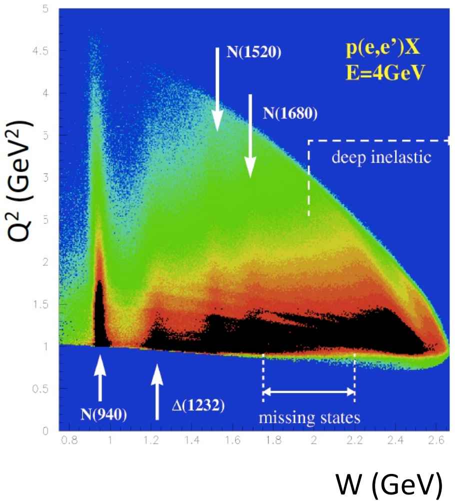
Baryon spectroscopy: new results and perspectives

Annalisa D'Angelo
University of Rome Tor Vergata & INFN Rome Tor Vergata
for the **CLAS Collaboration**



Outline:

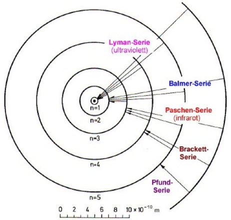
- Motivation for light baryon spectroscopy
- Establishing N* states – polarized photoreactions
- Identifying the effective degrees of freedom: mesons electro-production
- Signature for hybrid baryons
- Outlook & conclusions

Jefferson Lab

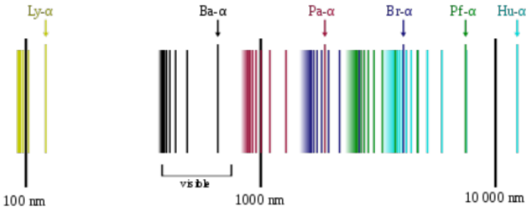
clas

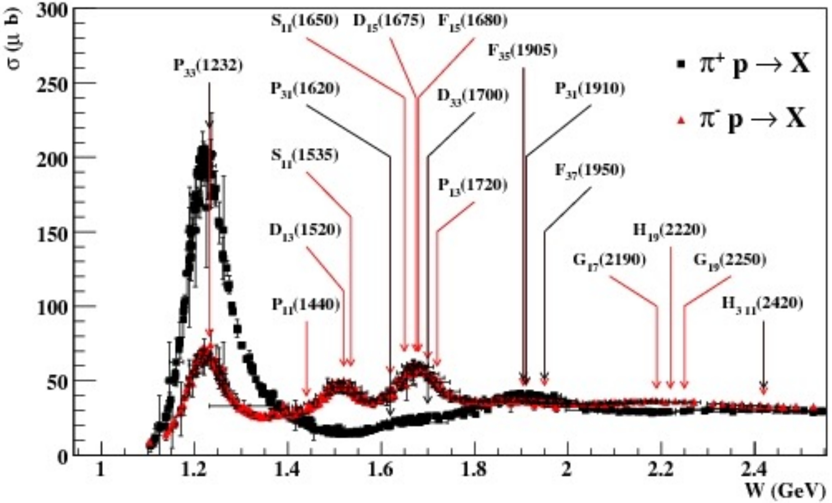
Why N* ? From the Hydrogen Spectrum to QCD

Niels Bohr (1922)



Spectral series of hydrogen





- Understanding the hydrogen atom's ground state requires understanding its excitation spectrum.

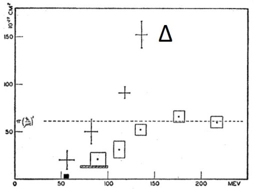
→ From Bohr model of the atom to QED.

- Understanding the proton's ground state requires understanding its excitation spectrum.

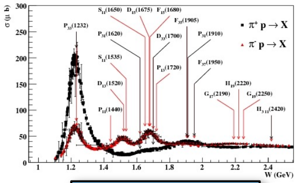
→ From the Constituent Quark model to QCD.

Historical Markers

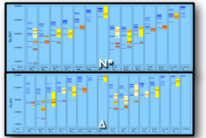
1952: First glimpse of the Δ(1232) in πp scattering shows internal structure of the proton.



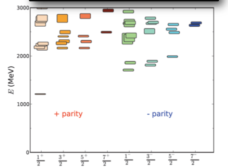
1964: Baryon resonances essential in establishing the quark model and the color degrees of freedom.



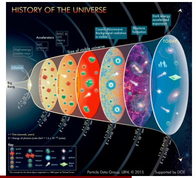
1989: Broad effort to address the missing baryon puzzle.



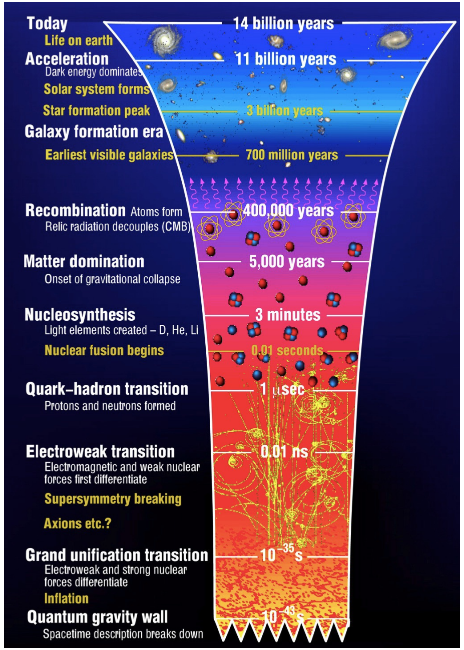
2010: First successful attempt to predict the nucleon spectrum in LQCD.



2015: Understanding of the baryon spectrum is needed to quantify the transition from QGP to the confined phase in the early universe.



Strong QCD is born ~ 1μsec after the Big Bang



T ~ 700, 000, 000 yrs: Galaxies

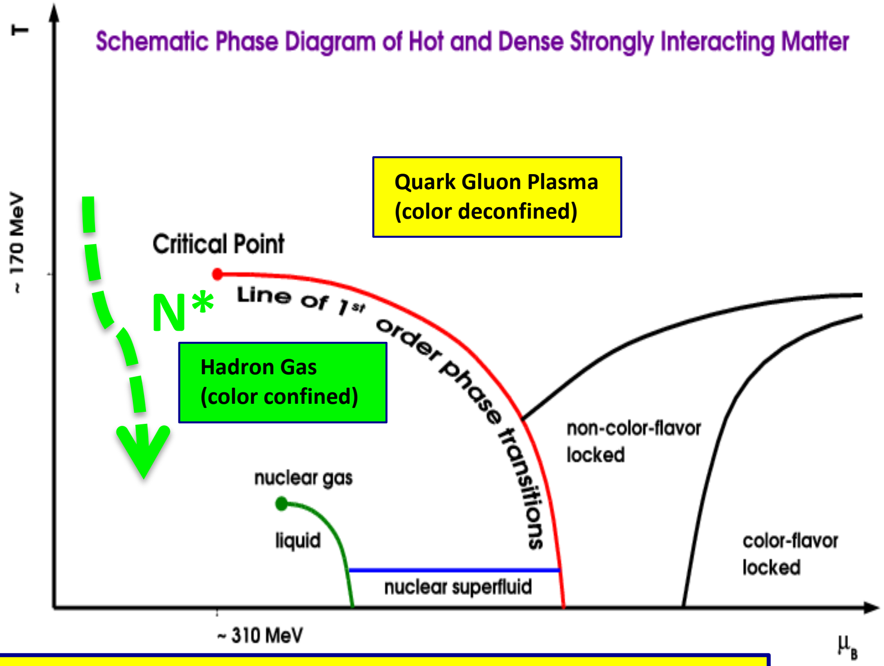
T ~ 400, 000 yrs: Atoms

T ~ : 10^2 s: Nuclei

T ~ 10^{-6} s: Nucleons

T~ 10^{-9} s: QGP

T ~ 10^{-6} s: Transition from the QGP to Nucleons

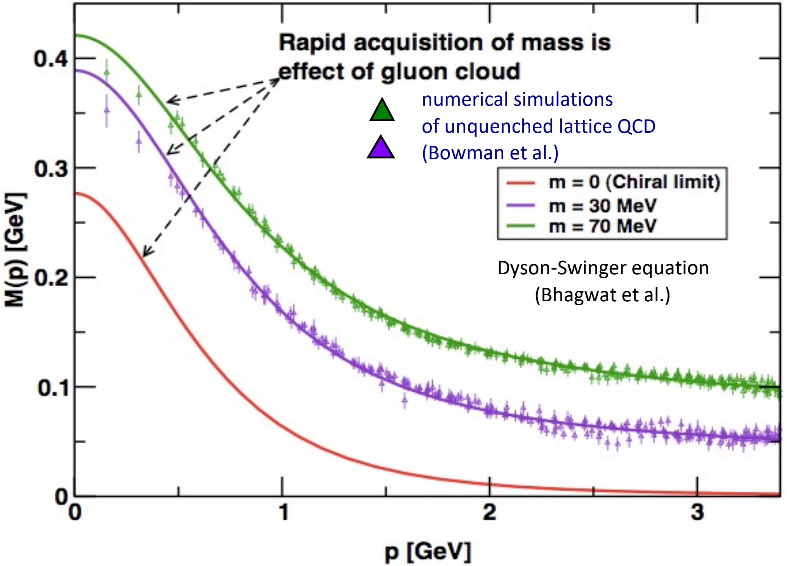


Dramatic events occur in the microsecond old Universe.

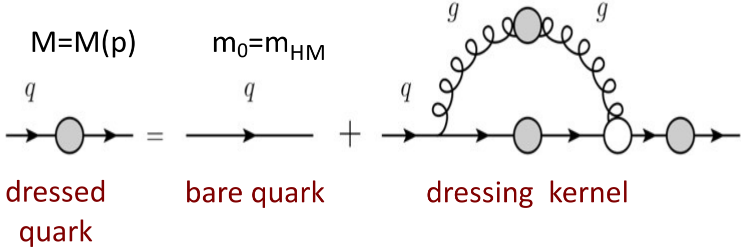
- The transition from the QGP to the baryon phase is dominated by excited baryons. A quantitative description requires more states than found to date => **missing baryons.**
- During the transition the quarks acquire **dynamical mass** and the **confinement of color** occurs.

Critical QCD Questions Addressed

- How do massless quarks acquire mass?



Effective quark mass depends on its momentum



mass composition

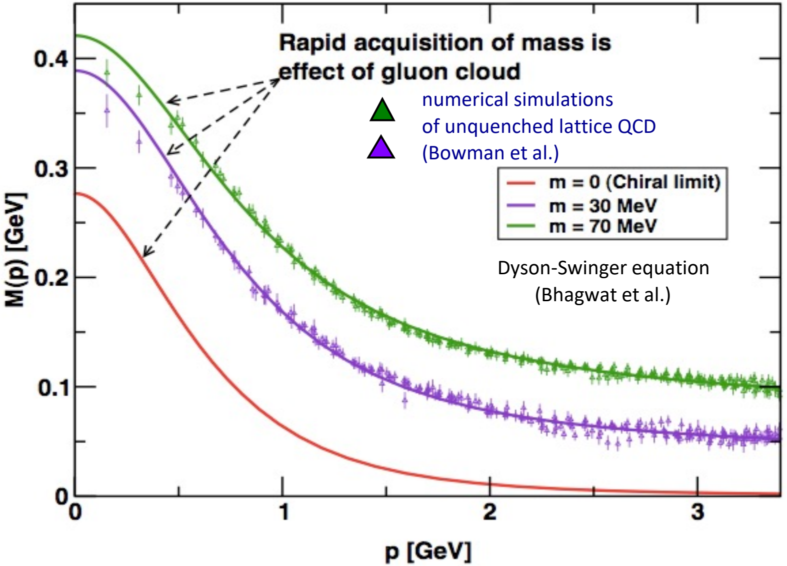
<2%	Higgs mechanism
>98%	non-perturbative strong interaction

→ **Measure the Q^2 dependence of electrocoupling amplitudes**

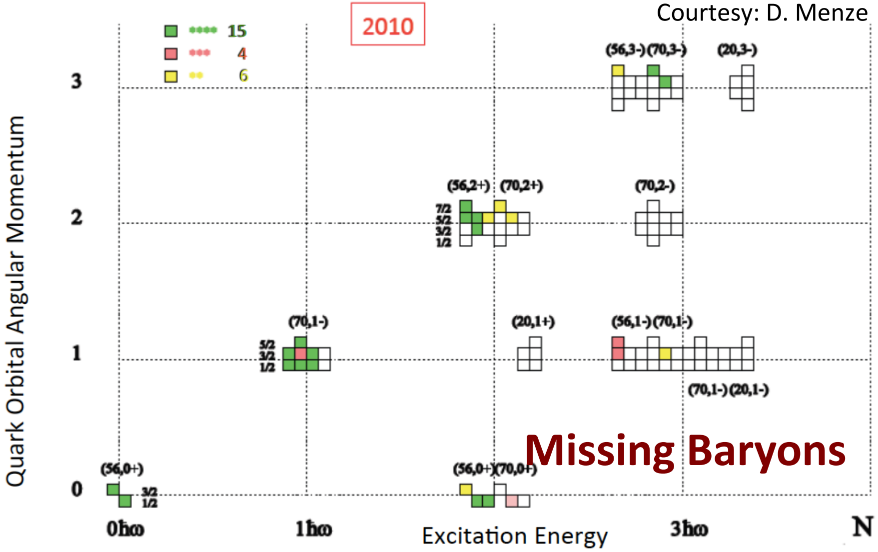
Constituent quark models and SU(6)xO(3)

- Current-quarks of perturbative QCD evolve into constituent quarks at low momentum

→ Connection between constituent and current quarks.



Courtesy: D. Menze

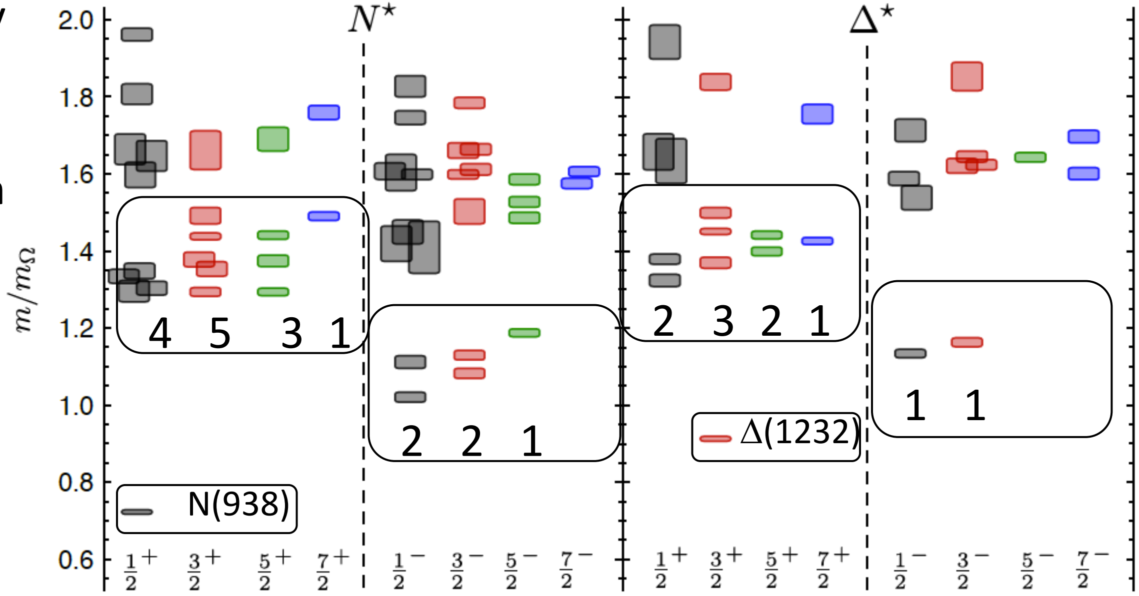


- QCD-inspired Constituent Quark models: states classified by isospin, parity and spin within each oscillator band. Many projected q^3 states are still missing or uncertain.

LQCD N* & Δ Spectra

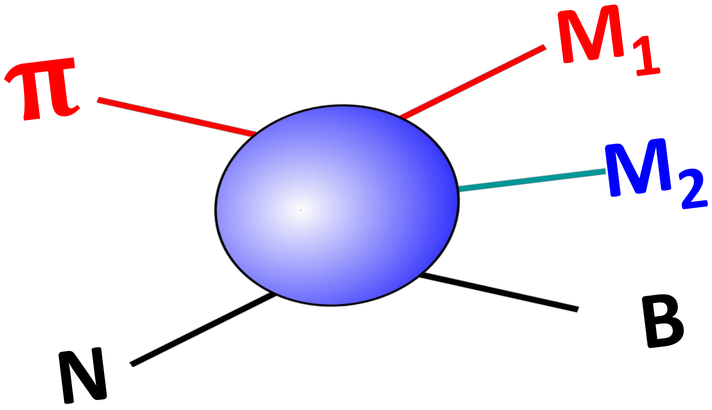
- Exhibit the SU(6)×O(3)-symmetry features
- Counting of levels consistent with non-rel. quark model
- Striking similarity with quark model
- No parity doubling

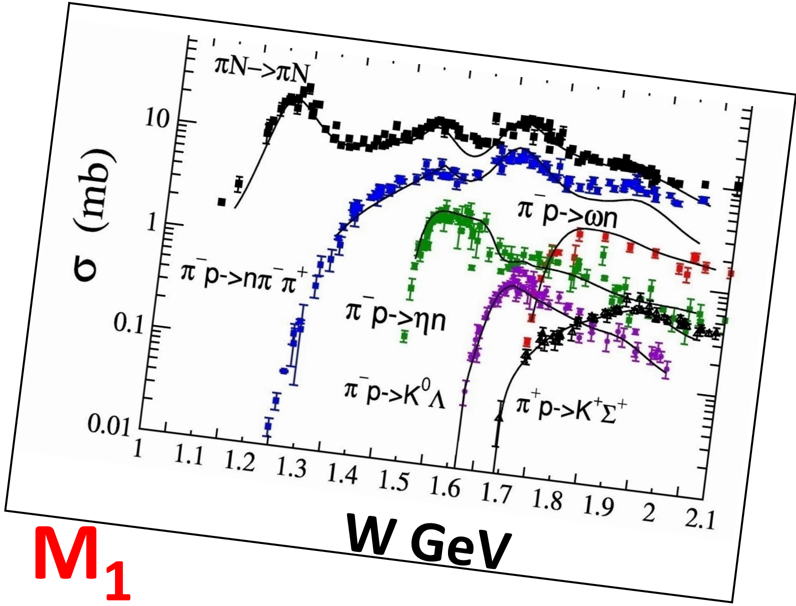
Problems are not solved!

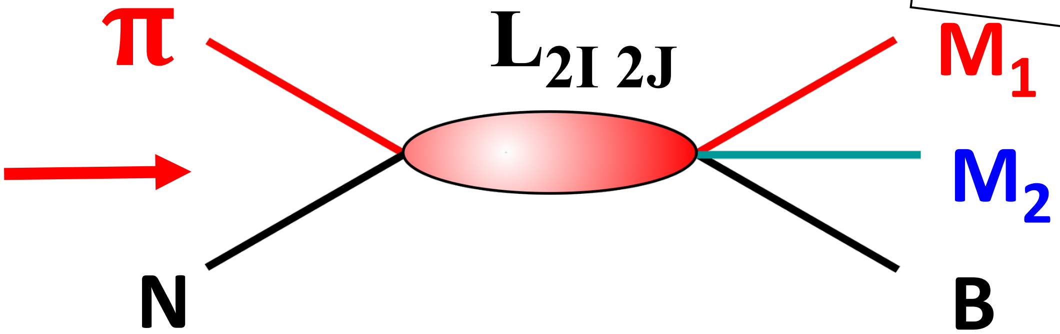


Robert G. Edwards, Jozef J. Dudek, David G. Richards, Stephen J. Wallace
Phys.Rev. D84 (2011) 074508

Establishing the N* and Δ Spectrum: πN scattering

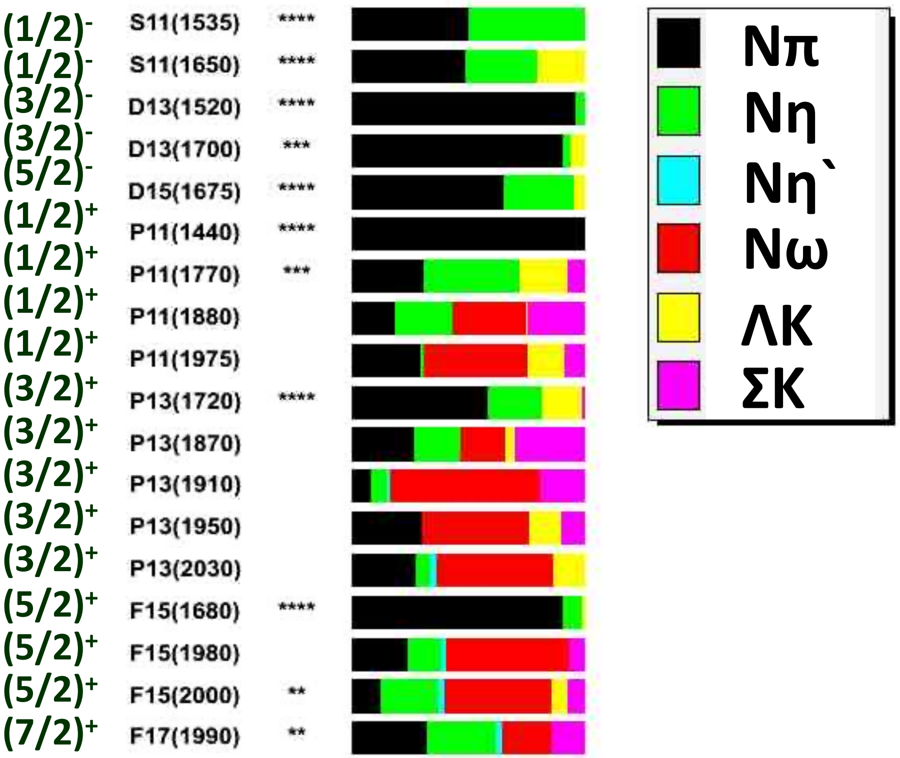




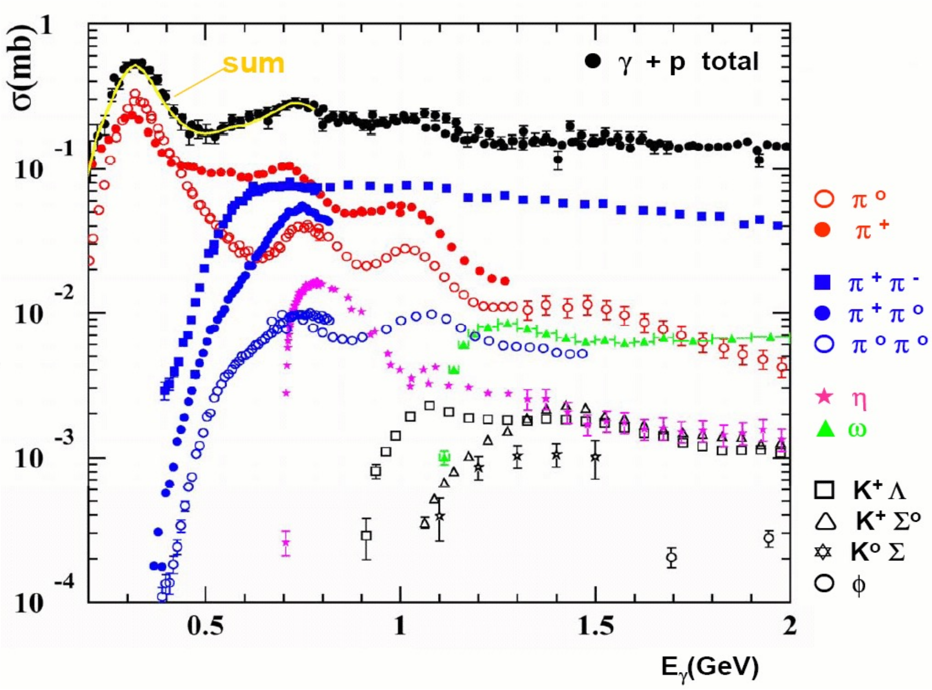


Establishing the N* and Δ Spectrum

Search all channels: not just πN

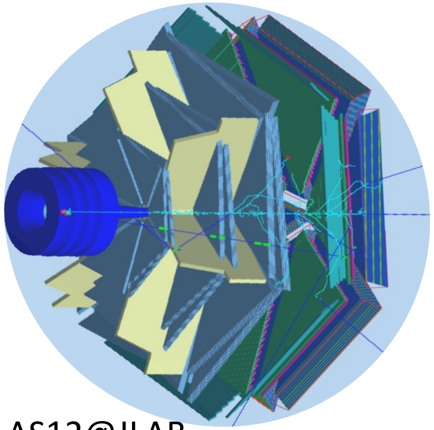


Photonuclear cross sections



N* Program – photo- & electro-production of mesons

The N* program is one of the key physics foundations of CLAS@JLab, A2@MAMI, CB@ELSA, BGOOD



CLAS12@JLAB

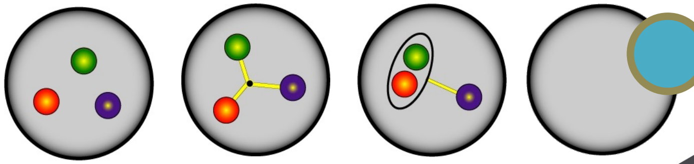
Detectors have been designed to measure cross sections and spin observables over a broad kinematic range for exclusive reaction channels:

πN, ωN, ϕN, ηN, $\eta' N$, $\pi\pi N$, KY, K*Y, KY*

- N* parameters do not depend on how they decay
- Different final states have different hadronic decay parameters and different backgrounds
- Agreement offers model-independent support for findings

- The program goal is to probe the *spectrum* of N* states and their *structure*
  - Probe the underlying degrees of freedom of the nucleon through studies of photoproduction and the Q^2 evolution of the electro-production amplitudes.

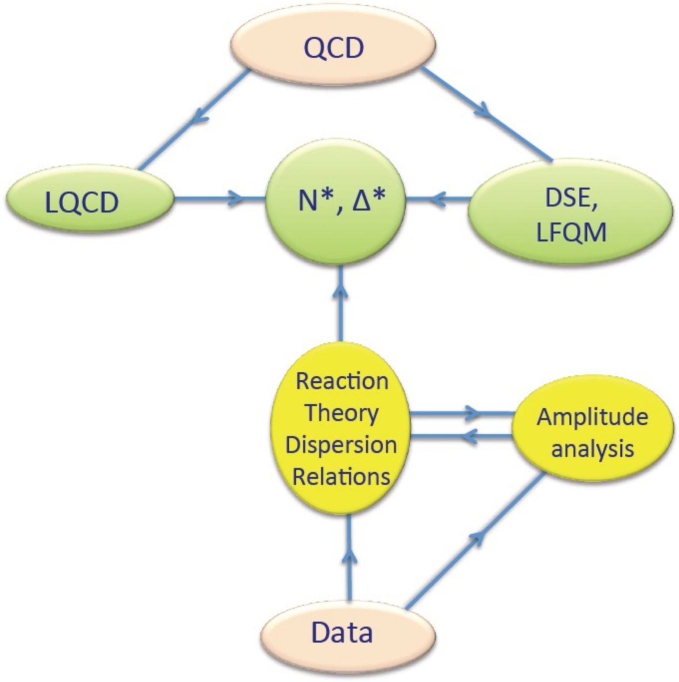
N* degrees of freedom??



Establishing the N* and Δ Spectrum

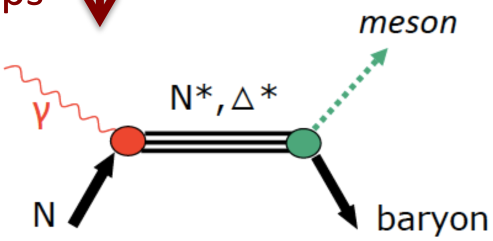
Experimental requirements:

- Precision measurements of photo-induced processes in wide kinematics, e.g.
  $\gamma p \rightarrow \pi N$, ηp, KY, .., $\gamma n \rightarrow \pi N$, $K^0 Y^0$, ..
- More complex reactions, e.g. $\gamma p \rightarrow \omega p$, $\rho\phi$, $\pi\pi p$, $\eta\pi N$, K^*Y, .. may be sensitive to high mass states through direct transition to ground state or through cascade decays
- Polarization observables are essential



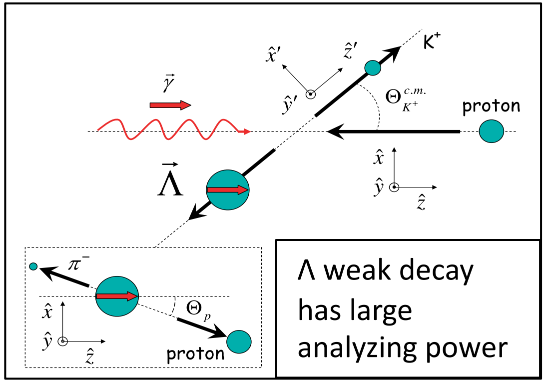
Engaging theoretical groups ↓

Extract s-channel resonances



Hadronic production & Electromagnetic production

Polarization Observables: Complete Experiment



The holy grail of baryon resonance analysis

- Process described by 4 complex, parity conserving 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

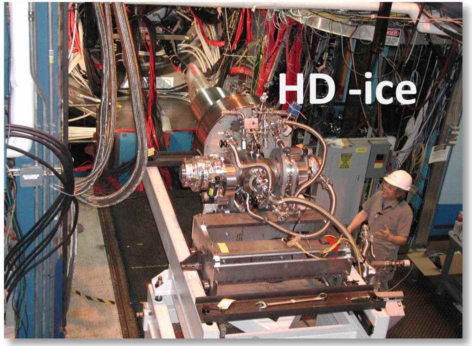
Beam (P^γ)		Target (P^T)			Recoil (P^R)			Target (P^T) + Recoil (P^R)								
					x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
		x	y	z				x	y	z	x	y	z	x	y	z
unpolarized	$d\sigma_0$		$\hat{T}$			$\hat{P}$		$\hat{T}_{x'}$		$\hat{L}_{x'}$		$\hat{\Sigma}$		$\hat{T}_{z'}$		$\hat{L}_{z'}$
$P_L^\gamma \sin(2\phi_\gamma)$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

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

Experimental set-up

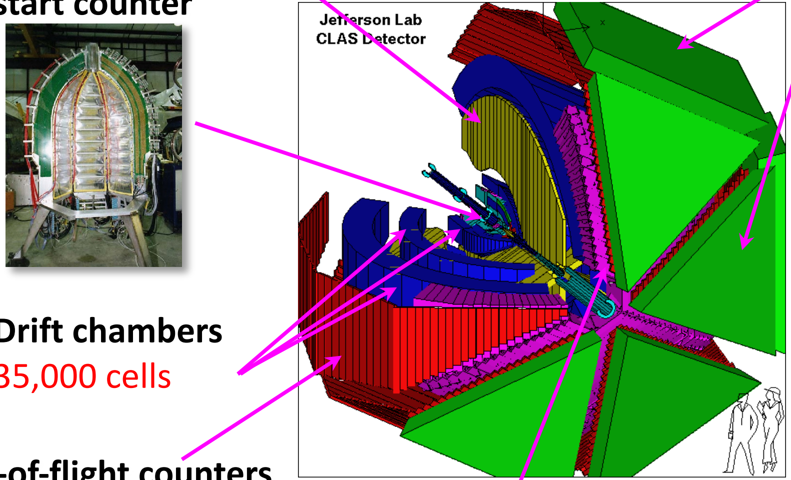
Polarized Frozen-spin Targets & CEBAF Large Acceptance Spectrometer

or



+

start counter



Torus magnet
6 superconducting coils

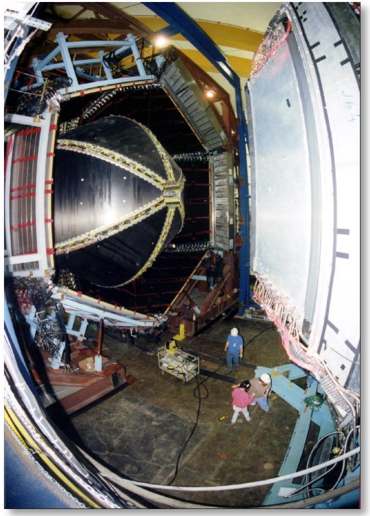
Electromagnetic calorimeters
Lead/scintillator, 1296 photomultipliers

Drift chambers
35,000 cells

Time-of-flight counters
plastic scintillators,
684 photomultipliers

Gas Cherenkov counters
e/π separation, 256 PMTs

Open CLAS detector



CLAS N* Experimental Program

✓-published, ✓-acquired

Proton targets

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

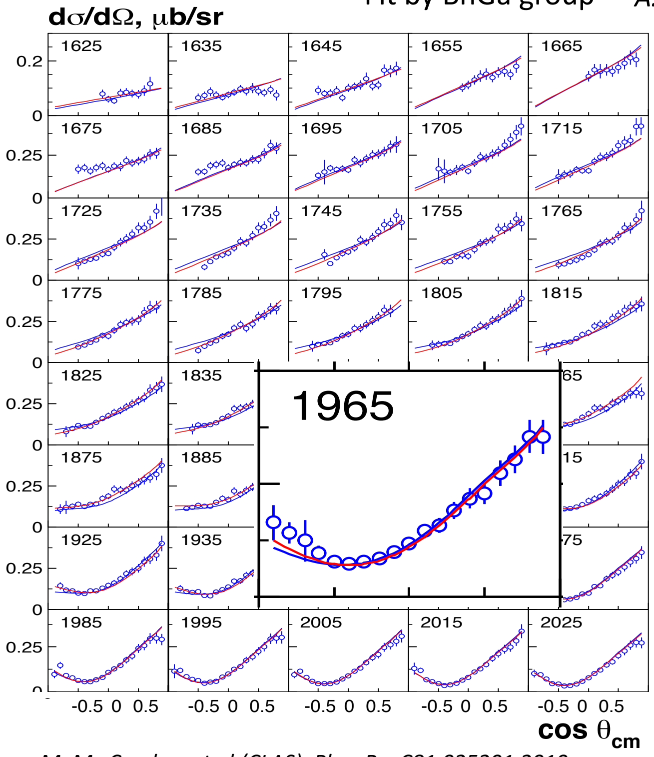
Neutron targets

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

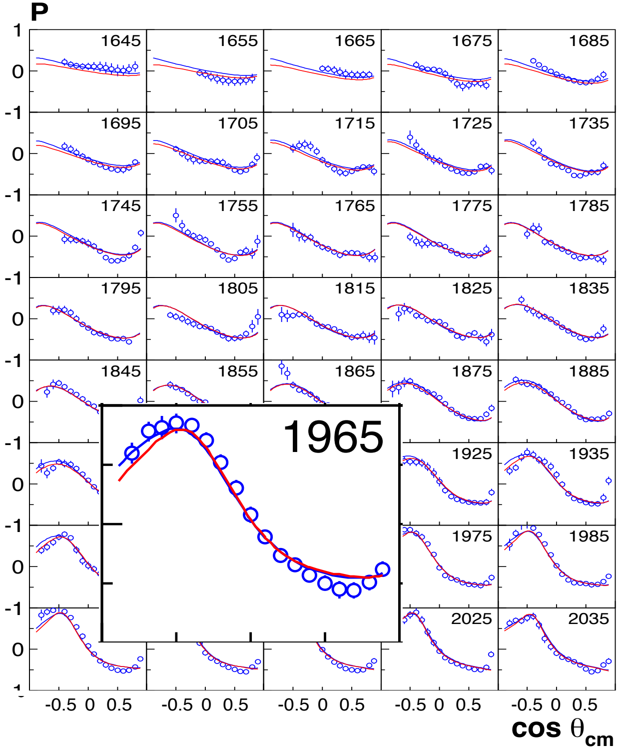
Establishing the N* spectrum – Precision & Polarization are essential

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

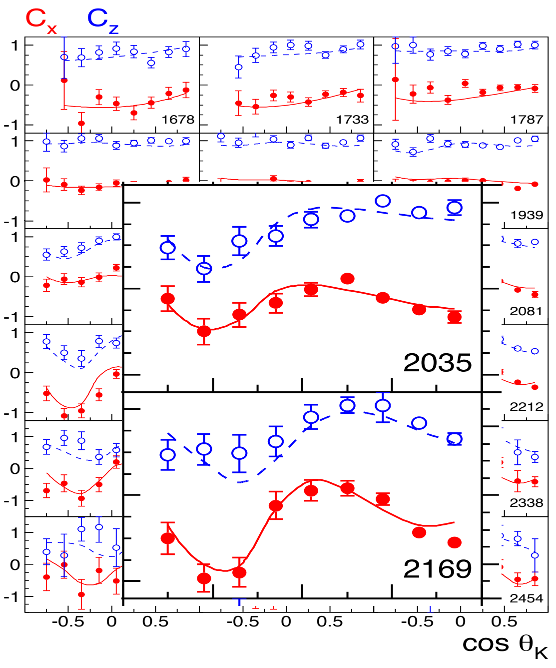
Fit by BnGa group *A.V. Anisovich et al, EPJ A48, 15 (2012)*



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



γ->Λ **Polarization** transfer

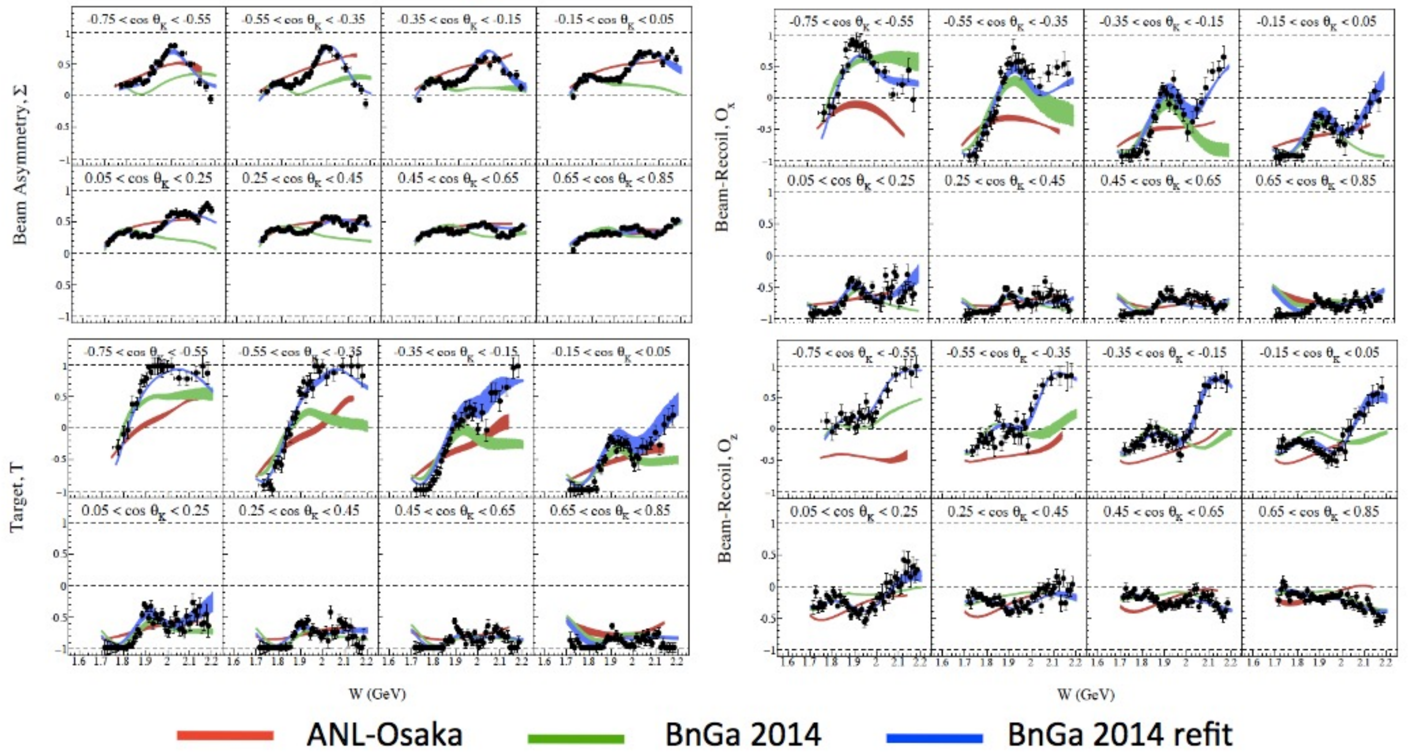


D. Bradford et al. (CLAS), Phys.Rev. C75, 035205, 2007

More N* from polarized $K^+ \Lambda$ photoproduction?

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

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

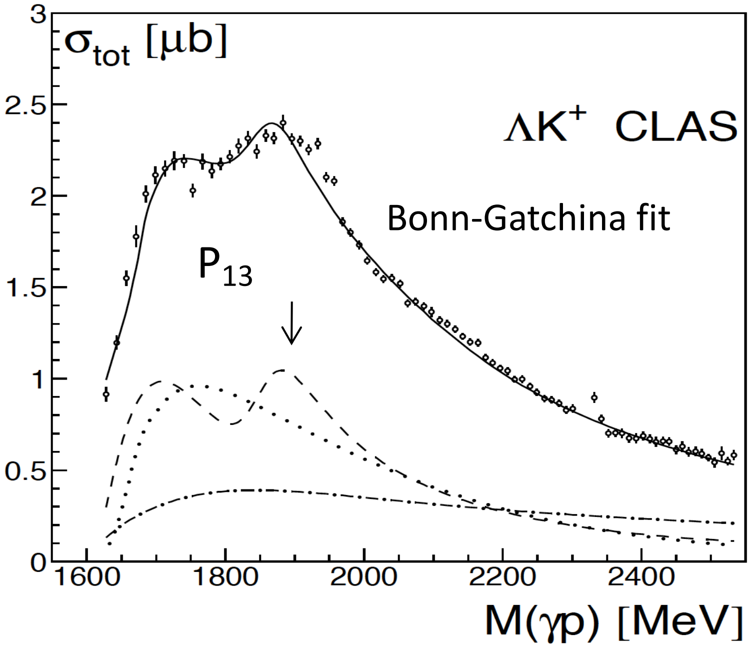


New Multipole Extraction

PRC96,055202 (2017)

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

- Bump first seen in SAPHIR $K^+ \Lambda$ data but due to systematics in the data misinterpreted as $J^P = 3/2^-$ (D–wave resonance).
- State was solidly established in Bn-Ga coupled-channel analysis making use of very precise KΛ polarized data, resulting in *** assignment in PDG2012. (P-wave resonance) and confirmed by more recent multipole extraction (PRL 119, 062004, 2017)
- State confirmed in an effective Langrangian resonance model analysis $\gamma p \rightarrow K^+\Lambda$ (*O. V. Maxwell, PRC85,034611, 2012*)
- State confirmed in a covariant isobar model single channel analysis $\gamma p \rightarrow K^+\Lambda$ (*T. Mart & M. J. Kholili, PRC86, 022201, 2012*).
- First baryon resonance observed and multiply confirmed in electromagnetic production.



Promoted to ** state in 2021 RPP**

Updated Spectrum of Baryon Resonances

- From 2000 to 2010 no new Baryon resonances in PDG. πN- scattering data and π-photoproduction only.
- Multi-channel models now include many photoproduction data. e.g. Bonn-Gatchina PWA analysis

State $N(mass)J^P$	PDG pre 2010	PDG 2012	PDG 2021
$N(1710)1/2^+$	***	***	****
$N(1880)1/2^+$		**	***
$N(1895)1/2^-$		**	****
$N(1900)3/2^+$	**	***	****
$N(1875)3/2^-$		***	***
$N(2120)3/2^-$		**	***
$N(2000)5/2^+$	*		**
$N(2060)5/2^-$		**	***

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

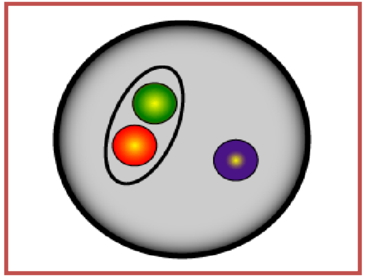
PRL 119, 062004, 2017)

Naming scheme has changed:
$L_{2I\ 2J}(E) \rightarrow J^P(E)$

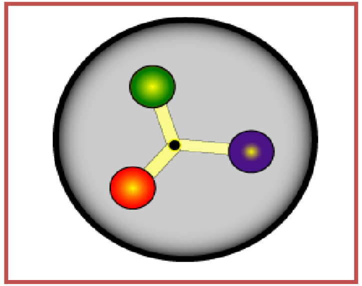
- Results from photoproduction now add to the PDG tables and determine properties of baryon resonances

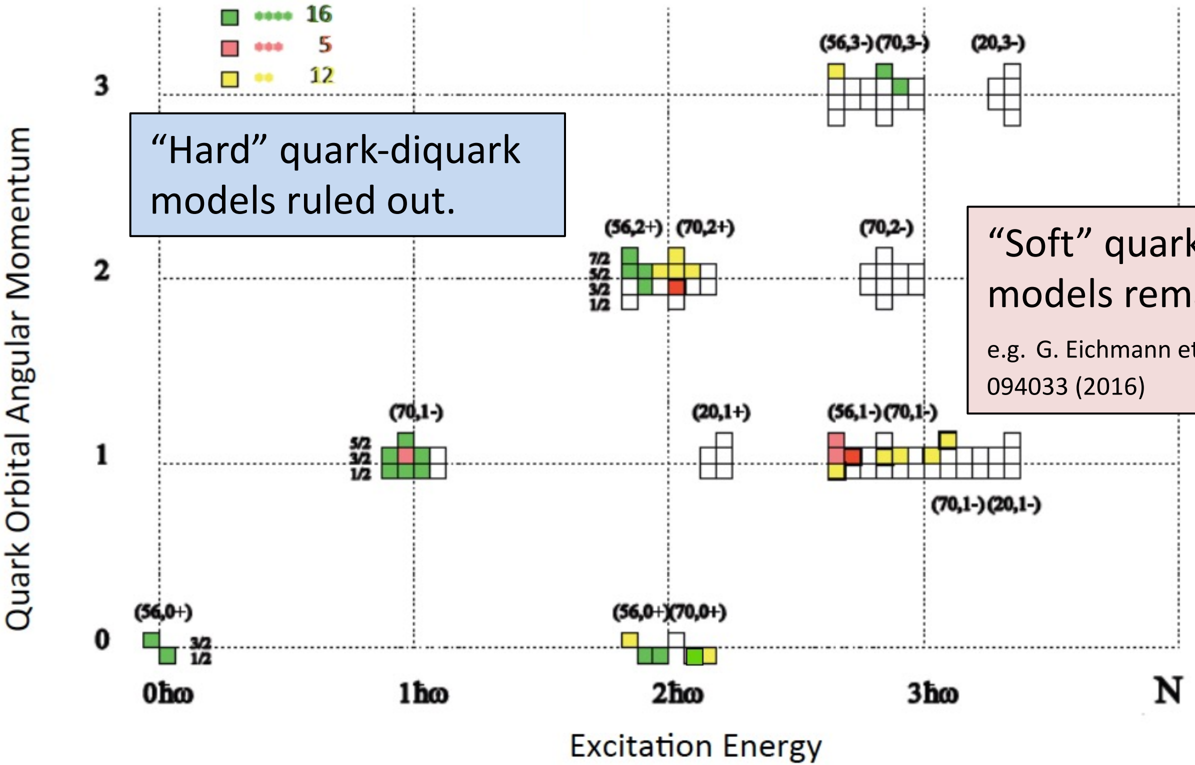
Do New States Fit into Q^3 QM ?

SU(6)xO(3)



vs





“Hard” quark-diquark models ruled out.

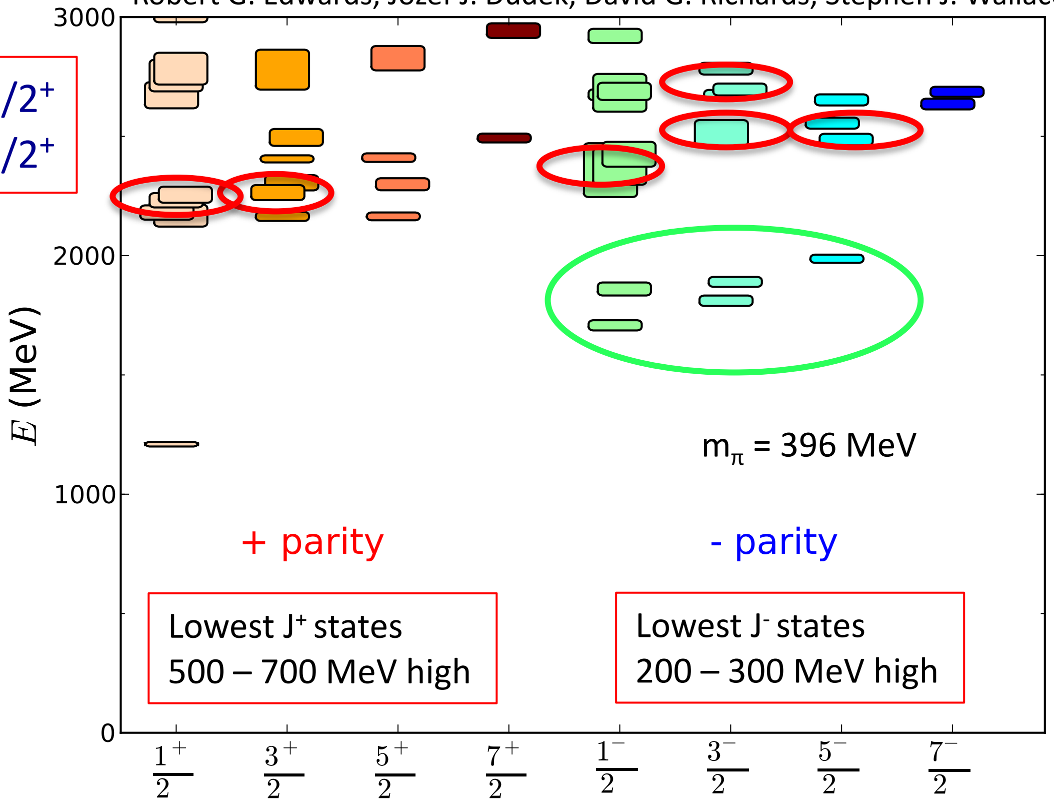
“Soft” quark-diquark models remain viable.

e.g. G. Eichmann et al. Phys. Rev. D 94, 094033 (2016)

Do New States Fit into LQCD Projections ?

Robert G. Edwards, Jozef J. Dudek, David G. Richards, Stephen J. Wallace **Phys.Rev. D84 (2011) 074508**

N(1900)3/2$^+$
N(1880)1/2$^+$



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

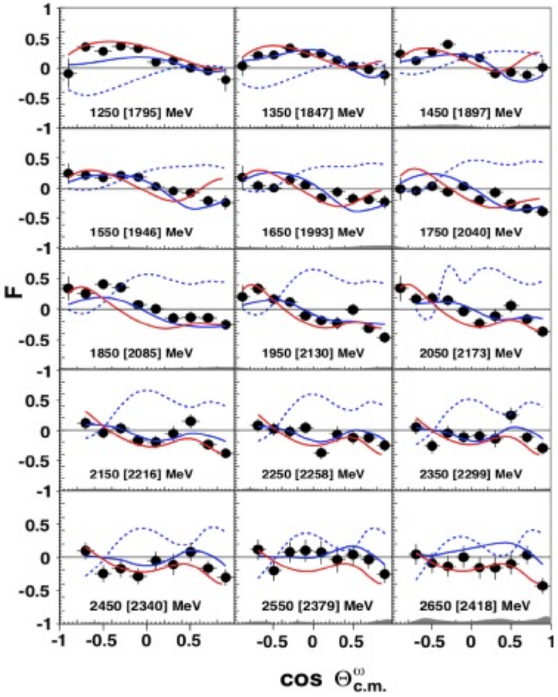
Ignoring the mass scale, new candidates fit the J^P values predicted from LQCD.

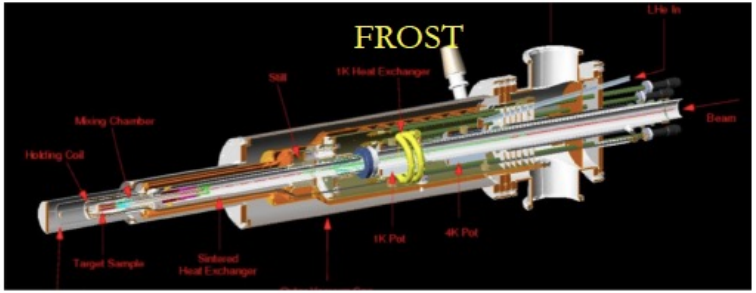
The field would really benefit from more realistic Lattice masses for N* states.

Known states:
N(1675)5/2$^-$
N(1700)3/2$^-$
N(1520)3/2$^-$
N(1650)1/2$^-$
N(1535)1/2$^-$

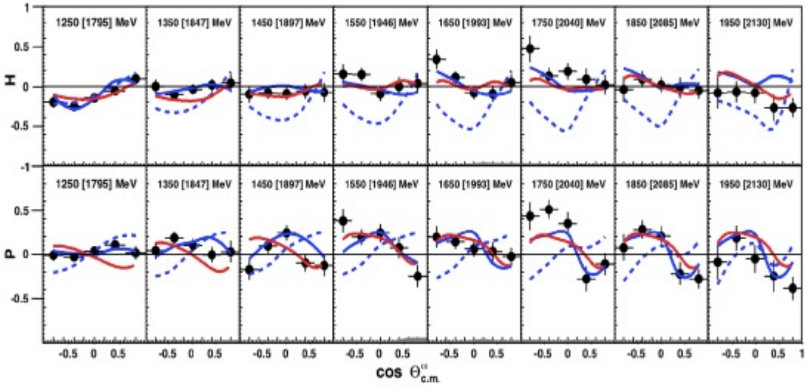
Beam-target asymmetries $\vec{\gamma}\,\vec{p} \to p\,\omega$

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





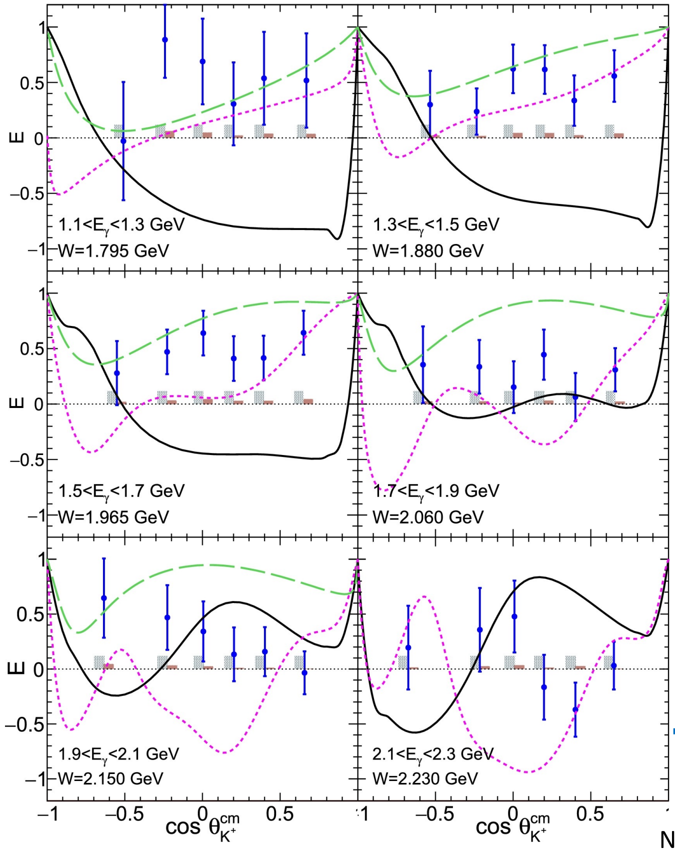
P. Roy et al. (CLAS), Phys.Rev. Lett. 122 (2019) 162301



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: $\vec{\gamma}\,\vec{n} \to K^+\,\Sigma^-$



Beam-Target helicity asymmetry E

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_0 (1 - P_T^{eff} P_\odot E)$$

Kaon-Maid2000

Kaon-Maid2017

Bonn-Gatchina 2017

↓

Bonn-Gatchina 2019

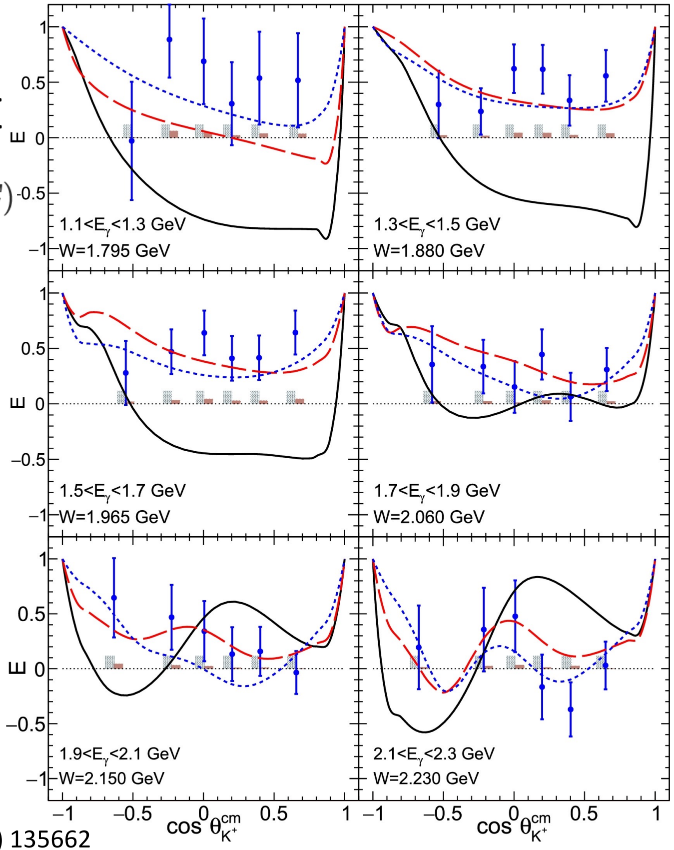
N(1895)1/2⁻ N(1720)3/2⁺

N(1900)3/2⁺

modified photo-couplings

Bonn-Gatchina 2019

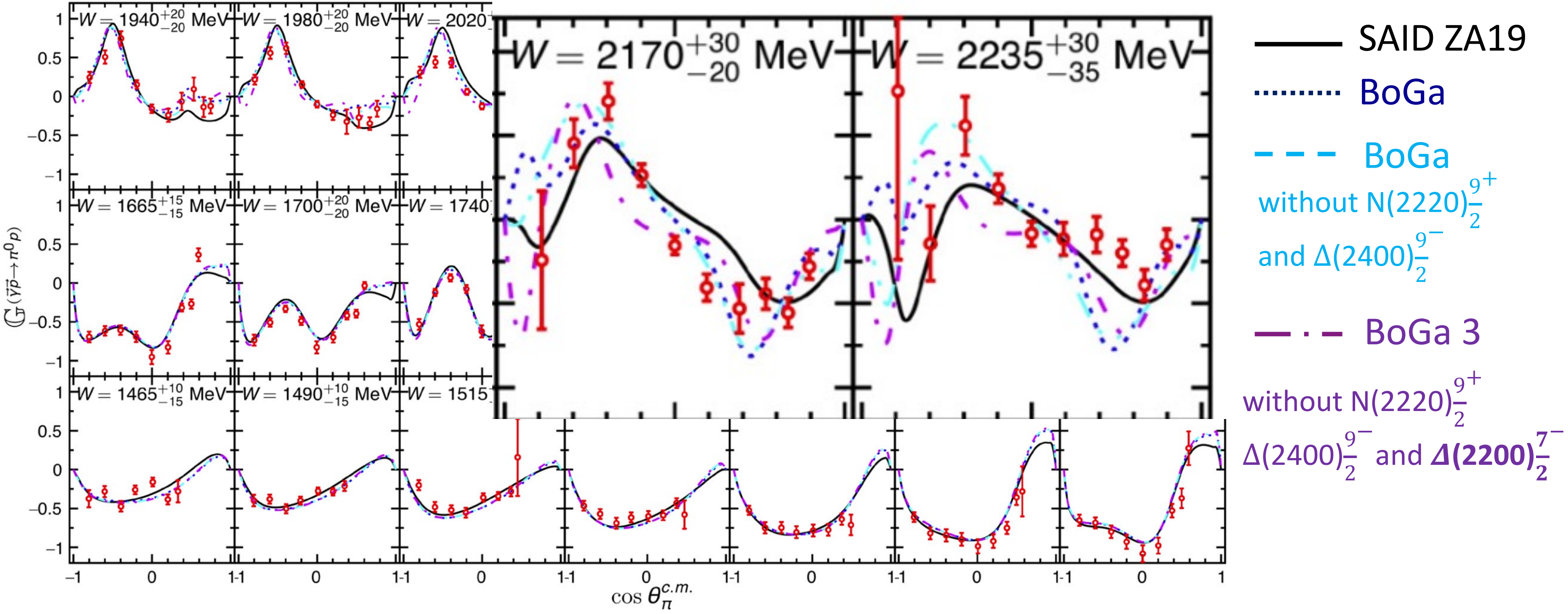
+ N(2170) 3/2⁺



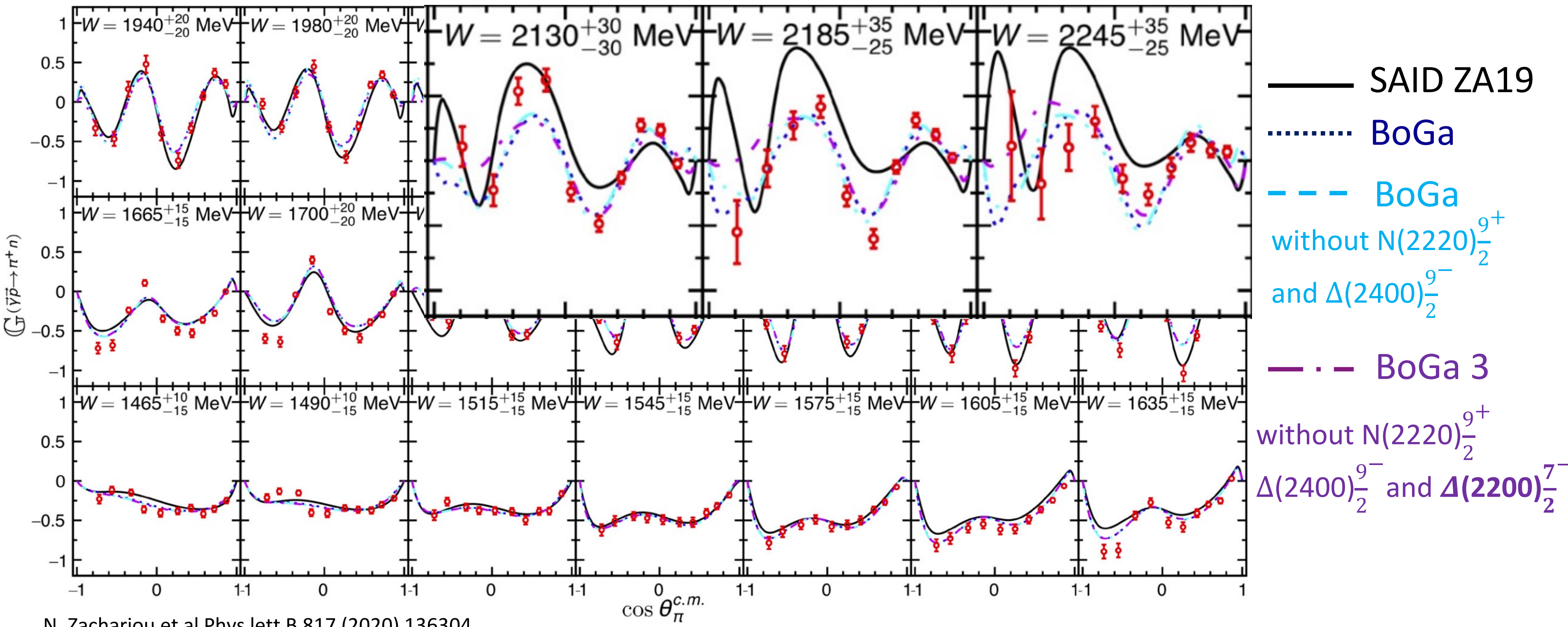
N. Zachariou et al Phys lett B 808 (2020) 135662

Beam-target asymmetry G in $\vec{\gamma} + \vec{p} \rightarrow \pi^0 + p$

N. Zachariou et al Phys lett B 817 (2020) 136304

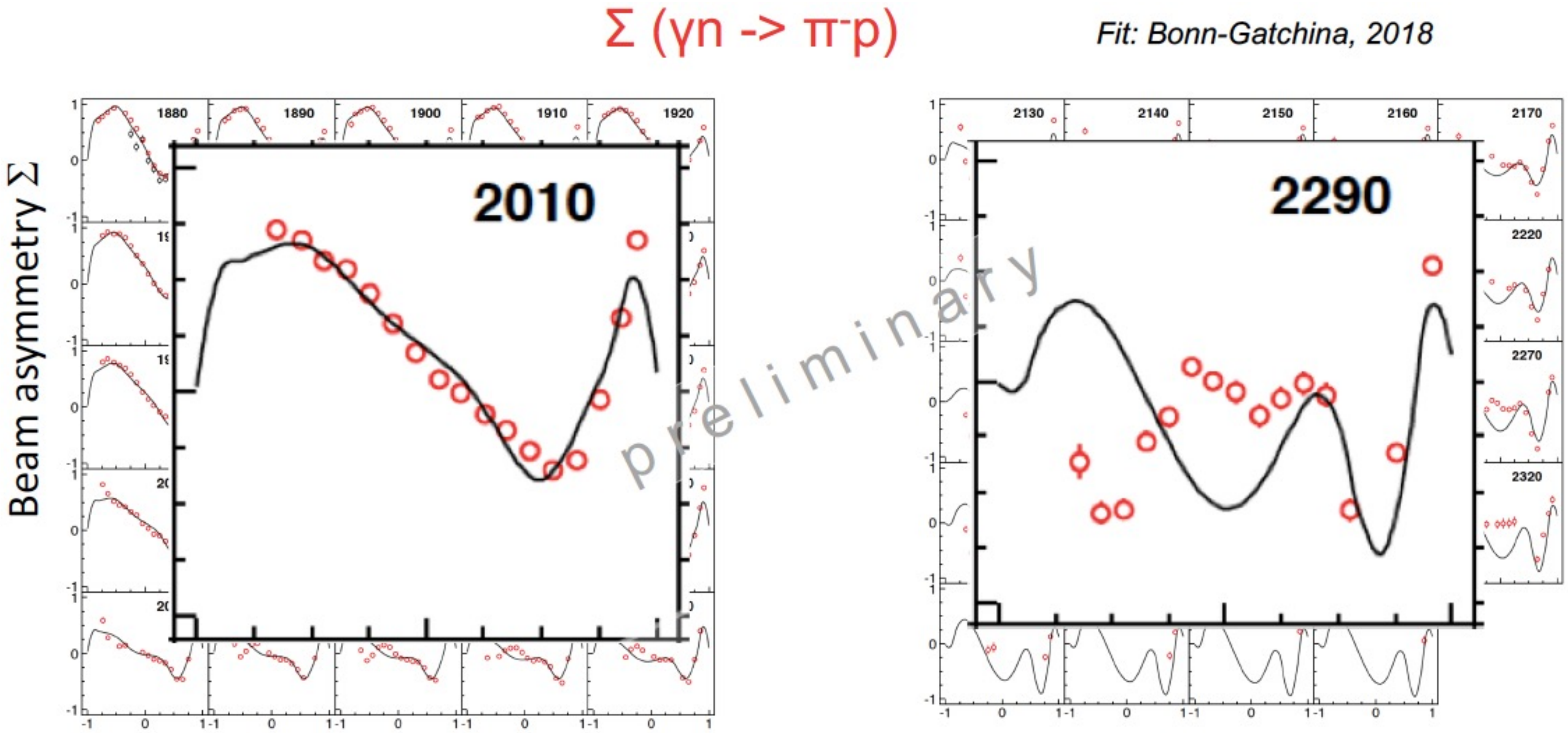


Beam-target asymmetry G in $\vec{\gamma} + \vec{p} \rightarrow \pi^{+}$ +n



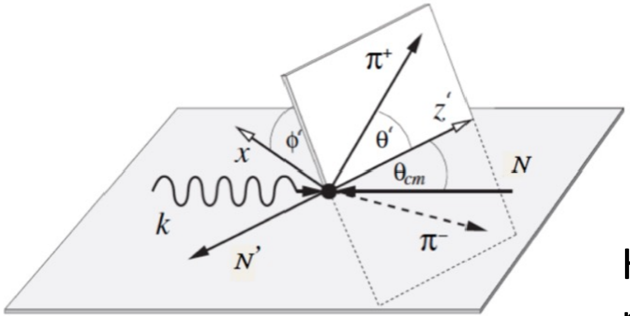
N. Zachariou et al Phys lett B 817 (2020) 136304

Search for Neutron States: $\vec{\gamma}\, n \rightarrow \pi^- p$



Fit requires additional new resonances above 2100 MeV

$\pi^+\pi^-$ photoproduction – polarized p target

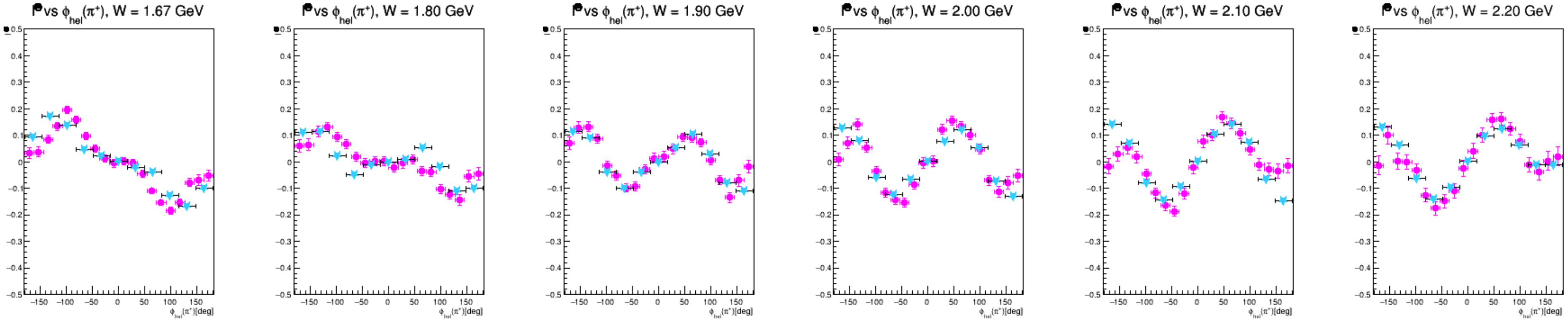


$I^{\odot}$ is expected to be odd

Measurements of polarization observables

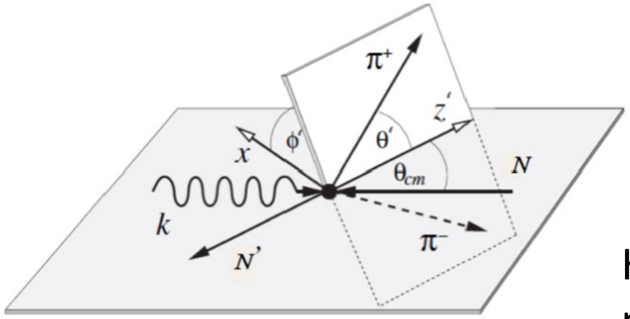
$$\frac{d\sigma}{dx_i} = \sigma_0\{(1 + \Lambda_z \cdot \mathbf{P_z}) + \delta_{\odot}(\mathbf{I}^{\odot} + \Lambda_z \cdot \mathbf{P}_z^{\odot})\}$$

HD-ice frozen-spin polarized target



Preliminary results by: A. Filippi (g14 data-set)

$\pi^+\pi^-$ photoproduction – polarized p target



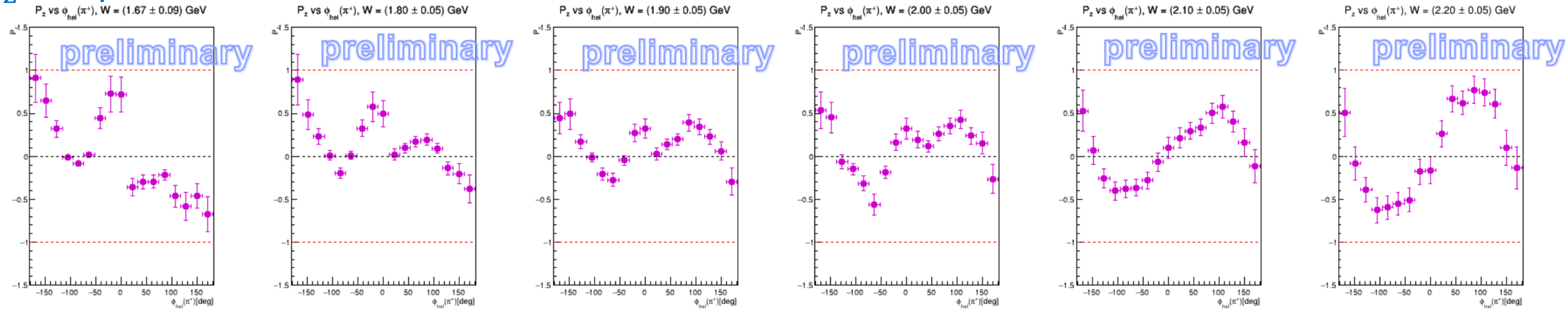
Measurements of polarization observables

$$\frac{d\sigma}{dx_i} = \sigma_0\{(1+\Lambda_z \cdot \mathbf{P_z}) + \delta_\odot(\mathbf{I}^\odot + \Lambda_z \cdot \mathbf{P}_z^\odot)\}$$

HD-ice frozen-spin polarized target

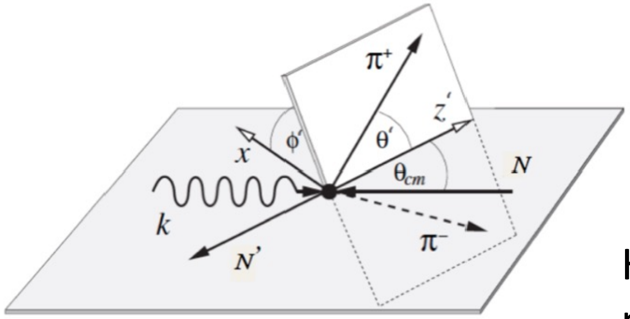
polarized p

P_z is expected to be even



Preliminary results by: A. Filippi (g14 data-set)

$\pi^+\pi^-$ photoproduction – polarized p target



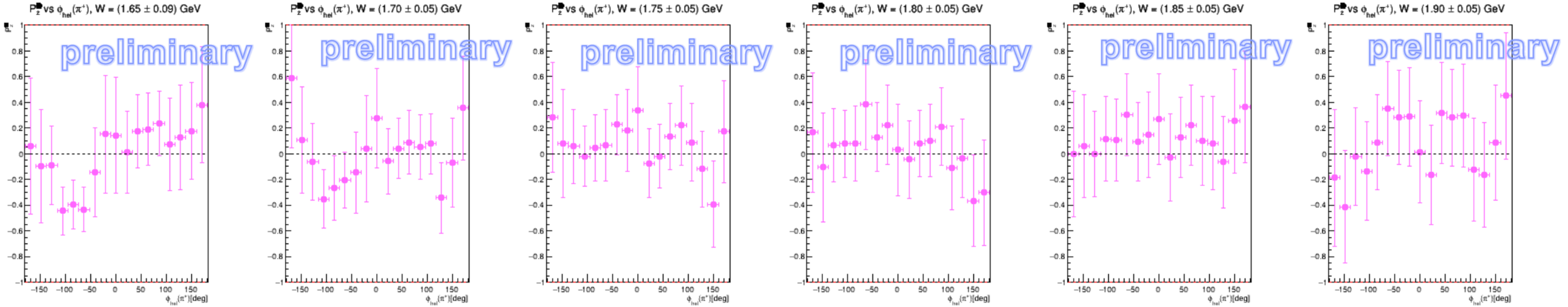
Measurements of polarization observables

$$\frac{d\sigma}{dx_i} = \sigma_0\{(1+\Lambda_z\cdot\mathbf{P_z}) + \delta_\odot(\mathbf{I}^\odot + \Lambda_z\cdot\mathbf{P}_z^\odot)\}$$

HD-ice frozen-spin polarized target

polarized p

$P_z^\odot$ is expected to be even

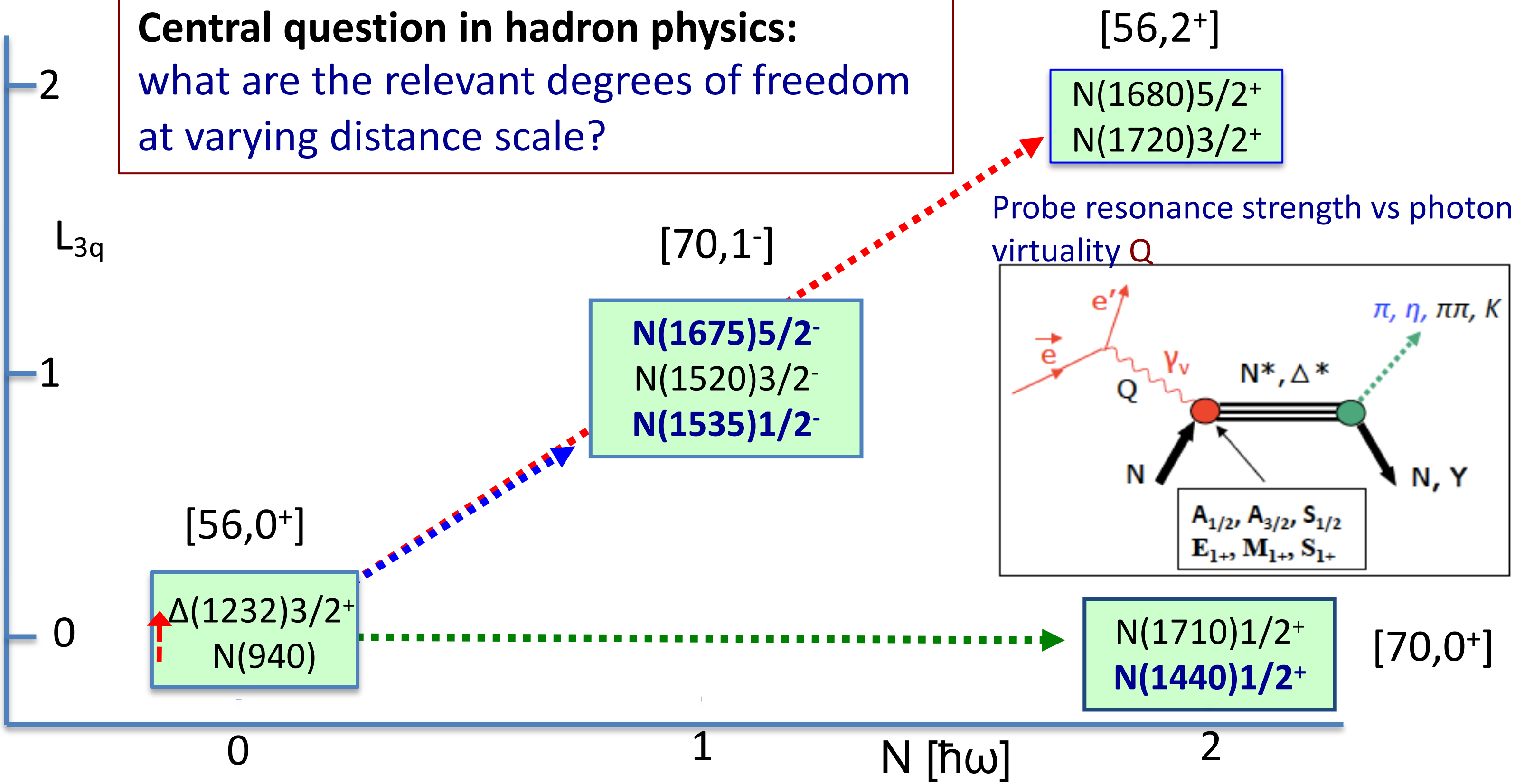


Preliminary results by: A. Filippi (g14 data-set)

Electroexcitation of N*/Δ resonances

Central question in hadron physics:
what are the relevant degrees of freedom at varying distance scale?

Probe resonance strength vs photon virtuality Q

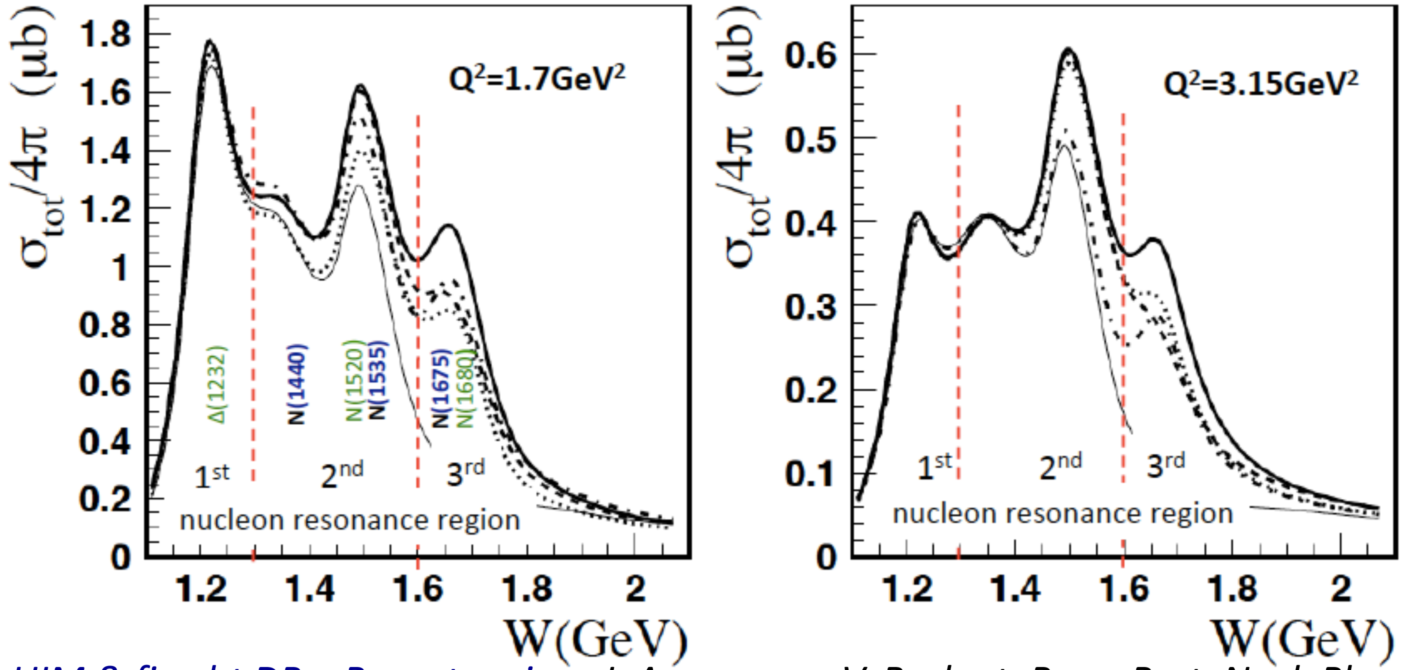


Total cross section at W < 2.1 GeV

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

Different states respond differently to changes in Q^2

Data: *K. Park et al. PRC 77 (2008) 015208; K. Park et al. PRC 91 (2015) 045203*



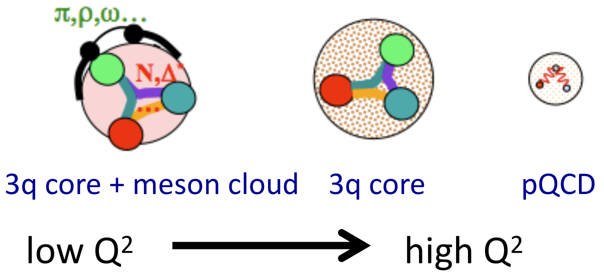
Analysis with UIM & fixed-t DR; *Recent review:* *I. Aznauryan, V. Burkert, Prog. Part. Nucl. Phys. 67 (2012) 1.*

Excited Nucleon Structure

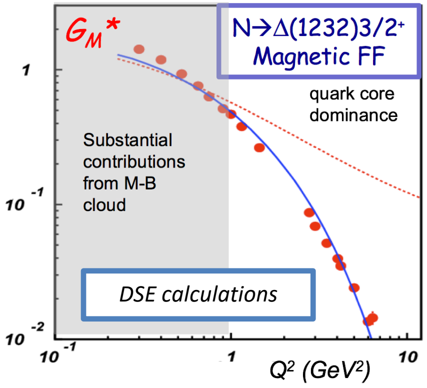
- Nucleon structure is more complex than what can be described accounting for quark degrees of freedom only

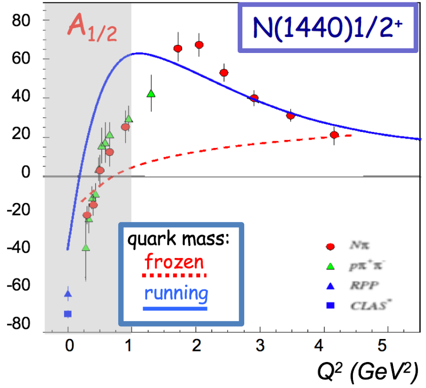
  - Low Q^2: *($Q^2 < 5$ GeV^2)* structure well described by adding an external meson cloud to inner quark core

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

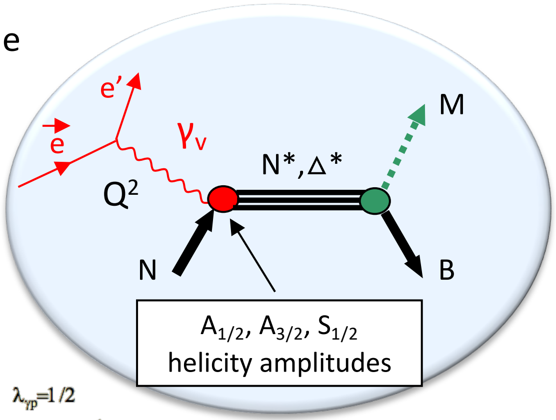


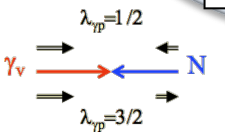
- Calculations of form factors and electrocoupling amplitudes are sensitive to the underlying quark mass distribution





CLAS results vs. QCD expectations with running quark mass

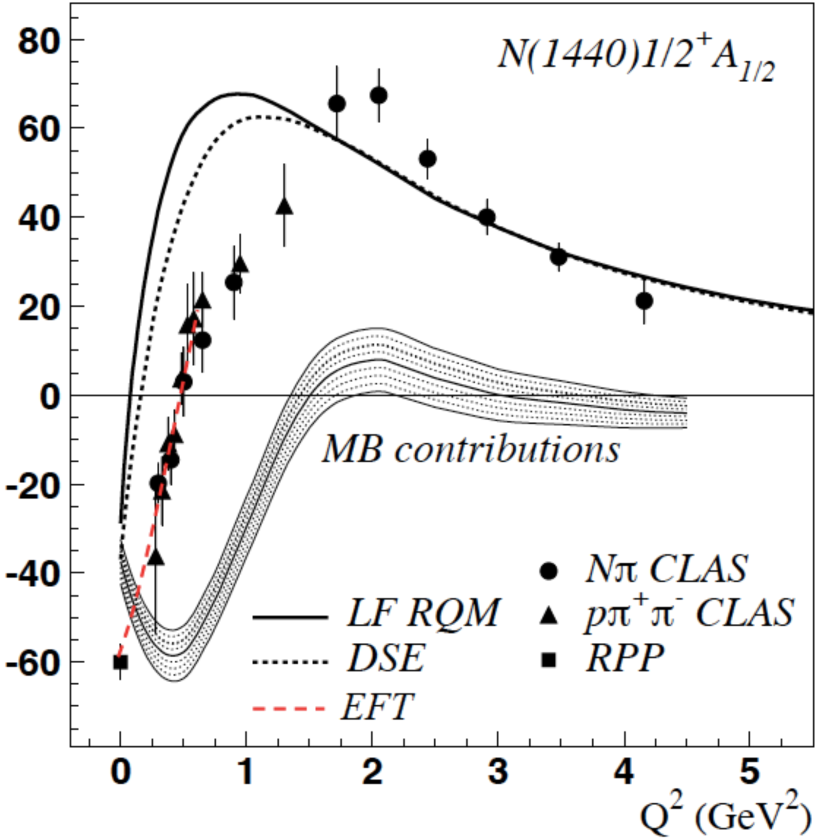




$A_{1/2}$, $A_{3/2}$ – transverse

$S_{1/2}$ - longitudinal

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., PRC94 (2016) 042201*
***EFT**: T. Bauer, S. Scherer, L. Tiator, PRC90 (2014) 015201*

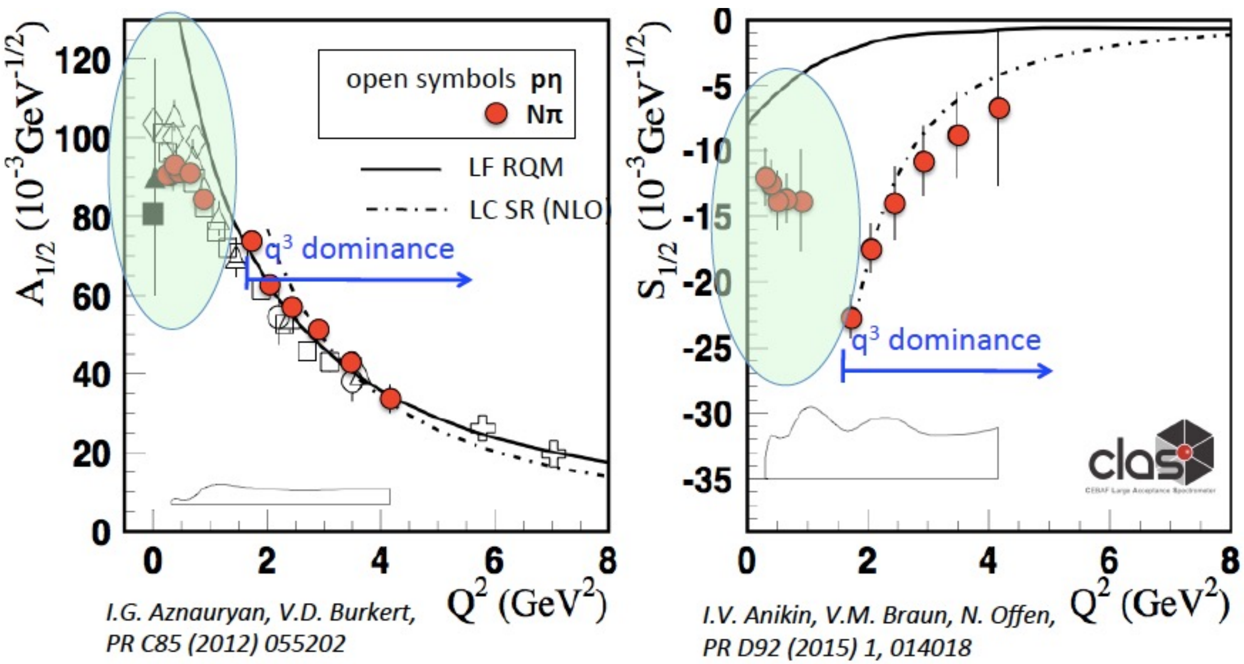
➔ Non-quark contributions are significant at $Q^2 < 2.0$ GeV^2. The behavior at $Q^2 < 0.5$ can be modeled in EFT.

➔ 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".

MB Contribution to electro-excitation of N(1535)1/2⁻

Is it a 3-quark state or a hadronic molecule?



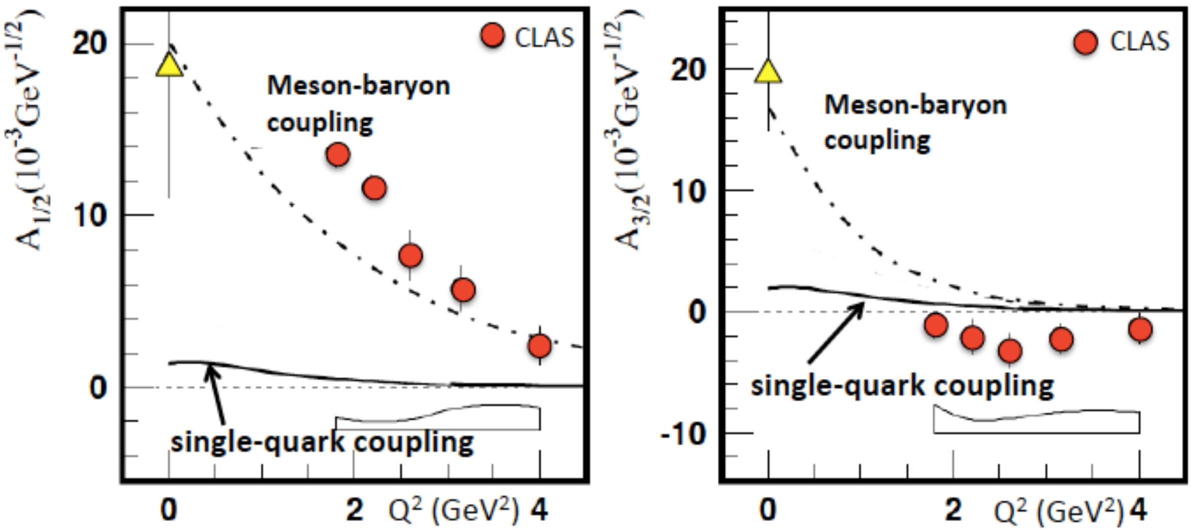
N(1535)1/2⁻ is consistent with the 1st orbital excitation of the nucleon.

- Meson-baryon cloud may account for discrepancies at low Q^2.

MB Contribution to electro-excitation of 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 the γ* p N(1675)5/2$^-$ directly.
- Can be verified on γ* n N(1675)5/2$^-$ which is not suppressed

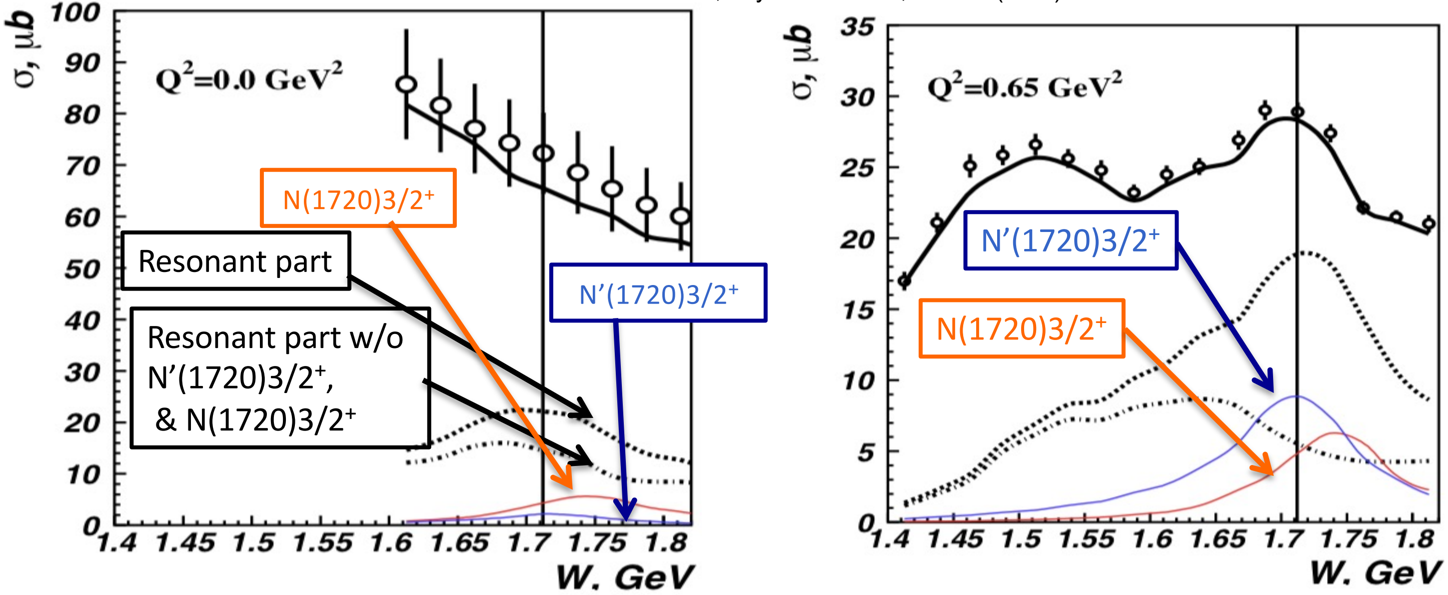
——— *E. Santopinto and M. M. Giannini, PRC 86, 065202 (2012)*

–·–· *B. Juliá-Díaz, T.-S.H. Lee, et al., PRC 77, 045205 (2008)*

$\pi^+\pi^-p$ CLAS data - Newly Discovered N'(1720)3/2+

$\pi^+\pi^-p$ **photo**production $\pi^+\pi^-p$ **electro**production

V.I. Mokeev et al., Phys. Lett. B 805, 135457 (2020)



- Evidence of a new N'(1720)3/2+ resonance from the combined analysis of CLAS photo- and electroproduction of the $\pi^+\pi^-p$ channel
- First result on Q^2 evolution of the new resonance electrocoupling

Hybrid Hadrons: Hadrons with Explicit Gluonic Degrees of Freedom

Hybrid hadrons with dominant gluonic contributions are predicted to exist by QCD.

Experimentally:

- **Hybrid mesons** $|q\bar{q}g\rangle$ states may have exotic quantum numbers J^{PC} not available to pure $|q\bar{q}\rangle$ states   GlueX, MesonEx, COMPASS, PANDA ….

- **Hybrid baryons** $|qqqg\rangle$ have the same quantum numbers J^P as $|qqq\rangle$ electroproduction with CLAS12 (Hall B).

Theoretical predictions:

✧ MIT bag model - T. Barnes and F. Close, Phys. Lett. 123B, 89 (1983).

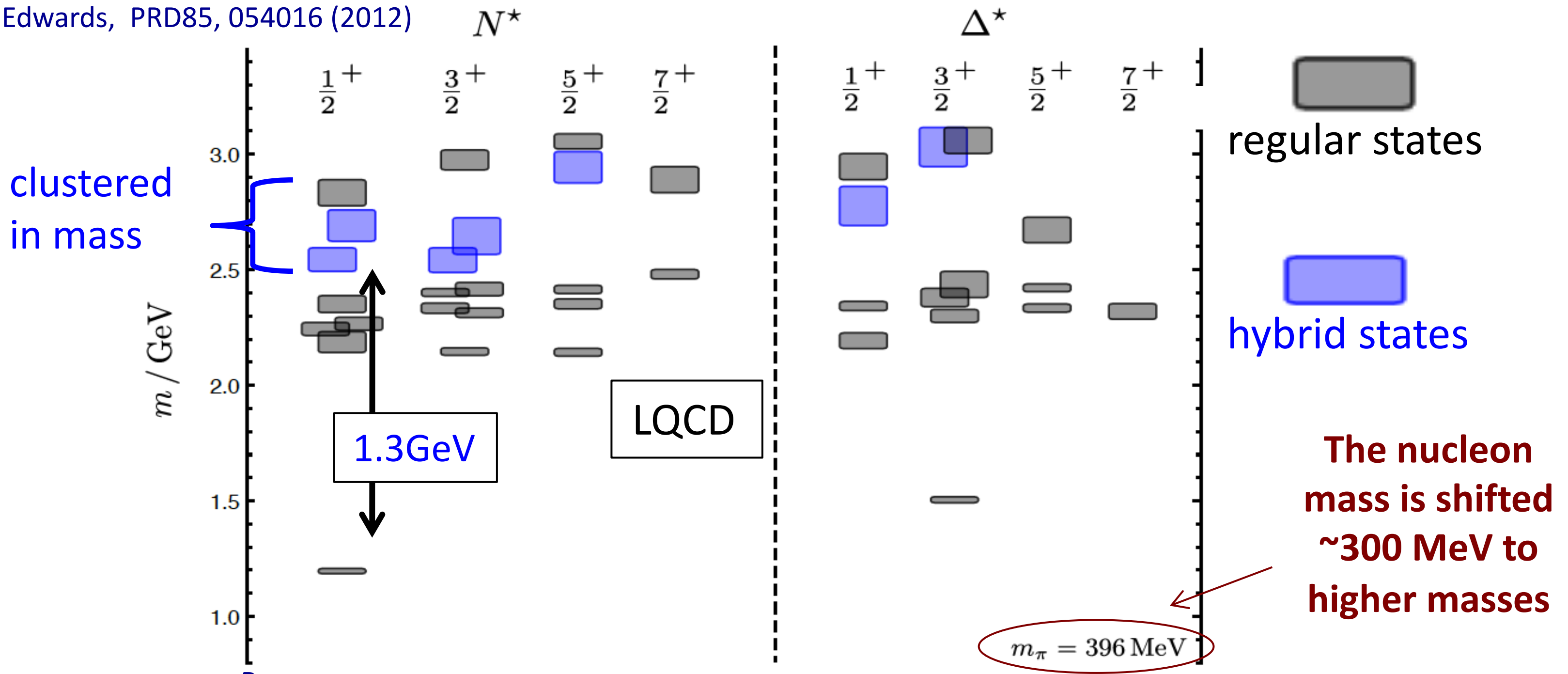
✧ QCD Sum Rule - L. Kisslinger and Z. Li, Phys. Rev. D 51, R5986 (1995).

✧ Flux Tube model - S. Capstick and P. R. Page, Phys. Rev. C 66, 065204 (2002).

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

Hybrid Baryons in LQCD

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



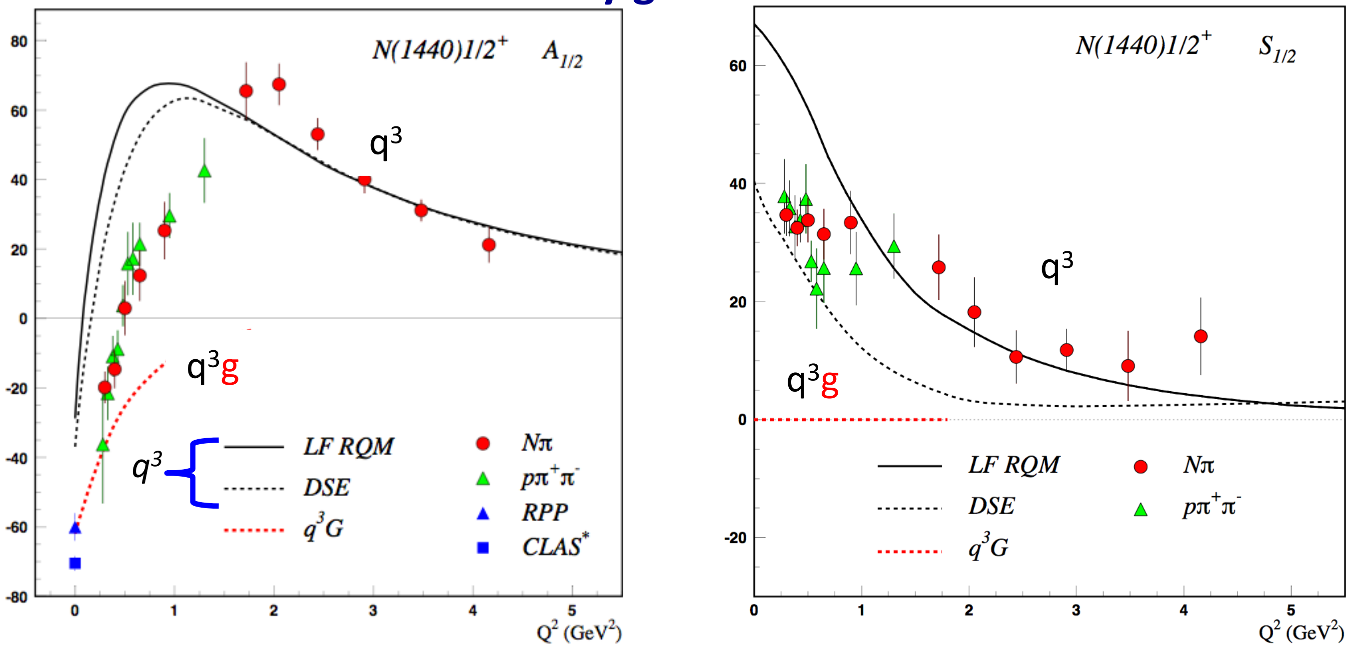
Hybrid states have same J^P values as qqq baryons. How to identify them?

- Overpopulation of N $1/2^+$ and N $3/2^+$ states compared to QM projections.
- **$A_{1/2}$ ($A_{3/2}$) and $S_{1/2}$ show different Q^2 evolution.**

Separating q^3g from q^3 states ?

CLAS results on electrocouplings clarified nature of the Roper.

Will CLAS12 data be able to identify gluonic contributions ?



For hybrid "Roper", $A_{1/2}(Q^2)$ drops off faster with Q^2 and $S_{1/2}(Q^2) \sim 0$.

Hybrid Baryon Signatures

Based on available knowledge, the ***signatures*** for hybrid baryons consist of***:***

- **Extra resonances** with $J^p=1/2^+$ and $J^p=3/2^+$, with masses > 1.8 GeV and decays into $N\pi\pi$ or KY final states.
- A **drop** of the transverse helicity amplitudes $A_{1/2}(Q^2)$ and $A_{3/2}(Q^2)$ faster than for ordinary three quark states, because of extra glue-component in valence structure.
- A **suppressed** longitudinal amplitude $S_{1/2}(Q^2)$ in comparison with transverse electro-excitation amplitude ($J^P=1/2^+$).

Candidate reaction channels are:

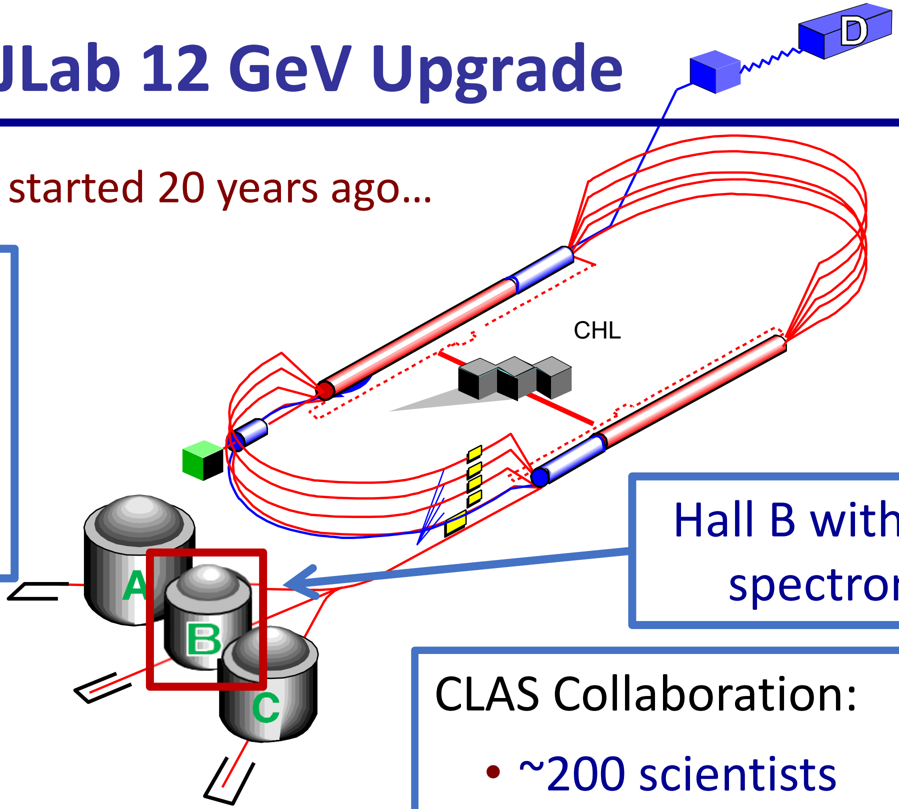
$$e\,p \rightarrow e\,p\,\pi^+\,\pi^-$$

$$e\,p \rightarrow e\,K^+\Lambda,\ e\,K^+\Sigma^0$$

CLAS12 and the JLab 12 GeV Upgrade

The JLab 12 GeV upgrade project started 20 years ago…

- 2000-2004: Science case
- 2004-2008: R&D
- 2006-2009: Design and Engineering
- 2009-2015: Construction
- 2012-2017: Installation



Hall B with CLAS12 spectrometer

Scope of the 12 GeV upgrade project:

- Double the accelerator beam energy
- New Hall D
- Upgrades to existing Halls A, B, C

CLAS Collaboration:

- ~200 scientists
- 55 institutions
- 12 countries

CLAS12

Forward Detector (FD)

- TORUS magnet
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- Forward TOF System
- Pre-shower calorimeter
- E.M. calorimeter

Central Detector (CD)

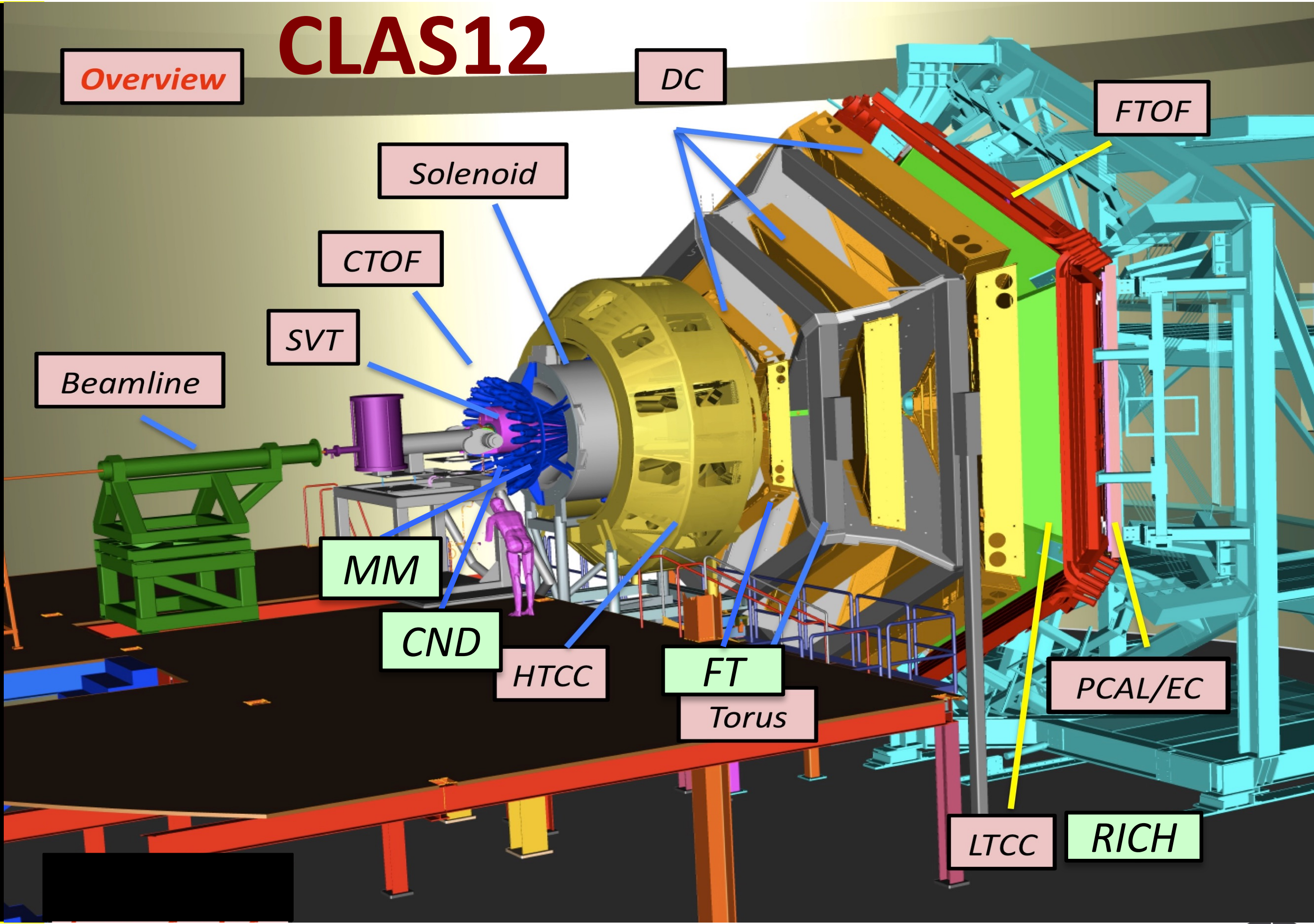
- SOLENOID magnet
- Silicon Vertex Tracker
- Central Time-of-Flight

Beamline

- Cryo Target
- Moller polarimeter
- Shielding
- Photon Tagger

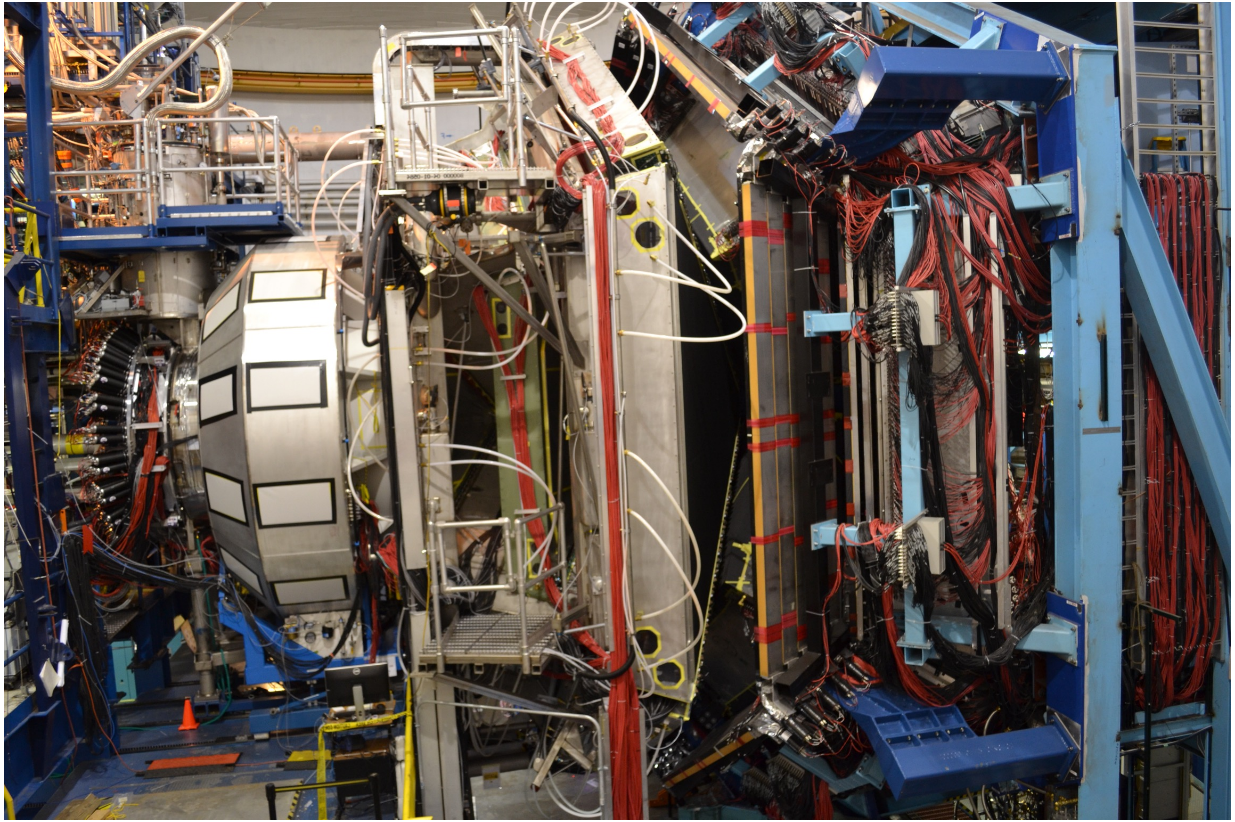
Upgrade to the baseline

- Central Neutron Detector
- MicroMegas
- Forward Tagger
- RICH detector
- Polarized target

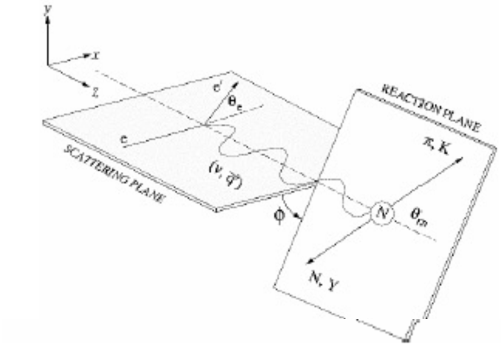


CLAS12 Spectrometer

beam



Electroexcitation kinematics



$$\frac{d^4\sigma}{dQ^2 dW\, d\Omega_K} = \Gamma(Q^2, W) \times \frac{d\sigma}{d\Omega_K}(Q^2, W, \Theta_K, \varepsilon, \phi)$$

Virtual photon flux

Electroproduction cross section

Transverse

Transverse-tra e interference

Helicity structure

$$\frac{d\sigma}{d\Omega_K} = \sigma_T + \varepsilon_L \sigma_L + \varepsilon \sigma_{TT} \cos(2\phi) + \sqrt{2\varepsilon_L(\varepsilon + 1)}\, \sigma_{LT} \cos(\phi) + h\sqrt{2\varepsilon_L(1-\varepsilon)}\, \sigma_{LT'}$$

σ_u
"Unseparated"

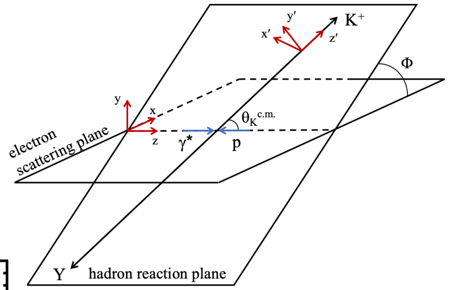
Longitudinal (sensitive to J=0$^{\pm}$ exchange in t-channel: mesons, diquarks)

Transverse-longitudinal interference

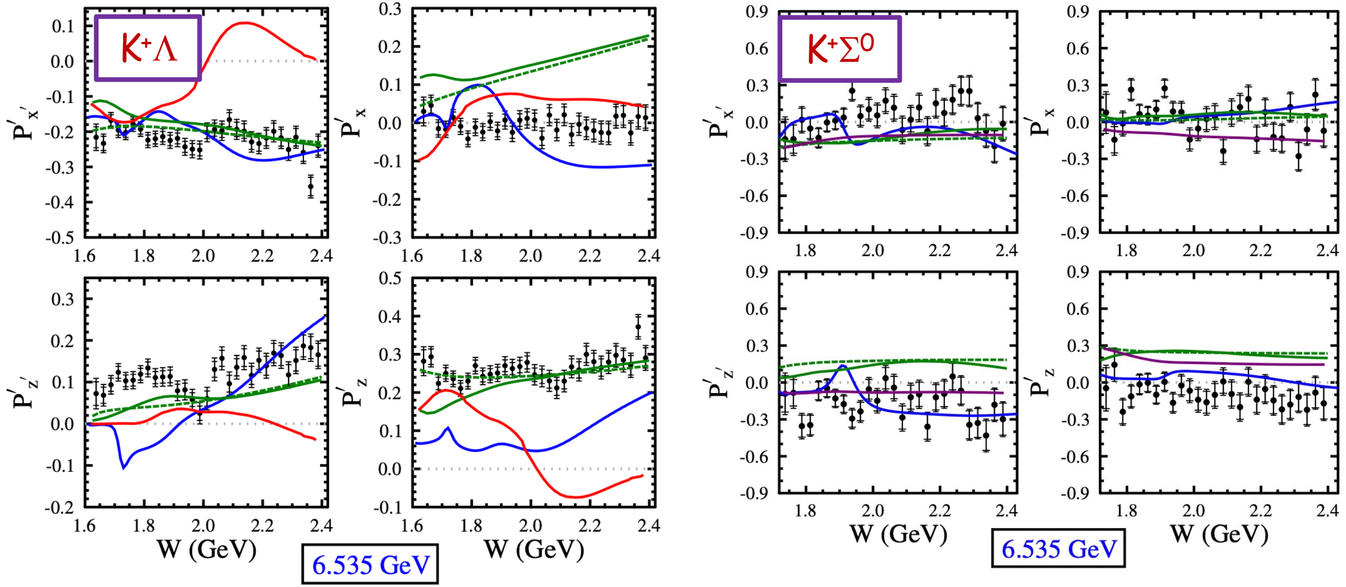
Measured σ are decomposed using UIM or fixed-t DR to extract N* & Δ helicity amplitudes.

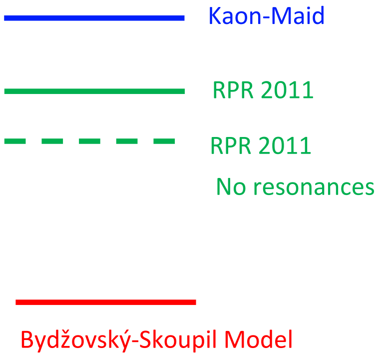
Beam-Recoil Transferred Polarization in K^+Y Electroproduction

- 6.535 GeV and 7.546 GeV electrons on LH_2 target
- Extract beam-recoil transferred polarization from longitudinally polarized beam electron to final state hyperon vs. Q^2, W, cos $q_K^{c.m.}$
- Part of program to study spectrum and structure of excited nucleon states



D.S. Carman, A. D., L. Lanza, V. I. Mokeev et al., Phys Rev C105, 065201 (2022)





Summary

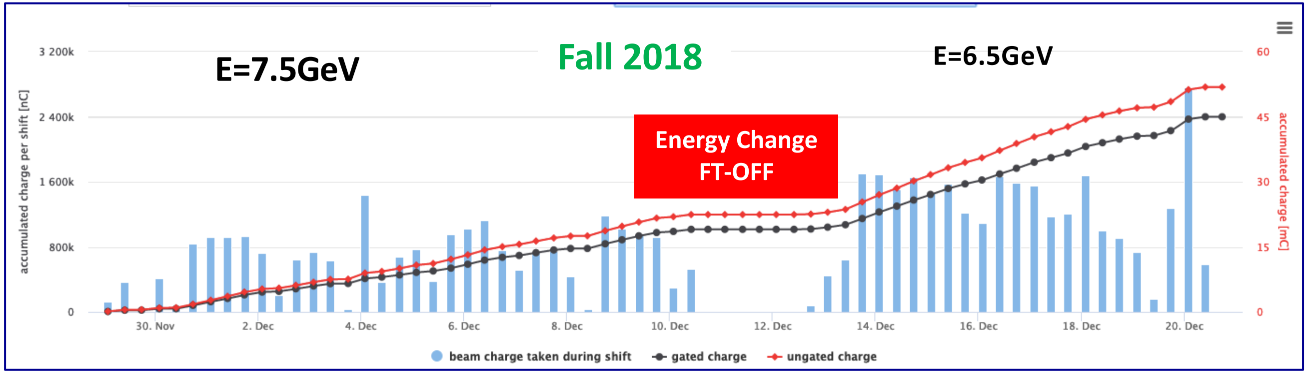
- Major progress made in the last years in the search for N* and Δ states.
  - Polarization observables in photo-production have provided crucial constraints
  - New states have been found and can be accommodated in CQM and LQCD schemes.
    - ➢ Naïve (non-dynamical) di-quark models are ruled out.

- Knowledge of Q^2-dependence of electrocouplings is necessary to understand the nature (the internal structure) of the excited states.
  - ➢ Roper is the first radial excitation of the q^3 core, obscured at large distances by meson-cloud effects.
  - ➢ Leading electrocoupling amplitudes of prominent low-mass states (e.g. $N(1535)1/2^-$) is well modeled by DSE/QCD, LC SR and LF RQM for $Q^2 > 2$ GeV.

- Search for hybrid baryons with explicit gluonic degrees of freedom is possible investigating the low Q^2 evolution of high-mass resonance (2-3 GeV) electrocoupligs:
  - ➢ Looking for suppressed $A^{1/2}$, $A^{3/2}$, $S^{1/2}$ at low Q^2

BACKUP SLIDES

Run Group K Production



CHARGE

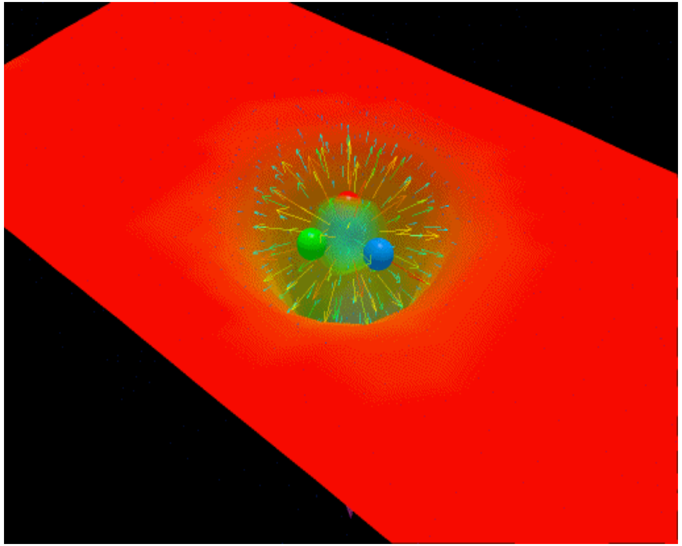
RUN CONDITIONS – FALL 2018	
Torus Current	100% (3375 A) - negative outbending
Solenoid	-100 %
FT	**ON @ 7.5 GeV -> OFF @ 6.5 GeV**
Beam/Target	Polarized electrons, unpolarized LH_2 target
Luminosity	~ 5 10^{34} $cm^{-2}s^{-1}$ @ 7.5 GeV 10^{35} $cm^{-2}s^{-1}$ @ 6.5 GeV **FULL LUMINOSITY**

15.6 G EVENTS

Beam Energy	Beam Current	Tgt	Trigger	Collected Events
7.5 GeV	35 nA	LH_2	e in CLAS e in FT + 1 Fwd Hadron	3.5 G
7.5 GeV	45 nA	LH_2	e in CLAS - prescaled e in FT + 1 Fwd Hadron	4.3 G
6.5 GeV	60 nA	LH_2	e in CLAS	7.8 G

Critical QCD Questions Addressed

- The light N* spectrum: what is the role of glue?



Derek B. Leinweber – University of Adelaide

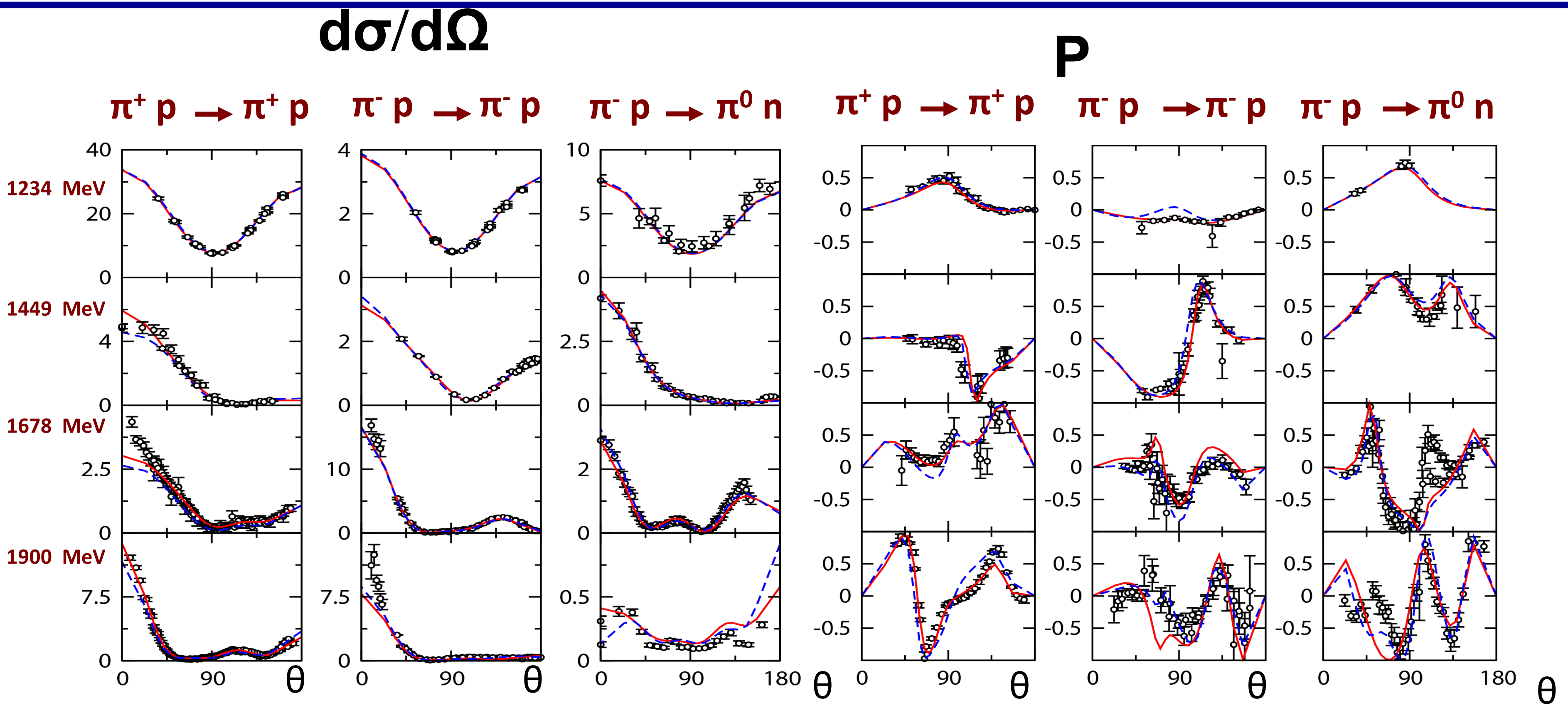
"Nucleons are the stuff of which our world is made.

As such they must be ***at the center of any discussion of why the world*** *we actually experience* ***has the character it does."***

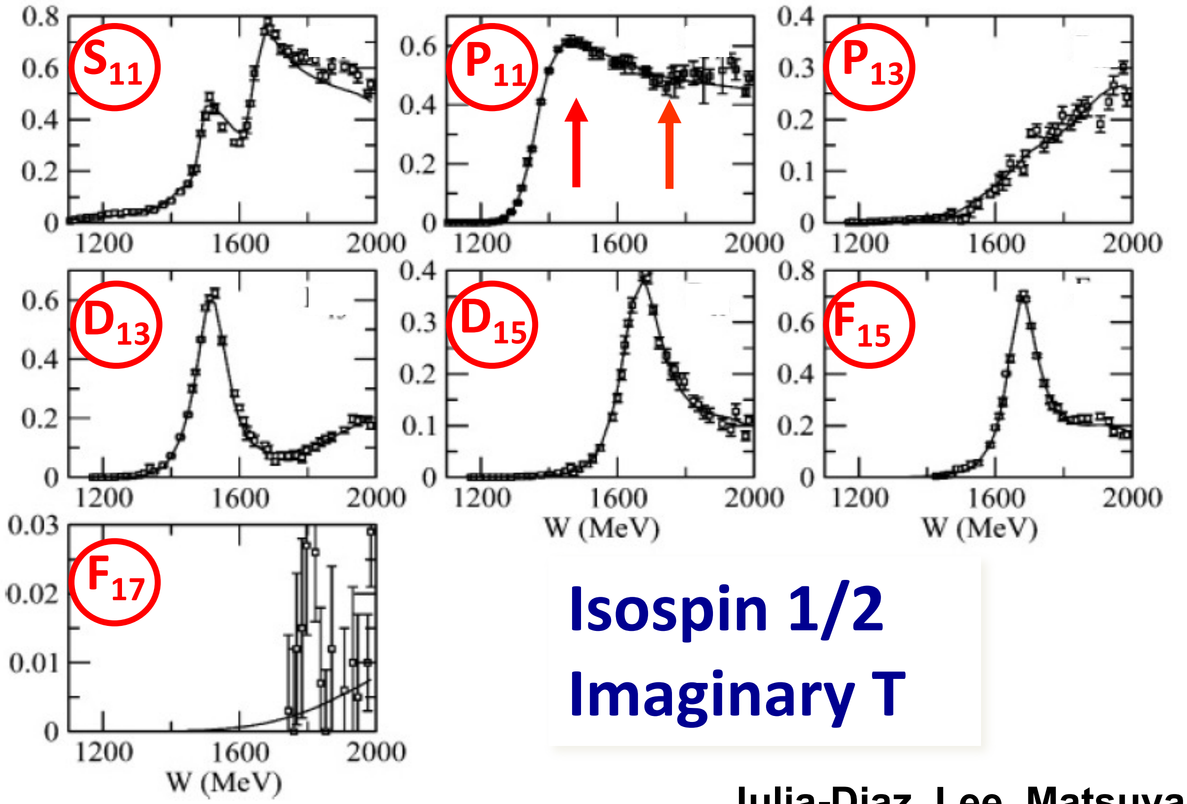
Nathan Isgur, NStar2000, Newport News, Virginia

→ **Search for new baryon states**

Establishing the N* and Δ Spectrum: πN Scattering



Establishing the N* and Δ Spectrum: πN Amplitudes

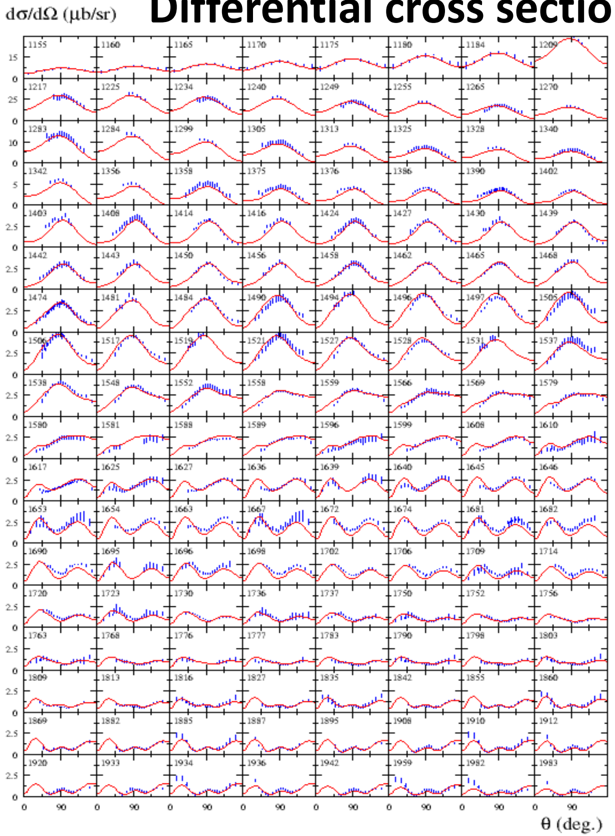


Isospin 1/2
Imaginary T

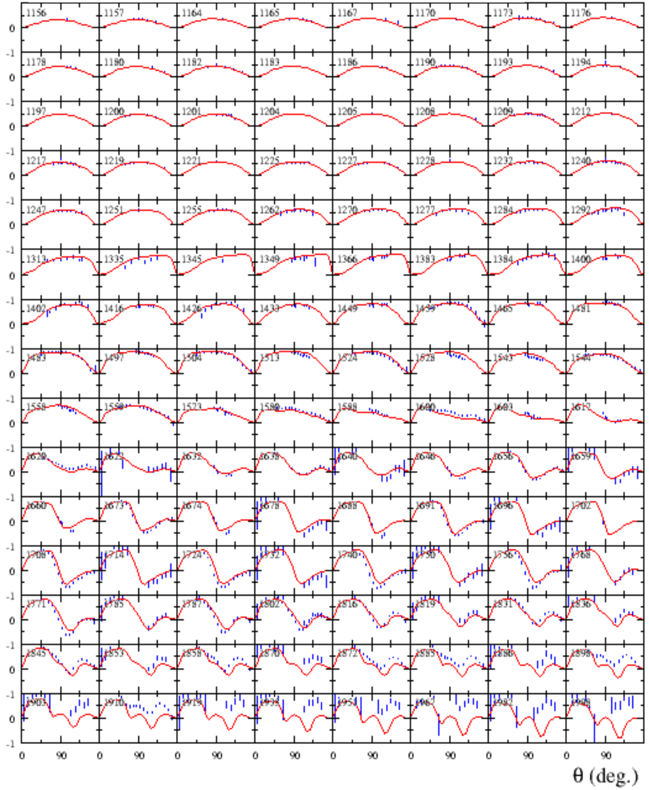
Julia-Diaz, Lee, Matsuyama, Sato

Establishing the N* and Δ Spectrum: γ + p ➔ π^0 + p

Differential cross section



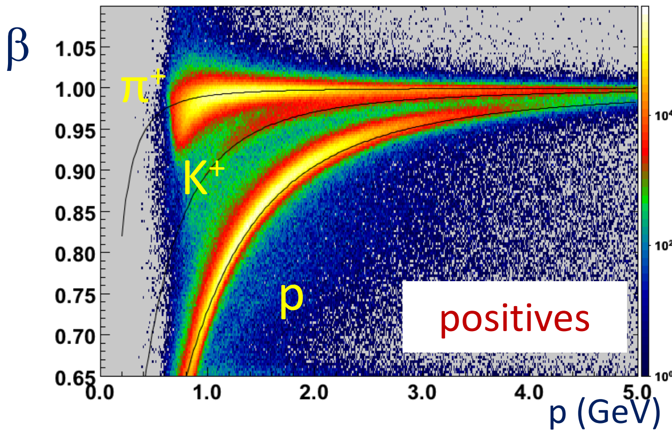
Σ Beam Asymmetry

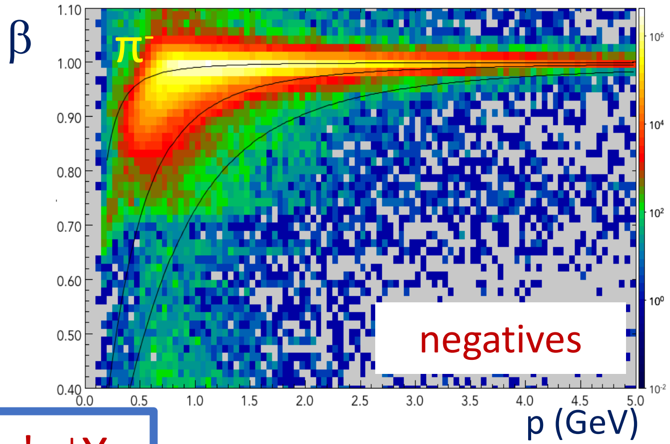


Kamano
Nakamura
Lee &
Sato, 2012

T single
G E F double
polarization
observables
also available

Event Reconstruction





$ep \rightarrow e'\pi^+X$