From the CLAS to the CLAS12 N* Program

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UNIVERSITY OF SOUTH CAROLINA

Exploring Hadrons with Electromagnetic Probes: Structure, Excitations, Interactions

November 2-3, 2017

Thomas Jefferson National Accelerator Facility

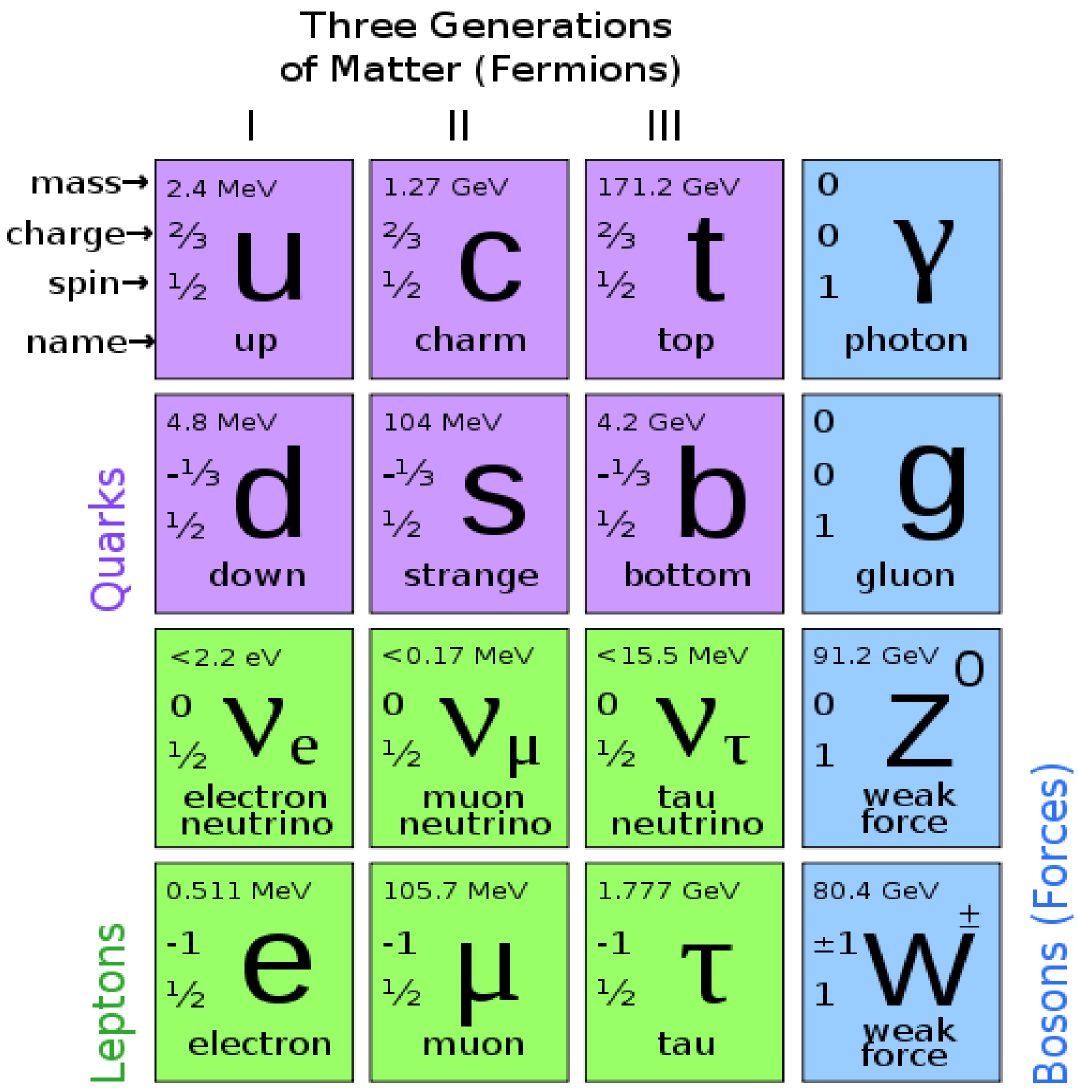
Newport News, VA

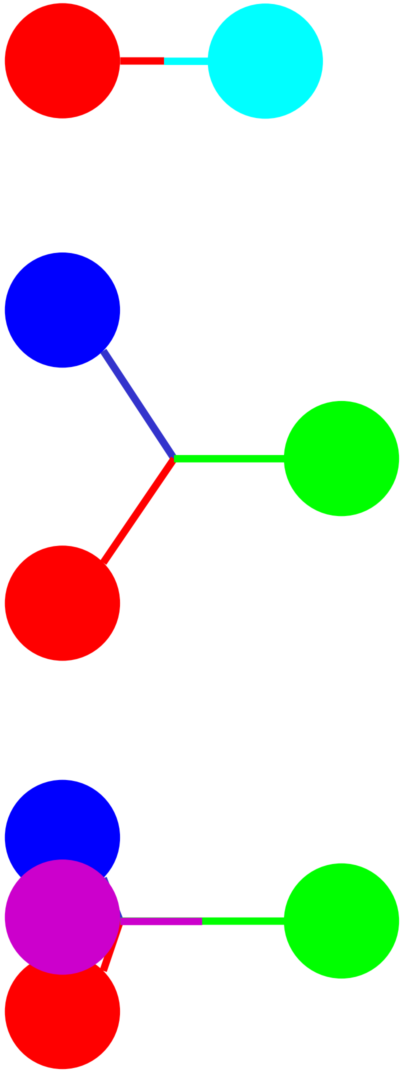
- **γNN* Vertexcouplings:** A unique exploration of baryon and quark structure?
- **Analysis and New Results:** Phenomenological but consistent!
- **Outlook:** New experiments with extended scope! ➞ **We want you …**

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

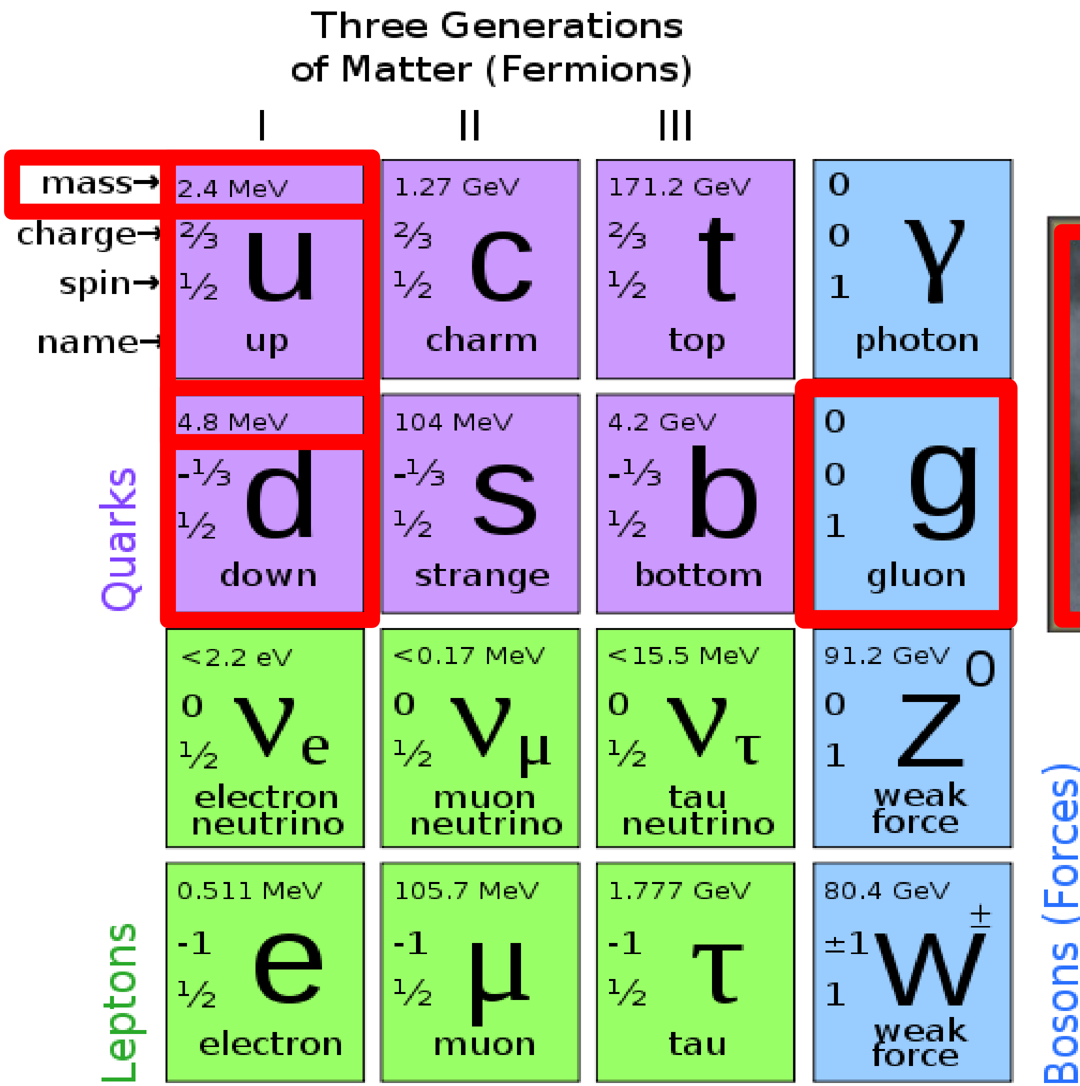
Spectroscopy

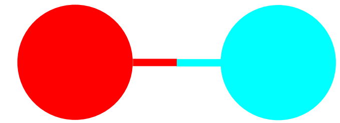
Build your Mesons and Baryons …

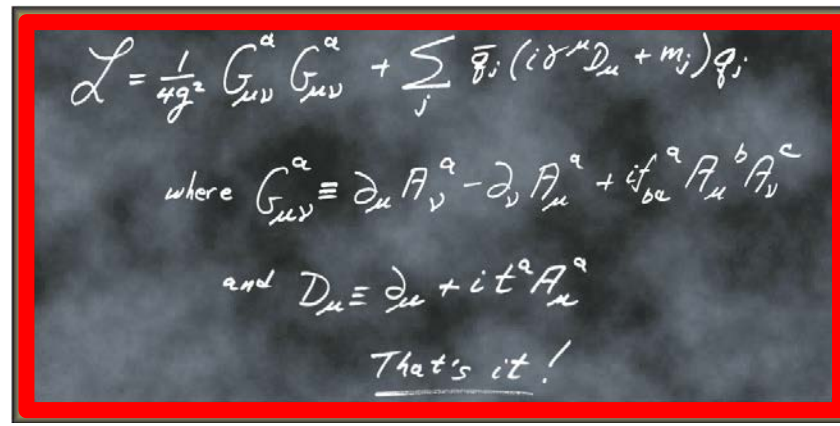




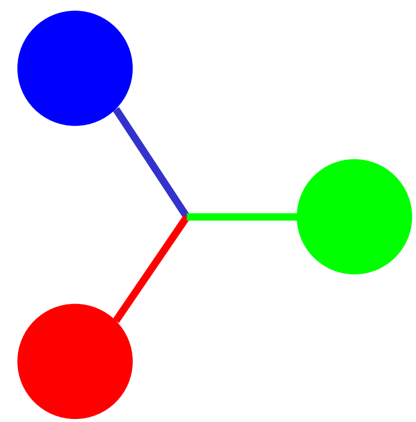
Build your Mesons and Baryons …







Frank Wilczek, Physics Today, August 2000

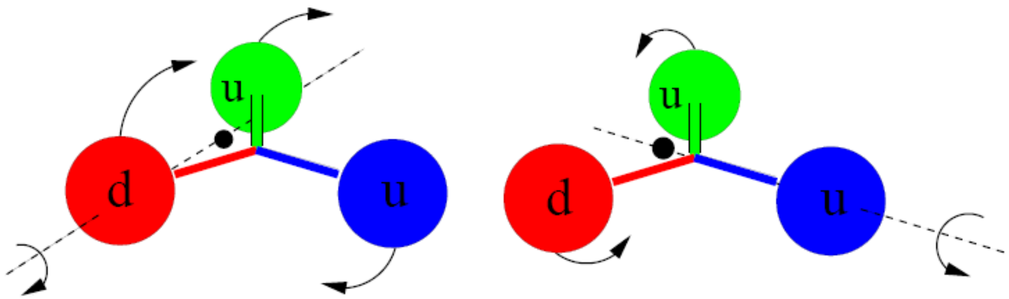


N and Δ Excited Baryon States …

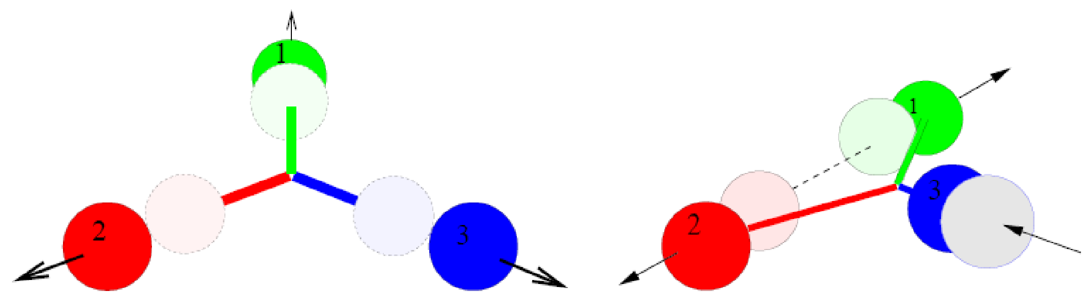
Simon Capstick

➢ Orbital excitations

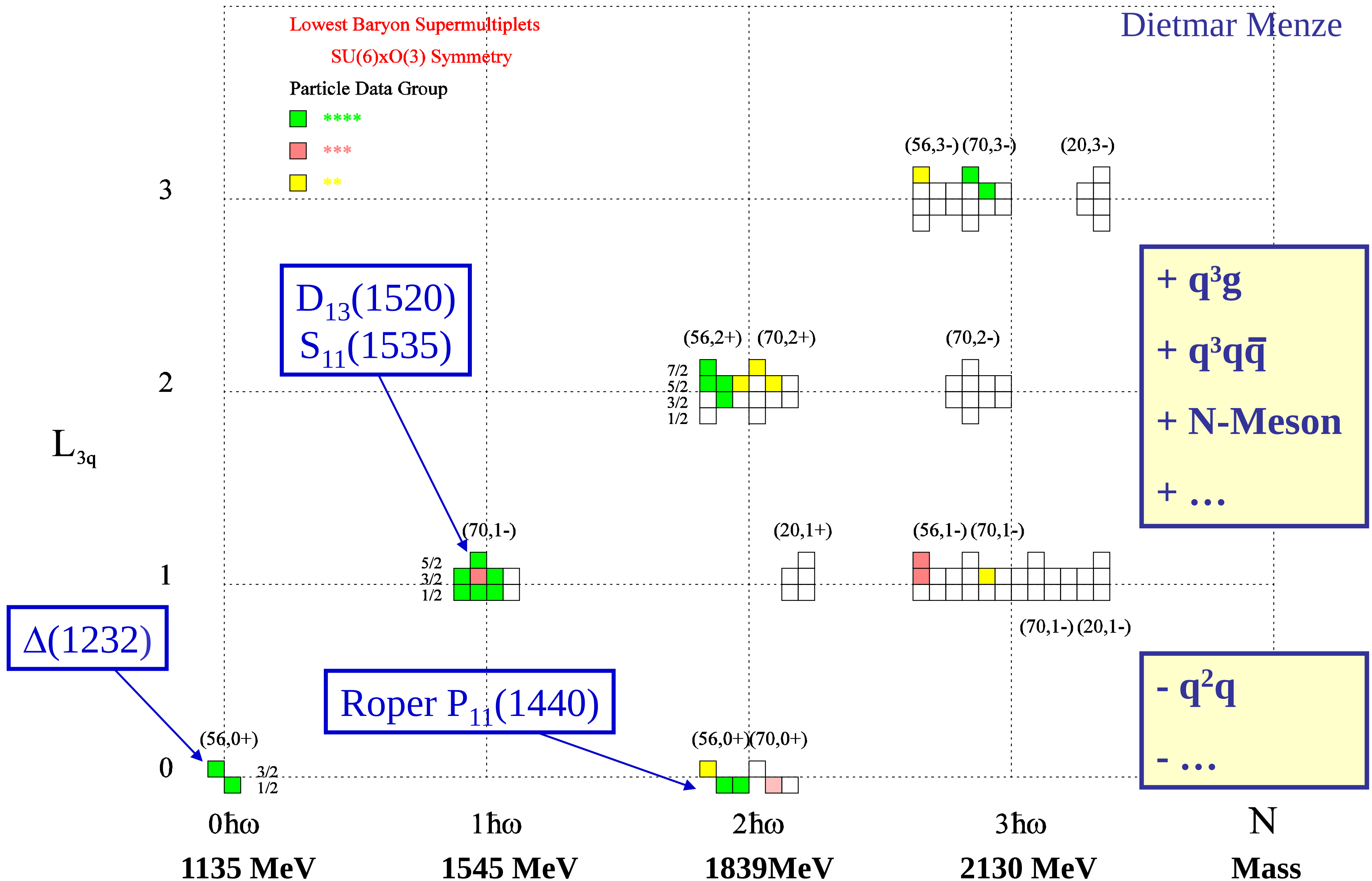
(two distinct kinds in contrast to mesons)



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

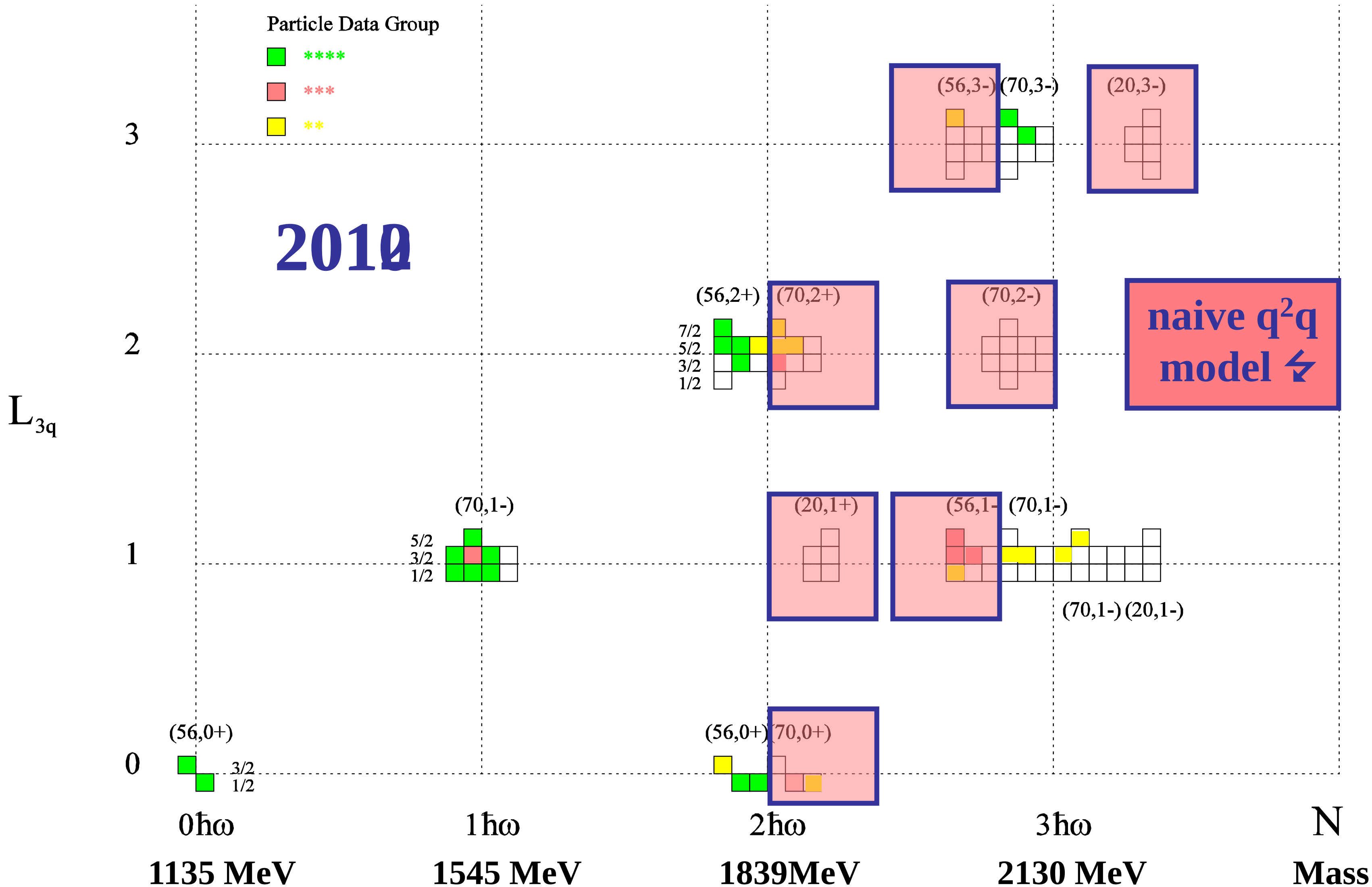


Quark Model Classification of N*



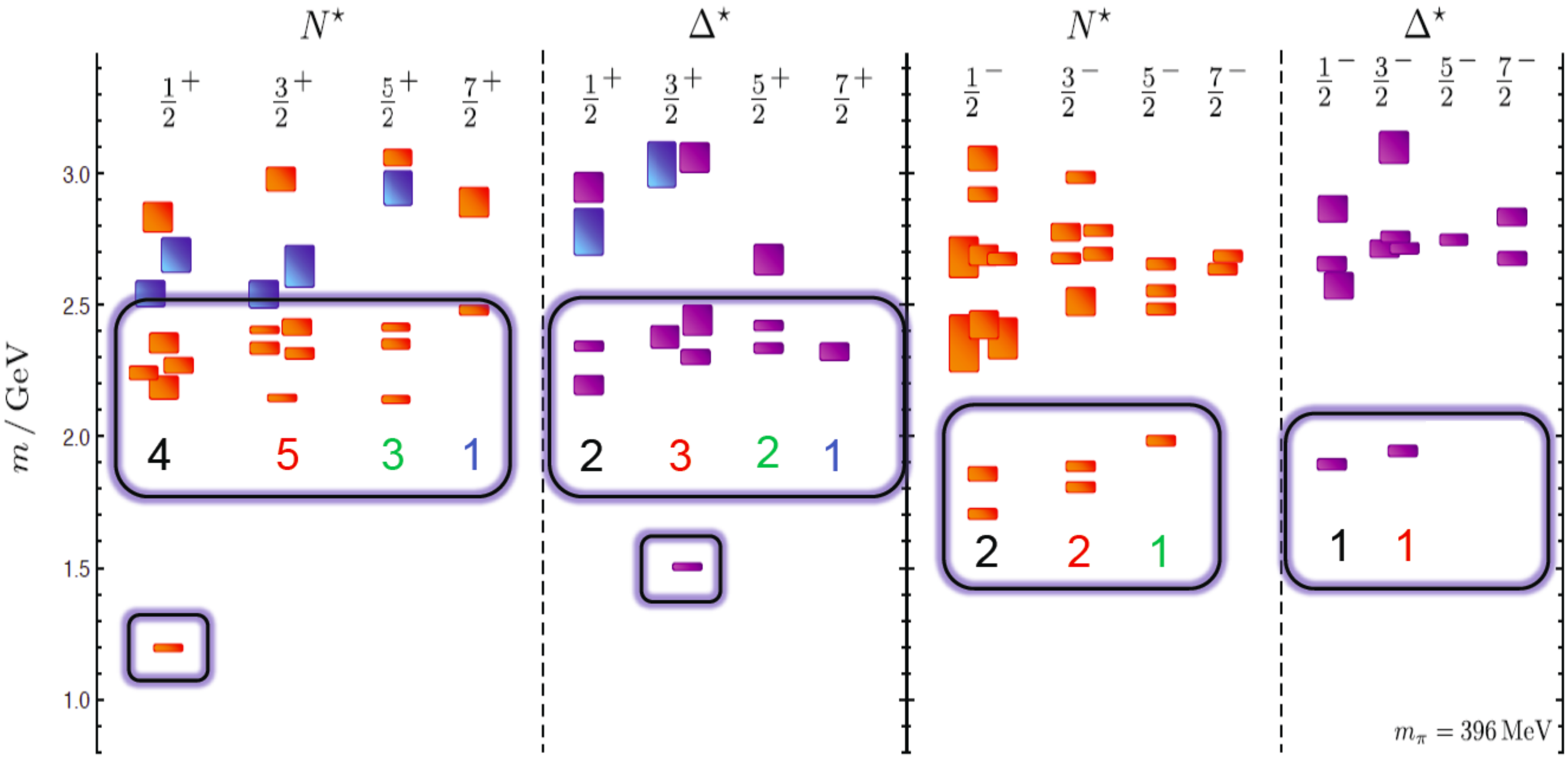
Quark Model Classification of N*

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



N* Spectrum in LQCD

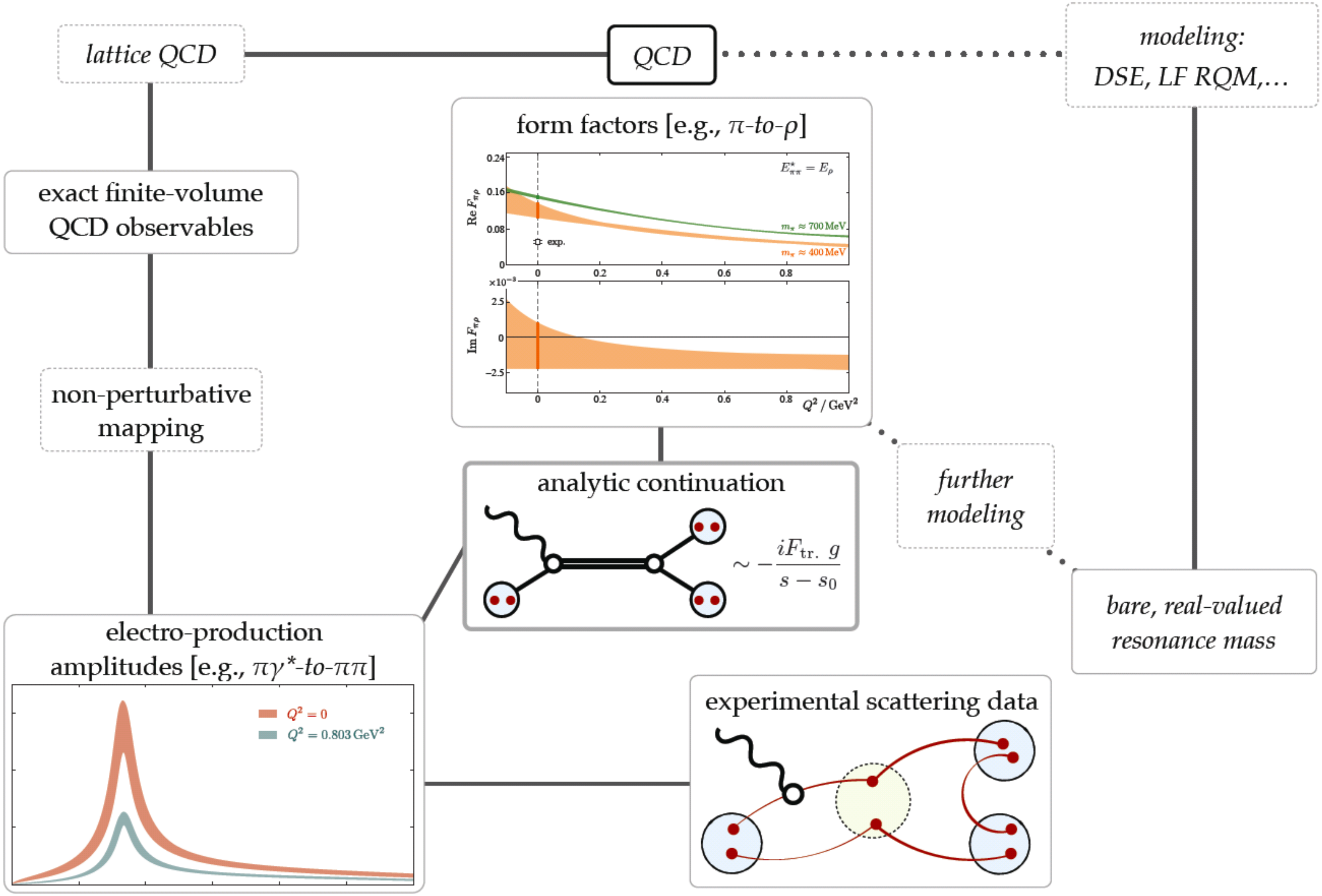
The strong interaction physics is encoded in the nucleon excitation spectrum that spans the degrees of freedom from meson-baryon and dressed quarks to elementary quarks and gluons.



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

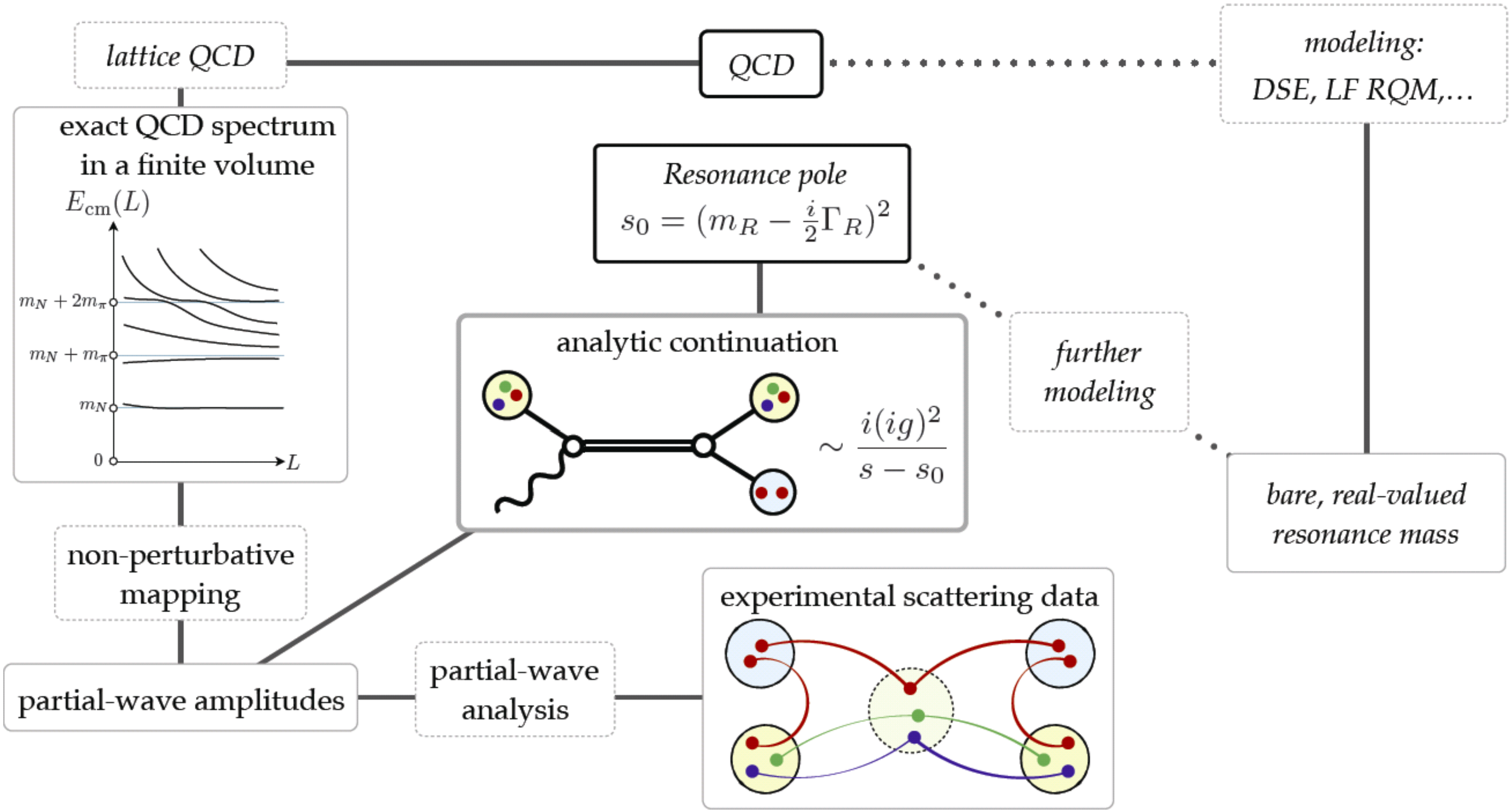
New LQCD Data Analysis Approach



Scattering processes and resonances from lattice QCD

Raul A. Briceno, Jozef J. Dudek, and Ross D. Young, arXiv:1706.06223 [hep-lat]

New LQCD Data Analysis Approach



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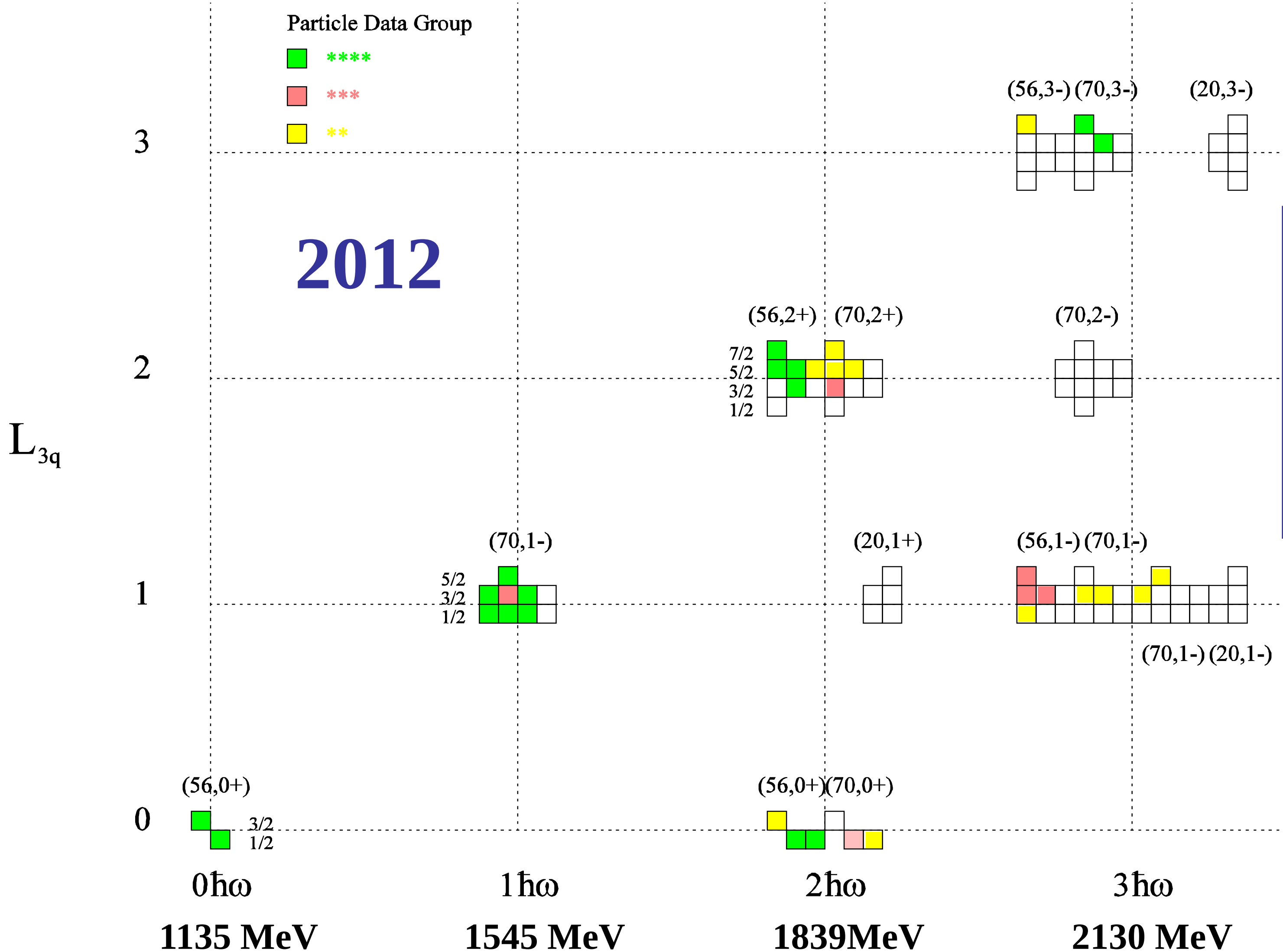


+ q^3g

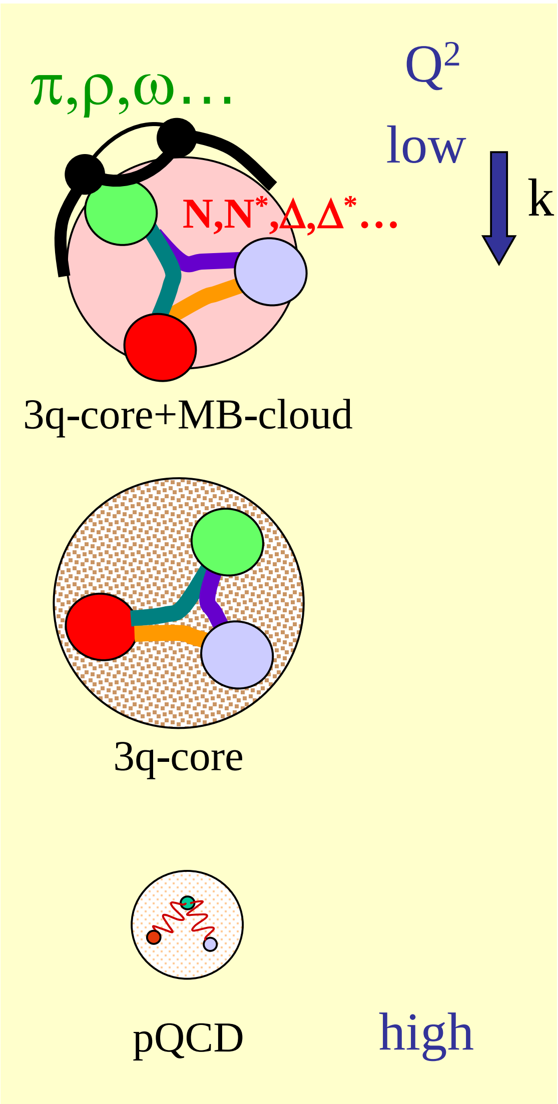
+ $q^3q\bar{q}$

+ N-Meson

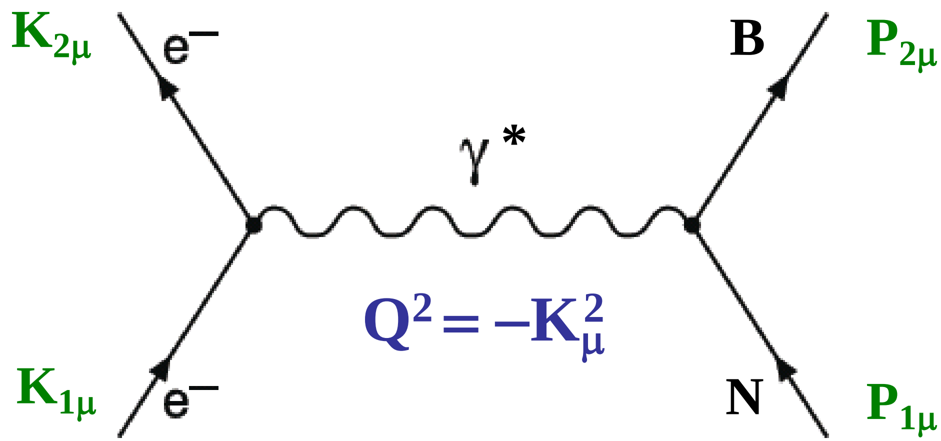
+ …

Transition Form Factors

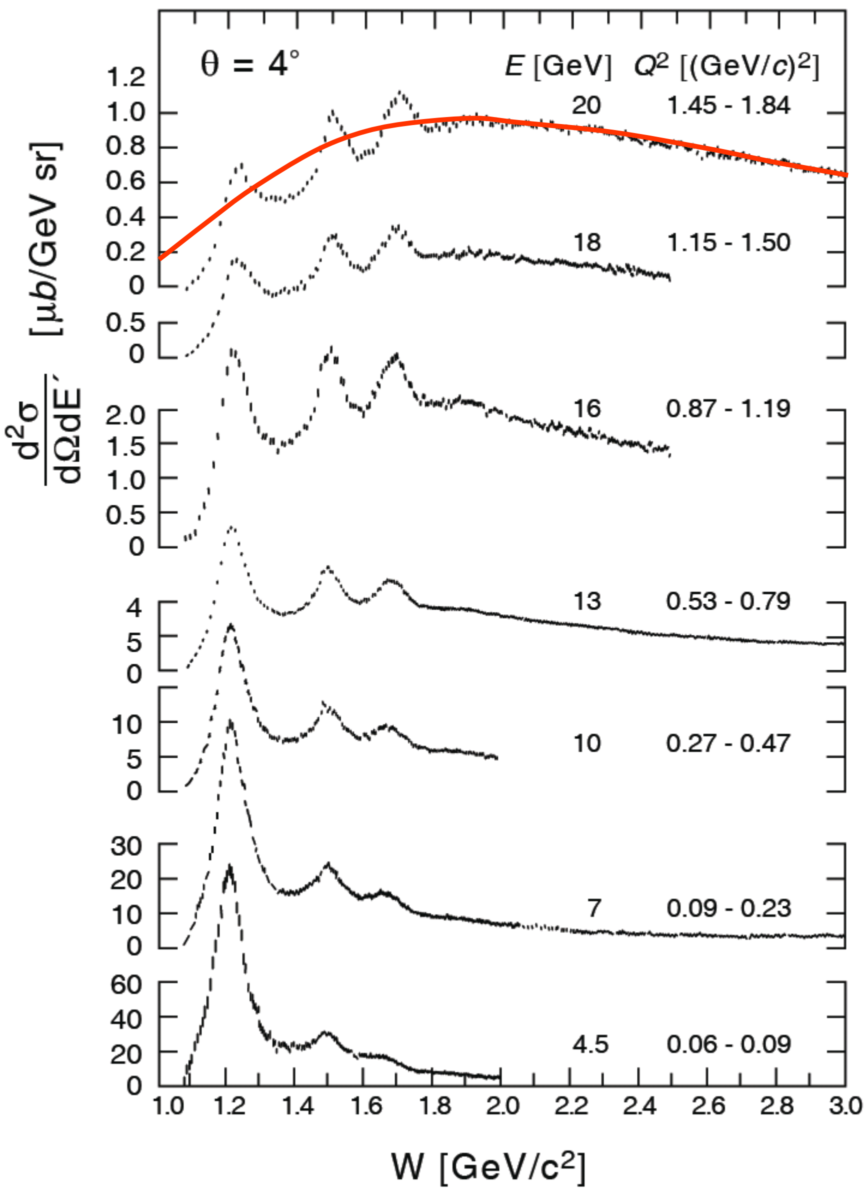
Hadron Structure with Electromagnetic Probes



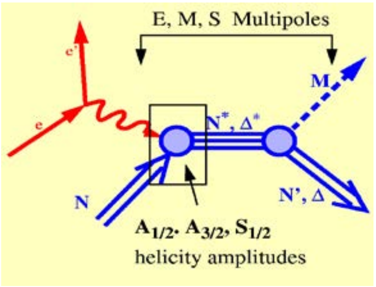
- Study the structure of the nucleon spectrum in the domain where dressed quarks are the major active degree of freedom.
- Explore the formation of excited nucleon states in interactions of dressed quarks and their emergence from QCD.

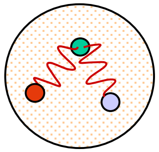


Baryon Excitations and Quasi-Elastic Scattering



hard and confined



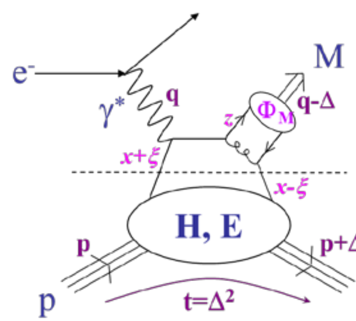


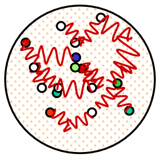
Elastic Form Factors

Transition Form Factors

hard

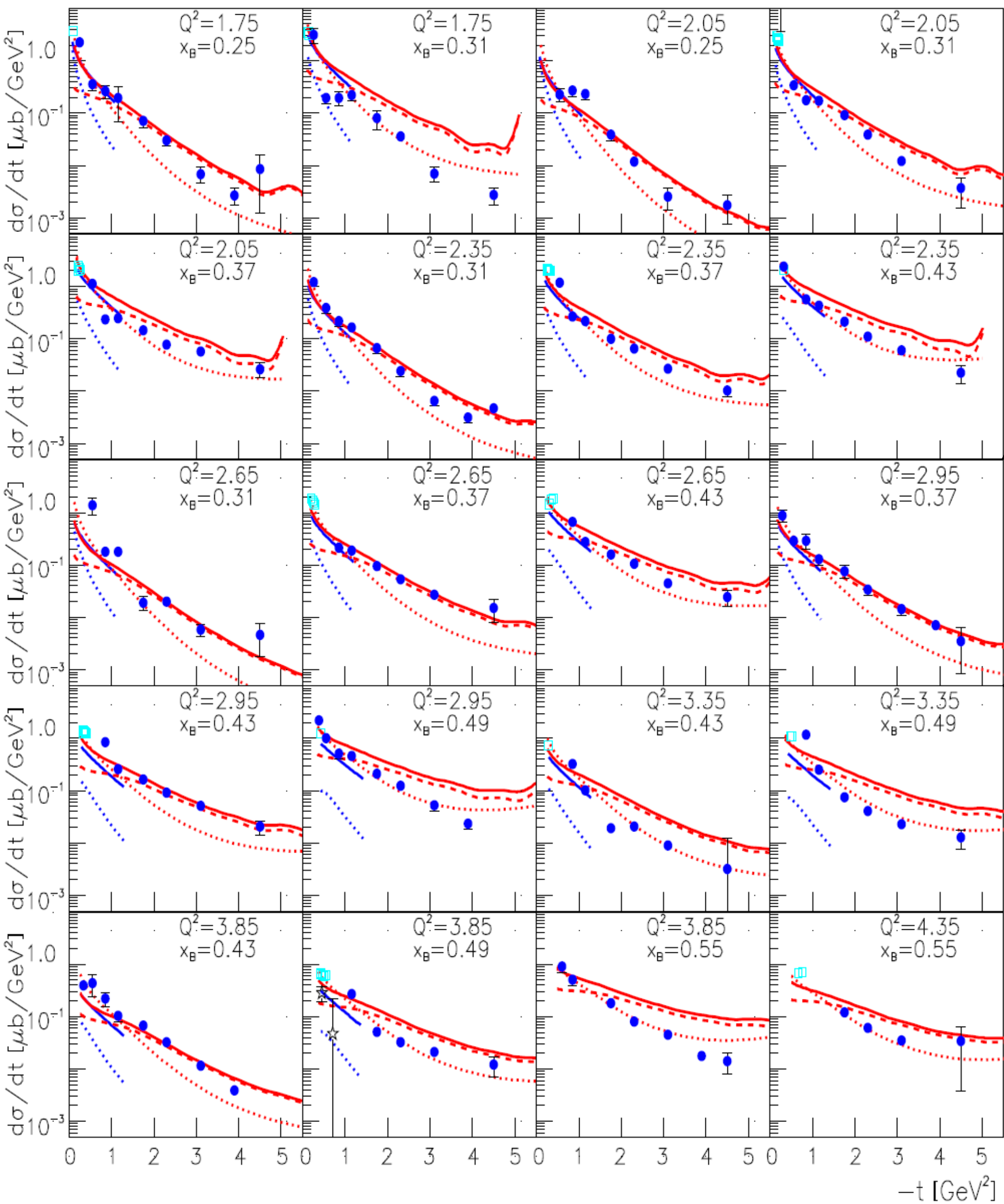
soft

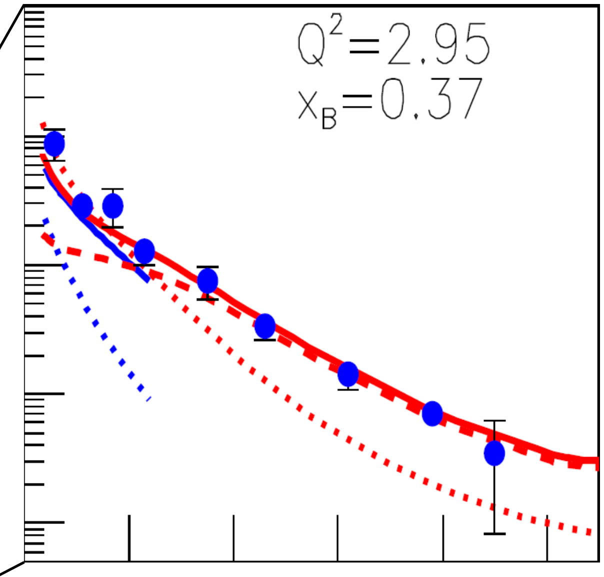




Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Deep Exclusive π^+ Electroproduction off the Proton





K. Park et al., Eur. Phys. J. A 49 (2013) 16

The red solid ($d\sigma/dt$), dotted ($d\sigma_L/dt$), and dashed ($d\sigma_T/dt$) curves are the calculations from a hadronic model (Regge phenomenology) with (Q^2, t)-dependent form factors at the photon-meson vertices. The blue solid and dotted curves are the calculations of $d\sigma/dt$ and $d\sigma_L/dt$, respectively, of a partonic model (handbag diagrams).

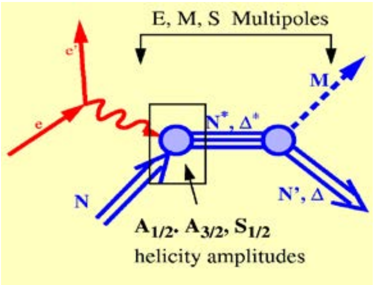
Structure Analysis of the Baryon

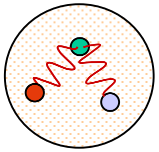
Demolition of a chimney at the "Henninger Brewery" in Frankfurt am Main, Germany, on 2 December 2006

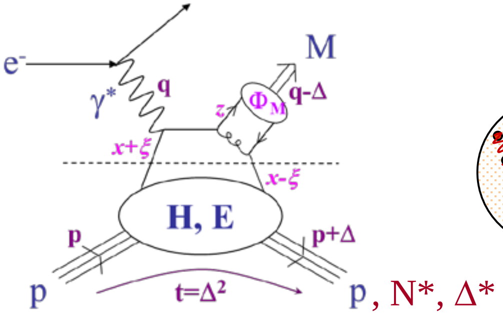
hard and confined

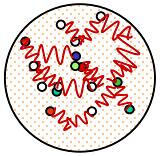
hard and soft

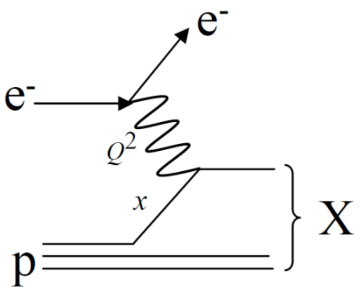
quasi-elastic











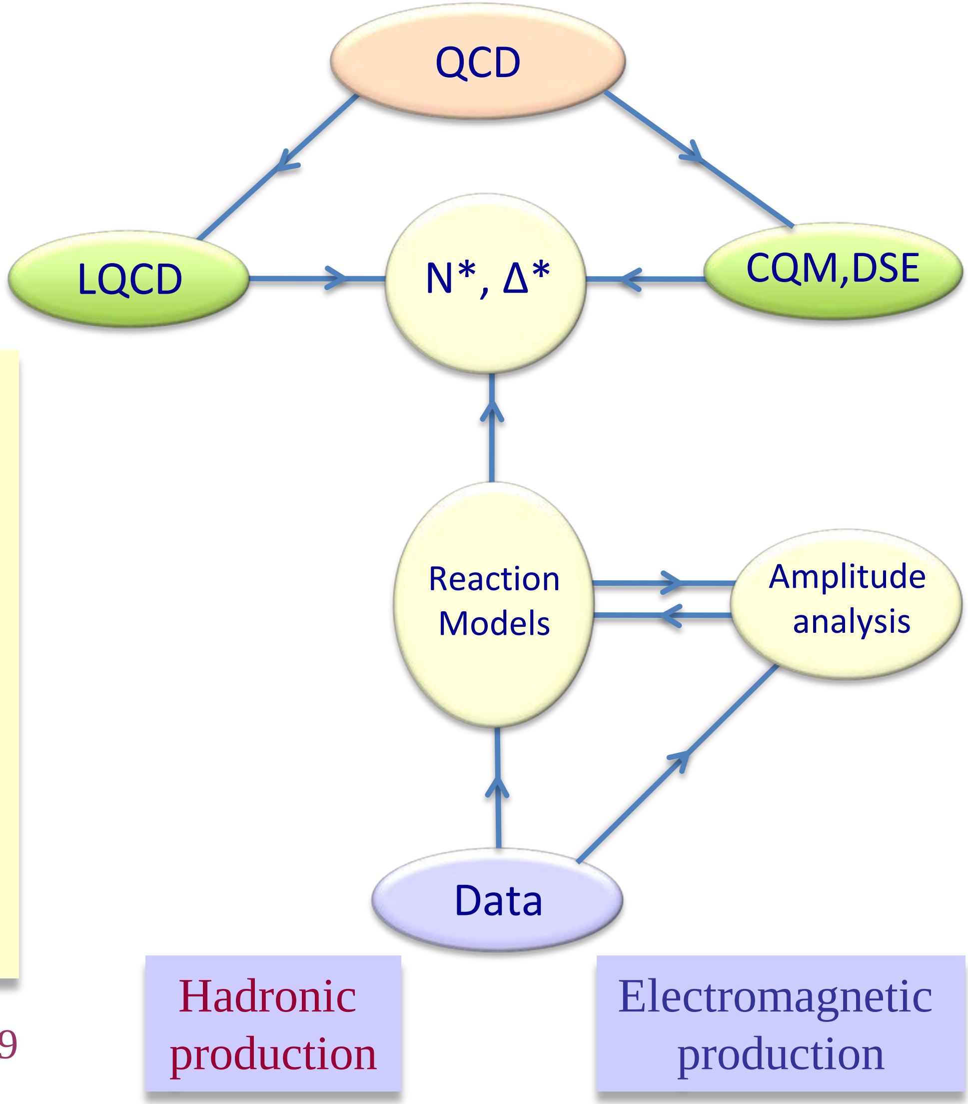
γ_vNN*
Extraction
and Physics

Data-Driven Data Analyses

Consistent Results

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

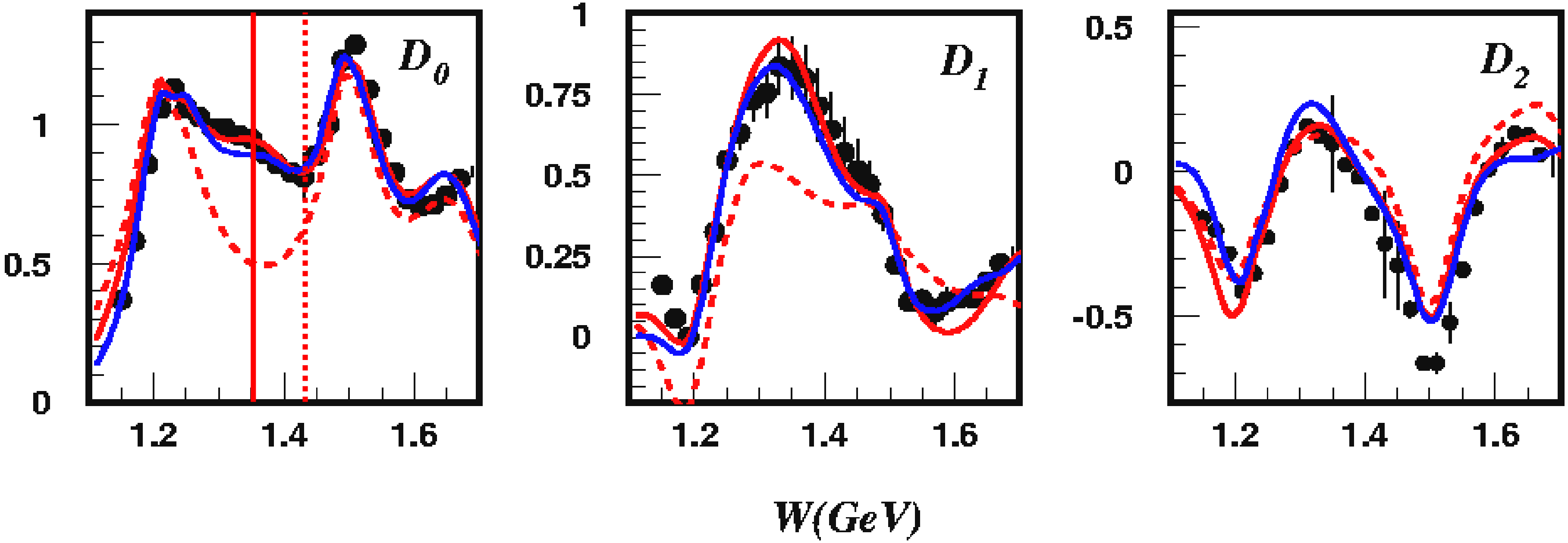
Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013) 1-99



Legendre Moments of Unpolarized Structure Functions

K. Park *et al.* (CLAS), Phys. Rev. C77, 015208 (2008)

Q^2=2.05GeV^2



$$\sigma_T + \epsilon\sigma_L = \sum_{l=0}^{n} D_l^{T+L} P_l(\cos\theta_\pi^*)$$

I. Aznauryan —— DR fit

I. Aznauryan - - - DR fit w/o P_{11}

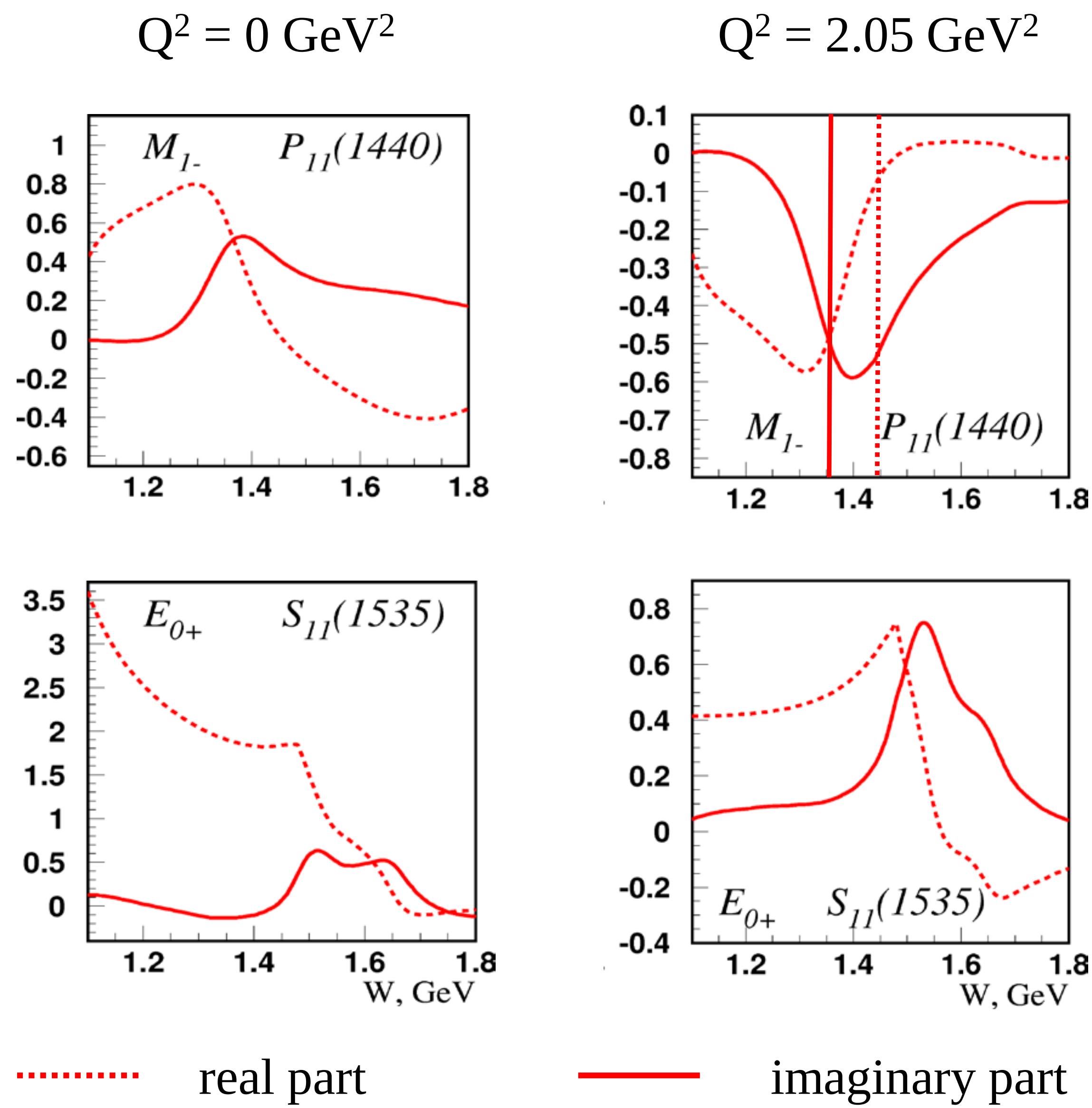
I. Aznauryan —— UIM fit

Two conceptually different approaches DR and UIM are consistent. CLAS data provide rigid constraints for checking validity of the approaches.

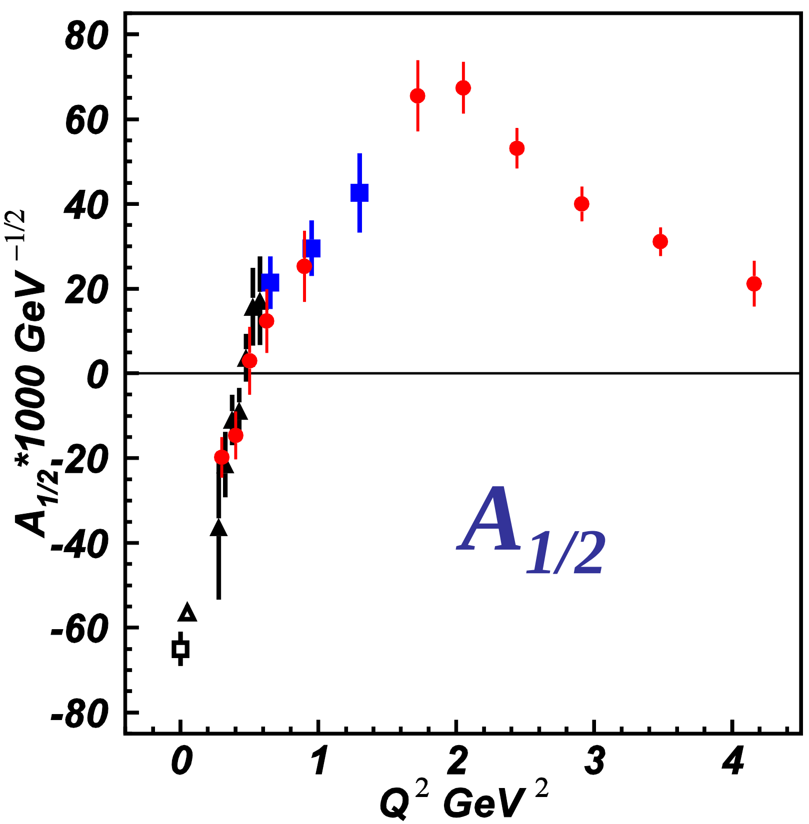
Energy-Dependence of π^+ Multipoles for P_{11}, S_{11}

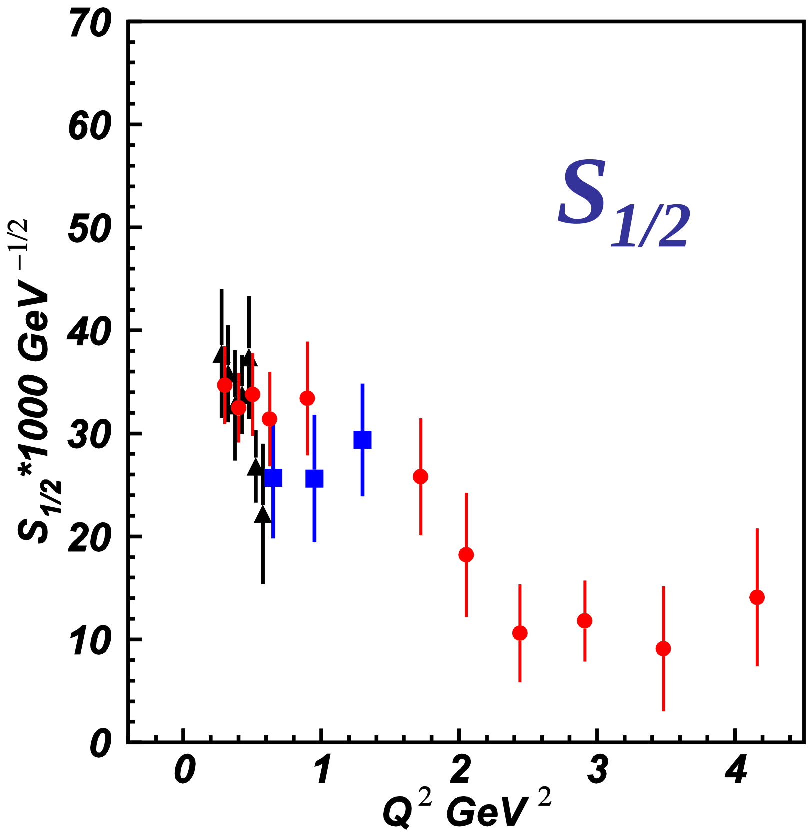
The study of some baryon resonances becomes easier at higher Q^2.

Cross sections are extracted in many other single meson baryon final states.



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



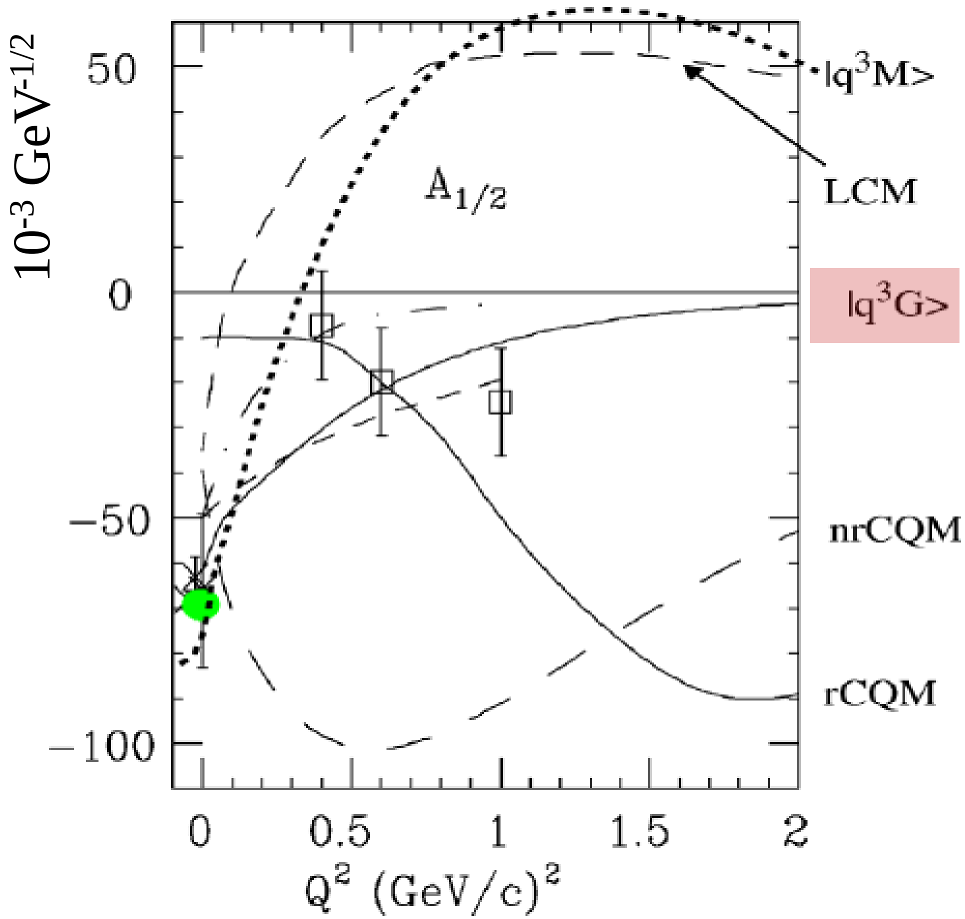


□ PDG ● Nπ (UIM, DR) ▲ Nππ (JM) 2012 ■ Nππ (JM) preliminary

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.

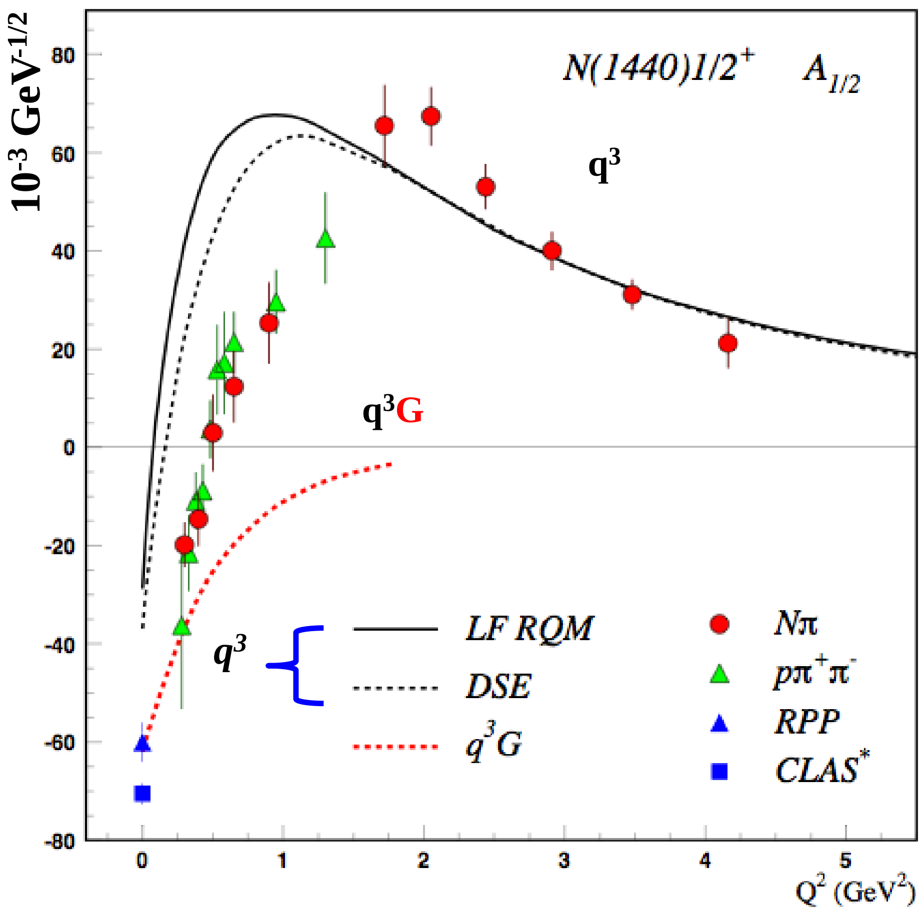
Phys. Rev. C 80, 055203 (2009) 1-22 and Phys. Rev. C 86, 035203 (2012) 1-22

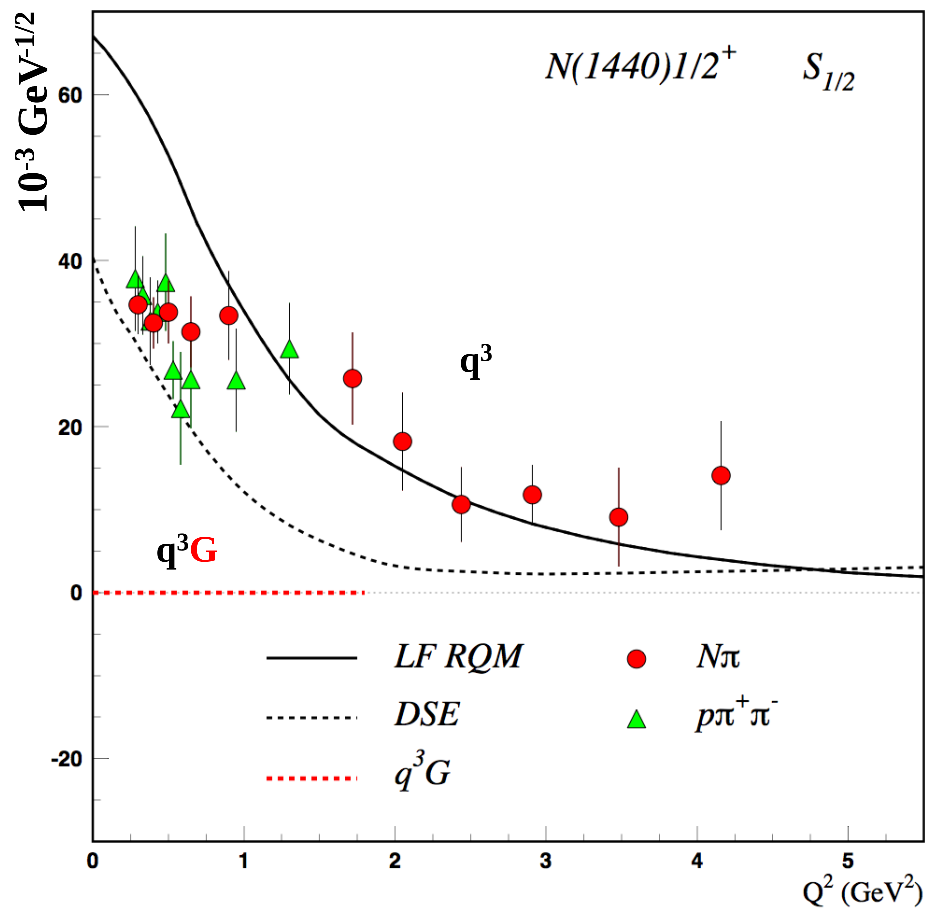
Electrocouplings of N(1440)P_{11} History



- 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

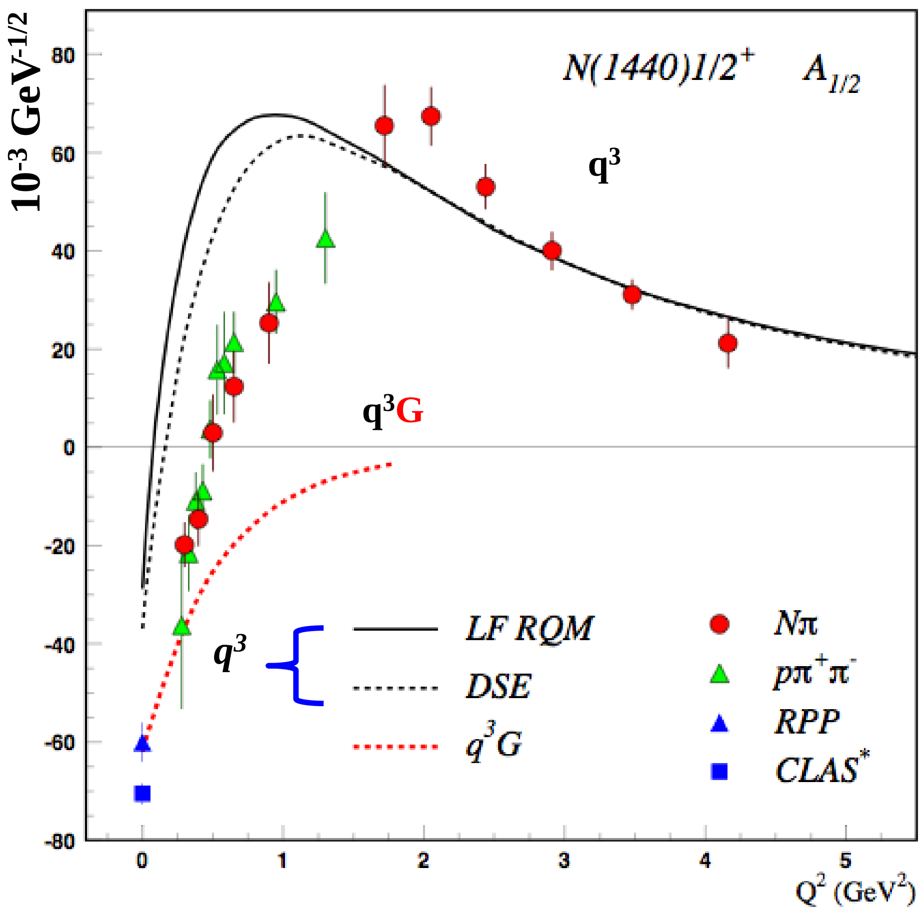




- $A_{1/2}$ has zero-crossing near Q^2=0.5 and becomes dominant amplitude at high Q^2.
- Consistent with radial excitation at high Q^2 and large meson-baryon coupling at small Q^2.
- Eliminates gluonic excitation (q^3G) as a dominant contribution.

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

- $A_{1/2}$ 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.

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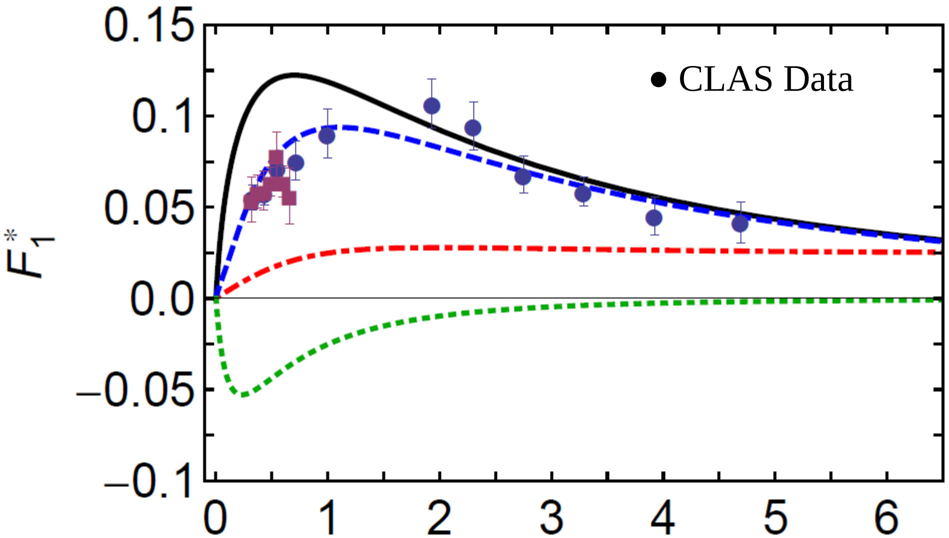
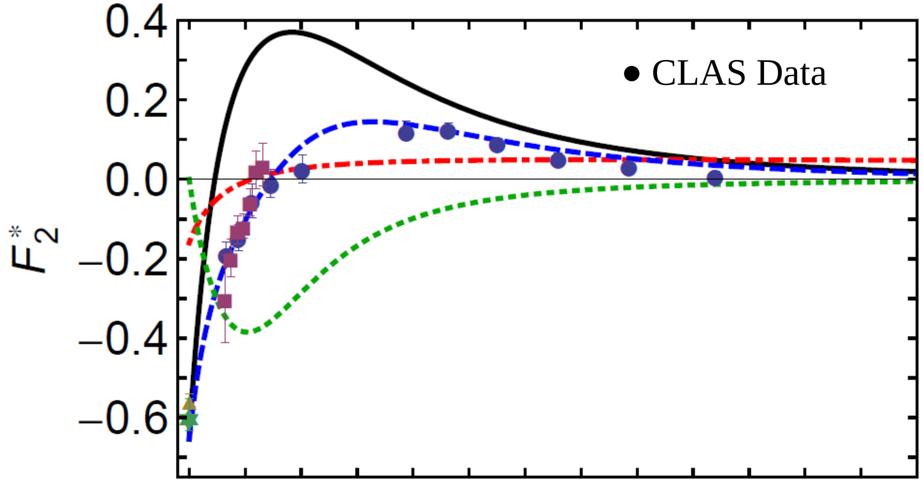
Roper Transition Form Factors in DSE Approach

N(1440)P_{11}

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



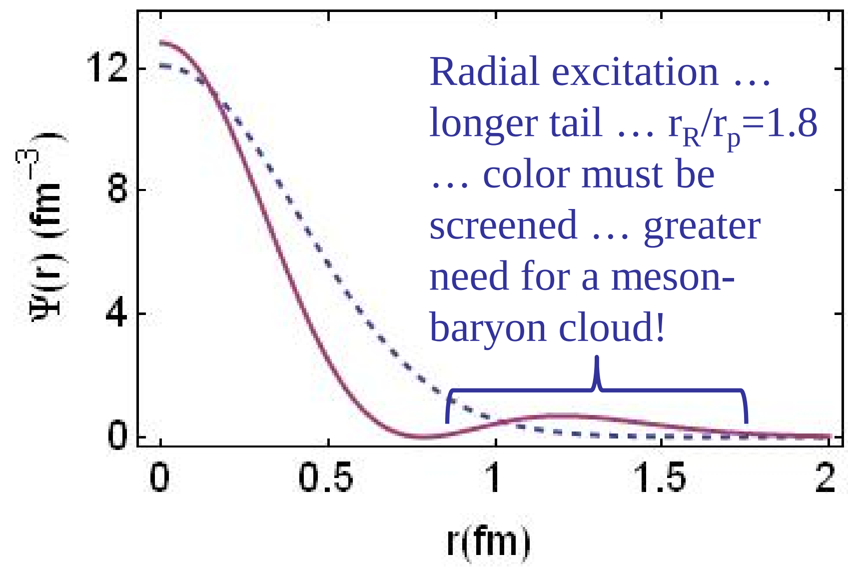


DSE Contact

DSE Realistic

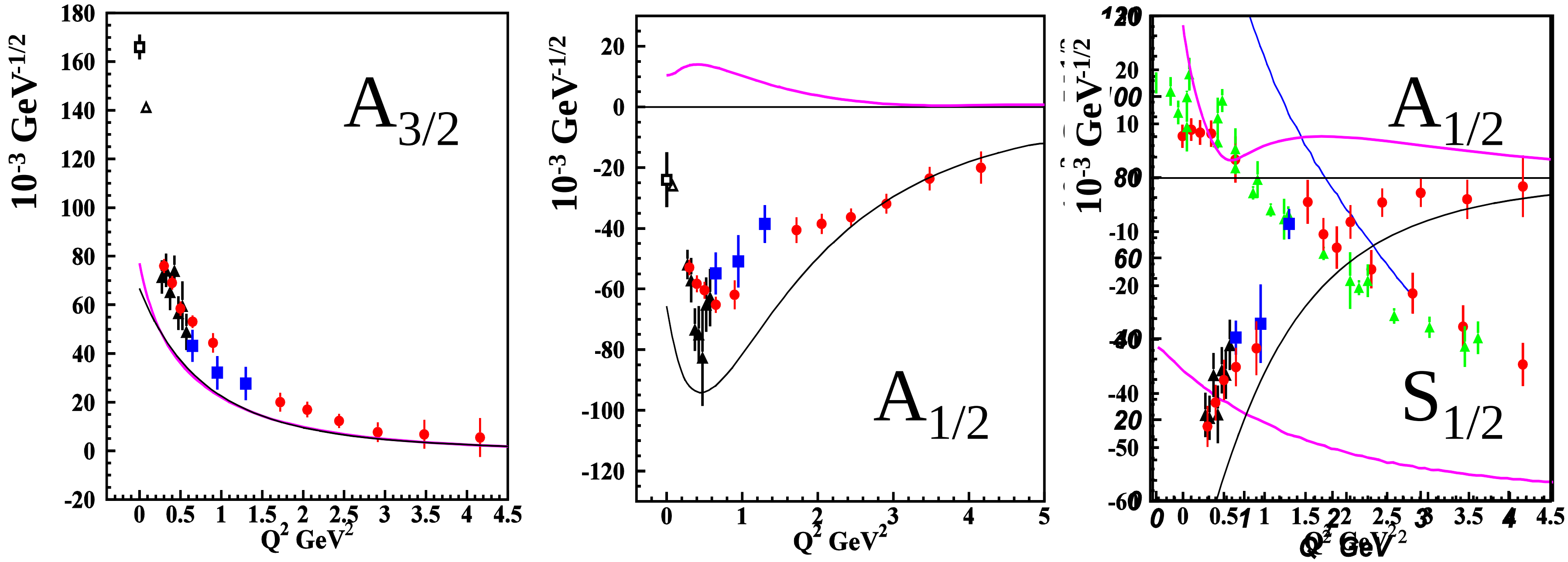
Inferred meson-cloud contribution

Anticipated complete result



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

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

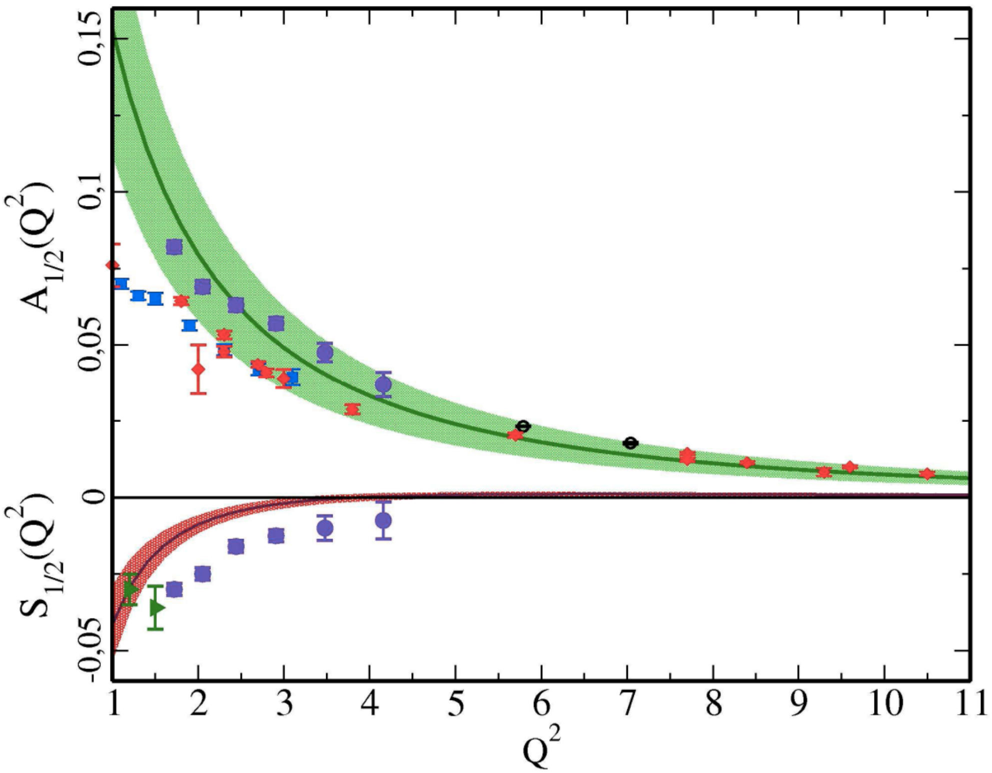
$\pi^+\pi^-p$ 2010

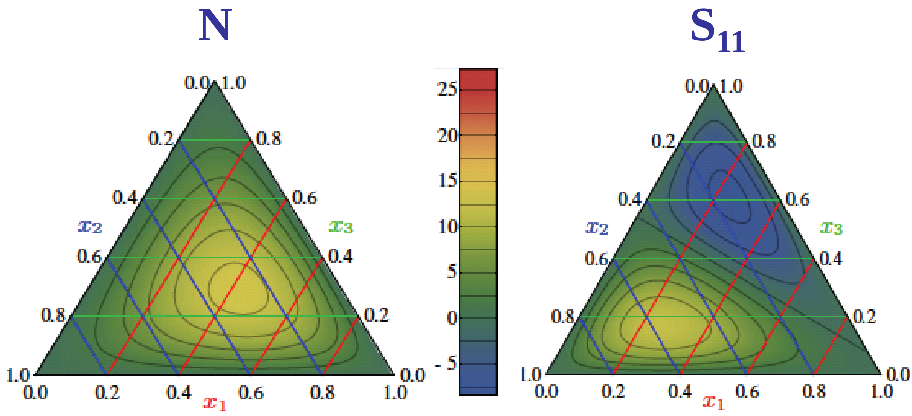
Nπ 2009

ηp CLAS/Hall-C

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.

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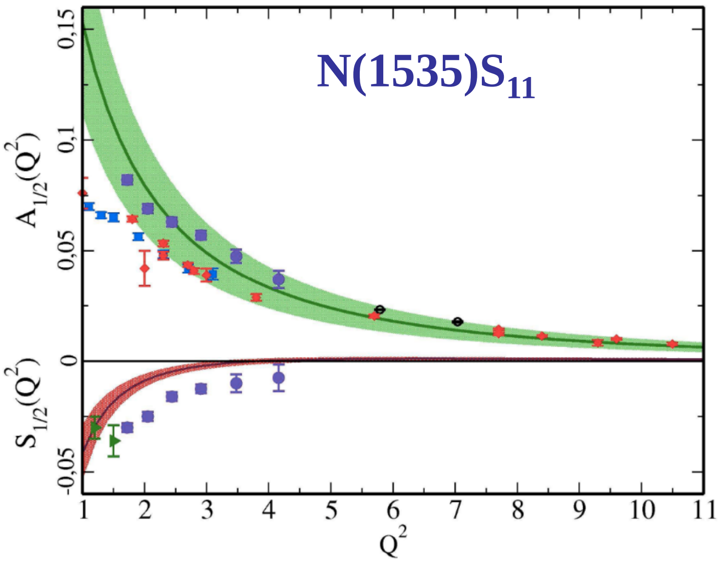
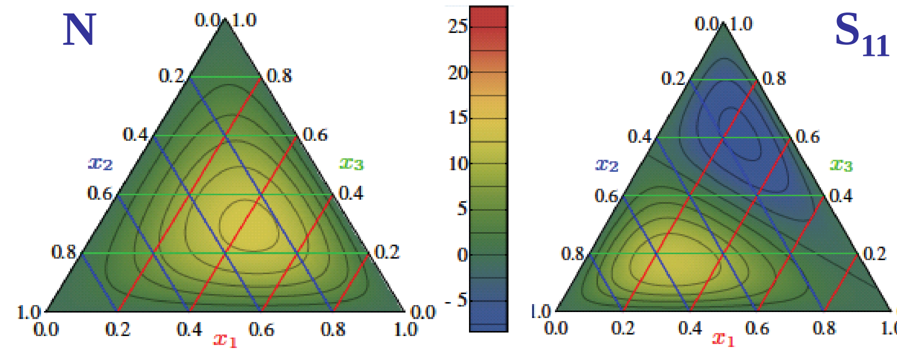
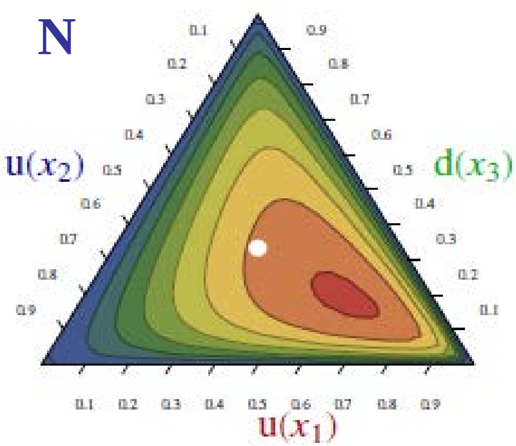
LQCD, LCSR, and DSE Approaches

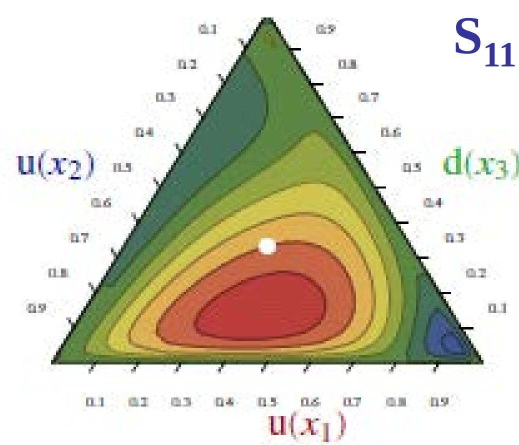




x_i is the momentum fraction of i-th valence quark

I.V. Anikin *et al.*, Phys. Rev. **D92**, 014018 (2015) and V.M. Braun *et al.*, Phys. Rev. **D89**, 094511 (2014)

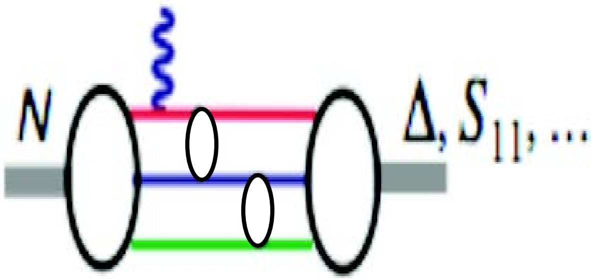


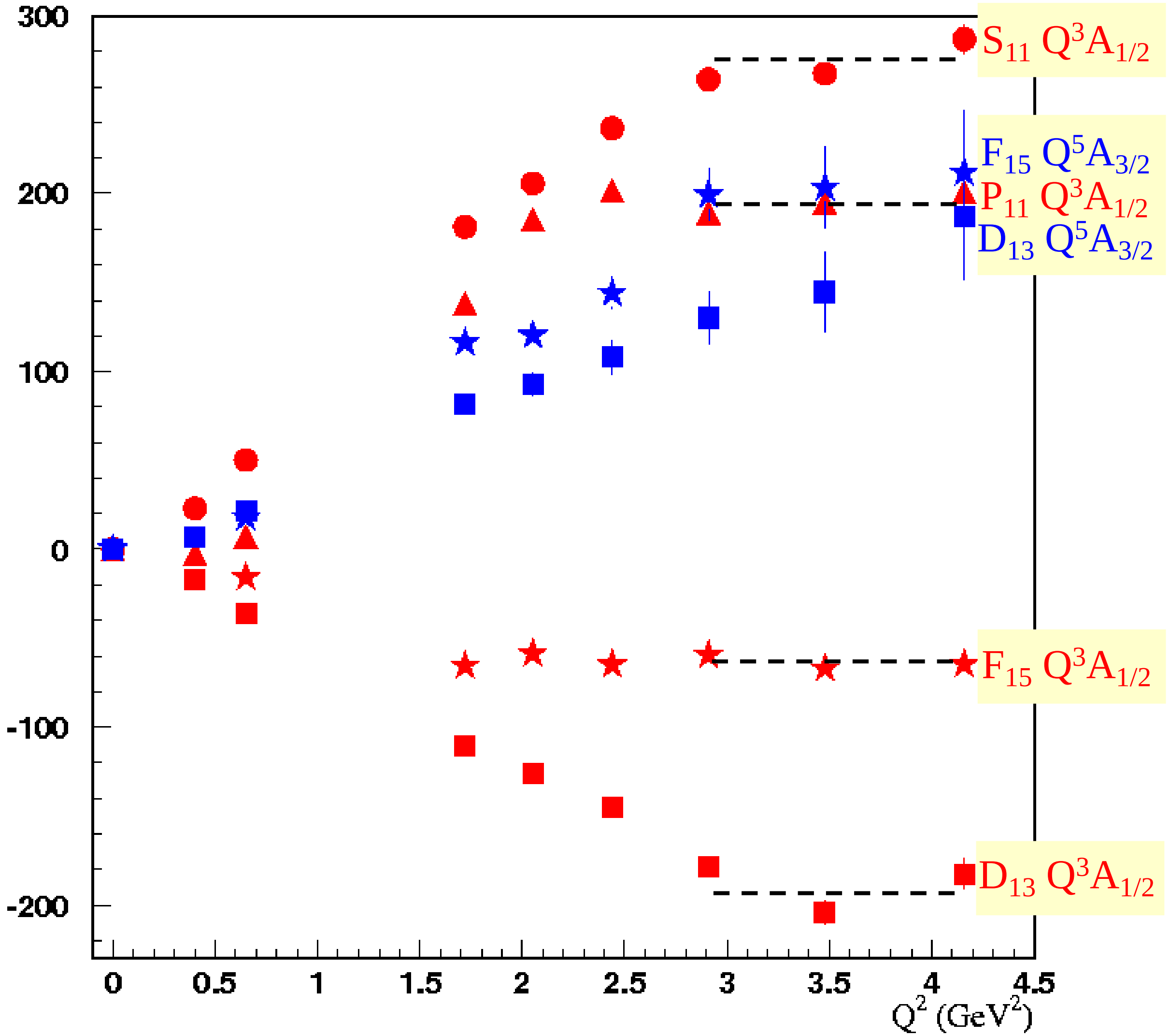


C.D. Roberts and C. Merzag, EPJ Web Conf. **137**, 01017 (2017)

Evidence for the Onset of Precocious Scaling?

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

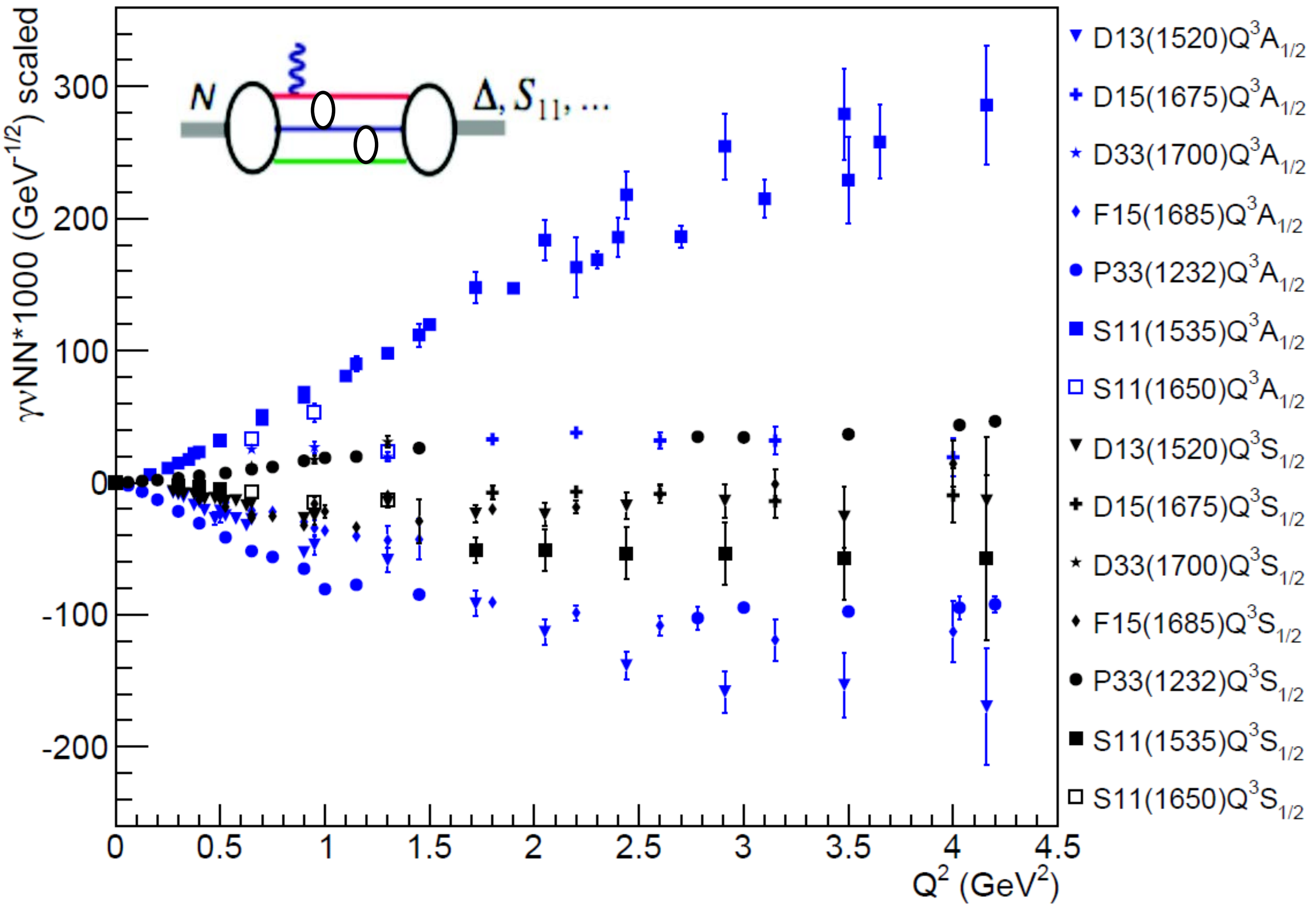




- $A_{1/2} \propto 1/Q^3$
- $A_{3/2} \propto 1/Q^5$

Evidence for the Onset of Precocious Scaling?

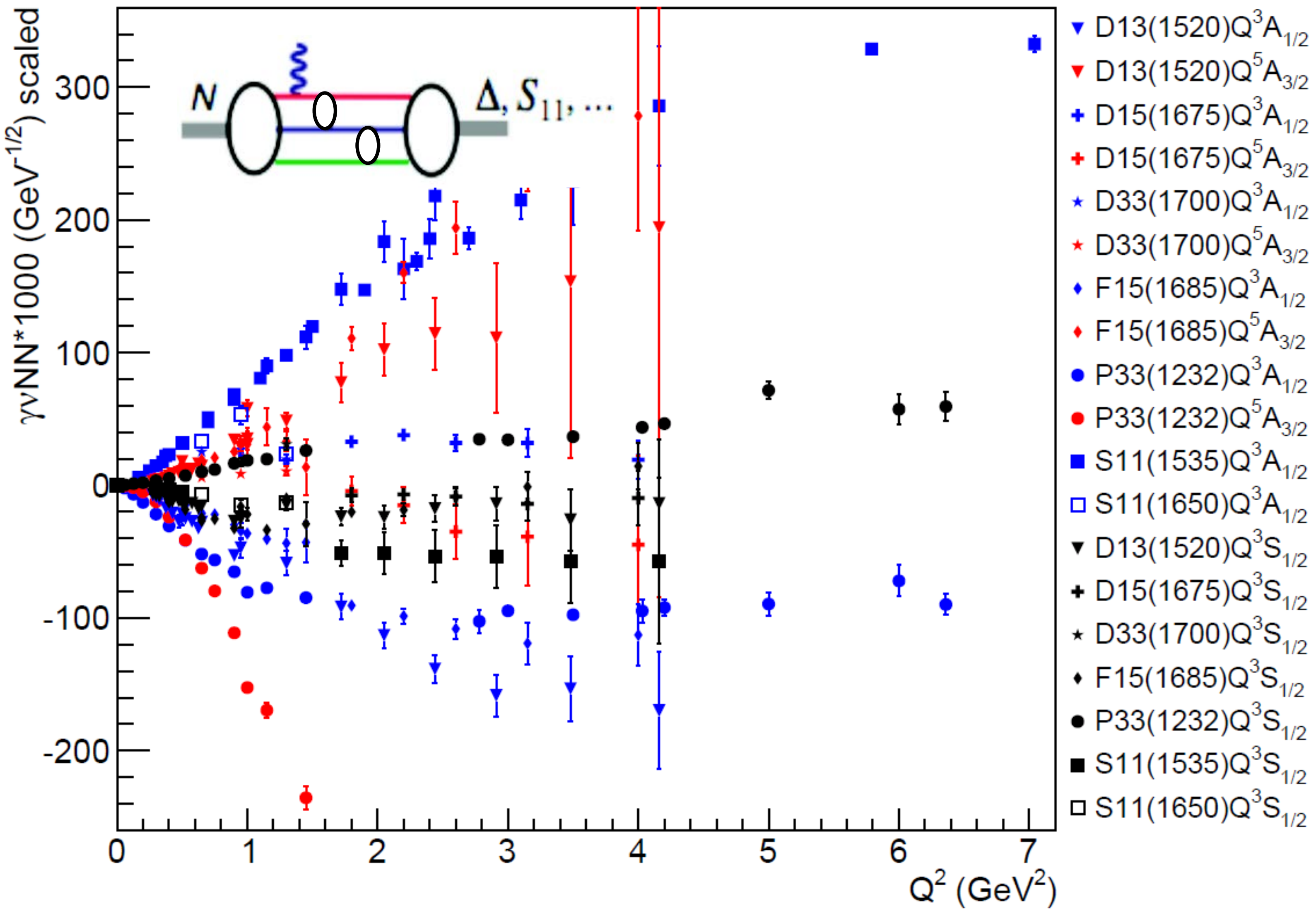
Ye Tian



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

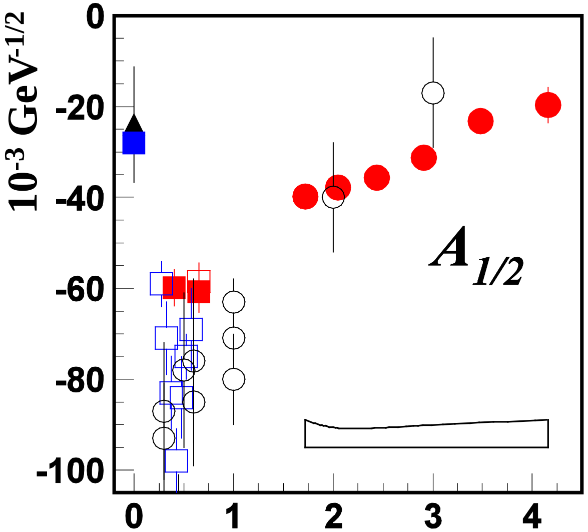
Evidence for the Onset of Precocious Scaling?

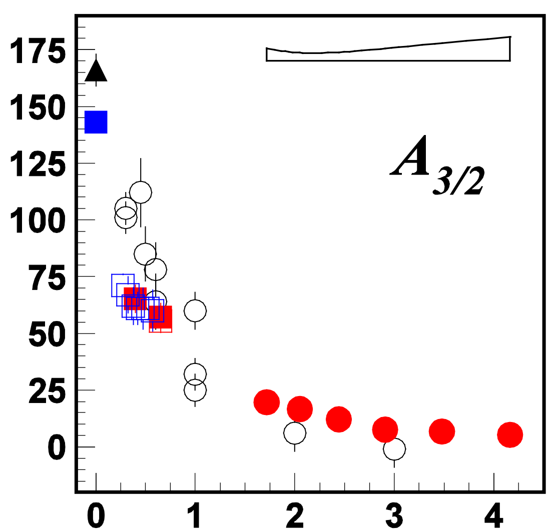
Ye Tian



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

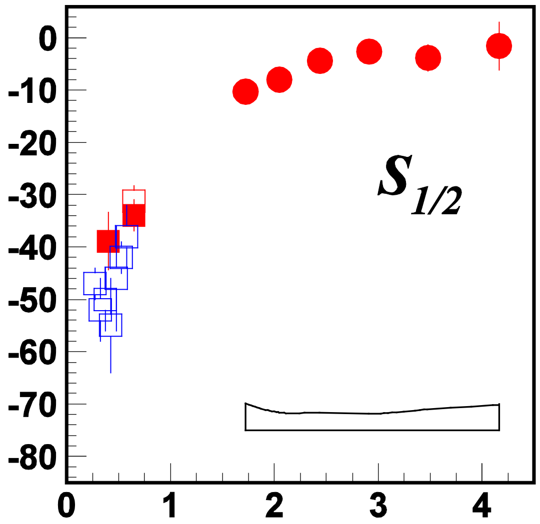
N(1520)D_{13} Helicity Asymmetry

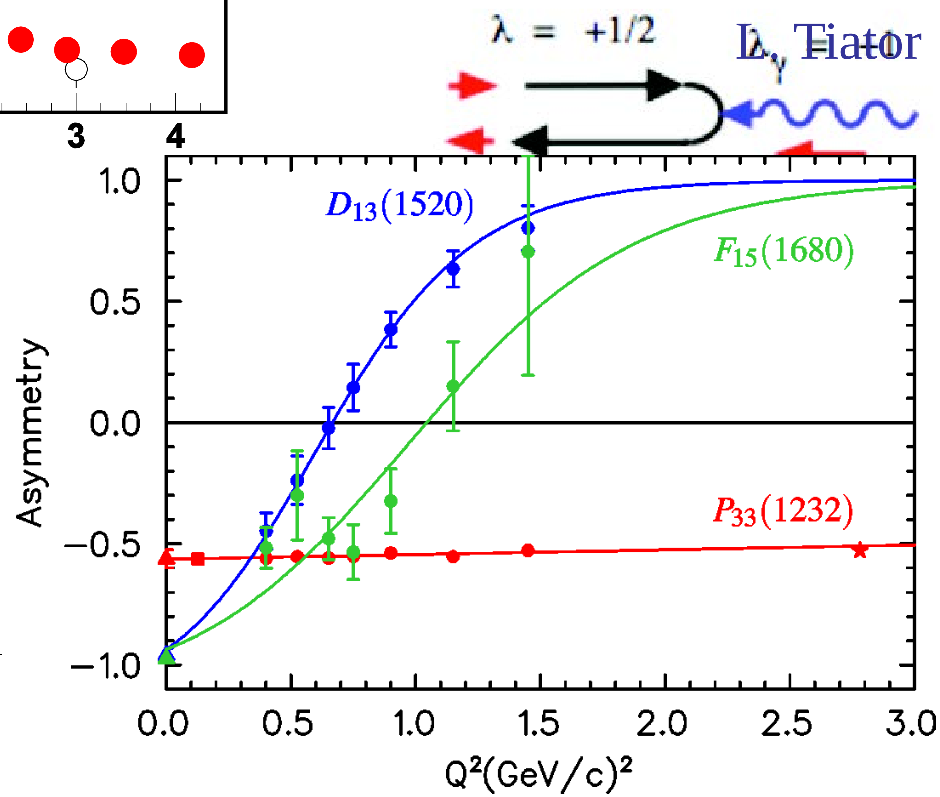




$$A_{hel} = \frac{A_{1/2}^2 - A_{3/2}^2}{A_{1/2}^2 + A_{3/2}^2}$$

$A_{1/2}$



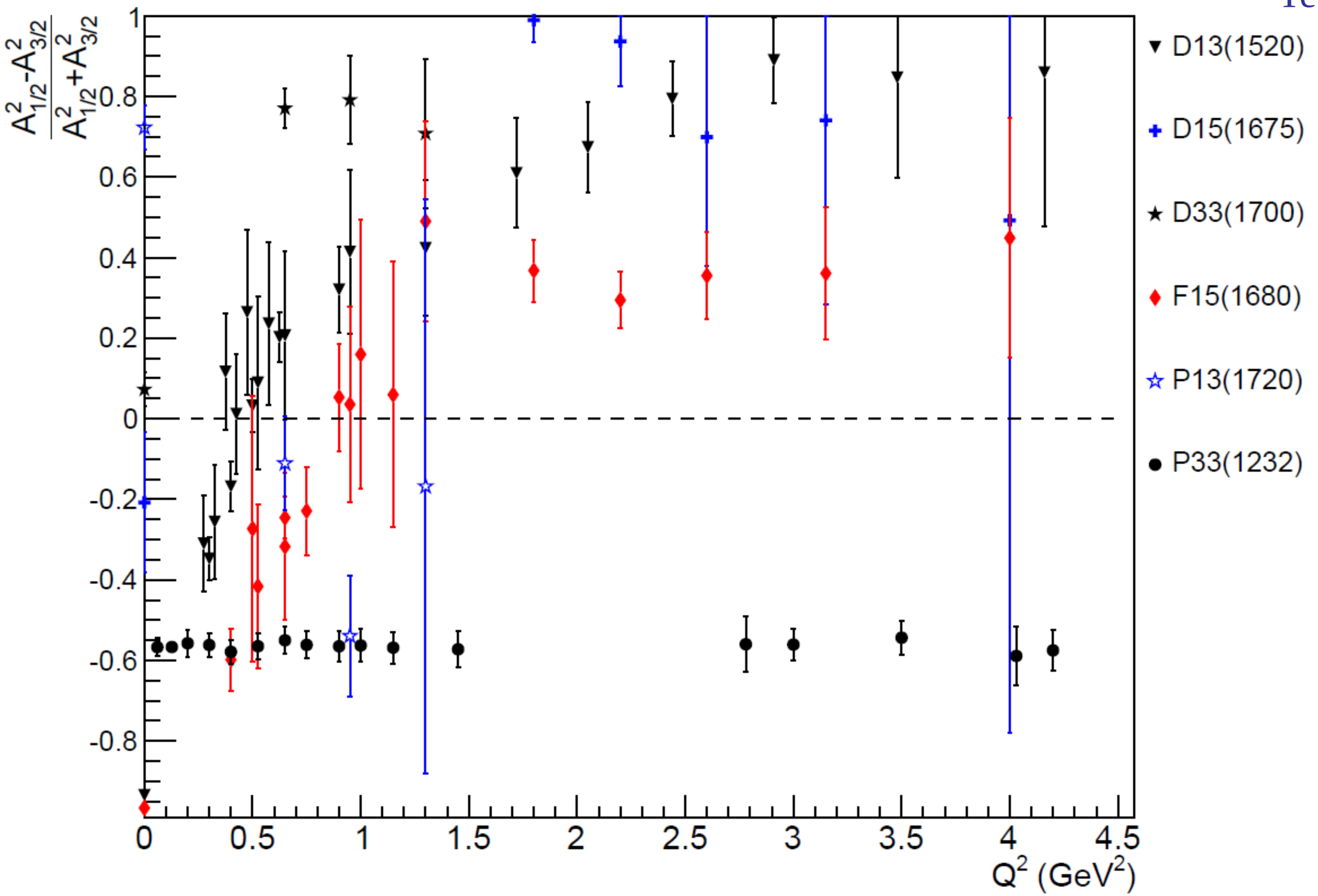


○ world data

▲ PDG estimation ● ■ Nπ (UIM, DR)

γNN* Helicity Asymmetries

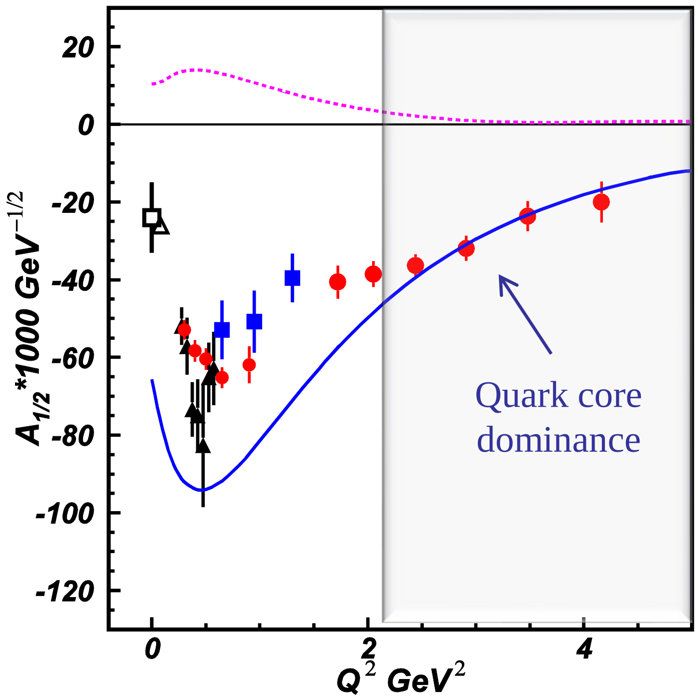
Ye Tian



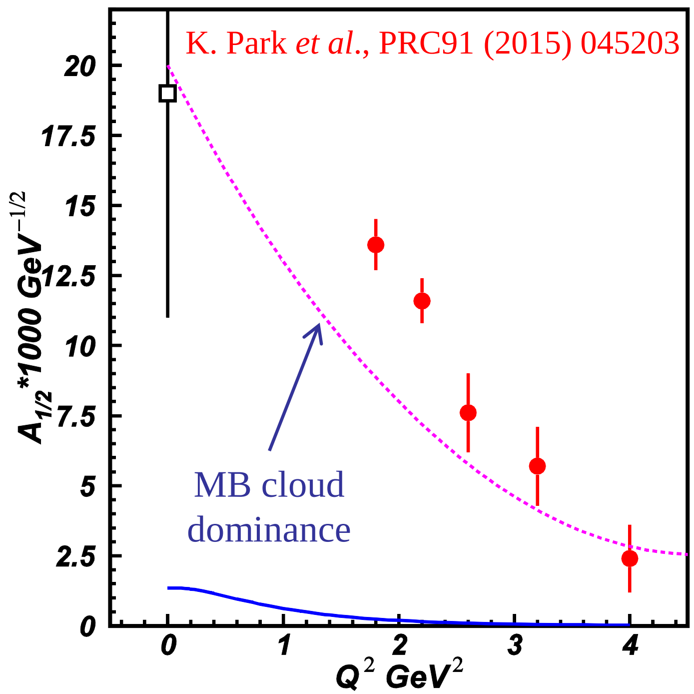
V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)

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$^-$

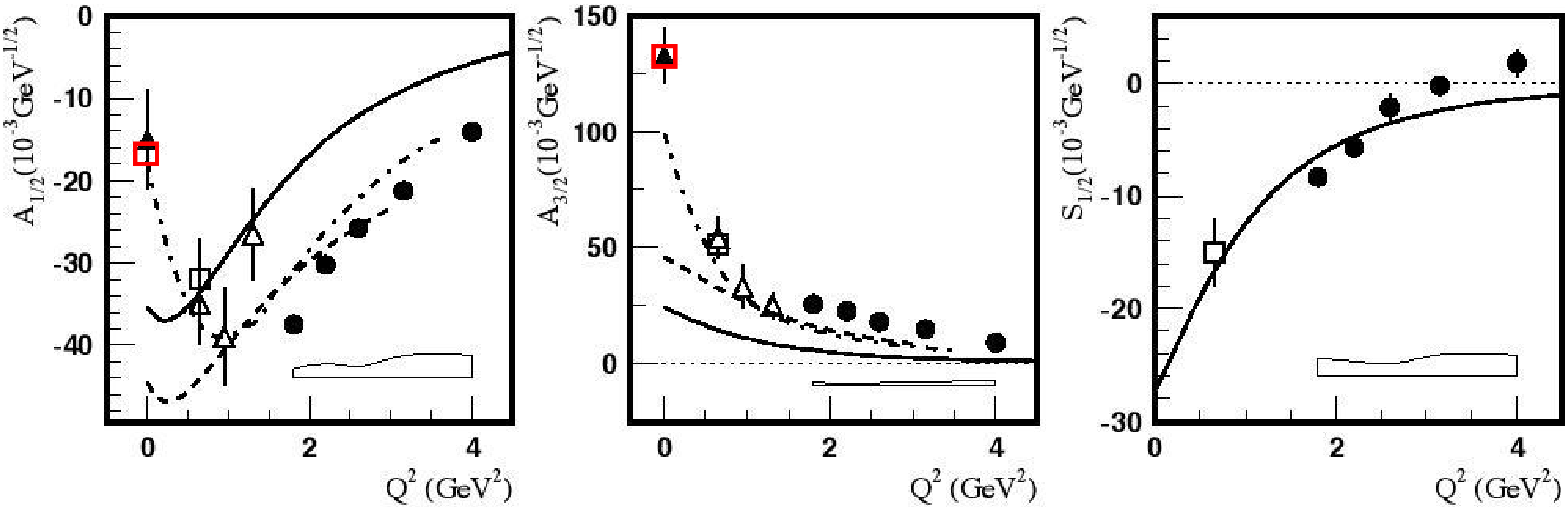
sheds light on the transition from the confined quark to the colorless meson-baryon structure and its dependents on the N* quantum numbers.

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.

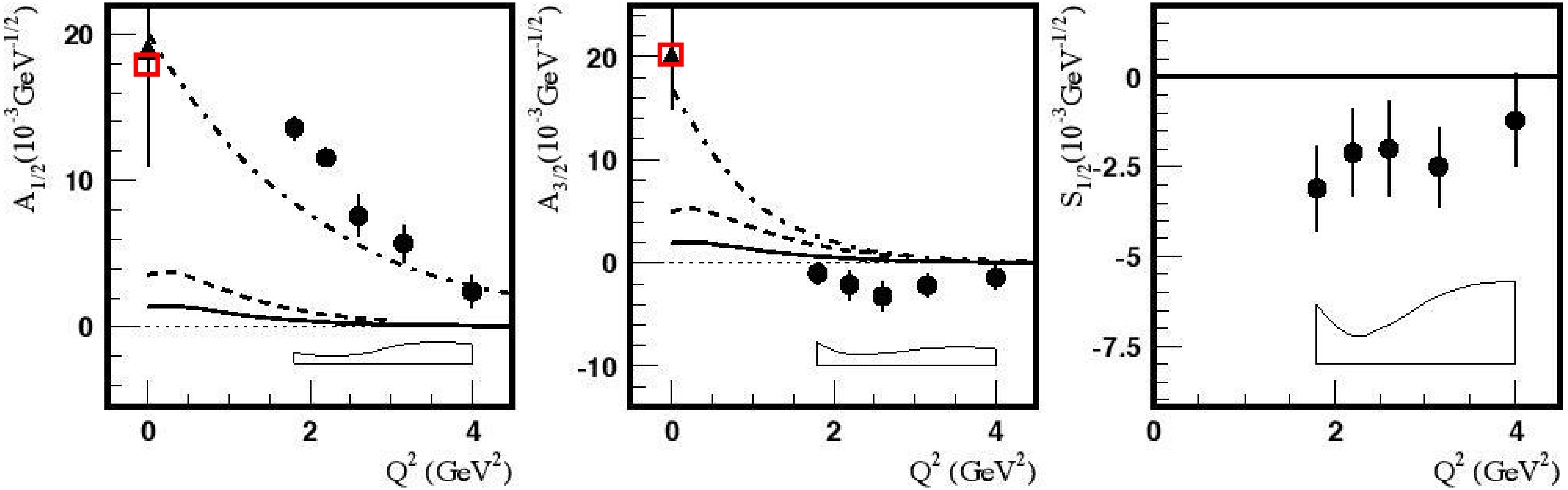
- · - · Z. Lee and F. Close

——— 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)

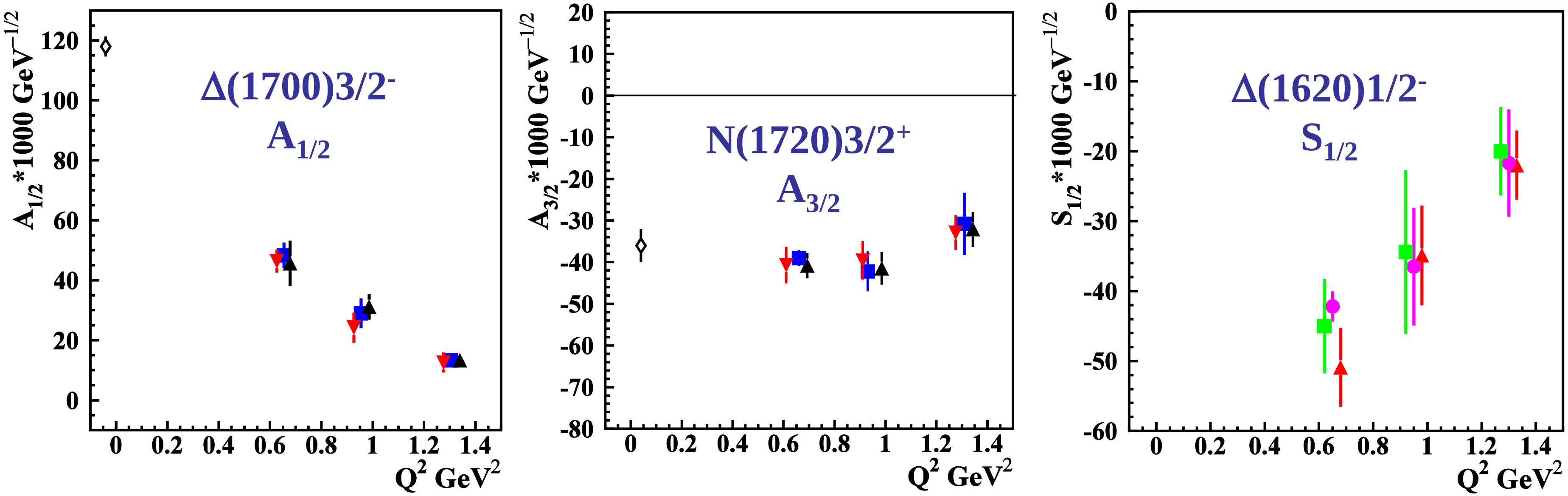
- - - D. Merten, U. Löring et al.

-·-· 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 Δ(1620)1/2$^-$, N(1650)1/2$^-$, N(1680)5/2$^+$, Δ(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

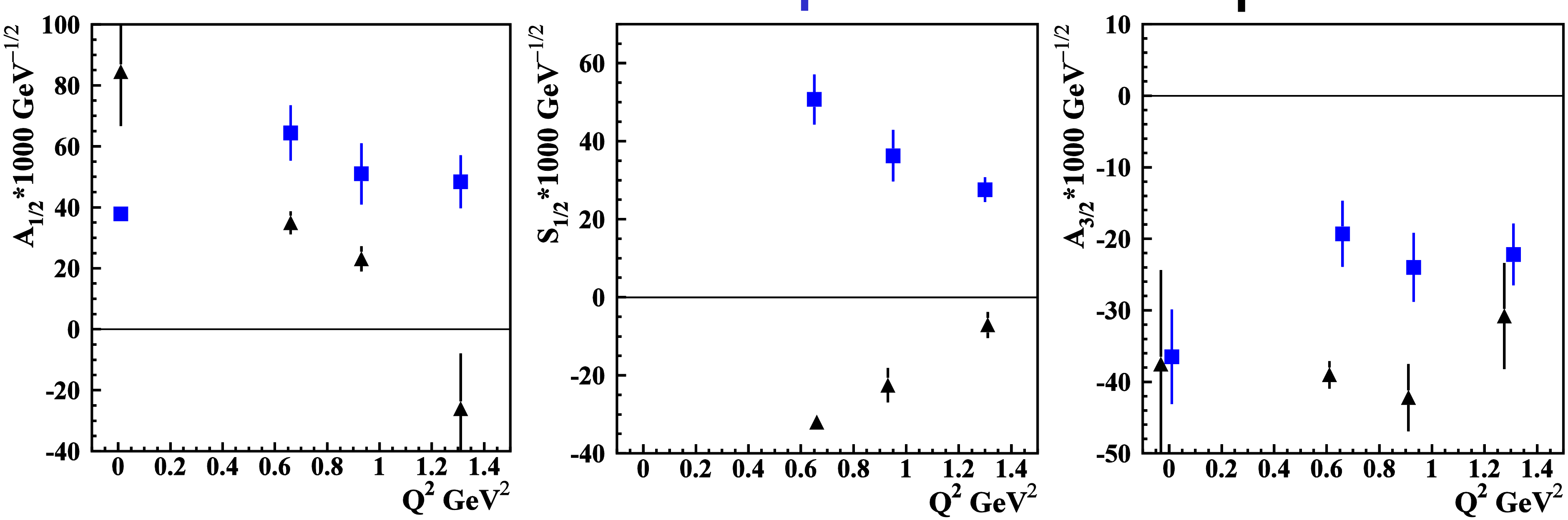
N* hadronic decays from JM15 that incorporates N’(1720)$3/2^+$

Resonance	BF(πΔ), %	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**

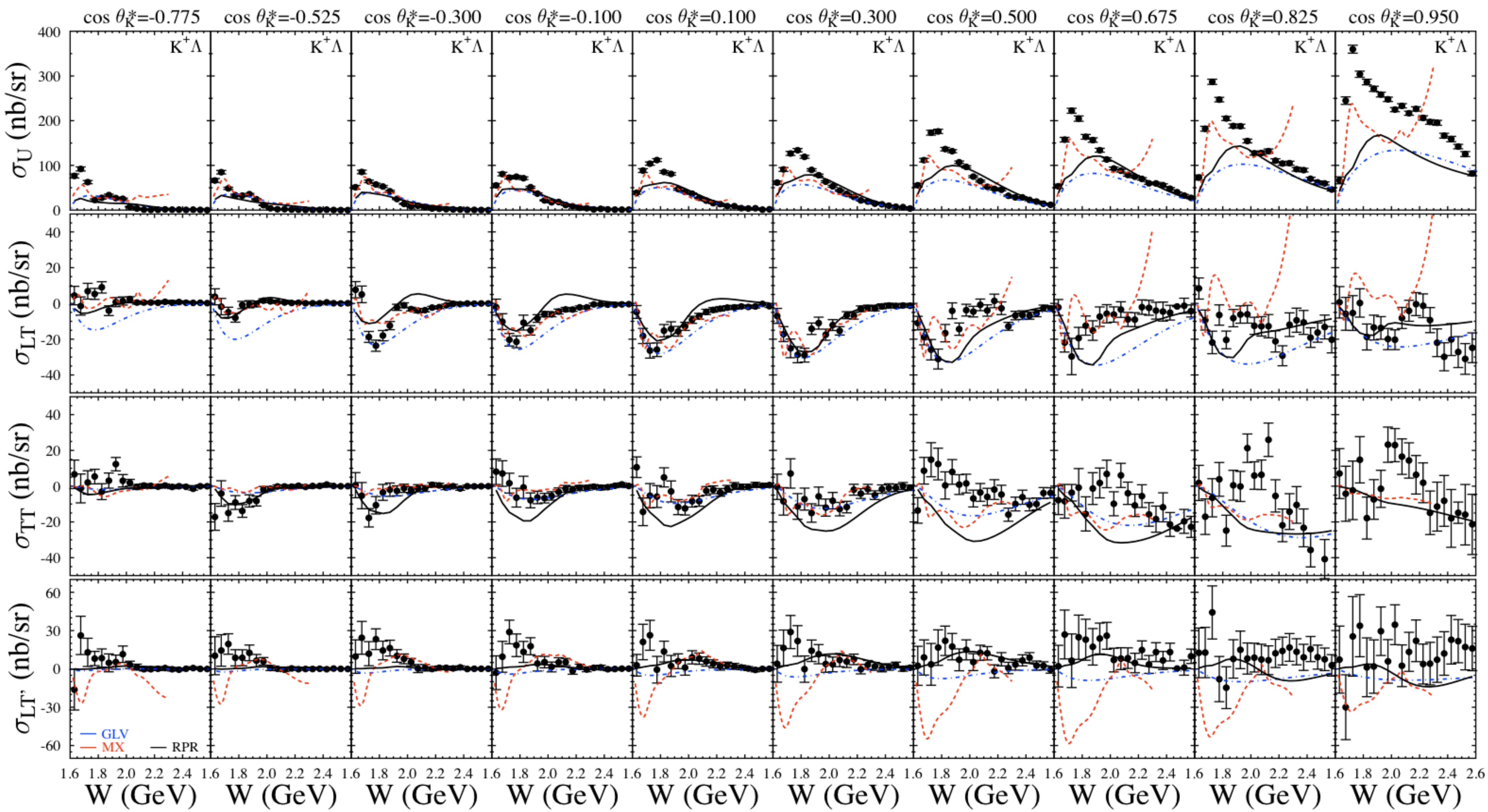
A successful description of $\pi^+\pi^-p$ photo- and electro-production cross sections at Q^2=0, 0.65, 0.95, and 1.30 GeV^2 has been achieved by implementing a new N’(1720)$3/2^+$ state with Q^2-independent hadronic decay widths of all resonances that contribute at W~1.7 GeV, that allows us to claim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



$K^+\Lambda$ Structure Functions



[Carman et al., PRC 87, 025204 (2013)]

E = 5.499 GeV, W: thr – 2.6 GeV, Q^2 *= 1.80, 2.60, 3.45 GeV*^{2} CLAS12 experiments E12-06-108A and E12-16-010A

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

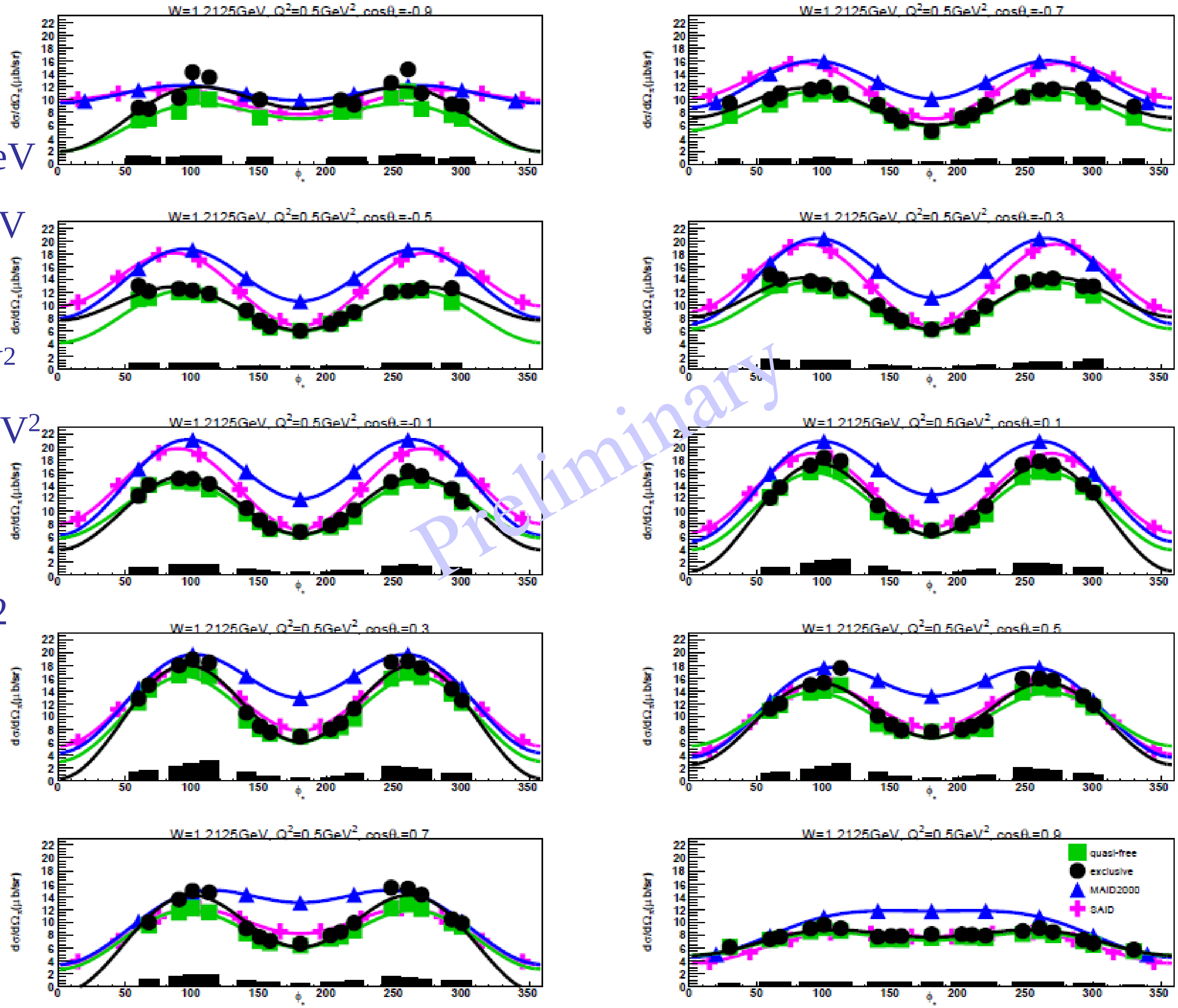
Δcos(θ) = 0.2

cos(θ) = 0.7

ϕ = 20°

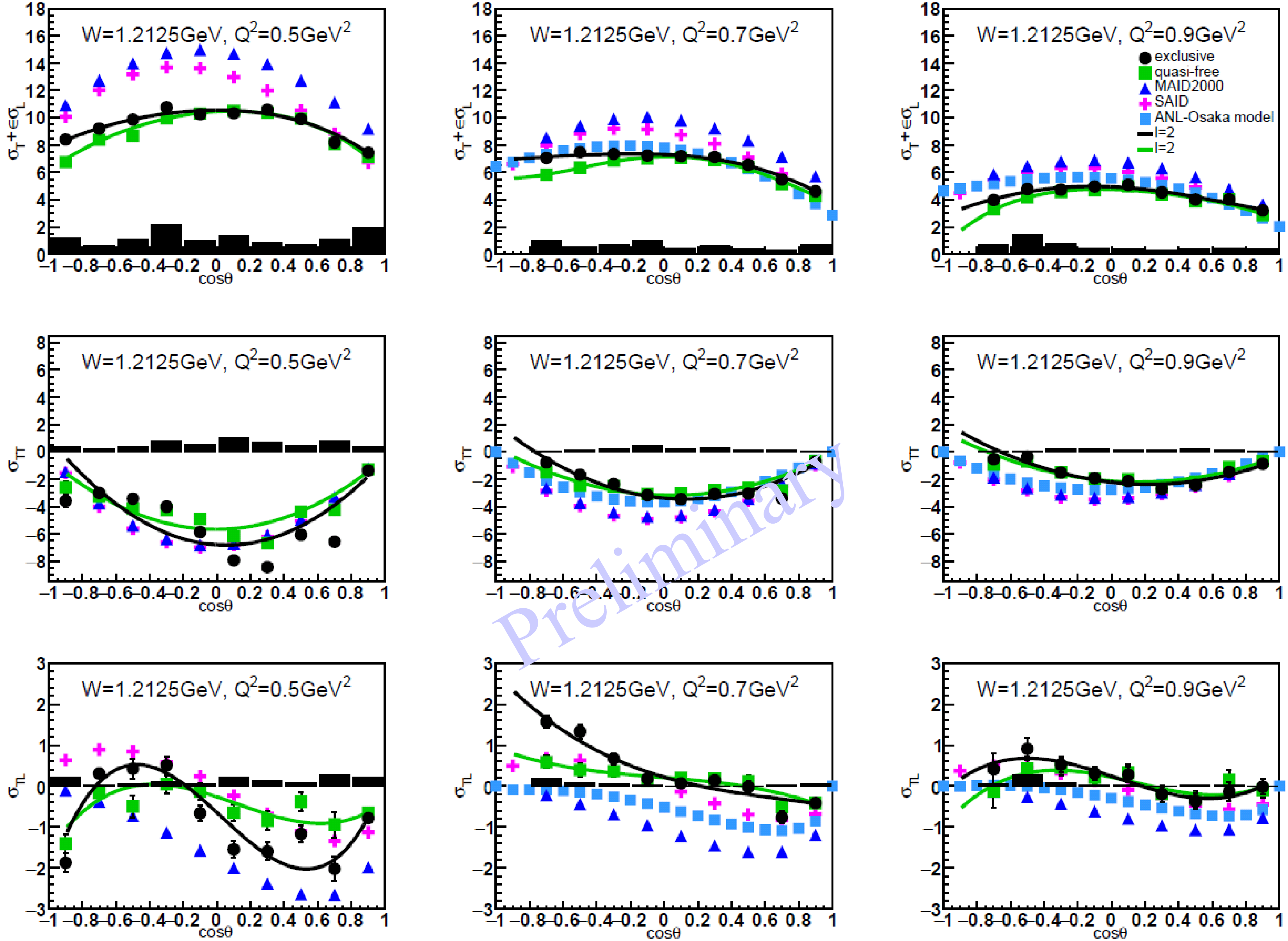
$\Delta\phi$ = 40°

ϕ = 340°



Single π⁻ Electroproduction off the Deuteron

Ye Tian

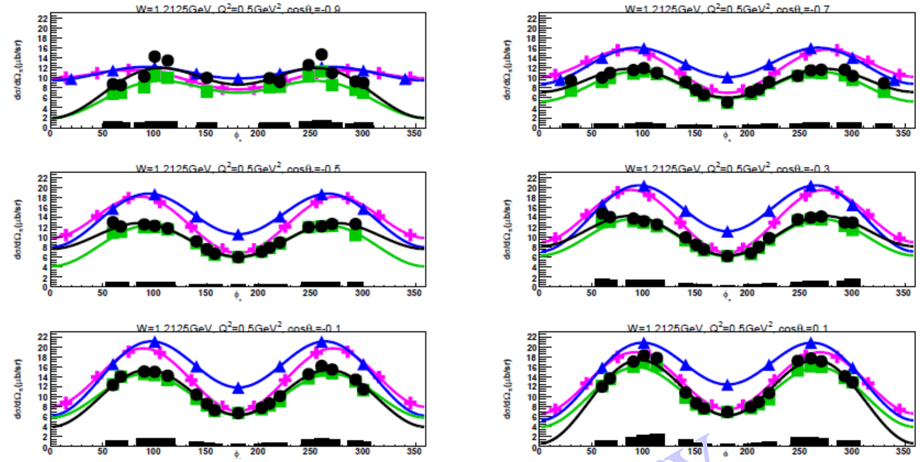


Single π⁻ Electroproduction off the Deuteron

Q^2 = 0.5 GeV^2

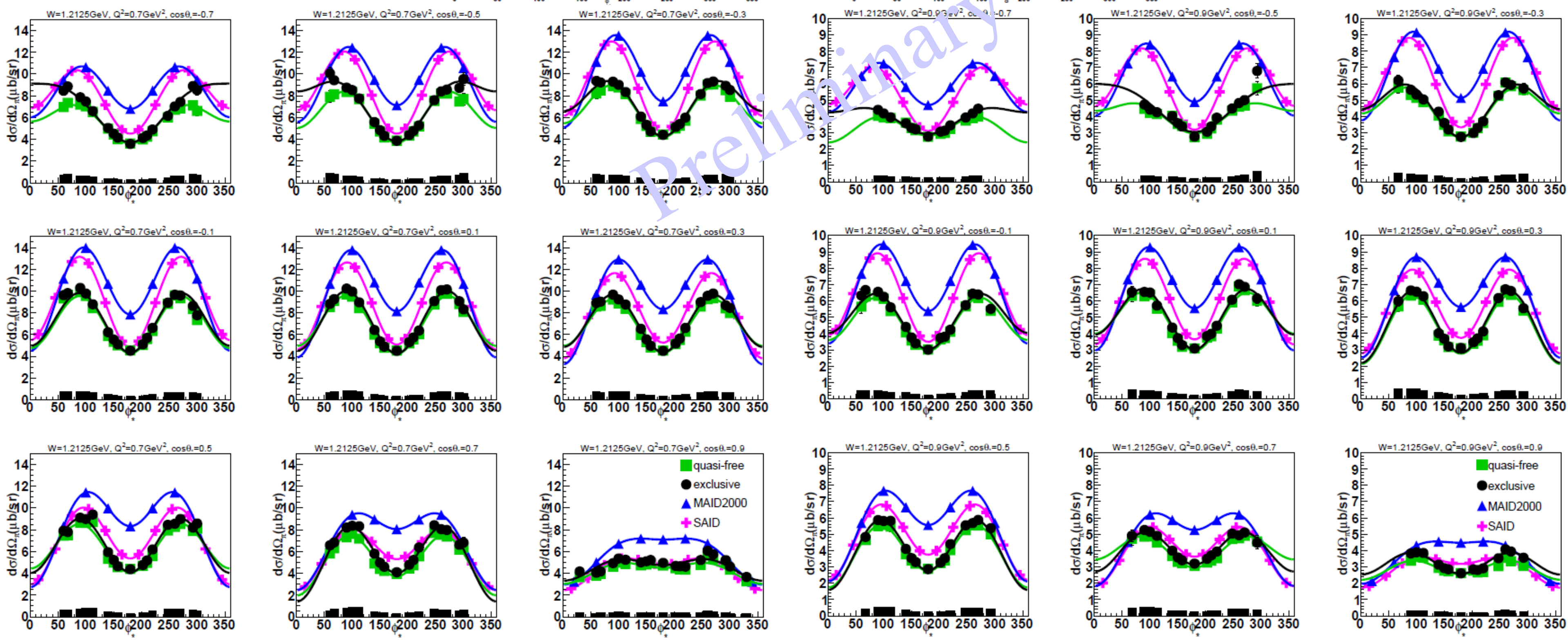
W = 1212 MeV

Ye Tian



Q^2 = 0.7 GeV^2

Q^2 = 0.9 GeV^2

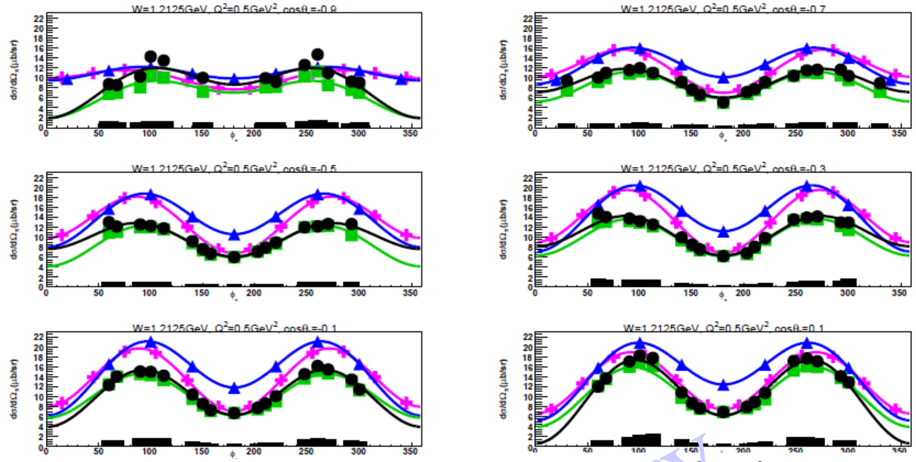


Single π^- Electroproduction off the Deuteron

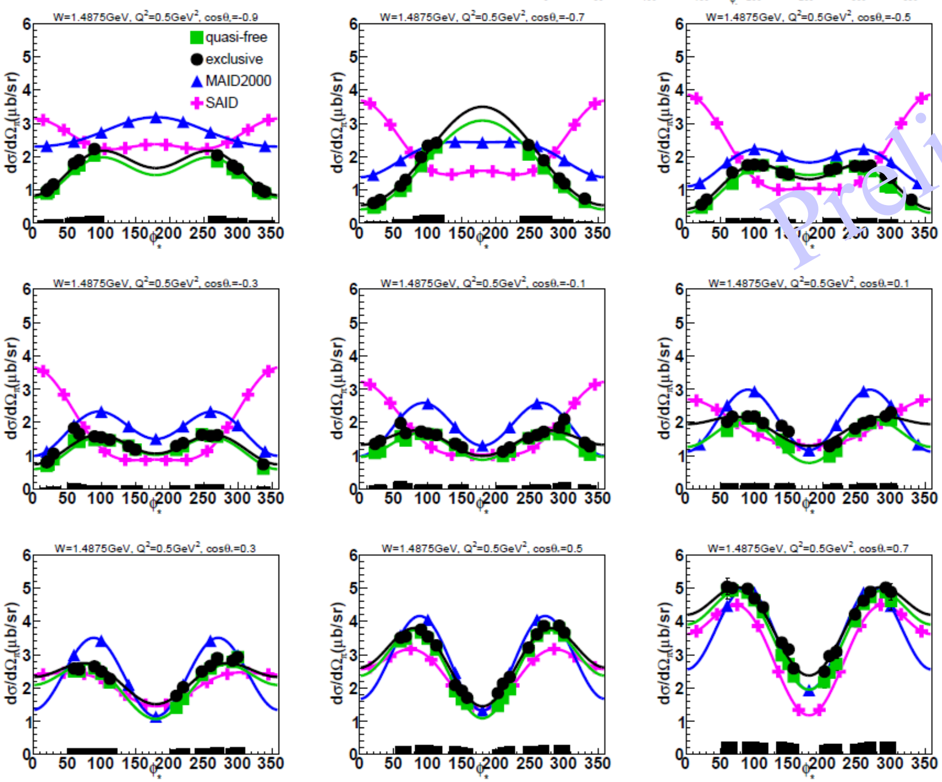
$Q^2 = 0.5\ GeV^2$

Ye Tian

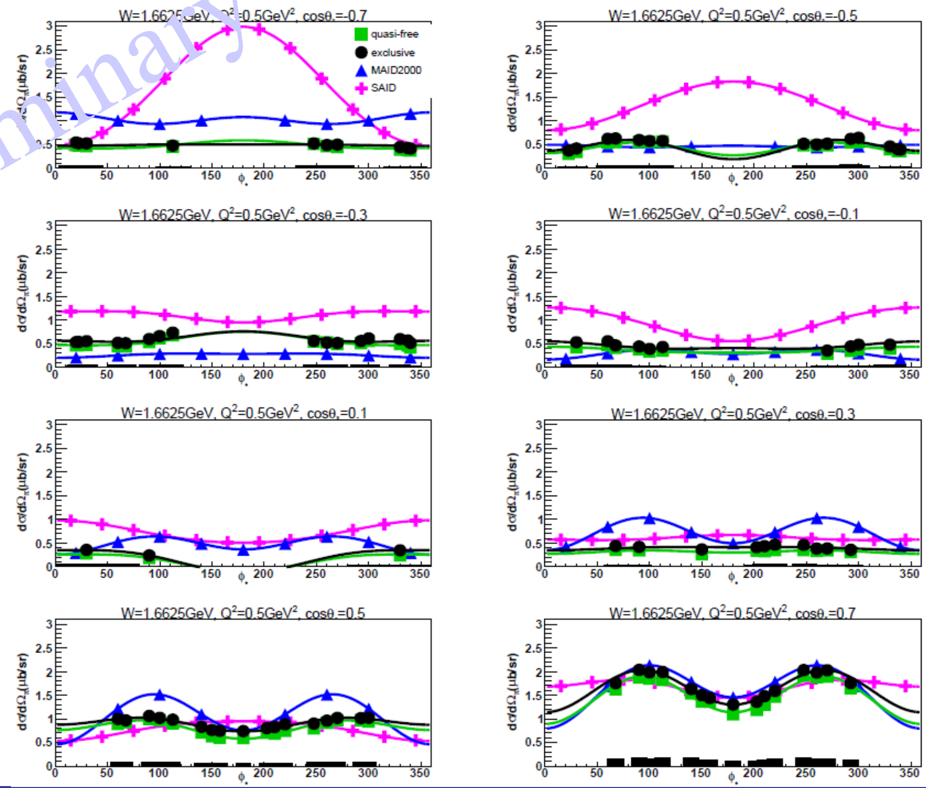
W = 1212 MeV



W = 1488 MeV

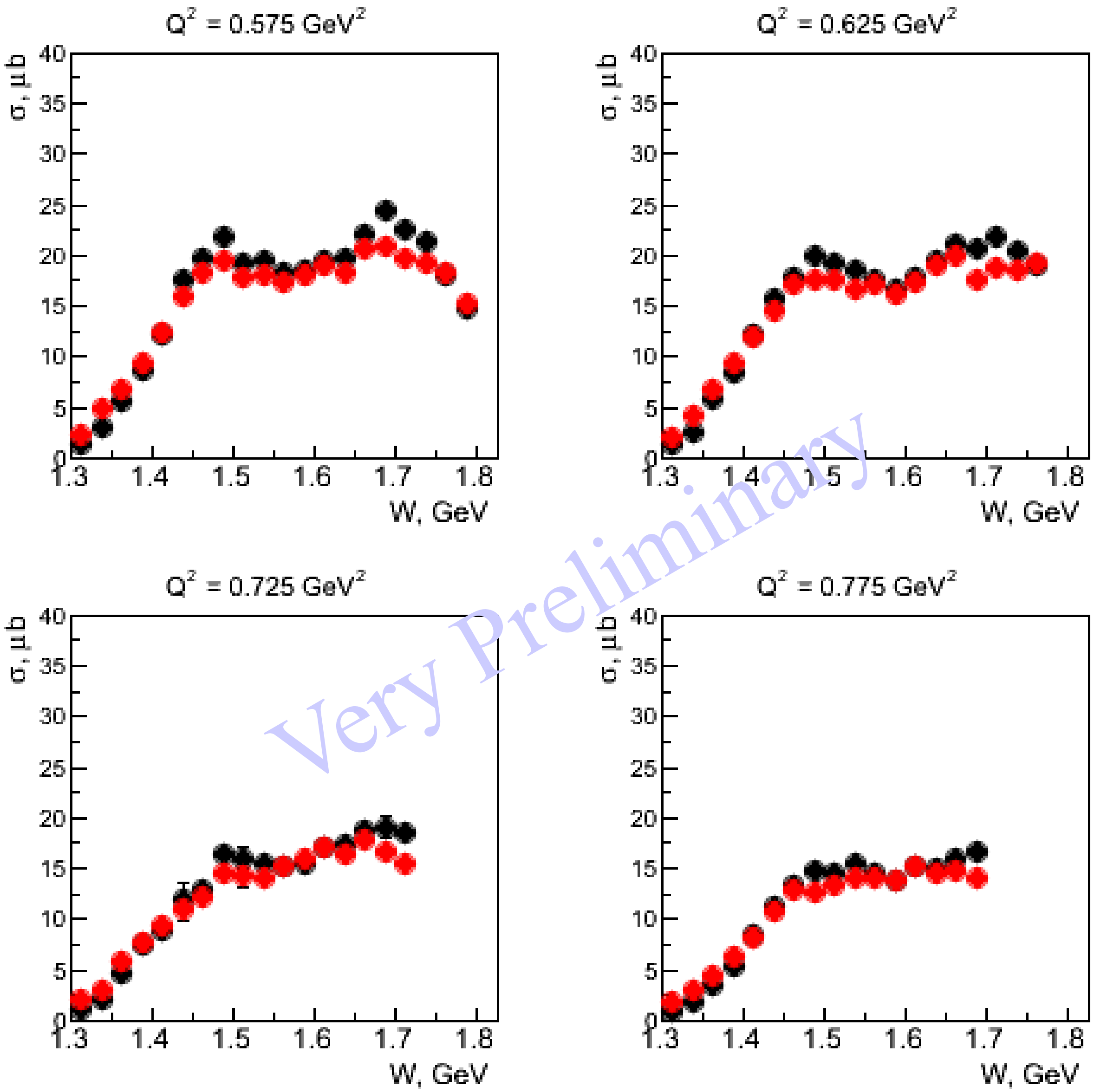


W = 1662 MeV



Unfolding Fermi Smearing via Event Generator

Iuliia Skorodomina
and Gary Hollis



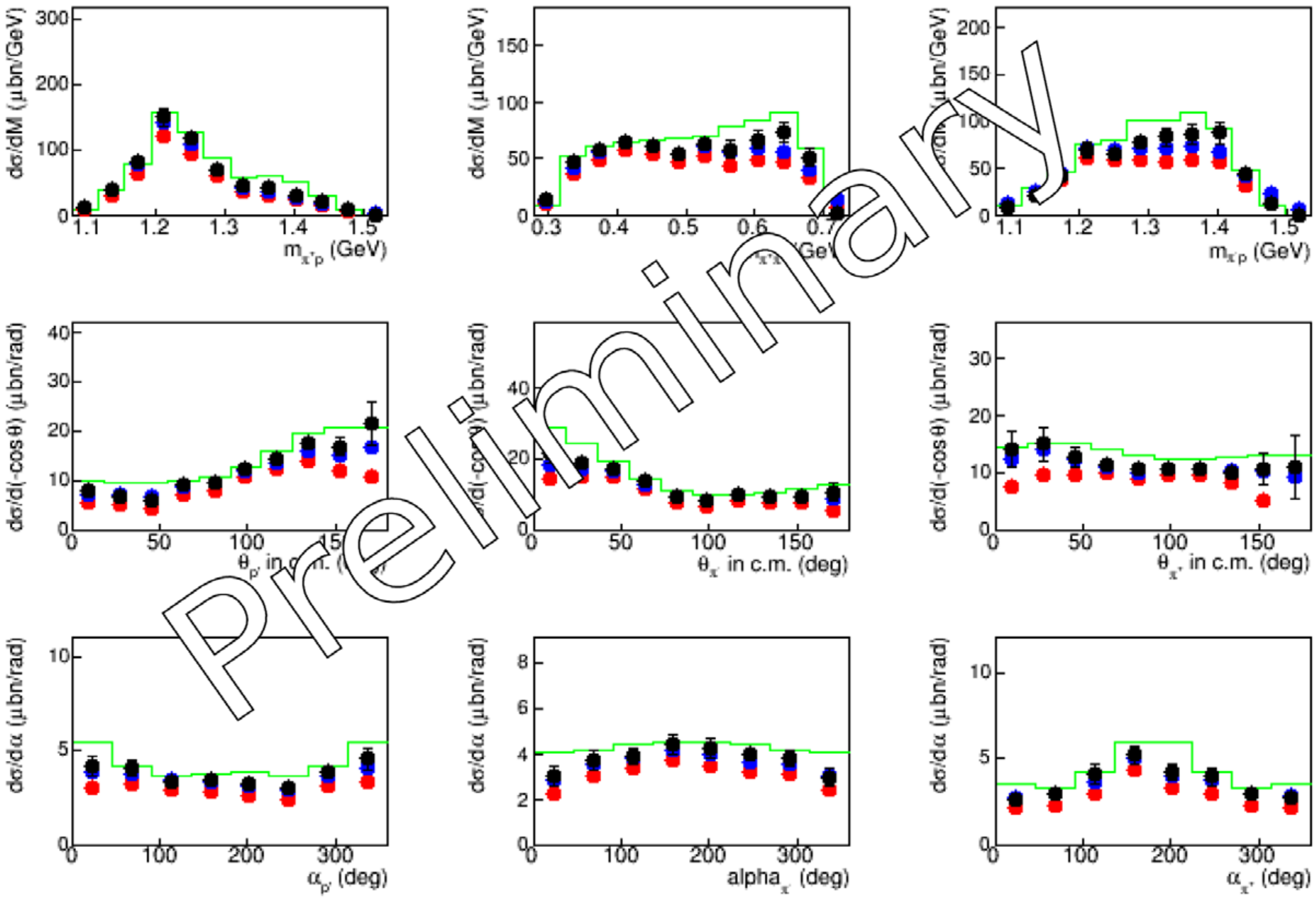
Black bullets – integrated cross section with Fermi correction

Red bullets – integrated cross Section without Fermi correction

π^- missing topology

Comparison with Free Proton Cross Section

Iuliia

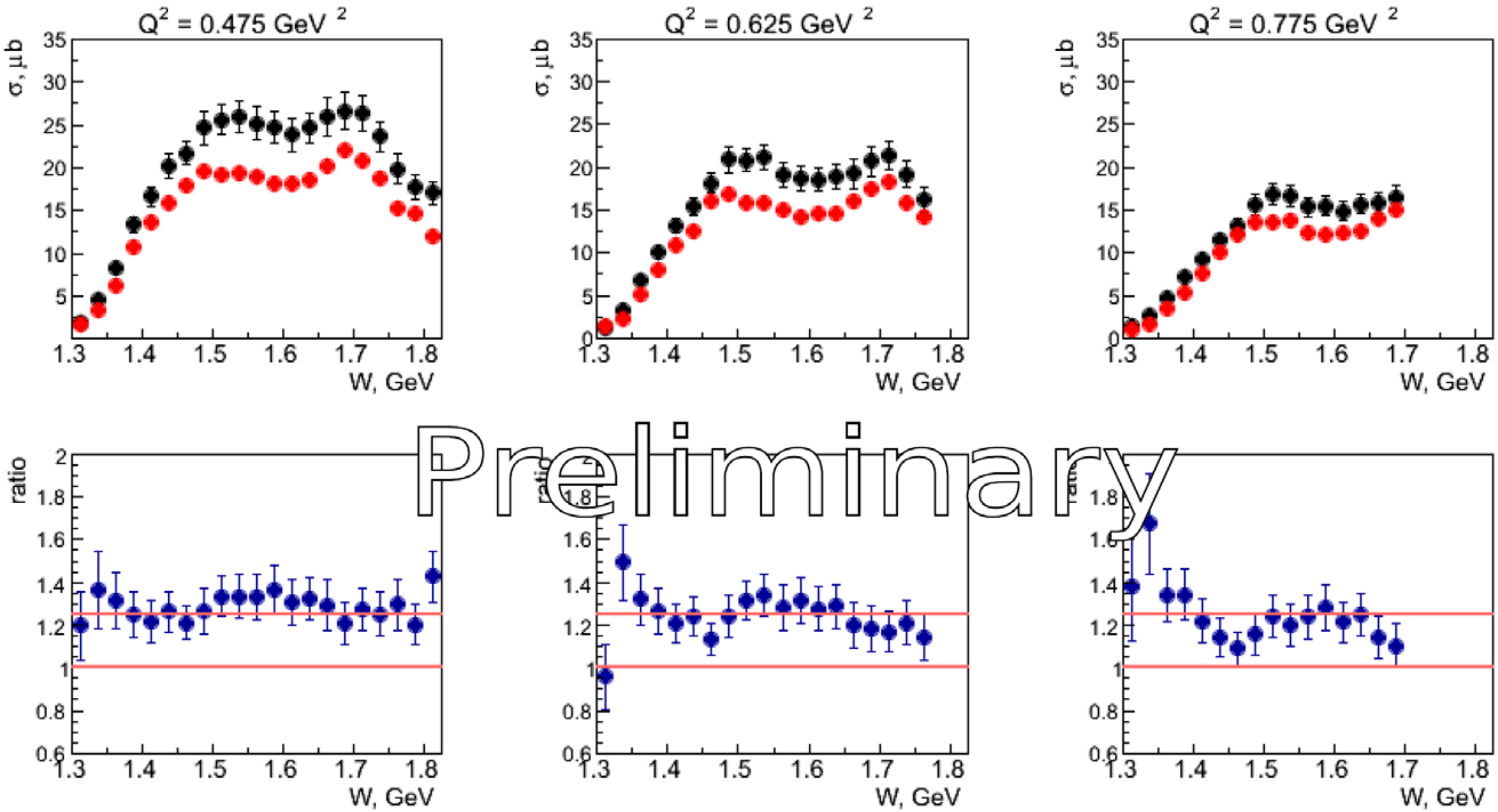


Red – empty cells are NOT filled **Blue** – empty cells are filled

Black – Fermi correction is applied **Green Curve** – TWOPEG off free proton

Comparison with Free Proton Cross Section

Iuliia

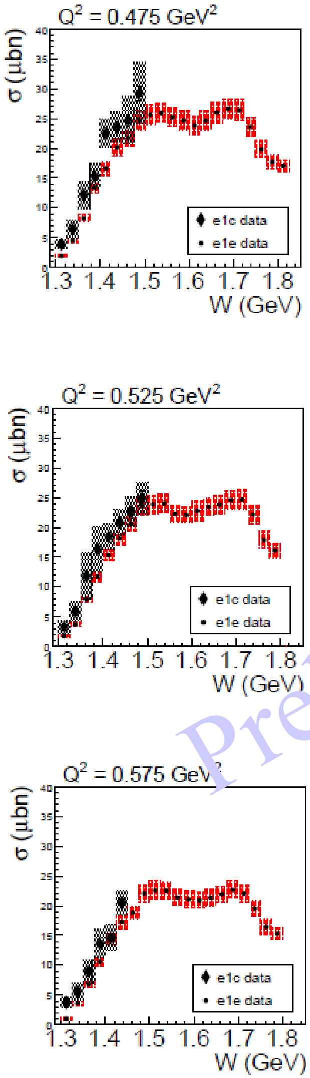


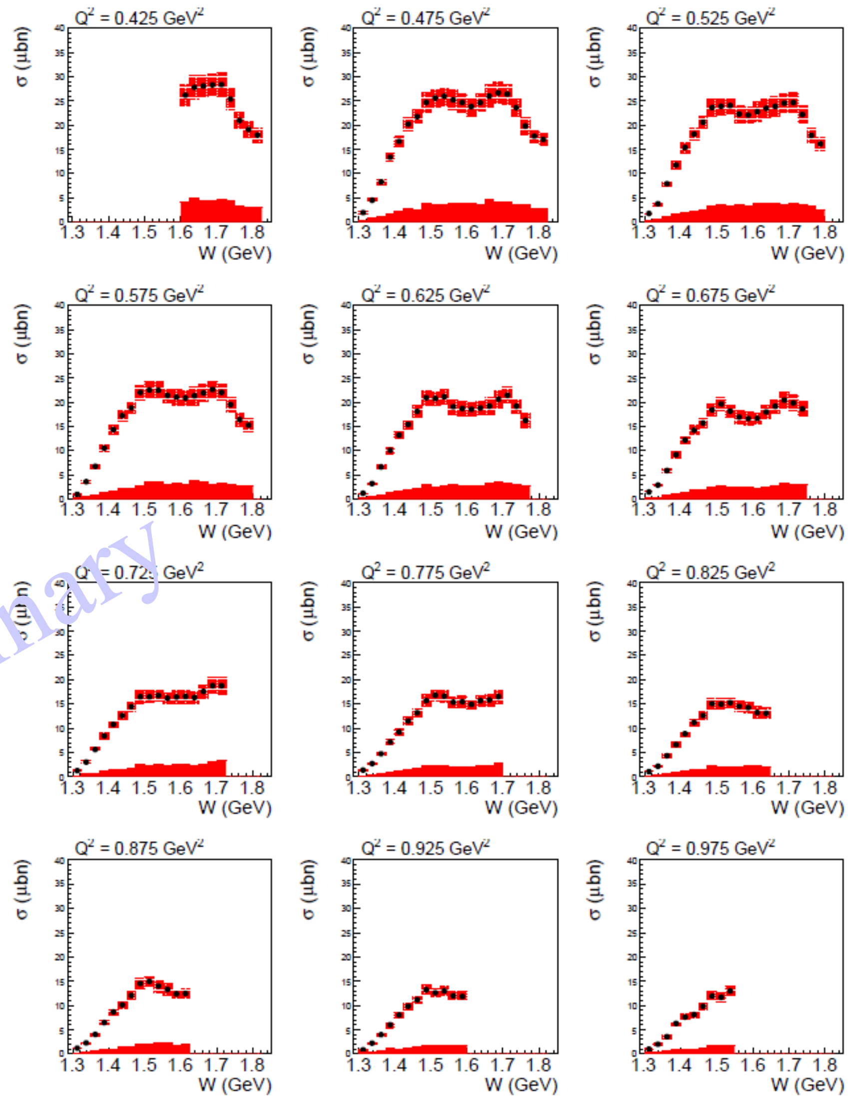
Black bullets – free proton cross sections (e1e at E_{beam} = 2.039 GeV)
error bars show both statistical and systematical uncertainties
G. Fedotov under paper review

Red bullets – bound proton quasi-free cross sections (e1e at E_{beam} = 2.039 GeV)
error bars show statistical uncertainty only

Integrated $N\pi^+\pi^-$ Cross Sections

Gleb Fedotov



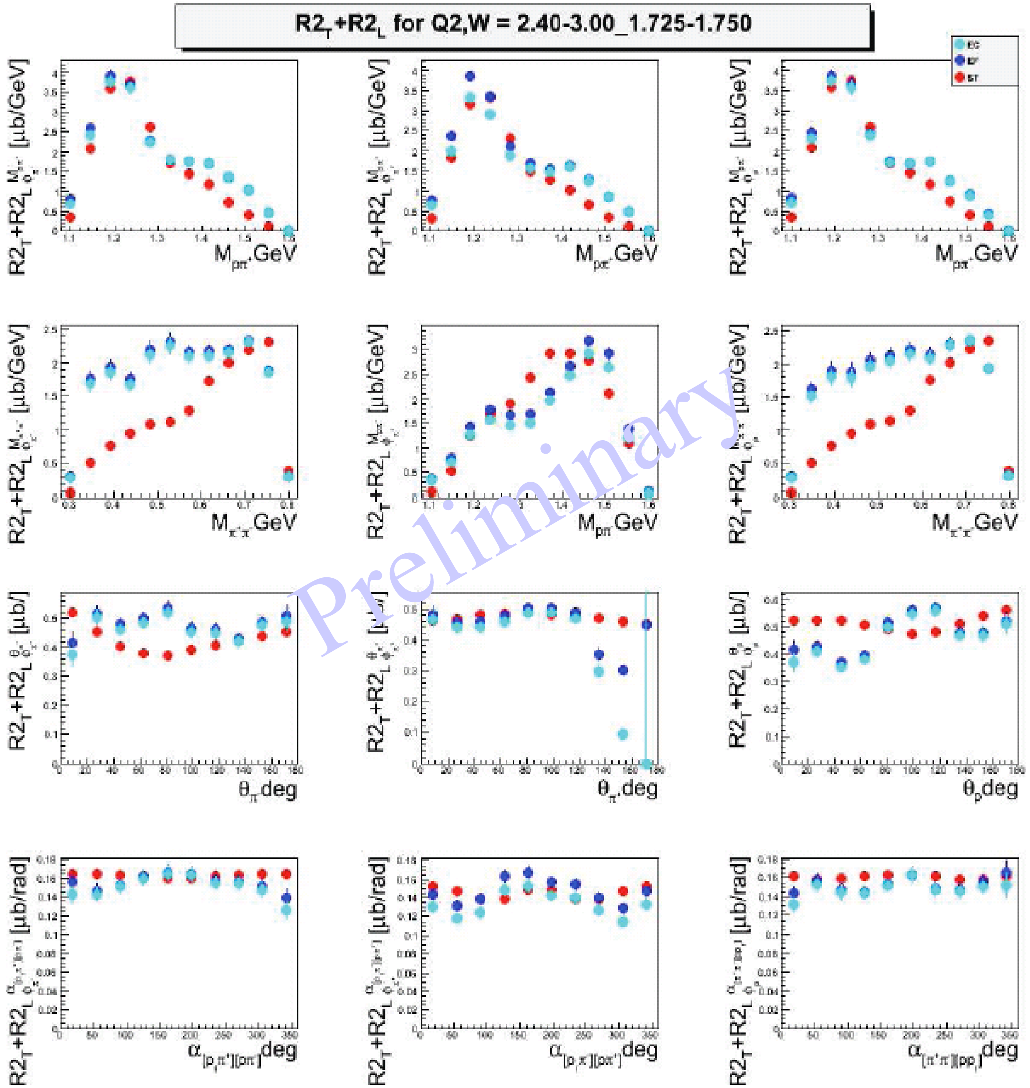


Black hatched already published data (Fedotov *et al.*, PRC79, 015204 (2009)) and red hatched new e1e data in the overlap region.

φ-dependent Nππ Single-Differential Cross Sections

Q^2, W bin $= [2.4, 3.0) GeV^2, [1.725, 1.750) GeV$

Arjun Trivedi
Evgeny Isupov



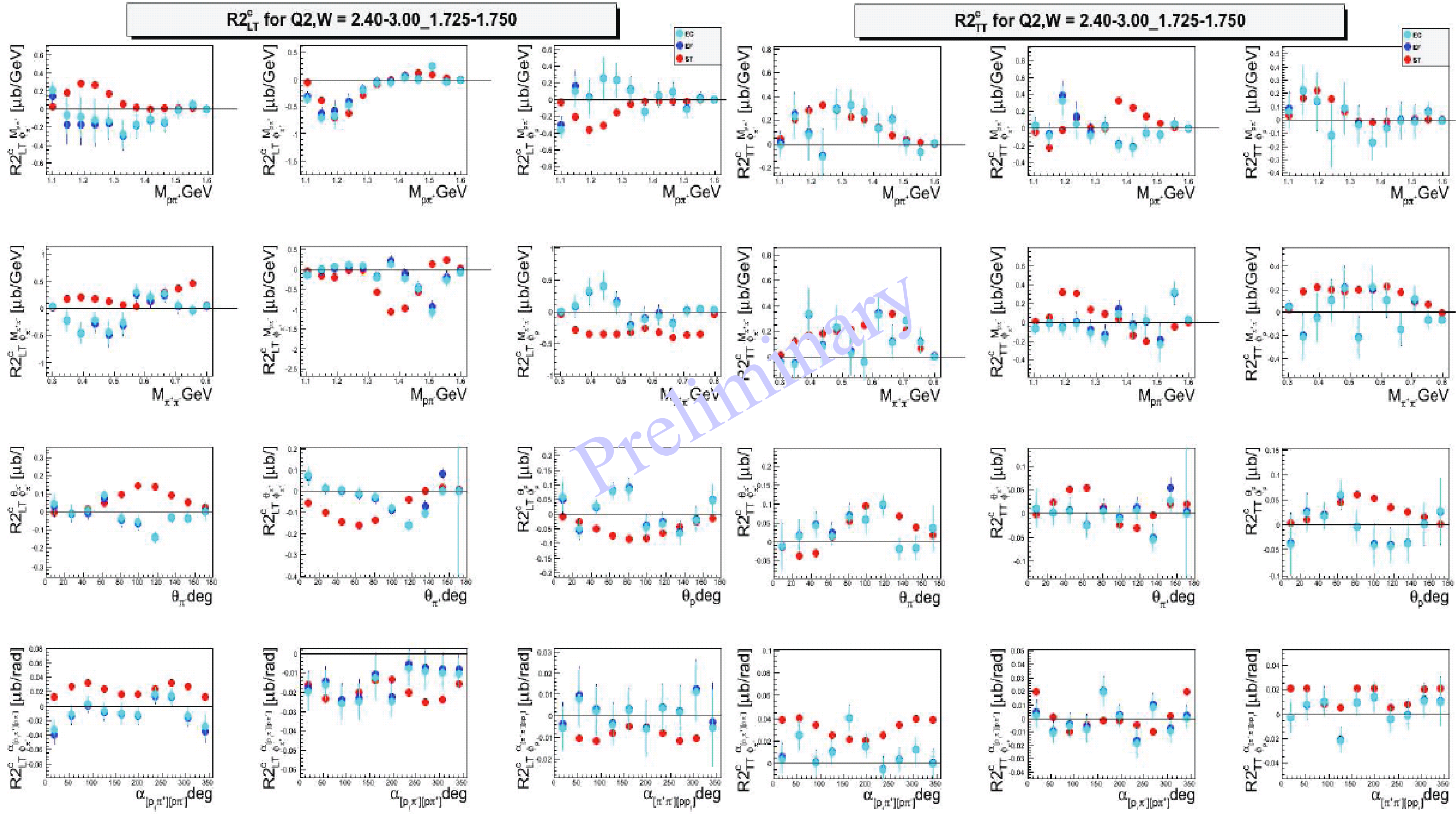
- normalized
- hole filled
- TWOPEG

$$\left(\frac{d^2\sigma}{dX_{ij}d\phi_i}\right) = R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}} + R2_{LT}{}^{c,X_{ij}}\cos\phi_i + R2_{TT}{}^{c,X_{ij}}\cos 2\phi_i + \delta_{X_{ij}\alpha_i}\left(R2_{LT}{}^{s,\alpha_i}\sin\phi_i + R2_{TT}{}^{s,\alpha_i}\sin 2\phi_i\right)$$

φ-dependent Nππ Single-Differential Cross Sections

Q^2, W bin $= [2.4, 3.0) GeV^2, [1.725, 1.750) GeV$

Arjun Trivedi

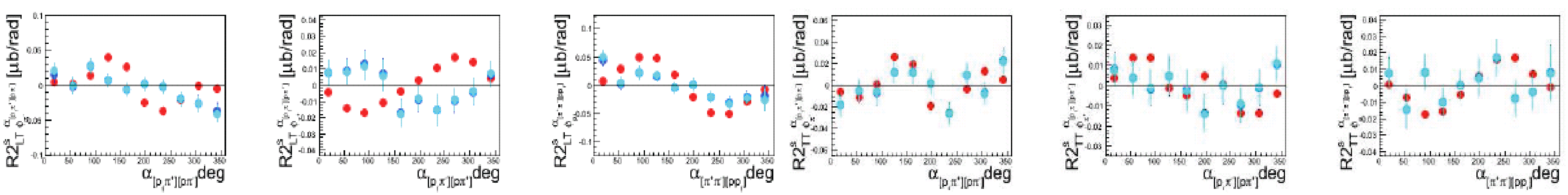


$$\left(\frac{d^2\sigma}{dX_{ij}d\phi_i}\right) = R2_T^{X_{ij}} + R2_L^{X_{ij}} + \underline{R2_{LT}^{c,X_{ij}} \cos\phi_i} + \underline{R2_{TT}^{c,X_{ij}} \cos 2\phi_i} + \delta_{X_{ij}\alpha_i}\left(R2_{LT}^{s,\alpha_i}\sin\phi_i + R2_{TT}^{s,\alpha_i}\sin 2\phi_i\right)$$

φ-dependent Nππ Single-Differential Cross Sections

$Q^2, W \text{ bin} = [2.4, 3.0) GeV^2, [1.725, 1.750) GeV$ Arjun Trivedi

Chris McLauchlin extracts the beam helicity dependent differential cross sections.

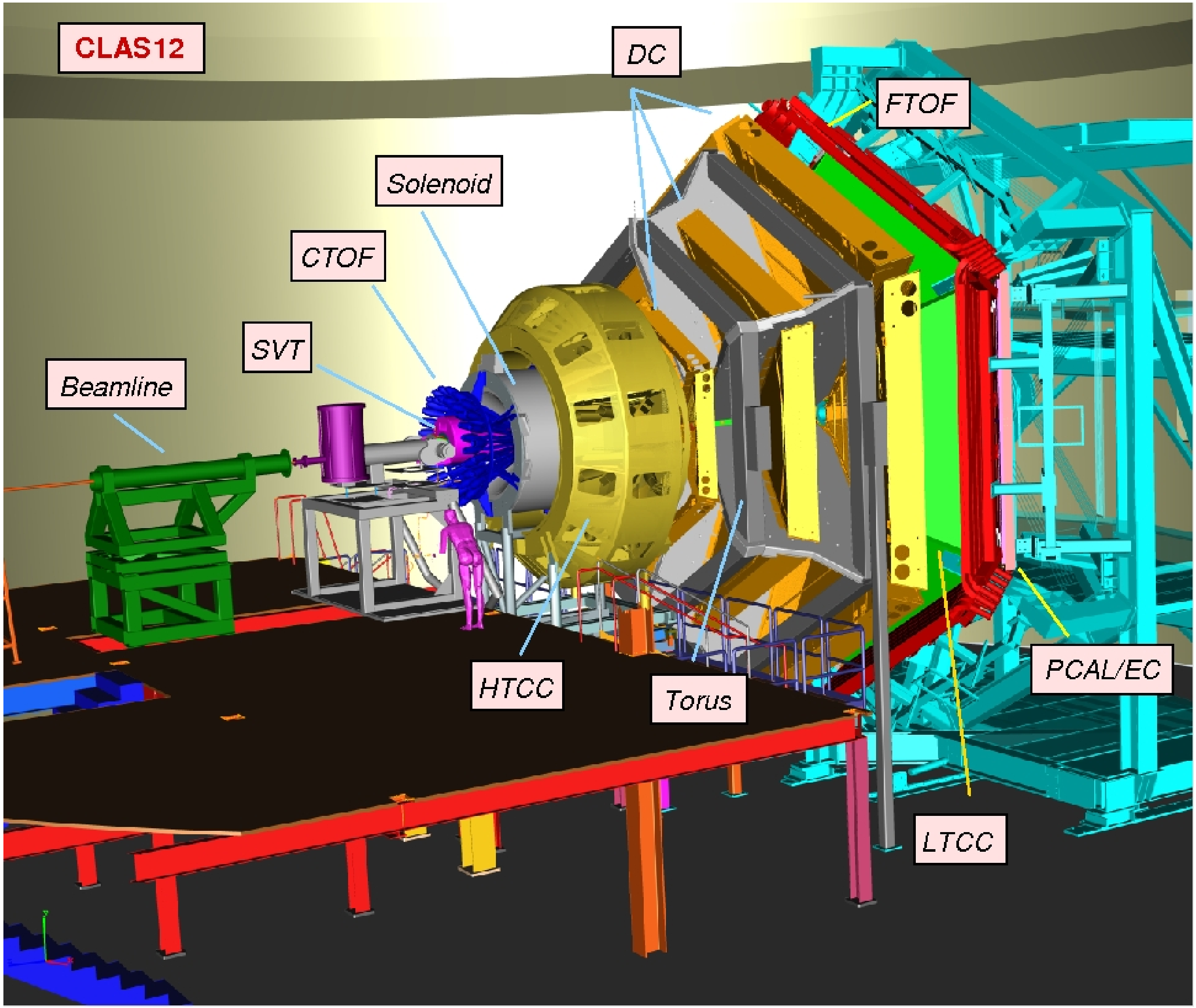


$$\left(\frac{d^2\sigma}{dX_{ij}\,d\phi_i}\right) = R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}} + R2_{LT}{}^{c,X_{ij}} \cos\phi_i + R2_{TT}{}^{c,X_{ij}} \cos 2\phi_i + \delta_{X_{ij}\alpha_i}\left(\underline{R2_{LT}{}^{s,\alpha_i} \sin\phi_i} + \underline{R2_{TT}{}^{s,\alpha_i} \sin 2\phi_i}\right)$$

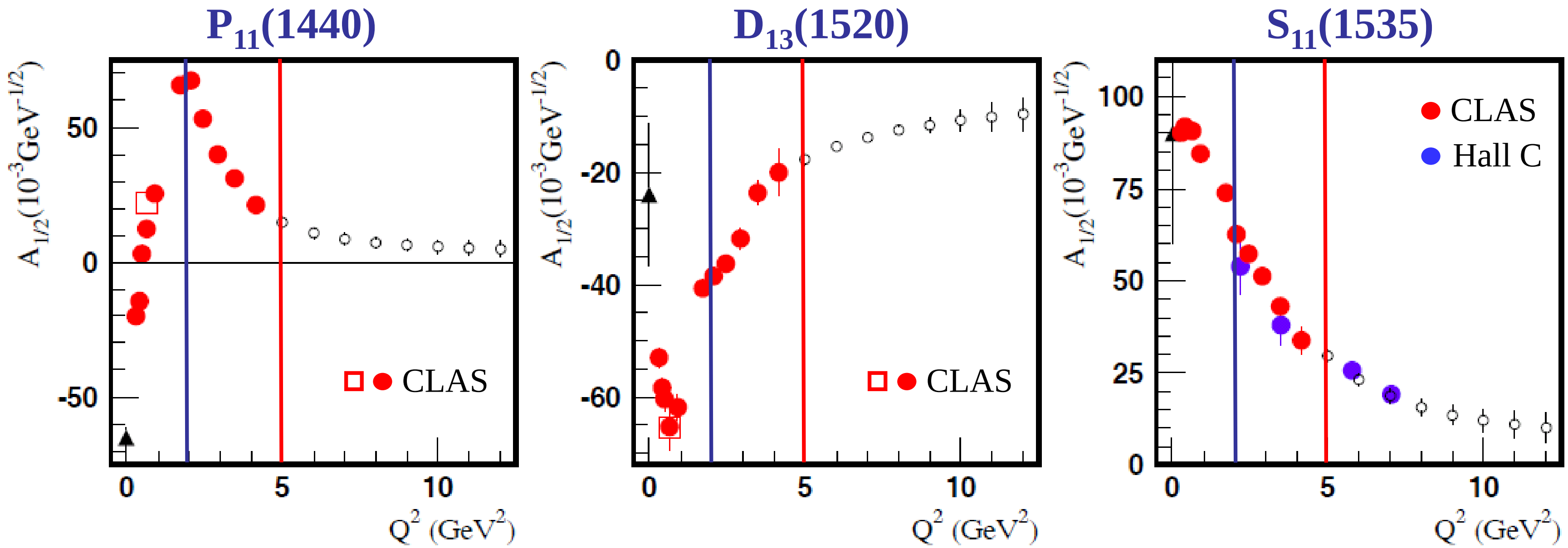
CLAS12

CLAS12 Baseline Equipment

- Optimized for exclusive and semi-inclusive reactions
- Large coverage in θ and ϕ angles
- Small angle capabilities
- Design operating luminosity of 10^{35} $cm^{-2}s^{-1}$
- Particle ID up to high momenta for e^-/π^-, γ/π^o, and $\pi/K/p$ separation
- Good momentum and angle resolution
- Operate Polarized Target



Anticipated N* Electrocouplings from Combined Analyses of Nπ/Nππ



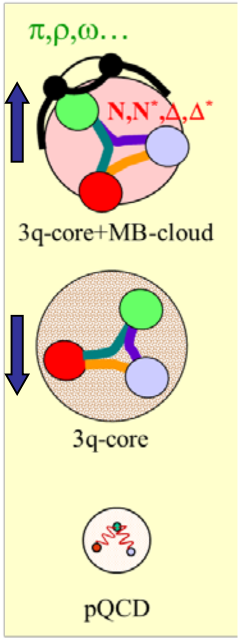
Open circles represent projections and all other markers the available results with the 6-GeV electron beam

➢ 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. $S_{11}(1650)$, $F_{15}(1685)$, $D_{33}(1700)$, $P_{13}(1720)$, …

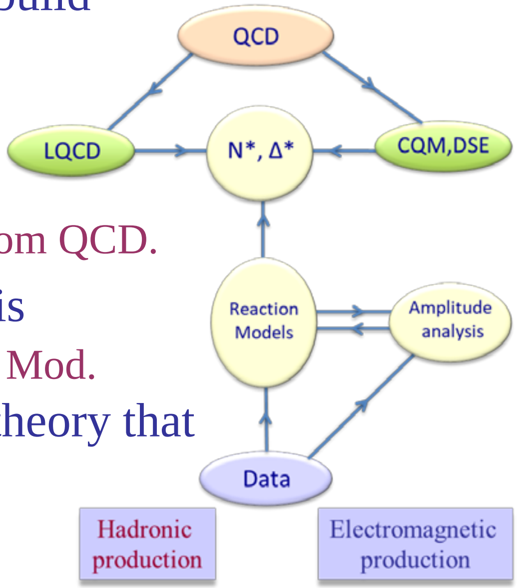
➢ The approved CLAS12 experiments E12-09-003 (NM, Nππ) and E12-06-108A (KY) are currently the only experiments that can provide data on γ_vNN* electrocouplings for almost all well established excited proton states at the highest photon virtualities ever achieved in N* studies up to Q^2 of 12 GeV^2, see 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 (E12-16-010) ,
  - 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 (E12-16-010 A).



- Comparing these results with LQCD, DSE, LCSR, and rCQM will build further insights into
  - the strong interaction of dressed quarks and their confinement,
  - the QCD β-function and the origin of 98% of nucleon mass, and
  - the emergence of bare quark dressing and dressed quark interactions from QCD.
- A close collaboration of experimentalists and theorists has formed, is growing, 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 strong QCD theory that describes the strong interaction from current quarks to nuclei.



ECT*2015, INT2016, NSTAR2017, …