Nucleon Resonances and their Structure

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UNIVERSITY OF SOUTH CAROLINA

MENU 2016

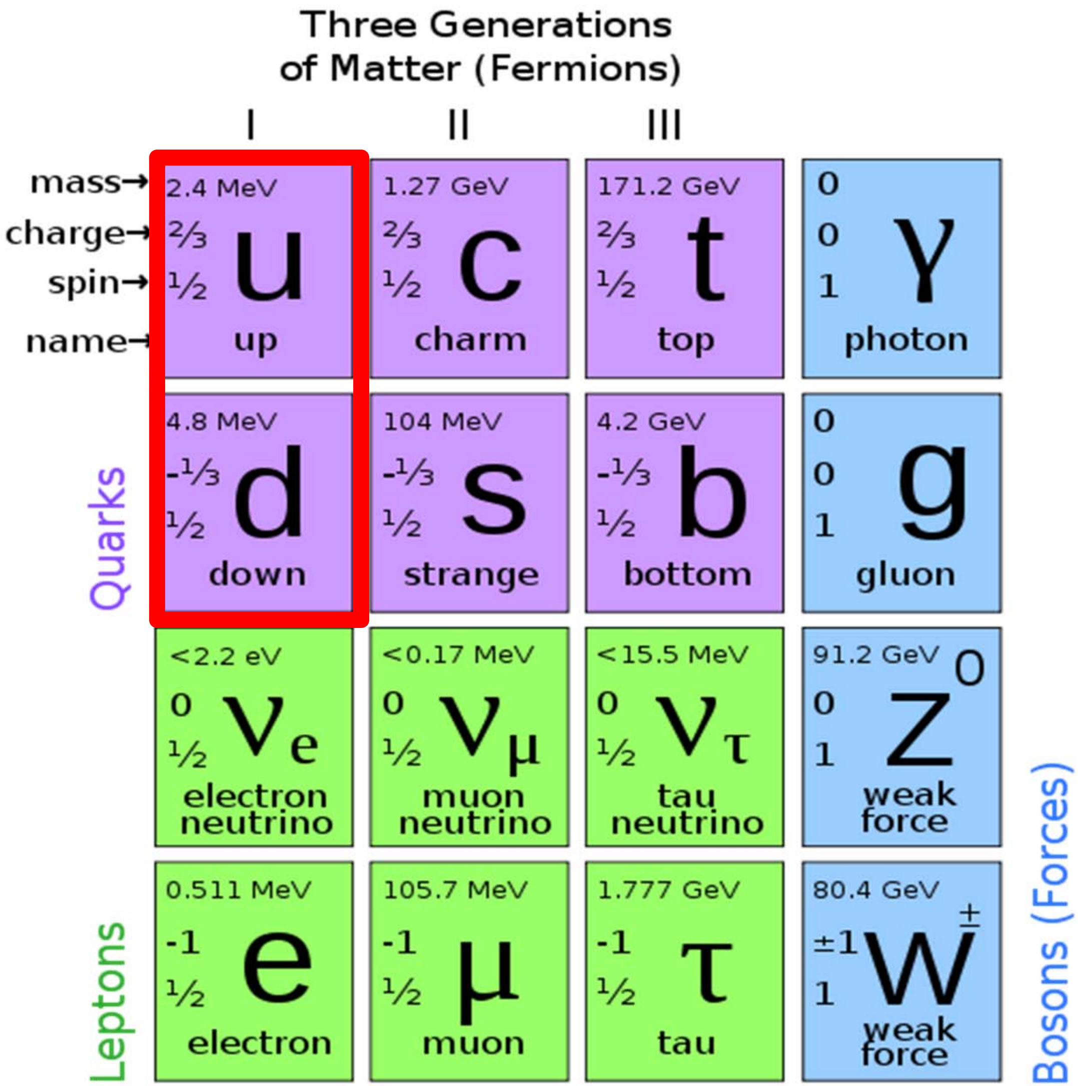
The 14th International Conference on Meson-Nucleon Physics
and the Structure of the Nucleon
July 25 - 30, Kyoto, Japan

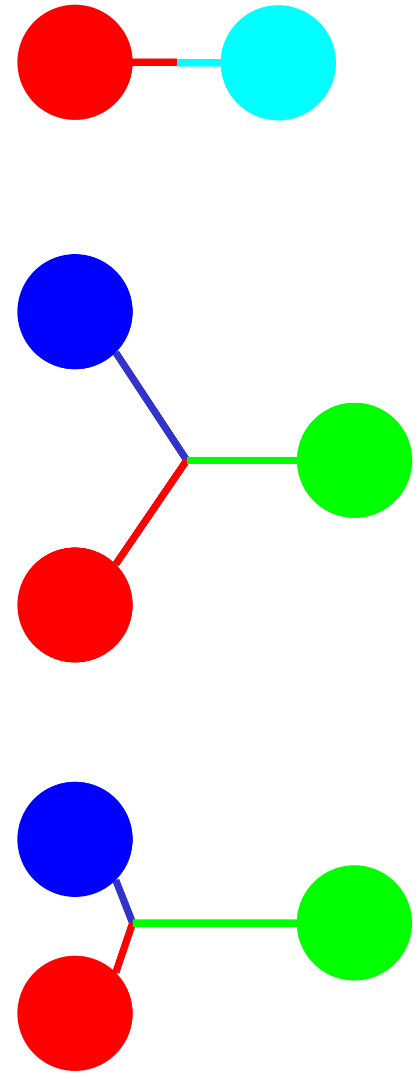
- **γNN* Vertexcouplings:** A unique exploration of baryon and quark structure?
- **Analysis and New Results:** Phenomenological but consistent!
- **Outlook:** New experiments with extended scope and kinematics!
- **QCD based Theory:** Can we solve non-perturbative QCD and confinement?

This work is supported in parts by the National Science Foundation under Grant PHY 1505615.

Spectroscopy

Build your Mesons and Baryons …

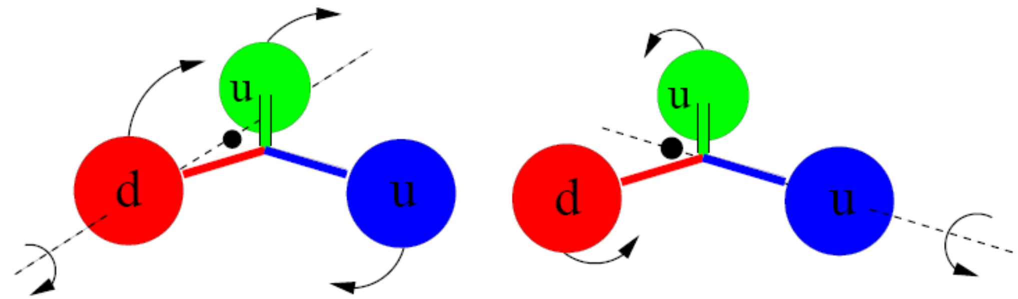




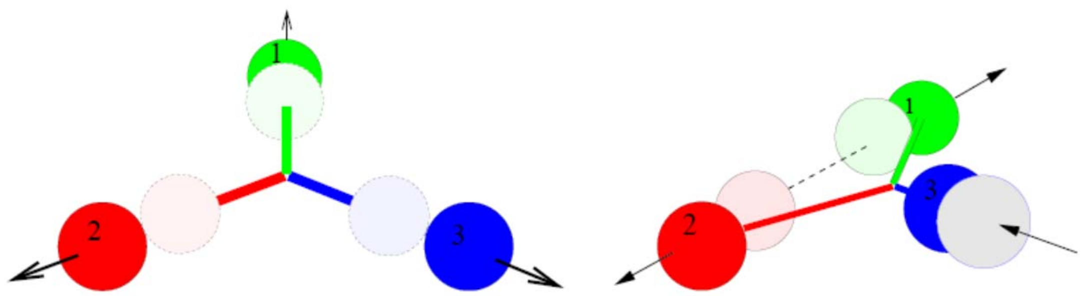
N and Δ Excited Baryon States …

Simon Capstick

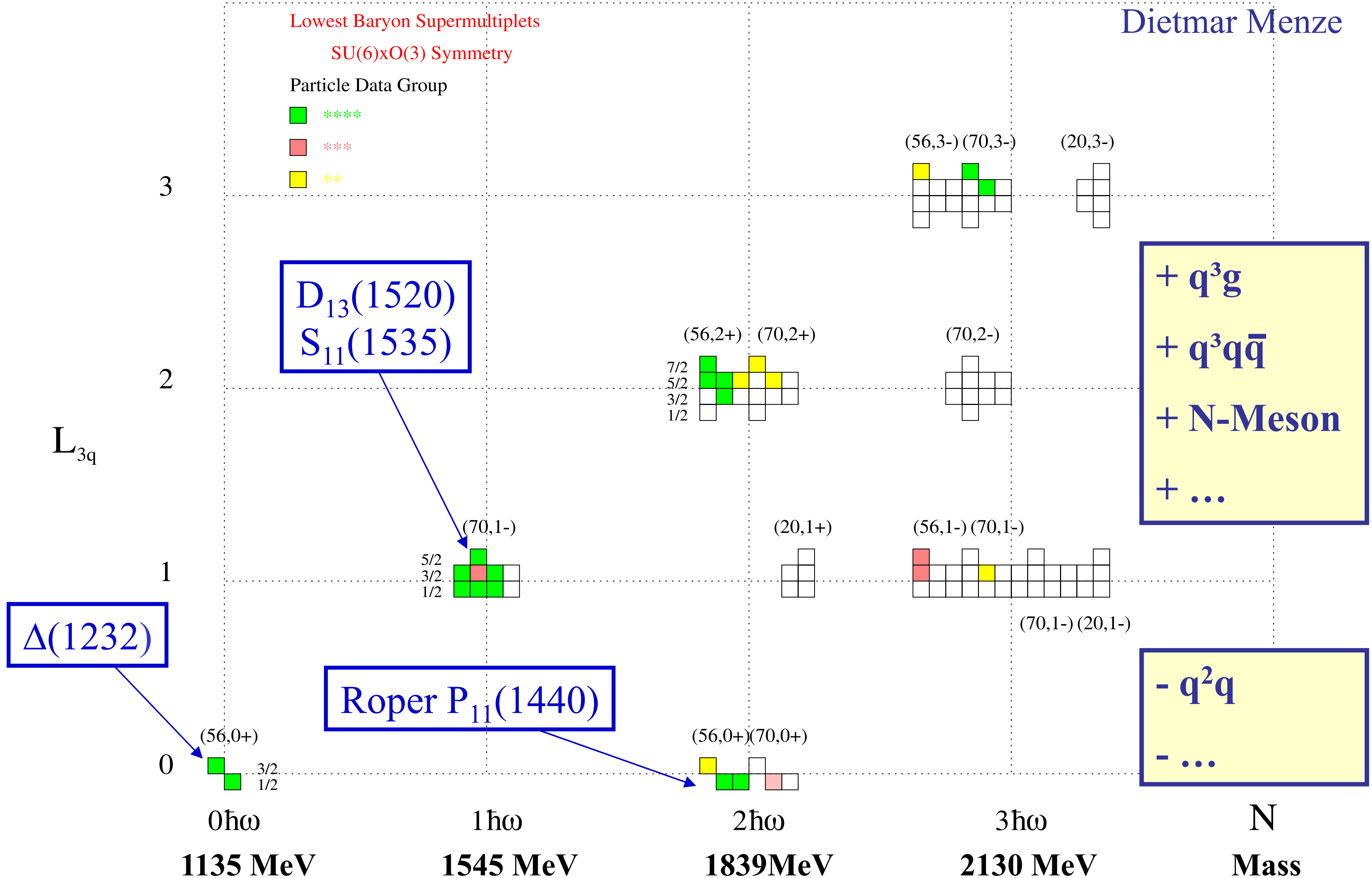
- Orbital excitations (two distinct kinds in contrast to mesons)



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

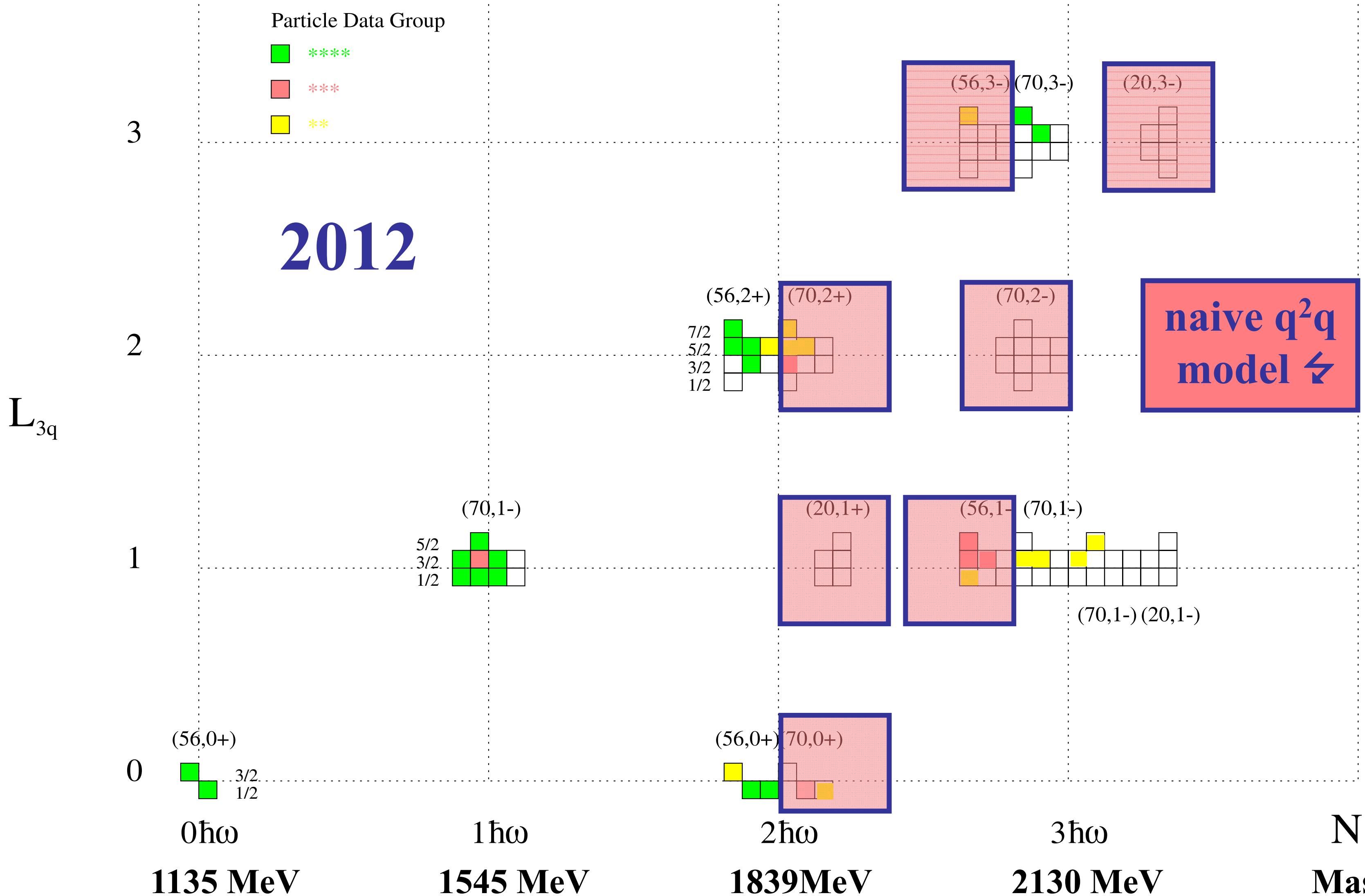


Quark Model Classification of N*



Quark Model Classification of N*

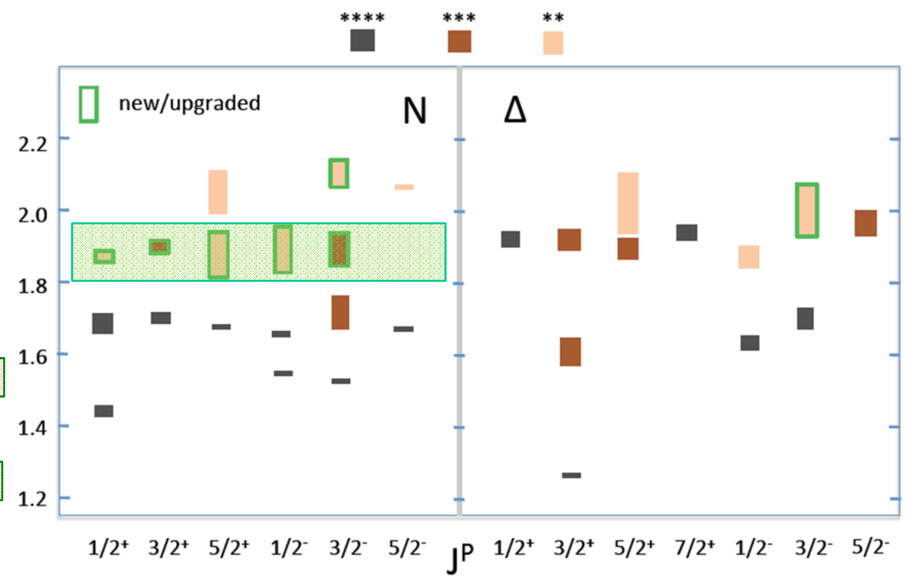
BnGa energy-dependent coupled-channel PWA of CLAS $K^+\Lambda$ and other data



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

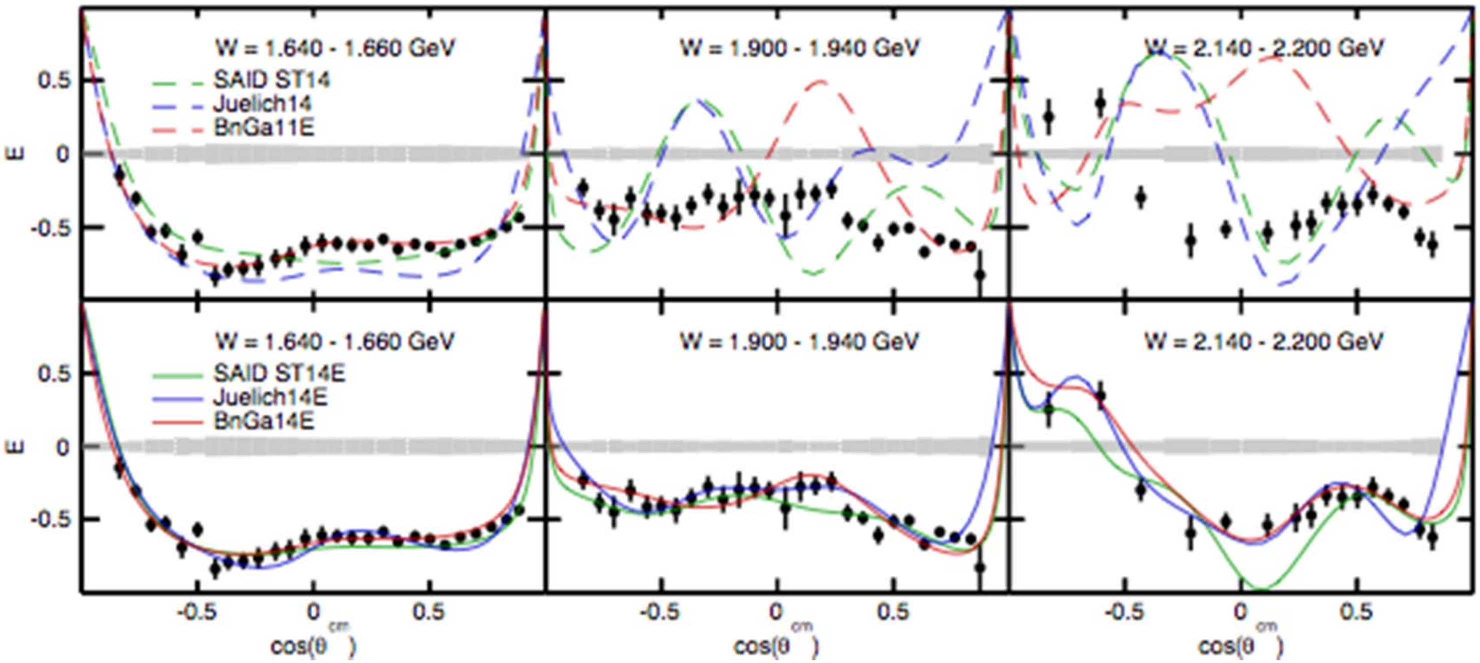


Are we observing parity doublets with the new states or not?

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

New FROST Results from $\vec{\gamma}\vec{p} \rightarrow \pi^+ n$

W = 1.650 GeV **W = 1.920 GeV** **W = 2.170 GeV**



before fit

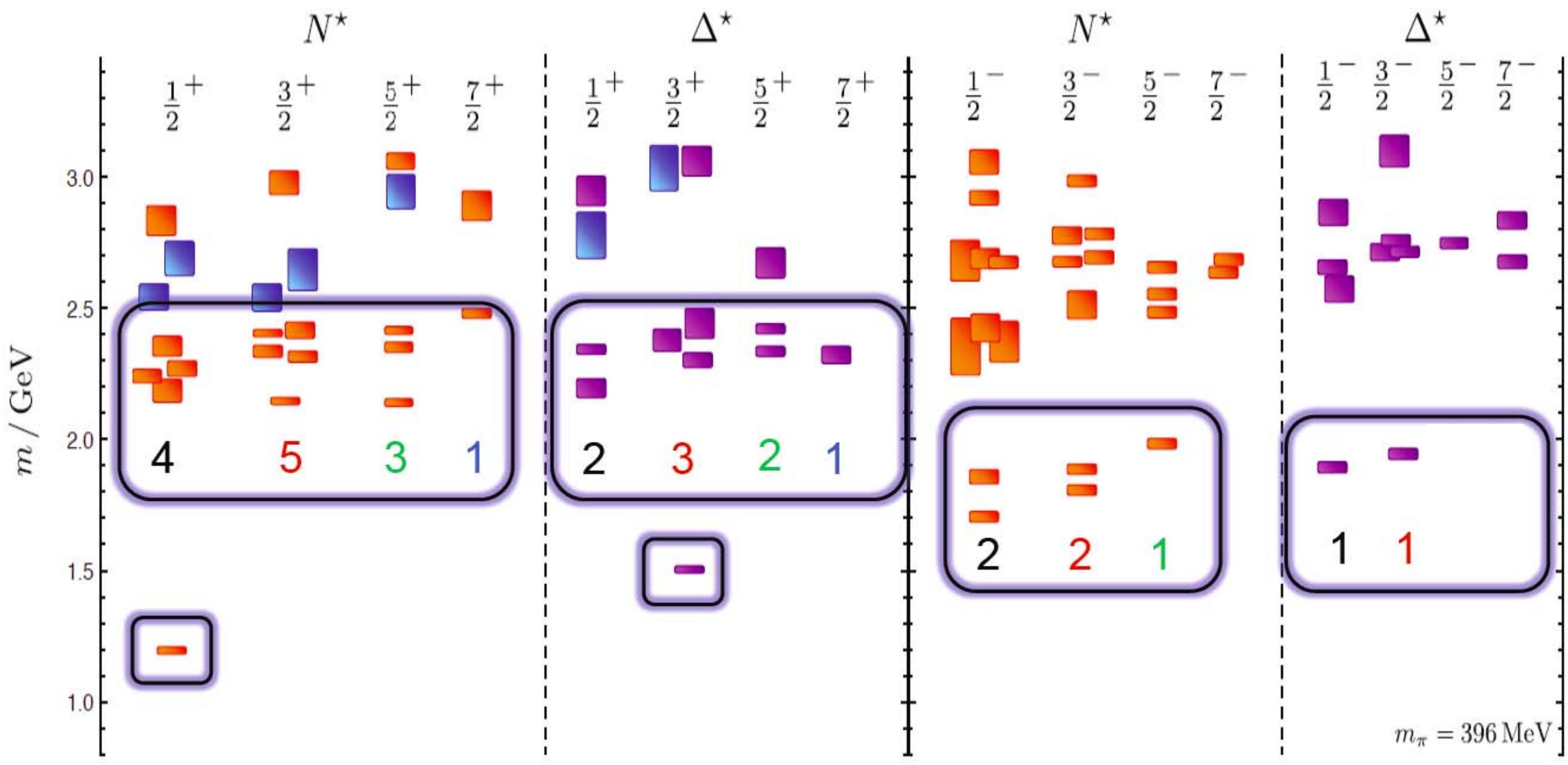
after fit

- FROST experiment produced 900 data points of the **double-polarization observable E** in π^+ photoproduction with circularly polarized beam on longitudinally polarized protons for W = 1240 - 2260 MeV.
- Significant improvements of the description of the data in SAID, Jülich, and BnGa partial-wave analyses after fitting.
- New evidence found in this data for a $\Delta(2200)7/2^-$ resonance (BnGa analysis).

S. Strauch *et al.*, Phys. Let. B **750** (2015) 53 and A.V. Anisovich *et al.*, arXiv:1503.05774

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.

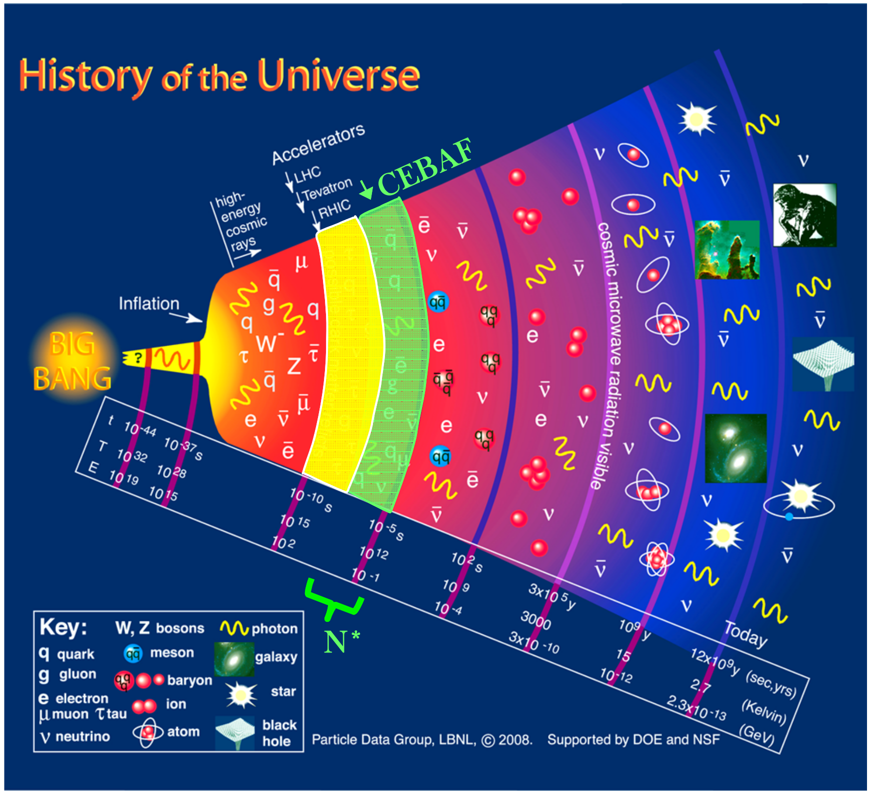


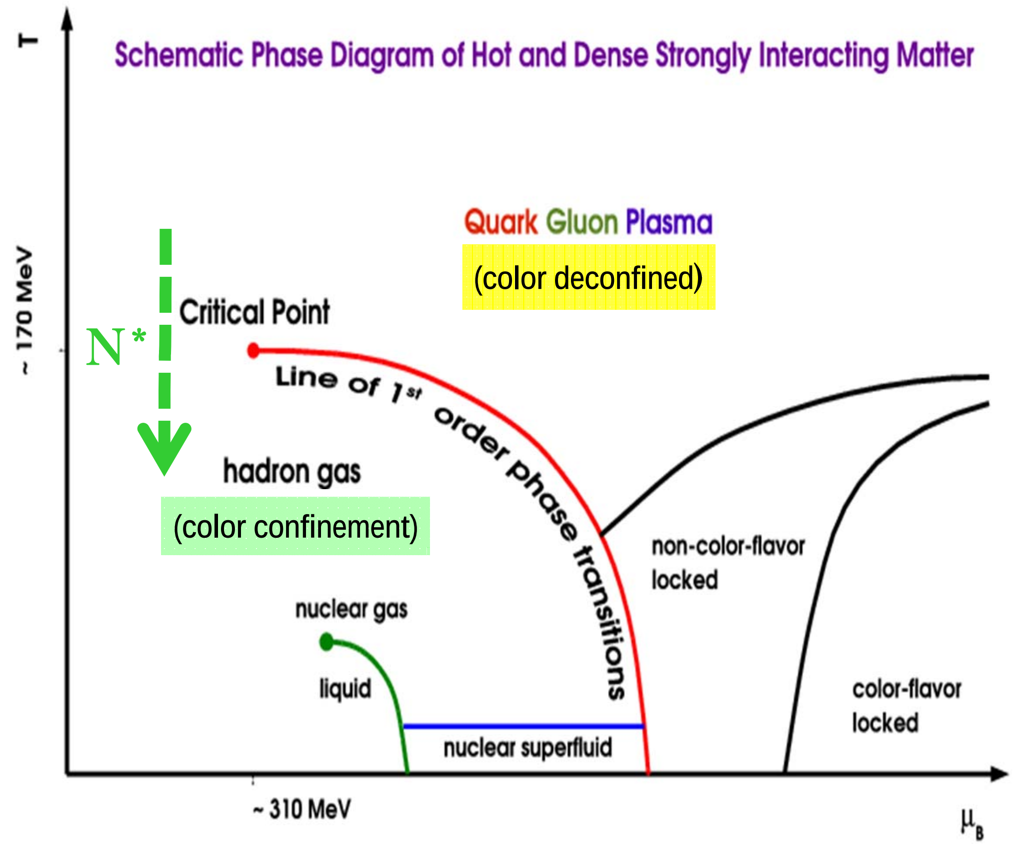
LQCD predicts states with the same quantum numbers as CQMs with underlying SU(6)xO(3) symmetry.

R. Edwards *et al.*, arXiv:1104.5152, 1201.2349

Evolution of the Early Universe

Volker Burkert



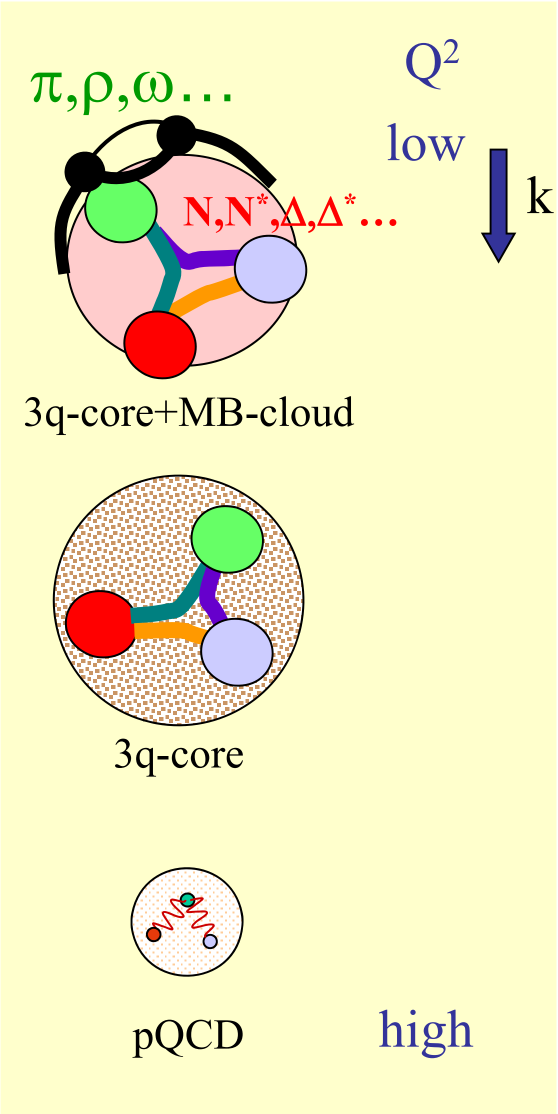


Dramatic events occur in the microsecond old Universe

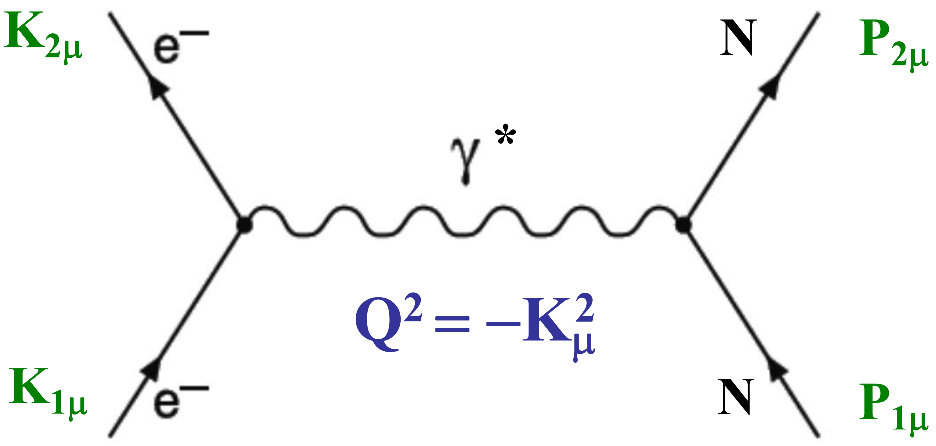
- Transition from the QGP to the baryon phase is dominated by excited baryons.
- A quantitative description requires more states than found to date → missing baryons.
- During the transition the quarks acquire dynamical mass and become confinement.

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.



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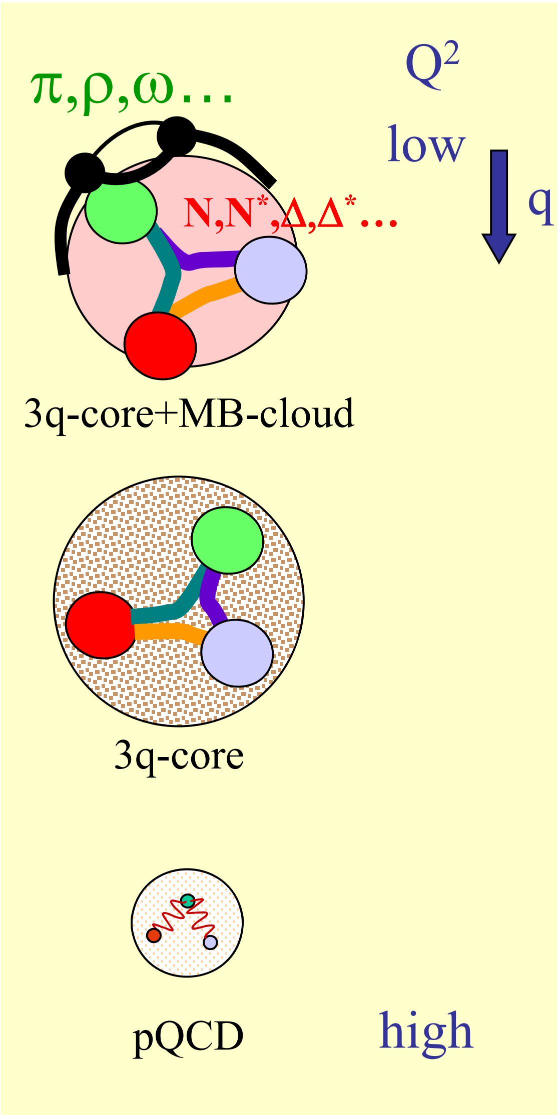

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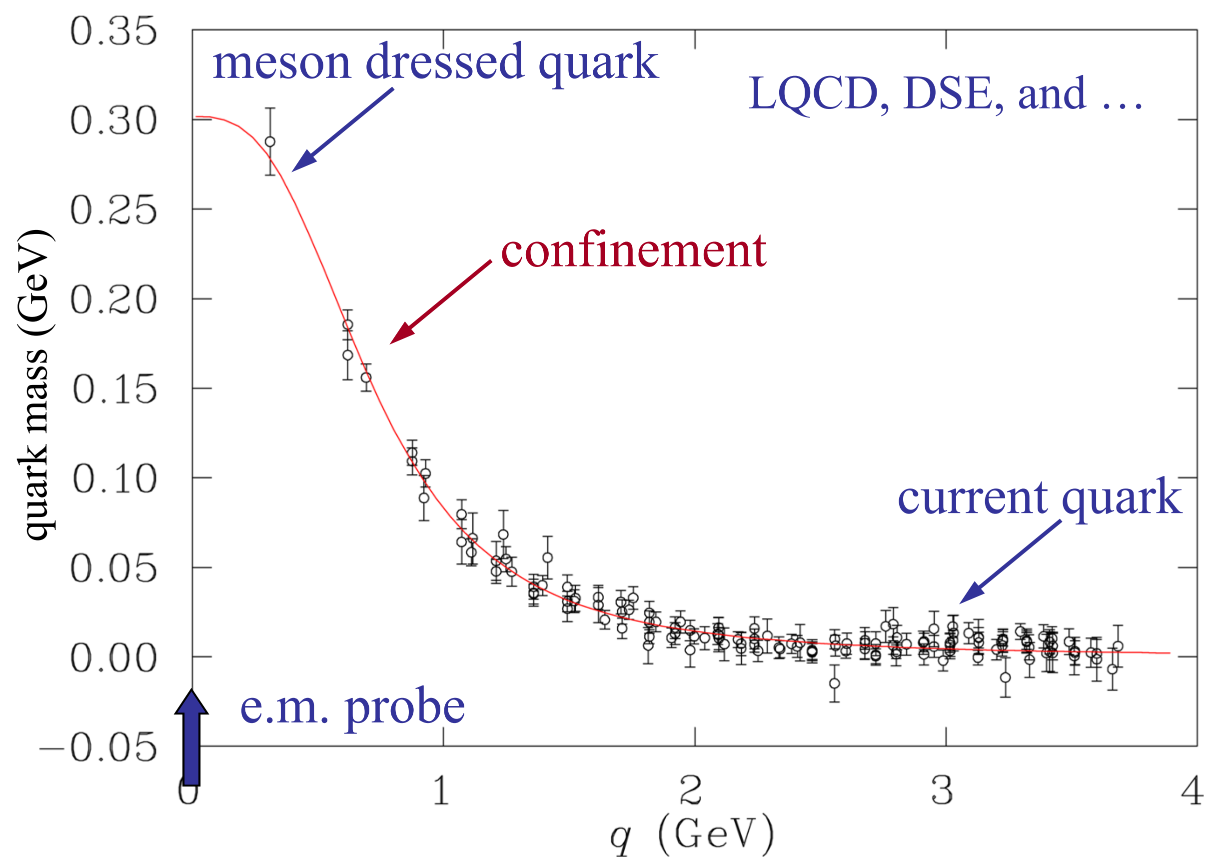
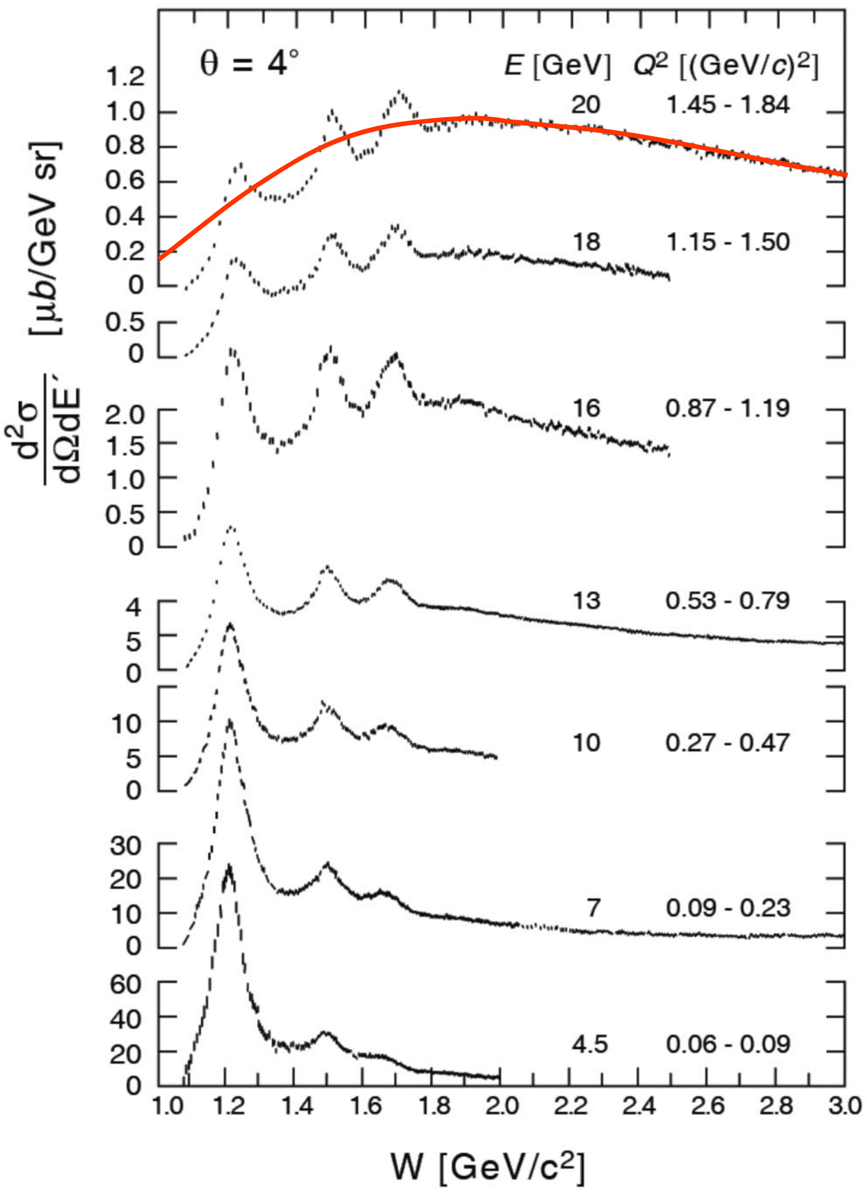
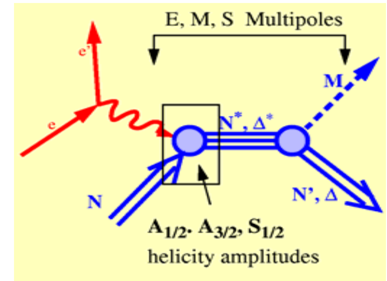
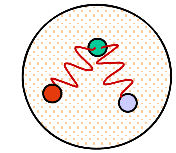


Baryon Excitations and Quasi-Elastic Scattering

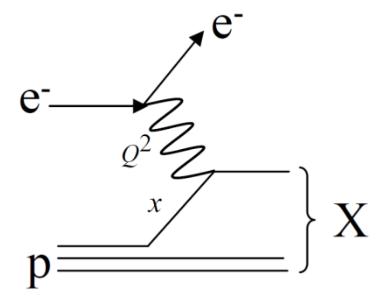


hard and confined



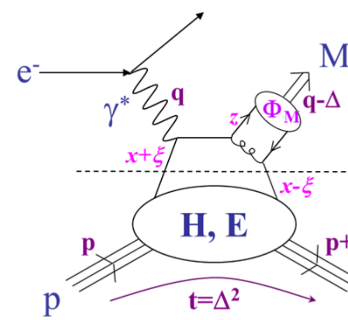


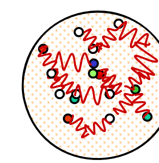
quasi-elastic



hard

soft





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

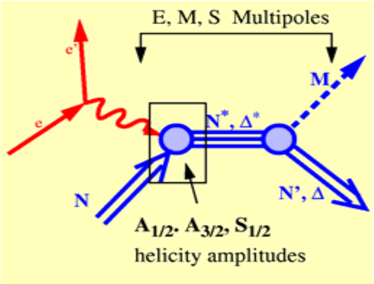
Structure Analysis of the Baryon

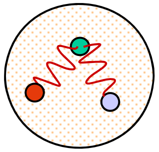
Demolition of a chimney at the "Henninger Brewery" in Frankfurt am Main, Germany, on 2 December 2006

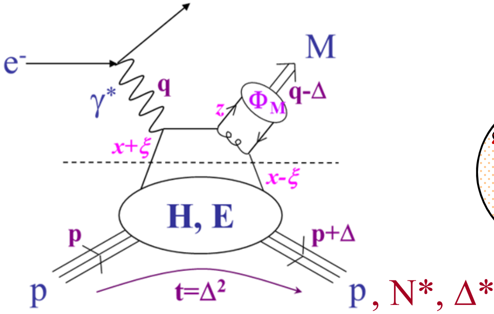
hard and confined

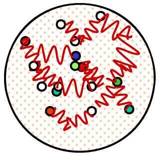
hard and soft

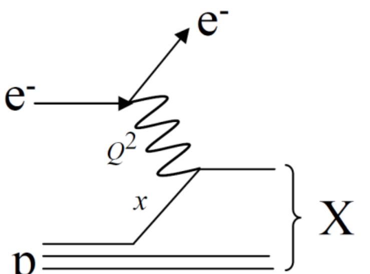
quasi-elastic











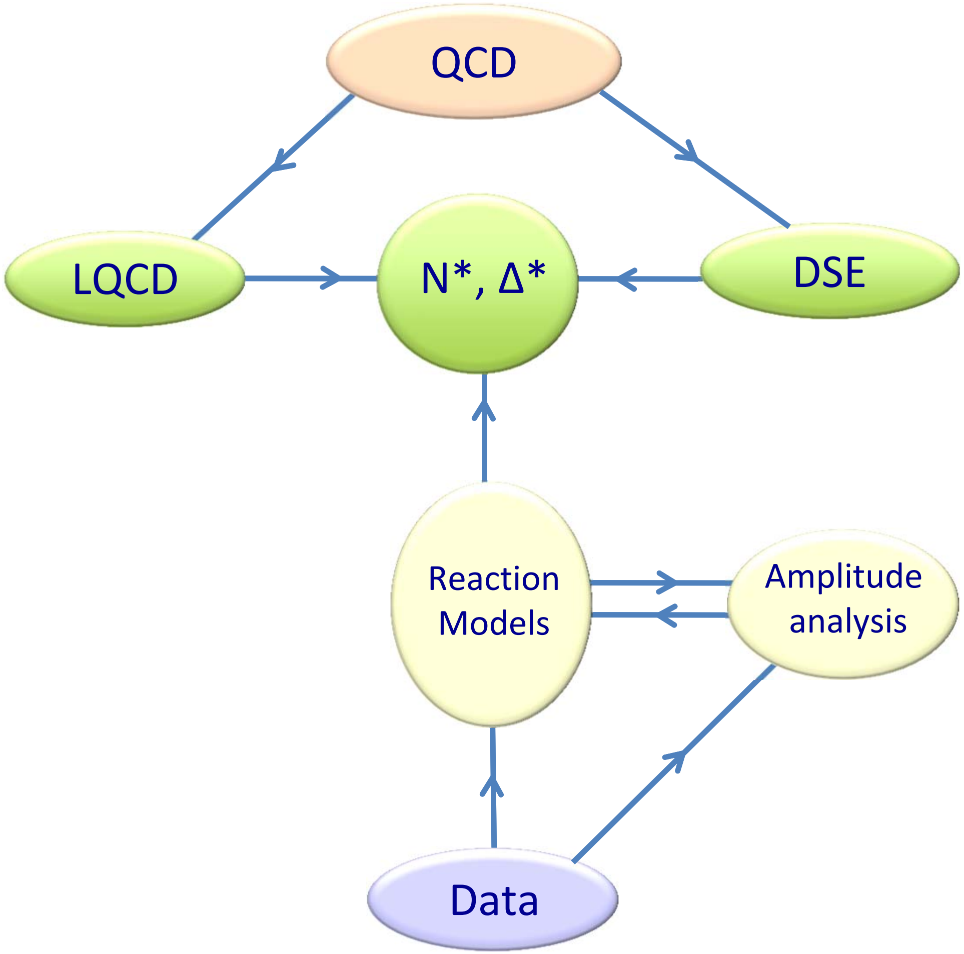
$\gamma_v NN^*$ Extraction

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

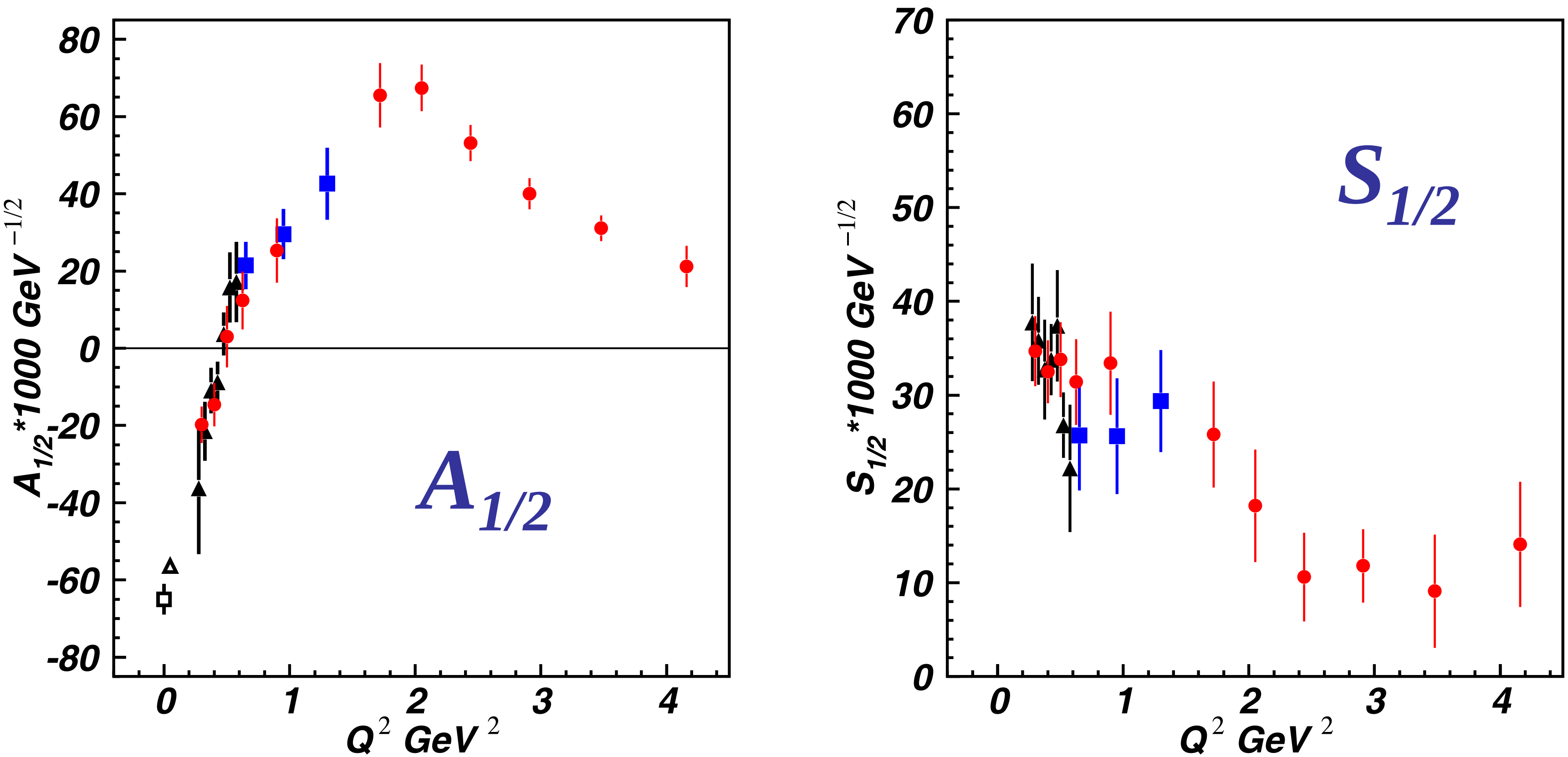
Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013) 1-99



Hadronic production

Electromagnetic production

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

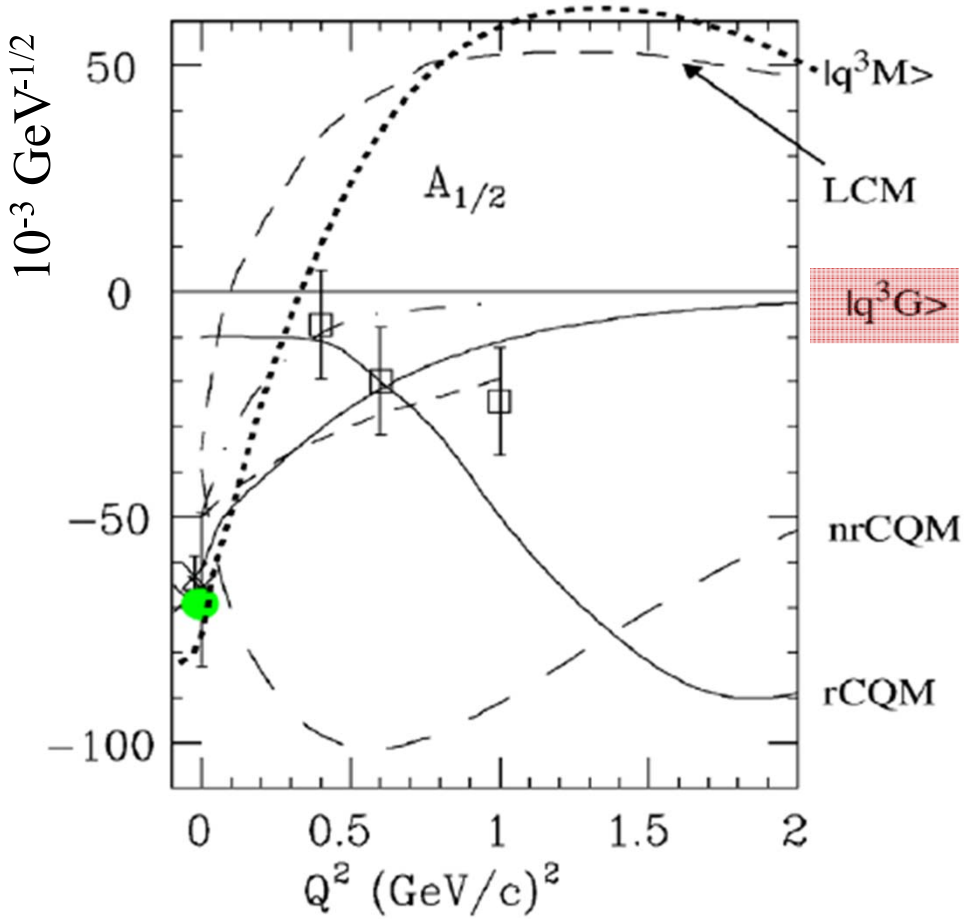


□ PDG ● Nπ (UIM, DR) ▲ Nππ (JM) 2012 ■ Nππ (JM) preliminary

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.

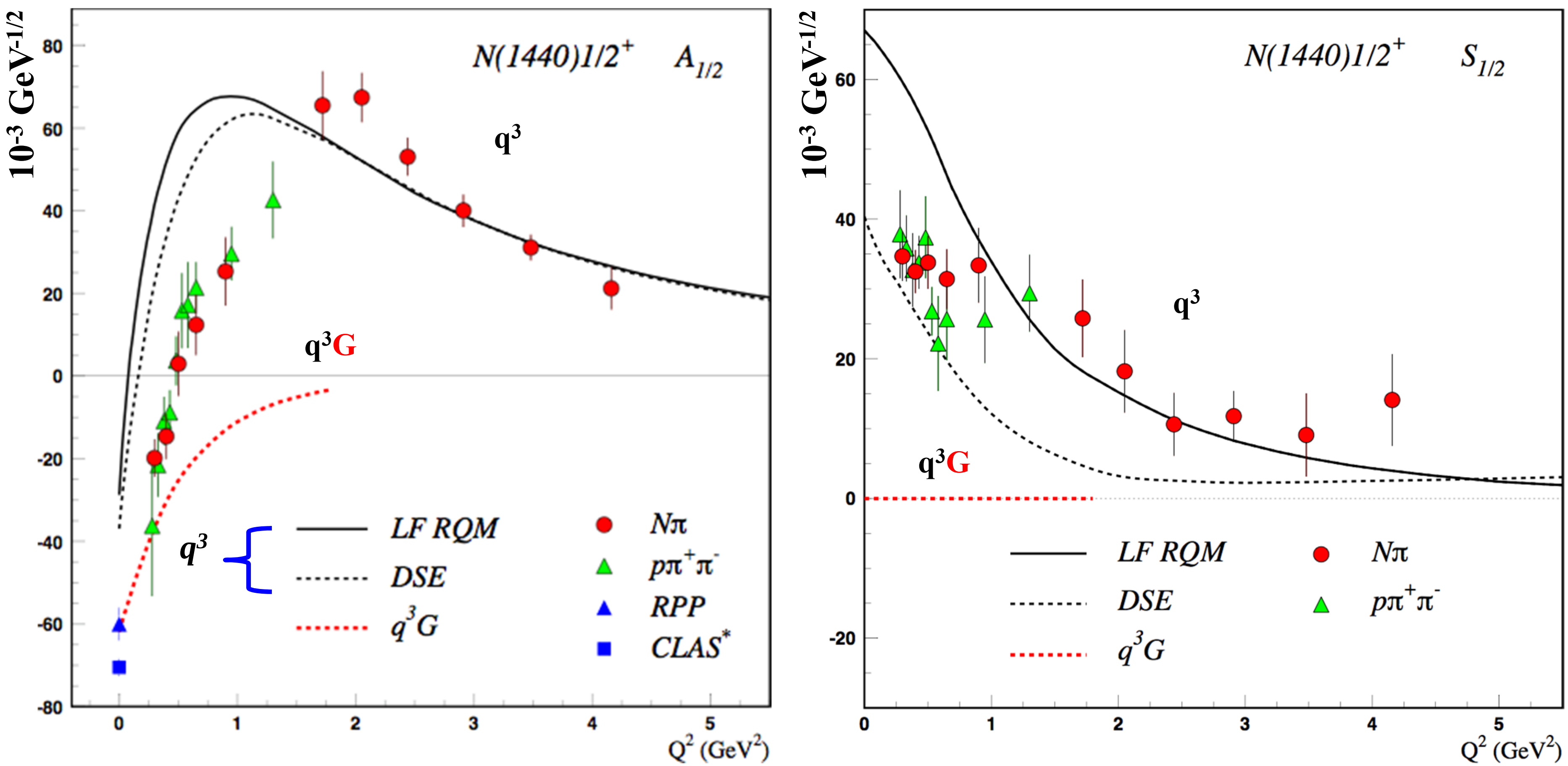
Phys. Rev. C 80, 055203 (2009) 1-22 and Phys. Rev. C 86, 035203 (2012) 1-22

Electrocouplings of N(1440)P_{11} History



- Lowest mass hybrid baryon should be $J^P=1/2^+$ as Roper.
- In 2002 Roper $A_{1/2}$ results were consistent with a hybrid state.

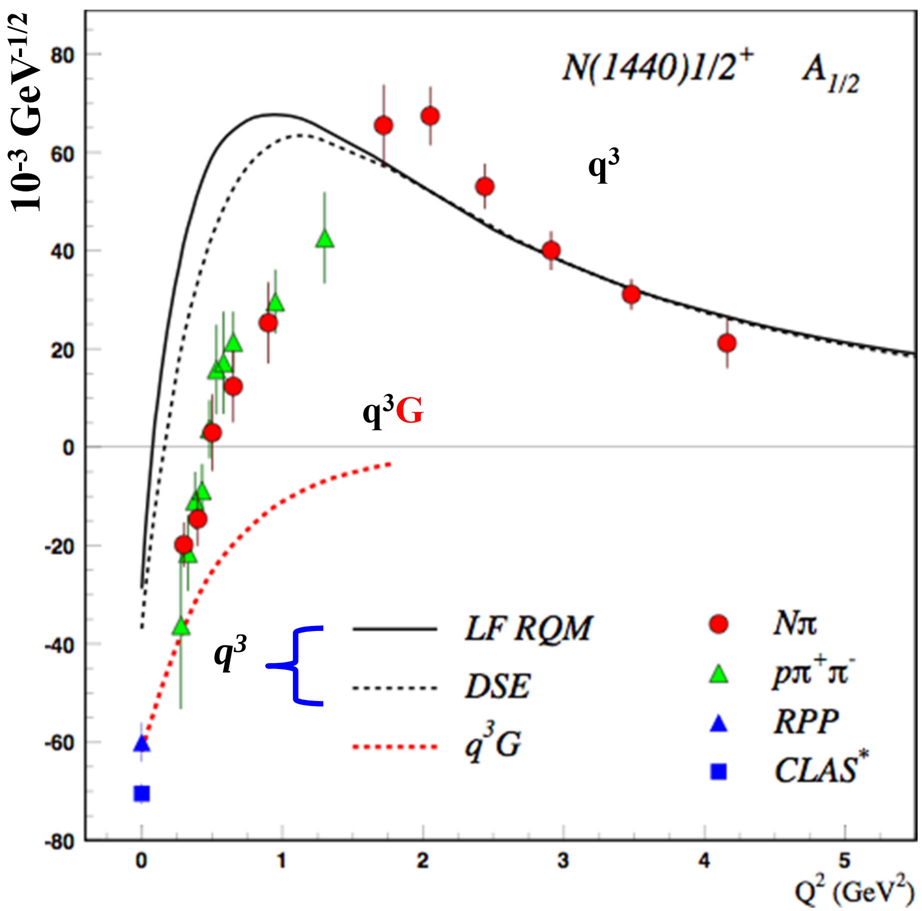
Electrocouplings of N(1440)P_{11} with CLAS



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

Nick Tyler closes the 1-2 GeV^2 gap for single pion production.

Electrocouplings of N(1440)P_{11} with CLAS



PDG 2013 update

+ q^3g

+ q^3qq

+ N-Meson

+ …

… all have distinctively different Q^2 dependencies

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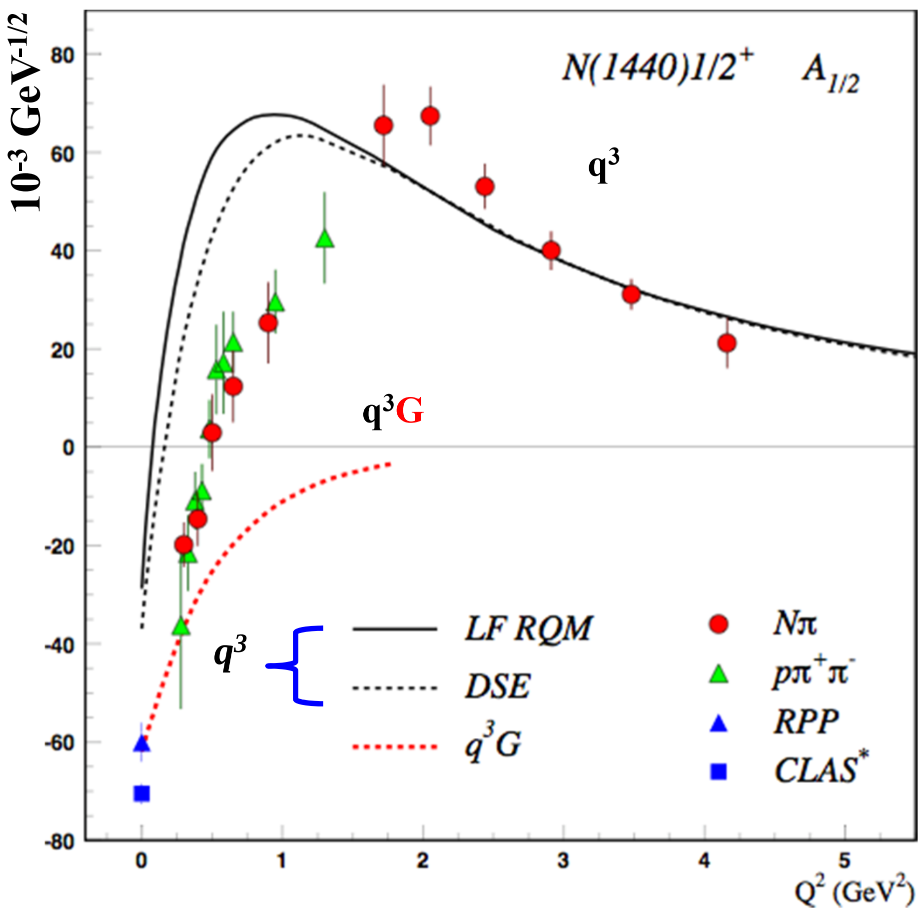
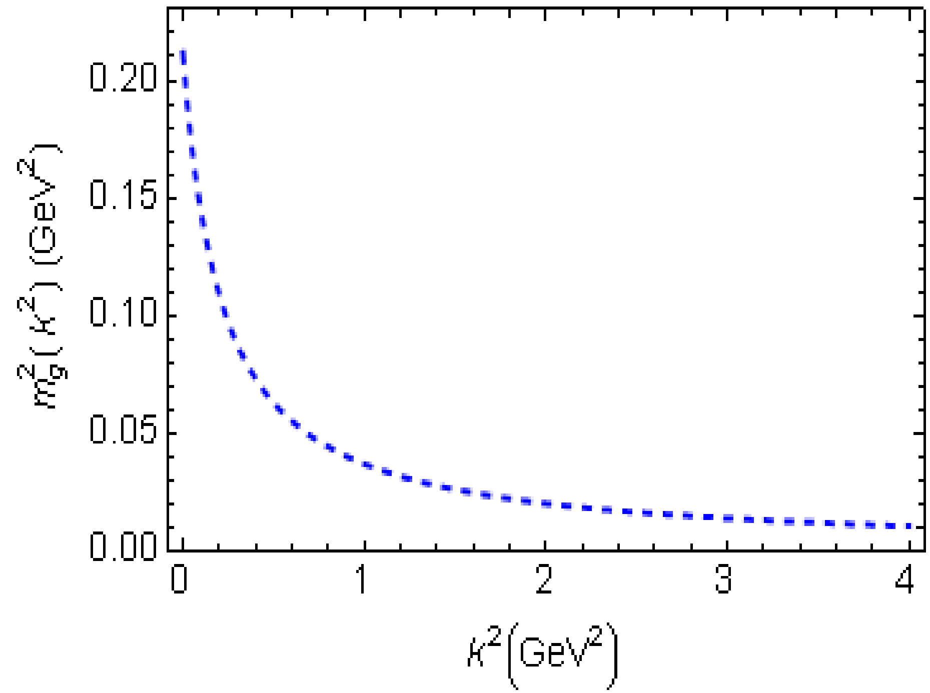


S. Qin *et al.*, Phys. Rev. C 84 (2011) 042202(R)



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New proposal on electroexcited gluon hybrids PR12-16-010 submitted to PAC44

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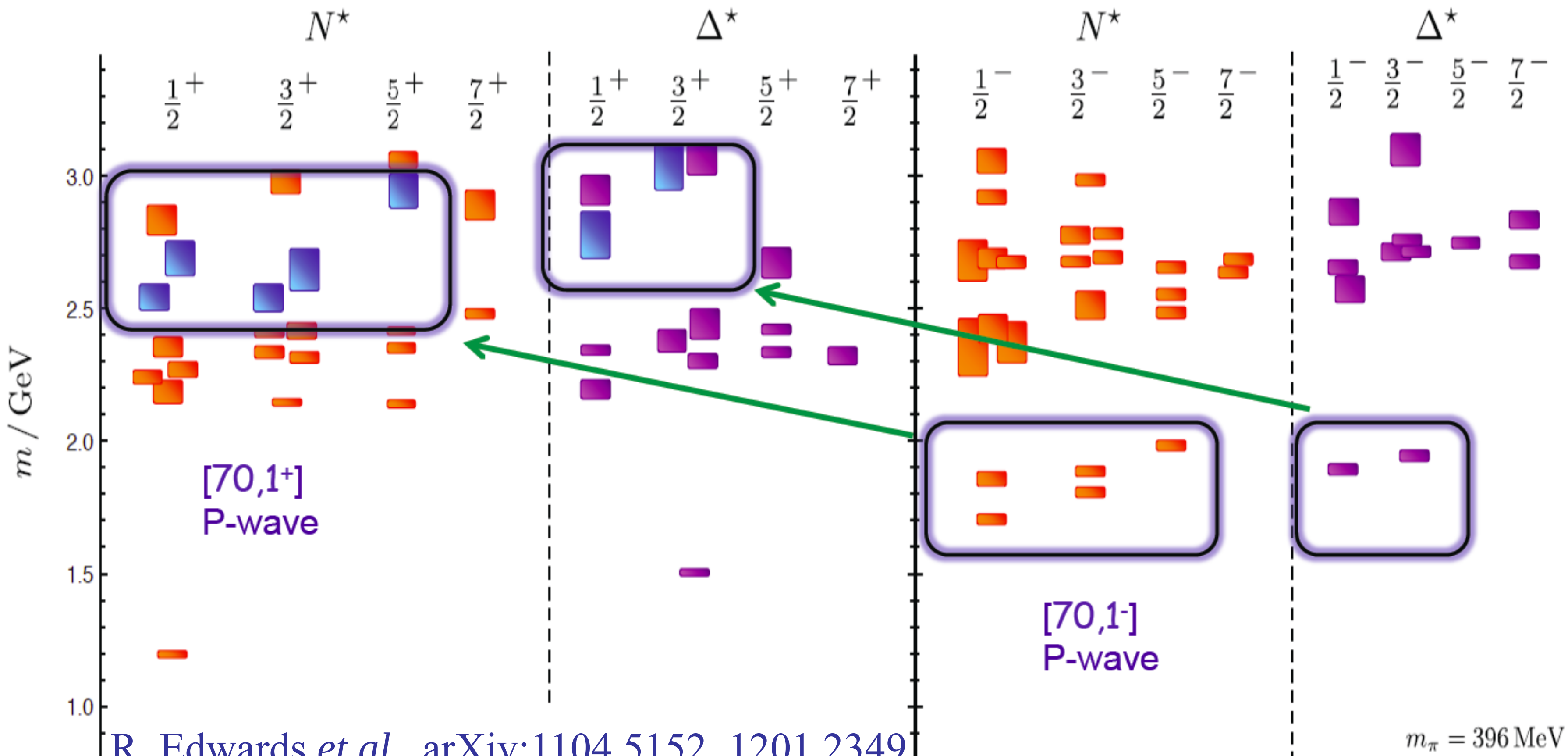


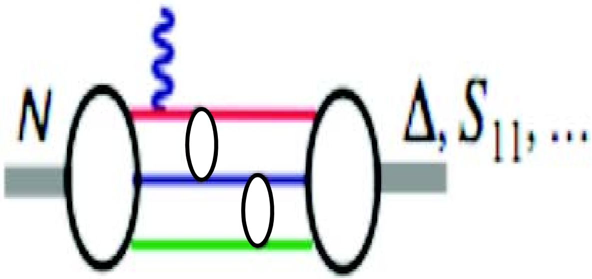
R. Edwards *et al.*, arXiv:1104.5152, 1201.2349

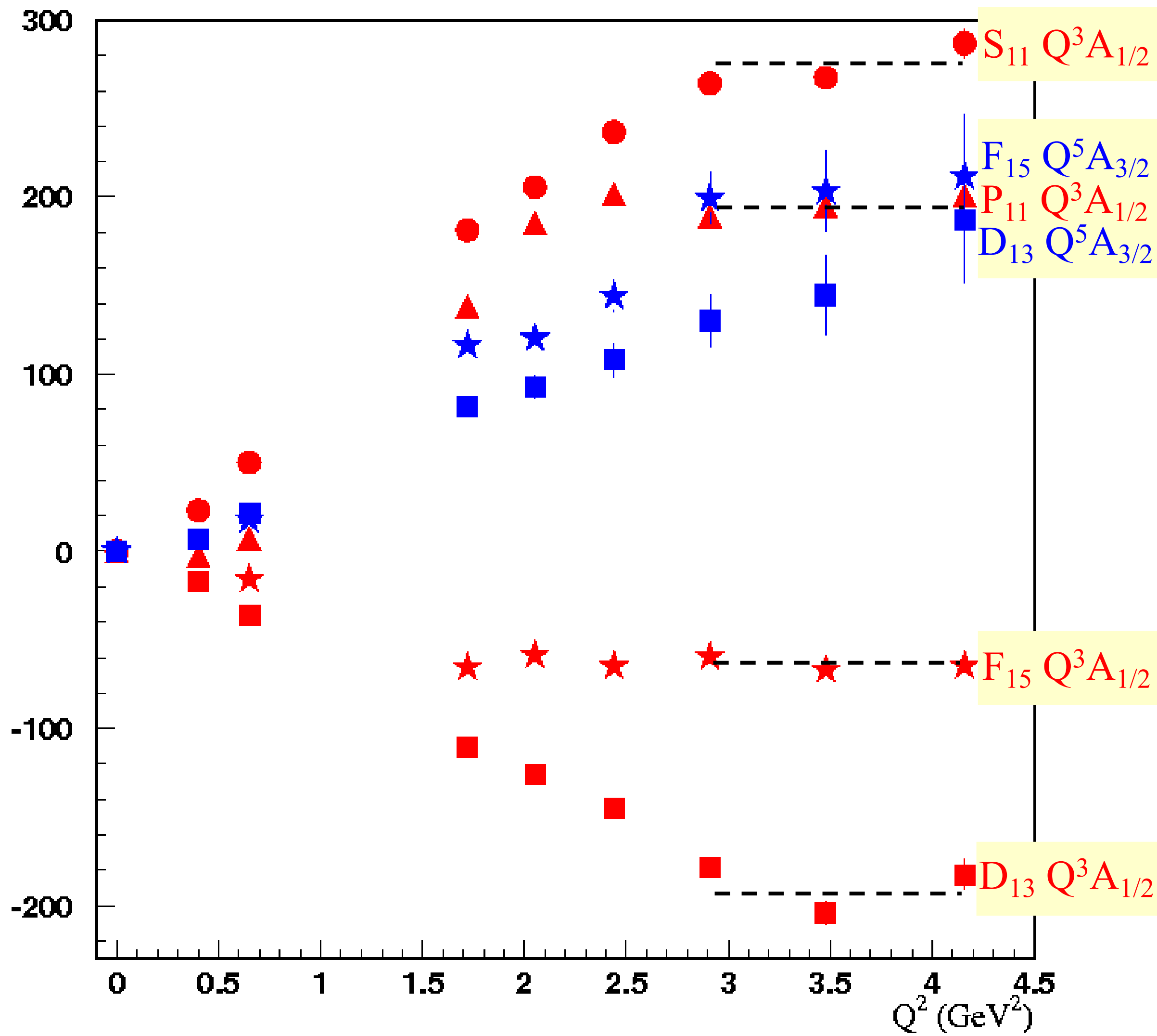
LQCD predicts hybrid baryon states replicating the negative parity multiplet structure.

New proposal on electroexcited gluon hybrids PR12-16-010 submitted to PAC44

Evidence for the Onset of Precocious Scaling?

I. G. Aznauryan *et al.*, Phys. Rev. C80, 055203 (2009)

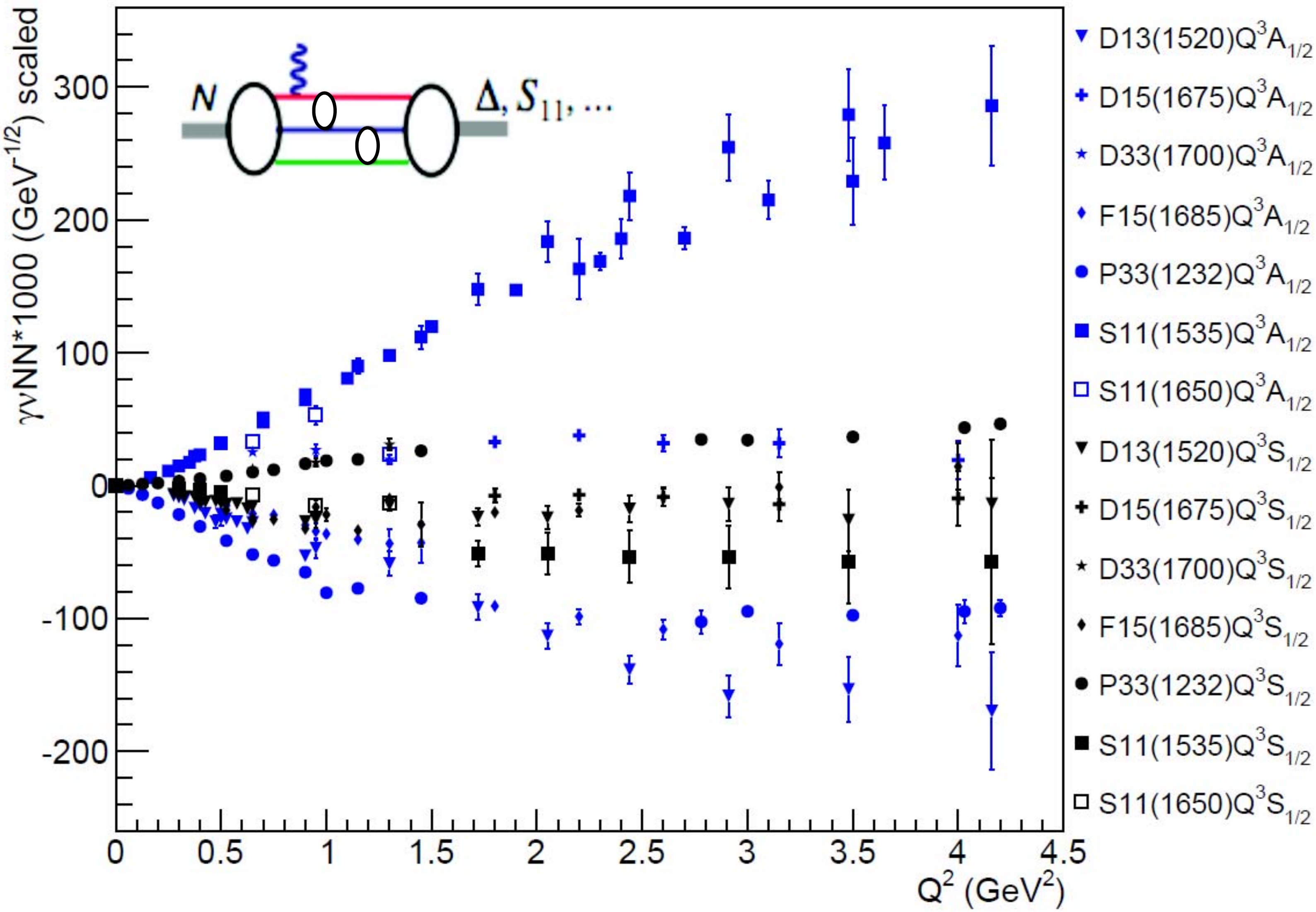




- $A_{1/2}$ α $1/Q^3$
- $A_{3/2}$ α $1/Q^5$

Evidence for the Onset of Precocious Scaling?

Ye Tian



V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)

Evidence for the Onset of Precocious Scaling?

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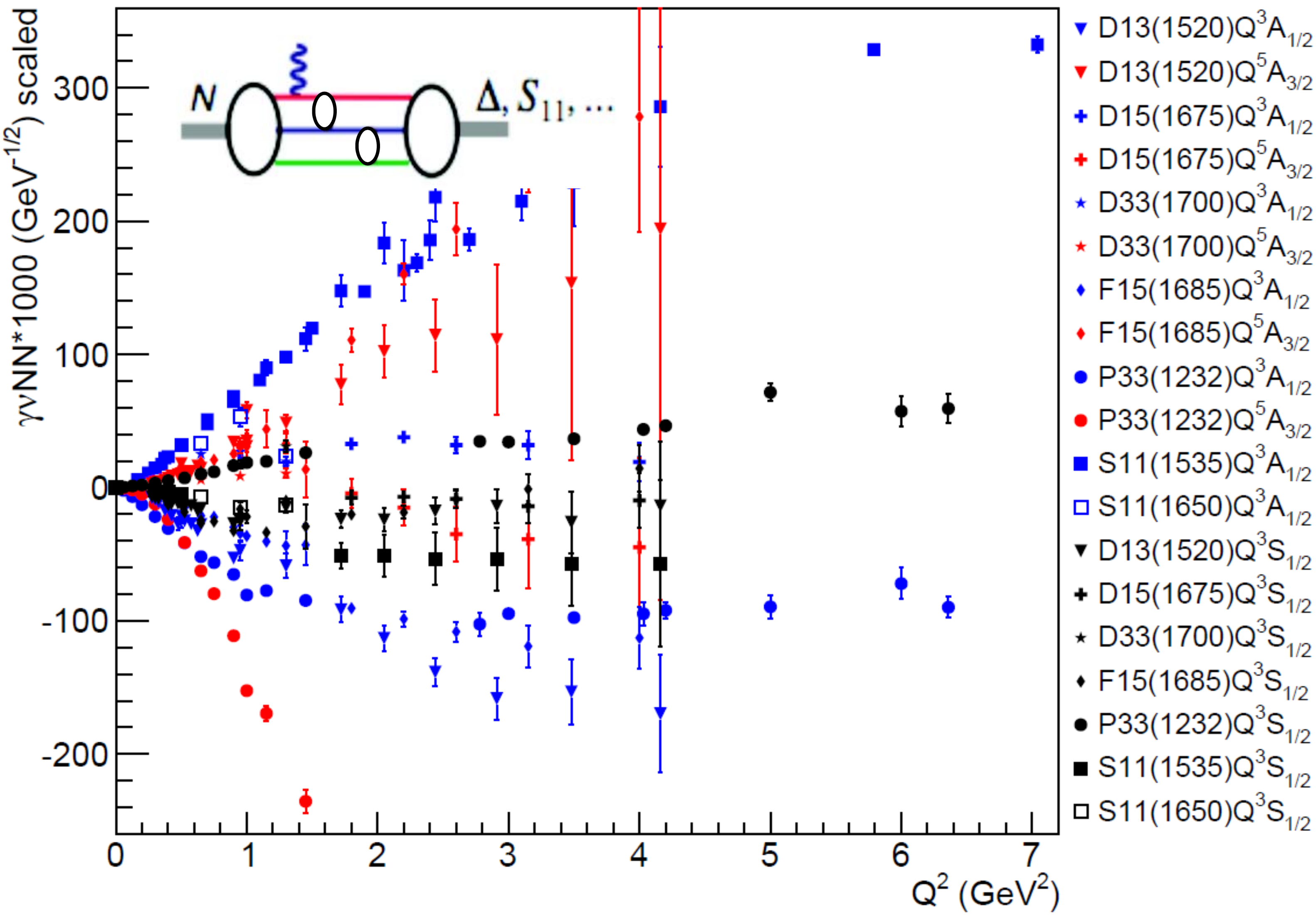
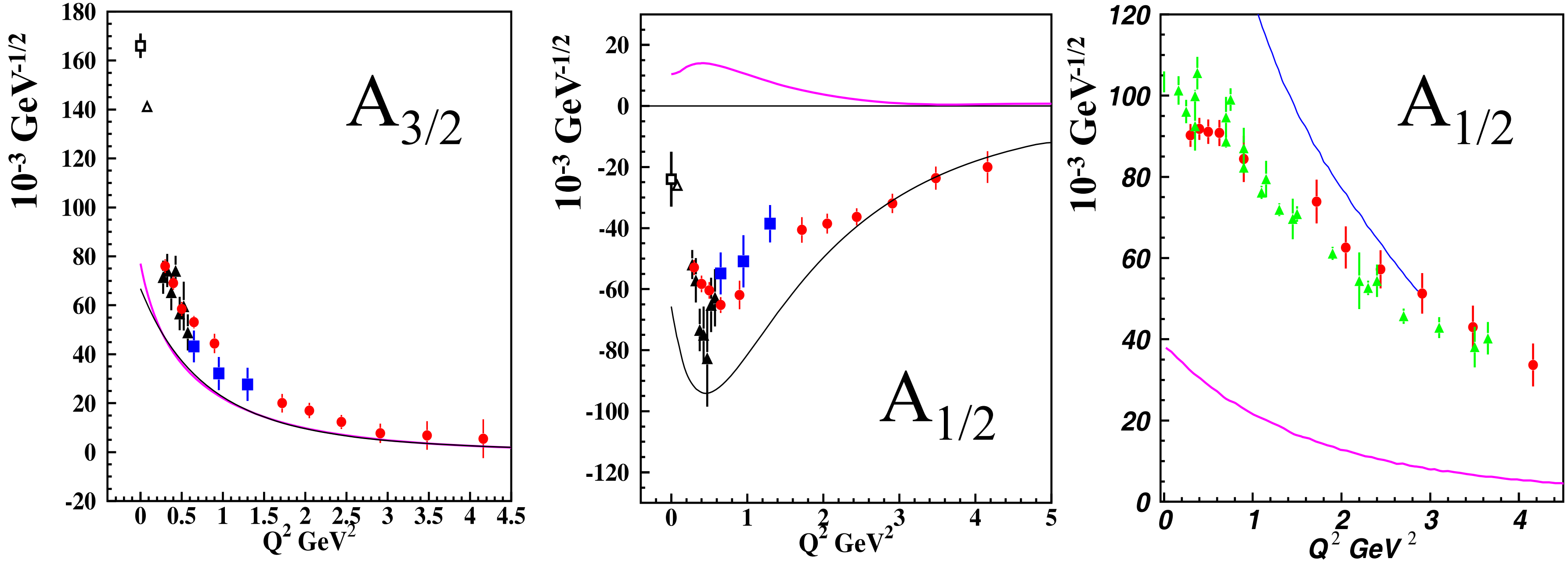


V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)

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)

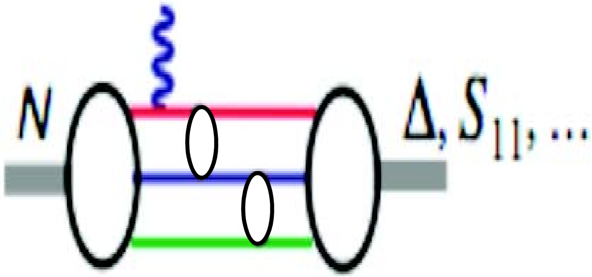
$\pi^+\pi^-p$ 2012

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

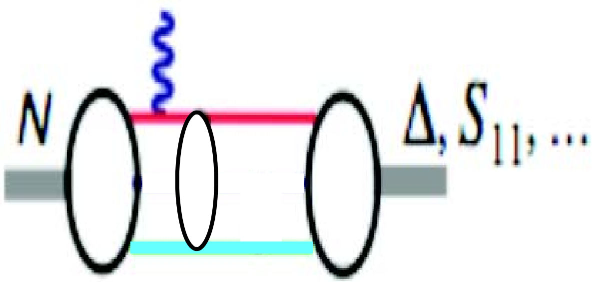
$N\pi$ 2009

ηp CLAS/Hall-C

Evidence for the Onset of Precocious Scaling?

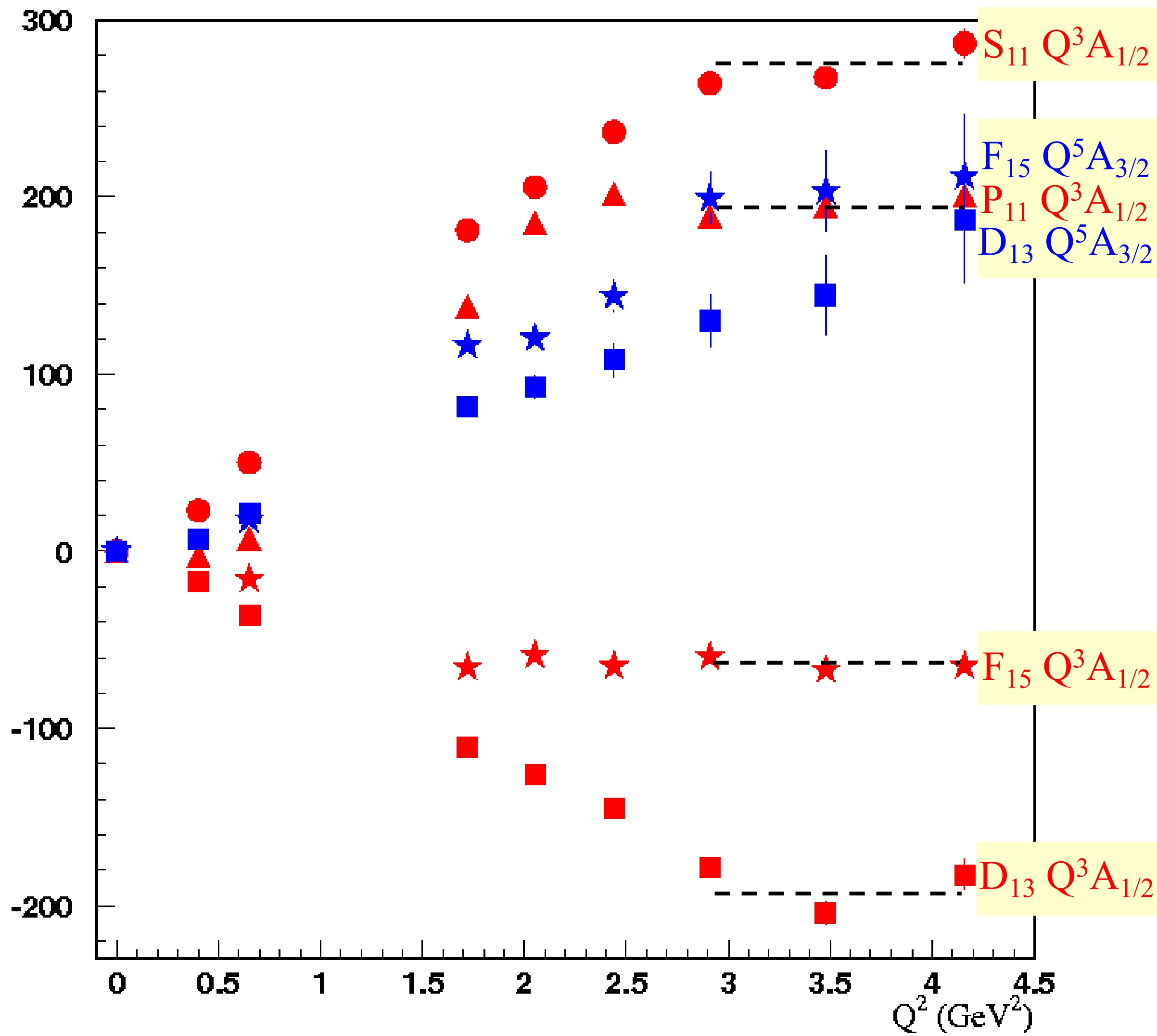


- $A_{1/2}$ α $1/Q^3$
- $A_{3/2}$ α $1/Q^5$
- G^*_M α $1/Q^4$

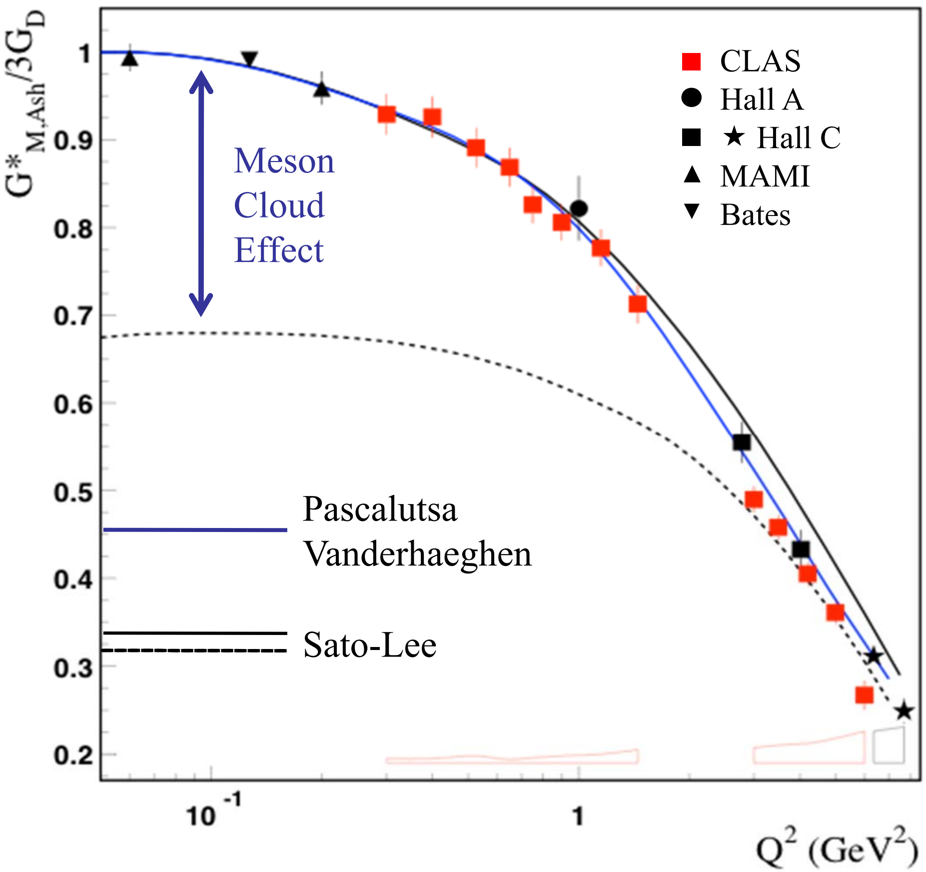


q^2q

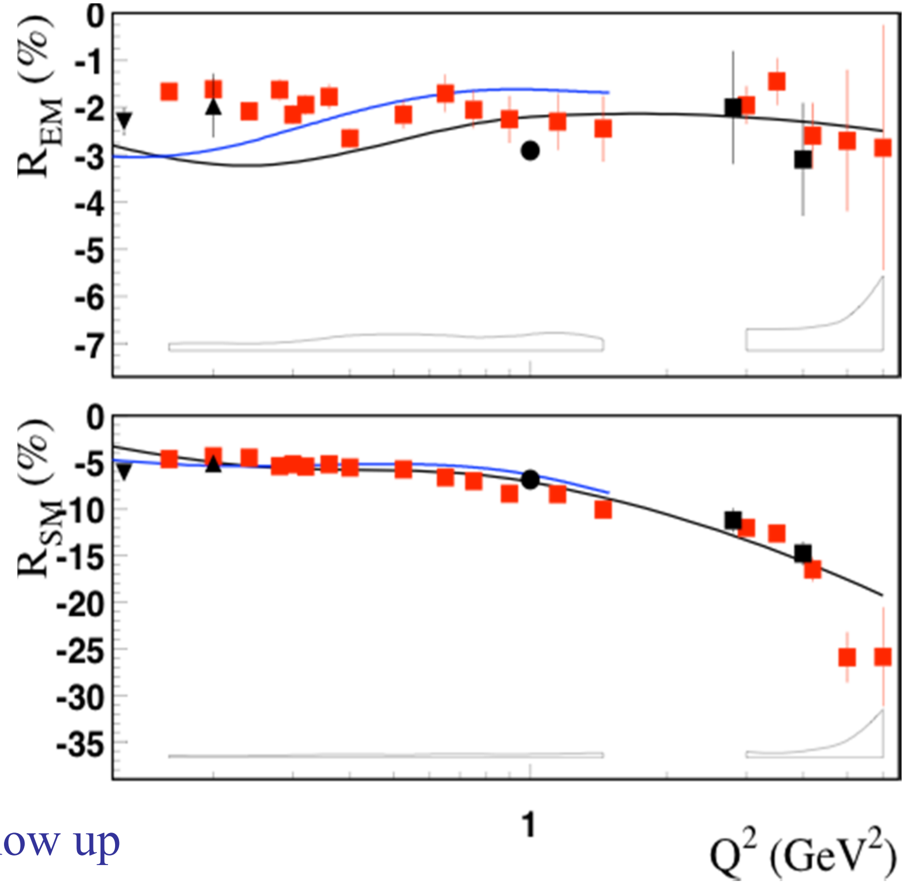
I. G. Aznauryan *et al.*, Phys. Rev. C80, 055203 (2009)



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



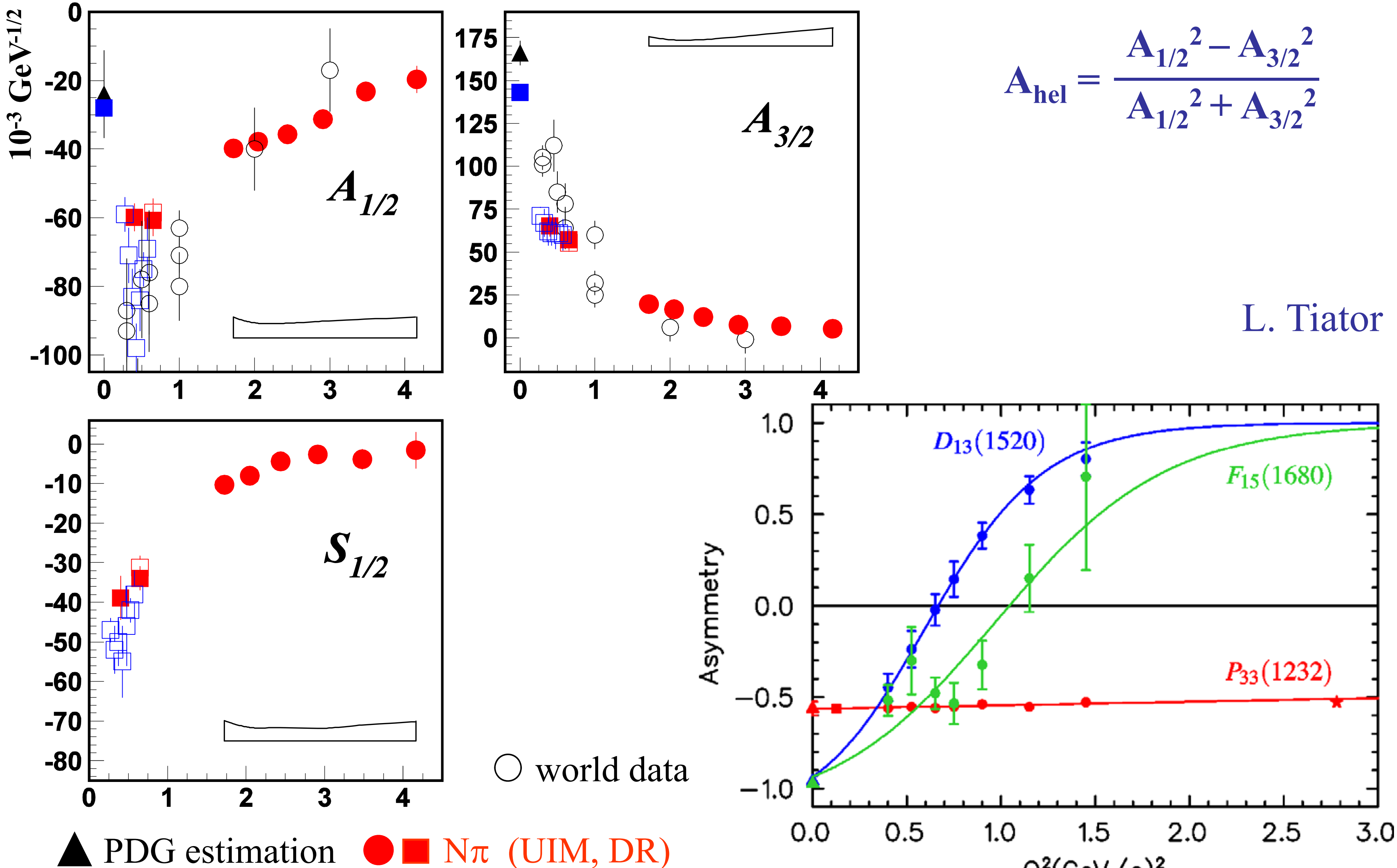
Phys. Rev. Lett. 97, 112003 (2006)



- 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

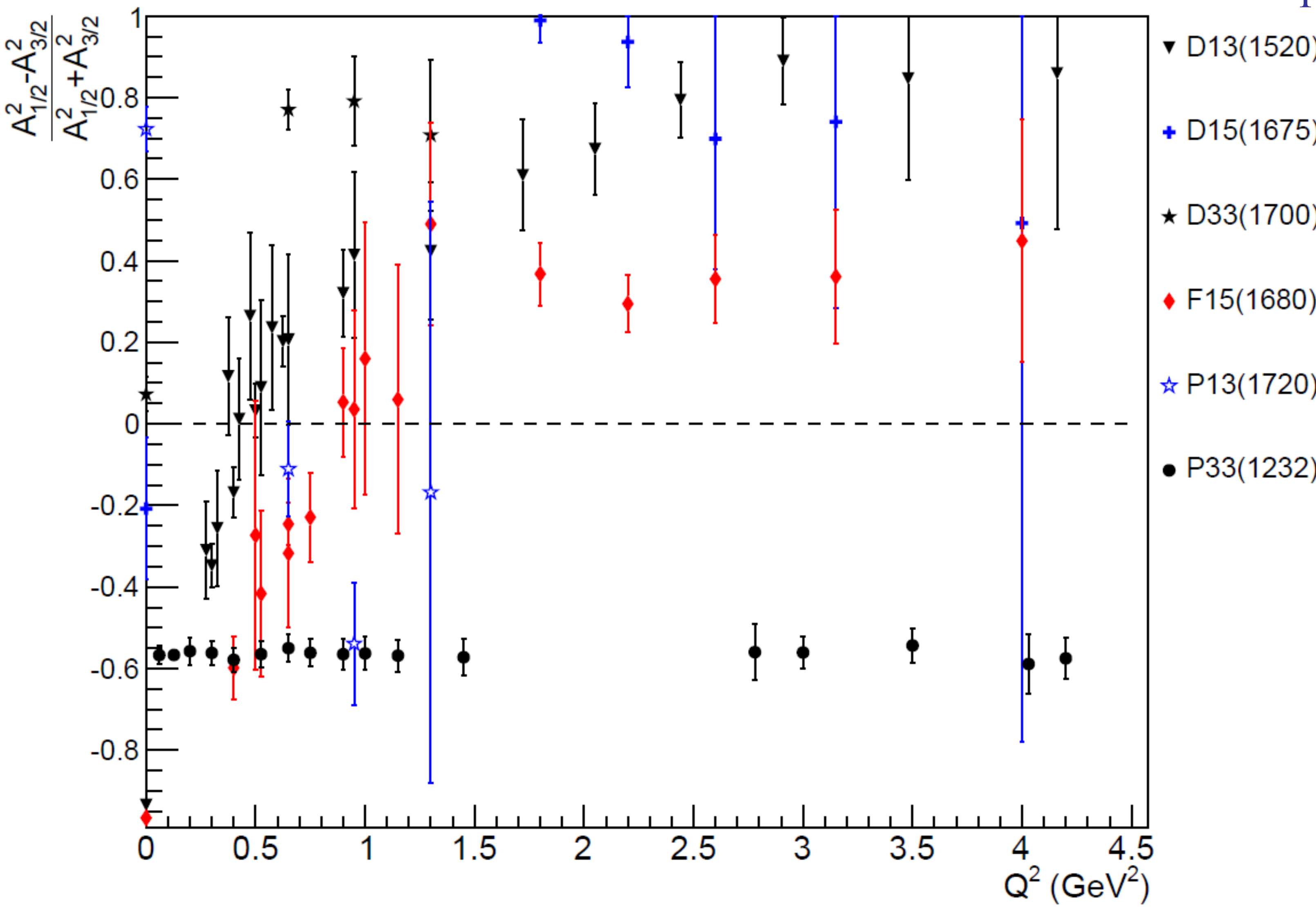
N(1520)D_{13} Helicity Asymmetry

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



γNN* Helicity Asymmetries

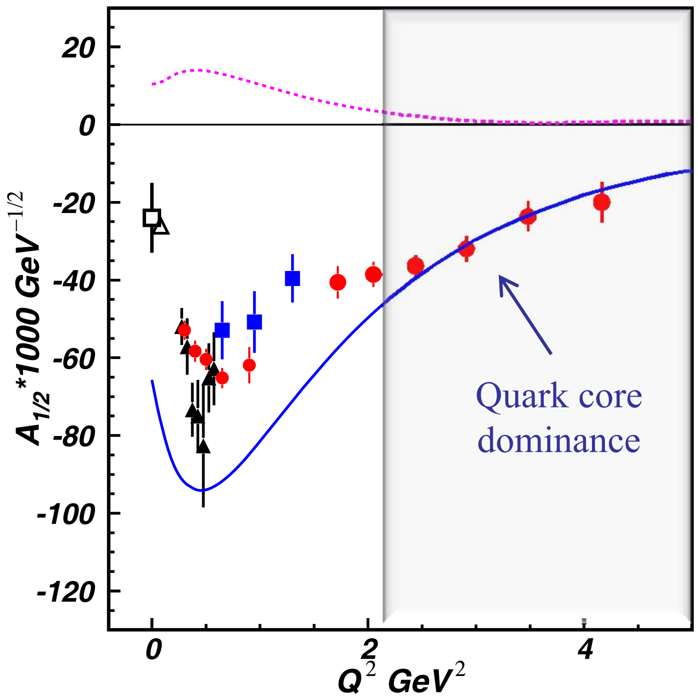
Ye Tian



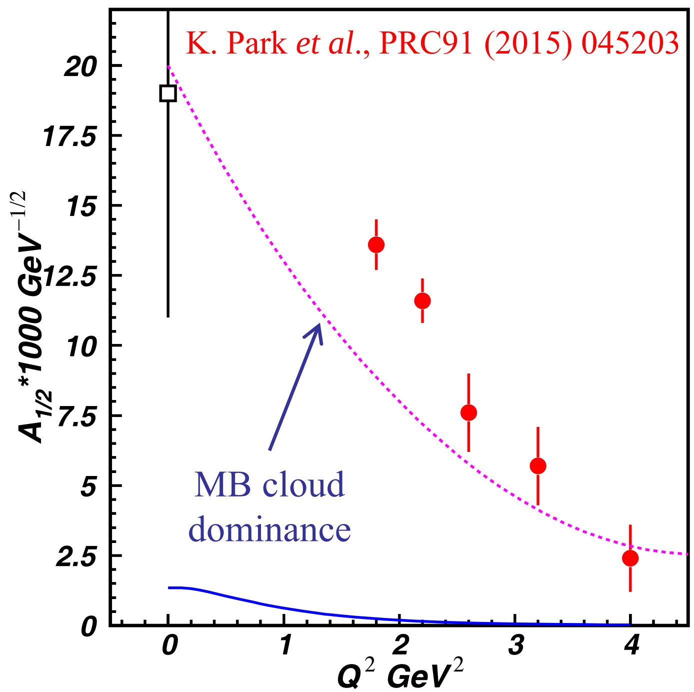
V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)

Interplay between Meson-Baryon Cloud and Quark Core

N(1520)3/2$^-$



N(1675)5/2$^-$



Argonne-Osaka MB dressing (absolute values)

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

The almost direct access to

- quark core from the data on N(1520)3/2$^-$
- meson-baryon cloud from the data on N(1675)5/2$^-$

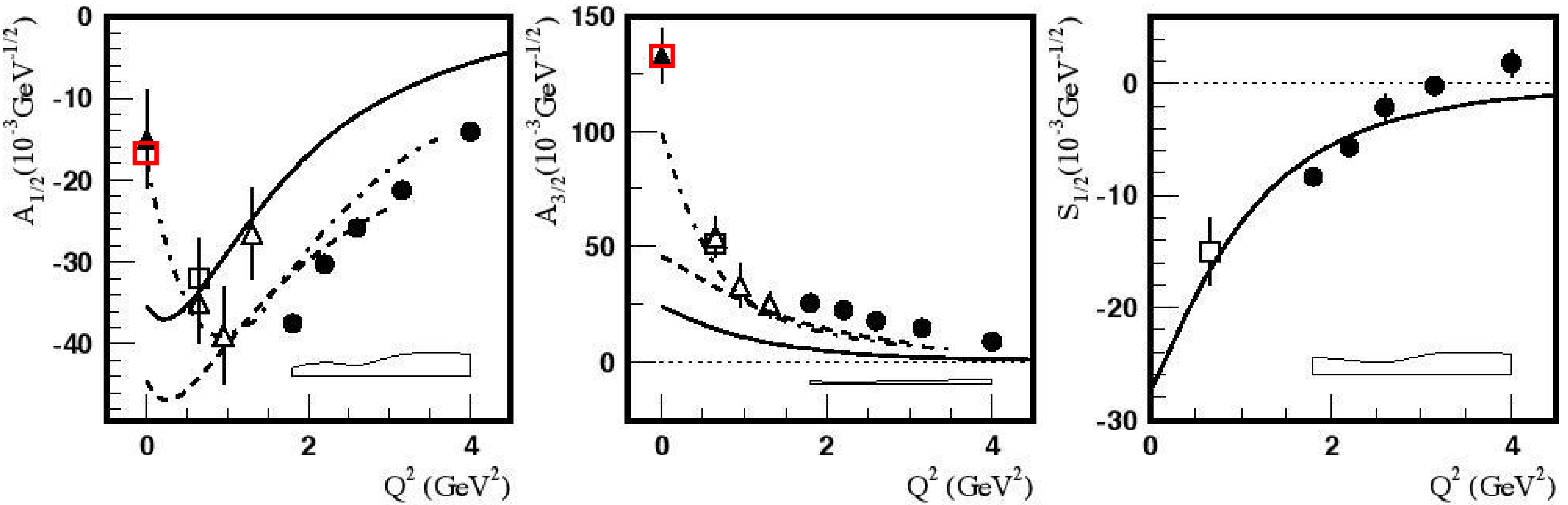
sheds light on the transition from the confined quark to the colorless meson-baryon structure and its dependents on the N* quantum numbers.

New Experimental Results & Approaches

Higher-Lying Resonance Electrocouplings

N(1680)F_{15}

Kijun Park



▲ RPP (PDG) Phys. Rev. D 86 (2012)

□ (red) M. Dugger Phys. Rev. C 76 (2007)

□ I.G. Aznauryan, Phys. Rev. C 72 (2005)

△ $N\pi\pi$: V. Mokeev (JM)

● $N\pi$: I.G. Aznauryan (UIM & DR)

K. Park *et al.*, Phys. Rev. C **91**, 045203 (2015)

- - - - D. Merten, U. Löring et al.

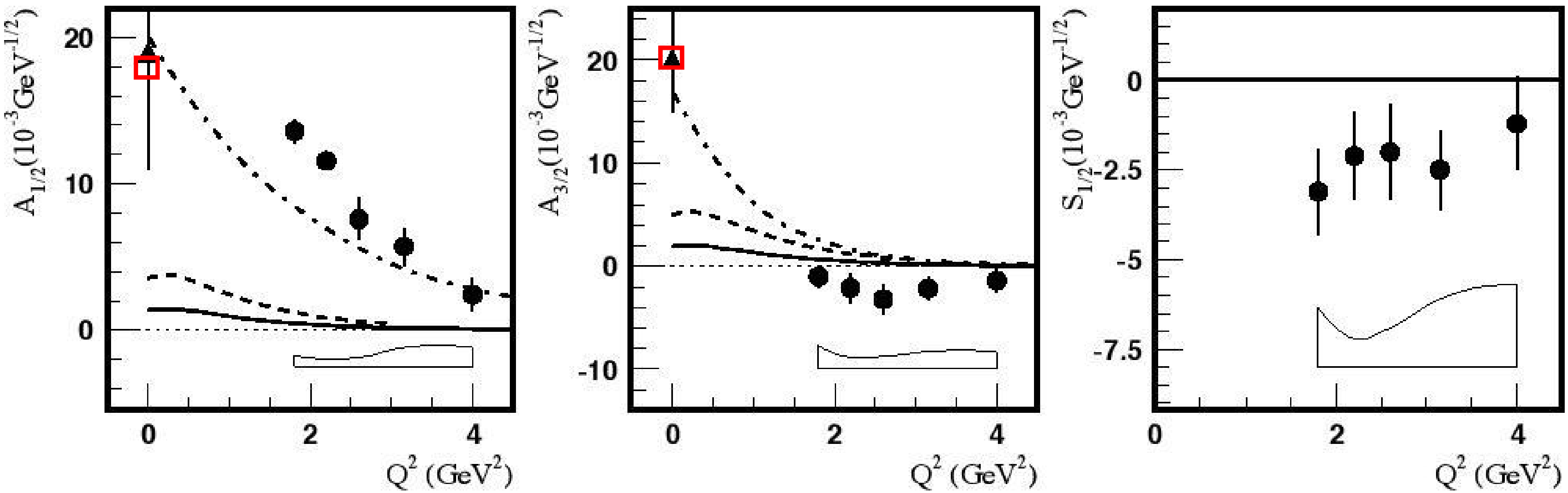
- · - · Z. Lee and F. Close

——— E. Santopinto and M.M. Gianini

Higher-Lying Resonance Electrocouplings

$N(1675)D_{15}$

Kijun Park



K. Park *et al.*, Phys. Rev. C **91**, 045203 (2015)

RPP (PDG) Phys. Rev. D 86 (2012)

M. Dugger Phys. Rev. C 76 (2007)

Nπ: I.G. Aznauryan (UIM & DR)

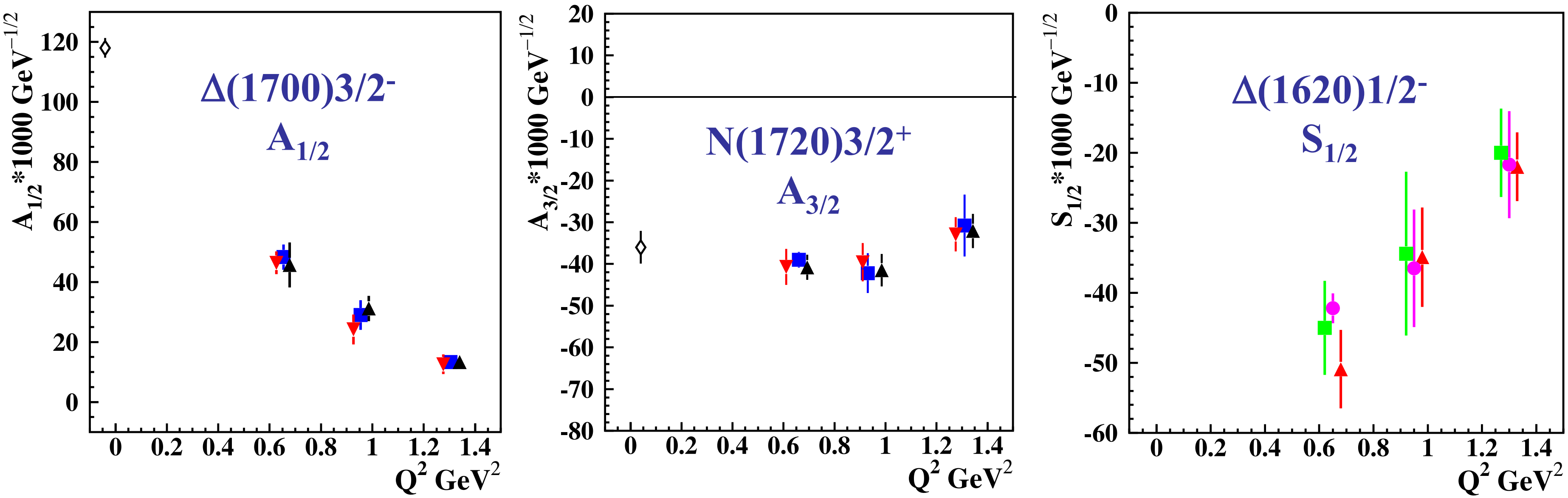
D. Merten, U. Löring et al.

B. Julia-Diaz, T.-S.H. Lee et al.

E. Santopinto and M.M. Gianini

Higher-Lying Resonance Electrocouplings

Viktor Mokeev



Independent fits in different W-intervals

green: 1.46<W<1.56 GeV
magenta: 1.56<W<1.66 GeV
red: 1.61<W<1.71 GeV
blue: 1.66<W<1.76 GeV
black: 1.71<W<1.81 GeV

result in consistent electrocouplings and hence offer sound evidence for their reliable extraction.

The $\pi^+\pi^-p$ electroproduction channel provides first preliminary results on the $\Delta(1620)1/2^-$, $N(1650)1/2^-$, $N(1680)5/2^+$, $\Delta(1700)3/2^-$, and $N(1720)3/2^+$ electrocouplings with good accuracy.

V. Mokeev *et al.*, Phys. Rev. C **93**, 025206

New N'(1720)3/2$^+$ State and its Properties

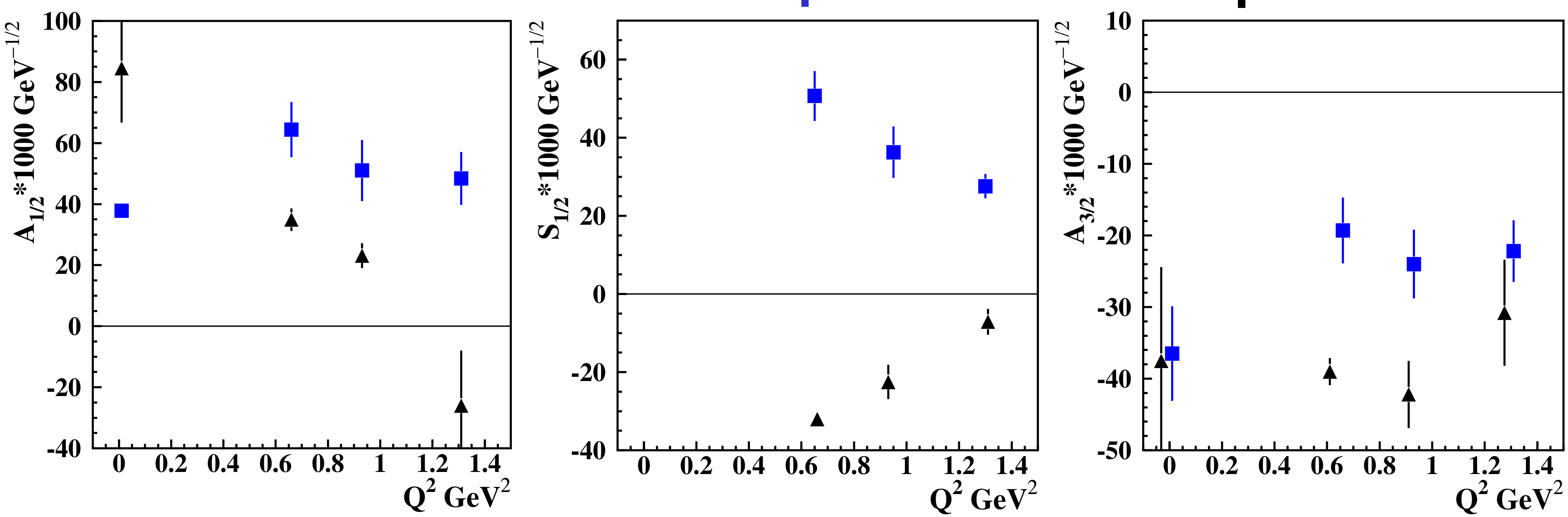
N* hadronic decays from JM15 that incorporates N'(1720)3/2$^+$

Resonance	BF($\pi\Delta$), %	BF(ρp), %
N'(1720)3/2$^+$		
electroproduction	**47-64**	**3-10**
photoproduction	**46-62**	**4-13**
N(1720)3/2$^+$		
electroproduction	**39-55**	**23-49**
photoproduction	**38-53**	**31-46**
Δ(1700)3/2$^-$		
electroproduction	**77-95**	**3-5**
photoproduction	**78-93**	**3-6**

A successful description of $\pi^+\pi^-p$ photo- and electro-production cross sections at Q^2=0, 0.65, 0.95, and 1.30 GeV^2 has been achieved by implementing a new N'(1720)3/2$^+$ state with Q^2-independent hadronic decay widths of all resonances that contribute at W~1.7 GeV, that allows us to claim the existence of a new N'(1720)3/2$^+$ state.

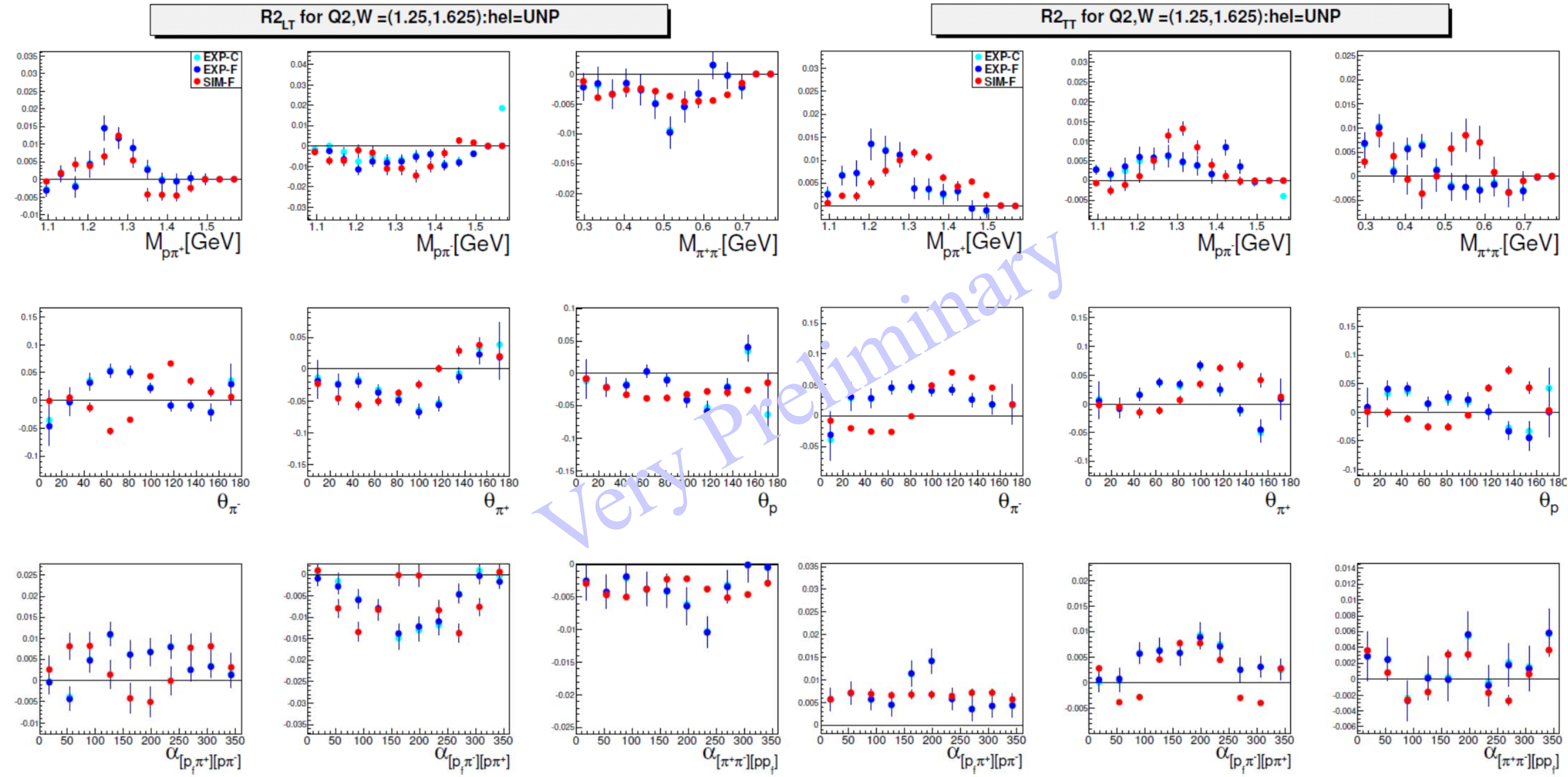
Mass: 1.715-1.735 GeV
Width: 120 6 MeV
N'(1720)3/2$^+$

Mass: 1.743-1.753 GeV
Width: 112 8 MeV
N(1720)3/2$^+$



φ-dependent Nππ Single-Differential Cross Sections

Q^2, W bin $= [1.25, 1.75) GeV^2, [1.625, 1.650) GeV$ Arjun Trivedi

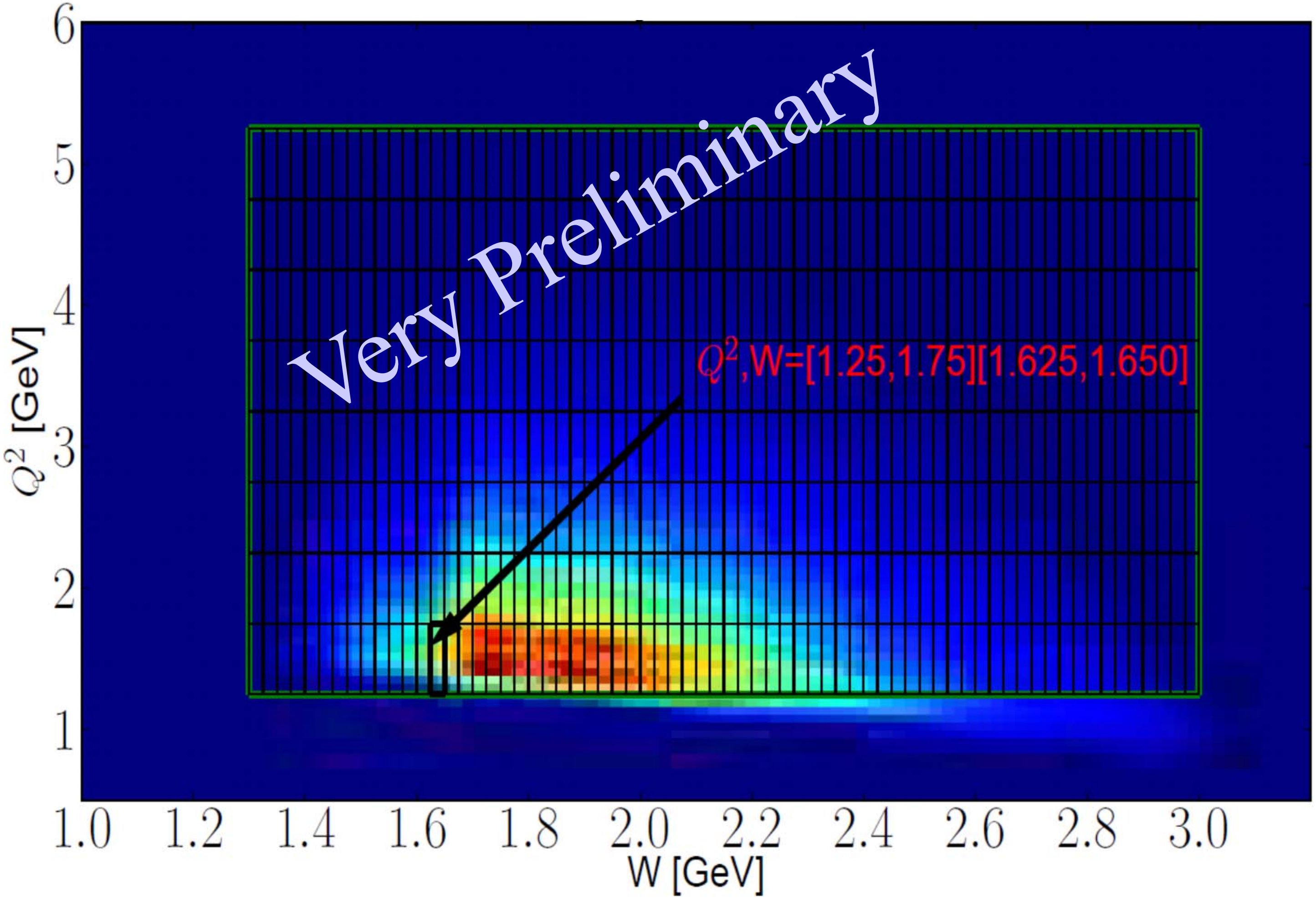


$$\left(\frac{d^2\sigma}{dX^{ij} d\phi^j}\right) = R2_T{}^{X_{ij}} + R2_l{}^{X_{ij}} + \underline{R2_{LT}{}^{X_{ij}} \cos\phi_j} + \underline{R2_{TT}{}^{X_{ij}} \cos 2\phi_j}$$

Chris McLauchlin extracts the beam helicity dependent differential cross sections.

φ-dependent Nππ Single-Differential Cross Sections

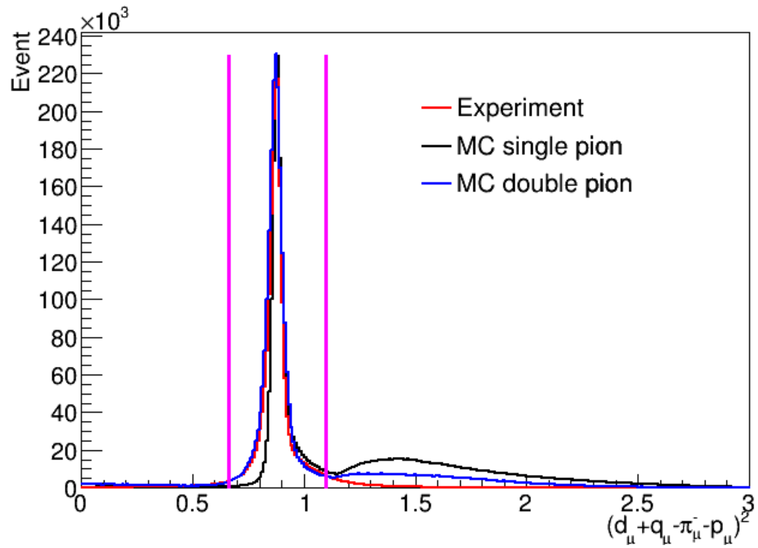
Q^2, W bin $= [1.25, 1.75)GeV^2, [1.625, 1.650)GeV$ Arjun Trivedi

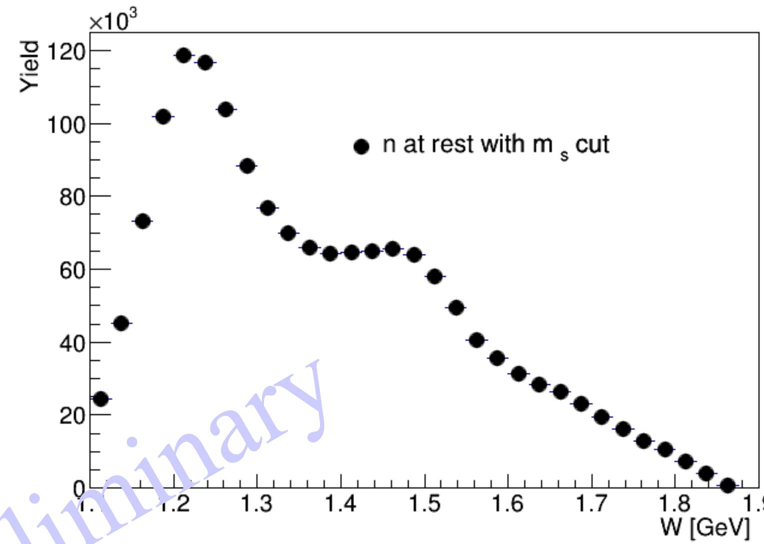


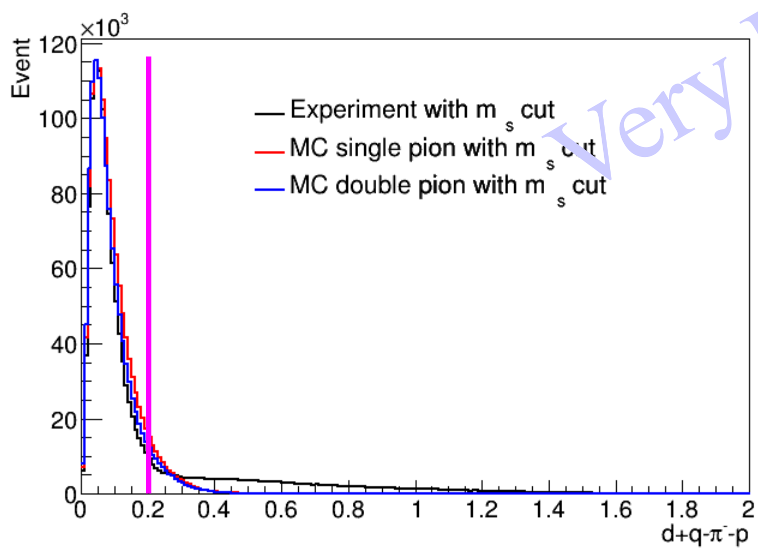
$$\left(\frac{d^2\sigma}{dX^{ij}d\phi^j}\right) = R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}} + \underline{R2_{LT}{}^{X_{ij}} \cos\phi_j} + \underline{R2_{TT}{}^{X_{ij}} \cos 2\phi_j}$$

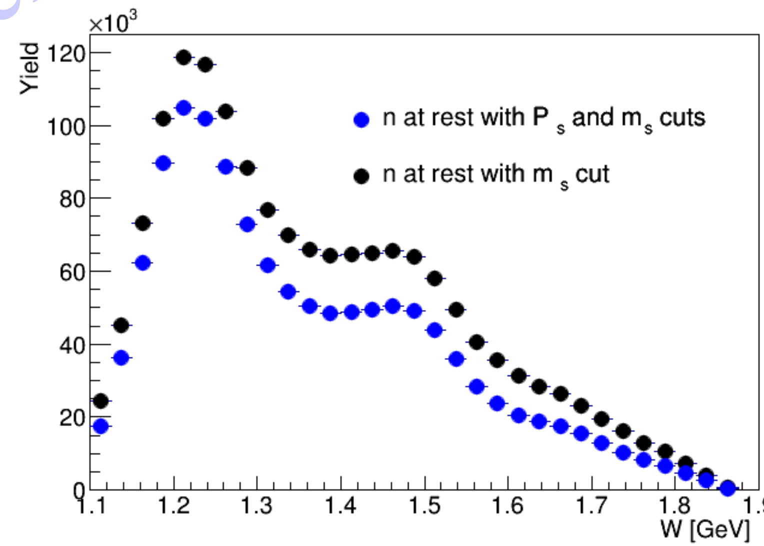
Single π Electroproduction off the Deuteron

Ye Tian



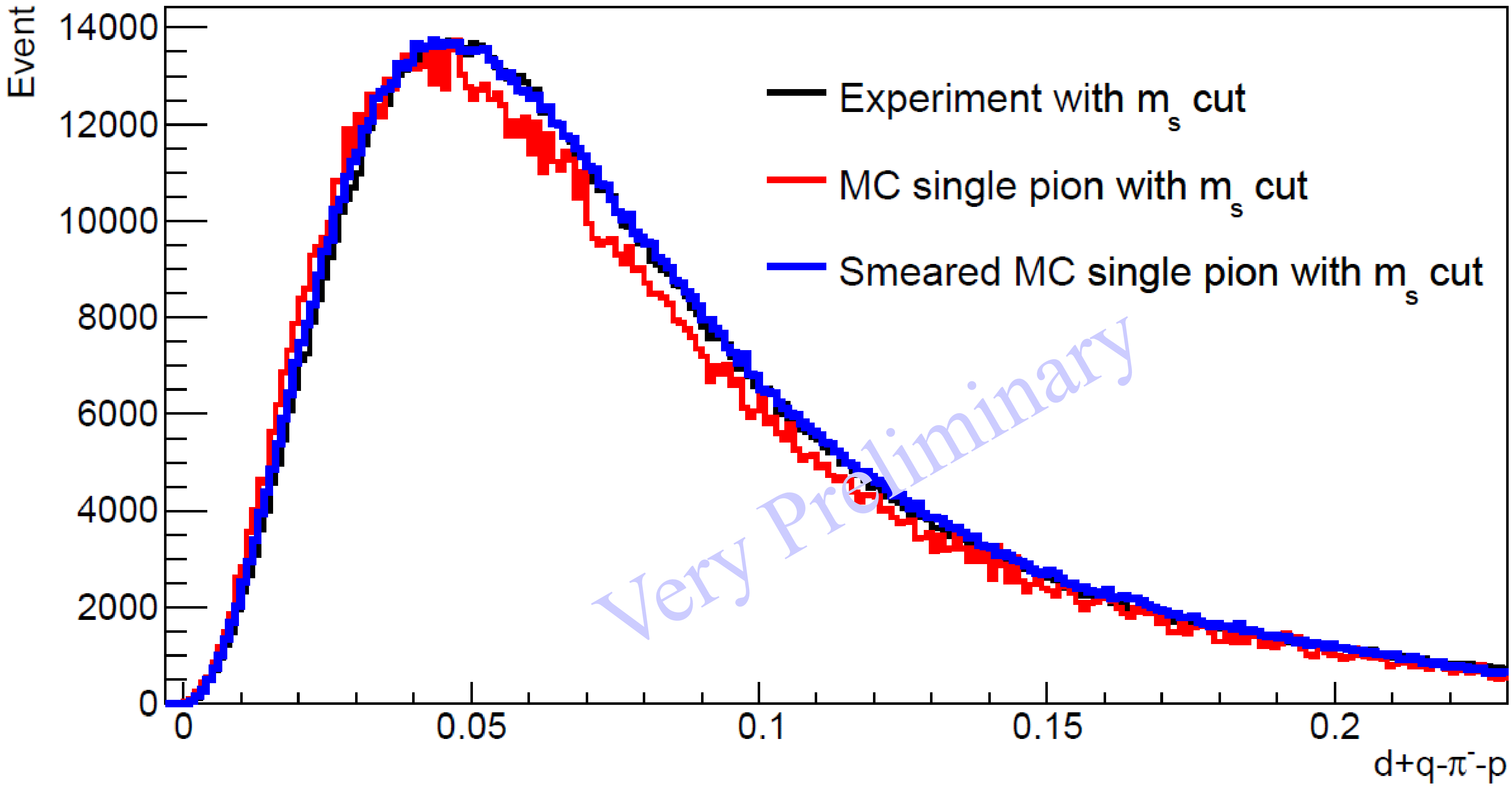






Single π Electroproduction off the Deuteron

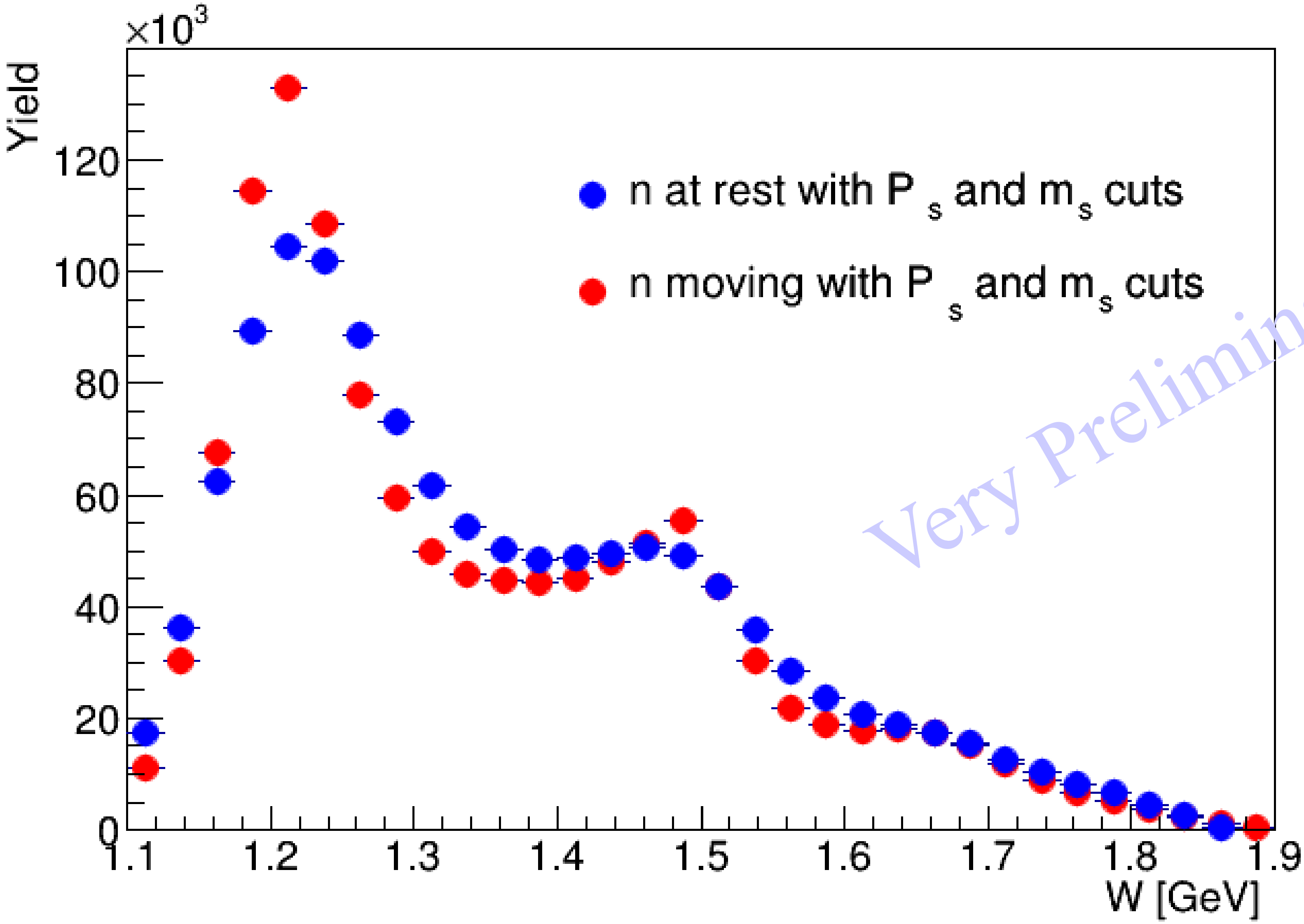
Ye Tian



Below a missing momentum of 0.2 GeV the **measured data** coincides with the **resolution smeared theoretical Fermi momentum distribution**.

Single π Electroproduction off the Deuteron

Ye Tian



Gary Hollis inclusive of the proton in the Deuteron with correction of Fermi smearing.

FSI for $\gamma n \to \pi^- p$

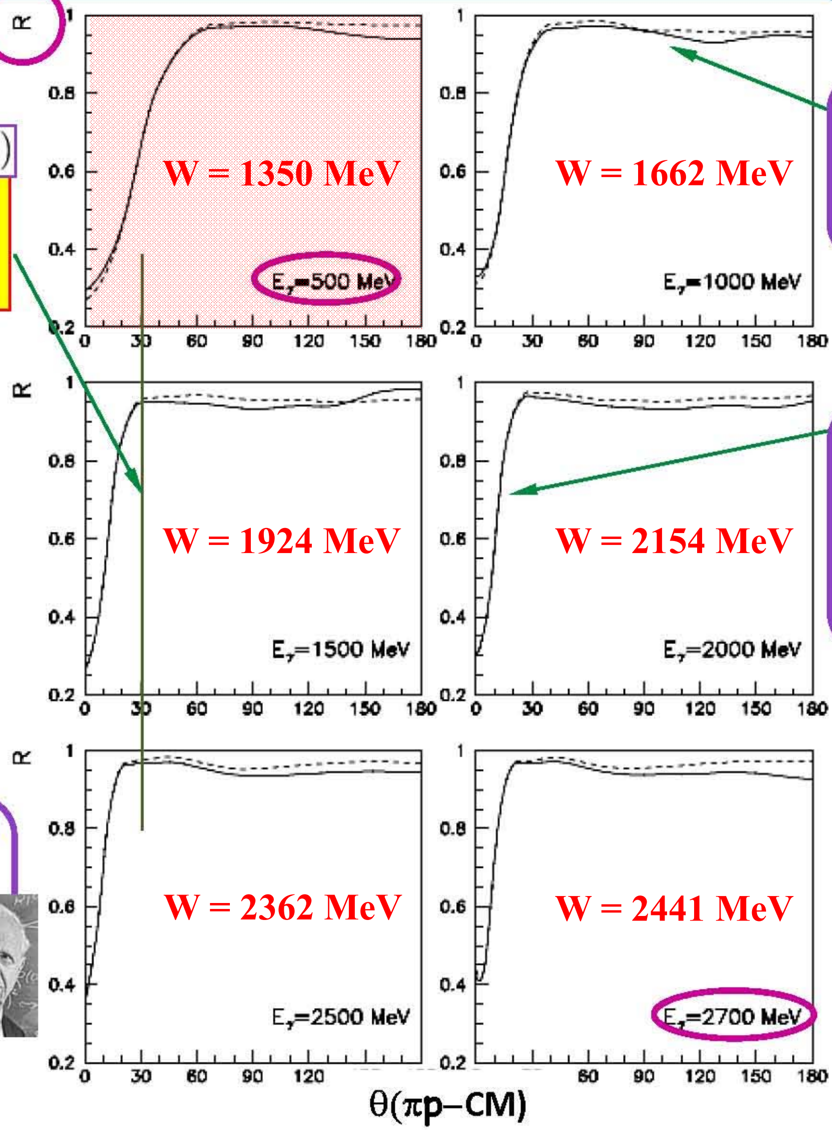
[V. Tarasov, A. Kudryavtsev, W. Briscoe, H. Gao, IS, Phys Rev C **84**, 035203 (2011)]

$$R_{FSI} = (d\sigma/d\Omega_{\pi p})/(d\sigma^{IA}/d\Omega_{\pi p})$$

Cuts:
p_s > 200 MeV/c
p_f > 200 MeV/c

CLAS data:
E > 1 GeV
θ > 32 deg

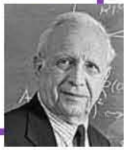
- There is no large sensitivity to cuts.



- For **CLAS** data
  - The **FSI** correction factor **R < 1**.
  - The behavior is smooth vs. **θ**.
  - The effect **Δσ/σ ≤ 10%**.

- There is a **sizeable FSI** effect from **S-wave** part of **pp-FSI** at small angles.
- This region **narrows** as the E_γ increases.

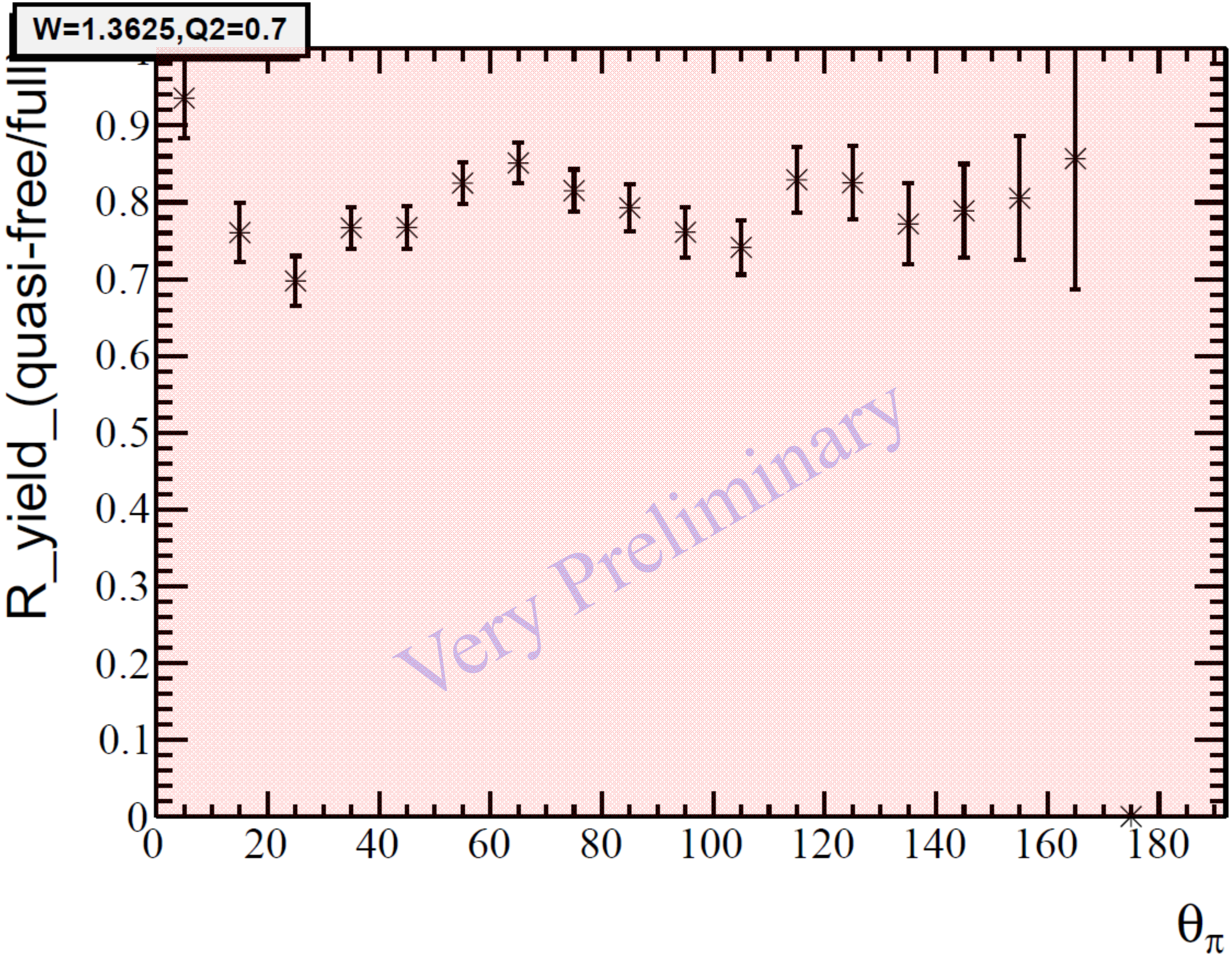
- Our estimation of the **Glauber FSI** corrections gives the value of 5%.
- **Previous** estimations gave the order of **15-30**%.



--- $[IA + NN_{fsi}] / IA$
___ $[IA + (NN+\pi N)_{fsi}] / IA$

Single π Electroproduction off the Deuteron

Ye Tian

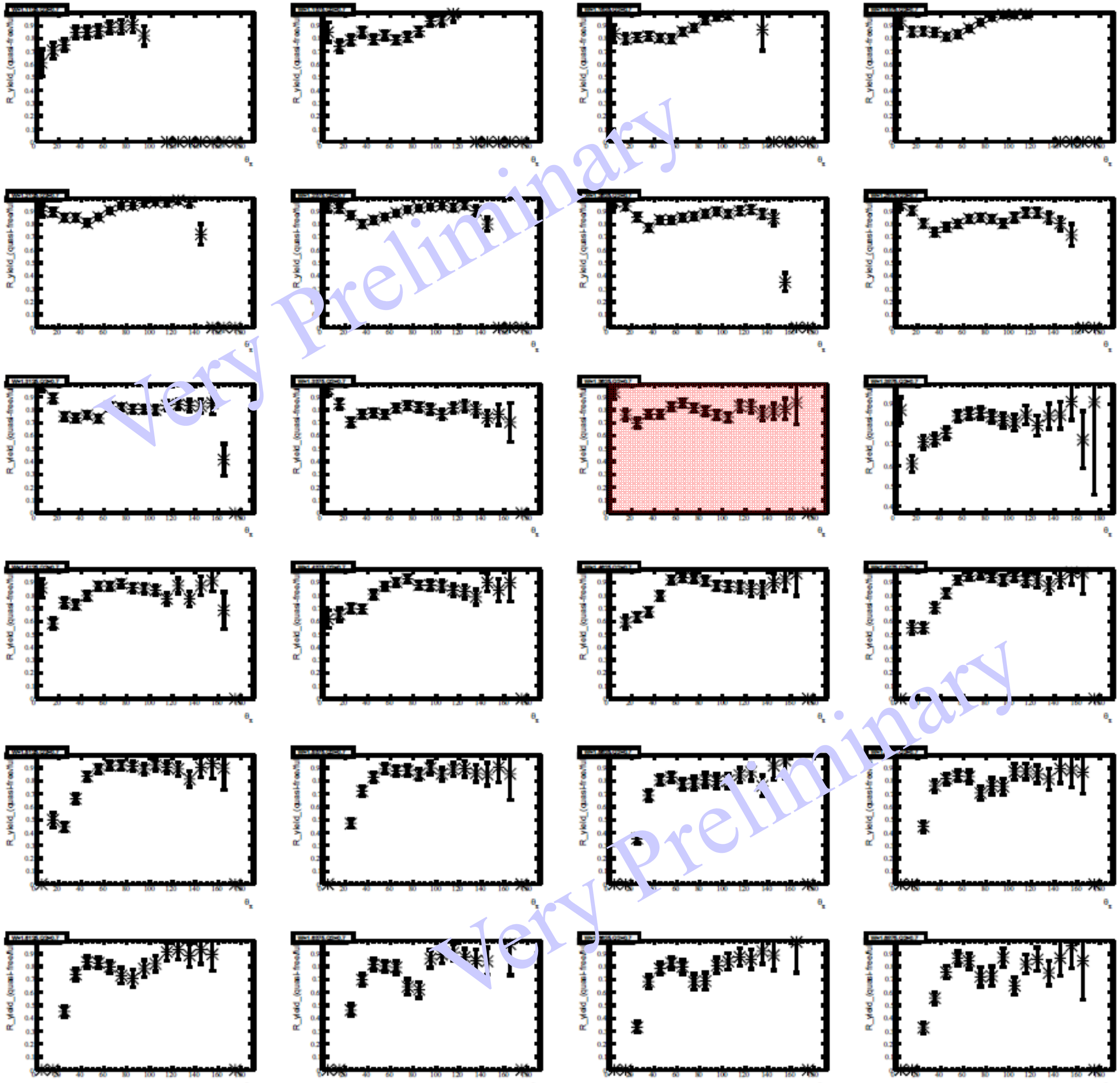


Single π Electroproduction off the Deuteron

W = 1125 MeV

ΔW = 25 MeV

Ye Tian



$Q^2 = 0.7\ GeV^2$

$\Delta Q^2 = 0.2\ GeV^2$

W = 1685 MeV

Single π Electroproduction off the Deuteron

Ye Tian

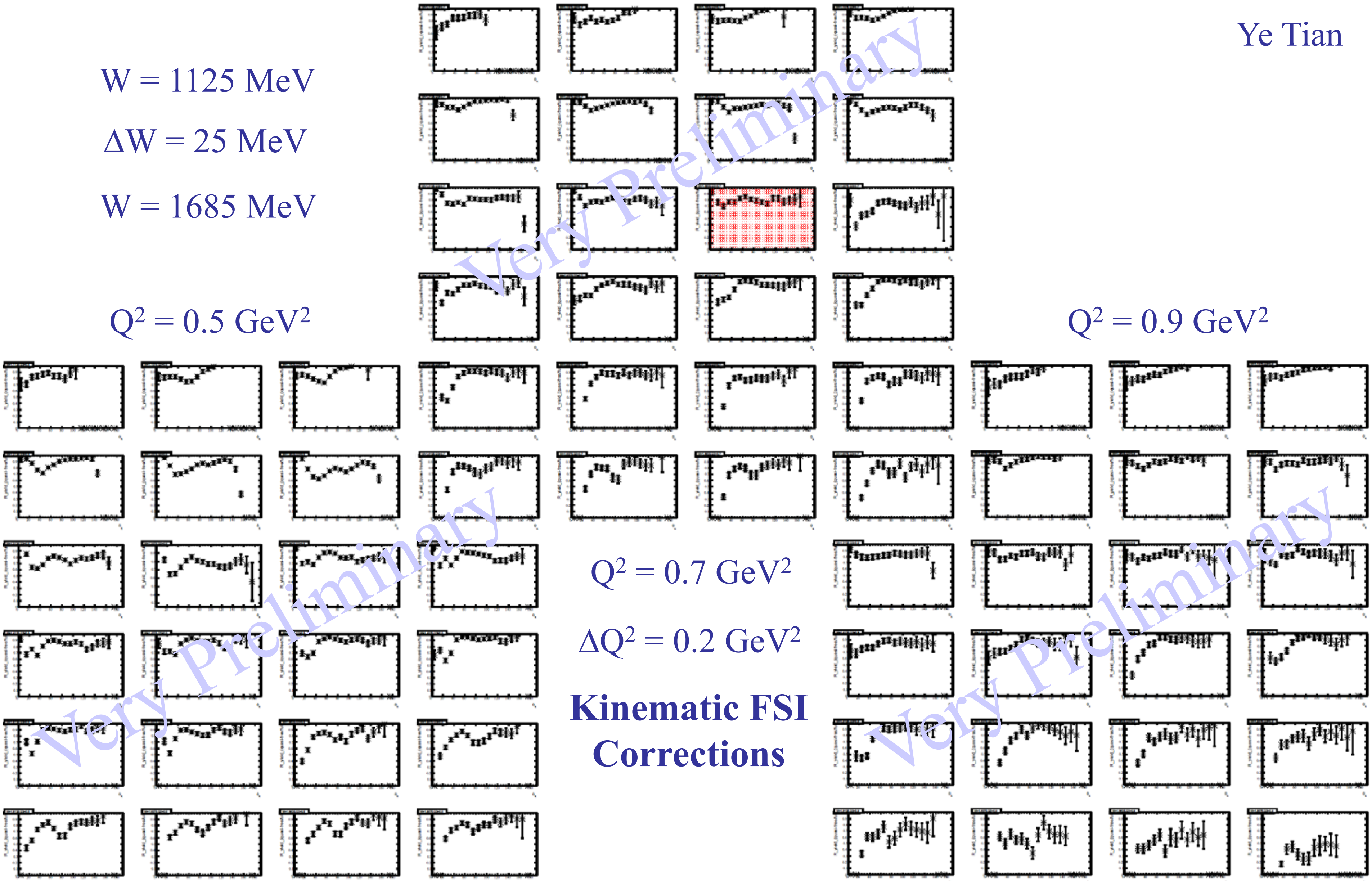
W = 1125 MeV

ΔW = 25 MeV

W = 1685 MeV

$Q^2 = 0.5\ \text{GeV}^2$

$Q^2 = 0.9\ \text{GeV}^2$



$Q^2 = 0.7\ \text{GeV}^2$

$\Delta Q^2 = 0.2\ \text{GeV}^2$

Kinematic FSI Corrections

Single π⁻ Electroproduction off the Deuteron

Ye Tian

W = 1212 MeV

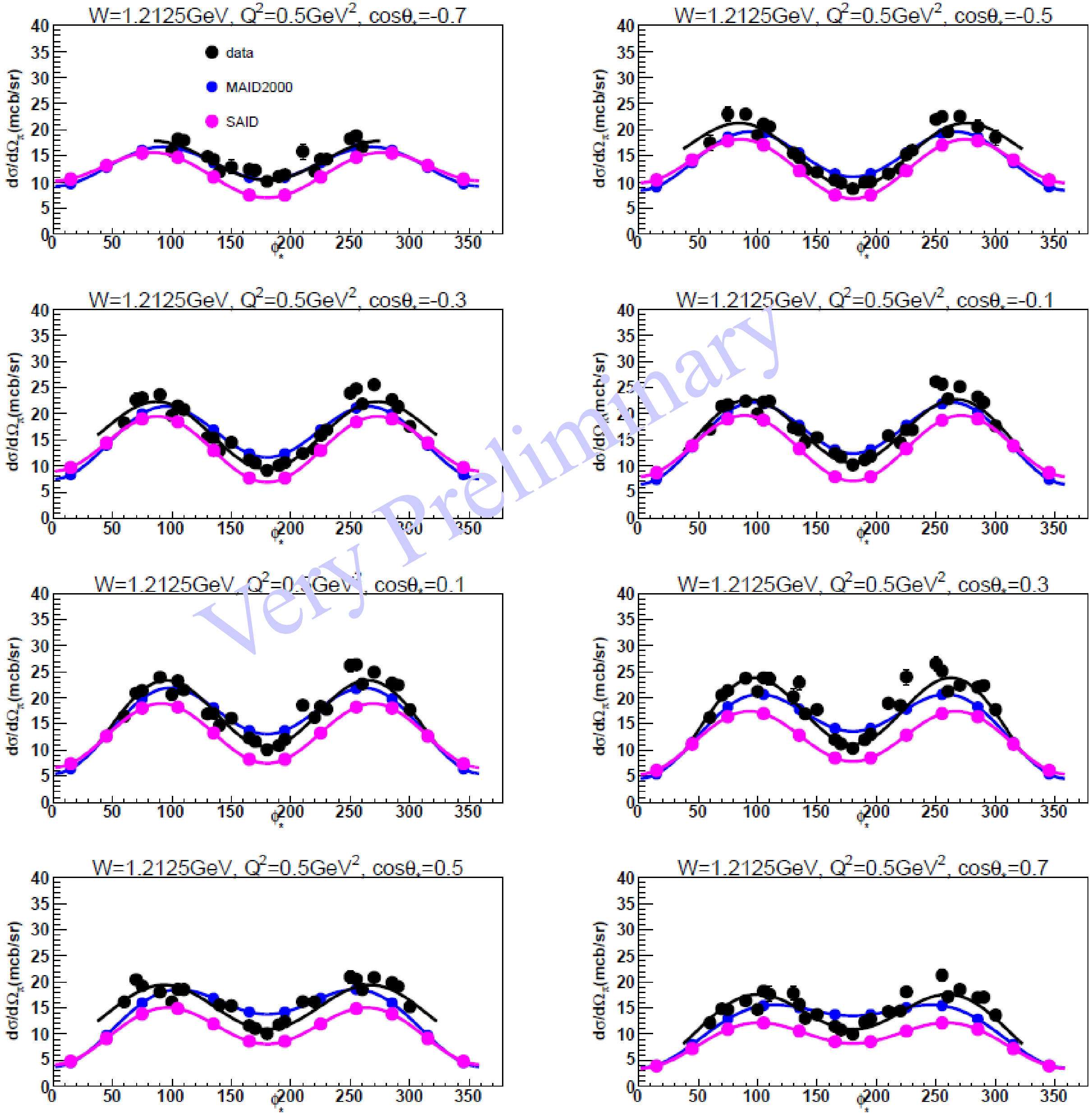
ΔW = 25 MeV

$Q^2 = 0.5\ GeV^2$

$\Delta Q^2 = 0.2\ GeV^2$

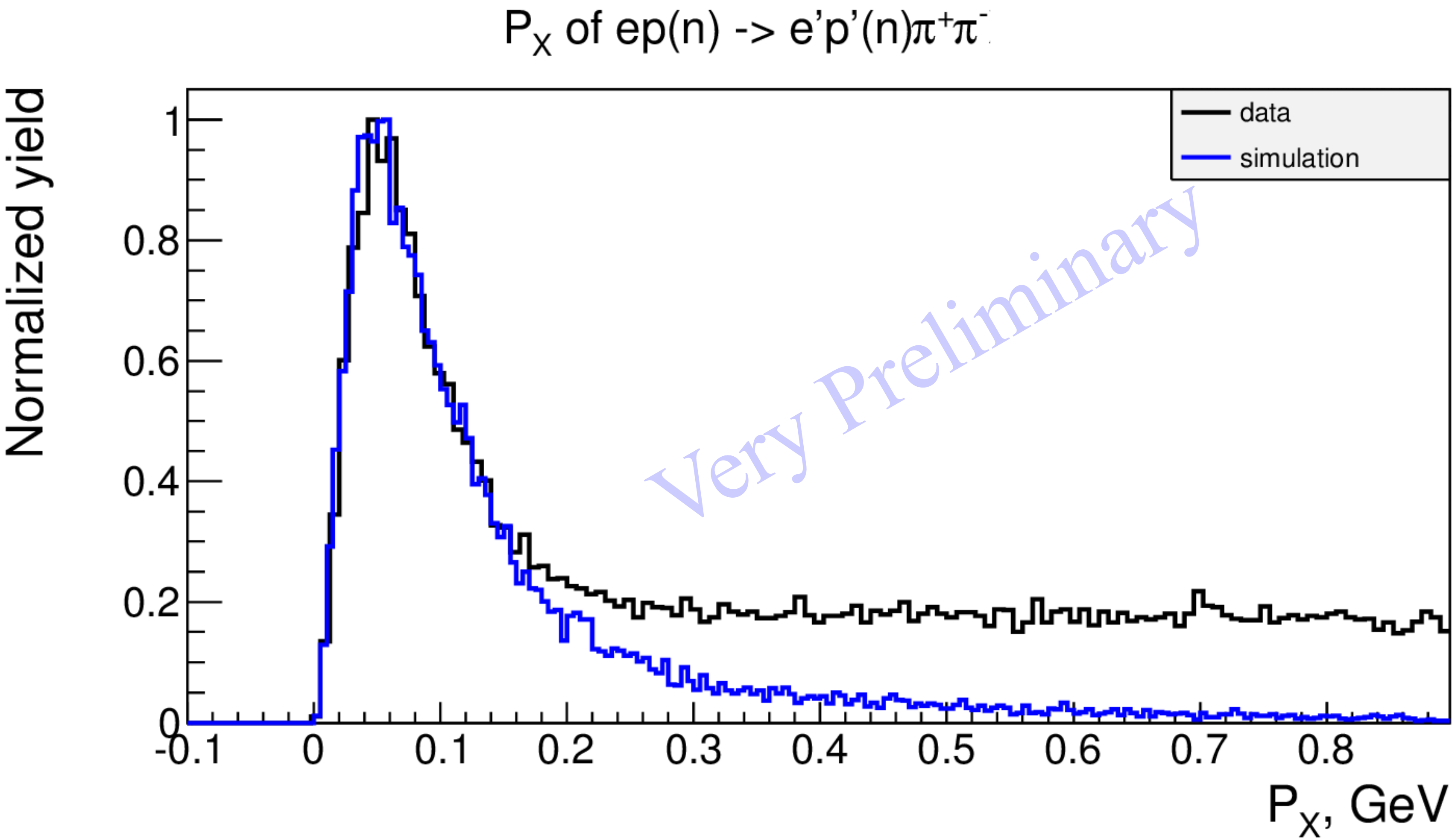
cos(θ) = -0.7
Δcos(θ) = 0.2
cos(θ) = 0.7

ϕ = 15°
Δϕ = 30°
ϕ = 345°



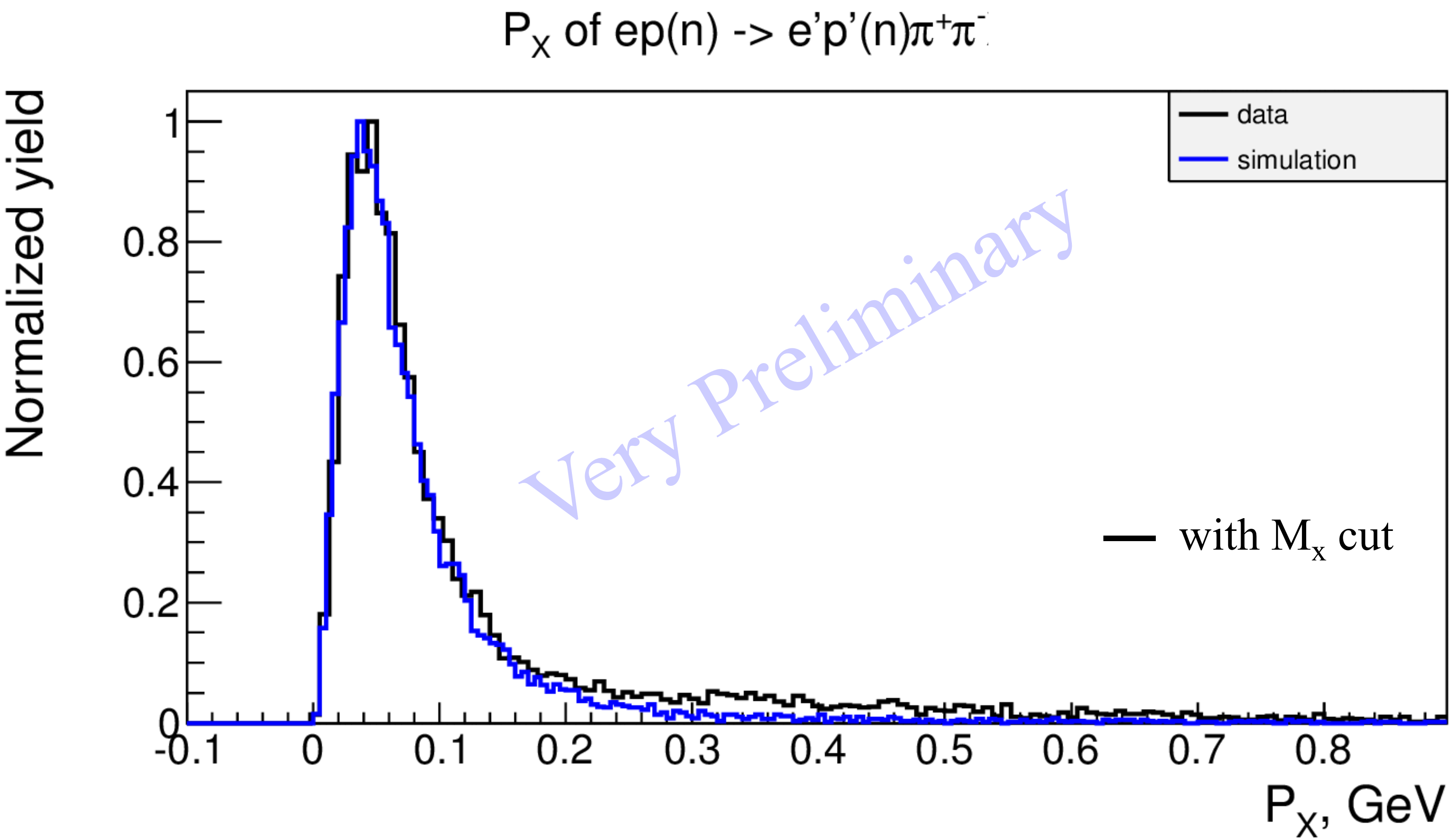
Double π Electroproduction off the Deuteron

Iuliia Skorodomina



Double π Electroproduction off the Deuteron

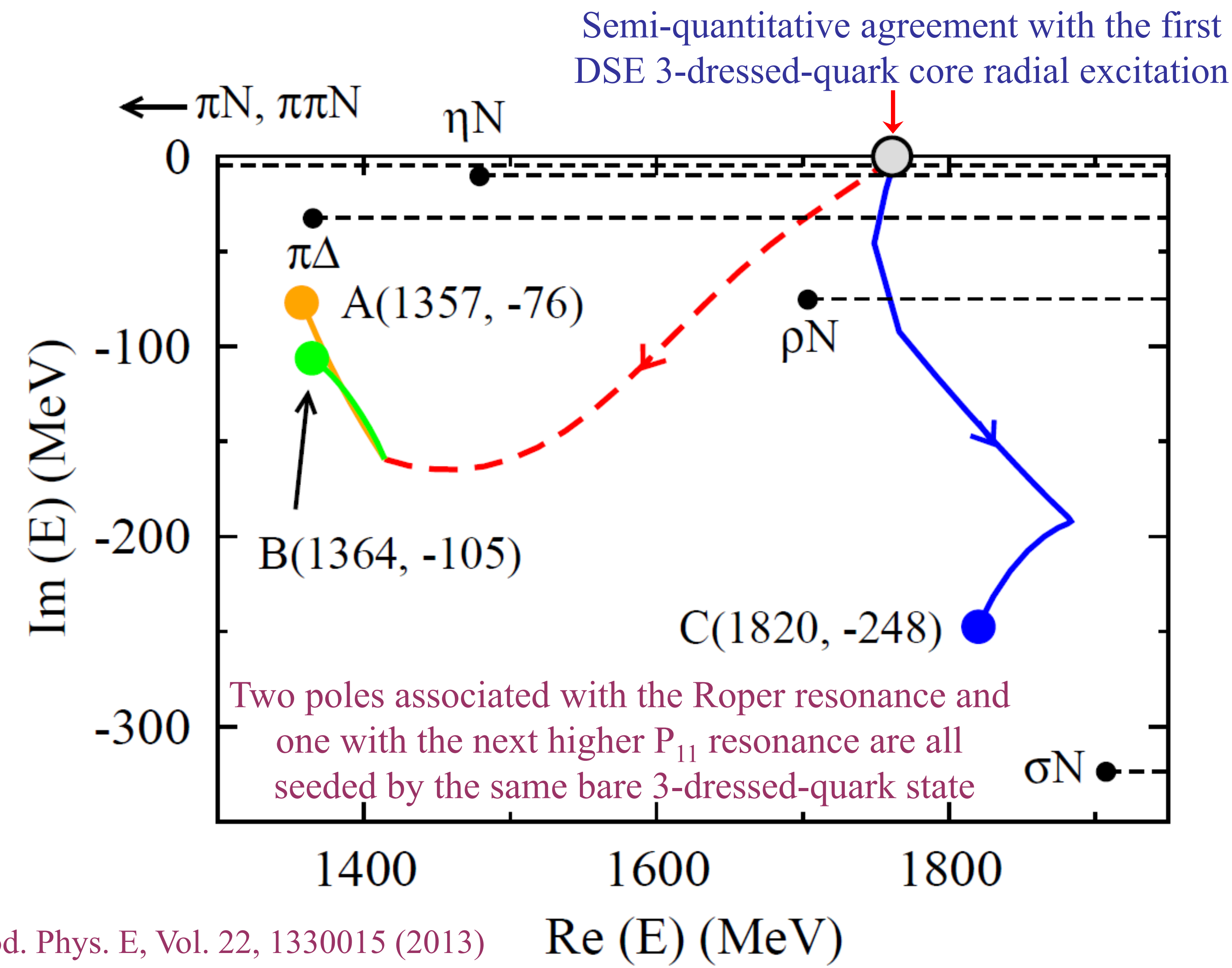
Iuliia Skorodomina



QCD-Based Models and Theory

For some highlighted examples see posted presentation or
Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013)

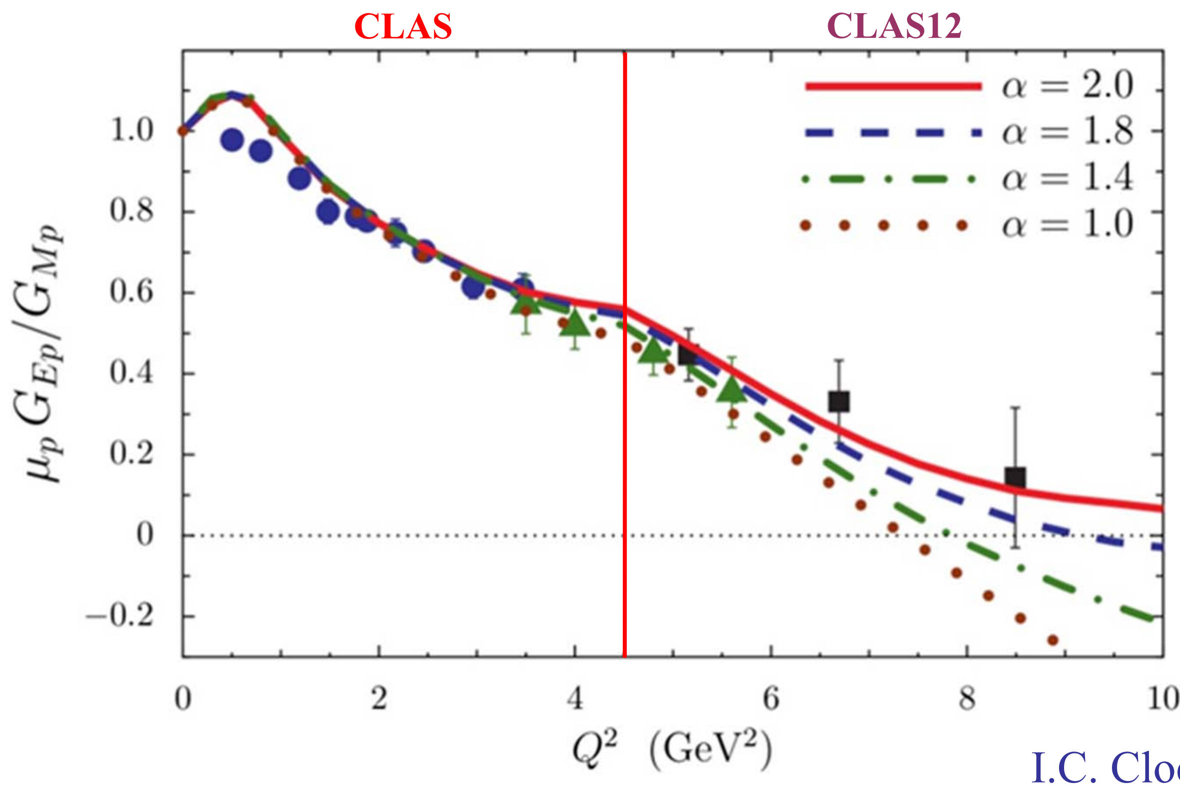
DSE and EBAC/ANL-Osaka Approaches



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

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.

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

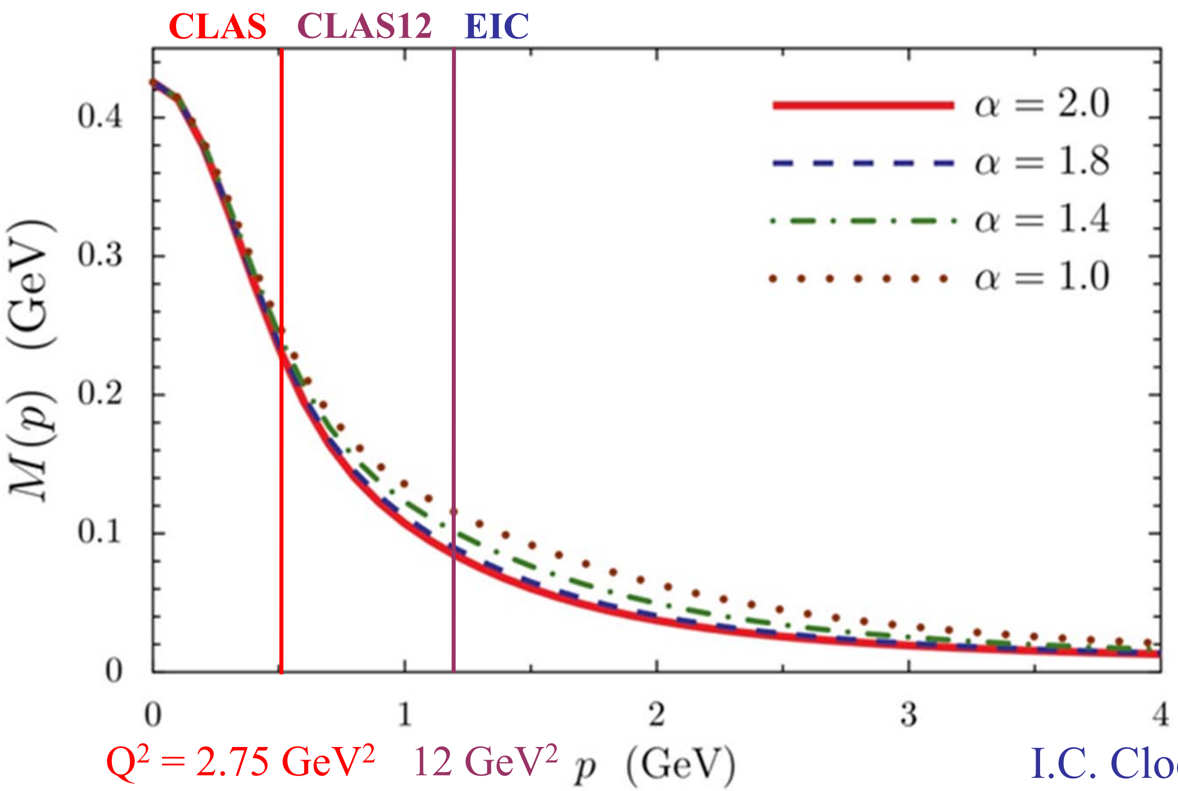
I.C. Cloet *et al*., Phys. Rev. Lett. **111**, 101803

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

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.

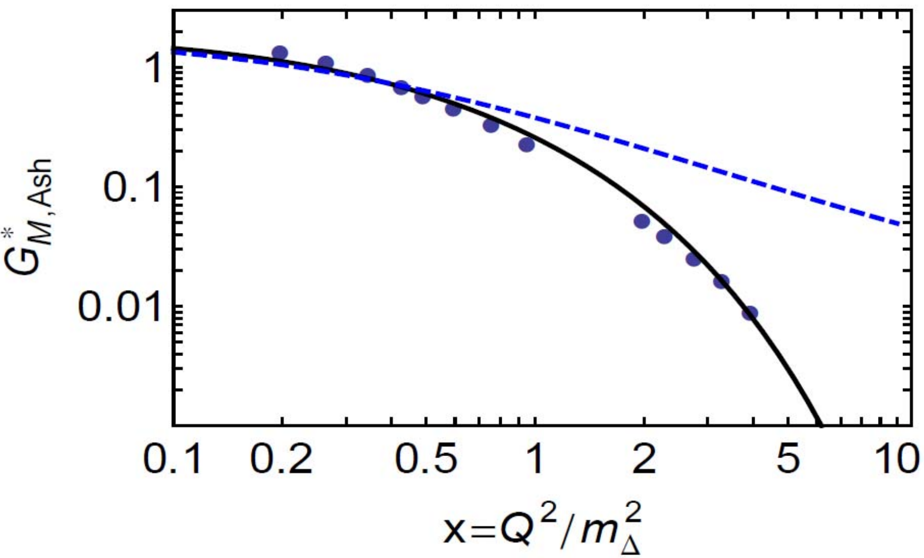
I.C. Cloet *et al*., Phys. Rev. Lett. **111**, 101803

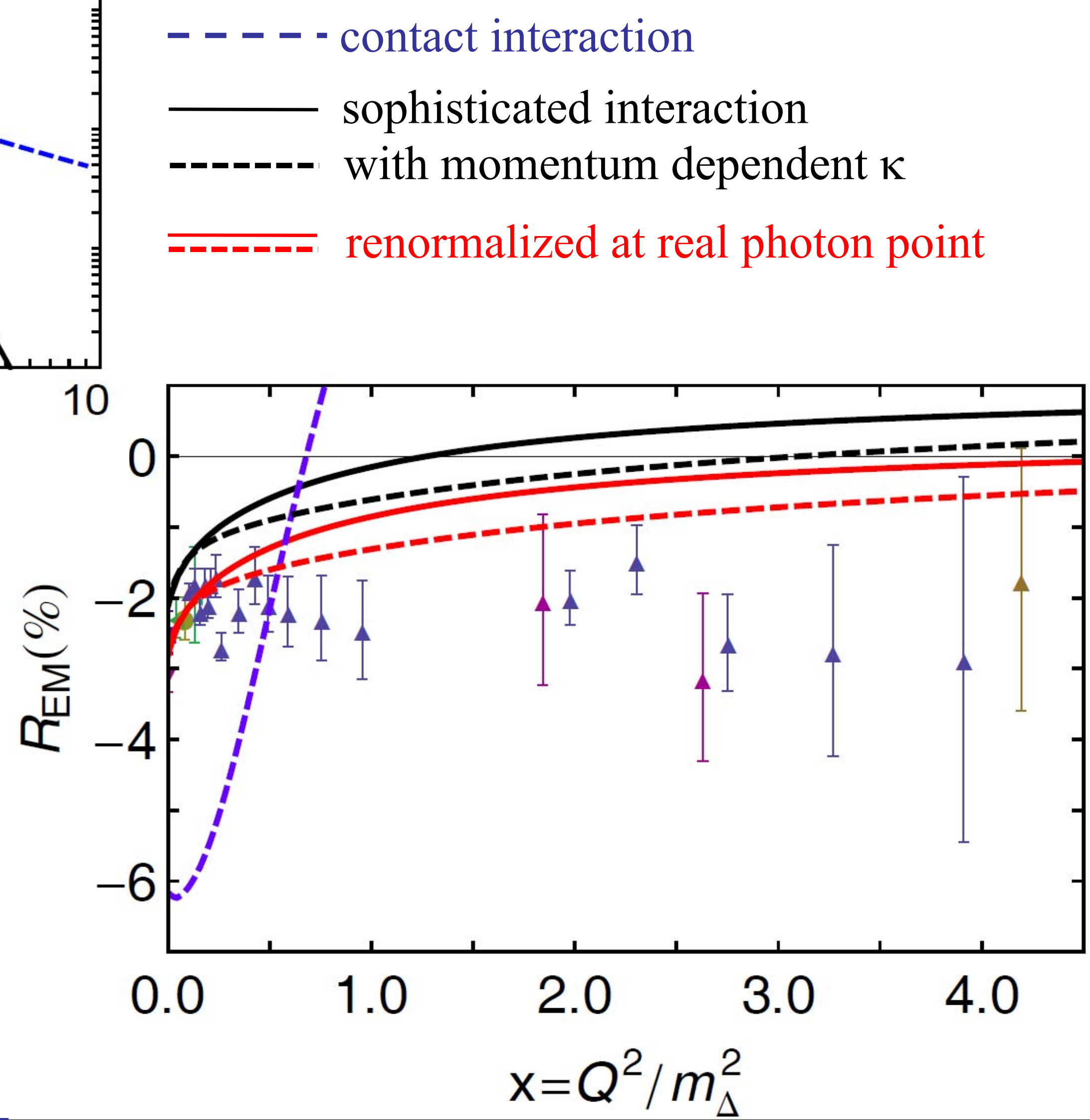
DSE electrocouplings of several excited nucleon states will become available as part of the commitment of the Argonne NL.

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

Anomalous Magnetic Moment in DSE Approach

J. Segovia





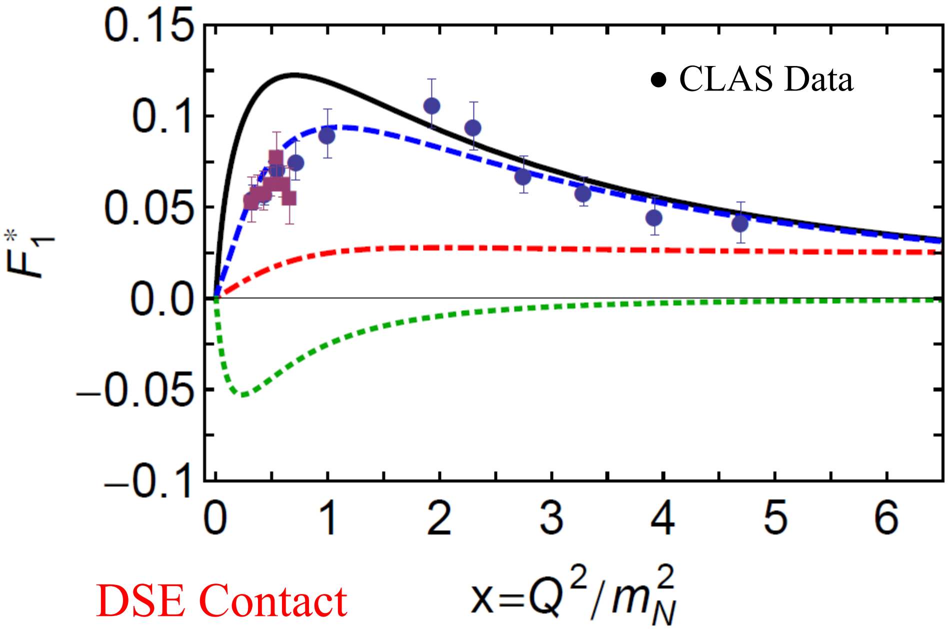
J. Segovia *et al.*, FBS 55 (2014) 1185-1222

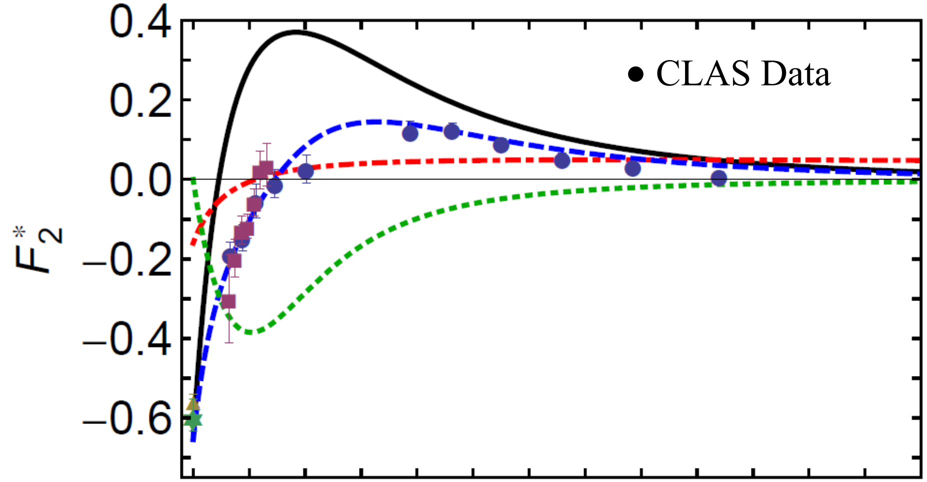
The DSE calculation of R_{EM} zero crossing is sensitive to the momentum dependent anomalous magnetic moment of the dressed-quark.

Roper Transition Form Factors in DSE Approach

$N(1440)P_{11}$

J. Segovia *et al.*, Phys. Rev. Lett. **115**, 171801



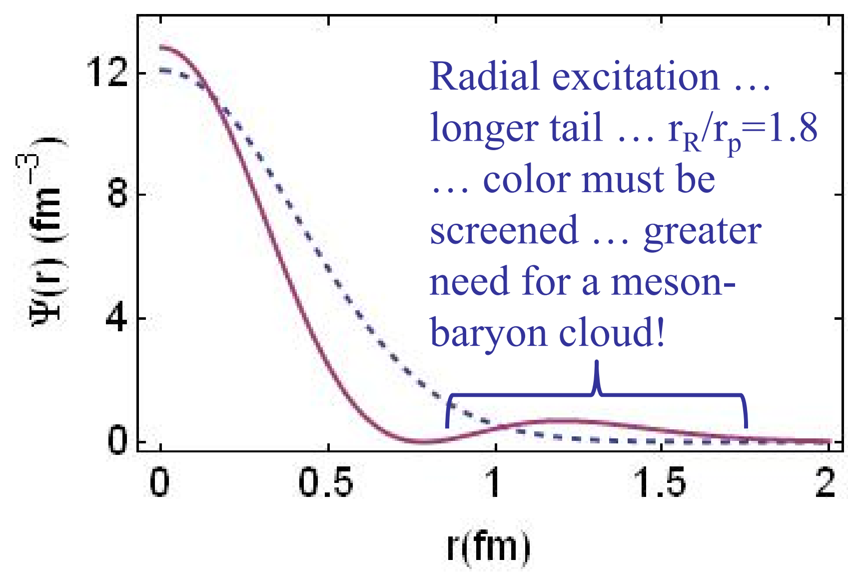


DSE Contact

DSE Realistic

Inferred meson-cloud contribution

Anticipated complete result

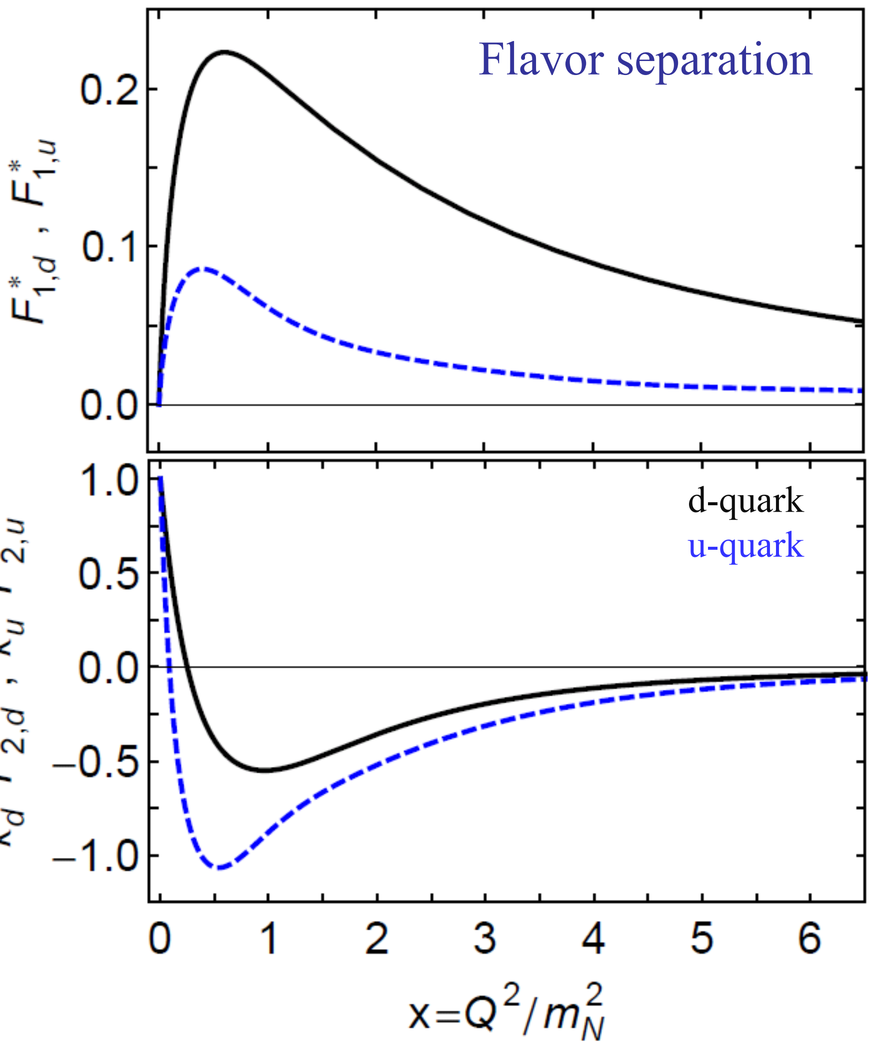


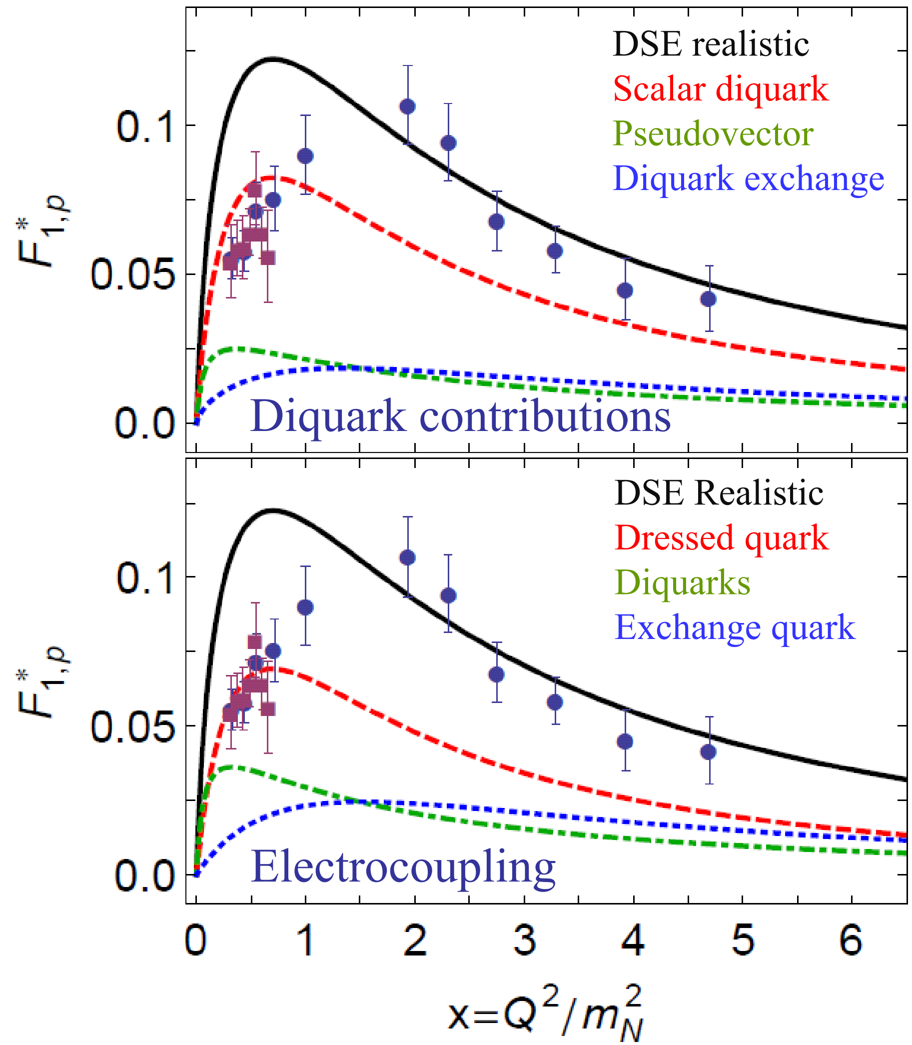
Importantly, the existence of a zero in F_2 is not influenced by meson-cloud effects, although its precise location is.

Roper Transition Form Factors in DSE Approach

N(1440)P_{11}

J. Segovia and C.D. Roberts, arXiv:1607.04405

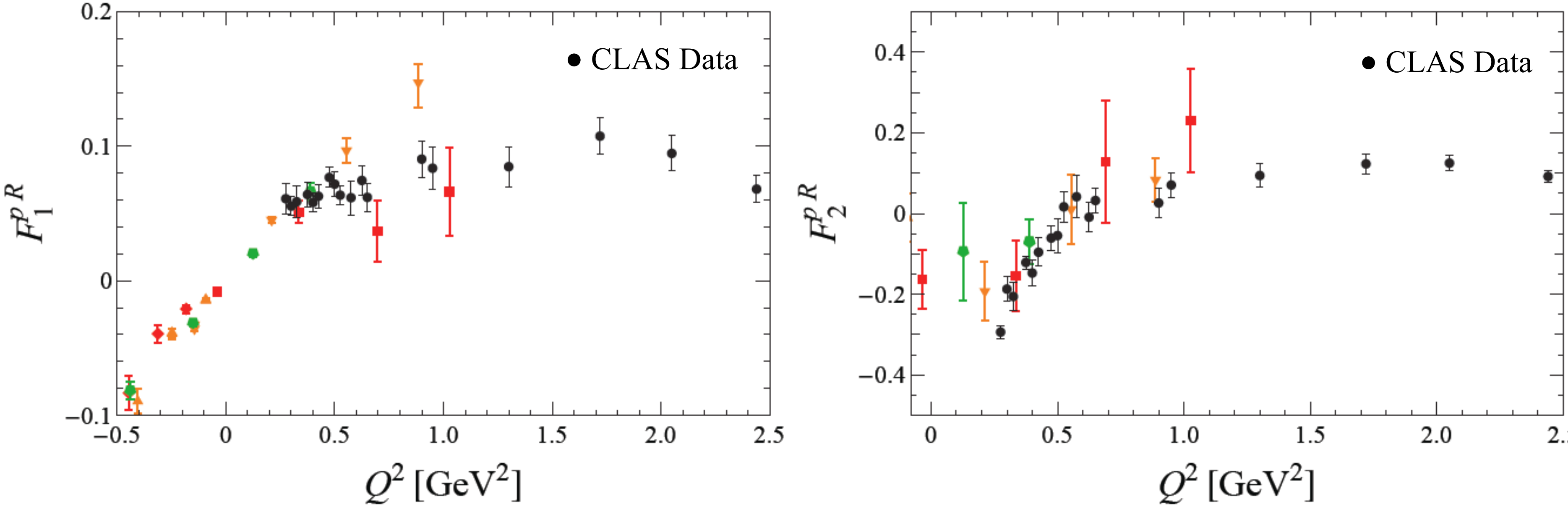




Roper Transition Form Factors in LQCD

N(1440)P_{11}

Huey-Wen Lin and S.D. Cohen



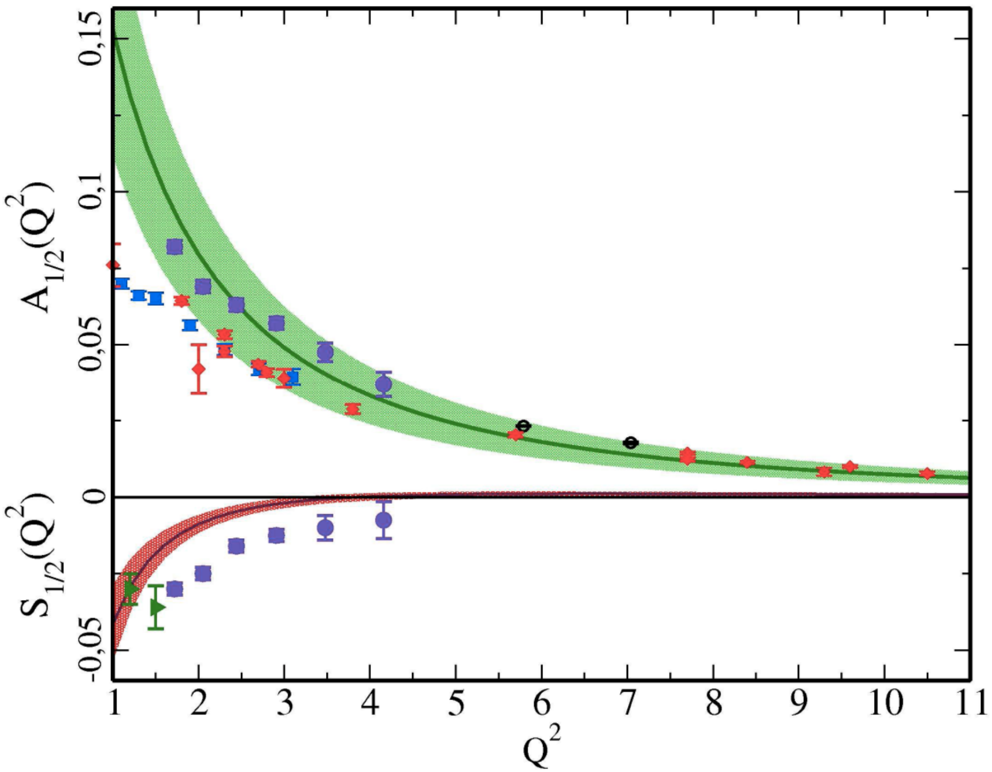
Lattice QCD calculations of the p(1440)P_{11} transition form factors have been carried out with various pion masses, m_π= **390**, **450**, and **875** MeV. Particularly remarkable is the zero crossing in F_2 that appears at the current statistics in the unquenched but not in the quenched calculations.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

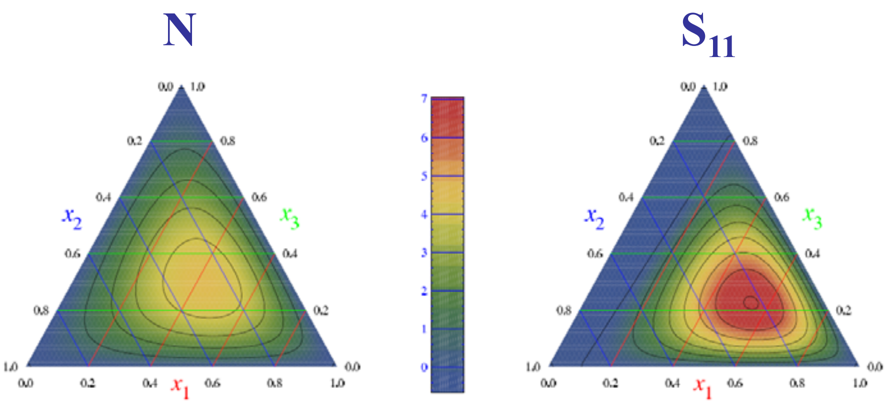
LQCD calculations of N* electrocouplings will be extended to $Q^2 = 10$ GeV^2 near the physical π-mass as part of the commitment of the JLab LQCD and EBAC groups in support of this proposal.

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

LQCD & Light Cone Sum Rule (LCSR) Approach

N(1535)S_{11}





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.

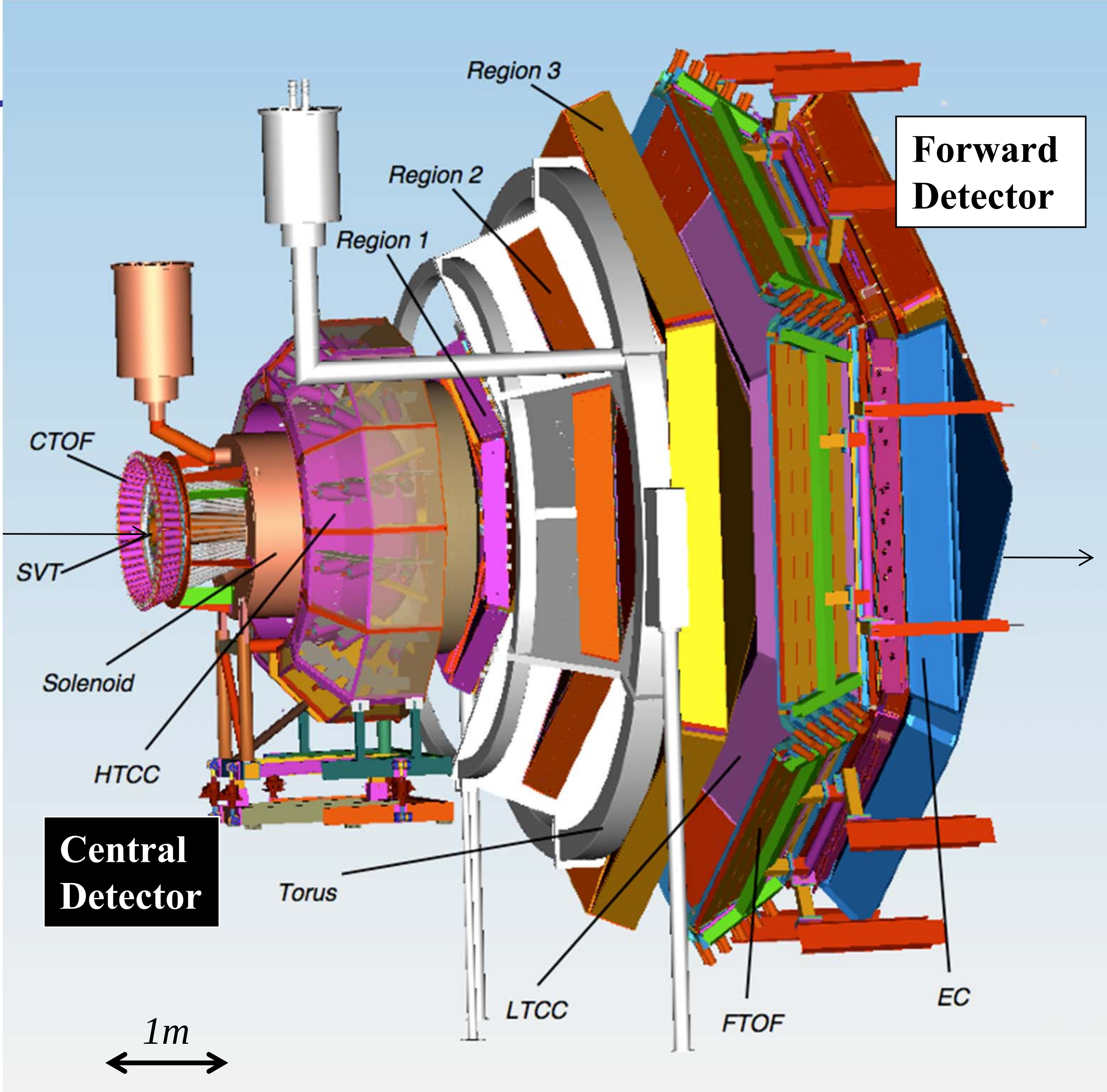
Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013) 1-99

CLAS12

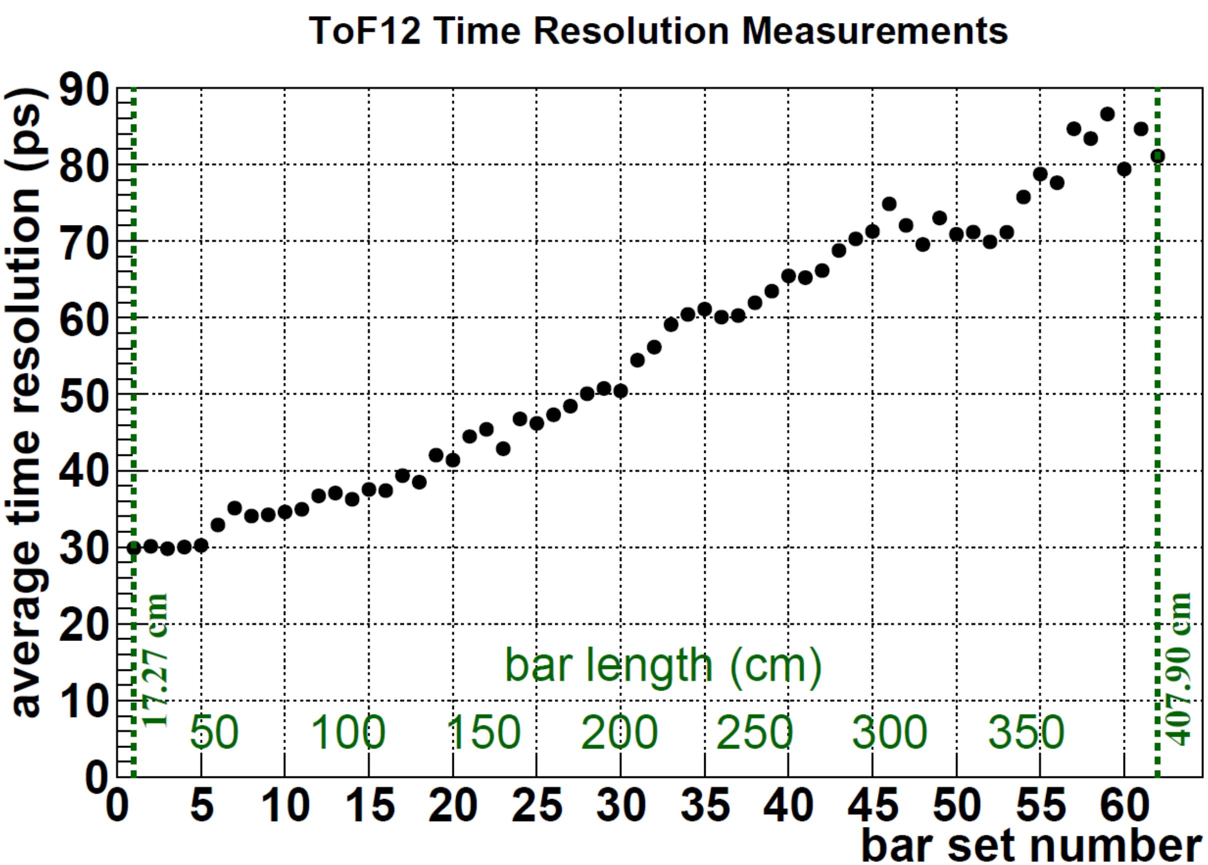
CLAS12

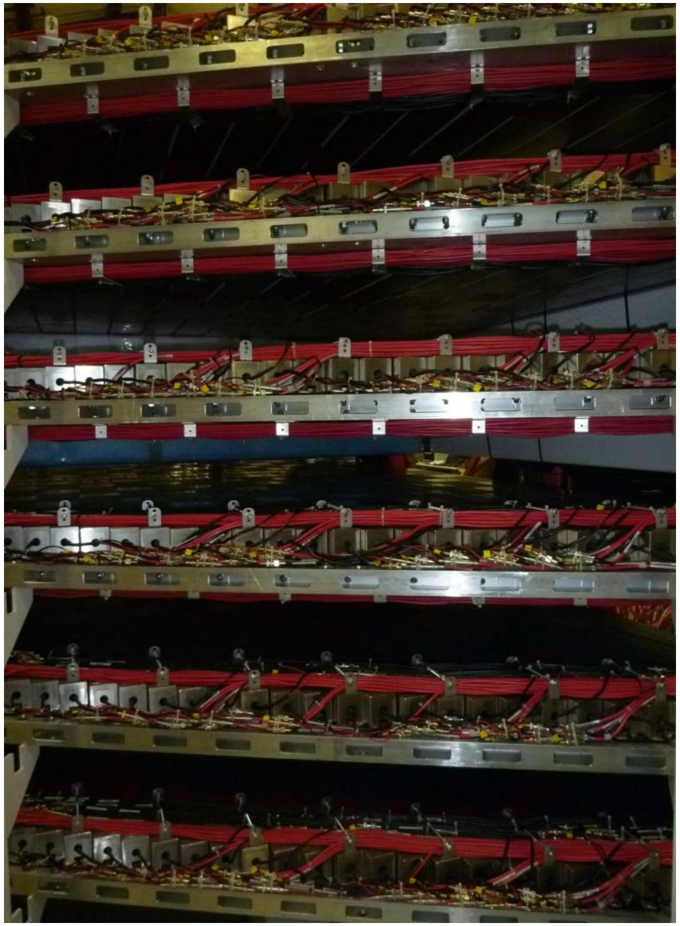
- Luminosity > 10^{35} $cm^{-2}s^{-1}$
- Hermeticity
- Polarization

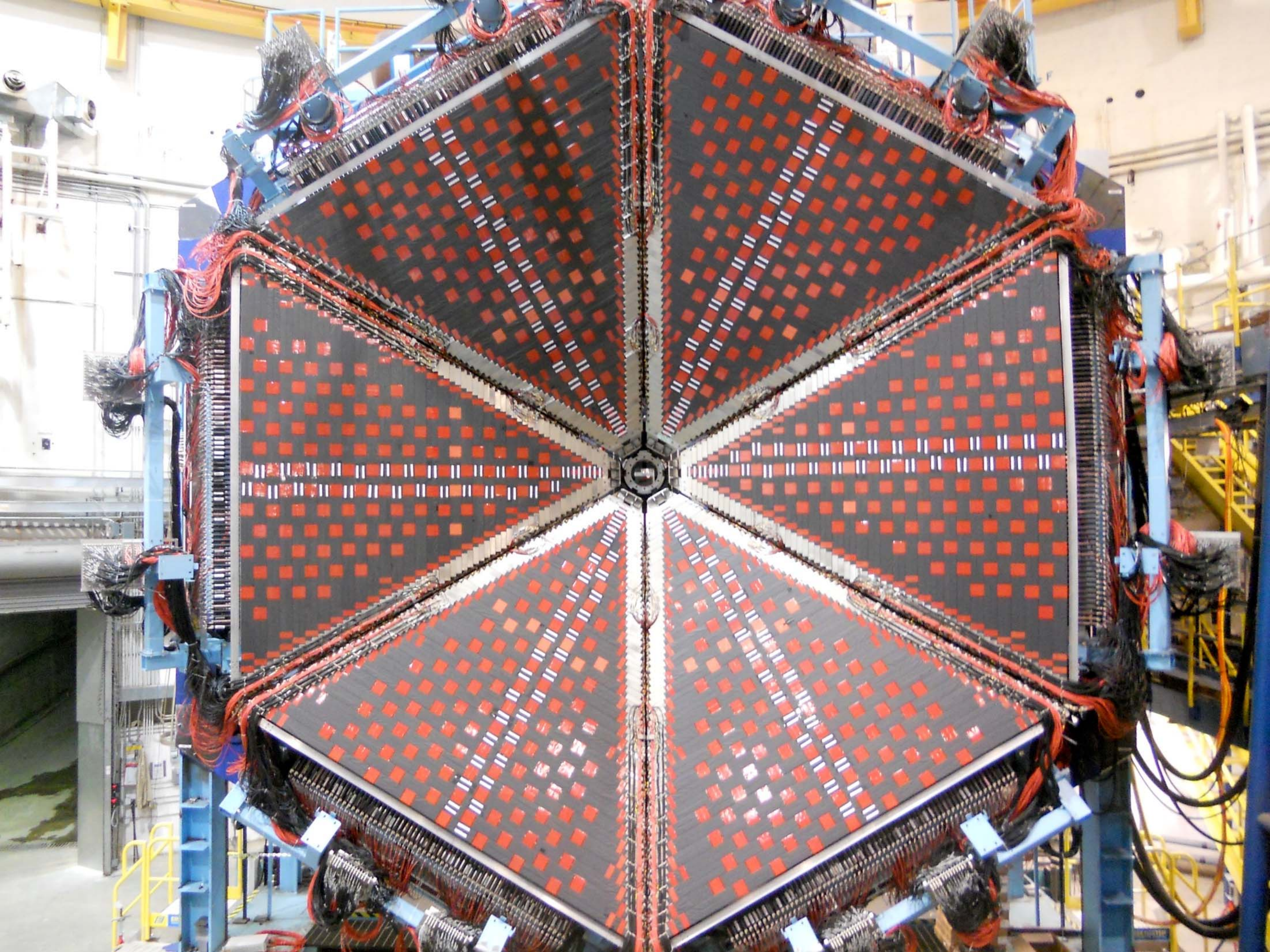
- Baryon Spectroscopy
- Elastic Form Factors
- N to N* Form Factors
- GPDs and TMDs
- DIS and SIDIS
- Nucleon Spin Structure
- Color Transparency
- …



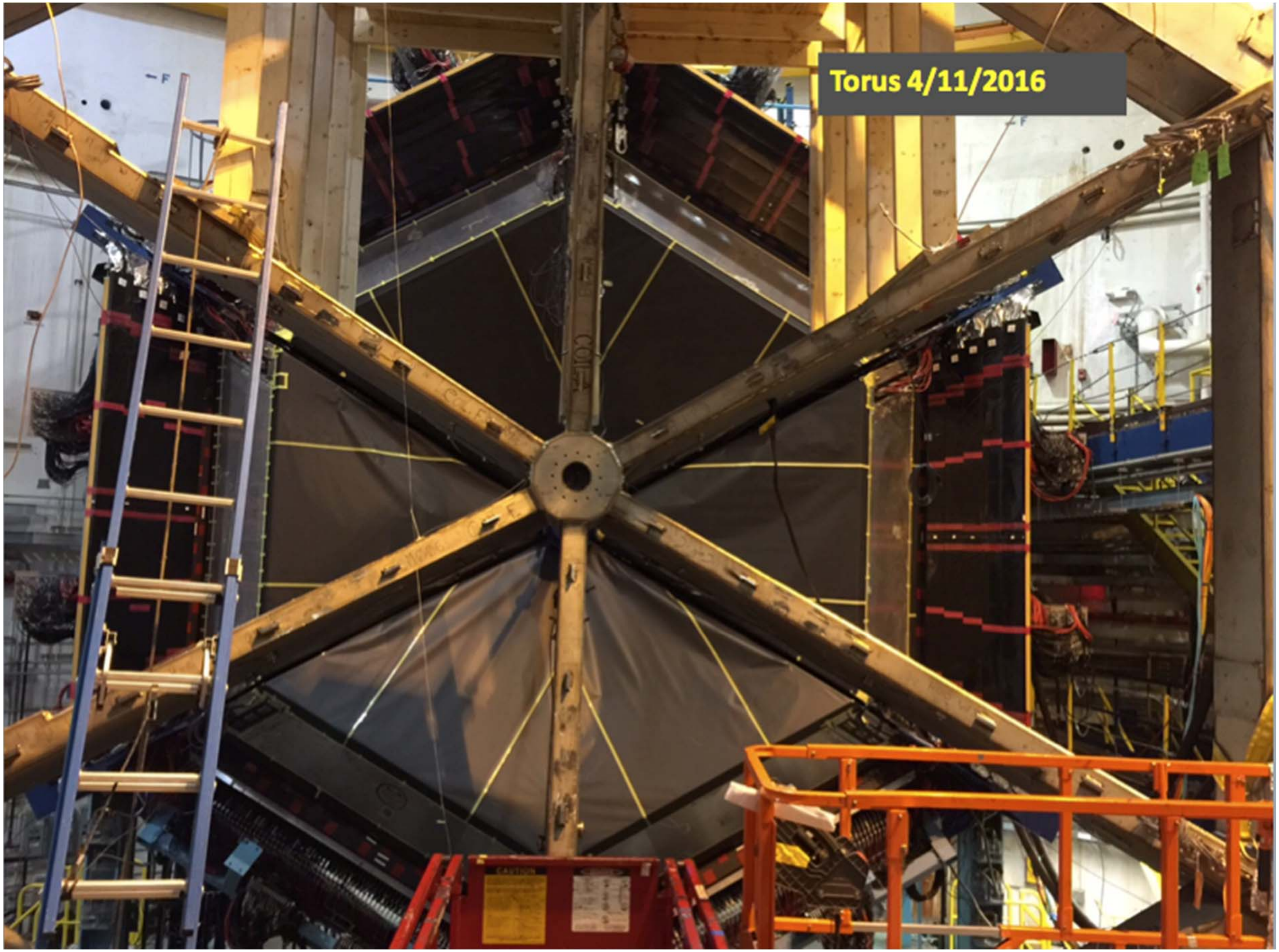
New Forward Time of Flight Detector for CLAS12



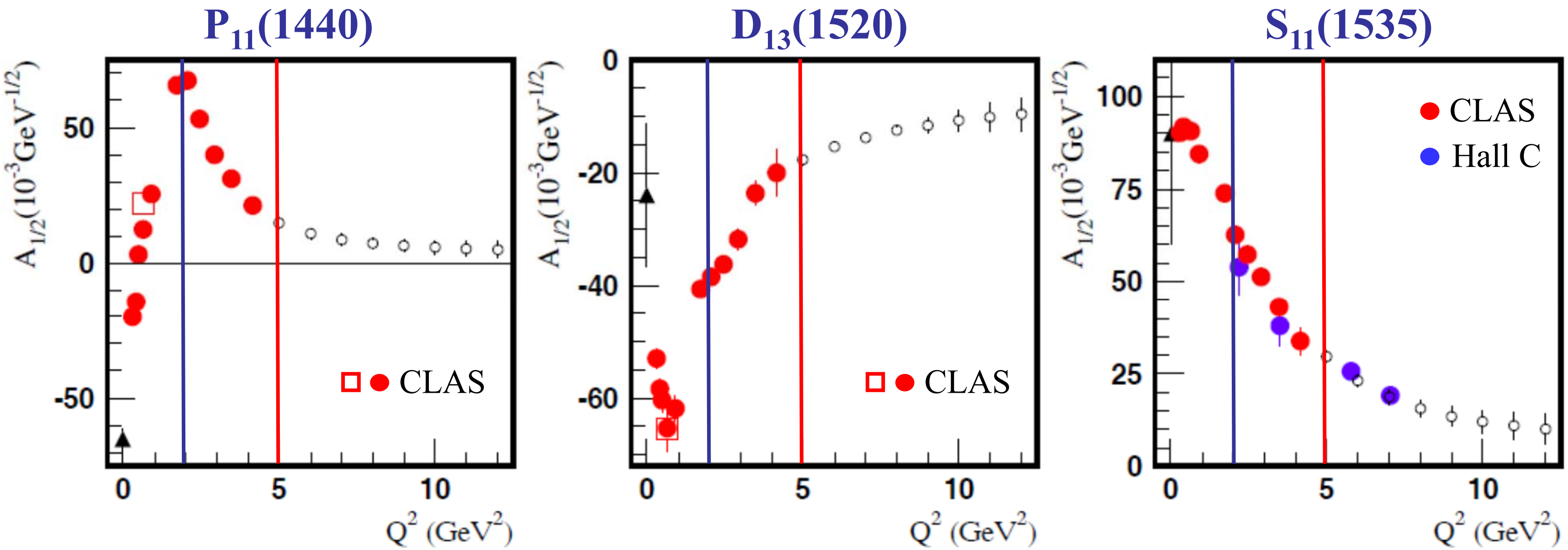




Torus, LTCC, and FTOF Fully Installed



Anticipated N* Electrocouplings from Combined Analyses of Nπ/Nππ



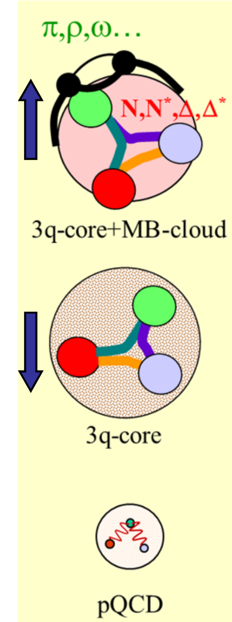
Open circles represent projections and all other markers the available results with the 6-GeV electron beam

- 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 $\gamma_v NN^*$ 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 http://boson.physics.sc.edu/~gothe/research/pub/whitepaper-9-14.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 (PR12-16-010) ,
  - establish a repertoire of high precision spectroscopy parameters, and
  - measure light-quark-flavor separated electrocouplings over an extended Q^2-range, both to lower and higher Q^2, for a wide variety of N* states (PR12-16-010 A).



- Comparing these results with DSE, LQCD, LCSR, and rCQM will build further 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 close 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. **ECT*2015 and INT2016.**