Experimental Overview on Baryon Spectroscopy: Current and Future

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clas
CEBAF Large Acceptance Spectrometer

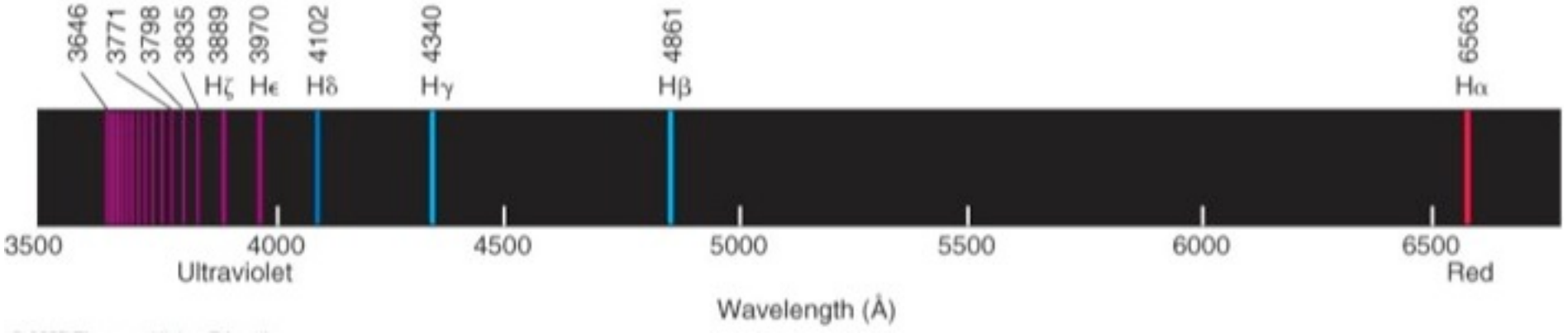
APS Division of Nuclear Physics: 2014 Long-Range Plan
Joint Town Meetings on QCD, Temple University
September 13-15, 2014, Philadelphia, PA

- **γNN* Vertexcouplings:** A unique window into baryon and quark structure?
- **Analysis and new Results:** Phenomenological but consistent.
- **QCD based Theory:** Can we solve non-perturbative QCD and confinement?
- **Outlook:** New experiments with extended scope and kinematics.

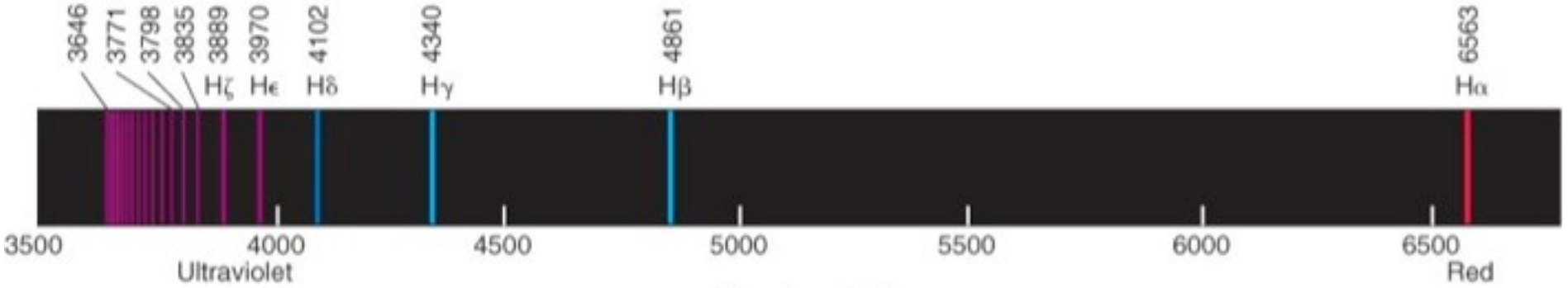
This work is in parts supported by the US National Science Foundation under the Grant PHY-1205782

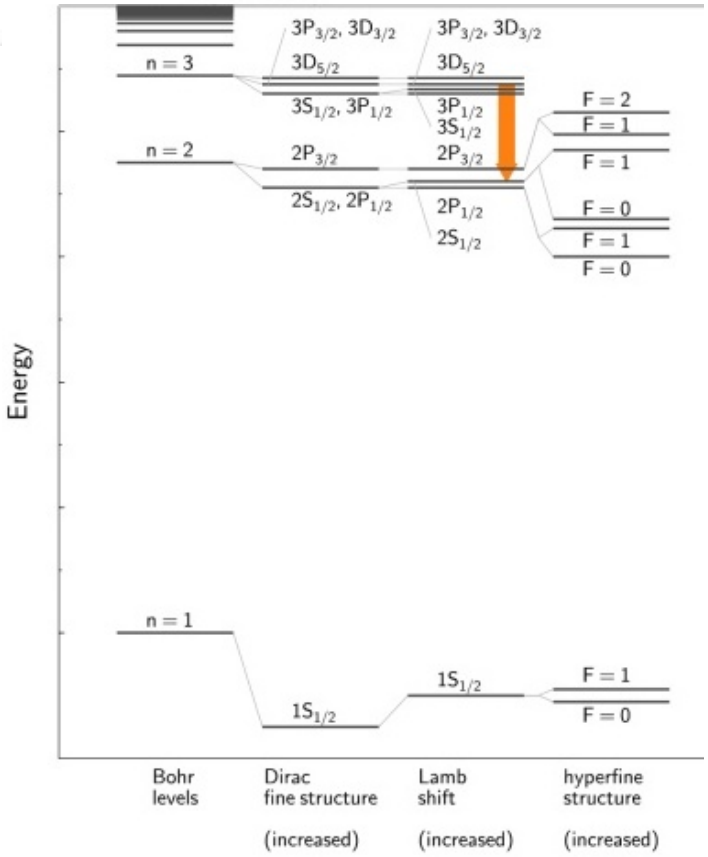
Spectroscopy

Hydrogen Spectroscopy and QED



Hydrogen Spectroscopy and QED





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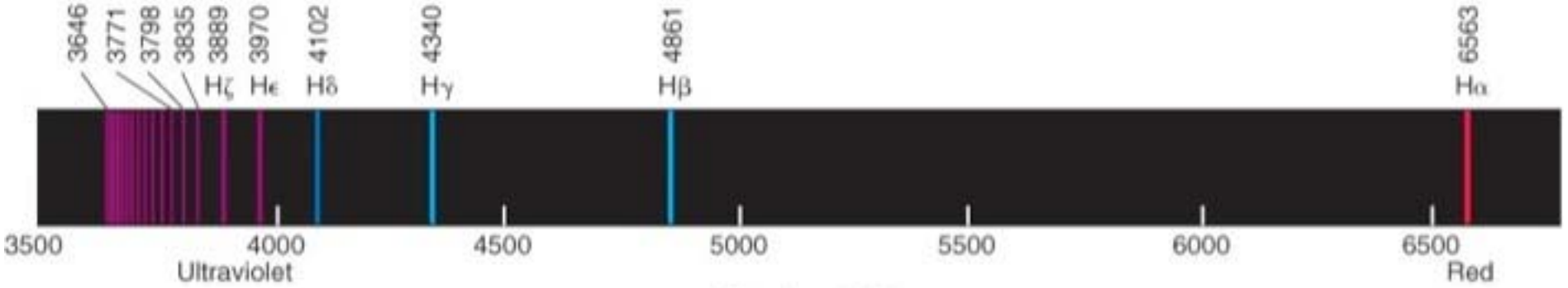
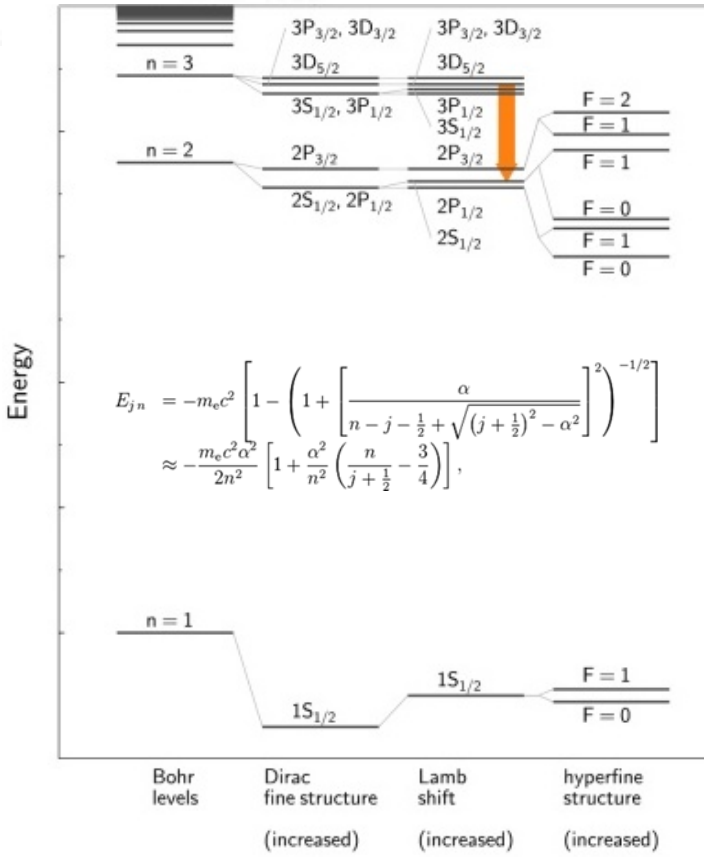
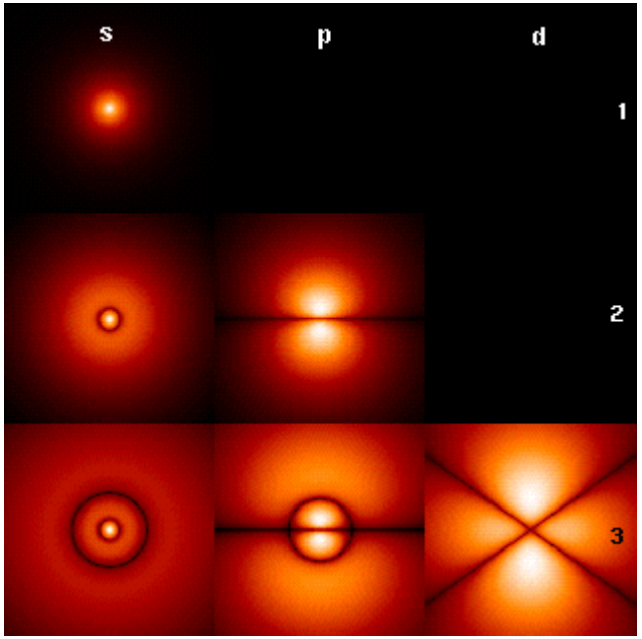




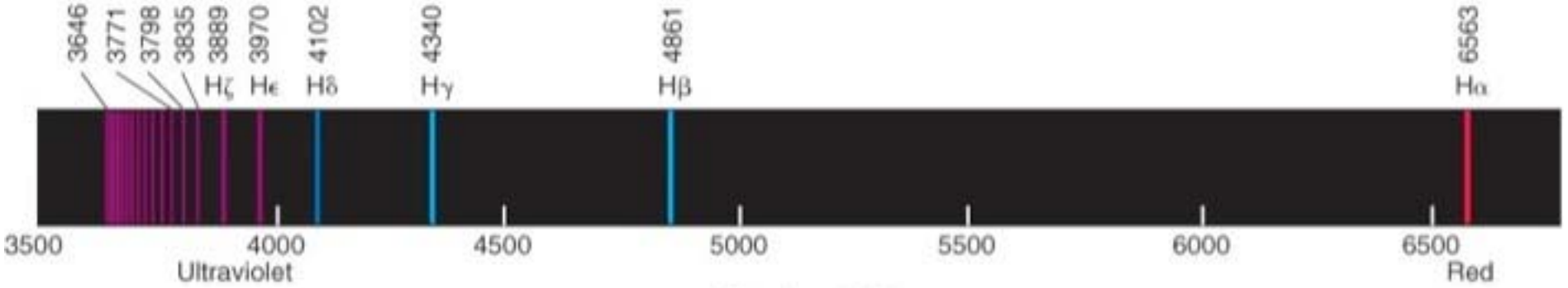
$$E_{jn} = -m_e c^2 \left[1 - \left(1 + \left[\frac{\alpha}{n - j - \frac{1}{2} + \sqrt{\left(j + \frac{1}{2}\right)^2 - \alpha^2}} \right]^2 \right)^{-1/2} \right]$$
$$\approx -\frac{m_e c^2 \alpha^2}{2n^2} \left[1 + \frac{\alpha^2}{n^2} \left(\frac{n}{j + \frac{1}{2}} - \frac{3}{4} \right) \right],$$

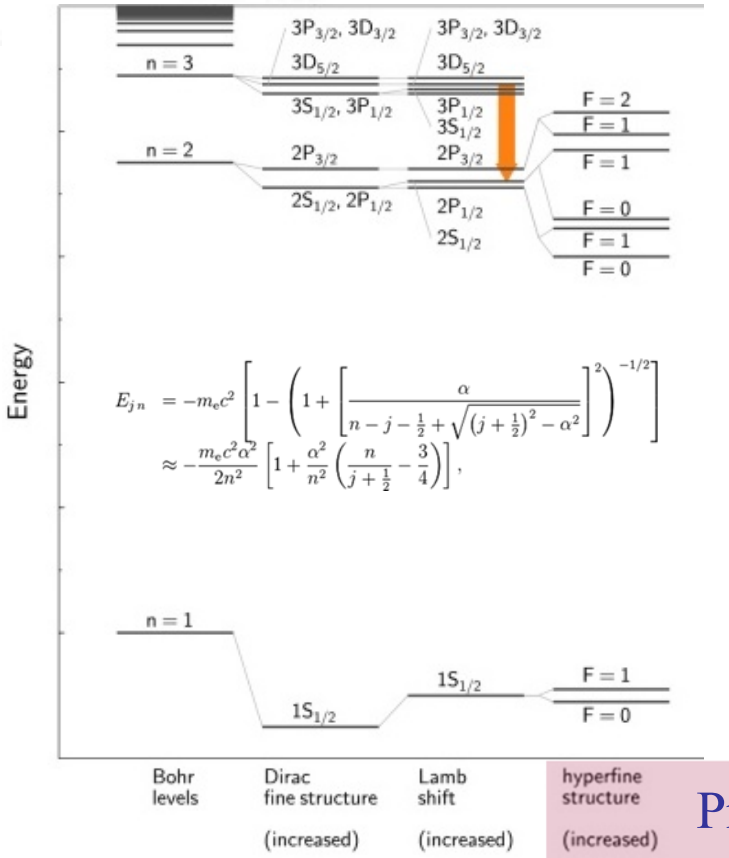
QED



$$\psi_{n\ell m}(r, \vartheta, \varphi) = \sqrt{\left(\frac{2}{na_0}\right)^3 \frac{(n-\ell-1)!}{2n(n+\ell)!}} e^{-\rho/2} \rho^\ell L_{n-\ell-1}^{2\ell+1}(\rho) Y_\ell^m(\vartheta, \varphi)$$

Hydrogen Spectroscopy and QED





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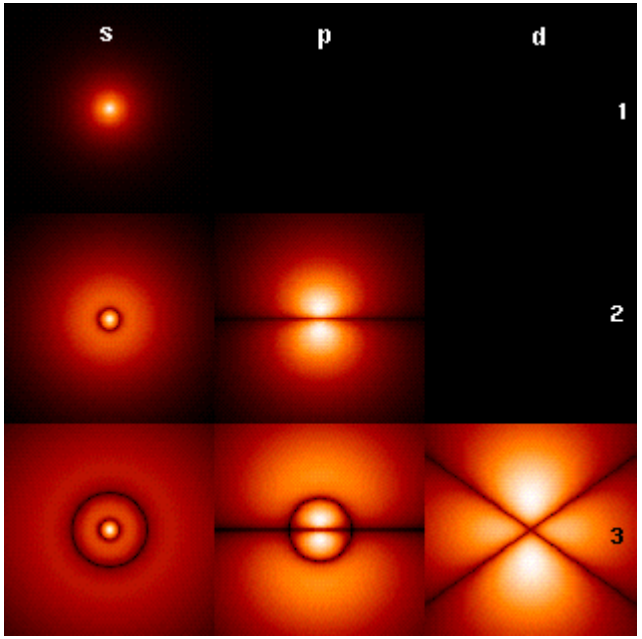
Q E D



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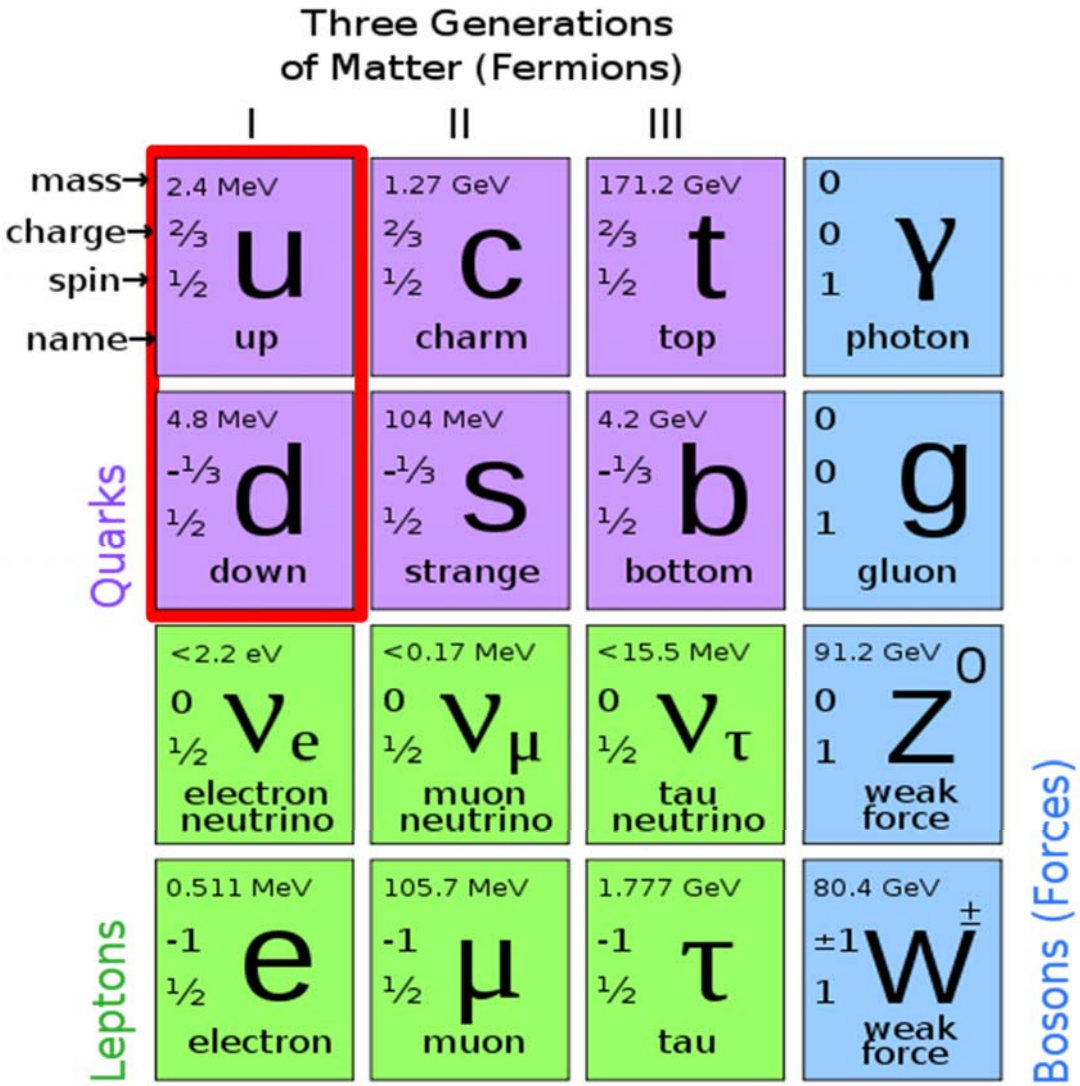
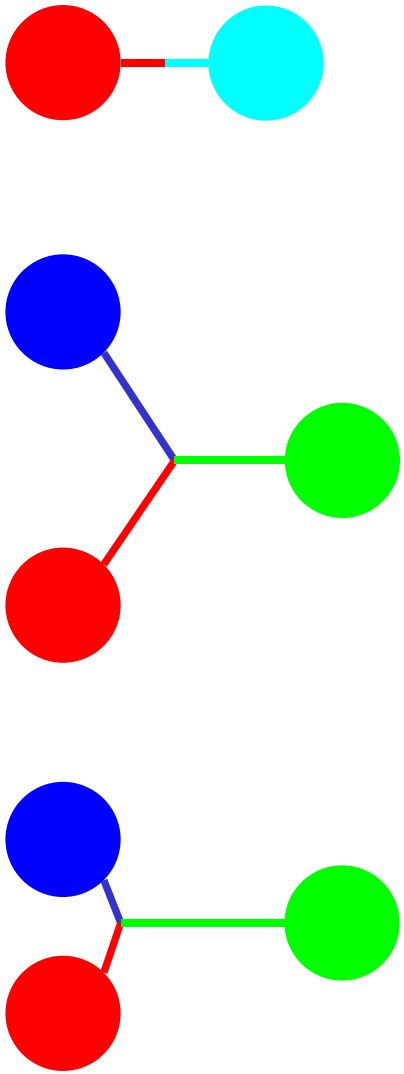
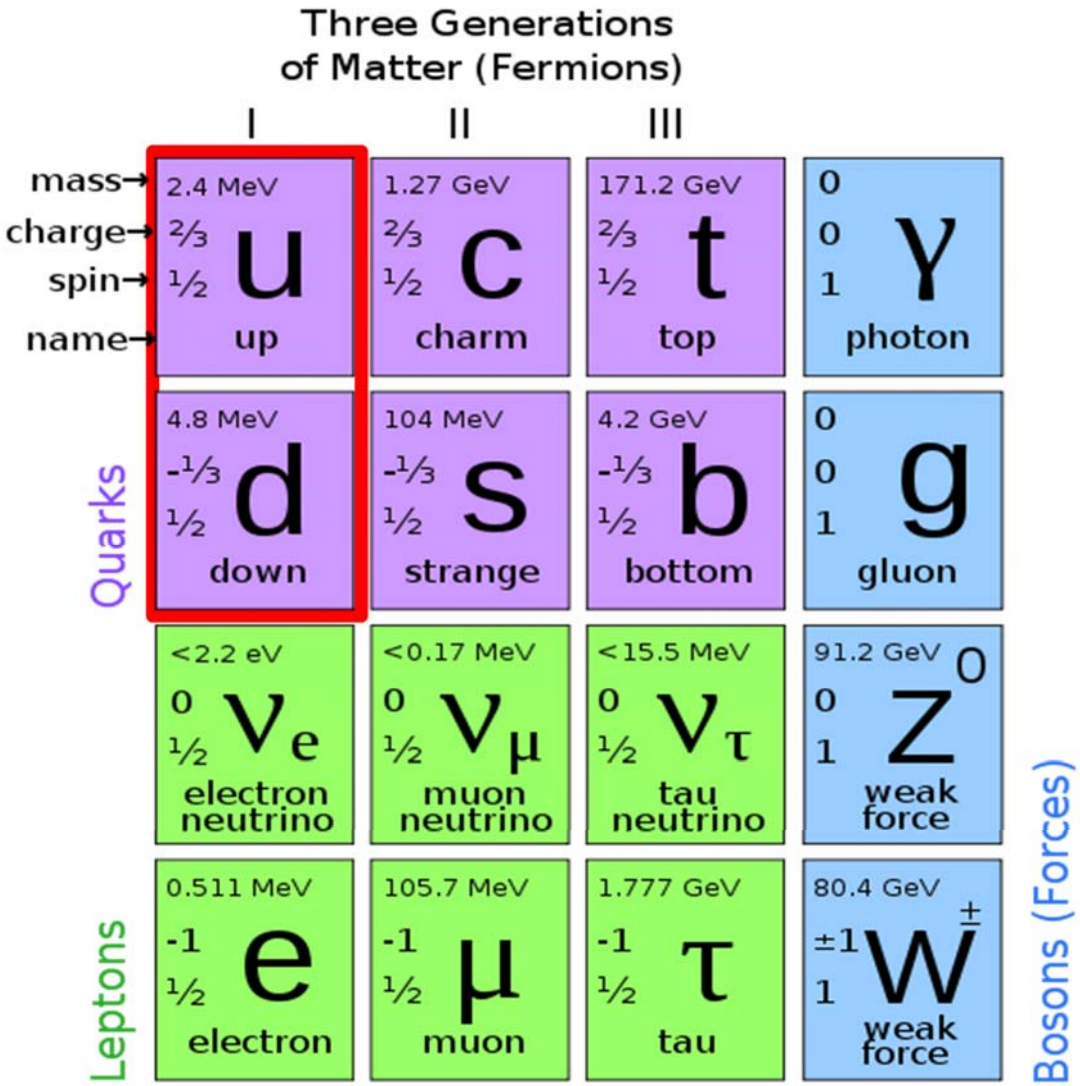
Proton Radius Puzzle

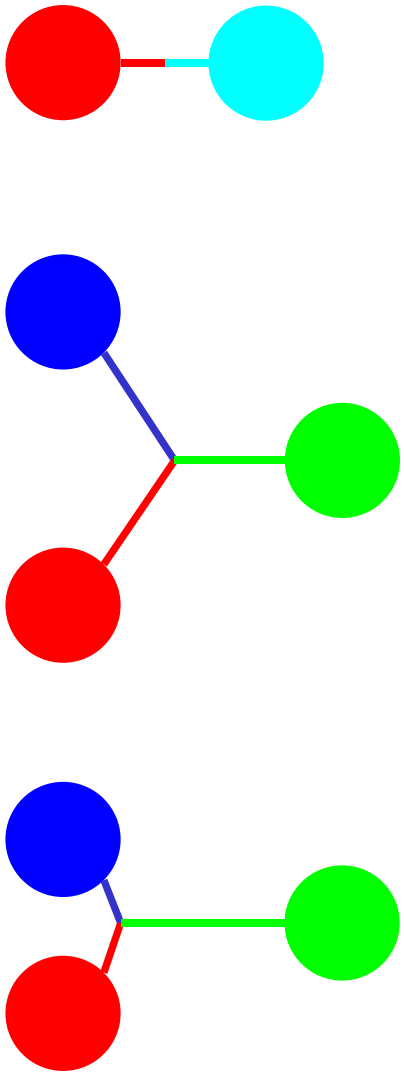
Hadron Spectroscopy: Meson, Baryons, …





Hadron Spectroscopy: Meson, Baryons, …

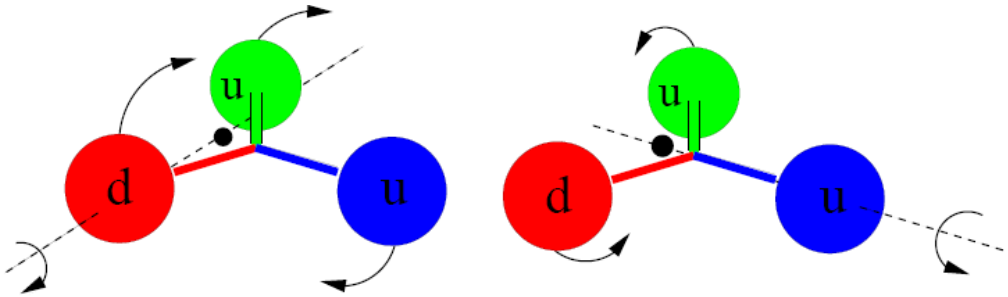




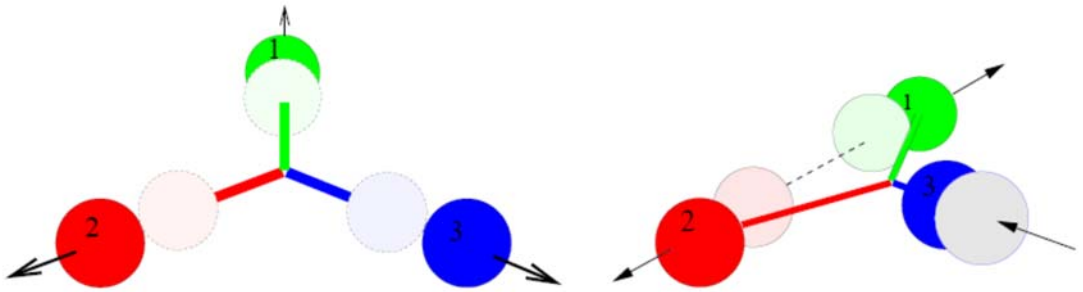
N and Δ Excited Baryon States …

Simon Capstick

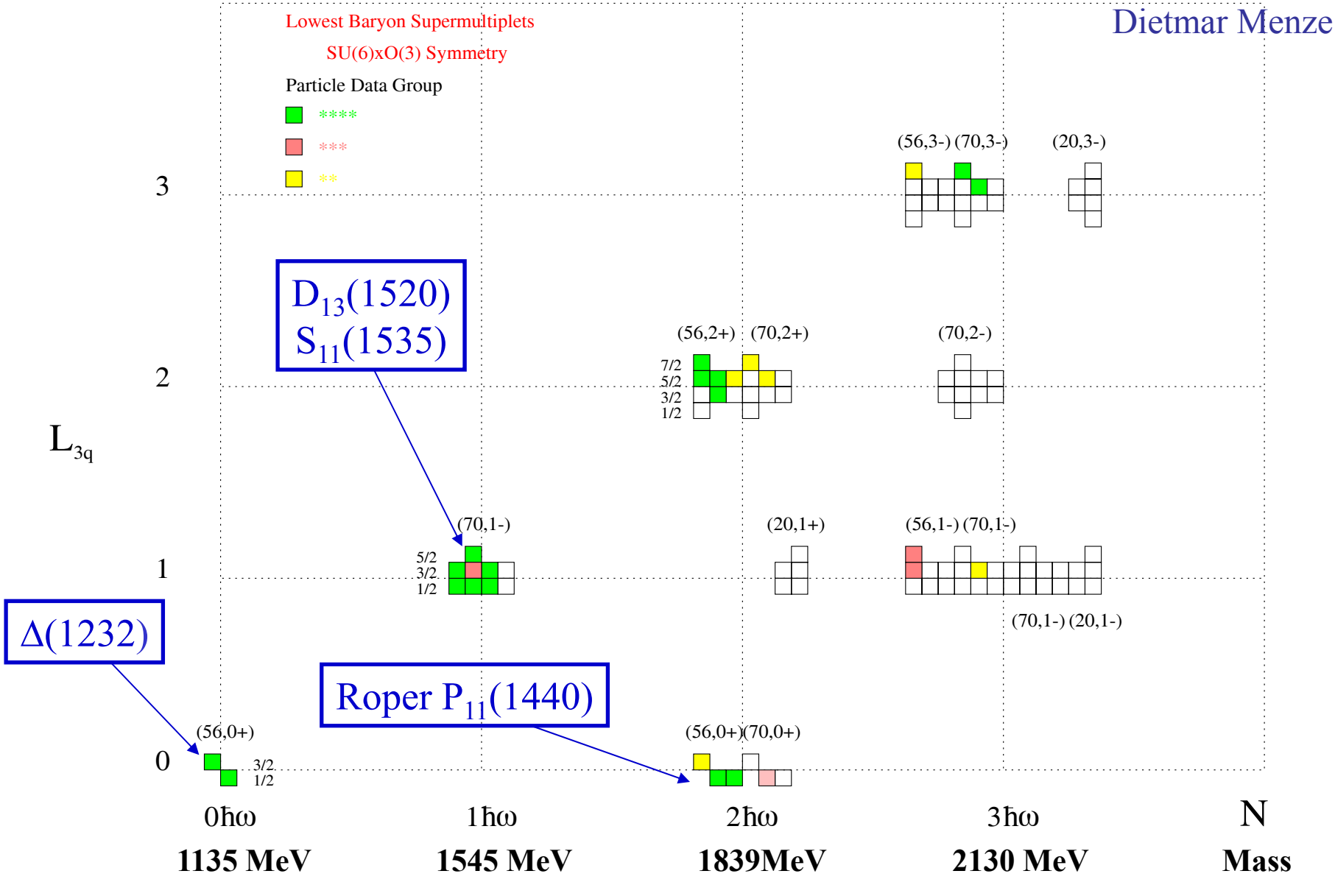
- Orbital excitations (two distinct kinds in contrast to mesons)



- Radial excitations (also two kinds in contrast to mesons)



Quark Model Classification of N*



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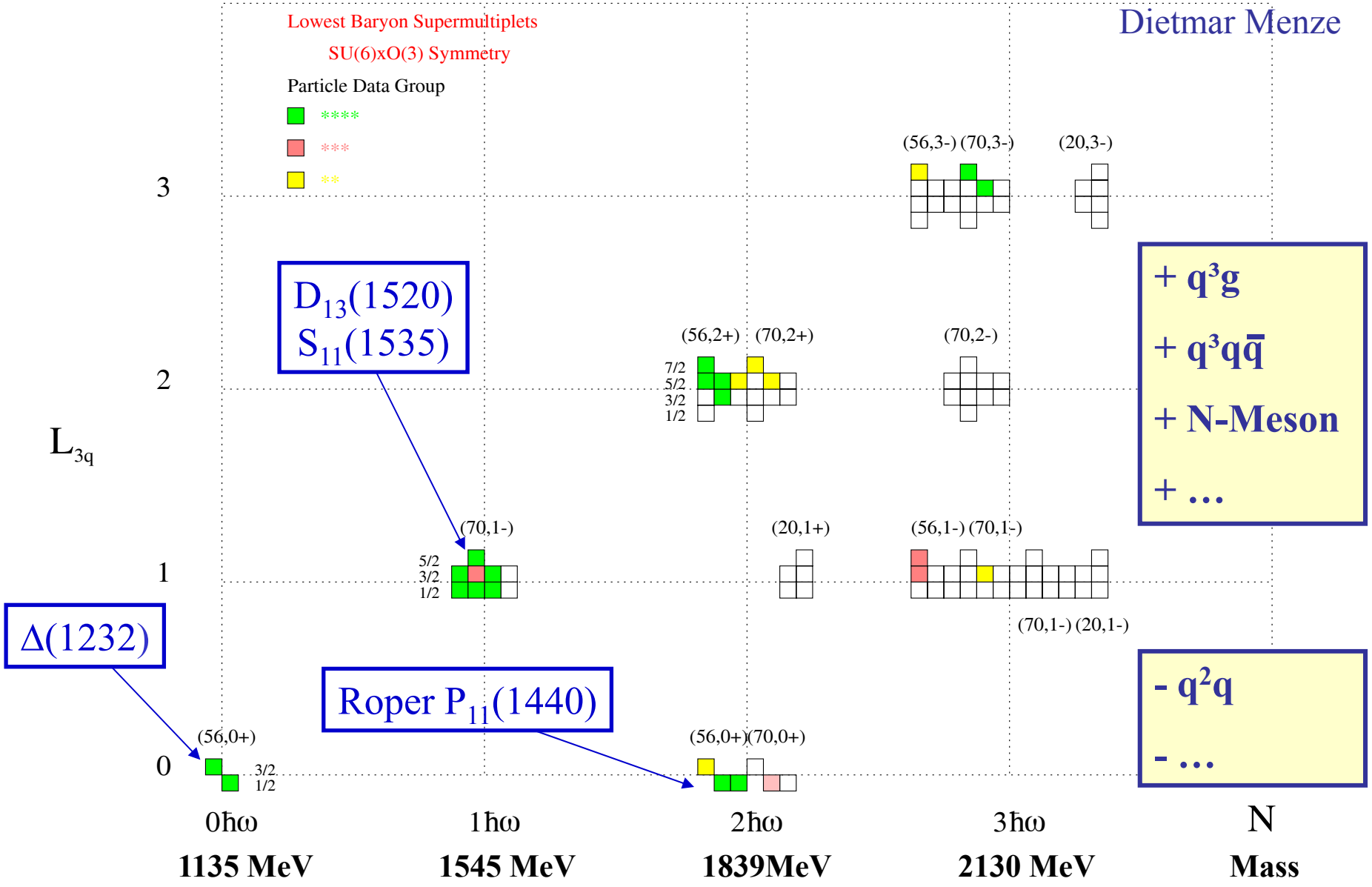

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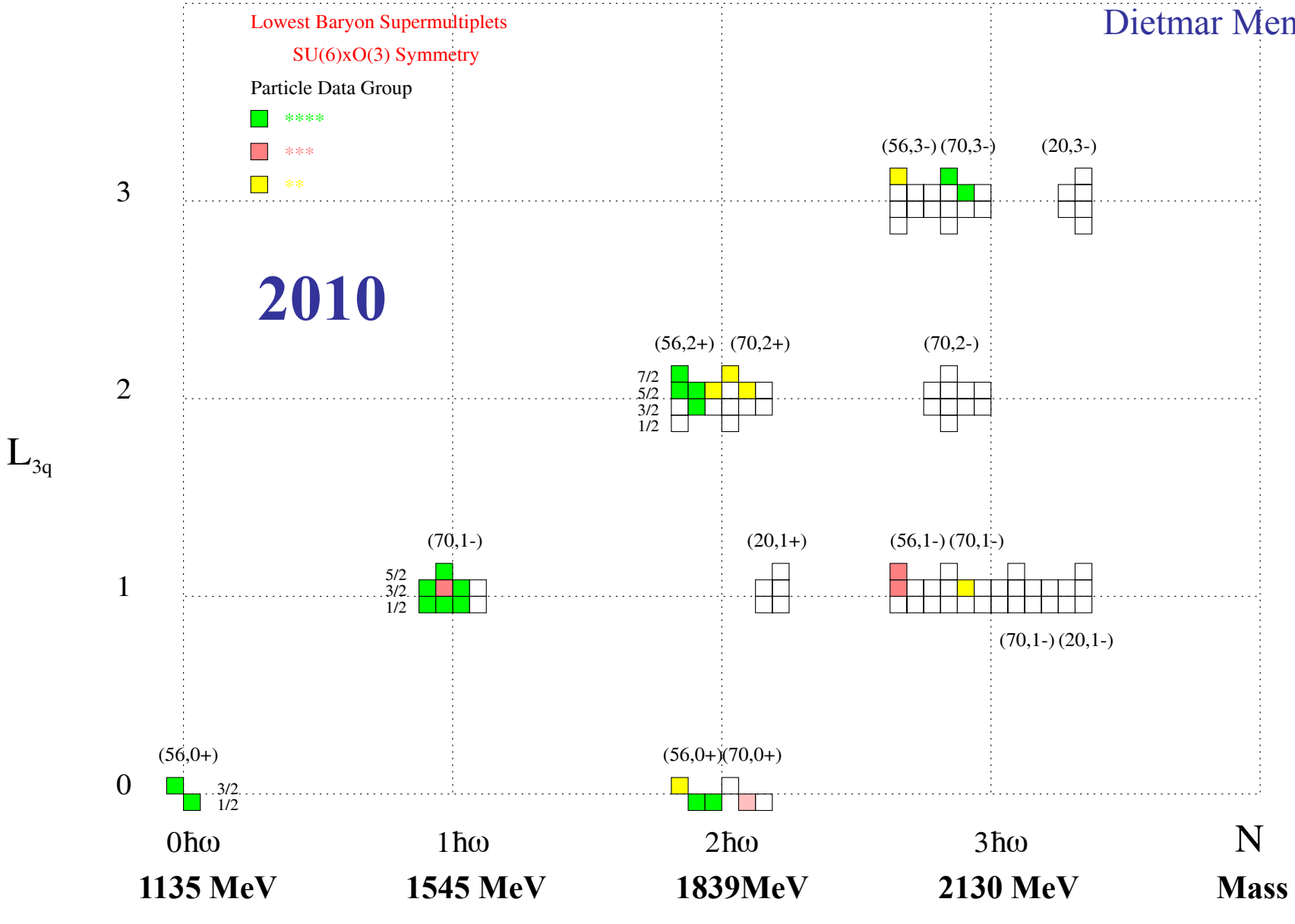
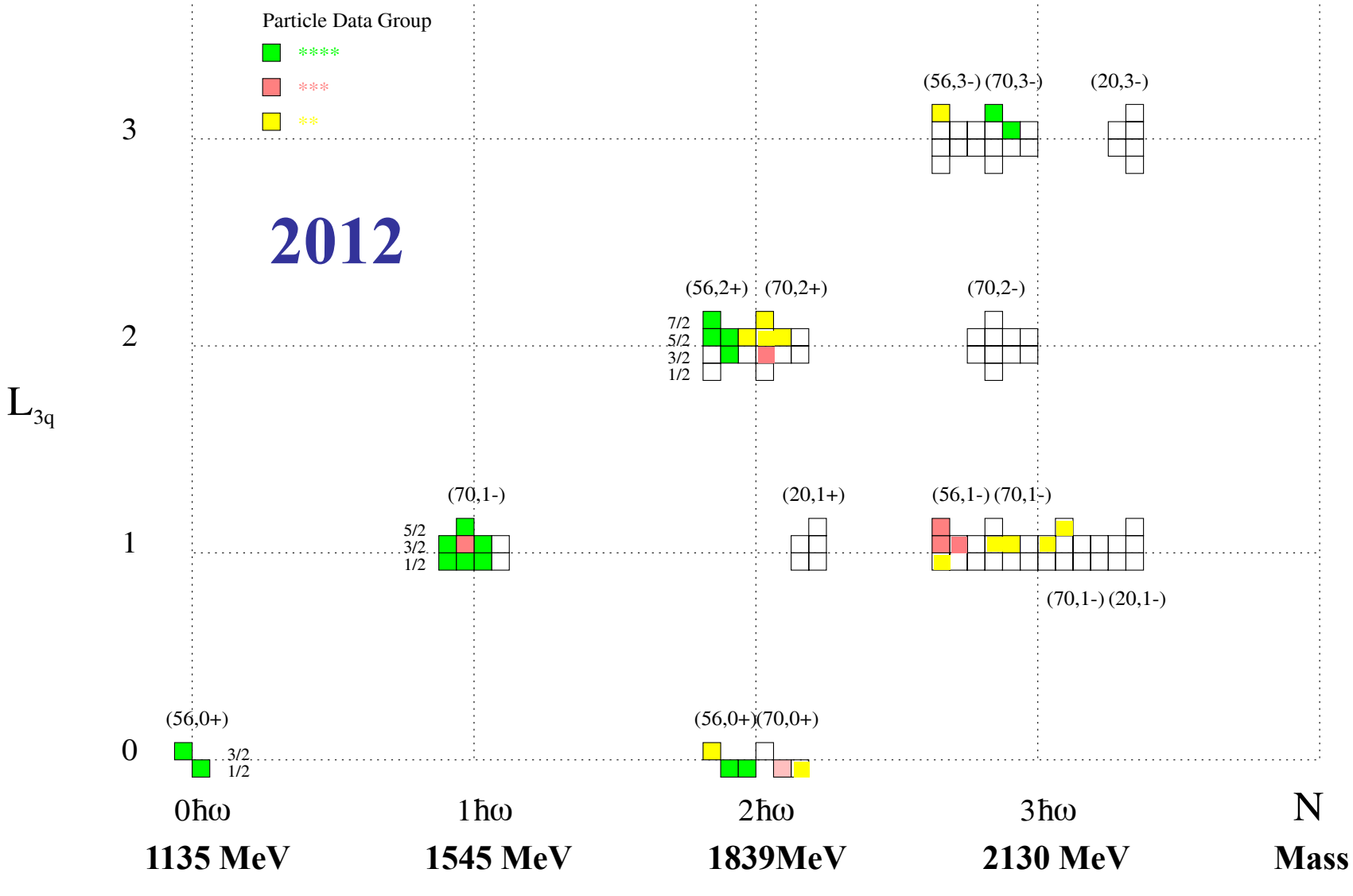


Quark Model Classification of N*

BnGa energy-dependent coupled-channel PWA of CLAS $K^+\Lambda$ and other data



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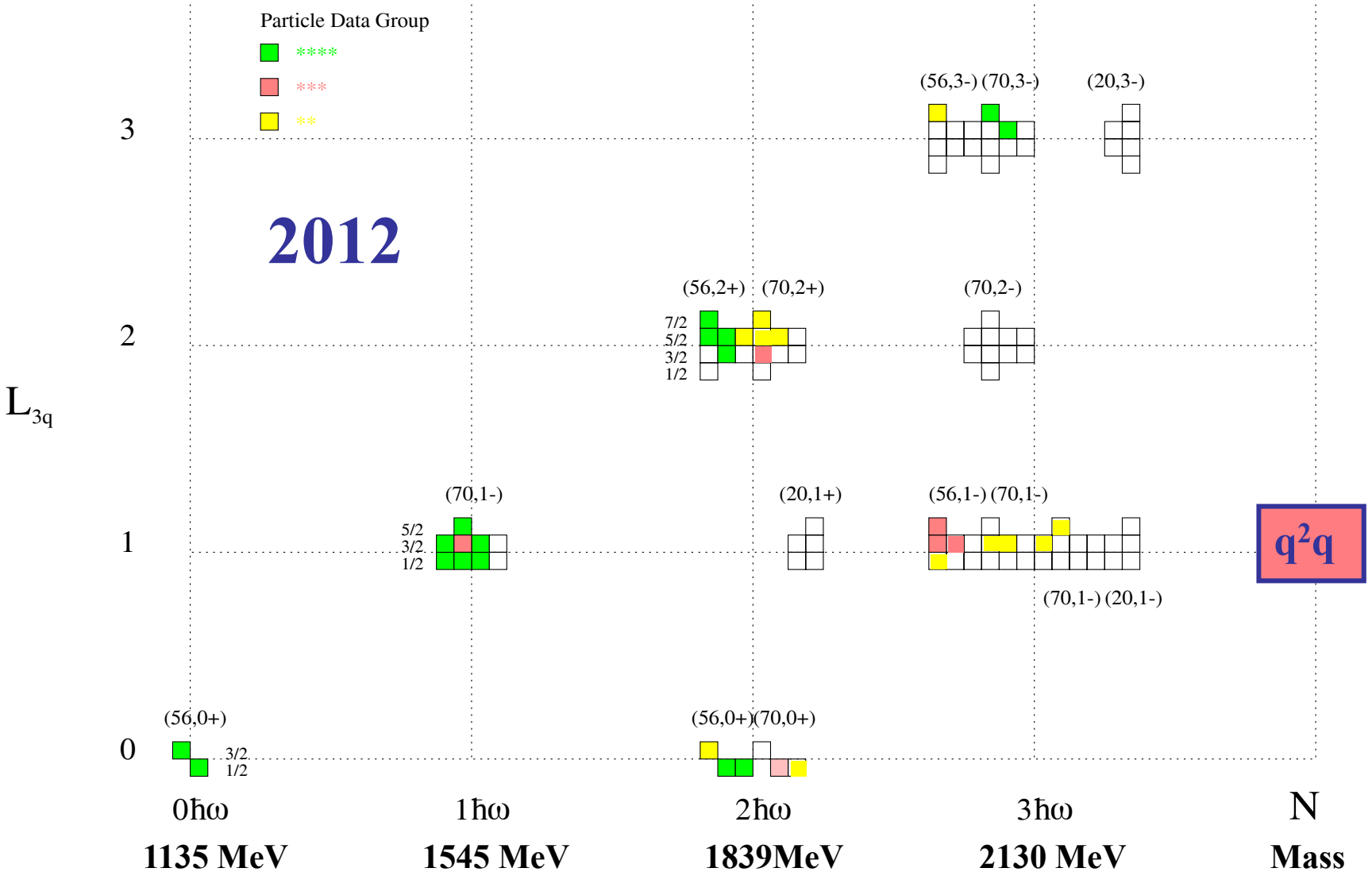
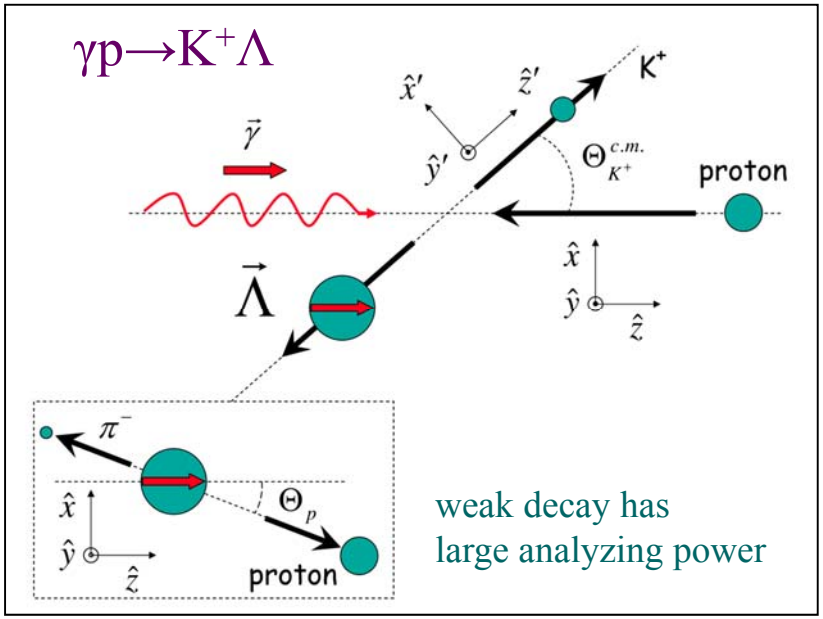


FROST/HD $\vec{\gamma}\vec{N} \rightarrow \pi N, \eta N, K\vec{\Lambda}, K\vec{\Sigma}, N\pi\pi, N\omega, \ldots$

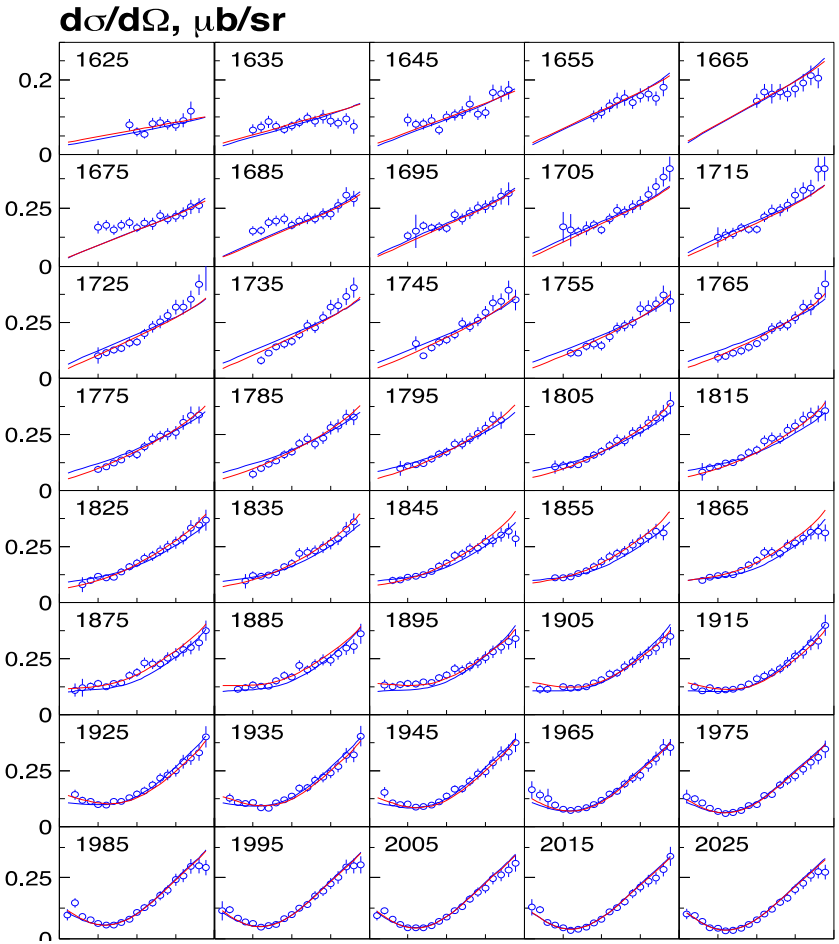


- Single pseudo-scalar meson production process is described by 4 complex, parity conserving amplitudes.
- 8 well-chosen measurements are needed to determine all amplitudes.
- For hyperon finals state 16 observables are measured in CLAS ⇛ large redundancy in determining the photoproduction amplitudes ⇛ allows for many cross checks and increased accuracy.
- 8 observables measured in reactions without recoil polarization.

Photon beam		*Target*			*Recoil*			*Target - Recoil*								
					x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
		x	y	z				x	y	z	x	y	z	x	y	z
unpolarized	σ_0		T			P		$T_{x'}$		$L_{x'}$		Σ		$T_{z'}$		$L_{z'}$
linearly P_γ	Σ	H	P	G	$O_{x'}$	T	$O_{z'}$	$L_{z'}$	$C_{z'}$	$T_{z'}$	E		F	$L_{x'}$	$C_{x'}$	$T_{x'}$
circular P_γ		F		E	$C_{x'}$		$C_{z'}$		$O_{z'}$		G		H		$O_{x'}$	

CLAS Results on $\vec{\gamma}\vec{p} \rightarrow K^+\vec{\Lambda} \rightarrow K^+p\pi$

Bonn-Gatchina Coupled Channel Analysis, A.V. Anisovich et al., EPJ A48, 15 (2012)



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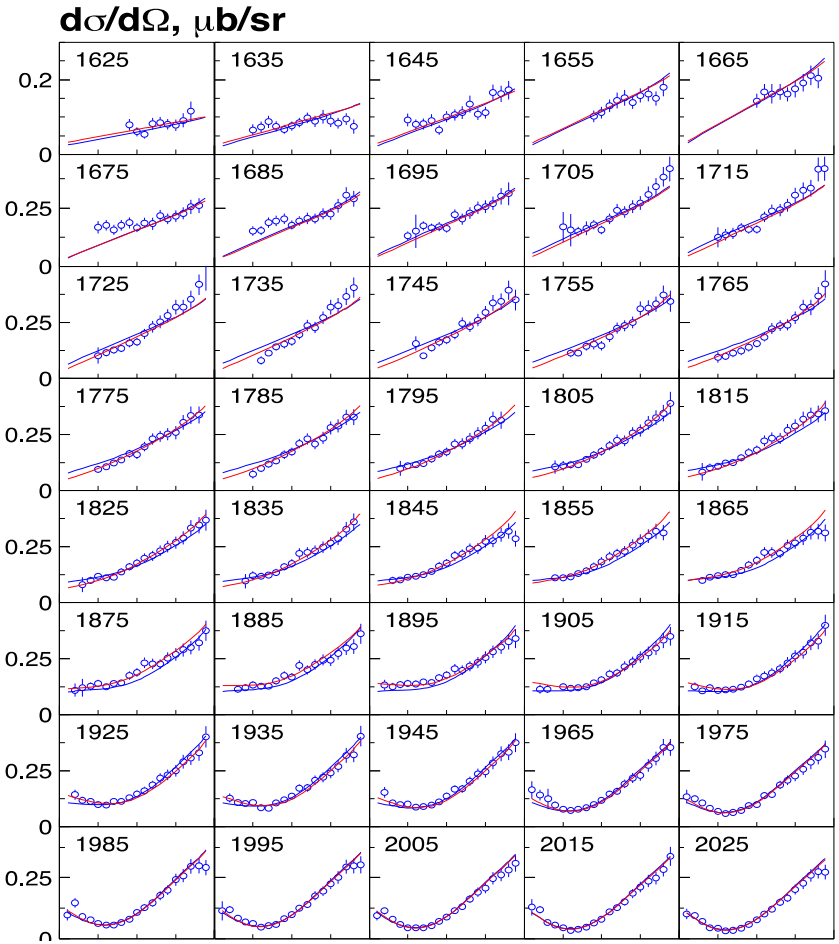

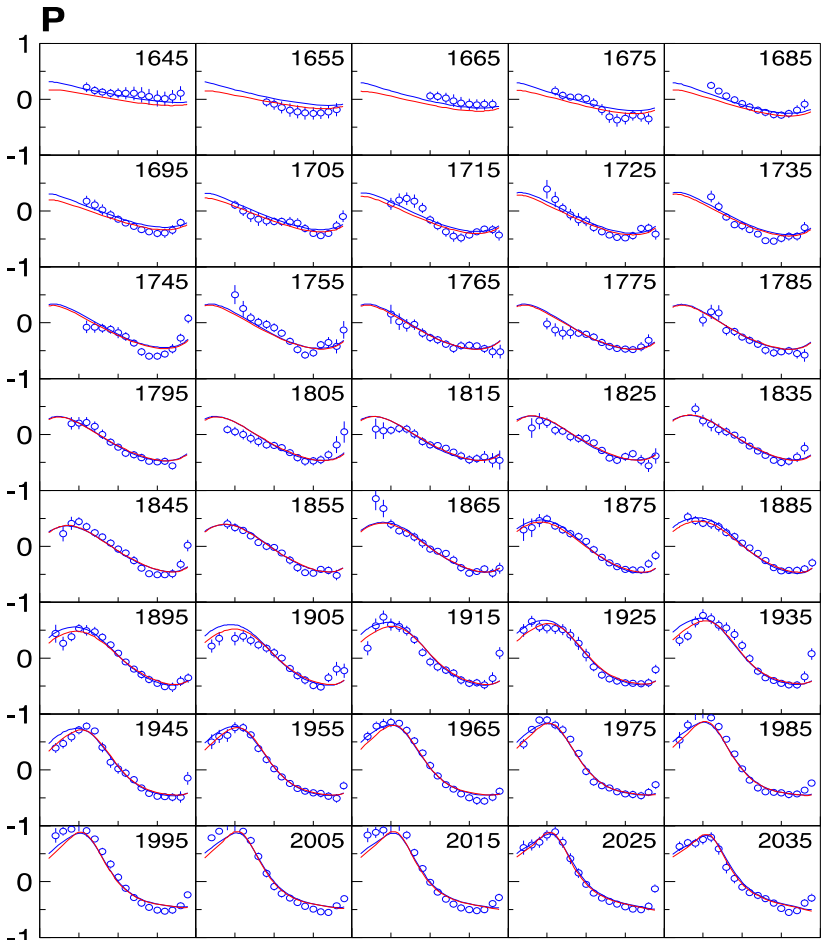

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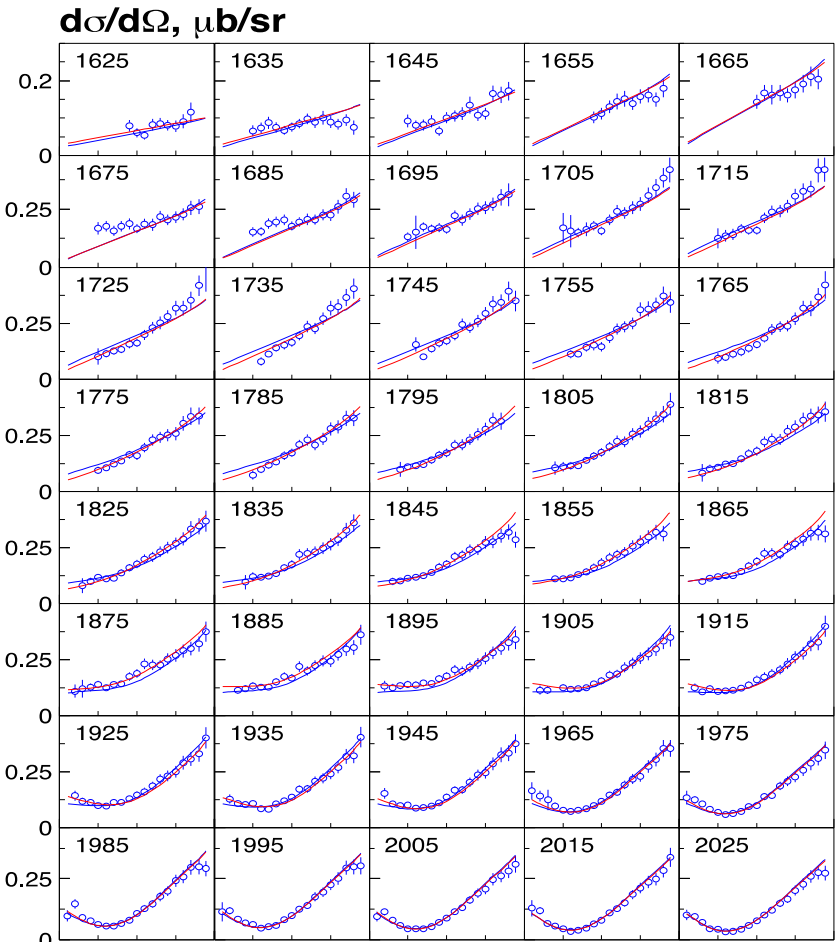
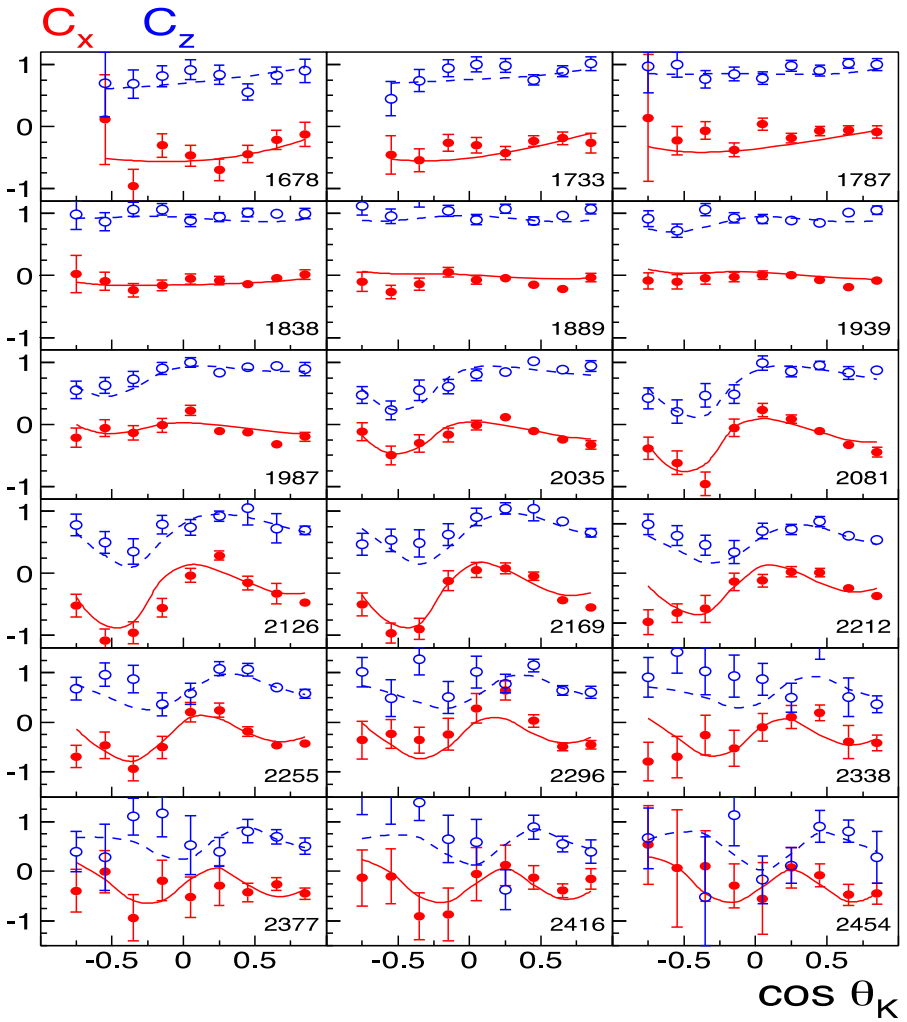
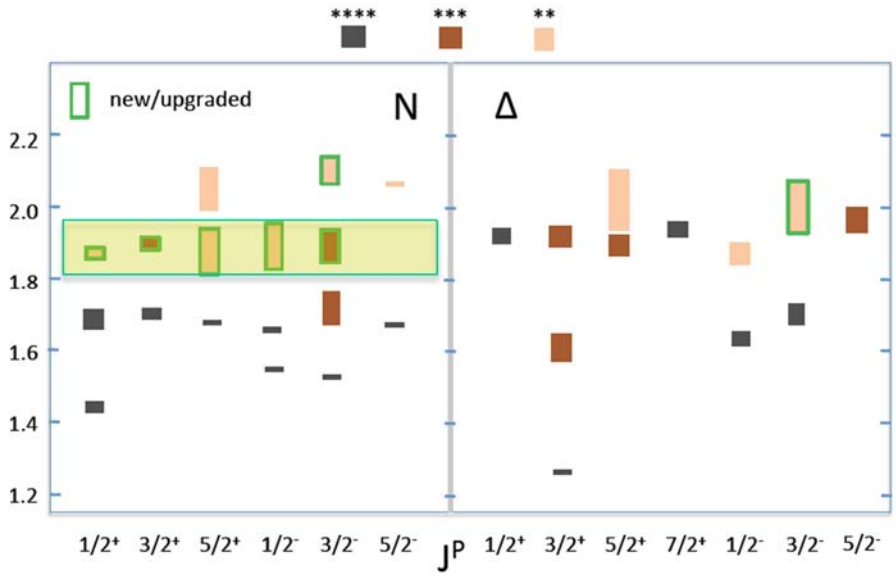




N/Δ Spectrum in RPP 2012

N^*	J^P $(L_{2I,2J})$	2010	2012	Δ	J^P $(L_{2I,2J})$	2010	2012
p	$1/2^+$ (P_{11})	****	****	Δ(1232)	$3/2^+$ (P_{33})	****	****
n	$1/2^+$ (P_{11})	****	****	Δ(1600)	$3/2^+$ (P_{33})	***	***
$N(1440)$	$1/2^+$ (P_{11})	****	****	Δ(1620)	$1/2^-$ (S_{31})	****	****
$N(1520)$	$3/2^-$ (D_{13})	****	****	Δ(1700)	$3/2^-$ (D_{33})	****	****
$N(1535)$	$1/2^-$ (S_{11})	****	****	Δ(1750)	$1/2^+$ (P_{31})	*	*
$N(1650)$	$1/2^-$ (S_{11})	****	****	Δ(1900)	$1/2^-$ (S_{31})	**	**
$N(1675)$	$5/2^-$ (D_{15})	****	****	Δ(1905)	$5/2^+$ (F_{35})	****	****
$N(1680)$	$5/2^+$ (F_{15})	****	****	Δ(1910)	$1/2^+$ (P_{31})	****	****
$N(1685)$			*				
$N(1700)$	$3/2^-$ (D_{13})	***	***	Δ(1920)	$3/2^+$ (P_{33})	***	***
$N(1710)$	$1/2^+$ (P_{11})	***	***	Δ(1930)	$5/2^-$ (D_{35})	***	***
$N(1720)$	$3/2^+$ (P_{13})	****	****	Δ(1940)	$3/2^-$ (D_{33})	*	**
$N(1860)$	$5/2^+$		**				
$N(1875)$	$3/2^-$		***				
$N(1880)$	$1/2^+$		**				
$N(1895)$	$1/2^-$		**				
$N(1900)$	$3/2^+$ (P_{13})	**	***	Δ(1950)	$7/2^+$ (F_{37})	****	****
$N(1990)$	$7/2^+$ (F_{17})	**	**	Δ(2000)	$5/2^+$ (F_{35})	**	**
$N(2000)$	$5/2^+$ (F_{15})	**	**	Δ(2150)	$1/2^-$ (S_{31})	*	*
~~$N(2080)$~~	D_{13}	**		Δ(2200)	$7/2^-$ (G_{37})	*	*
~~$N(2090)$~~	S_{11}	*		Δ(2300)	$9/2^+$ (H_{39})	**	**
$N(2040)$	$3/2^+$		*				
$N(2060)$	$5/2^-$		**				
$N(2100)$	$1/2^+$ (P_{11})	*	*	Δ(2350)	$5/2^-$ (D_{35})	*	*
$N(2120)$	$3/2^-$		**				
$N(2190)$	$7/2^-$ (G_{17})	****	****	Δ(2390)	$7/2^+$ (F_{37})	*	*
~~$N(2200)$~~	D_{15}	**		Δ(2400)	$9/2^-$ (G_{39})	**	**
$N(2220)$	$9/2^+$ (H_{19})	****	****	Δ(2420)	$11/2^+$ $(H_{3,11})$	****	****
$N(2250)$	$9/2^-$ (G_{19})	****	****	Δ(2750)	$13/2^-$ $(I_{3,13})$	**	**
$N(2600)$	$11/2^-$ $(I_{1,11})$	***	***	Δ(2950)	$15/2^+$ $(K_{3,15})$	**	**
$N(2700)$	$13/2^+$ $(K_{1,13})$	**	**				

High-statistics and high-precision photoproduction data from JLAB, MAMI, ELSA, GRAAL

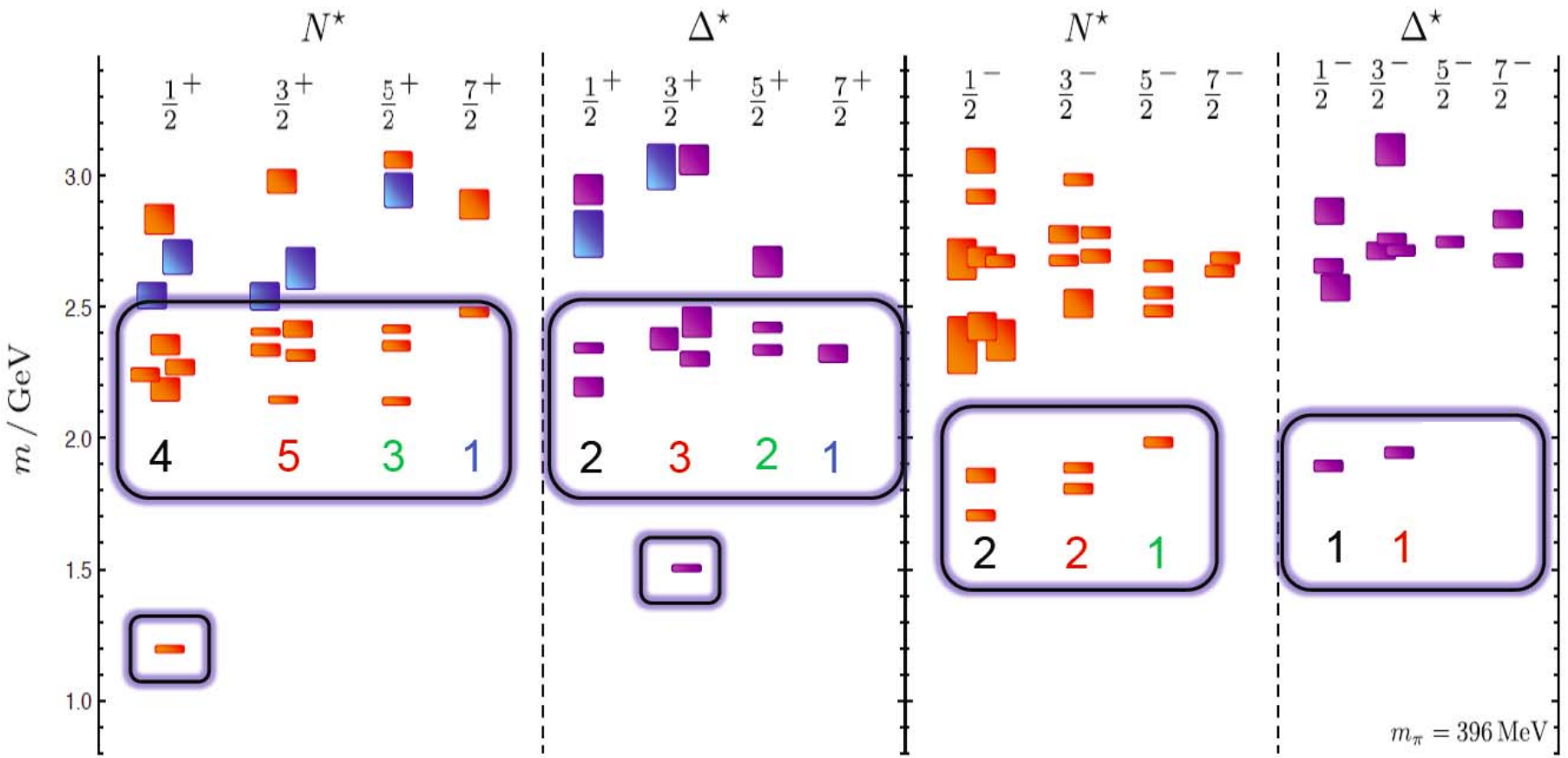


Are we observing parity doublets with the new states?

V. Crede & W. Roberts, Rep. Prog. Phys. 76 (2013)

N* Spectrum in LQCD

The strong interaction physics is encoded in the nucleon excitation spectrum that spans the degrees of freedom from meson-baryon and dressed quarks to elementary quarks and gluons.



LQCD predicts states with the same quantum numbers as CQMs with underlying SU(6)xO(3) symmetry.

R. Edwards et al.
arXiv:1104.5152, 1201.2349

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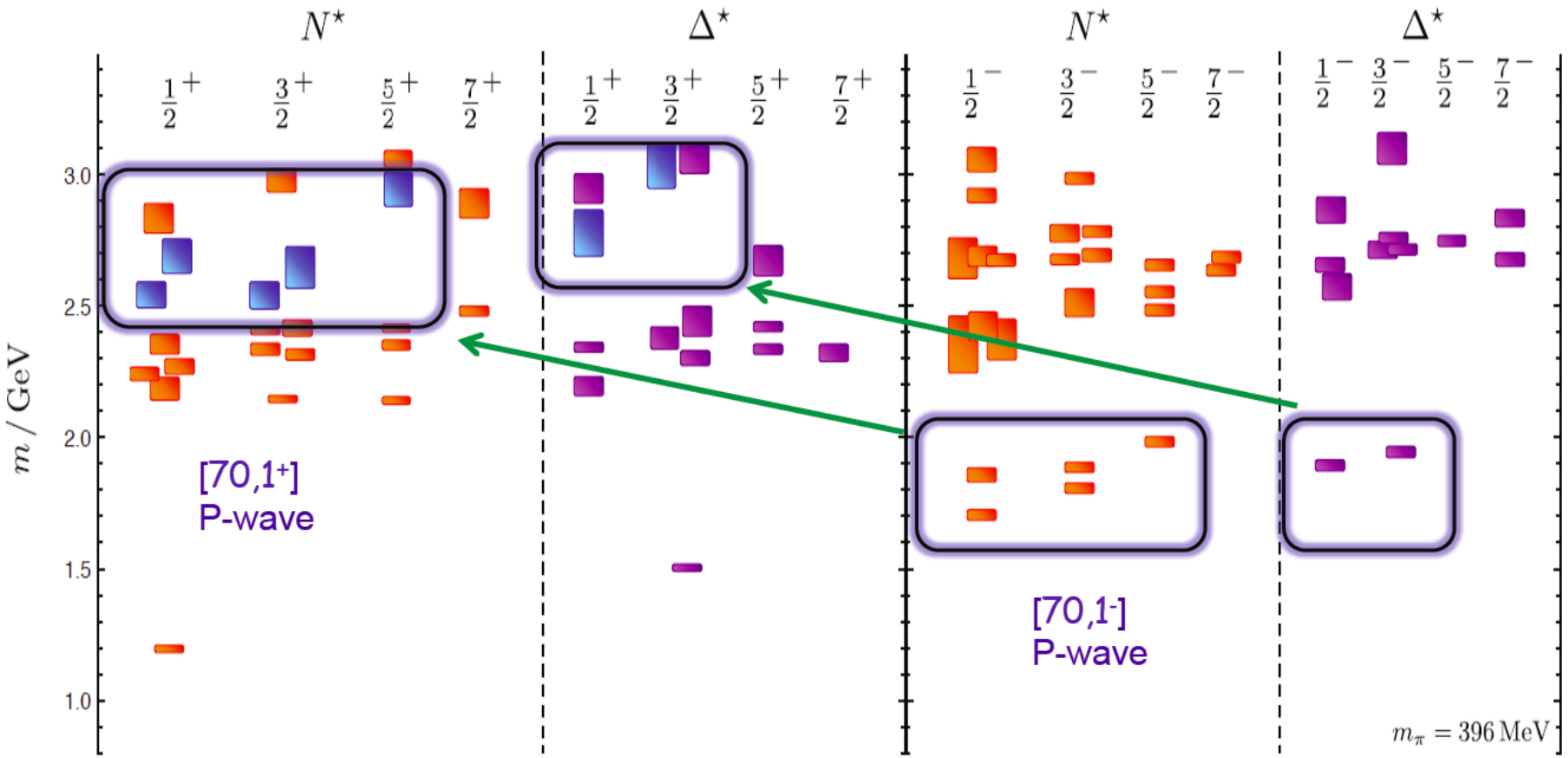
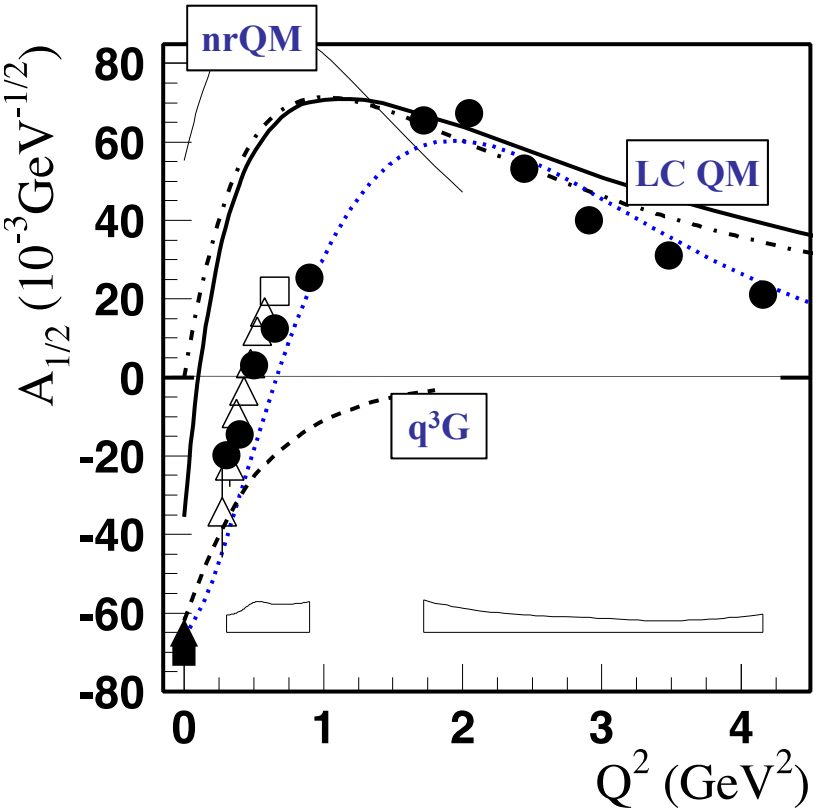


LQCD predicts hybrid baryon states replicating the negative parity multiplet structure.

Transition Form Factors and QCD Models

Roper resonance $P_{11}(1440)$



+ q^3g
+ $q^3q\bar{q}$
+ N-Meson
+ …

or

- q^2q
- …

… all have distinctively different Q^2 dependencies

Transition Form Factors and QCD Models

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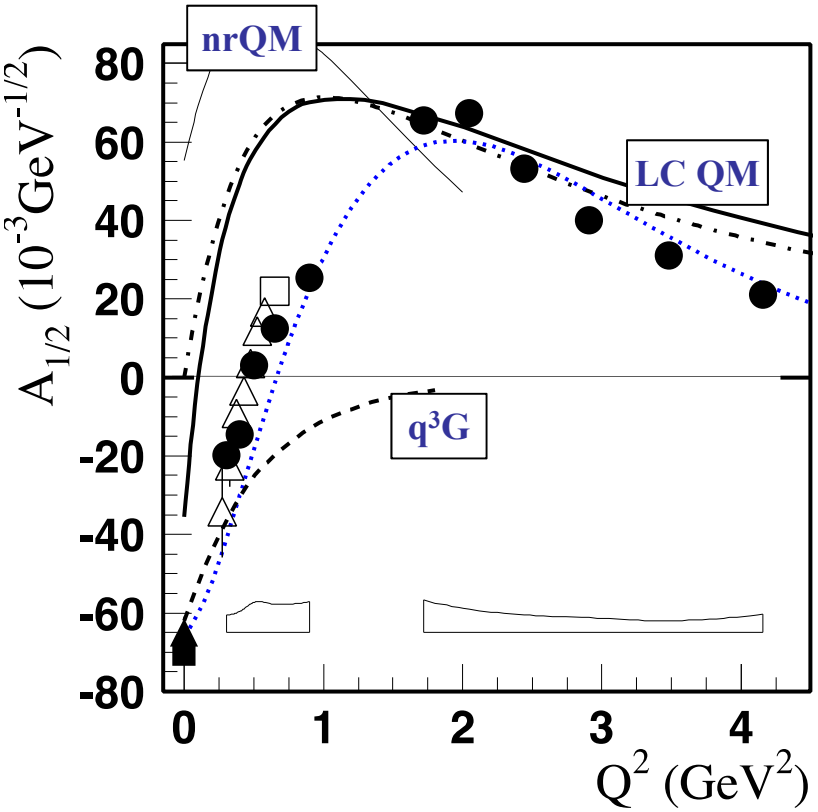
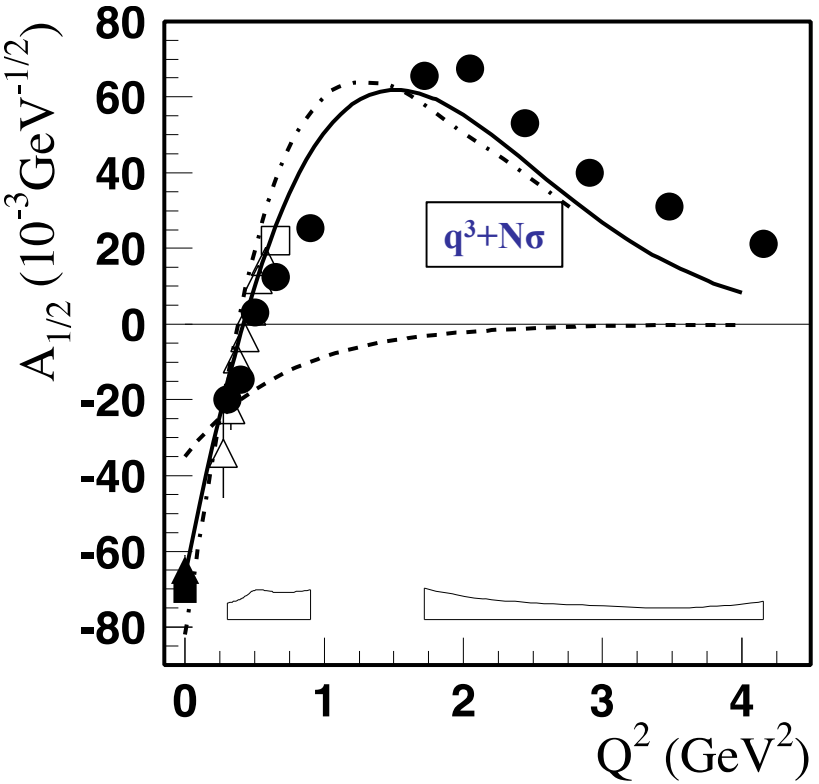


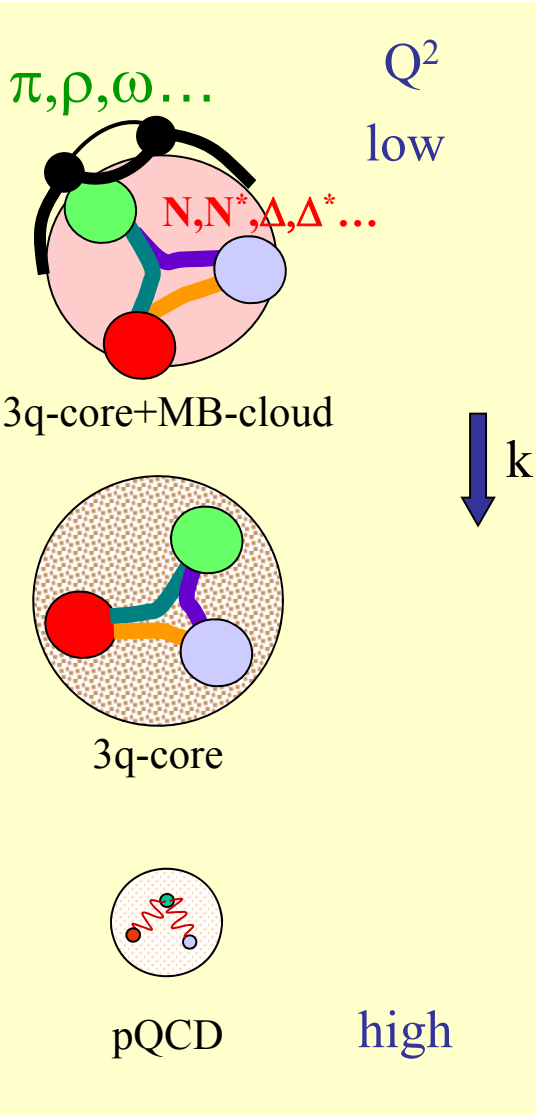
PDG 2013 update



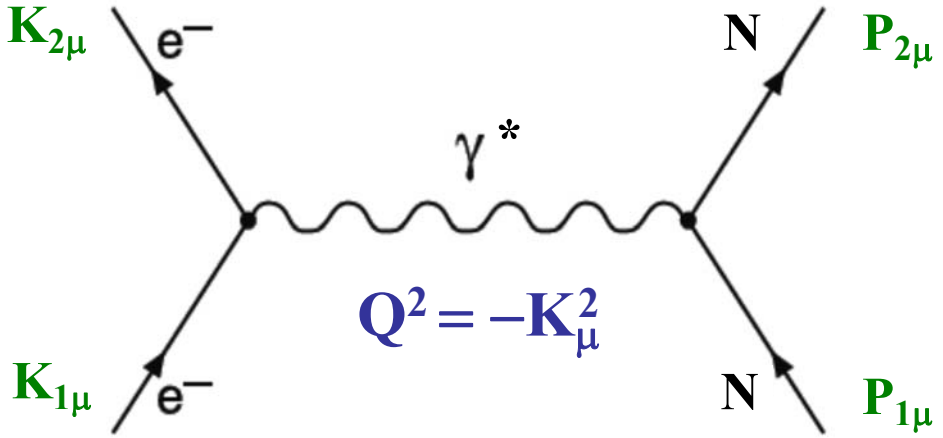
- $A_{1/2}$ has zero-crossing near Q^2=0.5 and becomes dominant amplitude at high Q^2.
- Eliminates gluonic excitation (q^3G) as a dominant contribution.
- Consistent with radial excitation at high Q^2 and large meson-baryon coupling at small Q^2.

Transition Form Factors

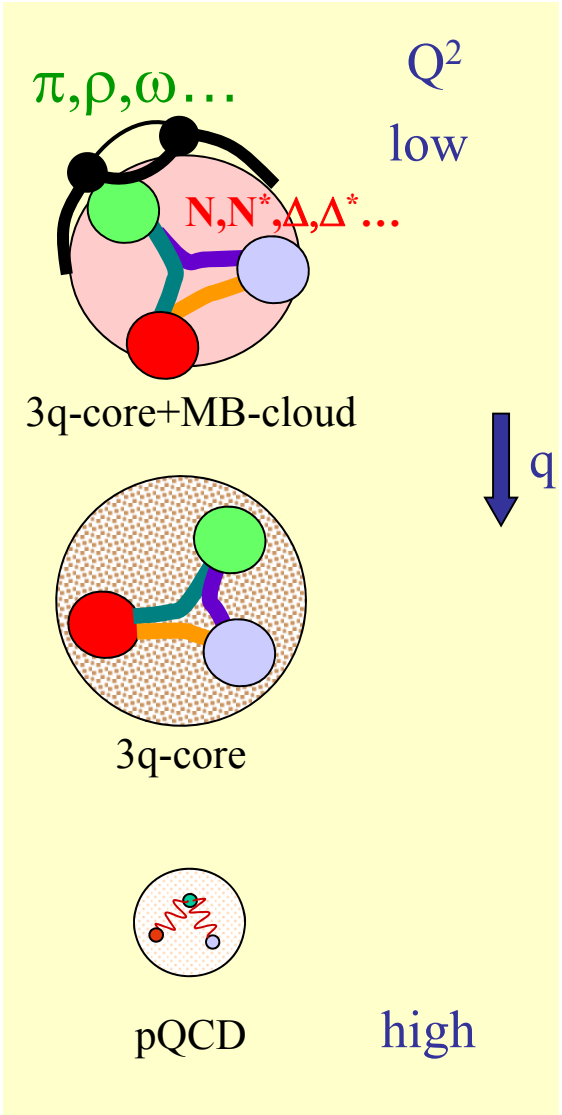
Hadron Structure with Electromagnetic Probes



- Study the structure of the nucleon spectrum in the domain where dressed quarks are the major active degree of freedom.
- Explore the formation of excited nucleon states in interactions of dressed quarks and their emergence from QCD.



Hadron Structure with Electromagnetic Probes



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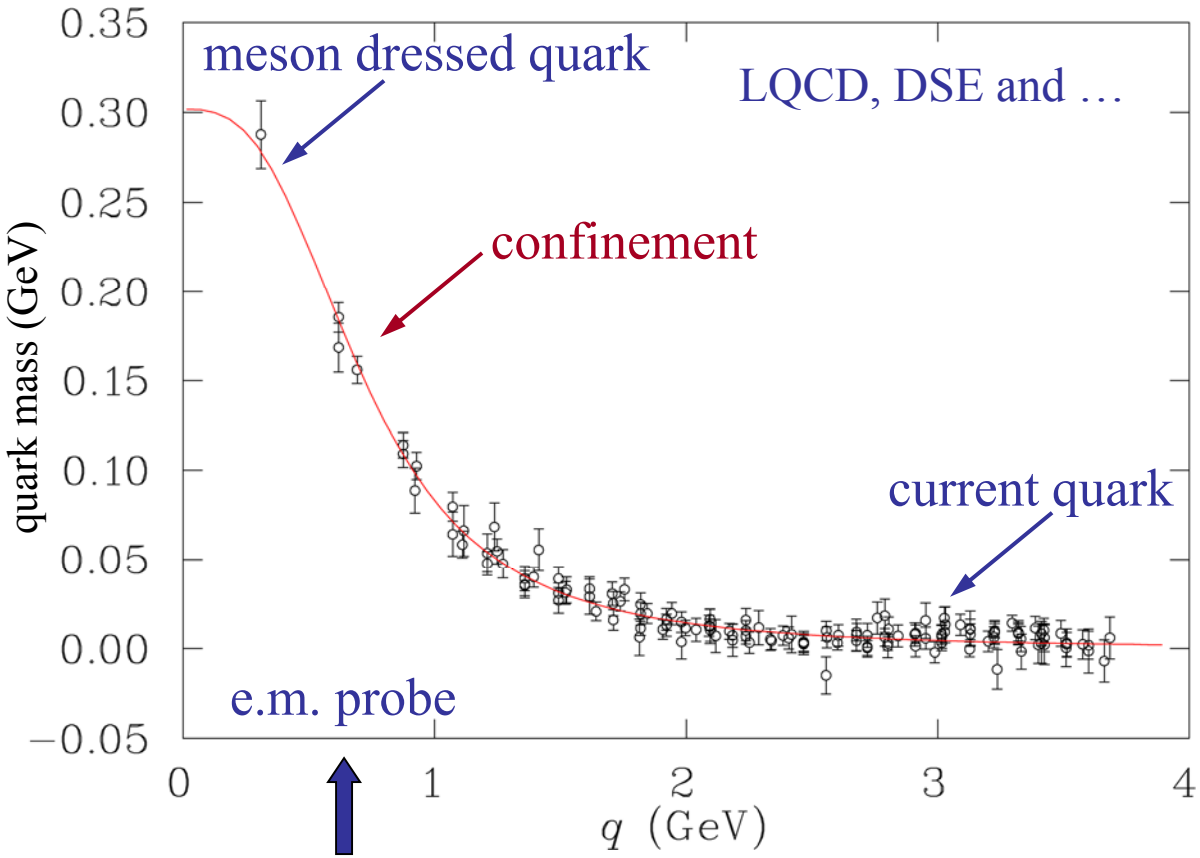
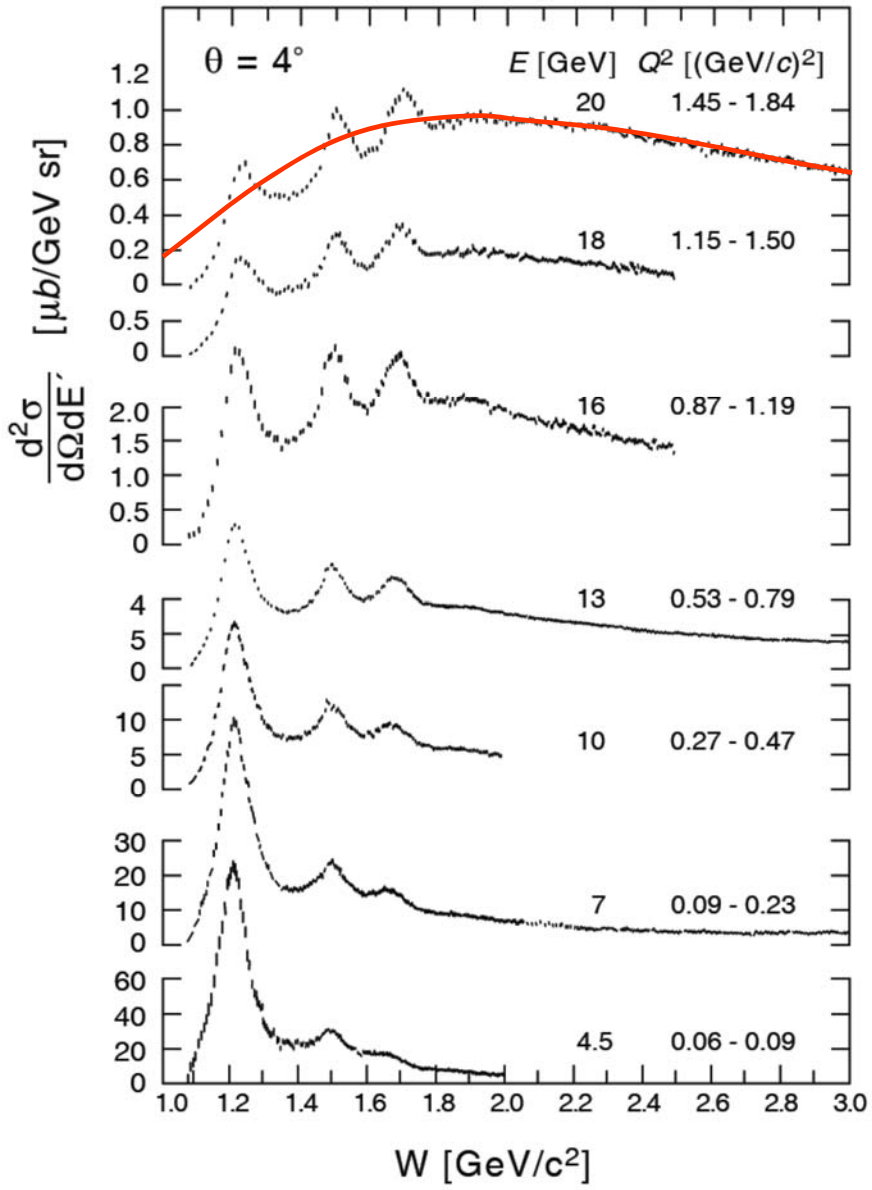
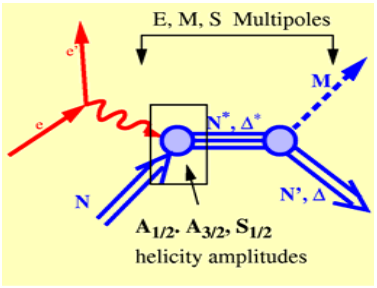


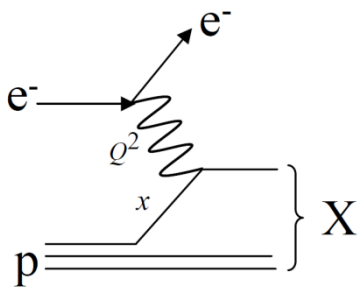
Baryon Excitations and Quasi-Elastic Scattering



hard and confined

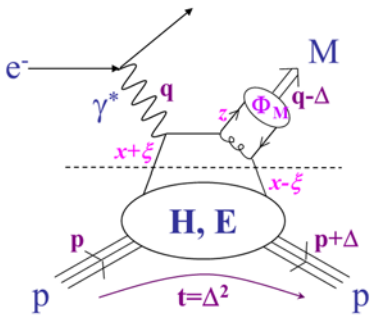


quasi-elastic



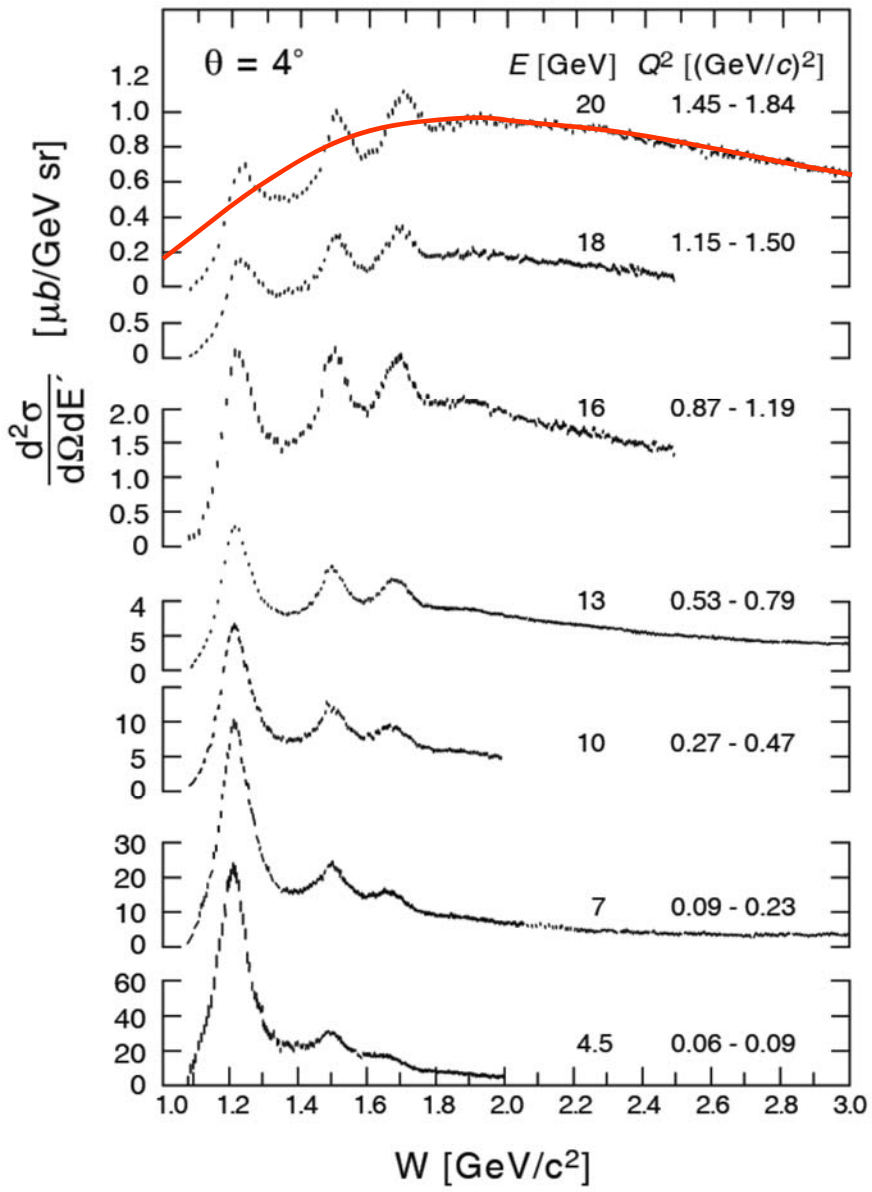
hard

soft

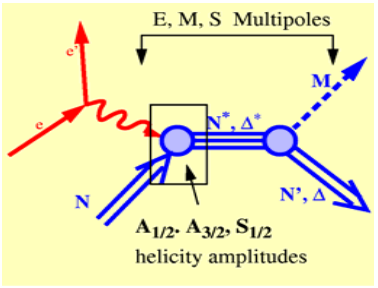


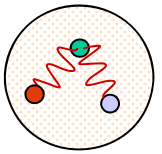
Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Baryon Excitations and Quasi-Elastic Scattering

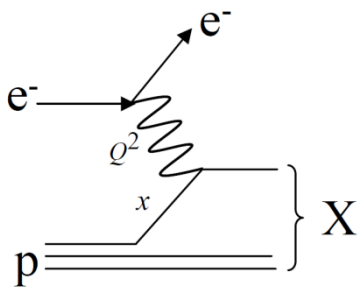


hard and confined



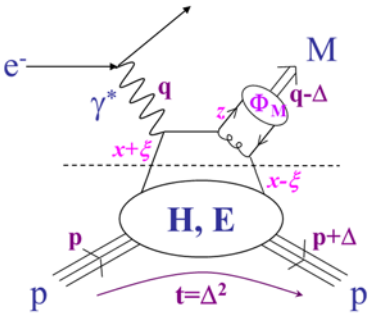


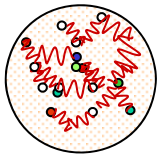
quasi-elastic



hard

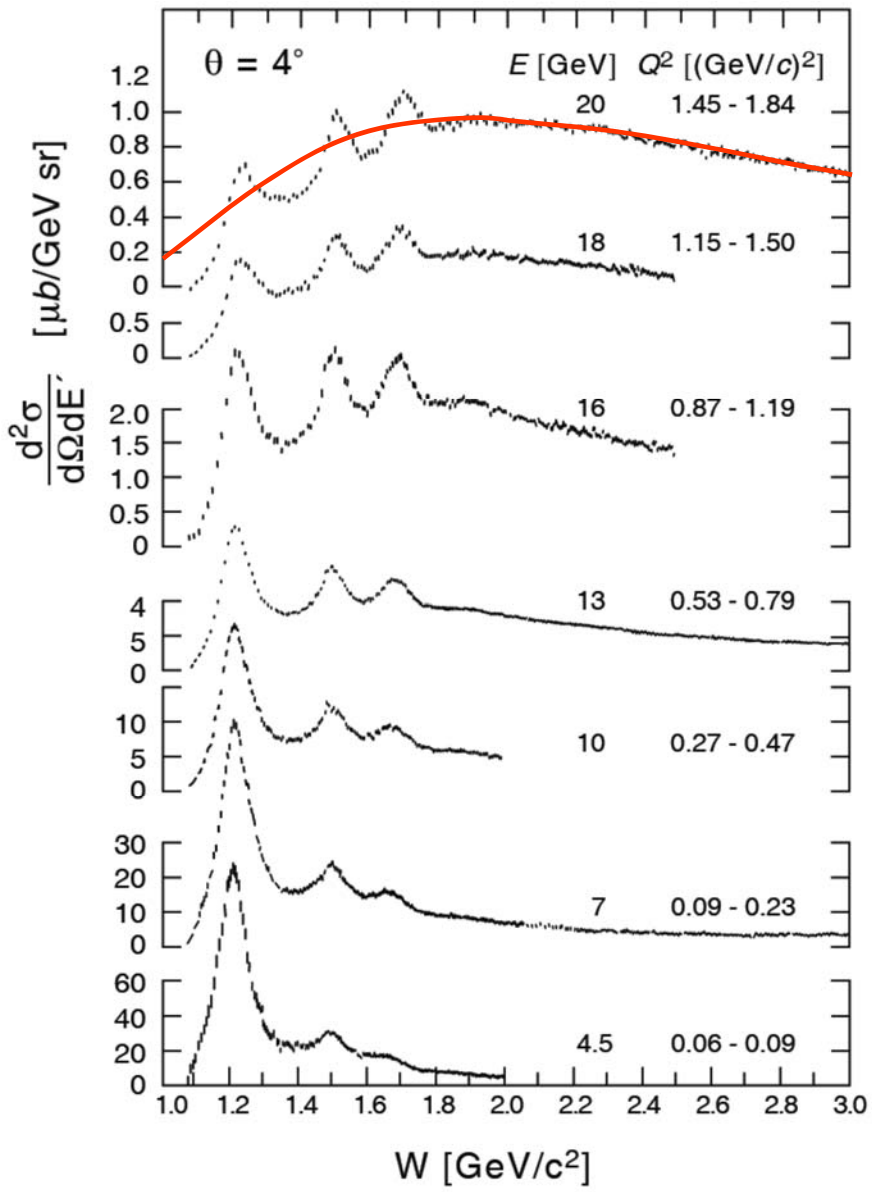
soft



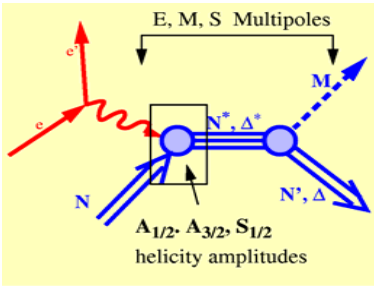


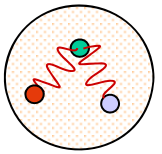
Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Baryon Excitations and Quasi-Elastic Scattering



hard and confined



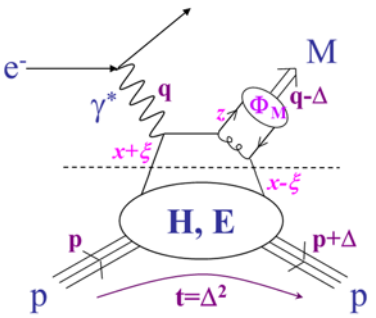


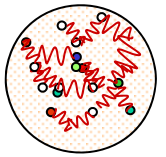
Elastic Form Factors

Transition Form Factors

hard

soft





Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Data-Driven Data Analyses

Consistent Results

- Single meson production:
  - Unitary Isobar Model (UIM)
  - Fixed-*t* Dispersion Relations (DR)
- Double pion production:
  - Unitarized Isobar Model (JM)
- Coupled-Channel Approach:
  - EBAC ⇒ Argonne-Osaka
  - JAW ⇒ Jülich-Athens-Washington
  - BoGa ⇒ Bonn-Gatchina

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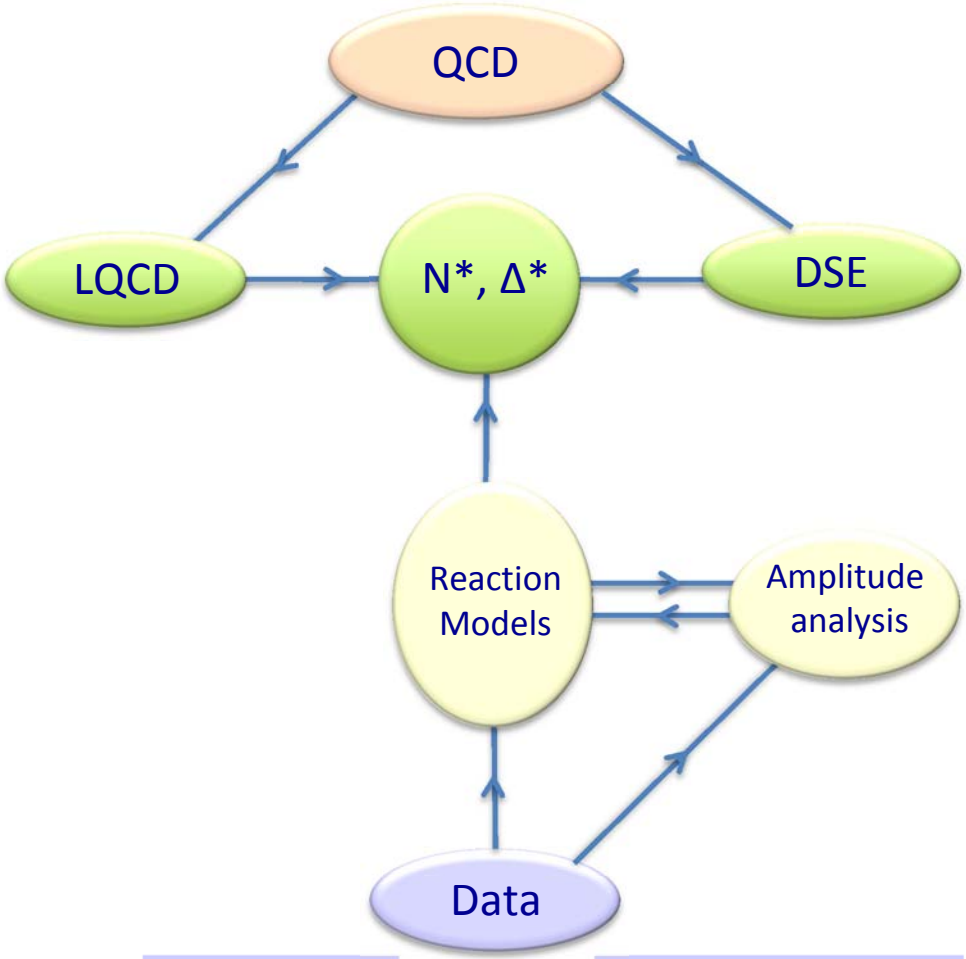
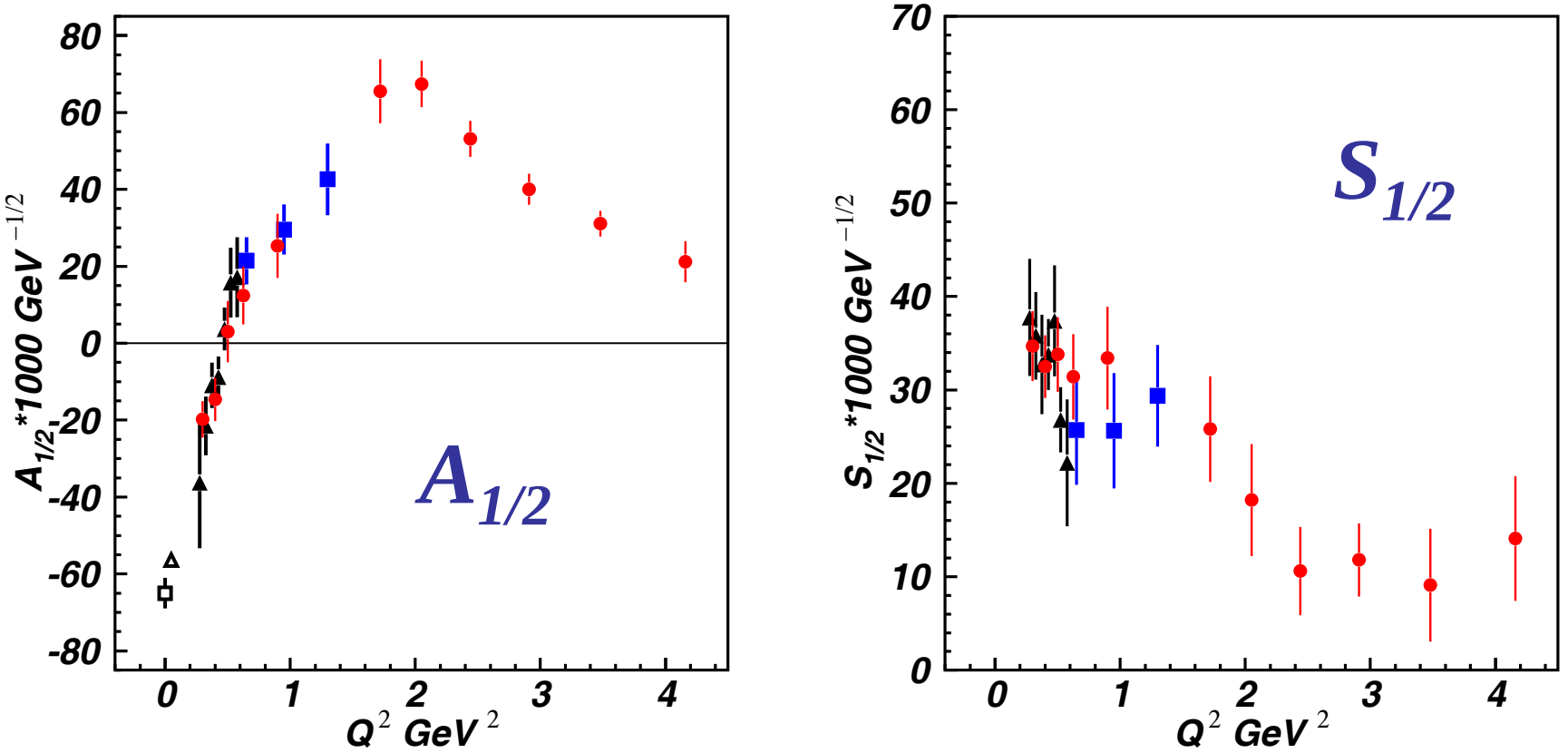


Electrocouplings of N(1440)P_{11} from CLAS Data

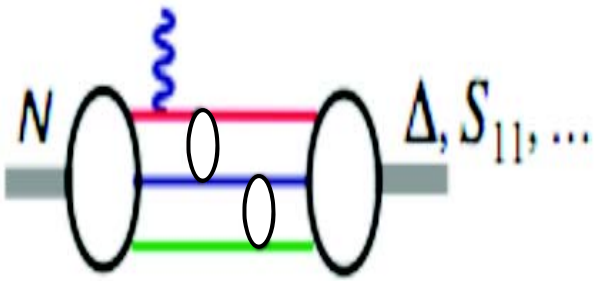


□ PDG ● Nπ (UIM, DR) ▲ Nππ (JM) 2012 ■ Nππ (JM) preliminary

Consistent results obtained in the low-lying resonance region by independent analyses in the exclusive Nπ and $p\pi^+\pi^-$ final-state channels – that have fundamentally different mechanisms for the nonresonant background – underscore the capability of the reaction models to extract reliable resonance electrocouplings.

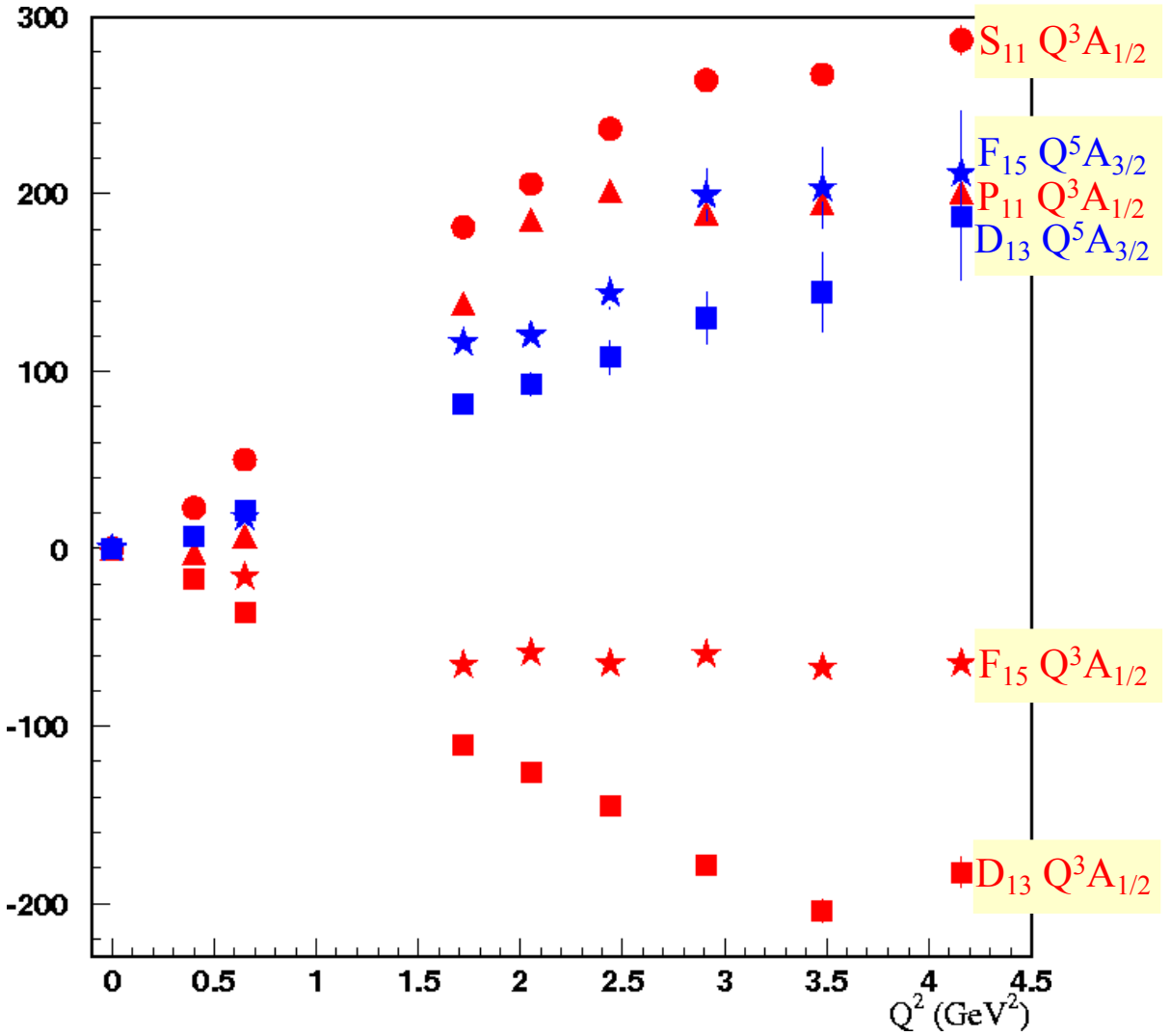
Phys. Rev. C 80, 055203 (2009) 1-22 and Phys. Rev. C 86, 035203 (2012) 1-22

Evidence for the Onset of Scaling?

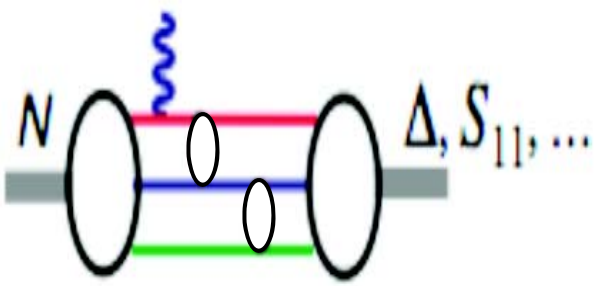


- $A_{1/2} \alpha 1/Q^3$
- $A_{3/2} \alpha 1/Q^5$

Phys. Rev. C80, 055203 (2009)



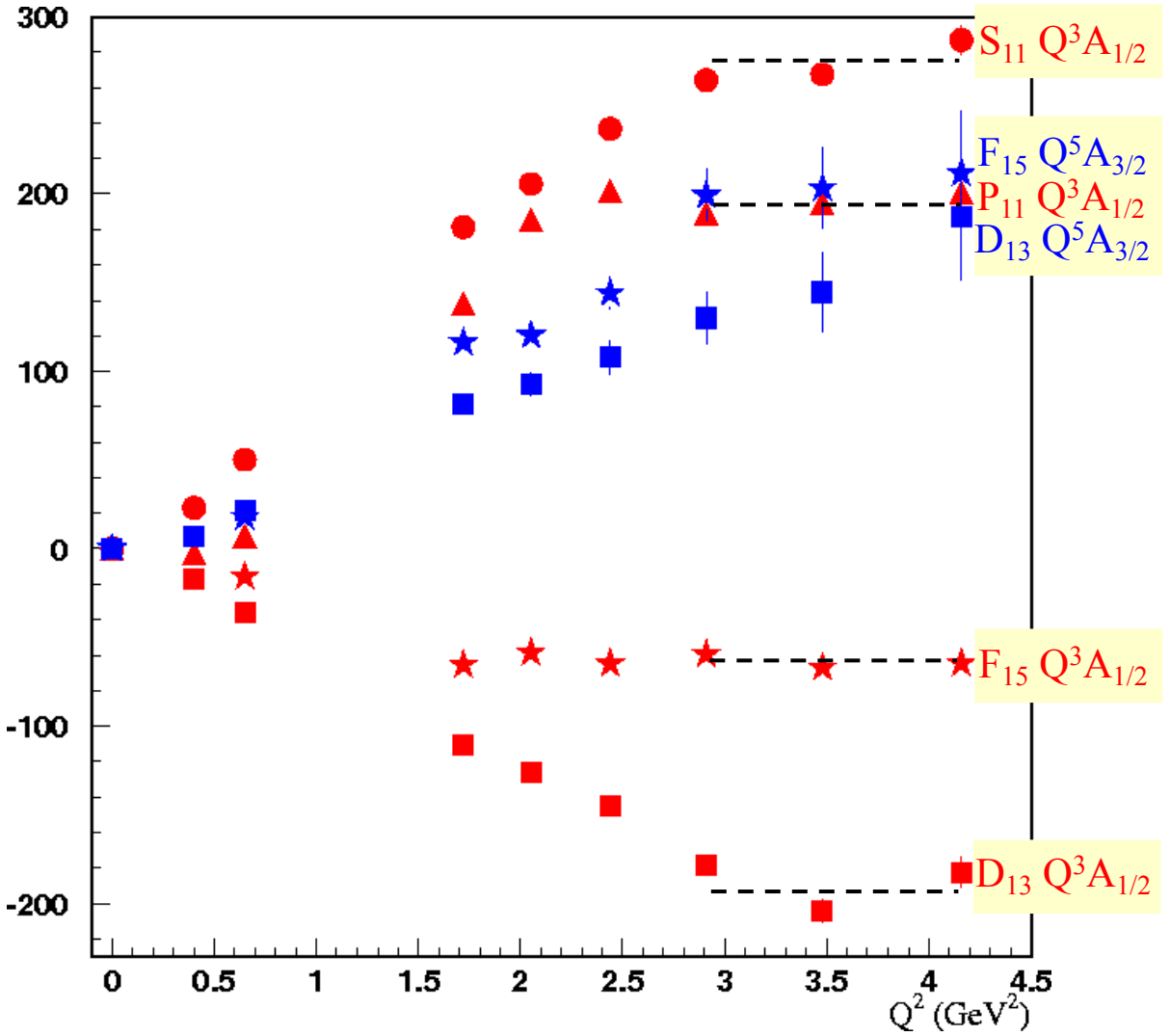
Evidence for the Onset of Scaling?



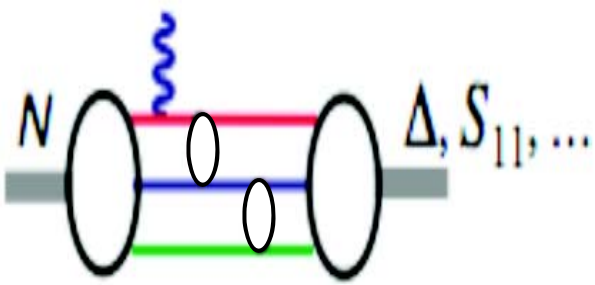
- $A_{1/2} \alpha 1/Q^3$
- $A_{3/2} \alpha 1/Q^5$

q^2q

Phys. Rev. C80, 055203 (2009)



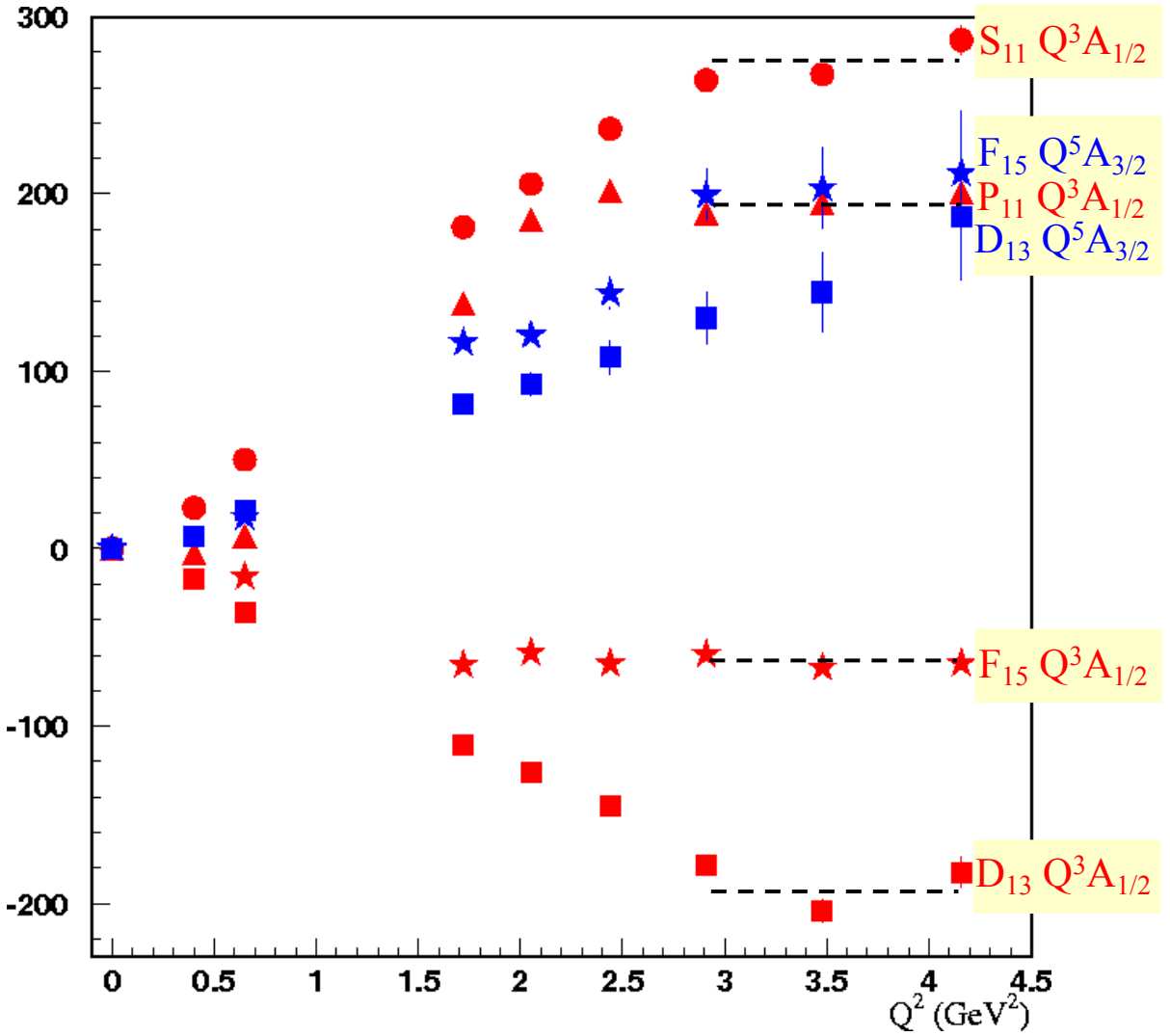
Evidence for the Onset of Scaling?



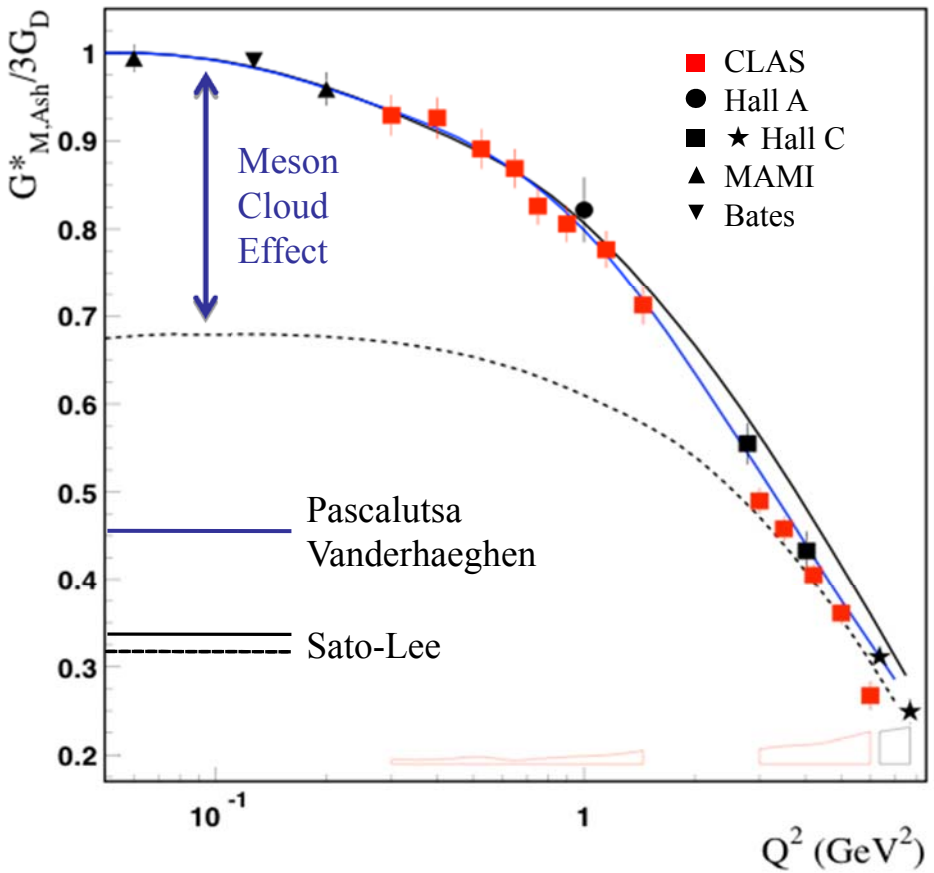
- $A_{1/2} \alpha 1/Q^3$
- $A_{3/2} \alpha 1/Q^5$
- $G_M^* \alpha 1/Q^4$

q^2q

Phys. Rev. C80, 055203 (2009)



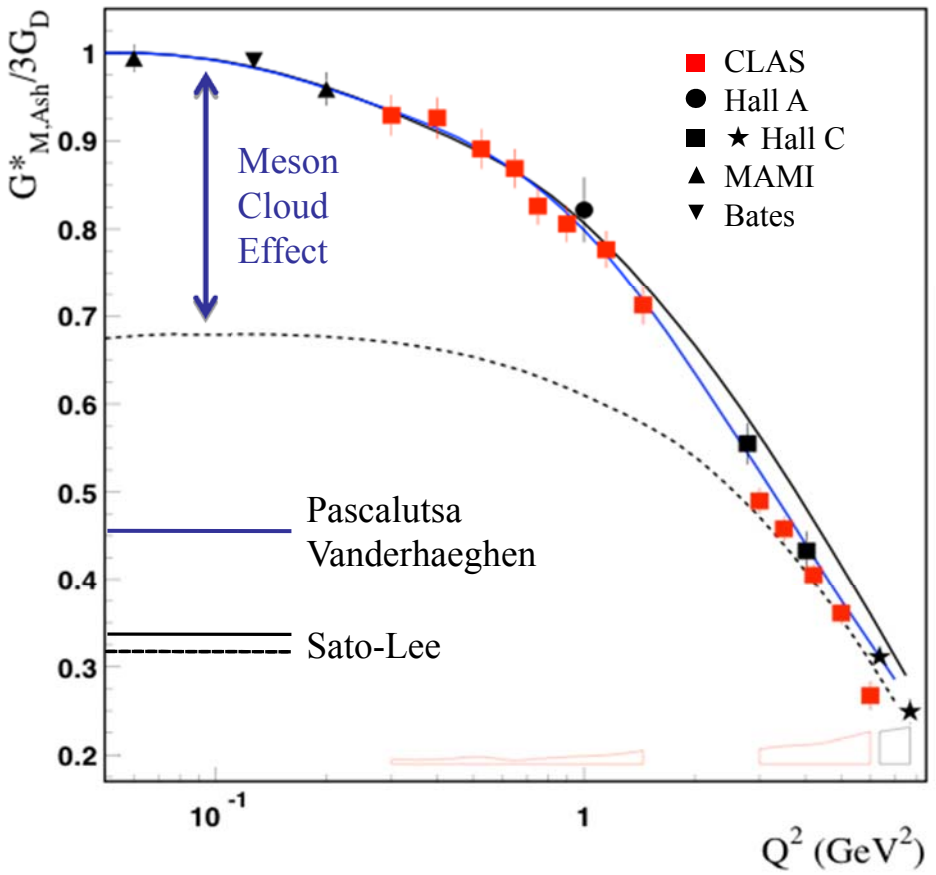
$N \rightarrow \Delta$ Multipole Ratios R_{EM} , R_{SM}



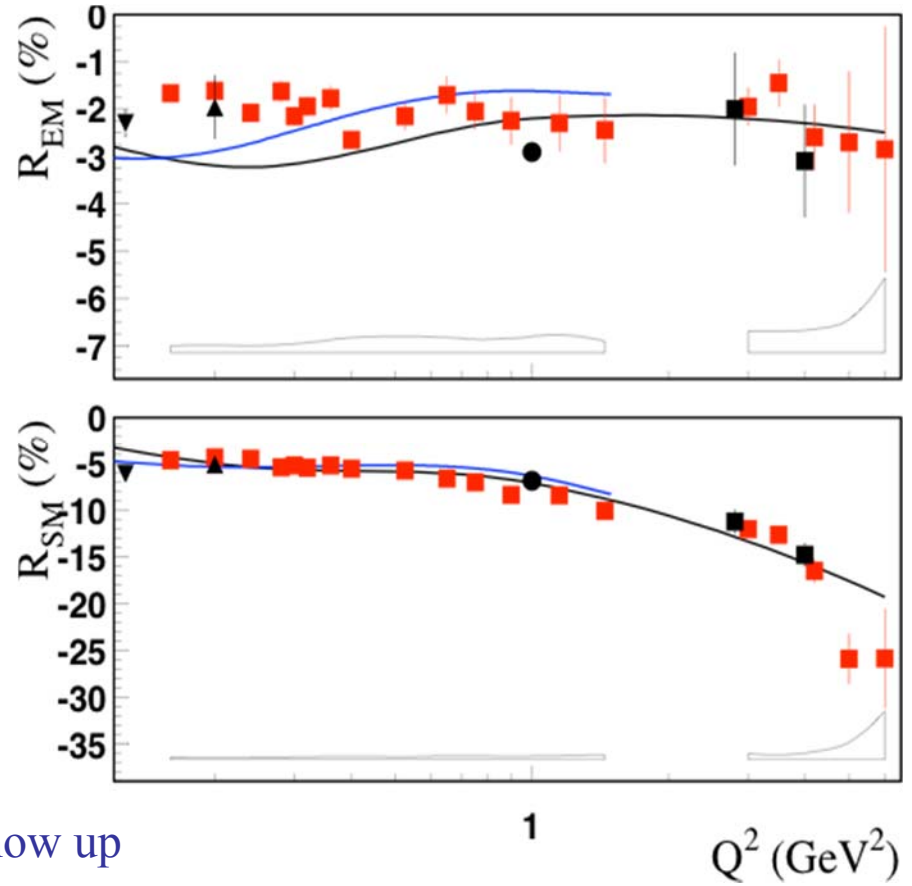
Phys. Rev. Lett. 97, 112003 (2006)

- $G^*_{M,J.-S.} \rightarrow 1/Q^4$ $G^*_{M,Ash} \rightarrow 1/Q^5$

$N \rightarrow \Delta$ Multipole Ratios R_{EM} , R_{SM}

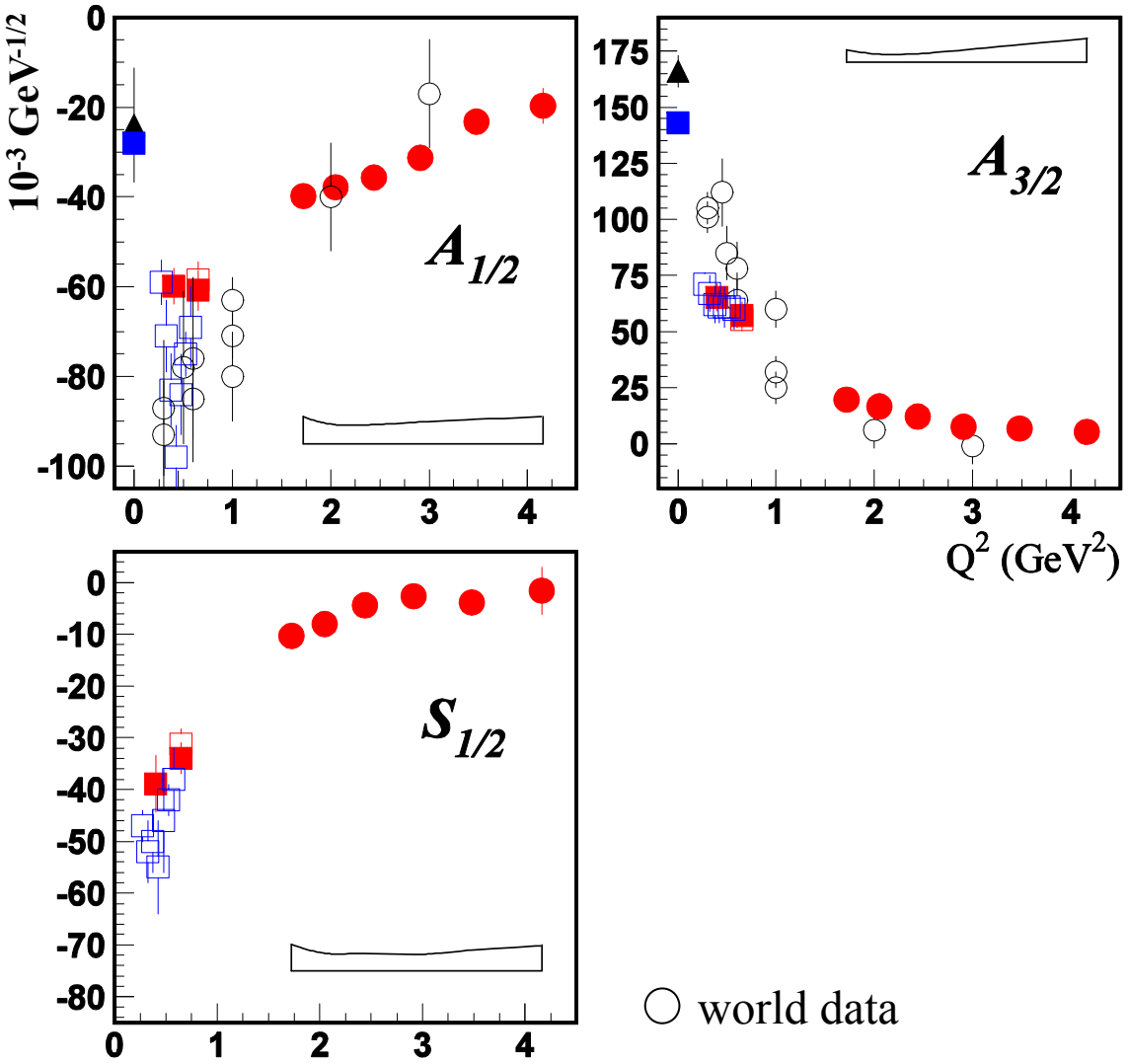


Phys. Rev. Lett. 97, 112003 (2006)



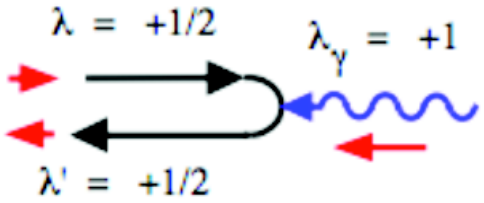
- New trend towards pQCD behavior does not show up
  - $R_{EM} \rightarrow +1$ $R_{SM} \rightarrow$ const
  - $G^*_{M,J.-S.} \rightarrow 1/Q^4$ $G^*_{M,Ash} \rightarrow 1/Q^5$
- CLAS12 can measure G^*_M, R_{EM}, and R_{SM} up to Q^2~12 GeV^2

$N(1520)D_{13}$ Helicity Asymmetry

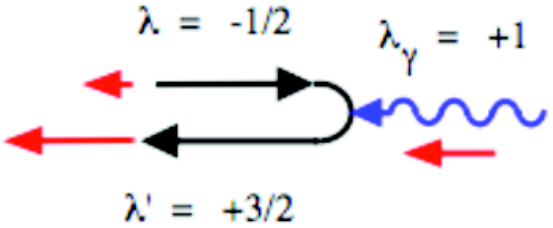


$$A_{hel} = \frac{A_{1/2}^2 - A_{3/2}^2}{A_{1/2}^2 + A_{3/2}^2}$$

$A_{1/2}$



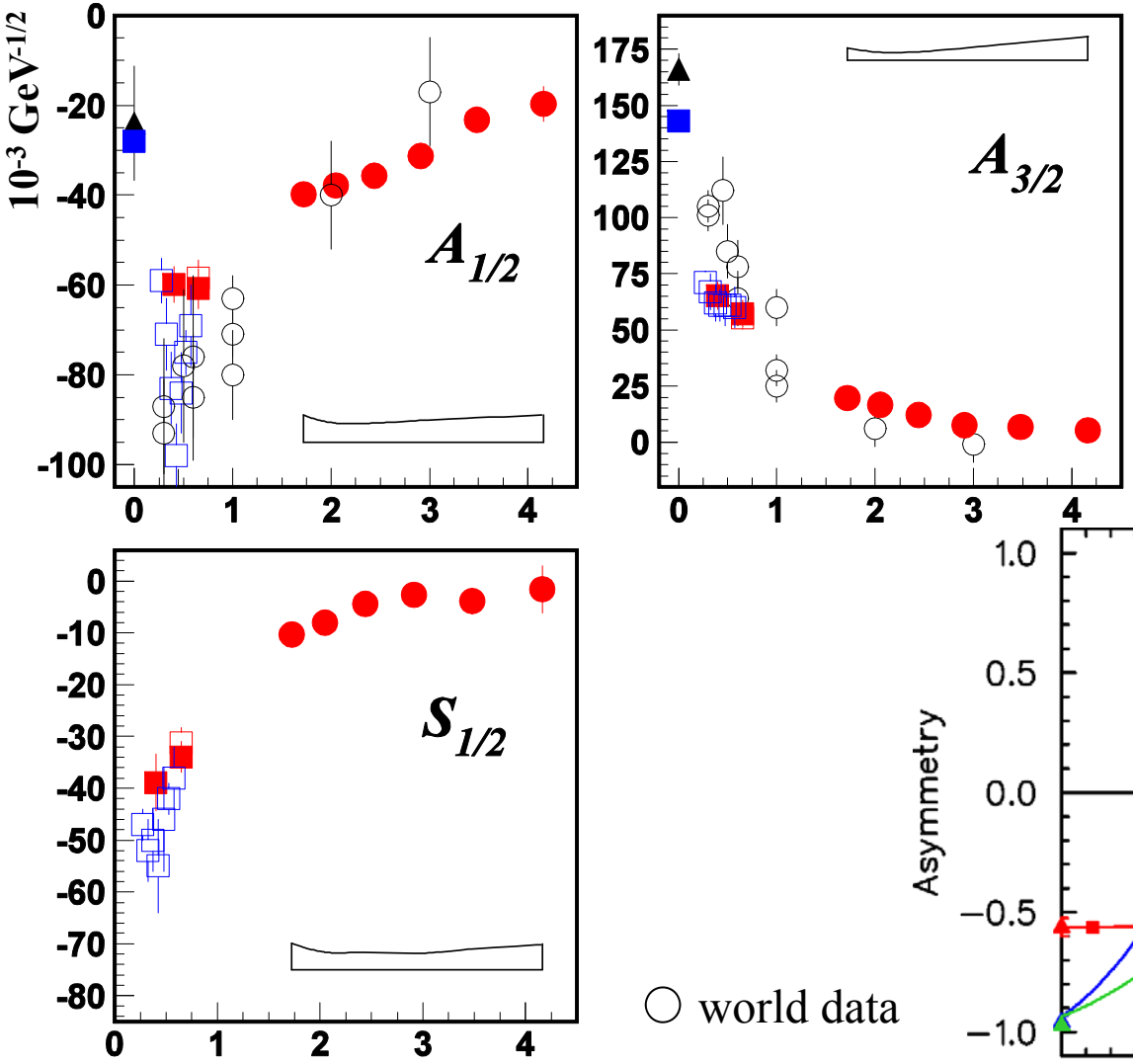
$A_{3/2}$



○ world data

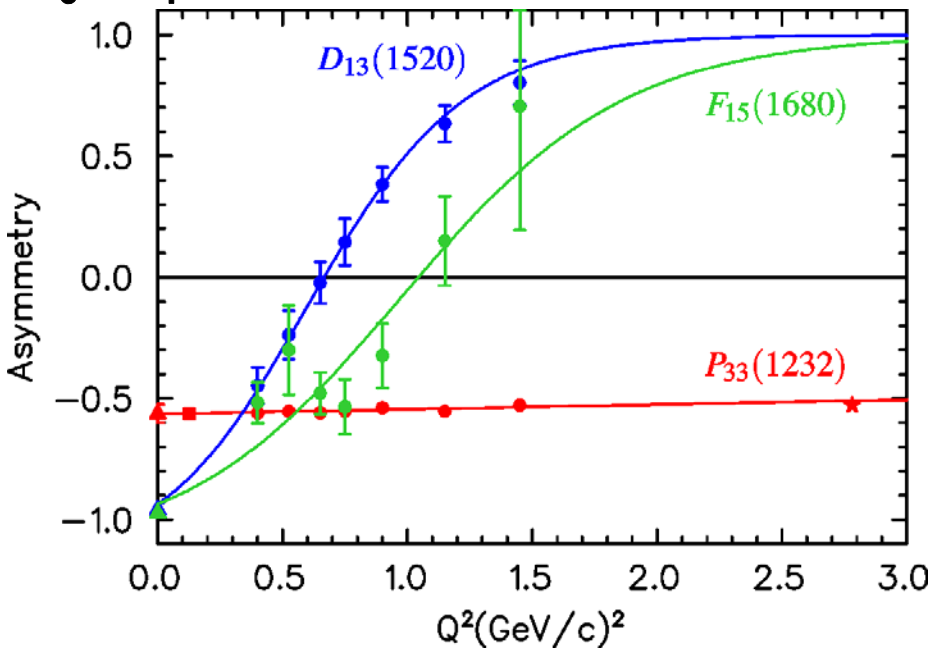
▲ PDG estimation ● ■ Nπ (UIM, DR) □ Nπ, Nππ combined analysis □ Nππ (JM)

$N(1520)D_{13}$ Helicity Asymmetry



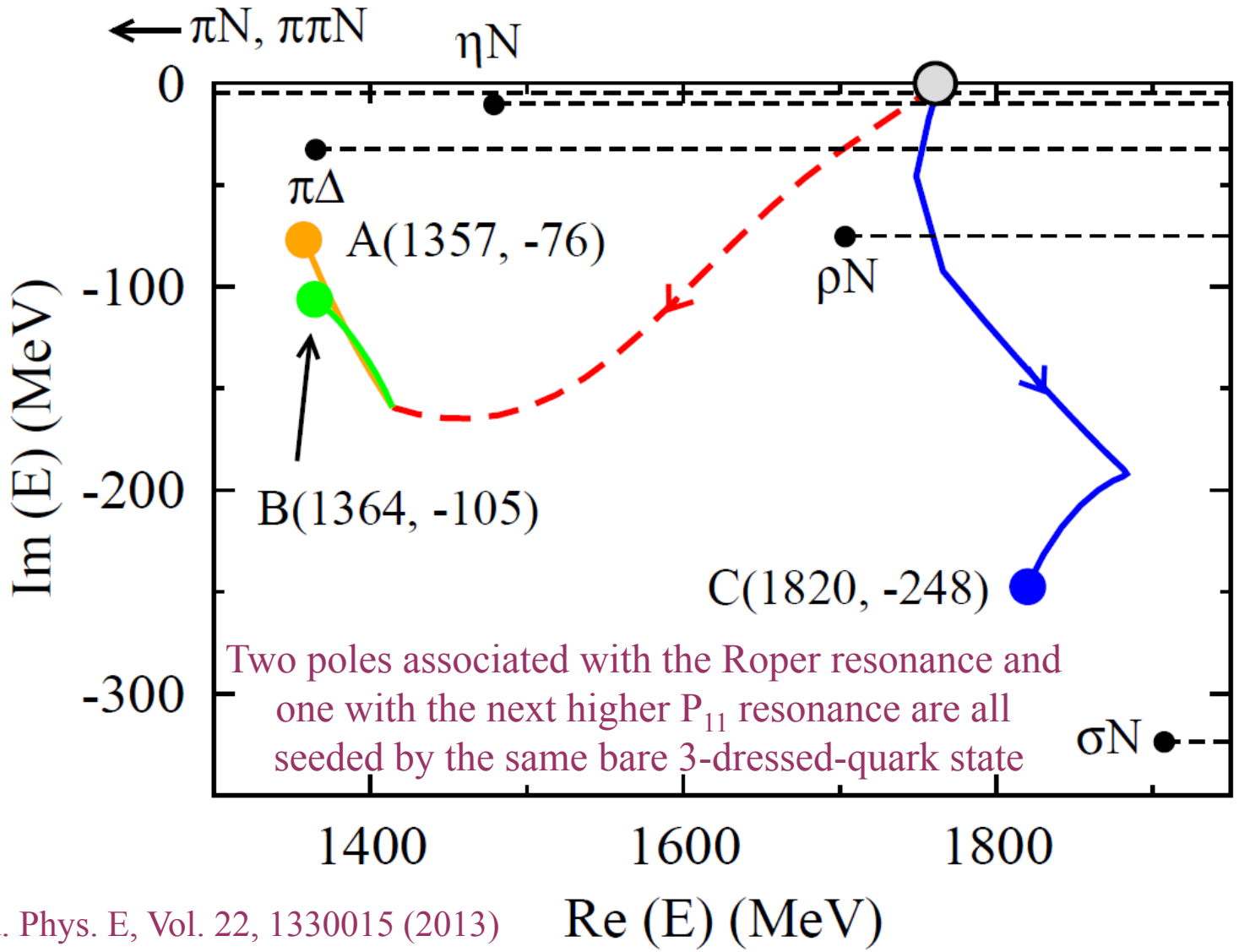
$$A_{hel} = \frac{A_{1/2}^2 - A_{3/2}^2}{A_{1/2}^2 + A_{3/2}^2}$$

L. Tiator



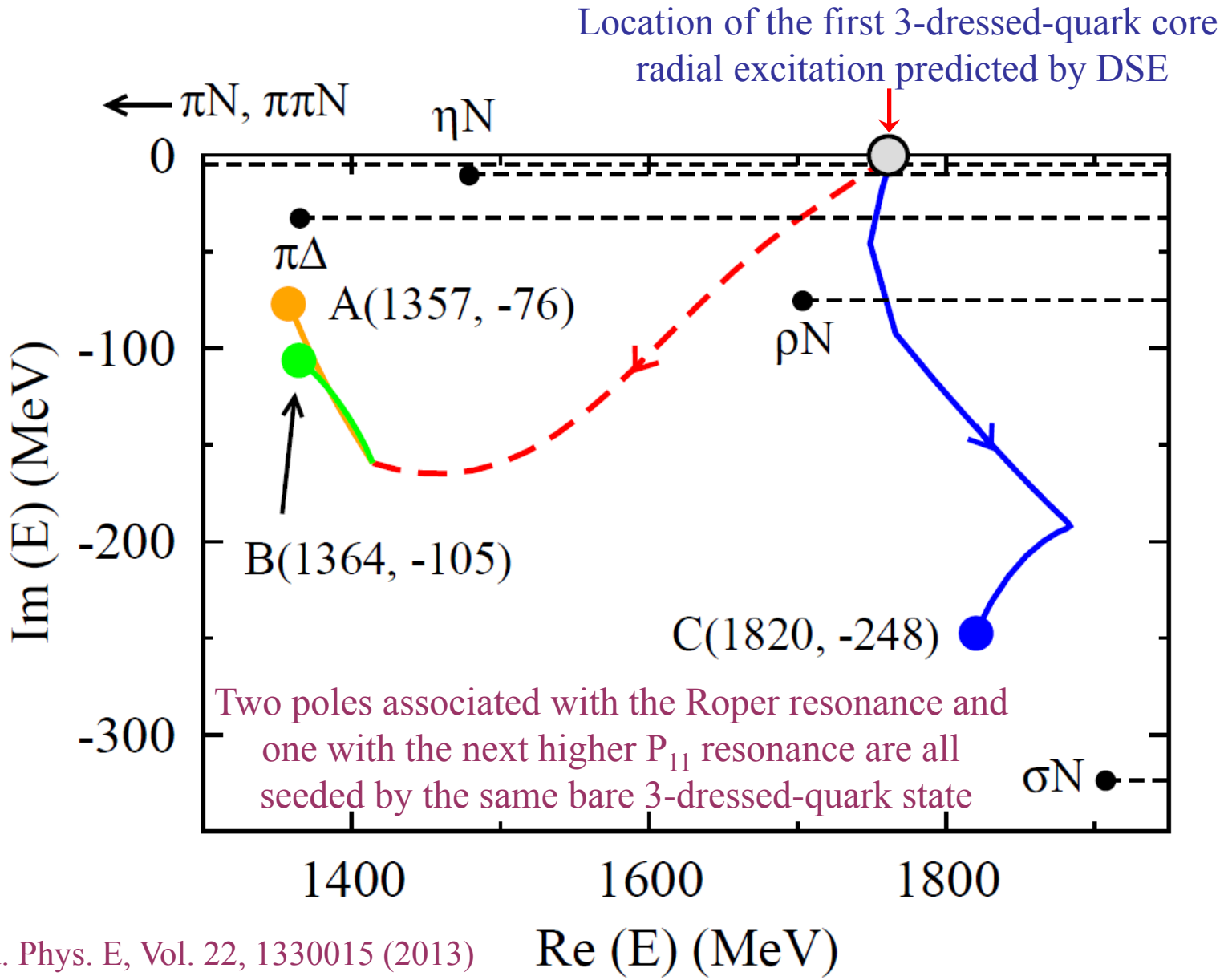
QCD-Based Models and Theory

DSE and EBAC/ANL-Osaka Approaches



Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013)

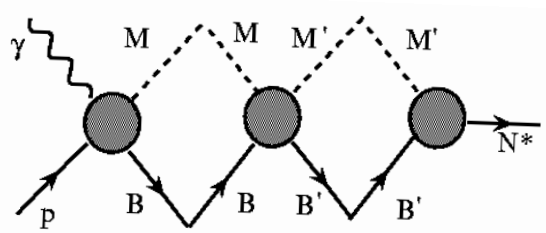
DSE and EBAC/ANL-Osaka Approaches



Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013)

Progress in Experiment and Phenomenology

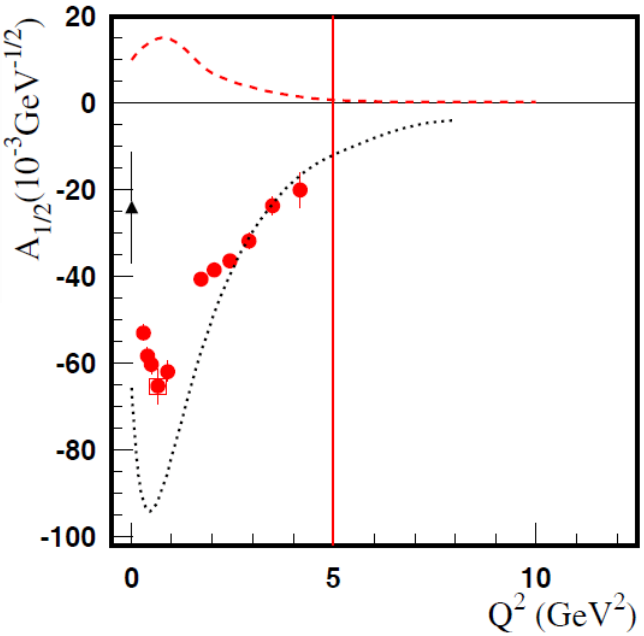
Meson-Baryon Dressing



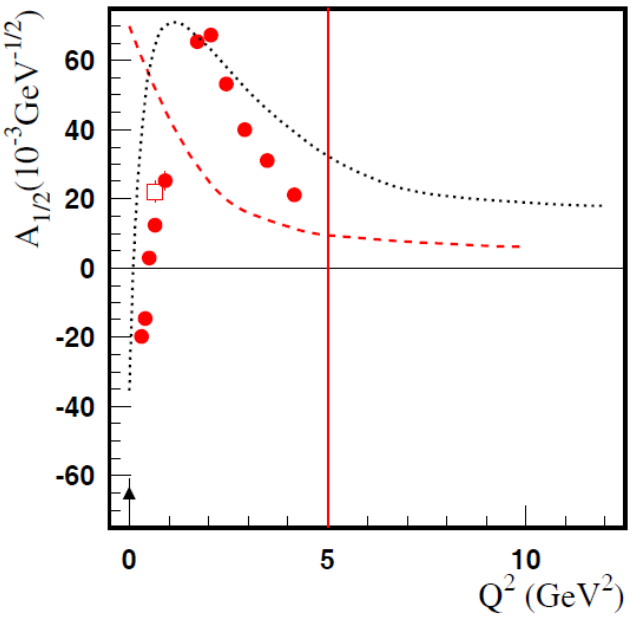
absolute meson-baryon cloud amplitudes (EBAC now ANL-Osaka)

quark core contributions (constituent quark models)

$D_{13}(1520)$



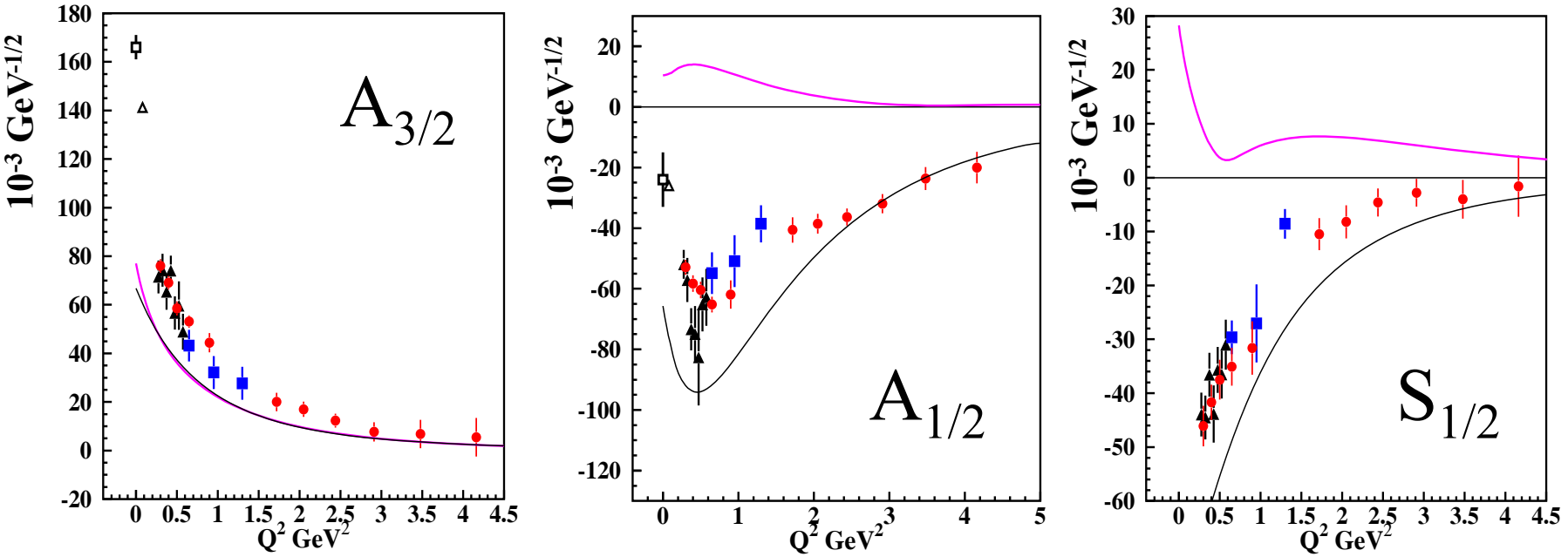
$P_{11}(1440)$



CLAS: Nπ and Nπ/Nππ combined (Phys. Rev. C80, 055203, 2009)

- Resonance structures can be described in terms of an internal quark core and a surrounding meson-baryon cloud whose relative contribution decreases with increasing Q^2.
- Data on $\gamma_v NN^*$ electrocouplings from exclusive meson electroproduction experiments at $Q^2 > 5$ GeV^2 will afford first direct access to the non-perturbative strong interaction among dressed quarks, their emergence from QCD, and the subsequent N* formation.

Electrocouplings of N(1520)D_{13}



Argonne Osaka / EBAC DCC MB dressing (absolute values)

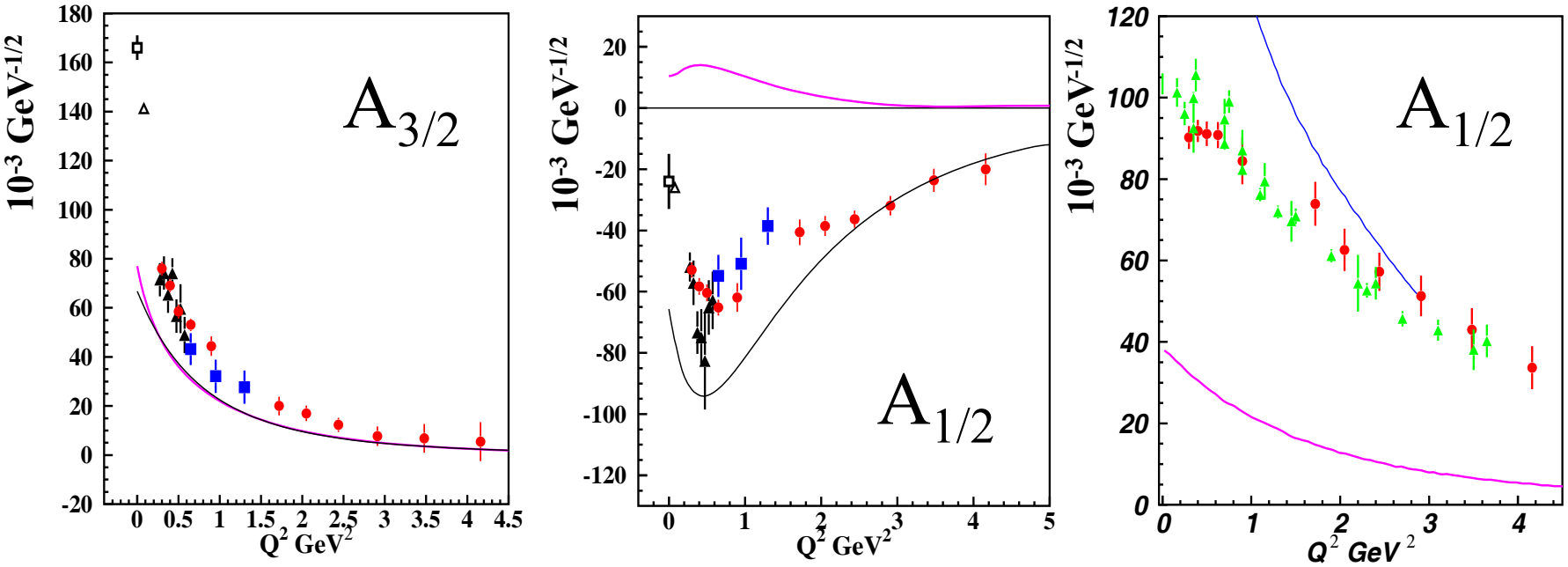
E. Santopinto, M. Giannini, hCQM PRC 86, 065202 (2012)

$\pi^+\pi^-p$ 2012

$\pi^+\pi^-p$ 2010

$N\pi$ 2009

Electrocouplings of $N(1520)D_{13}$ and $N(1535)S_{11}$



Argonne Osaka / EBAC DCC MB dressing (absolute values)

E. Santopinto, M. Giannini, hCQM PRC 86, 065202 (2012)

S. Capstick, B.D. Keister (rCQM) PRD51, 3598 (1995)

$\pi^+\pi^-p$ 2012

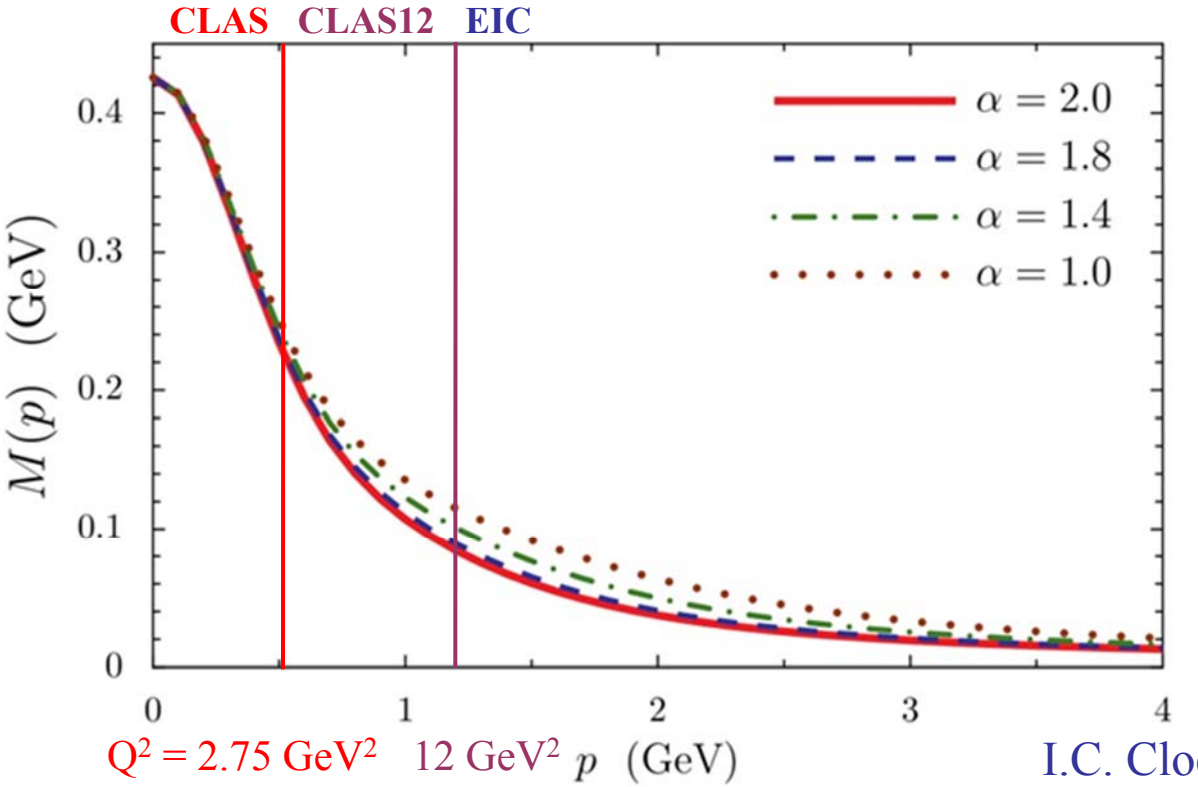
$\pi^+\pi^-p$ 2010

$N\pi$ 2009

ηp CLAS/Hall-C

Dyson-Schwinger Equation (DSE) Approach

DSE approaches provide links between dressed quark propagators, form factors, scattering amplitudes, and QCD.



N* electrocouplings can be determined by applying Bethe-Salpeter / Faddeev equations to 3 dressed quarks while the properties and interactions are derived from QCD.

Impact of a modified momentum dependence of the dressed-quark propagator.

I.C. Cloet et al., arXiv:1304.0855[nucl-th]

DSE electrocouplings of several excited nucleon states will become available as part of the commitment of the Argonne NL.

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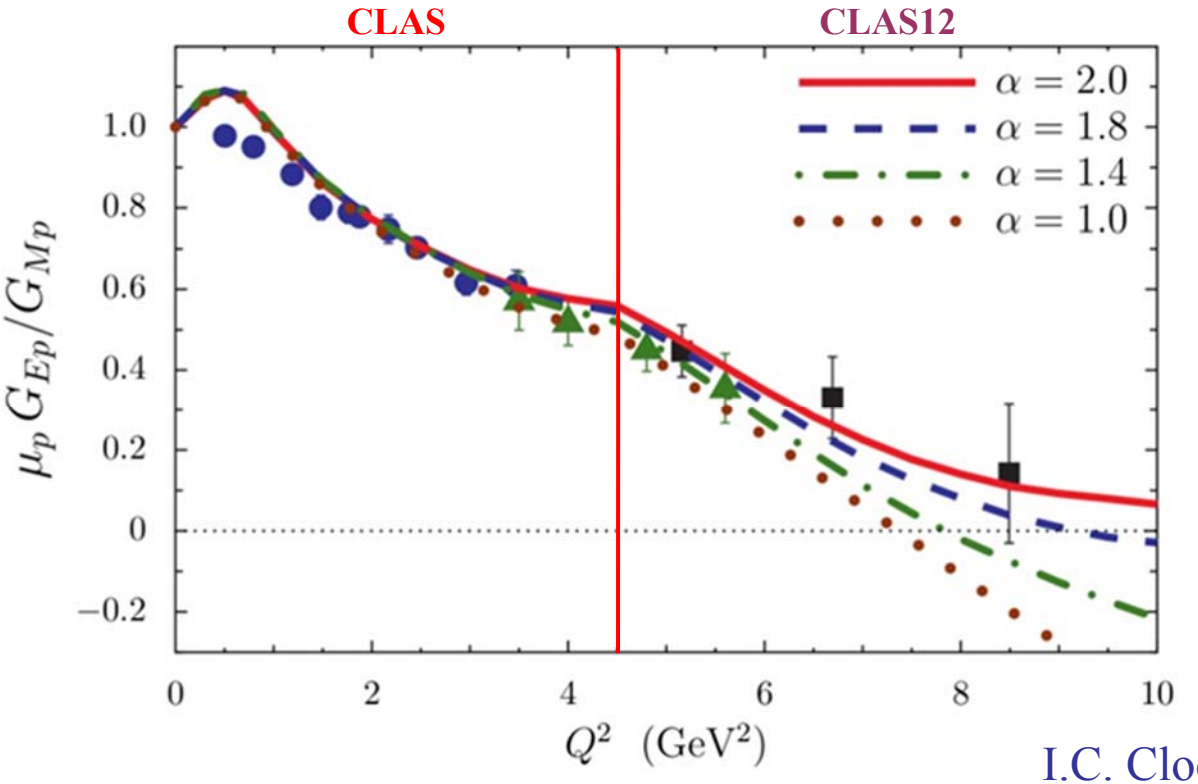


N* electrocouplings can be determined by applying Bethe-Salpeter / Faddeev equations to 3 dressed quarks while the properties and interactions are derived from QCD.

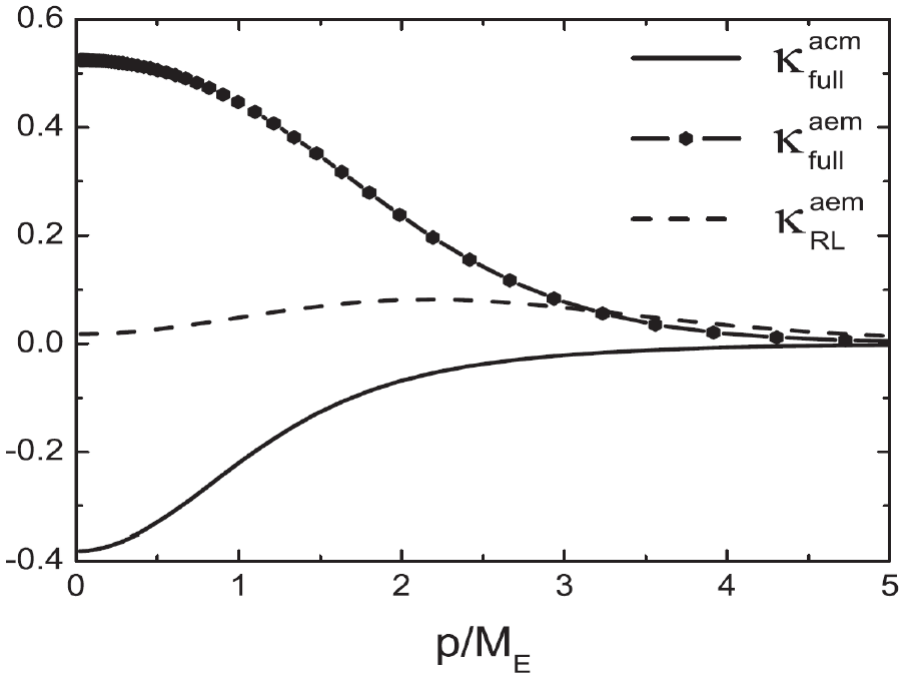
DSE calculations of elastic and transition form factors are very sensitive to the momentum dependence of the dressed-quark propagator.

I.C. Cloet et al., arXiv:1304.0855[nucl-th]

DSE electrocouplings of several excited nucleon states will become available as part of the commitment of the Argonne NL.

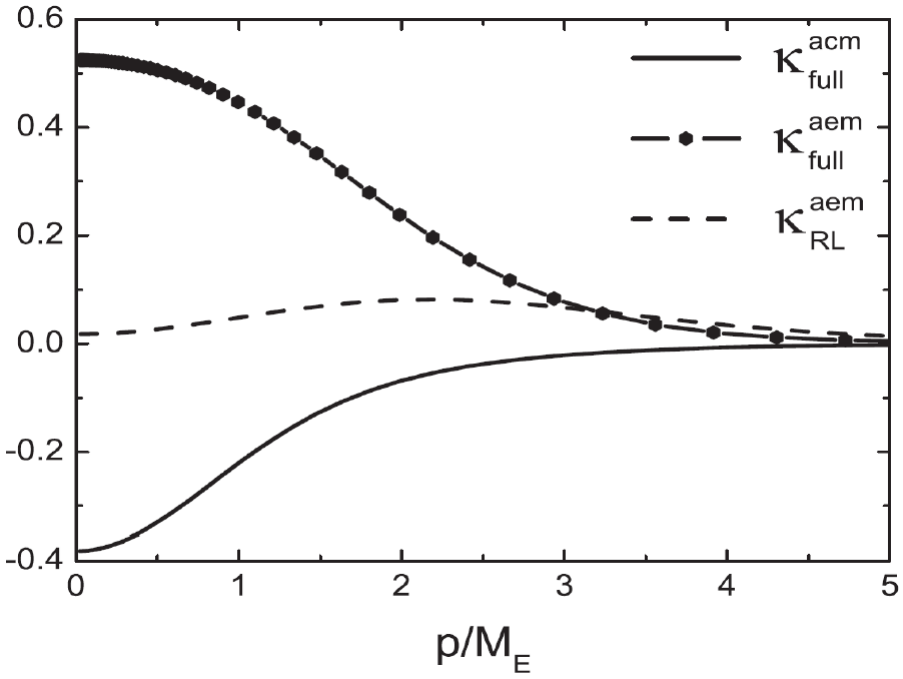
Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013) 1-99

Anomalous Magnetic Moment in DSE Approach



L. Chang et al., PRL 106 (2011) 072001

Anomalous Magnetic Moment in DSE Approach



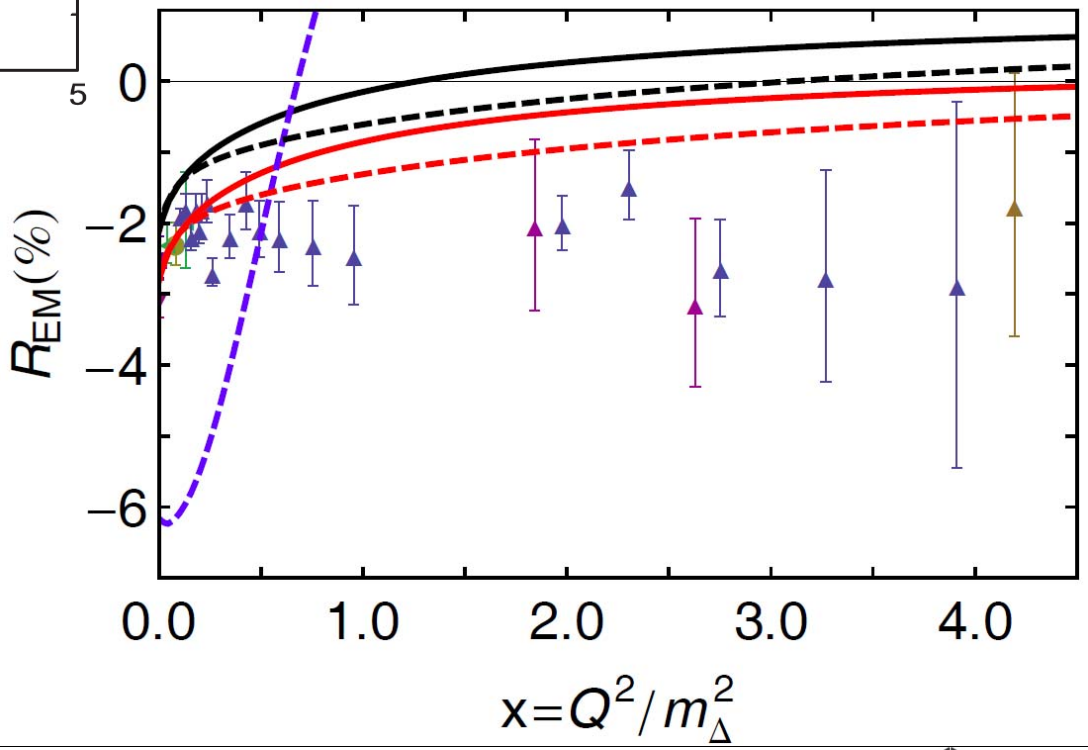
L. Chang et al., PRL 106 (2011) 072001

J. Segovia

contact interaction

sophisticated interaction with momentum dependent κ

renormalized at real photon point

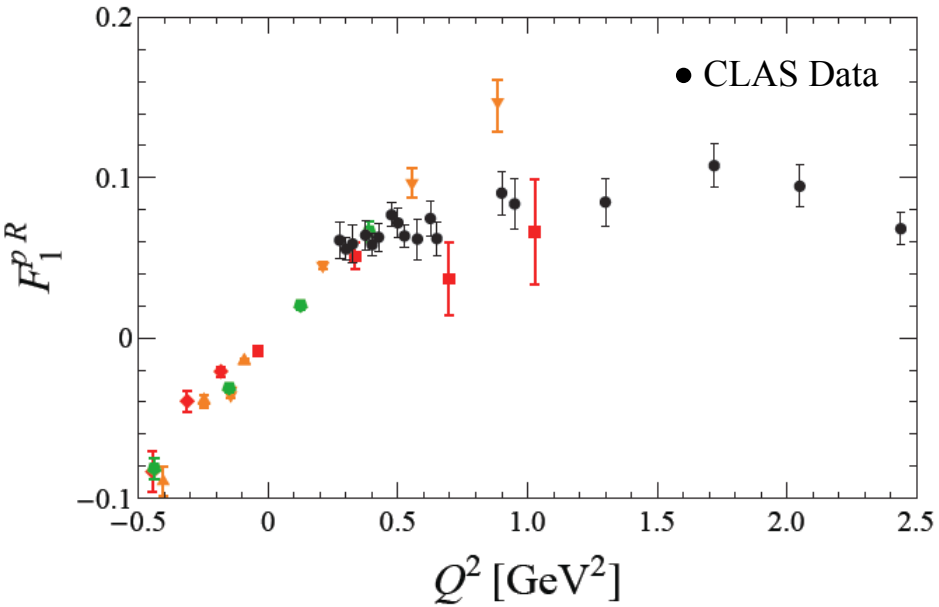


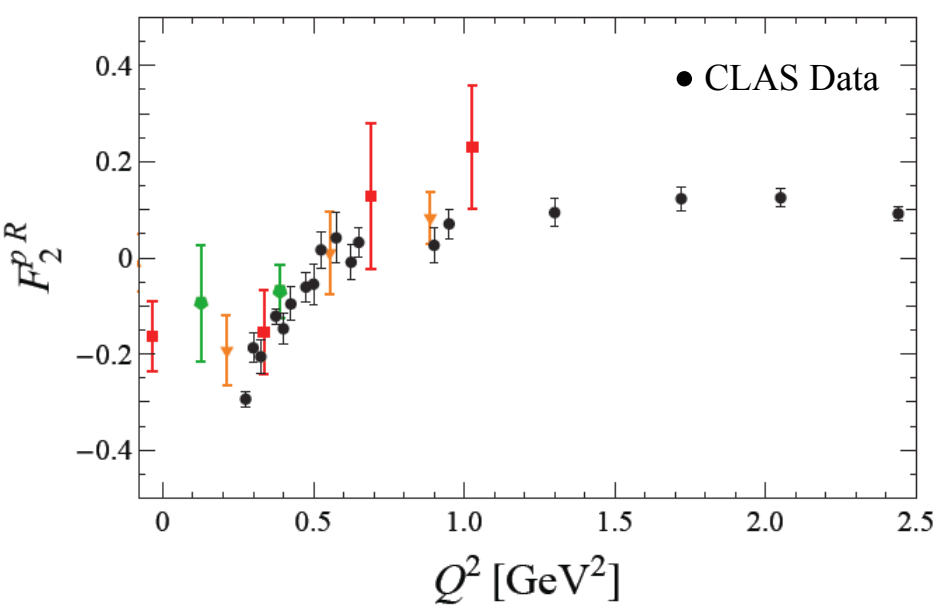
The DSE calculation of R_{EM} zero crossing is sensitive to the momentum dependent anomalous magnetic moment of the dressed-quark.

Roper Transition Form Factors in LQCD

p(1440)P_{11}

Huey-Wen Lin and S.D. Cohen



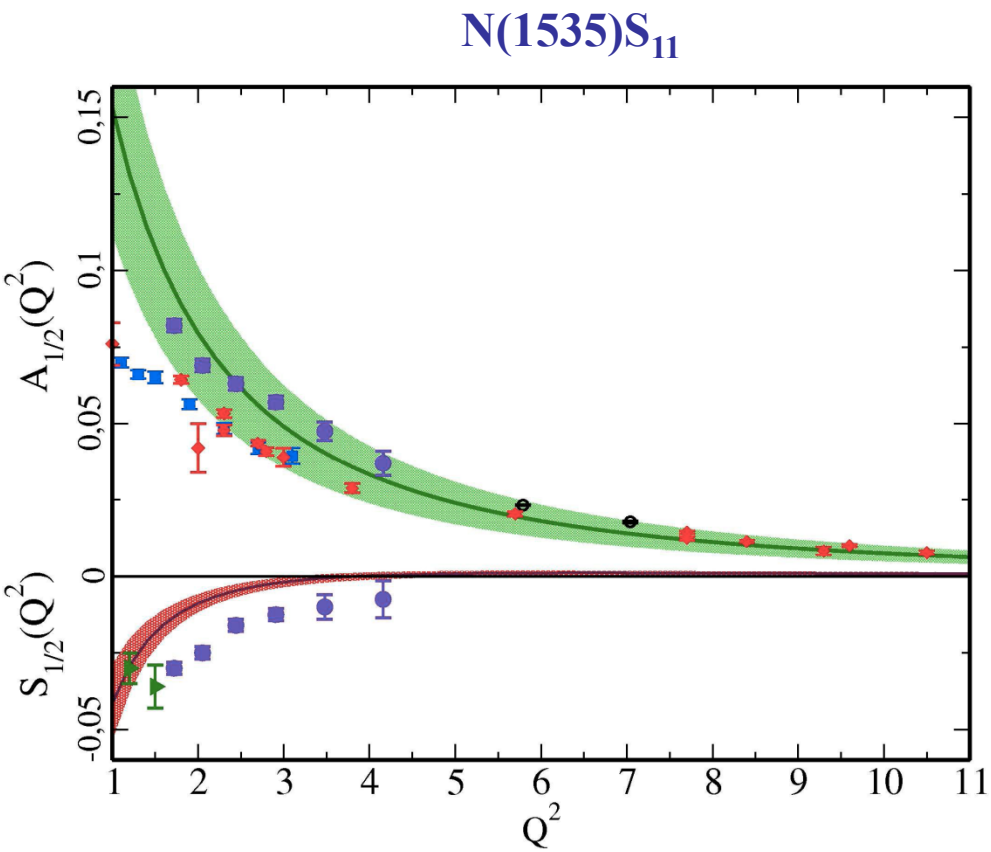


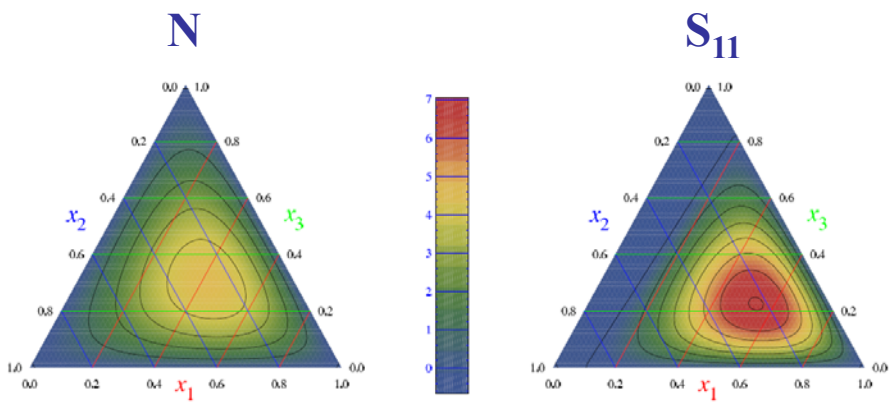
Lattice QCD calculations of the p(1440)P_{11} transition form factors have been carried out with various pion masses, m_π= **390**, **450**, and **875** MeV. Particularly remarkable is the zero crossing in F_2 that appears at the current statistics in the unquenched but not in the quenched calculations. This suggests that at low Q^2 the pion-cloud dynamics are significant in full QCD.

LQCD calculations of N* electrocouplings will be extended to $Q^2 = 10$ GeV^2 near the physical π-mass as part of the commitment of the JLab LQCD and EBAC groups in support of this proposal.

Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013) 1-99

LQCD & Light Cone Sum Rule (LCSR) Approach





LQCD is used to determine the moments of N* distribution amplitudes (DA) and the N* electrocouplings are determined from the respective DAs within the LCSR framework.

Calculations of $N(1535)S_{11}$ electrocouplings at Q^2 up to 12 GeV^2 are already available and shown by shadowed bands on the plot.

LQCD & LCSR electrocouplings of others N* resonances will be evaluated as part of the commitment of the University of Regensburg group.

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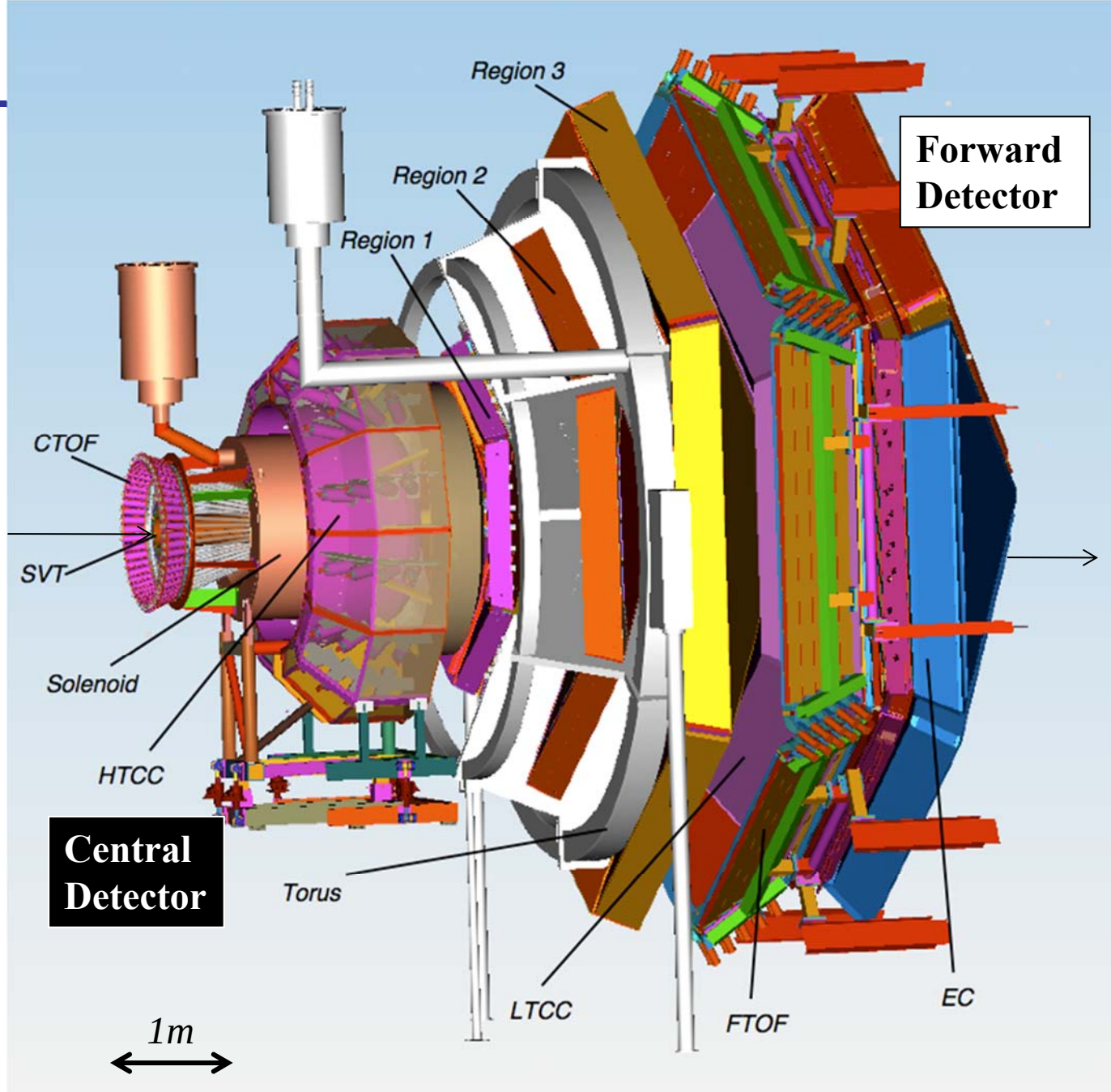
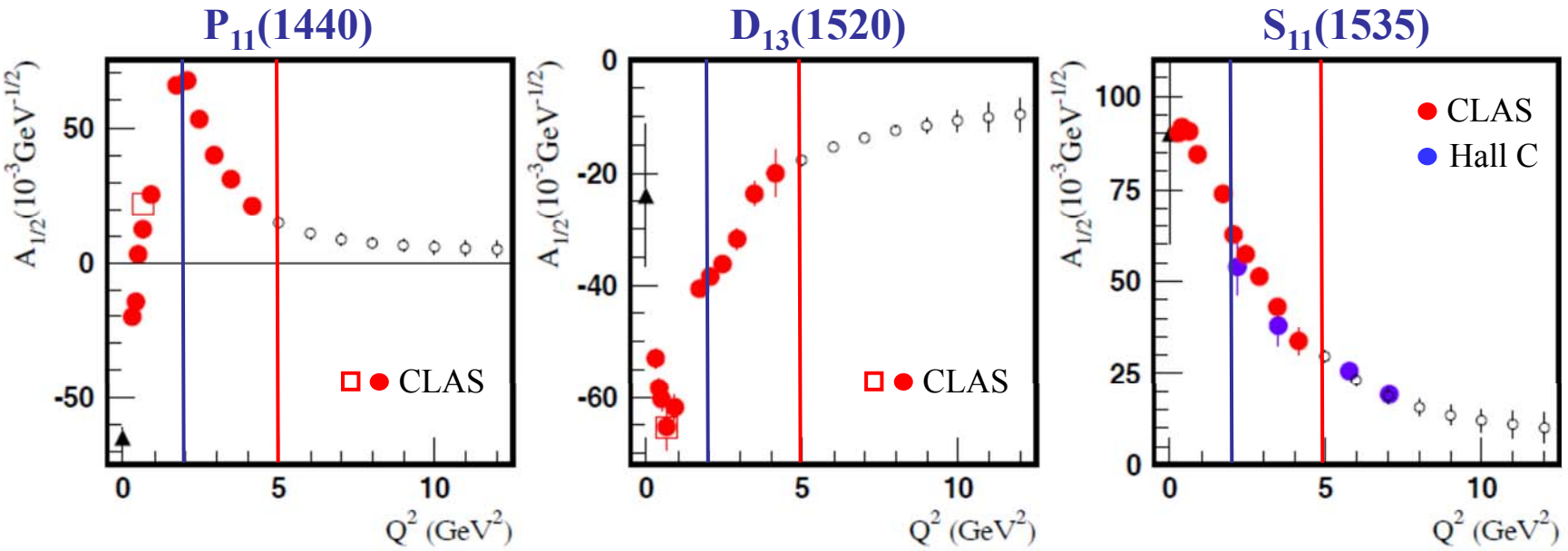
CLAS12

- Luminosity > 10^{35} $cm^{-2}s^{-1}$
- Hermeticity
- Polarization

- Baryon Spectroscopy
- Elastic Form Factors
- N to N* Form Factors
- GPDs and TMDs
- DIS and SIDIS
- Nucleon Spin Structure
- Color Transparency
- …



Anticipated N* Electrocouplings from Combined Analyses of Nπ/Nππ



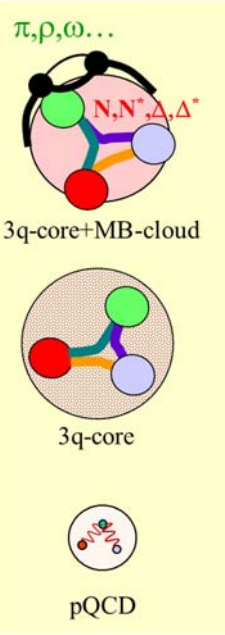
Open circles represent projections and all other markers the available results with the 6-GeV electron beam

➢ Examples of published and projected results obtained within 60d for three prominent excited proton states from analyses of Nπ and Nππ electroproduction channels. Similar results are expected for many other resonances at higher masses, e.g. $S_{11}(1650)$, $F_{15}(1685)$, $D_{33}(1700)$, $P_{13}(1720)$, …

➢ The approved CLAS12 experiments E12-09-003 (NM, Nππ) and E12-06-108A (KY) are currently the only experiments that can provide data on γ_vNN* electrocouplings for almost all well established excited proton states at the highest photon virtualities ever achieved in N* studies up to Q^2 of 12 GeV^2, see https://userweb.jlab.org/~carman/ky12/temple-final.pdf.

Summary

- First high precision photo- and electroproduction data have become available and led to a new wave of significant developments in reaction and QCD-based theories.
- New high precision hadro-, photo-, and electroproduction data off the proton and the neutron will stabilize coupled channel analyses and expand the validity of reaction models, allowing us to
  - investigate and search for baryon hybrids,
  - establish a repertoire of high precision spectroscopy parameters, and
  - measure light-quark-flavor separated electrocouplings over an extended Q^2-range for a wide variety of N* states.



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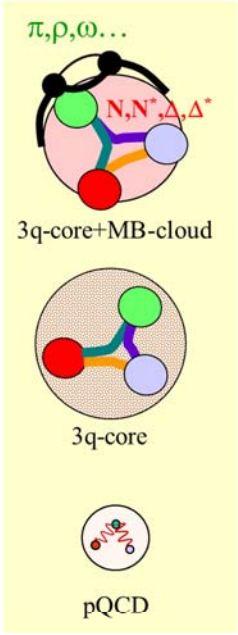
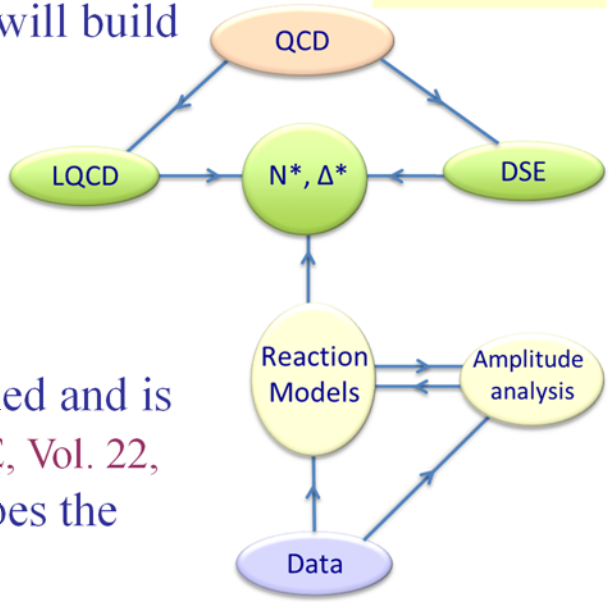
- Comparing these results with DSE, LQCD, LCSR, and rCQM will build insights into
  - the strong interaction of dressed quarks and their confinement,
  - the emergence of bare quark dressing and dressed quark interactions from QCD, and
  - the QCD β-function and the origin of 98% of nucleon mass.
- A tight collaboration of experimentalists and theorists has formed and is needed to push these goals, see Review Article Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013) 1-99, that shall lead to a QCD theory that describes the strong interaction from current quarks to nuclei.





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