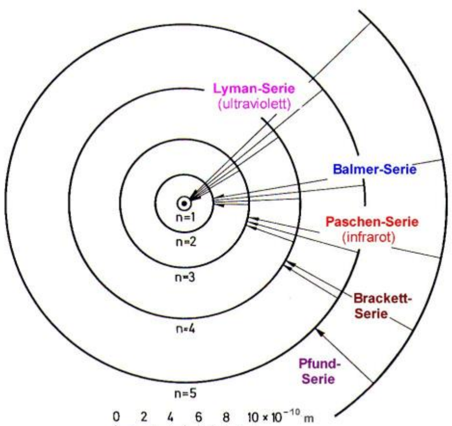
Dramatic events occur in the micro-second old universe during the transition from the QGP phase to hadron phase.

- Chiral symmetry is dynamically broken
- Quarks attain masses dynamically
- Color confinement occurs
- Transition driven by excited baryons

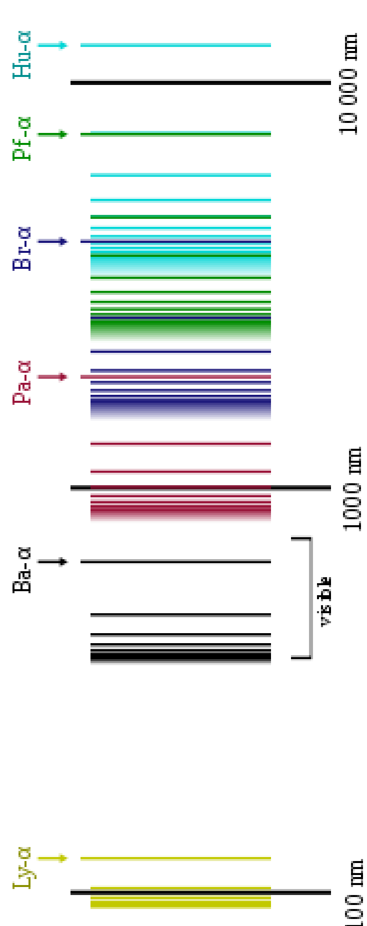
With existing accelerators we can explore these events in isolation

From the H spectrum to the N* spectrum

Niels Bohr, model of the hydrogen atom, 1913.



Spectral series of hydrogen



- Understanding the hydrogen atom requires understanding its emission spectrum of ***sharp energy levels***
- From the ***Bohr model*** to ***QED***

- Understanding the proton requires understanding its energy spectrum of ***broad energy levels***.

From the ***Quark model*** to ***strong QCD***

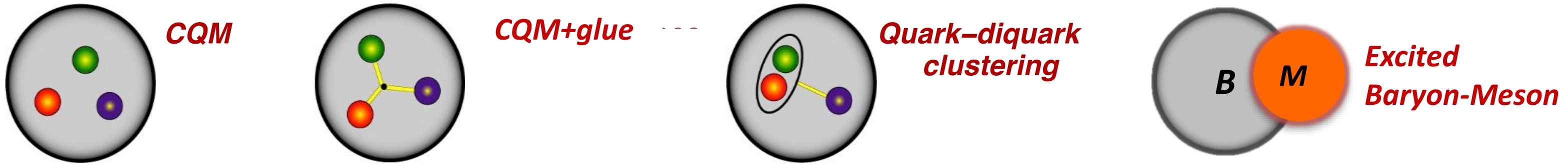
Role of experiment:

$\Rightarrow$ **Map the excitation spectrum more completely and accurately.**

What do we learn from excited baryons?

• Only now do we have experimental, phenomenological, and theoretical tools to more fully explore baryon spectrum and structure.

- The N* spectrum reflects the underlying degrees of freedom and the effective forces between them that relate to quark confinement.



- Vigorous experimental program is underway along two avenues
  - Search for undiscovered states in photoproduction (ELSA, JLab, MAMI, ..)
  - Identify the relevant degrees of freedom of prominent states versus distance scale in electroproduction (JLab/JLab12)

- New developments in theory – LQCD, DSE, LC SR, LF RQM, ...

Search for excited baryons – some reaction channels

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

γp→X

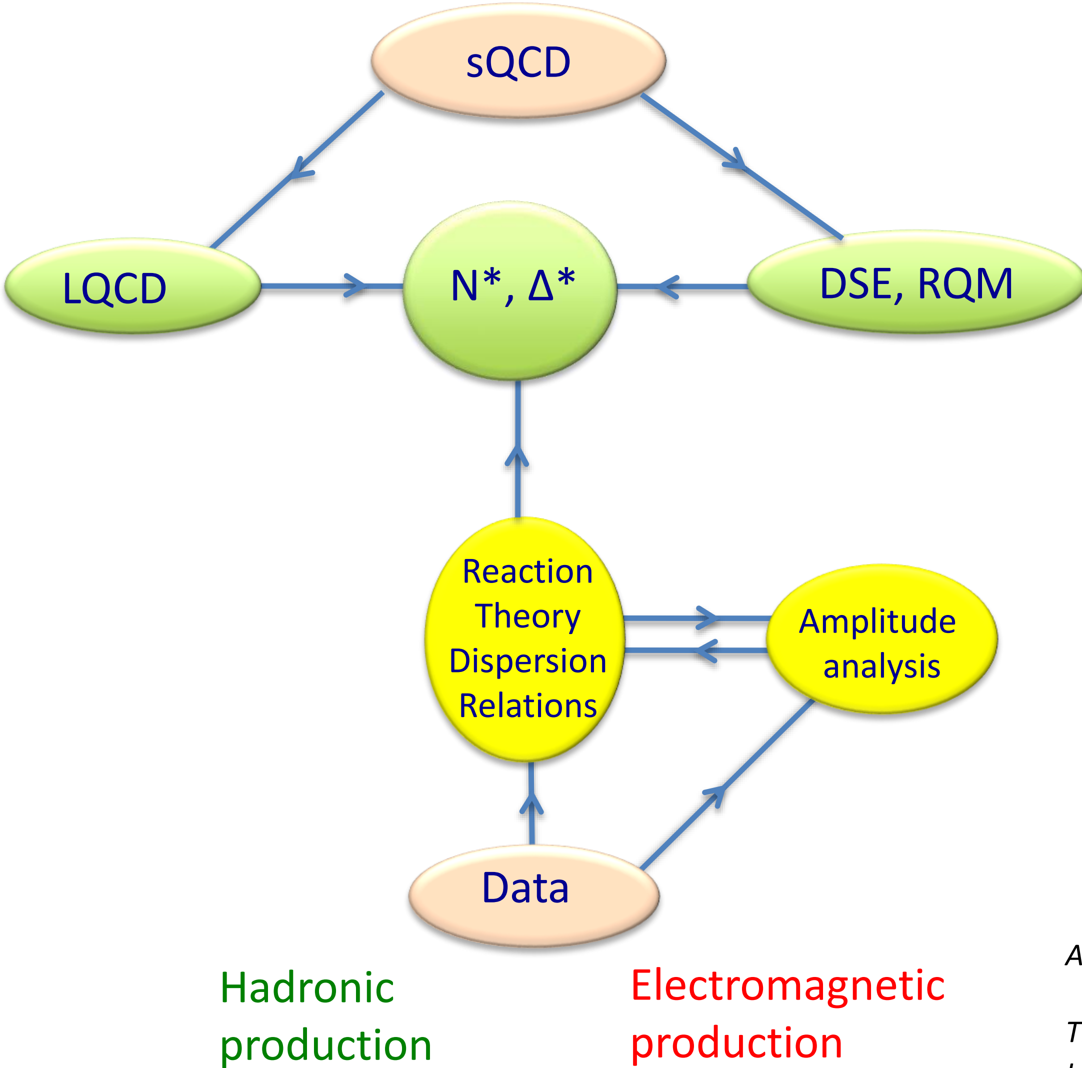
	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
$p\pi^0$	✔	✔	✓		✓	✓	✓	✓								
$n\pi^+$	✔	✔	✓		✔	✓	✓	✓								
$p\eta$	✔	✓	✓		✔	✓	✓	✓								
$p\eta'$	✔	✓	✓		✓	✓	✓	✓								
$p\omega/\phi$	✔	✓	✓		✓	✓	✓	✓	✔ SDME							
$K^+\Lambda$	✔	✔	✔	✔	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔	✔	✔
$K^+\Sigma^0$	✔	✔	✔	✔	✓	✓	✓	✓	✓	✓	✓	✓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

γn→X

	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
$p\pi^-$	✔	✔			✓	✓	✓									
$p\rho^-$	✓	✓			✓	✓	✓									
$K^-\Sigma^+$	✓	✓			✓	✓	✓									
$K^0\Lambda$	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓									✓	✓				

Establishing the N* and Δ* Spectrum

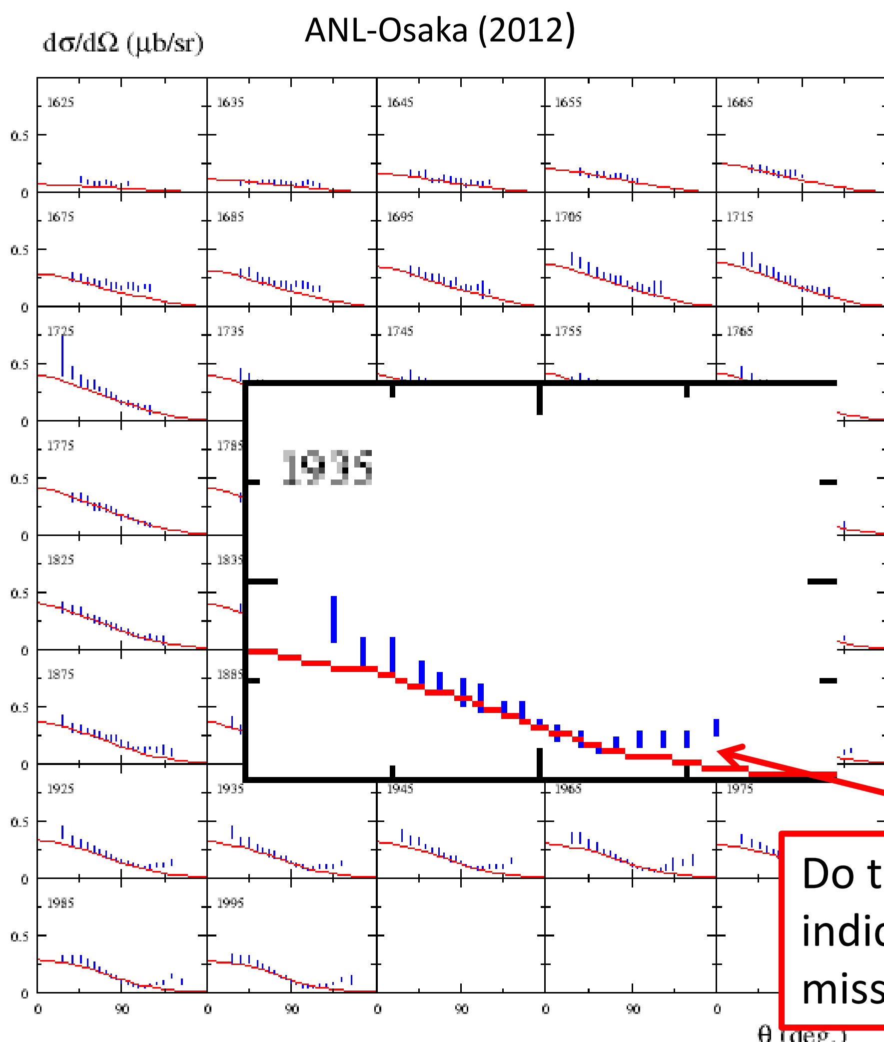
V.B., T.S.-H. Lee
IJMP E13 (2004)



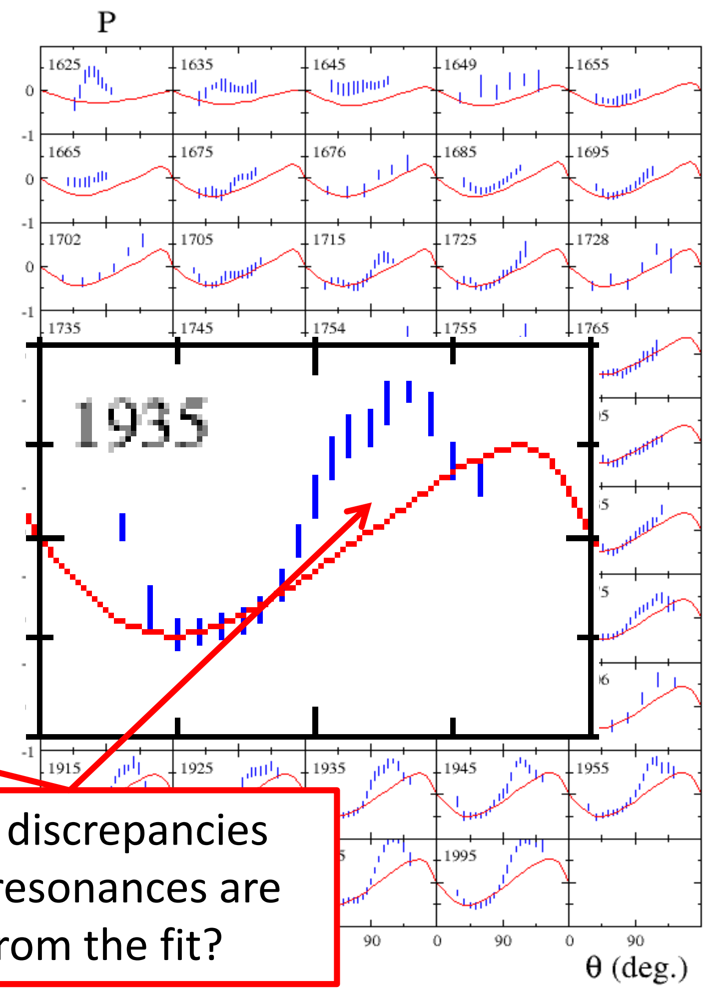
Aznauryan. V.B., PPNP 67 (2012)

Tiator, Drechsel, Kamalov, Vanderhaeghen, EPJST 198 (2011)

K⁺Λ Fit with PDG states < 2 GeV



Includes *, **** PDG states**



Do these discrepancies indicate resonances are missing from the fit?

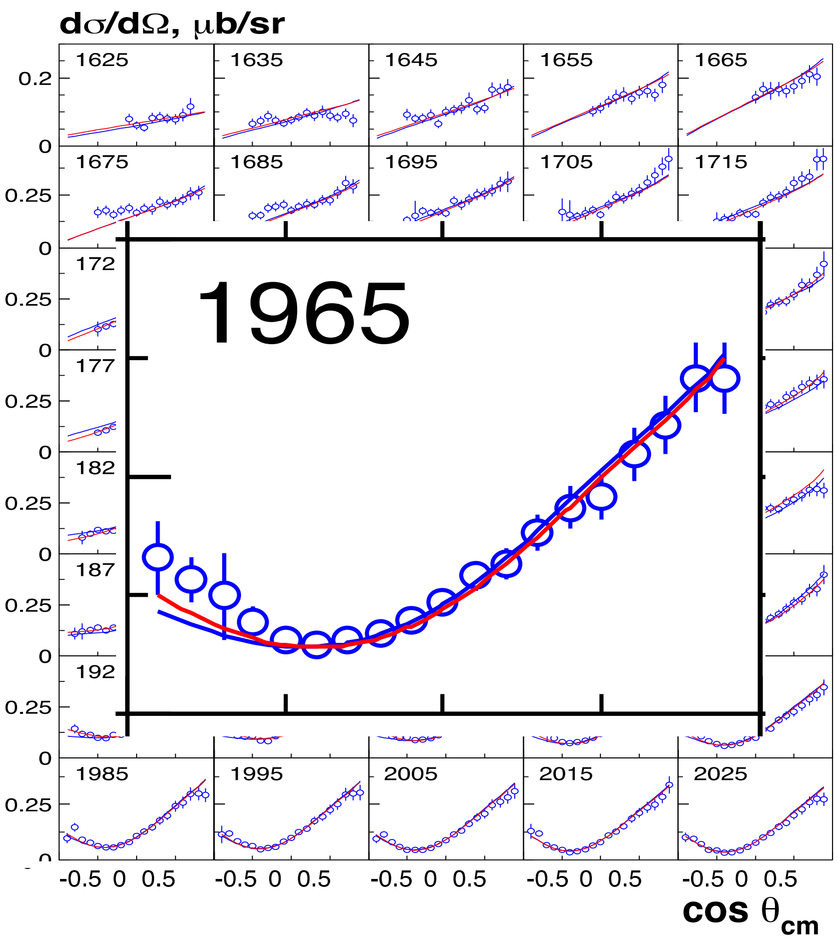
PDG(2010) states insufficient to fit KΛ data

Shows the importance of polarization data

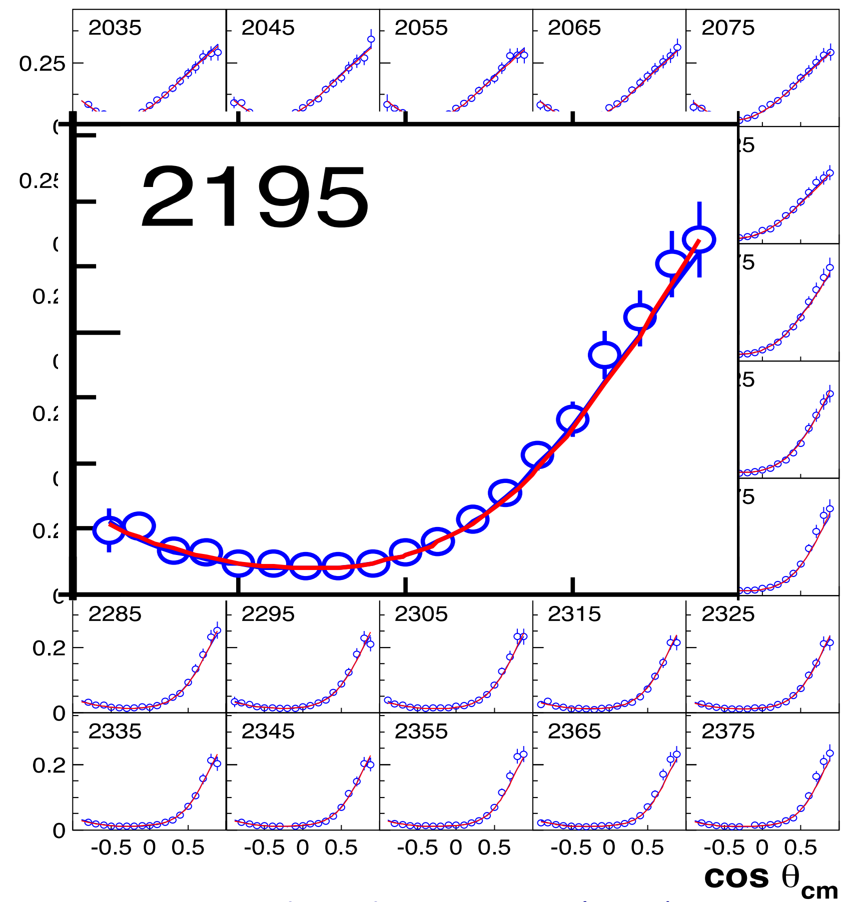
Establishing the N* spectrum, cont'd

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

BnGa group (2012)



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

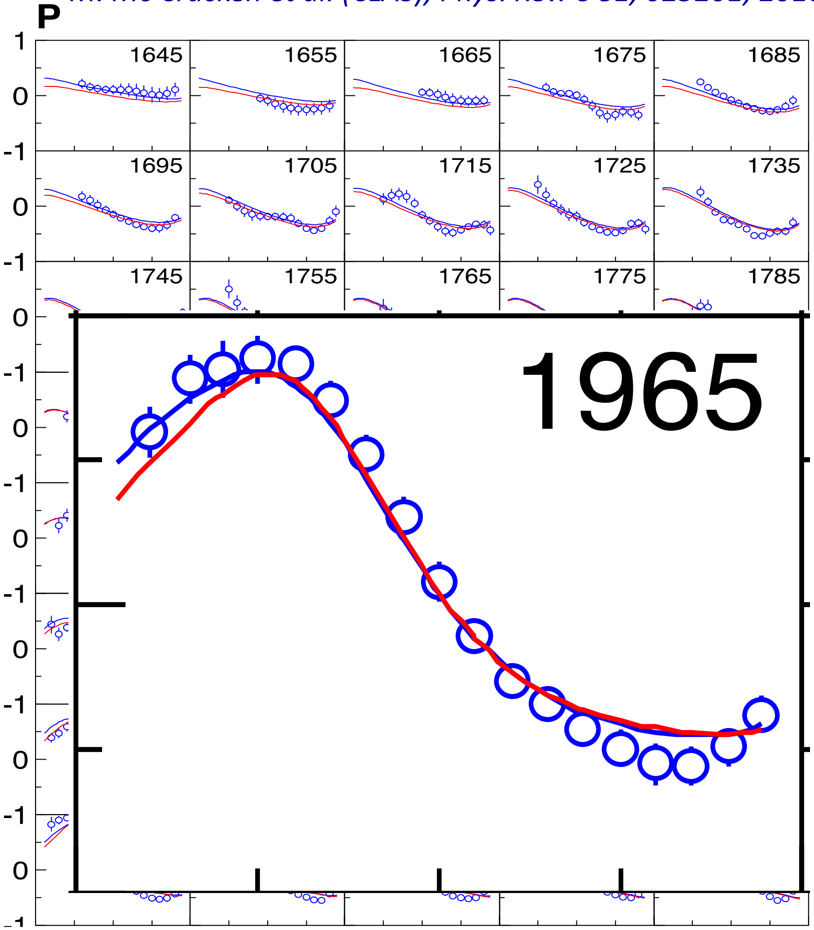


A.V. Anisovich et al, EPJ A48, 15 (2012)

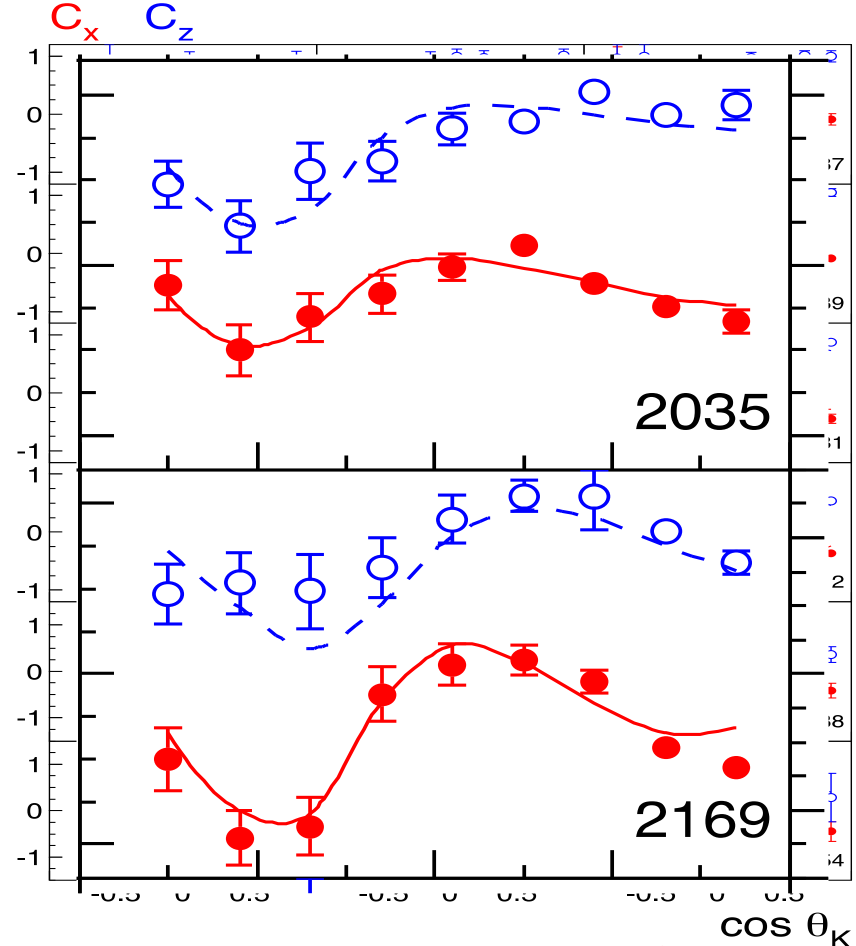
Establishing the N* spectrum, cont'd

Hyperon photoproduction $\vec{\gamma} p \to K^+ \vec{\Lambda} \to K^+ p \pi^-$

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



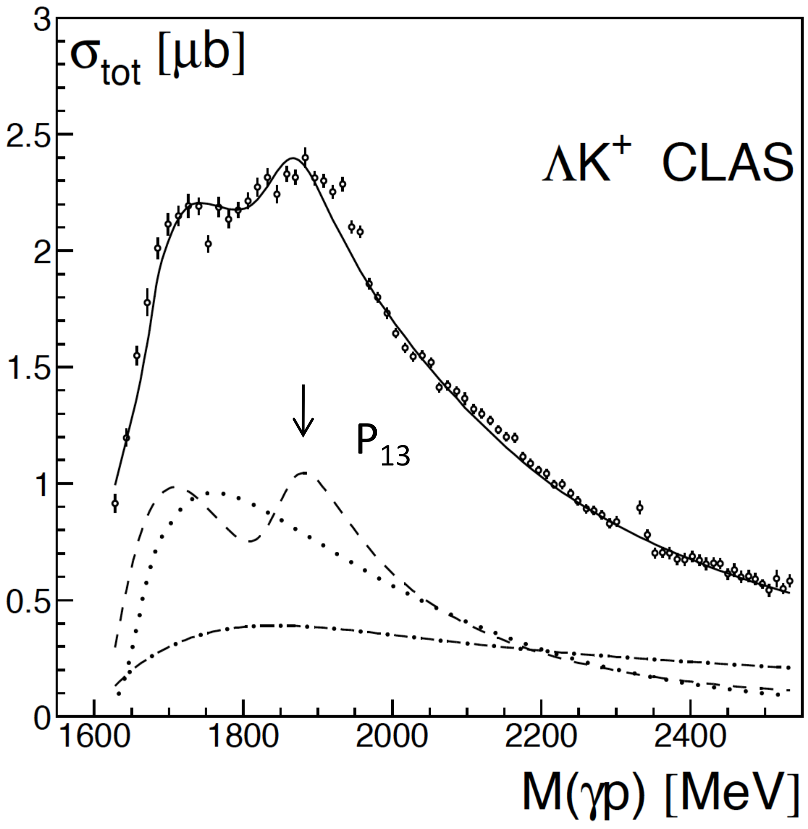
D. Bradford et al. (CLAS), Phys.Rev. C75, 035205, 2007



The high precision $K^+\Lambda$ data are the basis for the discovery of several N* states.

A new nucleon state: N(1900)3/2$^+$

- Bump first seen in SAPHIR cross section data but assigned to different J^P.
- State fully established in BnGa multi-channel analysis making use of very precise KΛ cross section and polarization data, and is now *** in RPP.
- State confirmed in an effective Langrangian resonance model analysis of $\gamma p \to K^+\Lambda$.
  O. V. Maxwell, PRC85, 034611
- State confirmed in a covariant isobar model single channel analysis of $\gamma p \to K^+\Lambda$.
  T. Mart, M. J. Kholili , PRC86, 022201
- First baryon resonance observed and multiply confirmed **in electromagnetic meson production**.
  => Candidate for **** state.



*** "Existence is very likely but further confirmation of decay modes is required".

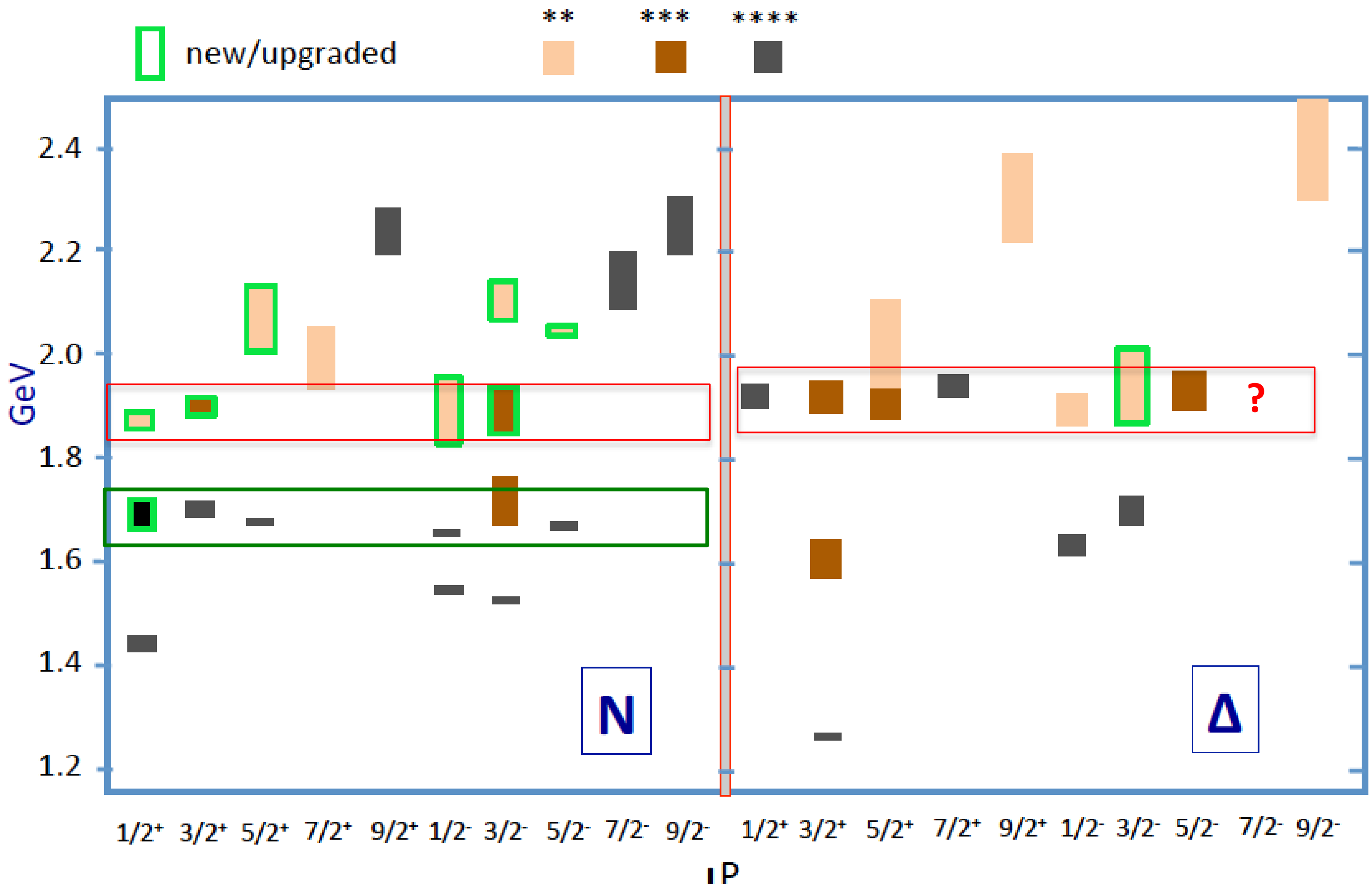
Evidence for new Baryons and Decays

State N((mass)J^P	PDG pre 2010	PDG 2016	KΛ/Σ	πN	Nγ
N(1710)$1/2^+$	***	****	****	****	****
N(1880)$1/2^+$		**	**	*	**
N(1895)$1/2^-$		**	**	*	**
N(1900)$3/2^+$	**	***	***	**	***
N(1875)$3/2^-$		***	***	*	***
N(2120)$3/2^-$		**	*	**	**
N(2000)$5/2^+$	*	**	**	*	**
N(2060)$5/2^-$		**	**	**	**

C. Patrignani et al.(Particle Data Group), Chin. Phys. C, 40, 100001 (2016).

http://pdg.lbl.gov/2016/reviews/rpp2016-rev-n-delta-resonances.pdf

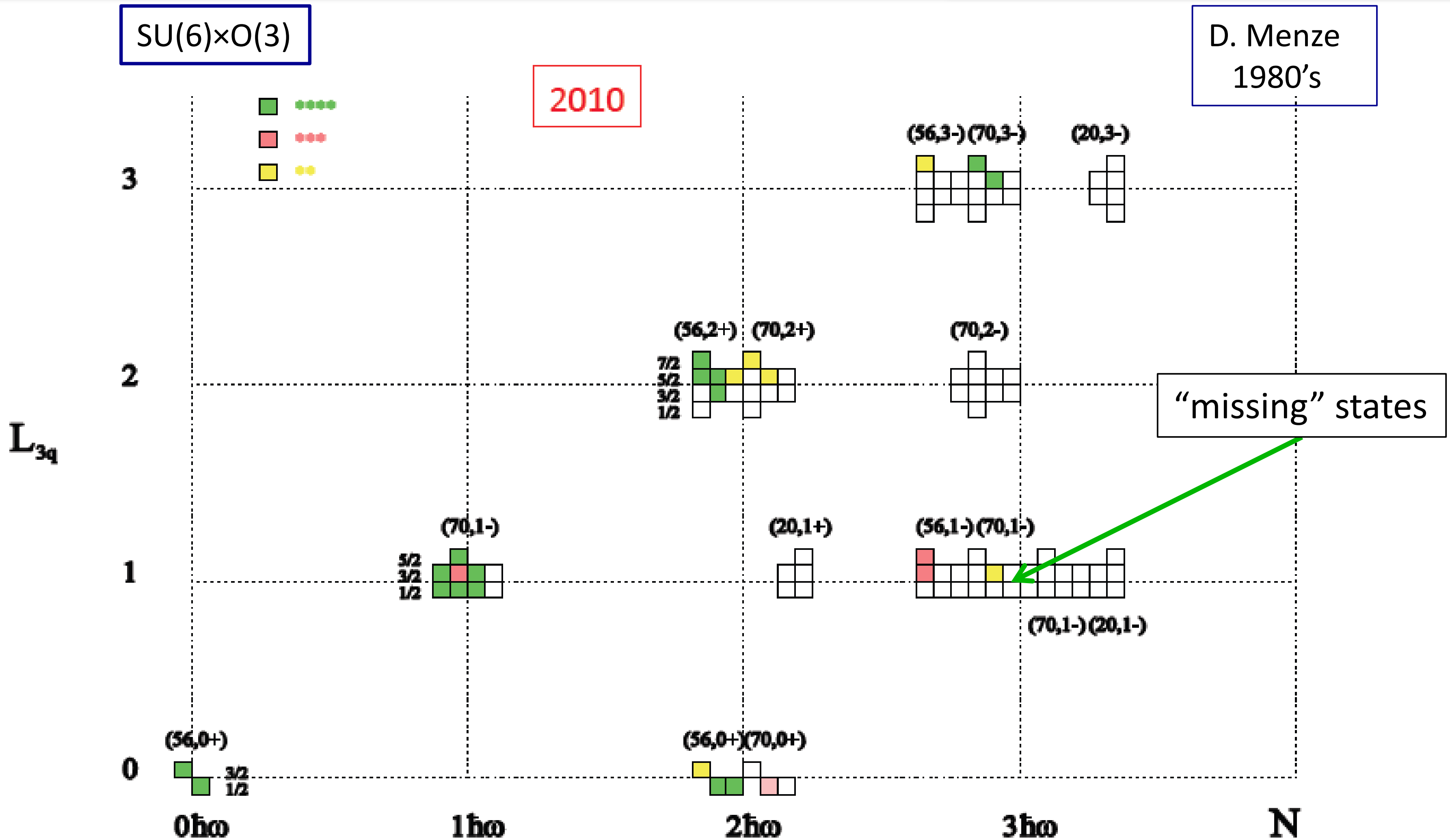
Lower mass N*/Δ* states in 2016



Mass degenerate spin multiplets or **parity duplets** from restoration of chiral symmetry?

Do new states fit into the **SU(6) spin-flavor symmetry** of the CQM?

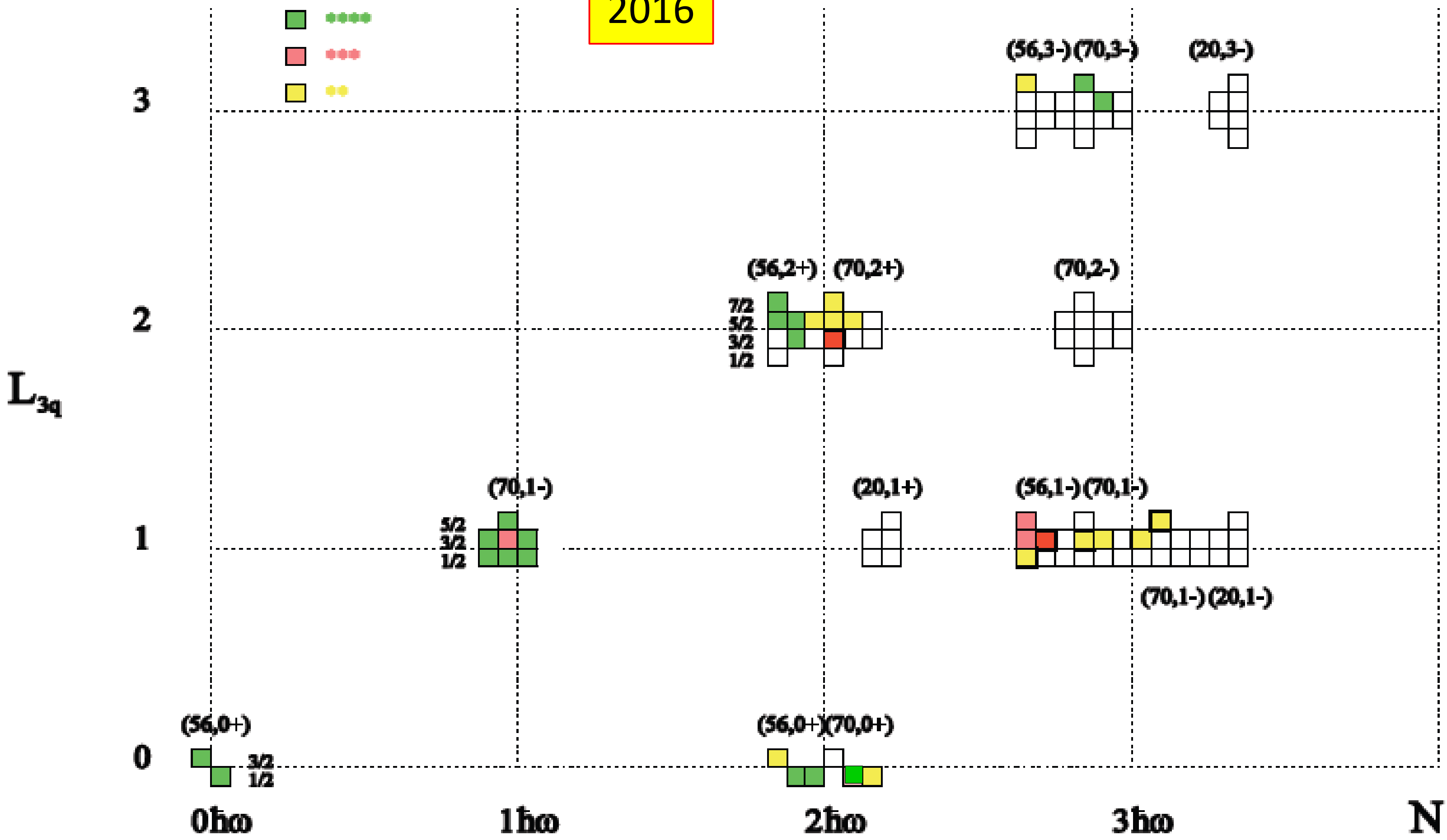
Status of light quark states in CQM



Do new states fit into CQM?

SU(6)×O(3)

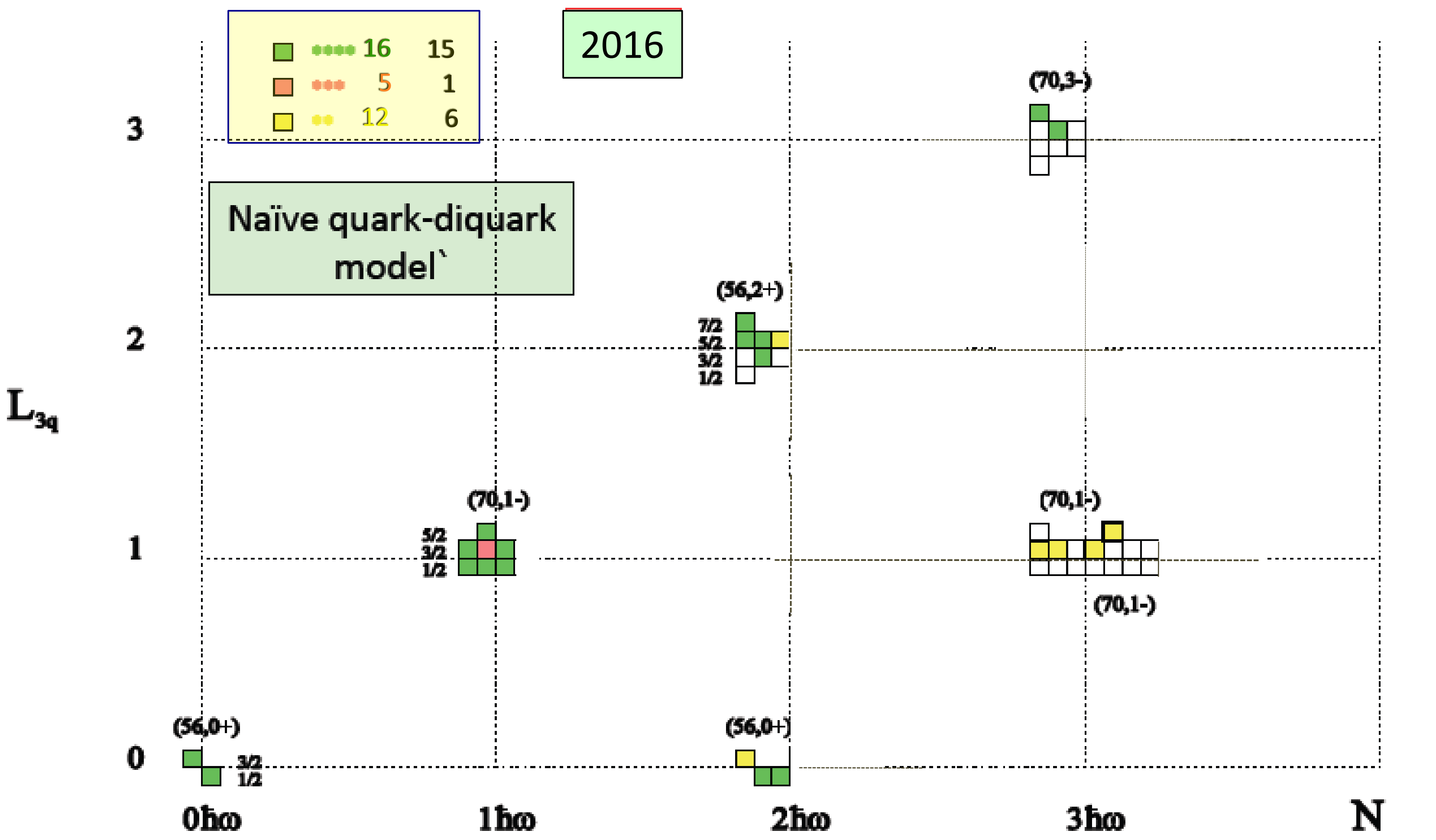
2016



Review: V. Credé, W. Roberts, Rept.Prog.Phys. 76, 2013

Just the first results of this effort. The campaign goes on …

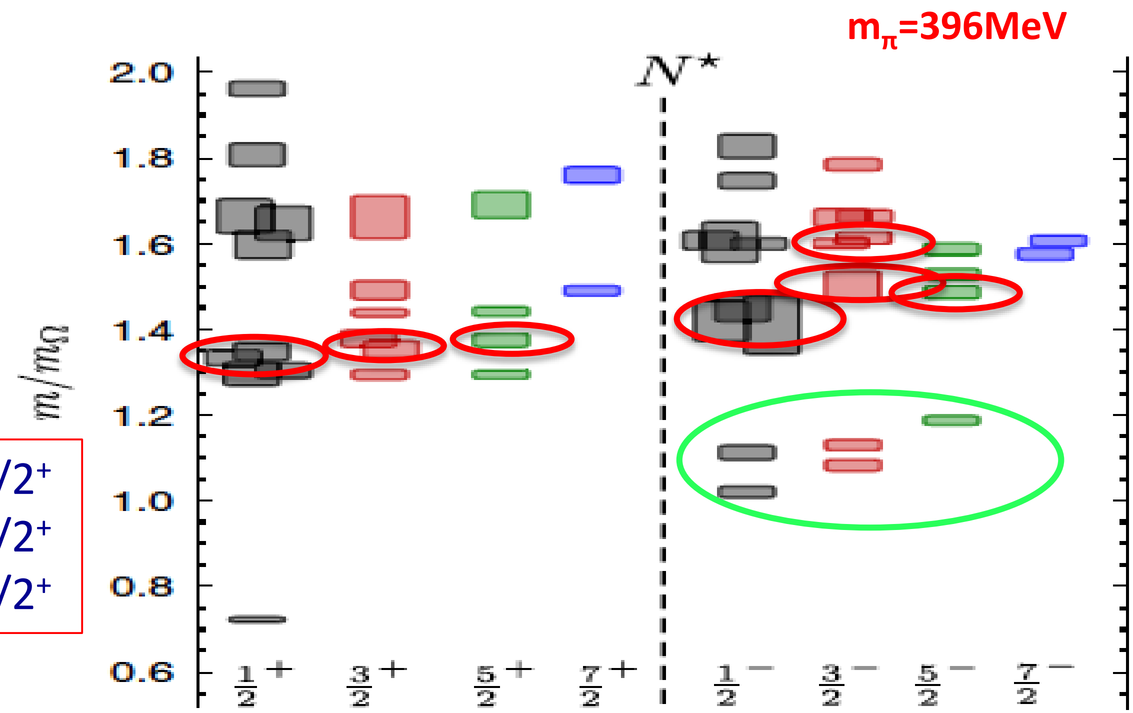
Do new states fit into (qq)q model?



Naïve version of quark-diquark model ruled out (point-like diquarks).

Do new states fit with LQCD projections?

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



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

N(1860)5/2⁺
N(1900)3/2⁺
N(1880)1/2⁺

Known states:
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

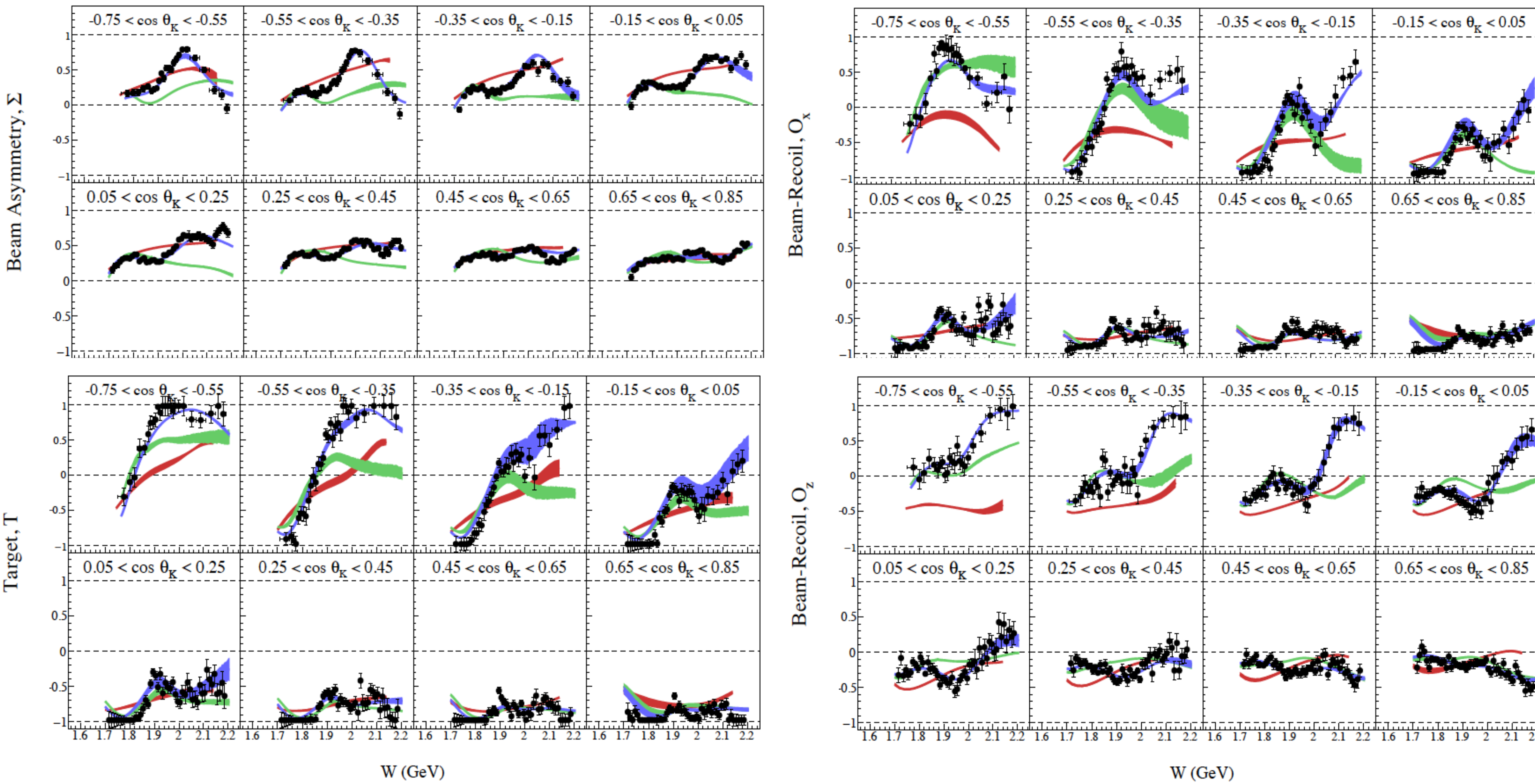
Lowest J^- states 200-300 MeV high

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

Polarized $K^+\Lambda$ production

$\tilde{\gamma} p \longrightarrow K^+ \vec{\Lambda}$

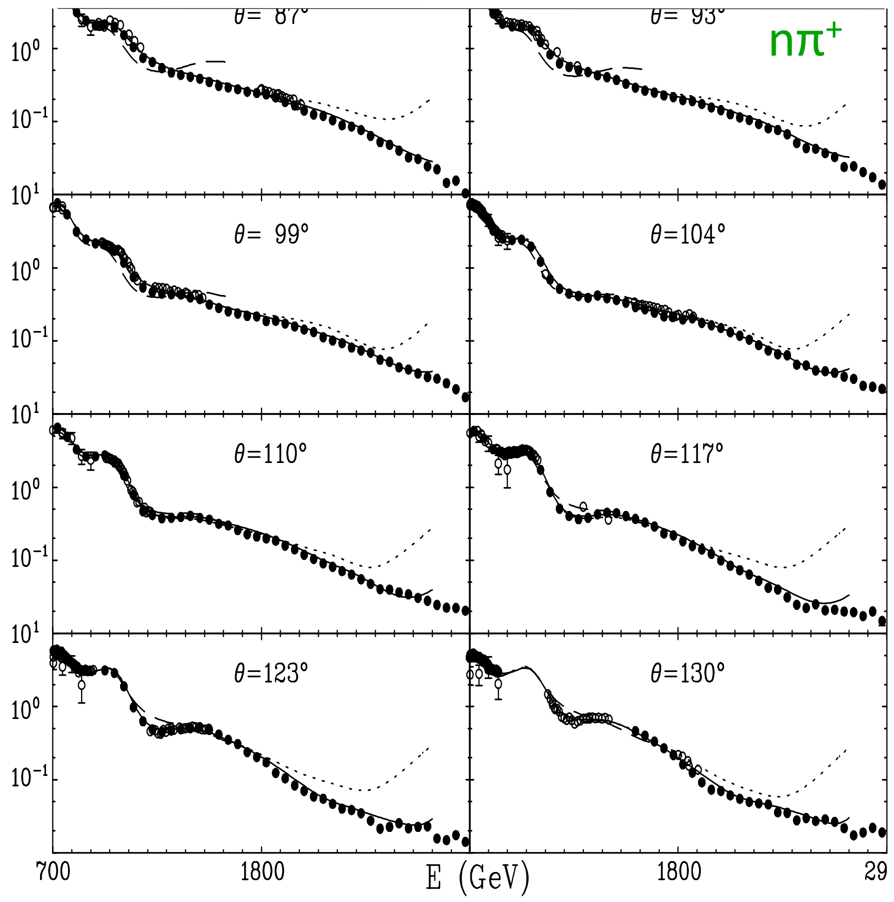
C.A. Paterson et al., PRC93 (2016) 065201



ANL-Osaka BnGa 2014 BnGa 2014 refit

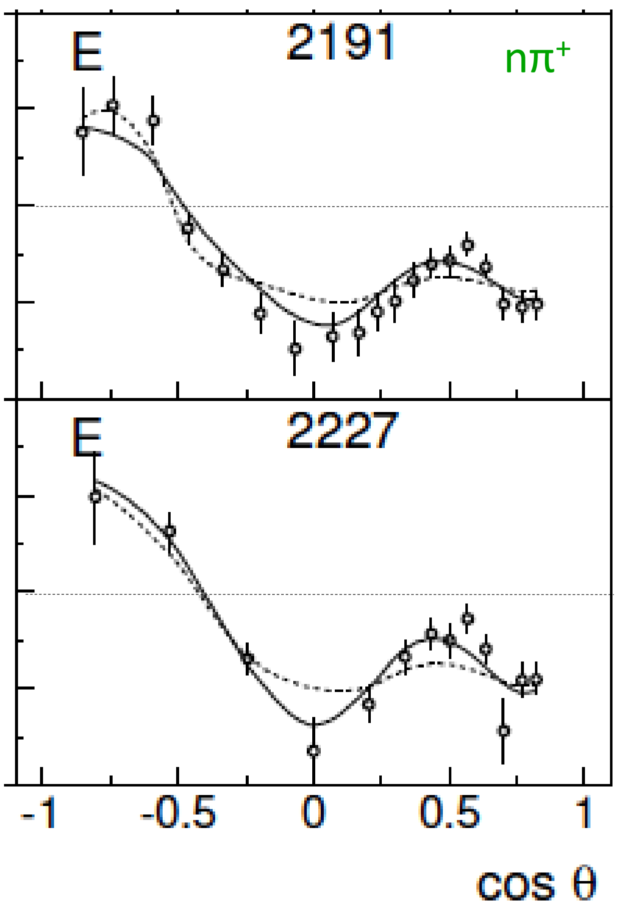
At high mass polarization is essential $\vec{p}(\vec{\gamma},\pi N)$

M. Dugger et al., Phys.Rev. C79 (2009) 065206



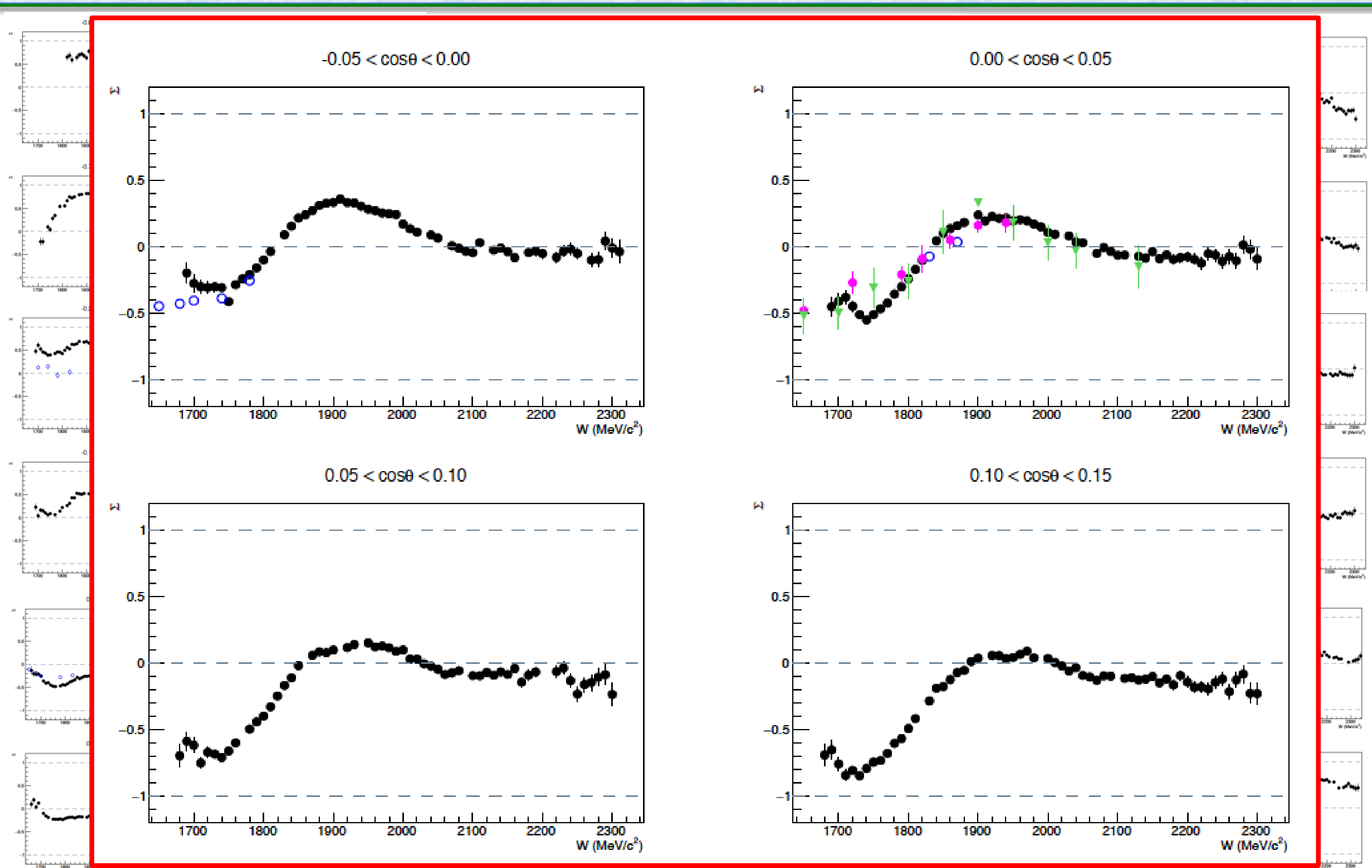
need polarization data at high masses

S. Strauch et al., Phys. Lett. B750, 53 (2015)



beam-target polarization asymmetry

Beam asymmetry off neutron Σ_n $\tilde{\gamma} n \rightarrow p\pi^-$

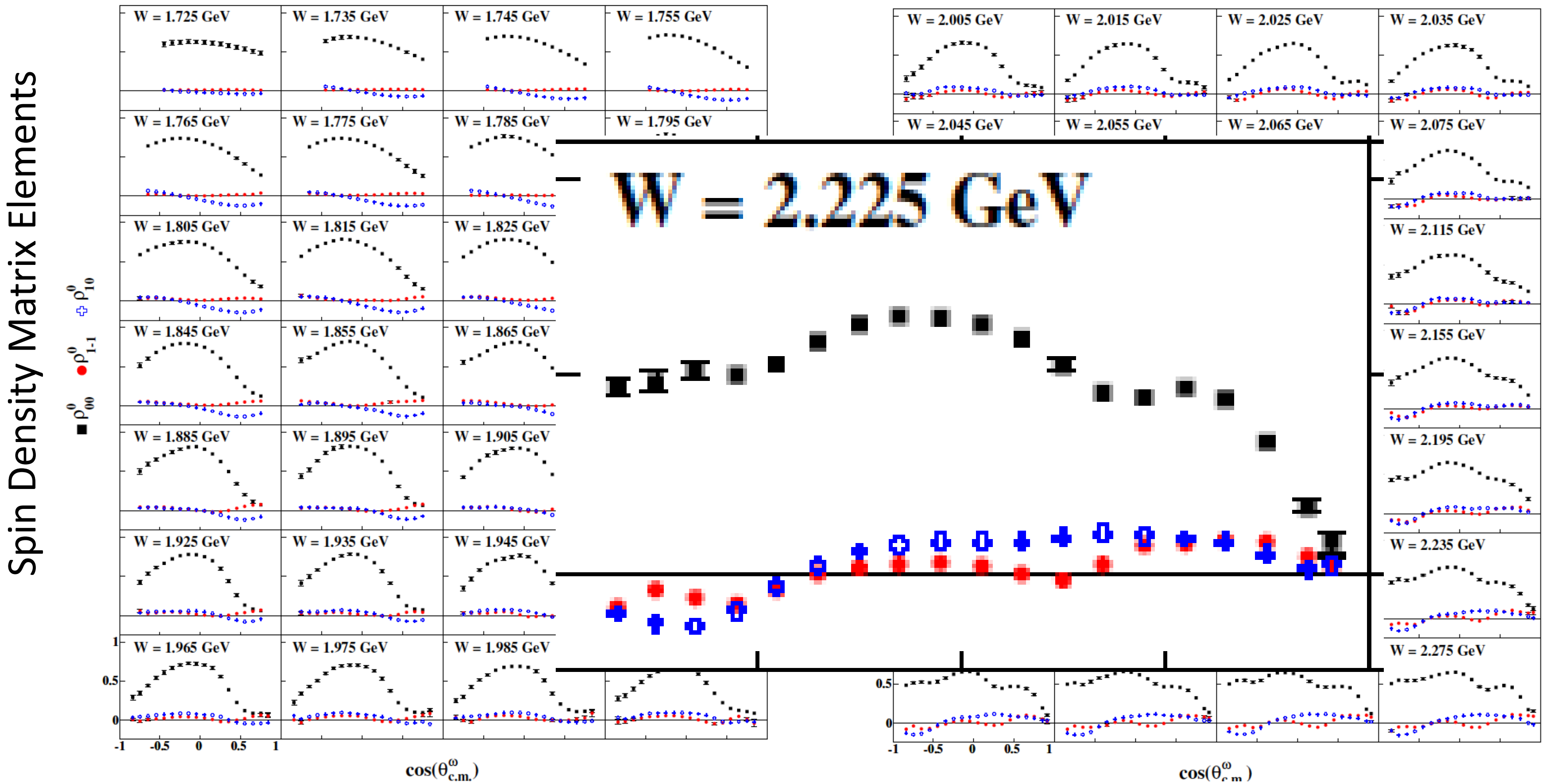


Data need to be included in multi channel partial wave analysis

Precision data to establish the N* spectrum

Reaction is isospin filter => only sensitive to I=1/2 states

SDME from $\gamma p \rightarrow p\omega \rightarrow p\pi^{+}\pi^{-}\pi^{0}$

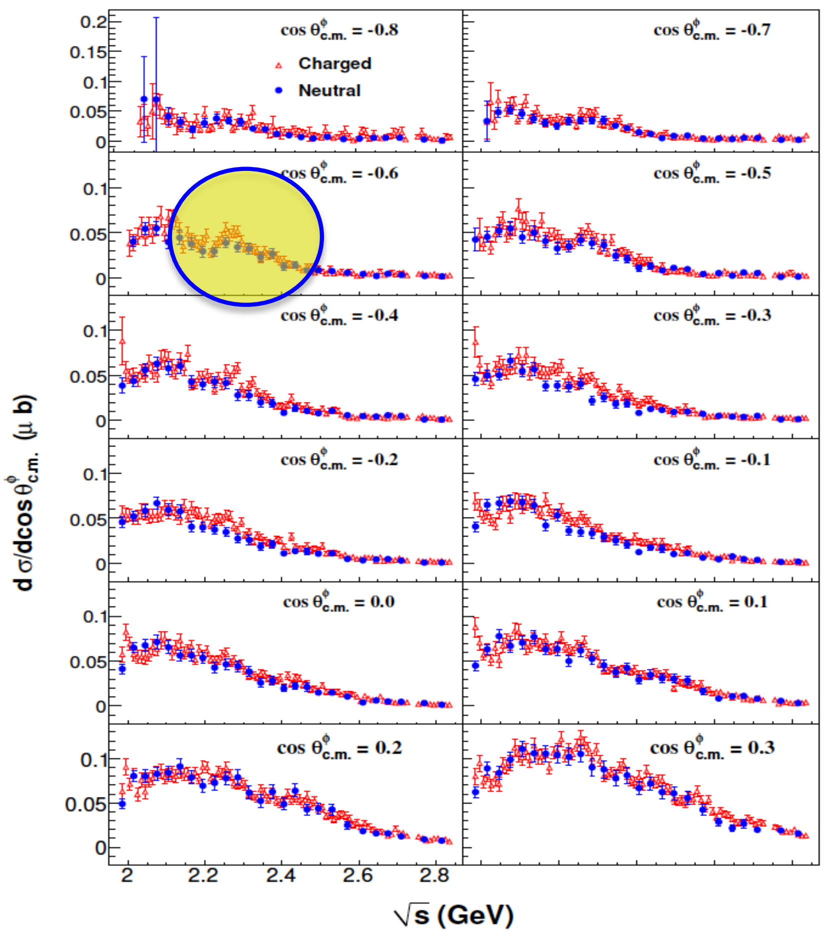


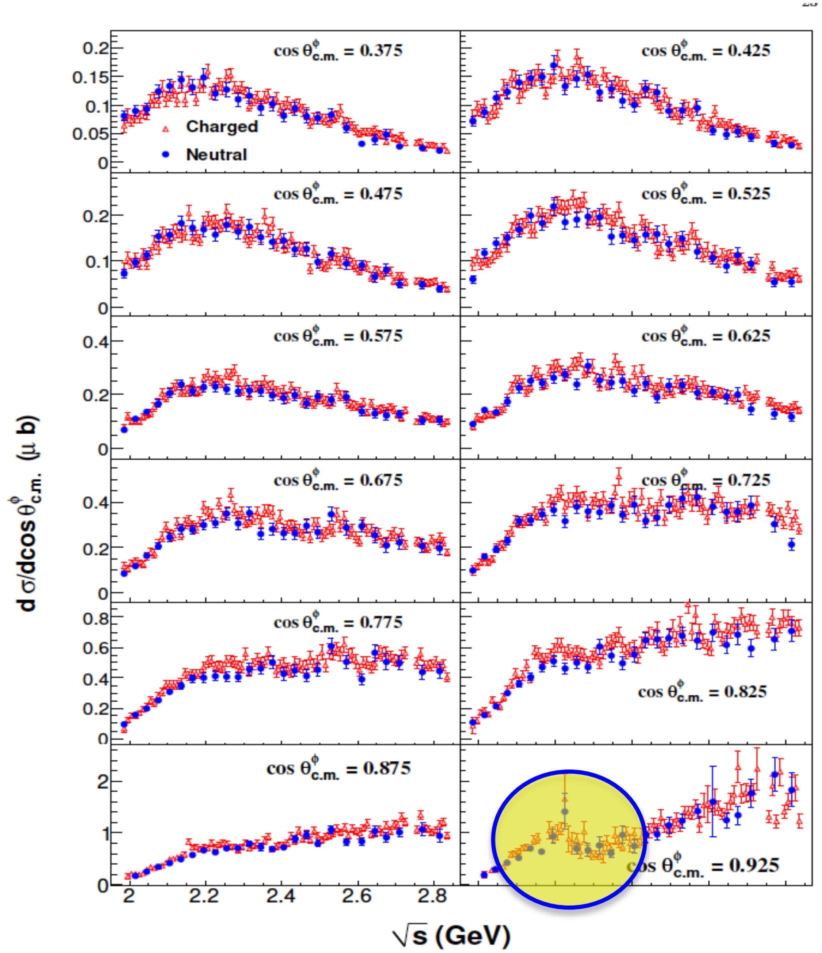
M. Williams, et al. (CLAS) , Phys.Rev. C80 (2009) 065208

Cross section of γp→pφ→pKK

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

B. Dey et al. (CLAS), PR C89 (2014) 5, 055208
K.P. Adhikari et al. (CLAS), PR C89 (2014) 5, 055206

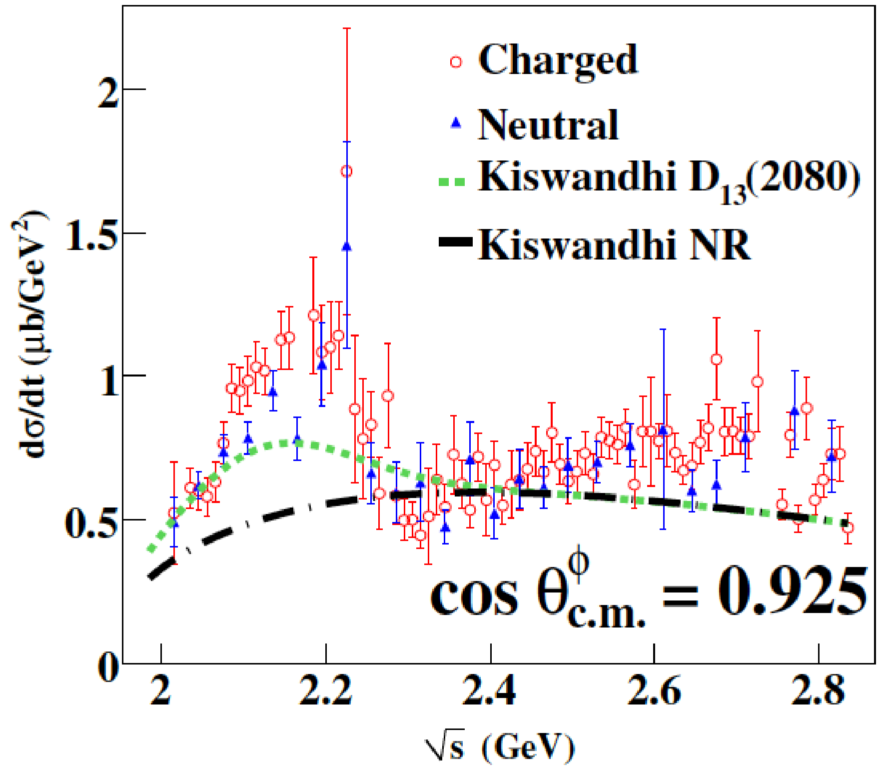




Channel sensitive to high mass N*s with large s-sbar content.

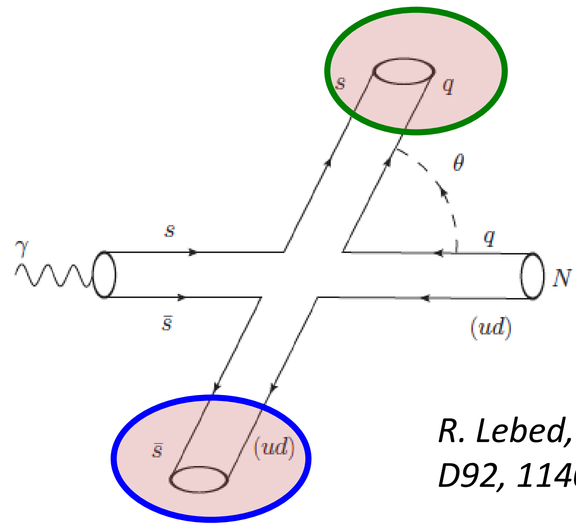
Pseudo pentaquark in $\gamma p \rightarrow p\phi \rightarrow pKK$?

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



B. Dey et al. (CLAS), PR C89 (2014) 5, 055208
K.P. Adhikari et al. (CLAS), PR C89 (2014) 5, 055206

Possible diquark-anti-triquark pair formation similar to what is proposed for the $P_c^+(4450)$ resonance seen in pJ/ψ.



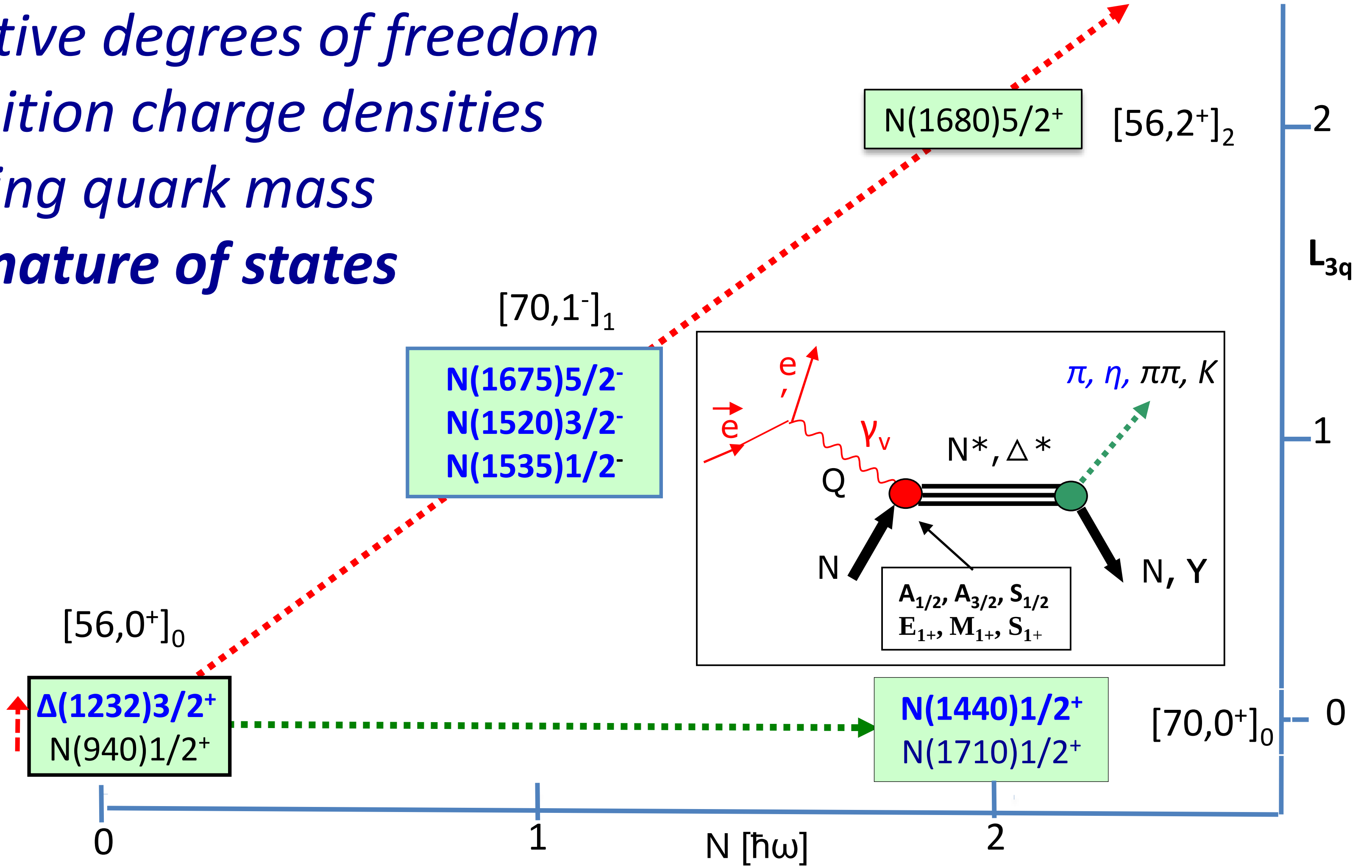
R. Lebed, Phys. Rev. D92, 114006 (2015)

Need to be included in multi channel pw analysis.

Structure of excited baryons

- *effective degrees of freedom*
- *transition charge densities*
- *running quark mass*

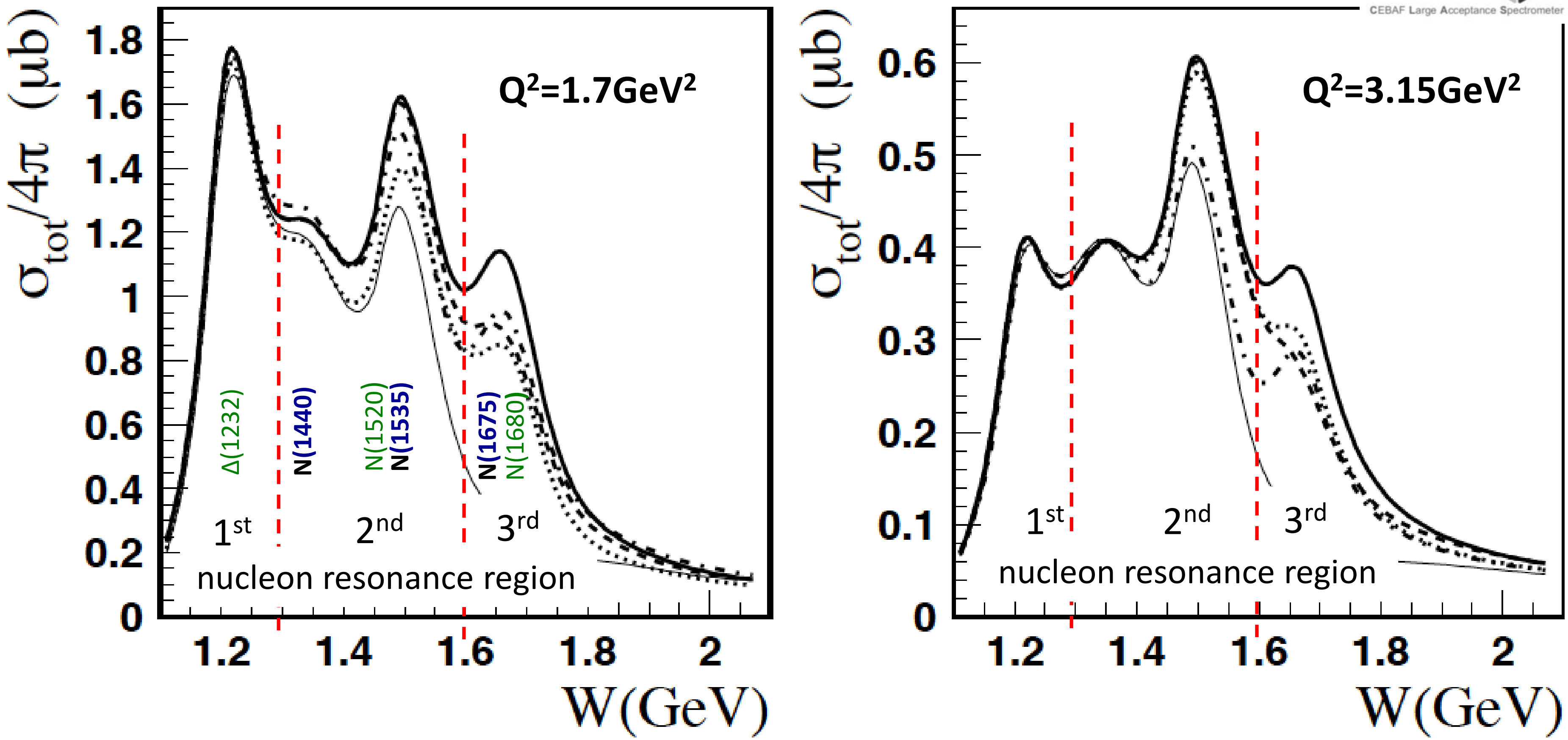
  => nature of states



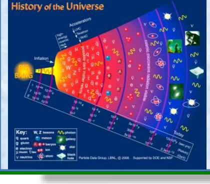
I.G. Aznauryan et al., Analysis of p(e,e'Nπ); V.I. Mokeev et al., Analysis of $p(e,e'p\pi^+\pi^-)$

Total cross section at W < 2.1 GeV

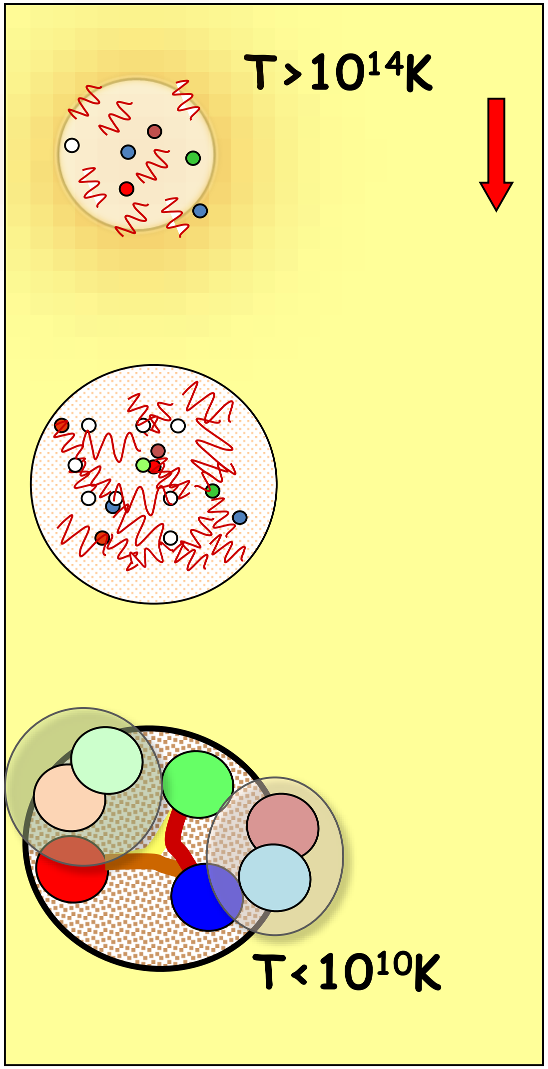
$\gamma^* p \longrightarrow \pi^+ n$

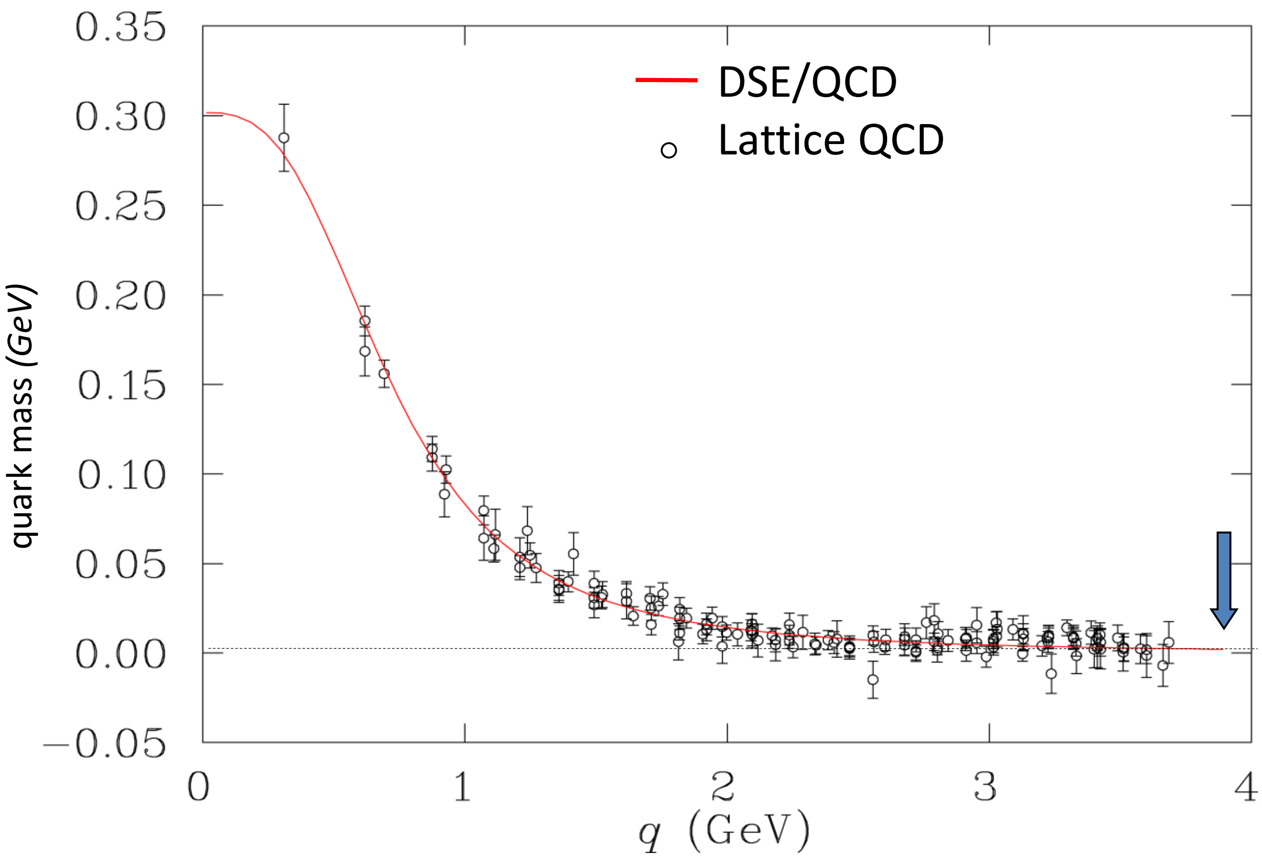


K. Park et al., PR C77 (2008) 015208; PR C91 (2015) 045203



How do light quarks acquire mass?

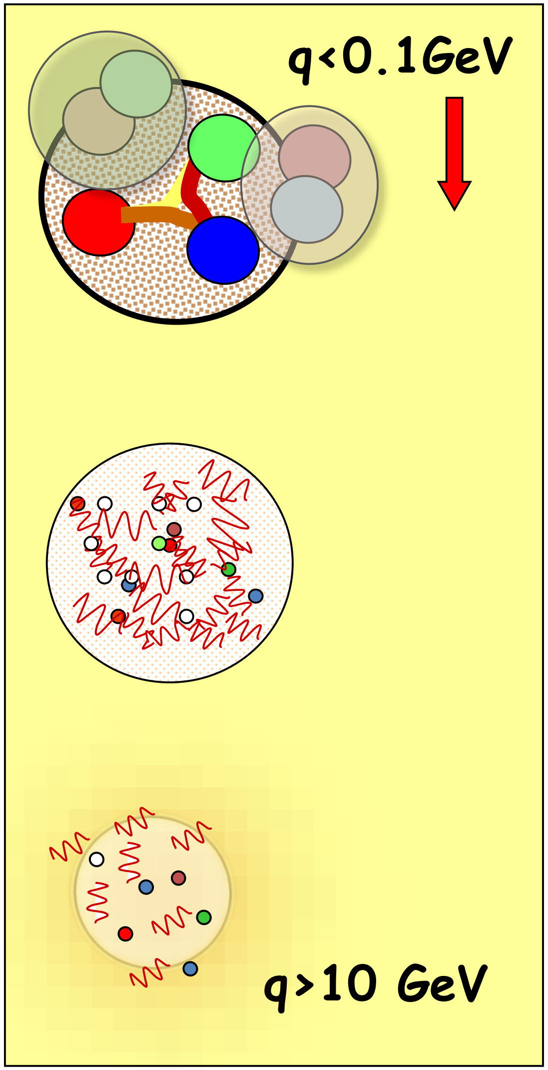


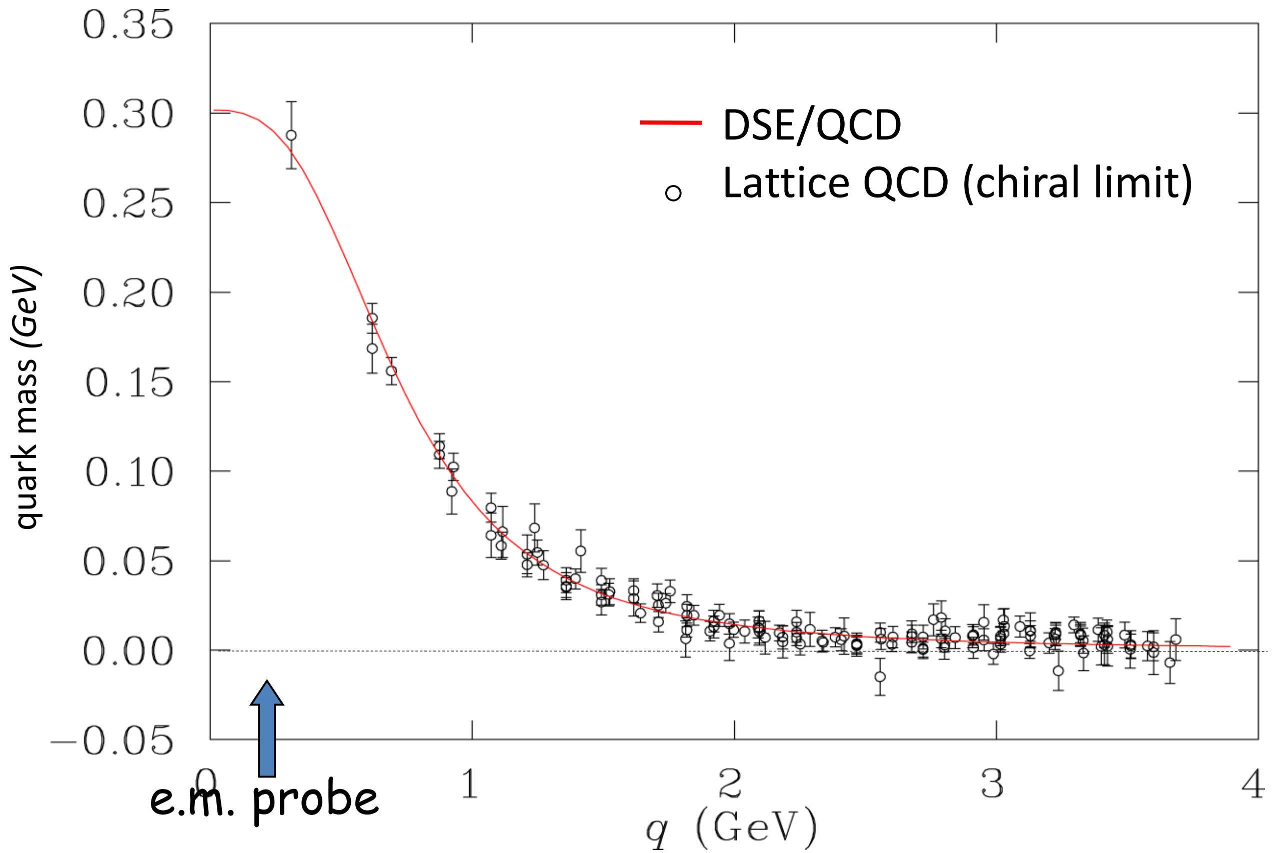


As the Universe cools down, the quarks acquire mass and form resonances before stable nucleons are formed.

=> Measure N* observables that are sensitive to the quark mass.

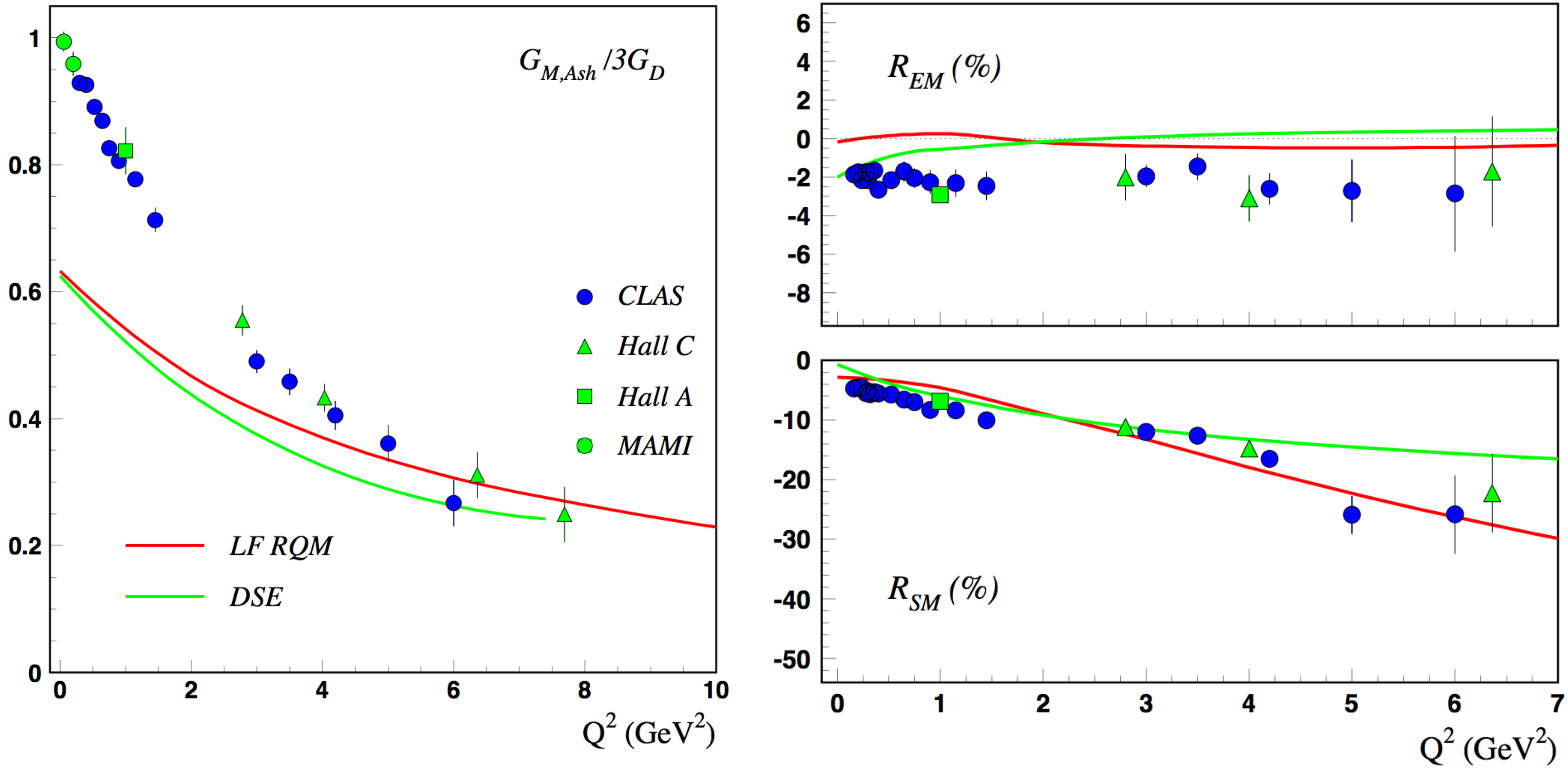
Quarks get stripped off their dressing





Electron beams allow changing the momentum transfer to a specific N*, which allows probing the running quark mass.

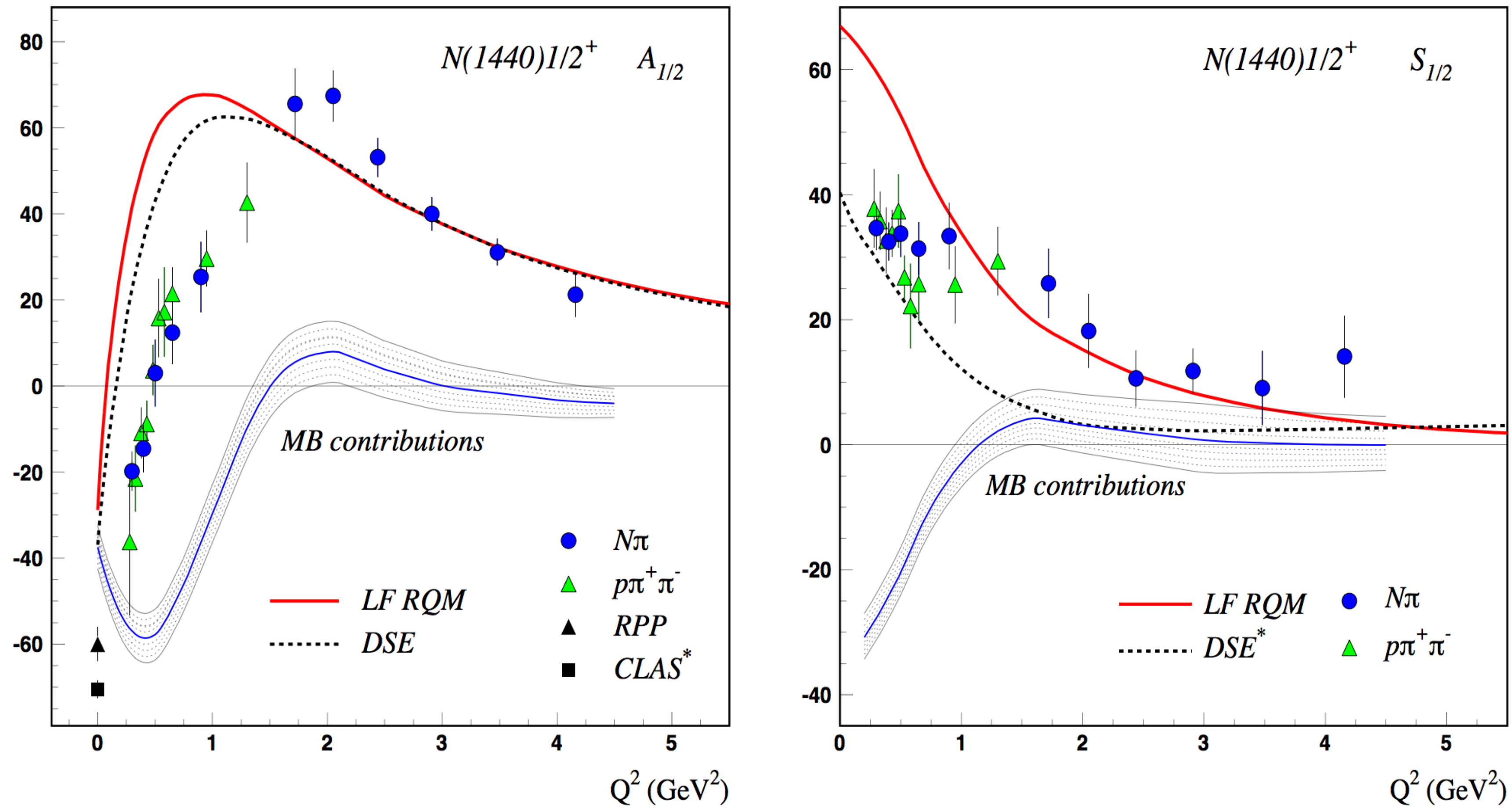
NΔ(1232)3/2⁺ transition form factors



- For G_M the MB contributions are significant at $Q^2 \leq$ 3-4 GeV^2
- No clear trend towards asymptotic behavior $R_{EM} \rightarrow$ +100%

Roper resonance N(1440)1/2+

DSE: J. Segovia, C.D. Roberts et al., PRC94 (2016) 042201 LF RQM: I. Aznauryan, V.B. arXiv:1603.06692

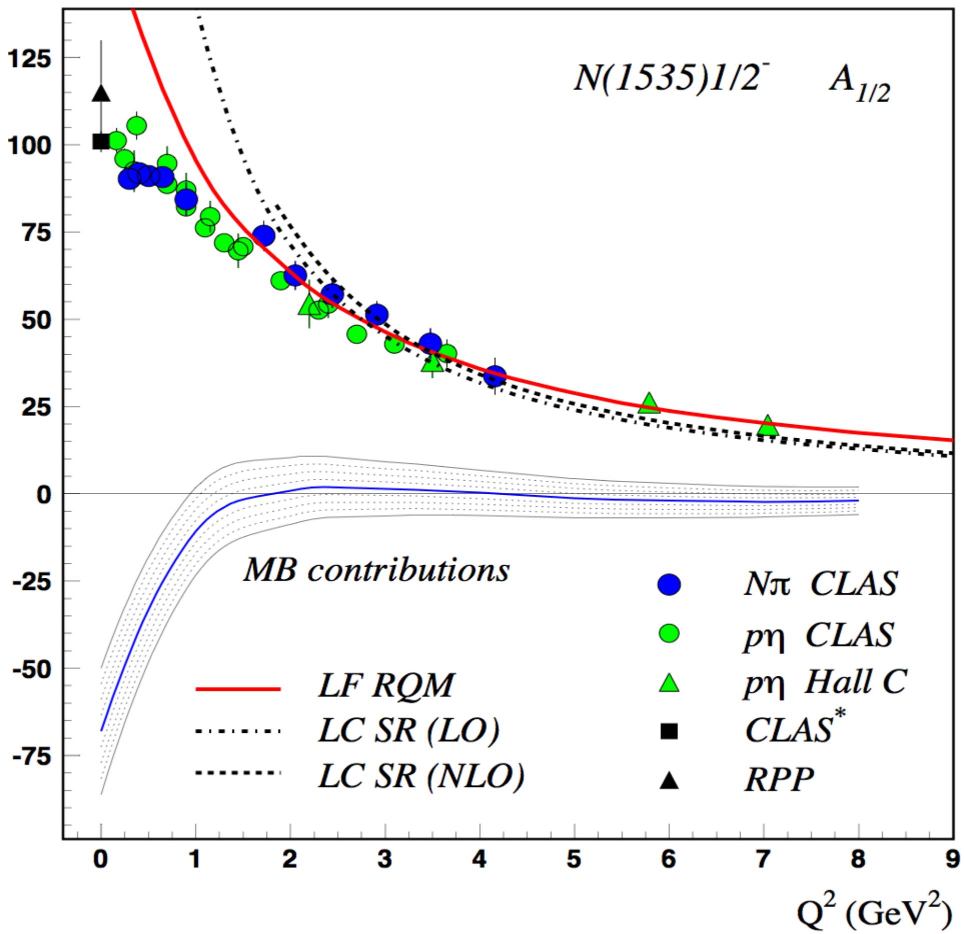


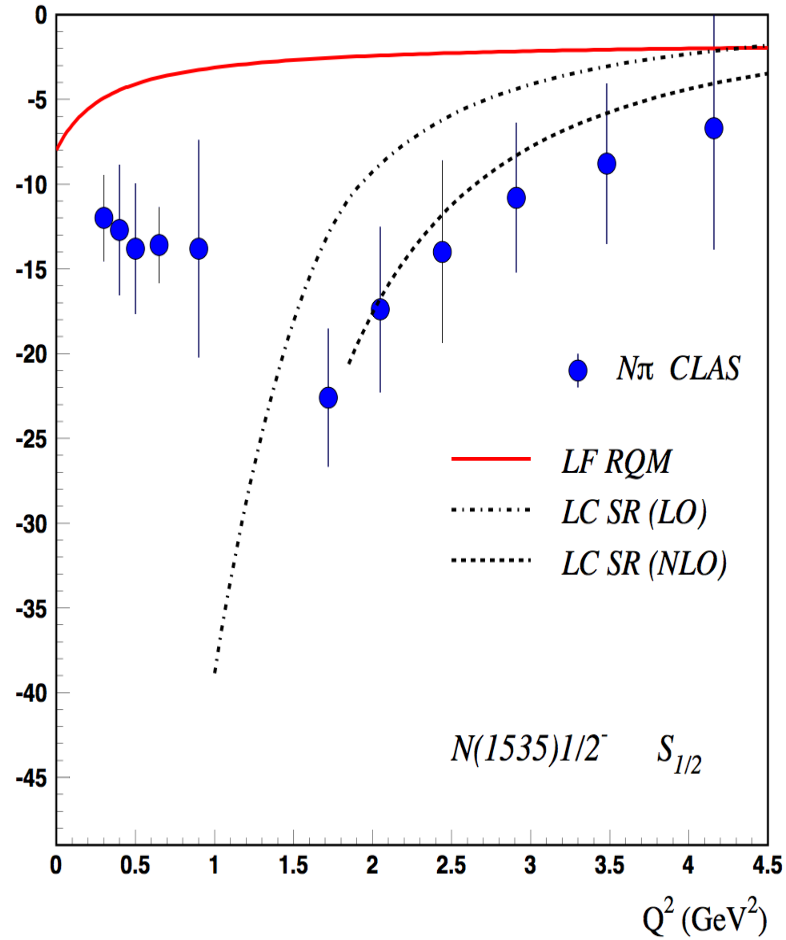
Non-quark contributions are significant at $Q^2 < 2.0$-2.5 GeV^2.

The 1st radial excitation of the 3-quark core emerges as the probe penetrates the MB cloud.

N(1535)1/2⁻ helicity amplitudes

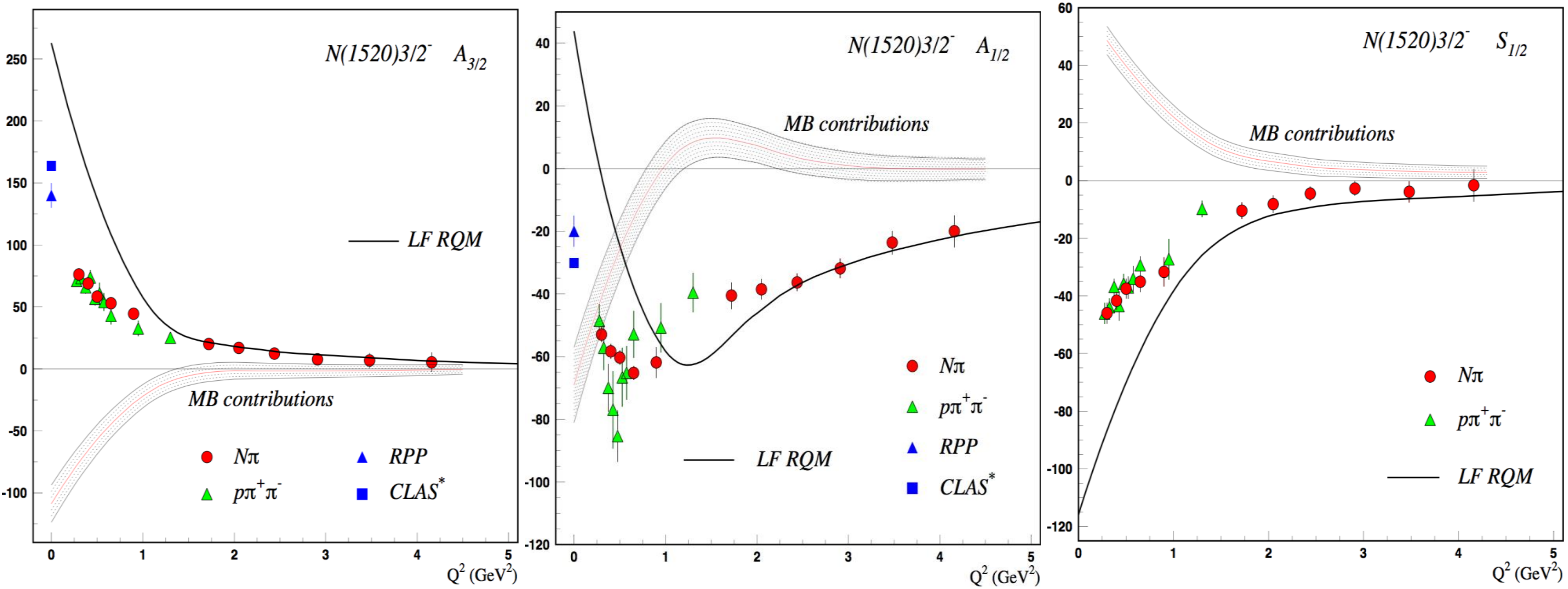
LC SR: I.V. Anikin, V.M. Braun, N. Offen, PRD92 (2015) 014018





Inferred MB contributions significant at $Q^2 < 1.5$ GeV^2.

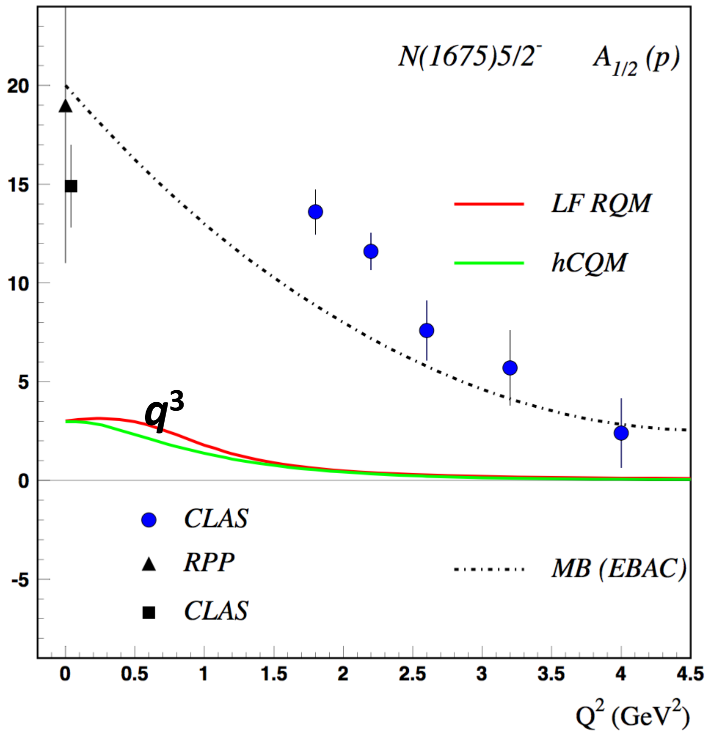
N(1520)3/2⁻ helicity amplitudes

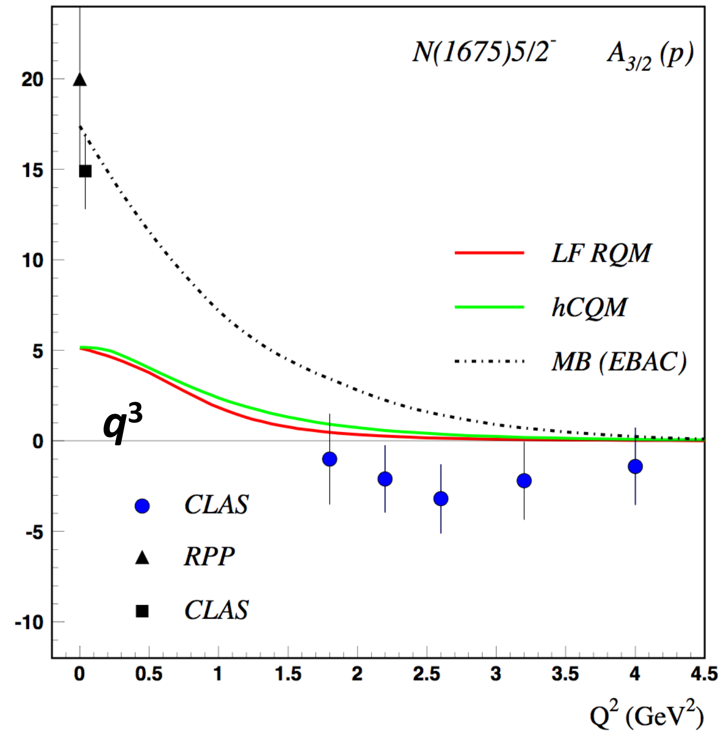


Inferred MB contributions significant at $Q^2 < 1.5\text{-}2.5$ GeV^2.

N(1675)5/2⁻ helicity amplitudes

On **proton target** the transverse amplitudes are predicted to be suppressed by 1966 Moorhouse selection rule. => Expect MB contributions to lead at all Q^2.





=> Meson-baryon contributions large for $A_{1/2}$ at $Q^2 \leq 3GeV^2$,
=> $A_{3/2}$ drops much faster with Q^2.

- **CQM predicts much larger amplitudes on neutrons**

Light Front γpN* transition charge densities

L. Tiator, M. Vanderhaeghen, Phys.Lett. B 672 (2009) 344

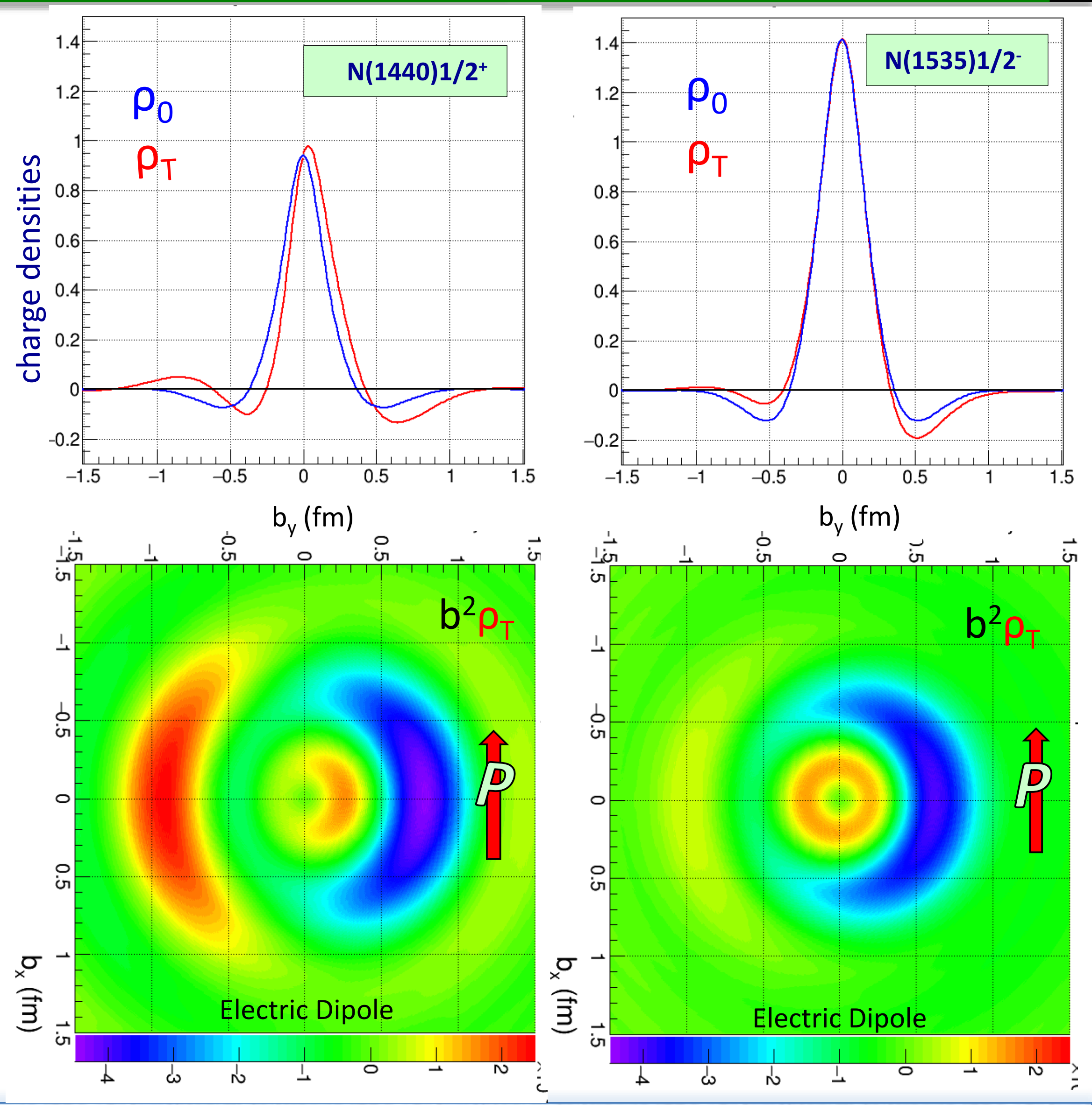
Fourier transform in Q^2 of transition form factors result in the IMF in transition charge densities from the proton to the two states.

The N(1440) exhibits a softer core and wider clouds than N(1535).

FT involves integral in Q^2 -> ∞

=> need data at higher Q^2.

courtesy F.X. Girod

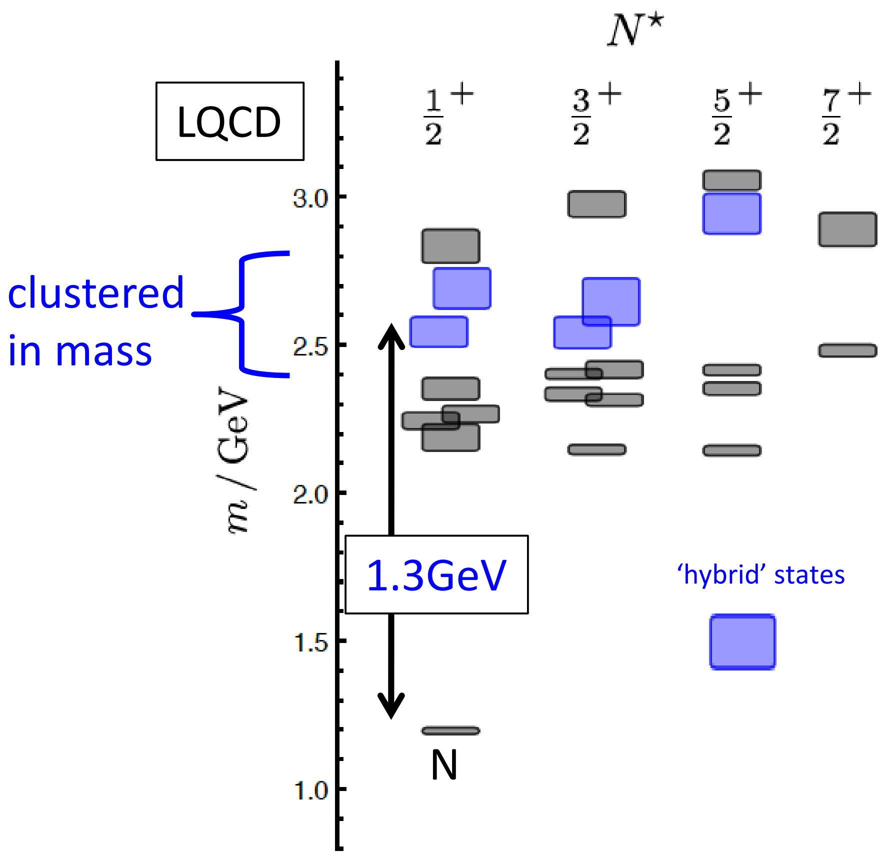


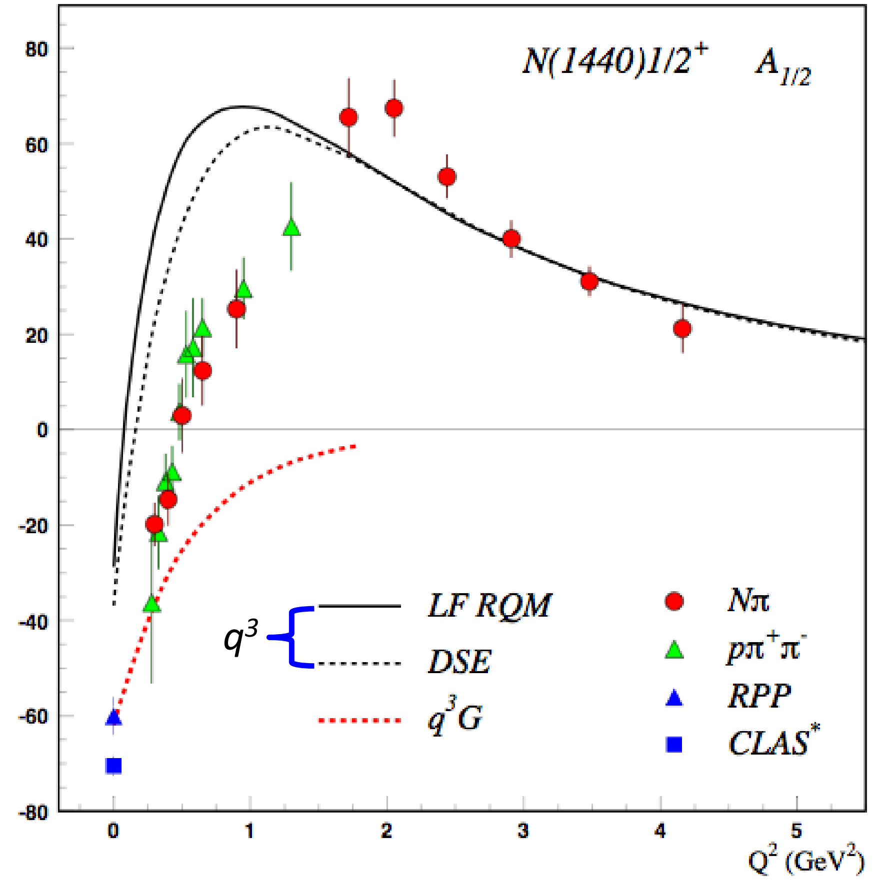
N* physics with CLAS12 at JLab12

- E12-09-003 - Electroexcitation of Nucleon Resonances at high Q^2
  R. Gothe et al.
- E12-06-108A – Exclusive N*->KY studies with CLAS12, D. Carman et al.
- E12-11-005A – Photoproduction of the very strangest baryons
  L. Guo et al.
- E12-16-10: Search for Hybrid Baryons with CLAS12 – A. D'Angelo et al.
- E12-16-010A – Exclusive N*->KY studies with CLAS12, D. Carman et al.

Hybrid Baryons q^3G

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

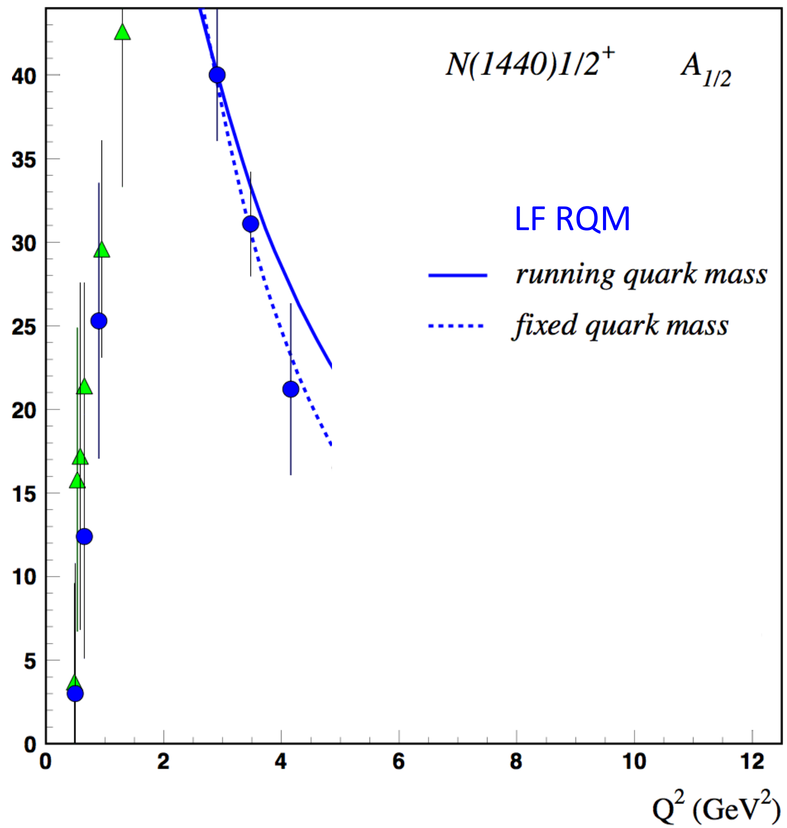




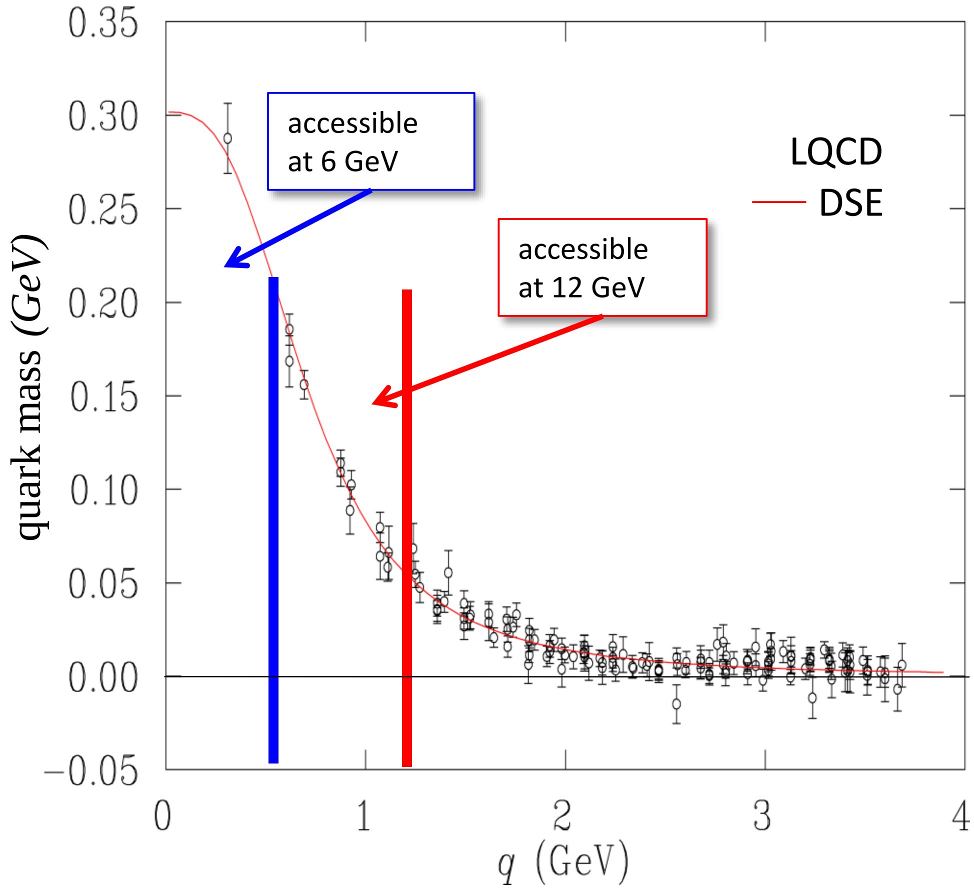
Cover very low Q^2 range with very high statistics using the Forward Tagger Facility in CLAS12

Probing the running quark mass at JLab12

Roper resonance



Running quark mass



Probe the transition of dressed quarks to elementary quarks.

Summary/Outlook

- Excited baryons played a critical role in the evolution of the universe from the QGP phase to the hadron freeze out phase.
- High precision photoproduction data are the basis for the discovery of baryons and to improve evidence for poorly known states. Polarization observables are essential at high masses.
- Multi-channel partial wave analysis frameworks have been key in further establishing the nucleon excitation spectrum.
- Vector meson cross section and polarization data have great potential but have not been (fully) included in coupled channel frameworks.
- Electroexcitation of prominent states supported by advances in theory (DSE, FF RQM) reveals the N* quark core at $Q^2 > 3$ GeV^2 and allows quantifying the meson-baryon contributions.

Outlook

- Charge transition density of the Roper N(1440) appears to have a softer central quark core and a wider "cloud" than the N(1535) transitions. Need to go to higher Q^2 to probe the quark core more accurately.
- The N* program at higher energies will probe the running quark mass function at high Q^2, search for gluonic excitations at low Q^2, and search for doubly strange (Ξ^*) and triply strange (Ω^{-*}) states.
- For the search of new states in meson electroproduction we need to expand the multi-channel partial wave analysis to include virtual photons.
- Strangeness channels and multi-meson channels may be key in searching for high mass states.