



STRONG2020 HaSP School

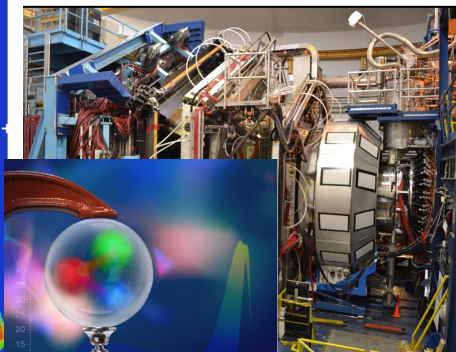
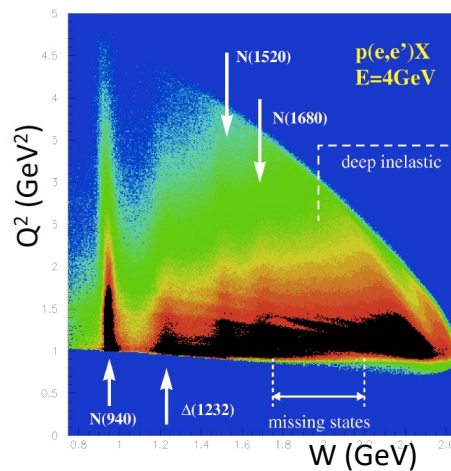
Salamanca  
5-14 September 2023

## Light Baryons Spectrum and Structure

Annalisa D'Angelo

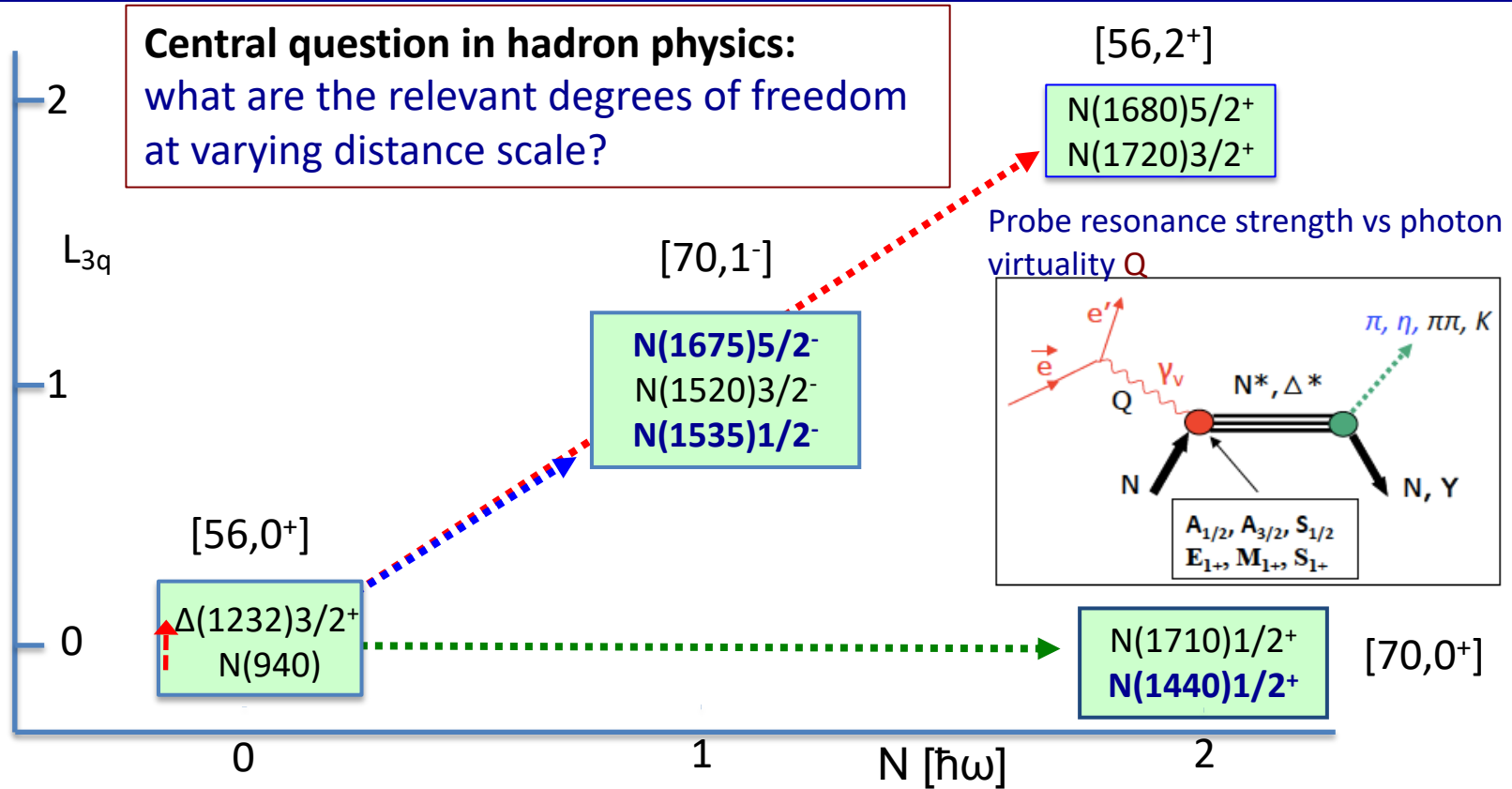
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# Electroexcitation of $N^*/\Delta$ resonances

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



# Evidence for New $N^*$ in KY and other Final States

State $N(\text{mass})J^P$	PDG pre 2010	PDG 2018	$K\Lambda$	$K\Sigma$	$N\gamma$
$N(1710)1/2^+$	***	*****	****	**	****
$N(1880)1/2^+$		***	**		**
$N(1895)1/2^-$		*****	**	*	**
$N(1900)3/2^+$	**	*****	***	**	***
$N(1875)3/2^-$		***	***	**	***
$N(2120)3/2^-$		***	**		**
$N(2000)5/2^+$	*	**	**	*	**
$N(2060)5/2^-$		***		**	**

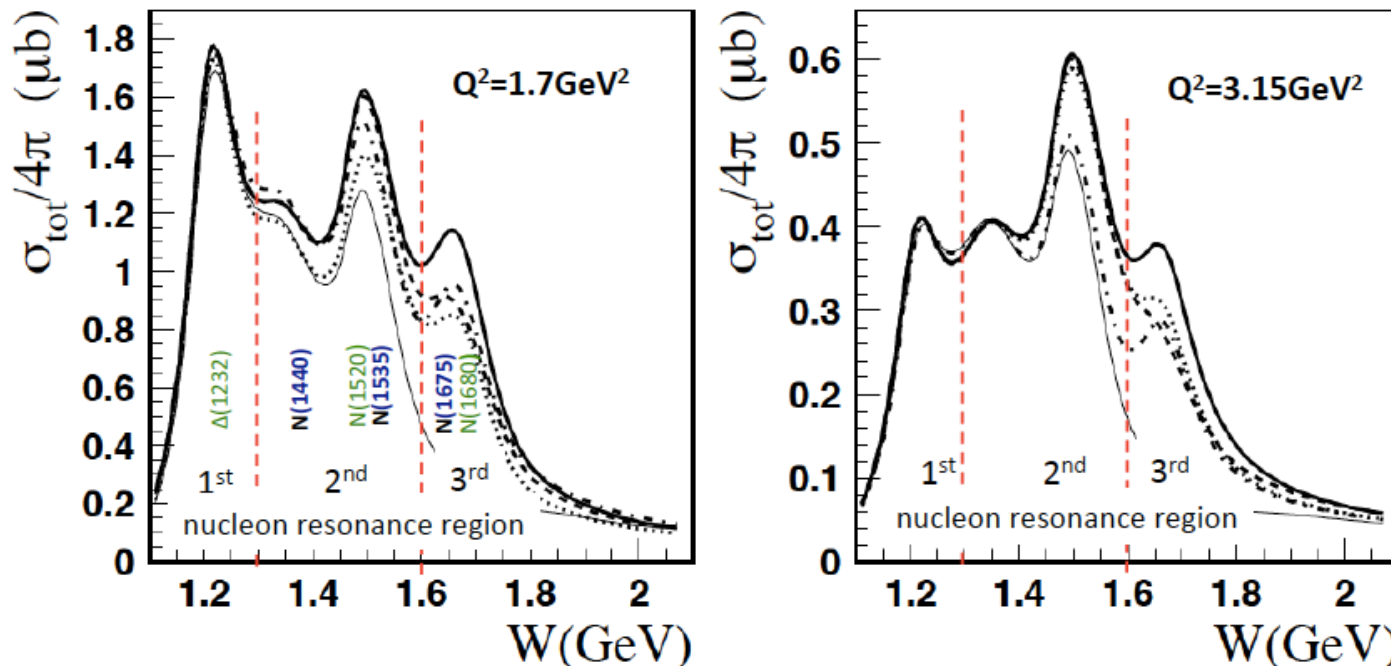
Study these states in electroproduction and extend to higher masses

# Total cross section at $W < 2.1$ GeV



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

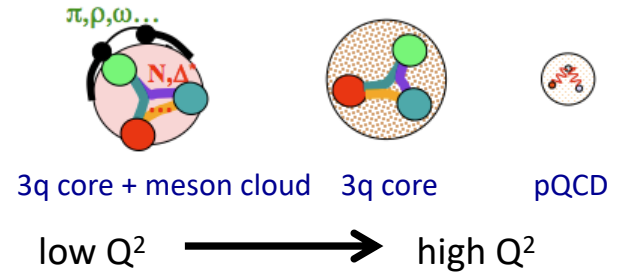


Analysis with UIM & fixed- $t$  DR; Recent review: I. Aznauryan, V. Burkert, Prog. Part. Nucl. Phys. 67 (2012) 1.

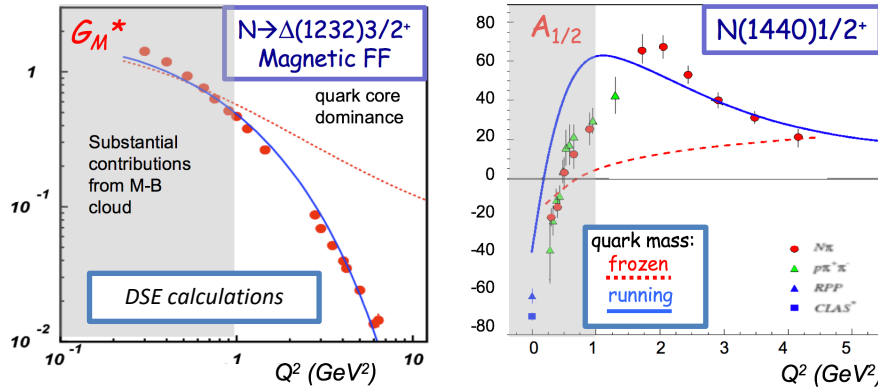
# Excited Nucleon Structure

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

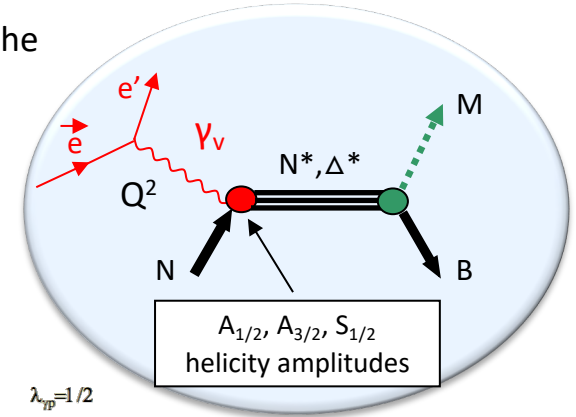
- **Low  $Q^2$ :** structure well described by adding an external meson cloud to inner quark core  
( $Q^2 < 5 \text{ GeV}^2$ )
- **High  $Q^2$ :** quark core dominates; transition from confinement to pQCD regime  
( $Q^2 > 5 \text{ GeV}^2$ )



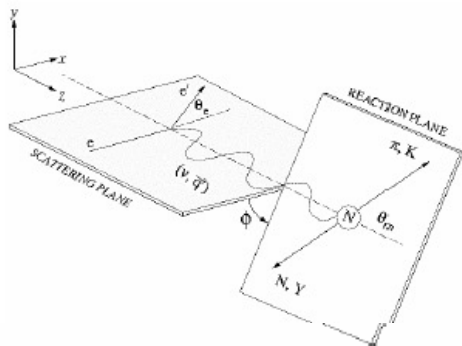
- Calculations of form factors and electrocoupling amplitudes are sensitive to the underlying quark mass distribution



CLAS results vs. QCD expectations with running quark mass



# 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  
interference

e

Helicity  
structure

$$\frac{d\sigma}{d\Omega_K} = \underbrace{\sigma_T + \varepsilon_L \sigma_L + \varepsilon \sigma_{TT}}_{\sigma_u \text{ "Unseparated"}} \cos(2\phi) + \sqrt{2\varepsilon_L(\varepsilon+1)} \underbrace{\sigma_{LT}}_{\text{Transverse-longitudinal interference}} \cos(\phi) + h \sqrt{2\varepsilon_L(1-\varepsilon)} \underbrace{\sigma_{LT'}}_{\text{Helicity structure}}$$

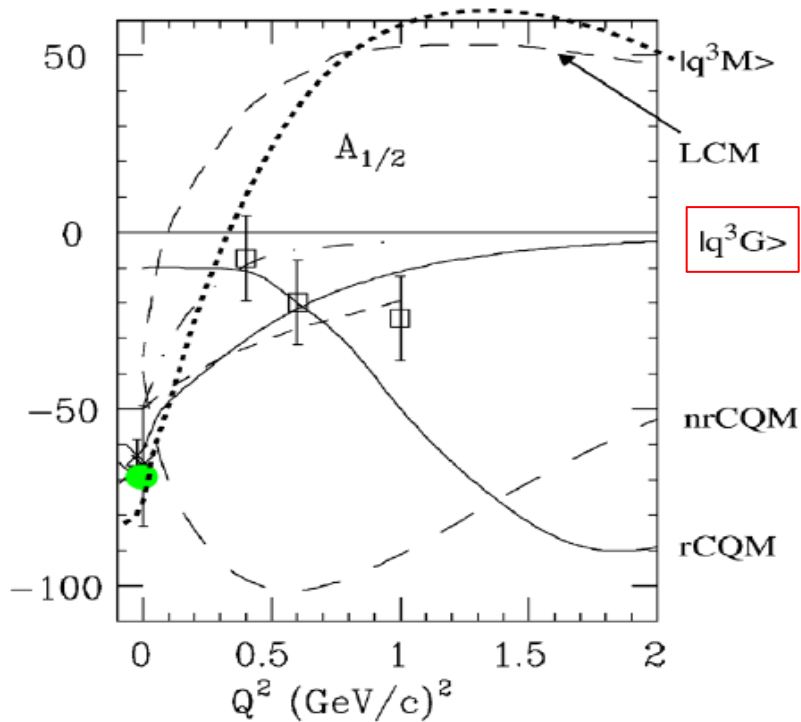
$\sigma_u$   
"Unseparated"

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

Transverse-longitudinal  
interference

Measured  $\sigma$  are decomposed using UIM or fixed-t DR to extract  $N^*$  &  $\Delta$  helicity amplitudes.

# Electrocouplings of the 'Roper' in 2002

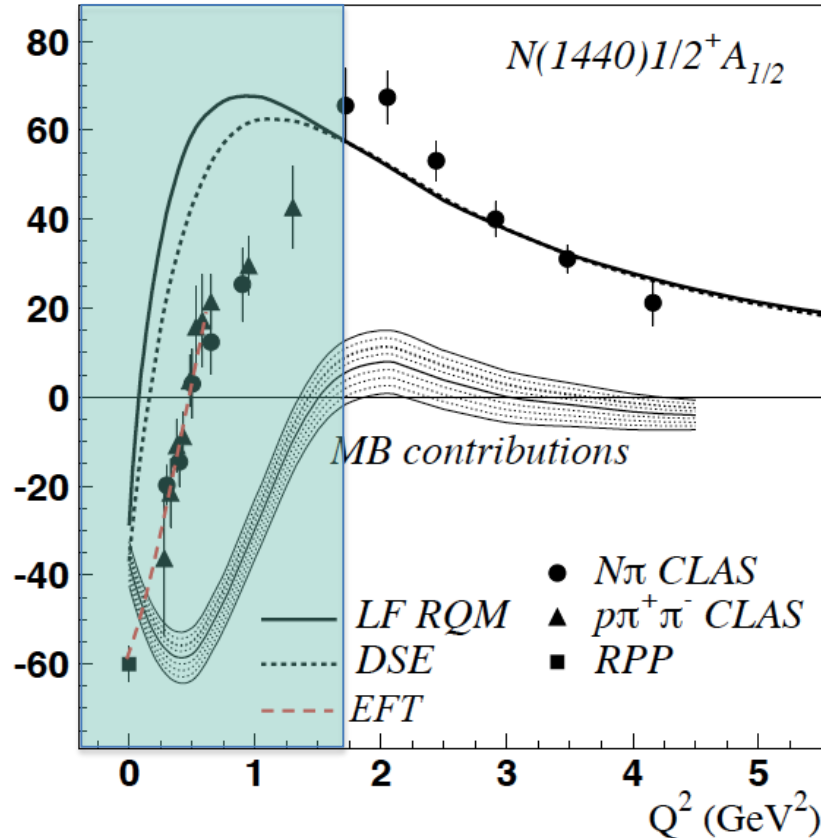


$N(1440)1/2^+$

Is the Roper a hybrid state?

In 2002 Roper amplitude  $A_{1/2}$  measurements were more consistent with **hybrid state** but data were limited with large uncertainties.

# 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

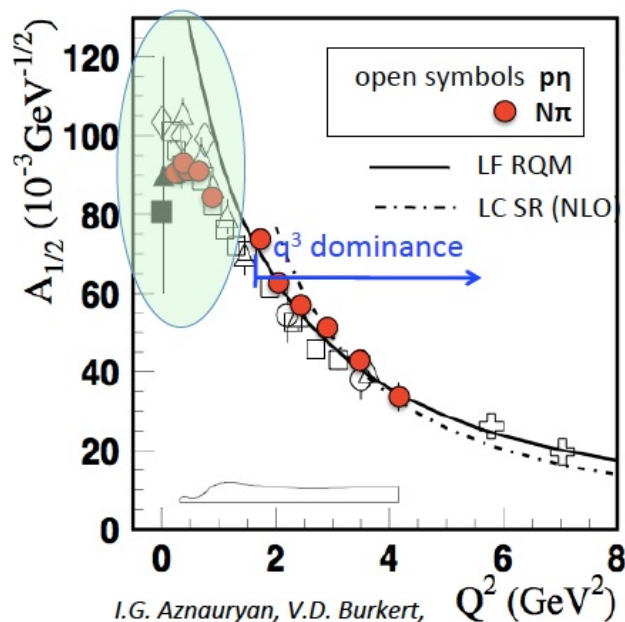
→ Non-quark contributions are significant at  $Q^2 < 2.0 \text{ GeV}^2$ . The behavior at  $Q^2 < 0.5$  can be modeled in EFT.

→ The 1<sup>st</sup> radial excitation of the  $q^3$  core emerges as the probe penetrates the MB cloud

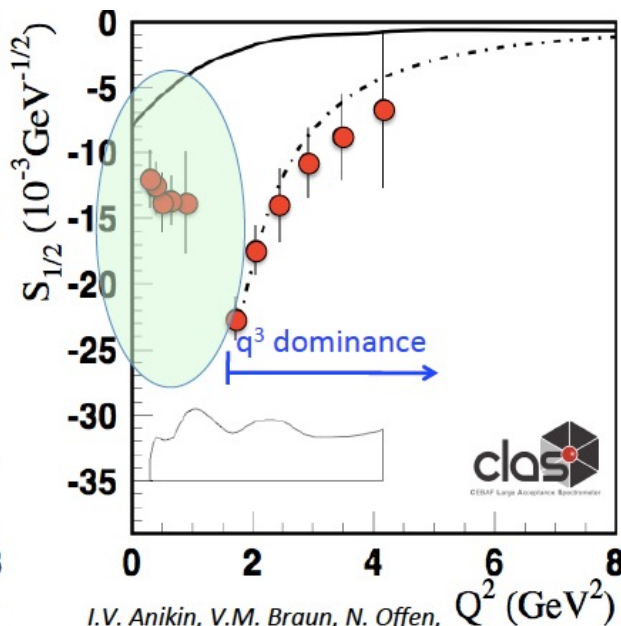
**“Nature” of the Roper – is consistent with the 1<sup>st</sup> radial excitation of its quark core surrounded by a meson-baryon “cloud”.**

# MB Contribution to electro-excitation of $N(1535)1/2^-$

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



*I.G. Aznauryan, V.D. Burkert,  
PR C85 (2012) 055202*



*I.V. Anikin, V.M. Braun, N. Offen,  
PR D92 (2015) 1, 014018*

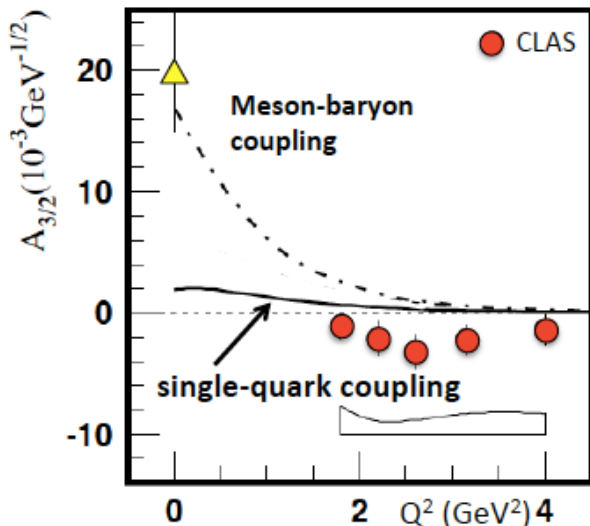
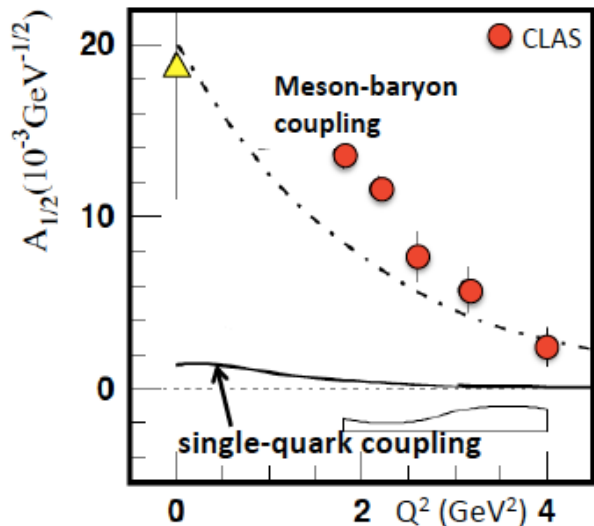
- Meson-baryon cloud may account for discrepancies at low  $Q^2$ .

# 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:

$$A_{1/2}^P = A_{3/2}^P = 0$$



- Measures the meson-baryon contribution to the  $\gamma^* p N(1675)5/2^-$  directly.
- Can be verified on  $\gamma^* n N(1675)5/2^-$  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)*

# Hybrid Baryons: Baryons with Explicit Gluonic Degrees of Freedom

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

## Experimentally:

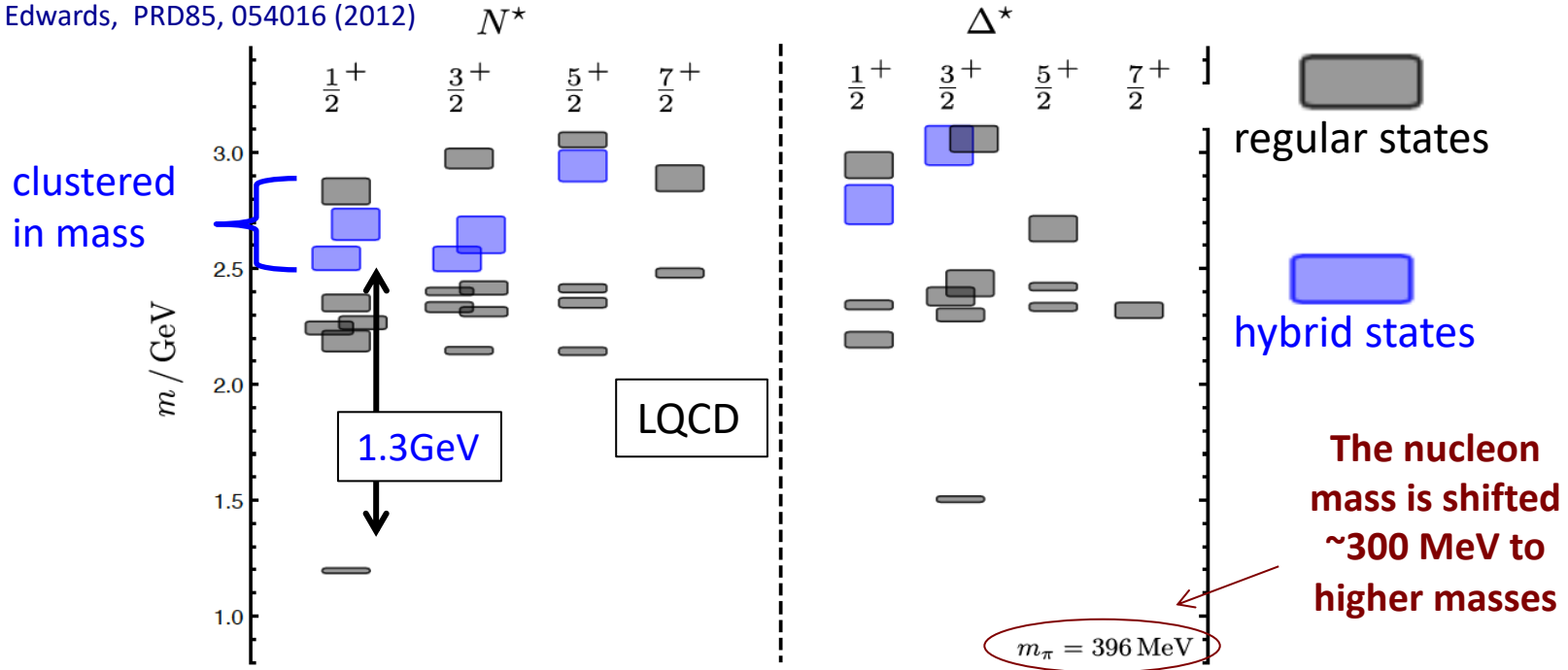
- **Hybrid mesons**  $|qqg\rangle$  states may have exotic quantum numbers  $J^{PC}$  not available to pure  $|qq\rangle$  states  
GlueX, MesonEx, COMPASS, PANDA ....
- **Hybrid baryons**  $|qqqg\rangle$  have the same quantum numbers  $J^P$  as  $|qqq\rangle$  electroproduction with CLAS12 (Hall B).

## 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)



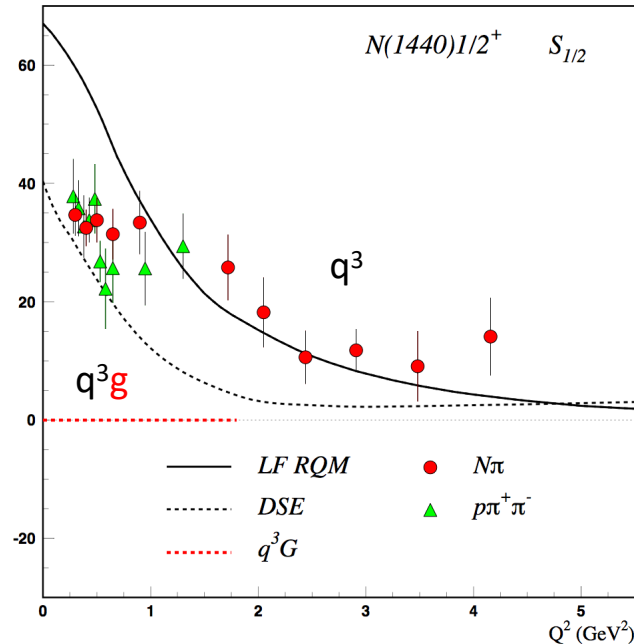
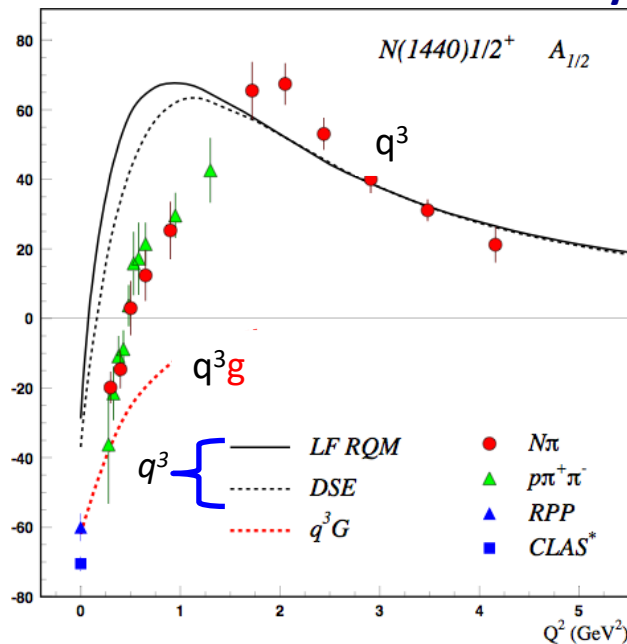
Hybrid states have same  $J^P$  values as  $qqq$  baryons. How to identify them?

- 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  $S_{1/2}(Q^2) \sim 0$ .**

# Baryon Spectroscopy Status Today

- Major progress made in the last  $\sim 8$  years in the search for  $N^*$  and  $\Delta$  states. All states can be accommodated in CQM and LQCD schemes.
  - Naïve (non-dynamical) di-quark models are ruled out.
- Knowledge of  $Q^2$ -dependence of electro-couplings 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.
- Search for hybrid baryons with explicit gluonic degrees of freedom would be possible investigating the low  $Q^2$  evolution of high-mass resonance (2-3 GeV) electro-couplings:
  - Looking for suppressed  $A^{1/2}$ ,  $A^{3/2}$ ,  $S^{1/2}$  at low  $Q^2$

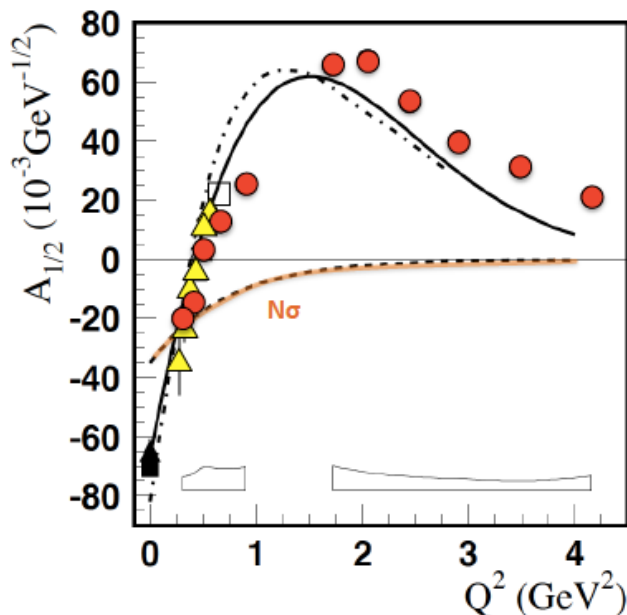
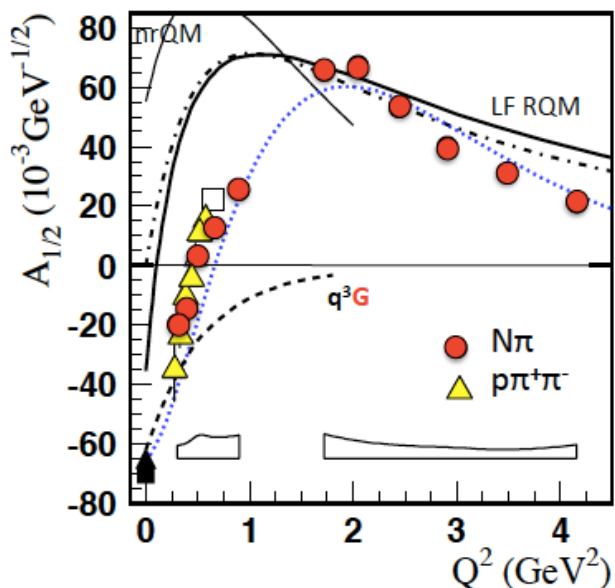
# Backup Slides

# Electrocouplings of the 'Roper' in 2012

I. Aznauryan et al. (CLAS), PRC 80, 055203 (2009)

V. Mokeev et al. (CLAS), PRC 86, 035203 (2012)

$N(1440)1/2^+$




..... L. Tiator et al., Chin Phys C33, (2009) 1069 (MAID fit)


———— I. Aznauryan et al. PRC 76, (2007) 025212


- - - - Z.P. Li et al. PRD 46, (1992) 70


———— I. T. Obukhovskiy et al. PRD 84, (2011) 014004

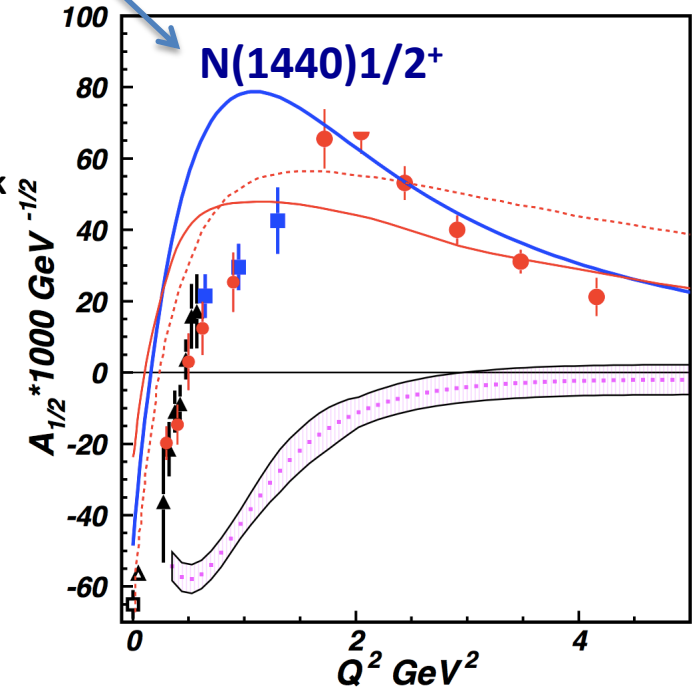
# Electrocouplings of the 'Roper' in 2016

  $N\pi$  loops to model MB cloud: **running quark mass** in LF RQM.  
I. G. Aznauryan, V.D. Burkert PR C 85 (2012) 055202.

  $N\sigma$  loops to model MB cloud in LF RQM: **frozen constituent quark mass** in LF RQM.  
I. T. Obukhovskiy et al. PRD 89, (2014) 0140032.

 **Quark-core** contributions from DSE/QCD  
J. Segovia et al. PRL 115 (2015) 171801.

 **Meson Baryon cloud** inferred from CLAS data as the difference between data and the quark-core evaluation in DSE/QCD.  
V. Mokeev et al., PR C 93 (2016) 025206.



The structure of the Roper is driven by the interplay of the core of three dressed quarks in the 1<sup>st</sup> radial excitation and the external meson-baryon cloud.