N* Structure of Free and Quasi-Free Electroexcited Nucleons

Ralf W. Gothe

UNIVERSITY OF SOUTH CAROLINA

VIth International Workshop on Non-Perturbative Aspects of Quantum Field Theories

April 24-28, 2017

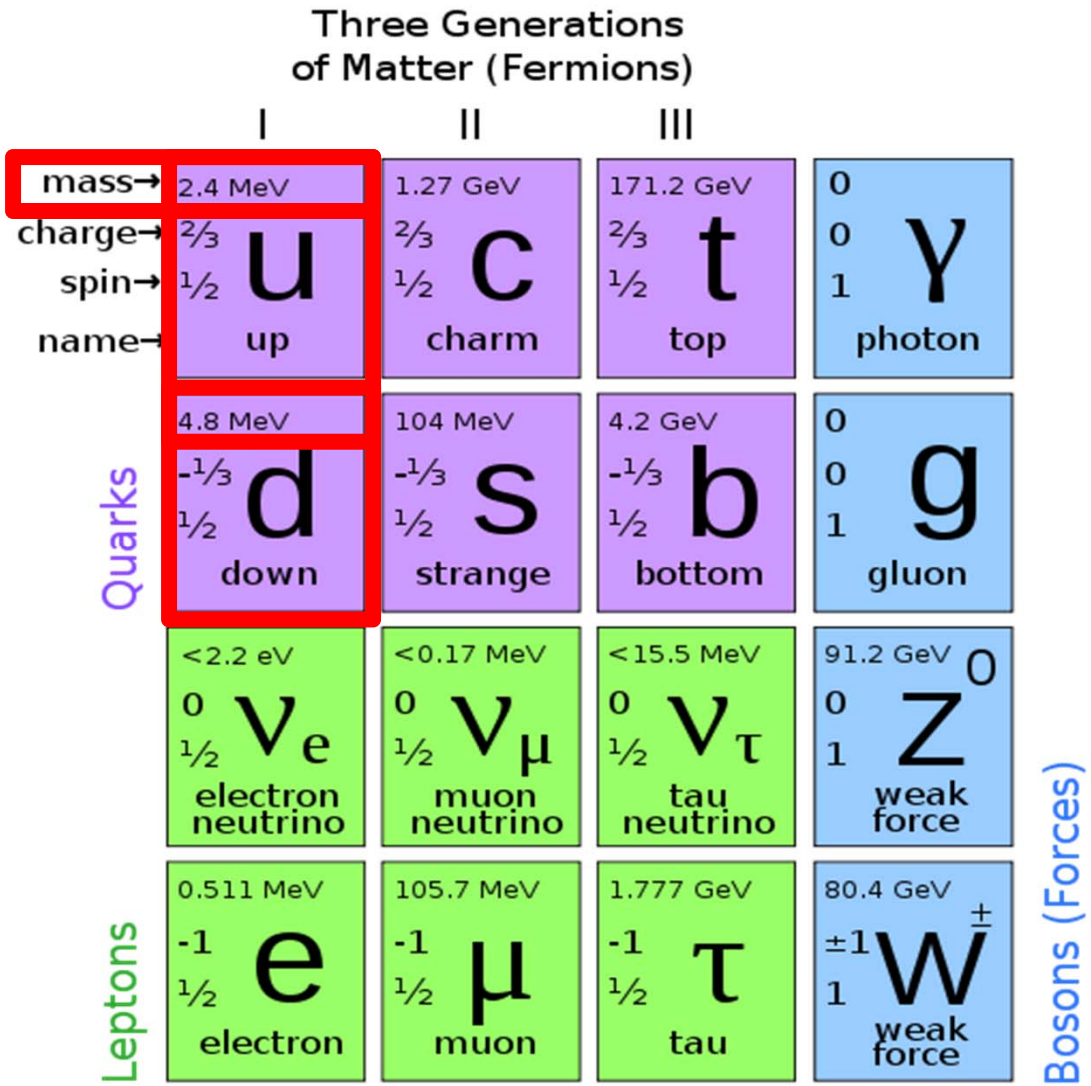
Tuxtla Gutiérrez, Mexico

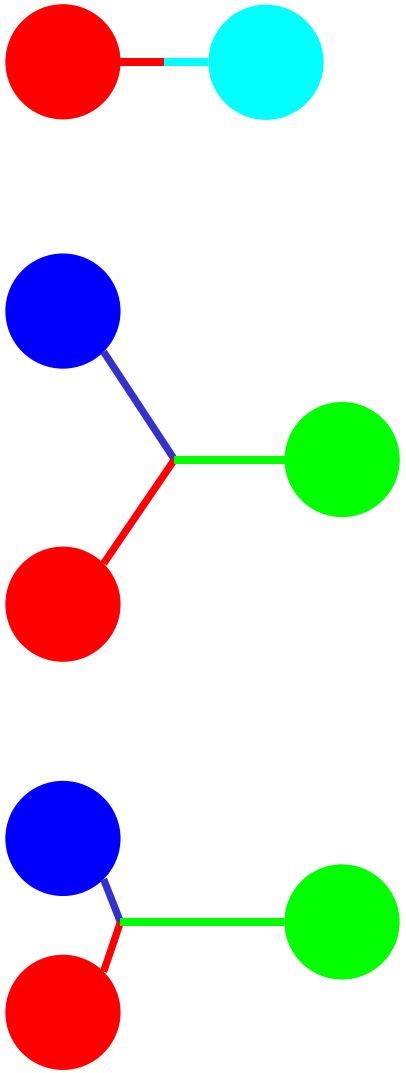
- **γNN* Vertexcouplings:** A unique exploration of baryon and quark structure?
- **Analysis and New Results:** Exclusive, quasi-free, and final state interaction!
- **Outlook:** New experiments with extended scope and kinematics!

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

Spectroscopy

Build your Mesons and Baryons …

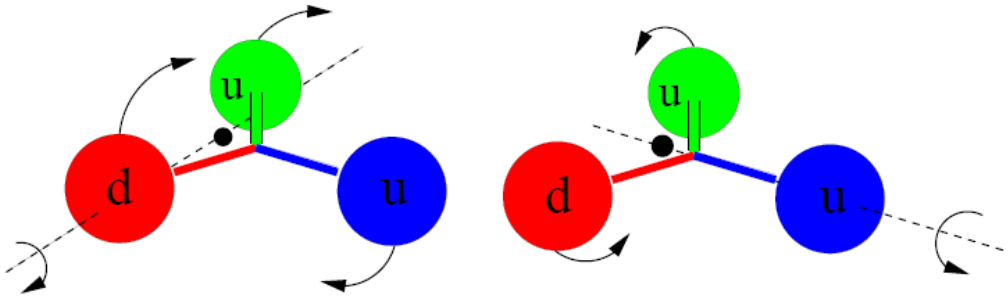




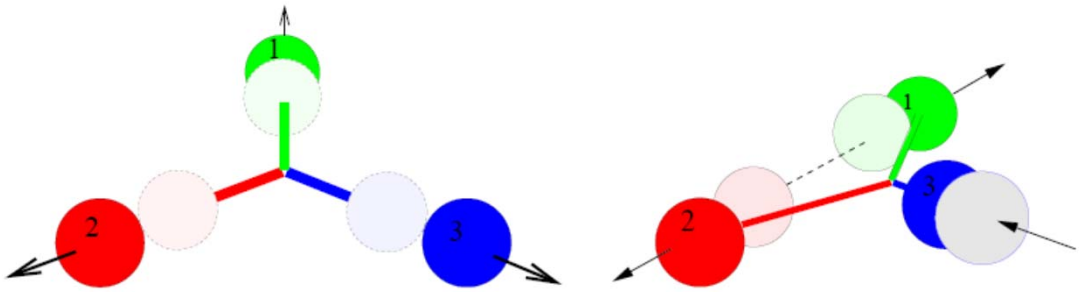
N and Δ Excited Baryon States …

Simon Capstick

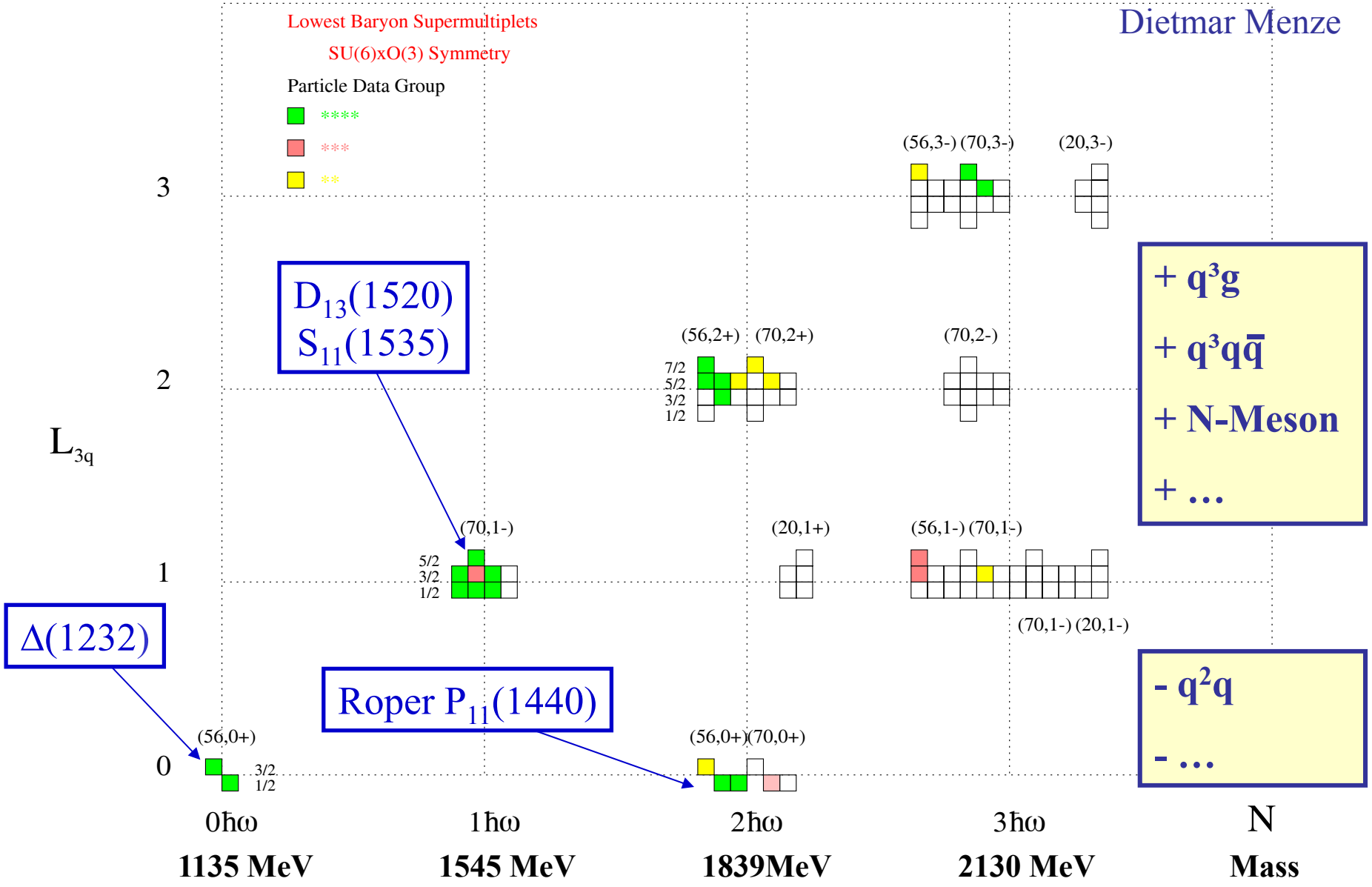
- Orbital excitations (two distinct kinds in contrast to mesons)



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

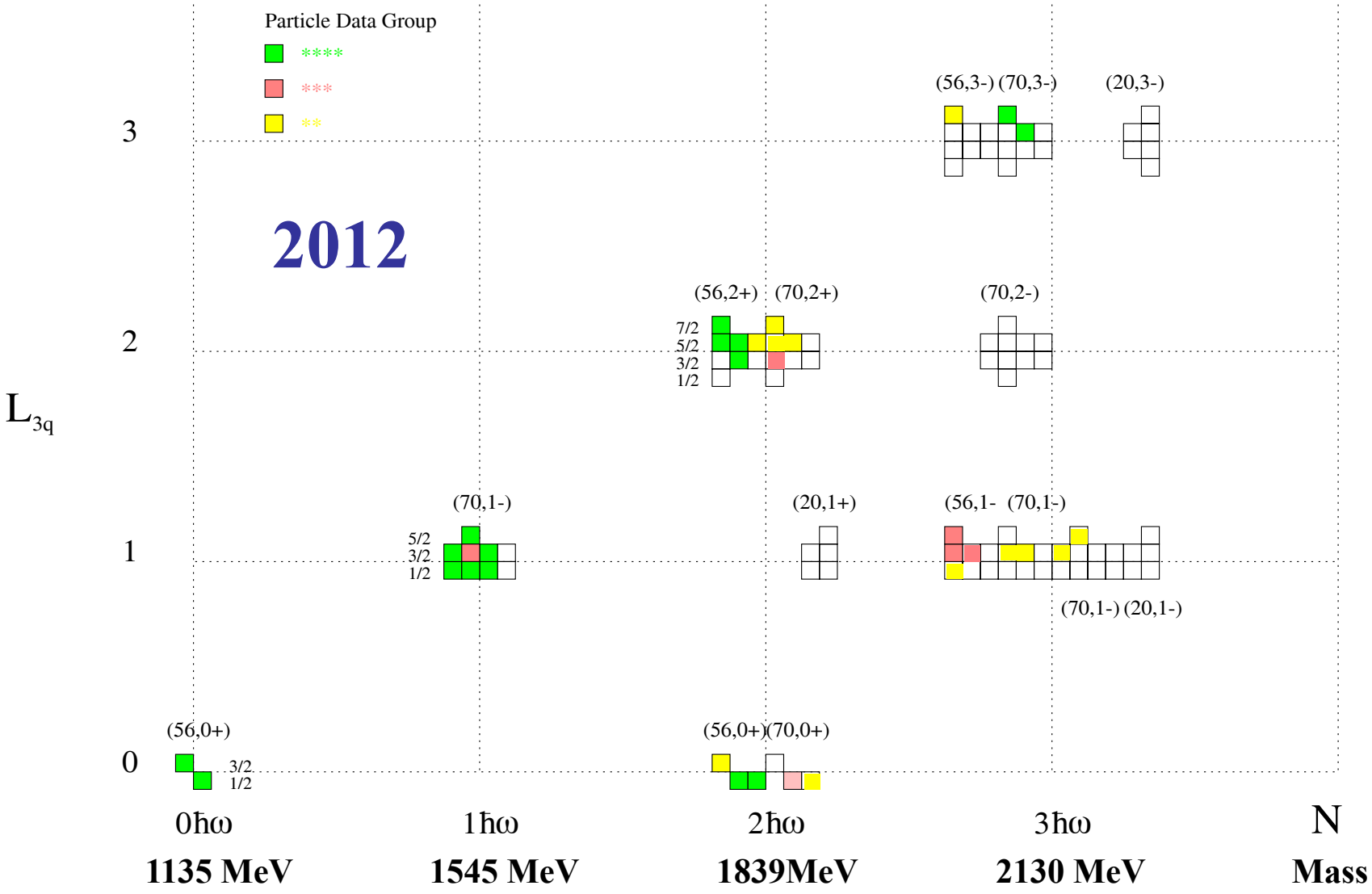


Quark Model Classification of N*



Quark Model Classification of N*

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



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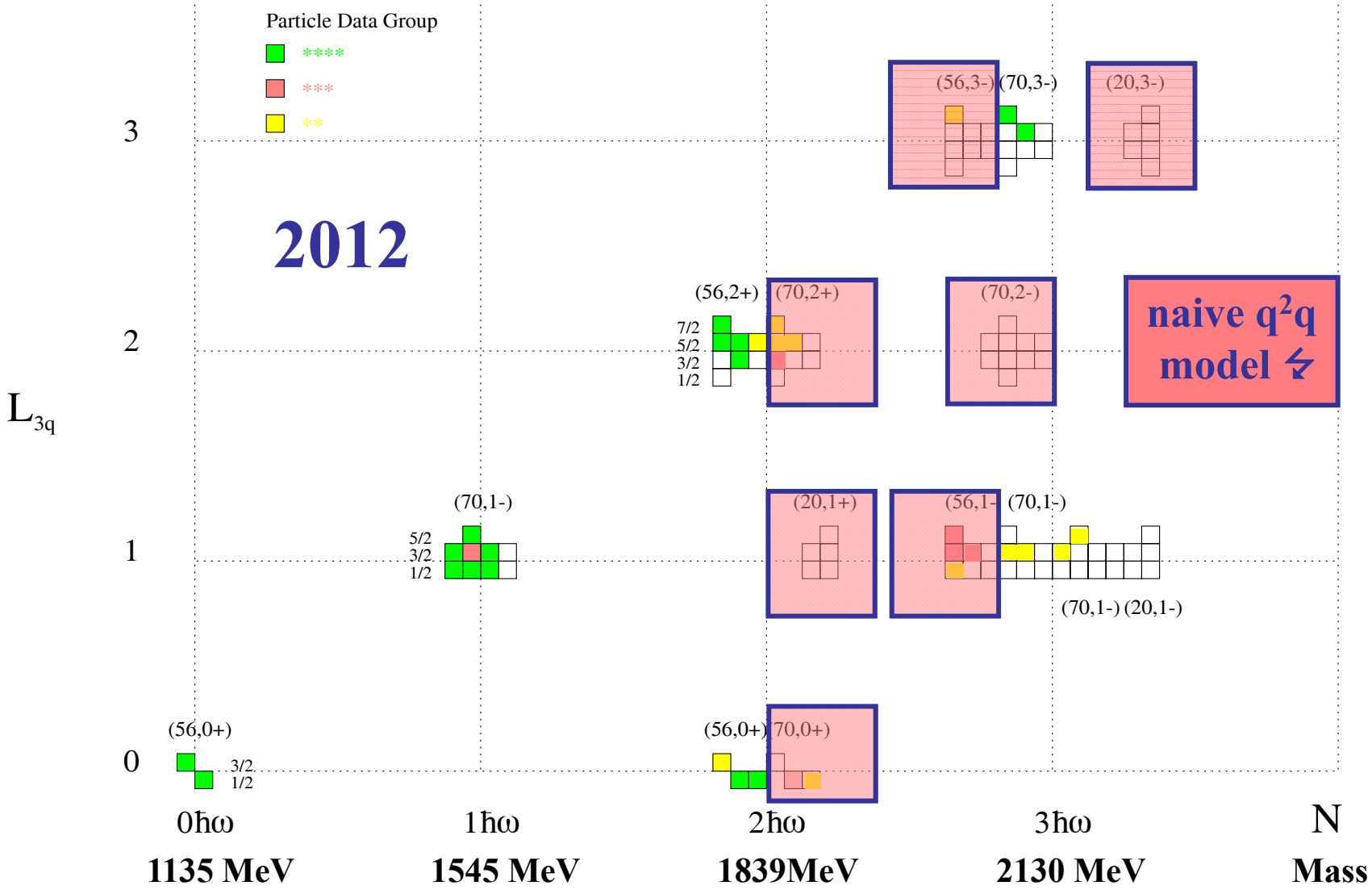
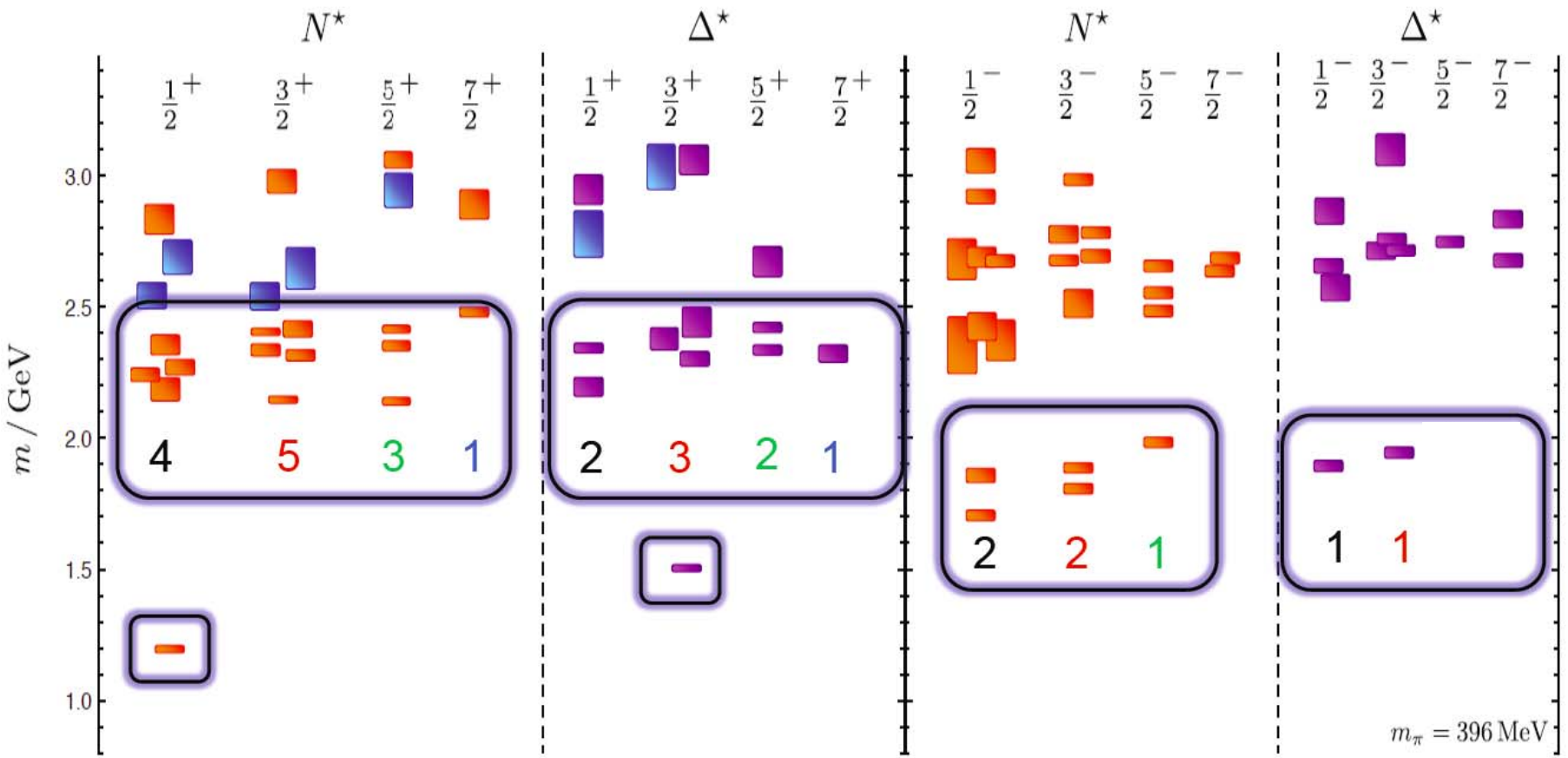


N* Spectrum in LQCD

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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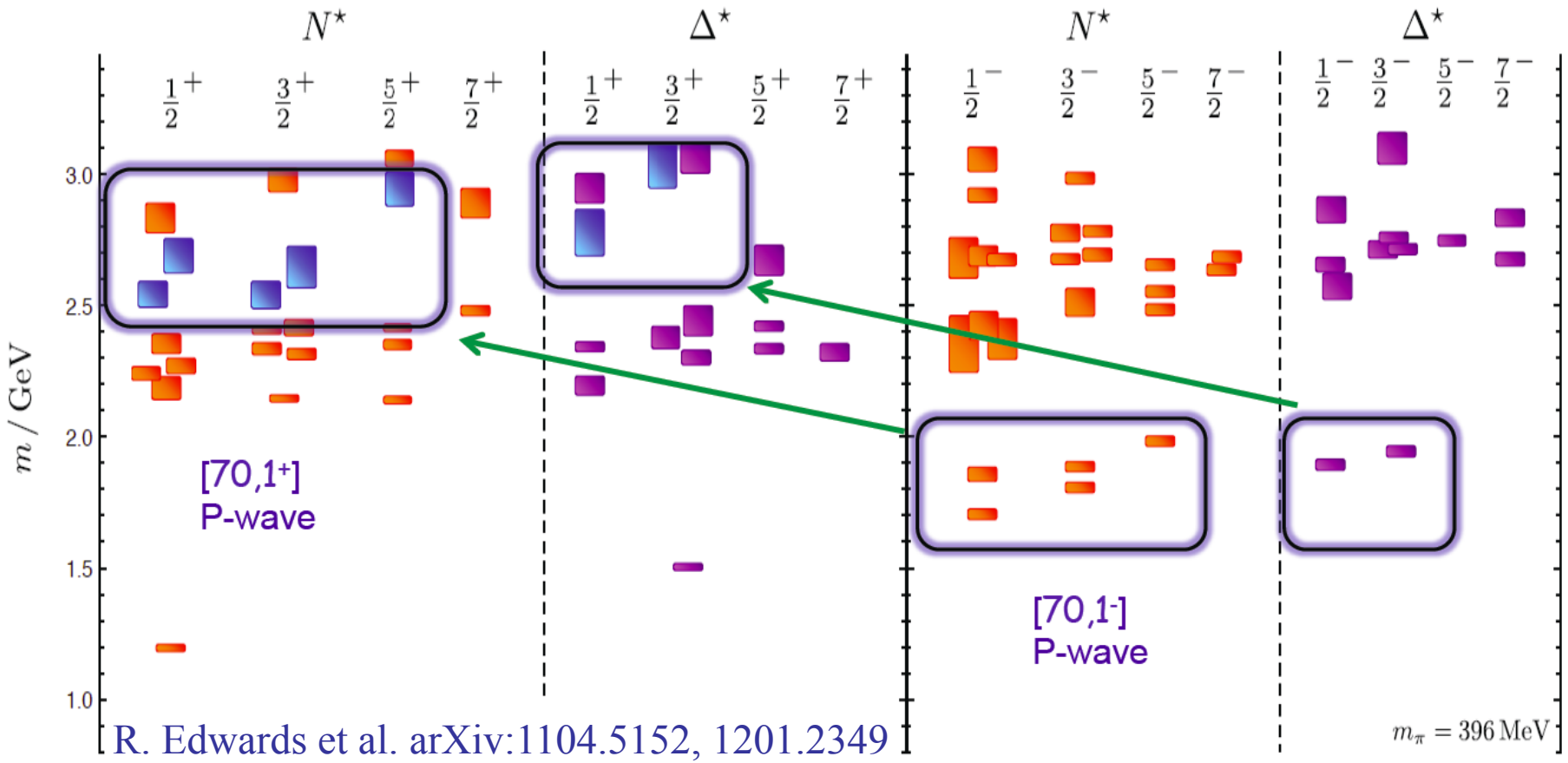


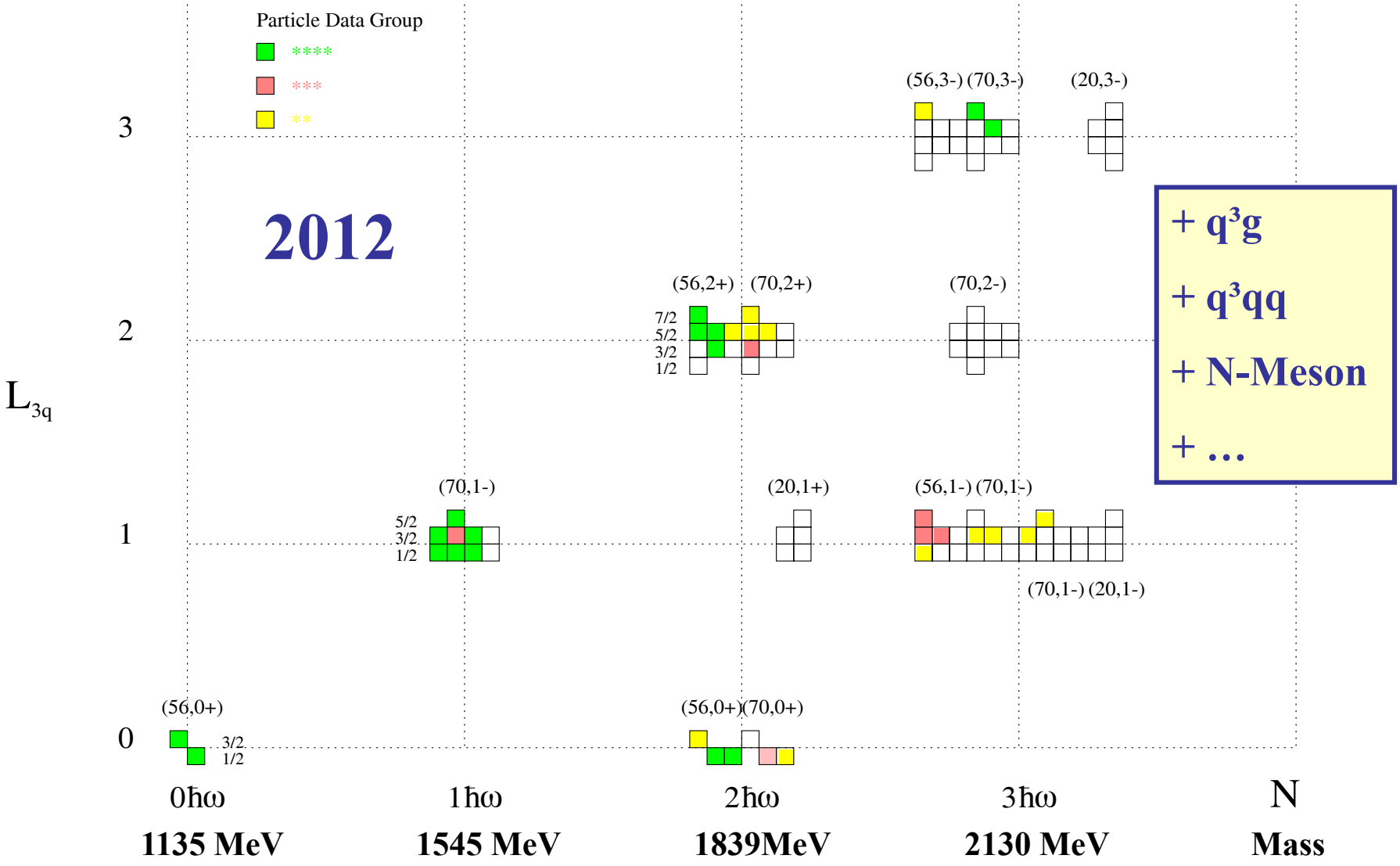
R. Edwards et al. arXiv:1104.5152, 1201.2349

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

New approved experiment on electroexcited baryon hybrids (E12-16-010).

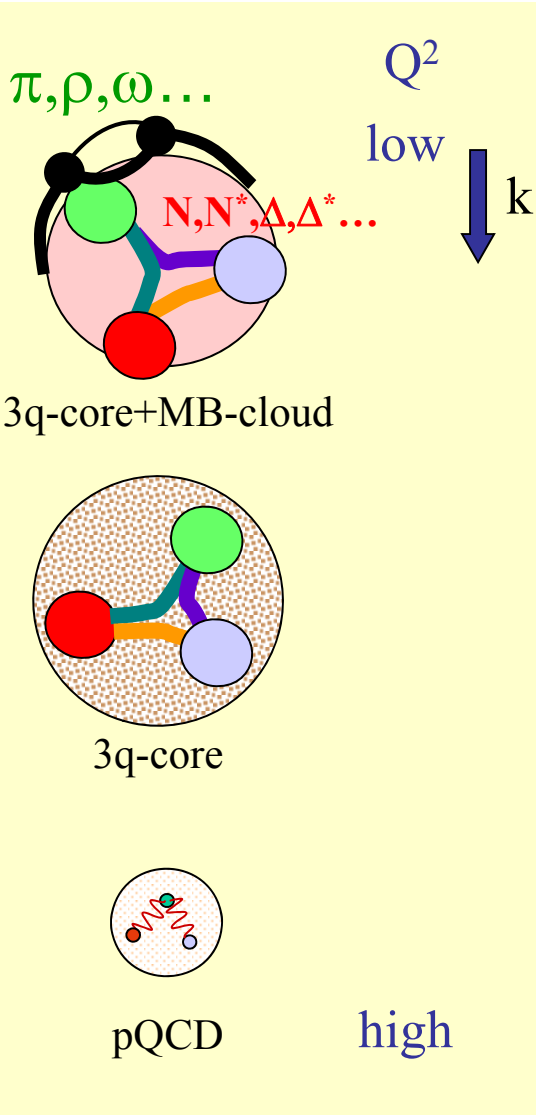
Quark Model Classification of N*

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

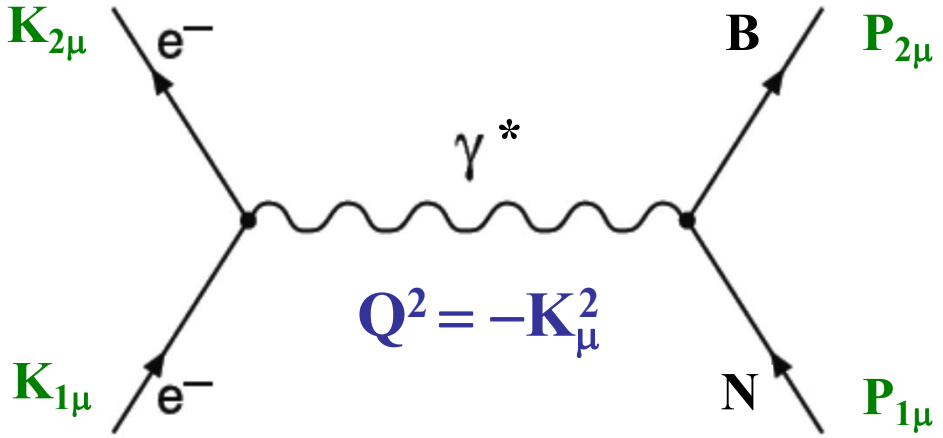


Transition Form Factors

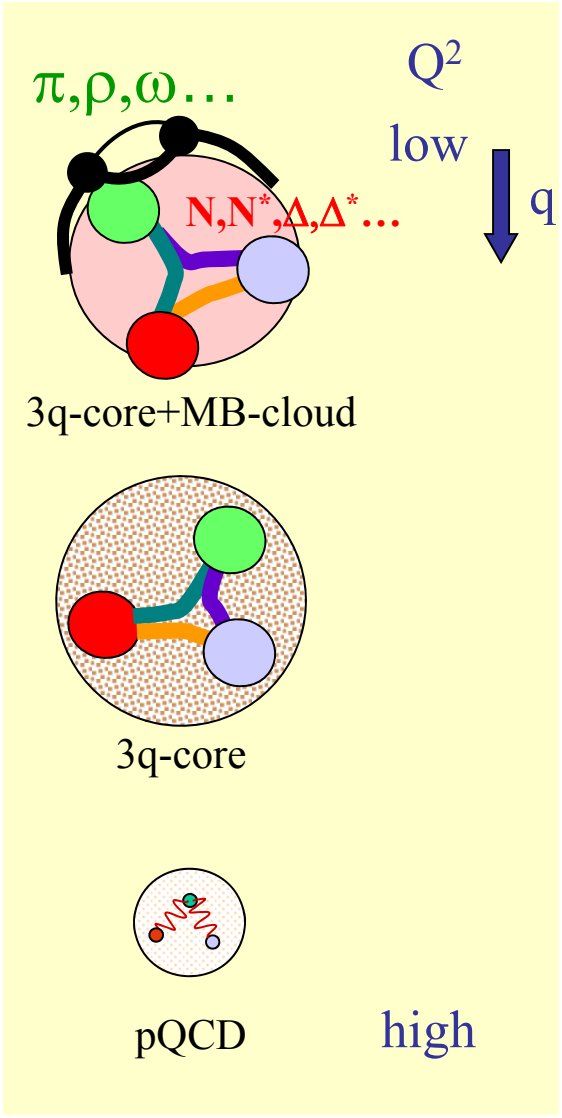
Hadron Structure with Electromagnetic Probes



- 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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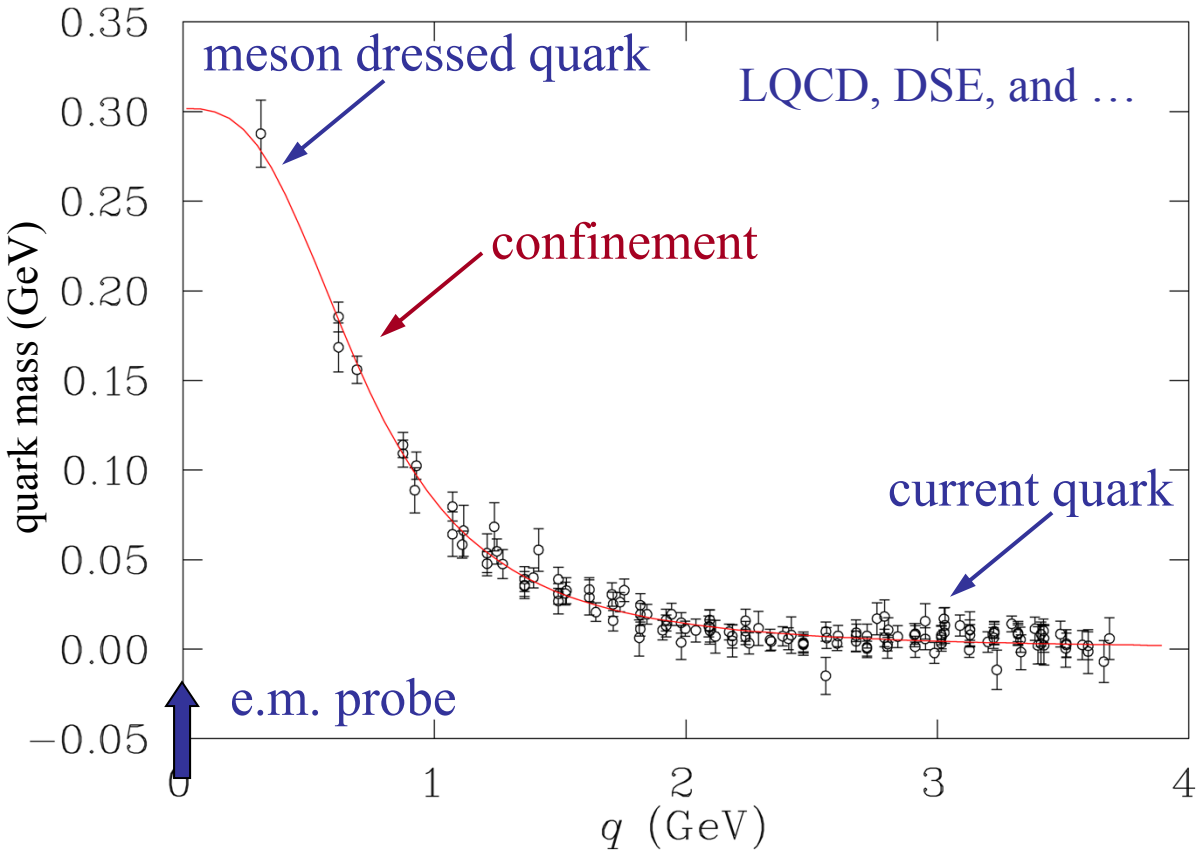
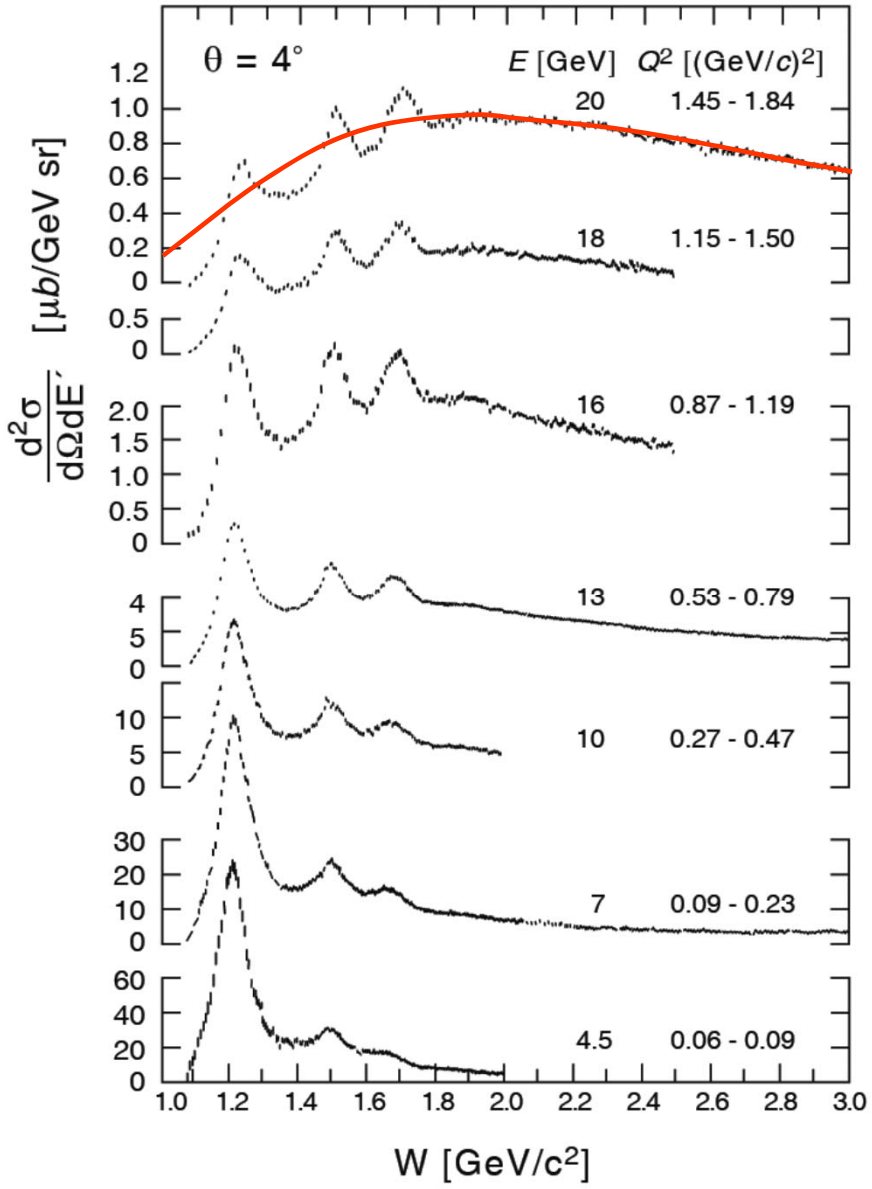
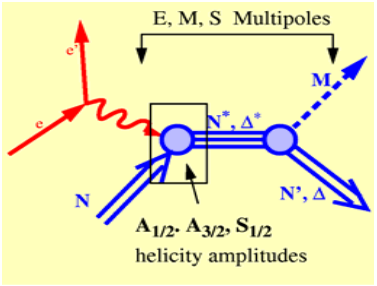
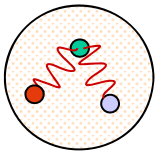


Baryon Excitations and Quasi-Elastic Scattering



hard and confined



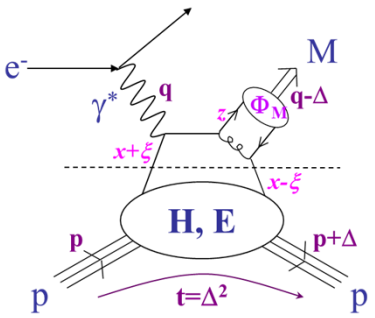


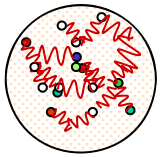
Elastic Form Factors

Transition Form Factors

hard

soft





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

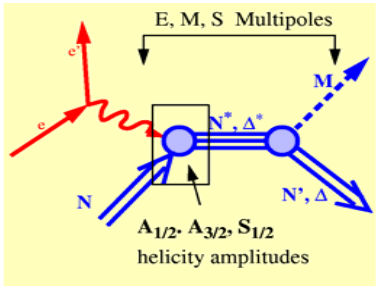
Structure Analysis of the Baryon

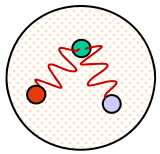
Demolition of a chimney at the "Henninger Brewery" in Frankfurt am Main, Germany, on 2 December 2006

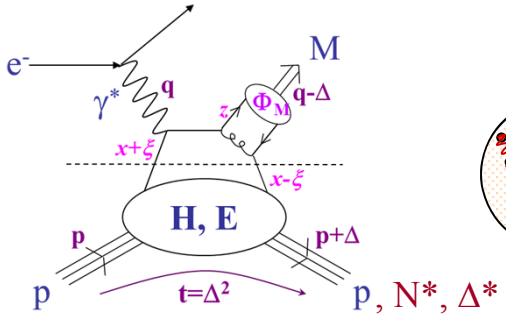
hard and confined

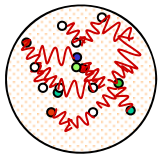
hard and soft

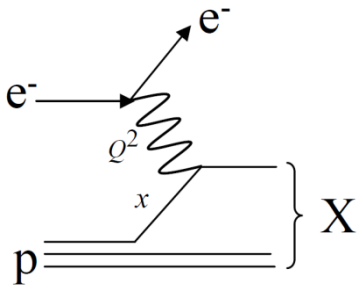
quasi-elastic







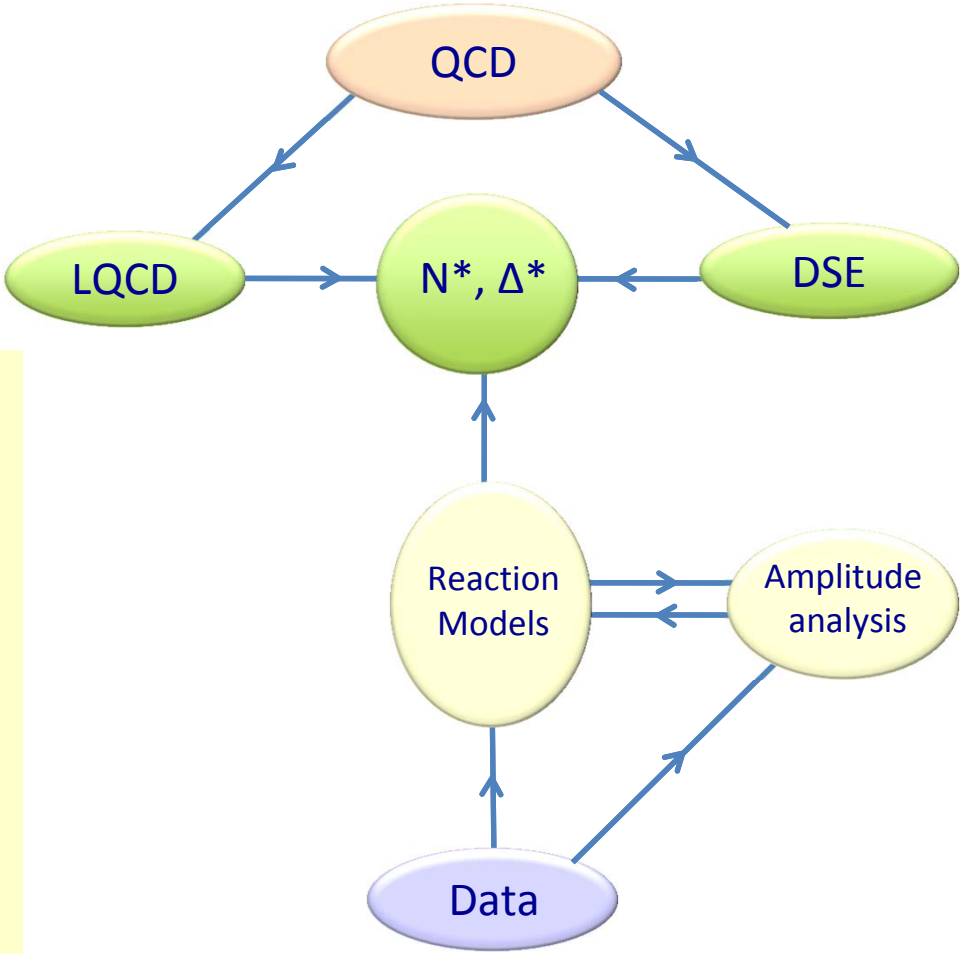




$\gamma_v NN^*$ Extraction

Data-Driven Data Analyses

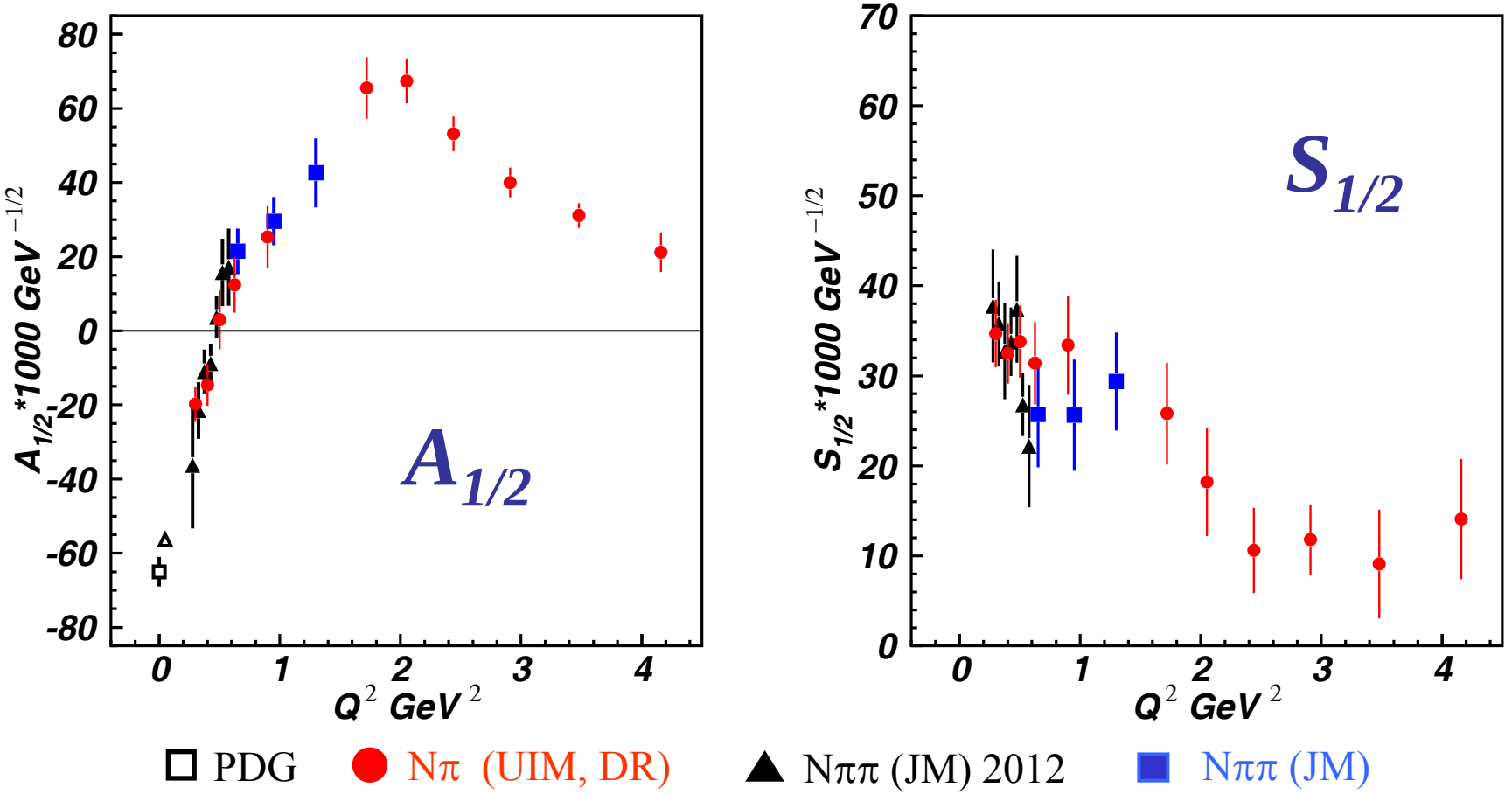
Consistent Results



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

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

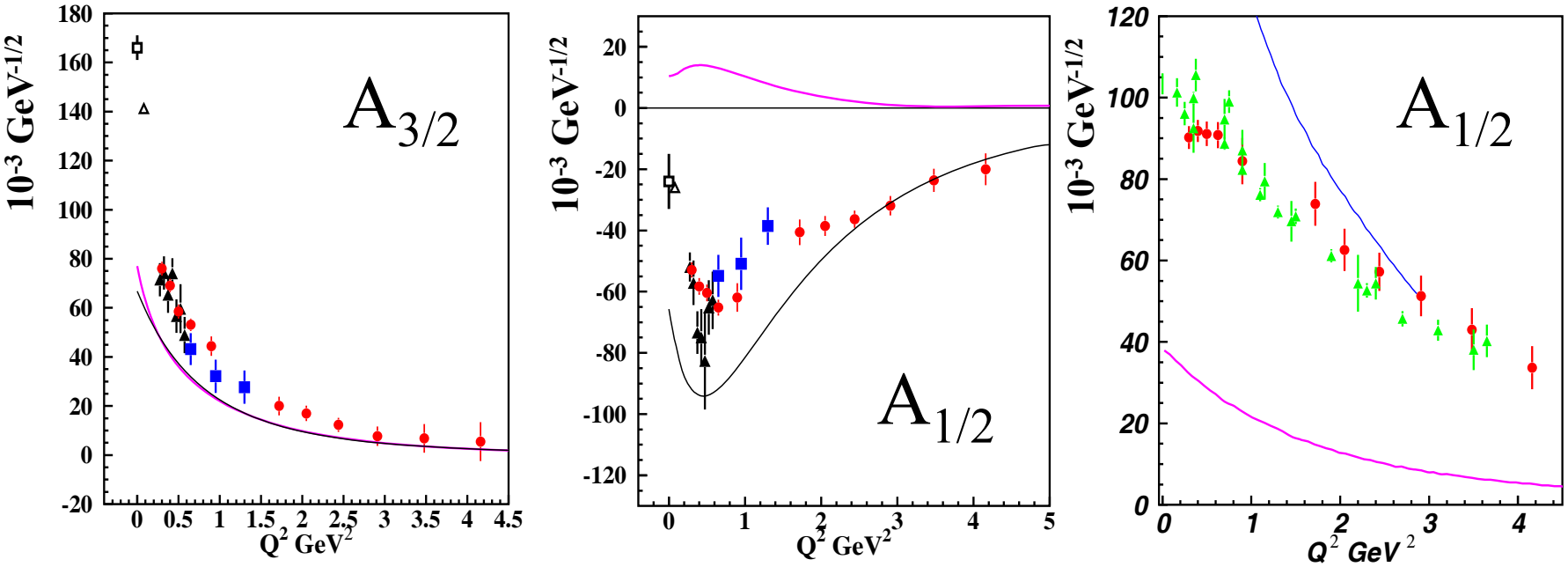
Electrocouplings of N(1440)P_{11} from CLAS Data



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

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

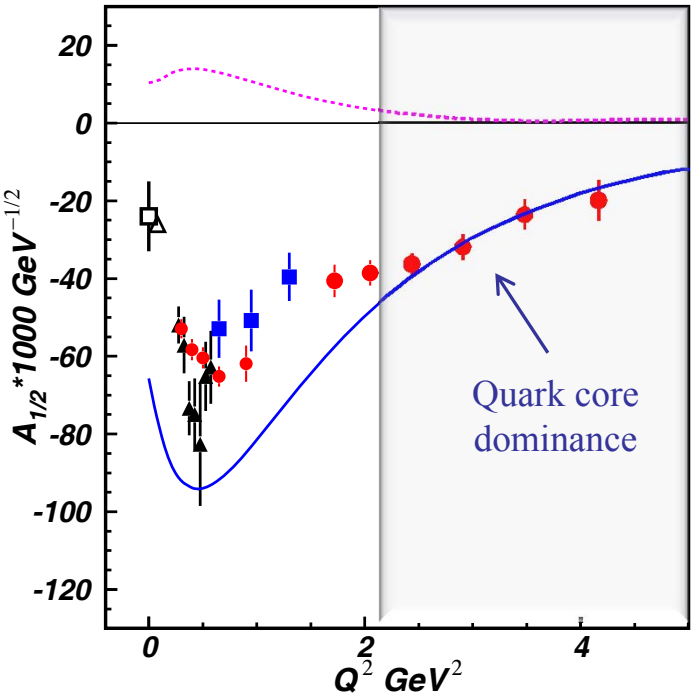
$\pi^+\pi^-p$ 2010

$N\pi$ 2009

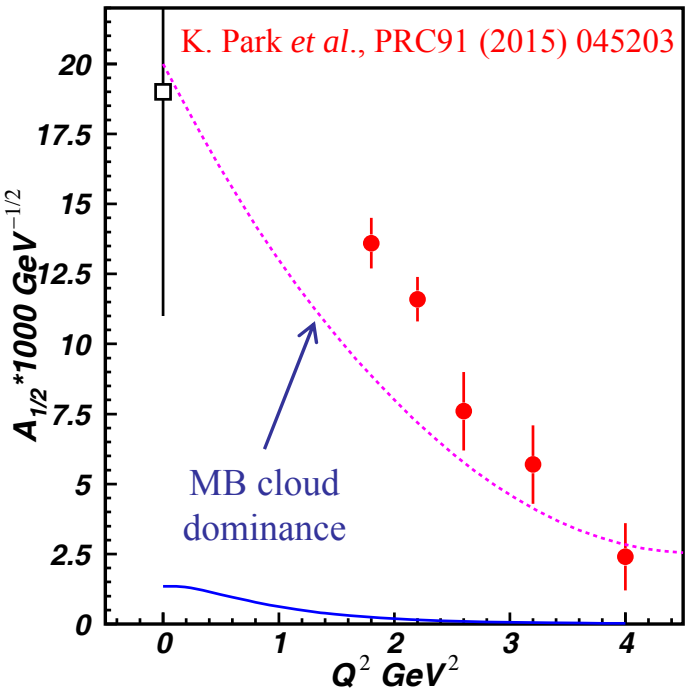
ηp CLAS/Hall-C

Interplay between Meson-Baryon Cloud and Quark Core

N(1520)3/2$^-$



N(1675)5/2$^-$



..... Argonne-Osaka MB dressing (absolute values)

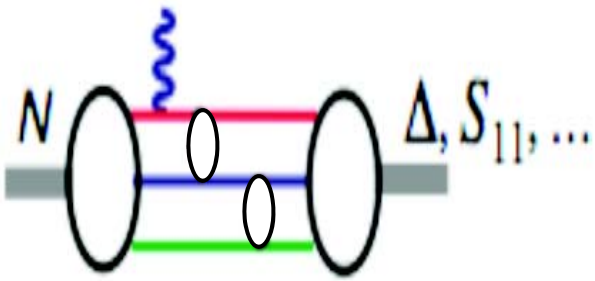
——— E. Santopinto and M. Giannini, PRC 86 (2012) 065202

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$^-$

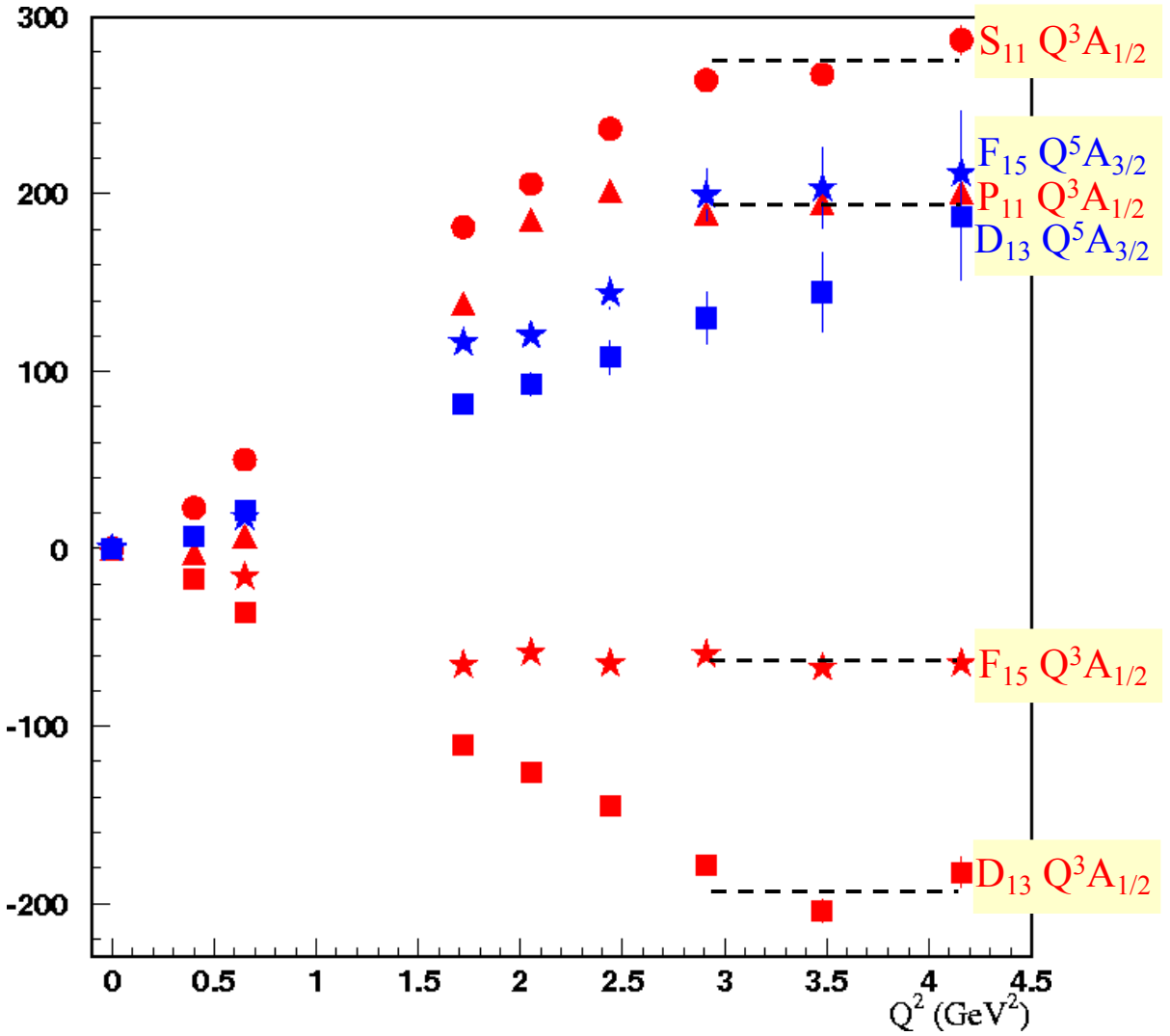
sheds light on the transition from the confined quark to the colorless meson-baryon structure and its dependents on the N* quantum numbers.

Evidence for the Onset of Precocious Scaling?



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

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



Evidence for the Onset of Precocious Scaling?

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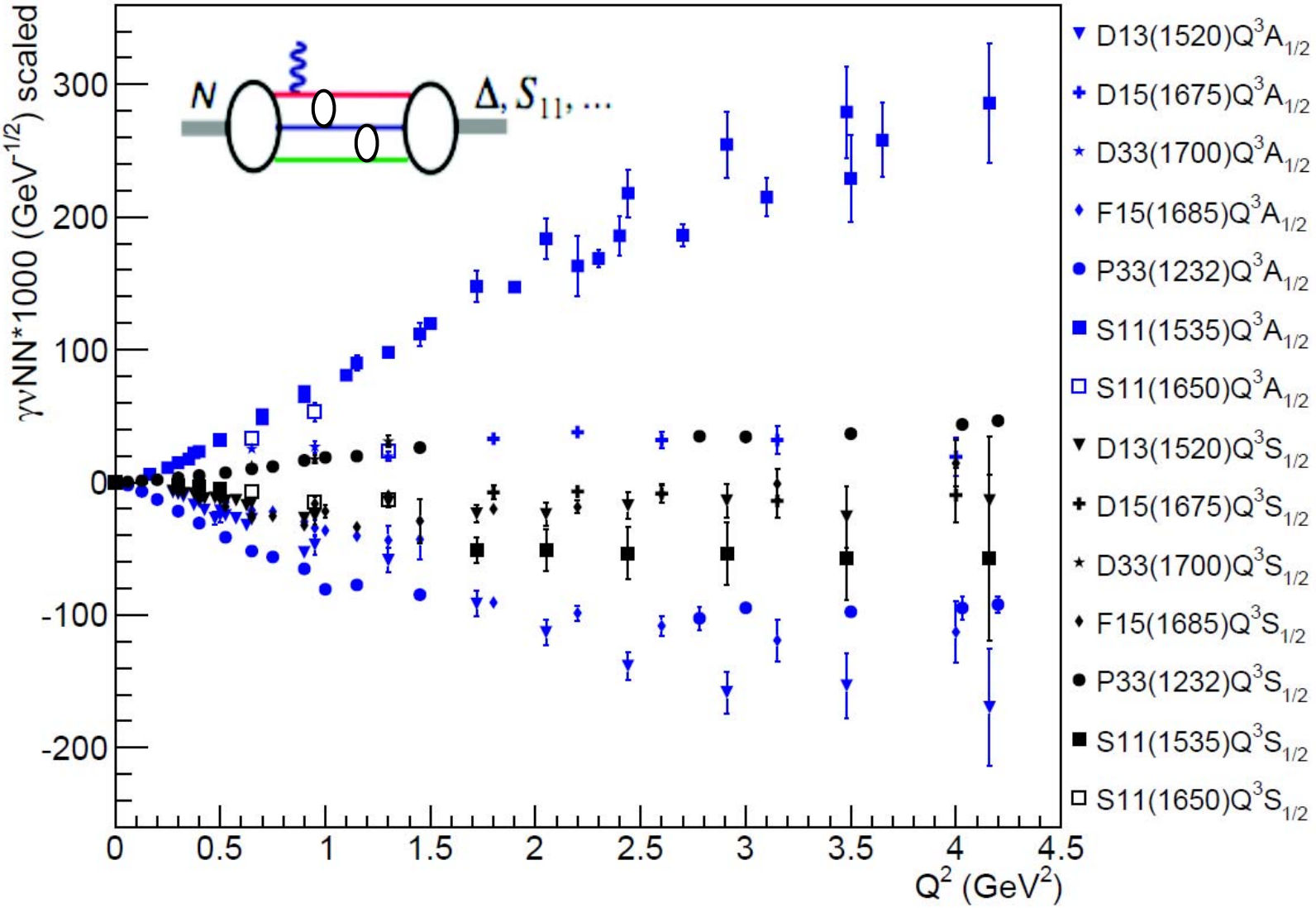

V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)

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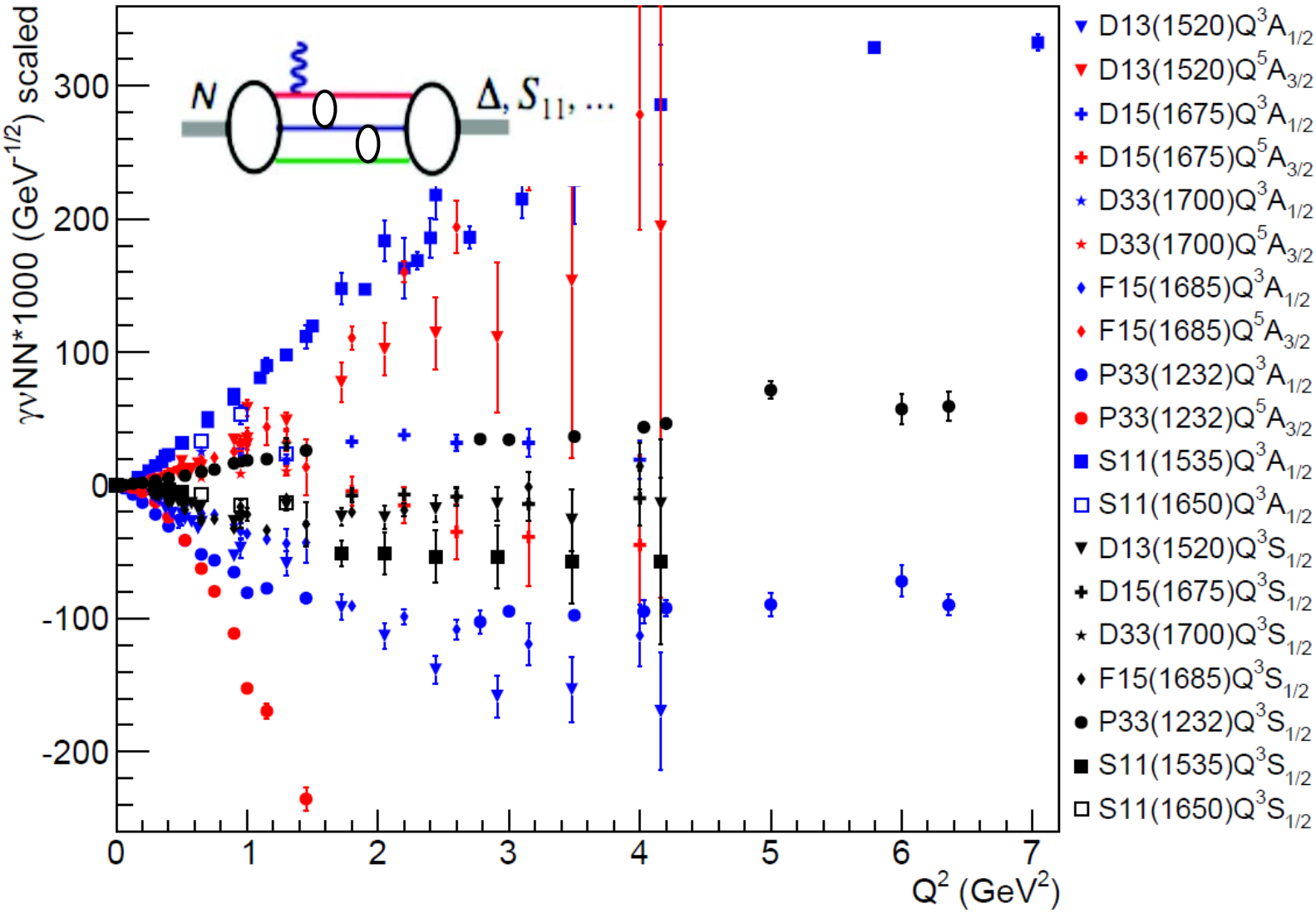

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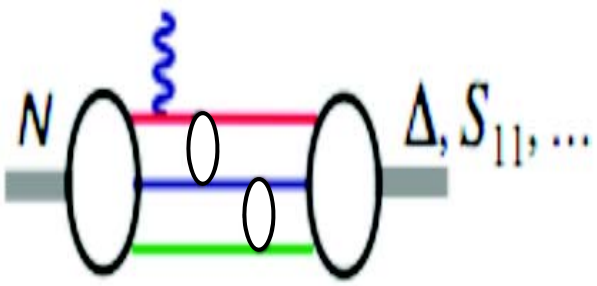
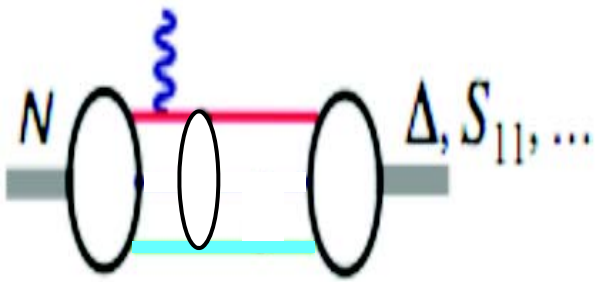
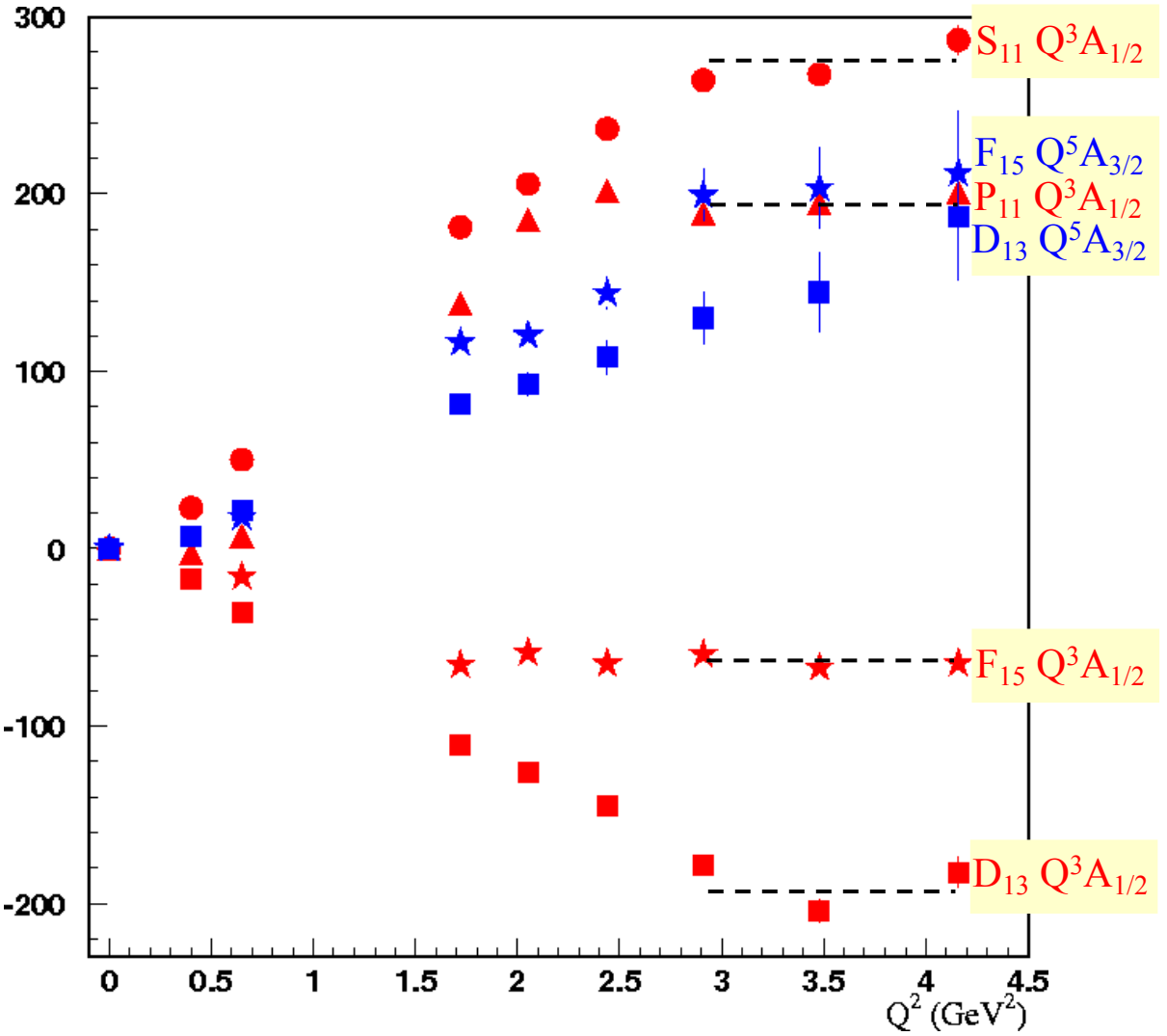


- $A_{1/2} \alpha 1/Q^3$
- $A_{3/2} \alpha 1/Q^5$
- $G_M^* \alpha 1/Q^4$

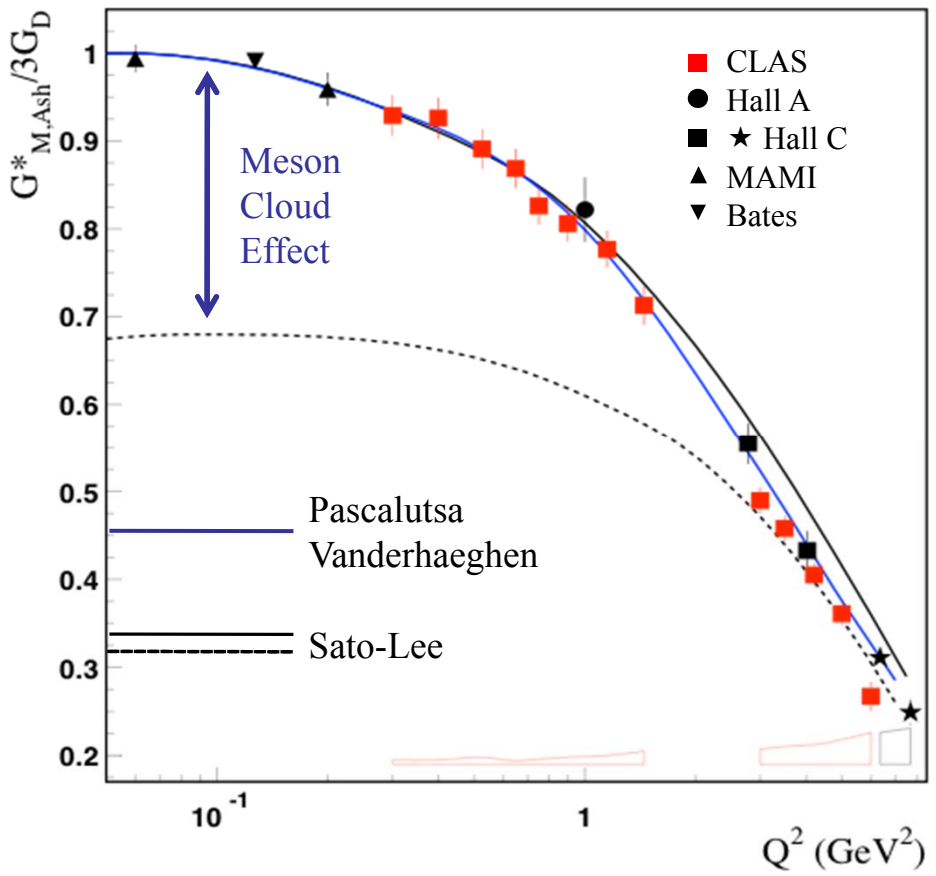


q^2q

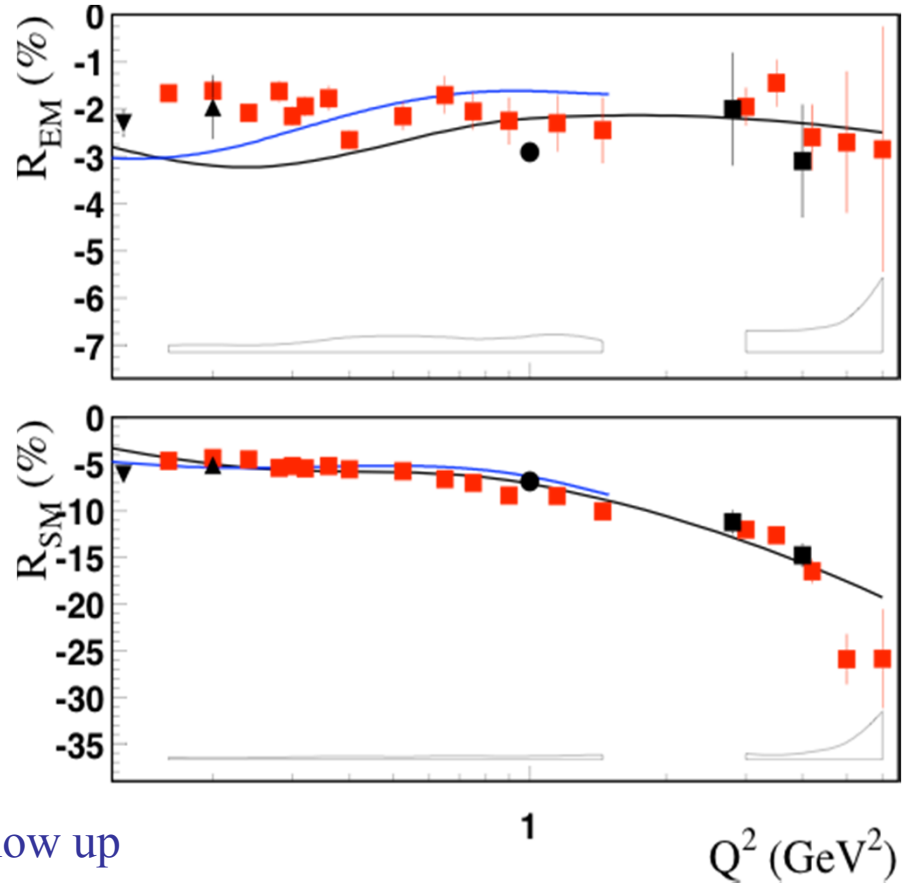
I. G. Aznauryan *et al.*, Phys. Rev. C80, 055203 (2009)



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



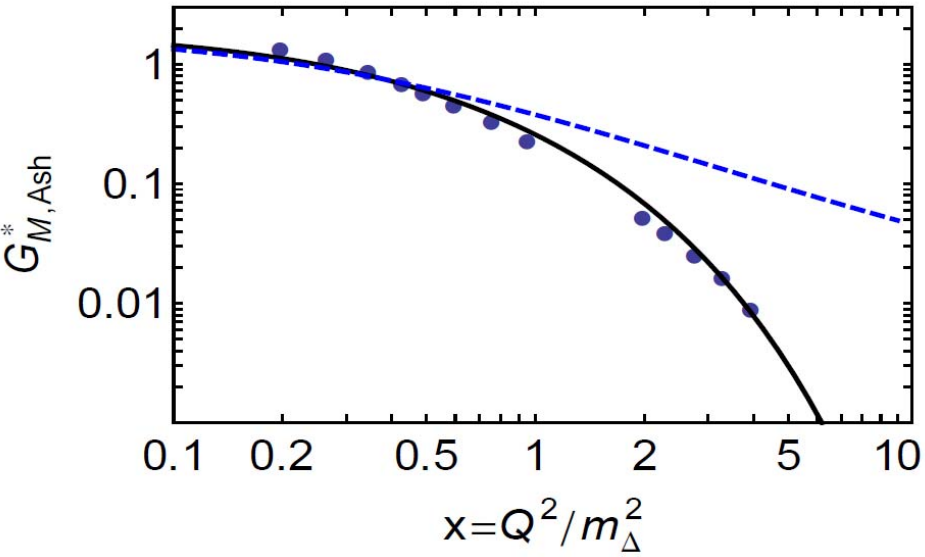
Phys. Rev. Lett. 97, 112003 (2006)



- 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

Anomalous Magnetic Moment in DSE Approach

J. Segovia

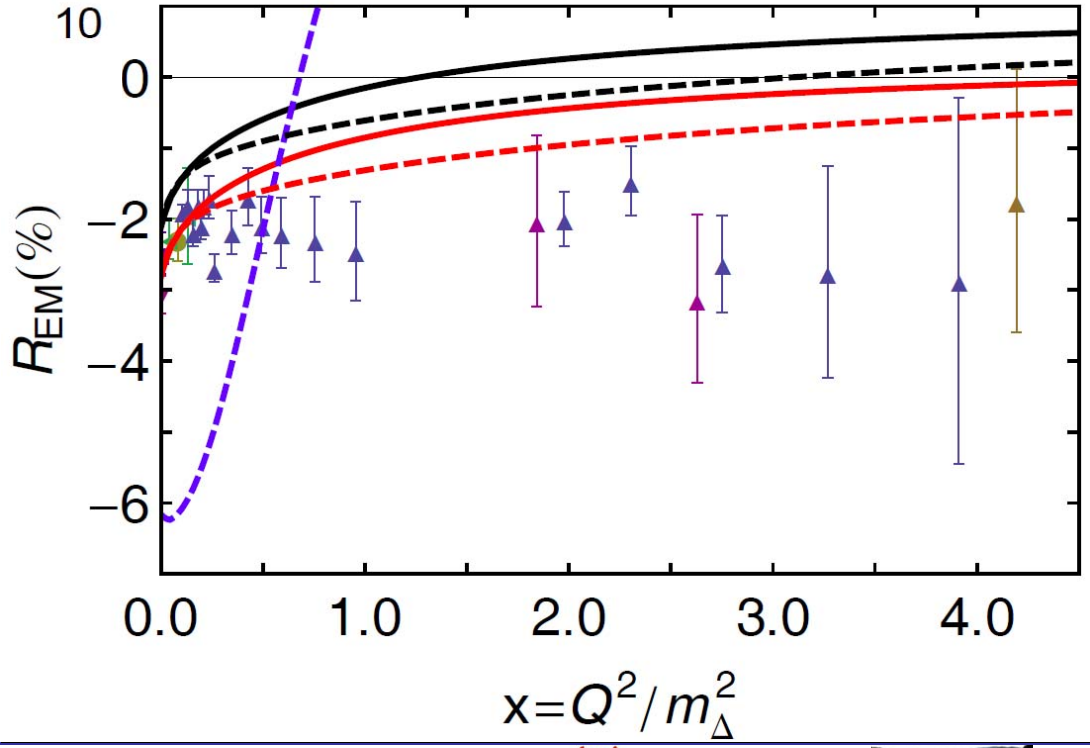


contact interaction

sophisticated interaction

with momentum dependent κ

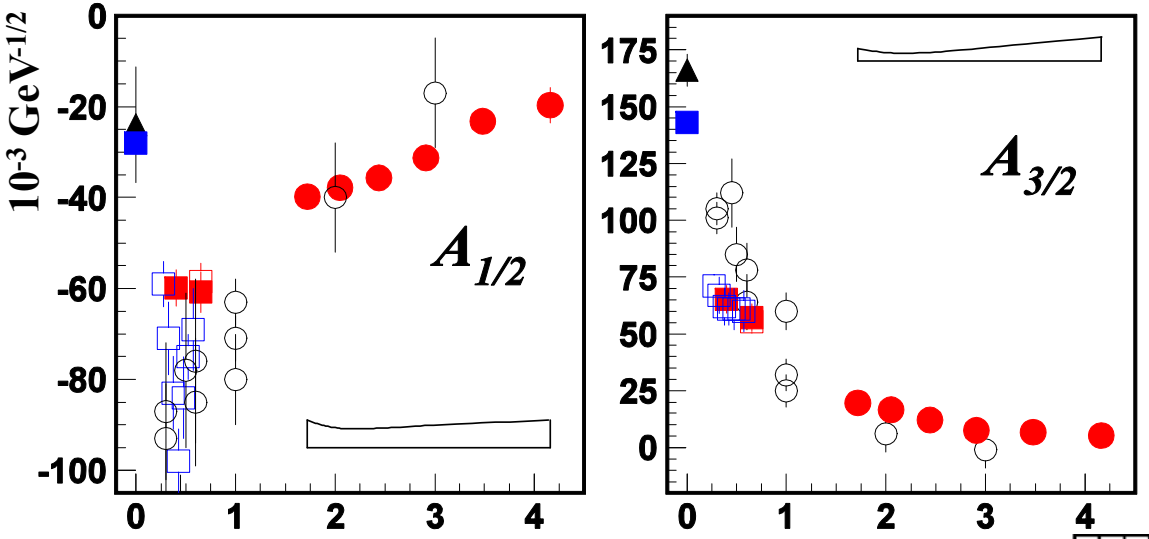
renormalized at real photon point



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

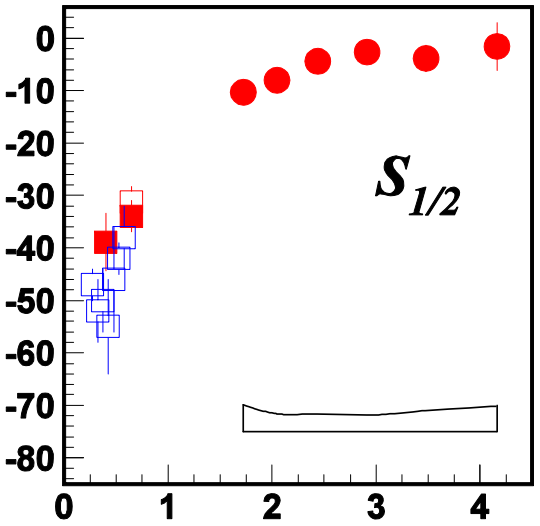
The DSE calculation of R_{EM} zero crossing is sensitive to the momentum dependent anomalous magnetic moment of the dressed-quark.

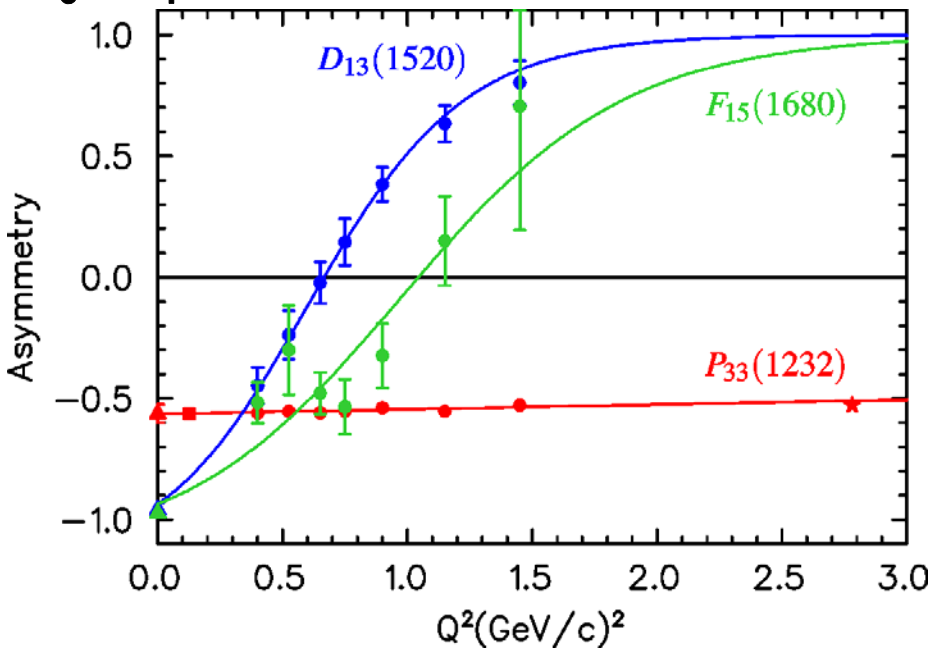
$N(1520)D_{13}$ Helicity Asymmetry



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

L. Tiator



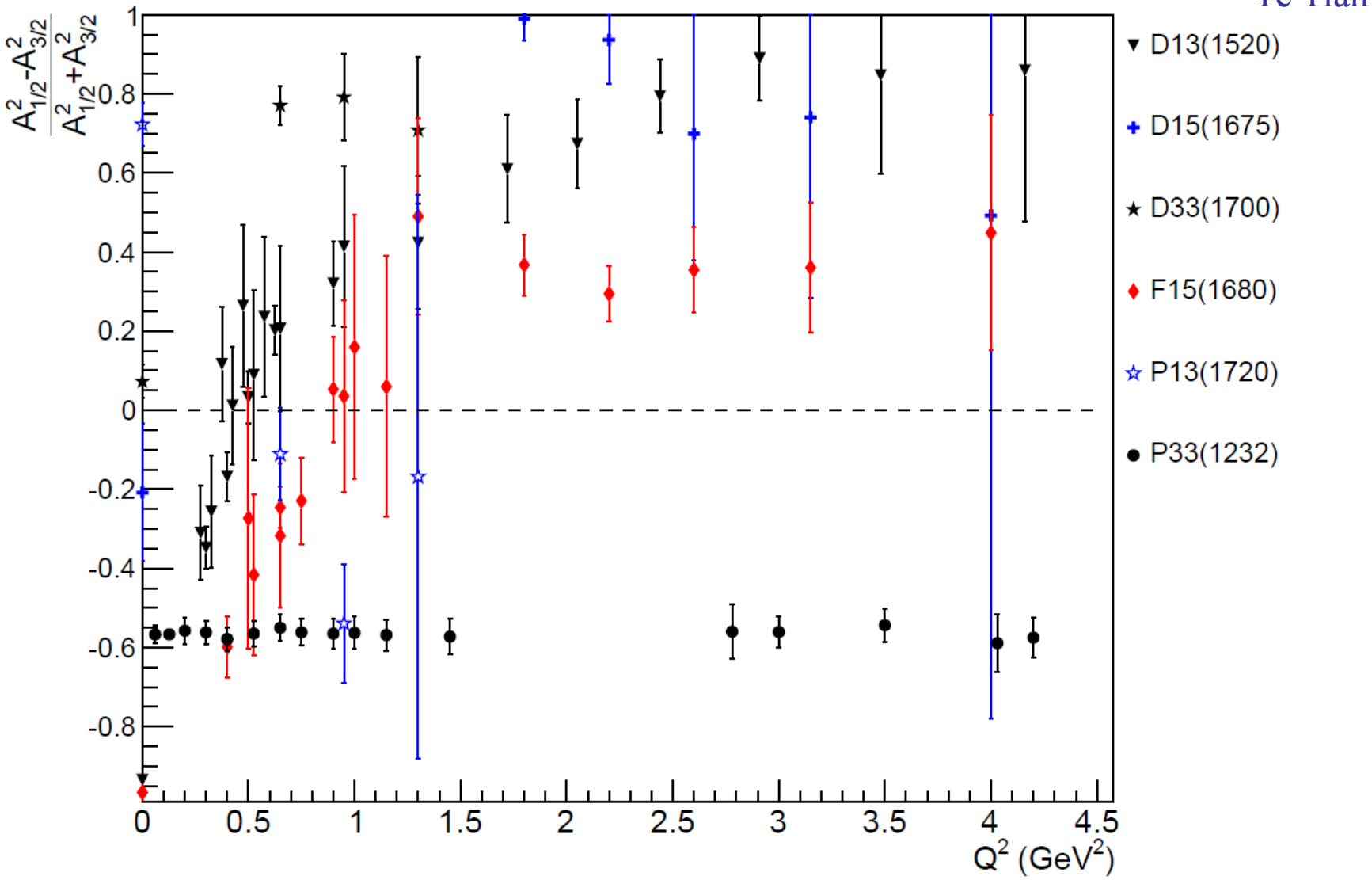


○ world data

▲ PDG estimation ● ■ Nπ (UIM, DR)

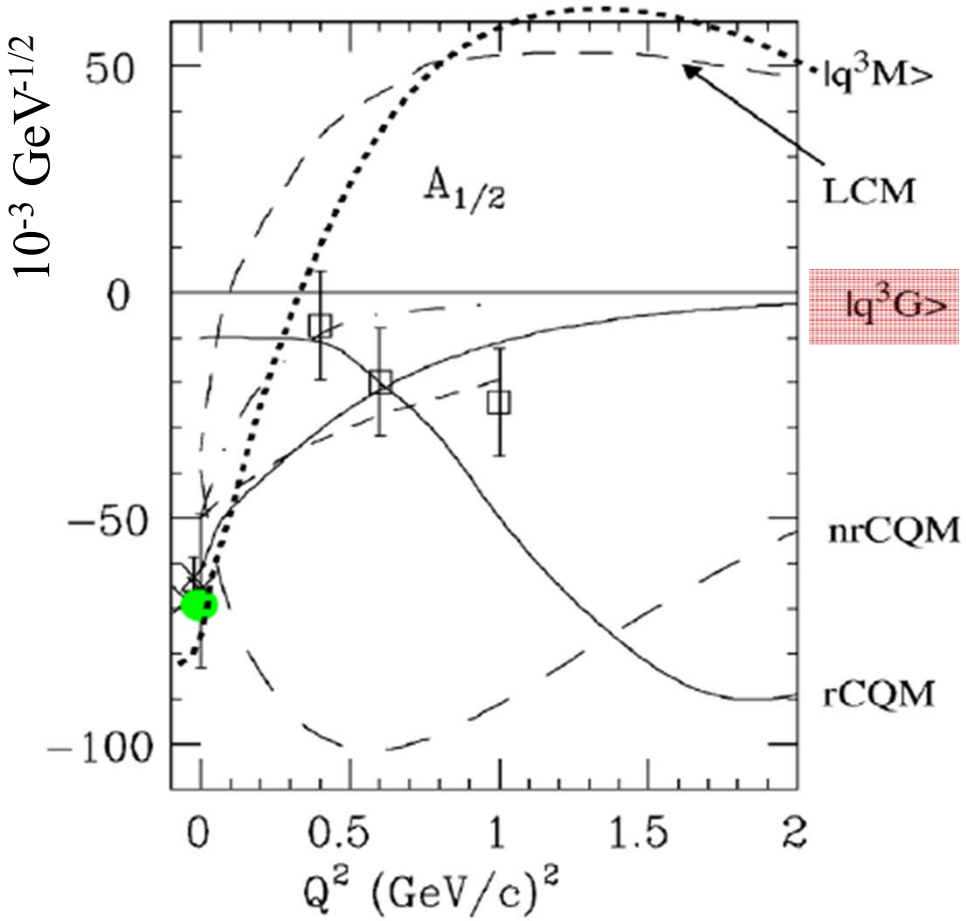
γNN* Helicity Asymmetries

Ye Tian



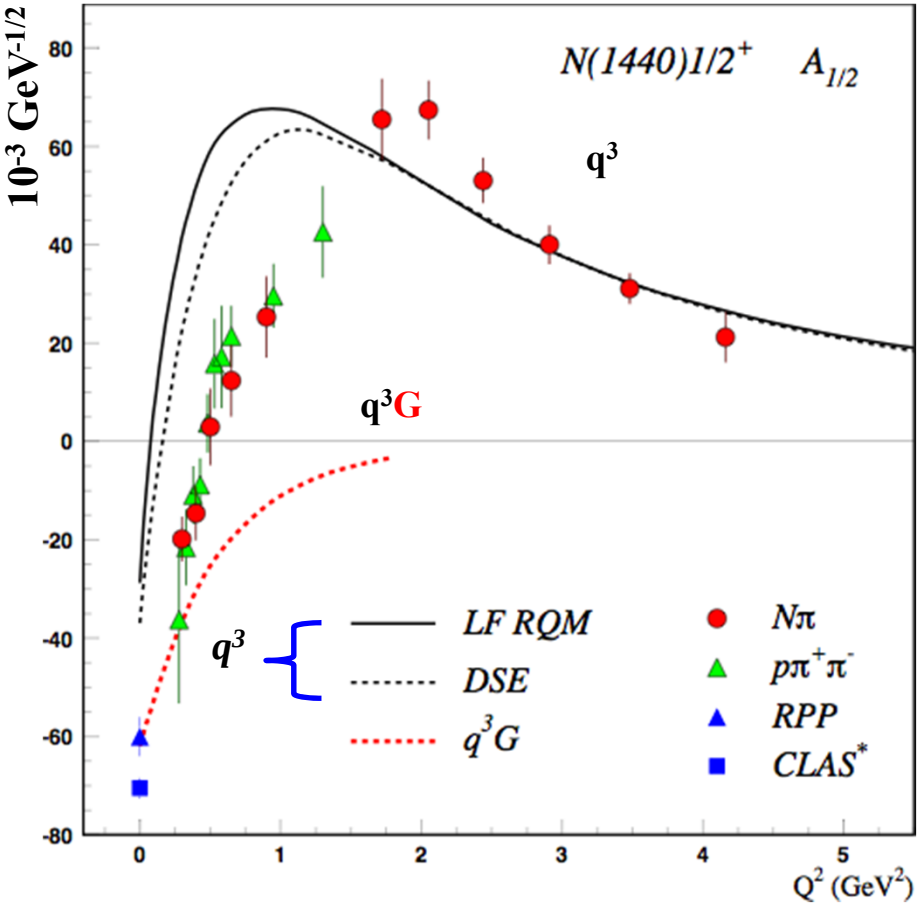
V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)

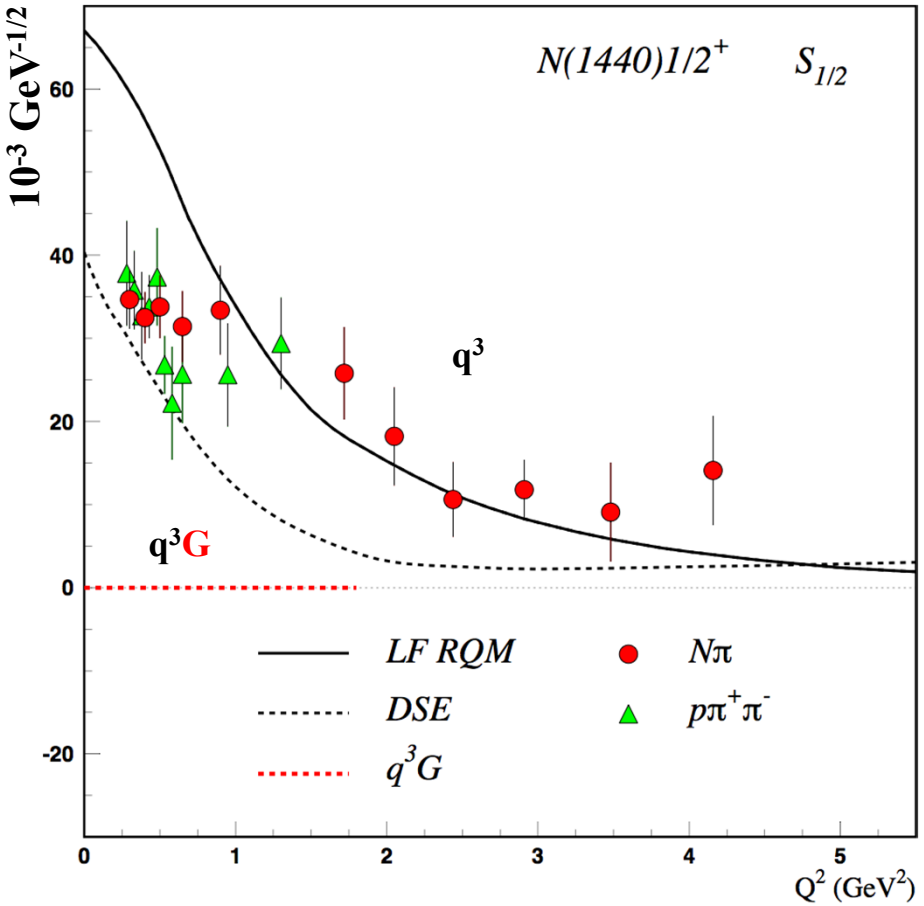
Electrocouplings of $N(1440)P_{11}$ History



- 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

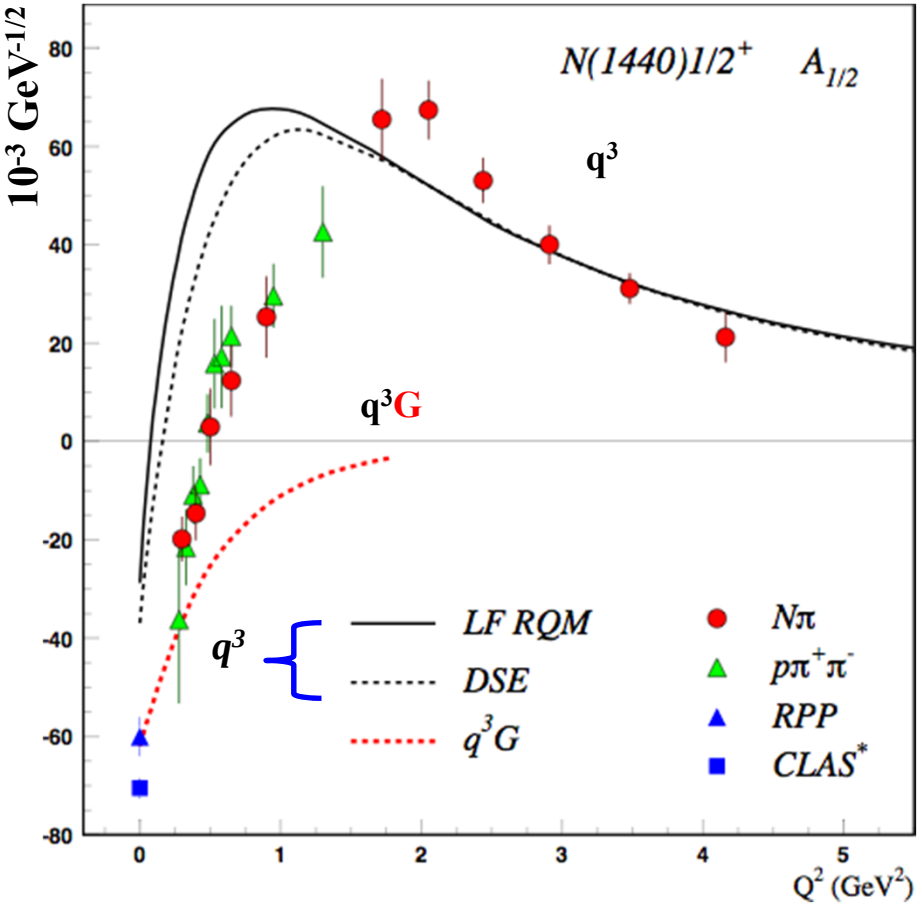




- $A_{1/2}$ has zero-crossing near Q^2=0.5 and becomes dominant amplitude at high Q^2.
- Consistent with radial excitation at high Q^2 and large meson-baryon coupling at small Q^2.
- Eliminates gluonic excitation (q^3G) as a dominant contribution.

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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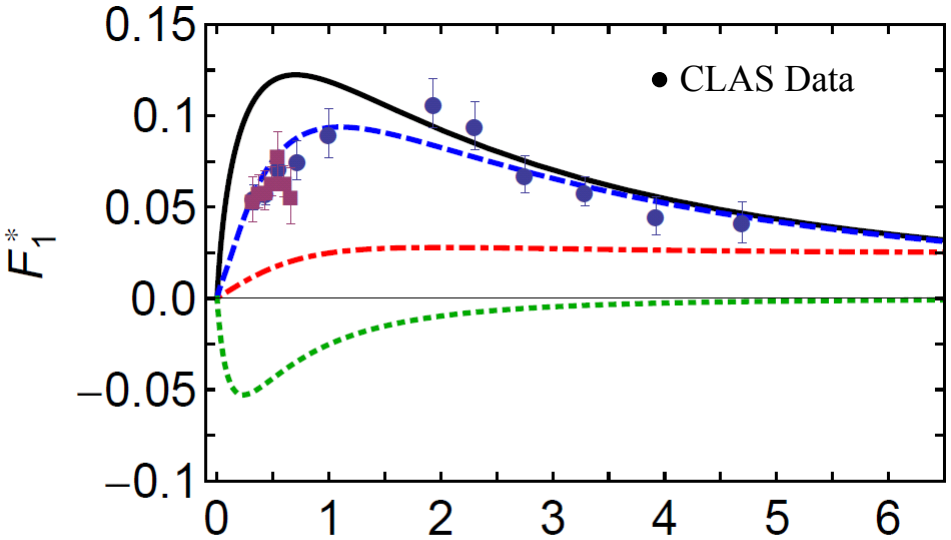
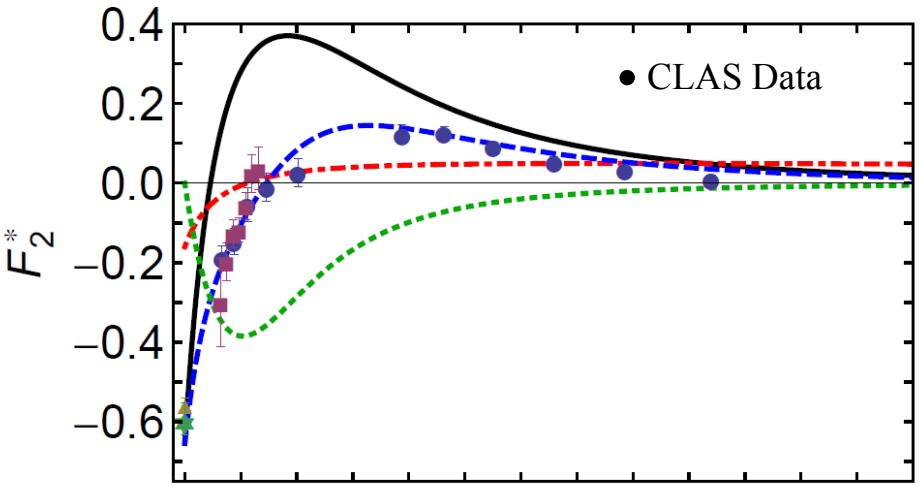
Roper Transition Form Factors in DSE Approach

$N(1440)P_{11}$

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





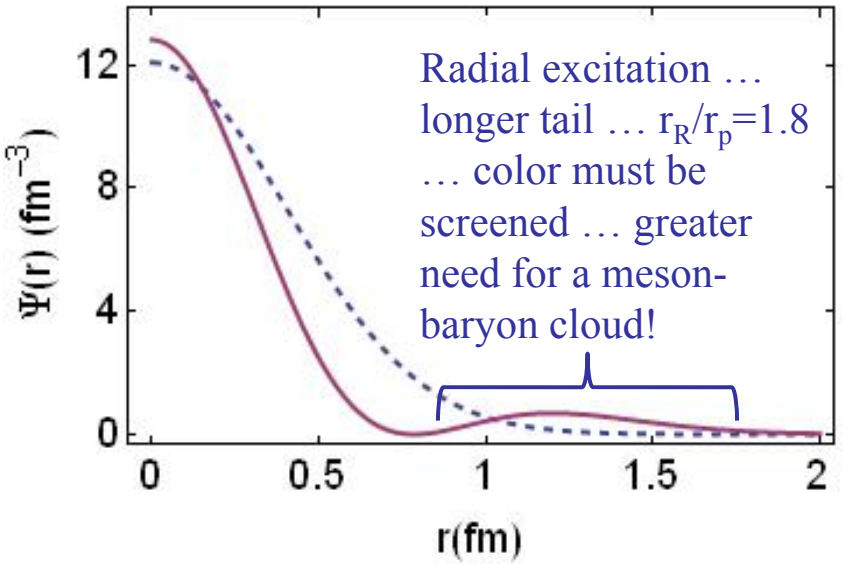
DSE Contact

DSE Realistic

Inferred meson-cloud contribution

Anticipated complete result

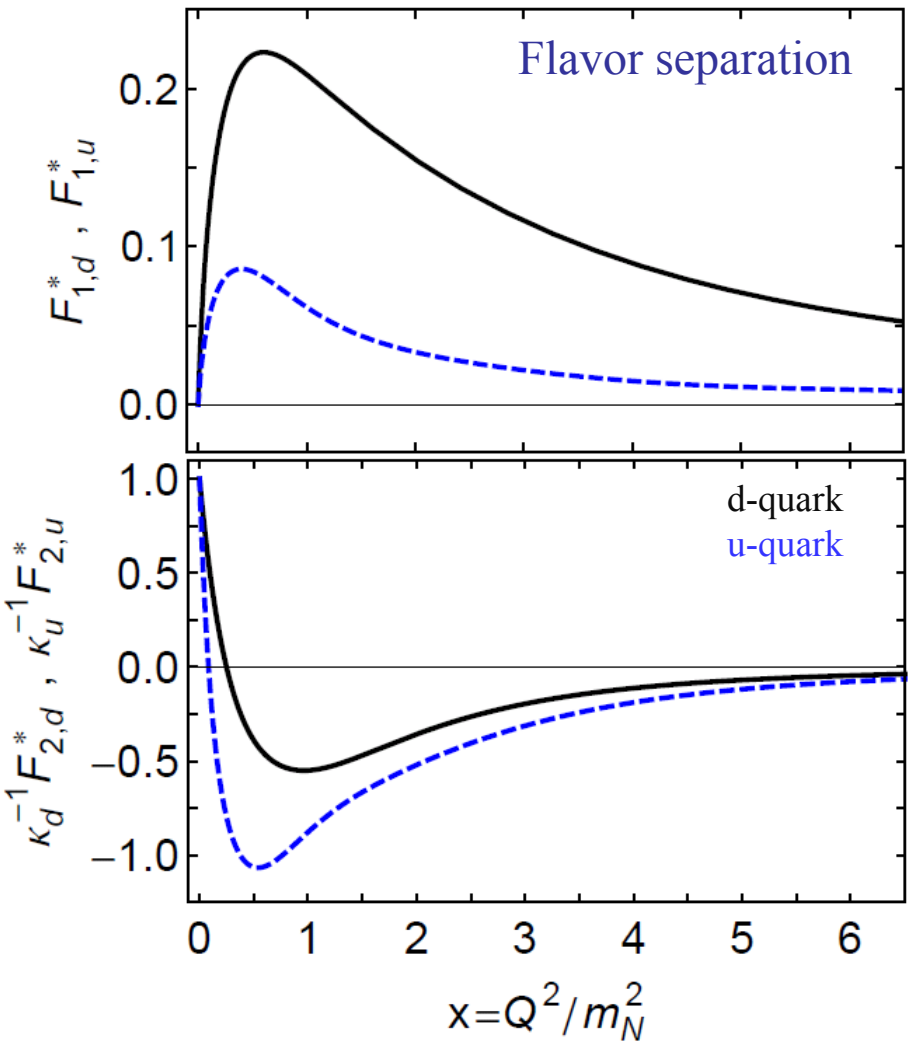
Importantly, the existence of a zero in F_2 is not influenced by meson-cloud effects, although its precise location is.

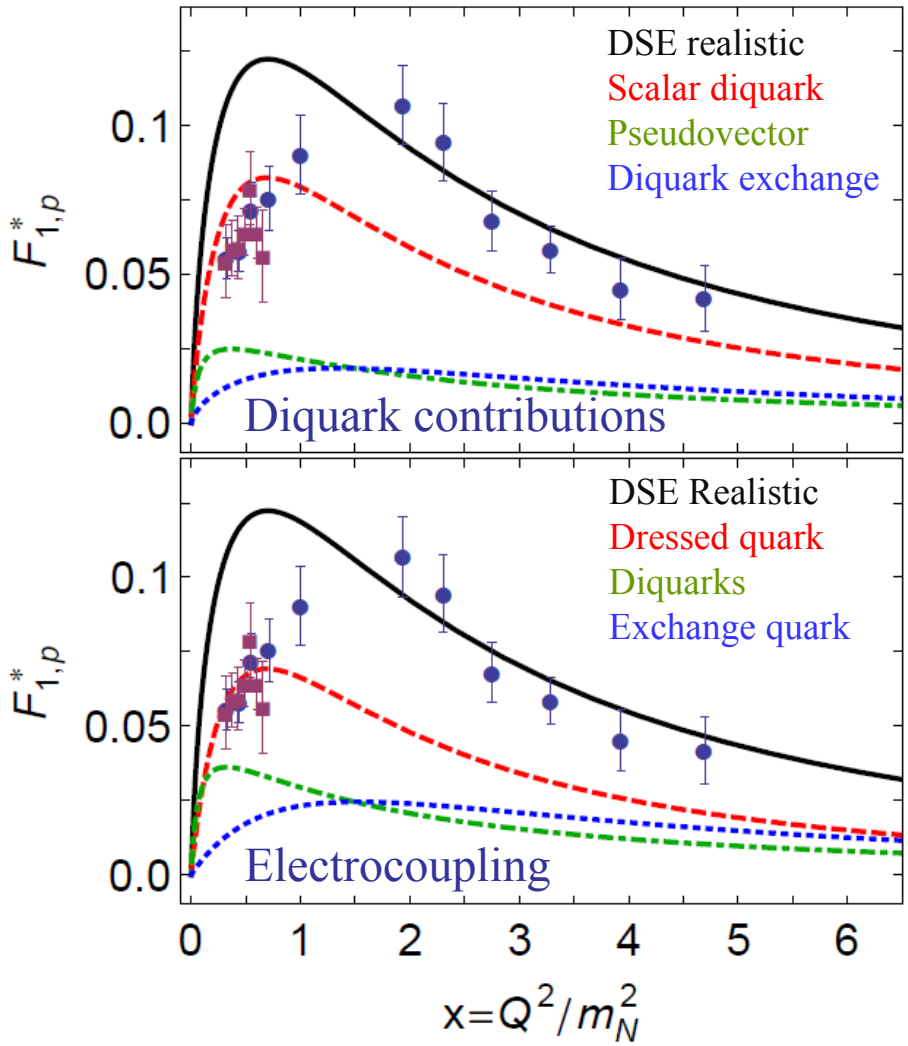


Roper Transition Form Factors in DSE Approach

$N(1440)P_{11}$

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

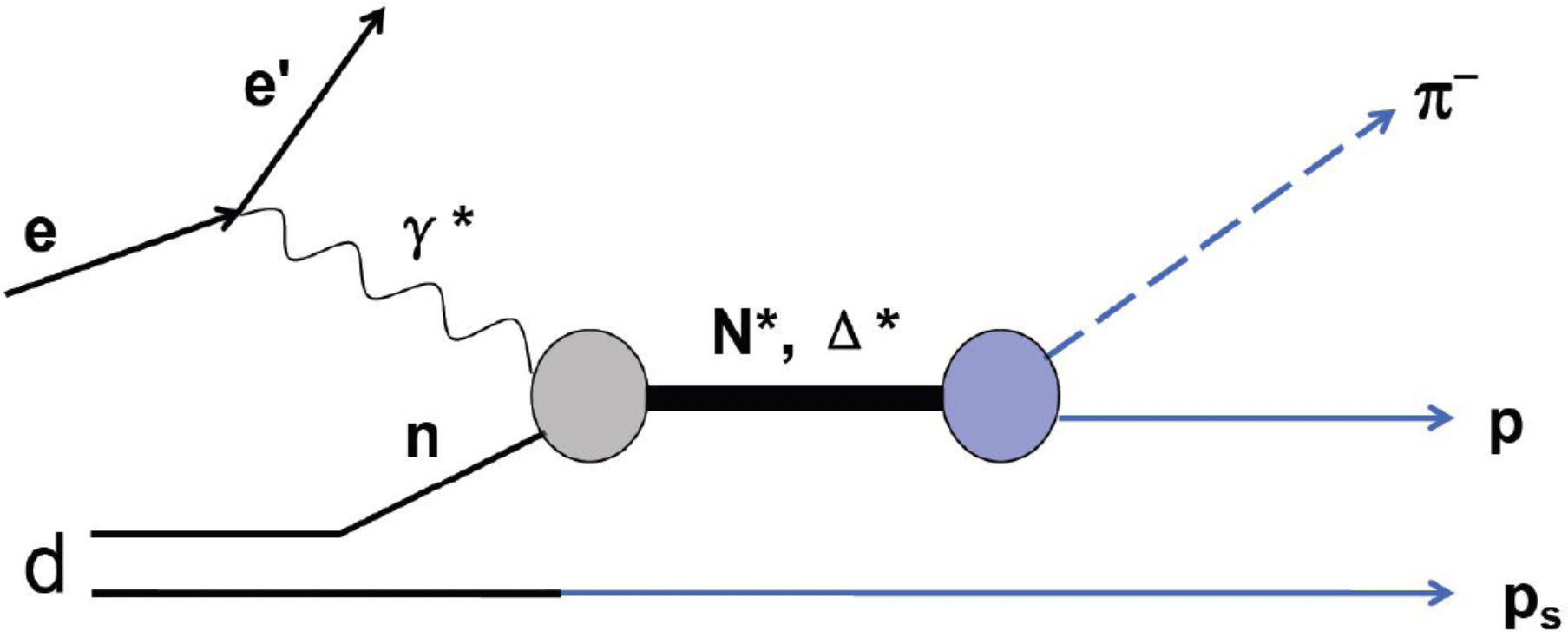




New Experimental Results & Approaches

Single π^- Electroproduction off the Deuteron

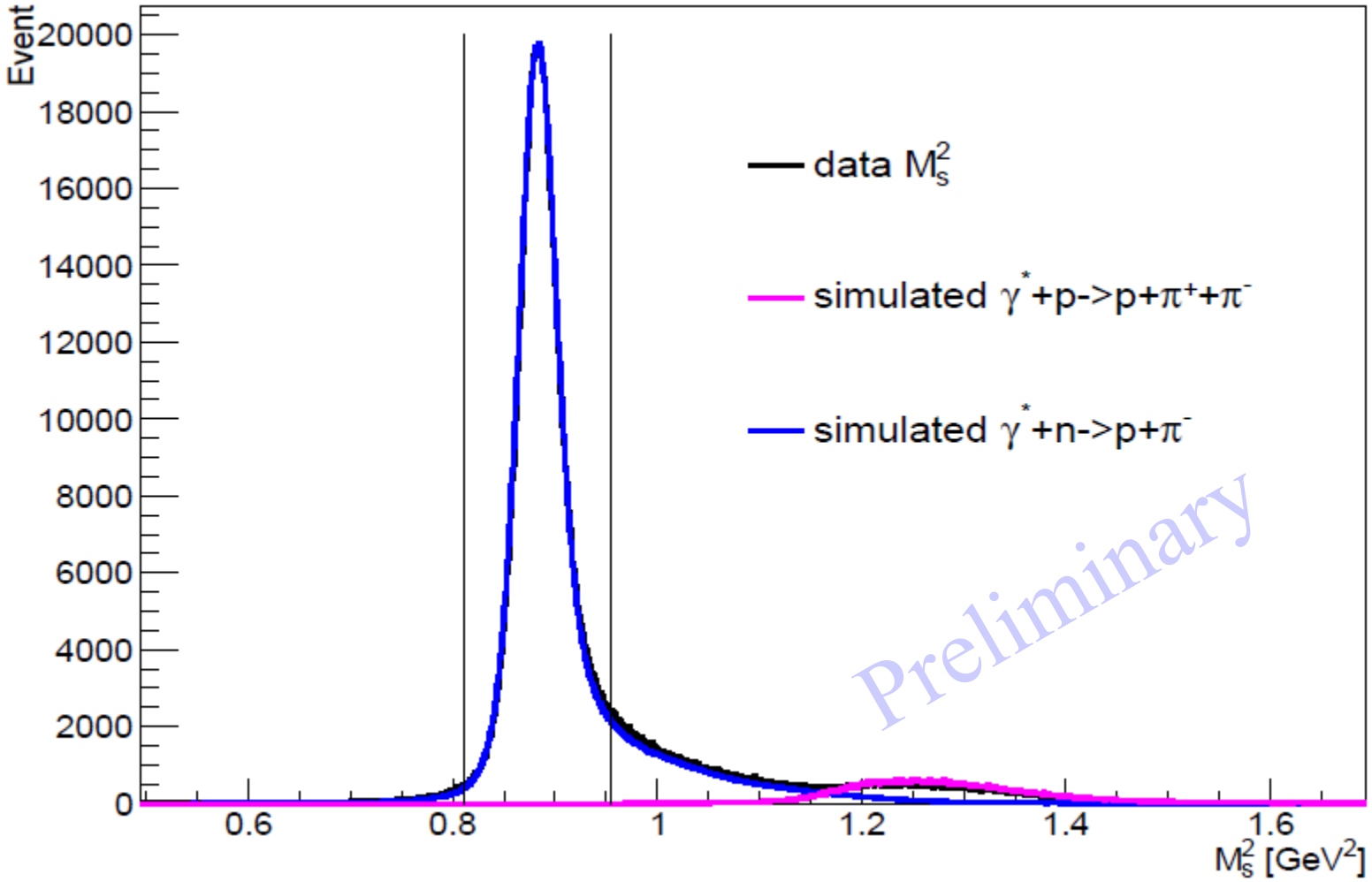
Ye Tian



Exclusive ⇨ Spectator ⇨ Quasi-Free ⇨ FSI

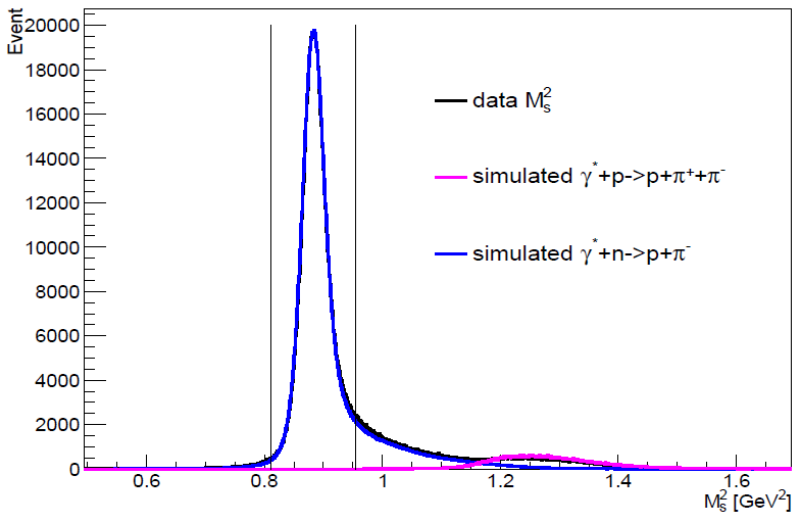
Single π^- Electroproduction off the Deuteron

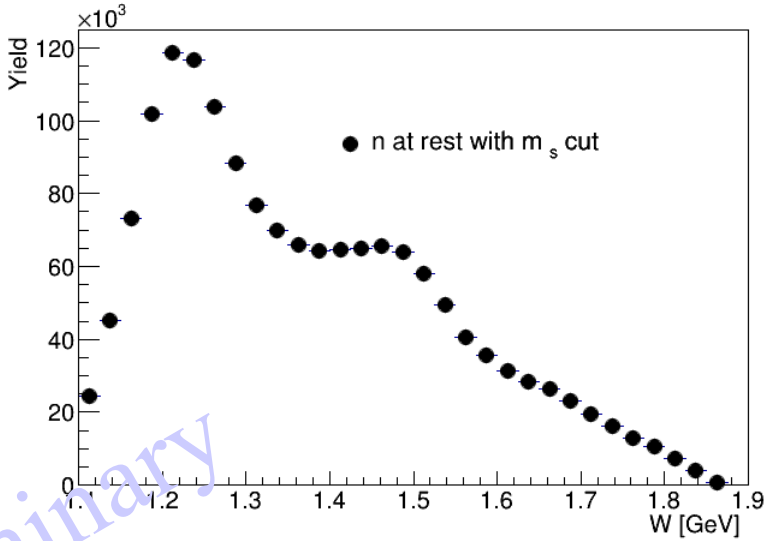
Ye Tian

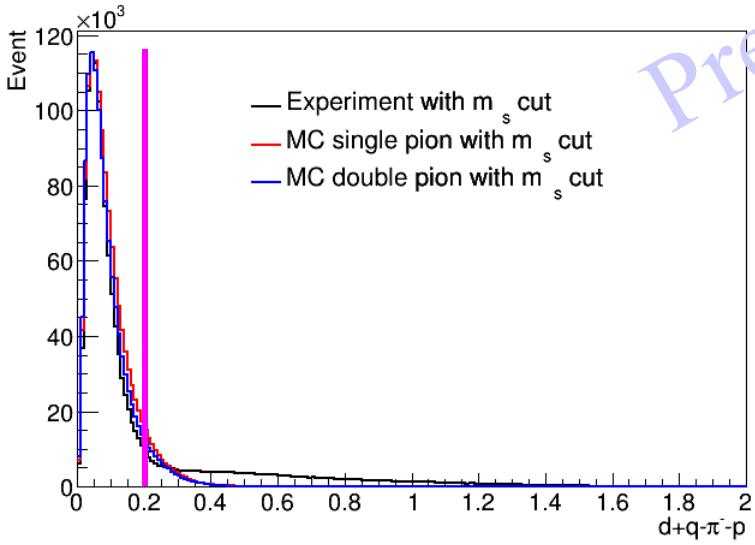


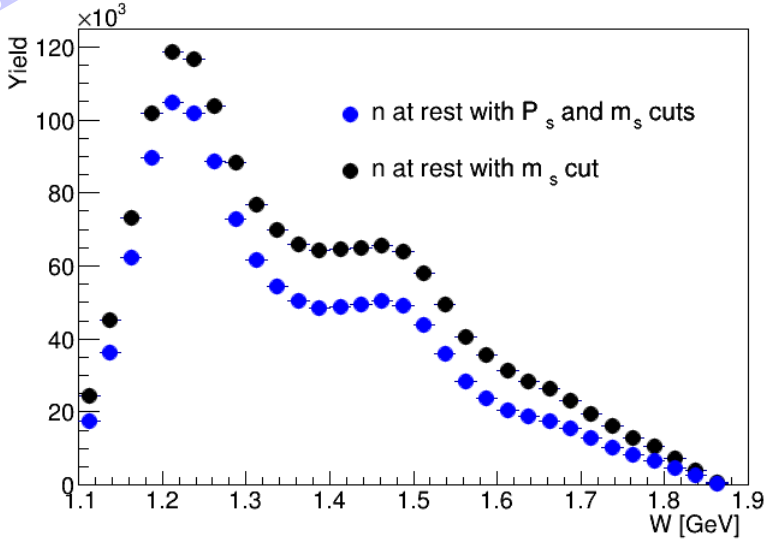
Single π^- Electroproduction off the Deuteron

Ye Tian



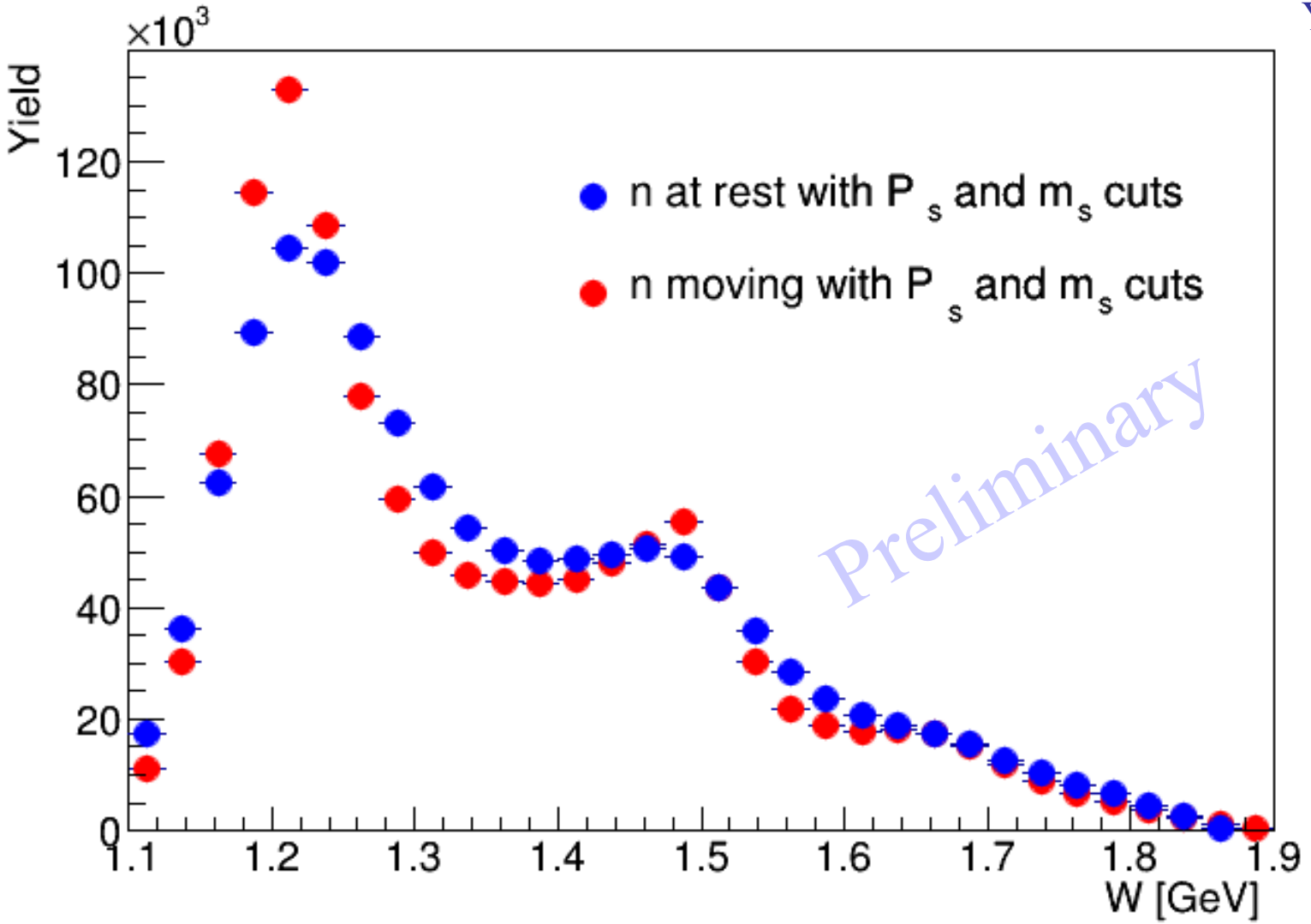






Single π^- Electroproduction off the Deuteron

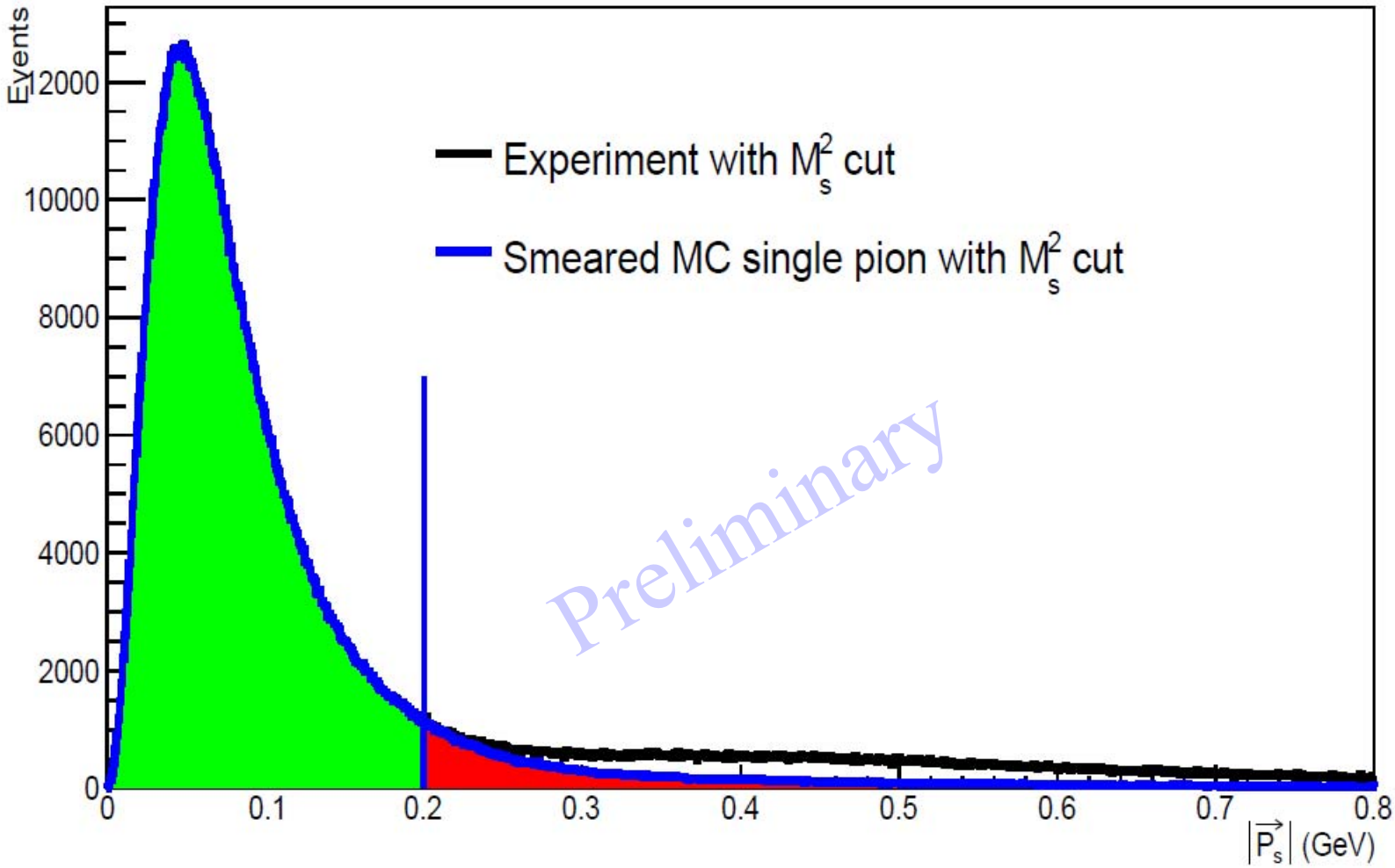
Ye Tian



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

Single π^- Electroproduction off the Deuteron

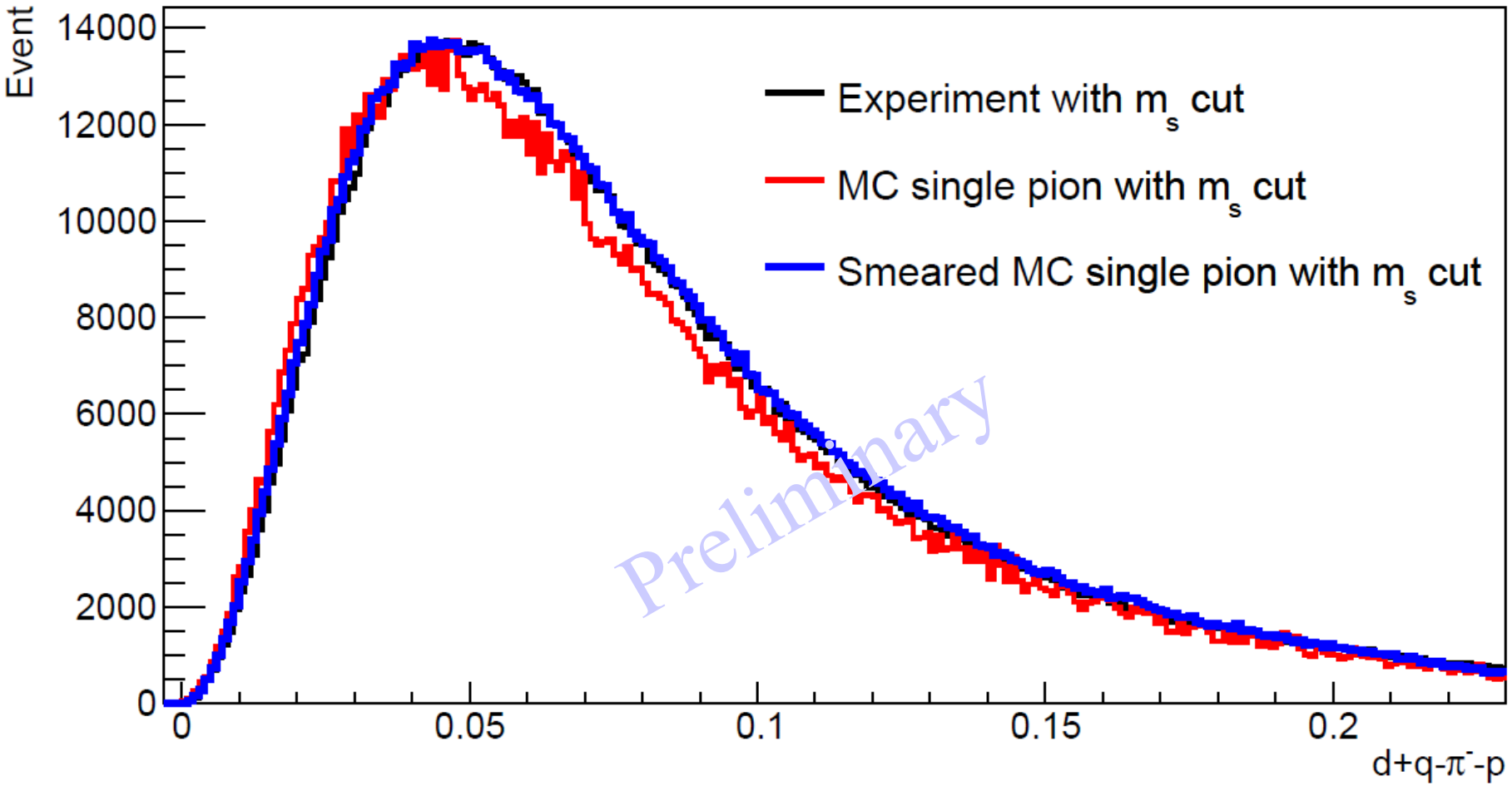
Ye Tian



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

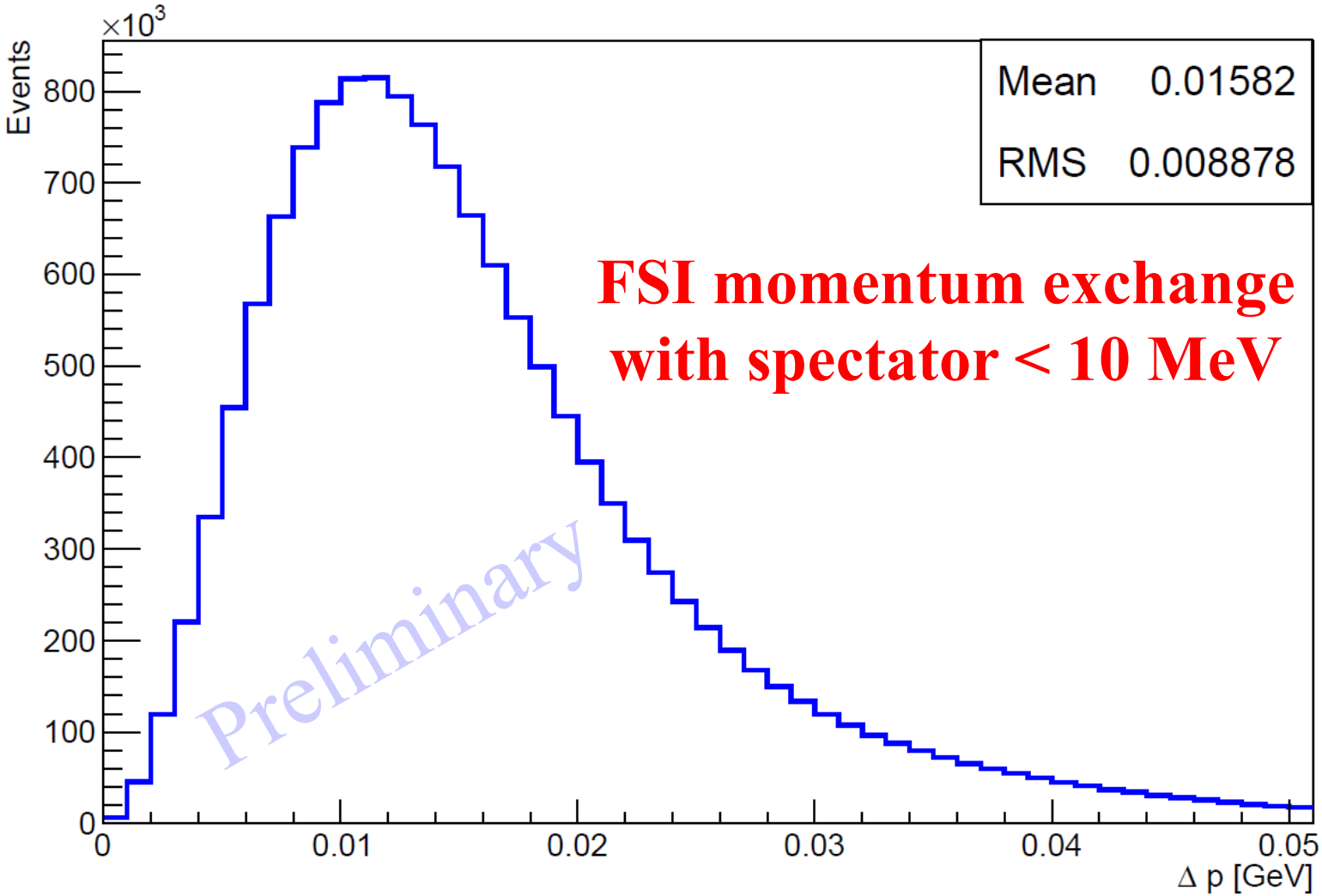
Ye Tian



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



Momentum resolution with CLAS of the reconstructed missing momentum of the second proton.

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

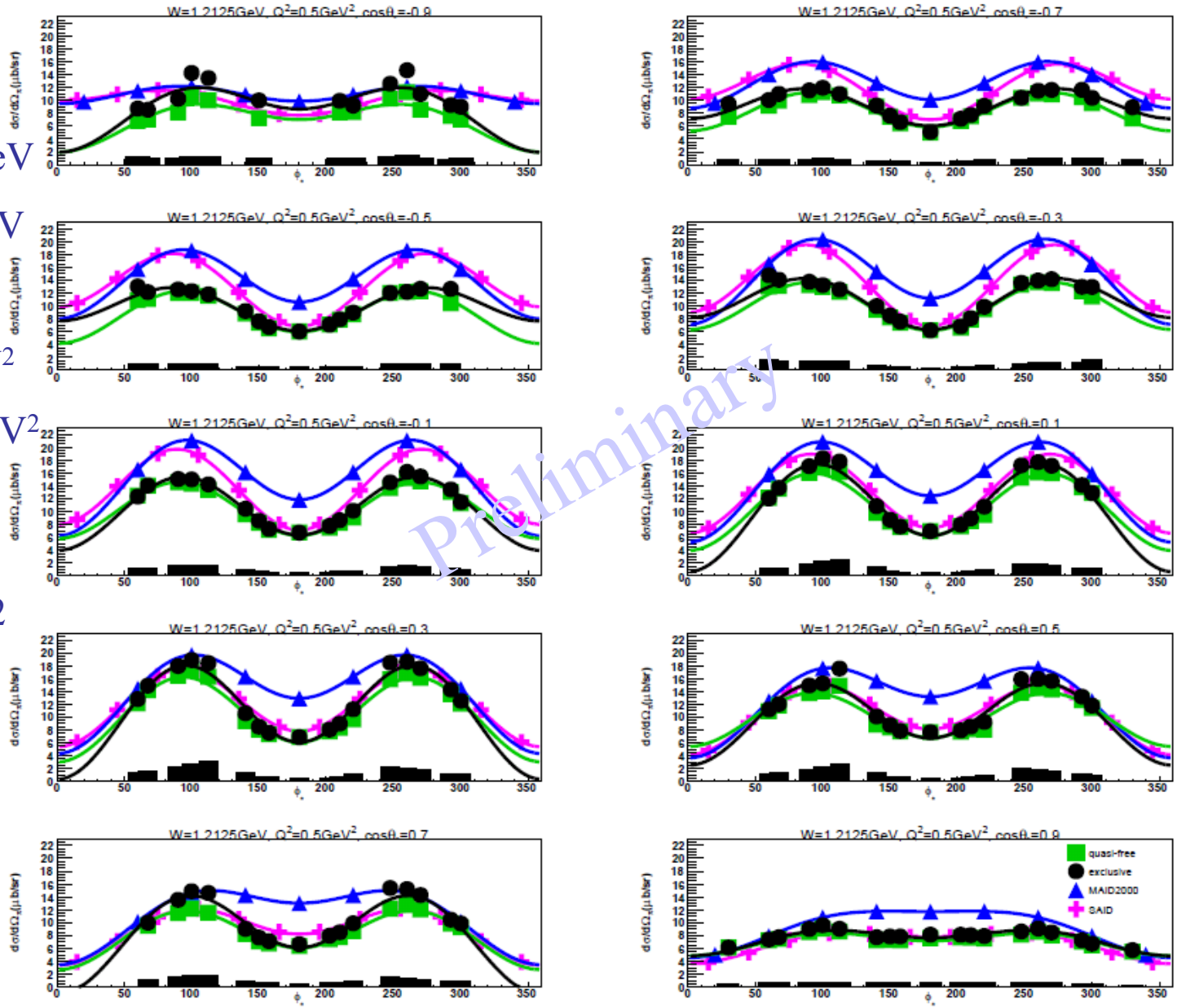
Δcos(θ) = 0.2

cos(θ) = 0.7

ϕ = 20°

Δϕ = 40°

ϕ = 340°

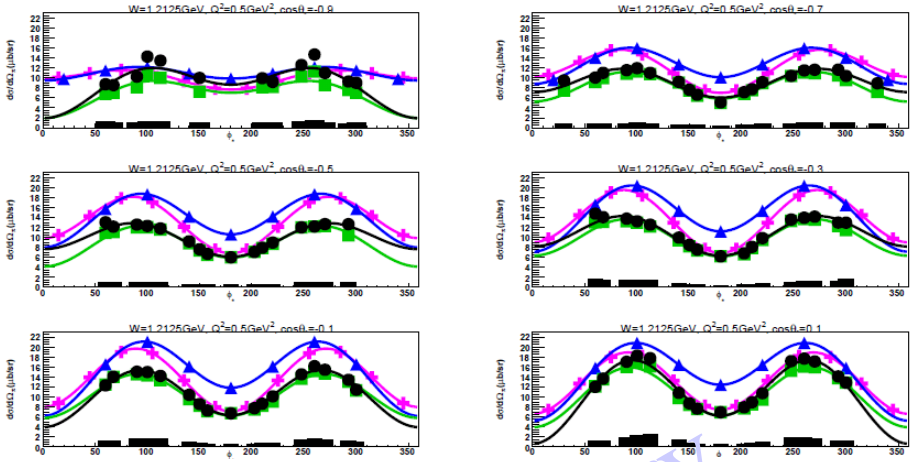


Single π^- Electroproduction off the Deuteron

$Q^2 = 0.5$ GeV^2

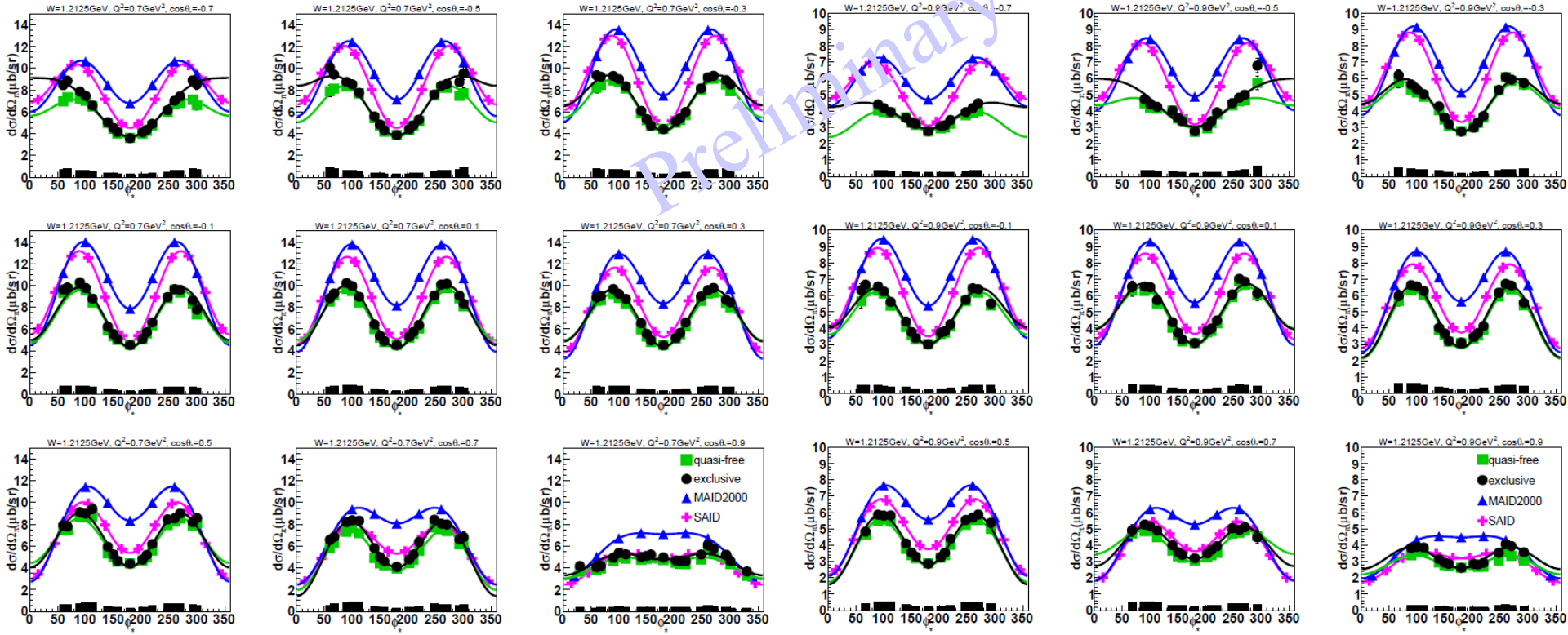
$W = 1212$ MeV

$Q^2 = 0.7$ GeV^2

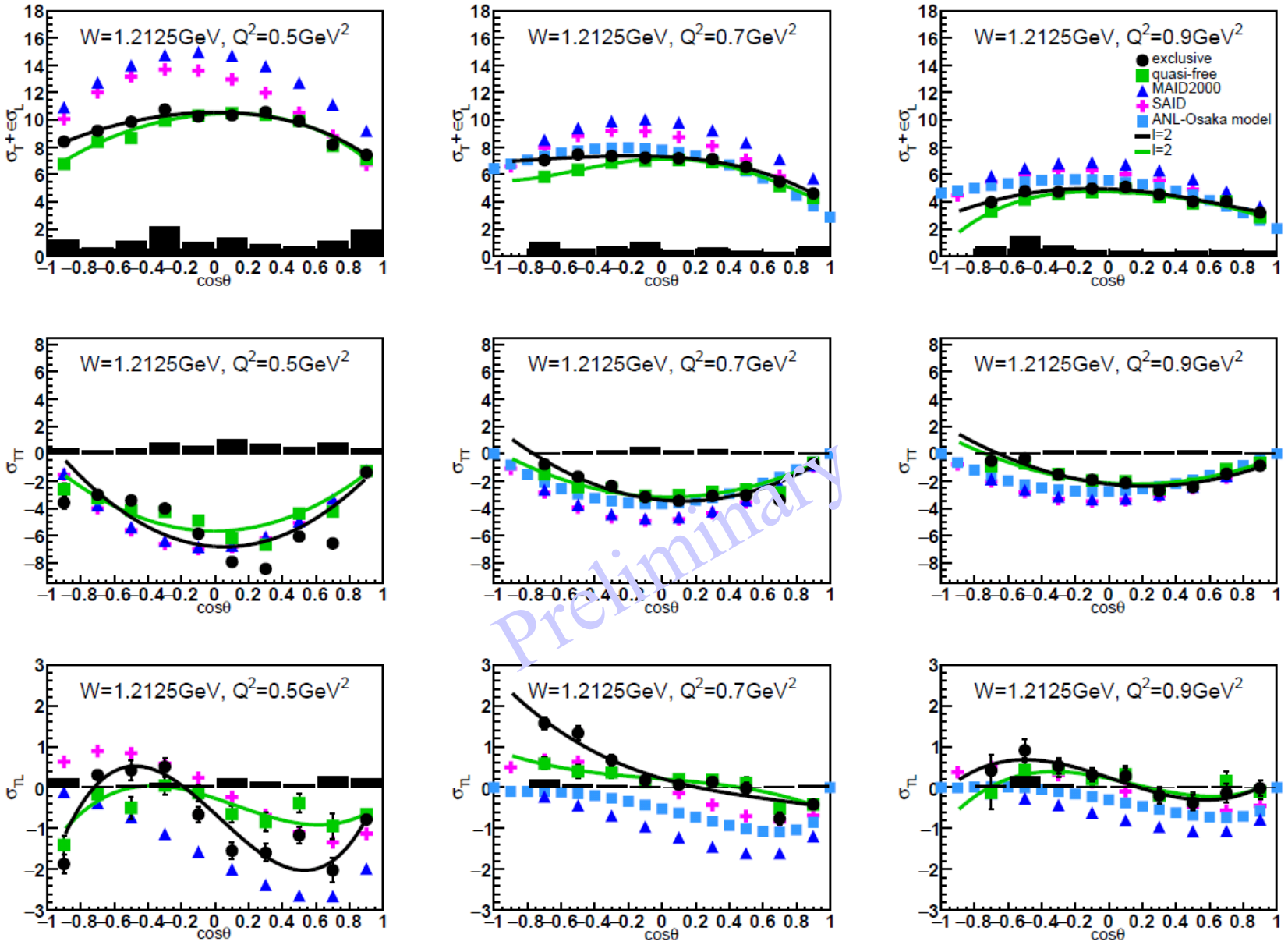


Ye Tian

$Q^2 = 0.9$ GeV^2



Single π^- Electroproduction off the Deuteron



Ye Tian

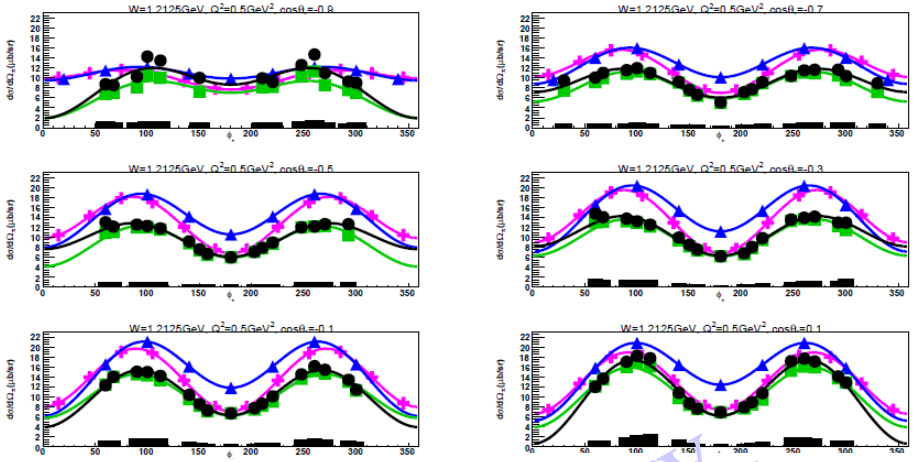
Single π^- Electroproduction off the Deuteron

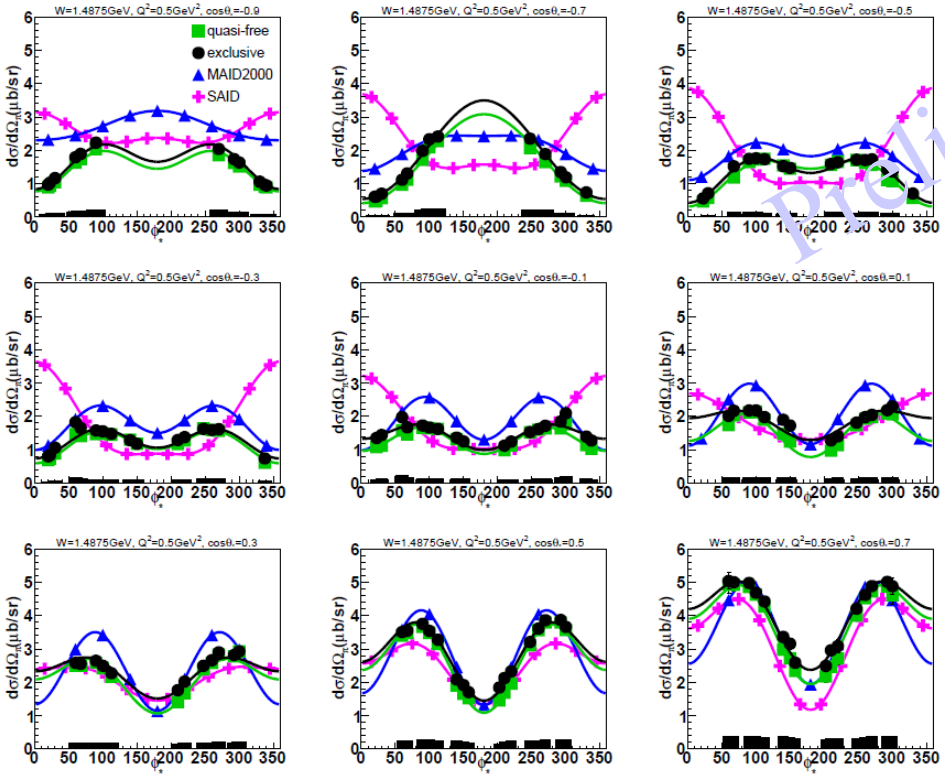
$Q^2 = 0.5$ GeV^2

$W = 1212$ MeV

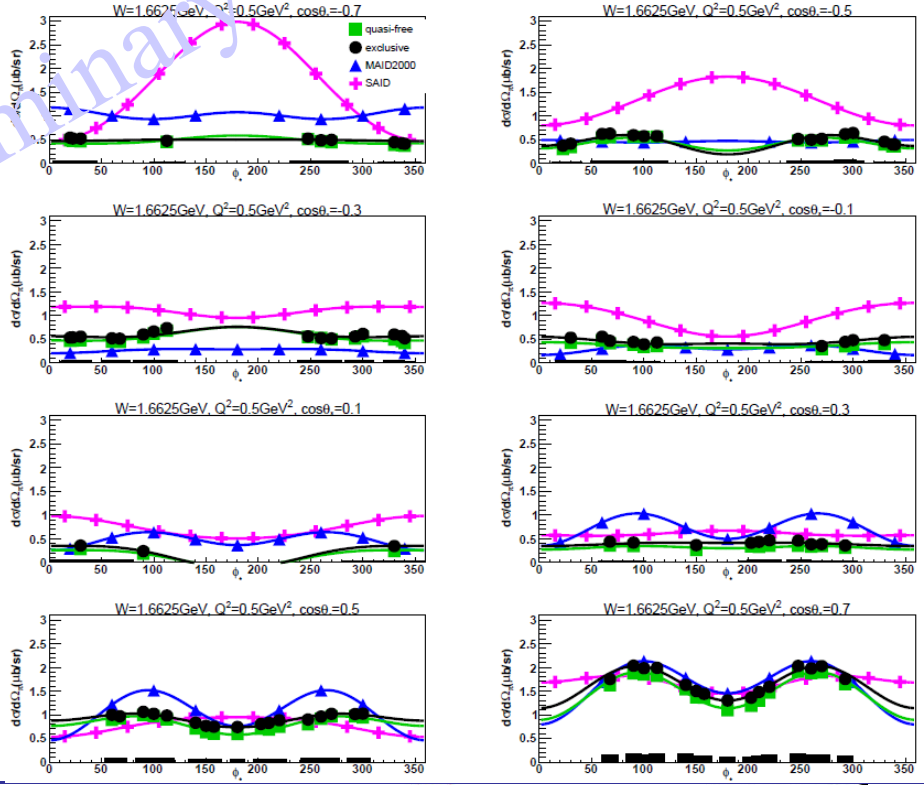
$W = 1488$ MeV

Ye Tian

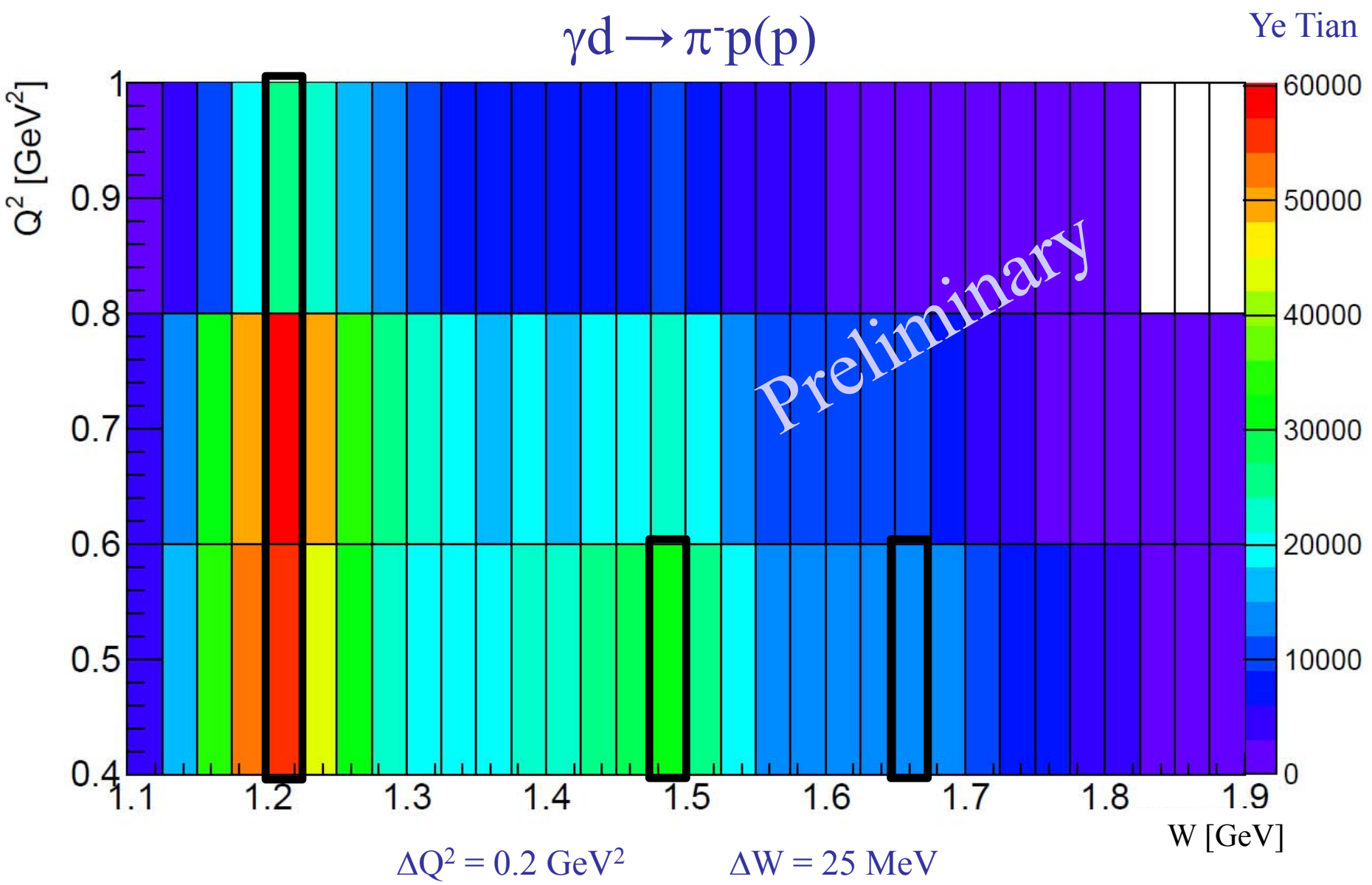




$W = 1662$ MeV



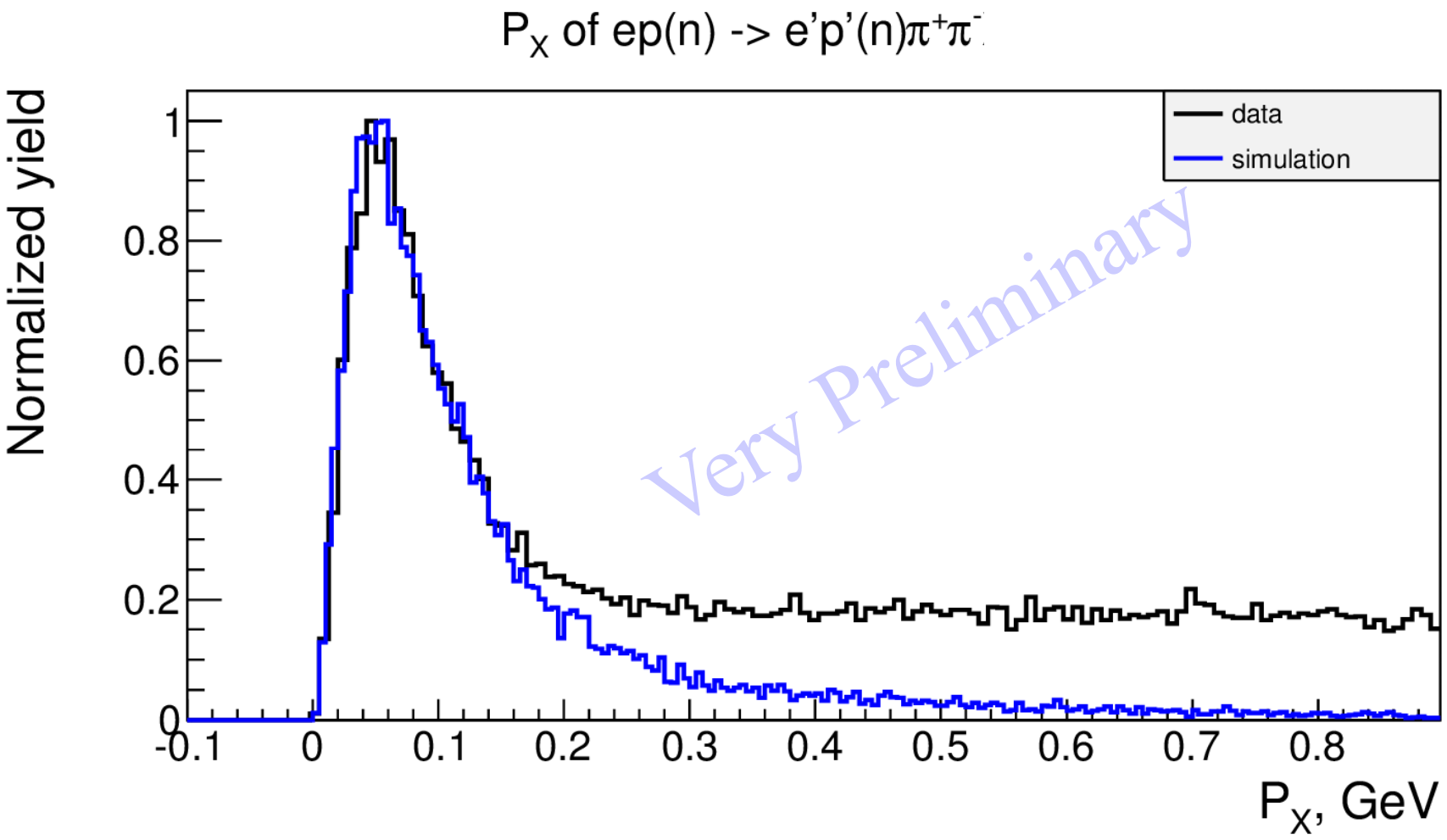
Single π^- Electroproduction off the Deuteron



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

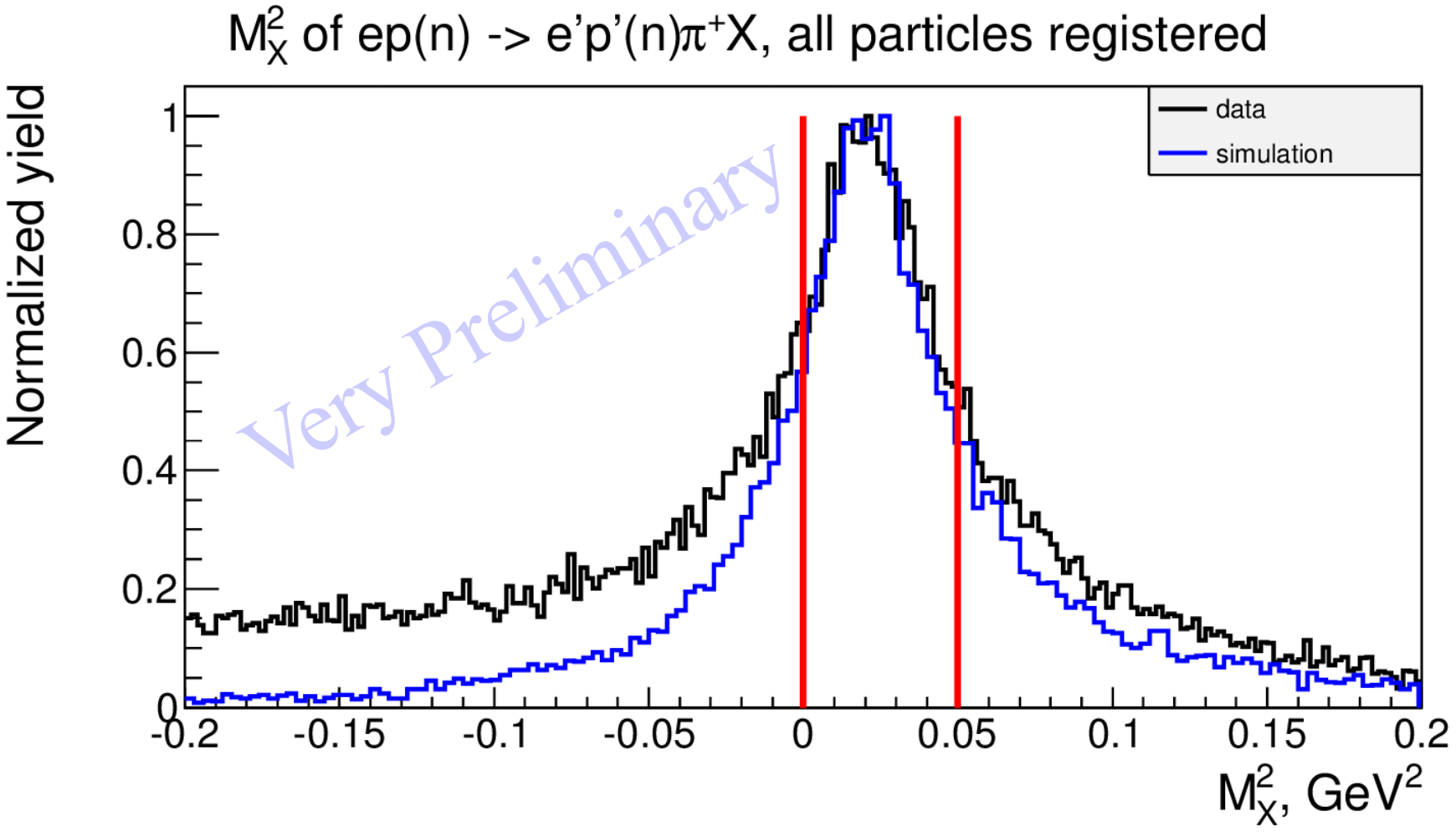
Exclusive $\pi^+\pi^-$ Electroproduction off the Deuteron

Iuliia Skorodomina



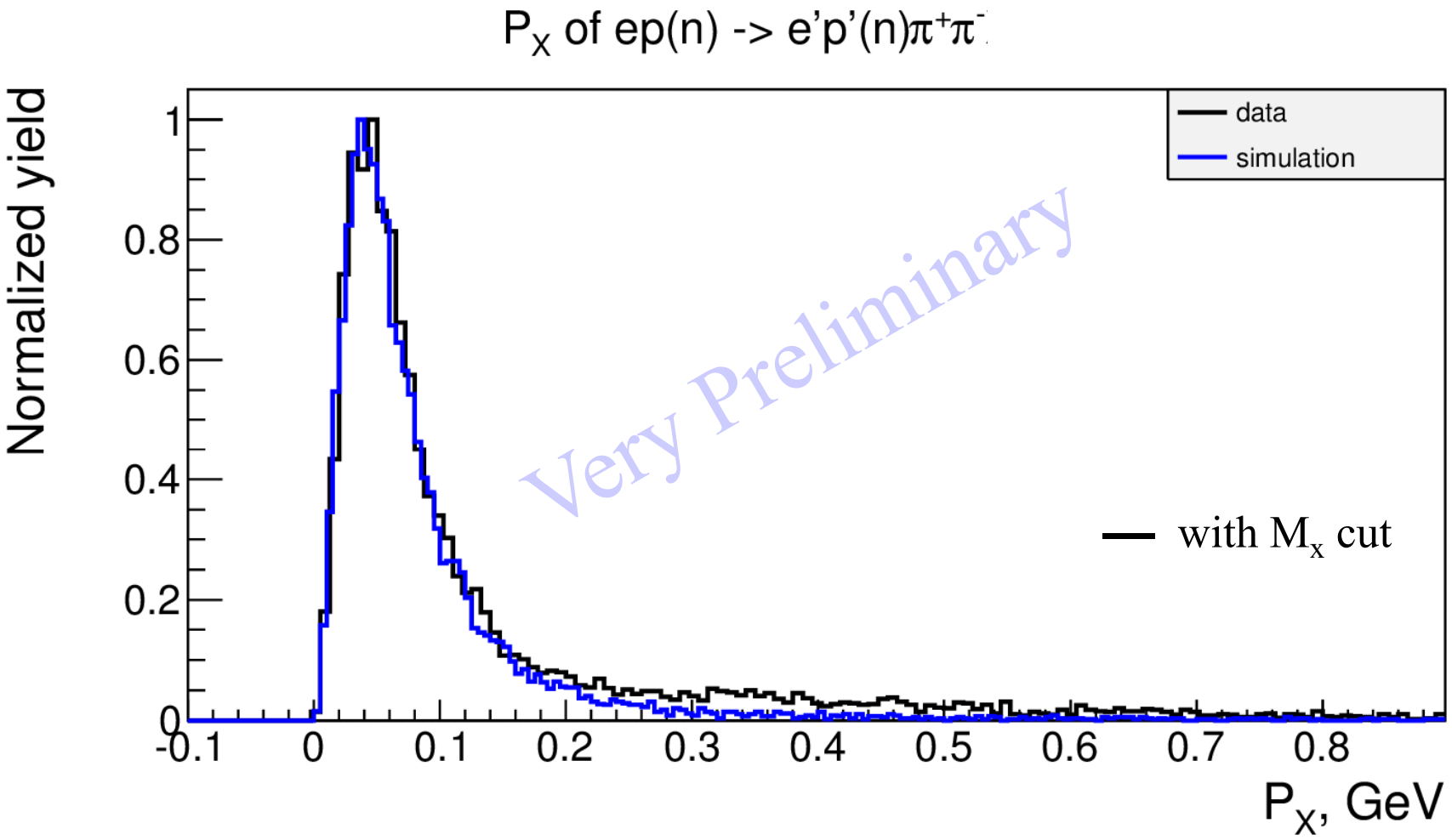
Exclusive $\pi^+\pi^-$ Electroproduction off the Deuteron

Iuliia Skorodomina



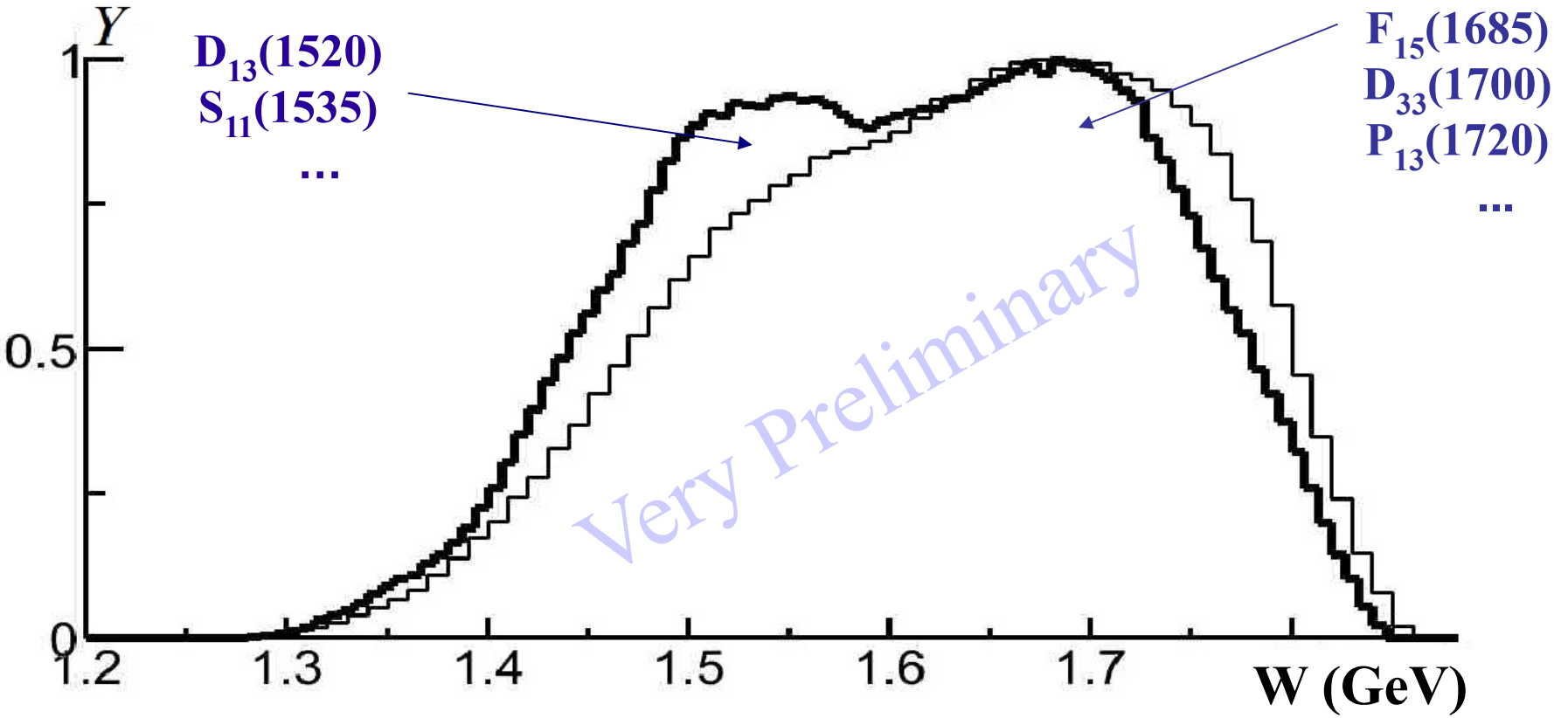
Exclusive $\pi^+\pi^-$ Electroproduction off the Deuteron

Iuliia Skorodomina



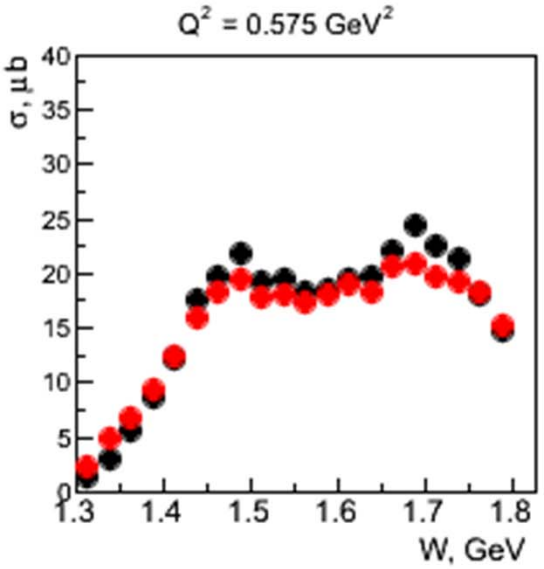
Exclusive $\pi^+\pi^-$ Electroproduction off the Deuteron

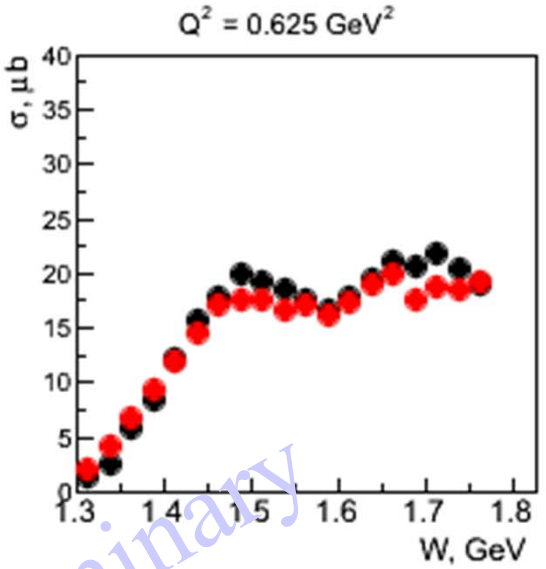
Iuliia Skorodomina

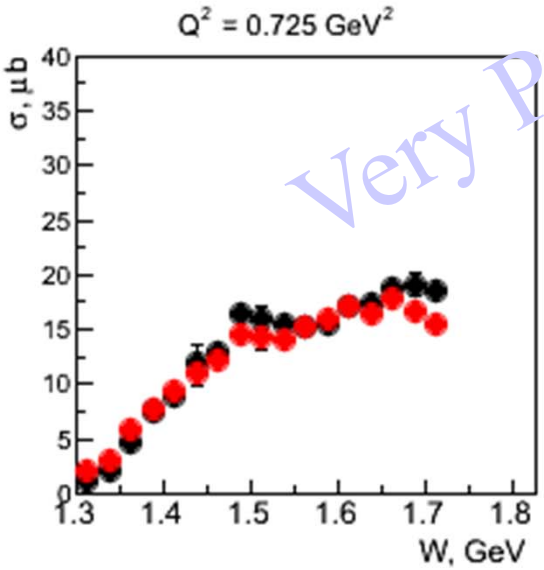


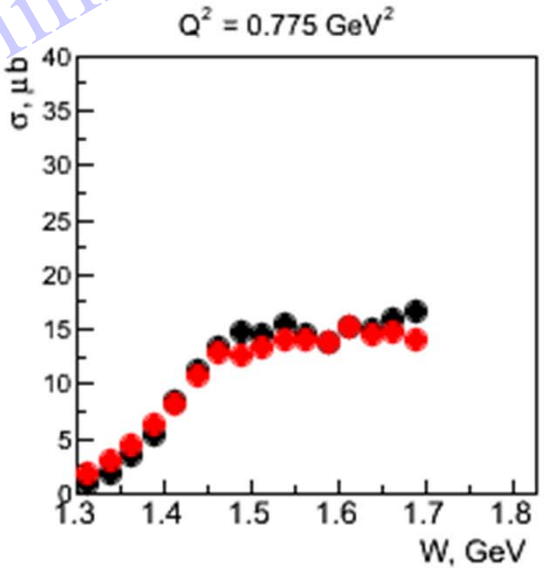
Bold curve W calculated from four-momenta of the final particles and thin curve W calculated from four-momenta of initial particles under the assumption that the target is at rest.

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

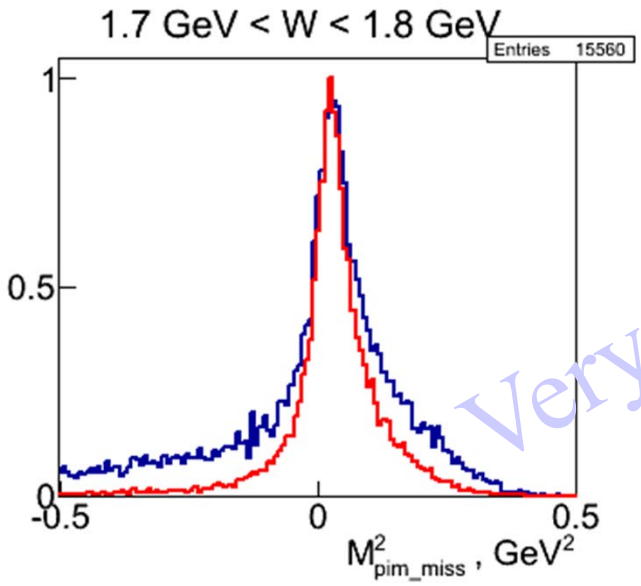
π^- missing topology

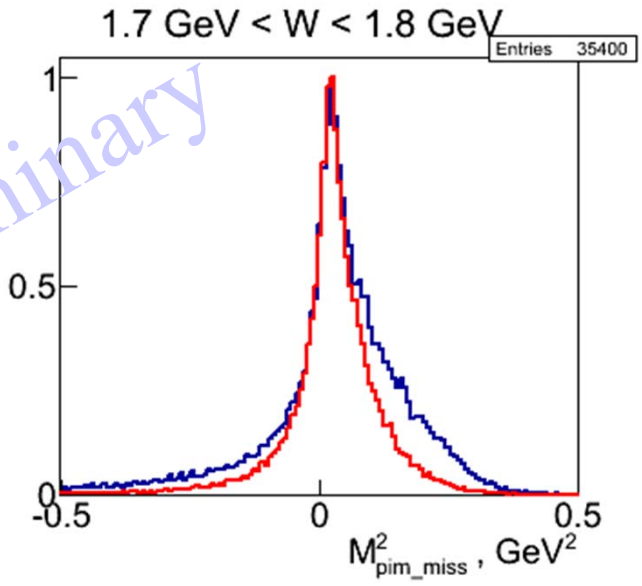
FSI in the p(n)π^+ π^- Final State

Final State Interactions depend strongly on: Iuliia Skorodomina

- invariant mass of final hadron system (W)
- scattering angles of final hadrons → FSI are topology dependent

$$M_x^2 = (P_e^\mu + P_p^\mu - P_{e'}^\mu - P_{p'}^\mu - P_{\pi^+}^\mu)^2$$





fully exclusive topology

π^- missing topology

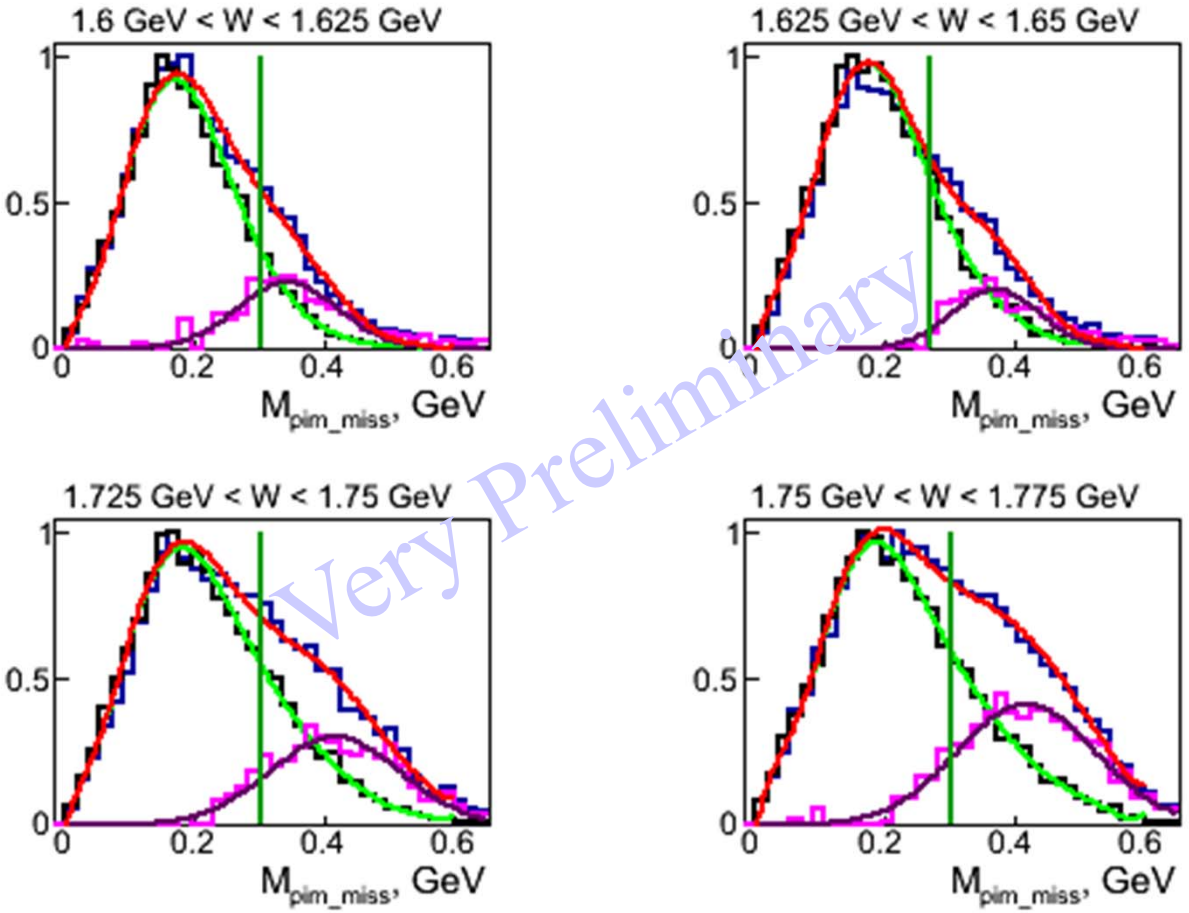
blue curve – data and **red curve** – simulation

Effective FSI Correction

Iuliia Skorodomina

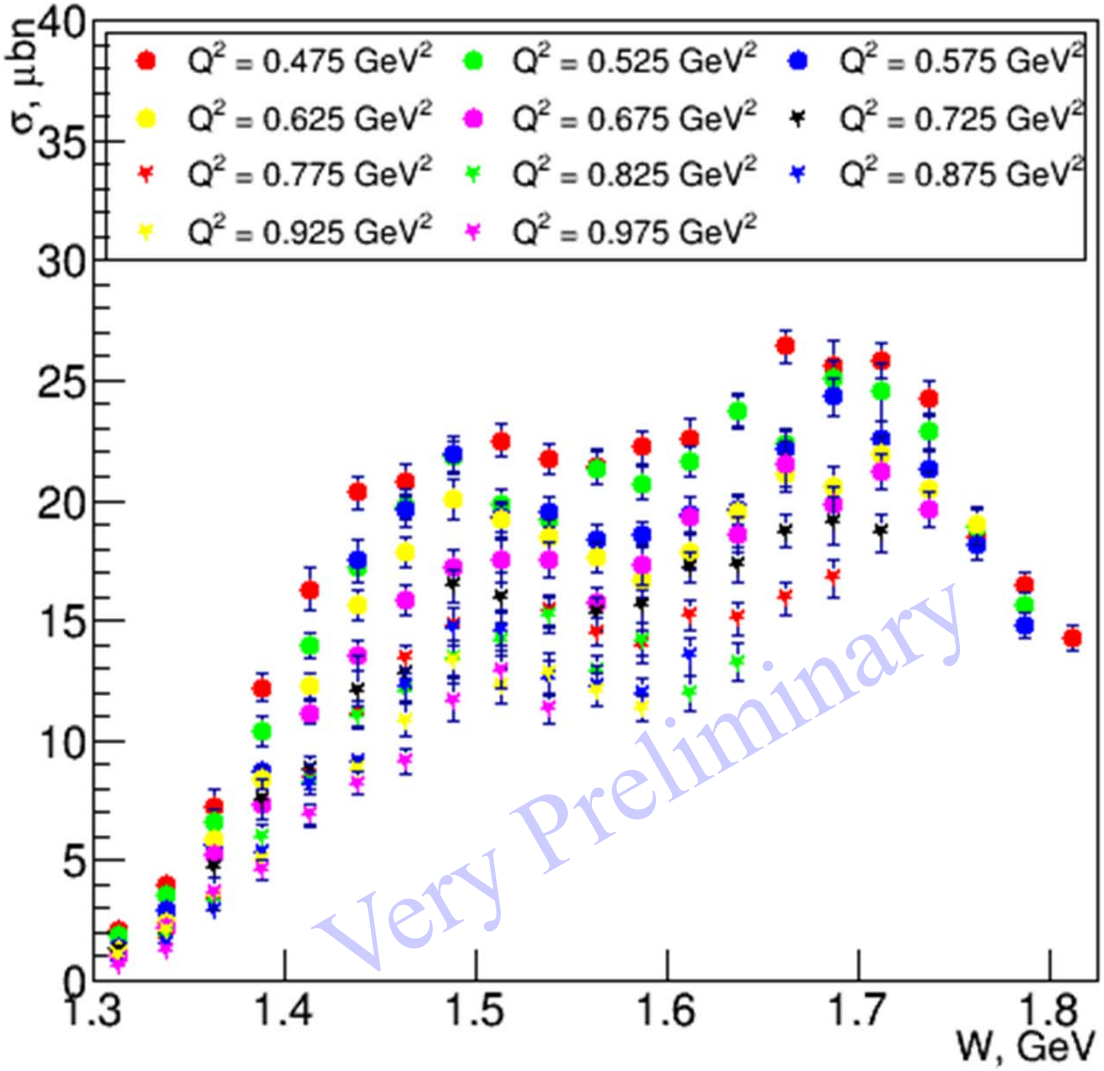
$$\frac{d\sigma_{corrected}}{dW\,dQ^2 d\tau} = \frac{d\sigma_{not\ corrected}}{dW\,dQ^2 d\tau} F_{fsi}(\Delta W, \Delta Q^2)$$

$$F_{fsi}(\Delta W, \Delta Q^2) = \frac{Area\ under\ green}{Area\ under\ red}$$



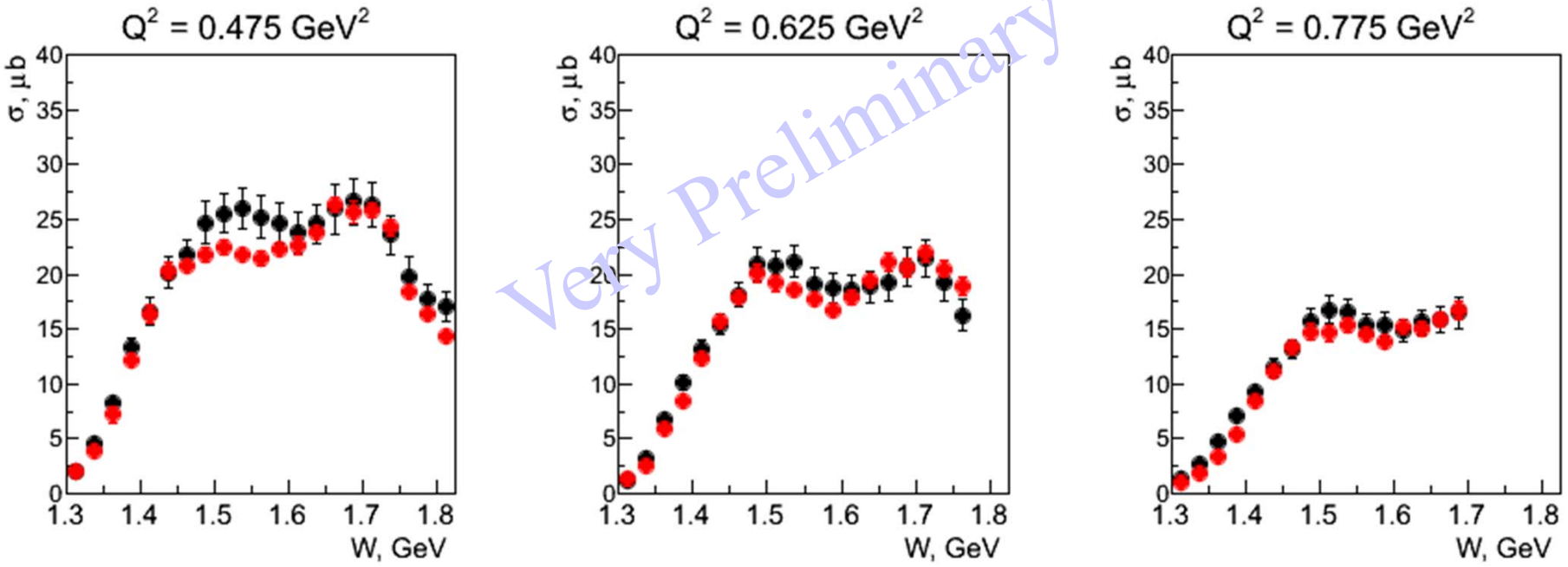
Integrated Cross Section off the Proton in Deuteron

Iuliia Skorodomina



Comparison with Free Proton Cross Section

Iuliia Skorodomina

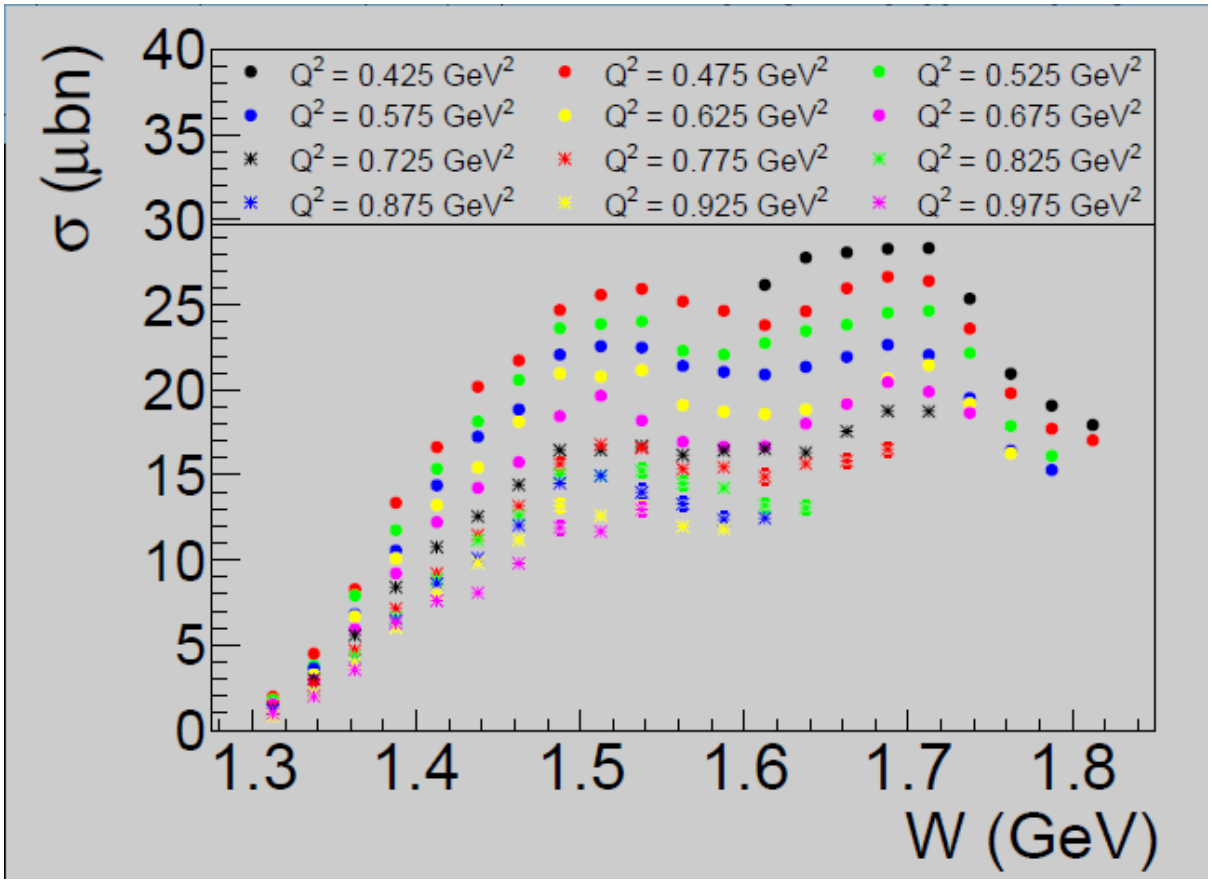


Black bullets – free proton cross sections (e1e at E_{beam} = 2.039 GeV)
error bars show both statistical and systematical uncertainties
G. Fedotov analysis note under review

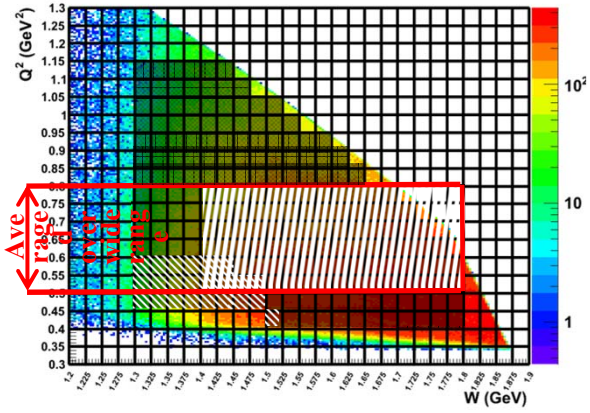
Red bullets – bound proton quasi-free cross sections (e1e at E_{beam} = 2.039 GeV)
error bars show statistical uncertainty only

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

Gleb Fedotov

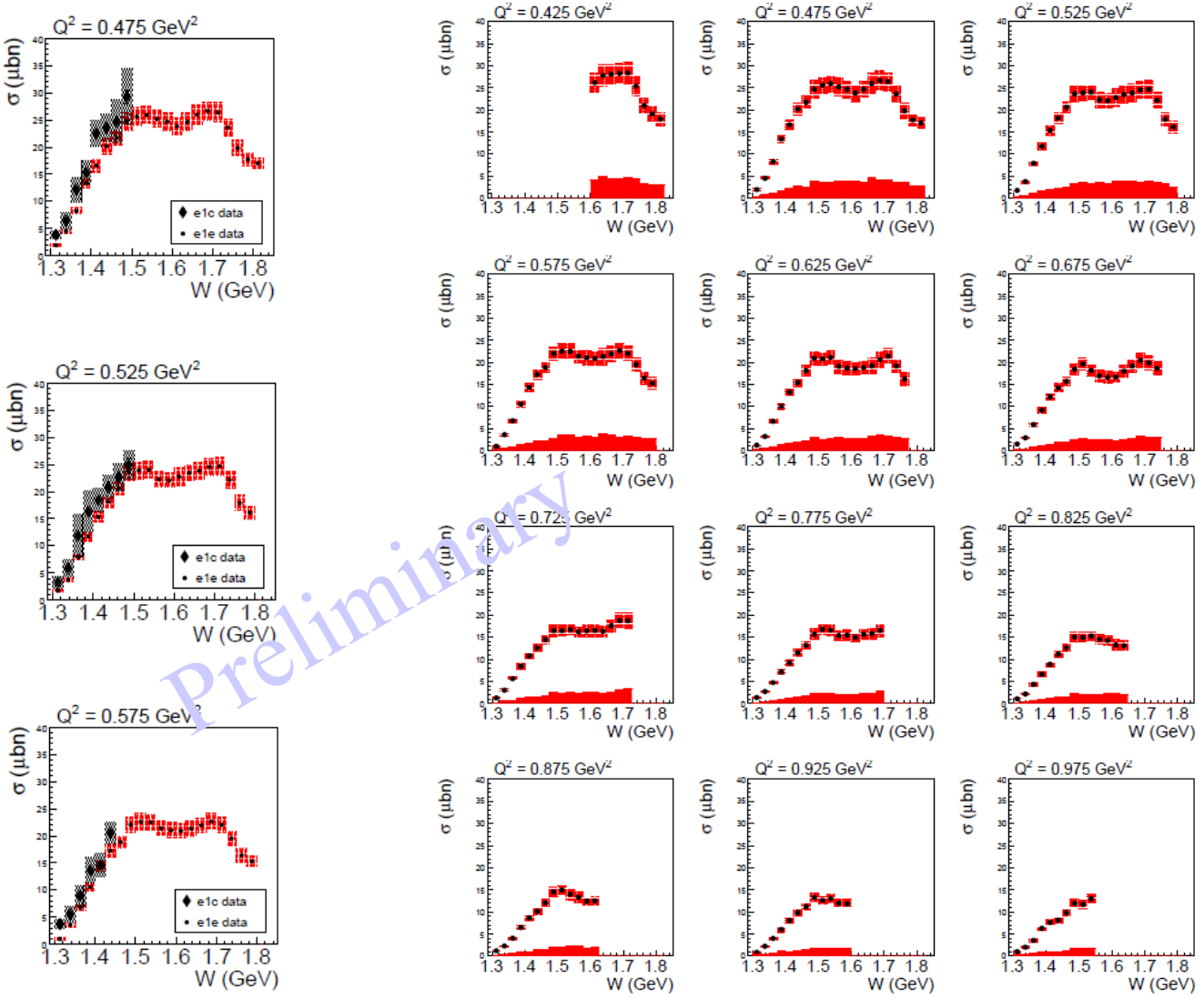


Preliminary



$p\pi^+\pi^-$ event yields over W and Q^2. Gray shaded area new e1e data set, hatched area at low Q^2 already published e1c data by G. 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 $N\pi^+\pi^-$ Cross Sections

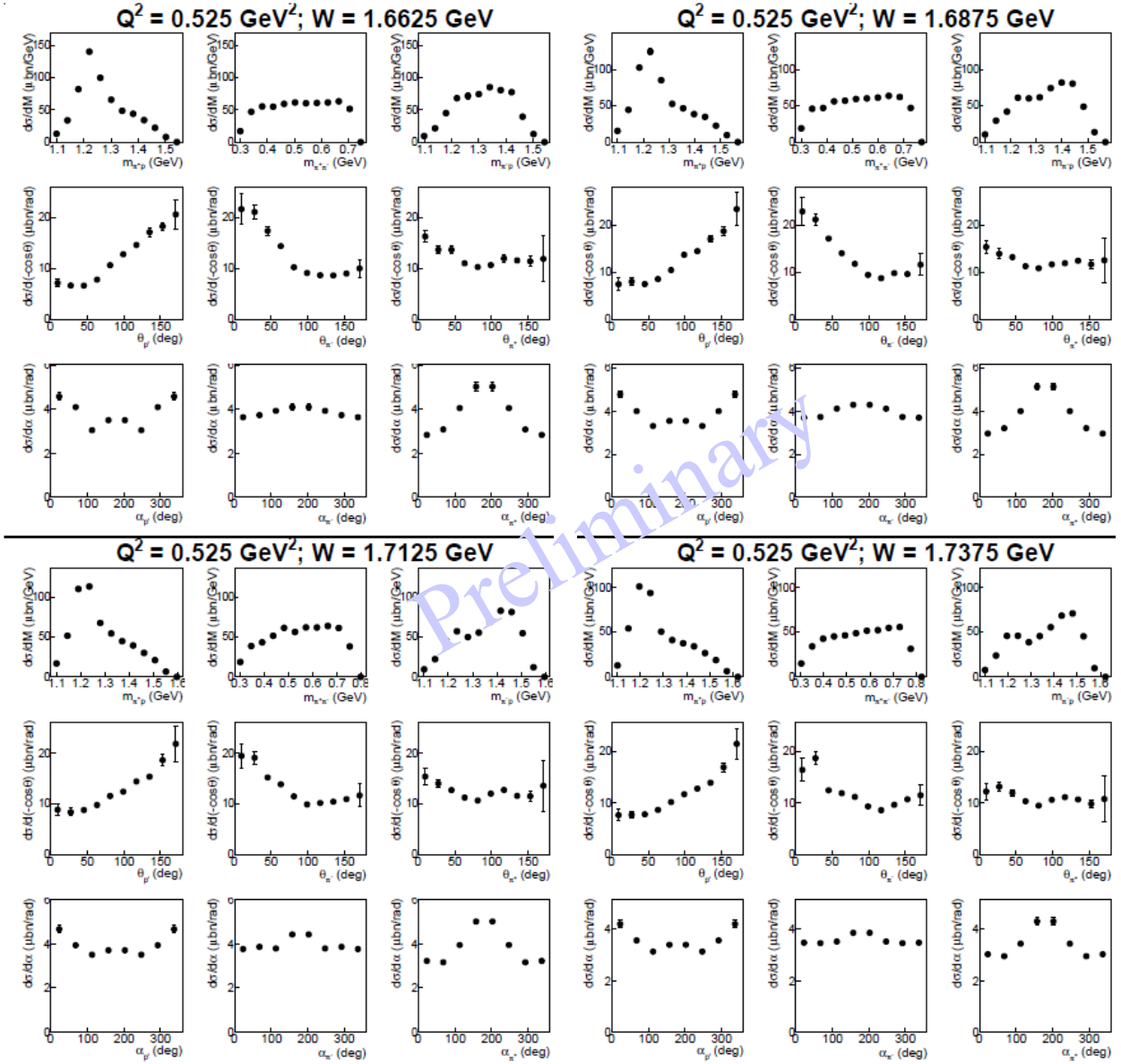


Gleb Fedotov

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

$N\pi^+\pi^-$ Single-Differential Cross Sections

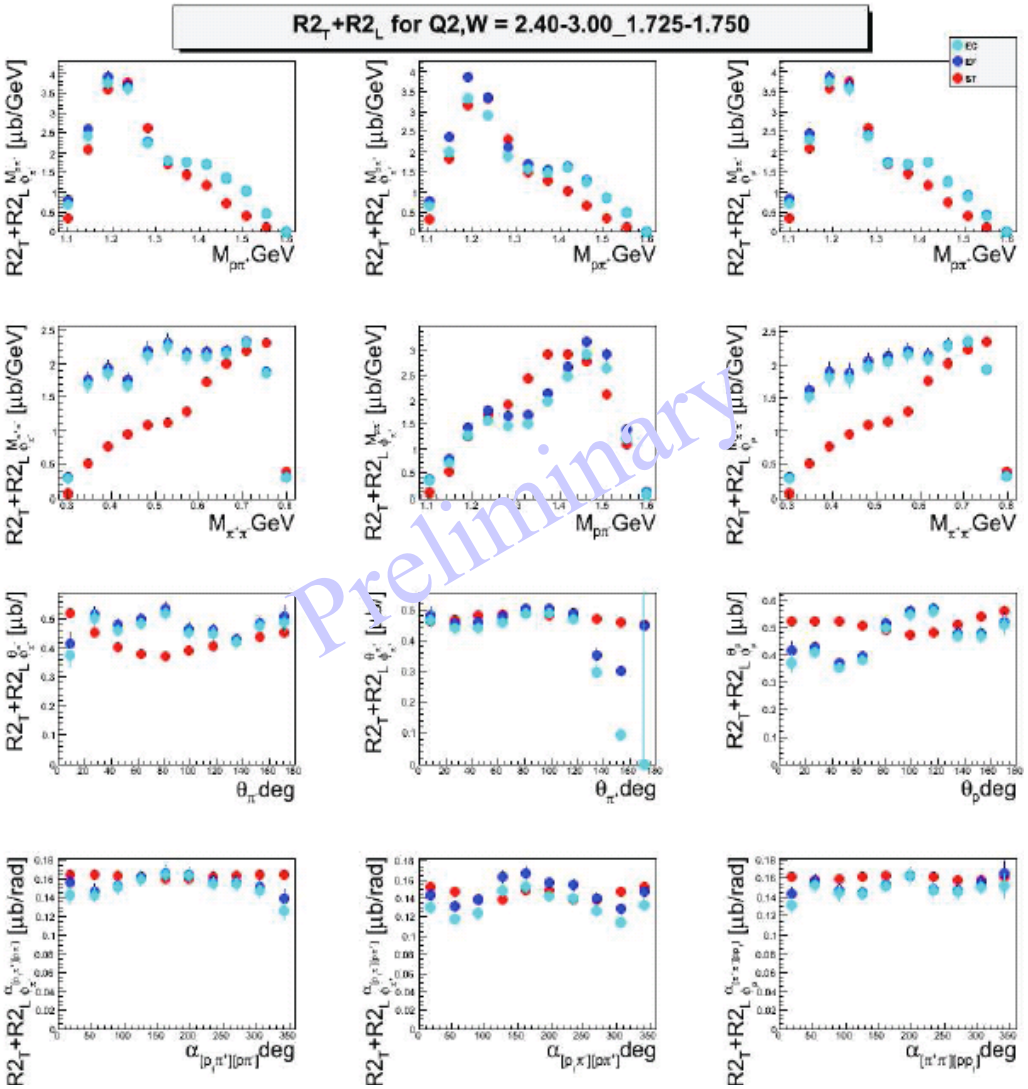
Gleb Fedotov



φ-dependent Nππ Single-Differential Cross Sections

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

Arjun Trivedi



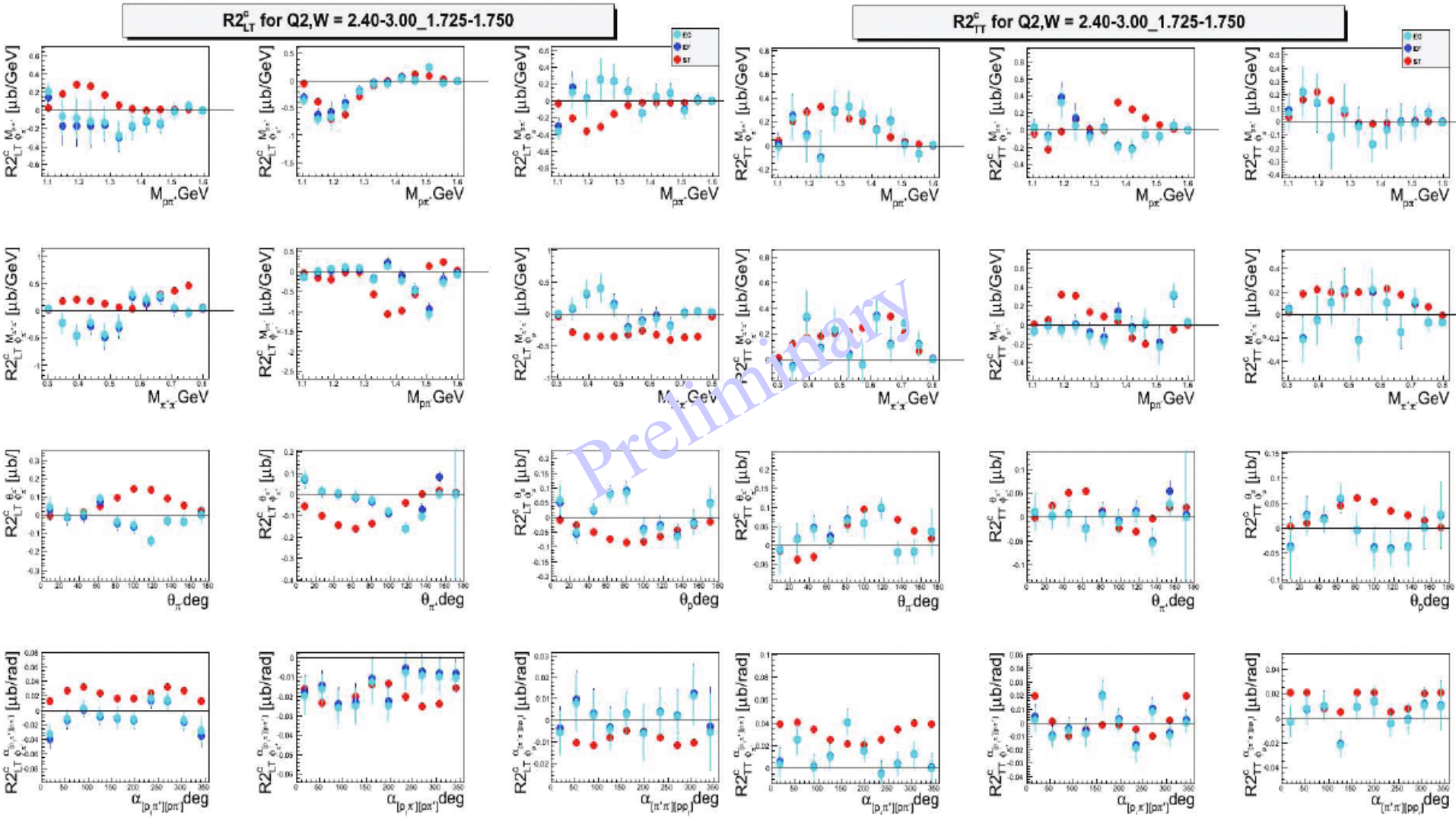
- normalized
- hole filled
- JM model

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

φ-dependent Nππ Single-Differential Cross Sections

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

Arjun Trivedi

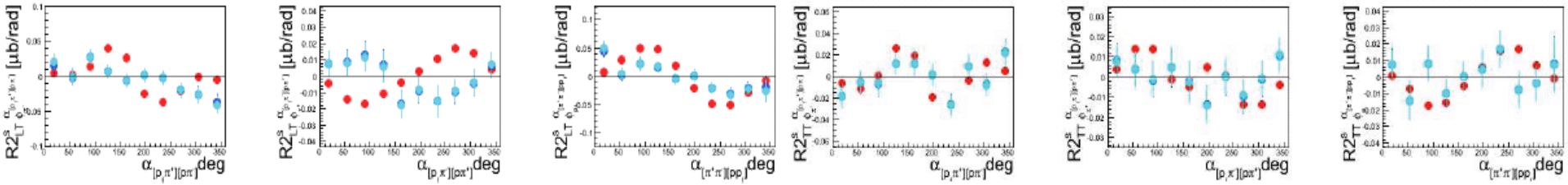


$$\left(\frac{d^2\sigma}{dX_{ij}\,d\phi_i}\right) = R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}} + R2_{LT}{}^{c,X_{ij}}\cos\phi_i + R2_{TT}{}^{c,X_{ij}}\cos 2\phi_i + \delta_{X_{ij}\alpha_i}\left(R2_{LT}{}^{s,\alpha_i}\sin\phi_i + R2_{TT}{}^{s,\alpha_i}\sin 2\phi_i\right)$$

φ-dependent Nππ Single-Differential Cross Sections

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

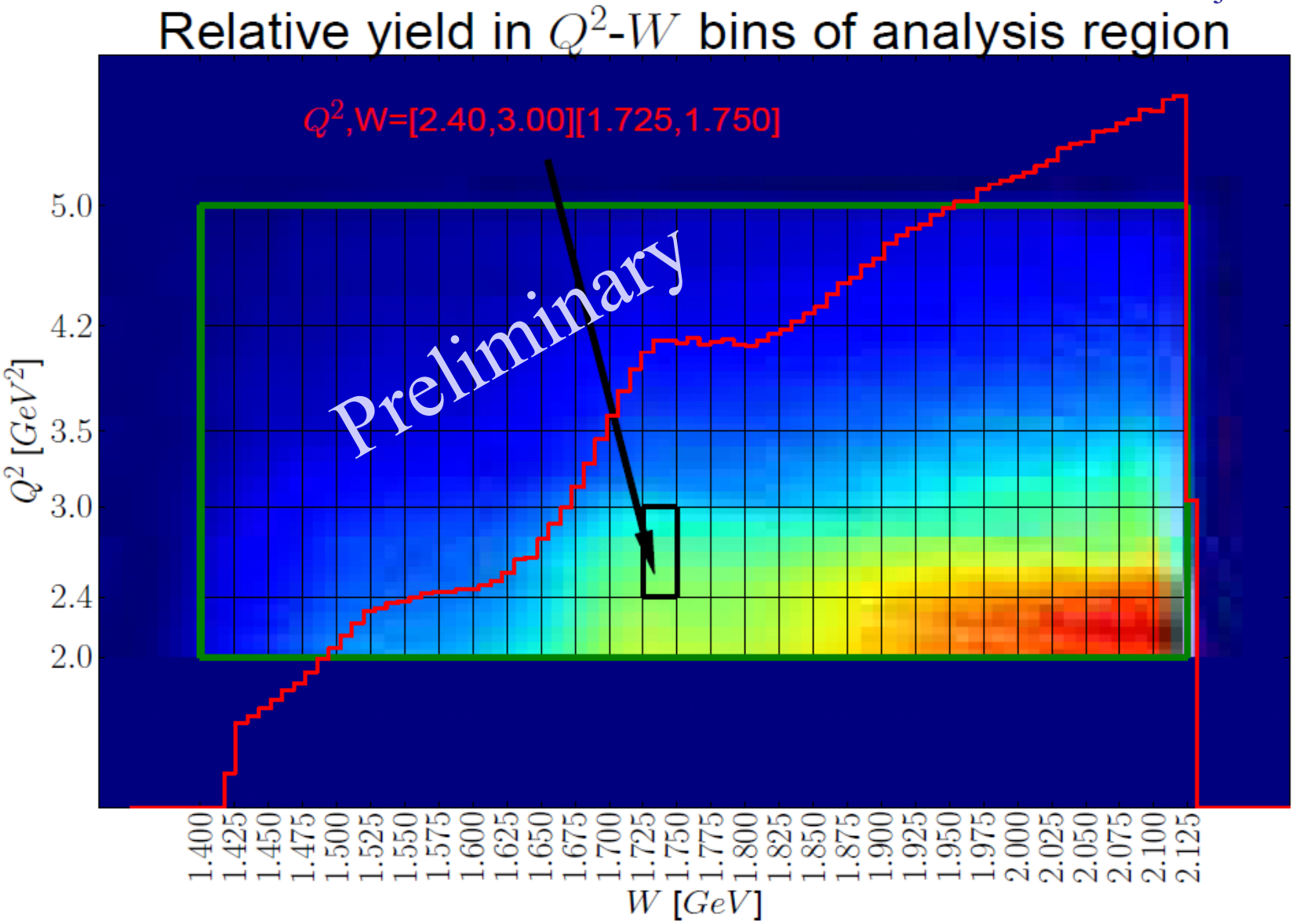
Chris McLauchlin extracts the beam helicity dependent differential cross sections.



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

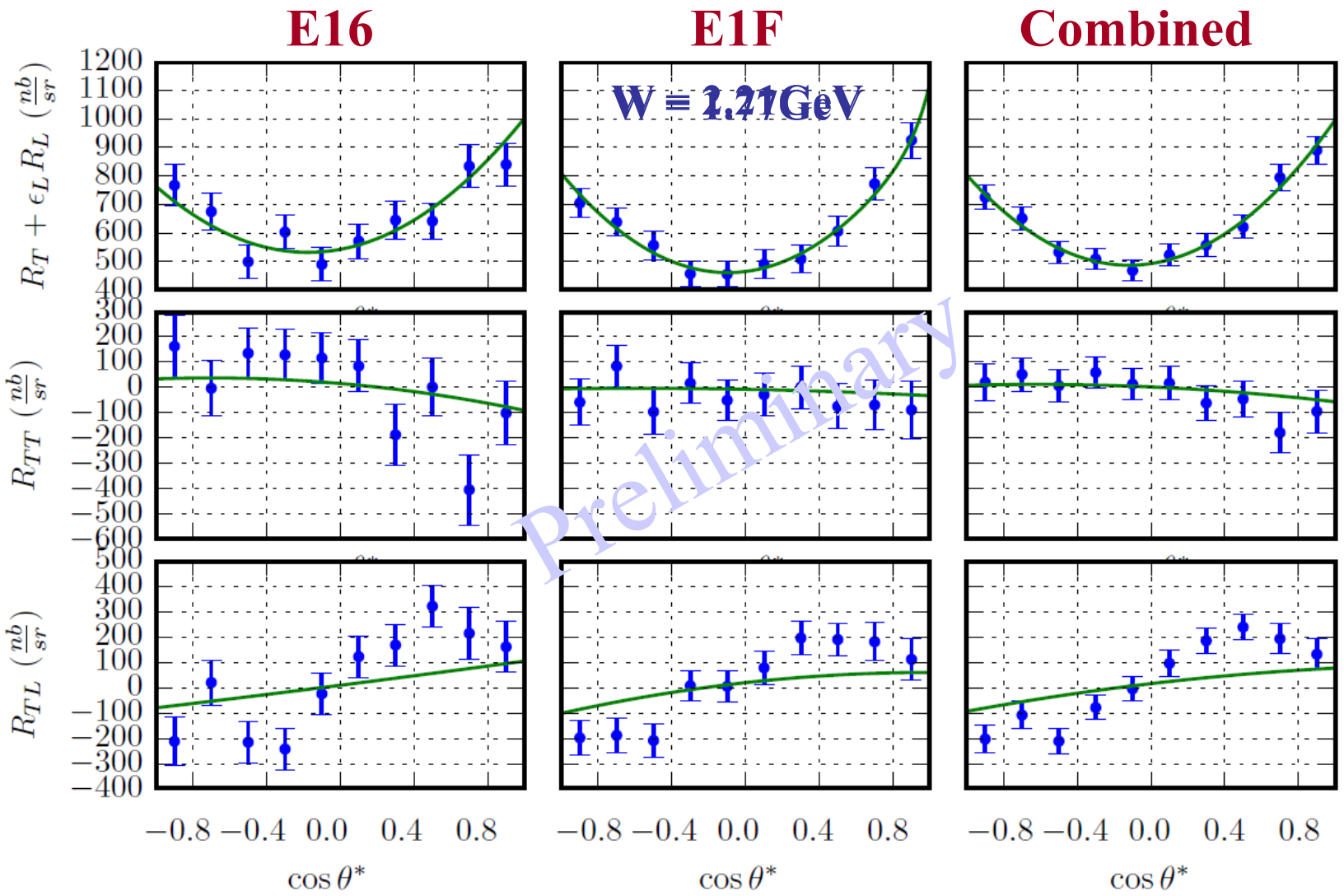
φ-dependent Nππ Single-Differential Cross Sections

Arjun Trivedi



High-Lying Resonances in ω Electroproduction

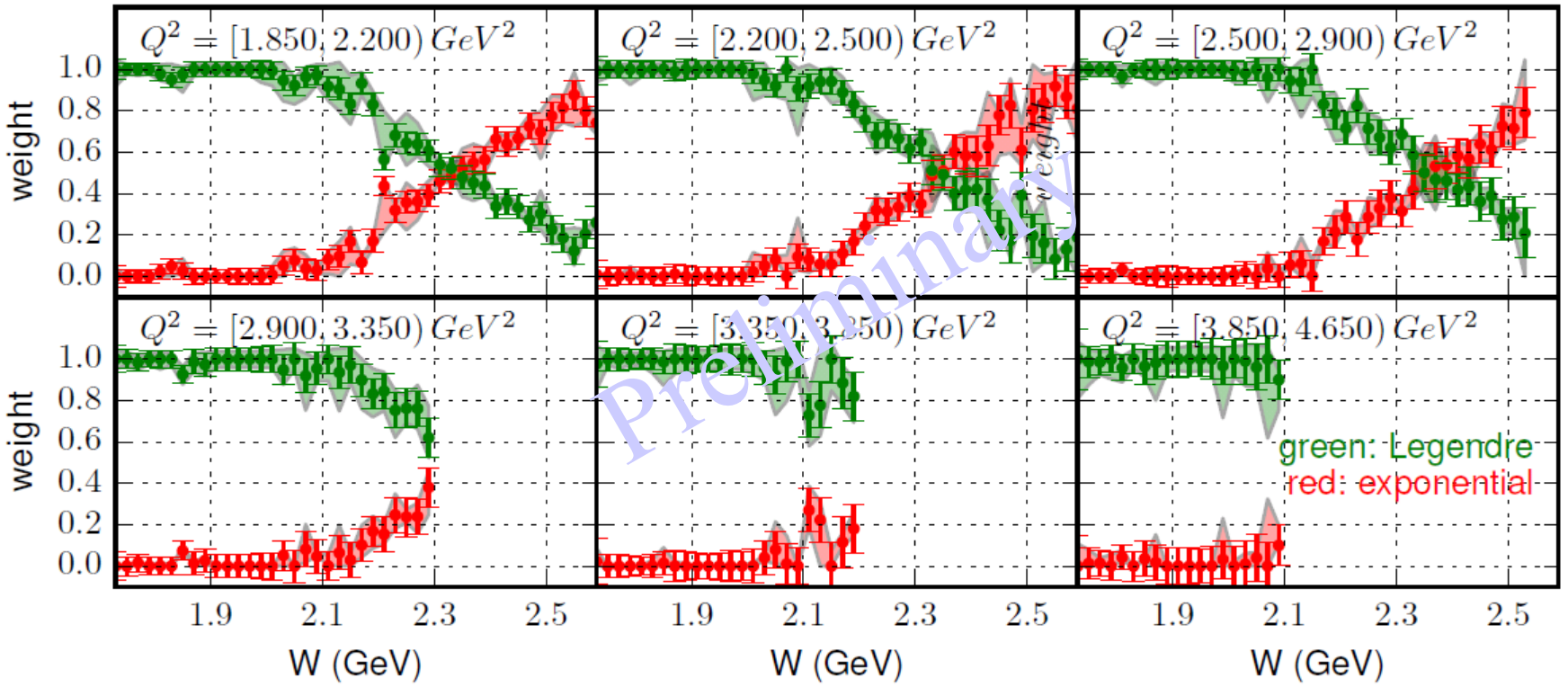
Evan Phelps



High-Lying Resonances in ω Electroproduction

Evan Phelps

E16 / E1F Combined

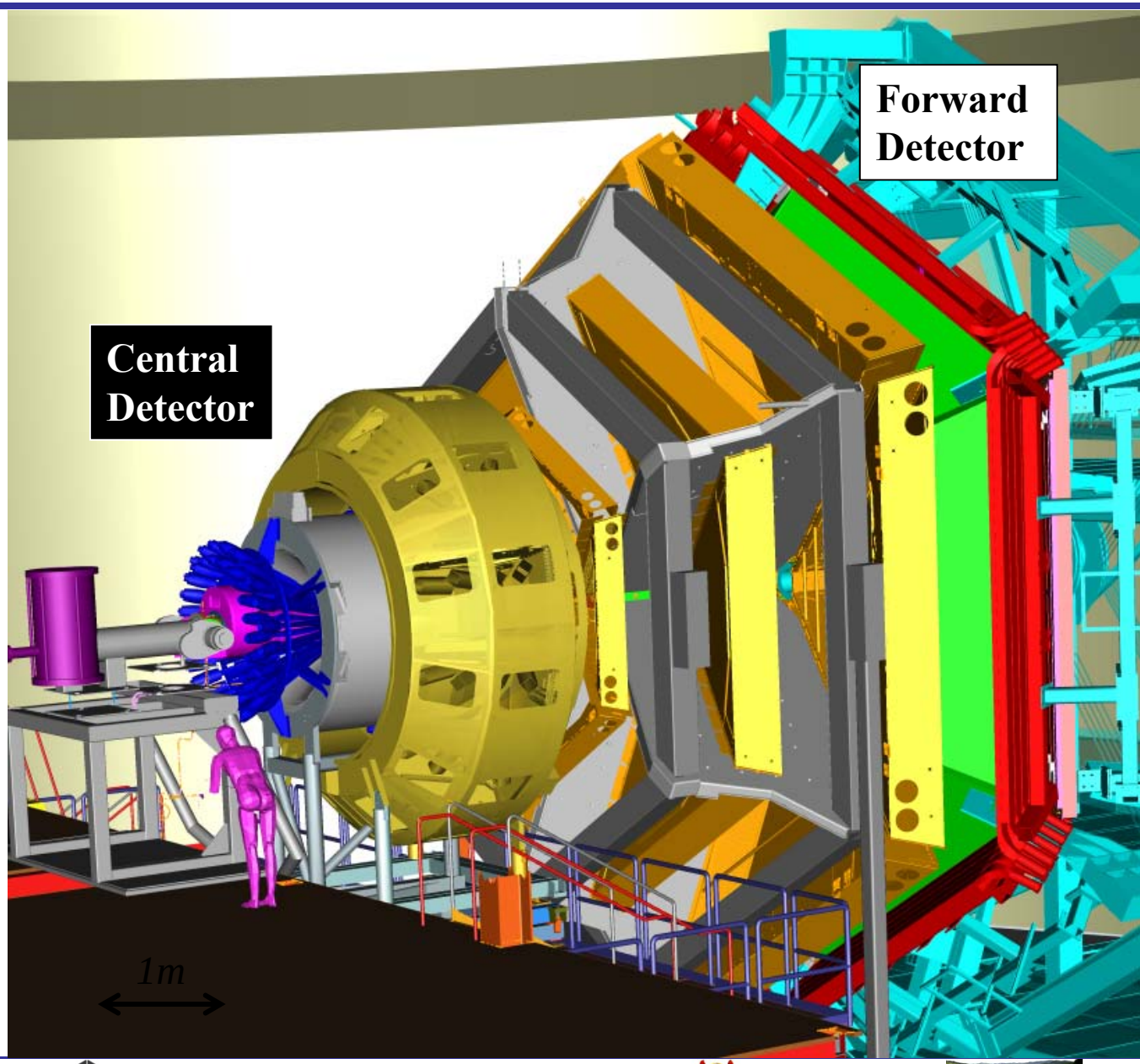


CLAS12

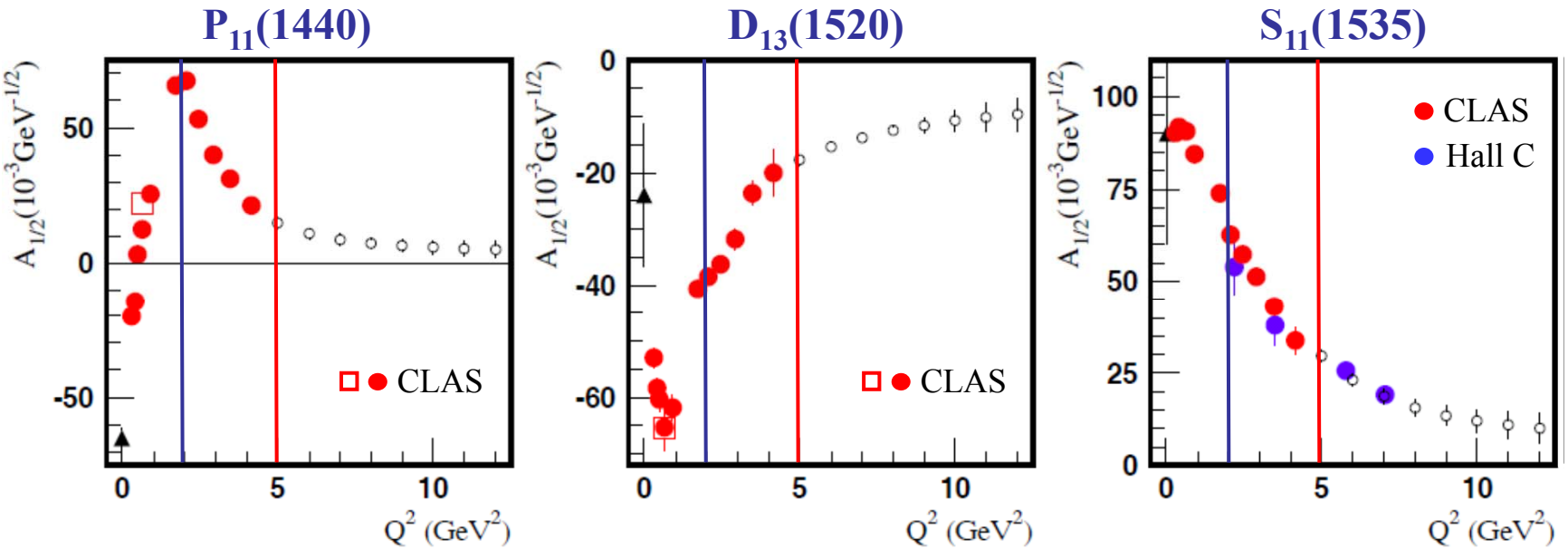
CLAS12

- 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
- …



Anticipated N* Electrocouplings from Combined Analyses of Nπ/Nππ



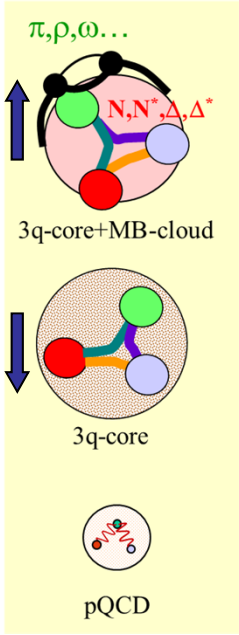
Open circles represent projections and all other markers the available results with the 6-GeV electron beam

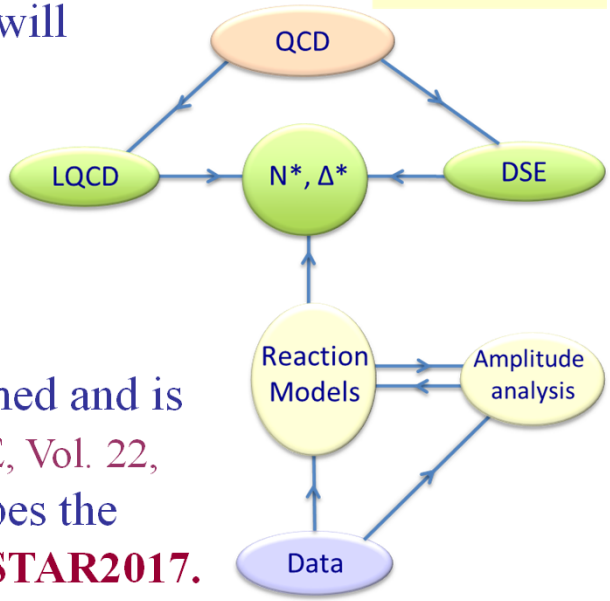
- Examples of published and projected results obtained within 60d for three prominent excited proton states from analyses of Nπ and Nππ electroproduction channels. Similar results are expected for many other resonances at higher masses, e.g. $S_{11}(1650)$, $F_{15}(1685)$, $D_{33}(1700)$, $P_{13}(1720)$,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

- 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 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. **INT2016 & NSTAR2017.**





11th International Workshop on the Physics of Excited Nucleons

- ✓ Baryon spectrum through meson photoproduction
- ✓ Baryon resonances in experiments with hadron beams and in the e^+e^- collisions
- ✓ Baryon resonances in ion collisions and their role in cosmology
- ✓ Baryon structure through meson electroproduction, transition form factors, and time-like form factors
- ✓ Amplitude analyses and baryon parameter extraction
- ✓ Baryon spectrum and structure from first principles of QCD
- ✓ Advances in the modeling of baryon spectrum and structure
- ✓ Facilities and future projects
- ✓ Other topics related to N* physics

August 20-23, 2017
at the University of South Carolina, Columbia, SC

http://nstar2017.physics.sc.edu/