Nucleon Electroexcitation and Baryon Structure with CLAS

Ralf W. Gothe
UNIVERSITY OF SOUTH CAROLINA

10th International Workshop on the Physics of Excited Nucleons
Icho Kaikan, Suita Campus, Osaka University
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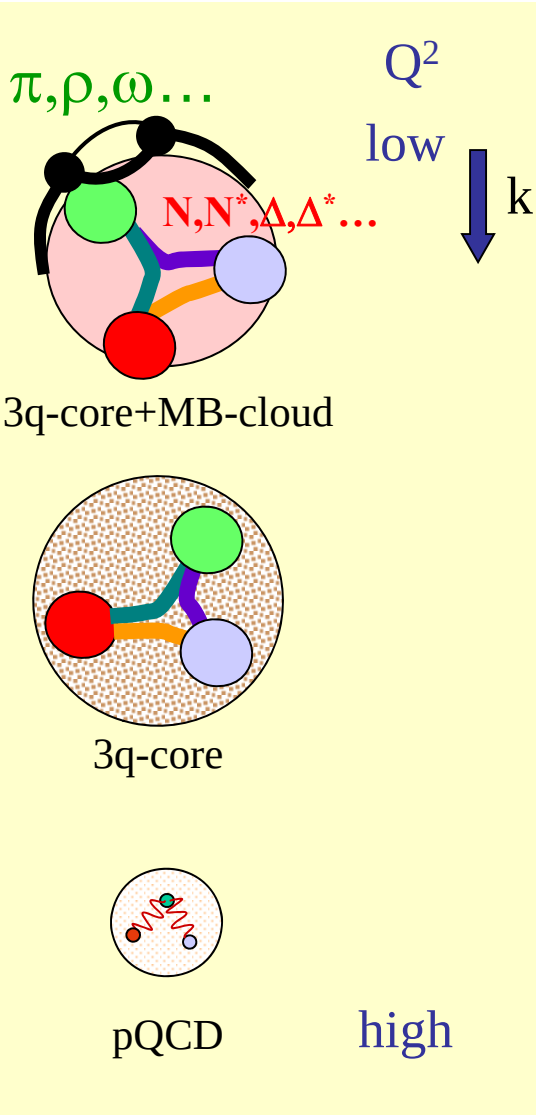
- **γ_vNN* Vertexcouplings:** A unique window into baryon and quark structure?
- **Analysis and New Results:** Phenomenological but consistent.
- **Outlook:** New experiments with extended scope and kinematics.
- **QCD based Theory:** Can we solve non-perturbative QCD and confinement?

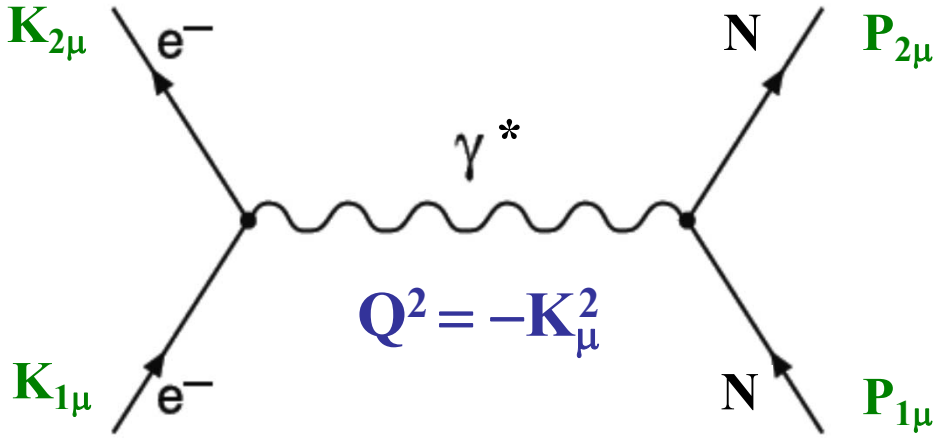
This work is in parts supported by the US National Science Foundation under the Grant PHY-1205782

Transition Form Factors

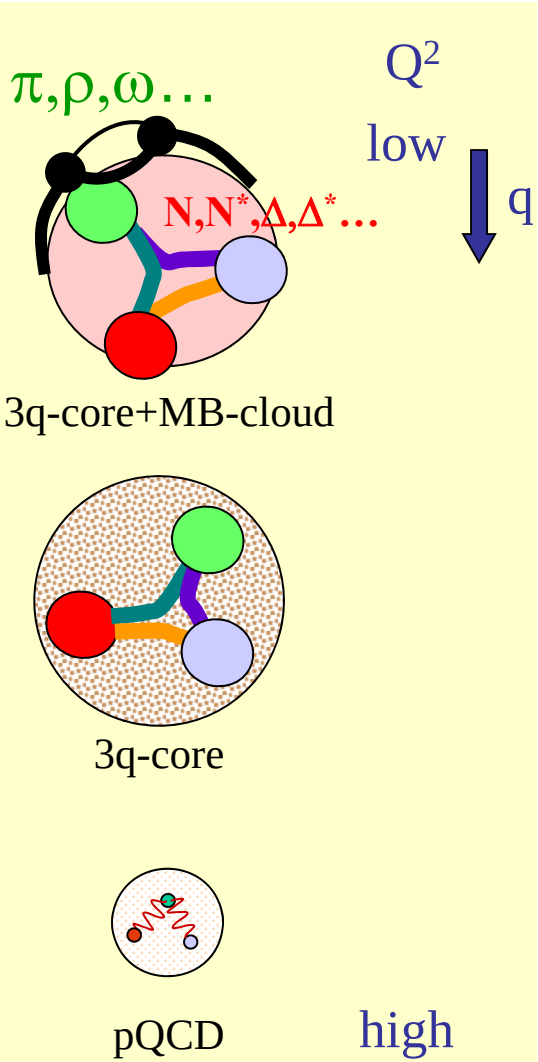
Hadron Structure with Electromagnetic Probes



- 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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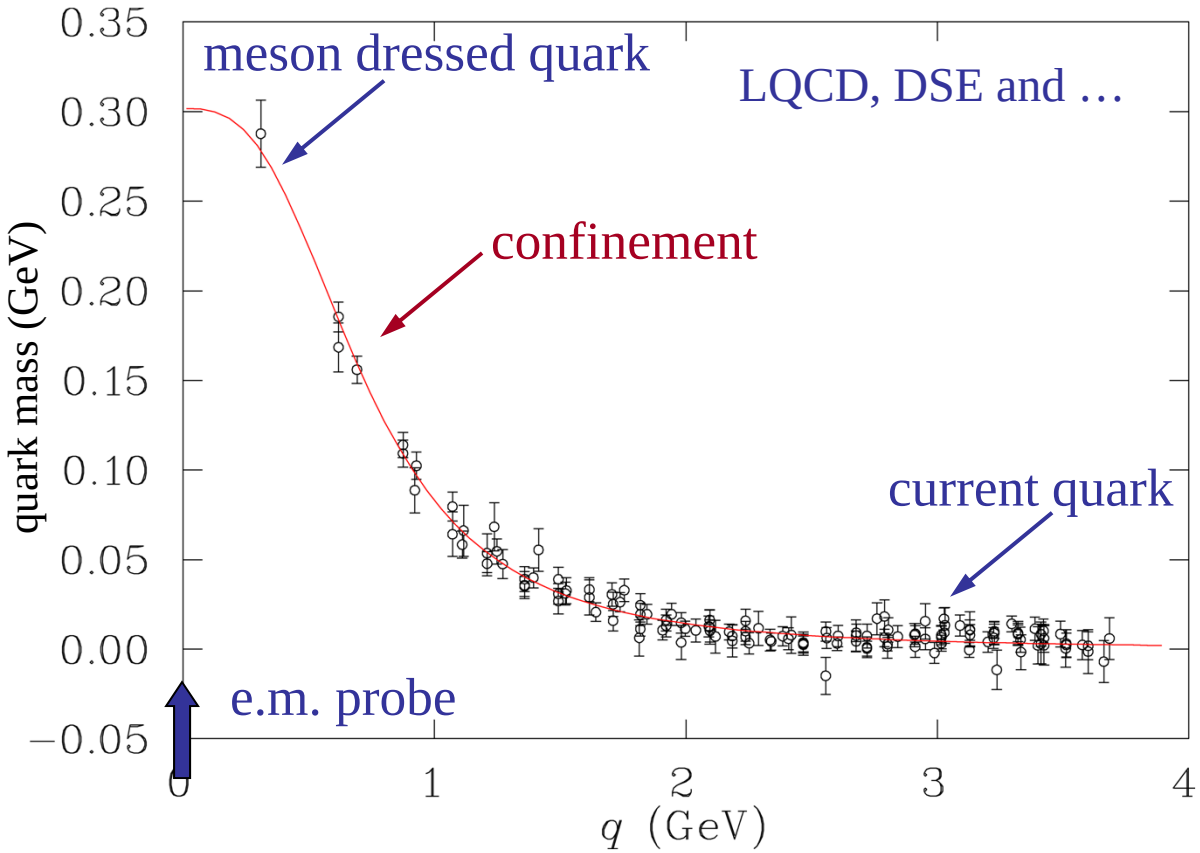
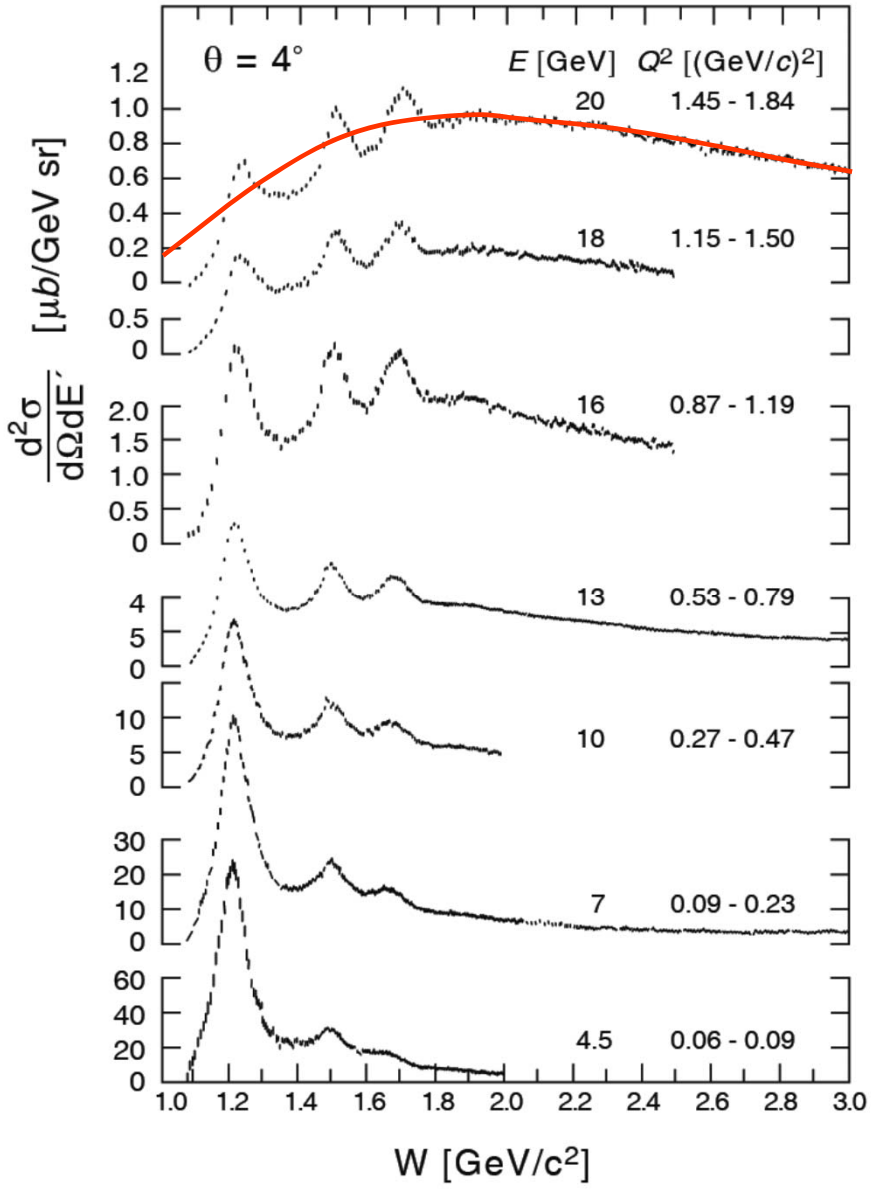
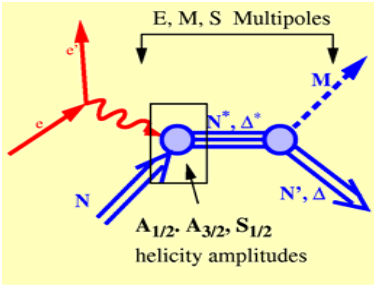
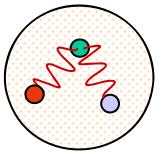


Baryon Excitations and Quasi-Elastic Scattering

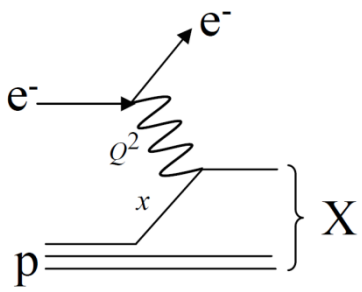


hard and confined



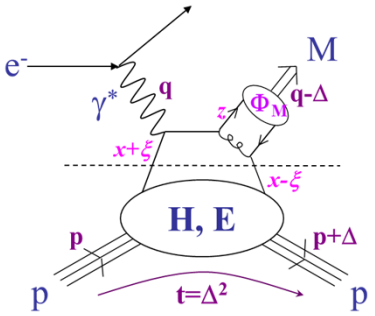


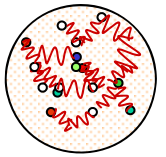
quasi-elastic



hard

soft

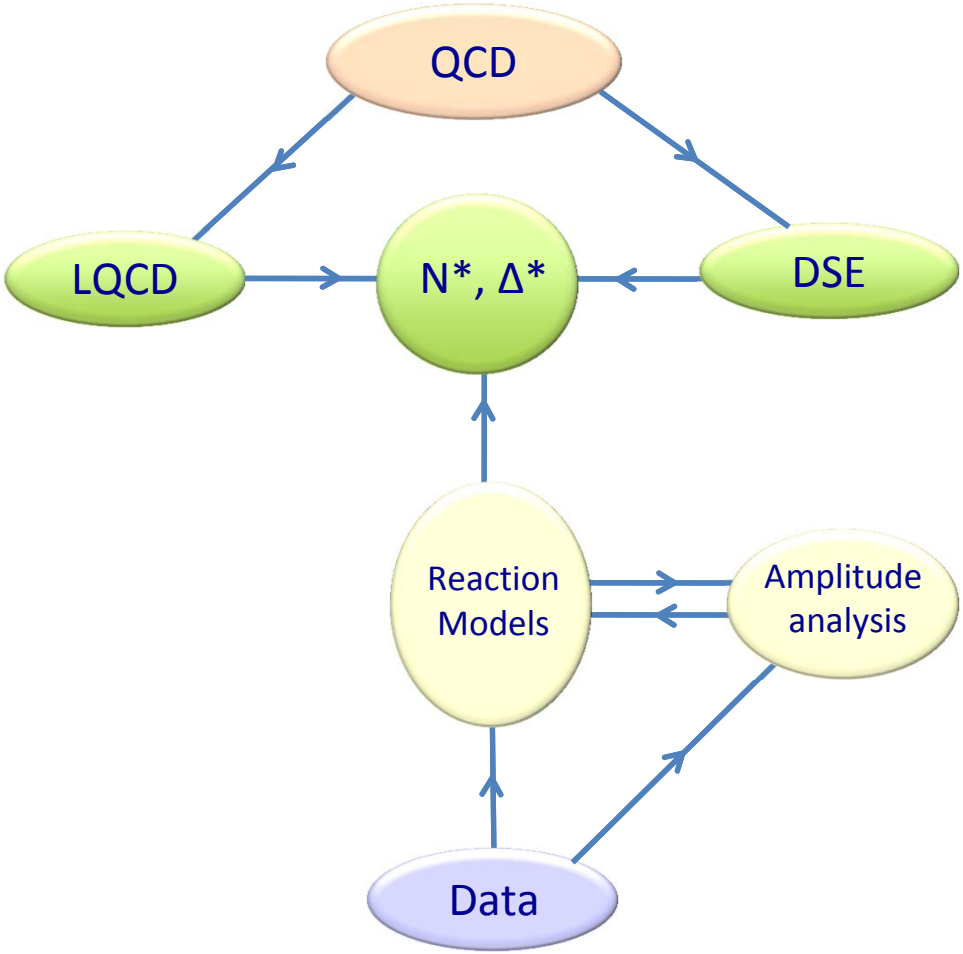




Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Data-Driven Data Analyses

Consistent Results



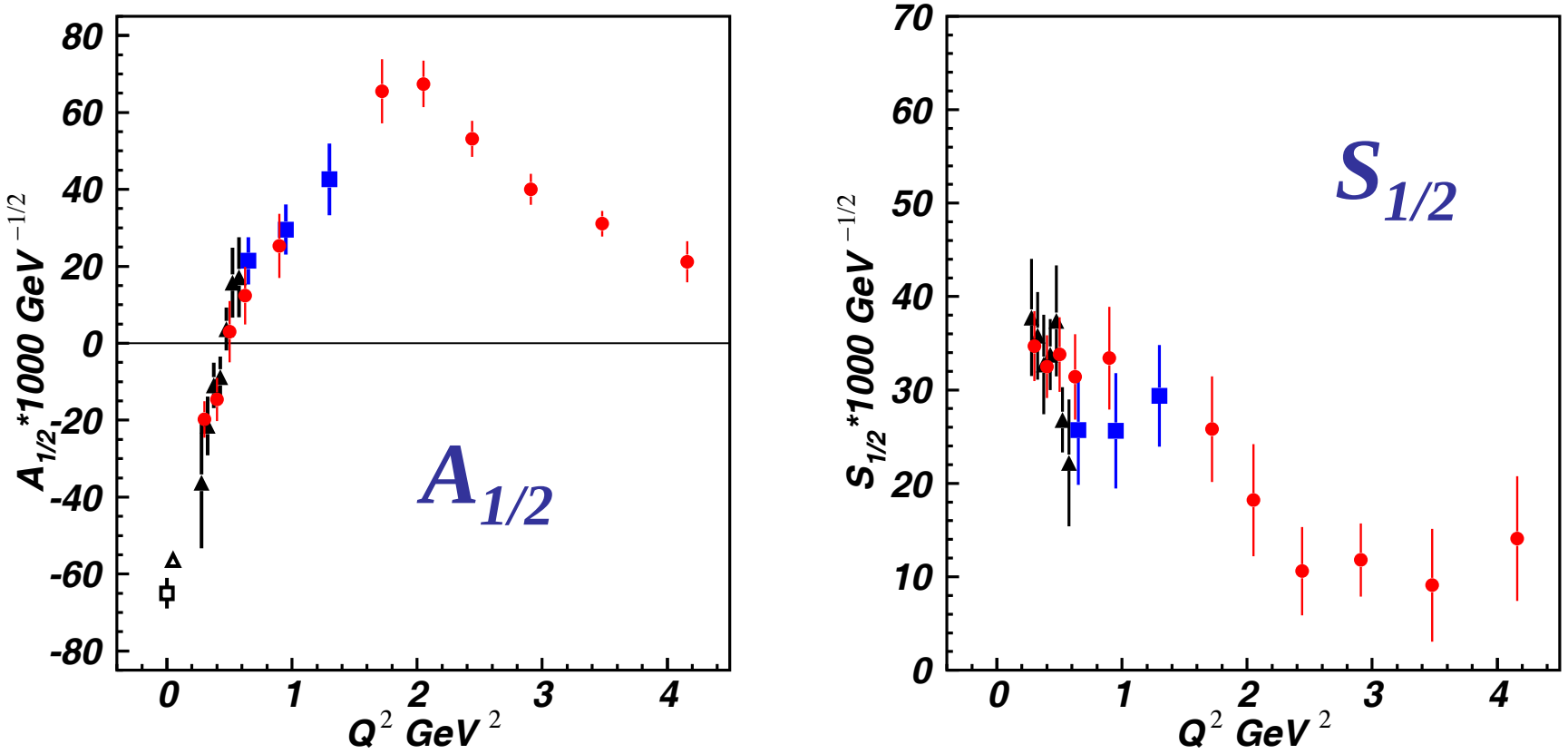
- Single meson production:
  - Unitary Isobar Model (UIM)
  - Fixed-*t* Dispersion Relations (DR)
- Double pion production:
  - Unitarized Isobar Model (JM)
- Coupled-Channel Approach:
  - EBAC ⇒ Argonne-Osaka
  - JAW ⇒ Jülich-Athens-Washington
  - BoGa ⇒ Bonn-Gatchina

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

Hadronic production

Electromagnetic production

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



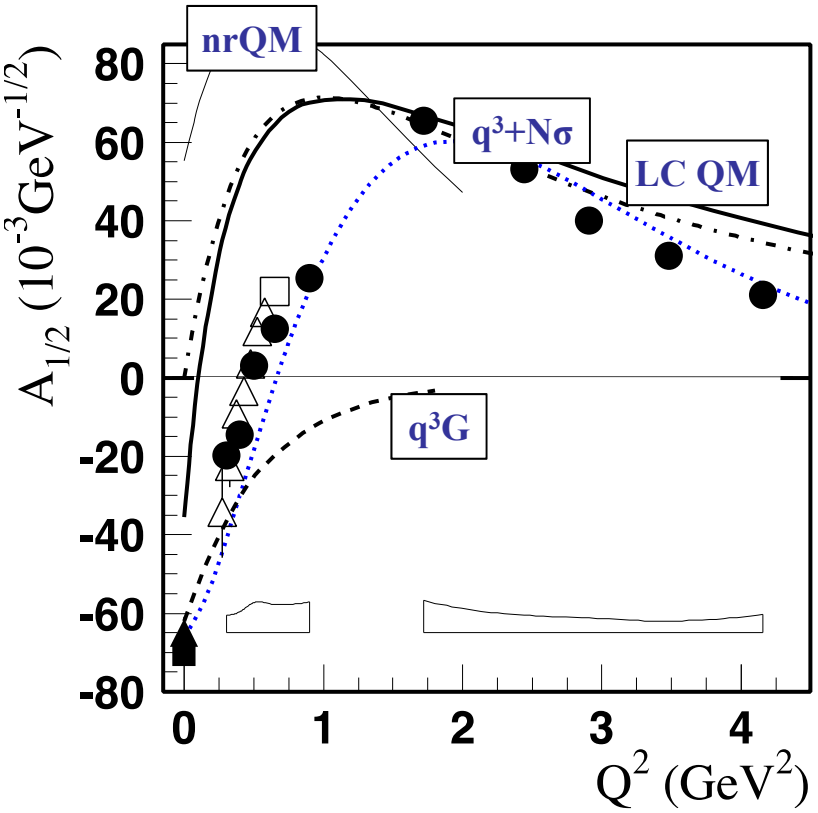
□ PDG ● Nπ (UIM, DR) ▲ Nππ (JM) 2012 ■ Nππ (JM) preliminary

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

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

- …

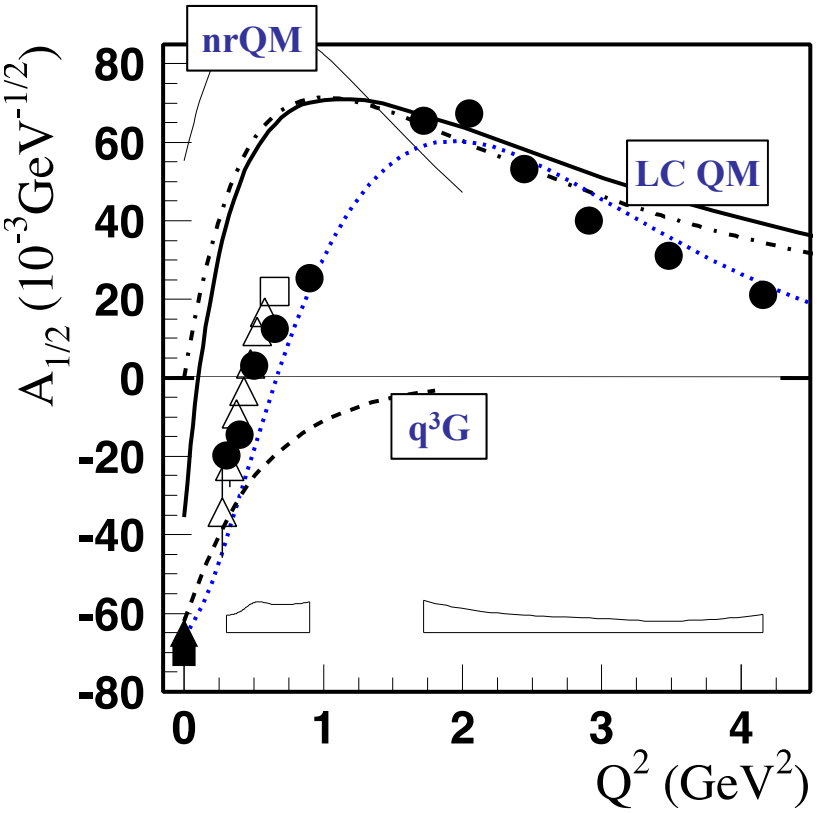
… all have distinctively different Q^2 dependencies

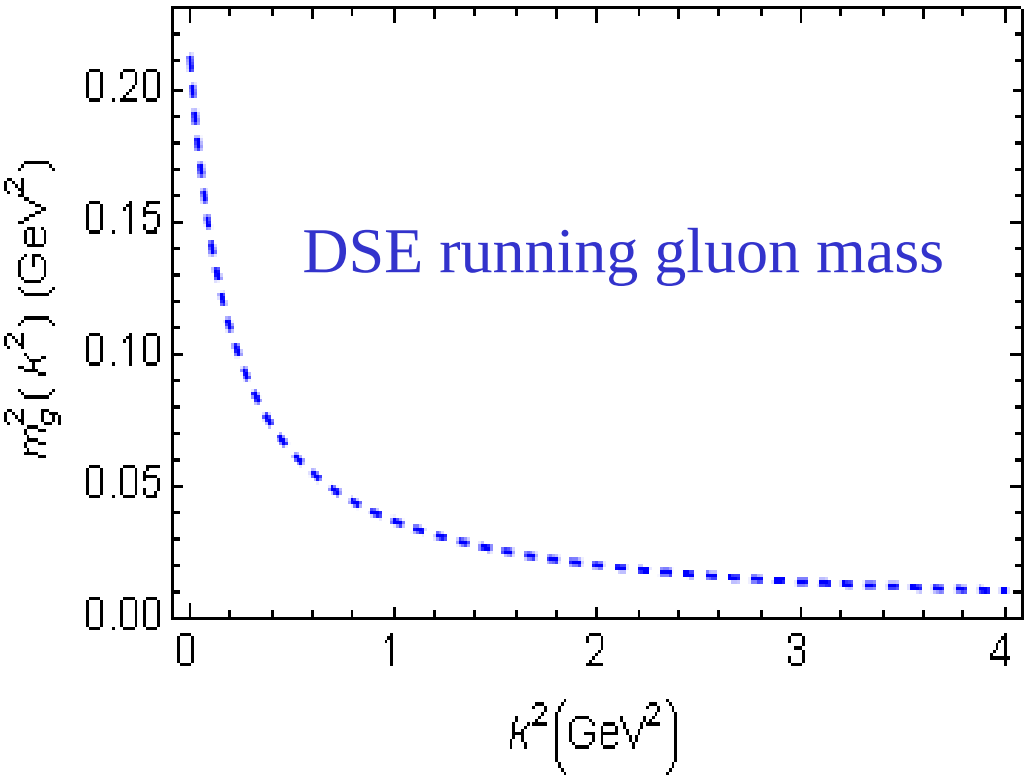
- $A_{1/2}$ has zero-crossing near Q^2=0.5 and becomes dominant amplitude at high Q^2.
- Consistent with radial excitation at high Q^2 and large meson-baryon coupling at small Q^2.
- Eliminates gluonic excitation (q^3G) as a dominant contribution.

Transition Form Factors and QCD Models

Roper resonance $P_{11}(1440)$

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





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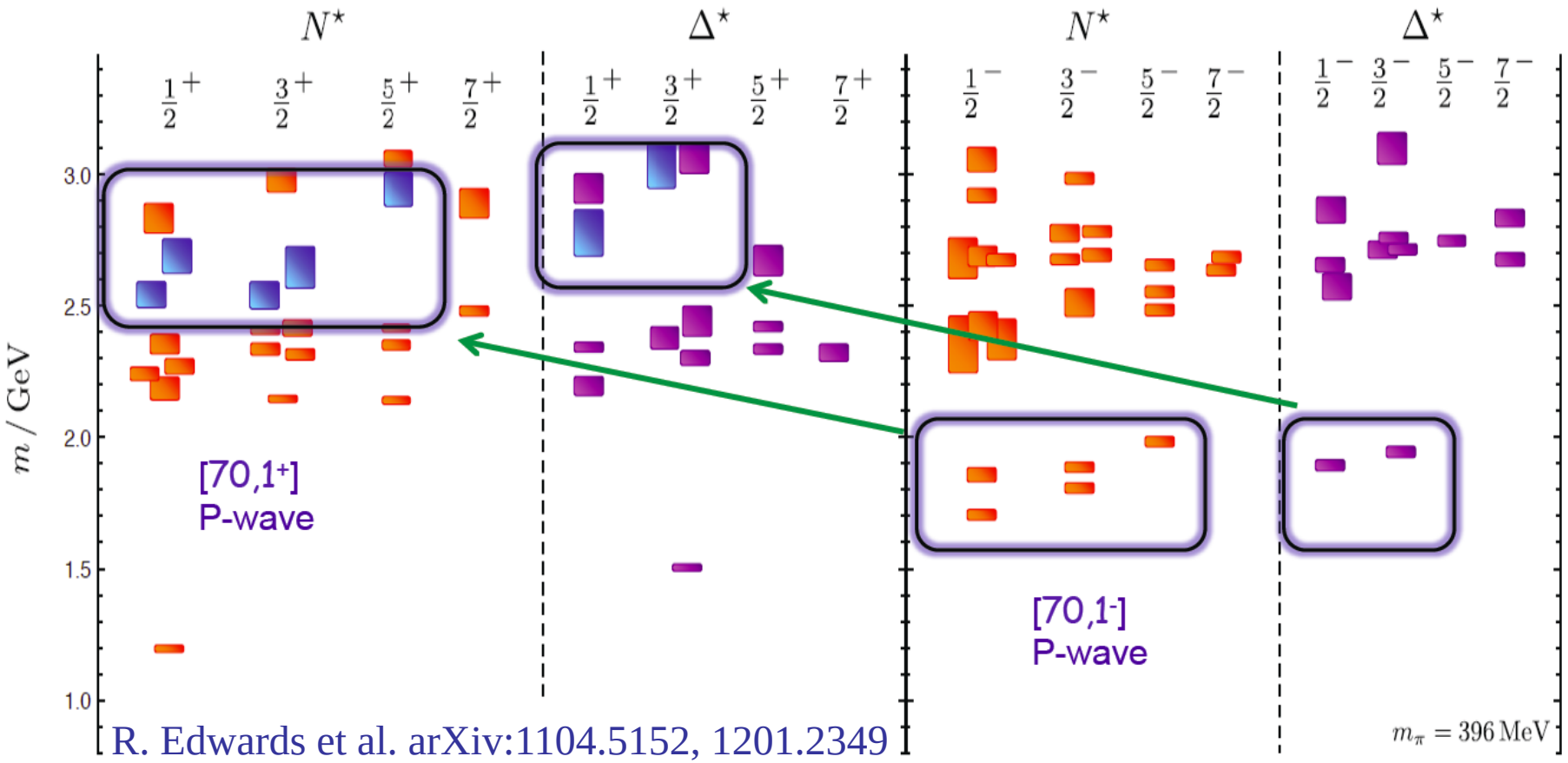
New Letter of Intend on electroexcited gluon hybrids submitted to PAC43.

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.

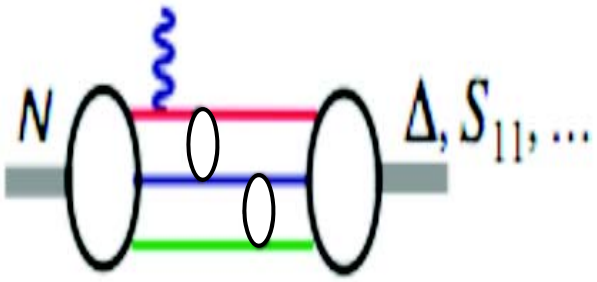


R. Edwards et al. arXiv:1104.5152, 1201.2349

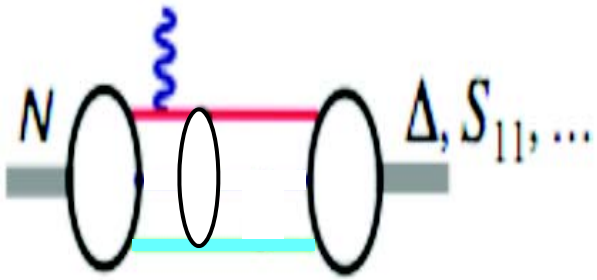
LQCD predicts hybrid baryon states replicating the negative parity multiplet structure.

New Letter of Intend on electroexcited gluon hybrids submitted to PAC43.

Evidence for the Onset of Scaling?

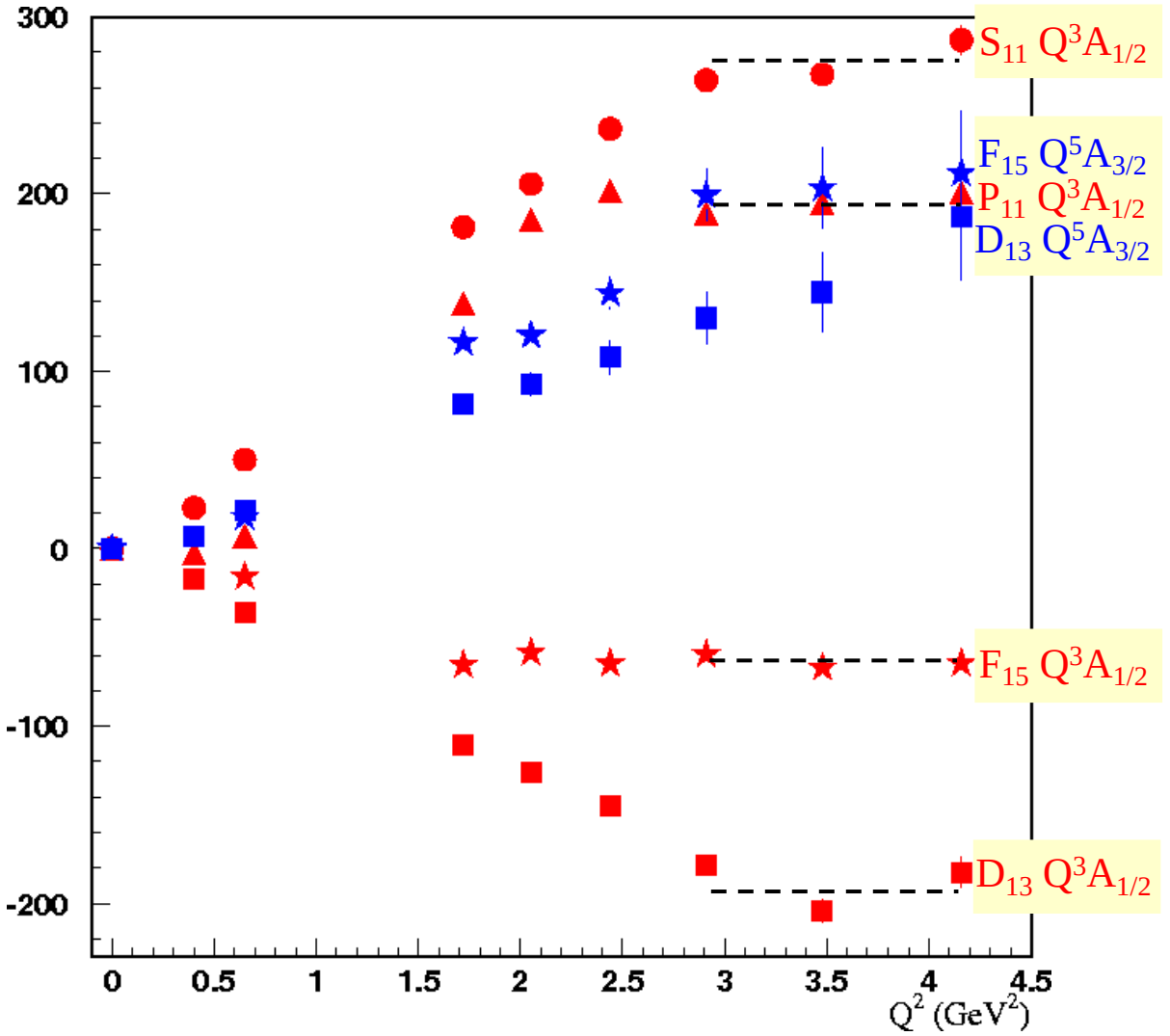


- $A_{1/2} \alpha 1/Q^3$
- $A_{3/2} \alpha 1/Q^5$
- $G_M^* \alpha 1/Q^4$

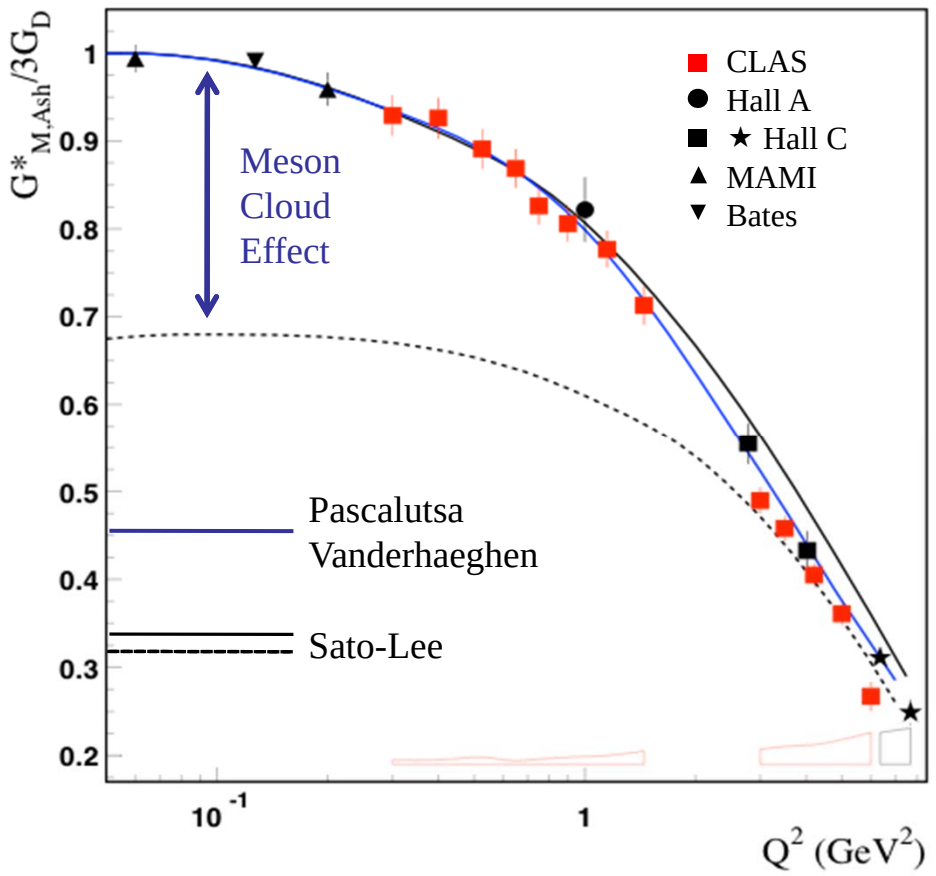


q^2q

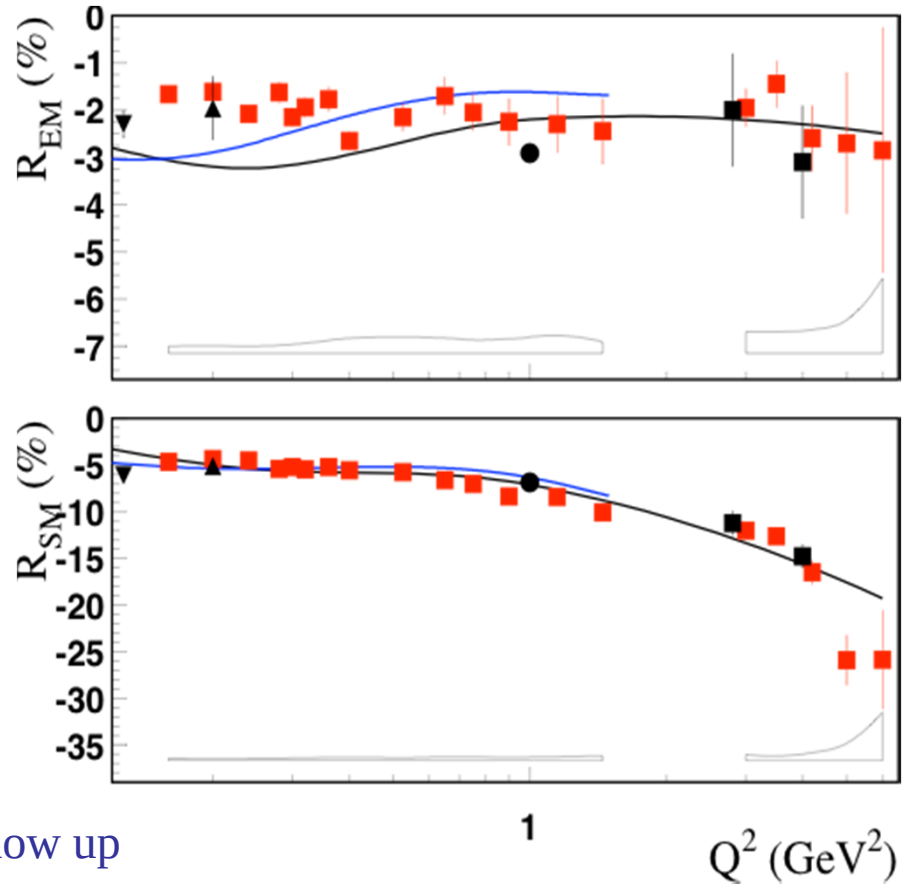
Phys. Rev. C80, 055203 (2009)



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

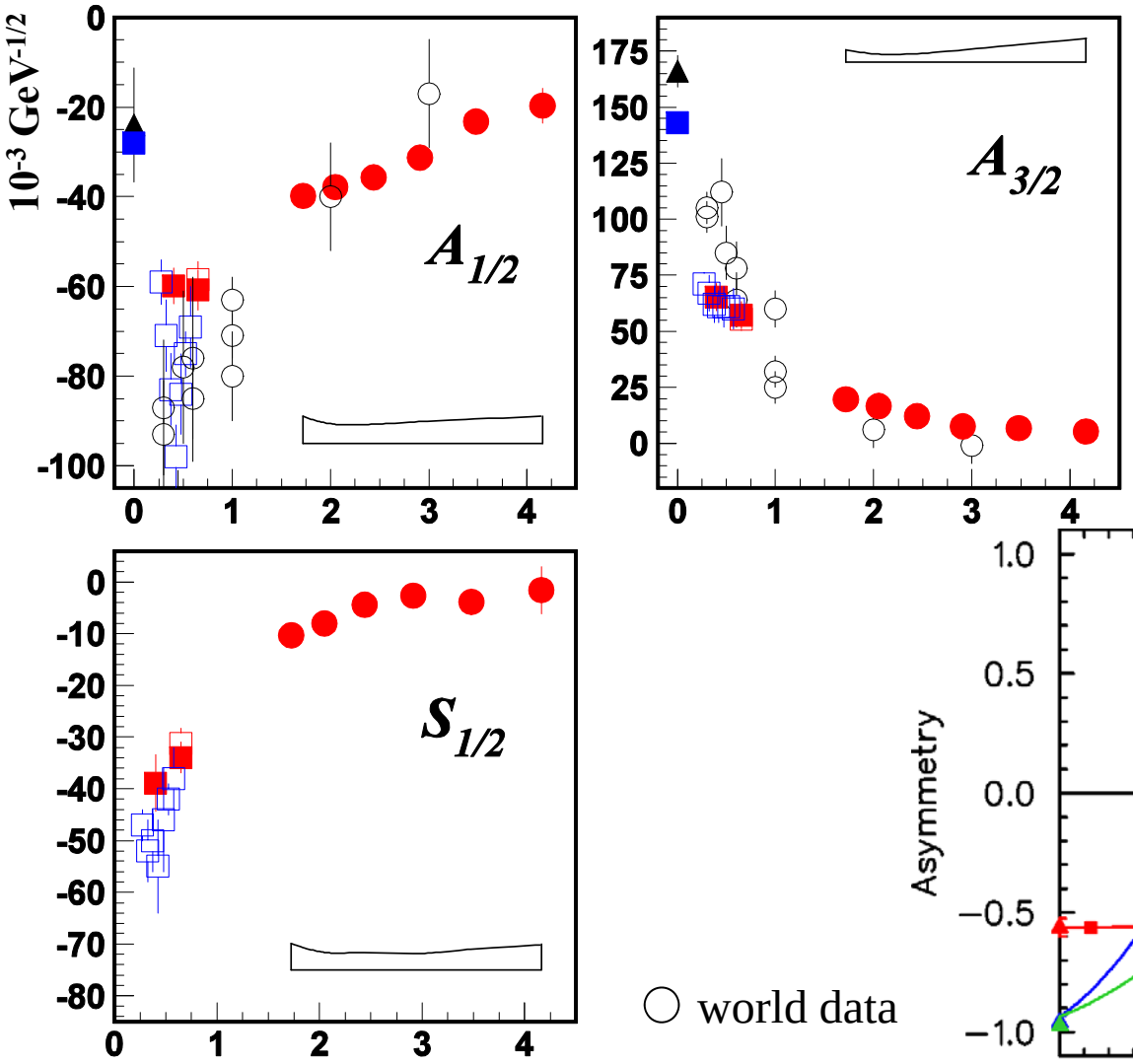


Phys. Rev. Lett. 97, 112003 (2006)



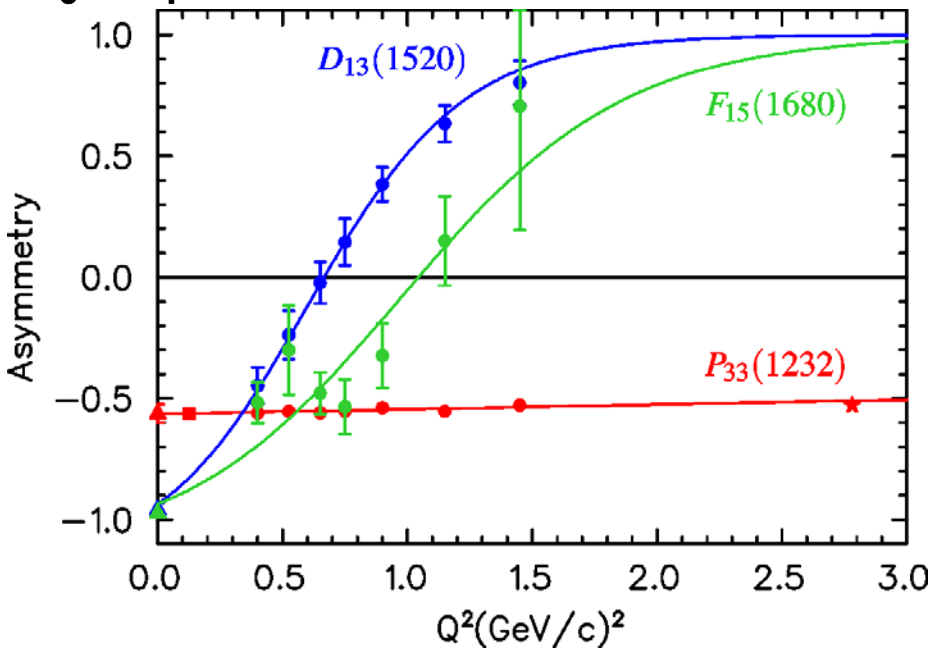
- New trend towards pQCD behavior does not show up
  - $R_{EM} \rightarrow +1$ $R_{SM} \rightarrow$ const
  - $G^*_{M,J.-S.} \rightarrow 1/Q^4$ $G^*_{M,Ash} \rightarrow 1/Q^5$
- CLAS12 can measure G^*_M, R_{EM}, and R_{SM} up to Q^2~12 GeV^2

$N(1520)D_{13}$ 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

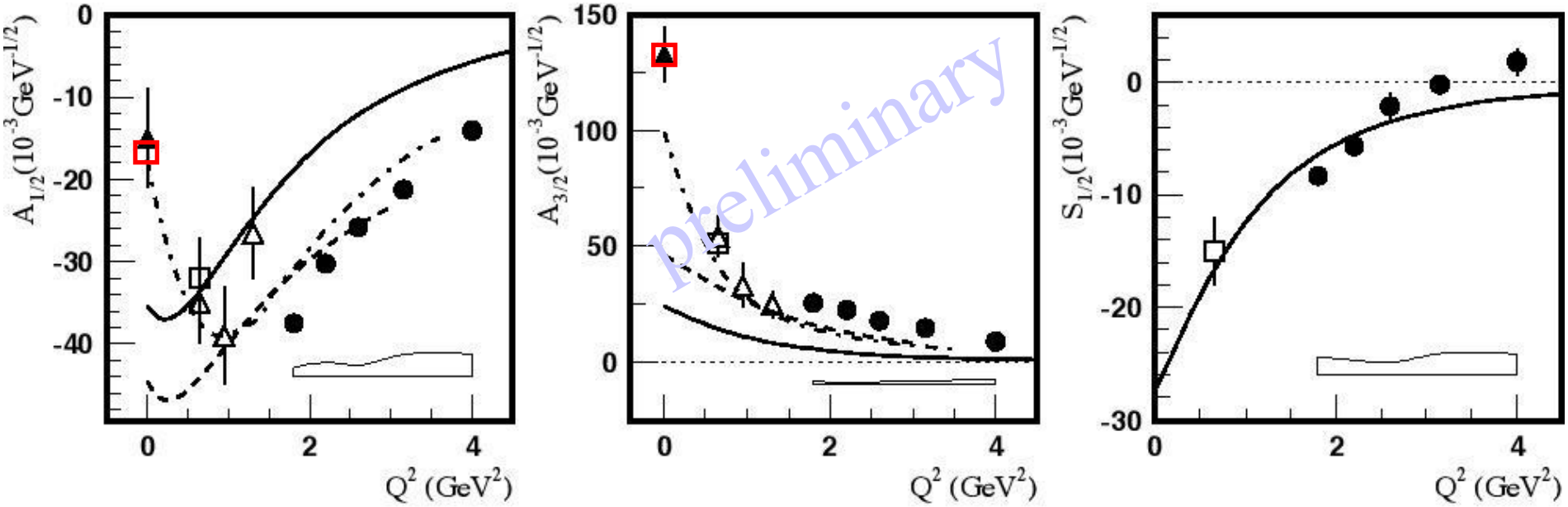
▲ PDG estimation ● ■ Nπ (UIM, DR)

New Experimental Results & Approaches

Higher-Lying Resonance Electrocouplings

$N(1680)F_{15}$

Kijun Park

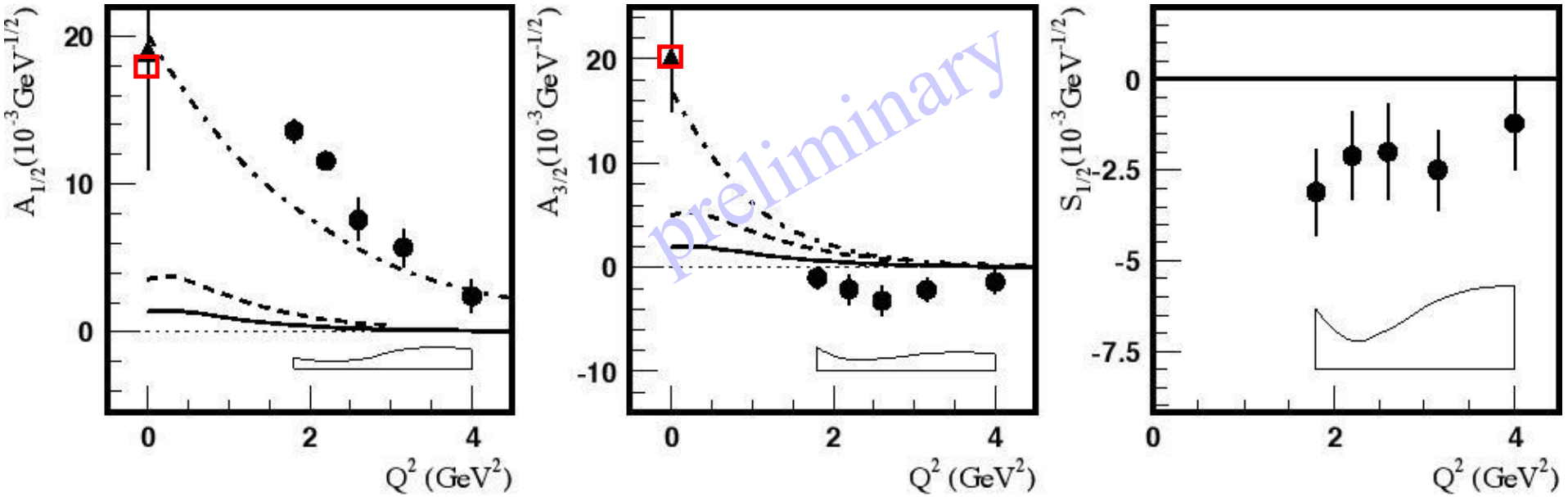


- ▲ RPP (PDG) Phys. Rev. D 86 (2012)
- □ M. Dugger Phys. Rev. C 76 (2007)
- □ I.G. Aznauryan, Phys. Rev. C 72 (2005)
- △ Nππ: V. Mokeev (JM)
- ● Nπ: I.G. Aznauryan (UIM & DR)
- – – – D. Merten, U. Löring et al.
- – · – · Z. Lee and F. Close
- —— E. Santopinto and M.M. Gianini

Higher-Lying Resonance Electrocouplings

$N(1675)D_{15}$

Kijun Park



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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

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

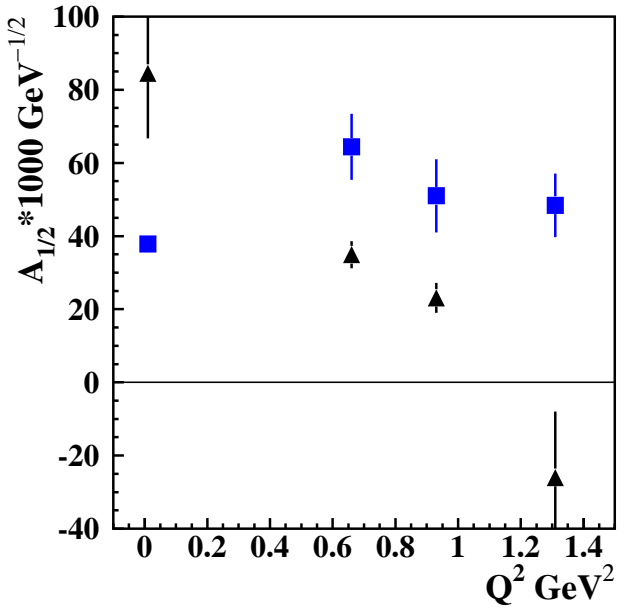
N* hadronic decays from JM15 that incorporates N'(1720)3/2$^+$

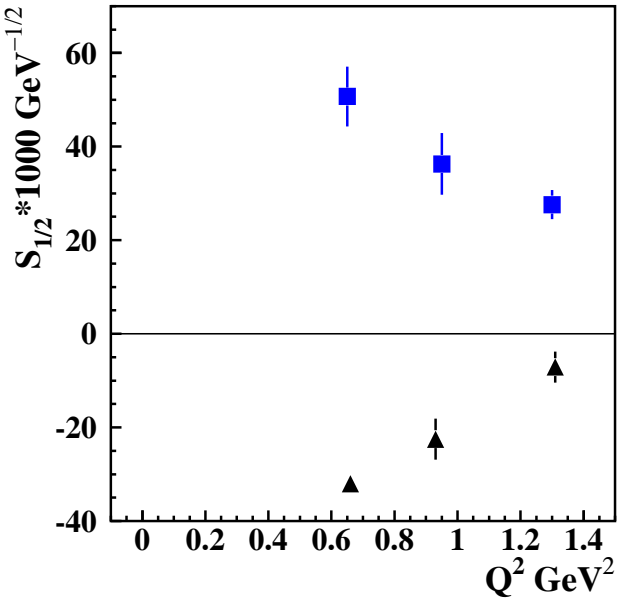
Resonance	BF(πΔ), %	BF(ρp), %
N'(1720)3/2$^+$		
electroproduction	**47-64**	**3-10**
photoproduction	**46-62**	**4-13**
N(1720)3/2$^+$		
electroproduction	**39-55**	**23-49**
photoproduction	**38-53**	**31-46**
Δ(1700)3/2$^-$		
electroproduction	**77-95**	**3-5**
photoproduction	**78-93**	**3-6**

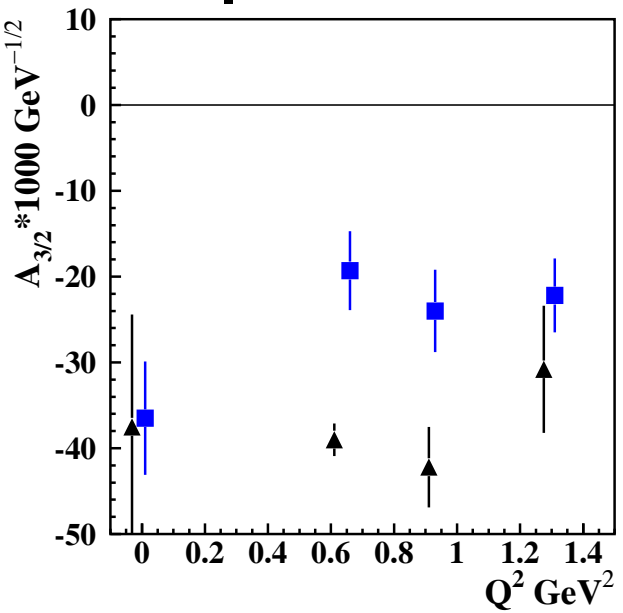
A successful description of $\pi^+\pi^-$p photo- and electro-production cross sections at Q^2=0, 0.65, 0.95, and 1.30 GeV^2 has been achieved by implementing a new N'(1720)3/2$^+$ state with Q^2-independent hadronic decay widths of all resonances that contribute at W~1.7 GeV, that allows us to claim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

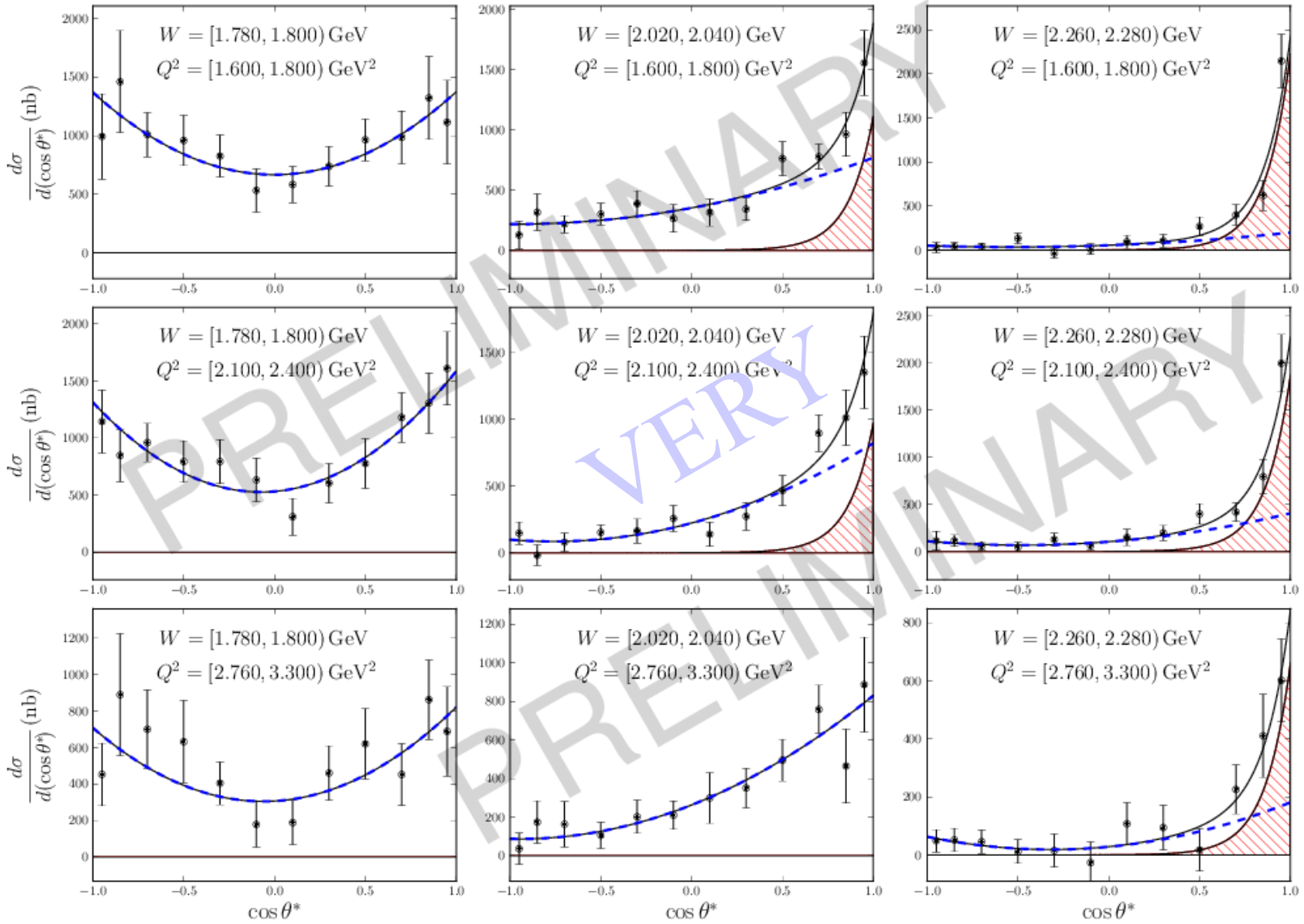




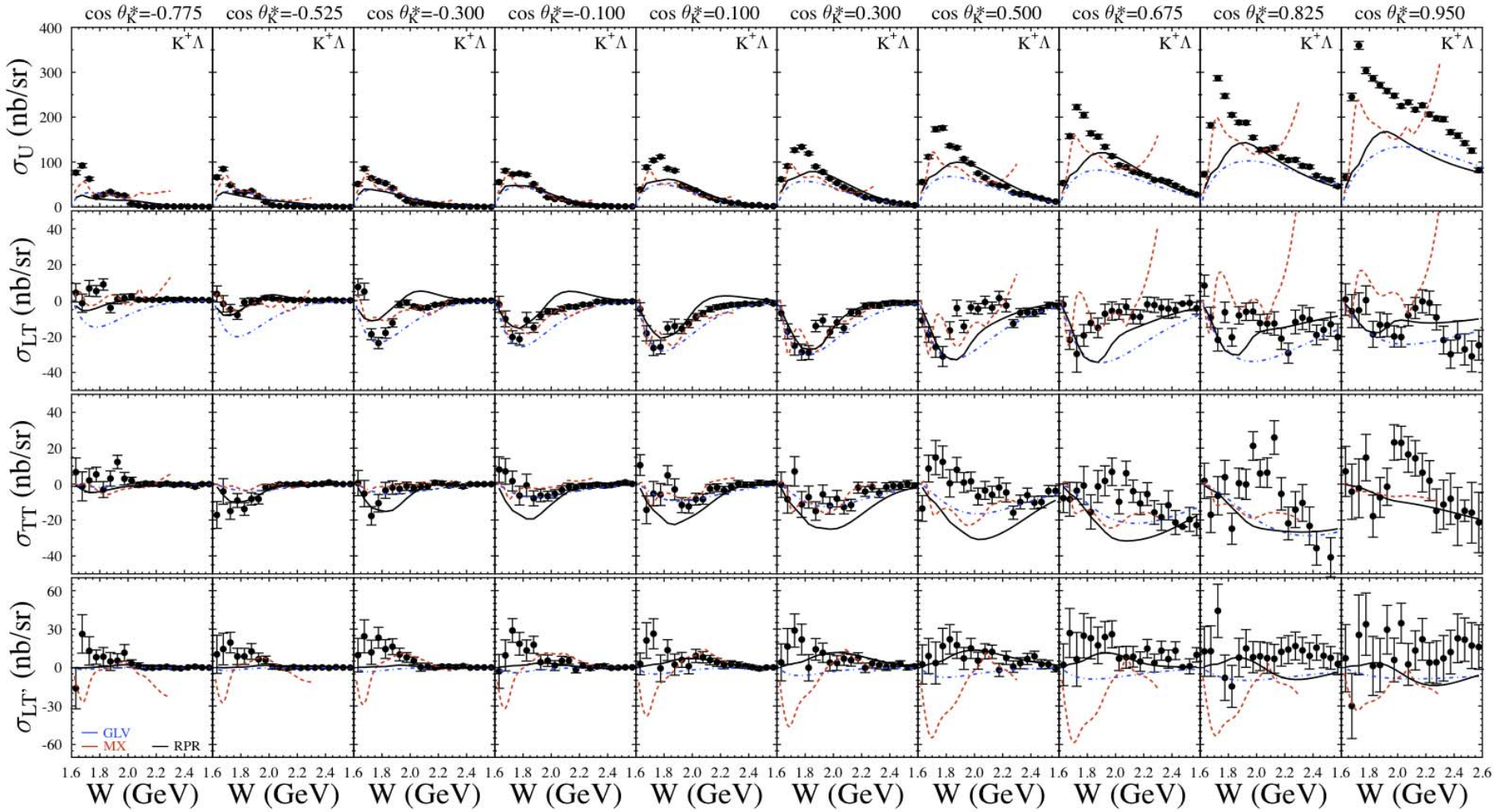


High-Lying Resonances in ω Electroproduction

Evan Phelps



$K^+\Lambda$ Structure Functions

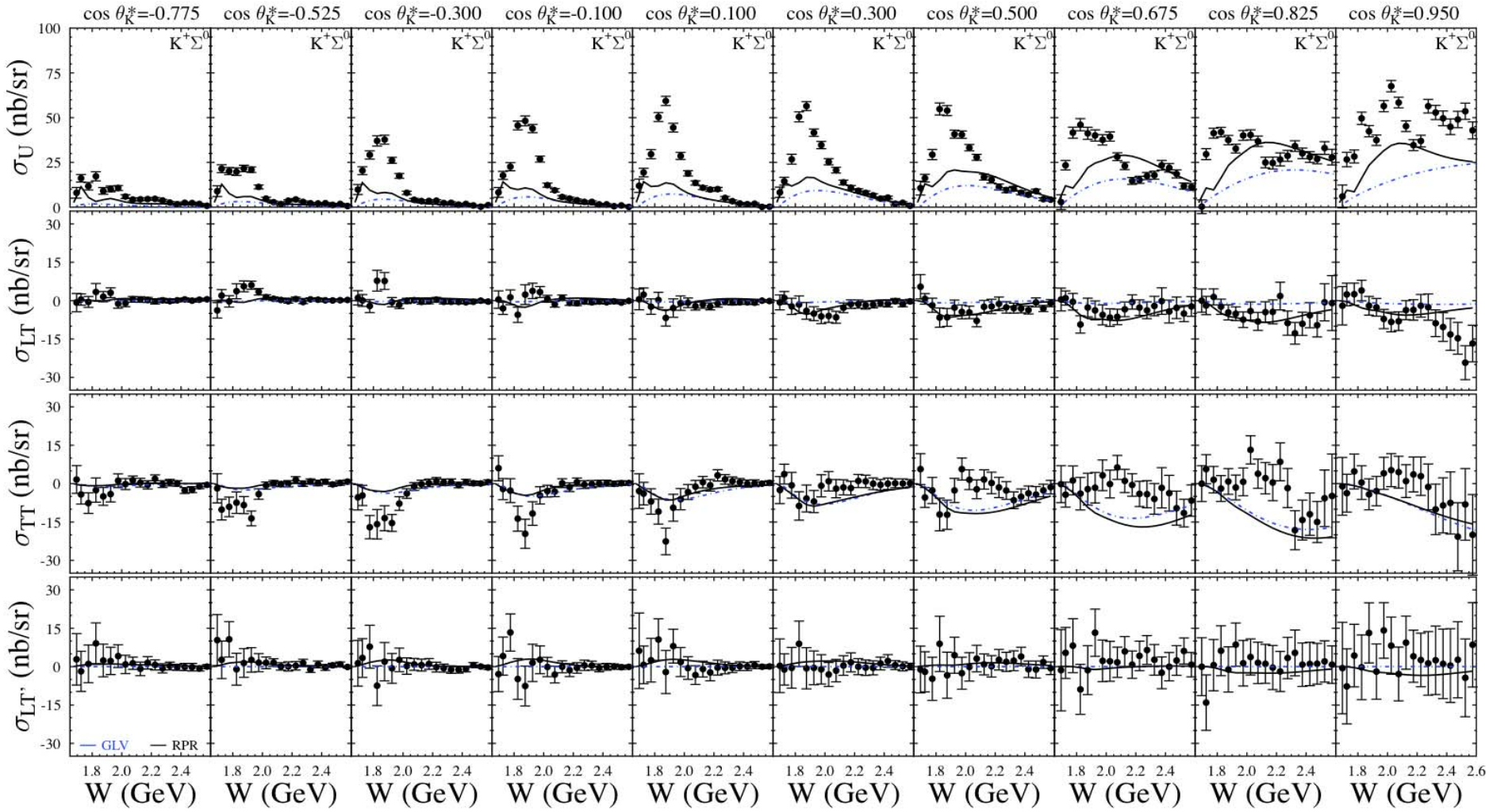


[Carman et al., PRC 87, 025204 (2013)]

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



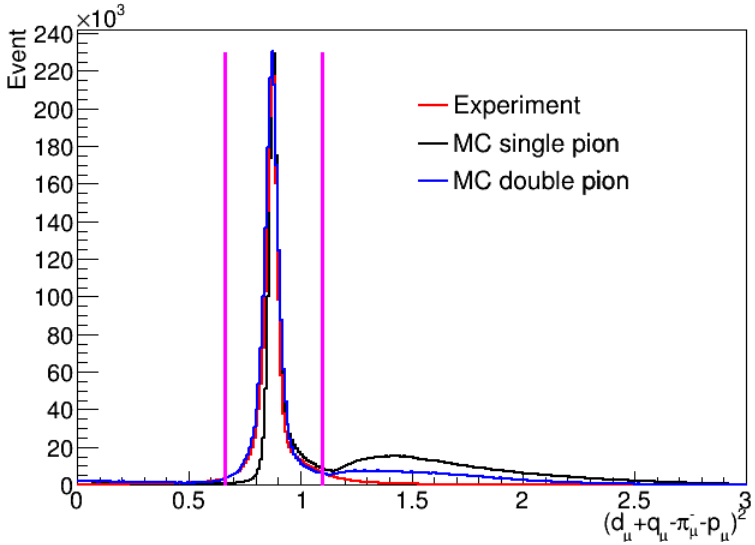
[Carman et al., PRC 87, 025204 (2013)]

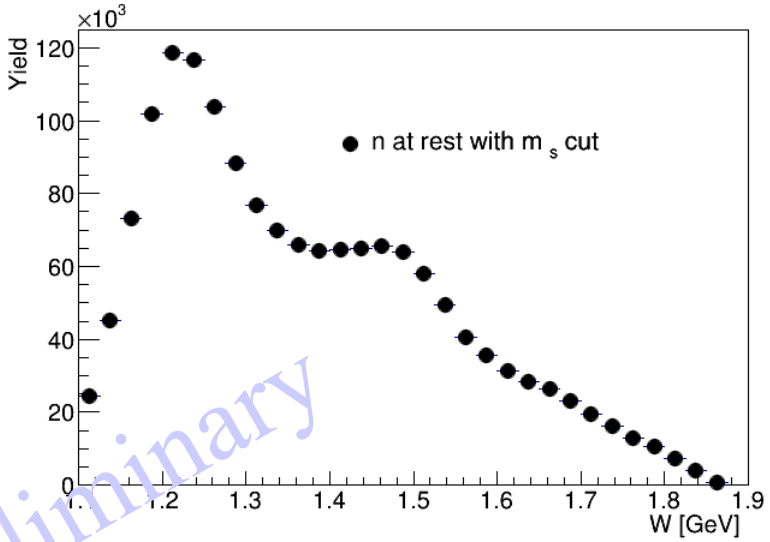
E = 5.499 GeV, W: thr – 2.6 GeV, Q^2 = 1.80, 2.60, 3.45 GeV^2

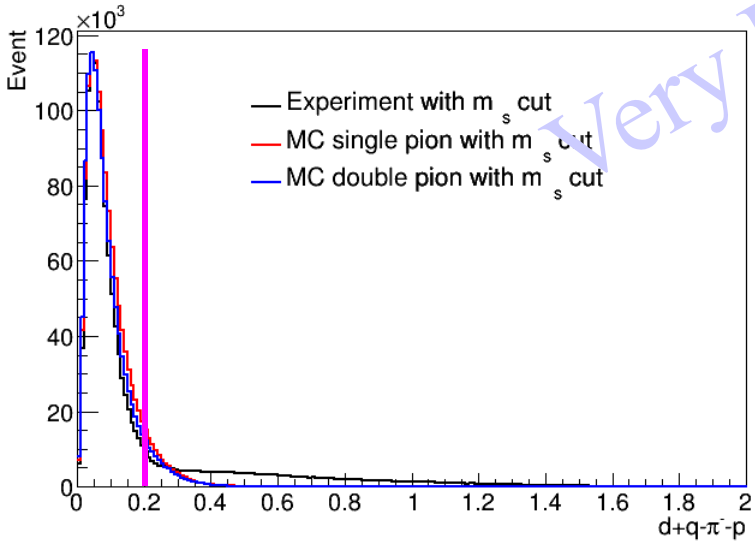
CLAS12 experiment E12-06-108A

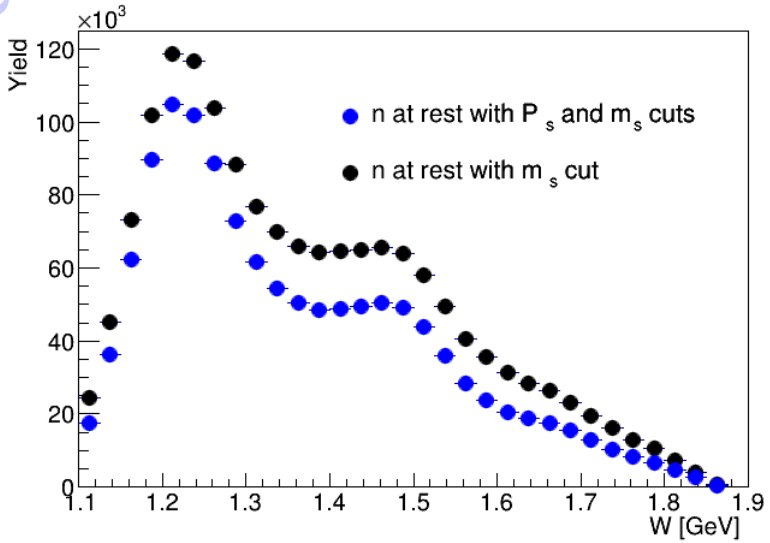
Single π Electroproduction off the Deuteron

Ye Tian





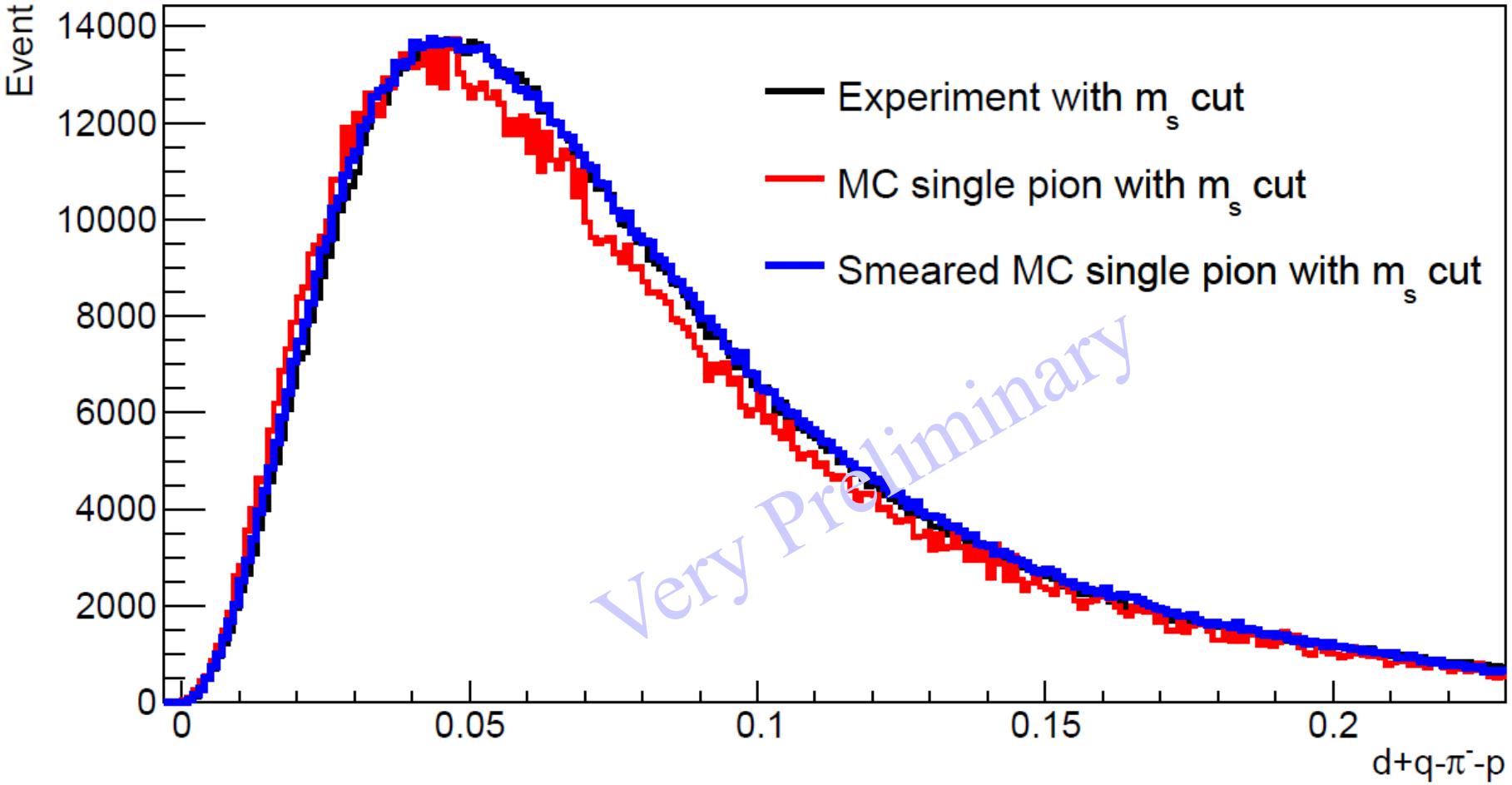




Very Preliminary

Single π Electroproduction off the Deuteron

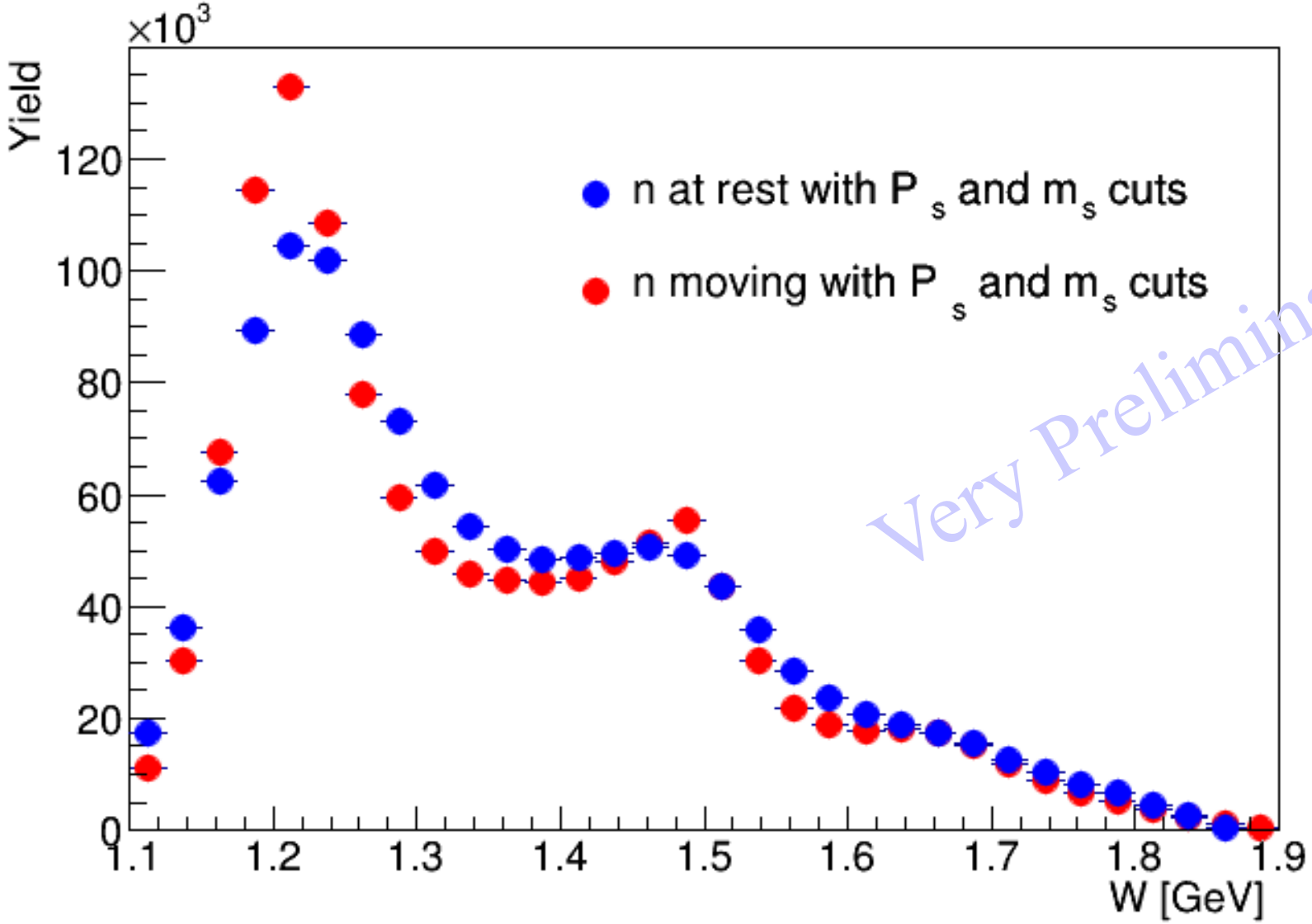
Ye Tian



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



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

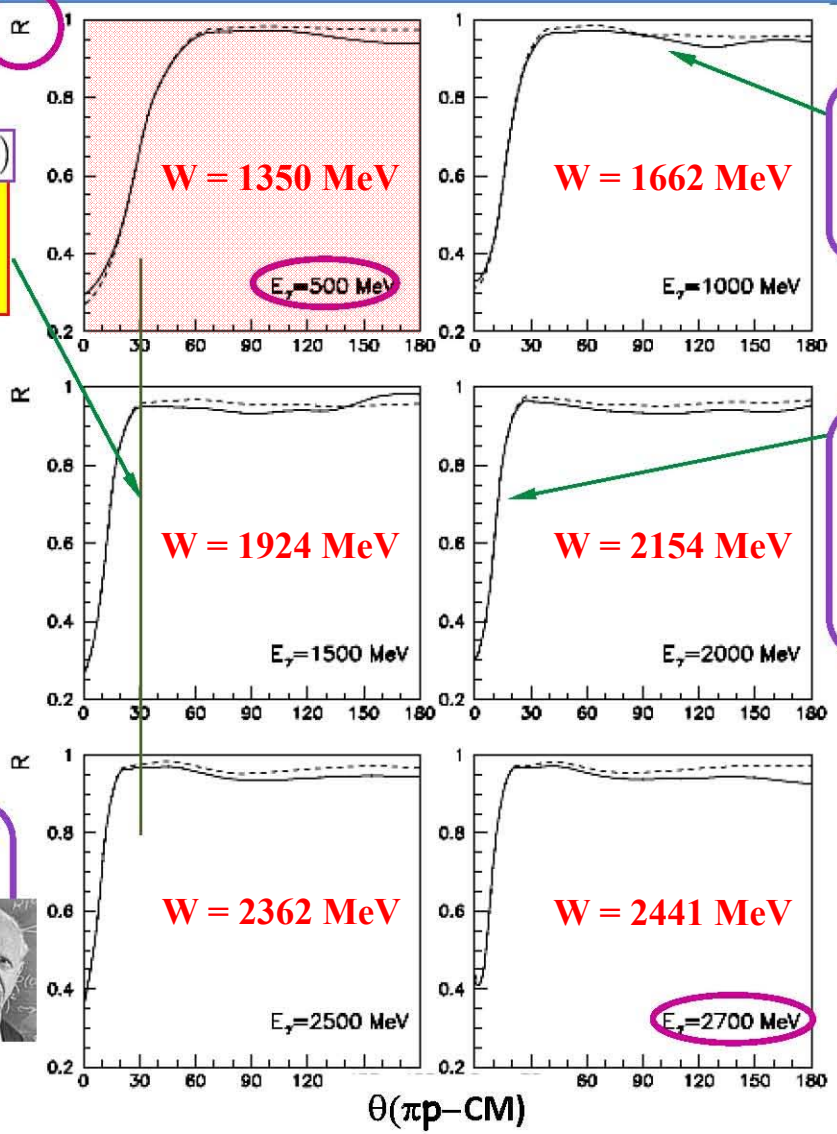
[V. Tarasov, A. Kudryavtsev, W. Briscoe, H. Gao, IS, Phys Rev C 84, 035203 (2011)]

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

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

CLAS data:
E > 1 GeV
θ > 32 deg

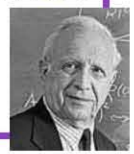
- There is no large sensitivity to cuts.



- For CLAS data
  - The FSI correction factor R < 1.
  - The behavior is smooth vs. θ.
  - The effect $\Delta\sigma/\sigma \leq 10\%$.

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

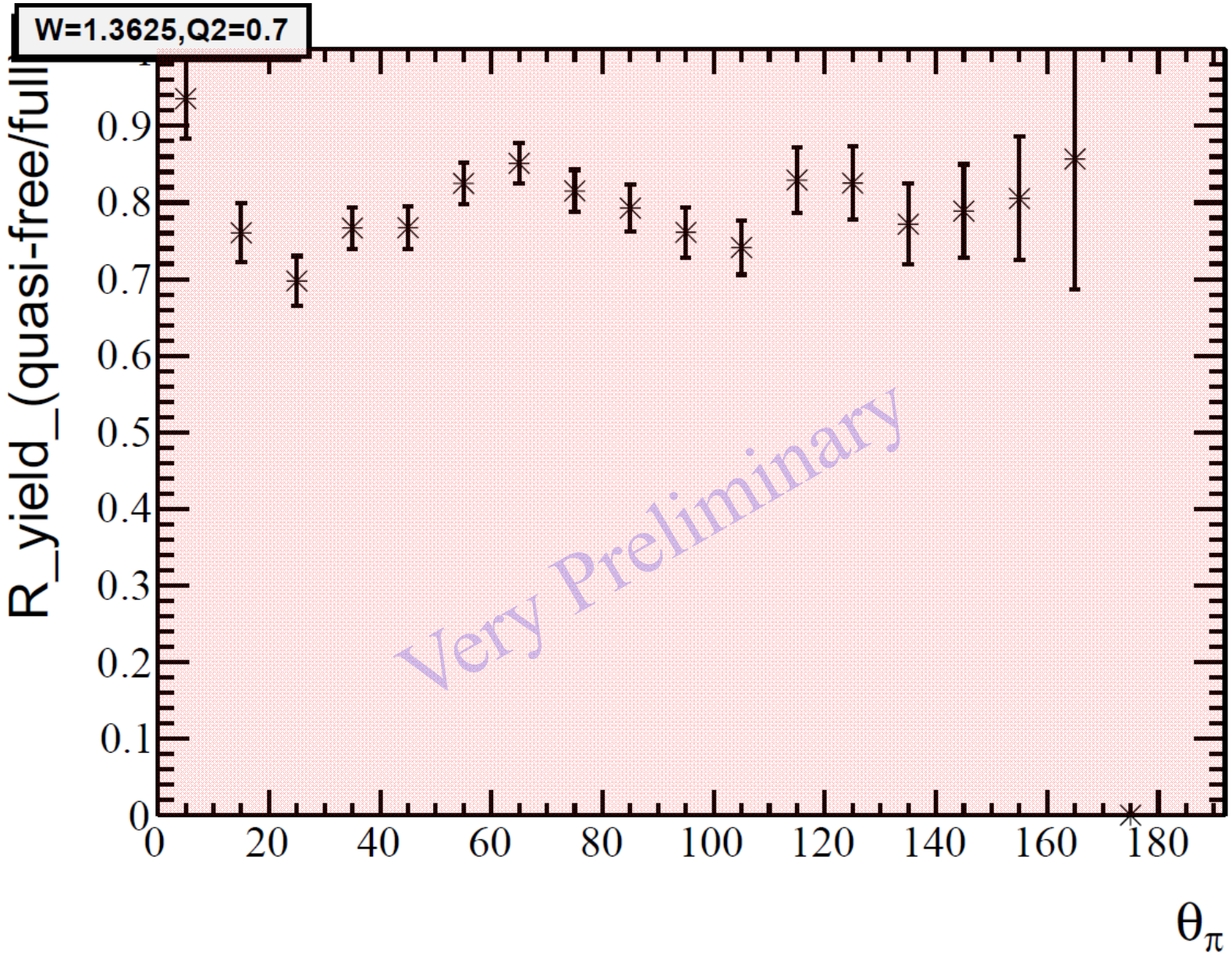
- Our estimation of the **Glauber FSI** corrections gives the value of 5%.
- **Previous** estimations gave the order of 15-30%.



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

Single π Electroproduction off the Deuteron

Ye Tian

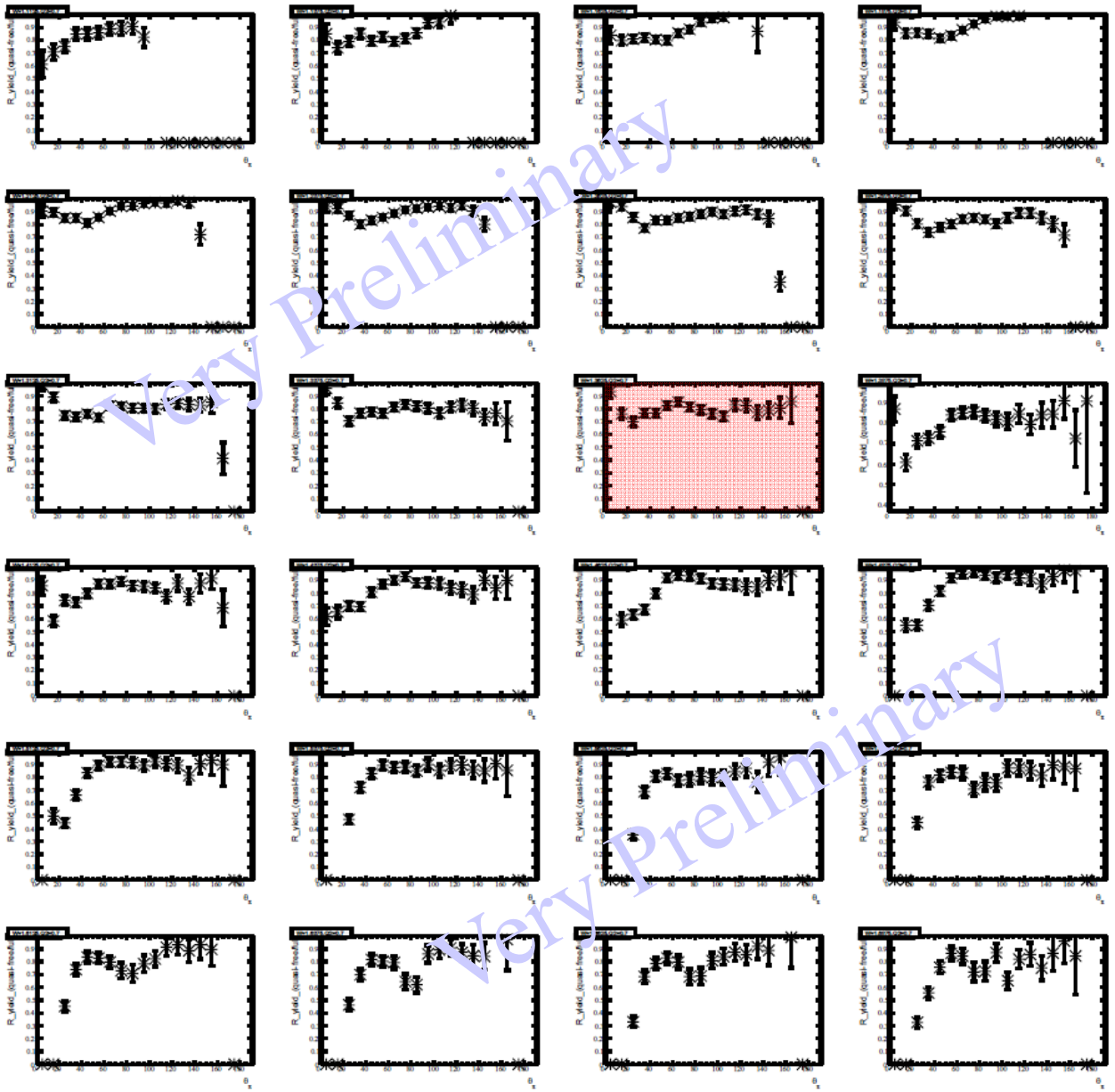


Single π Electroproduction off the Deuteron

W = 1125 MeV

ΔW = 25 MeV

Ye Tian



$Q^2 = 0.7$ GeV^2

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

W = 1685 MeV

Single π Electroproduction off the Deuteron

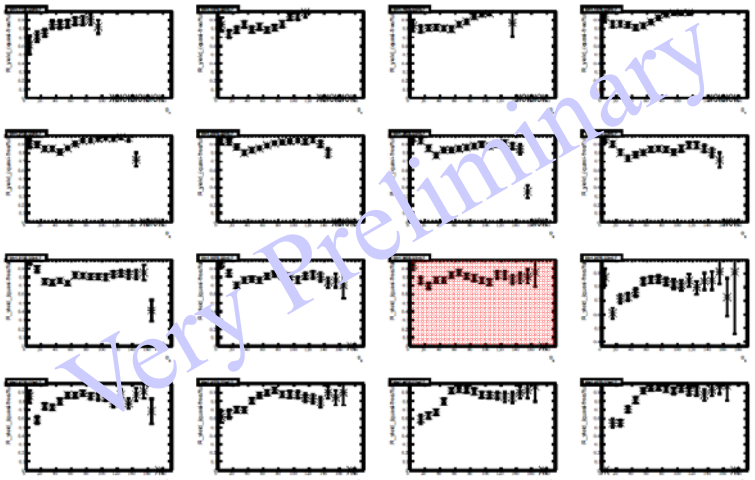
Ye Tian

W = 1125 MeV

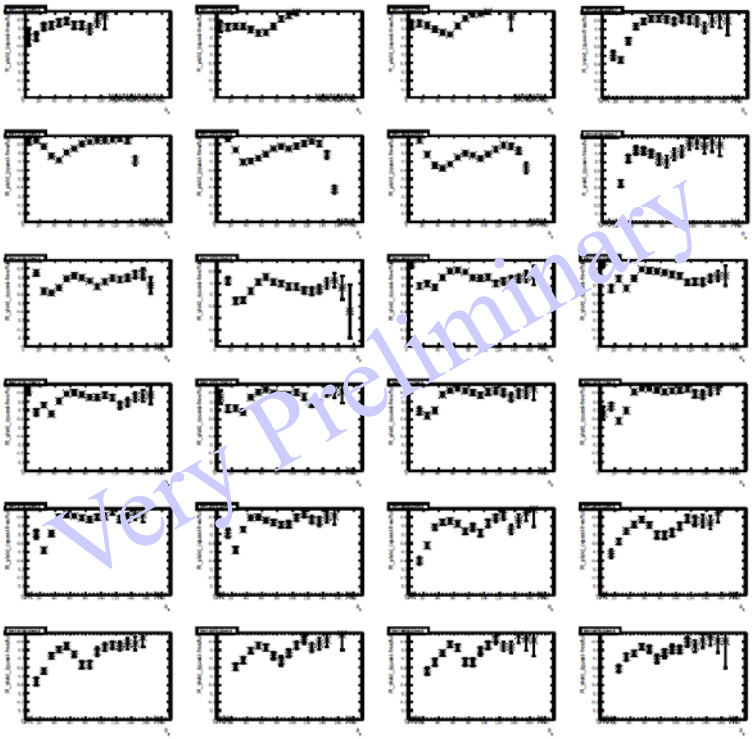
ΔW = 25 MeV

W = 1685 MeV

Q^2 = 0.5 GeV^2

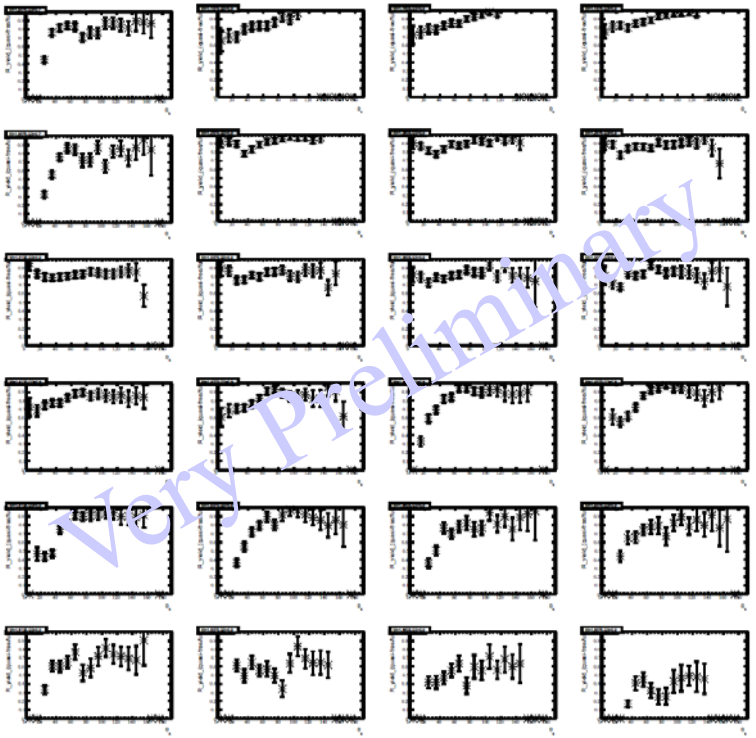


Q^2 = 0.9 GeV^2



Q^2 = 0.7 GeV^2

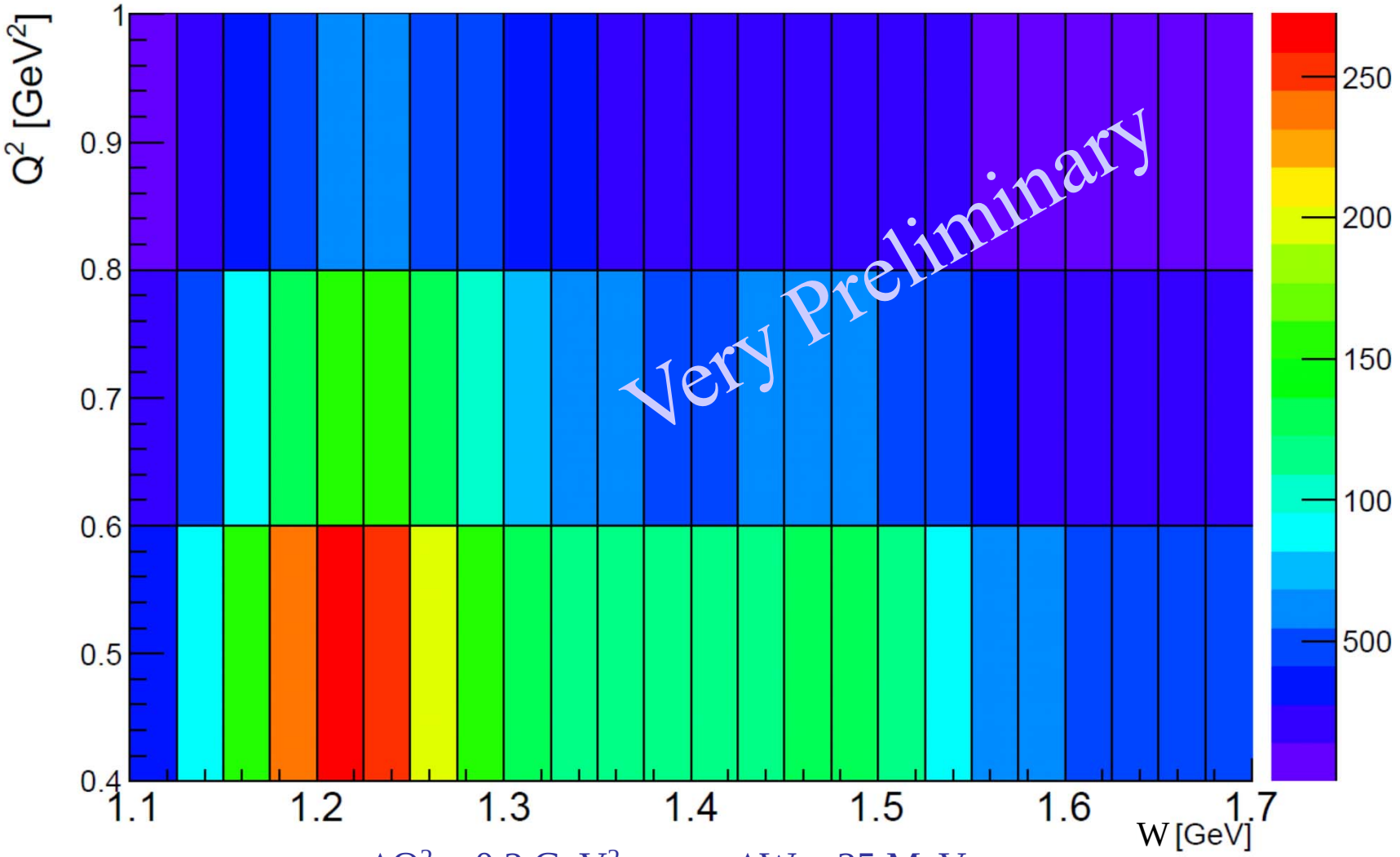
ΔQ^2 = 0.2 GeV^2



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 = 1212 MeV

ΔW = 25 MeV

Q^2 = 0.5 GeV^2

ΔQ^2 = 0.2 GeV^2

cos(θ) = -0.7

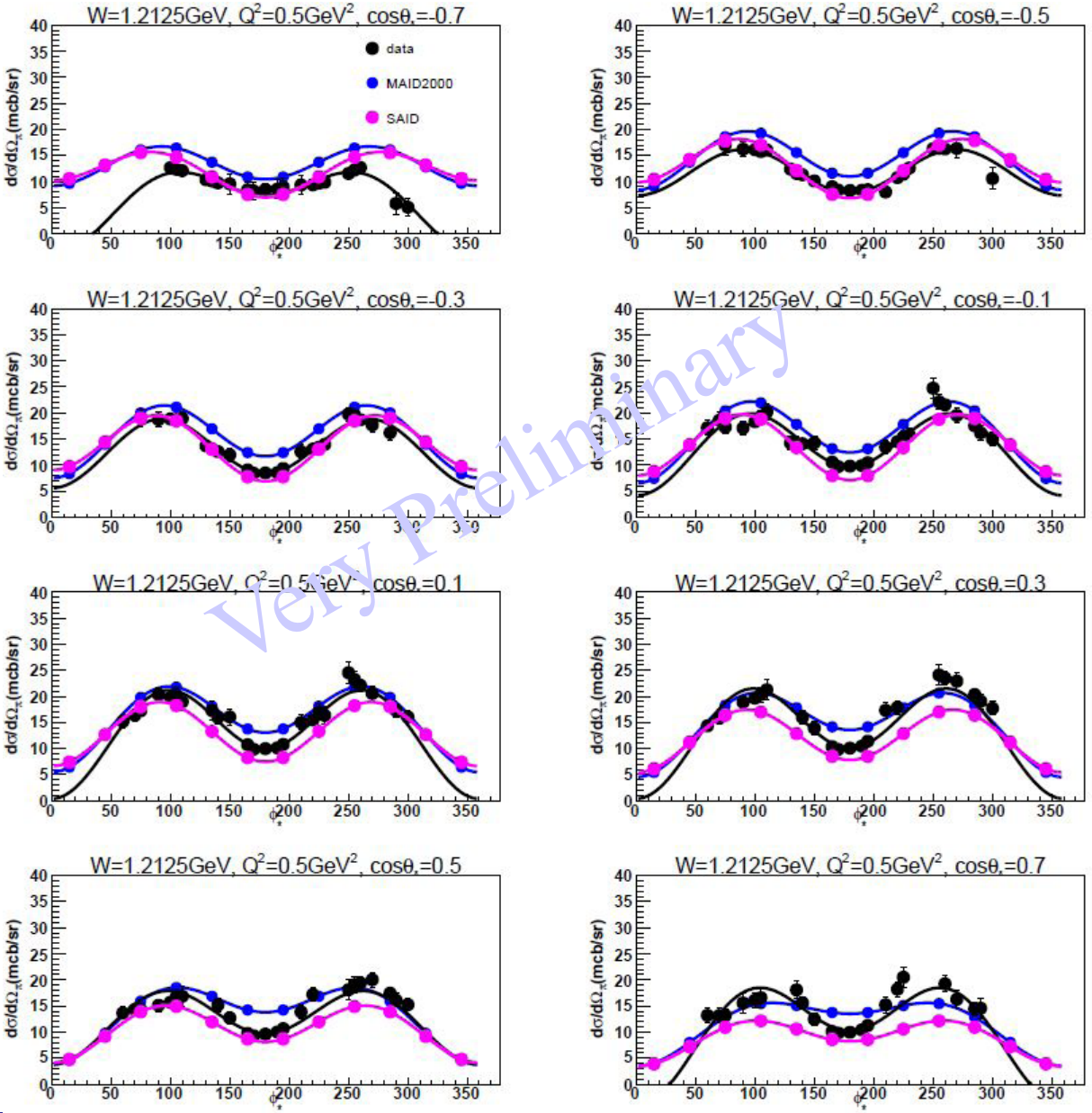
Δcos(θ) = 0.2

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

ΔQ^2 = 0.2 GeV^2

cos(θ) = -0.7

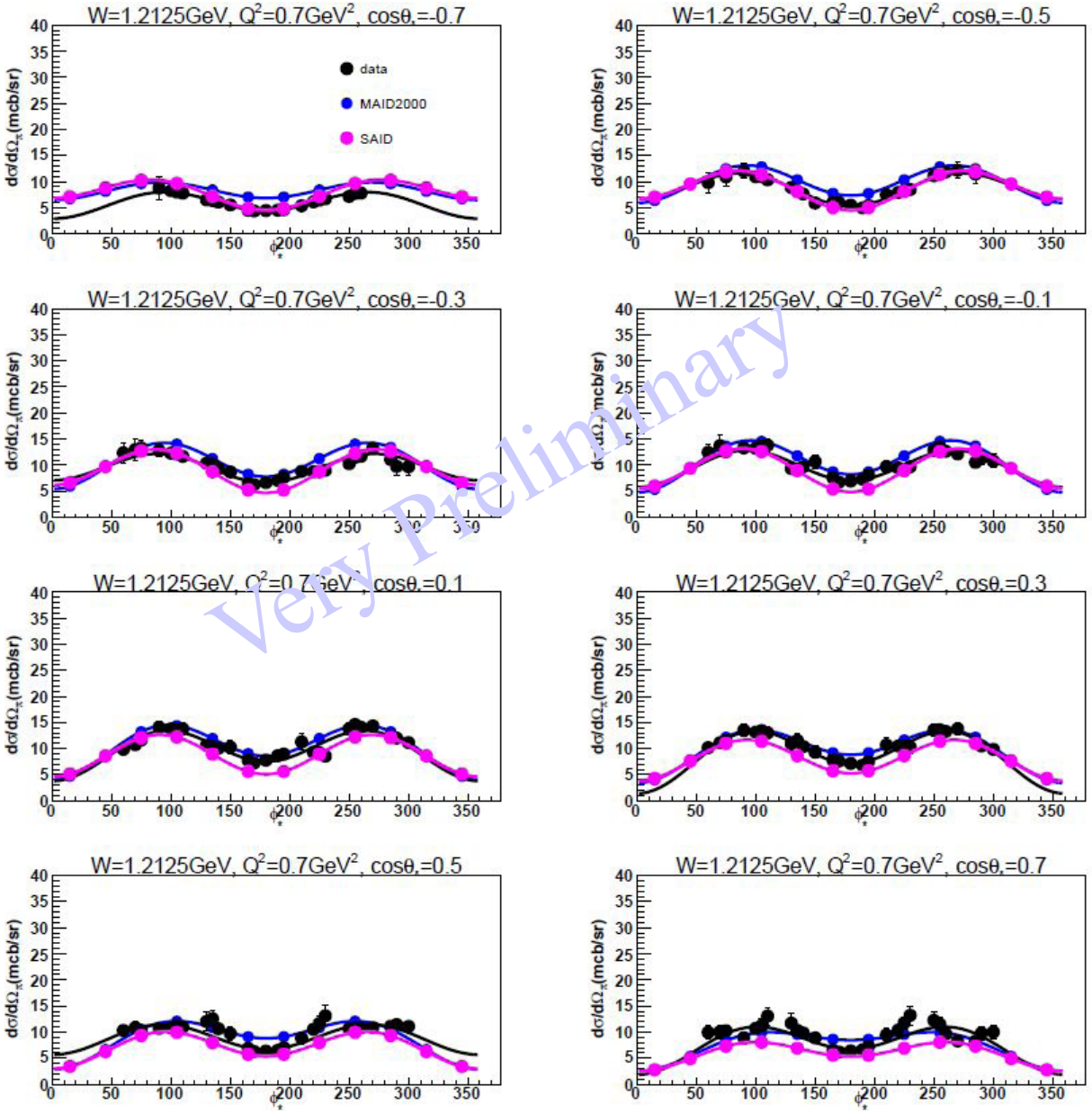
Δcos(θ) = 0.2

cos(θ) = 0.7

ϕ = 15°

Δϕ = 30°

ϕ = 345°



Single π^- Electroproduction off the Deuteron

Ye Tian

$W = 1212$ MeV

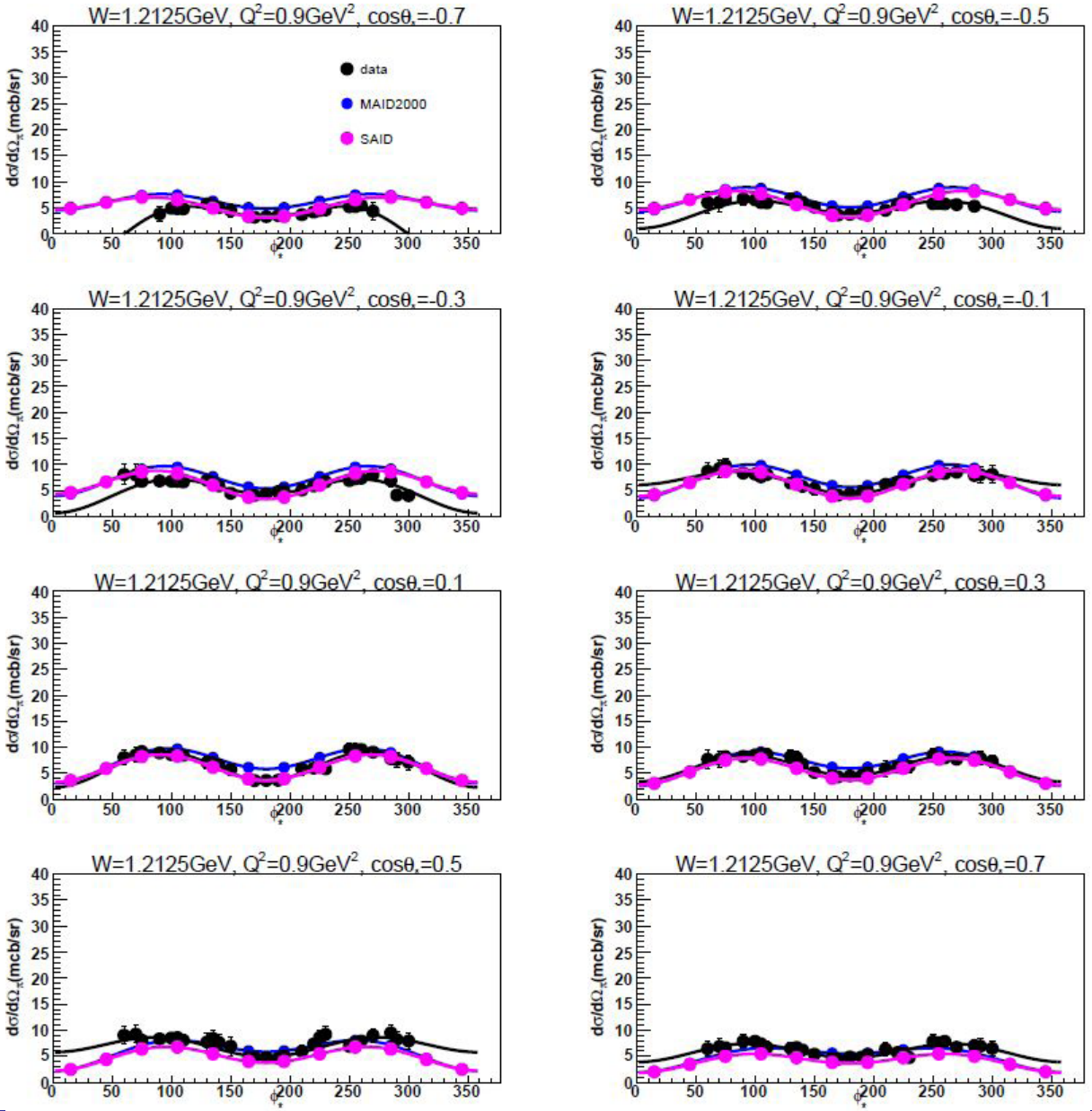
$\Delta W = 25$ MeV

$Q^2 = 0.9$ GeV^2

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

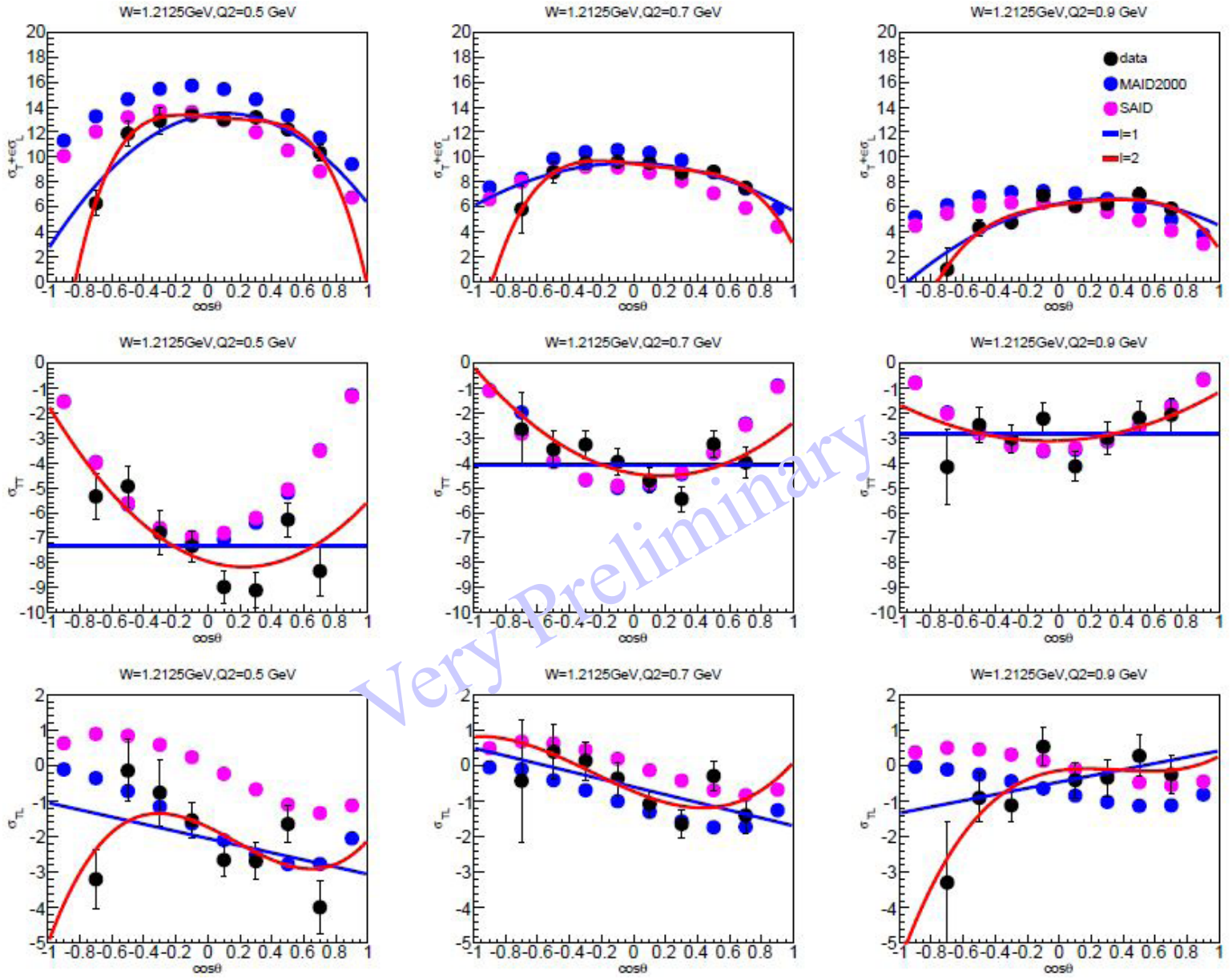
$\cos(\theta) = -0.7$
$\Delta\cos(\theta) = 0.2$
$\cos(\theta) = 0.7$

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



Single π^- Electroproduction off the Deuteron

Ye Tian



Single π^- Electroproduction off the Deuteron

Ye Tian

W = 1125 MeV

ΔW = 25 MeV

W = 1685 MeV

Q^2 = 0.7 GeV^2

ΔQ^2 = 0.2 GeV^2

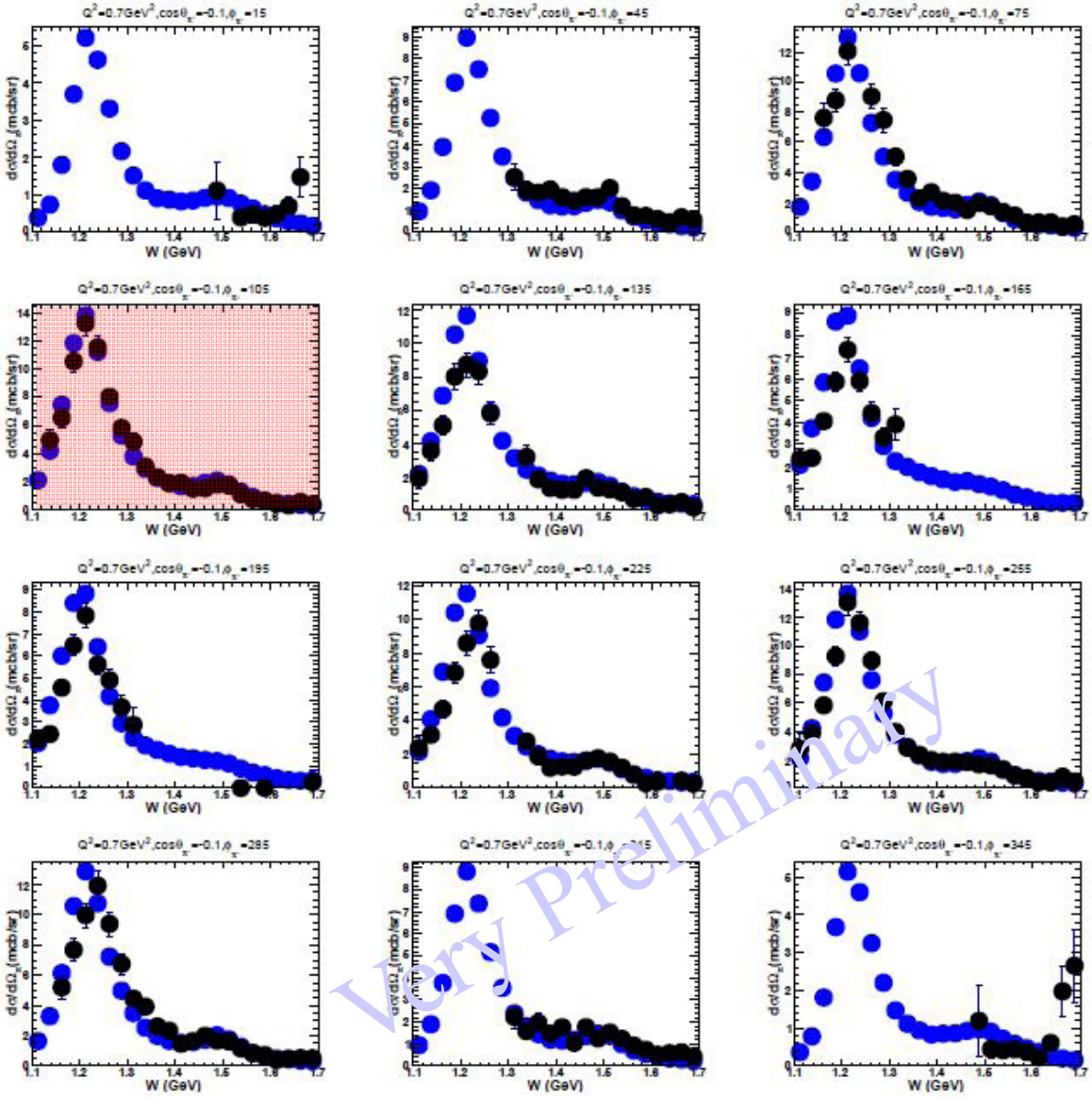
cos(θ) = -0.1

Δcos(θ) = 0.2

ϕ = 15°

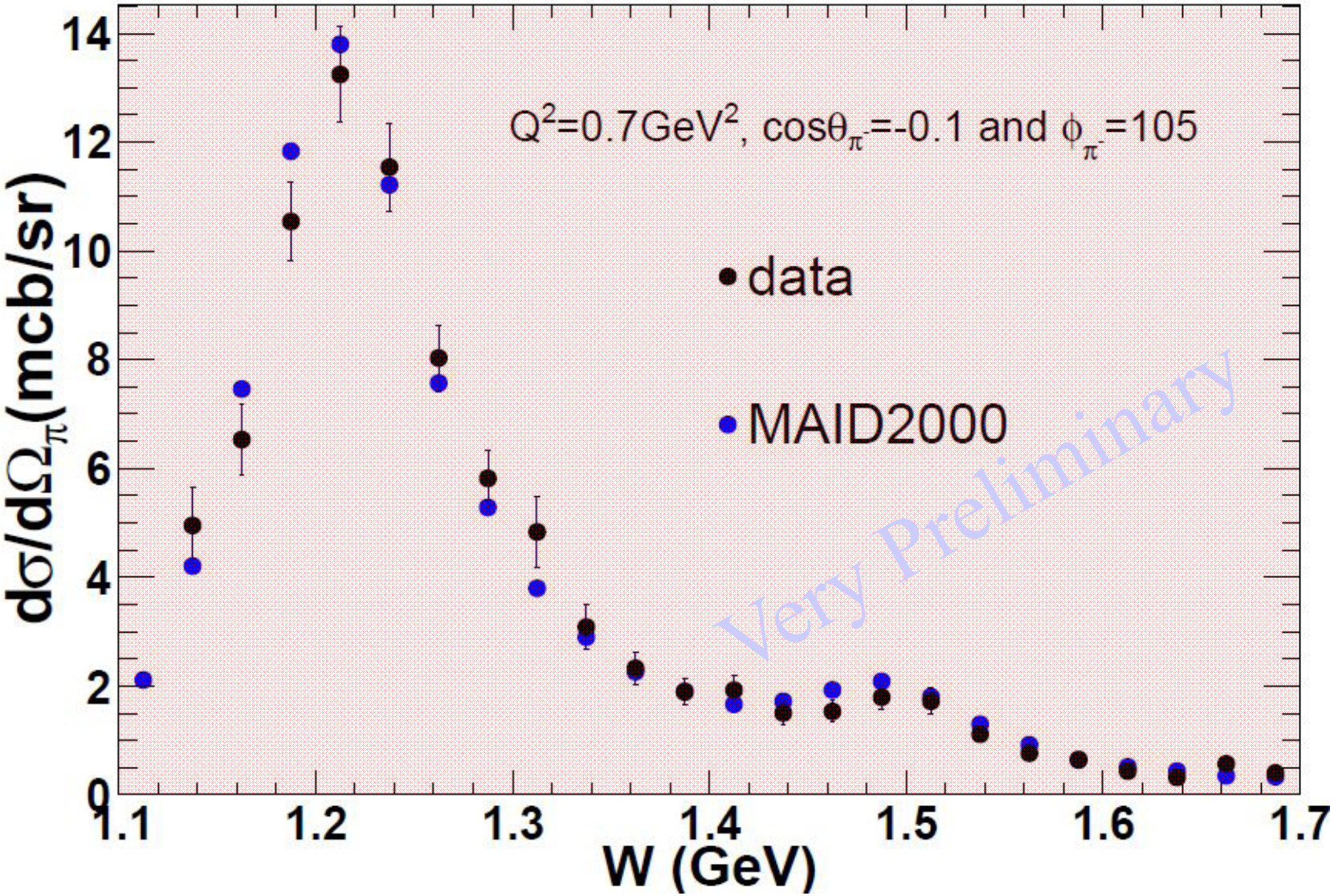
Δϕ = 30°

ϕ = 345°



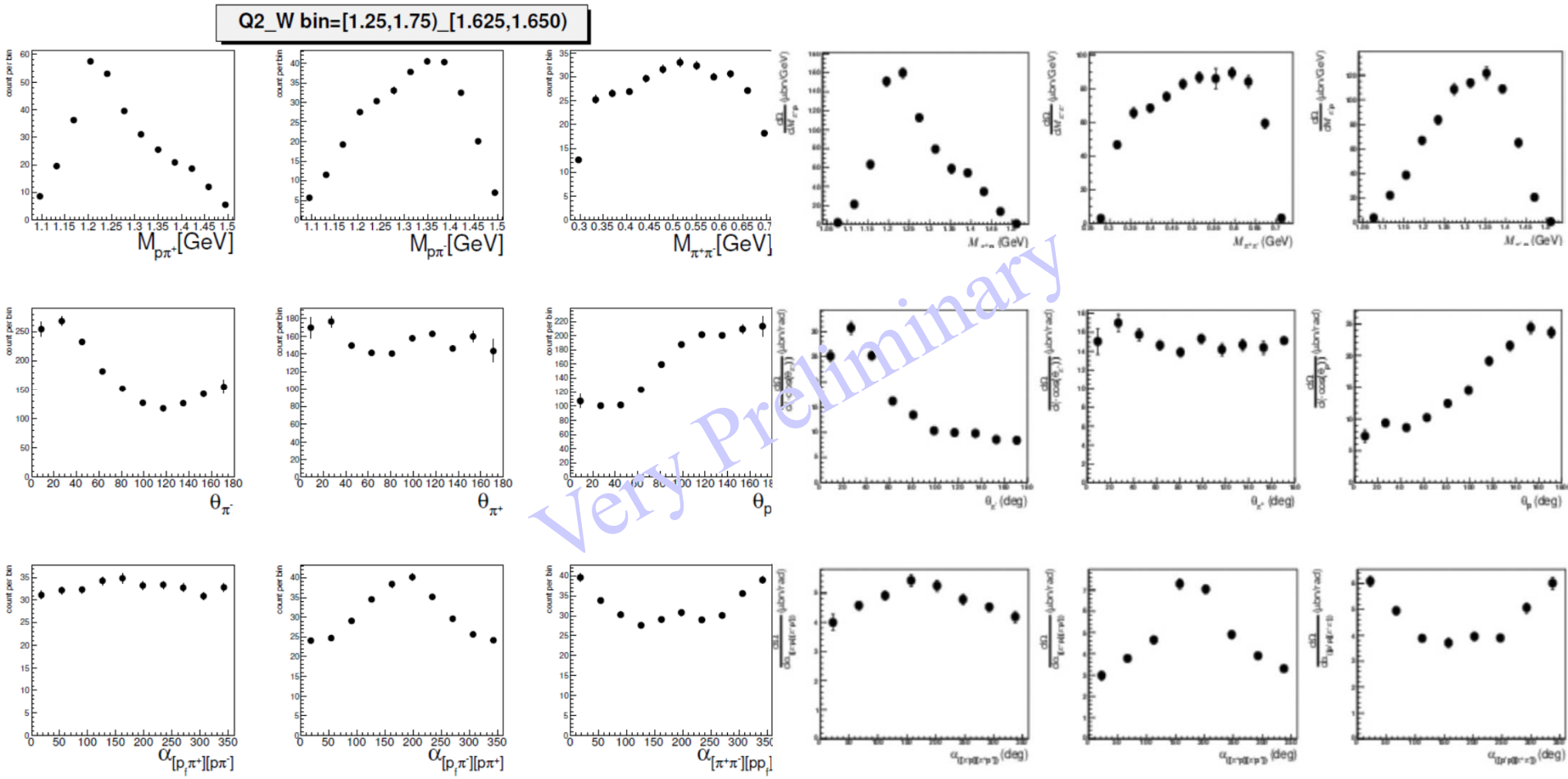
Single π^- Electroproduction off the Deuteron

Ye Tian



φ-dependent Nππ Single-Differential Cross Sections

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

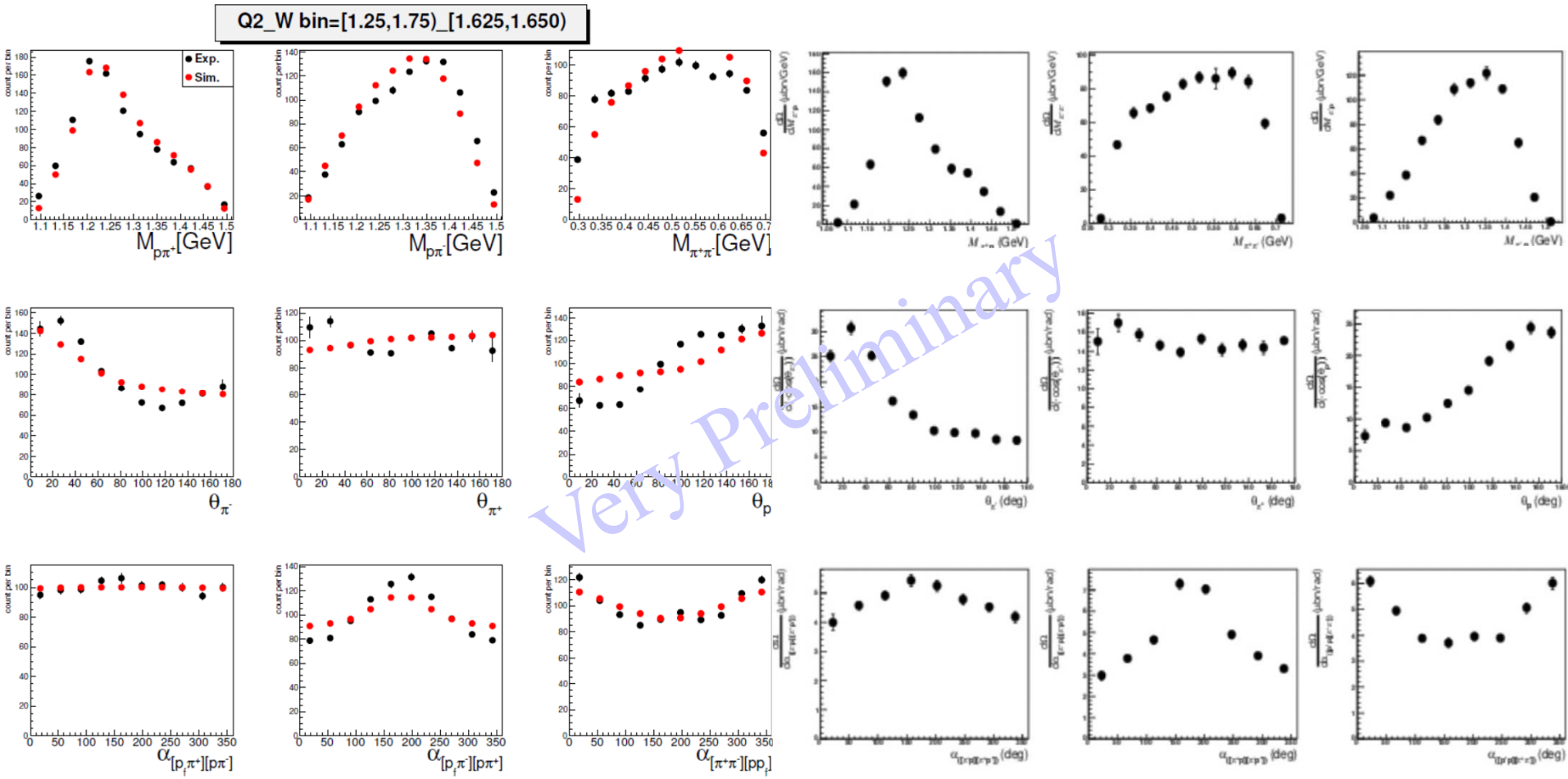


φ-integrated

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

φ-dependent Nππ Single-Differential Cross Sections

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

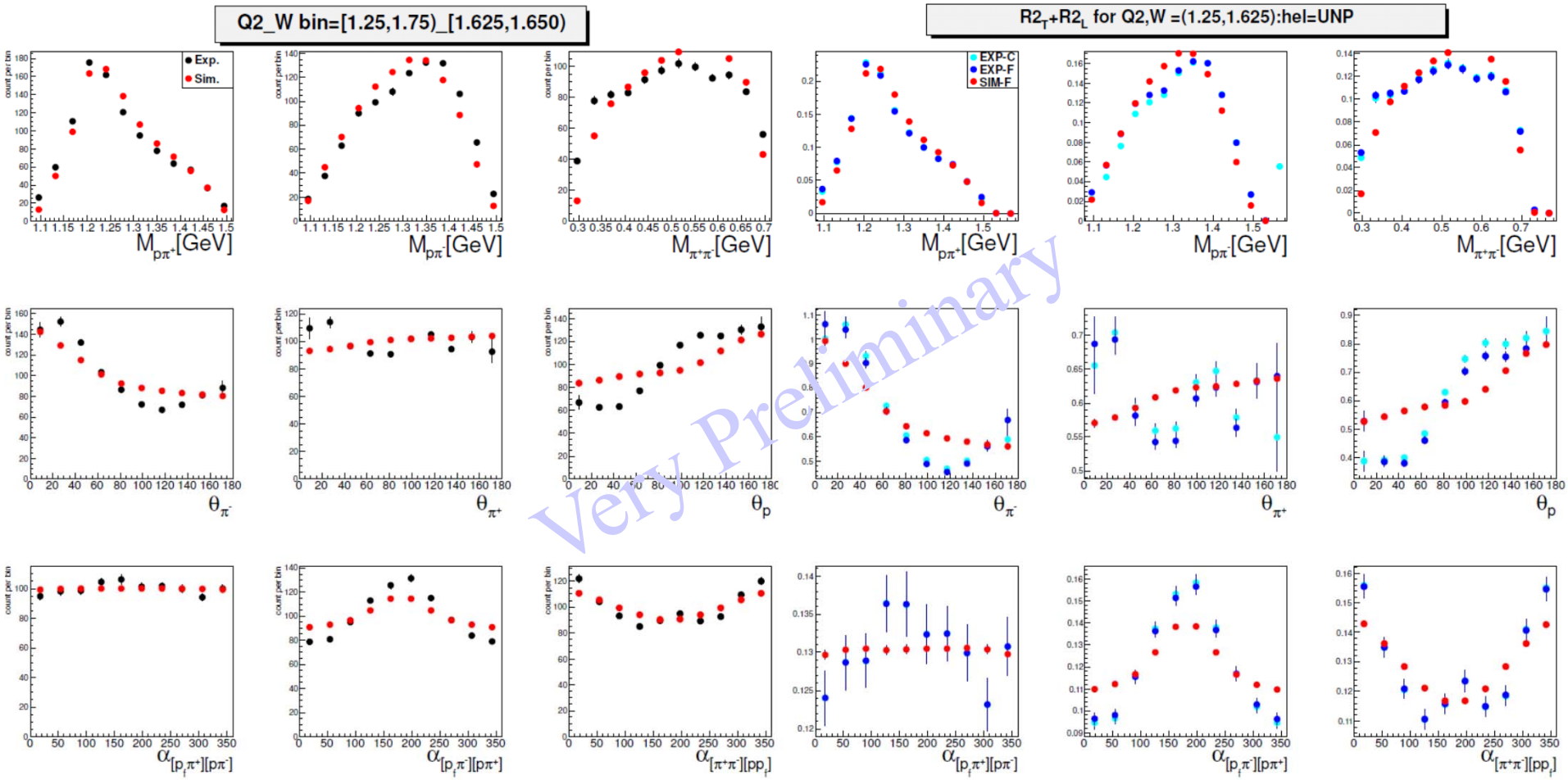


φ-integrated

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

φ-dependent Nππ Single-Differential Cross Sections

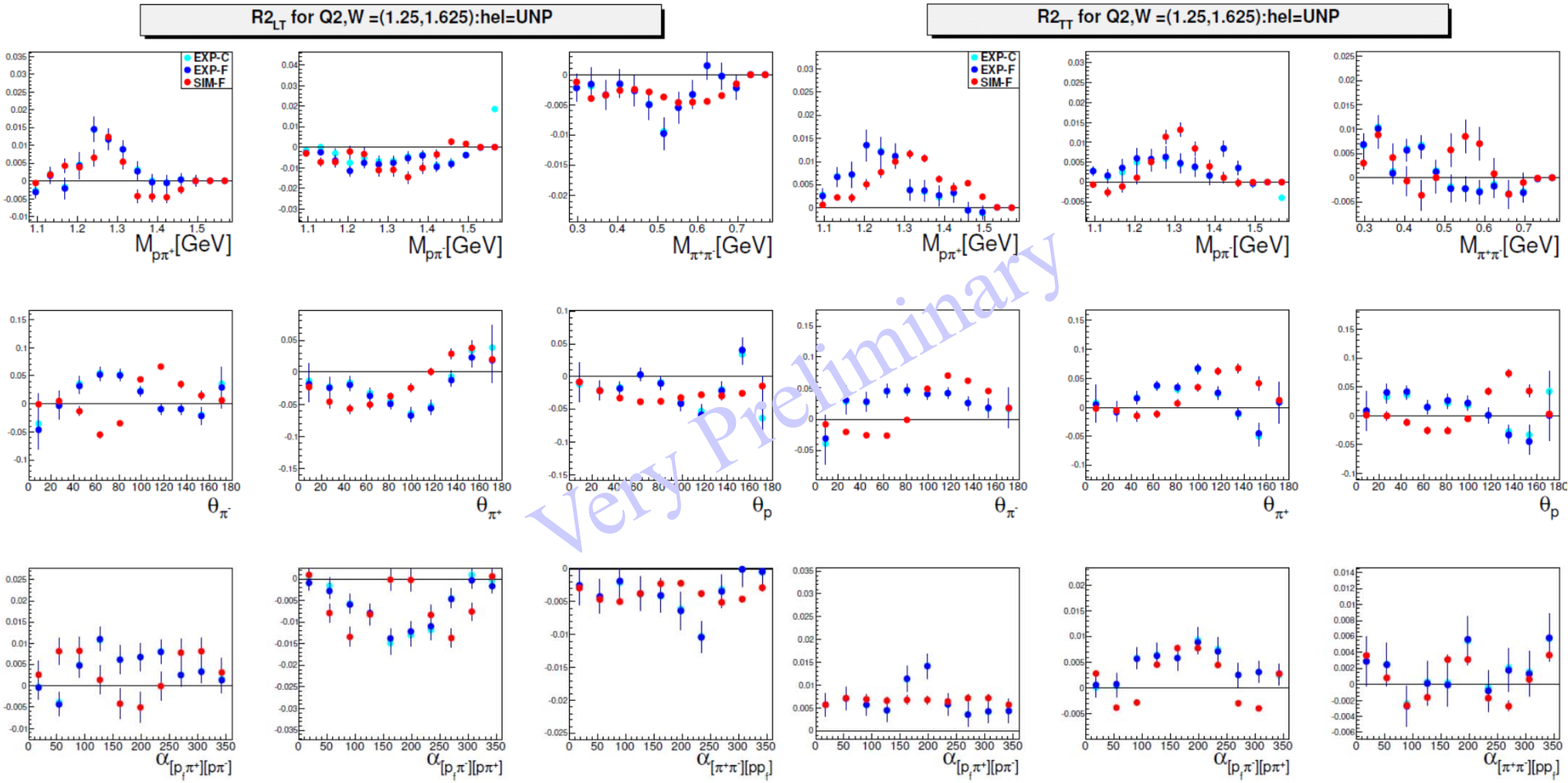
Q^2, W bin $= [1.25, 1.75) GeV^2, [1.625, 1.650) GeV$ Arjun Trivedi



φ-integrated φ-independent

φ-dependent Nππ Single-Differential Cross Sections

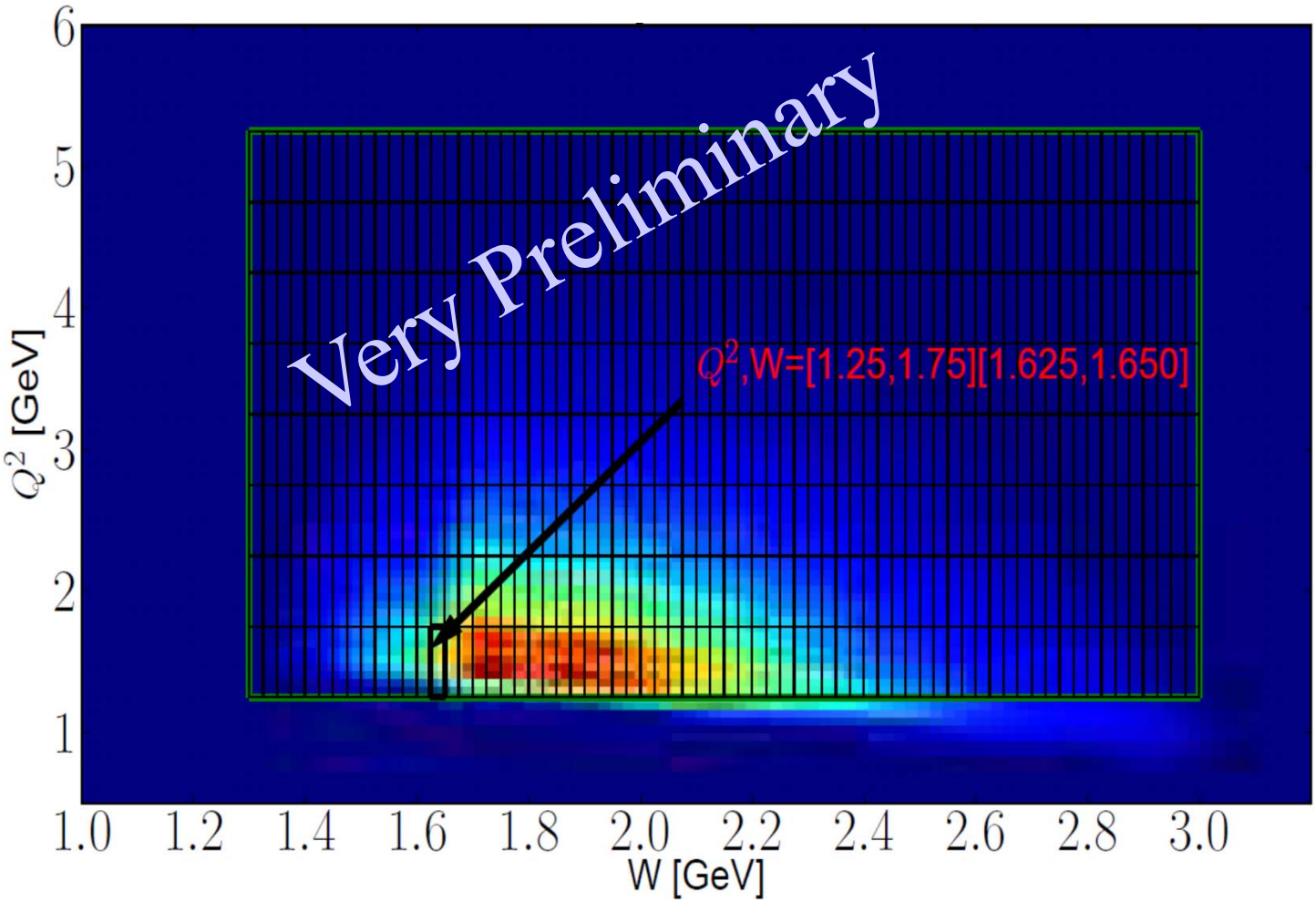
Q^2, W bin $= [1.25, 1.75) GeV^2, [1.625, 1.650) GeV$ Arjun Trivedi



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

φ-dependent Nππ Single-Differential Cross Sections

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

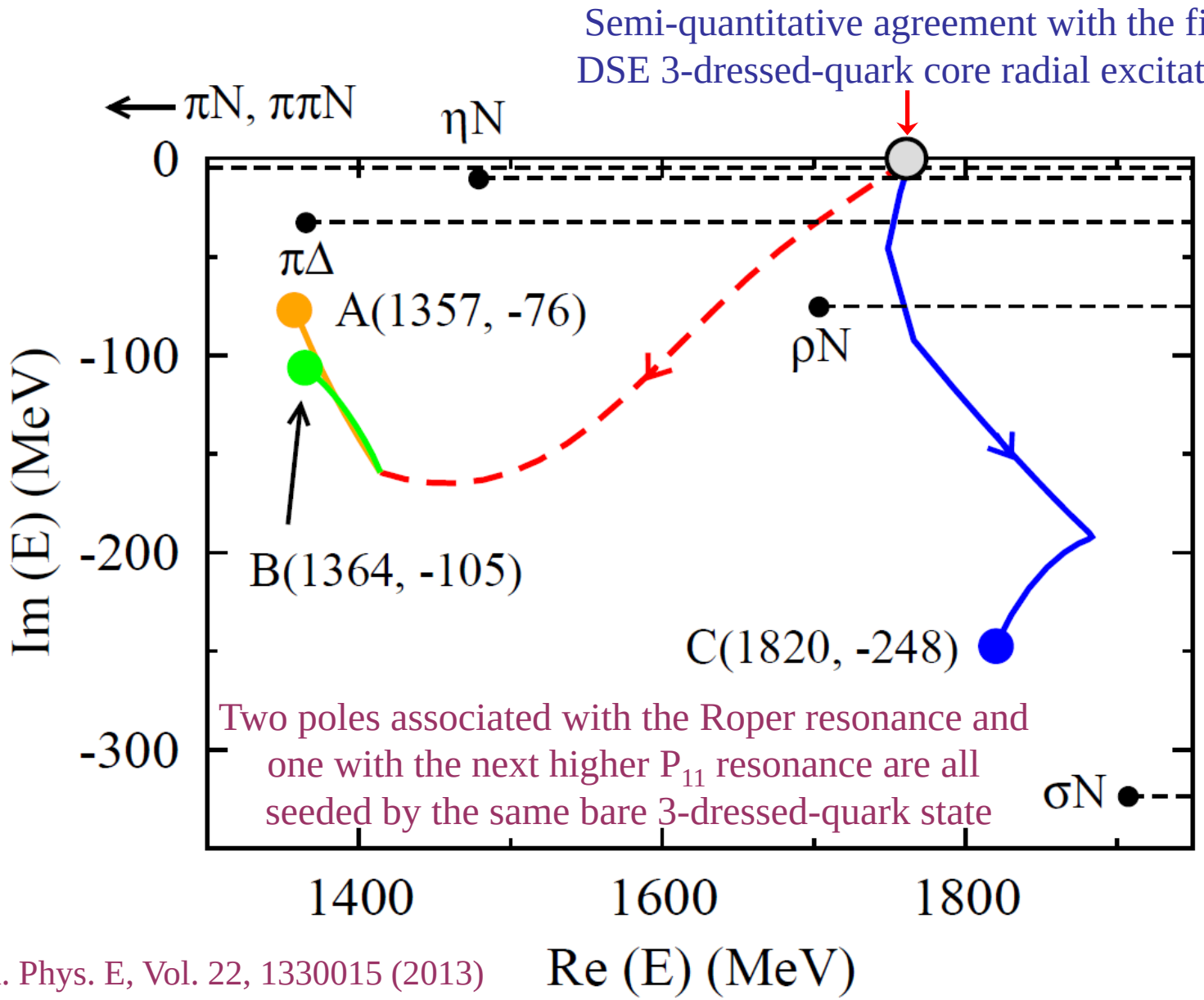


$$\left(\frac{d^2\sigma}{dX^{ij}d\phi^j}\right) = R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}} + R2_{LT}{}^{X_{ij}}\cos\phi_j + R2_{TT}{}^{X_{ij}}\cos 2\phi_j$$

QCD-Based Models and Theory

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

DSE and EBAC/ANL-Osaka Approaches



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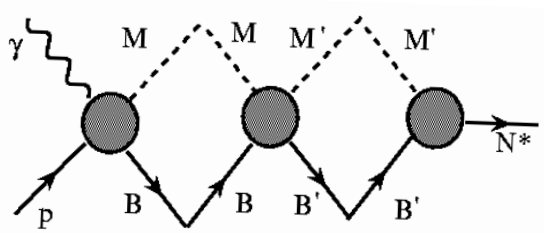
Progress in Experiment and Phenomenology

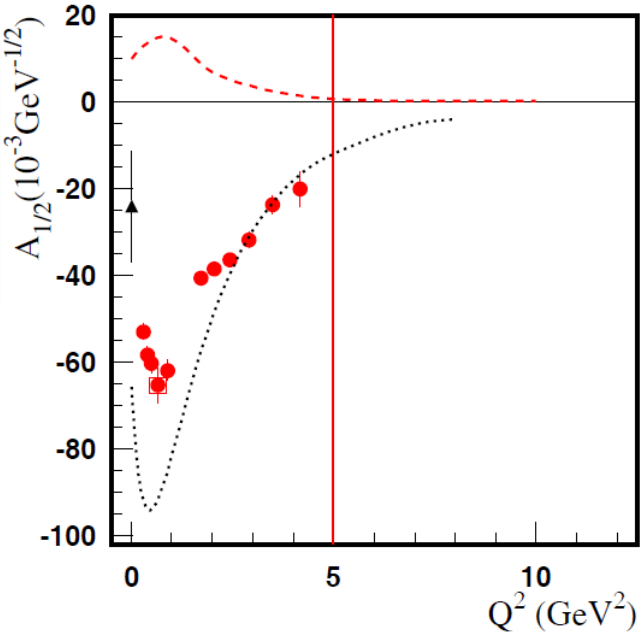
Meson-Baryon Dressing



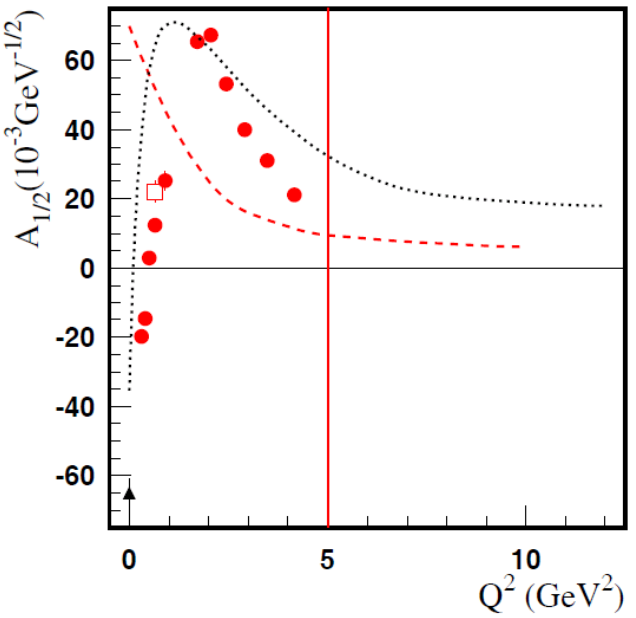
absolute meson-baryon cloud amplitudes (EBAC now ANL-Osaka)

quark core contributions (constituent quark models)

$D_{13}(1520)$



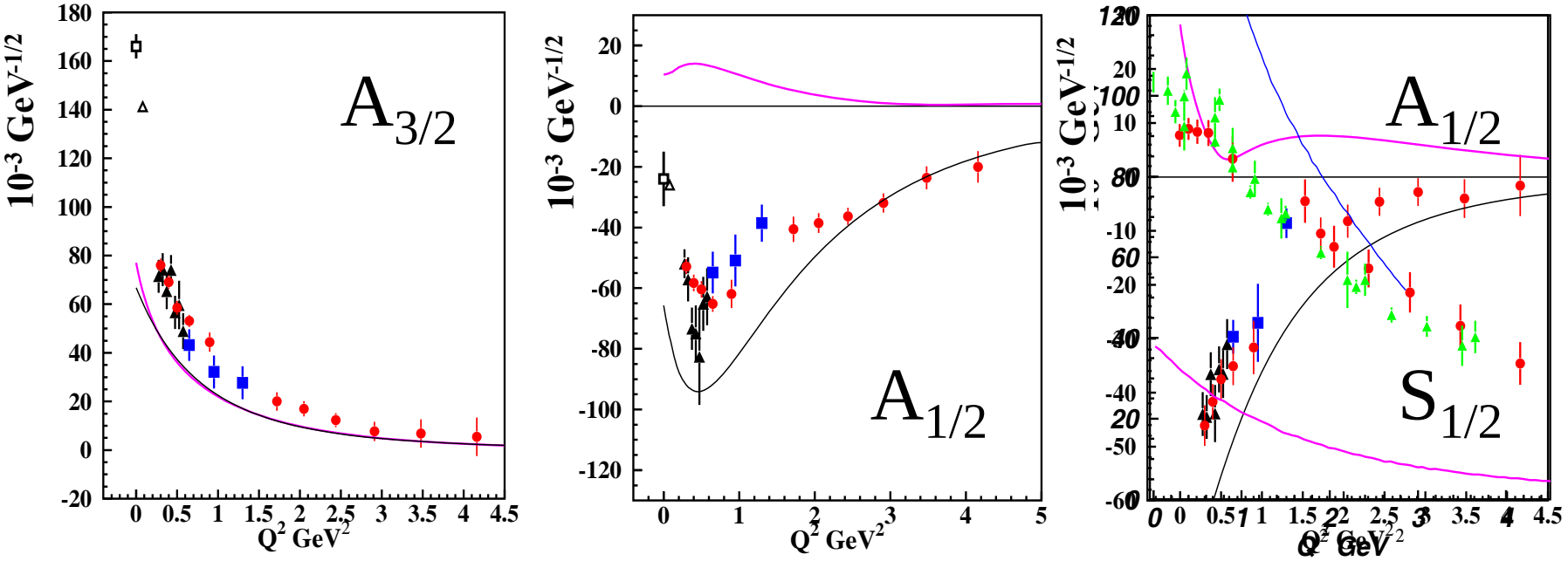
$P_{11}(1440)$



CLAS: Nπ and Nπ/Nππ 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 $N(1520)D_{13}$, $N(1680)F_{15}$, $N(1720)P_{13}$, $N(1535)S_{11}$



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

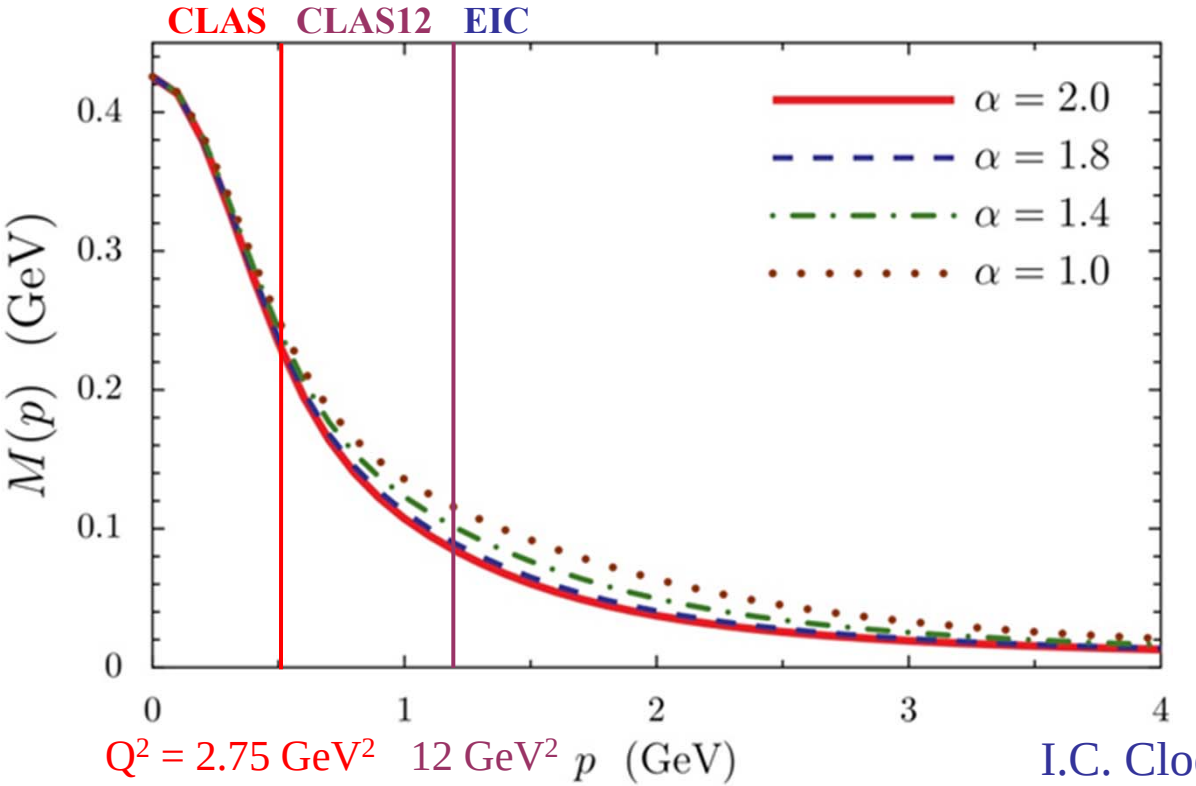
$\pi^+\pi^-p$ 2010

$N\pi$ 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.

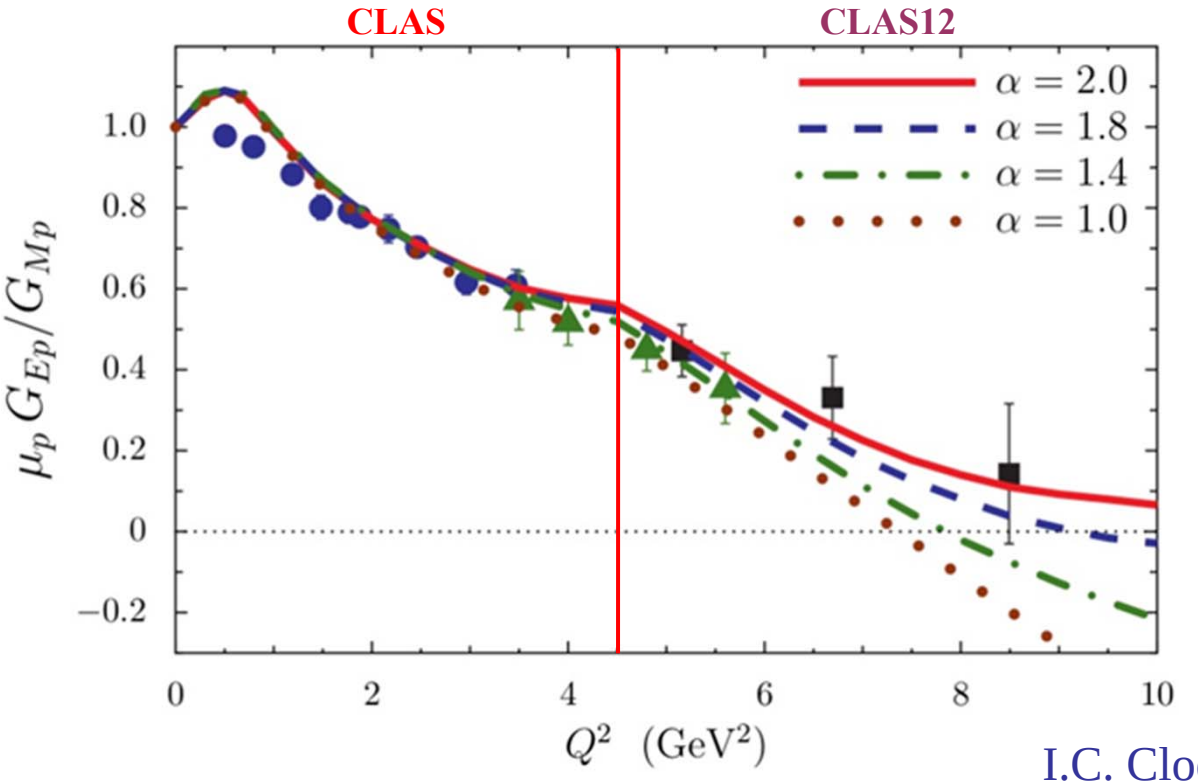
I.C. Cloet et al., arXiv:1304.0855[nucl-th]

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

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

Dyson-Schwinger Equation (DSE) Approach

DSE approaches provide links between dressed quark propagators, form factors, scattering amplitudes, and QCD.



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

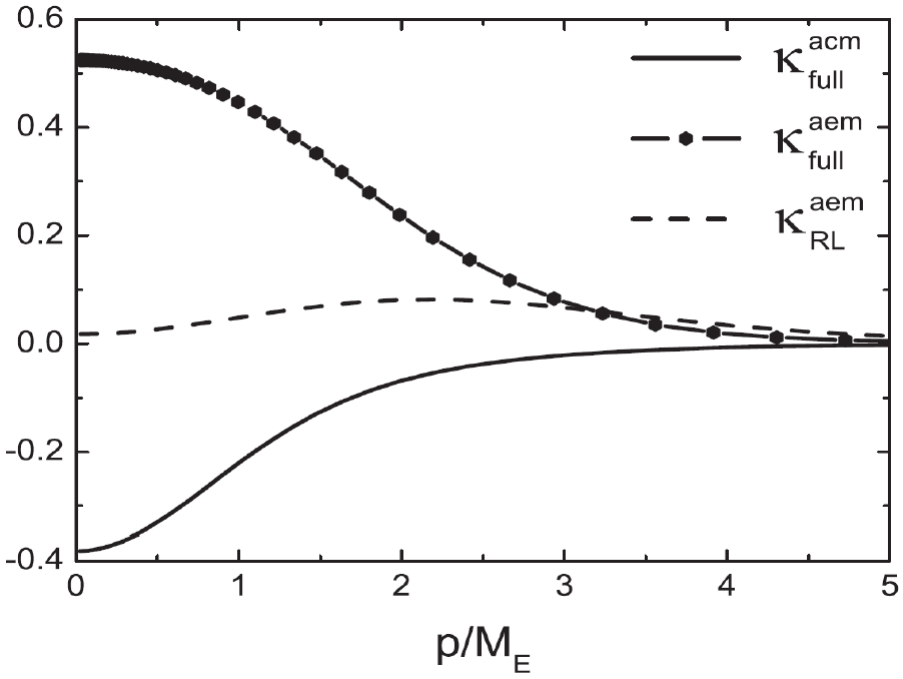
DSE calculations of elastic and transition form factors are very sensitive to the momentum dependence of the dressed-quark propagator.

I.C. Cloet et al., arXiv:1304.0855[nucl-th]

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

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

Anomalous Magnetic Moment in DSE Approach



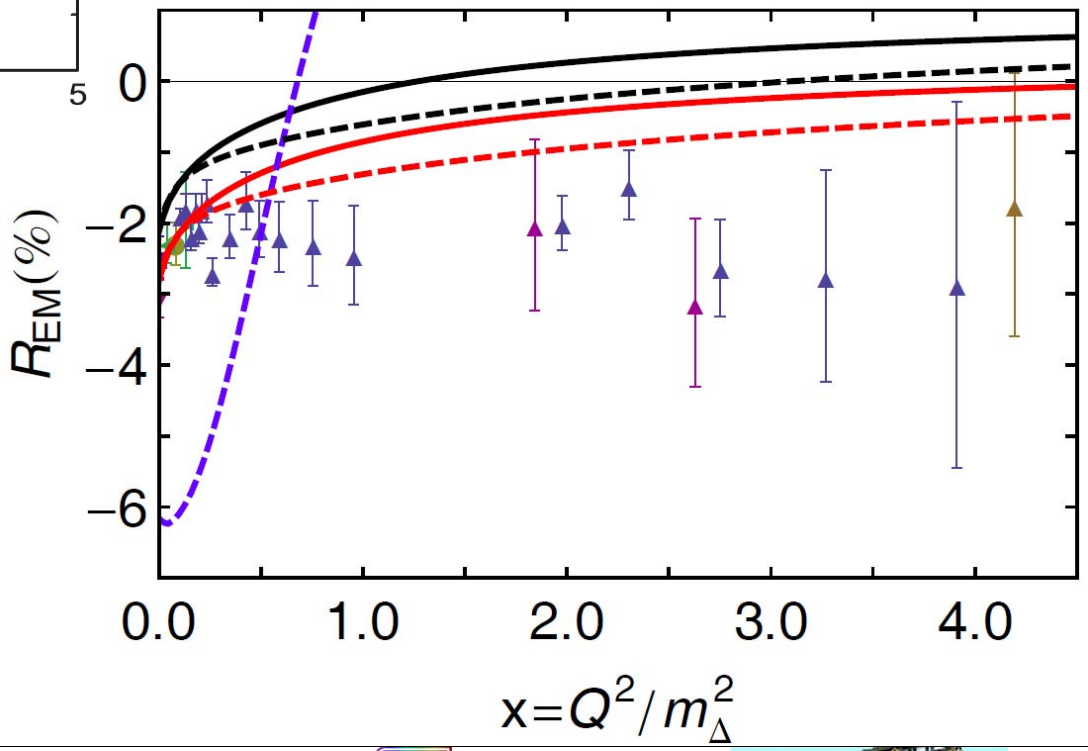
L. Chang et al., PRL 106 (2011) 072001

J. Segovia

contact interaction

sophisticated interaction with momentum dependent κ

renormalized at real photon point

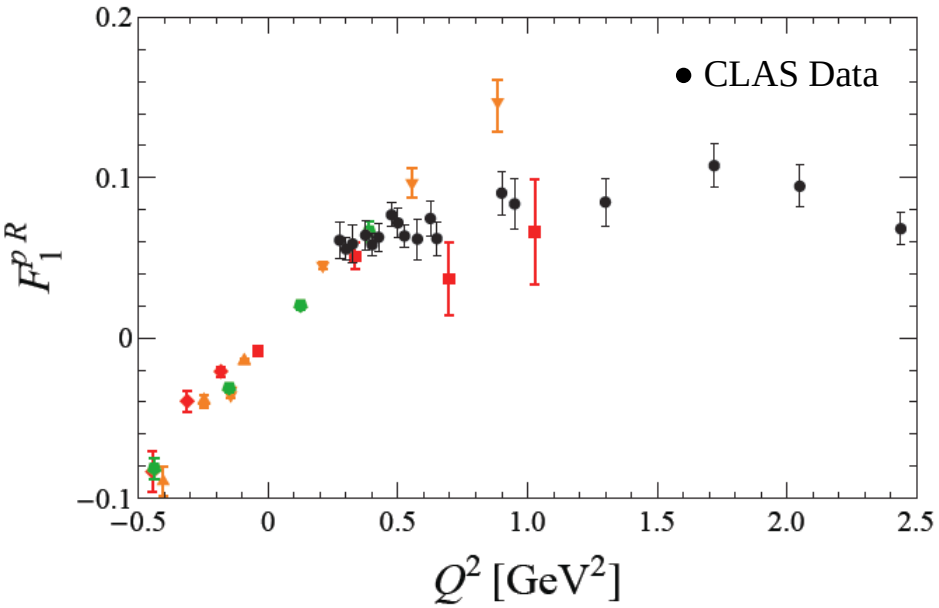


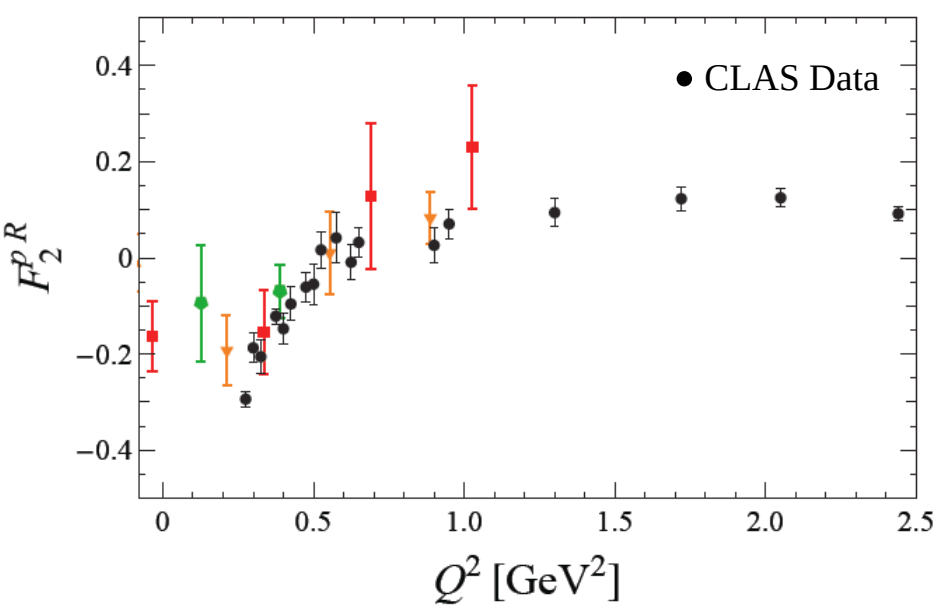
The DSE calculation of R_{EM} zero crossing is sensitive to the momentum dependent anomalous magnetic moment of the dressed-quark.

Roper Transition Form Factors in LQCD

$N(1440)P_{11}$

Huey-Wen Lin and S.D. Cohen





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

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

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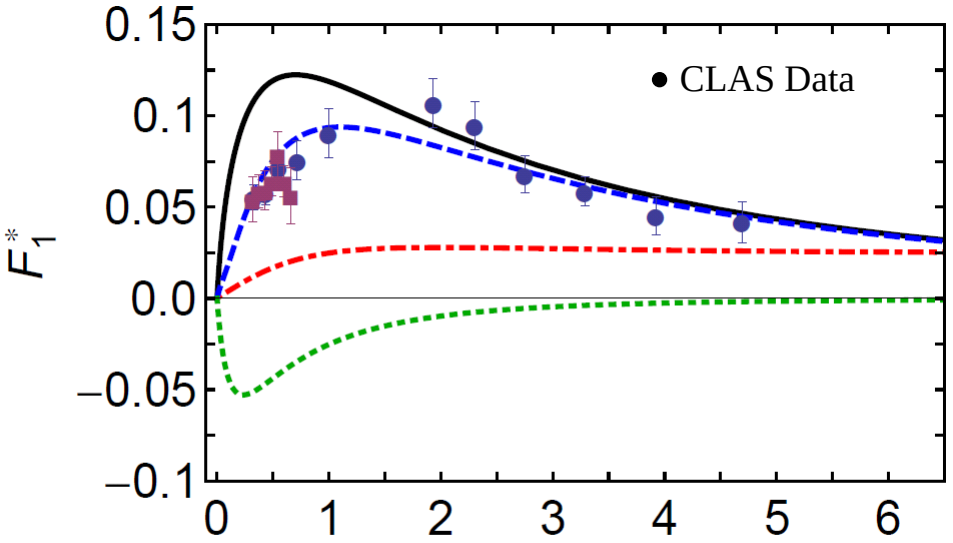
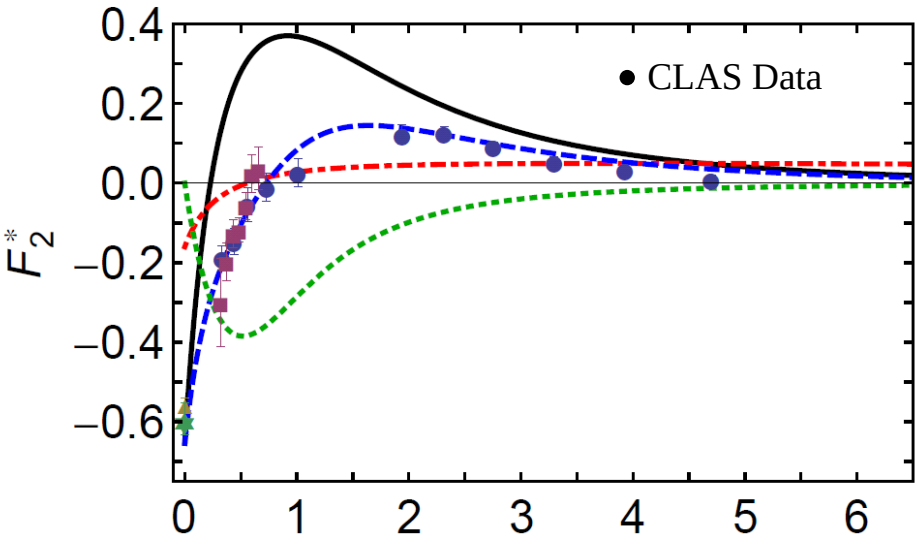
Roper Transition Form Factors in DSE Approach

$N(1440)P_{11}$

J. Segovia *et al.*, arXiv:1504.04386 [nucl-th]





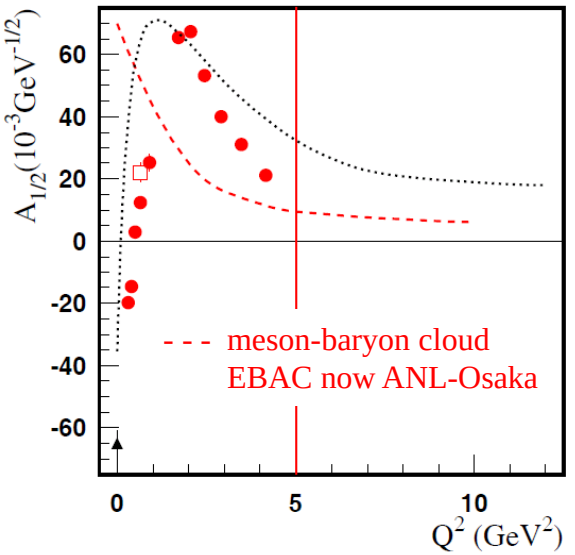
DSE Contact

DSE Realistic

Inferred meson-cloud contribution

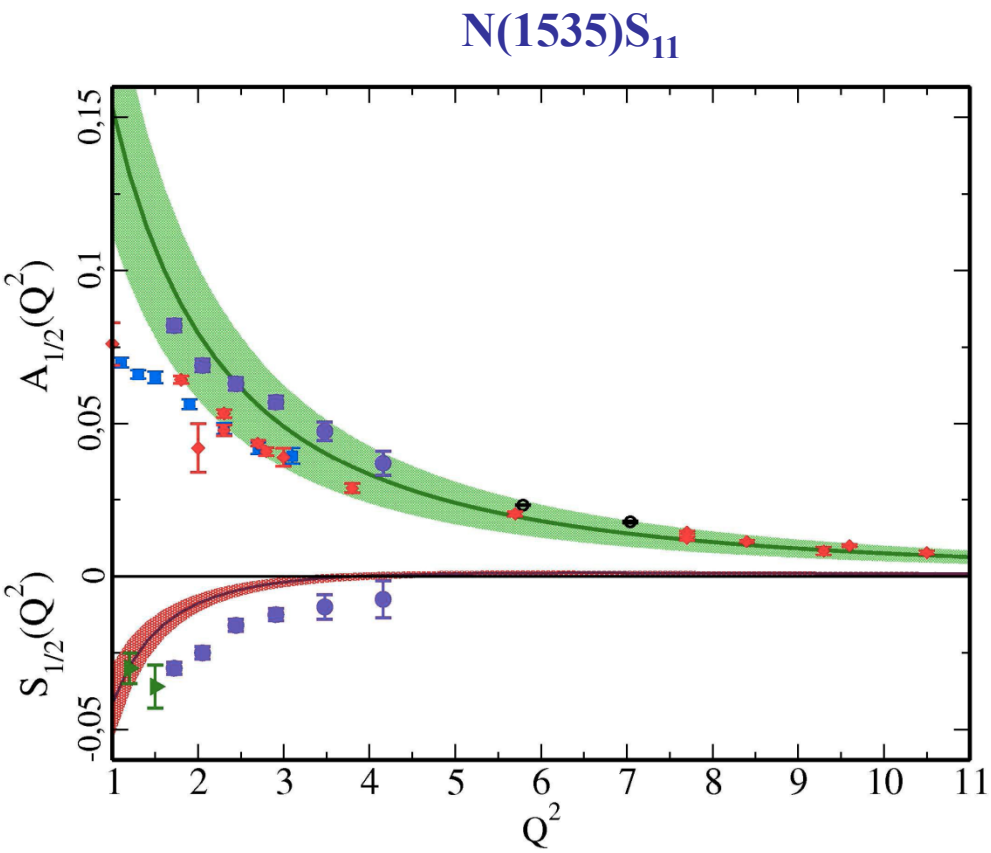
Anticipated complete result

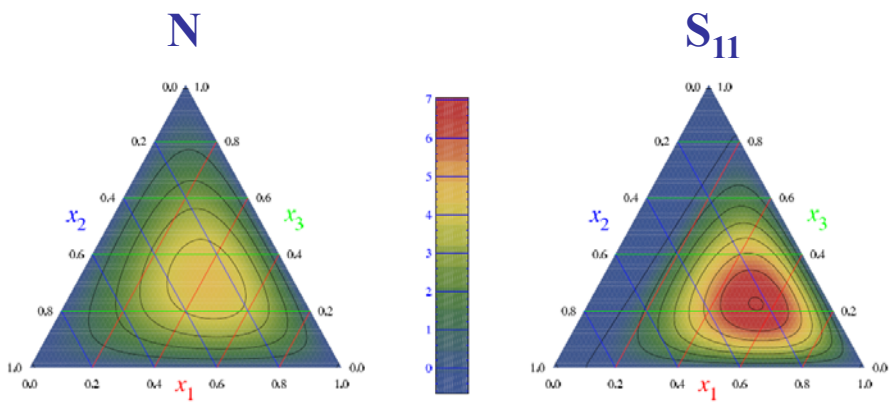
$x = Q^2/m_N^2$



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

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.

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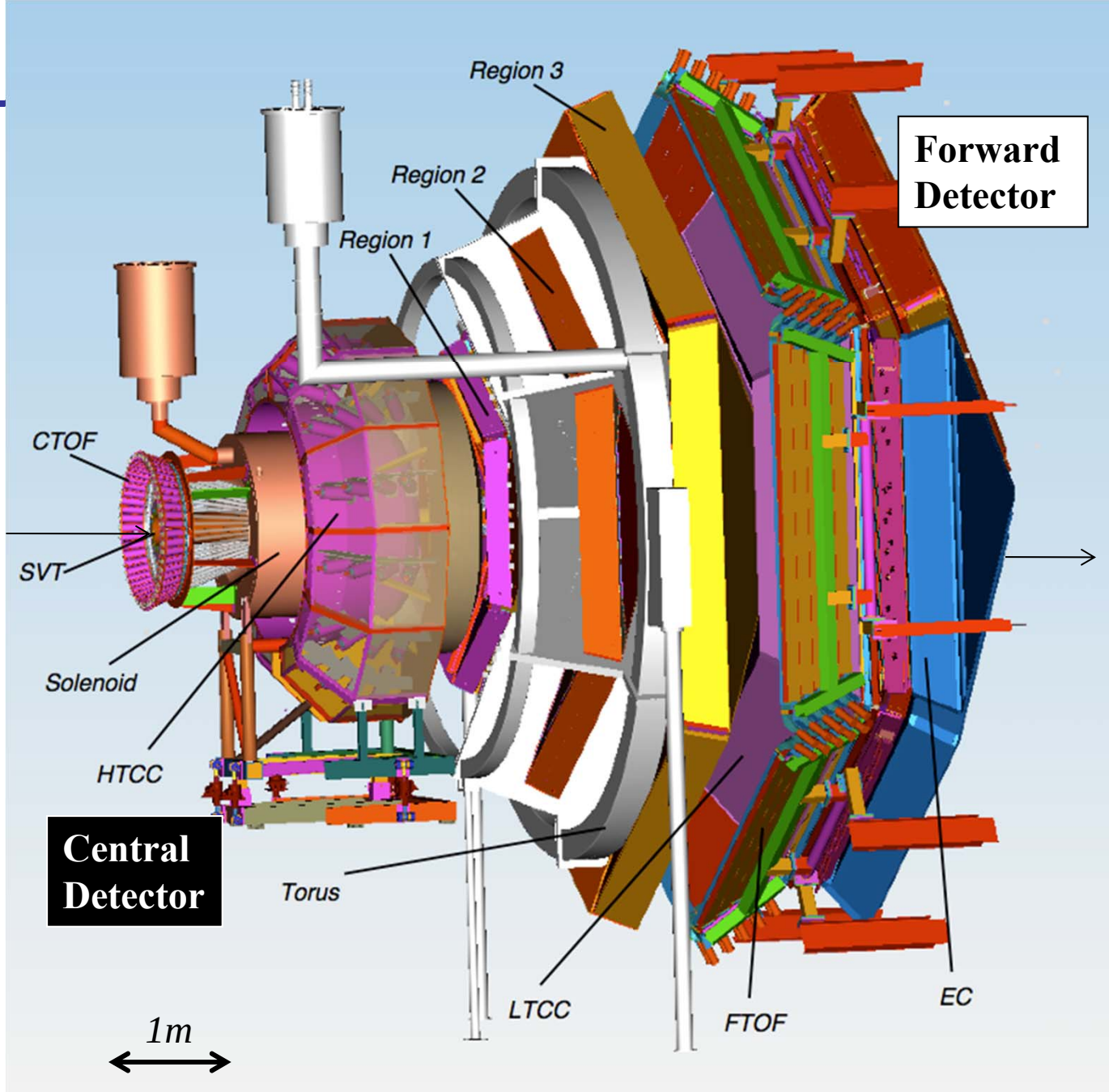
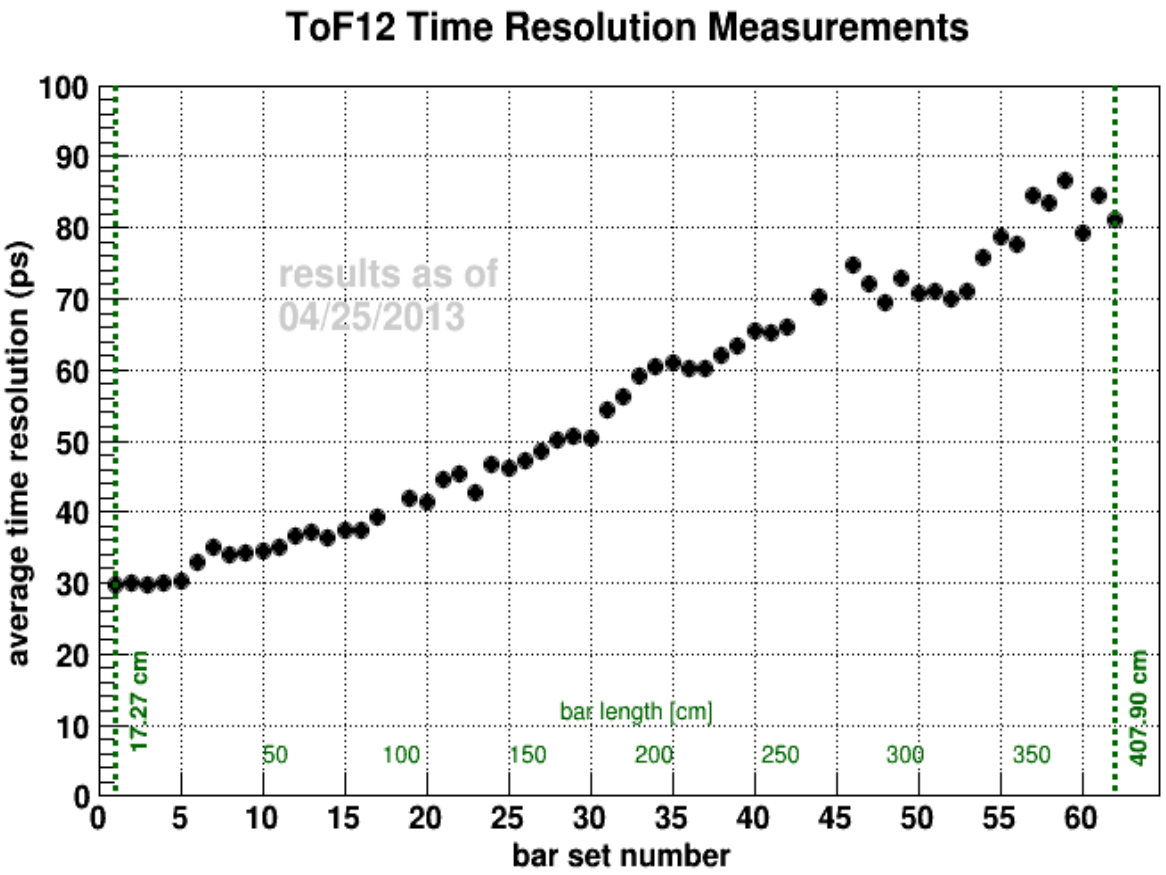
CLAS12

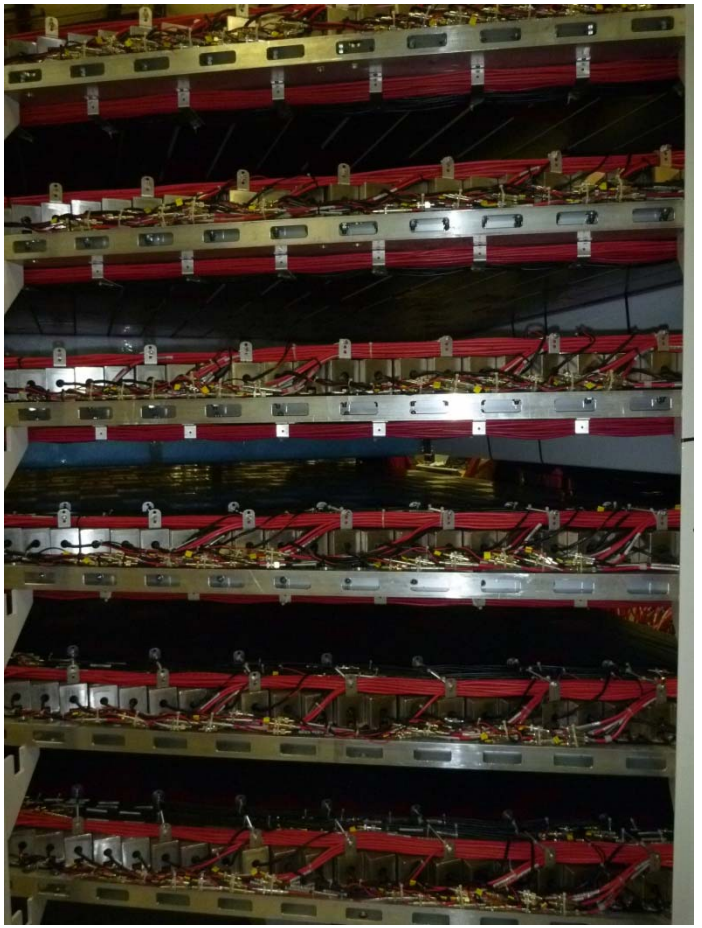
- Luminosity > 10^{35} $cm^{-2}s^{-1}$
- Hermeticity
- Polarization

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

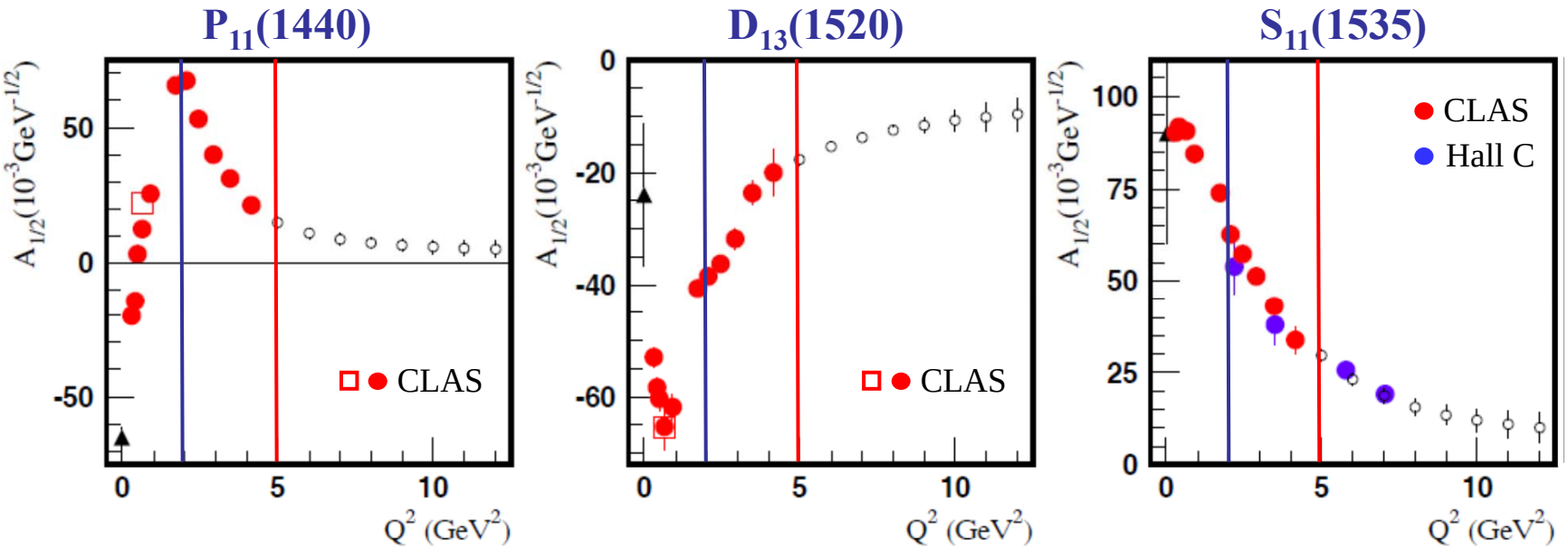


New Forward Time of Flight Detector for CLAS12





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,
  - 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.