Nucleon Resonances and their Structure

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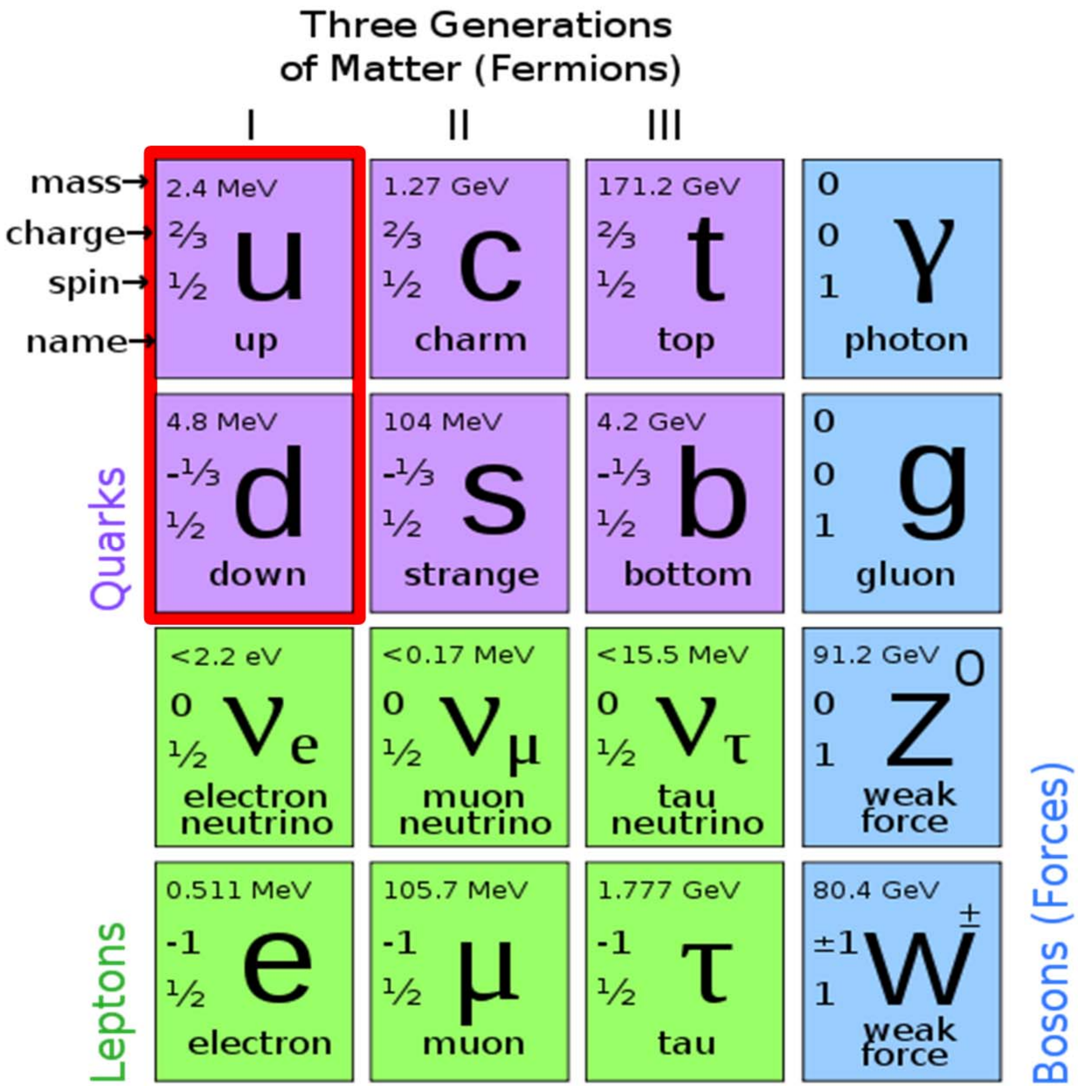
6th Workshop of the APS Topical Group on Hadron Physics
April 8-10, 2015, Baltimore, MD

- **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.

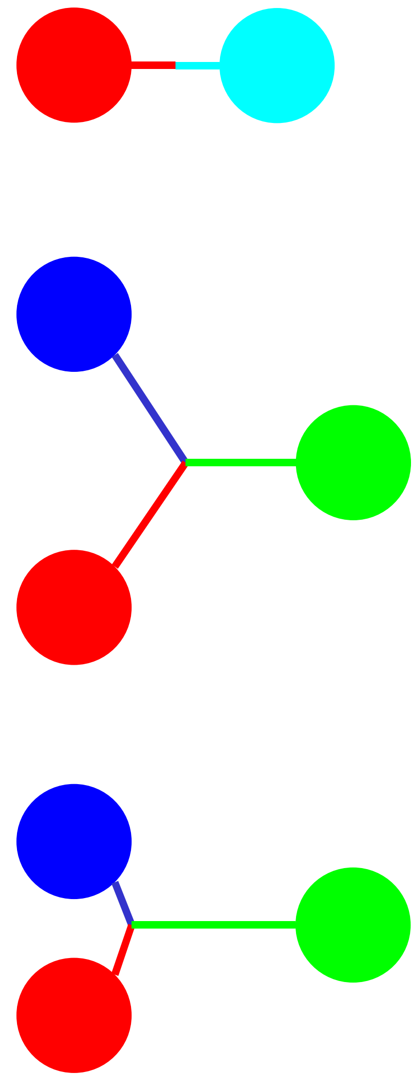
This work is in parts supported by the US National Science Foundation under the Grant PHY-1205782

Spectroscopy

Hadron Spectroscopy: Meson, Baryons, …



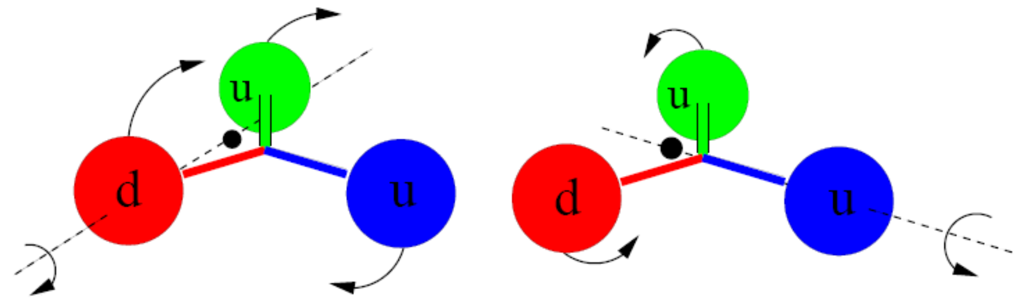
Q
C
D



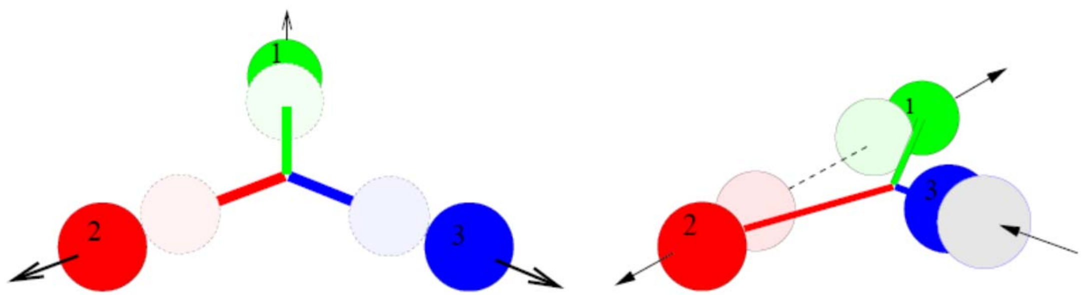
N and Δ Excited Baryon States …

Simon Capstick

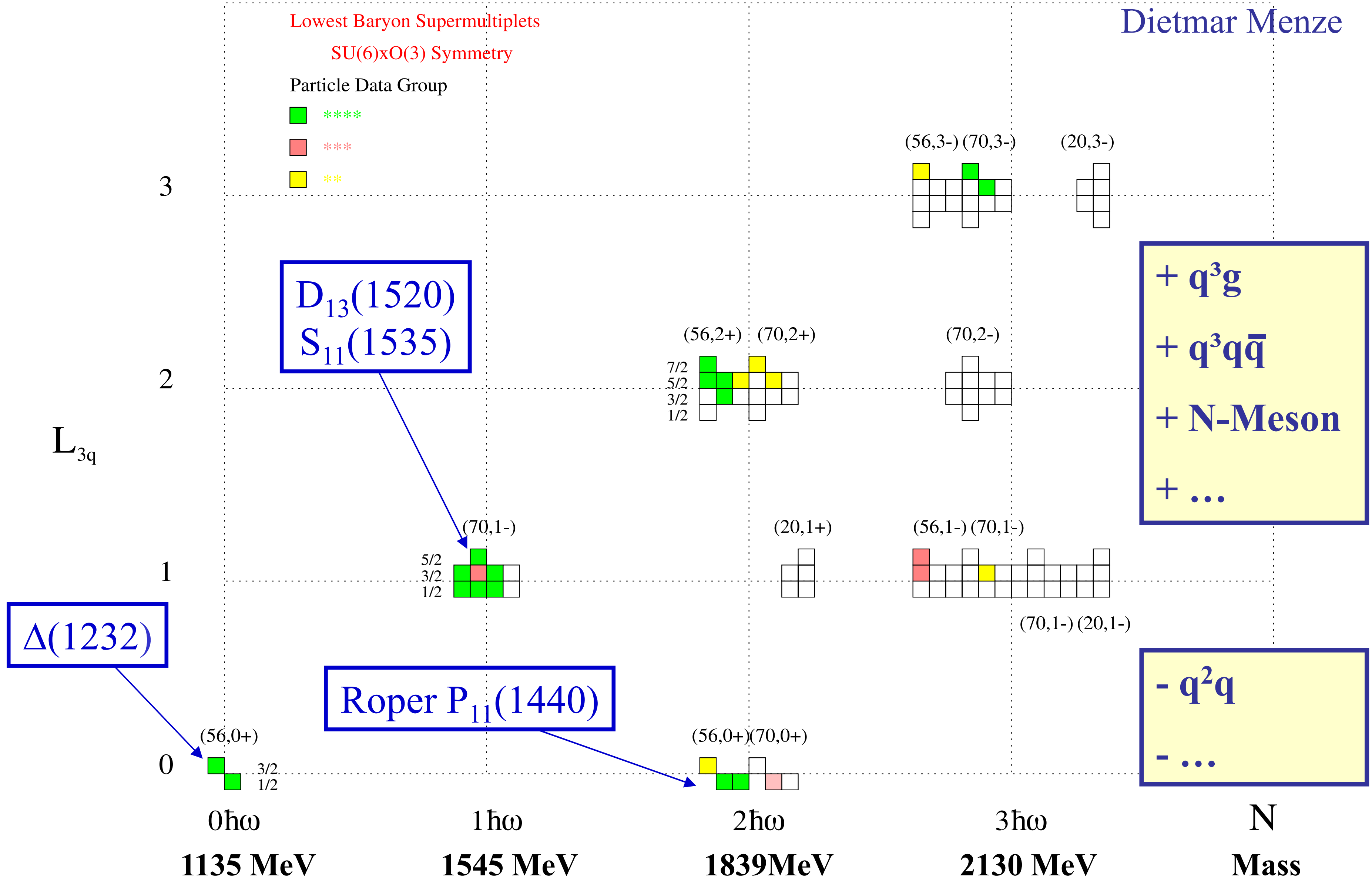
- Orbital excitations (two distinct kinds in contrast to mesons)



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

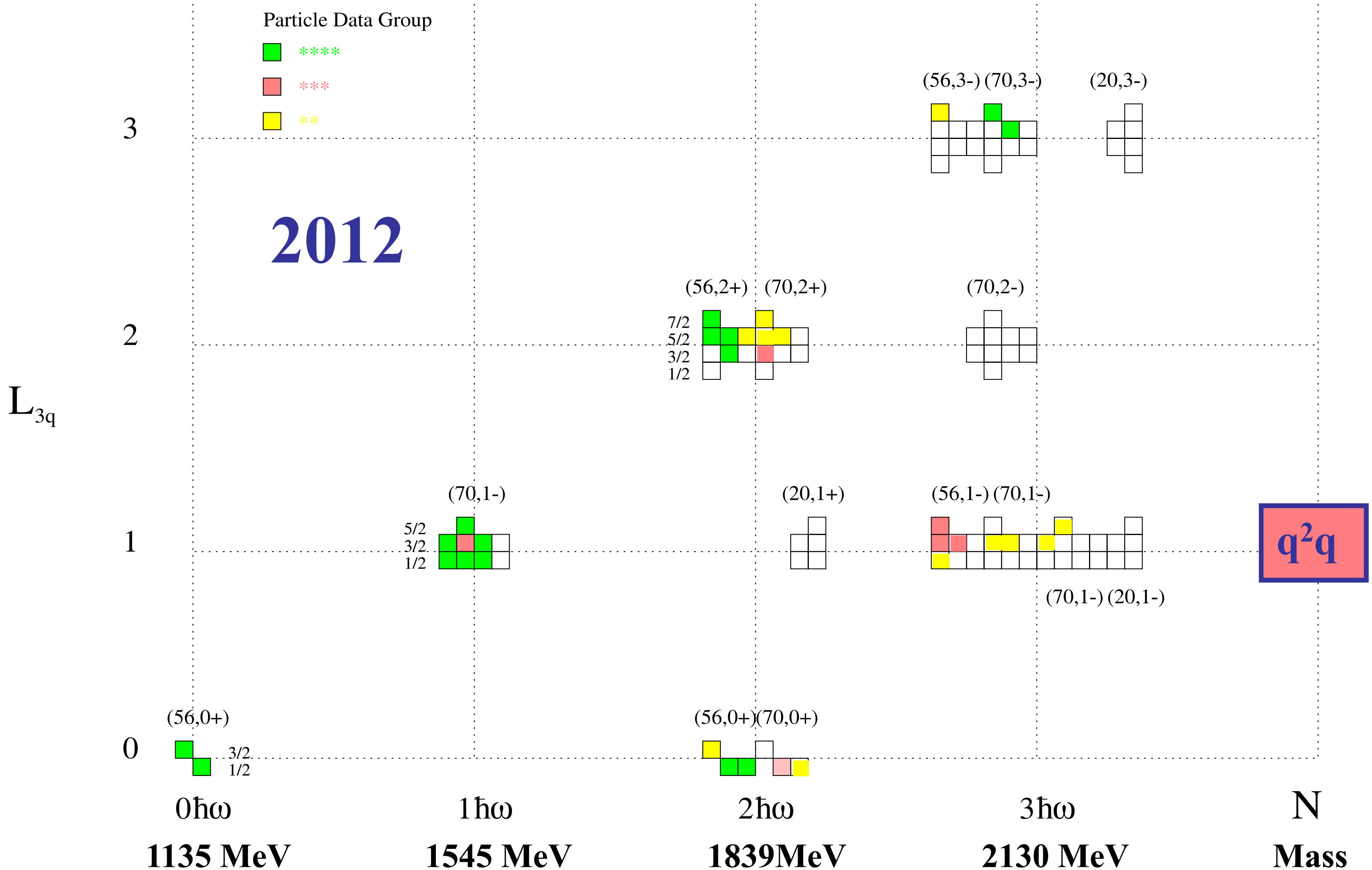


Quark Model Classification of N*



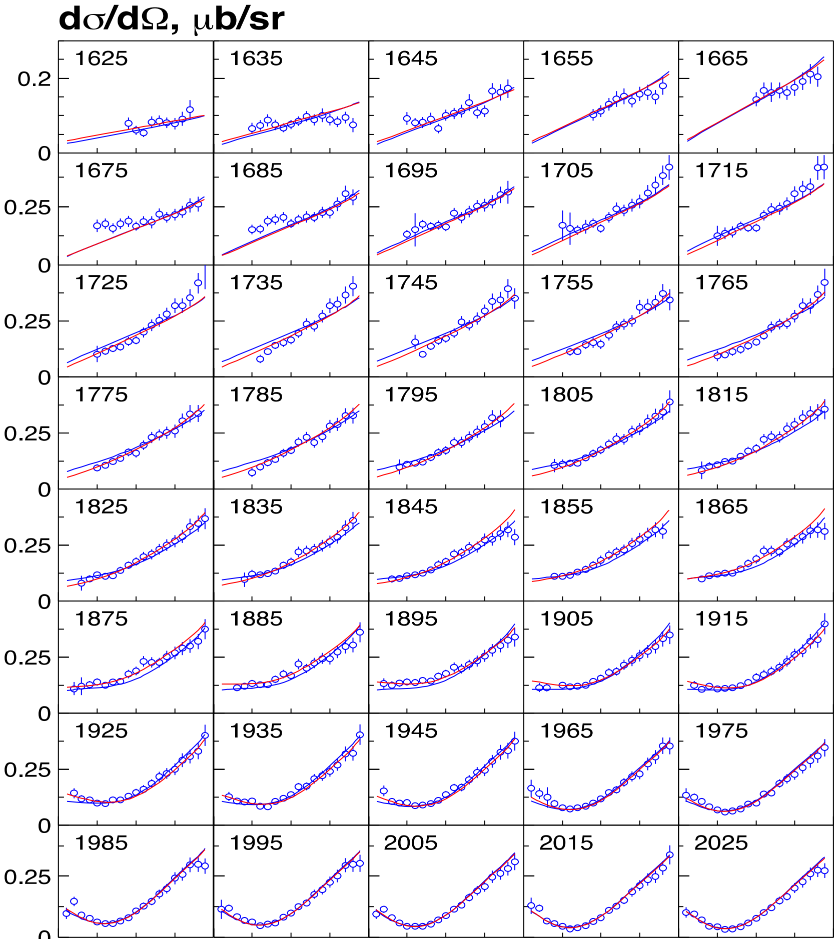
Quark Model Classification of N*

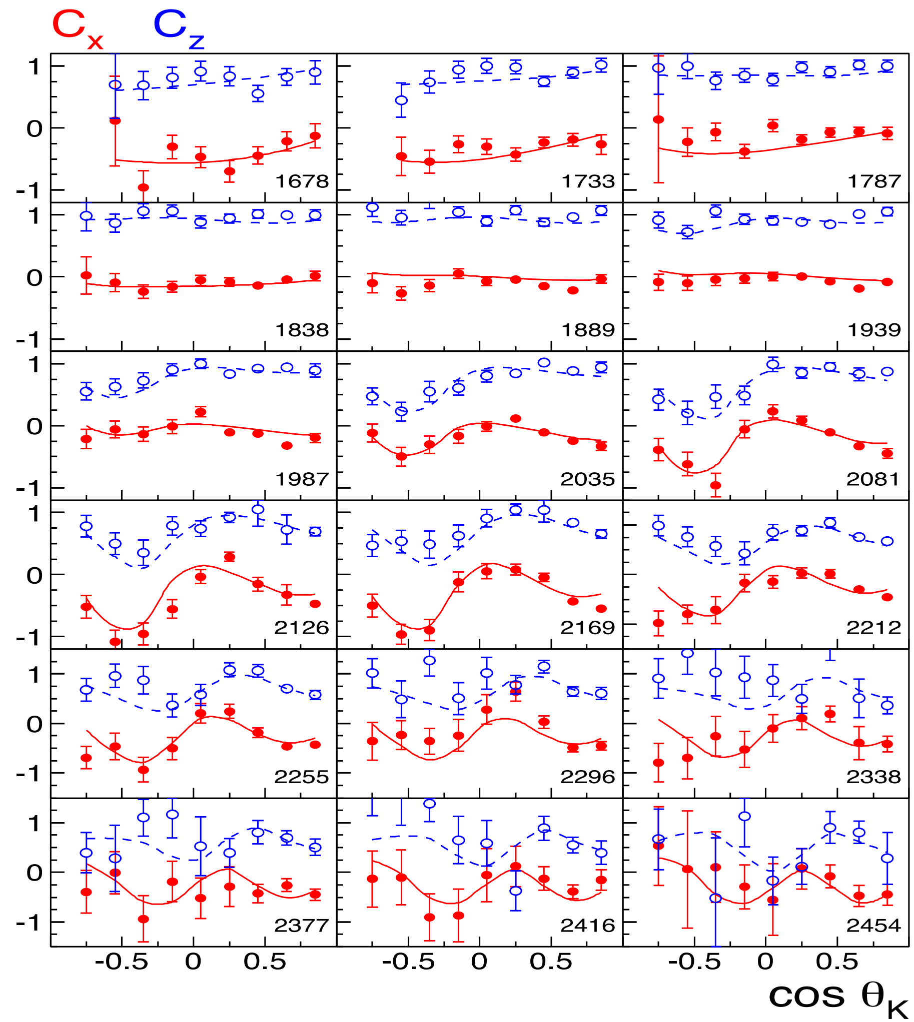
BnGa energy-dependent coupled-channel PWA of CLAS $K^+\Lambda$ and other data



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)

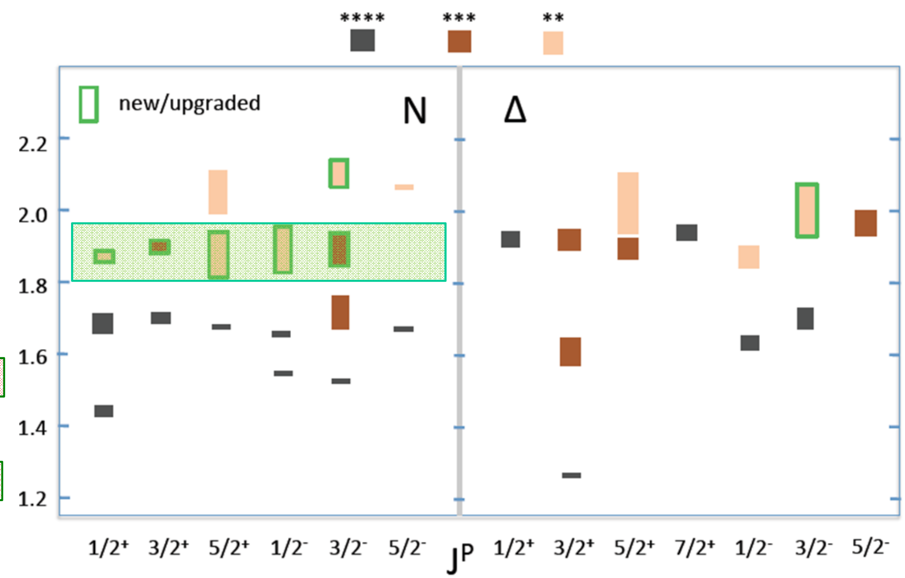




N/Δ Spectrum in RPP 2012

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

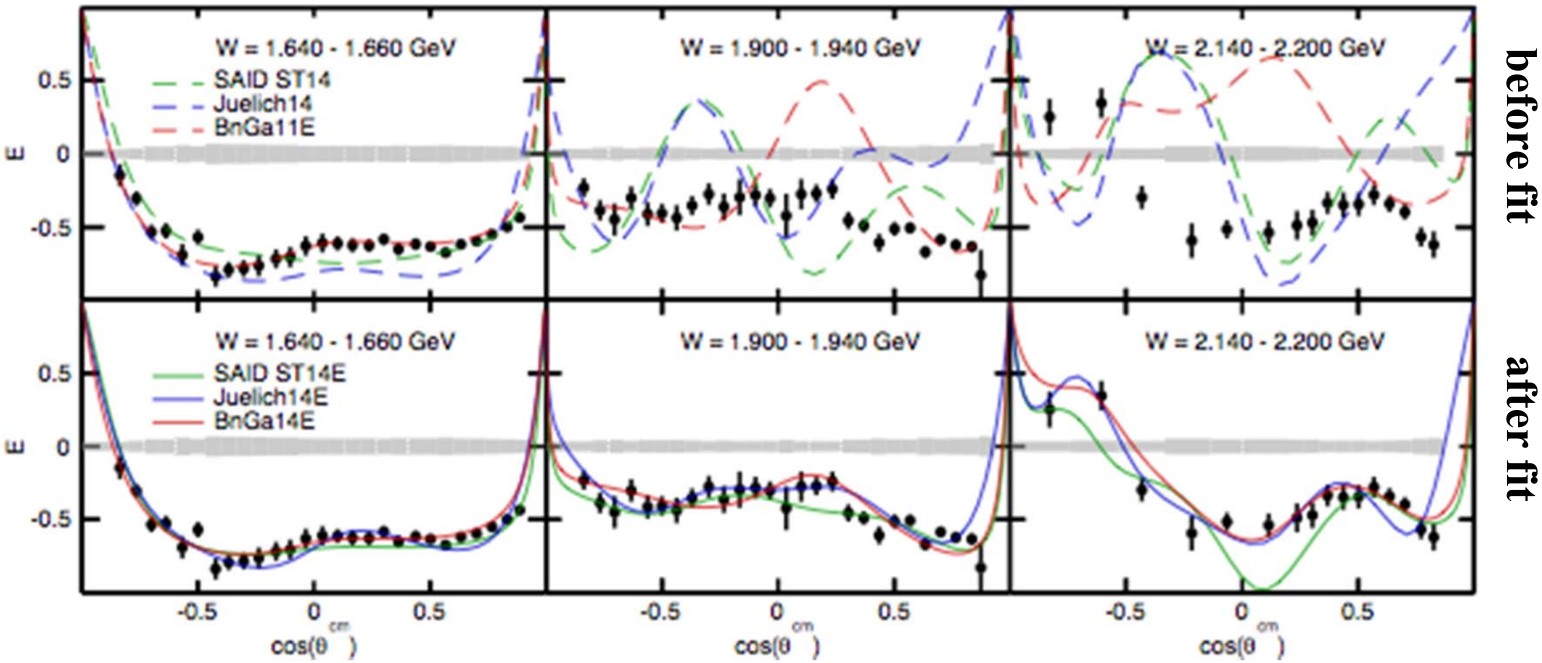


Are we observing parity doublets with the new states or not?

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

New FROST Results from $\vec{\gamma}\vec{p}\rightarrow\pi^0 p$

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

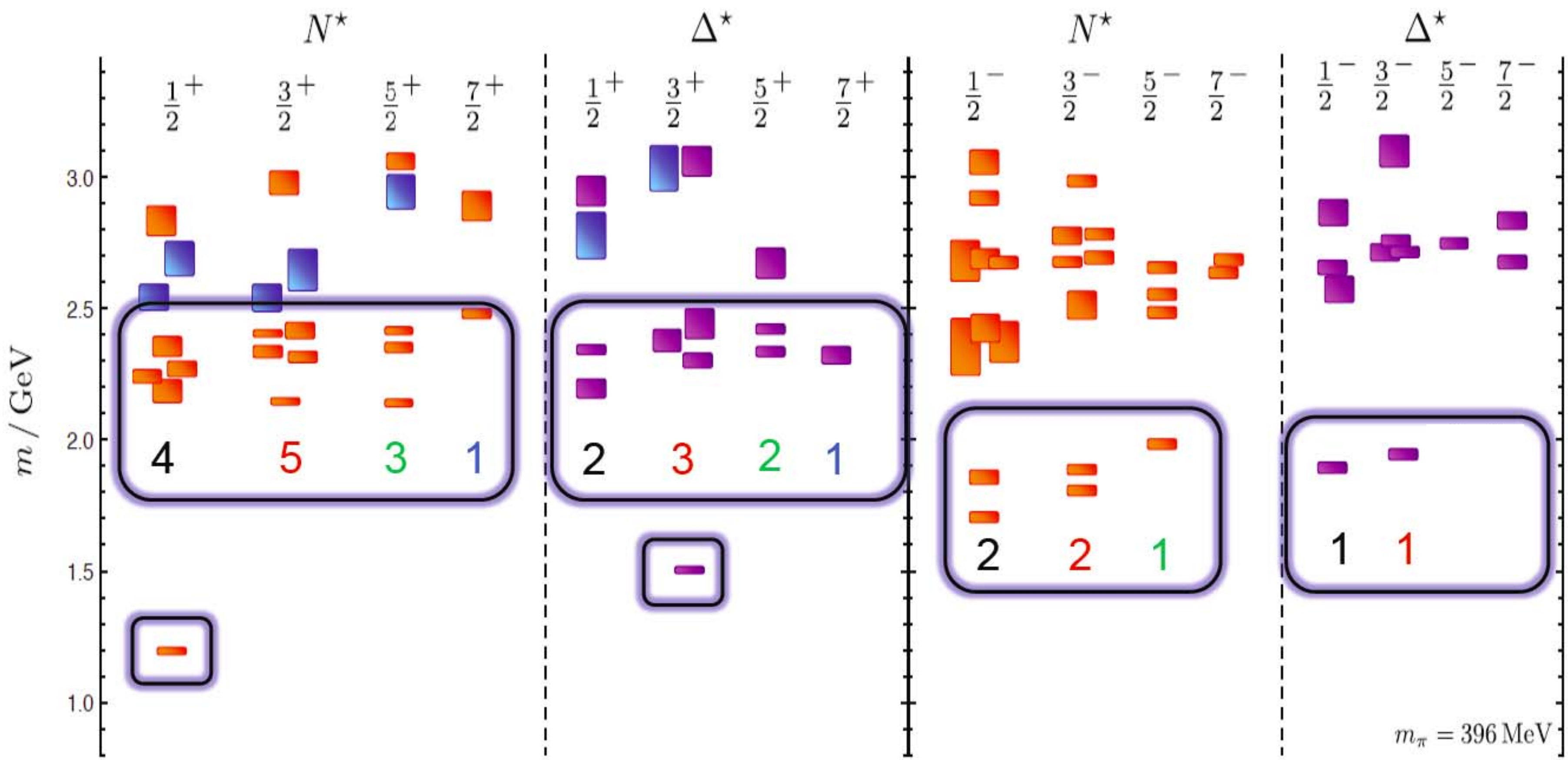


- FROST experiment produced 900 data points of the **double-polarization observable E** in π^+ photoproduction with circularly polarized beam on longitudinally polarized protons for W = 1240 - 2260 MeV.
- Significant improvements of the description of the data in SAID, Jülich, and BnGa partial-wave analyses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

S. Strauch *et al.*, arXiv:1503.05163 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

N* Spectrum in LQCD

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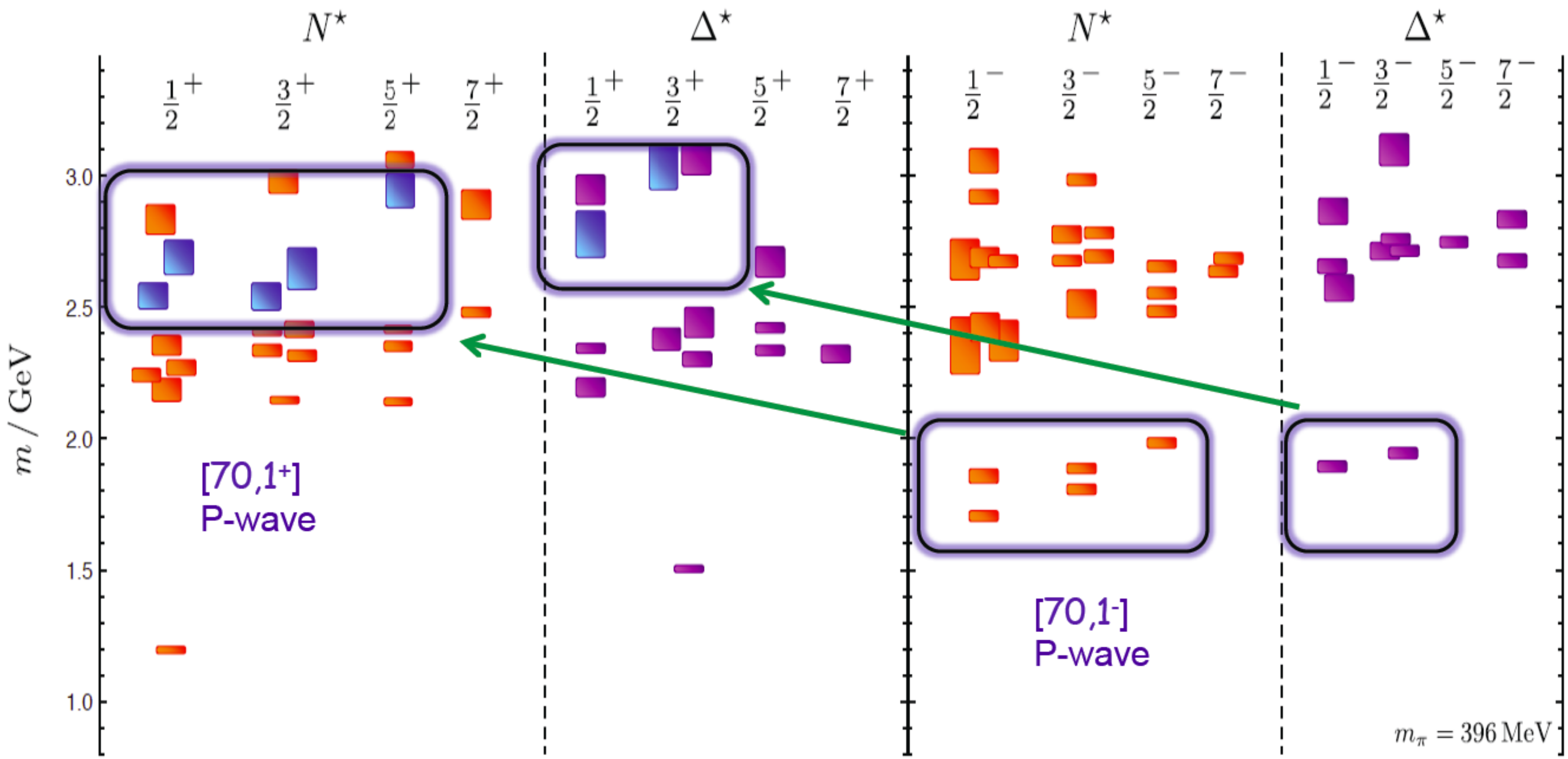
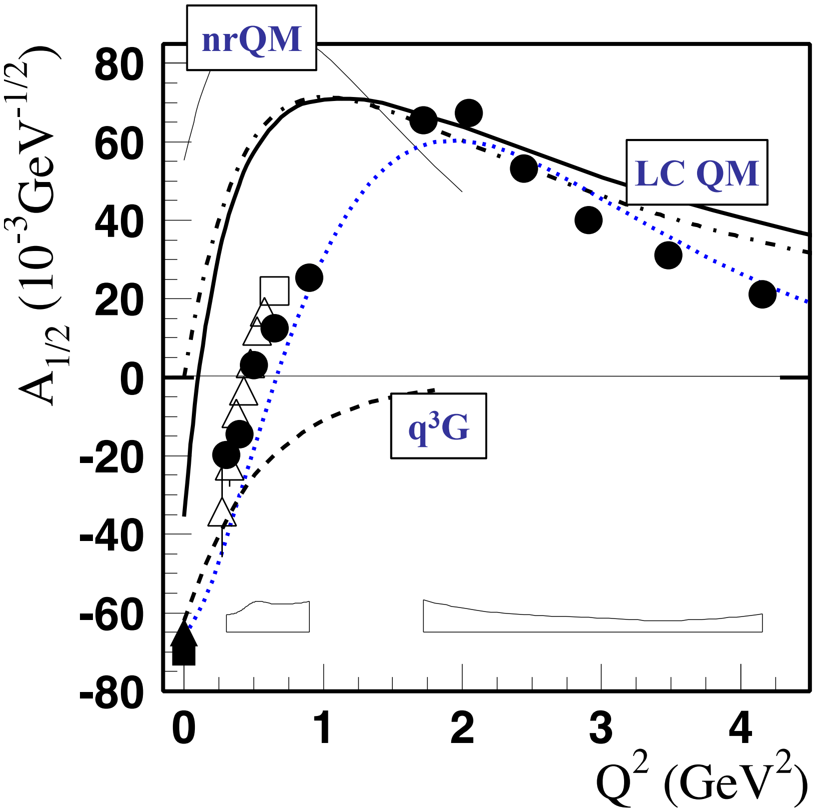


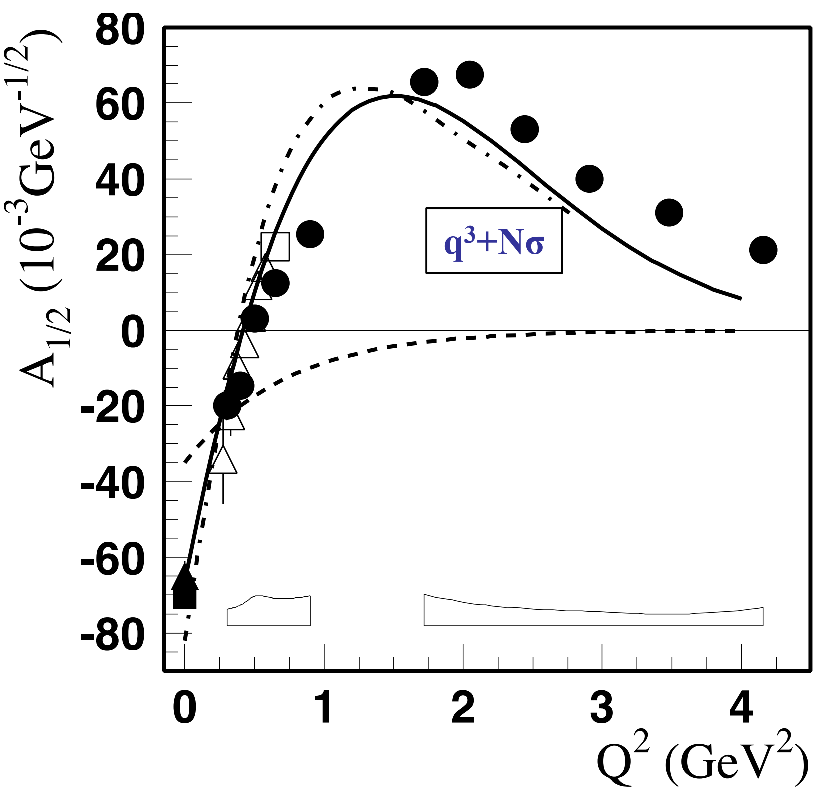
LQCD predicts hybrid baryon states replicating the negative parity multiplet structure.

Transition Form Factors and QCD Models

Roper resonance $P_{11}(1440)$



PDG 2013 update

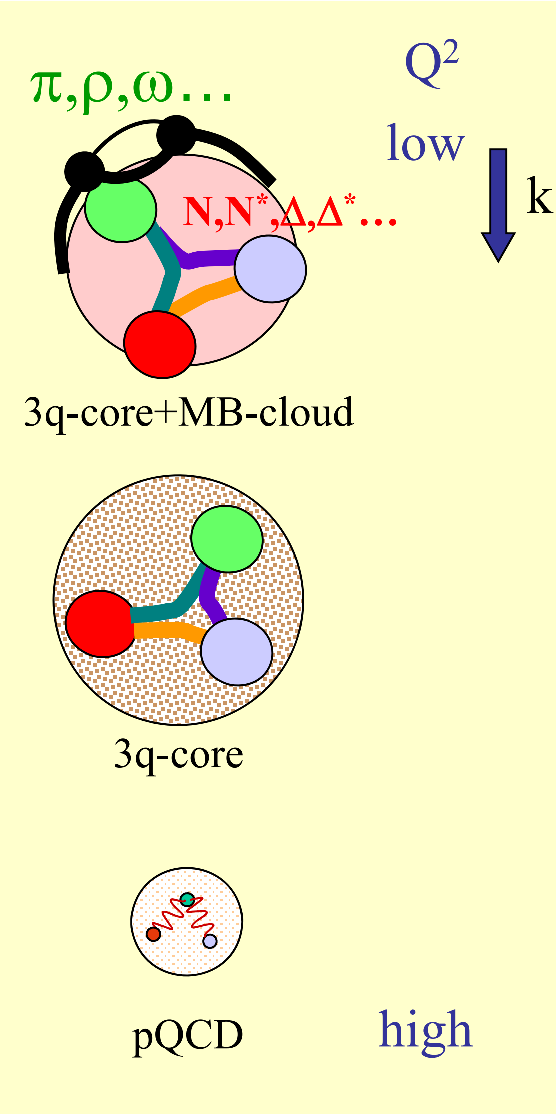


- $A_{1/2}$ has zero-crossing near Q^2=0.5 and becomes dominant amplitude at high Q^2.
- Consistent with radial excitation at high Q^2 and large meson-baryon coupling at small Q^2.
- Eliminates gluonic excitation (q^3G) as a dominant contribution.

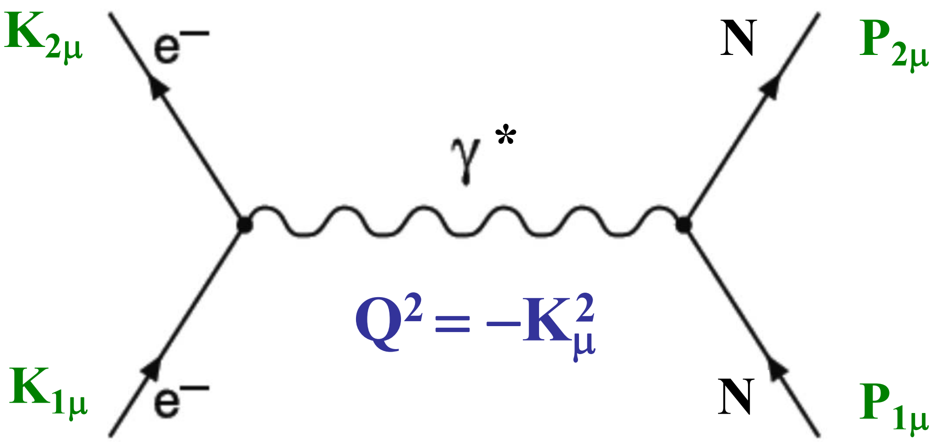
New Letter of Intend on electro-excited gluon hybrids is in preparation.

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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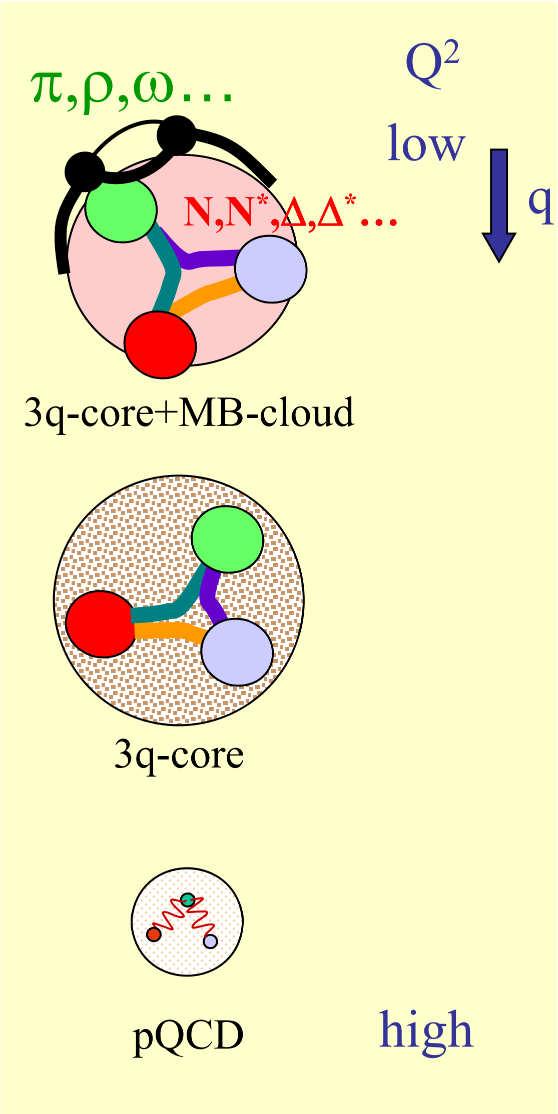
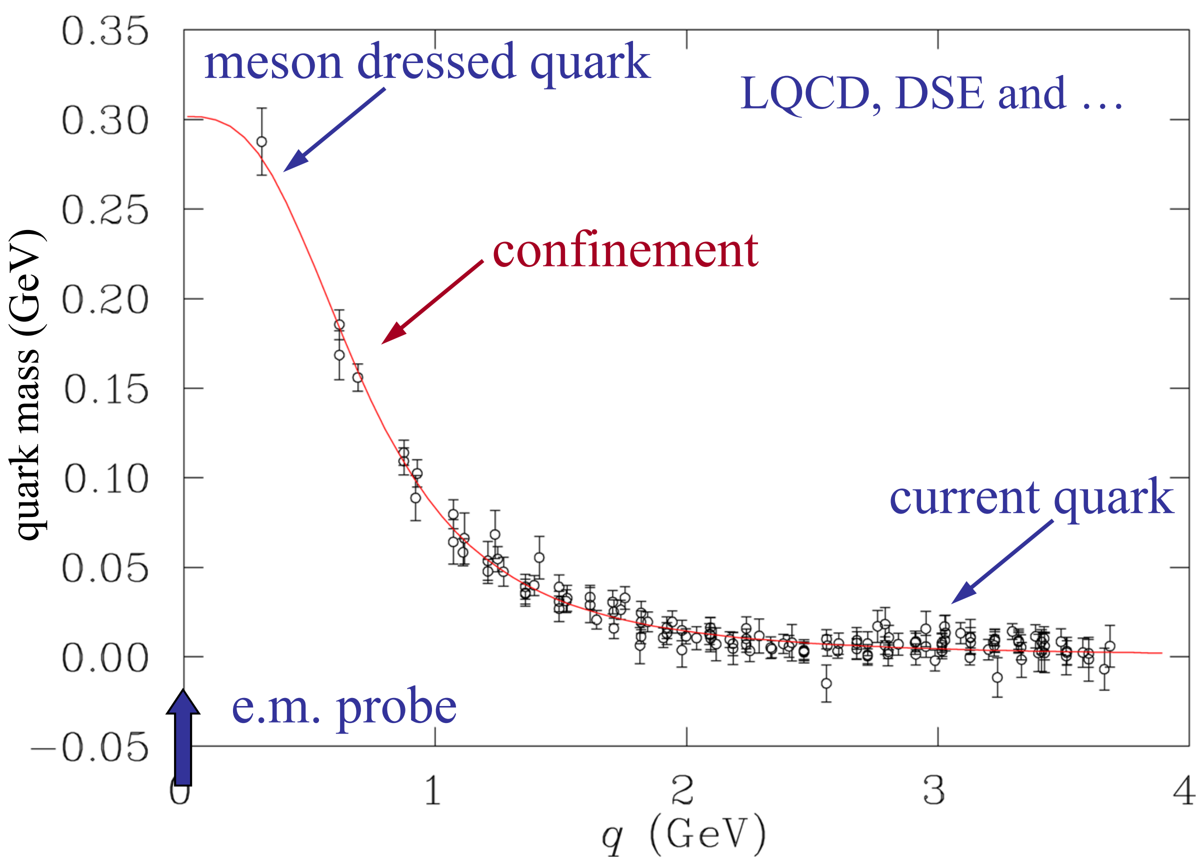
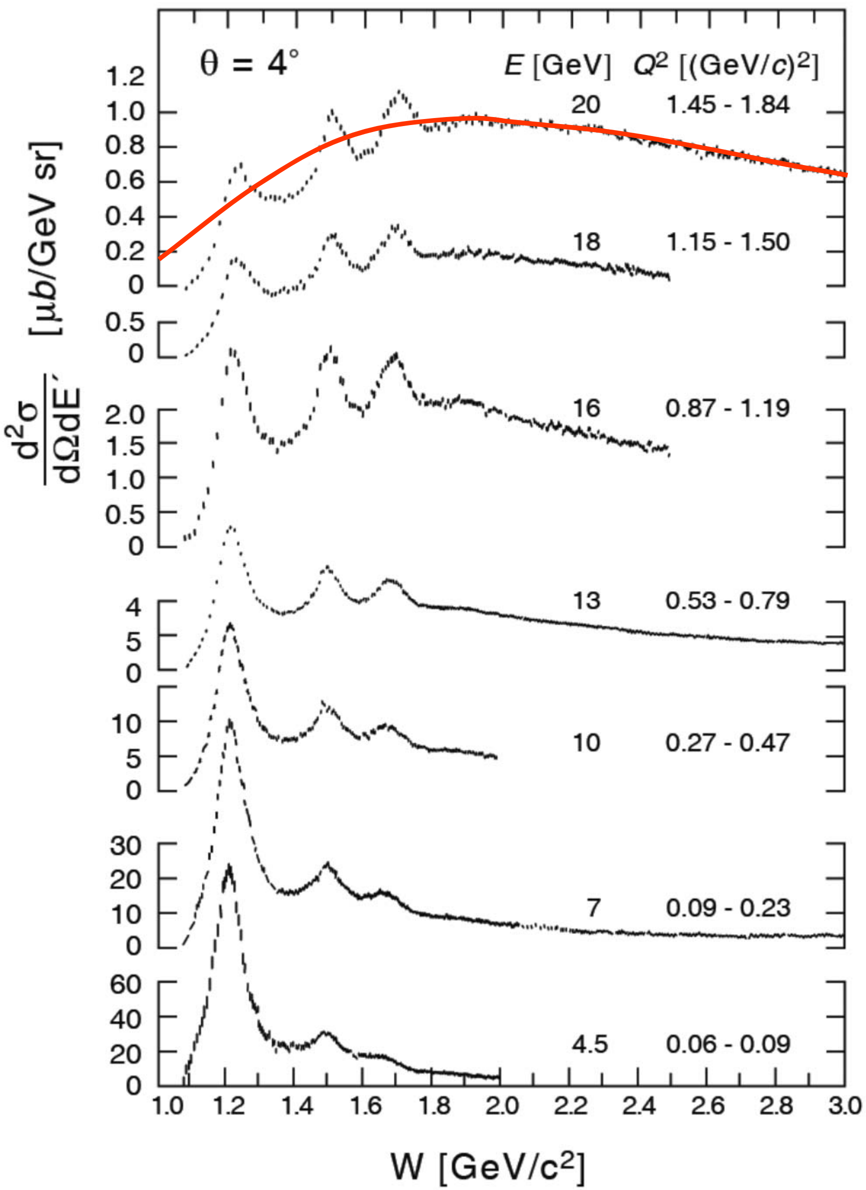
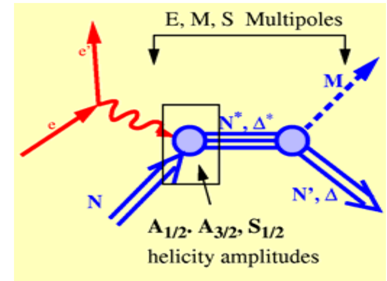


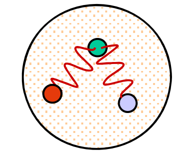


Baryon Excitations and Quasi-Elastic Scattering



hard and confined



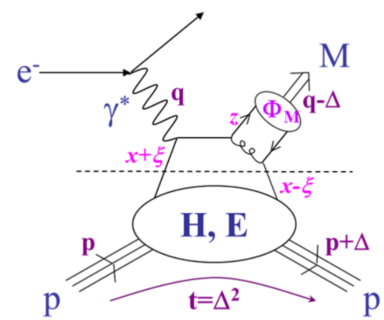


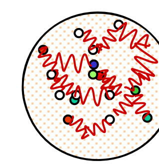
Elastic Form Factors

Transition Form Factors

hard

soft





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

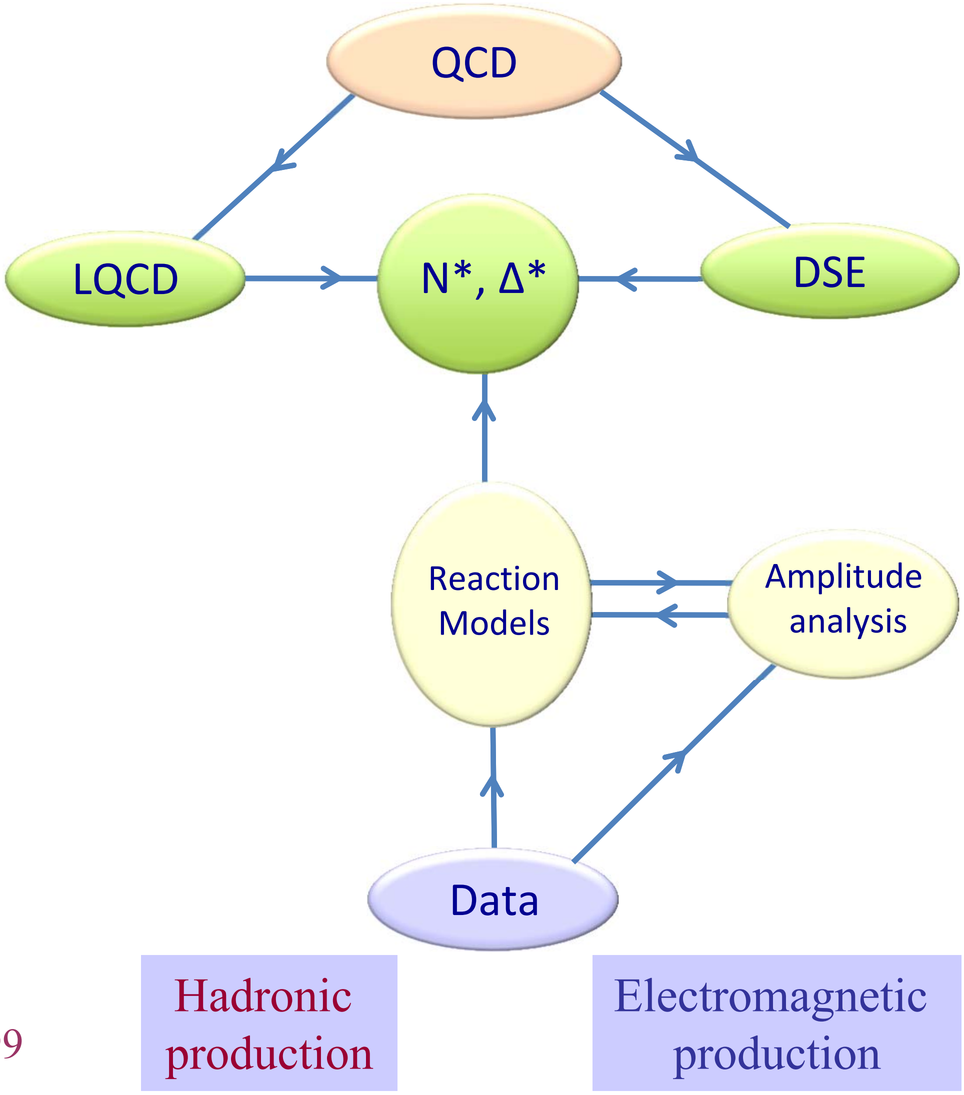
Data-Driven Data Analyses

Consistent Results

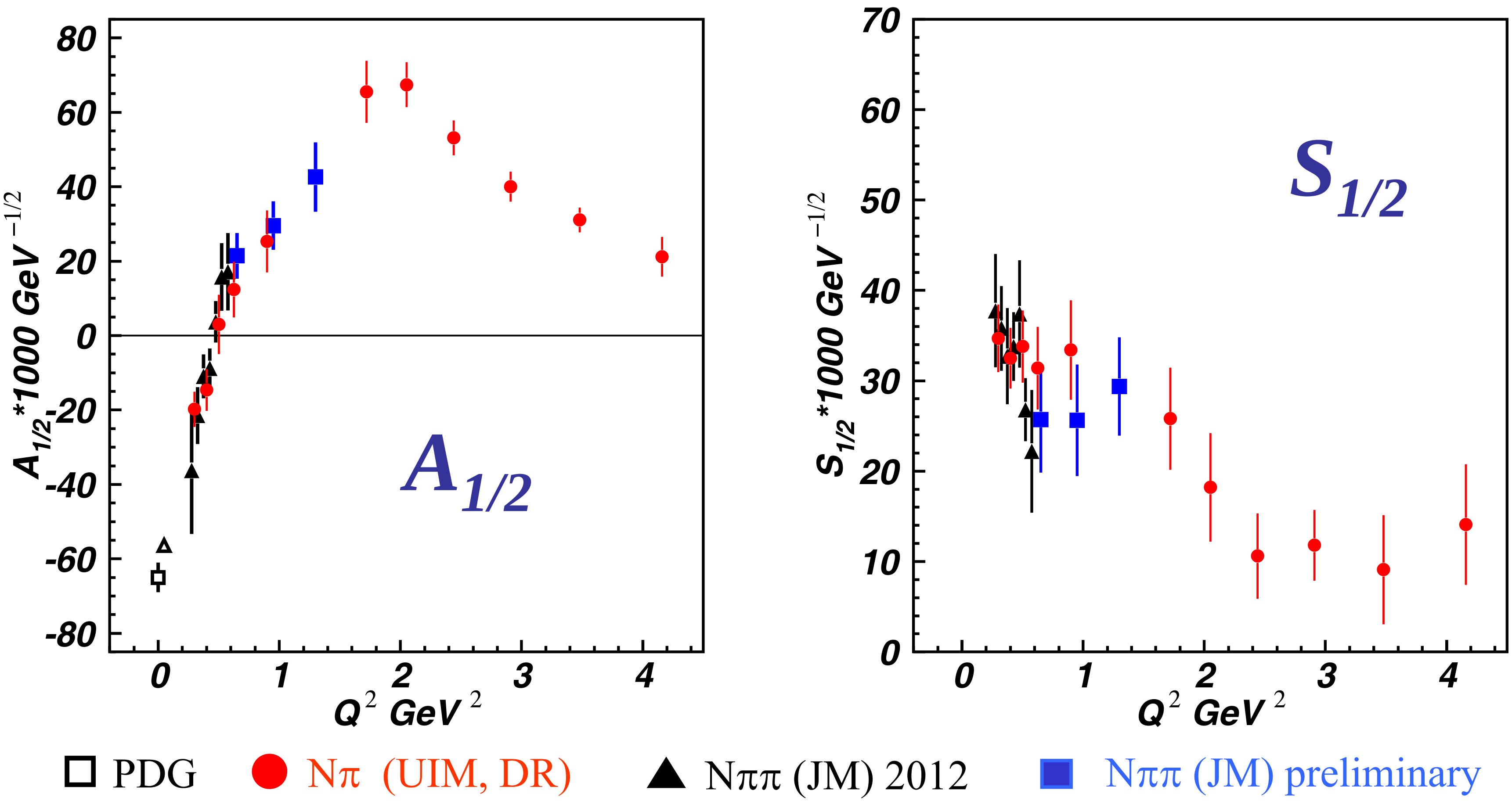
⬆

- **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

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



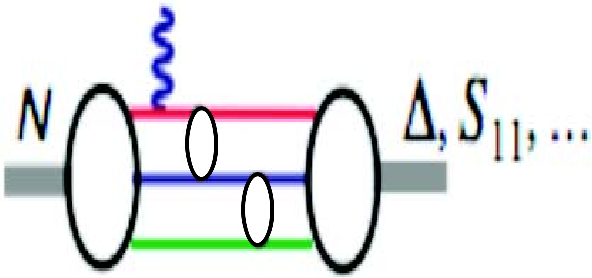
Electrocouplings of N(1440)P_{11} from CLAS Data



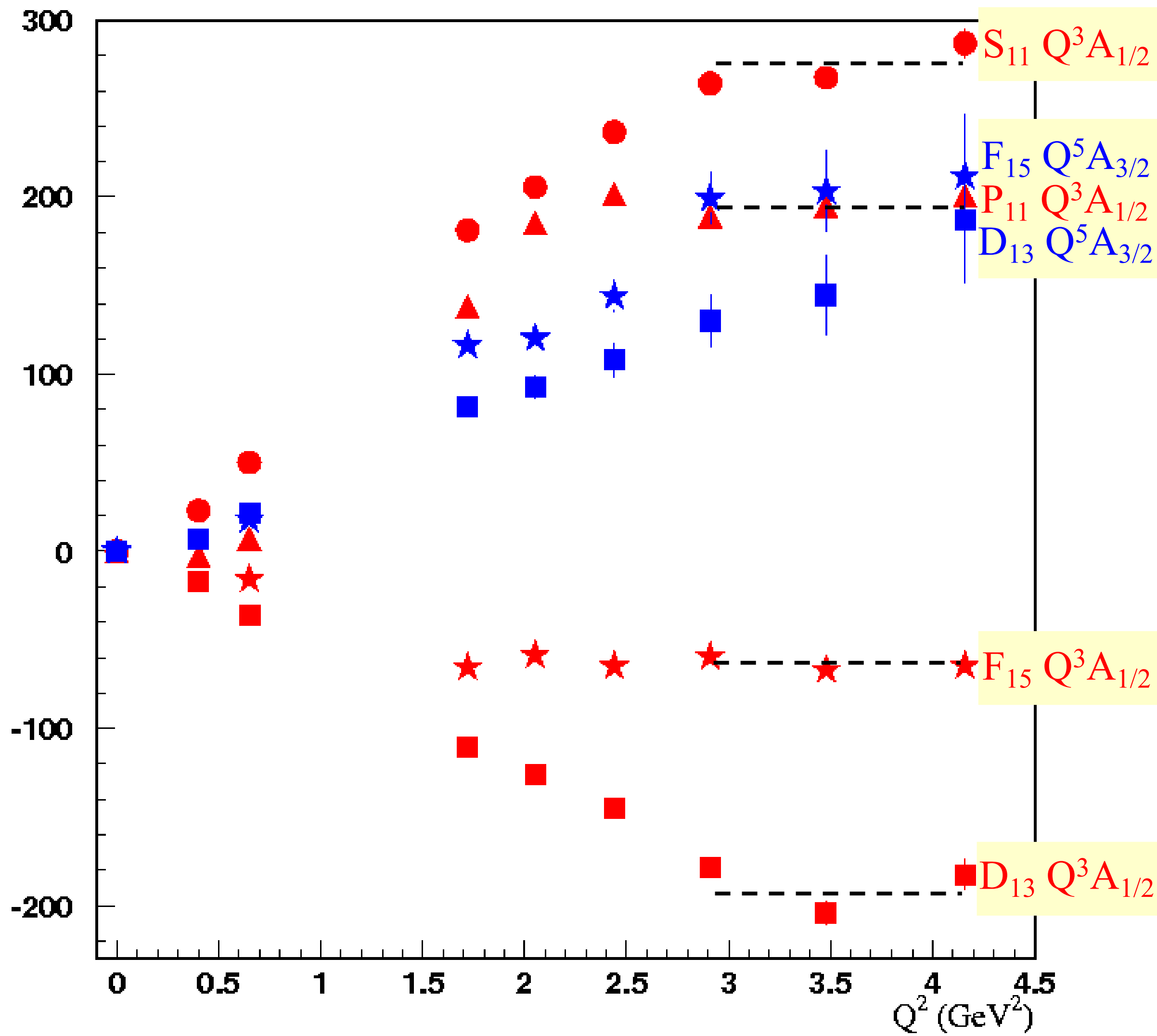
Consistent results obtained in the low-lying resonance region by independent analyses in the exclusive Nπ and $p\pi^+\pi^-$ final-state channels – that have fundamentally different mechanisms for the nonresonant background – underscore the capability of the reaction models to extract reliable resonance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

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

Evidence for the Onset of Scaling?



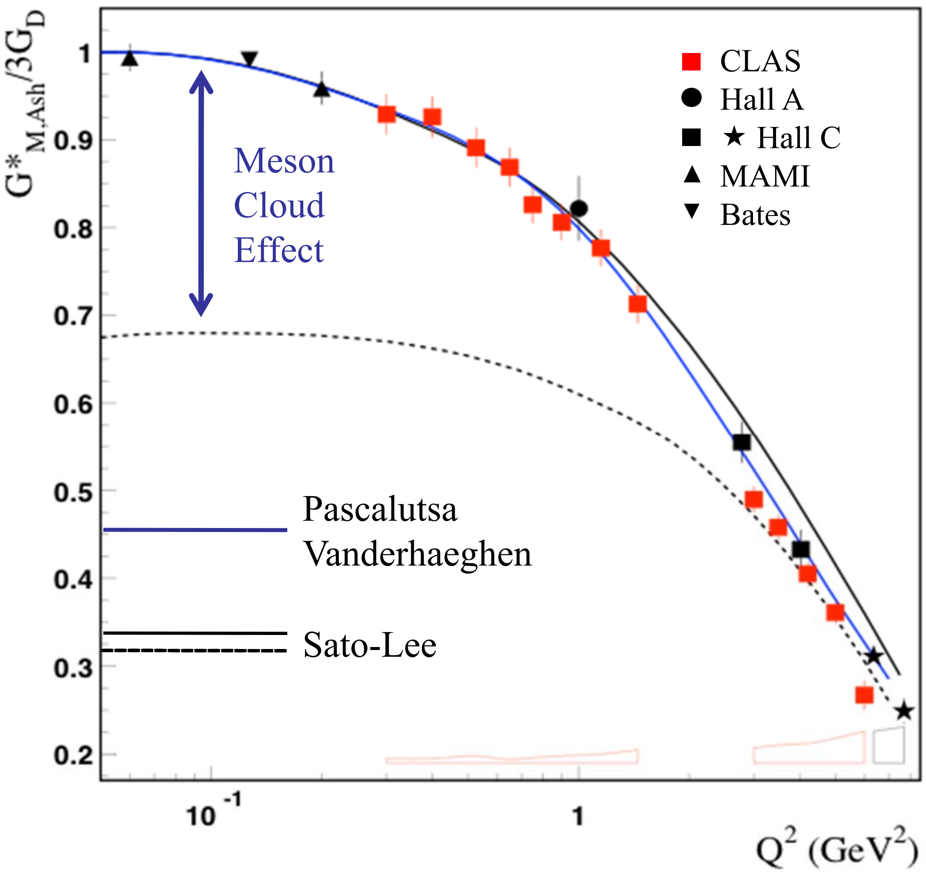
Phys. Rev. C80, 055203 (2009)



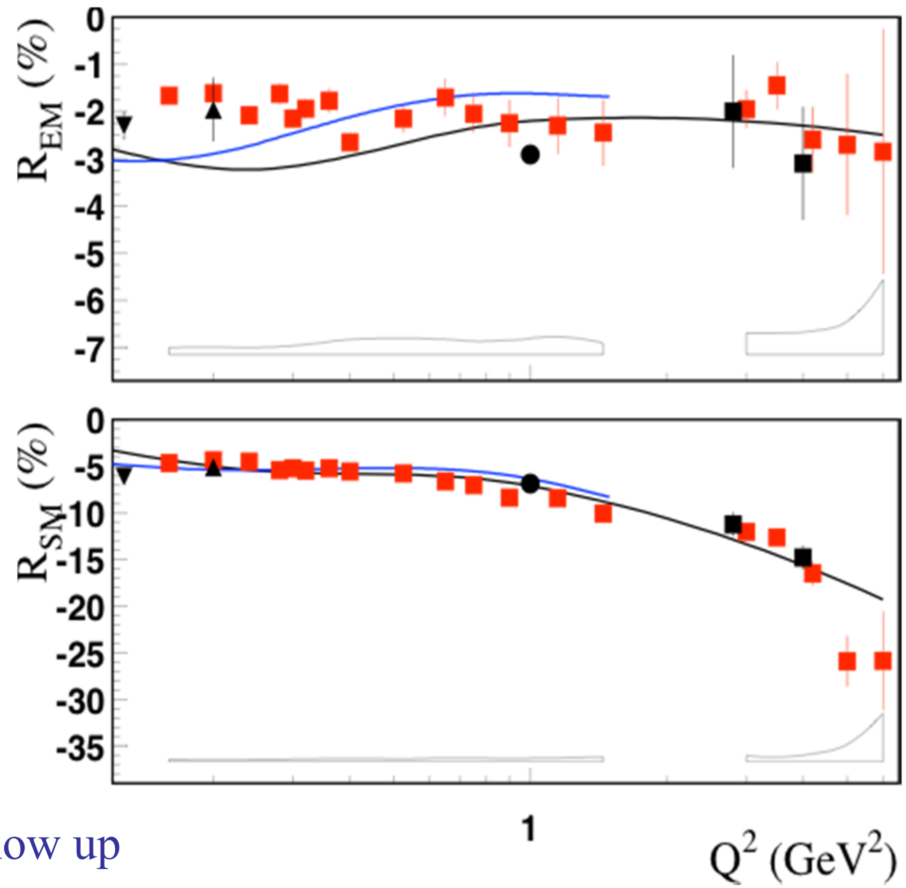
- $A_{1/2}$ α $1/Q^3$
- $A_{3/2}$ α $1/Q^5$
- G^*_M α $1/Q^4$

q^2q

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

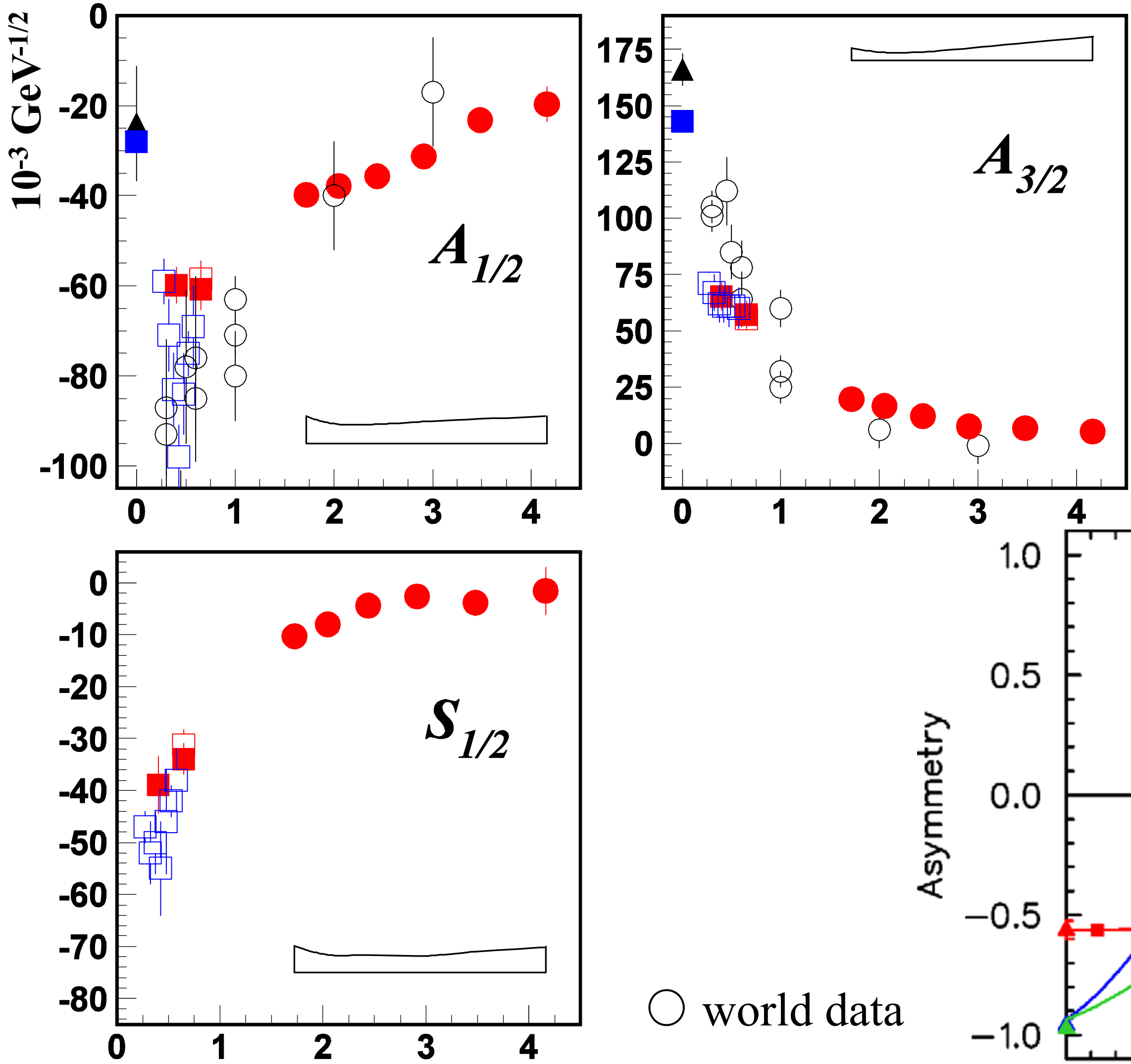


Phys. Rev. Lett. 97, 112003 (2006)



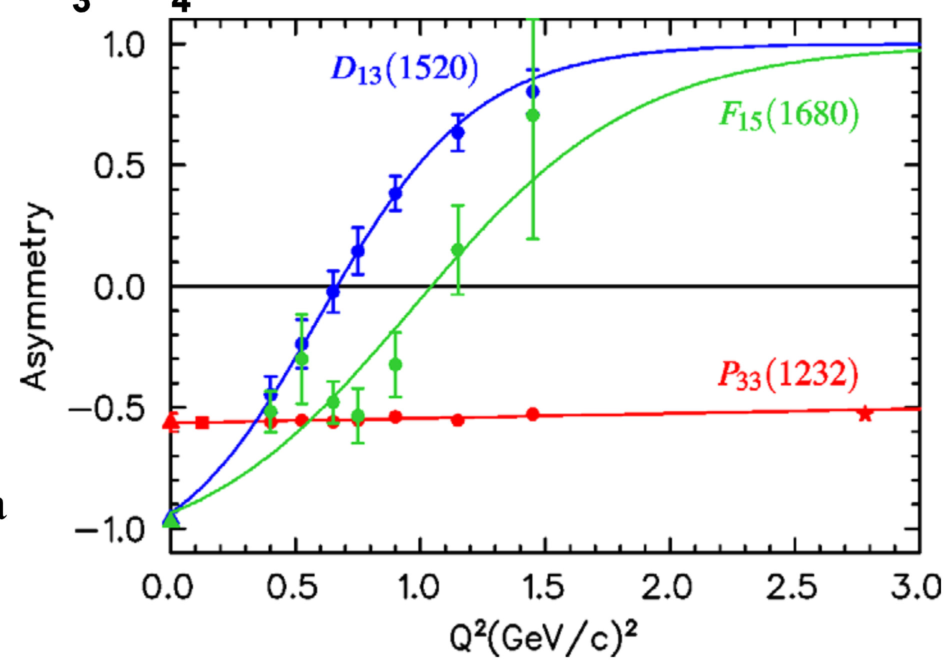
- New trend towards pQCD behavior does not show up
  - $R_{EM} \rightarrow +1$ $R_{SM} \rightarrow$ const
  - $G^*_{M,J.-S.} \rightarrow 1/Q^4$ $G^*_{M,Ash} \rightarrow 1/Q^5$
- CLAS12 can measure G^*_M, R_{EM}, and R_{SM} up to Q^2~12 GeV^2

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



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

L. Tiator



○ world data

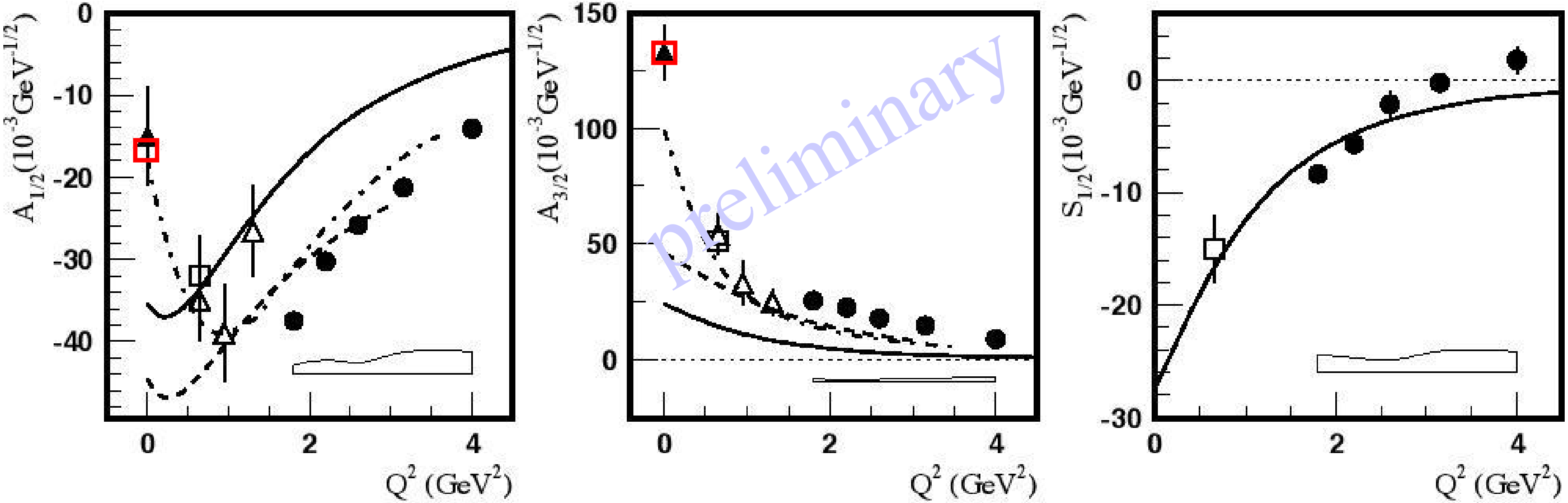
▲ PDG estimation ● ■ Nπ (UIM, DR)

New Experimental Results & Approaches

High-Lying Resonance Electrocouplings

$N(1680)F_{15}$

Kijun Park



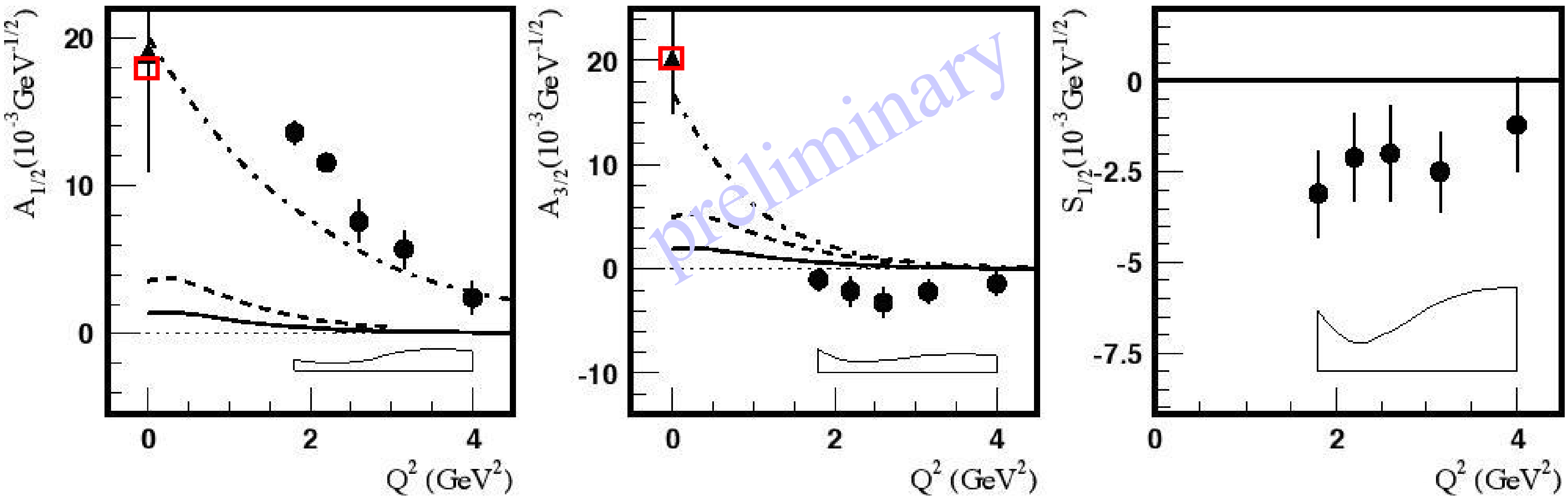
- ▲ RPP (PDG) Phys. Rev. D 86 (2012)
- □ (red) M. Dugger Phys. Rev. C 76 (2007)
- □ I.G. Aznauryan, Phys. Rev. C 72 (2005)
- △ Nππ: V. Mokeev (JM)
- ● Nπ: I.G. Aznauryan (UIM & DR)

- - - - D. Merten, U. Löring et al.
- · - · Z. Lee and F. Close
- —— E. Santopinto and M.M. Gianini

High-Lying Resonance Electrocouplings

N(1675)D_{15}

Kijun Park



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□ M. Dugger Phys. Rev. C 76 (2007)

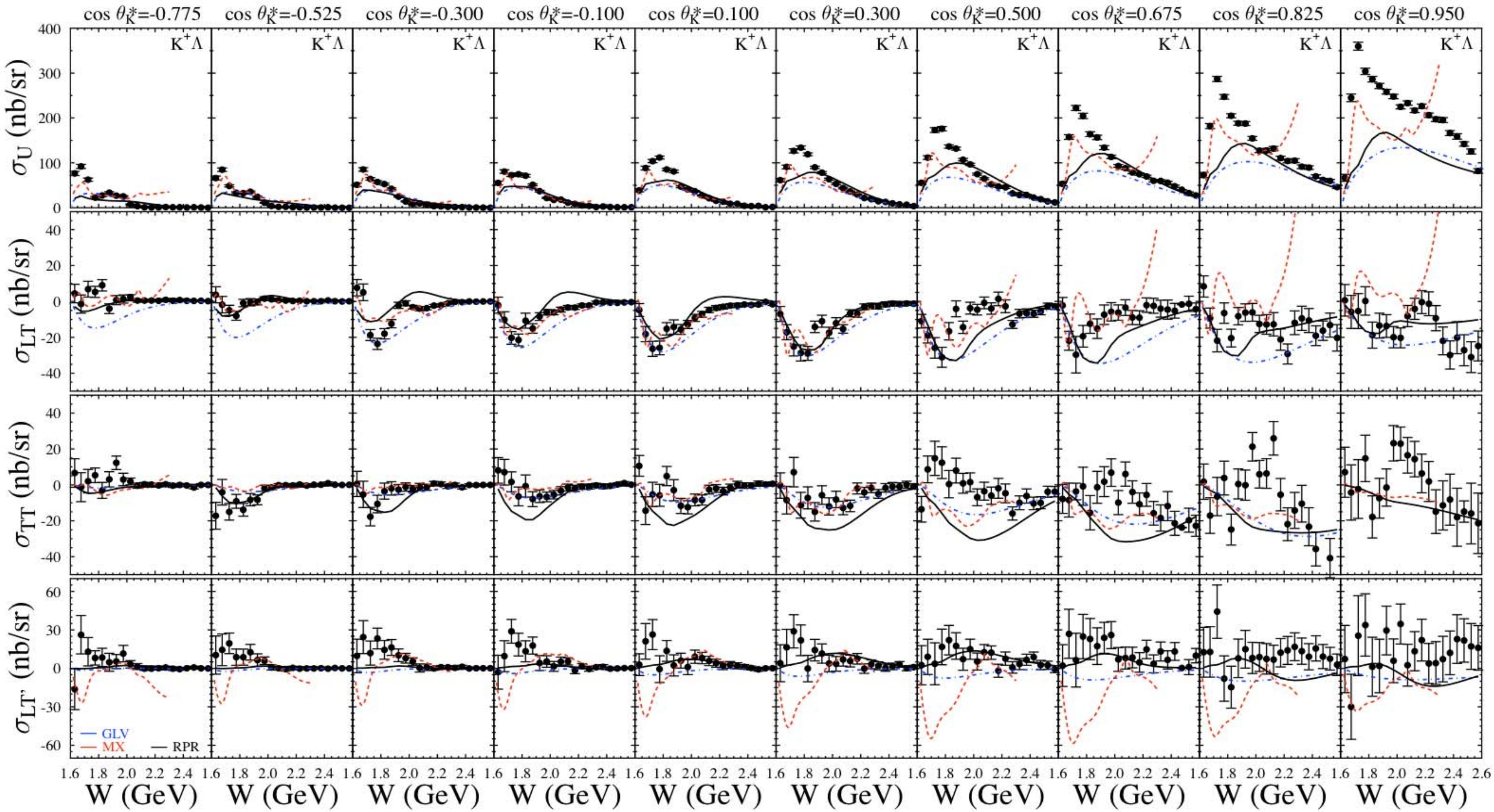
● Nπ: I.G. Aznauryan (UIM & DR)

- - - - D. Merten, U. Löring et al.

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

—— E. Santopinto and M.M. Gianini

$K^+\Lambda$ Structure Functions

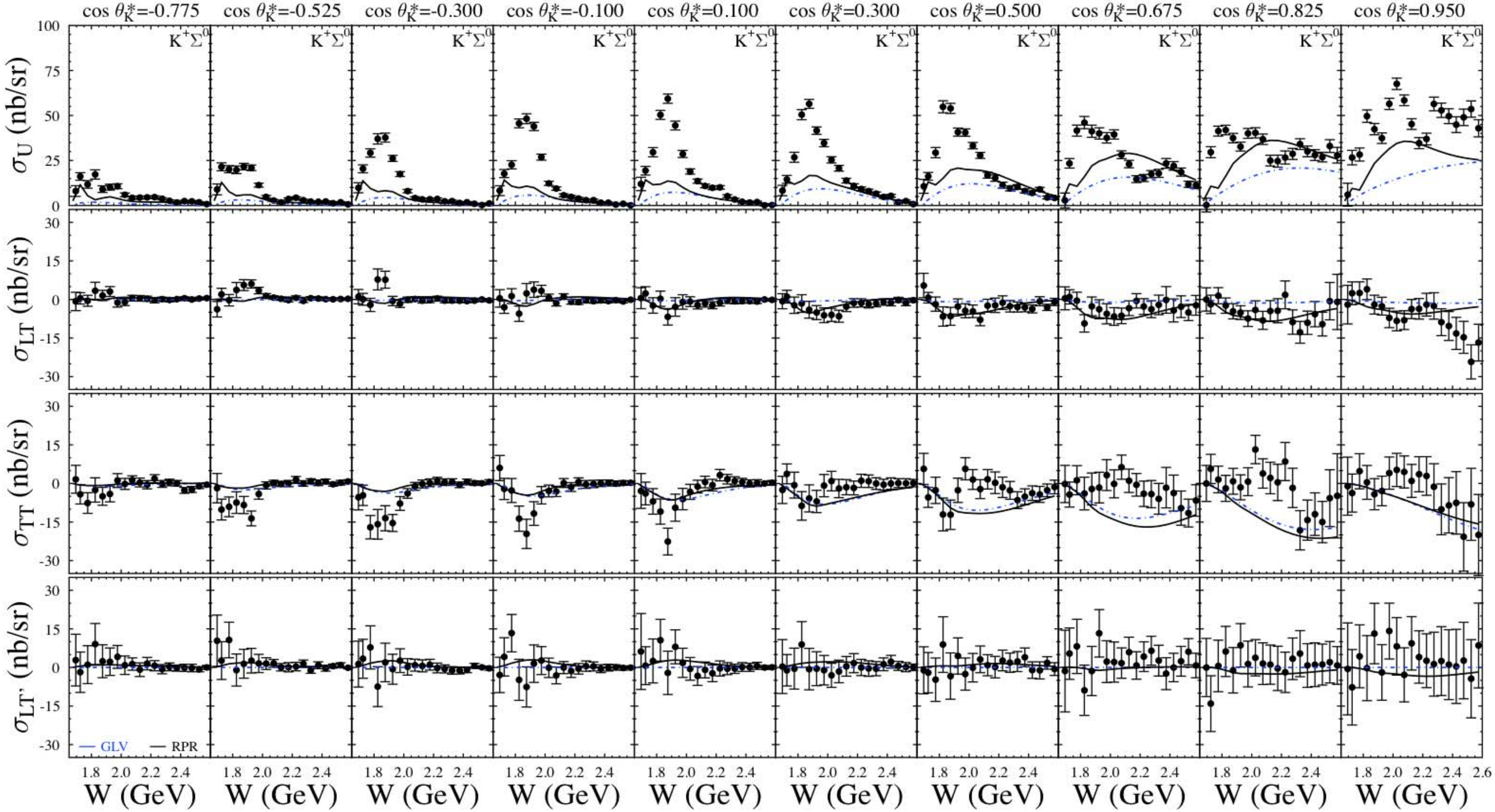


[Carman et al., PRC 87, 025204 (2013)]

E = 5.499 GeV, W: thr – 2.6 GeV, Q^2 *= 1.80, 2.60, 3.45 GeV*^{2}

CLAS12 experiment E12-06-108A

$K^+\Sigma^0$ Structure Functions



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

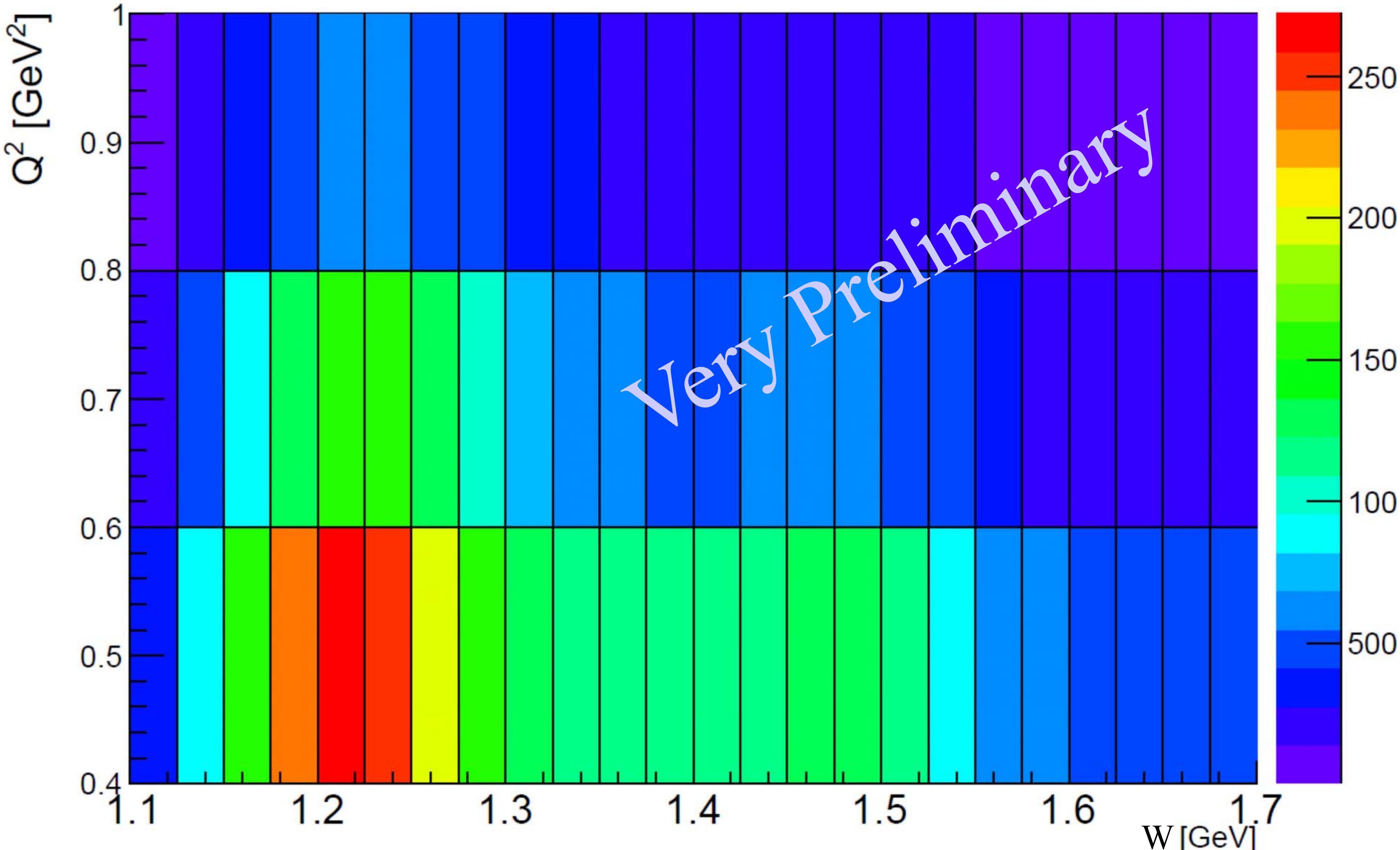
E = 5.499 GeV, W: thr – 2.6 GeV, Q^2 = 1.80, 2.60, 3.45 GeV^2

CLAS12 experiment E12-06-108A

Single π ⁻ Electroproduction off the Deuteron

$\gamma d \rightarrow \pi^- p(p)$

Ye Tian



$\Delta Q^2 = 0.2\ GeV^2$ $\Delta W = 25\ MeV$

Single π^- Electroproduction off the Deuteron

Ye Tian

W = 1125 MeV

ΔW = 25 MeV

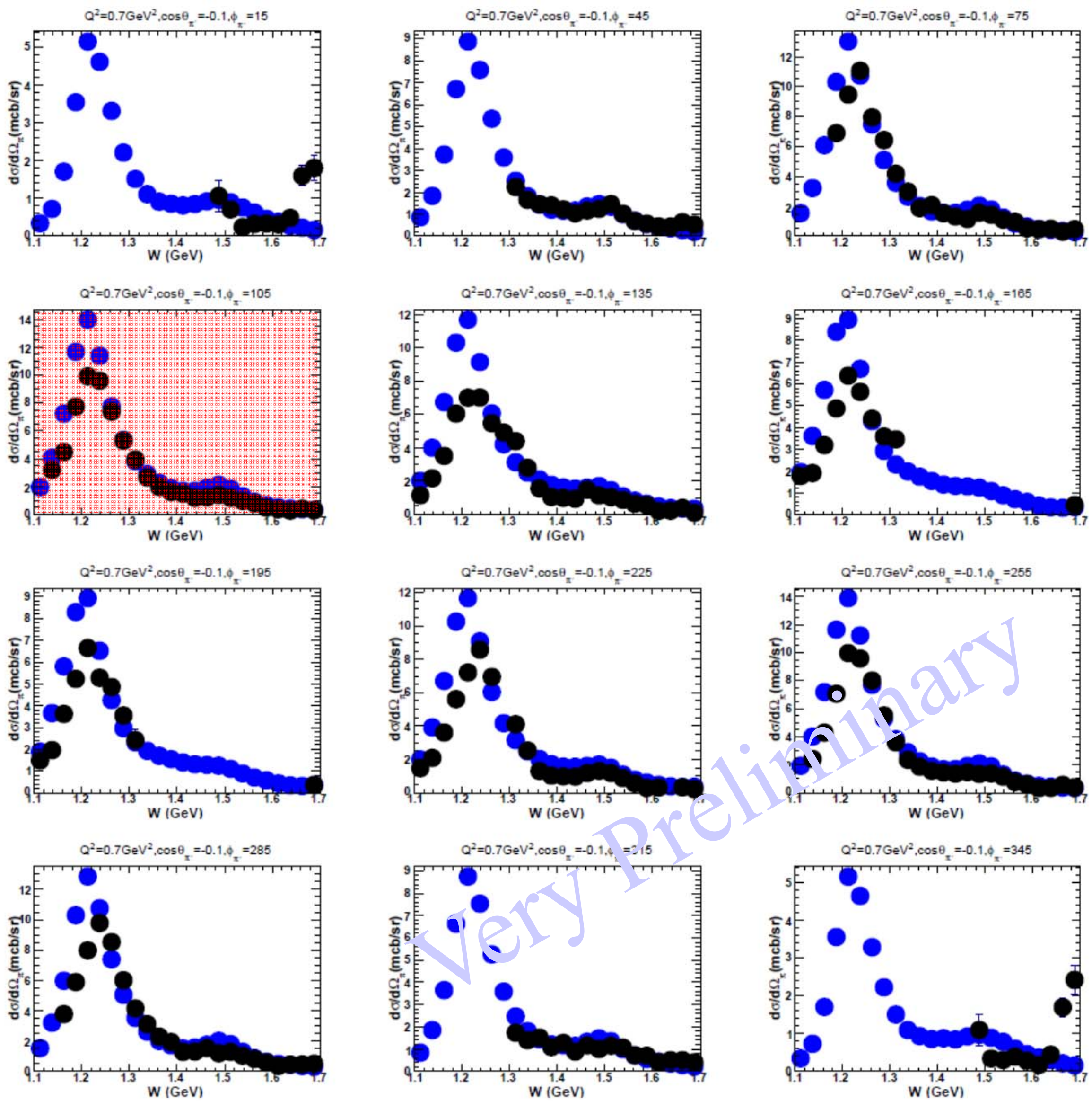
W = 1685 MeV

$Q^2 = 0.7\ GeV^2$

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

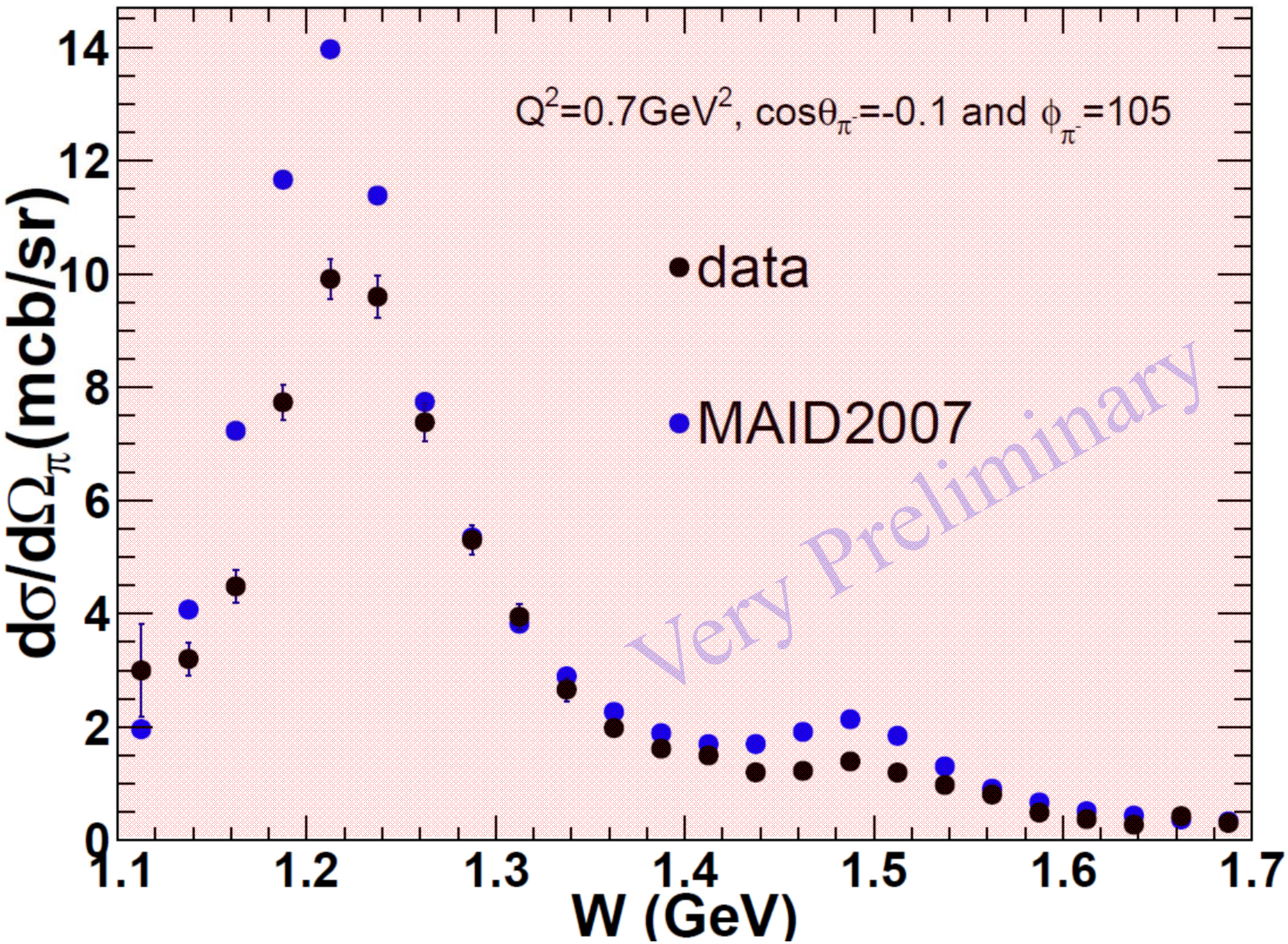
cos(θ) = -0.1
Δcos(θ) = 0.2

$\phi = 15^o$
$\Delta\phi = 30^o$
$\phi = 345^o$



Single π⁻ Electroproduction off the Deuteron

Ye Tian



Single π⁻ Electroproduction off the Deuteron

Ye Tian

W = 1212 MeV

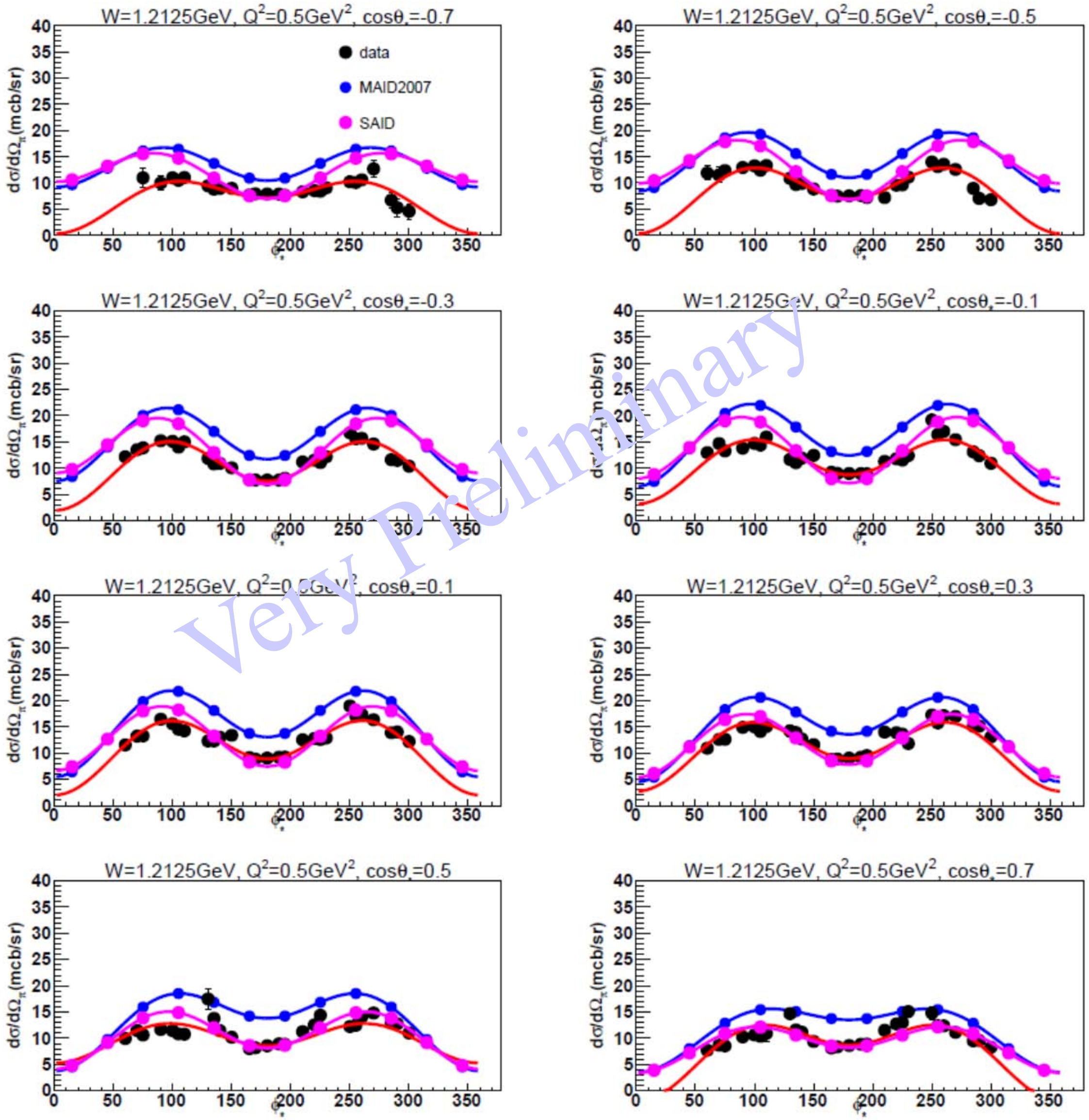
ΔW = 25 MeV

Q^2 = 0.5 GeV^2

ΔQ^2 = 0.2 GeV^2

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

ϕ = 15°
Δϕ = 30°
ϕ = 345°



Single π⁻ Electroproduction off the Deuteron

Ye Tian

W = 1212 MeV

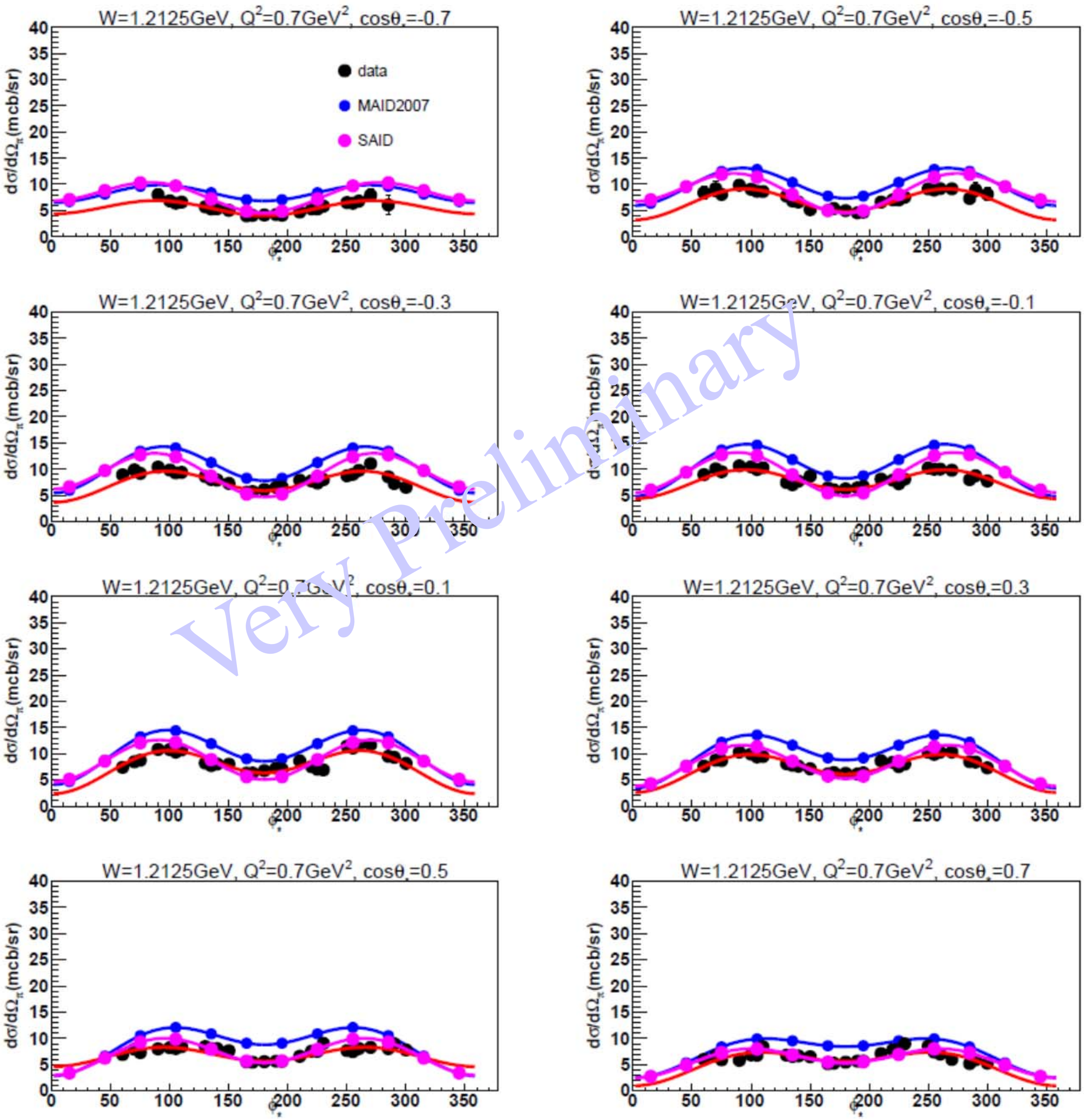
ΔW = 25 MeV

$Q^2 = 0.7$ 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°



Single π⁻ Electroproduction off the Deuteron

Ye Tian

W = 1212 MeV

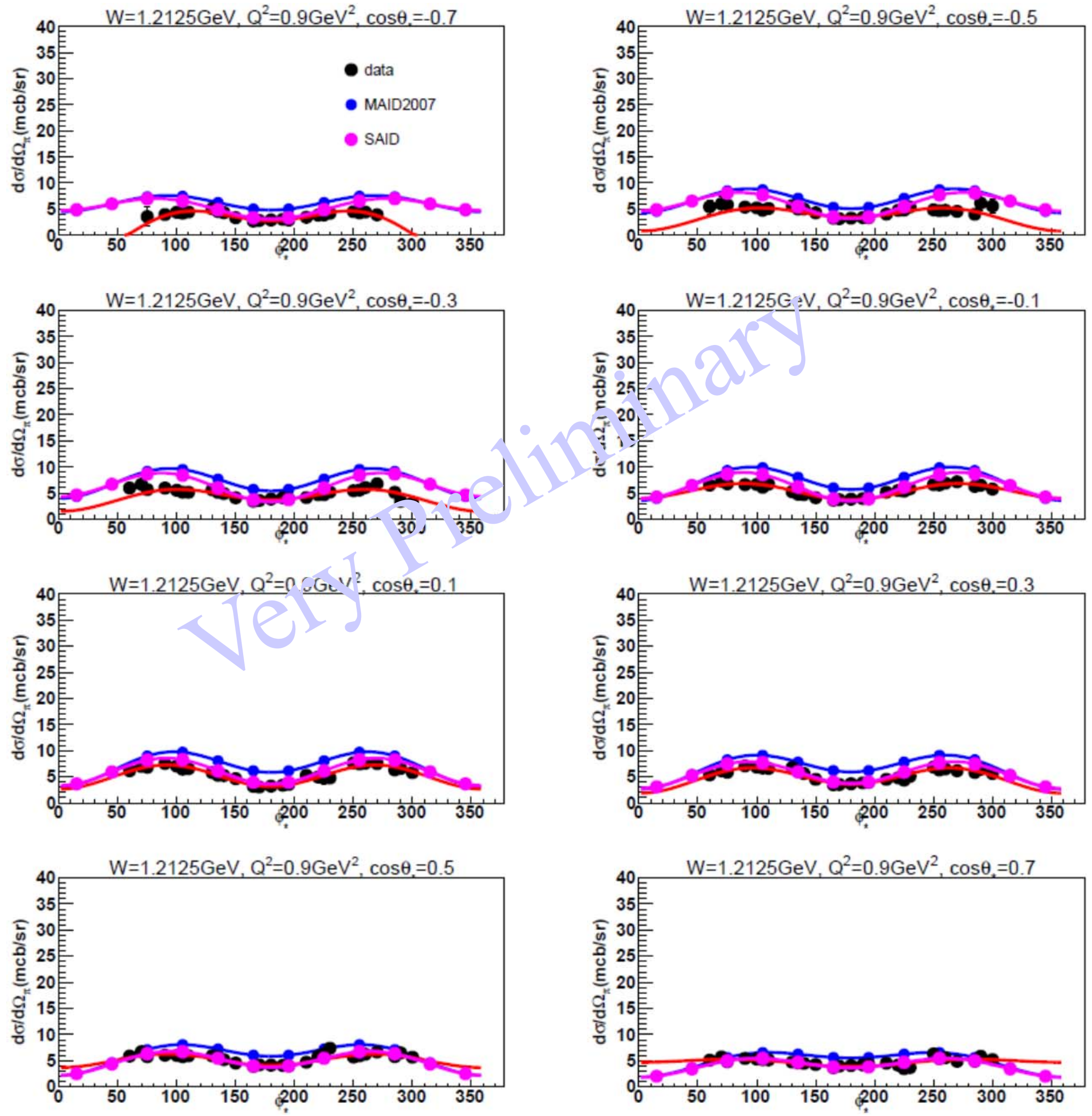
ΔW = 25 MeV

Q^2 = 0.9 GeV^2

ΔQ^2 = 0.2 GeV^2

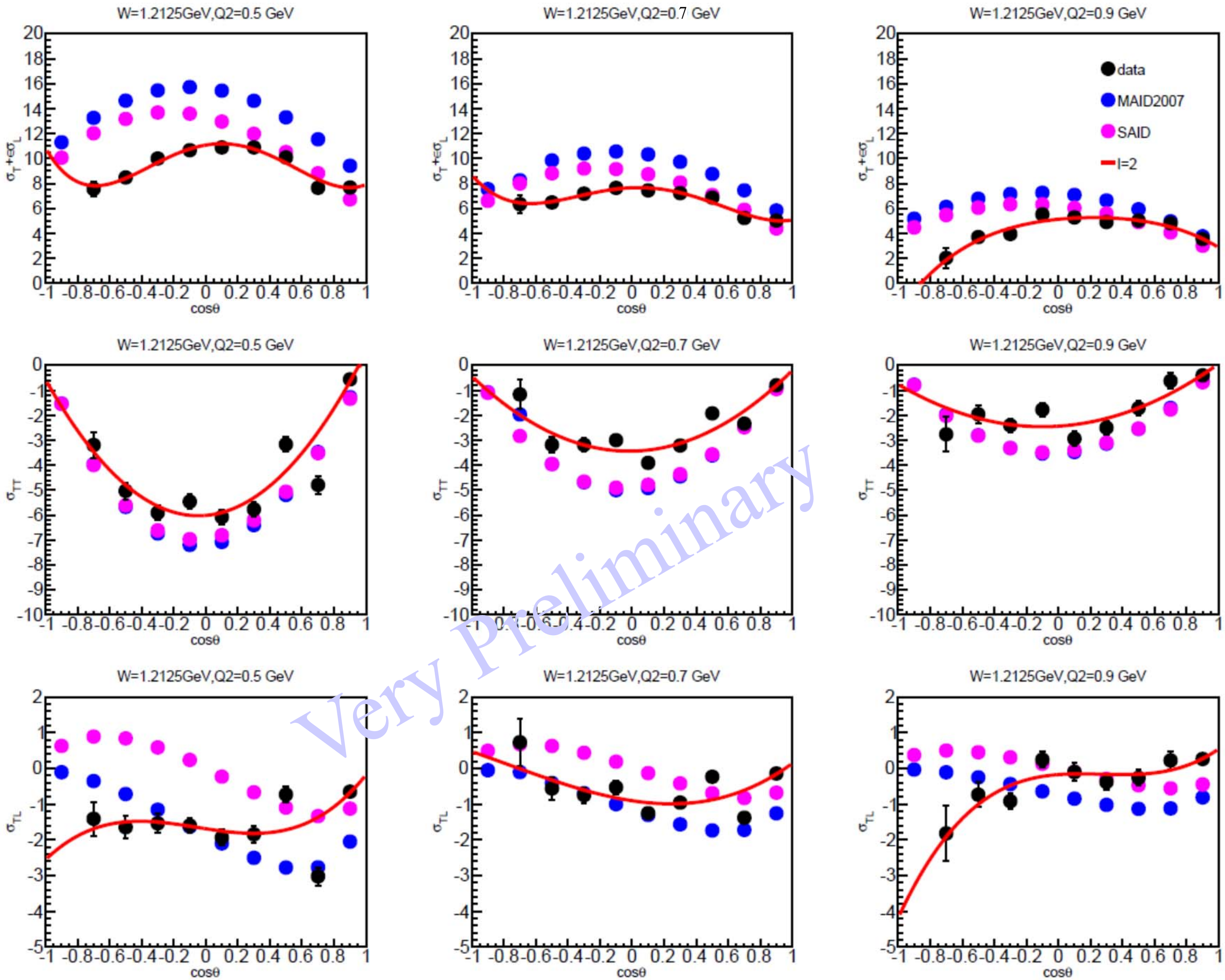
cos(θ) = -0.7
Δcos(θ) = 0.2
cos(θ) = 0.7

ϕ = 15°
Δϕ = 30°
ϕ = 345°



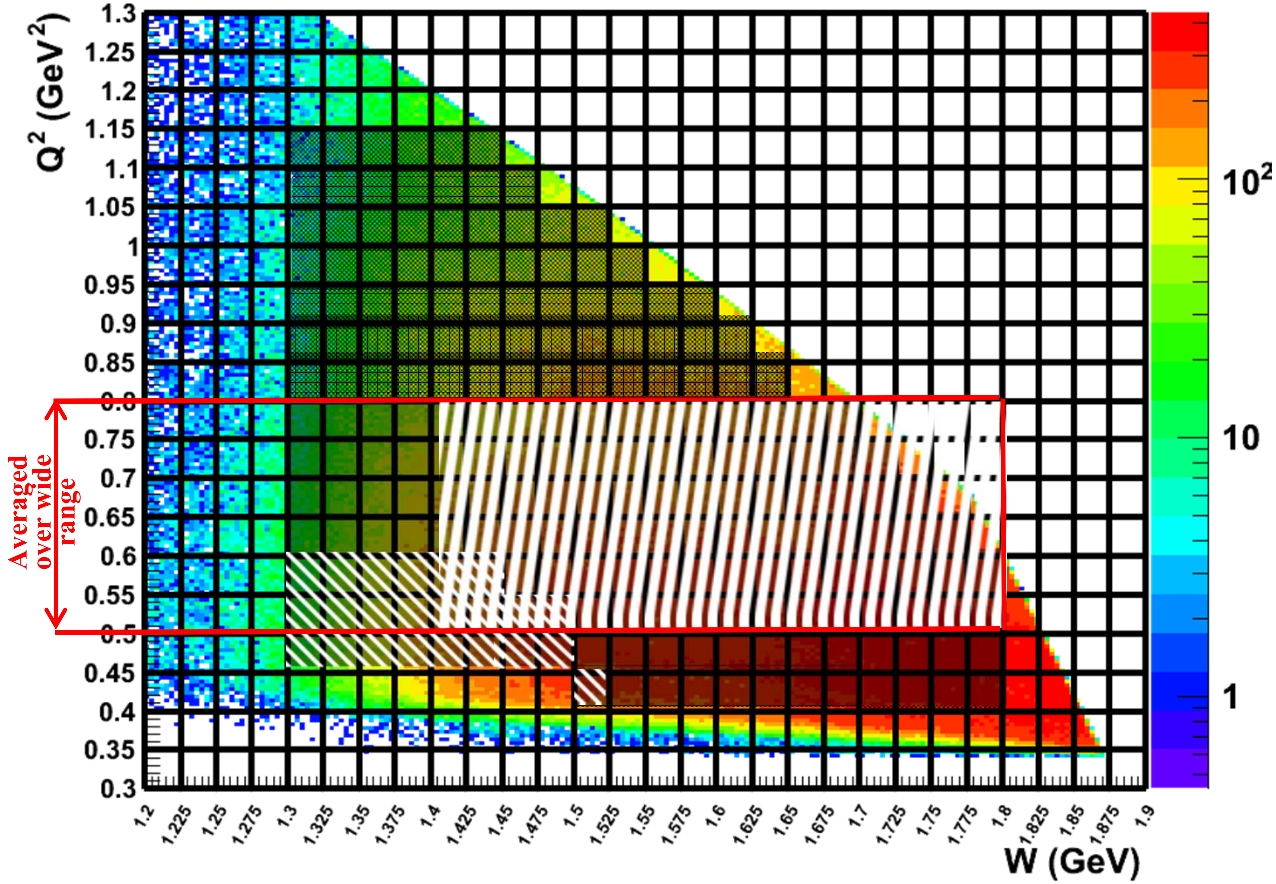
Single π⁻ Electroproduction off the Deuteron

Ye Tian



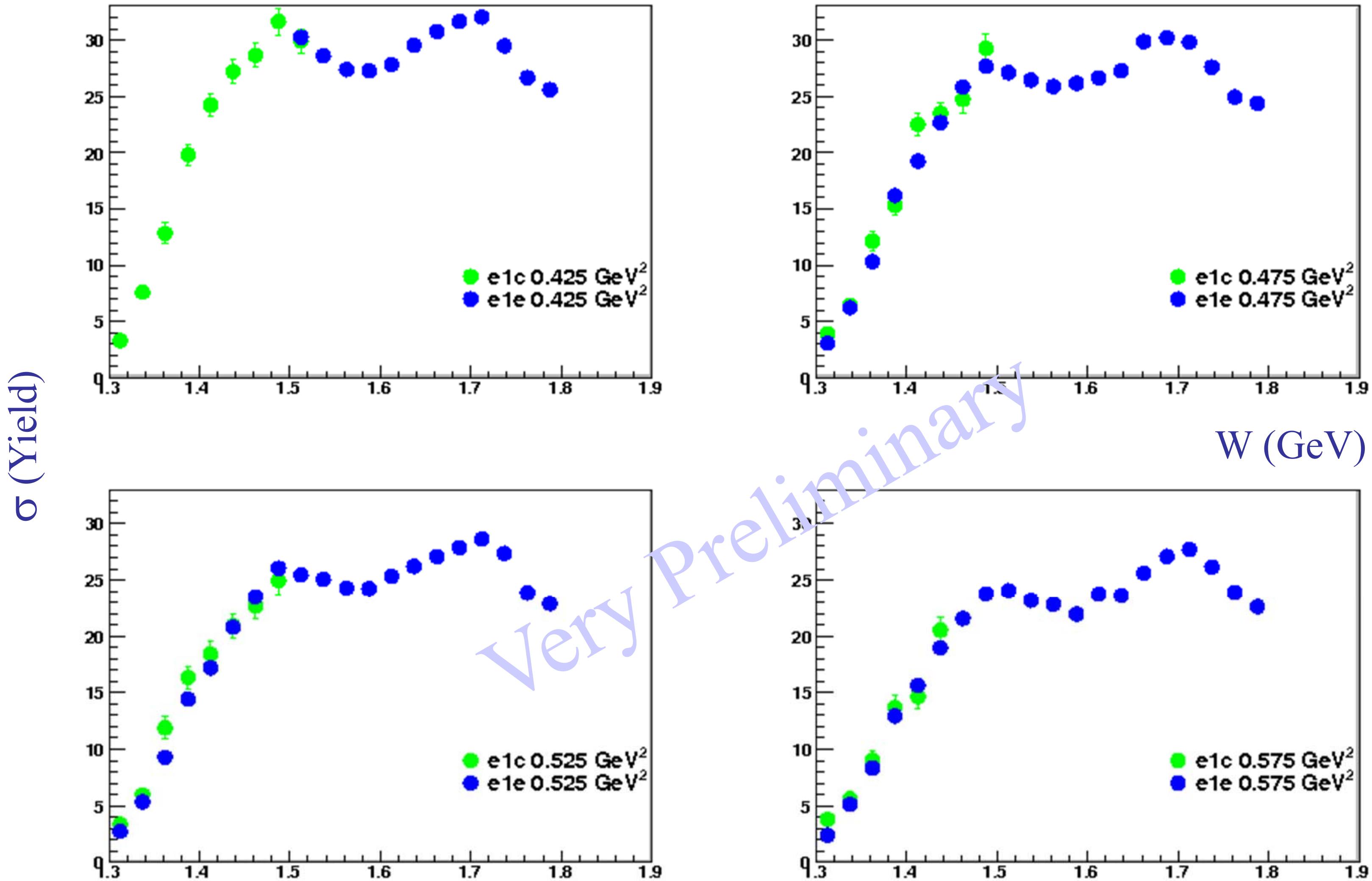
$N\pi^+\pi^-$ Electroproduction Kinematic Coverage

Gleb Fedotov



$p\pi^+\pi^-$ event yields over W and Q^2. Gray shaded area new e1e data set, hatched area at low Q^2 already published e1c data G. by Fedotov *et al.* and hatched area at higher Q^2 already published data in one large Q^2 bin by M. Ripani *et al.*.

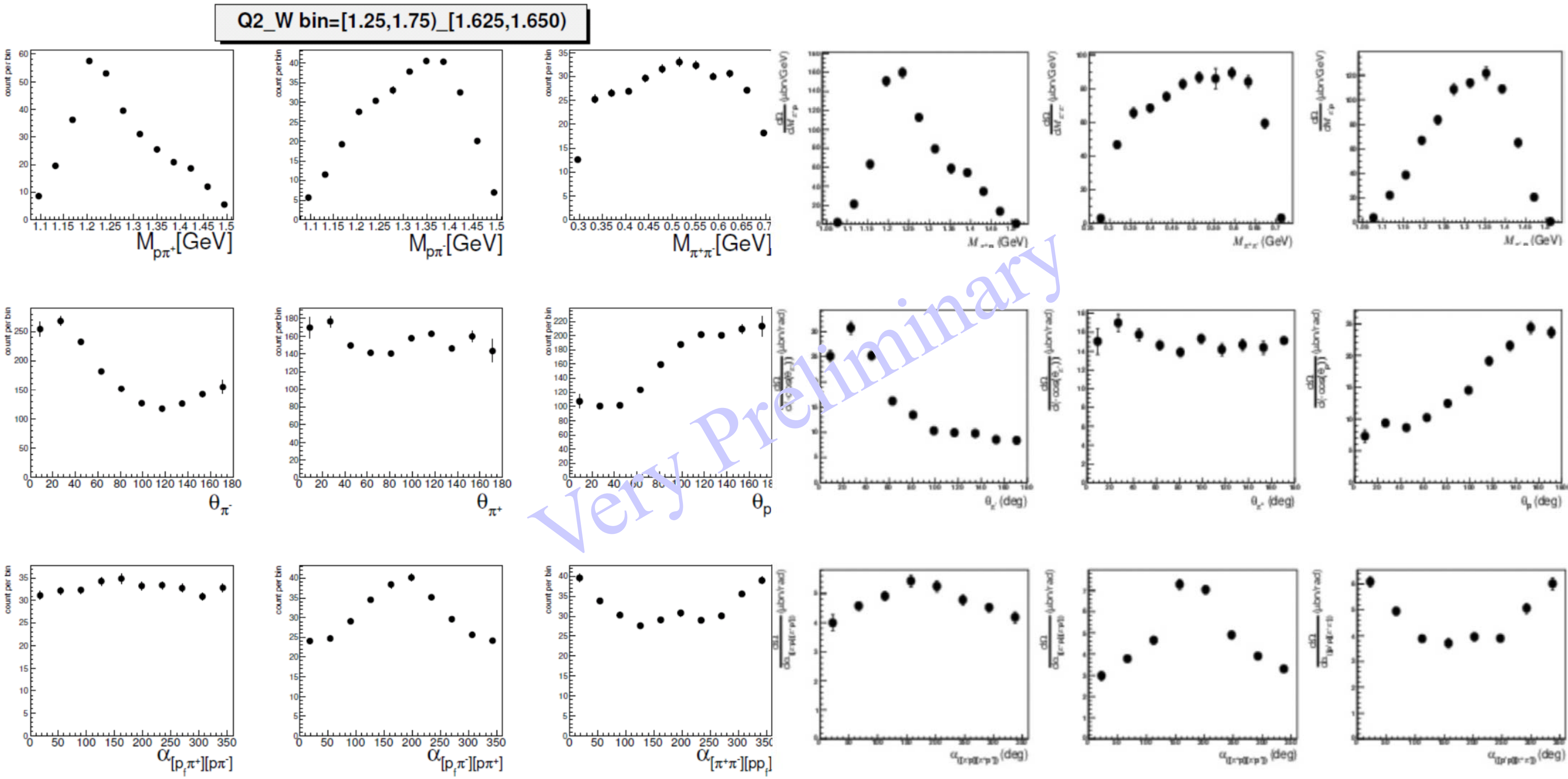
Integrated Nππ Cross Sections Compared to Existing Data



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

φ-dependent Nππ Single-Differential Cross Sections

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



φ-integrated

$Q^2 = 0.425 GeV^2$ Gleb Fedotov

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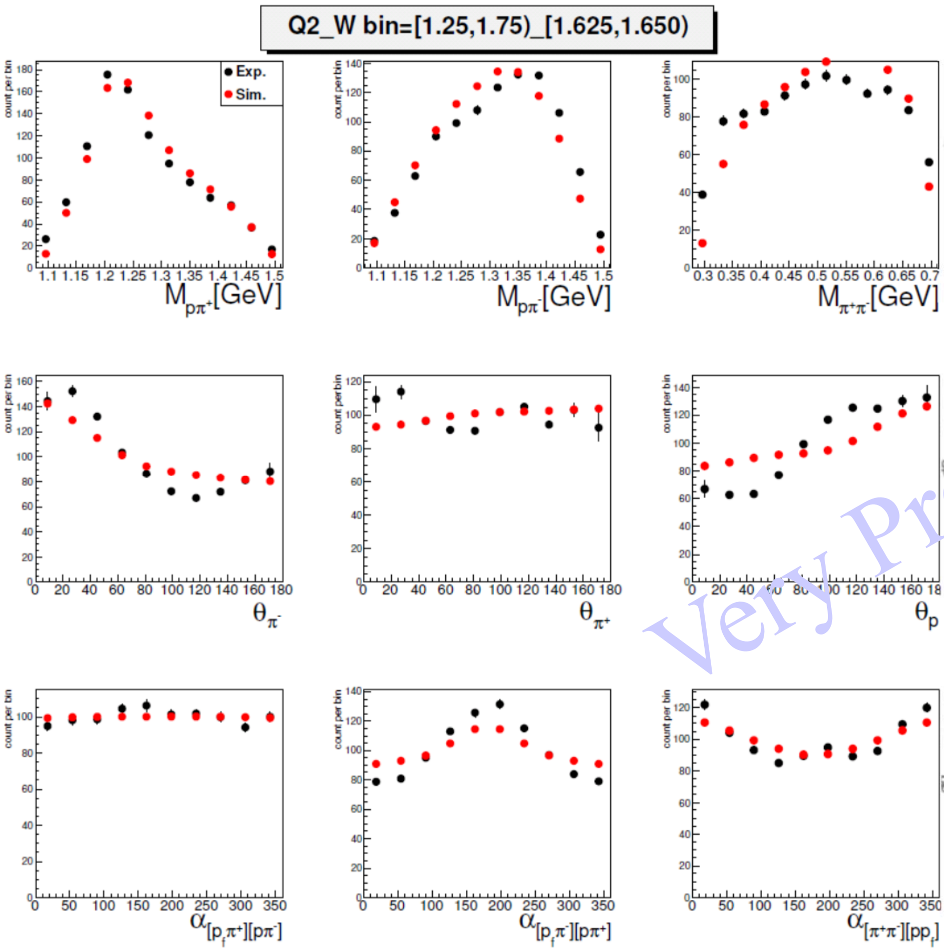

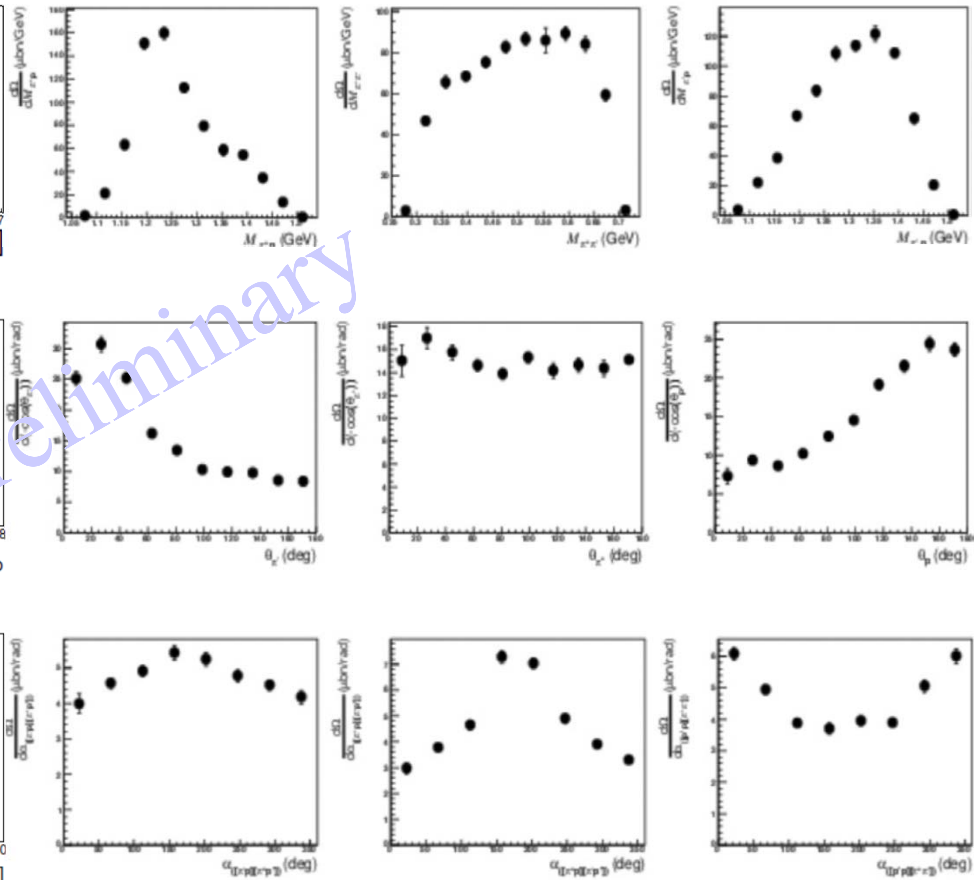

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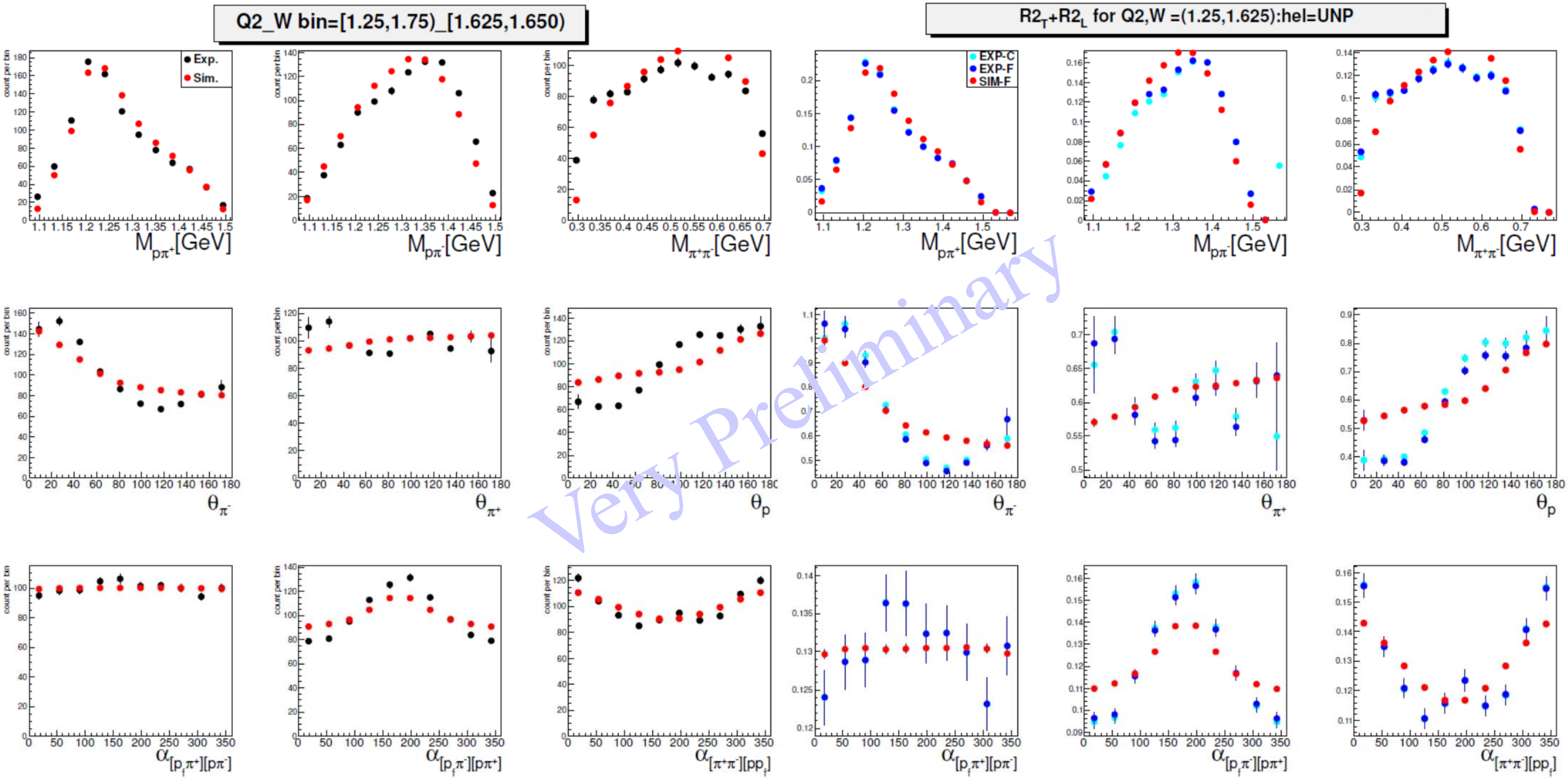

φ-integrated φ-independent

φ-dependent Nππ Single-Differential Cross Sections

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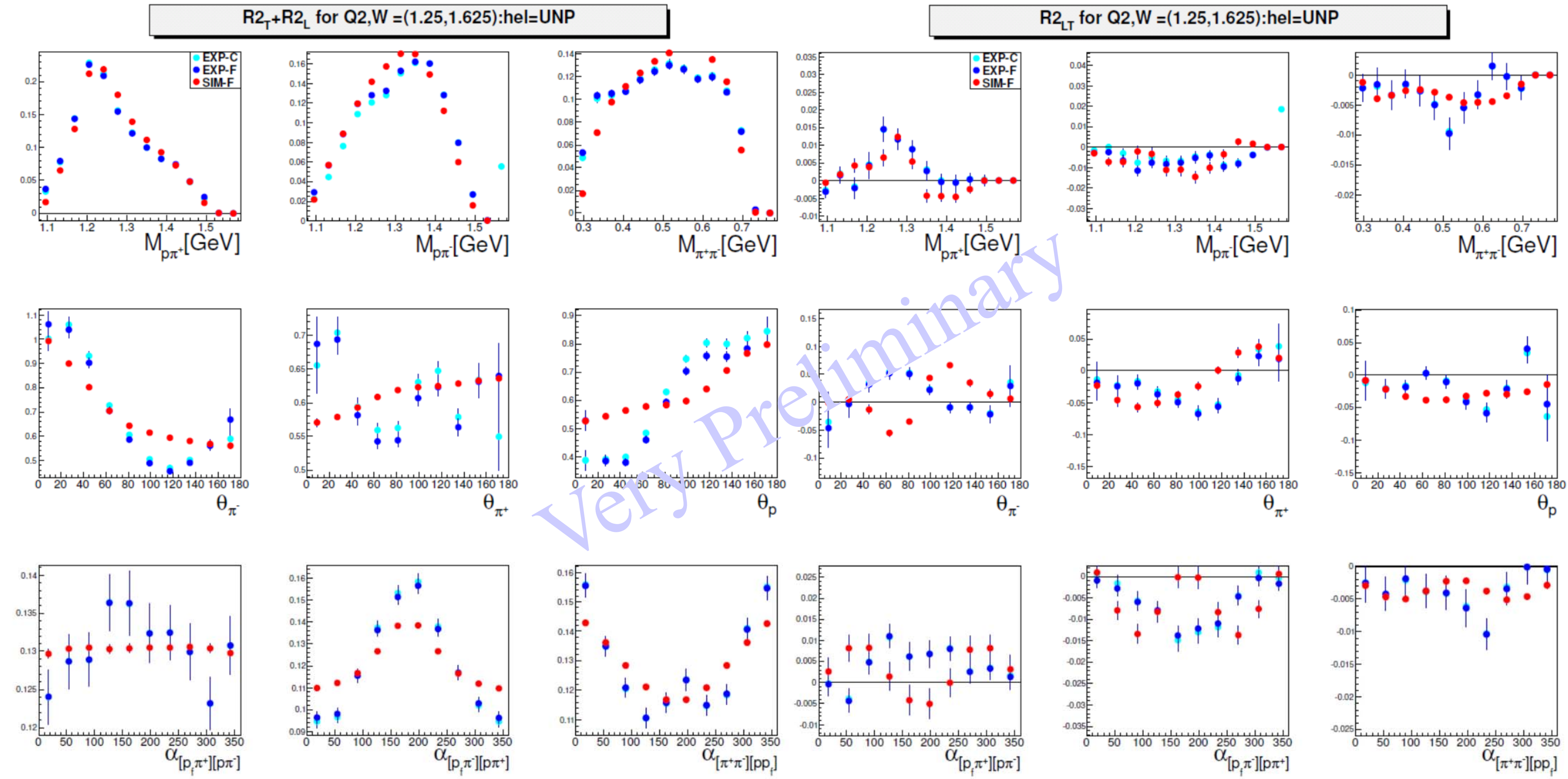
Arjun Trivedi



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

φ-independent

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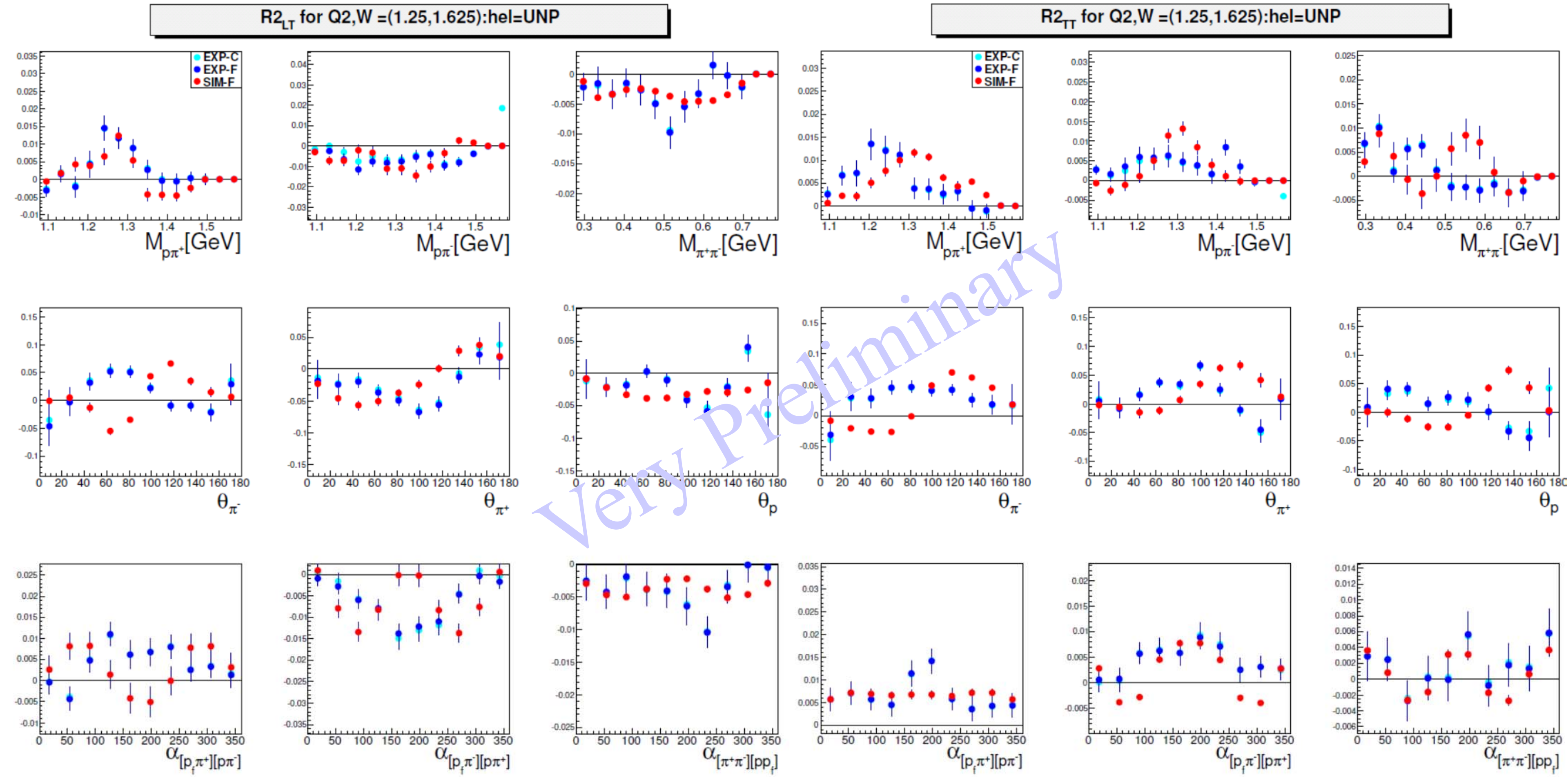

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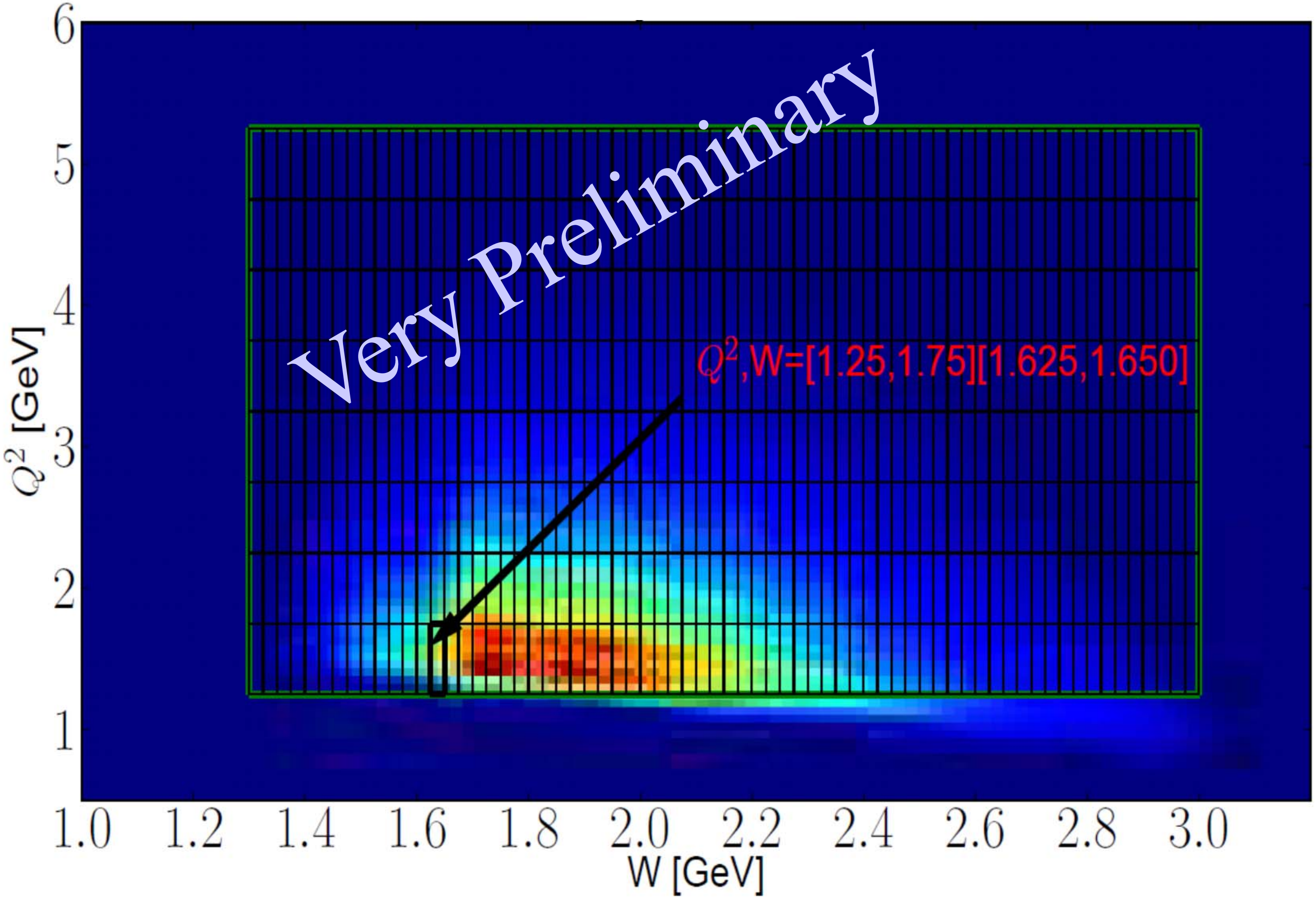

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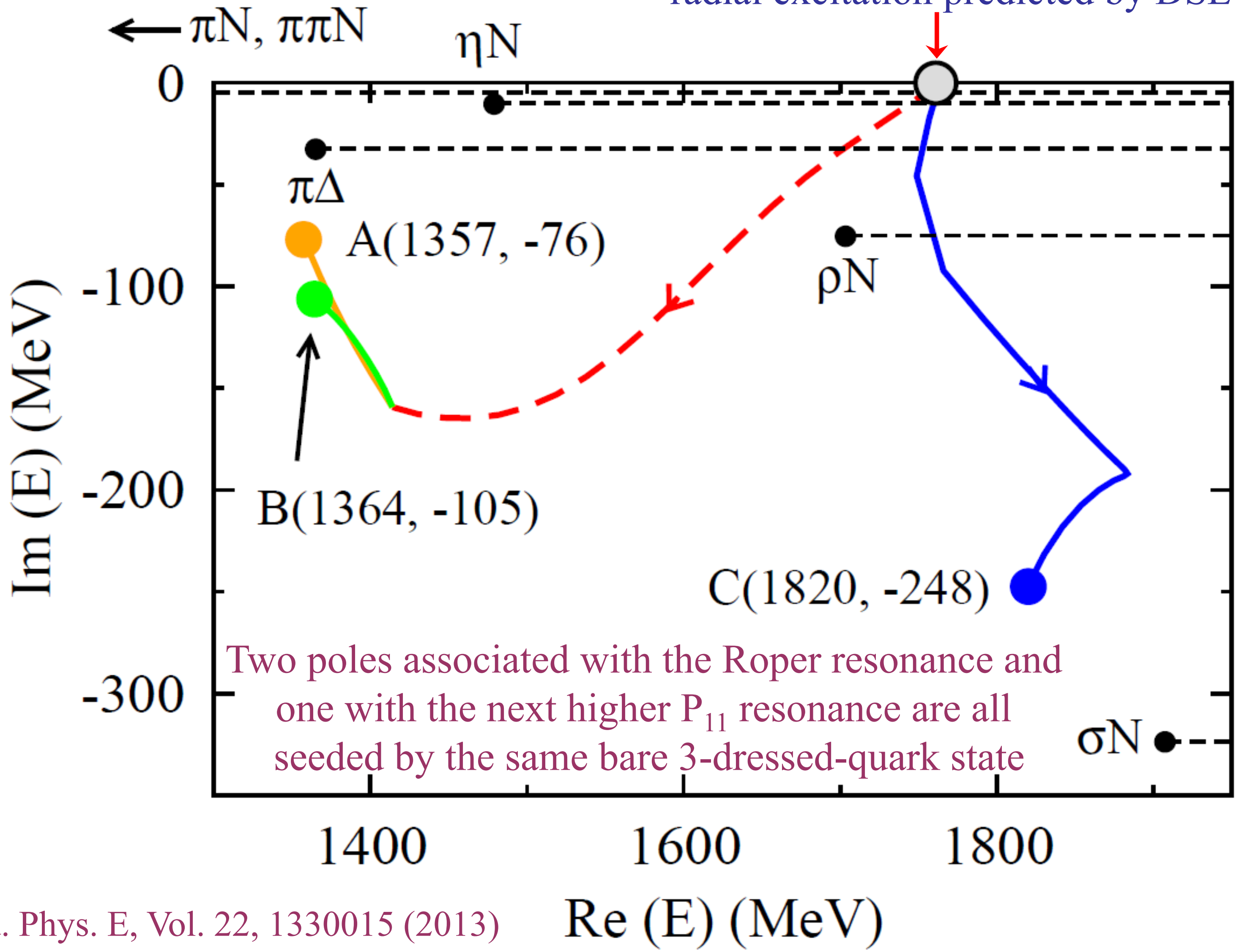
QCD-Based Models and Theory

DSE and EBAC/ANL-Osaka Approaches

Location of the first 3-dressed-quark core radial excitation predicted by DSE



Two poles associated with the Roper resonance and one with the next higher P_{11} resonance are all seeded by the same bare 3-dressed-quark state

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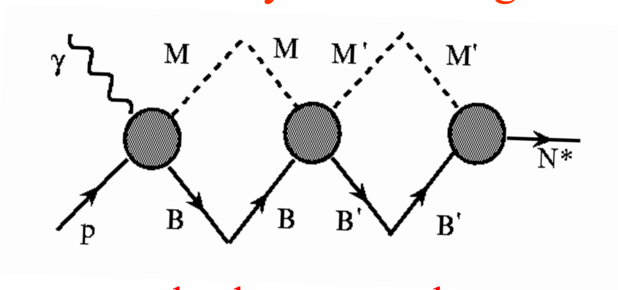
Progress in Experiment and Phenomenology

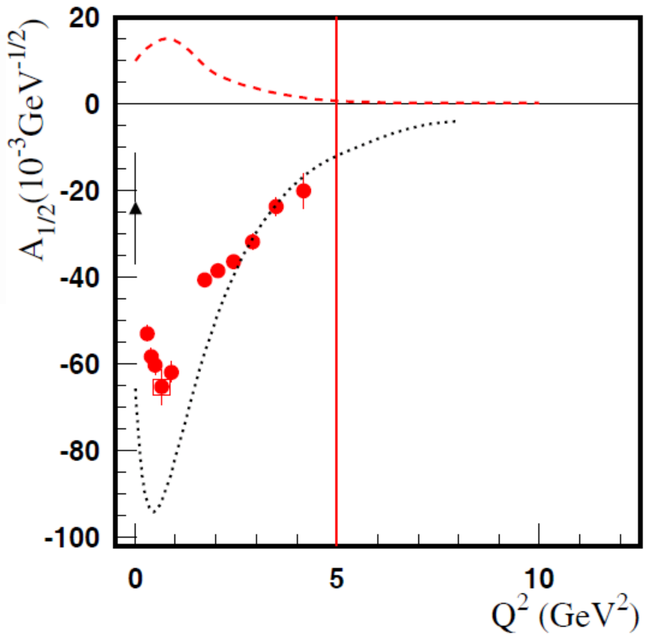
Meson-Baryon Dressing



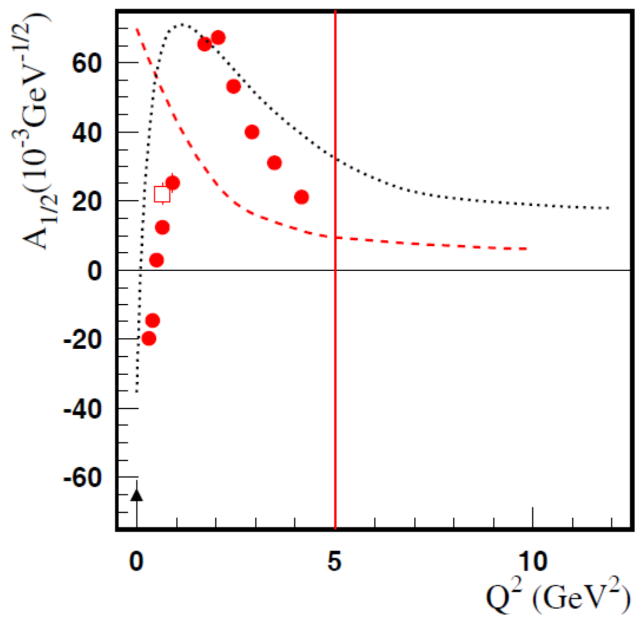
- - - absolute meson-baryon cloud amplitudes (EBAC now ANL-Osaka)

.... quark core contributions (constituent quark models)

$D_{13}(1520)$



$P_{11}(1440)$

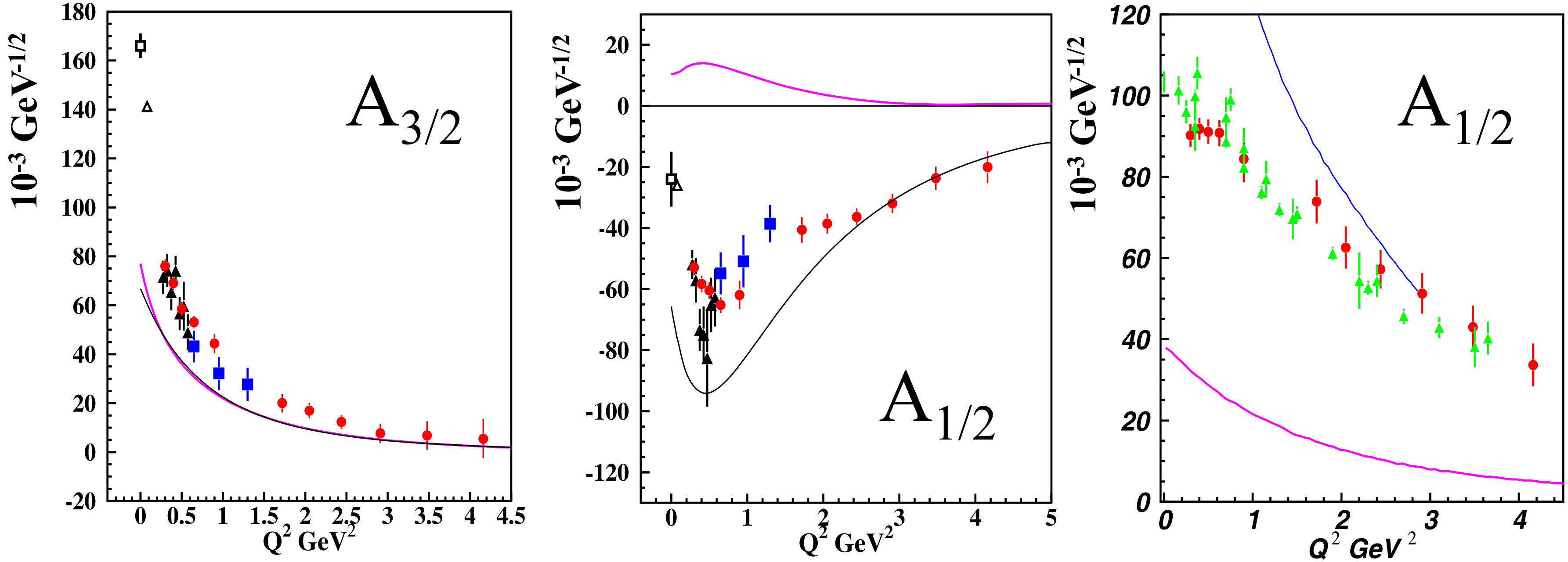


CLAS: $N\pi$ and $N\pi/N\pi\pi$ combined (Phys. Rev. C80, 055203, 2009)

➢ 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} 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

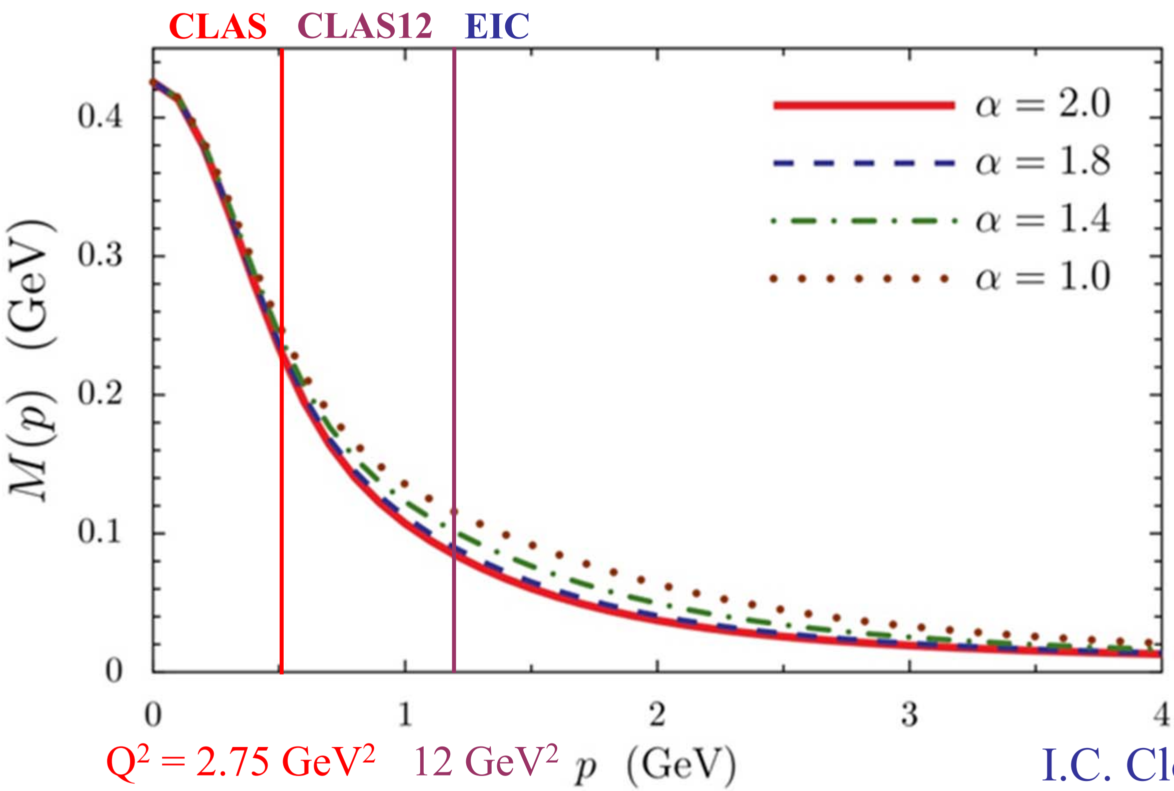
$\pi^+\pi^-p$ 2010

$N\pi$ 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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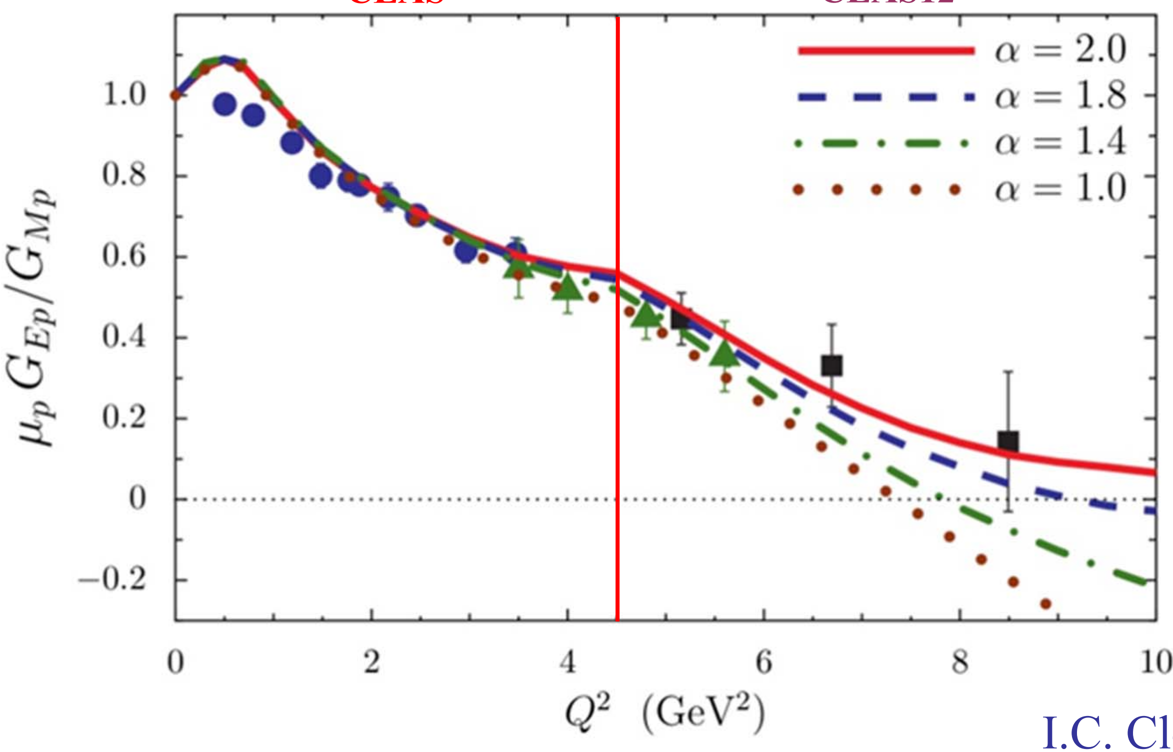

N* electrocouplings can be determined by applying Bethe-Salpeter / Faddeev equations to 3 dressed quarks while the properties and interactions are derived from QCD.

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]

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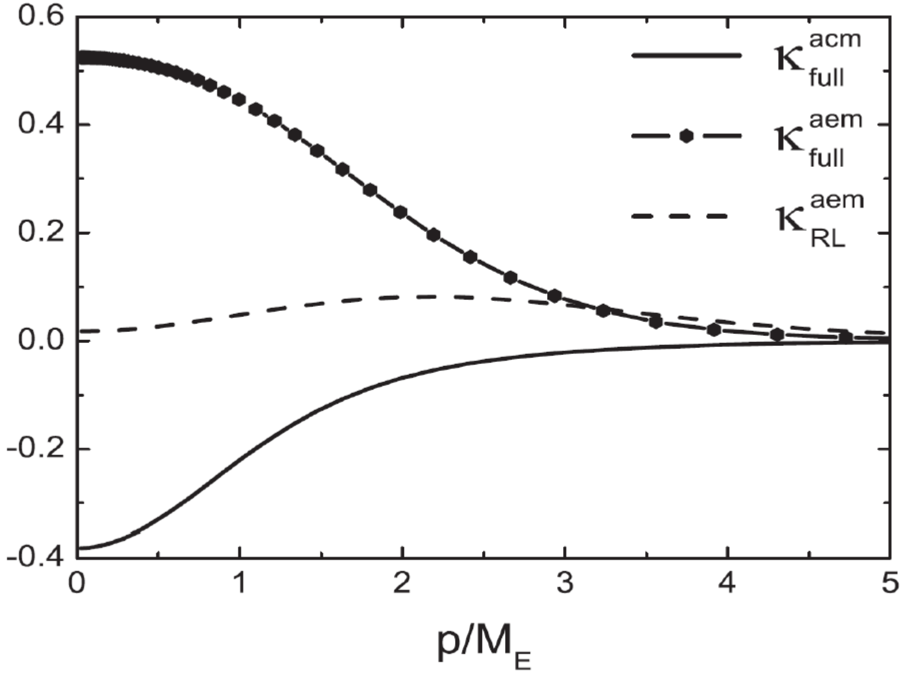
Anomalous Magnetic Moment in DSE Approach



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

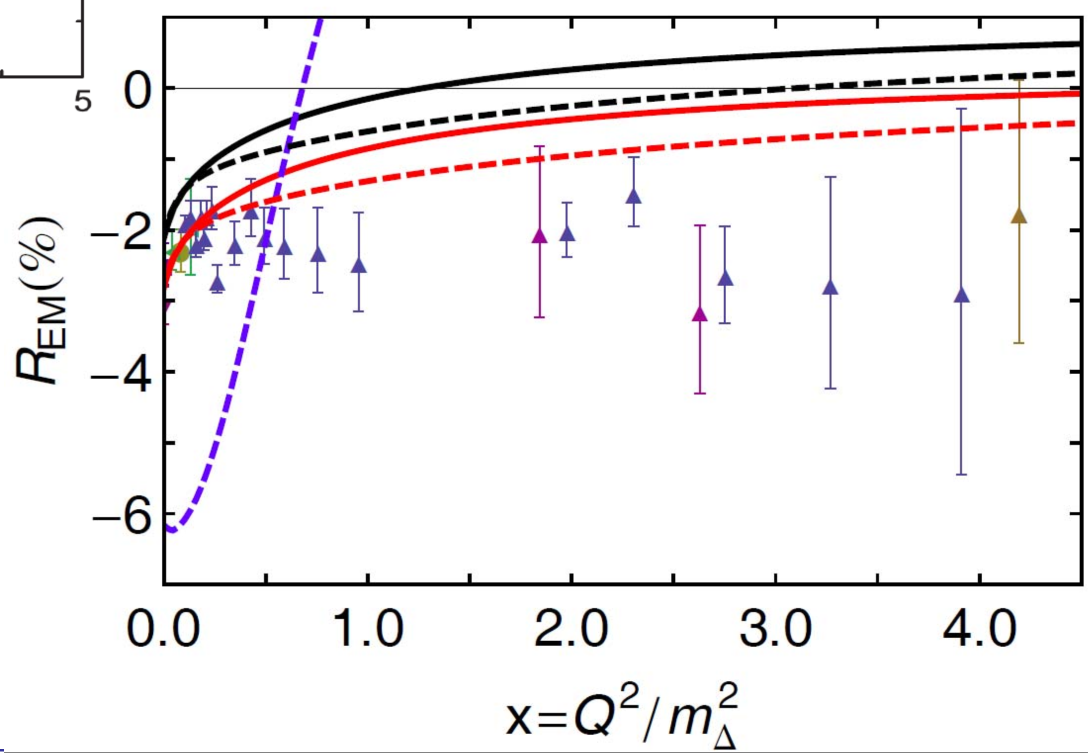
J. Segovia

contact interaction

sophisticated interaction

with momentum dependent κ

renormalized at real photon point

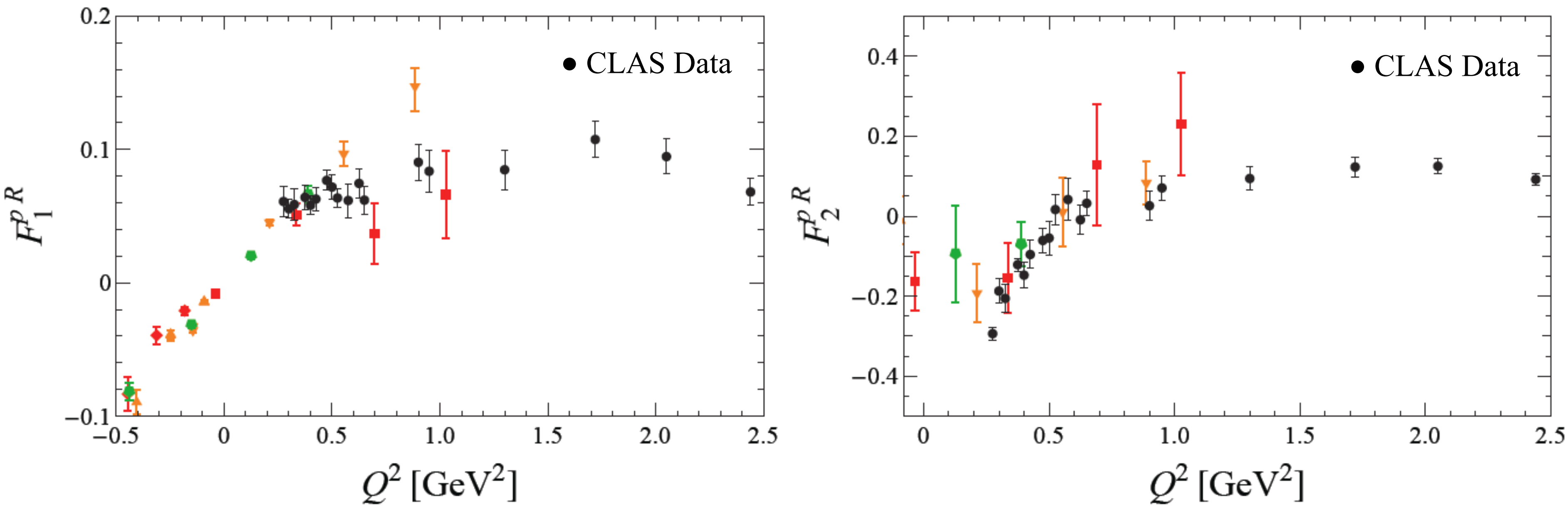


The DSE calculation of R_{EM} zero crossing is sensitive to the momentum dependent anomalous magnetic moment of the dressed-quark.

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.

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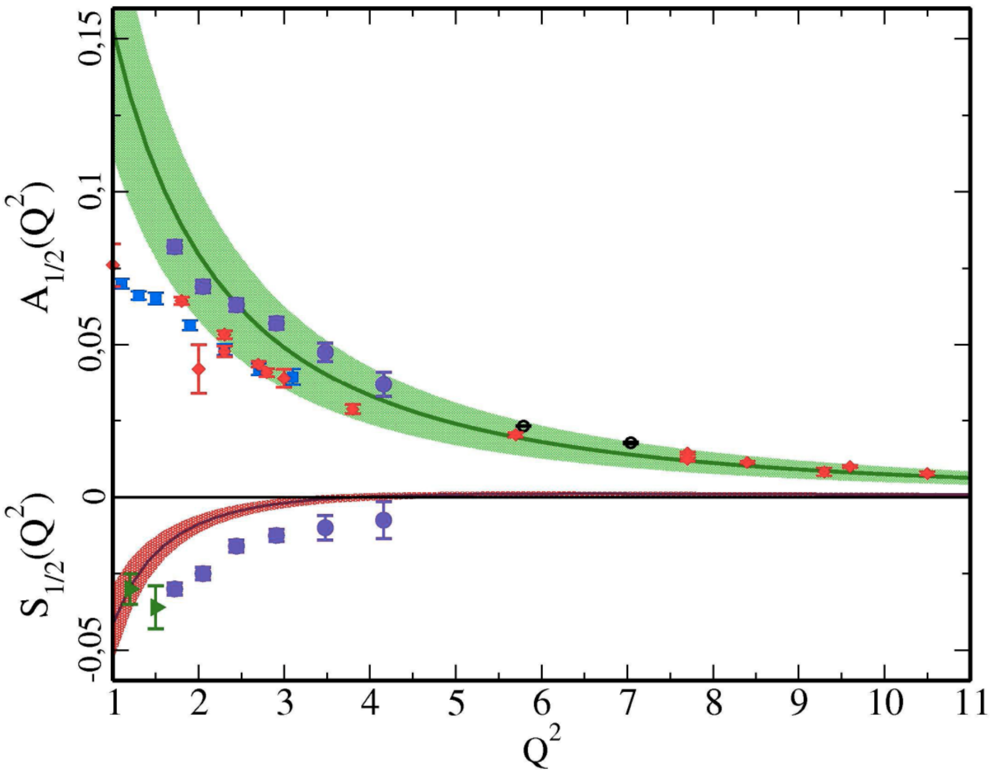
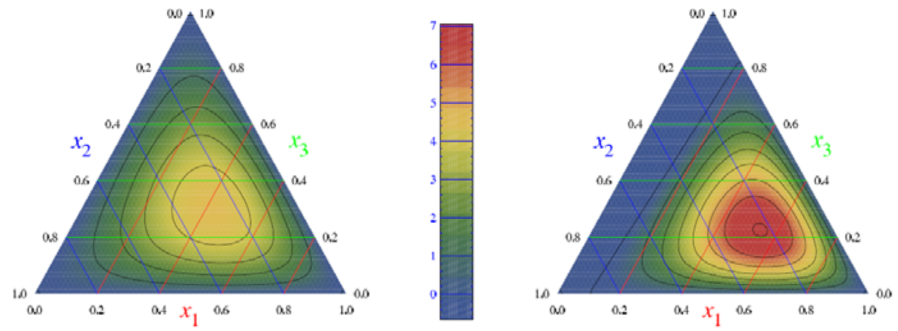
LQCD & Light Cone Sum Rule (LCSR) Approach

N(1535)S_{11}



N

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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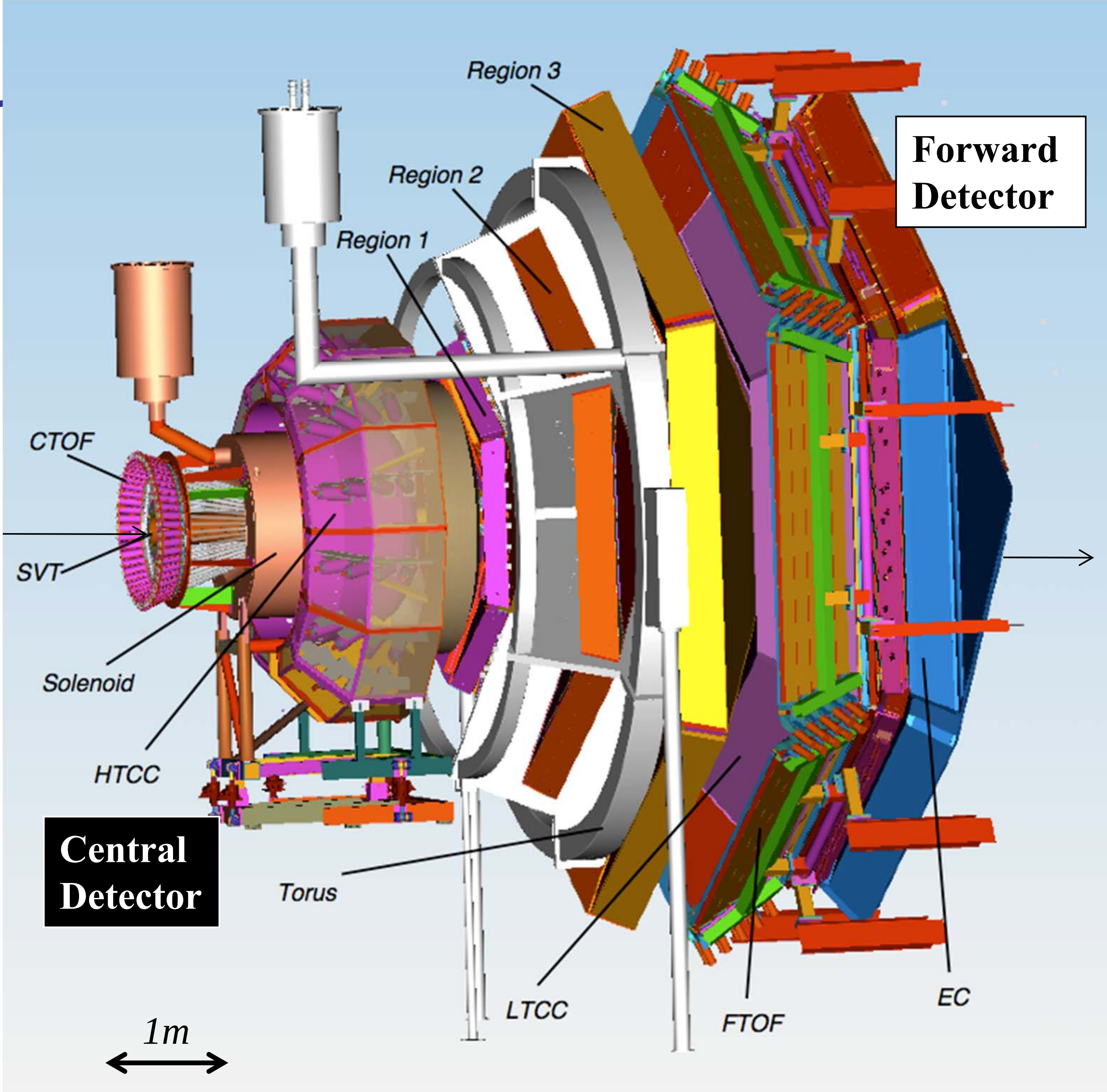
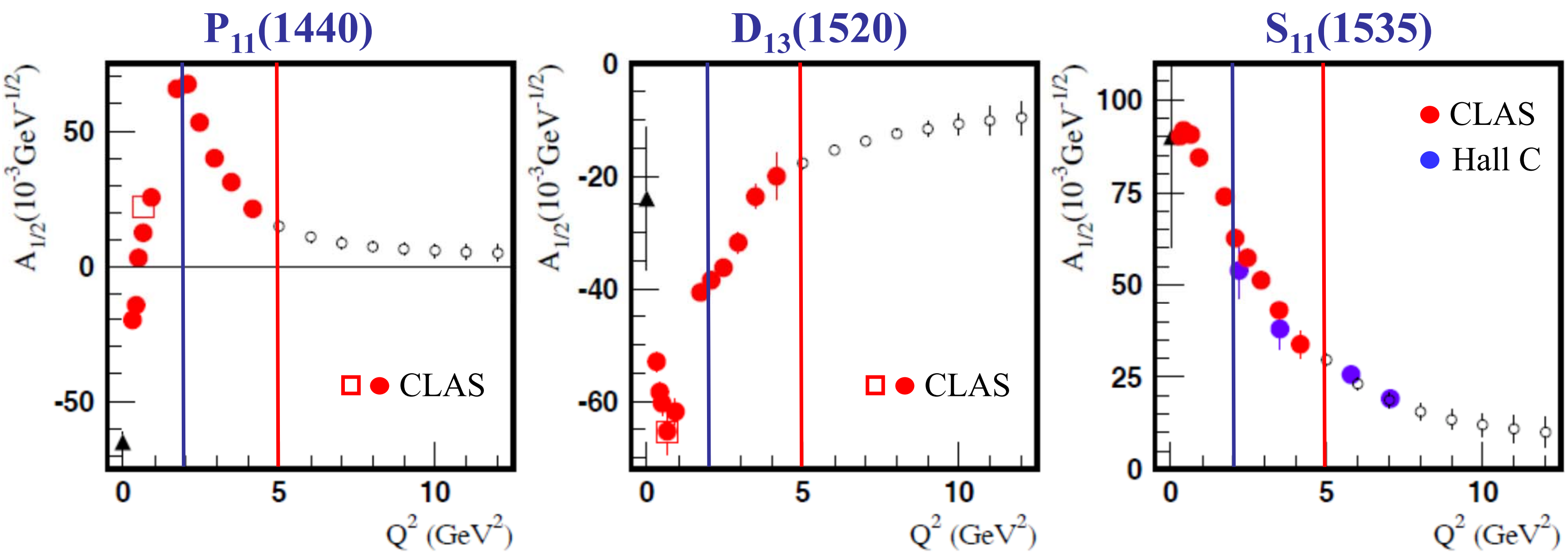
CLAS12

- 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

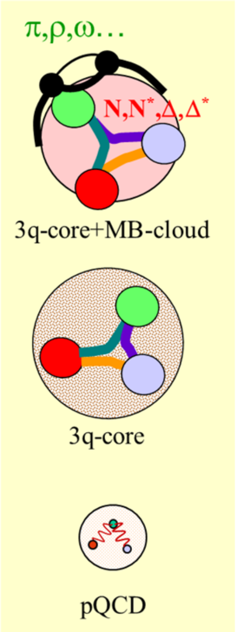


Open circles represent projections and all other markers the available results with the 6-GeV electron beam

- 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.
- 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.