Strong Interaction from Quarks to Nuclei

Ralf W. Gothe

UNIVERSITY OF SOUTH CAROLINA

Many manifestations of nonperturbative QCD

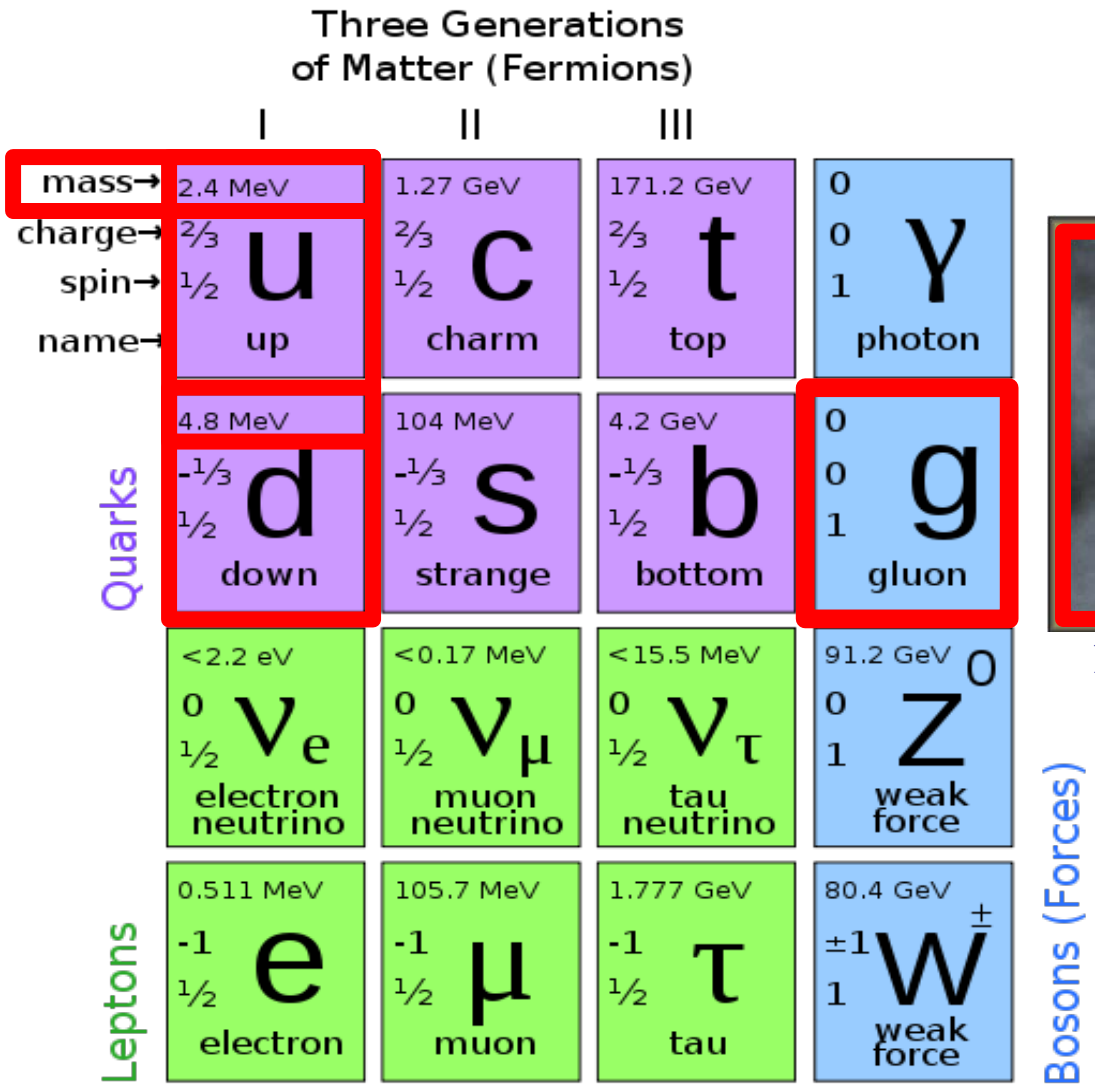
International workshop on nonperturbative phenomena in hadron and particle physics

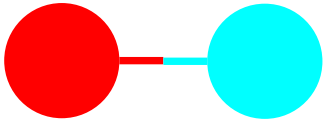
April 30 – May 5, 2018, Camburi, São Paulo, Brazil

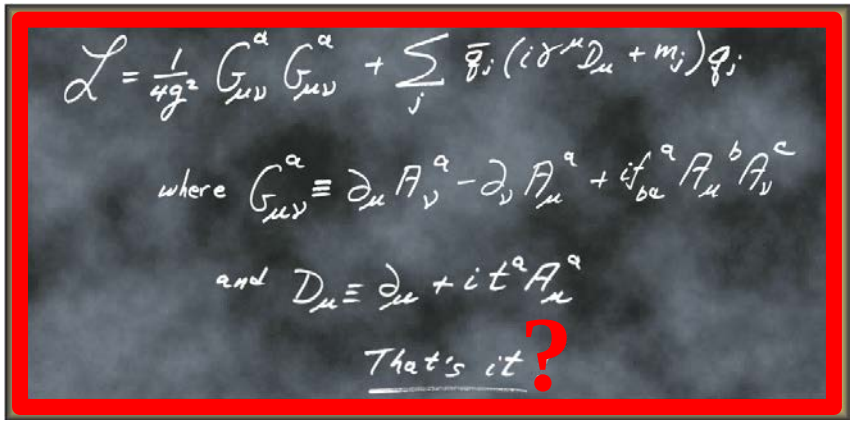
- **γ_vNN* Experiments:** The Best Access to the Quark and Baryon Structure?
- **Analysis and New Results:** Exclusive, quasi-free, and final state interaction!
- **Outlook:** New experiments with extended scope and kinematics!

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

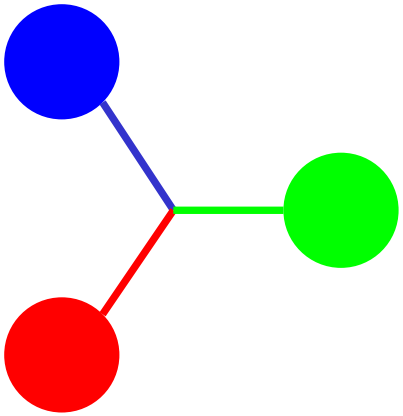
Build your Mesons and Baryons …



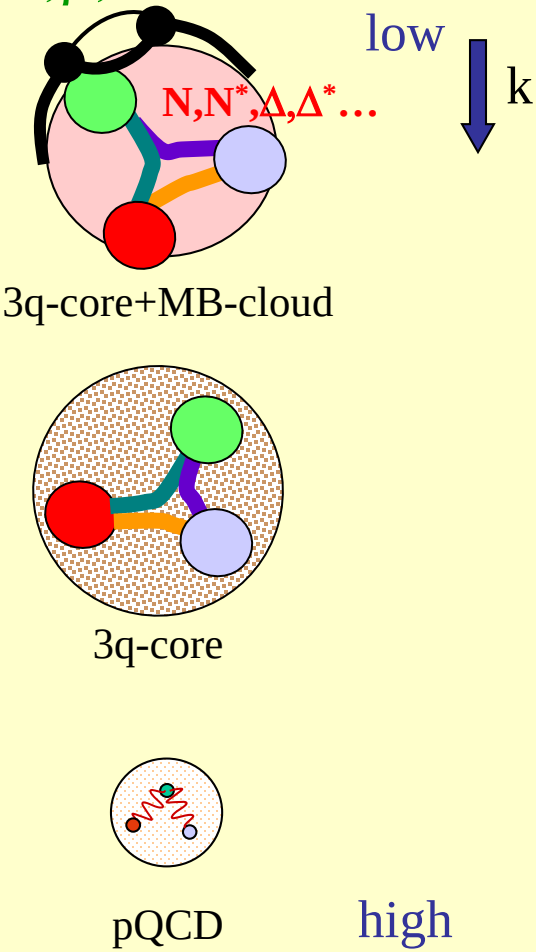




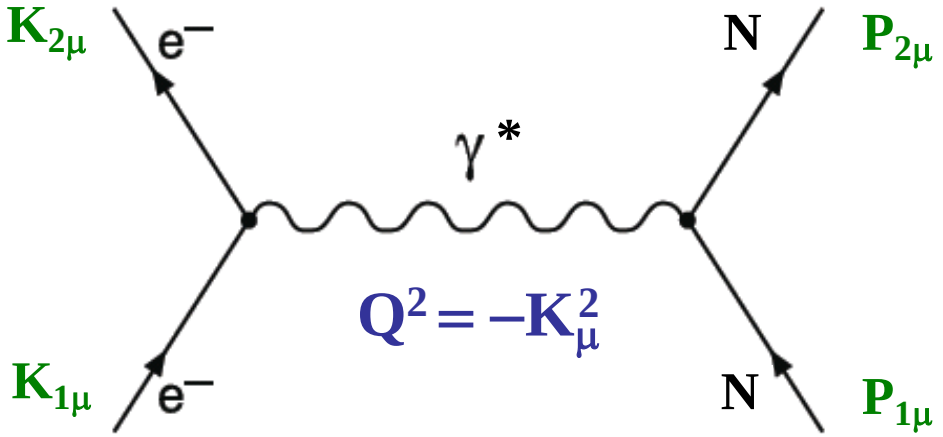
Frank Wilczek, Physics Today, August 2000



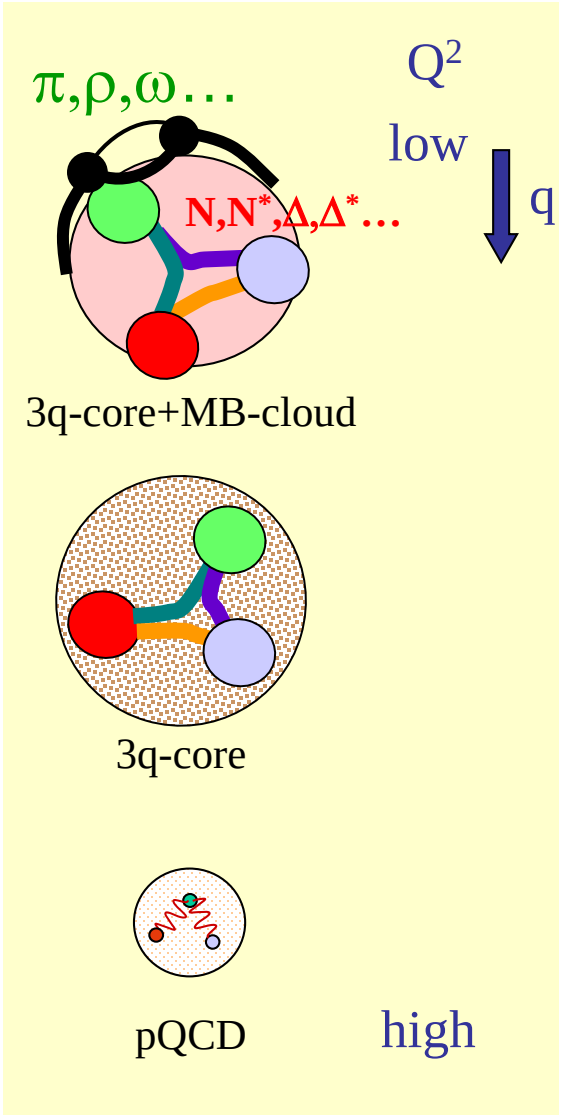
Hadron Structure with Electromagnetic Probes



- 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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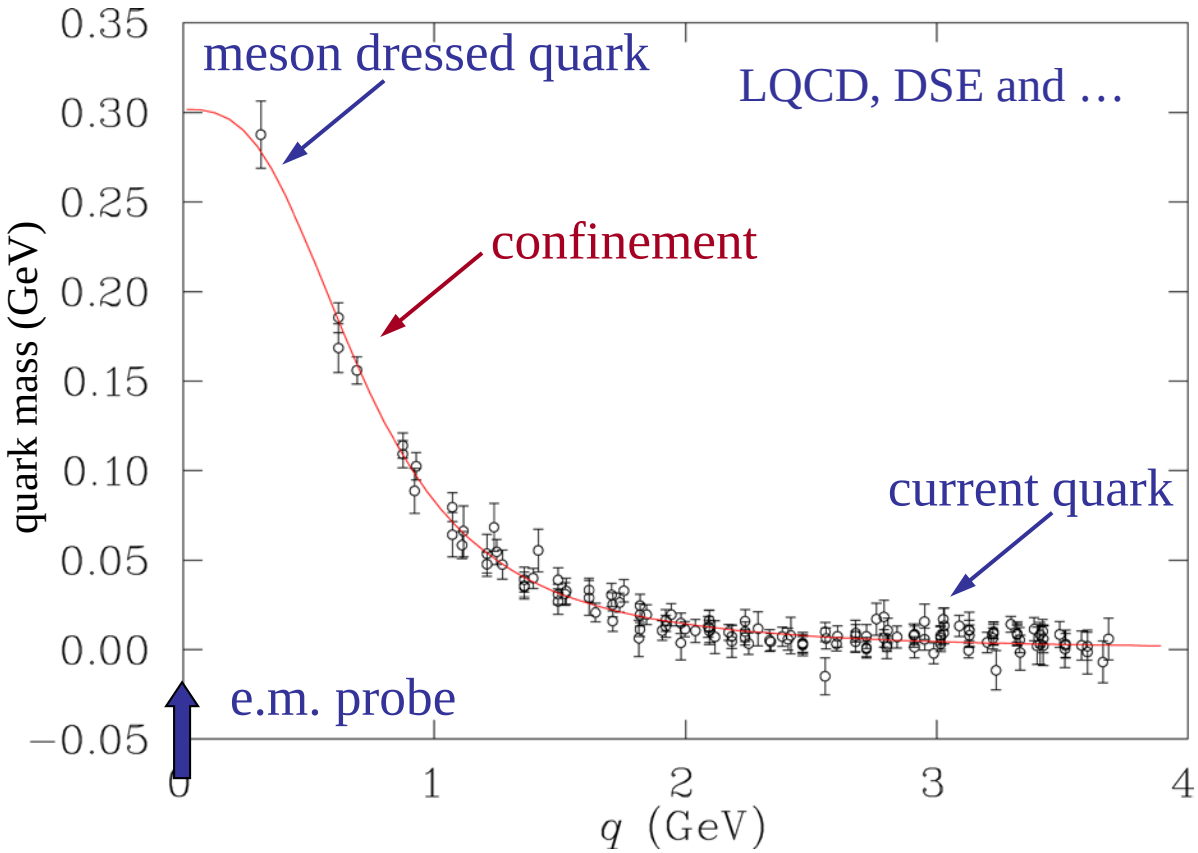
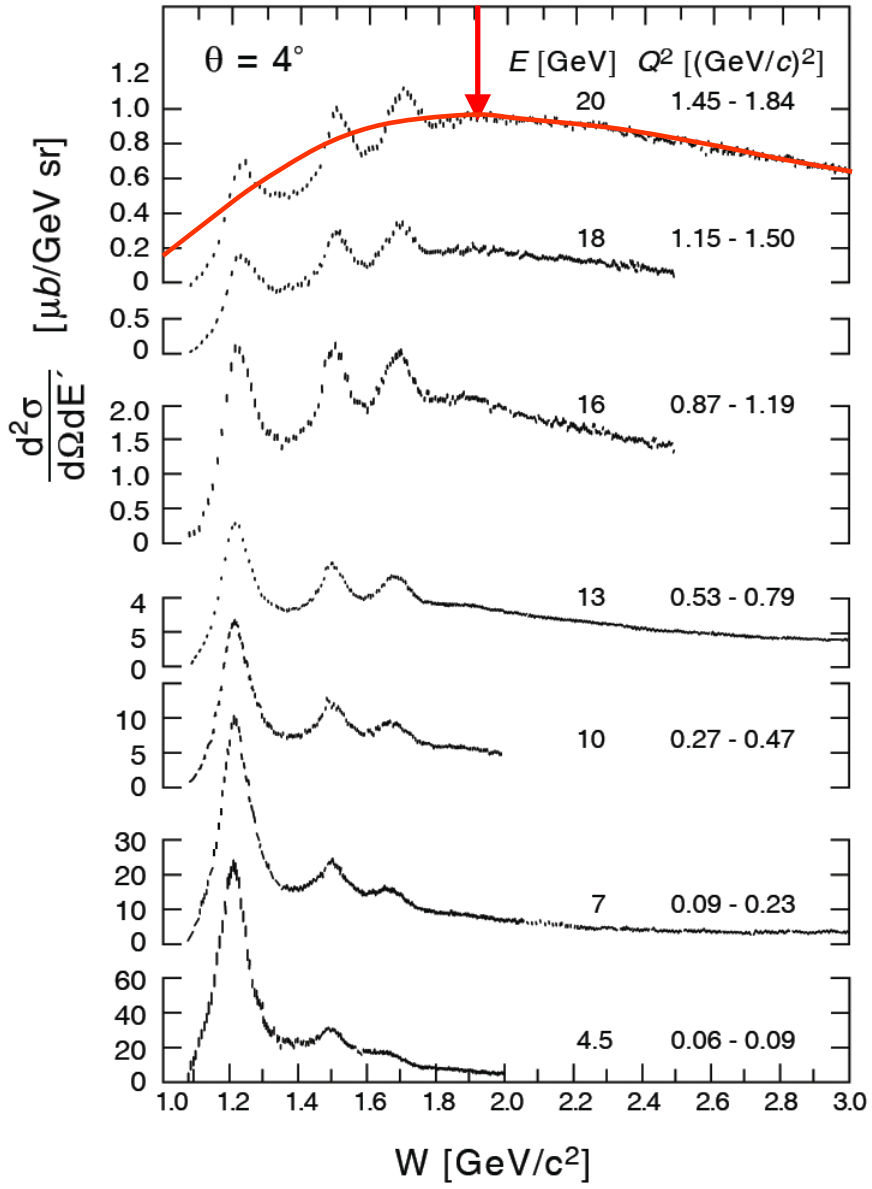
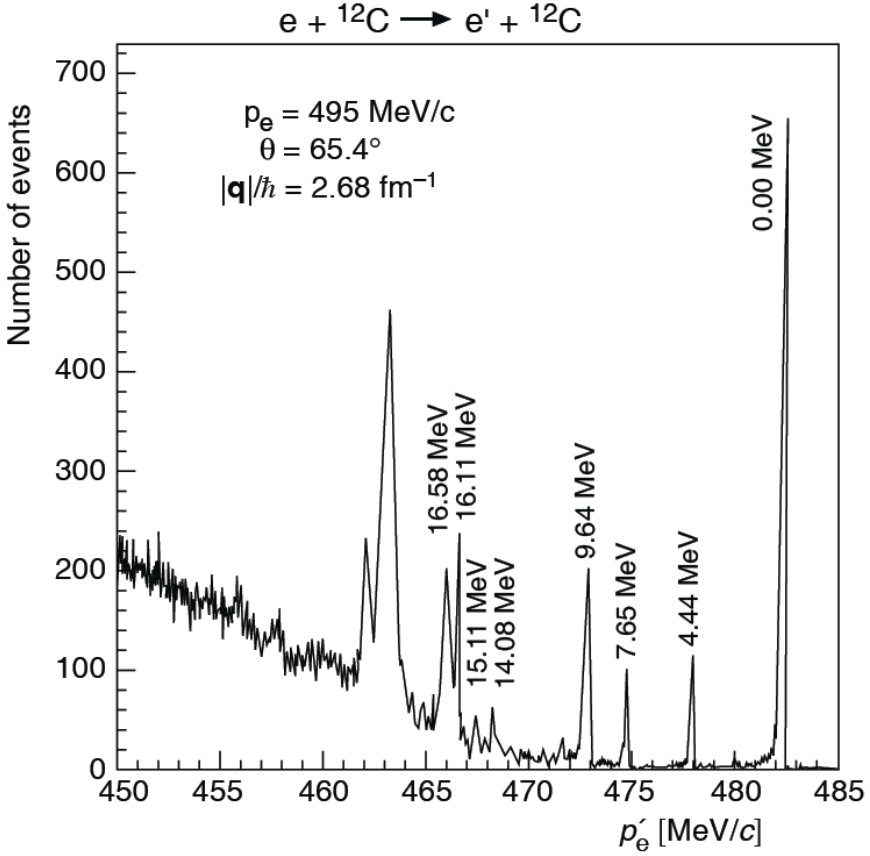


Baryon Excitations and Quasi-Elastic Scattering



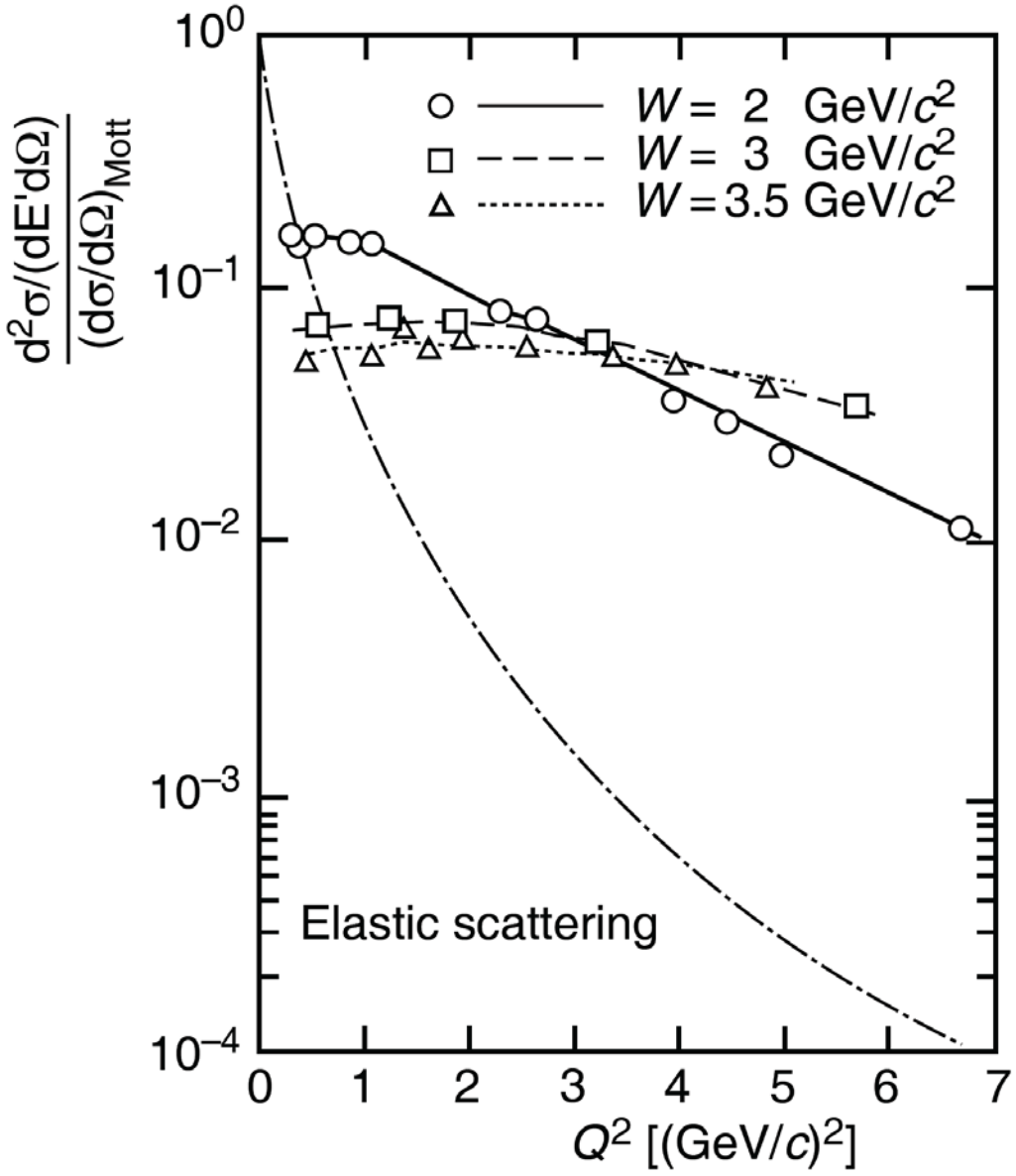
PRL **16** (1970) 1140, PR **D4** (1971) 2901
E.D. Bloom and F.J. Gilman

Paticle and Nuclei, Povh et al., MAMI B

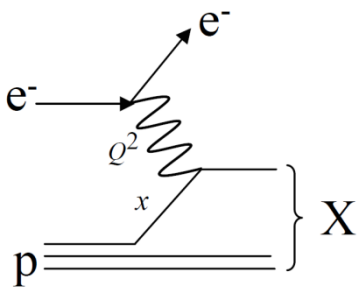


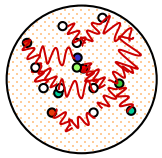
Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Baryon Excitations and Quasi-Elastic Scattering



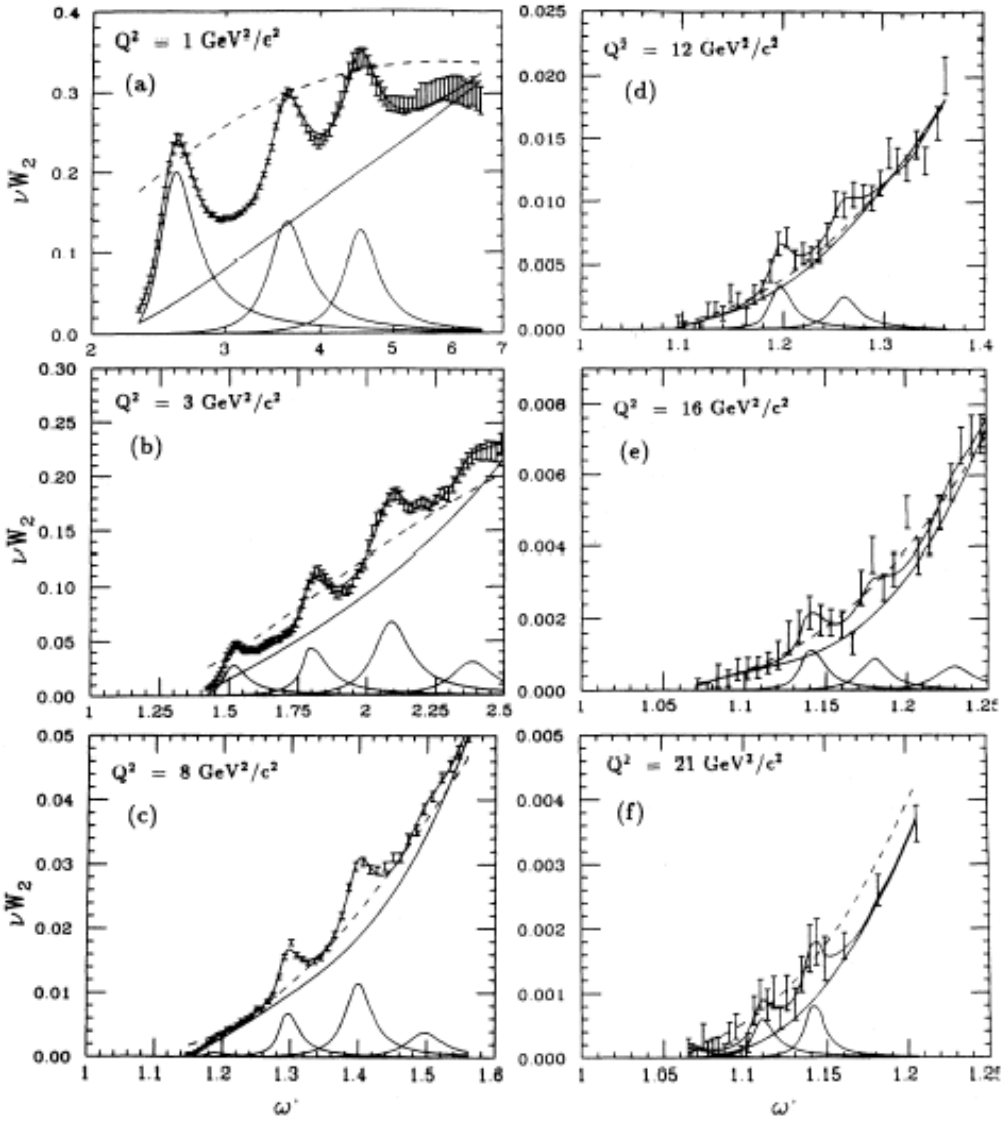
quasi-elastic off
point-like
constituents

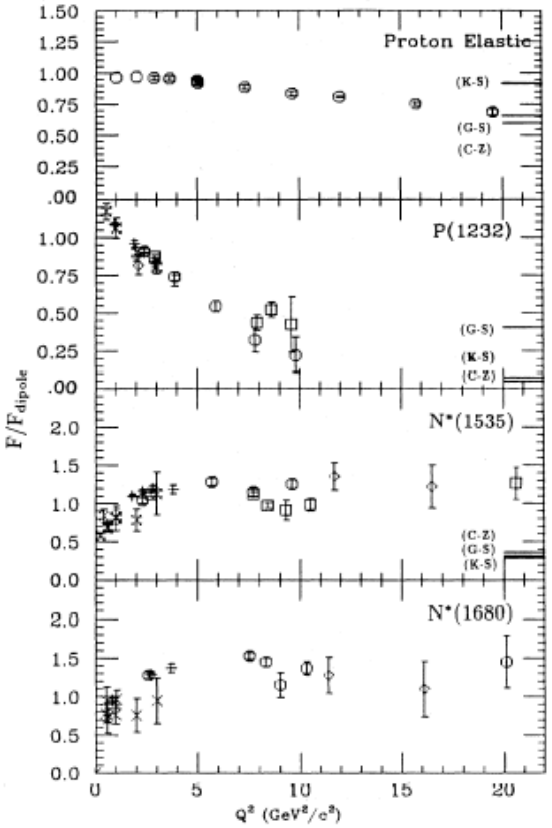




Deep Inelastic Scattering
M. Breidenbach et al.,
Phys. Rev. Lett. **23** (1969) 935

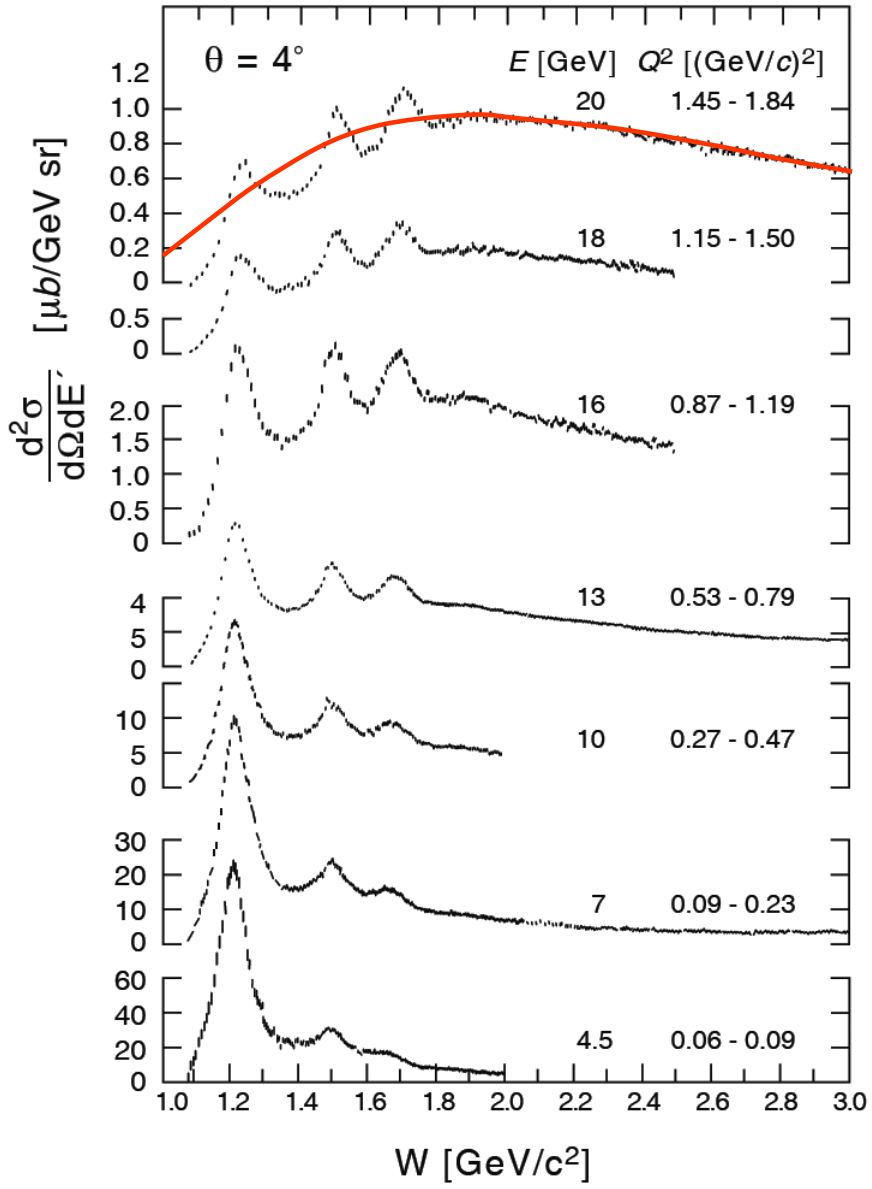
Inclusive Structure Function in the Resonance Region



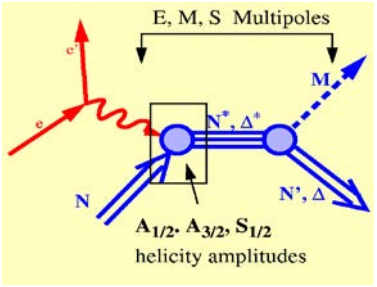


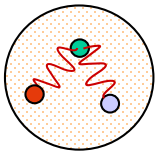
P. Stoler, PRPLCM 226, 3 (1993) 103-171

Baryon Excitations and Quasi-Elastic Scattering

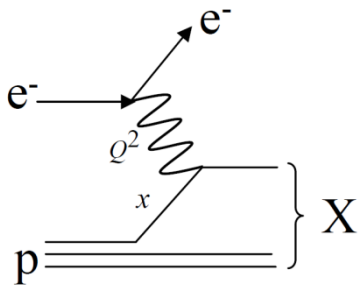


hard and confined



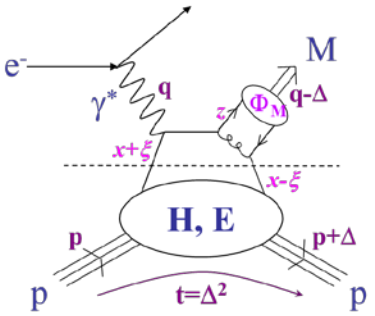


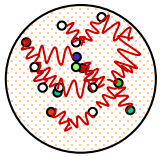
quasi-elastic



hard

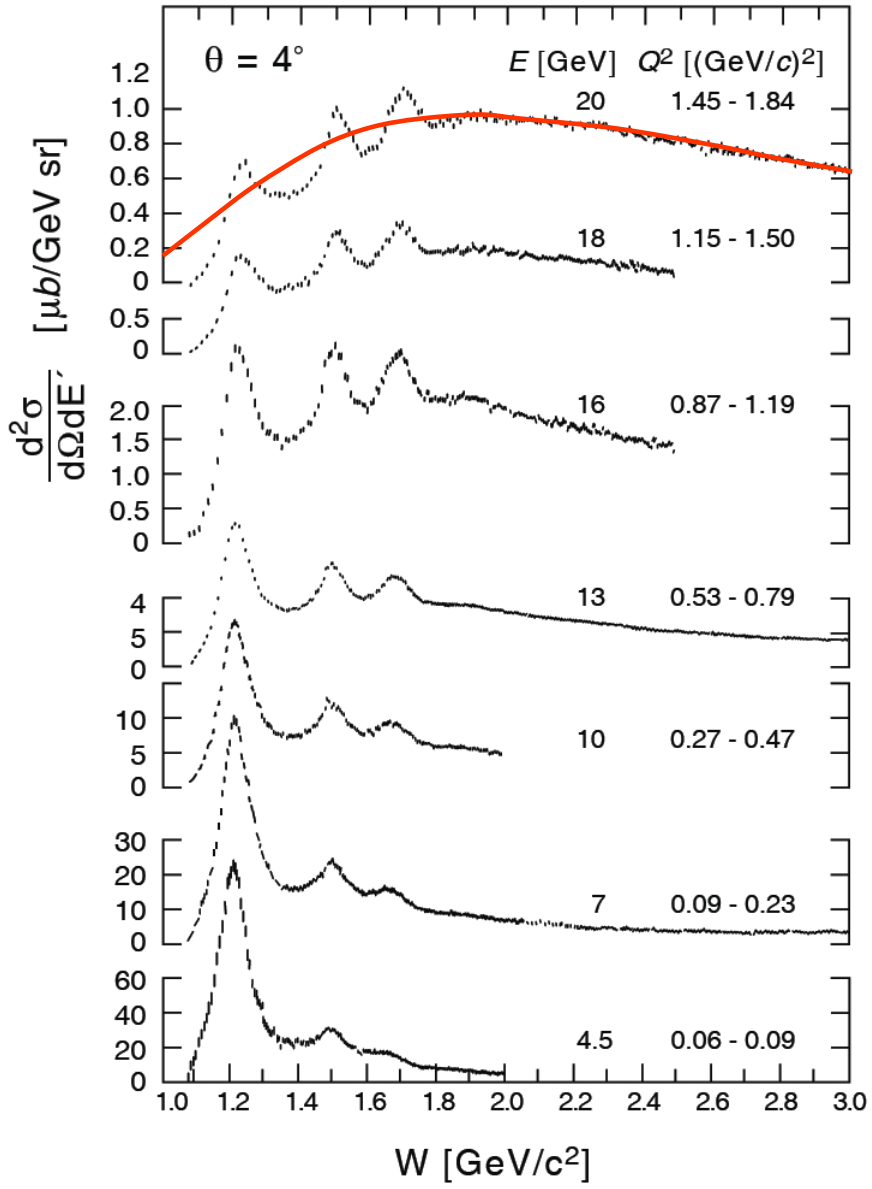
soft

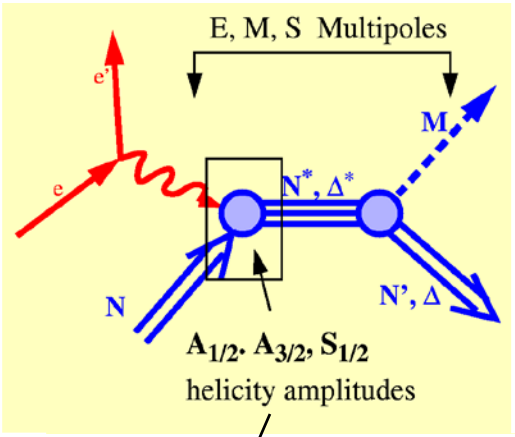


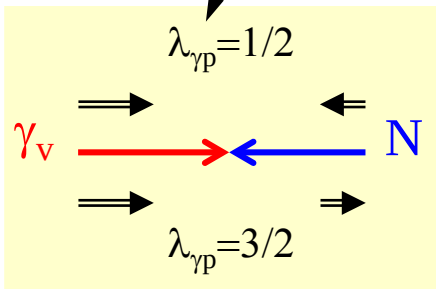


Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Baryon Excitations and Quasi-Elastic Scattering





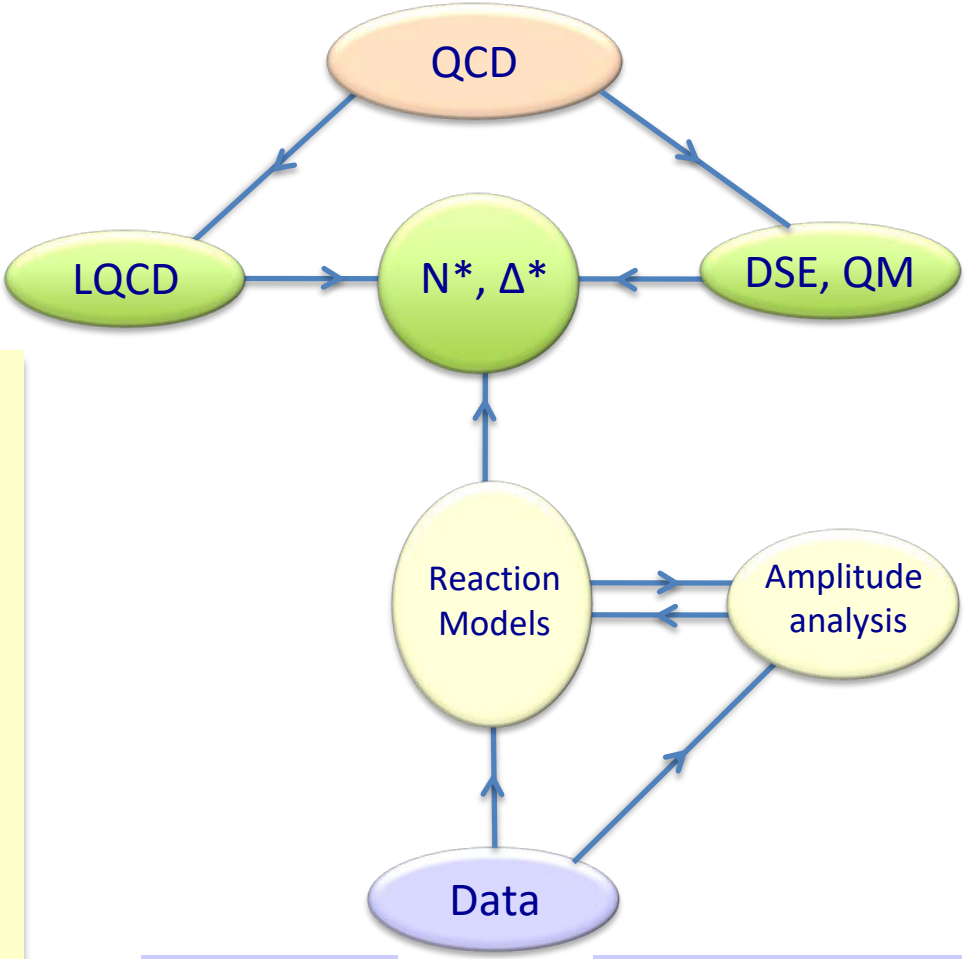


Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Transition Form Factors

Data-Driven Data Analyses

Consistent Results



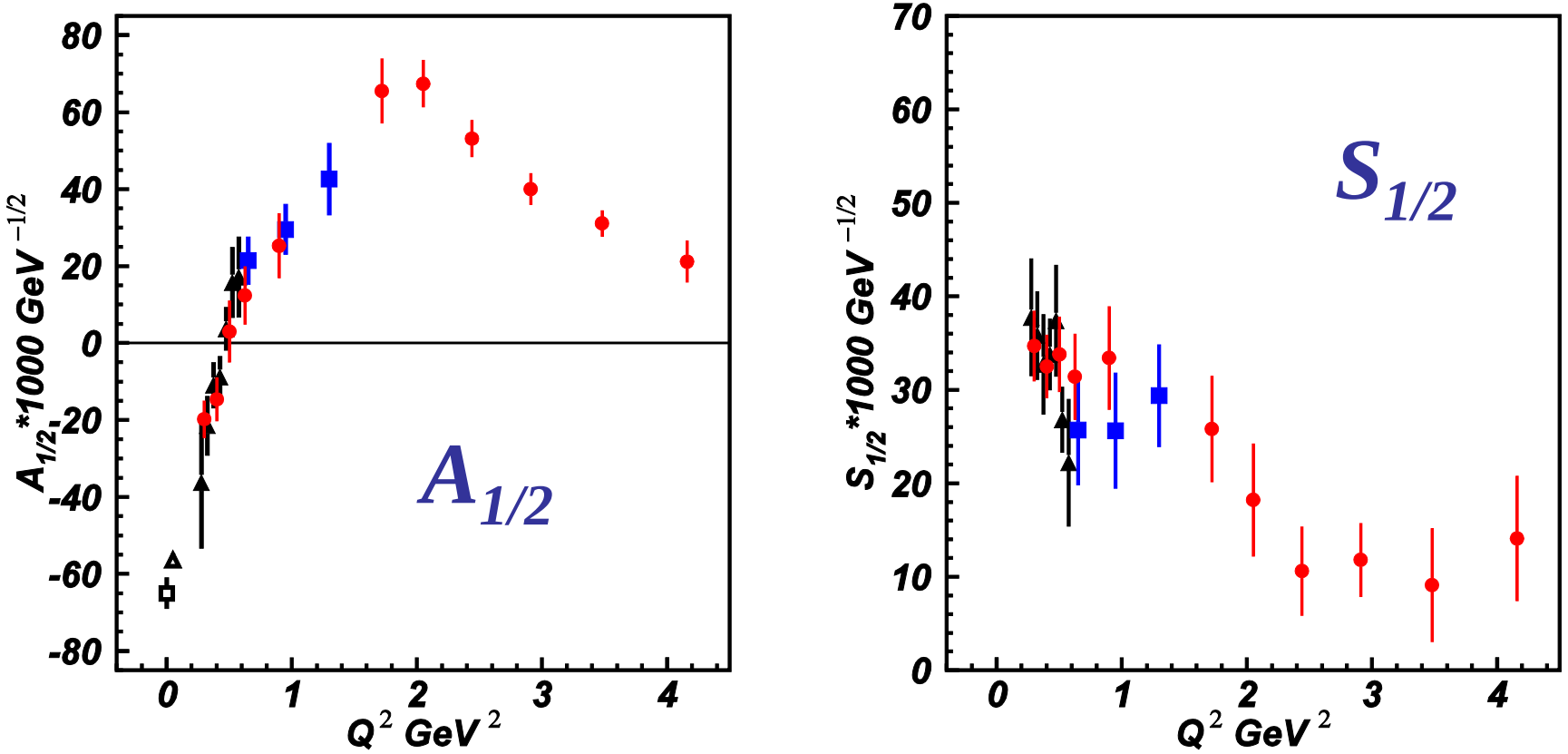
- Single meson production:
  - Unitary Isobar Model (UIM)
  - Fixed-*t* Dispersion Relations (DR)
- Double pion production:
  - Unitarized Isobar Model (JM)
- Coupled-Channel Approaches:
  - EBAC ⇒ Argonne-Osaka
  - JAW ⇒ Jülich-Athens-Washington ⇒ JüBo
  - BoGa ⇒ Bonn-Gatchina

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

Hadronic production

Electromagnetic production

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

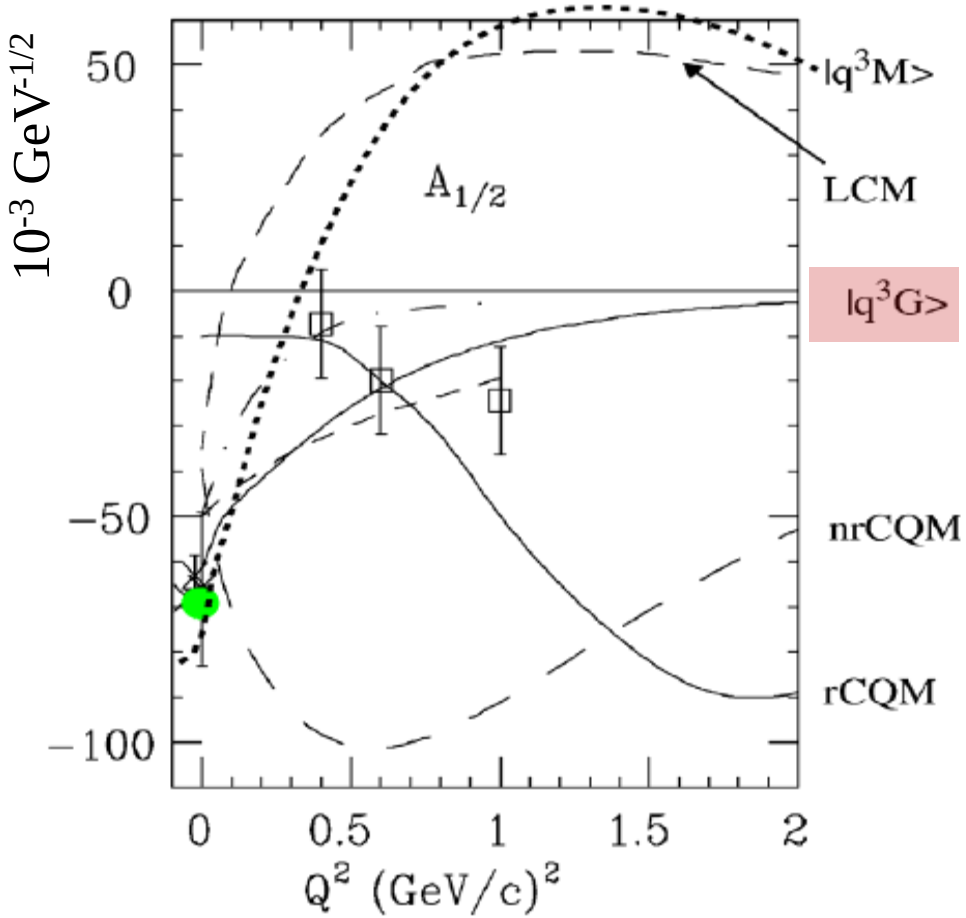


□ PDG ● Nπ (UIM, DR) ▲ Nππ (JM) 2012 ■ Nππ (JM) preliminary

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

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

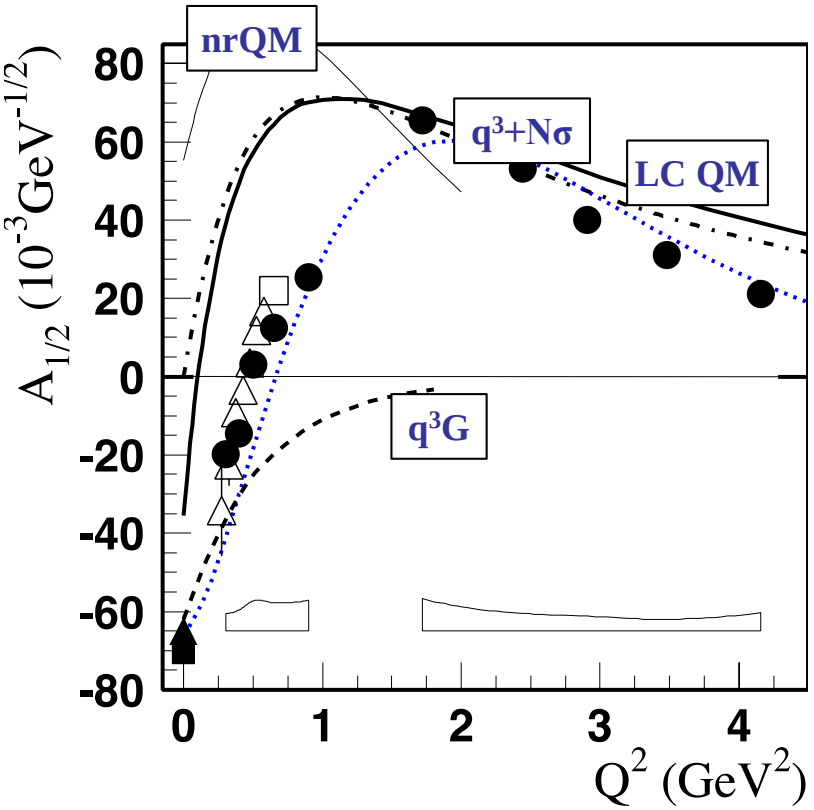
Electrocouplings of N(1440)P_{11} History



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

Transition Form Factors and QCD Models

Roper resonance $P_{11}(1440)$



PDG 2013 update

+ q^3g

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

+ N-Meson

+ …

or

- q^2q

- …

… all have distinctively different Q^2 dependencies

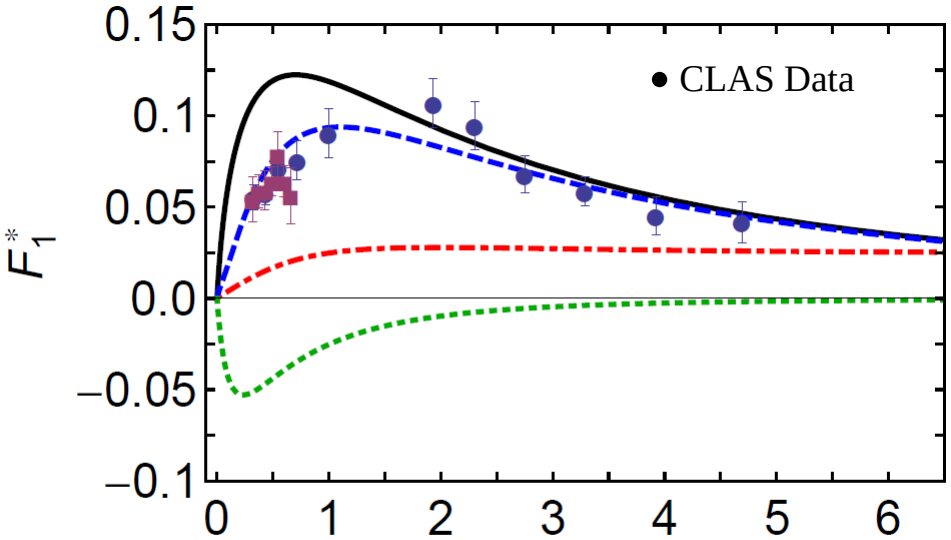
- $A_{1/2}$ has zero-crossing near Q^2=0.5 and becomes dominant amplitude at high Q^2.
- Consistent with radial excitation at high Q^2 and large meson-baryon coupling at small Q^2.
- Eliminates gluonic excitation (q^3G) as a dominant contribution.

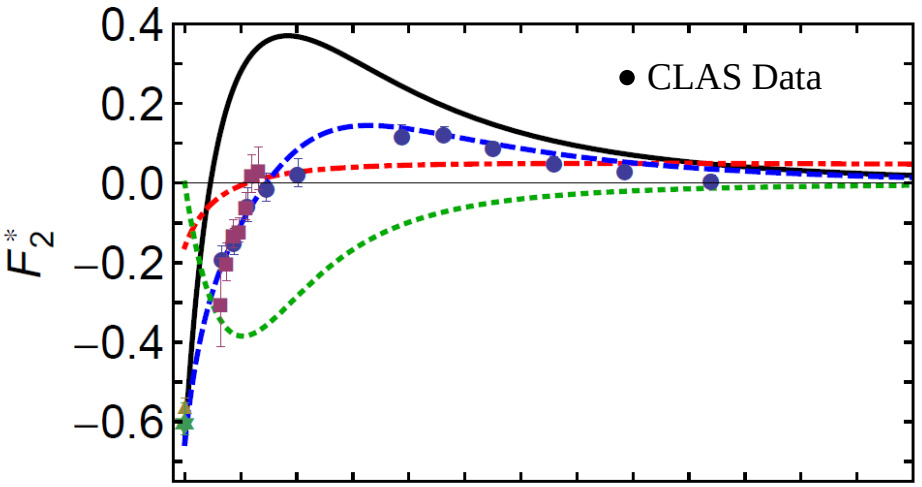
Nick Tyler closes the 1-2 GeV^2 gap for single pion production.

Roper Transition Form Factors in DSE Approach

$N(1440)P_{11}$

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





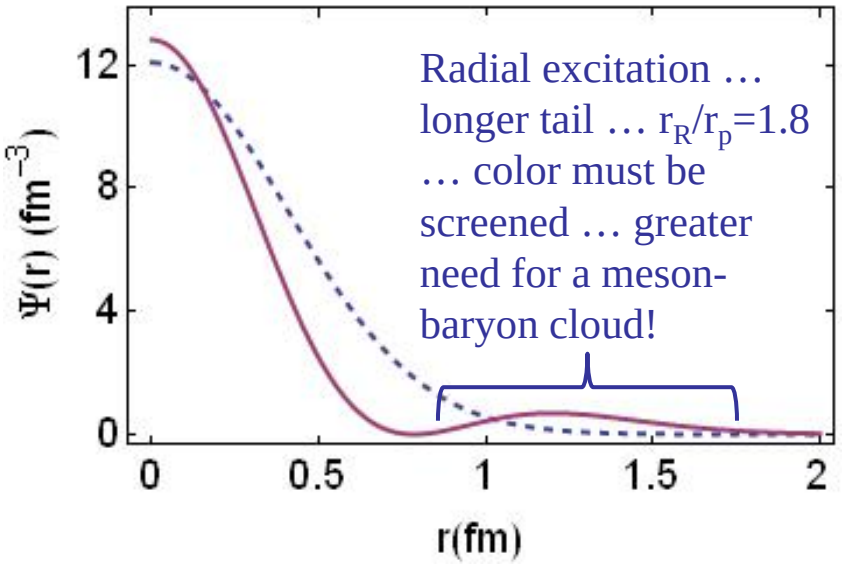
DSE Contact

DSE Realistic

Inferred meson-cloud contribution

Anticipated complete result

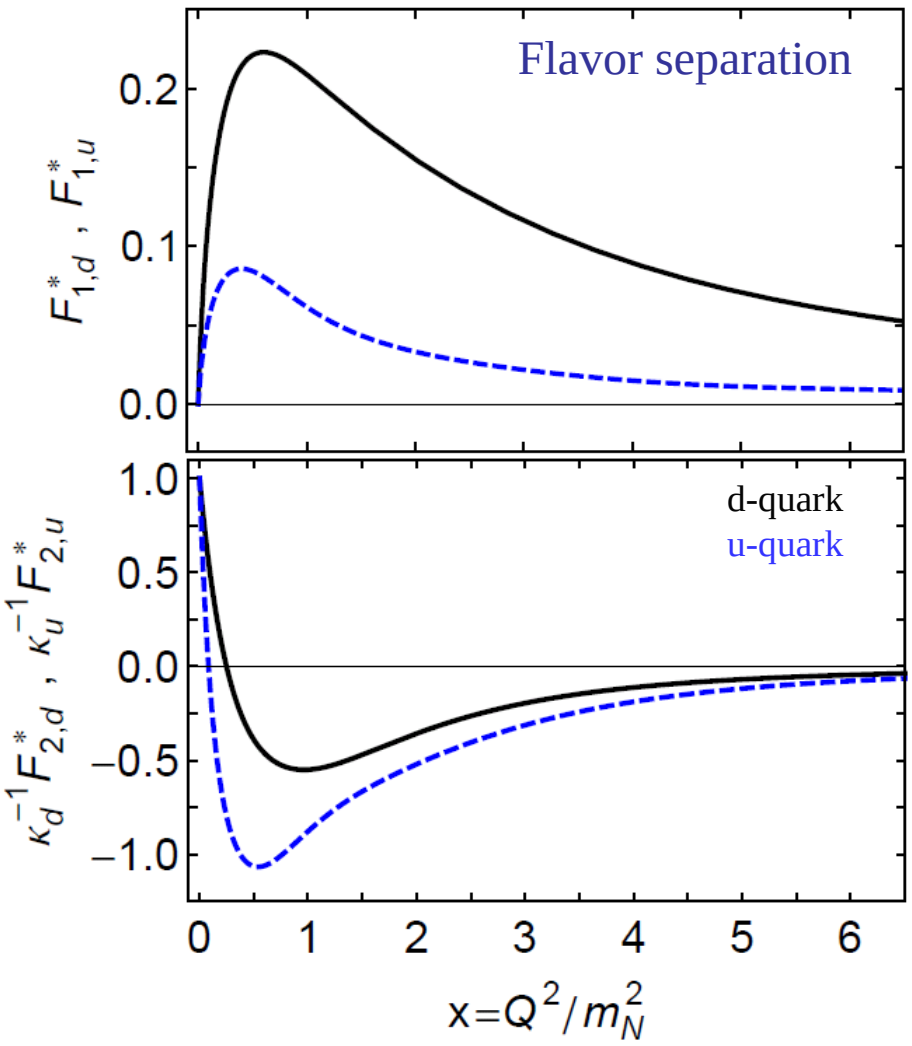
Importantly, the existence of a zero in F_2 is not influenced by meson-cloud effects, although its precise location is.

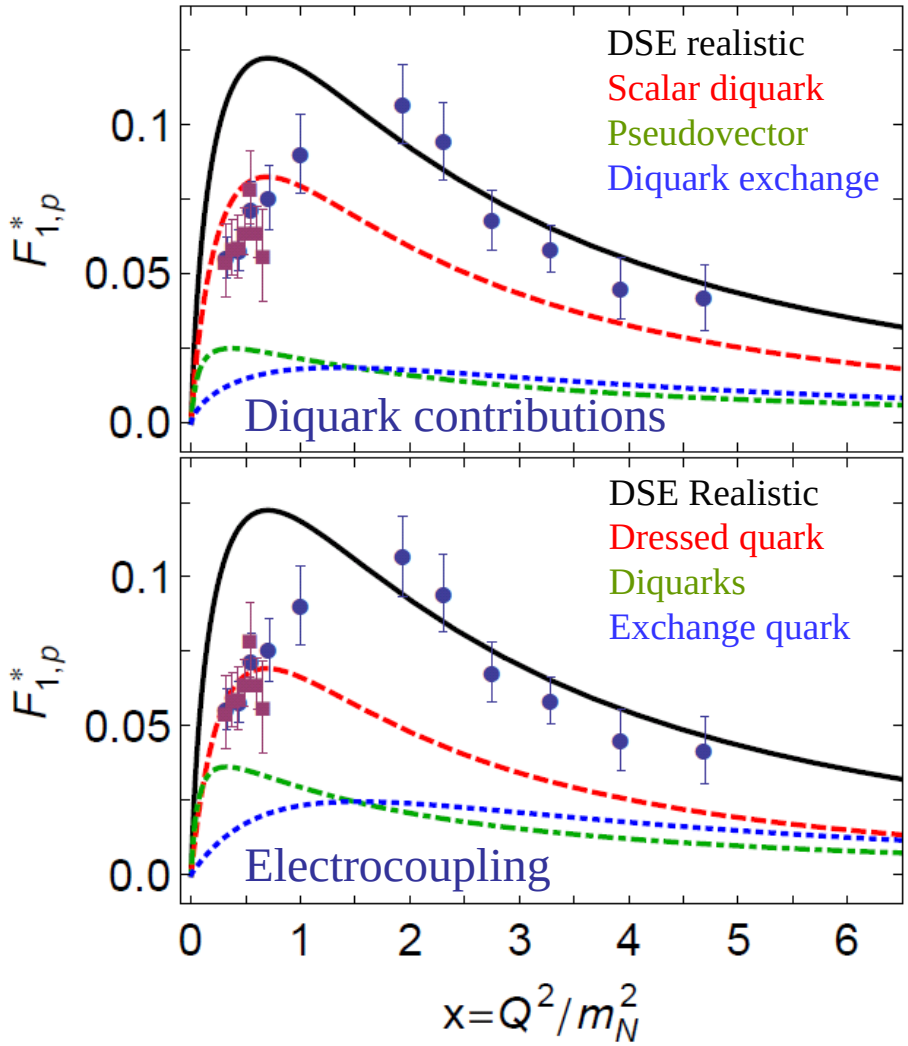


Roper Transition Form Factors in DSE Approach

N(1440)P$_{11}$

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

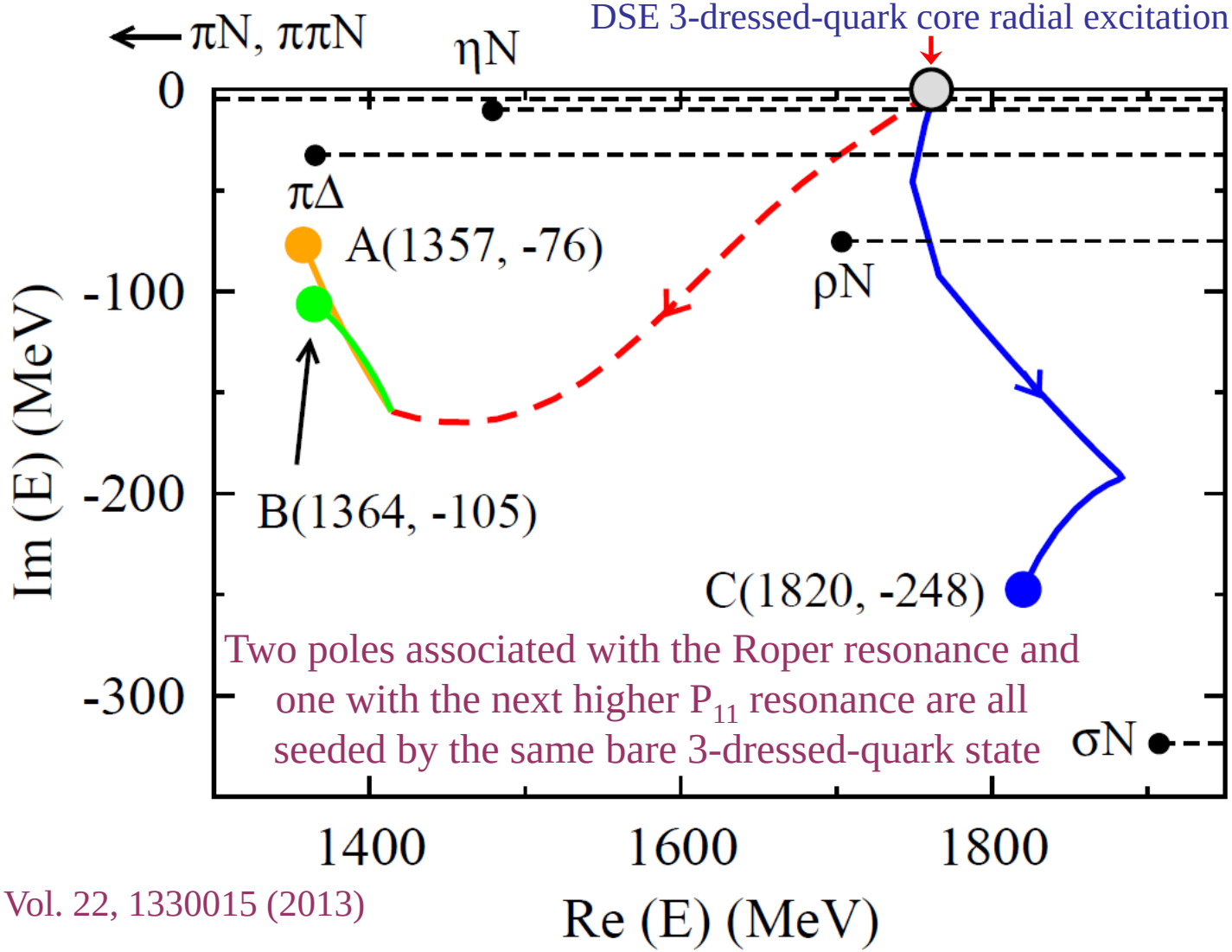




DSE and EBAC/ANL-Osaka Approaches

… more $(\pi,\pi\pi)$, $(\pi,\pi\eta)$, and (π,KY) data needed

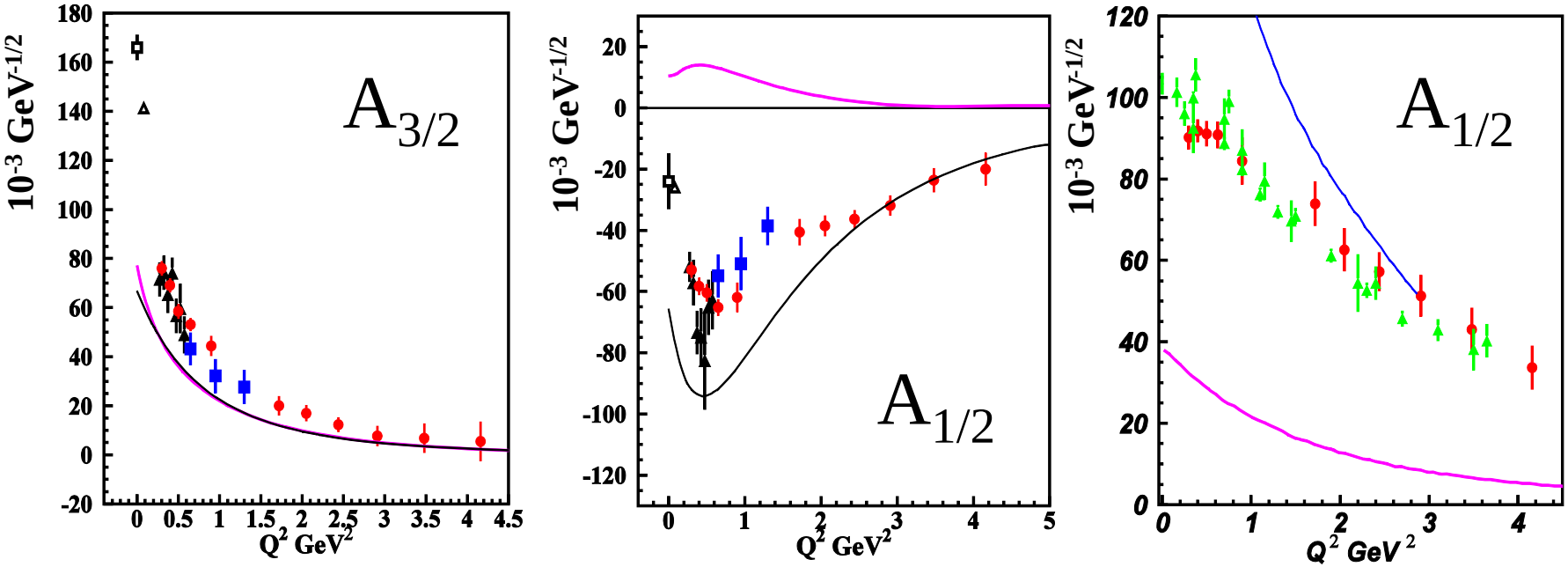
Semi-quantitative agreement with the first DSE 3-dressed-quark core radial excitation



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

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

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)

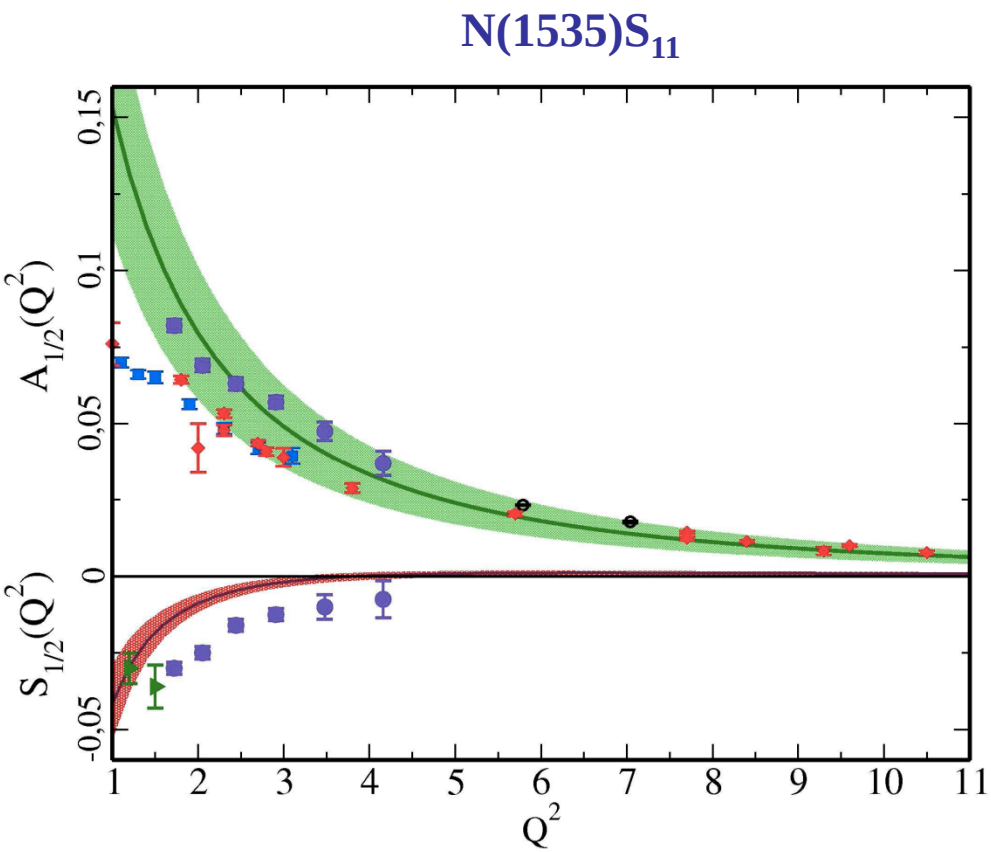
$\pi^+\pi^-p$ 2012

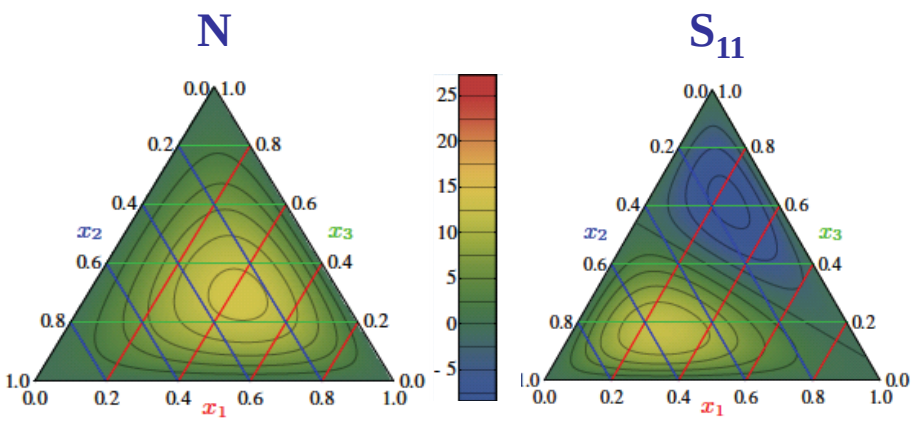
$\pi^+\pi^-p$ 2010

$N\pi$ 2009

ηp CLAS/Hall-C

LQCD & Light Cone Sum Rule (LCSR) Approach





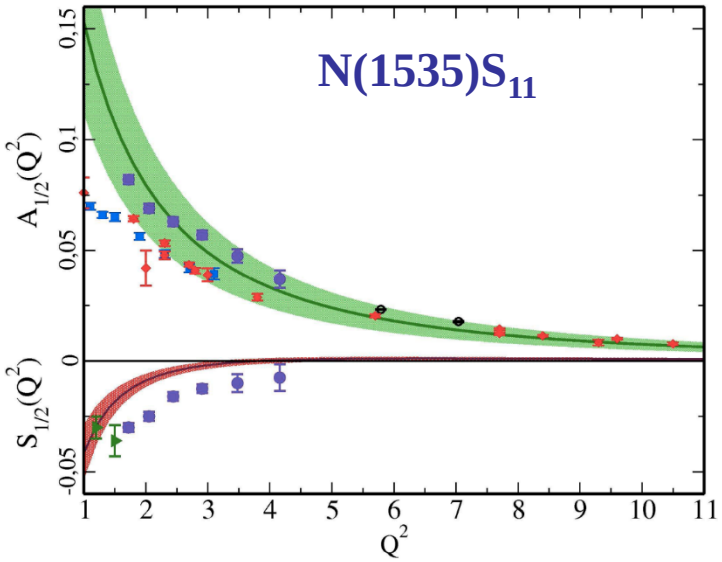
LQCD is used to determine the moments of N* distribution amplitudes (DA) and the N* electrocouplings are determined from the respective DAs within the LCSR framework.

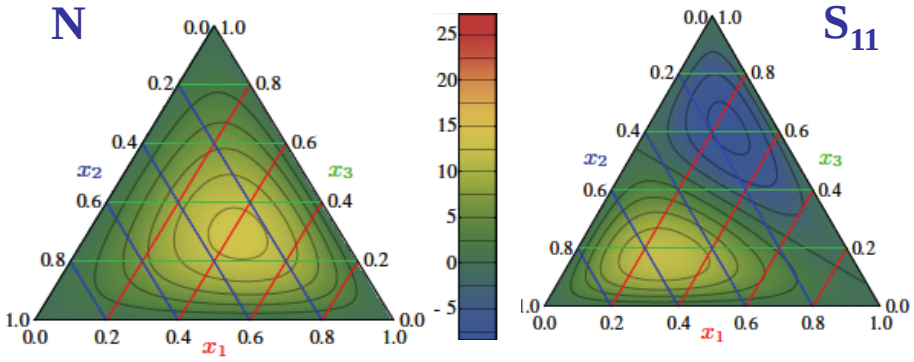
Calculations of $N(1535)S_{11}$ electrocouplings at Q^2 up to 12 GeV^2 are already available and shown by shadowed bands on the plot.

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

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

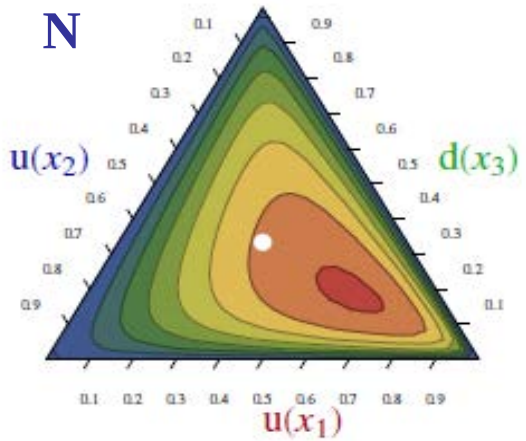
LQCD, LCSR, and DSE Approaches

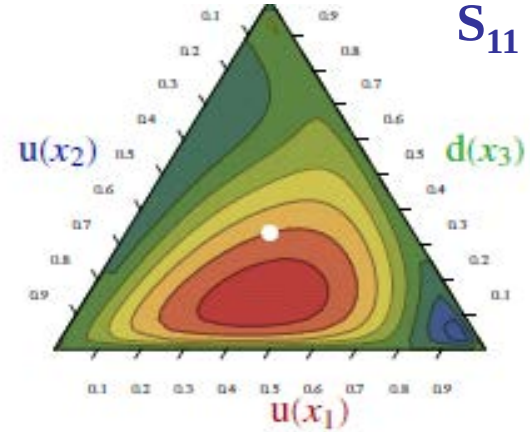




x_i is the momentum fraction of i-th valence quark

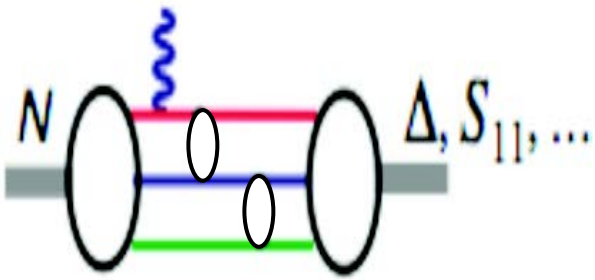
I.V. Anikin *et al.*, Phys. Rev. **D92**, 014018 (2015) and V.M. Braun *et al.*, Phys. Rev. **D89**, 094511 (2014)





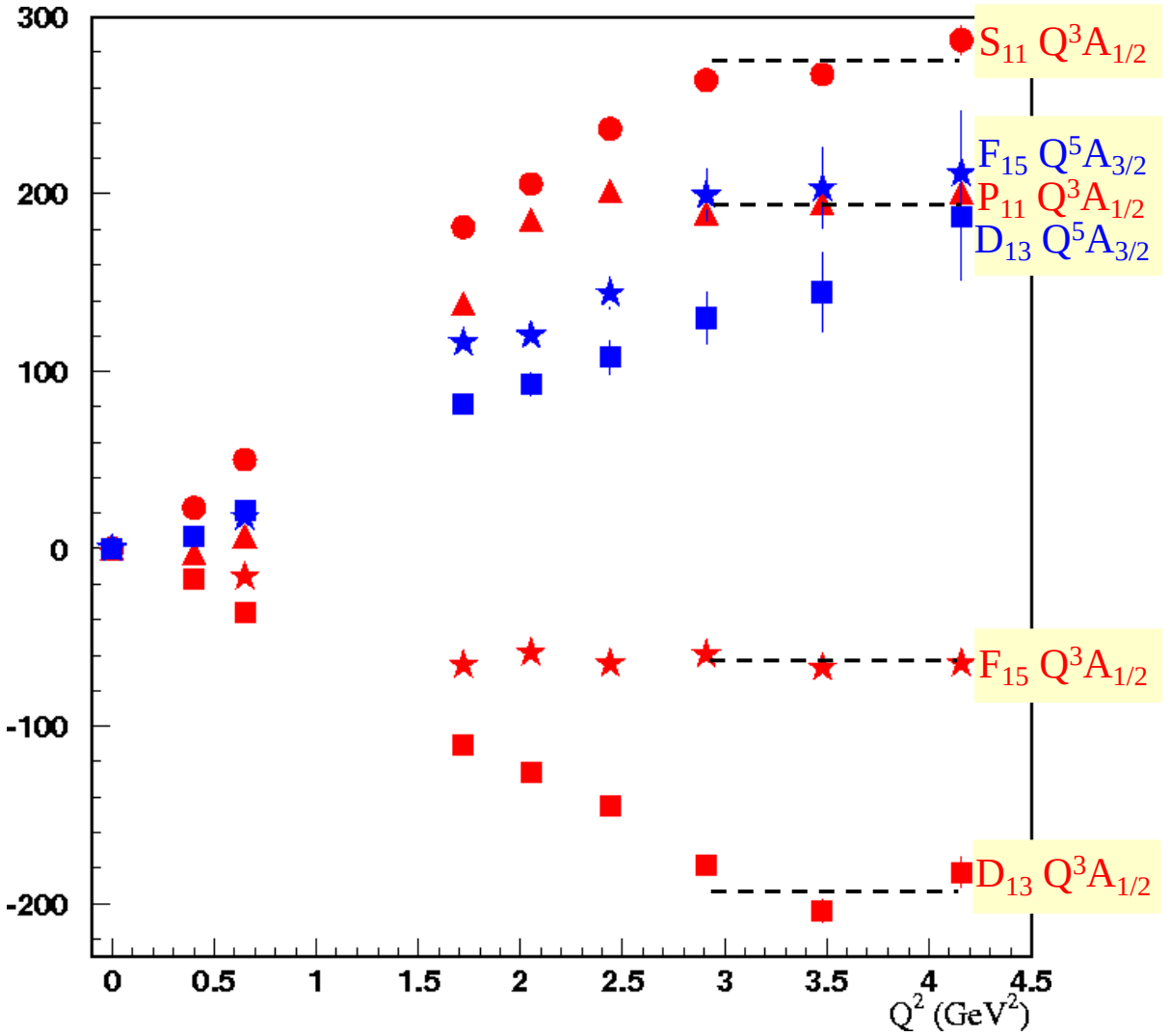
C.D. Roberts and C. Merzag, EPJ Web Conf. **137**, 01017 (2017)

Evidence for the Onset of Precocious Scaling?



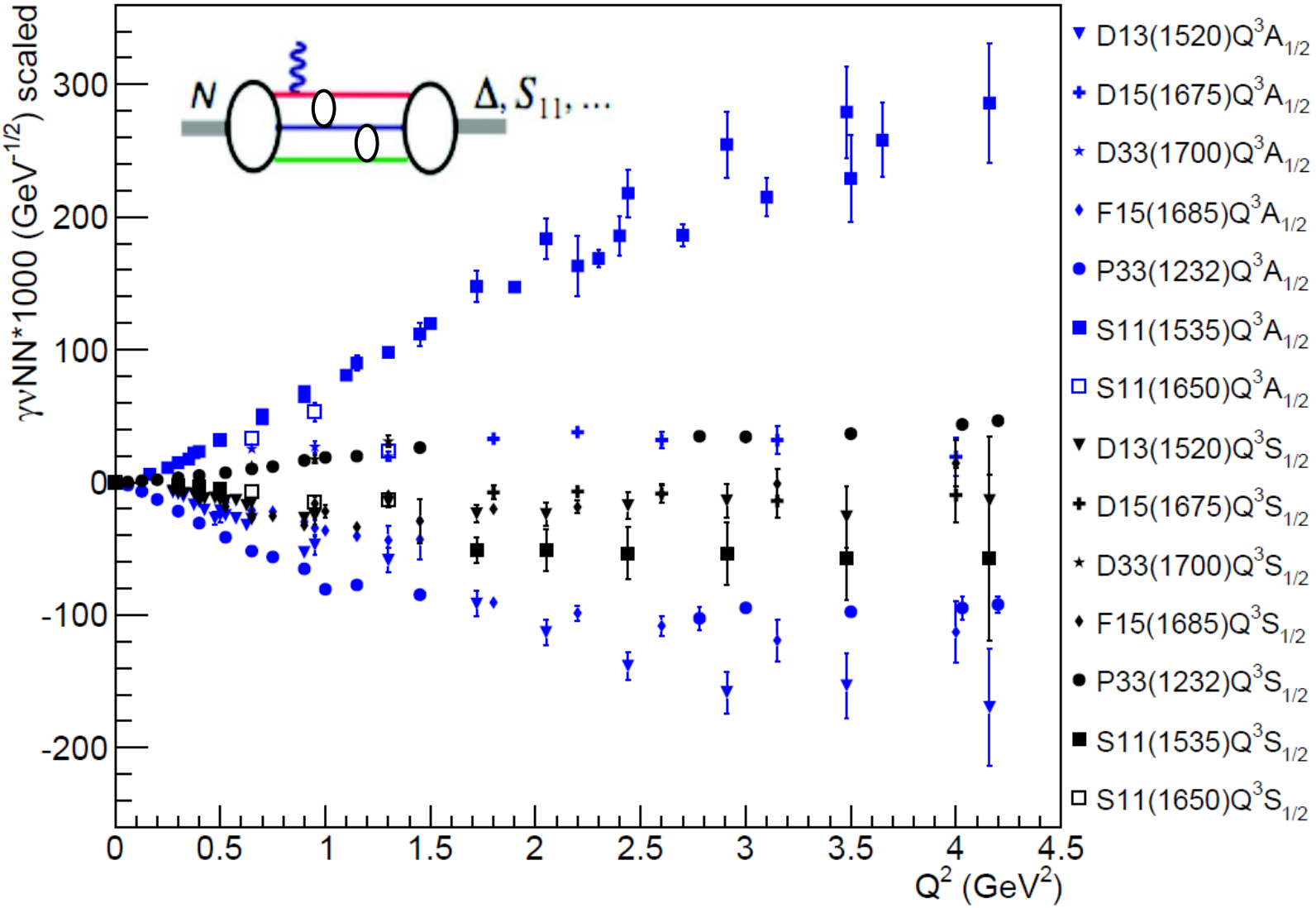
- $A_{1/2} \alpha 1/Q^3$
- $A_{3/2} \alpha 1/Q^5$

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



Evidence for the Onset of Precocious Scaling?

Ye Tian



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

Evidence for the Onset of Precocious Scaling?

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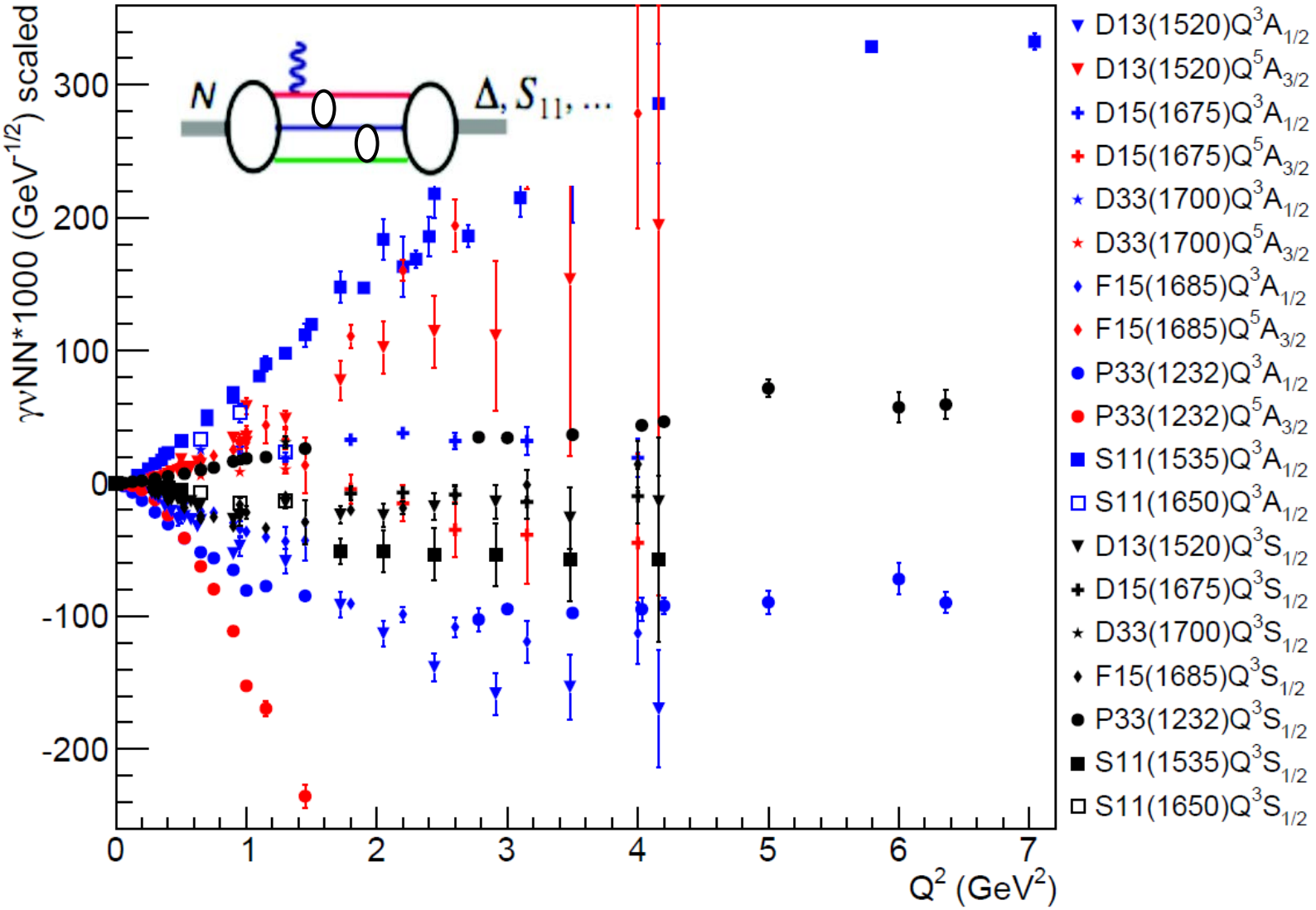
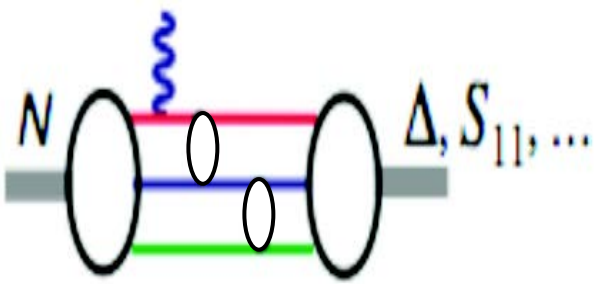
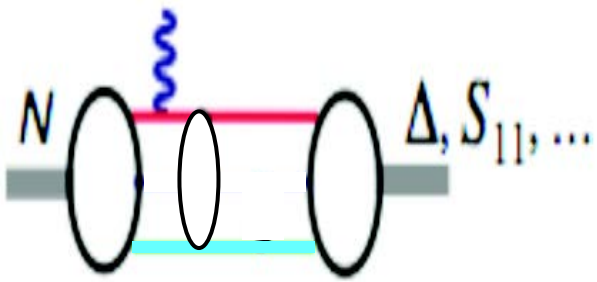


V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)

Evidence for the Onset of Scaling?

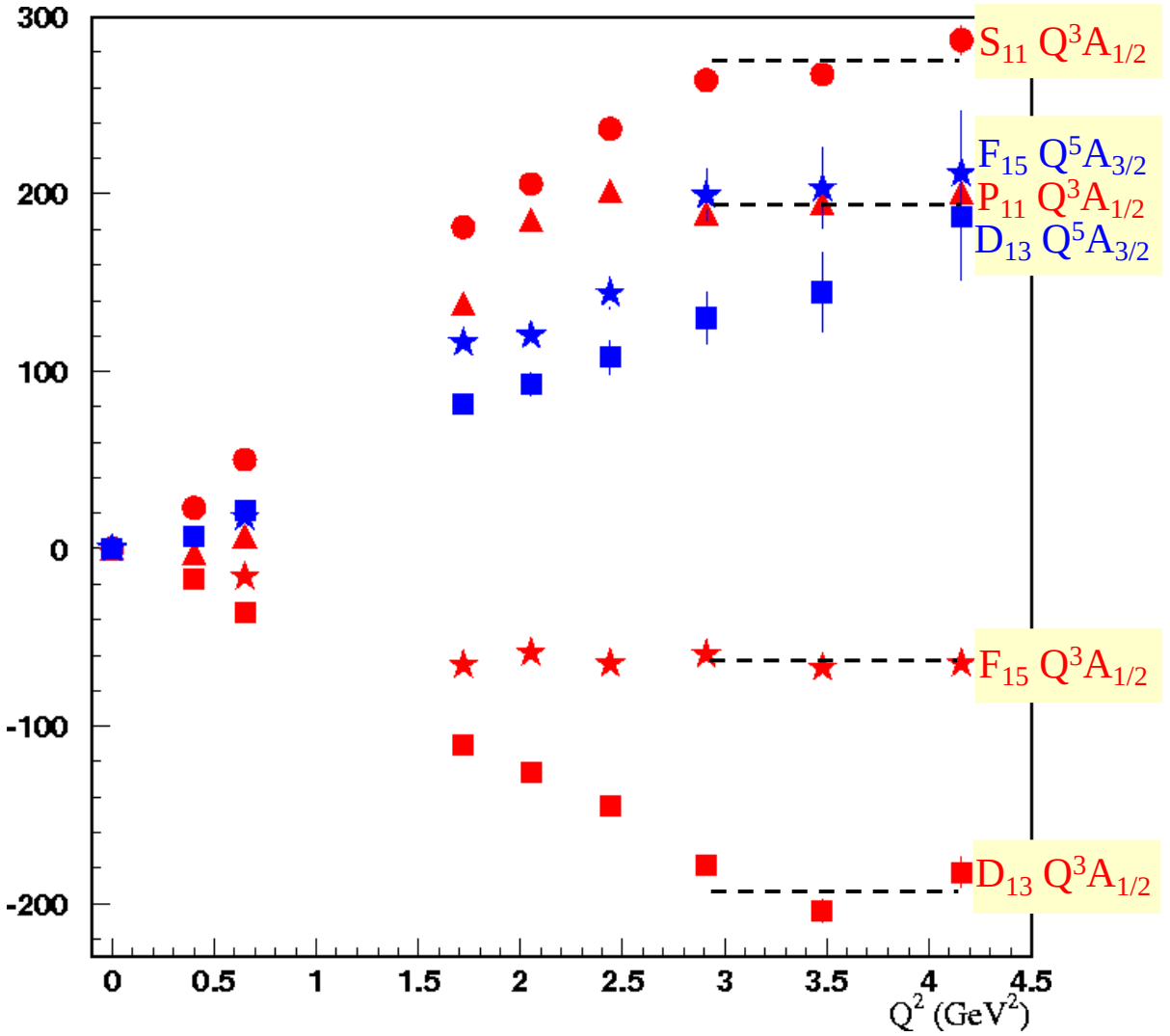


- $A_{1/2} \alpha 1/Q^3$
- $A_{3/2} \alpha 1/Q^5$
- $G_M^* \alpha 1/Q^4$

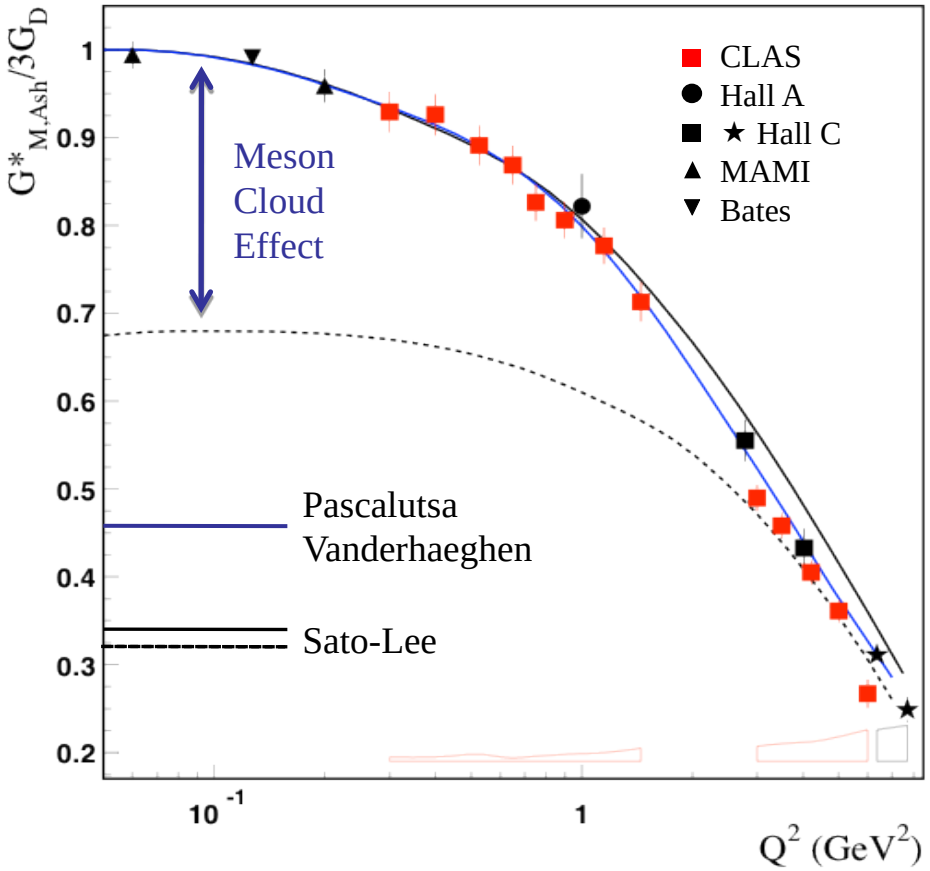


q^2q

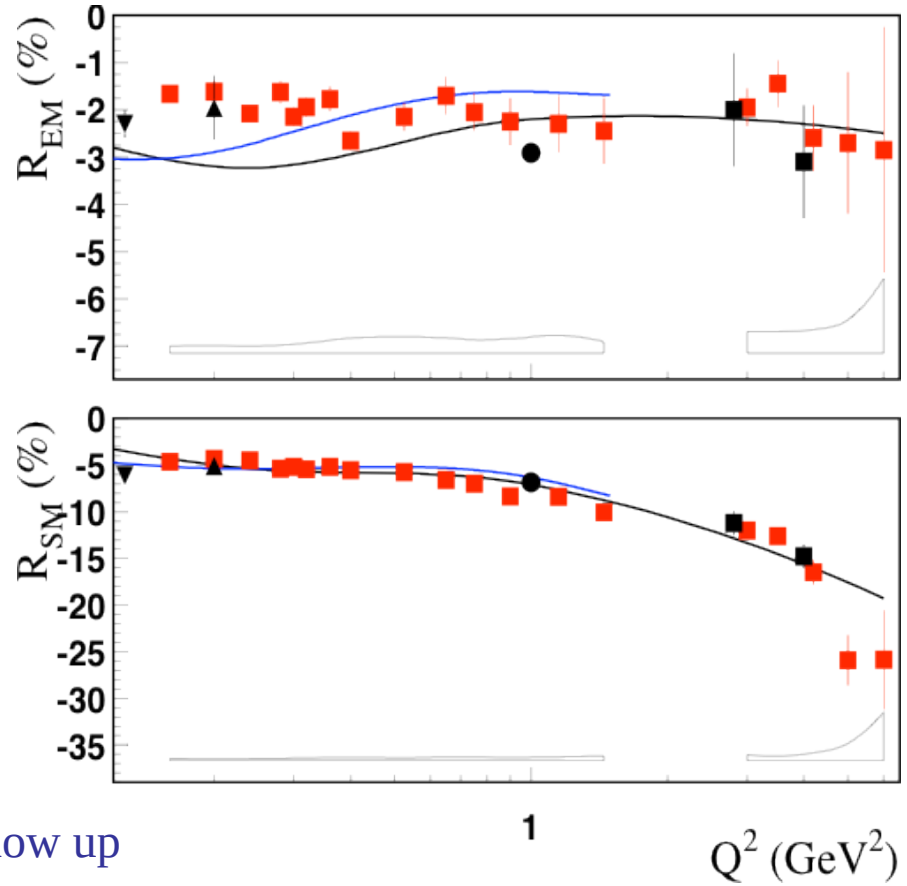
Phys. Rev. C80, 055203 (2009)



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

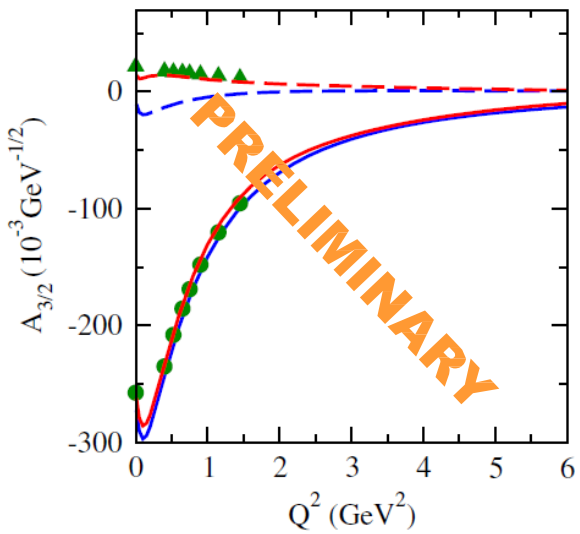


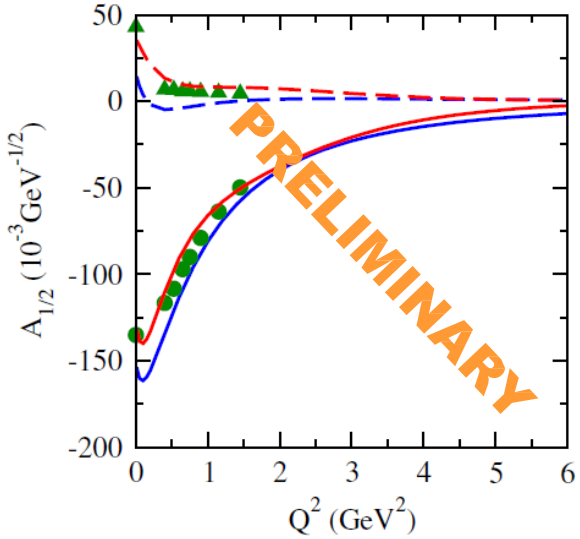
Phys. Rev. Lett. 97, 112003 (2006)

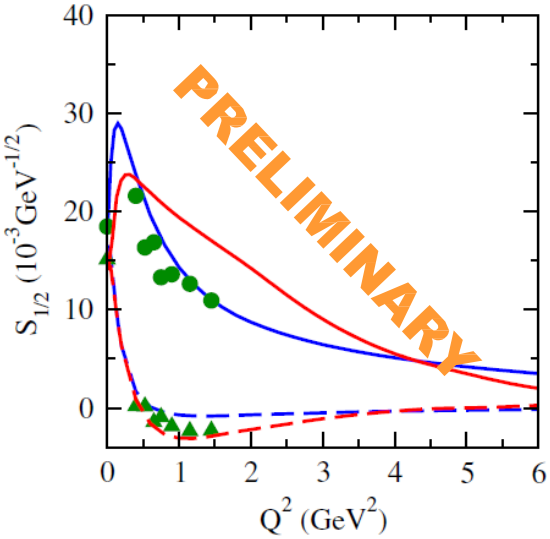


- New trend towards pQCD behavior does not show up
  - $R_{EM} \rightarrow +1$ $R_{SM} \rightarrow$ const
  - $G^*_{M,J.-S.} \rightarrow 1/Q^4$ $G^*_{M,Ash} \rightarrow 1/Q^5$
- CLAS12 can measure G^*_M, R_{EM}, and R_{SM} up to Q^2~12 GeV^2

$N \rightarrow \Delta$ Helicity Amplitudes







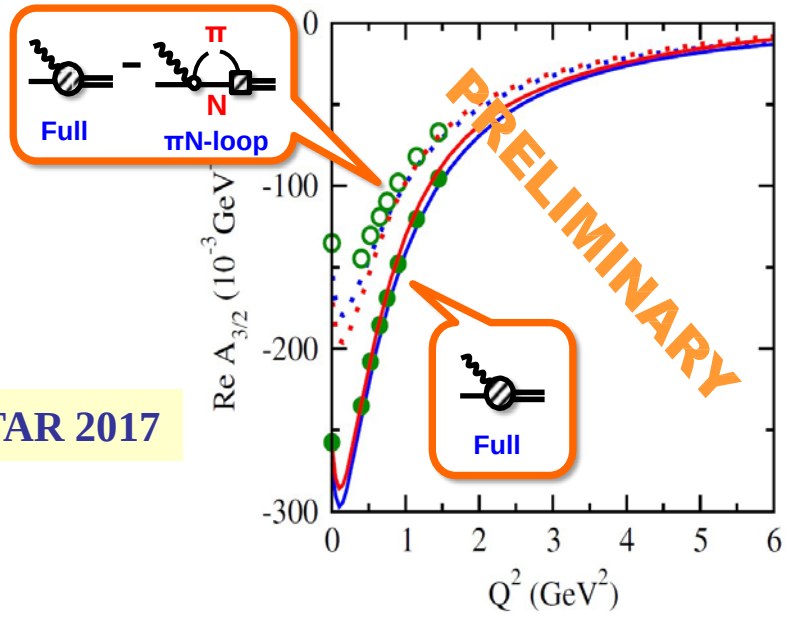
	Current	Previous	Sato-Lee
Re part	—	●	—
Im part	– –	▲	- - -

Current = coupled πN, ππN, ηN, KΛ, KΣ
2 bare states in P33

Previous = coupled πN, ππN, ηN
2 bare states in P33

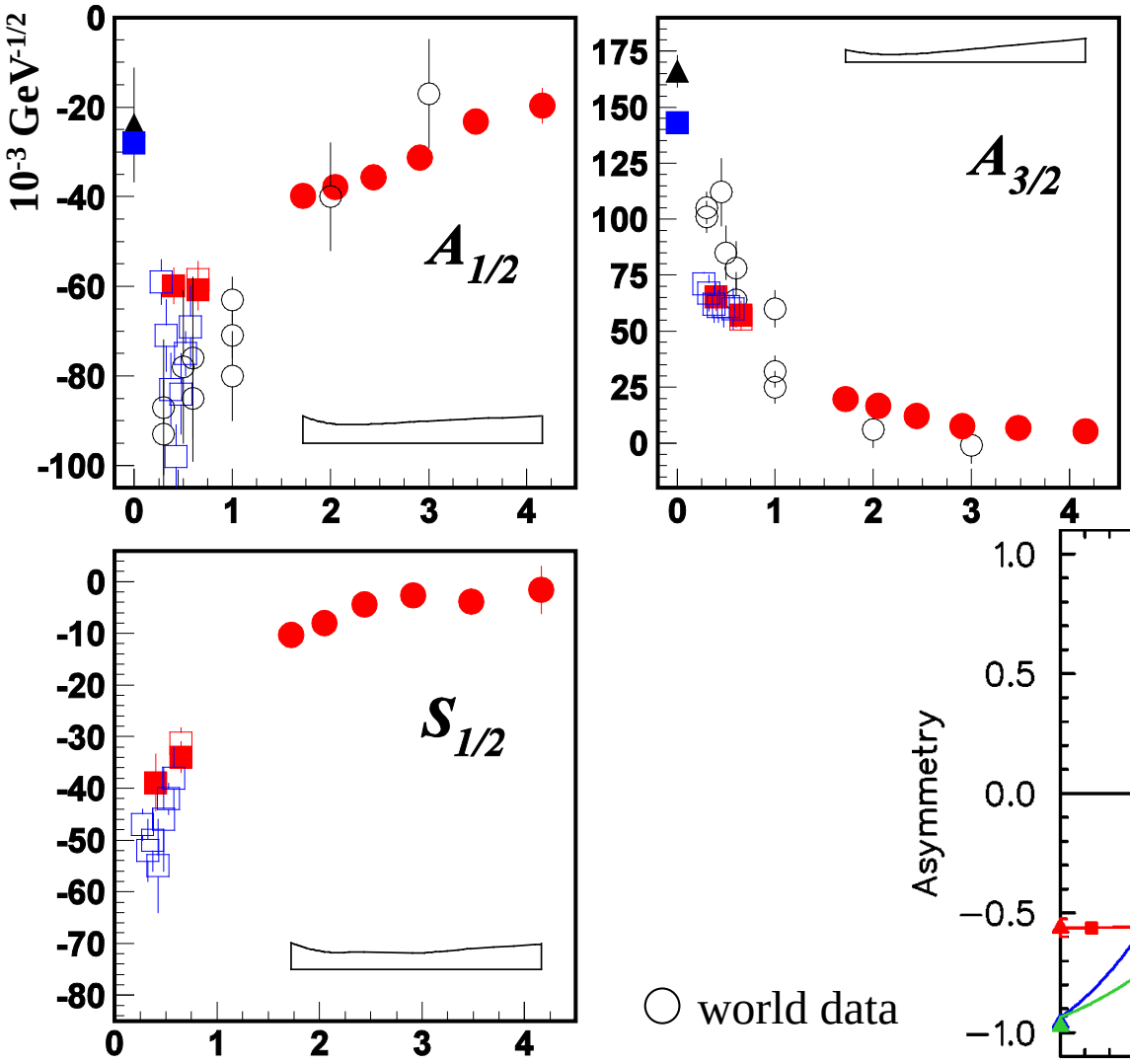
Sato-Lee = single πN
1 bare state in P33

Hiroyuki Kamano, NSTAR 2017



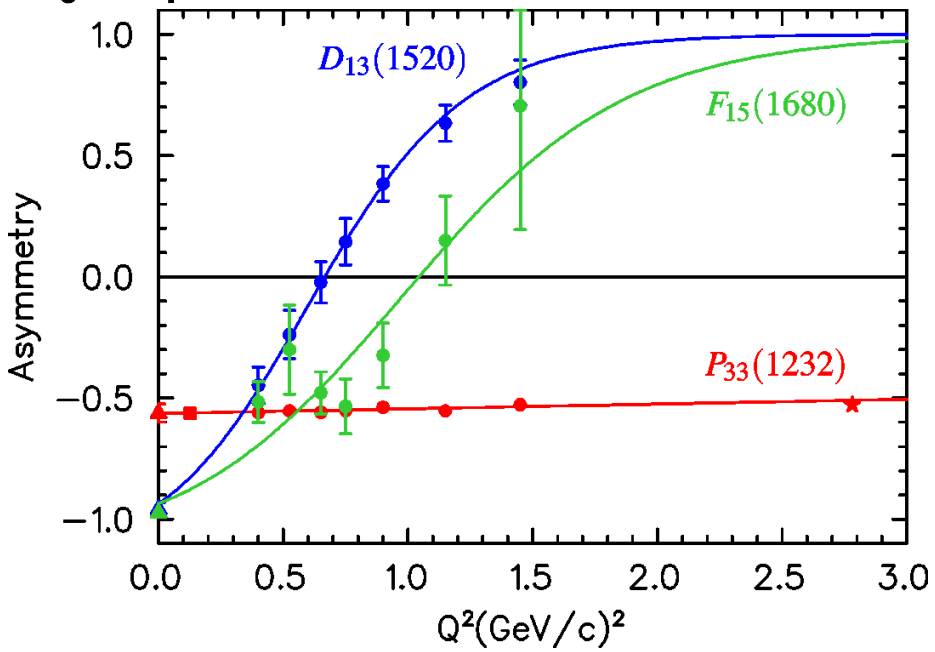
Previous: PRC80(2009)025207; 82(2010)045206
Sato-Lee: PRC63(2001)055201; 75(2007)015205

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



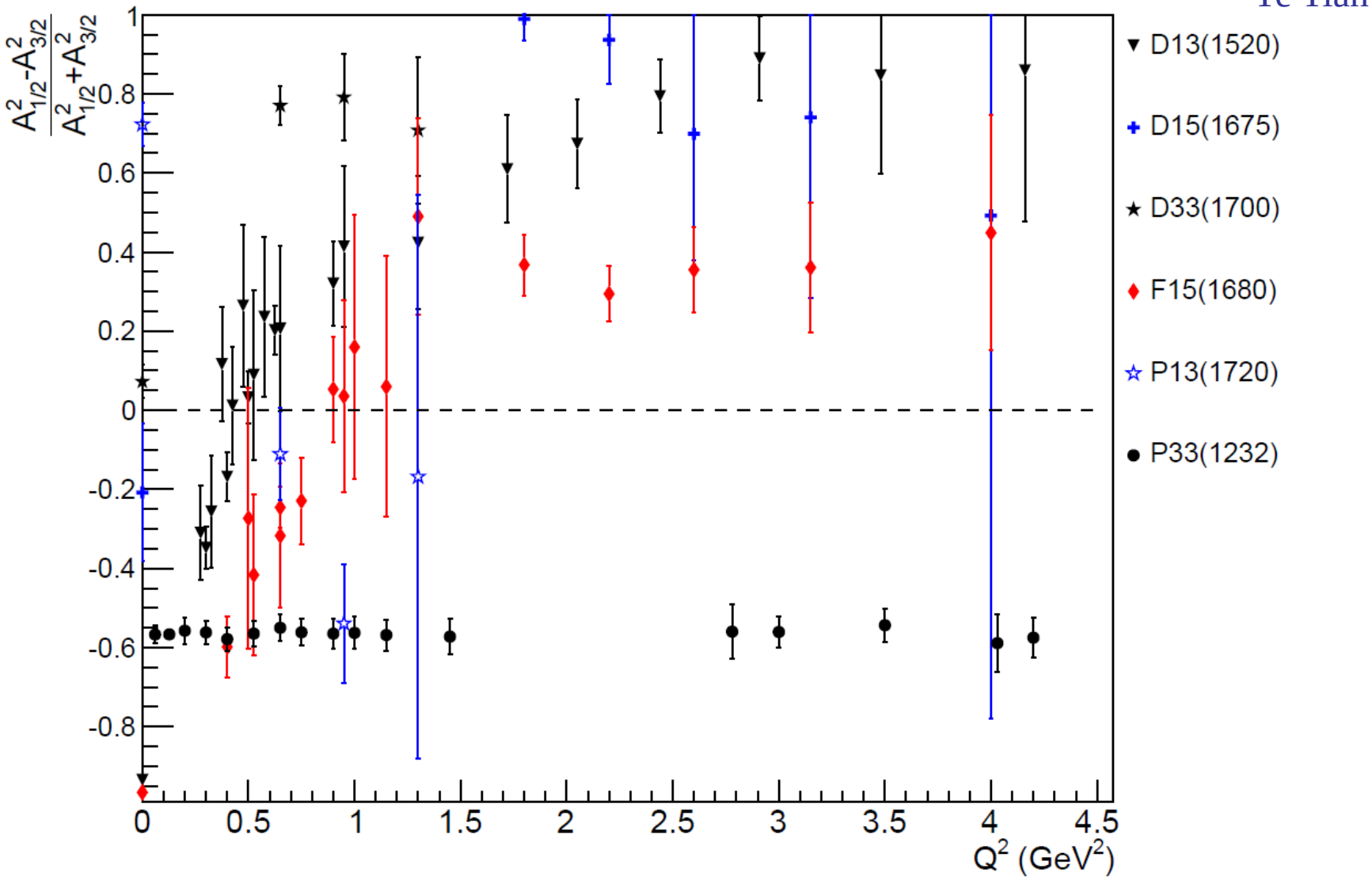
$$A_{hel} = \frac{A_{1/2}^2 - A_{3/2}^2}{A_{1/2}^2 + A_{3/2}^2}$$

L. Tiator



γNN* Helicity Asymmetries

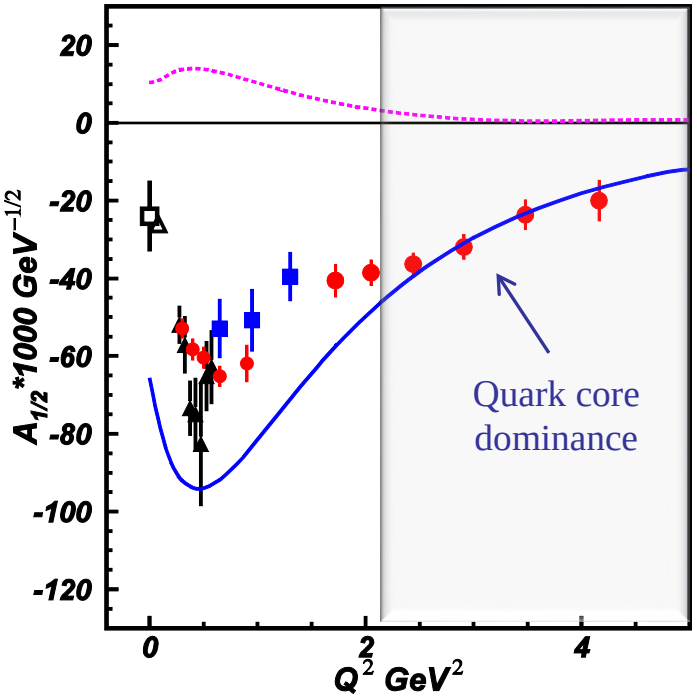
Ye Tian



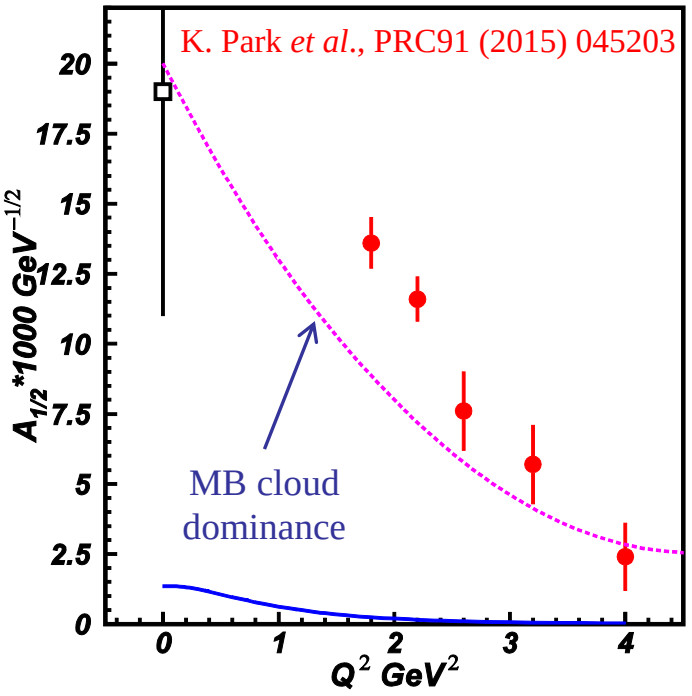
V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)

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$^-$

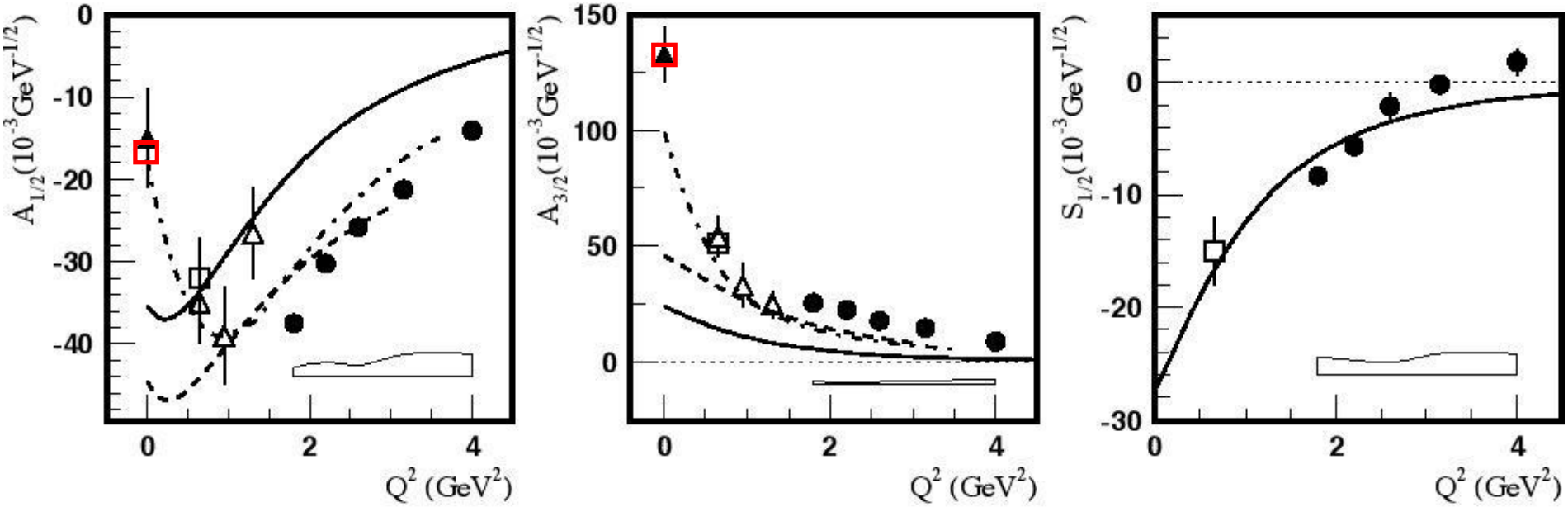
sheds light on the transition from the confined quark to the colorless meson-baryon structure and its dependents on the N* quantum numbers.

New Experimental Results & Approaches

Higher-Lying Resonance Electrocouplings

$N(1680)F_{15}$

Kijun Park



▲ RPP (PDG) Phys. Rev. D 86 (2012)

□ 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)

Phys. Rev. C **91**, 045203 (2015)

– – – D. Merten, U. Löring et al.

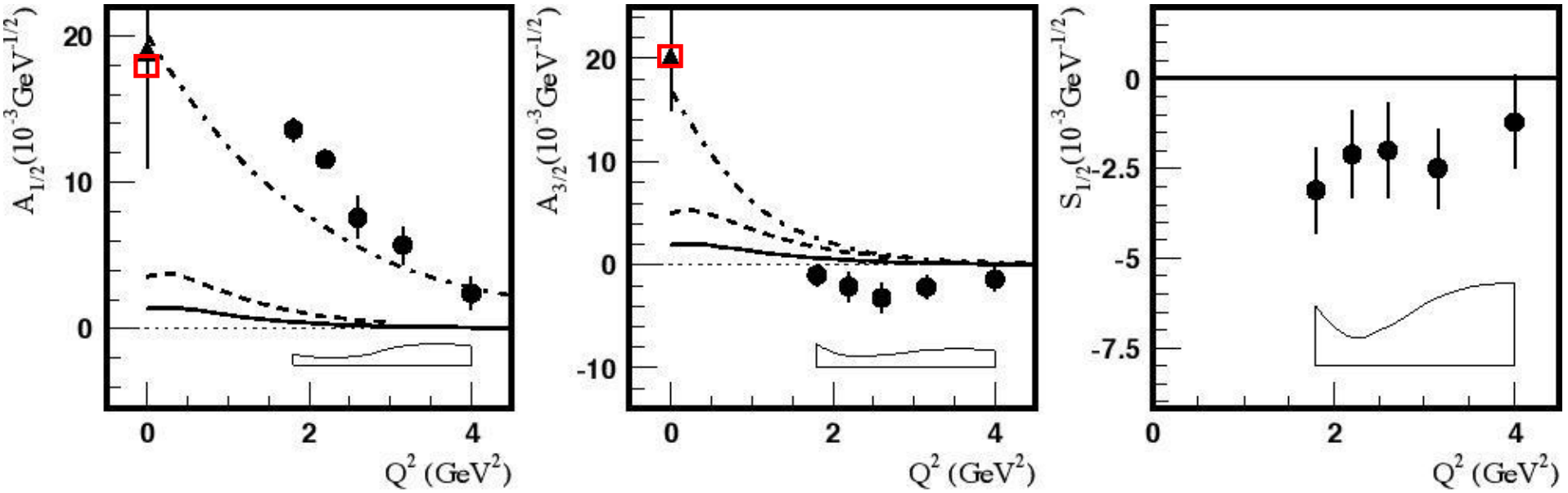
– · – · Z. Lee and F. Close

——— E. Santopinto and M.M. Gianini

Higher-Lying Resonance Electrocouplings

$N(1675)D_{15}$

Kijun Park



Phys. Rev. C **91**, 045203 (2015)

▲ RPP (PDG) Phys. Rev. D 86 (2012)

□ M. Dugger Phys. Rev. C 76 (2007)

● Nπ: I.G. Aznauryan (UIM & DR)

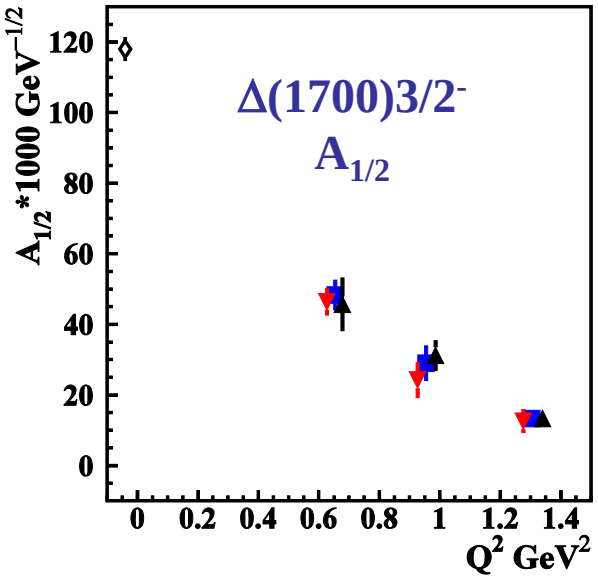
– – – D. Merten, U. Löring et al.

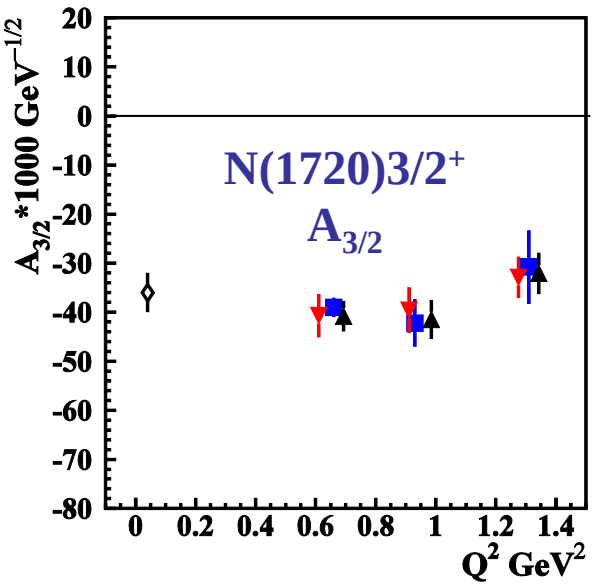
– · – · B. Julia-Diaz, T.-S.H. Lee et al.

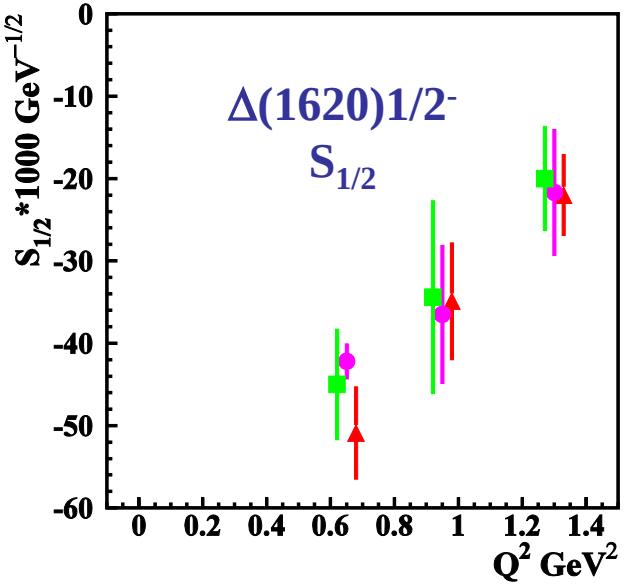
——— E. Santopinto and M.M. Gianini

Higher-Lying Resonance Electrocouplings

Viktor Mokeev







Independent fits in different W-intervals

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

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

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

Phys. Rev. C **93**, 025206 (2016)

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

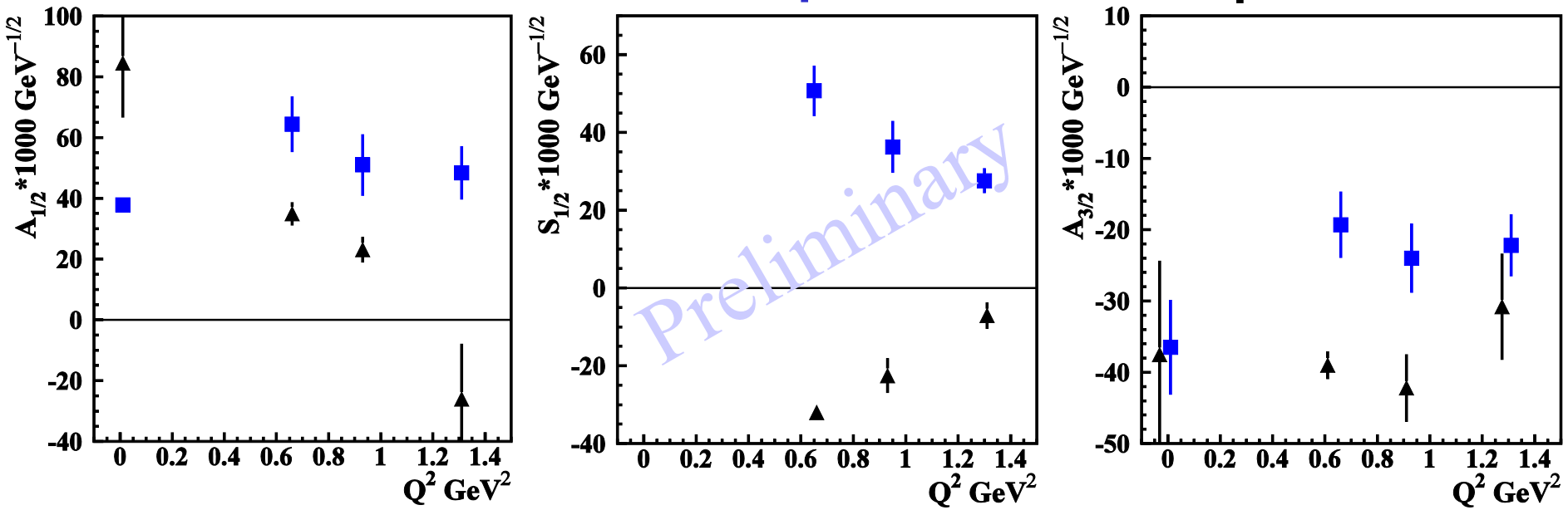
N* hadronic decays from JM15 that incorporates N'(1720)3/2$^+$

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.

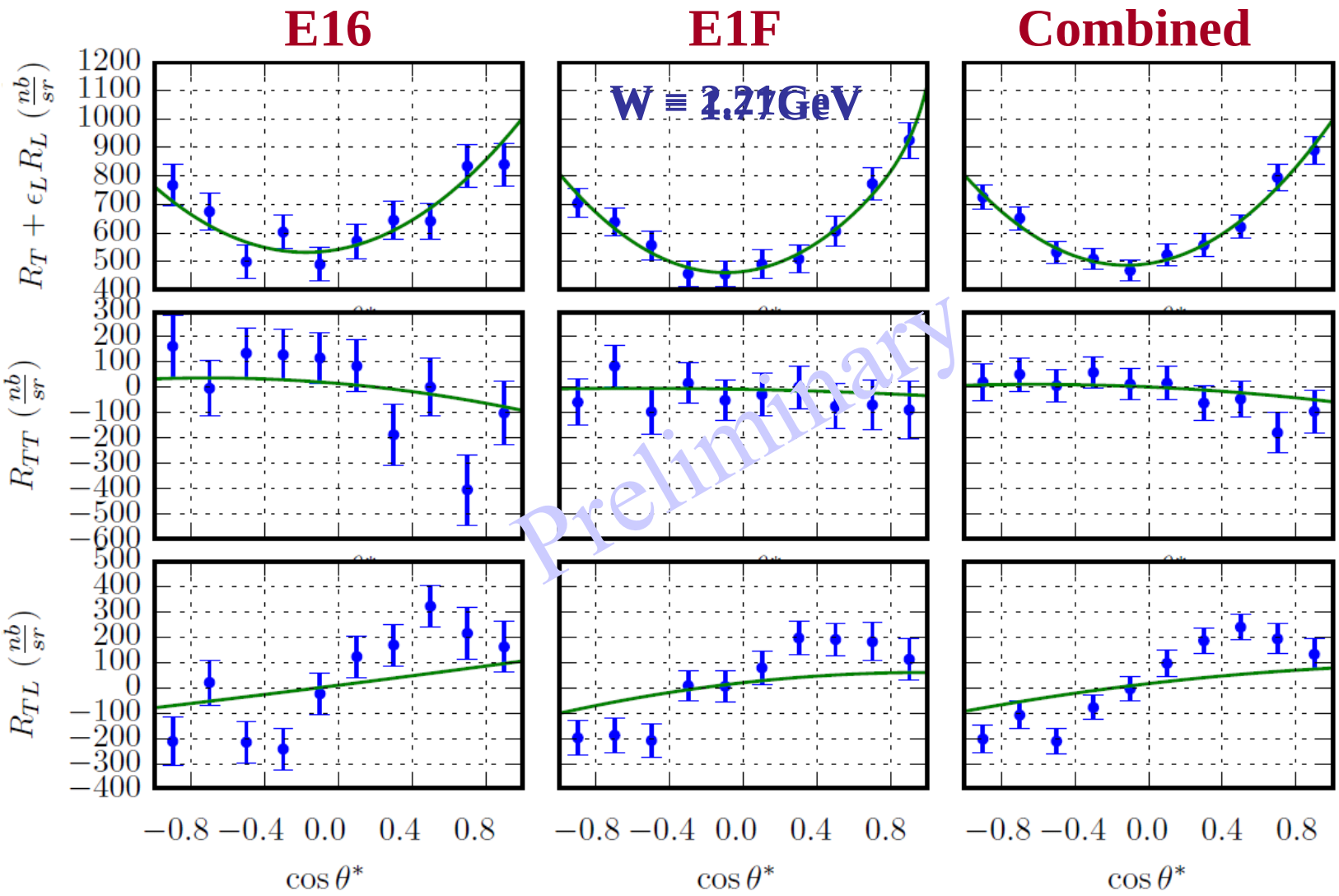
Mass: 1.715-1.735 GeV
Width: 120±6 MeV
N'(1720)3/2$^+$

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



High-Lying Resonances in ω Electroproduction

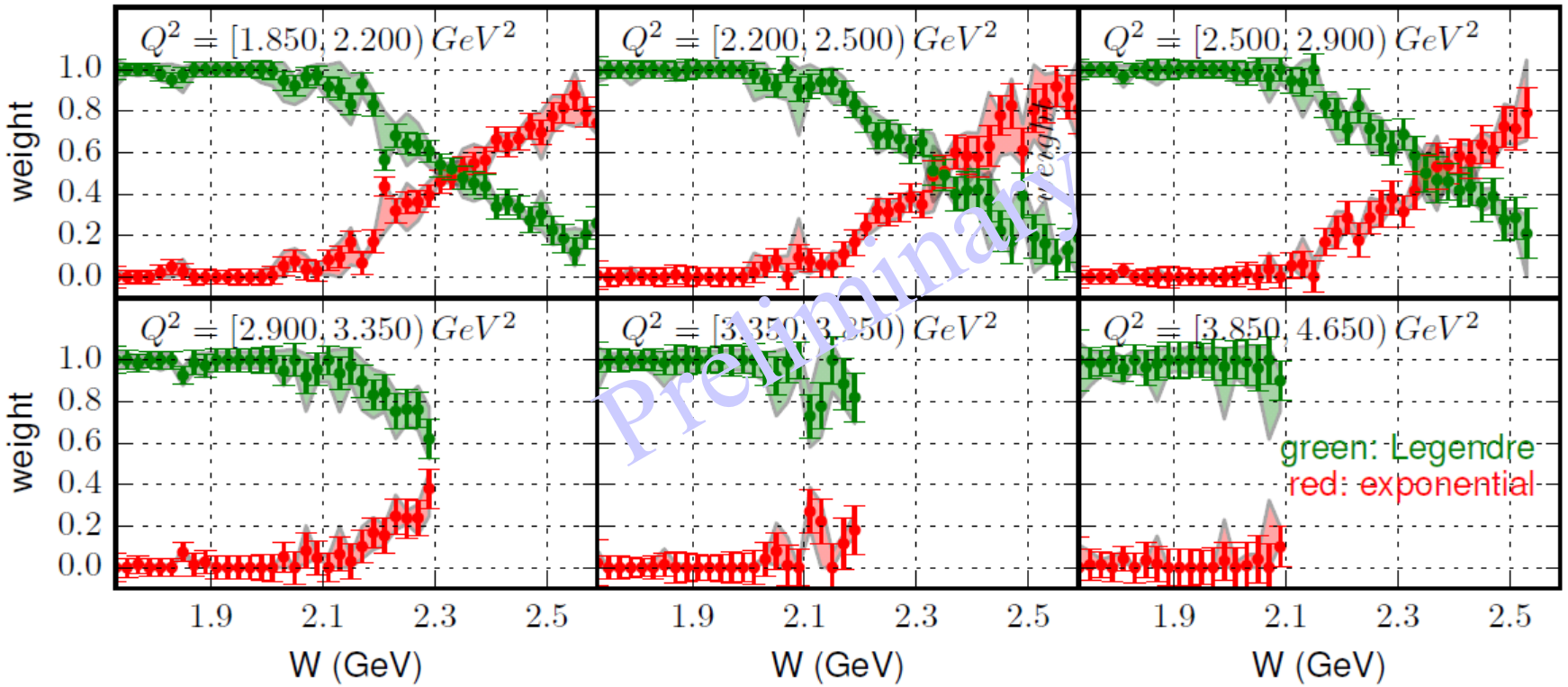
Evan Phelps



High-Lying Resonances in ω Electroproduction

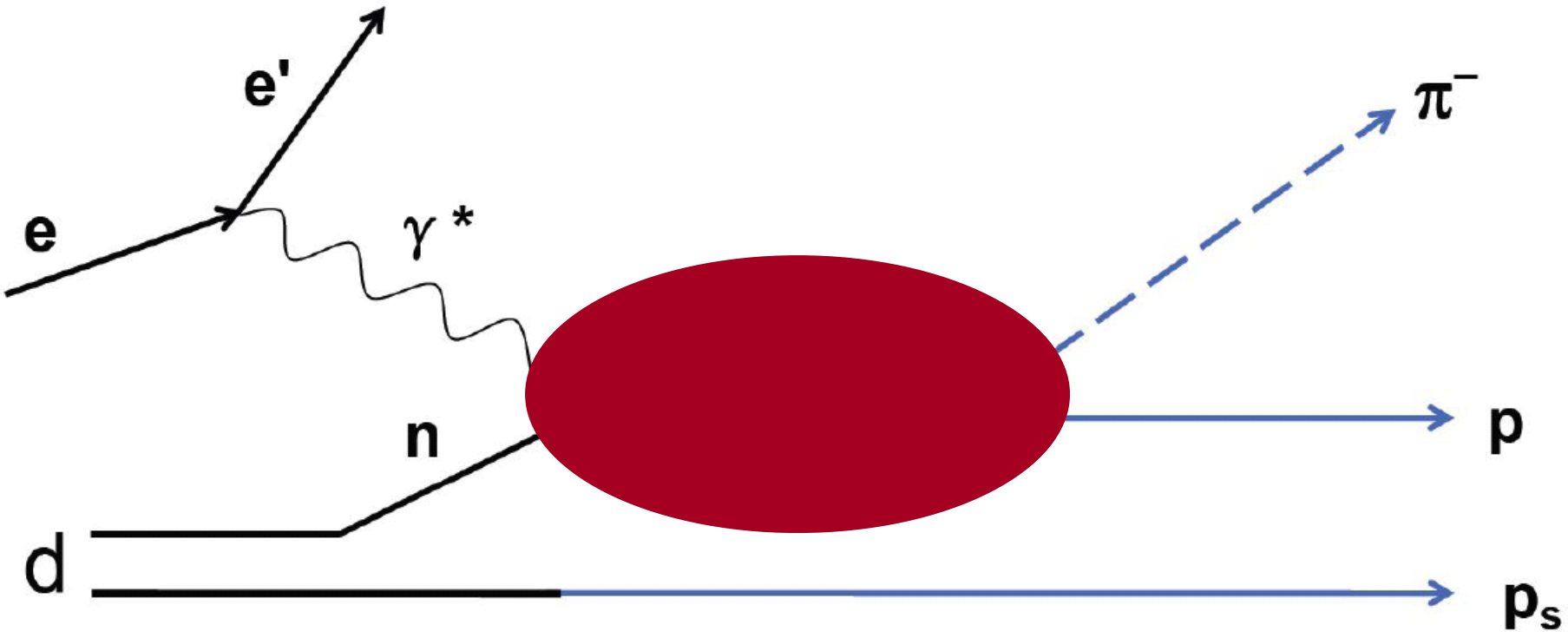
Evan Phelps

E16 / E1F Combined



Single π^- Electroproduction off the Deuteron

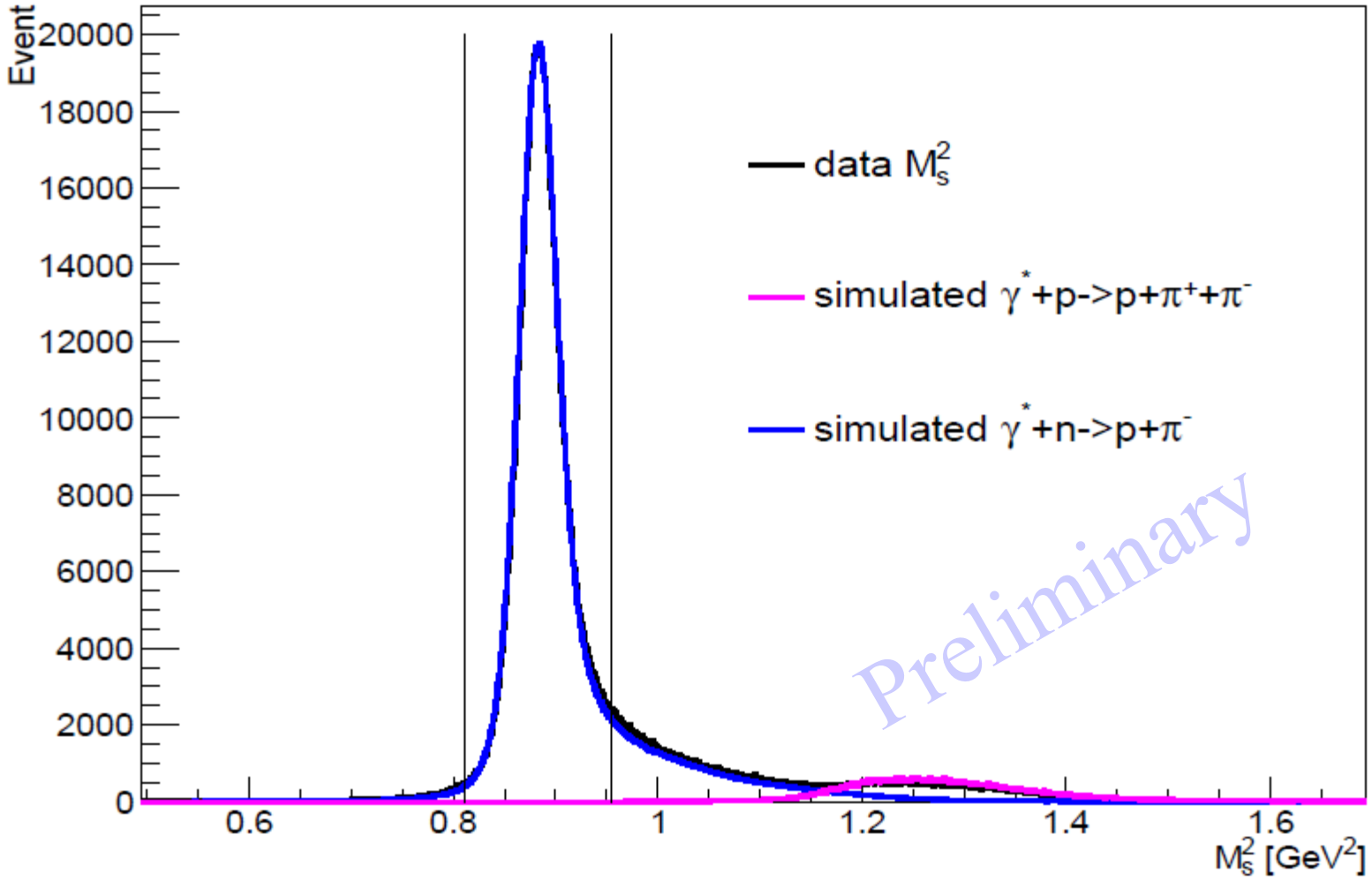
Ye Tian



Exclusive ⇒ Spectator ⇒ Quasi-Free ⇒ FSI

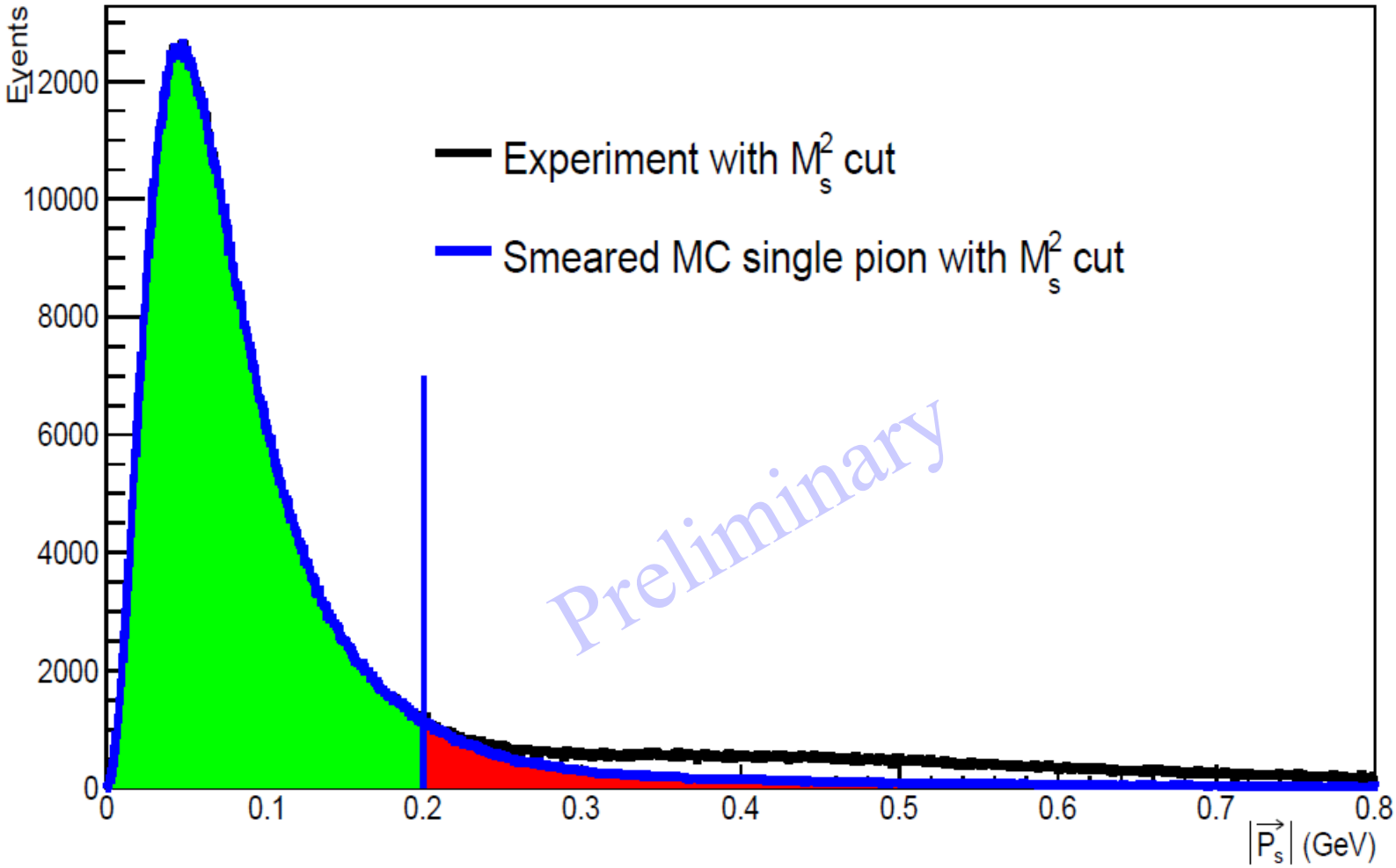
Single π^- Electroproduction off the Deuteron

Ye Tian



Single π^- Electroproduction off the Deuteron

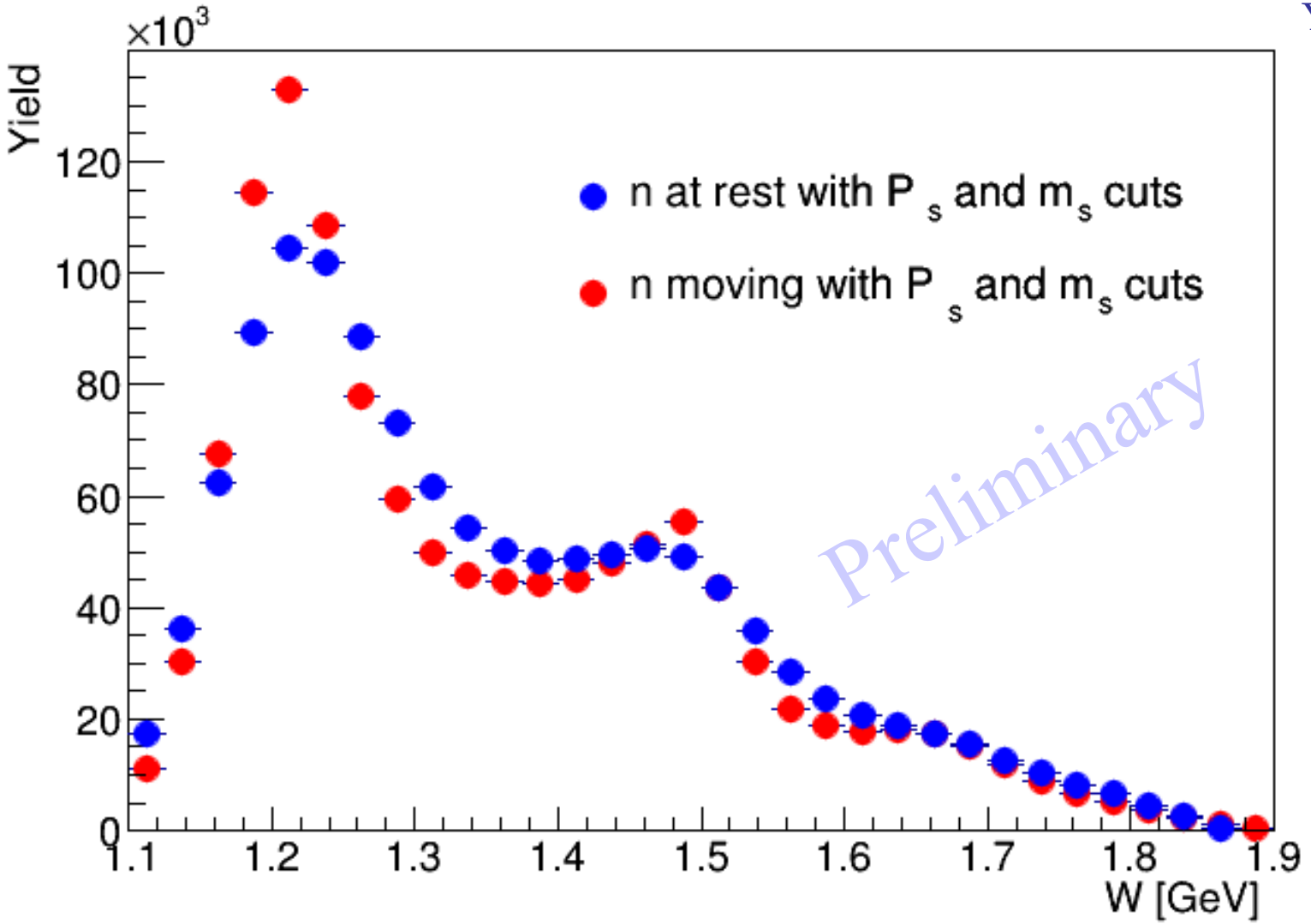
Ye Tian



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

Single π^- Electroproduction off the Deuteron

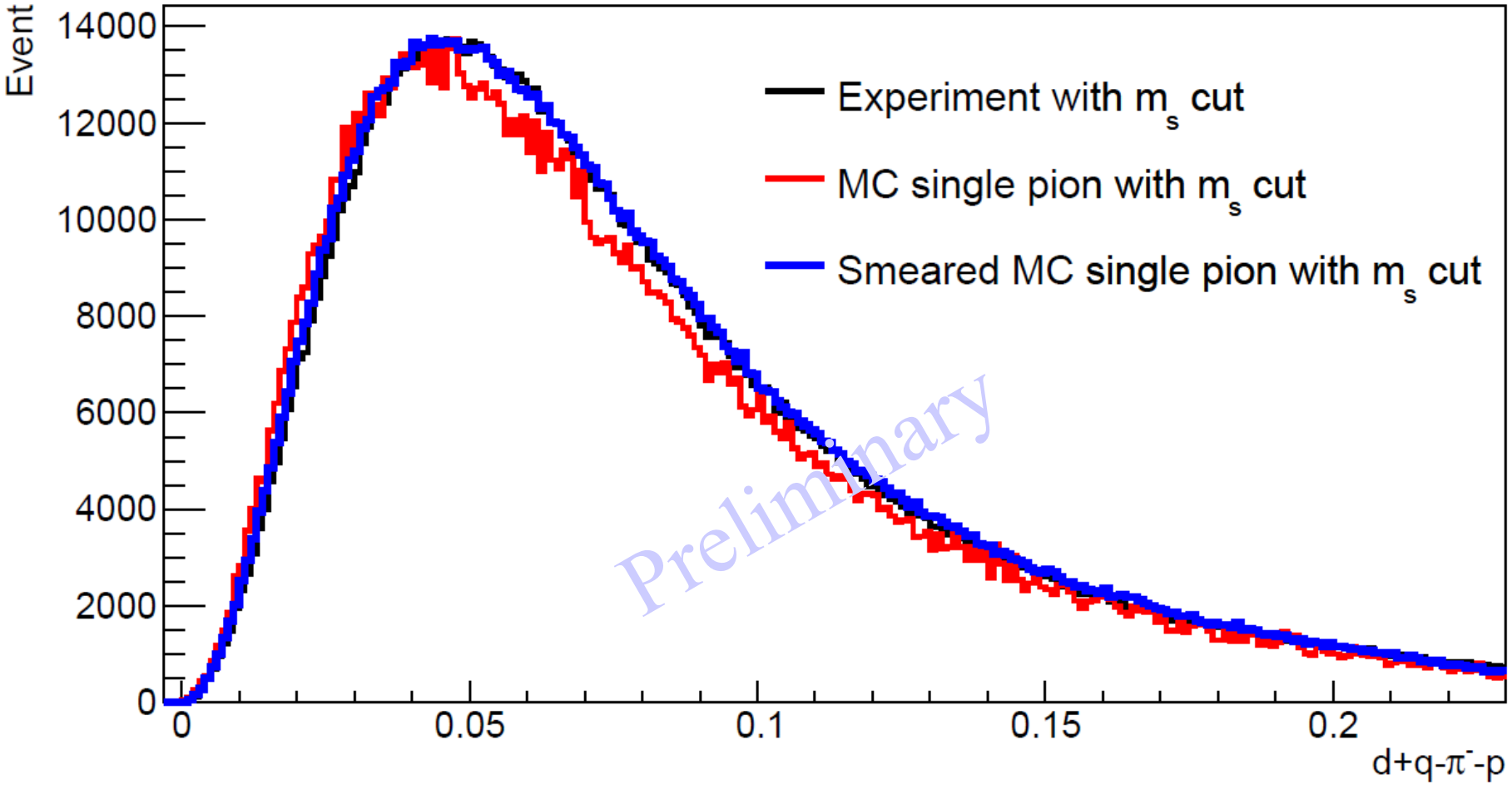
Ye Tian



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

Single π^- Electroproduction off the Deuteron

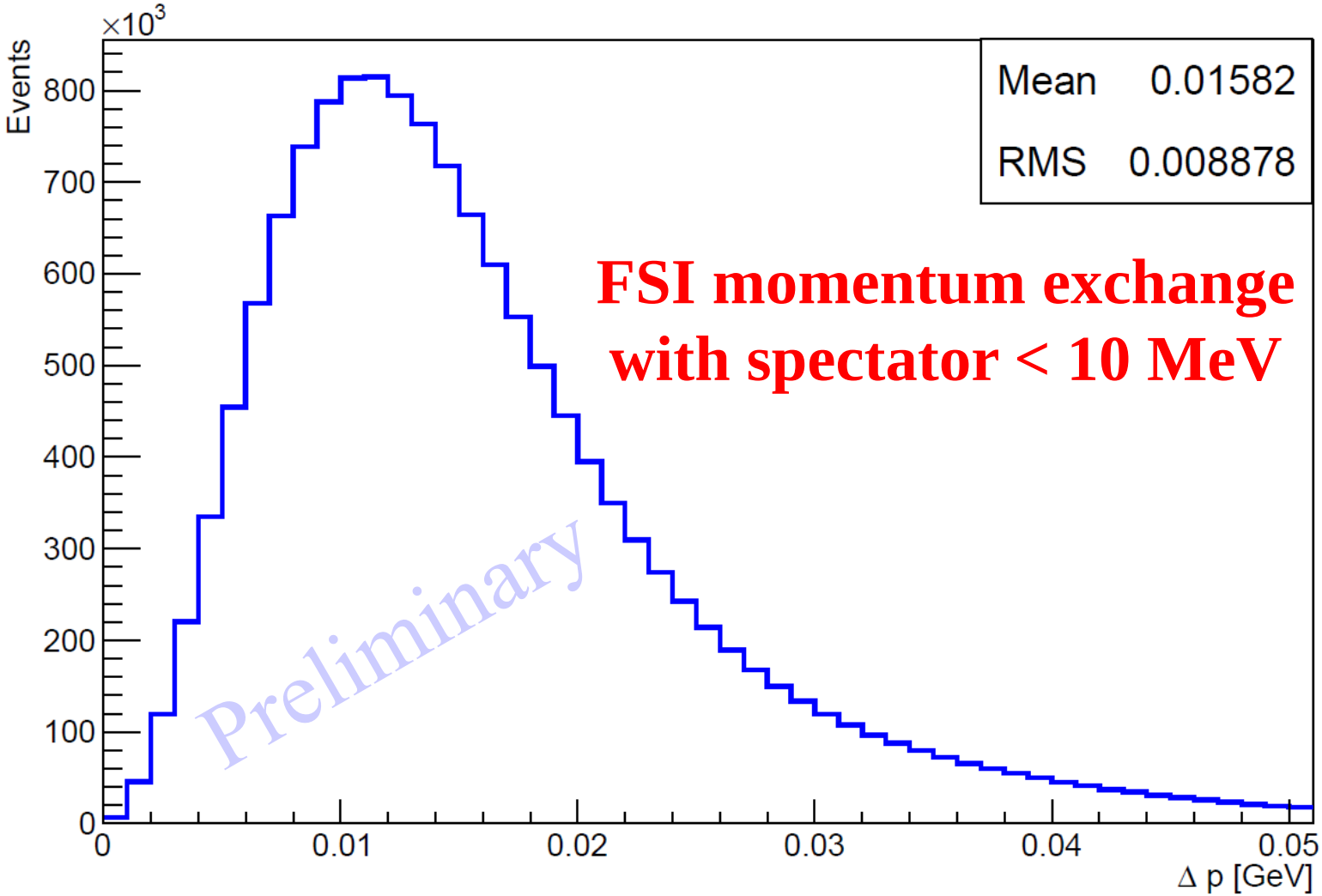
Ye Tian



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



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

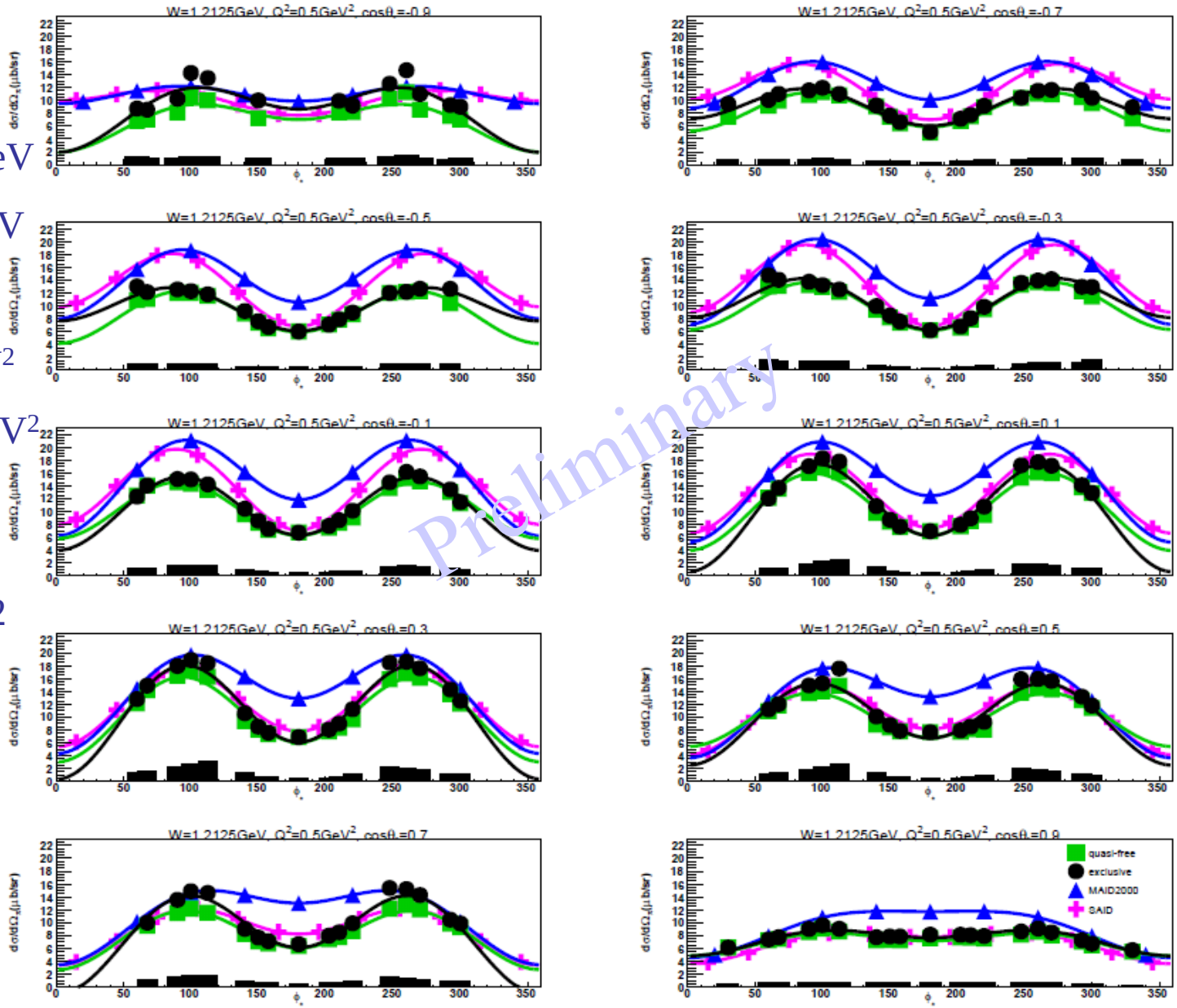
Δcos(θ) = 0.2

cos(θ) = 0.7

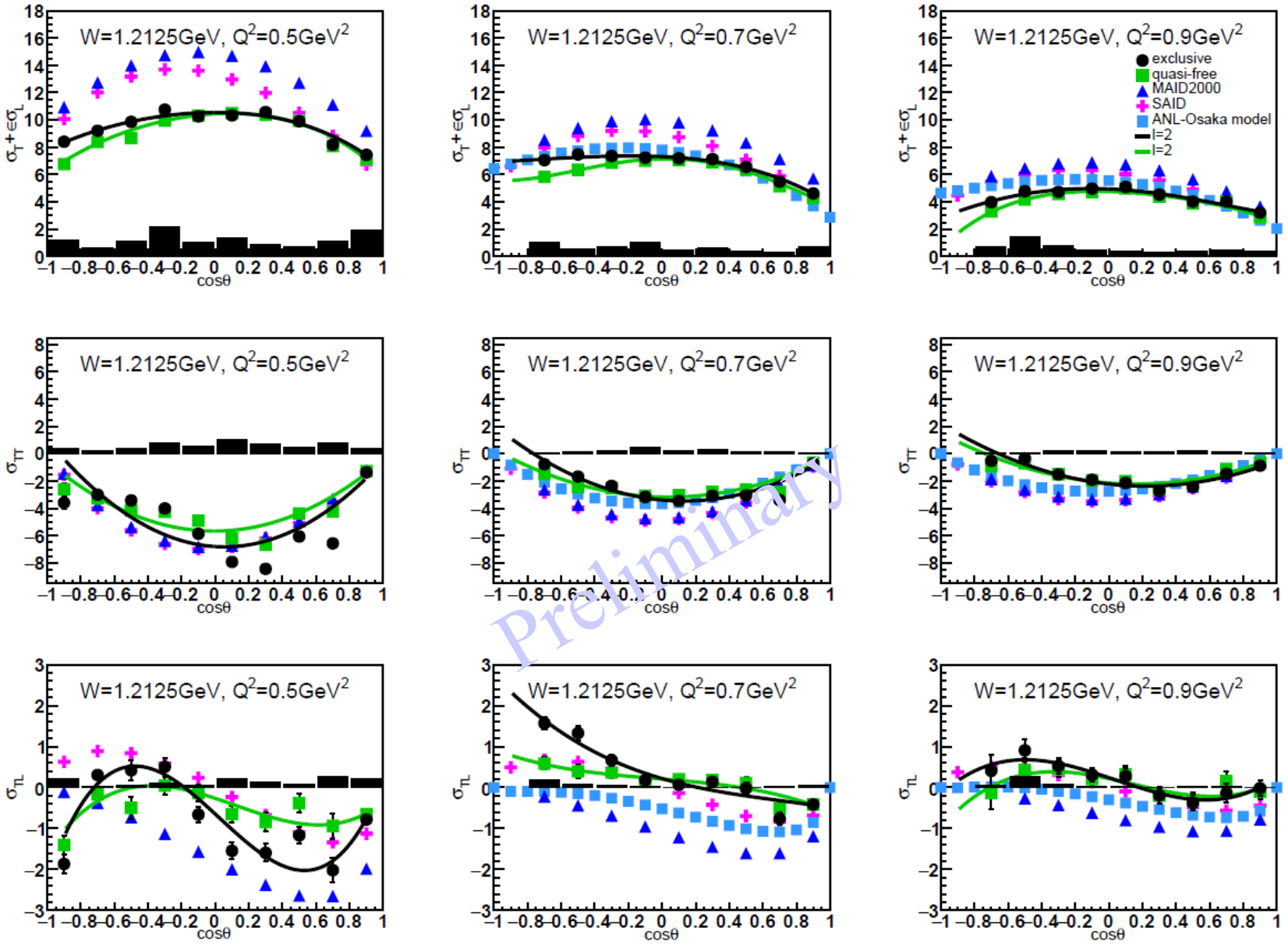
ϕ = 20°

Δϕ = 40°

ϕ = 340°



Single π^- Electroproduction off the Deuteron



Ye Tian

Single π^- Electroproduction off the Deuteron

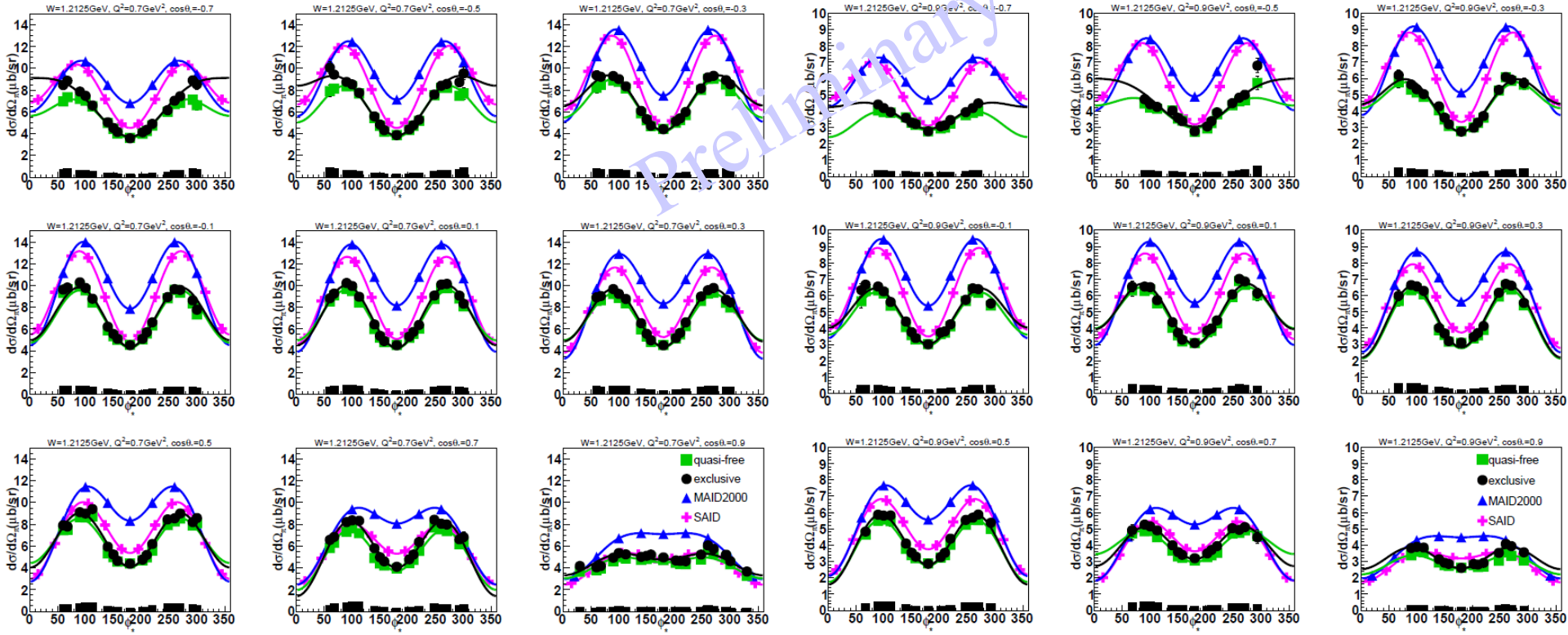
Q^2 = 0.5 GeV^2

W = 1212 MeV

Q^2 = 0.7 GeV^2

Q^2 = 0.9 GeV^2

Ye Tian



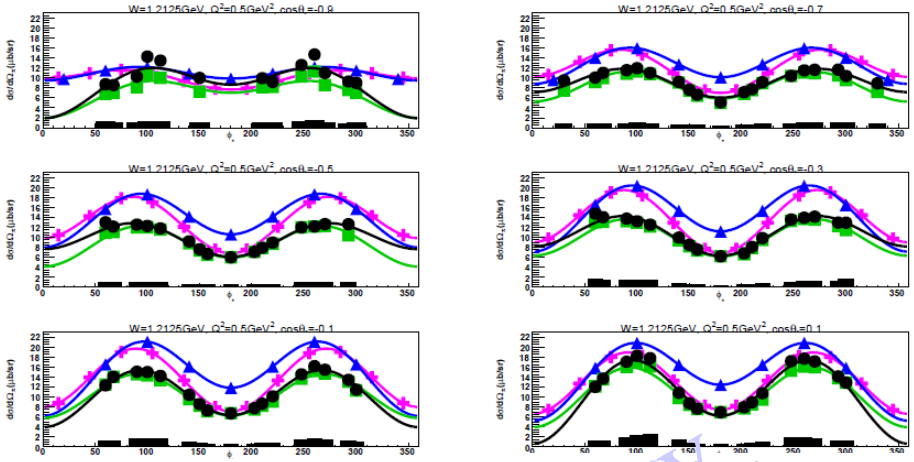
Single π^- Electroproduction off the Deuteron

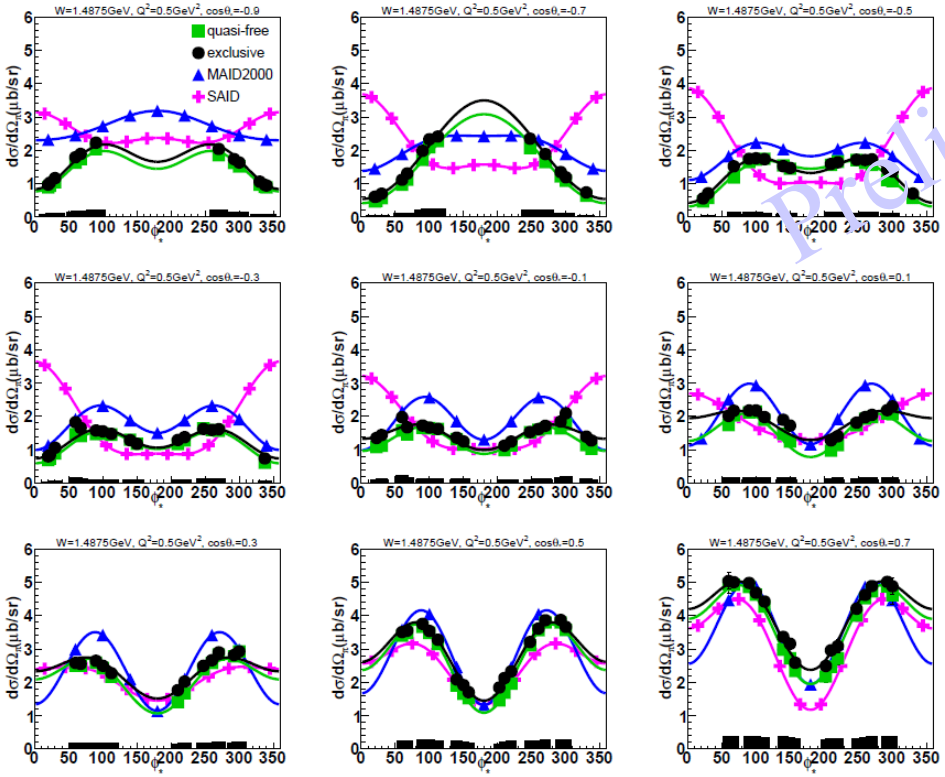
$Q^2 = 0.5$ GeV^2

W = 1212 MeV

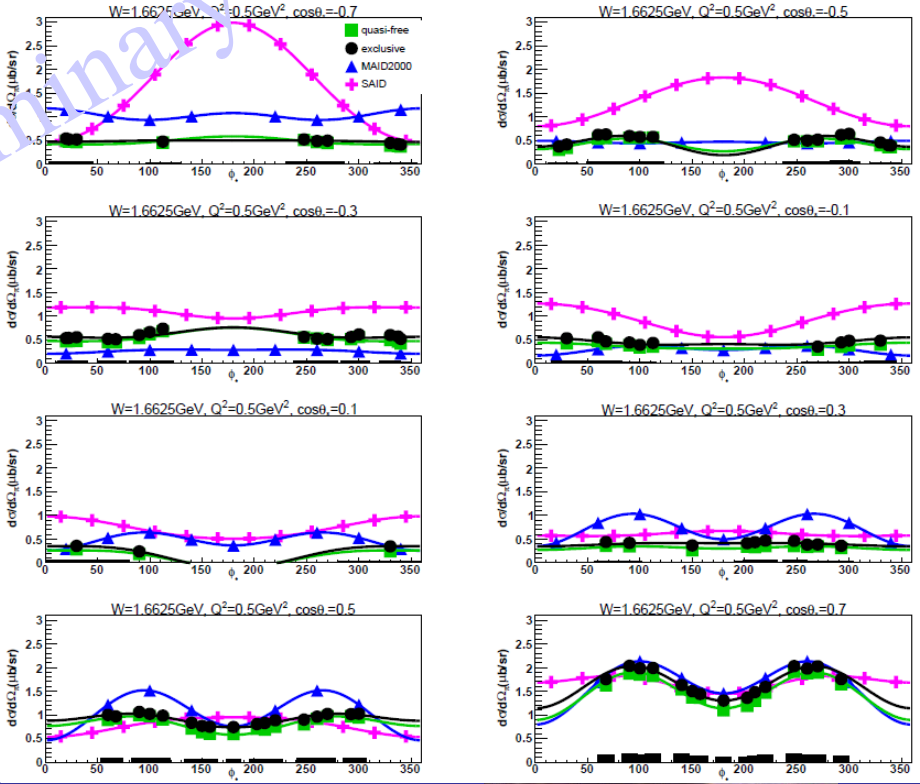
W = 1488 MeV

Ye Tian



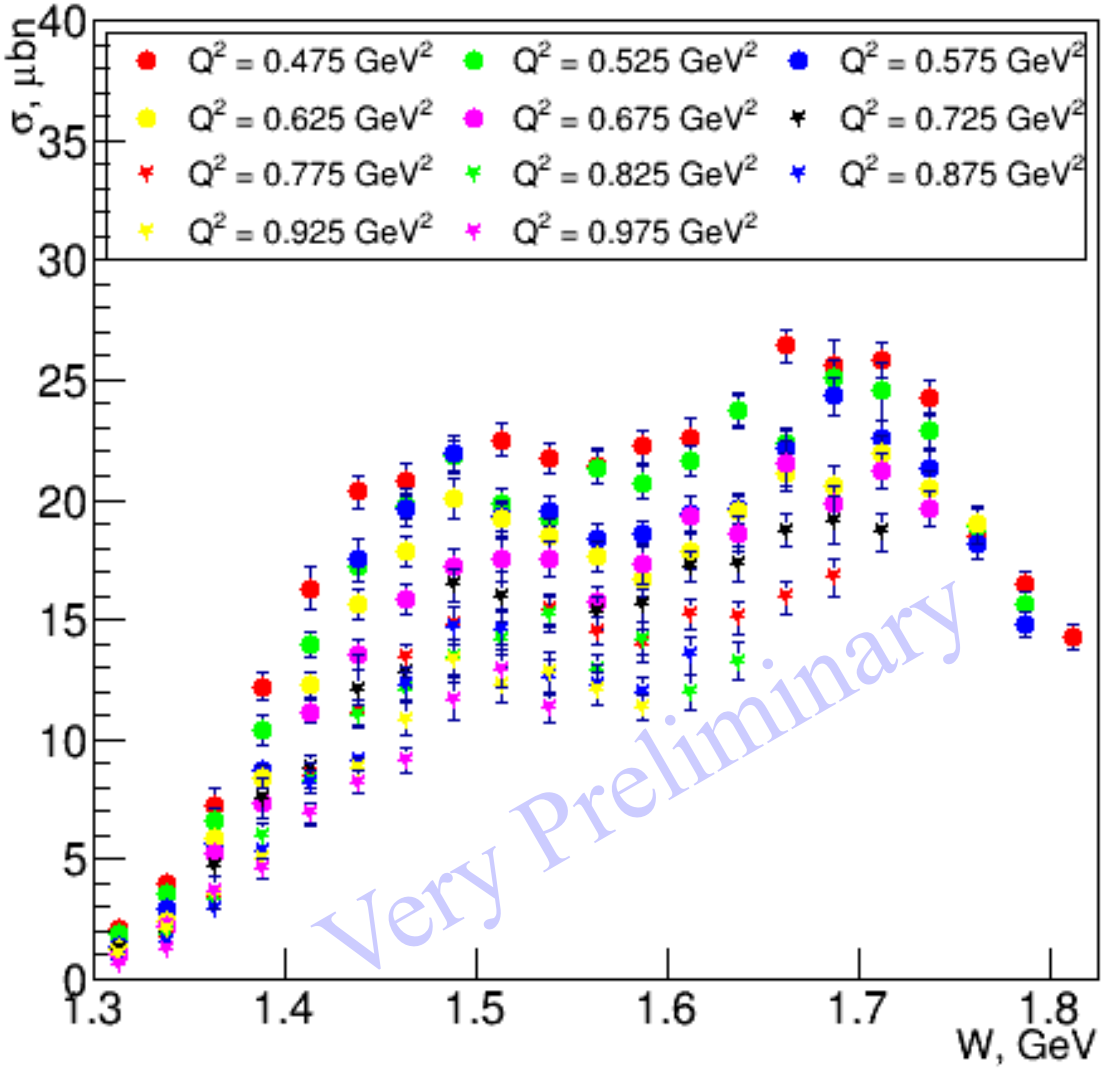


W = 1662 MeV



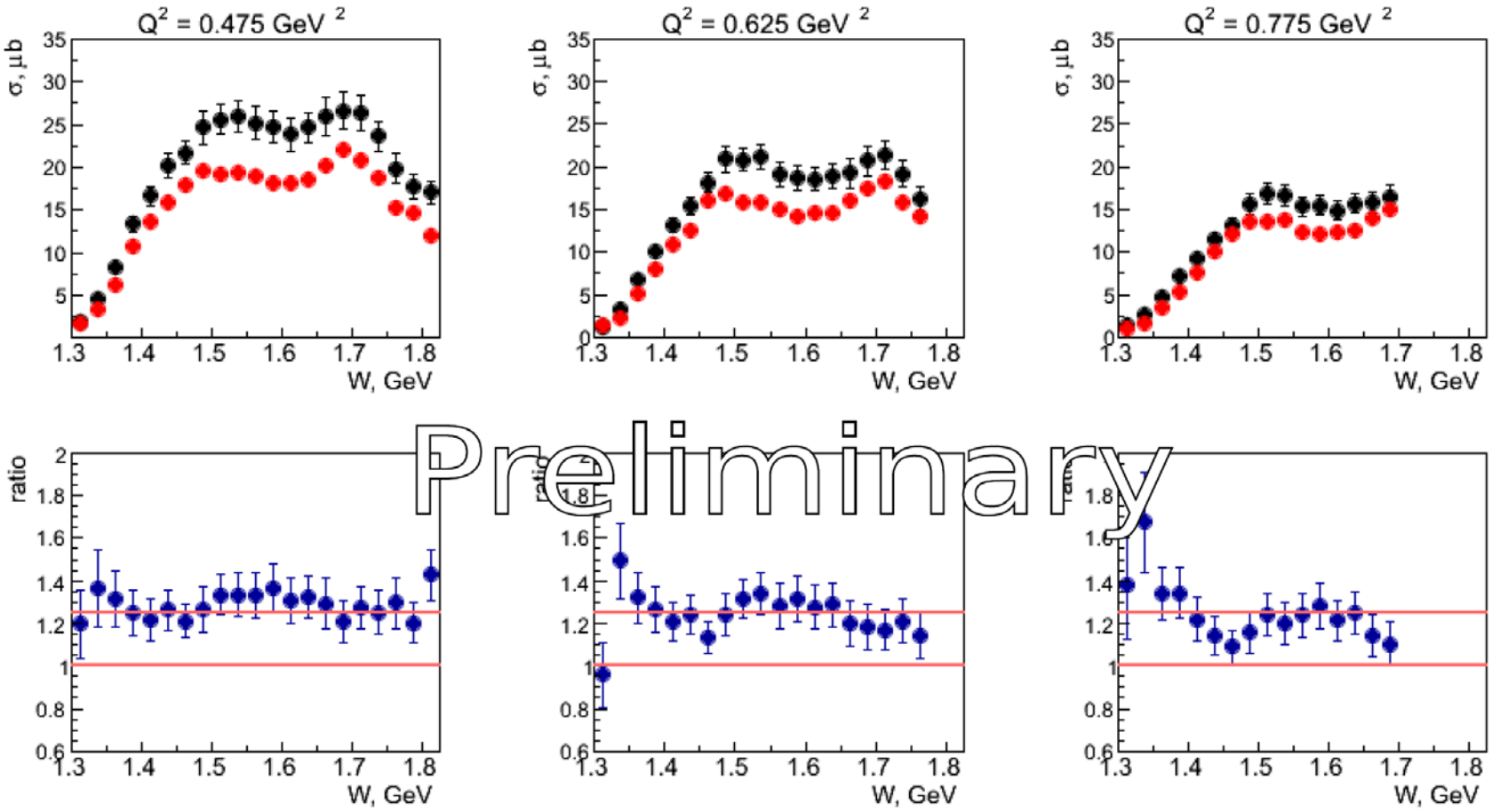
Integrated Cross Section off the Proton in Deuteron

Iuliia Skorodomina



Comparison with Free Proton Cross Section

Iuliia

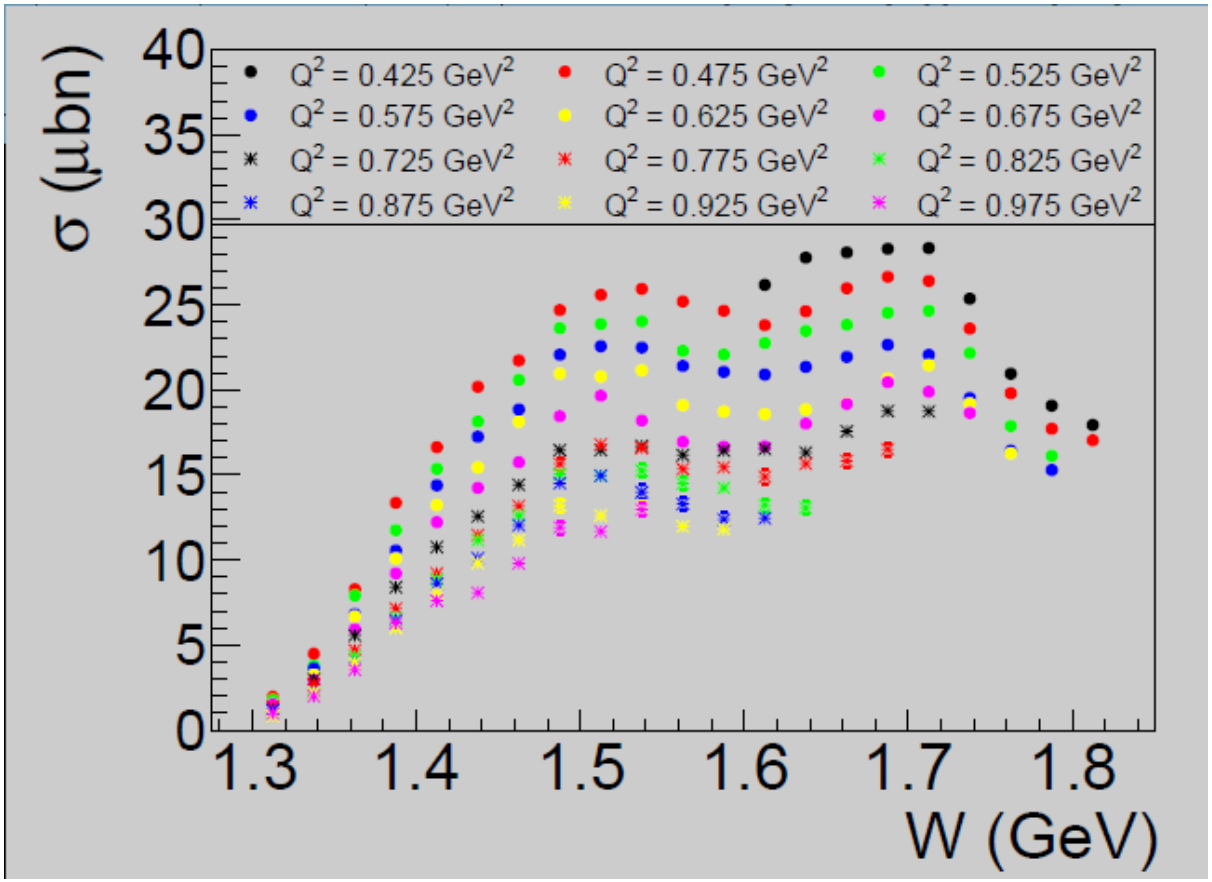


Black bullets – free proton cross sections (e1e at E_{beam} = 2.039 GeV)
error bars show both statistical and systematical uncertainties
G. Fedotov under paper review

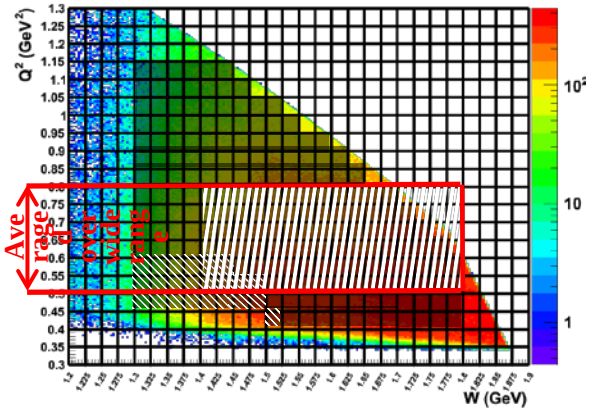
Red bullets – bound proton quasi-free cross sections (e1e at E_{beam} = 2.039 GeV)
error bars show statistical uncertainty only

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

Gleb Fedotov

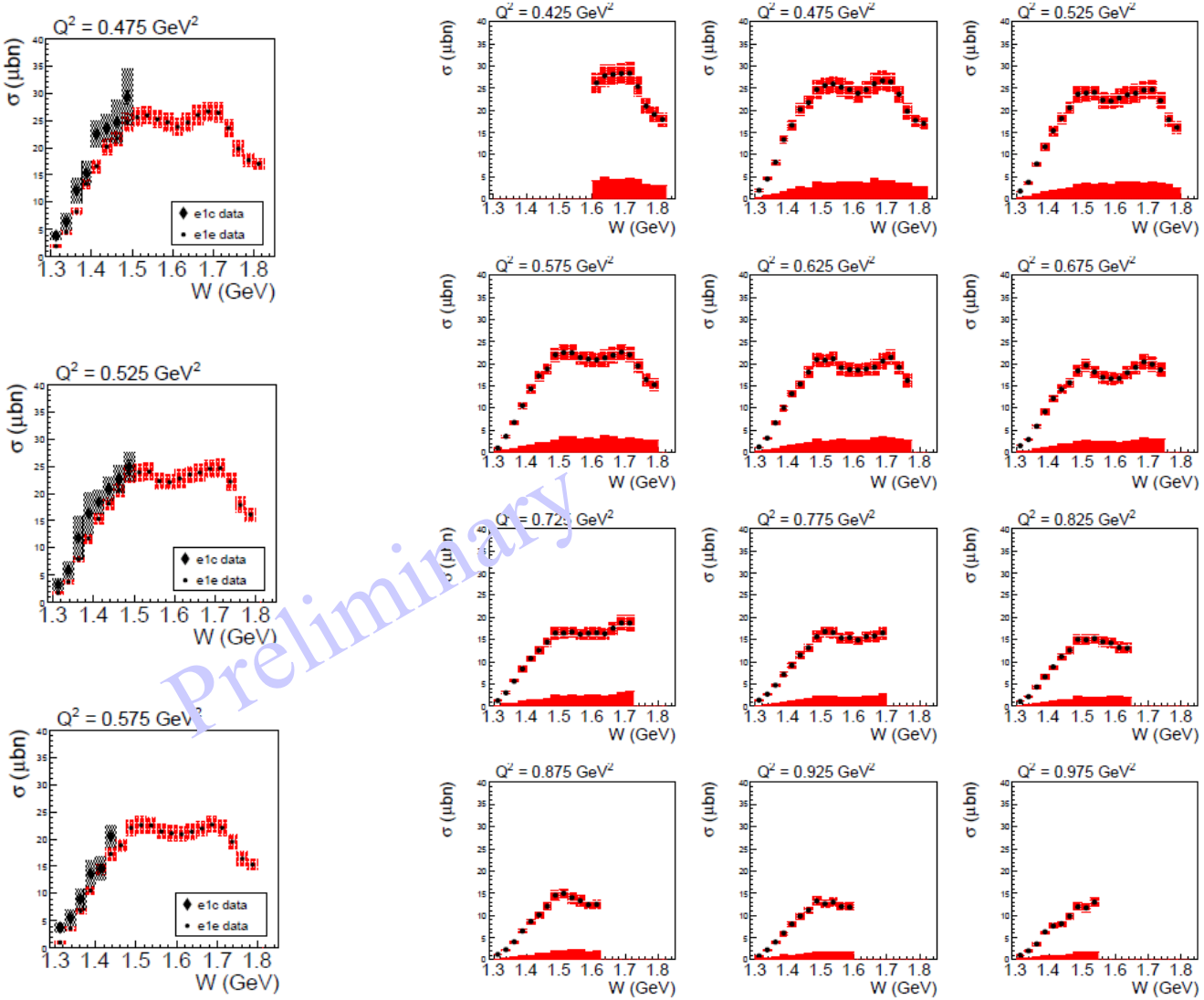


Preliminary



$p\pi^+\pi^-$ 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

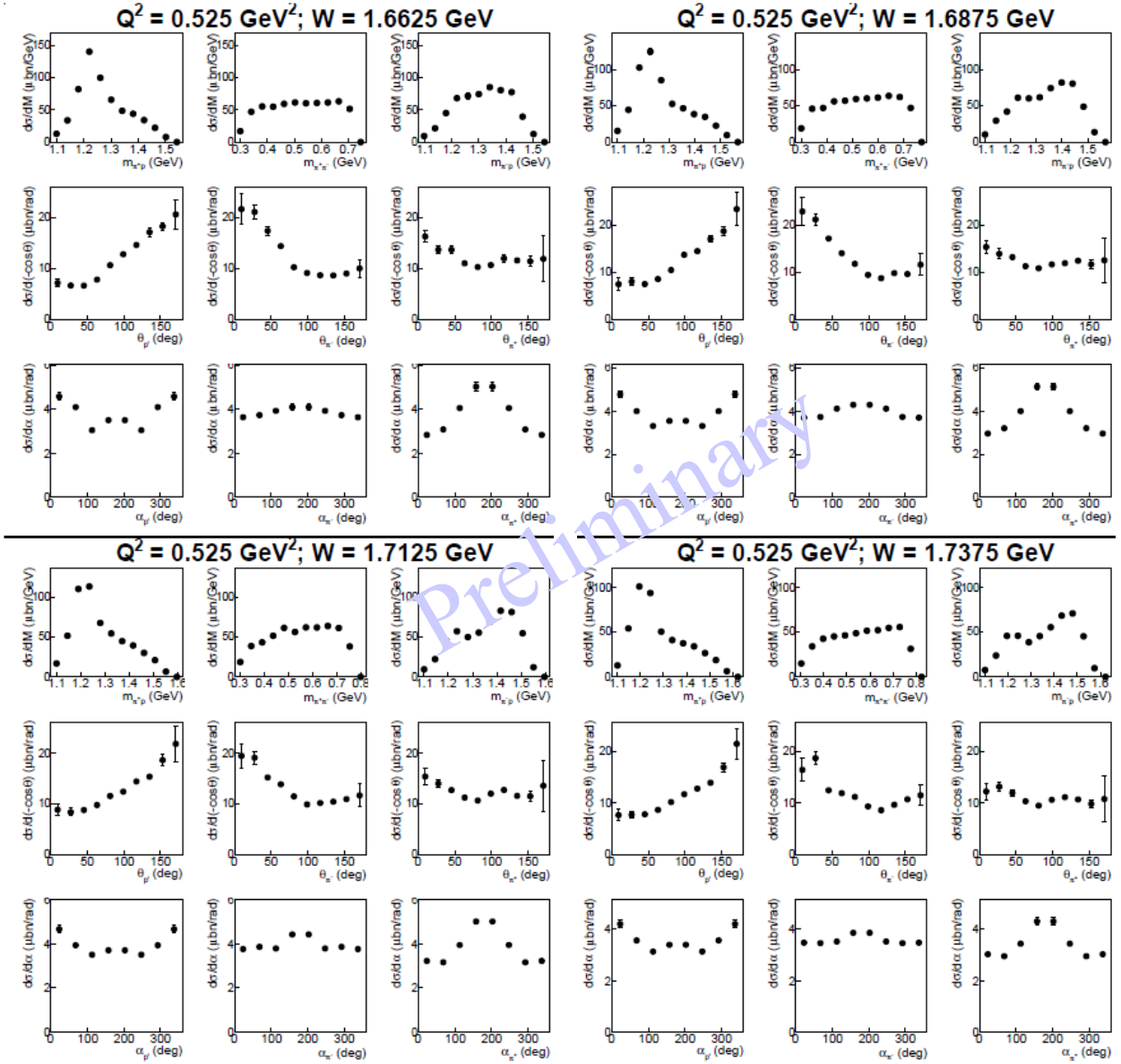


Gleb Fedotov

Preliminary

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

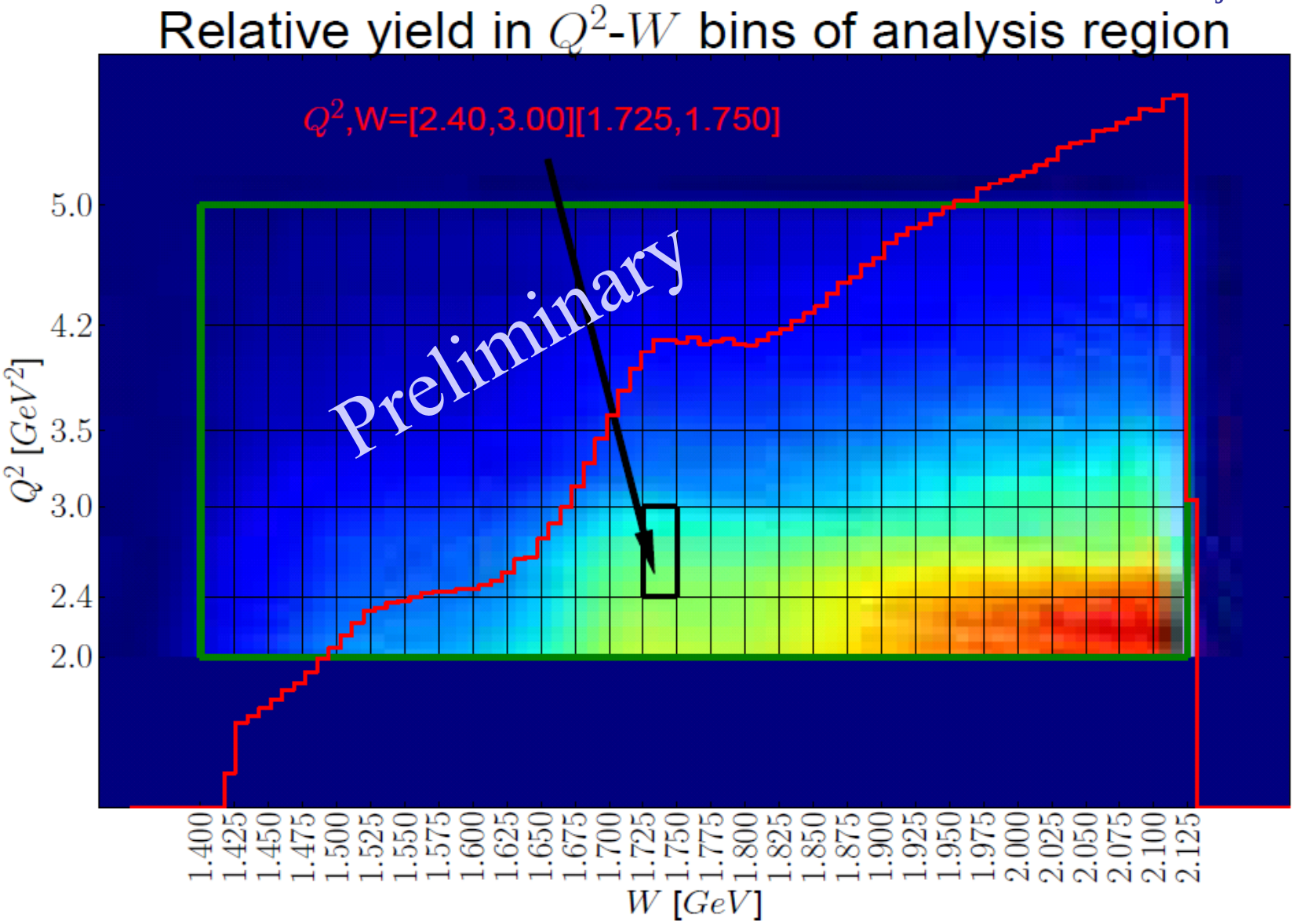
$N\pi^+\pi^-$ Single-Differential Cross Sections



Gleb Fedotov

φ-dependent Nππ Single-Differential Cross Sections

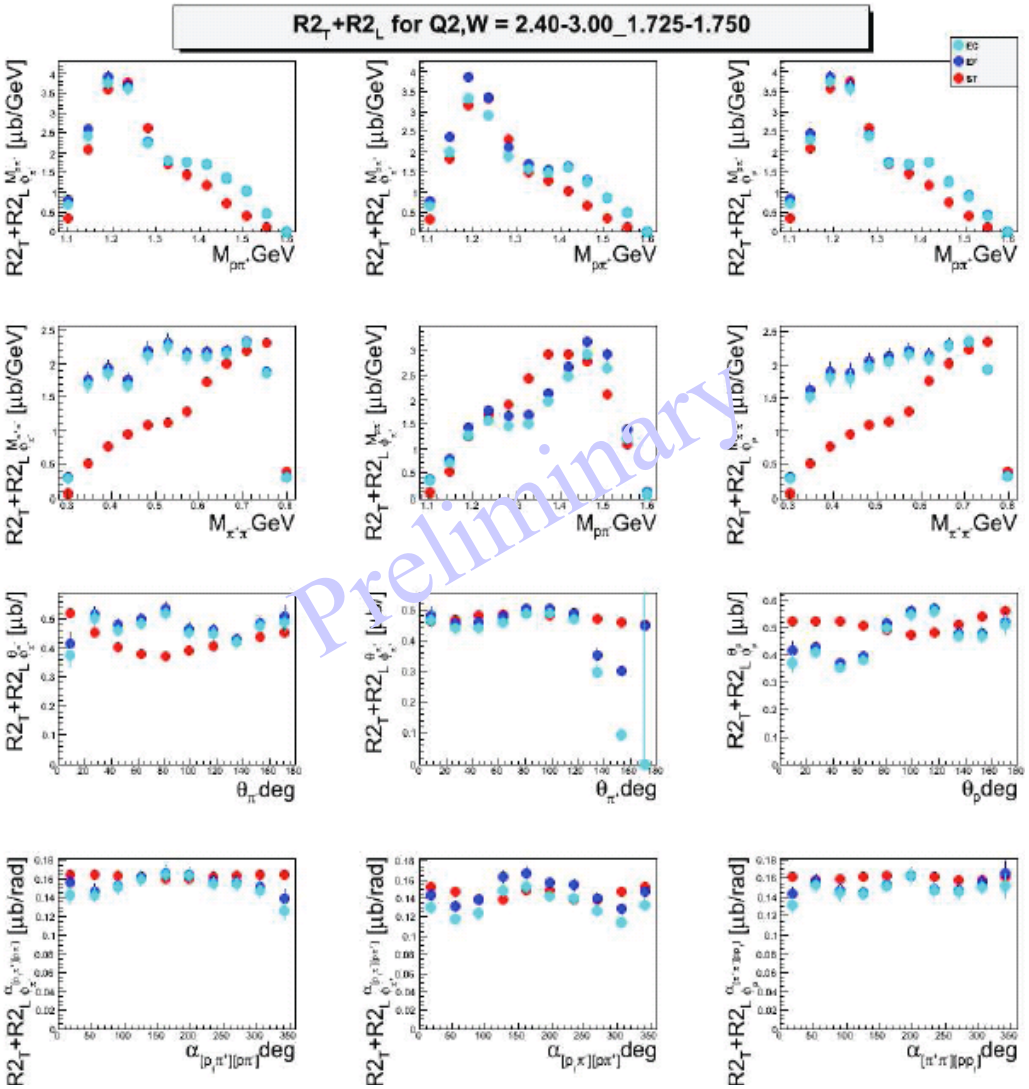
Arjun Trivedi



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



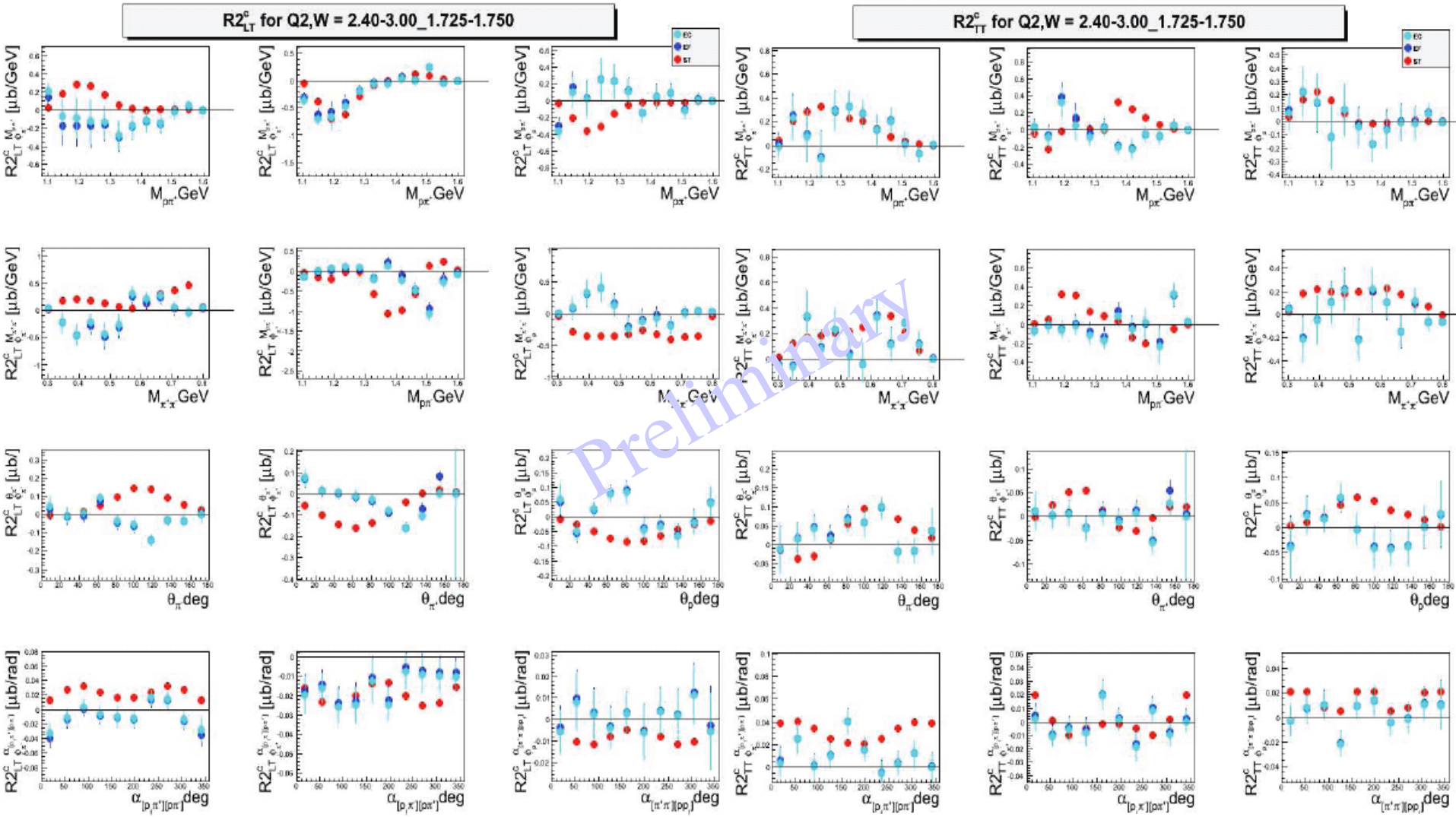
- normalized
- hole filled
- TWOPEG

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

φ-dependent Nππ Single-Differential Cross Sections

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

Arjun Trivedi

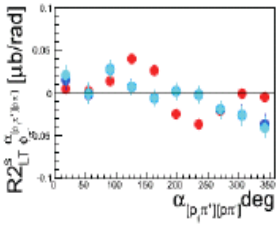
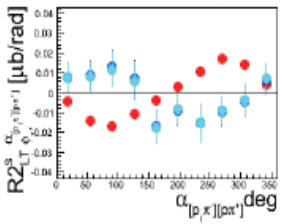
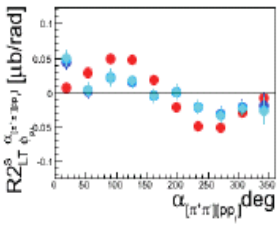
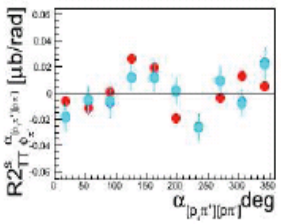
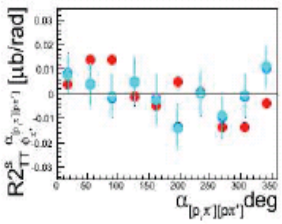
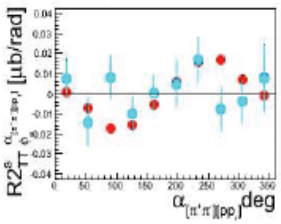


$$\left(\frac{d^2\sigma}{dX_{ij}\,d\phi_i}\right) = R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}} + R2_{LT}{}^{c,X_{ij}} \cos\phi_i + R2_{TT}{}^{c,X_{ij}} \cos 2\phi_i + \delta_{X_{ij}\alpha_i}\left(R2_{LT}{}^{s,\alpha_i} \sin\phi_i + R2_{TT}{}^{s,\alpha_i} \sin 2\phi_i\right)$$

φ-dependent Nππ Single-Differential Cross Sections

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

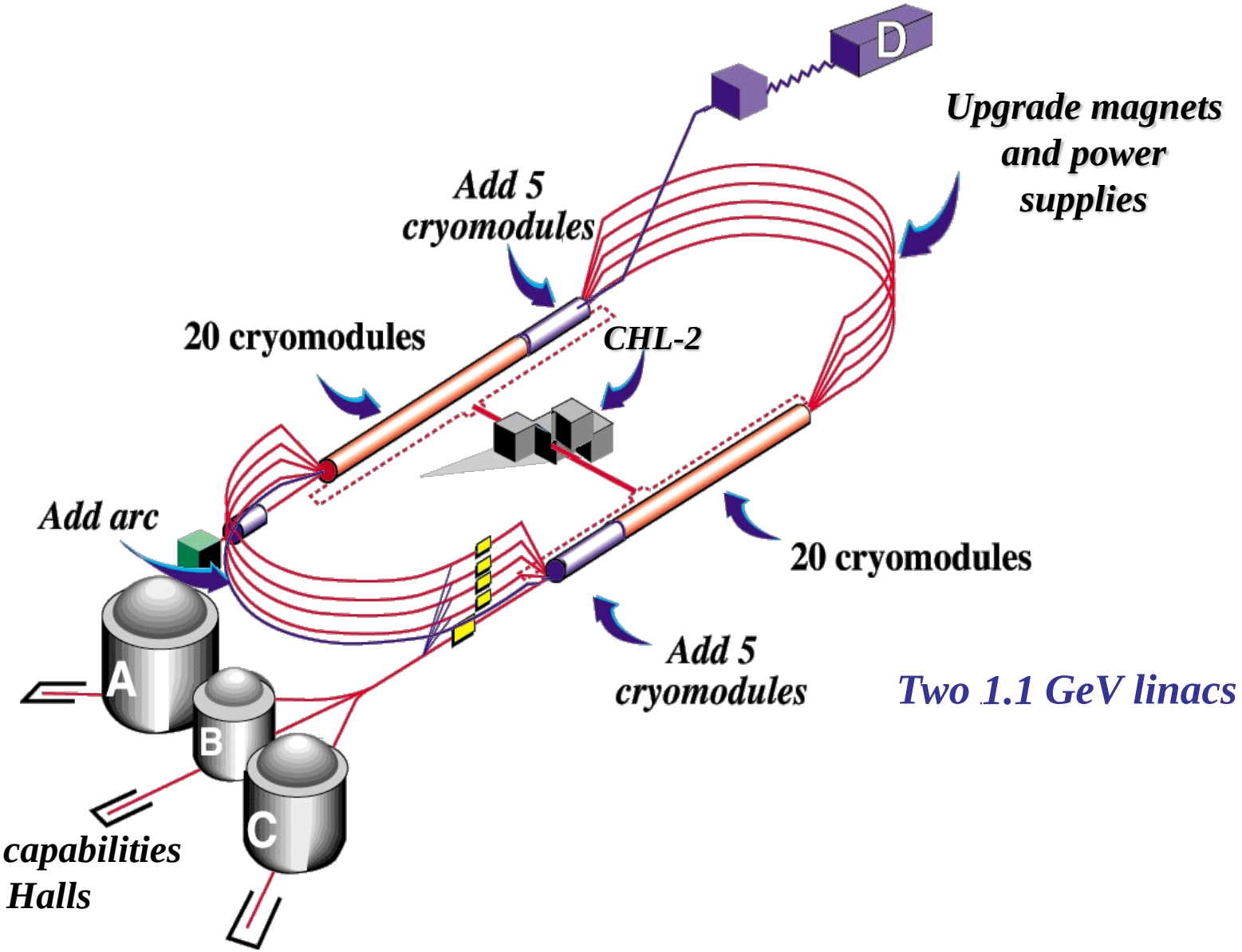
Chris McLauchlin extracts the beam helicity dependent differential cross sections.

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

CLAS12

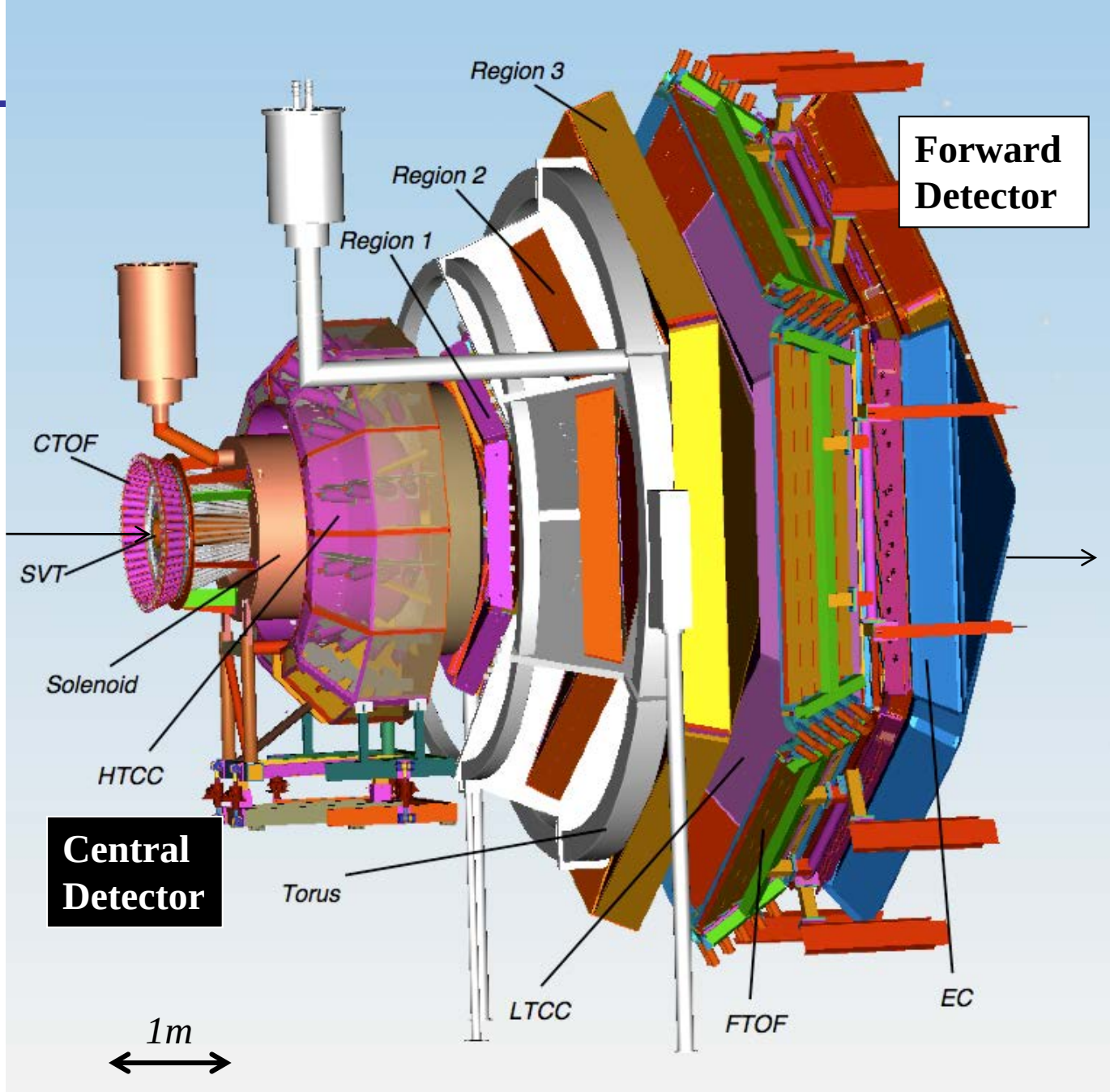
12 GeV CEBAF


D
Upgrade magnets and power supplies
Add 5 cryomodules
20 cryomodules
CHL-2
Add arc
20 cryomodules
Add 5 cryomodules
A
B
C
Two 1.1 GeV linacs
Enhanced capabilities in existing Halls

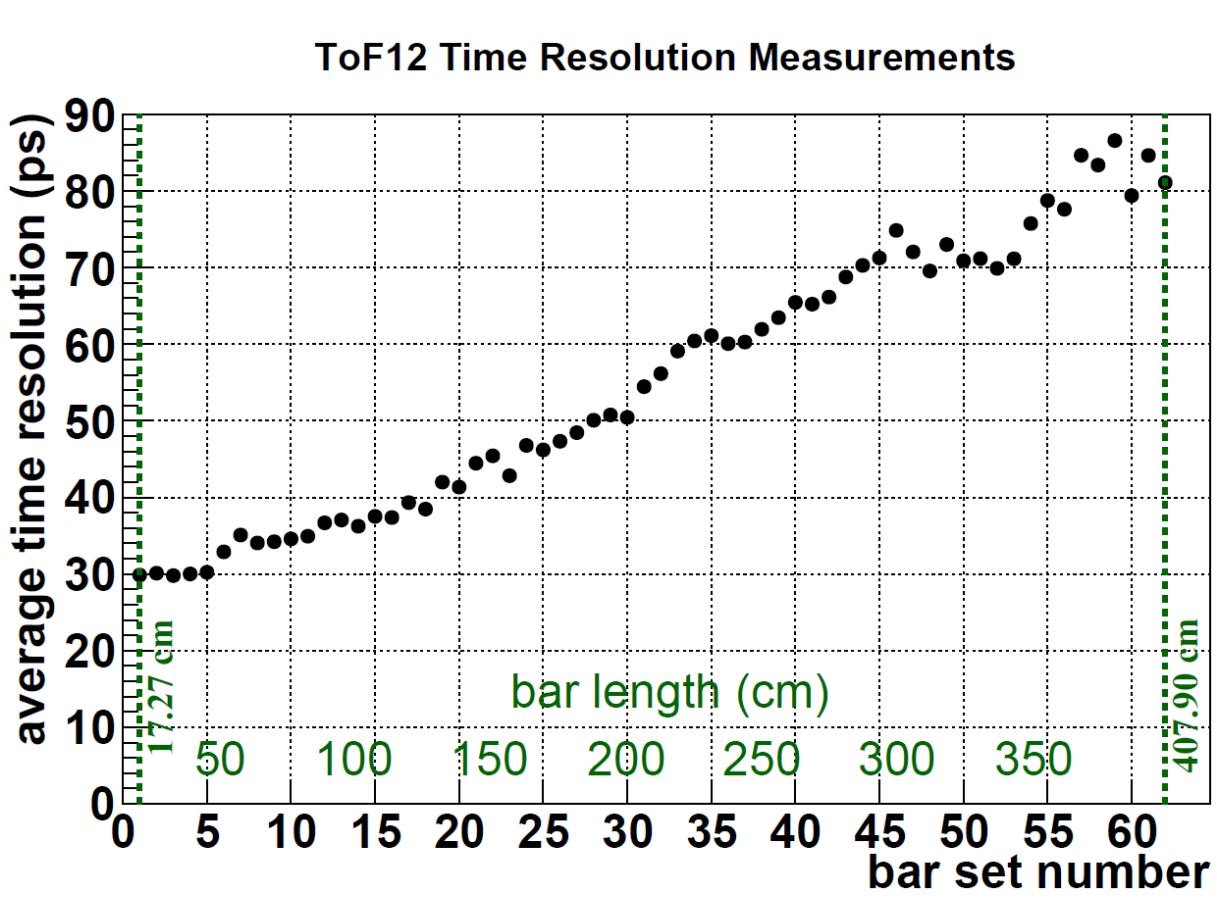
CLAS12

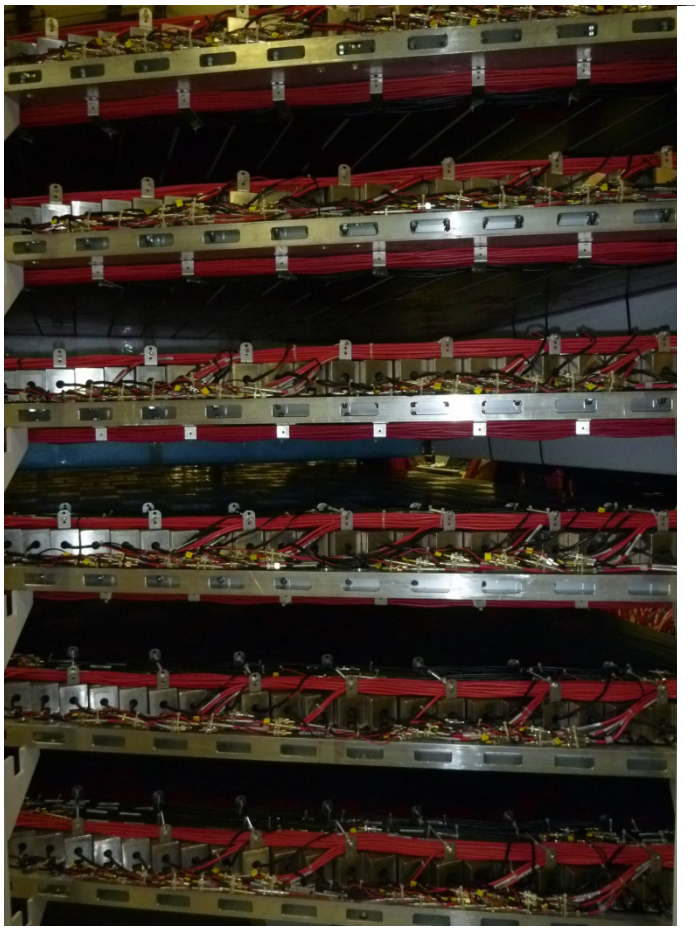
- Luminosity > 10^{35} $cm^{-2}s^{-1}$
- Hermeticity
- Polarization

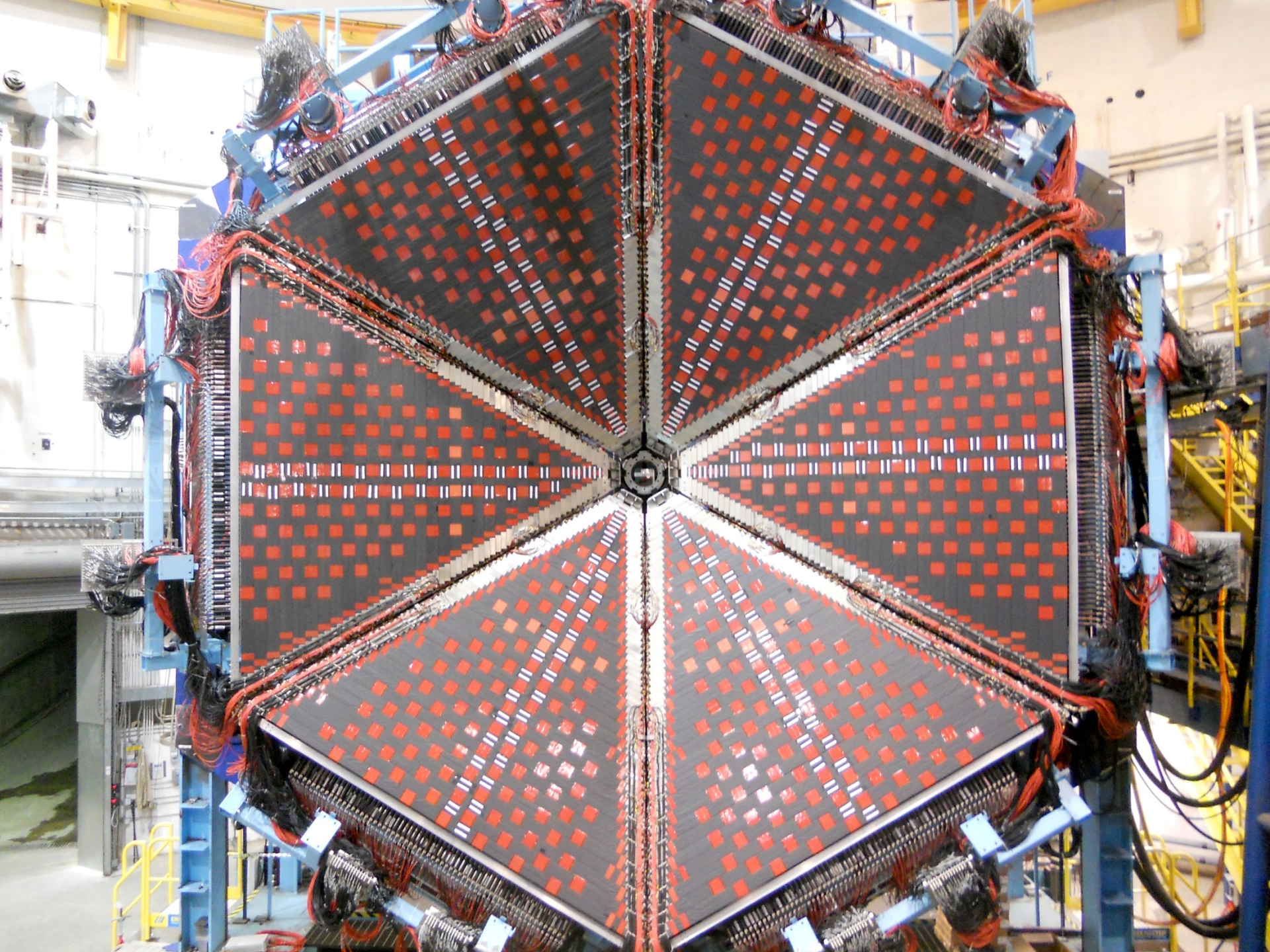
- Baryon Spectroscopy
- Elastic Form Factors
- N to N* Form Factors
- GPDs and TMDs
- DIS and SIDIS
- Nucleon Spin Structure
- Color Transparency
- …



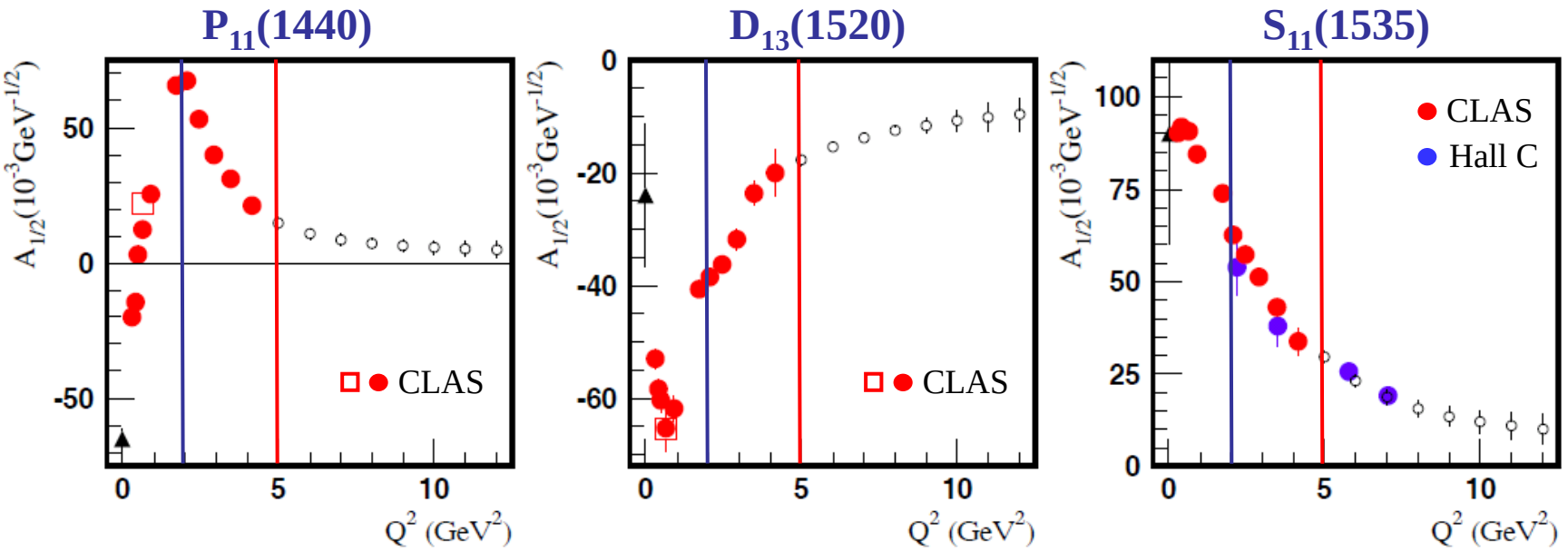
New Forward Time of Flight Detector for CLAS12







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 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, …