Exclusive Electroexcitation of Baryon Resonances with CLAS and CLAS12

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Quark Confinement and the Hadron Spectrum XI

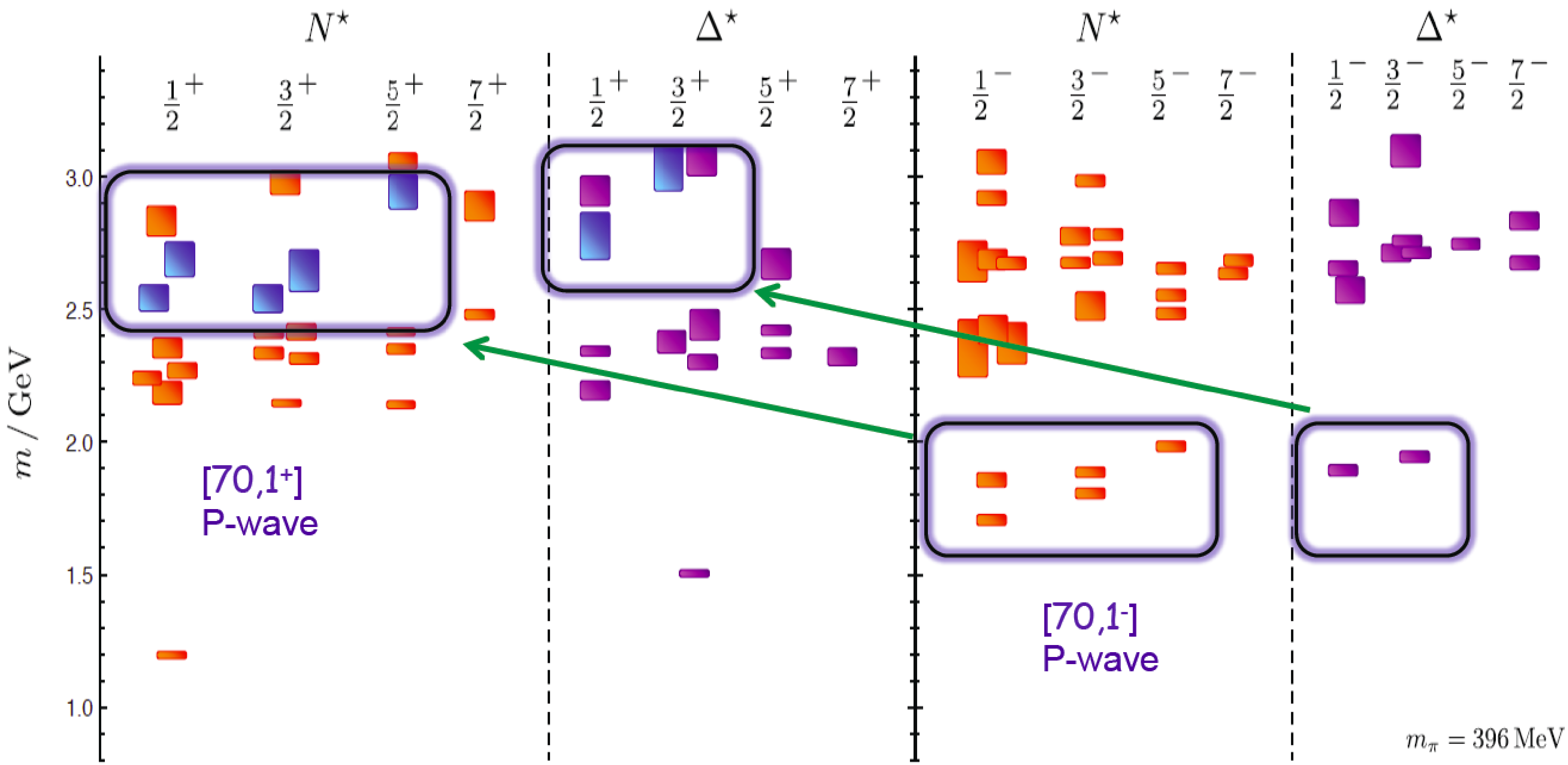
September 8-12, 2014, ST. Petersburg, Russia

- **γ_vNN* Electrocouplings:** A unique window into baryon and quark structure?
- **Analysis and new Results:** Phenomenological but consistent.
- **QCD based Theory:** Can we solve non-perturbative QCD and confinement?
- **Outlook:** New experiments with extended scope and kinematics.

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

N* Spectrum in LQCD

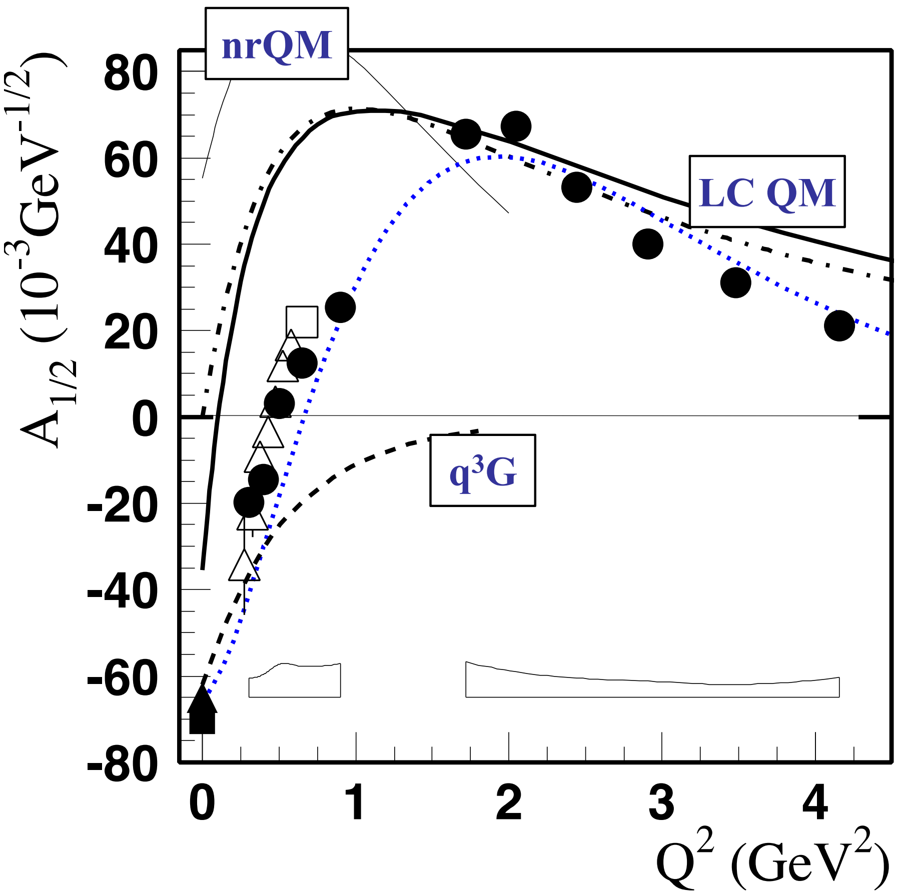
The strong interaction physics is encoded in the nucleon excitation spectrum that spans the degrees of freedom from meson-baryon and dressed quarks to elementary quarks and gluons.



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

Transition Form Factors and QCD Models

Roper resonance $P_{11}(1440)$



+ q^3g

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

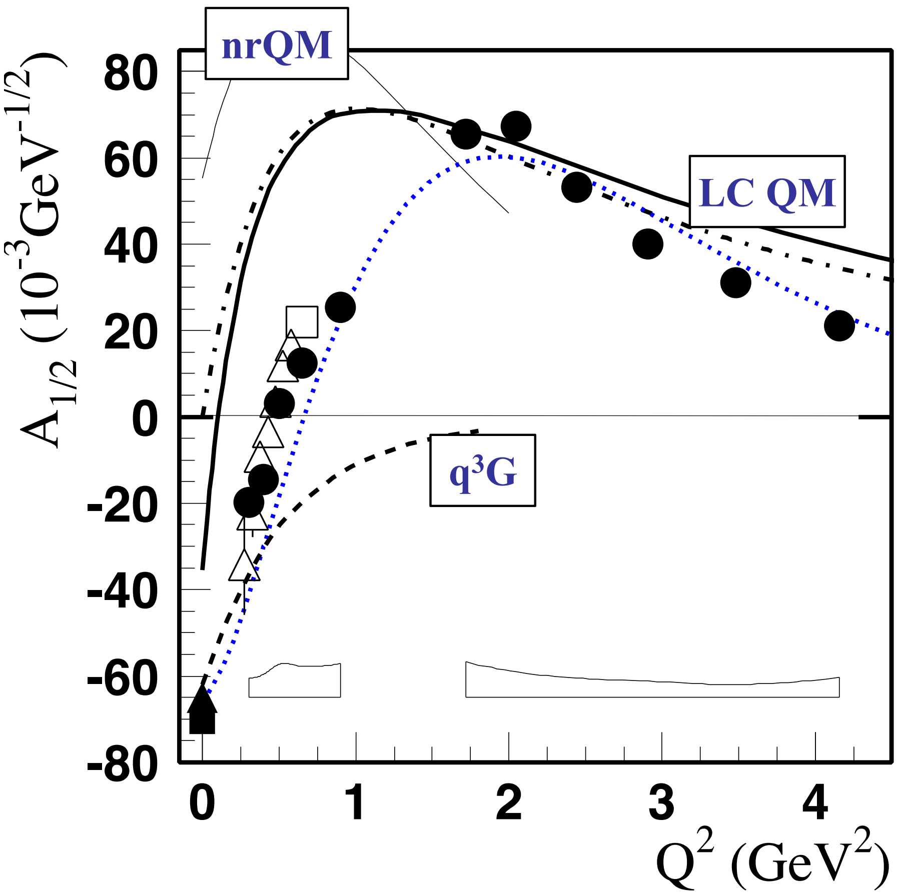
+ N-Meson

+ …

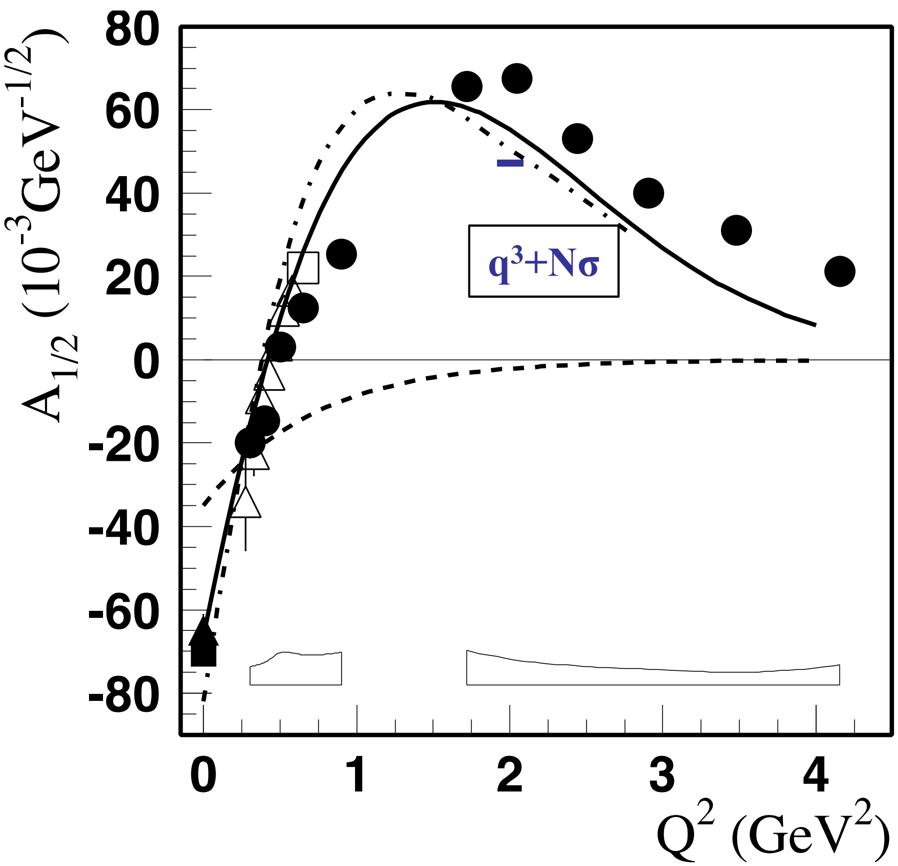
… all have distinctively different Q^2 dependencies

Transition Form Factors and QCD Models

Roper resonance $P_{11}(1440)$

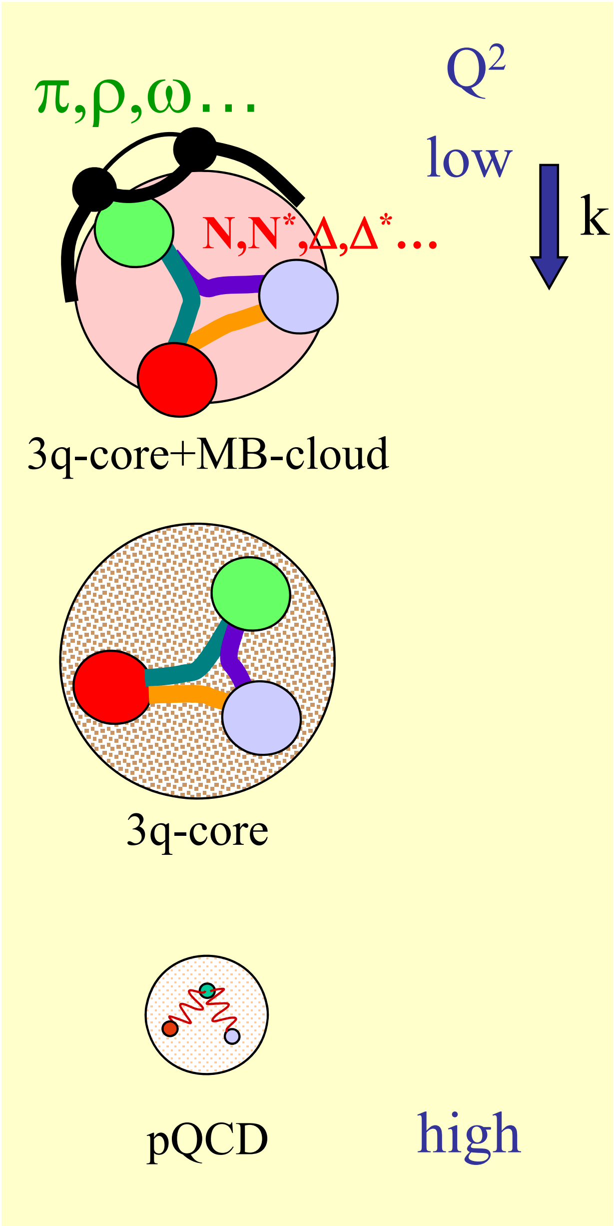


PDG 2013 update

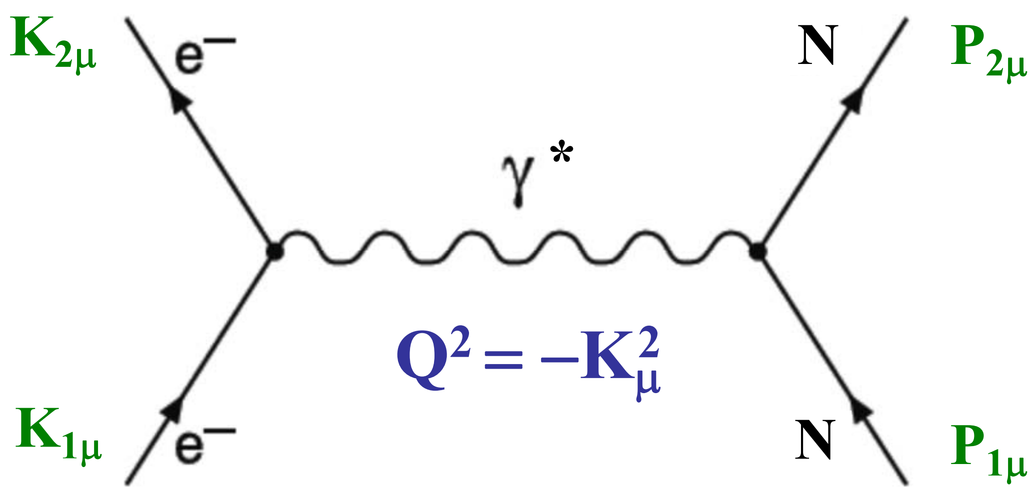


- $A_{1/2}$ has zero-crossing near Q^2=0.5 and becomes dominant amplitude at high Q^2
- Eliminates gluonic excitation (q^3G) as a dominant contribution
- Consistent with radial excitation at high Q^2 and large meson-baryon coupling at small Q^2

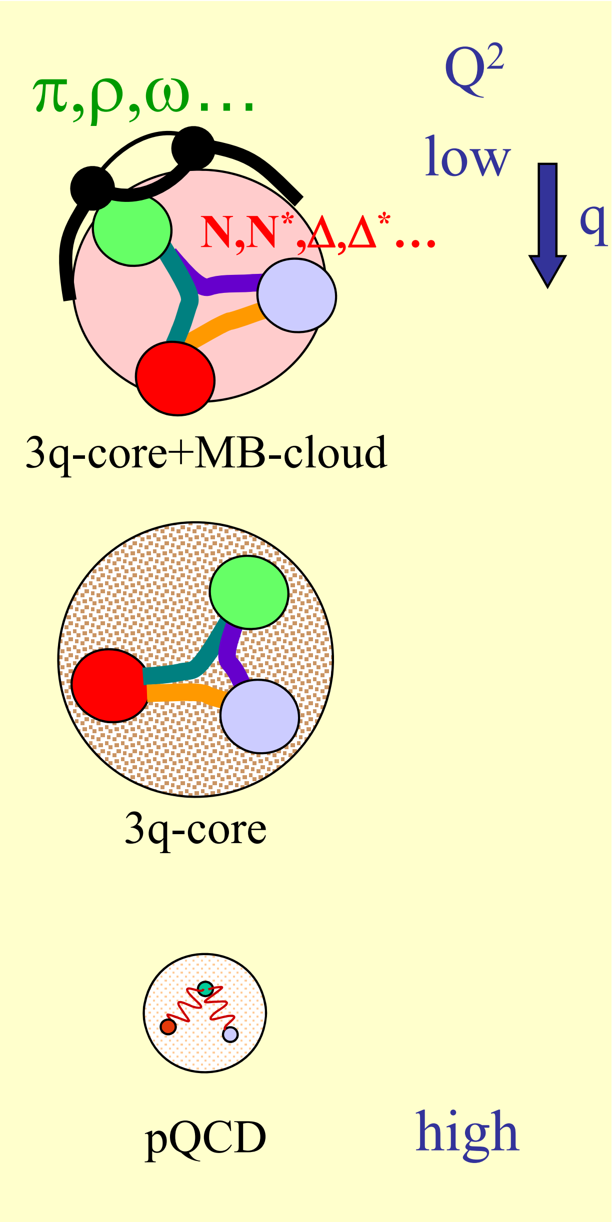
Hadron Structure with Electromagnetic Probes



- 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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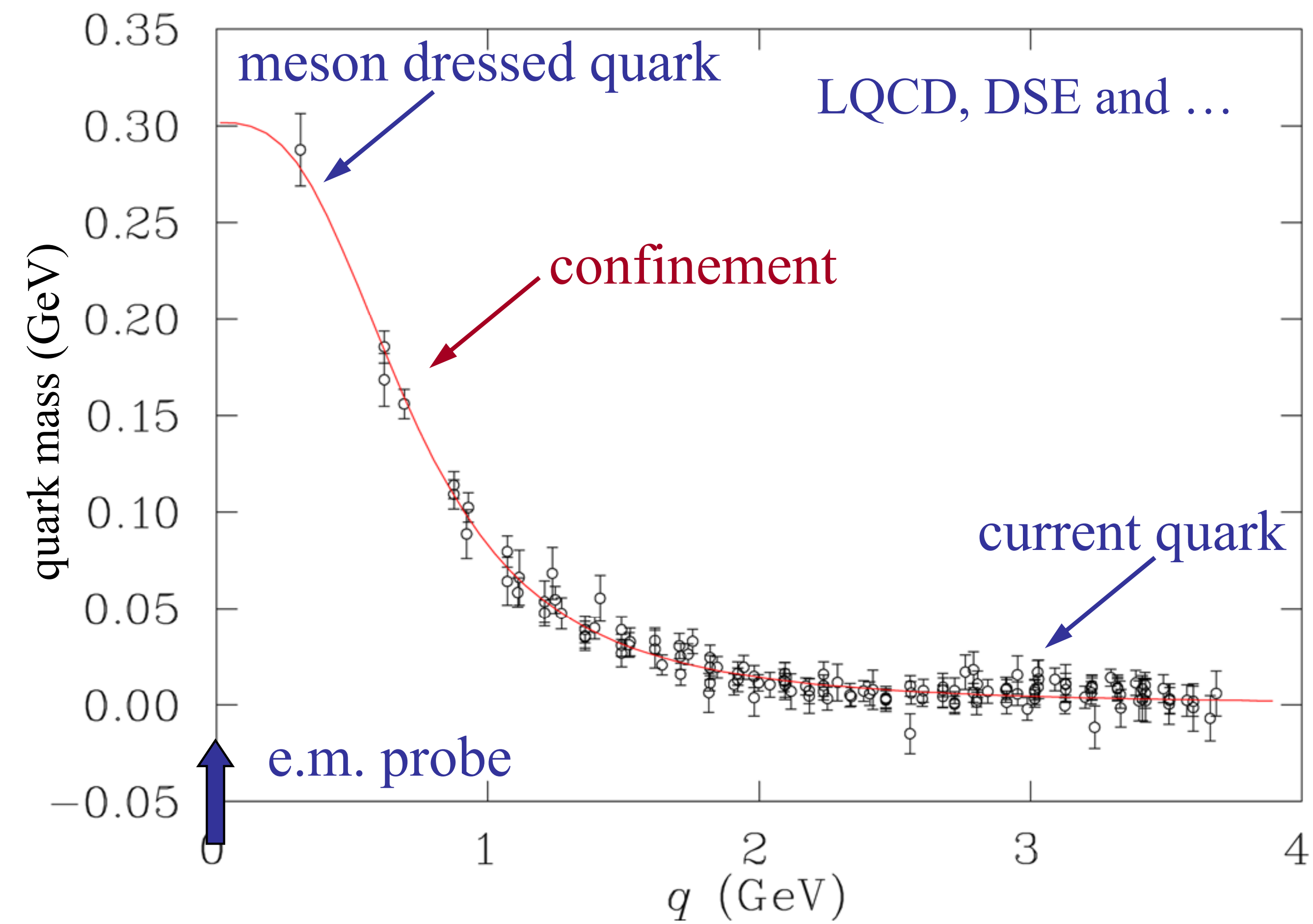
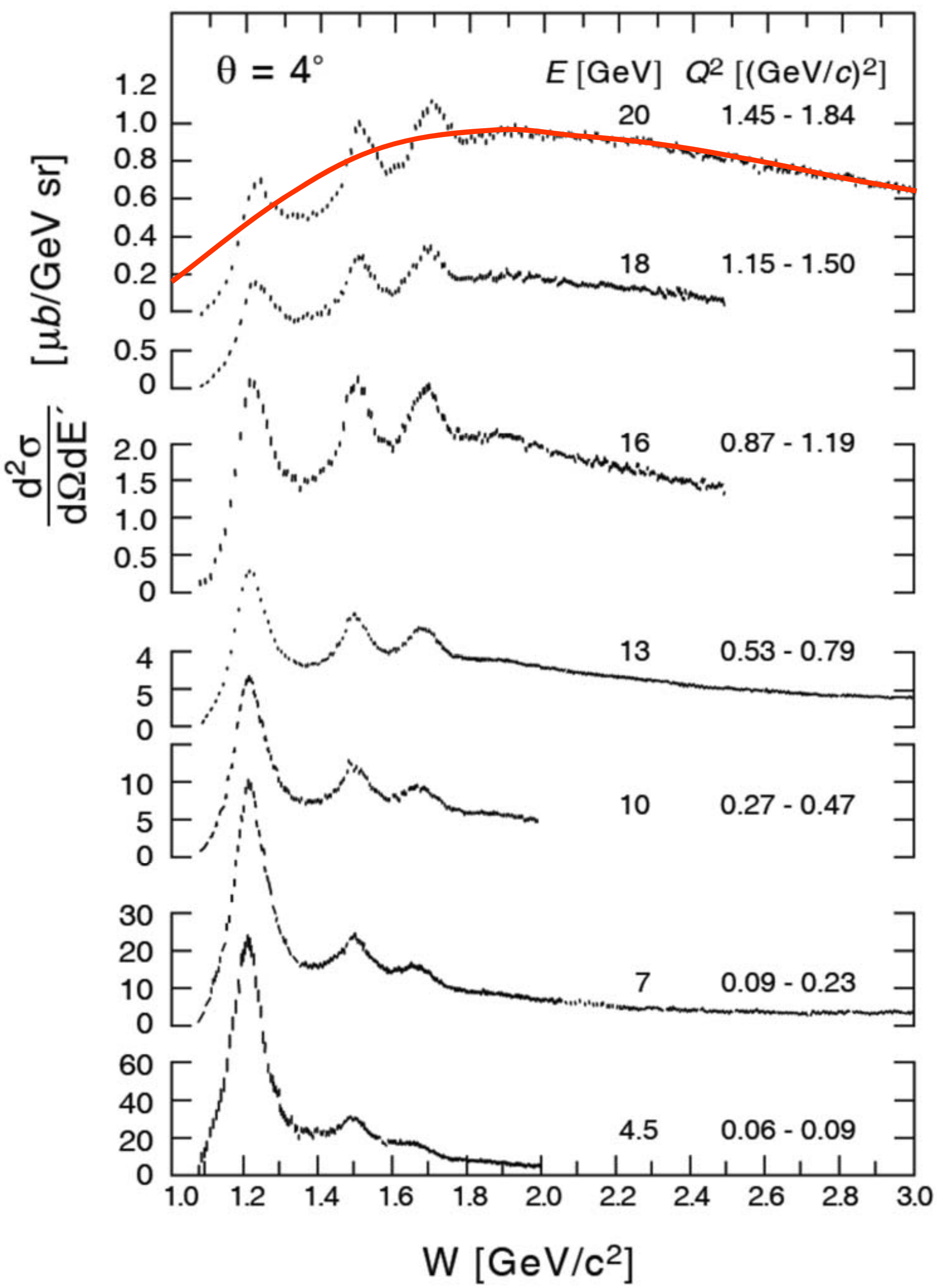
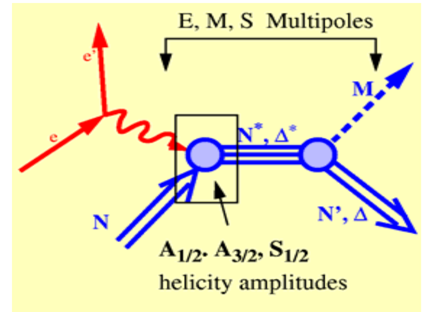


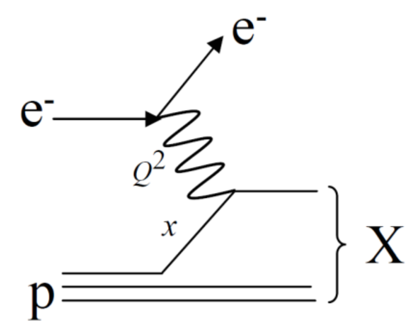
Baryon Excitations and Quasi-Elastic Scattering



hard and confined

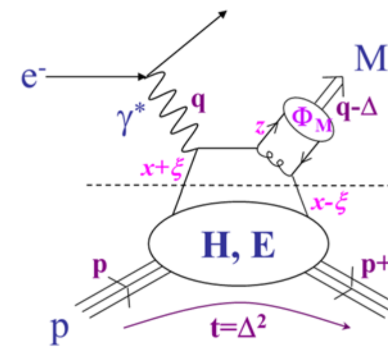


quasi-elastic



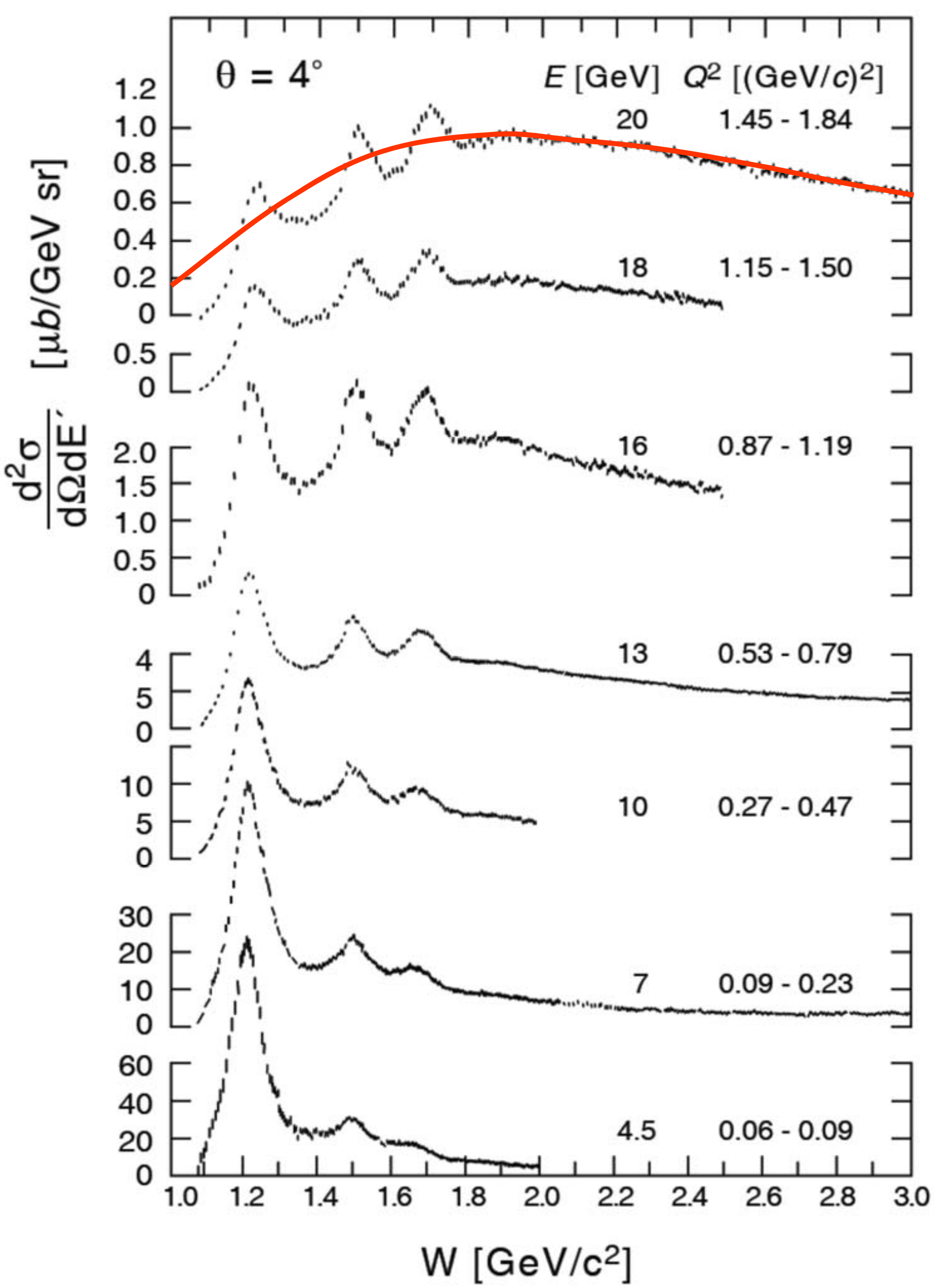
hard

soft

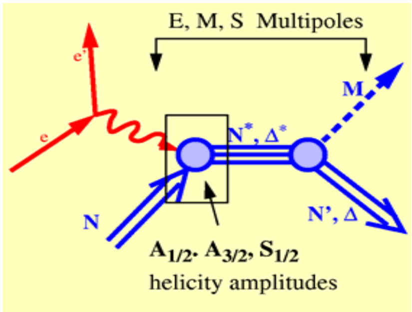


Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Baryon Excitations and Quasi-Elastic Scattering



hard and confined

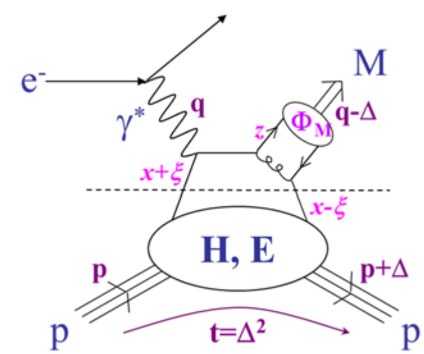


Elastic Form Factors

Transition Form Factors

hard

soft



Deep Inelastic Scattering

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

Data-Driven Data Analyses

Consistent Results

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

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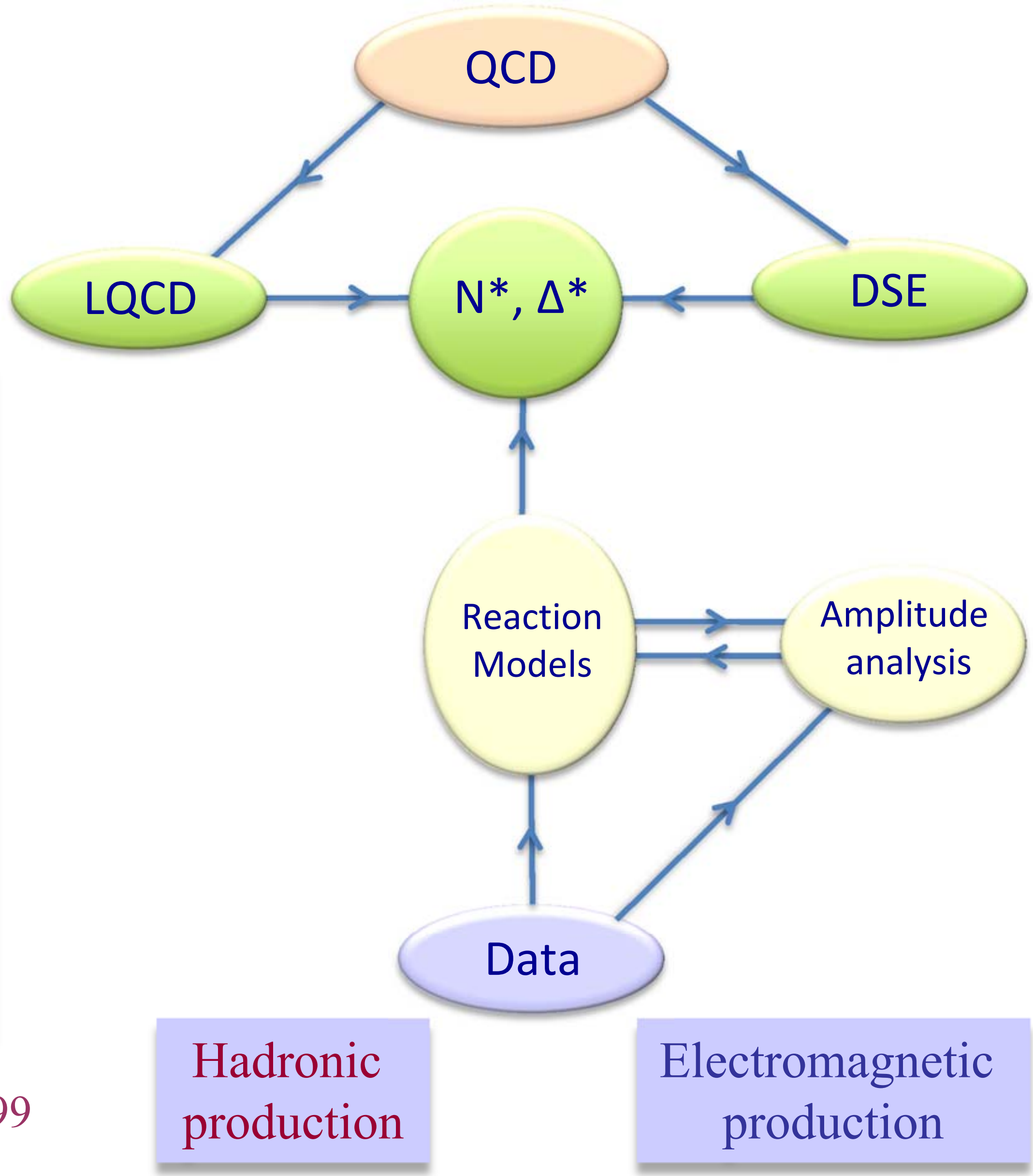
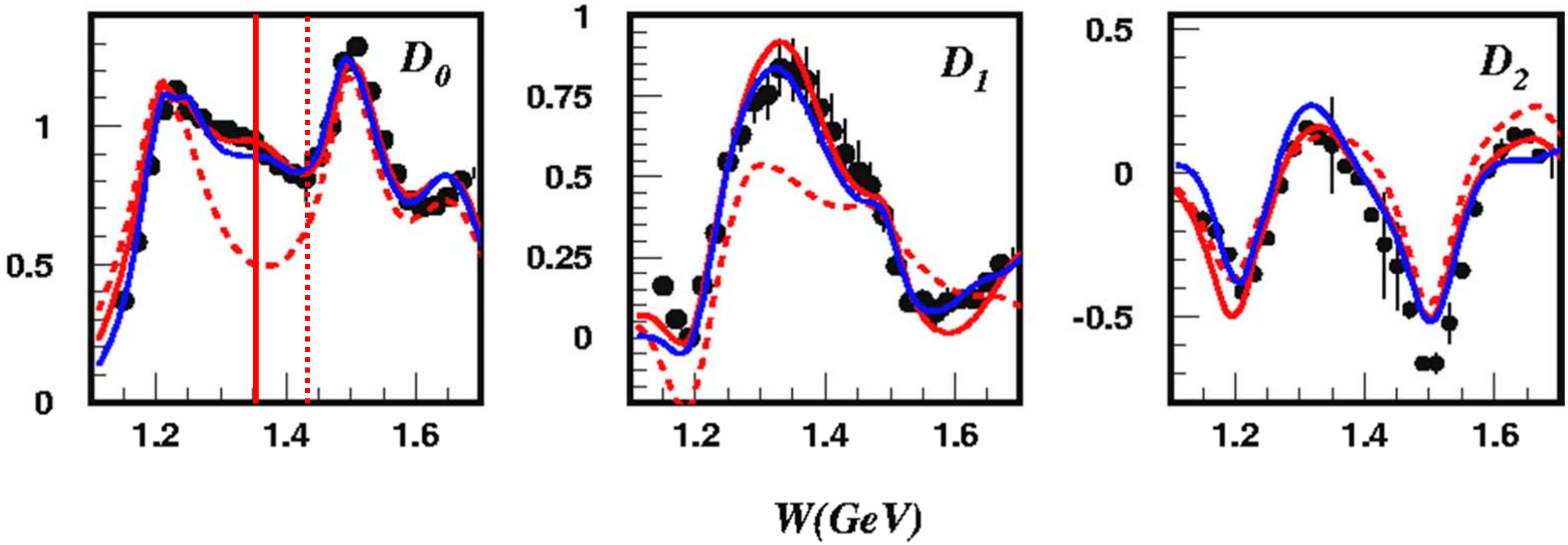


Legendre Moments of Unpolarized Structure Functions

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

Q^2=2.05GeV^2



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

I. Aznauryan —— DR fit

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

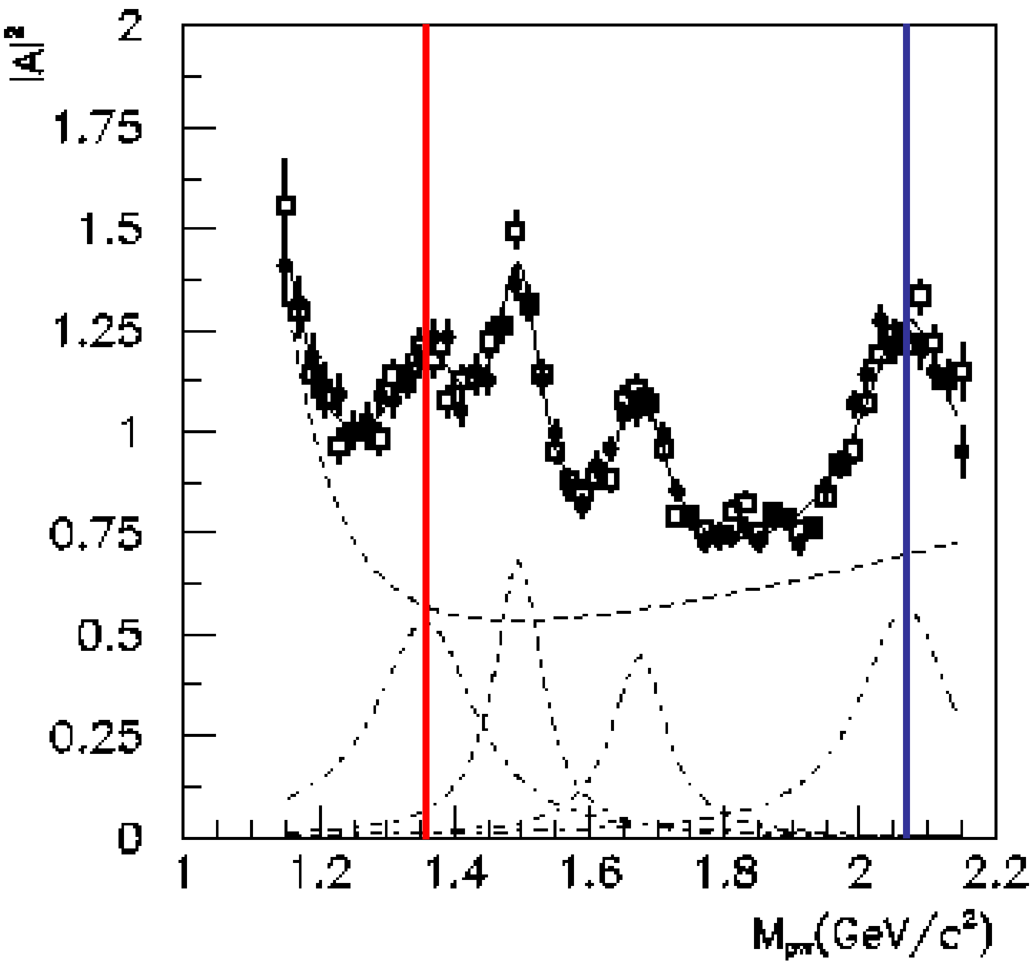
I. Aznauryan —— UIM fit

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

$J/\psi \rightarrow p\pi^-\bar{n}$ and $J/\psi \rightarrow \bar{p}\pi^+ n$

BES/BEPC, Phys. Rev. Lett. 97 (2006)

Bing-Song Zou



N*(1440): $M = 1358 \pm 17$
$\Gamma = 179 \pm 56$

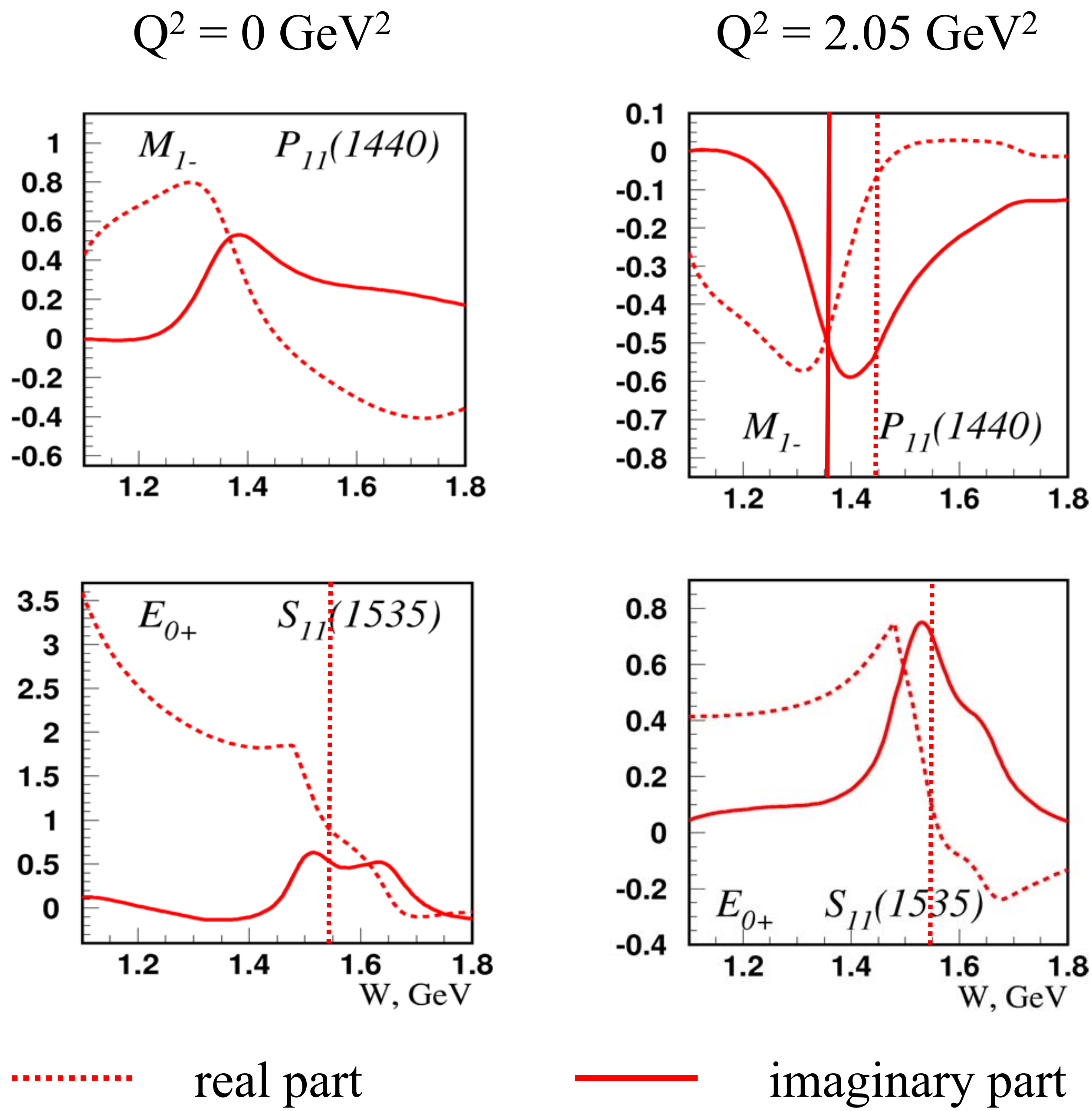
N*(2050): $M = 2068 \; {}^{+15}_{-40}$
$\Gamma = 165 \pm 42$

πN invariant mass / MC phase space

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

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

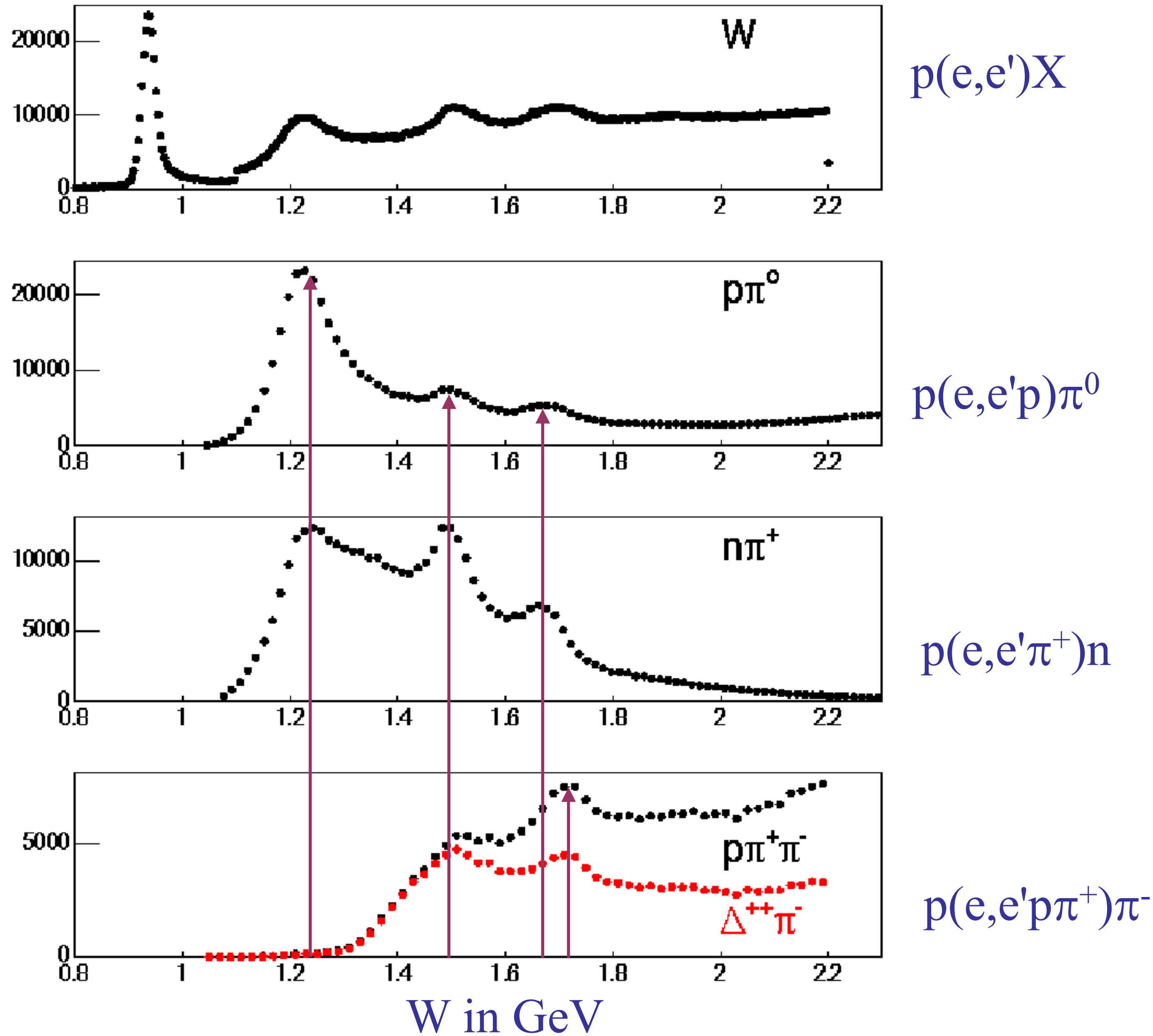
Cross sections are extracted in the $p\pi^0$, $p\pi^+$, $p\eta$; and more are currently under analysis in the $p\omega$ and $p\pi^-$ final states.



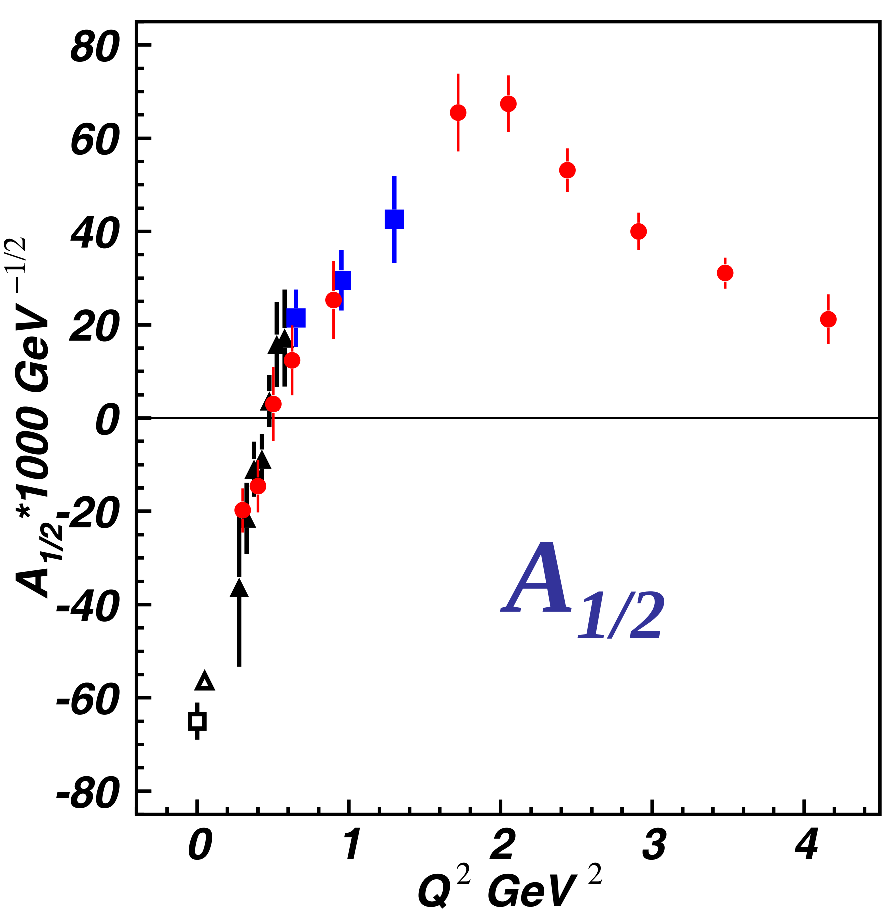
Nucleon Resonances in Nπ and Nππ Electroproduction

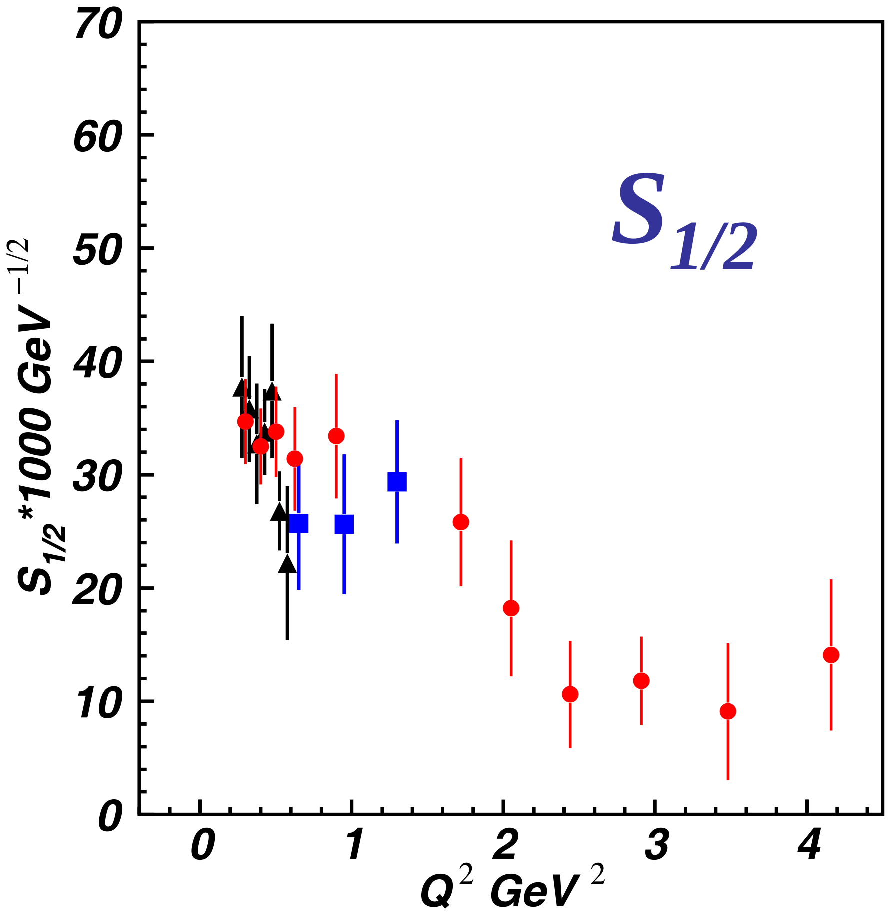
- Nππ channel is sensitive to N*s heavier than 1.4 GeV
- Provides information that is complementary to the Nπ channel
- Many higher-lying N*s decay preferentially into Nππ final states

$Q^2 < 4.0\,GeV^2$



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





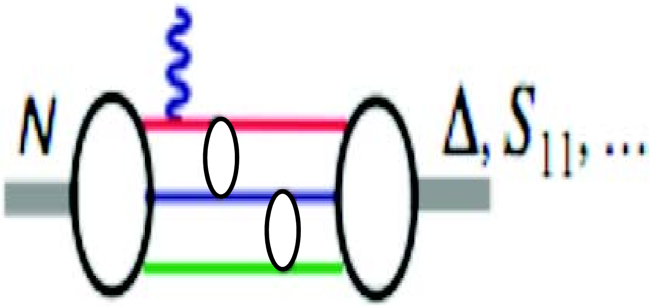
□ PDG ● Nπ (UIM, DR) ▲ Nππ (JM) 2012 ■ Nππ (JM) preliminary

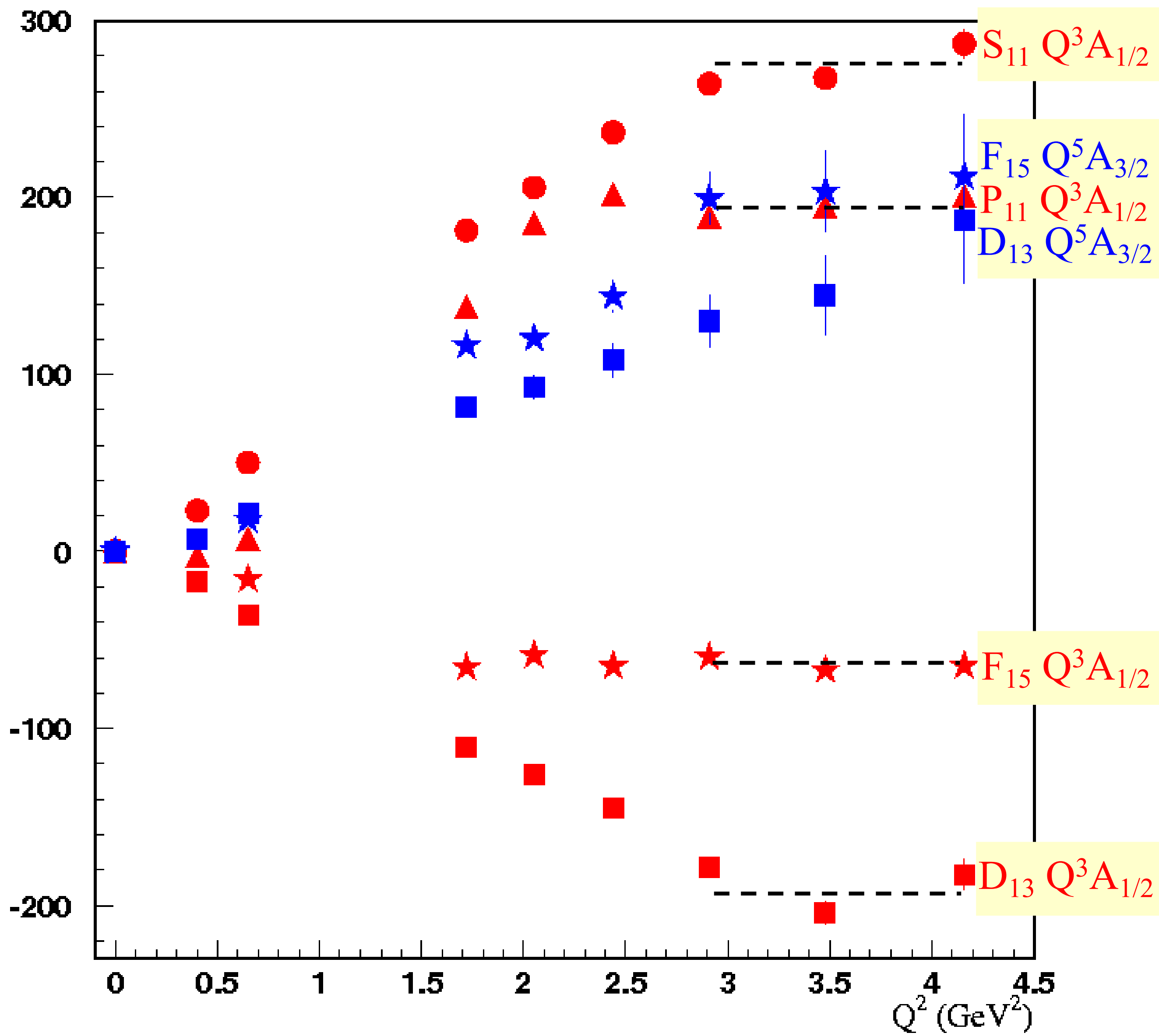
Consistent results obtained in the low-lying resonance region by independent analyses in the exclusive Nπ and $p\pi^+\pi^-$ final-state channels – that have fundamentally different mechanisms for the nonresonant background – underscore the capability of the reaction models to extract reliable resonance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

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

Evidence for the Onset of Scaling?

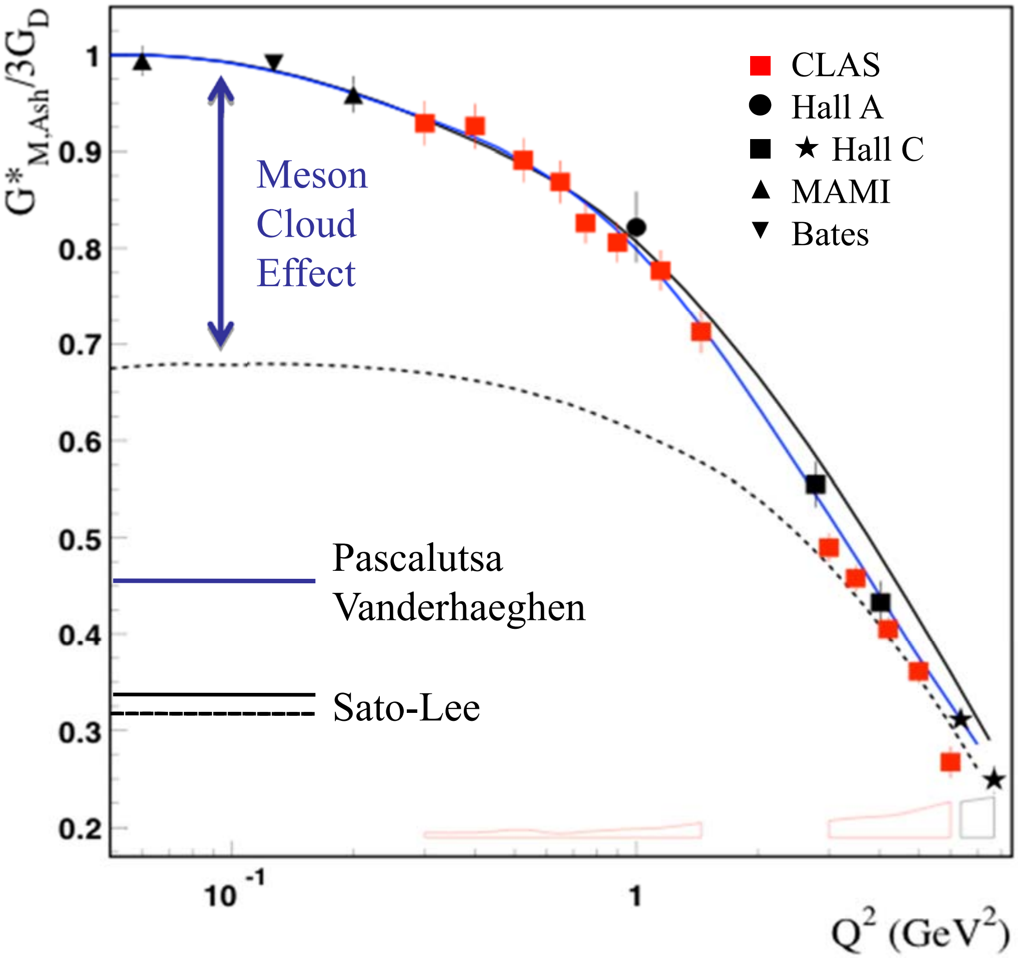
Phys. Rev. C80, 055203 (2009)



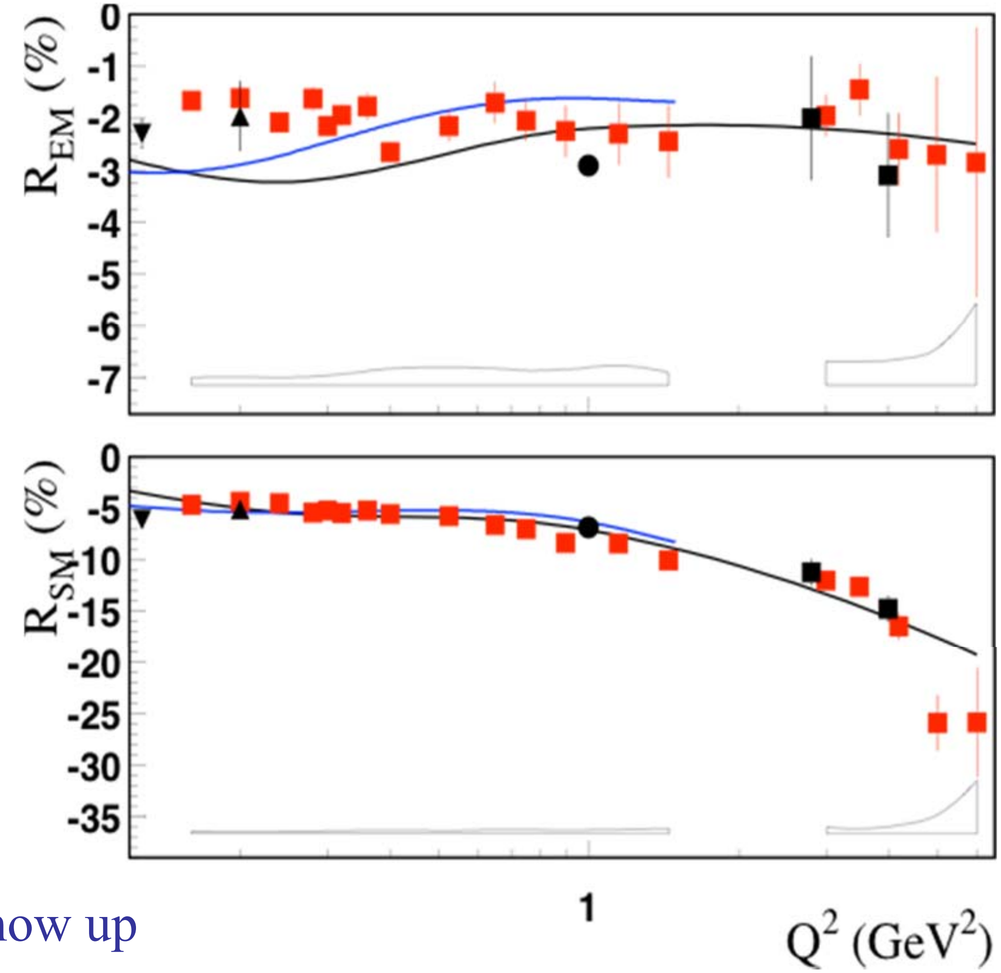


- $A_{1/2}$ α $1/Q^3$
- $A_{3/2}$ α $1/Q^5$
- G^*_M α $1/Q^4$

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

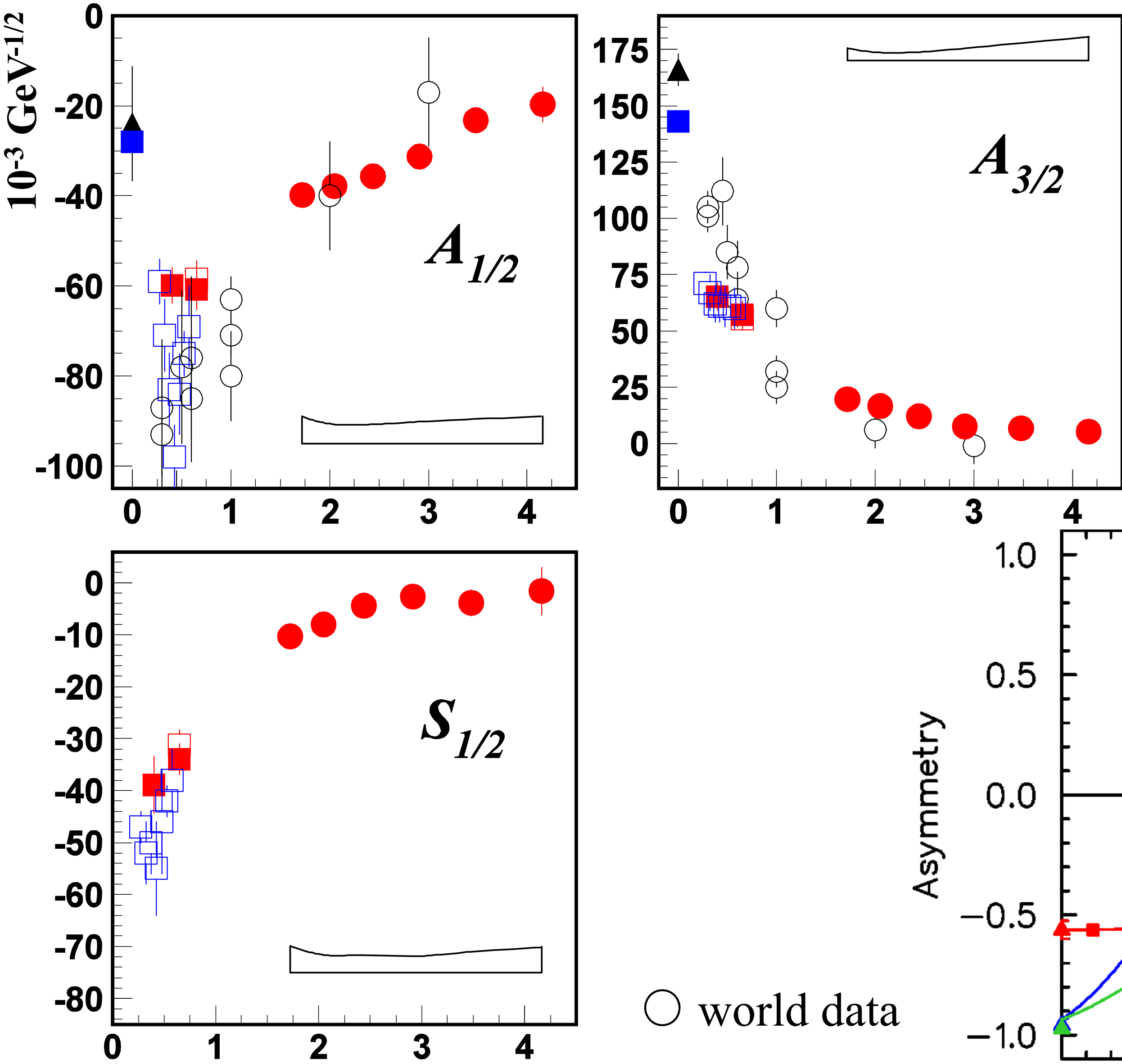


Phys. Rev. Lett. 97, 112003 (2006)



- 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

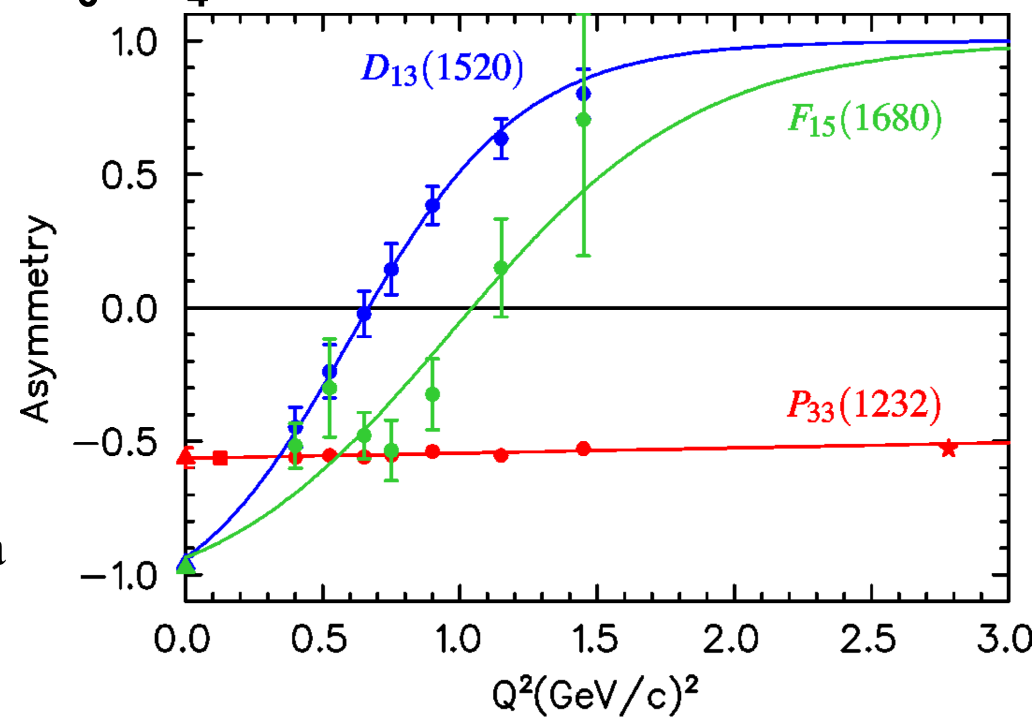
N(1520)D_{13} Helicity Asymmetry



▲ PDG estimation ● ■ Nπ (UIM, DR)

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

L. Tiator

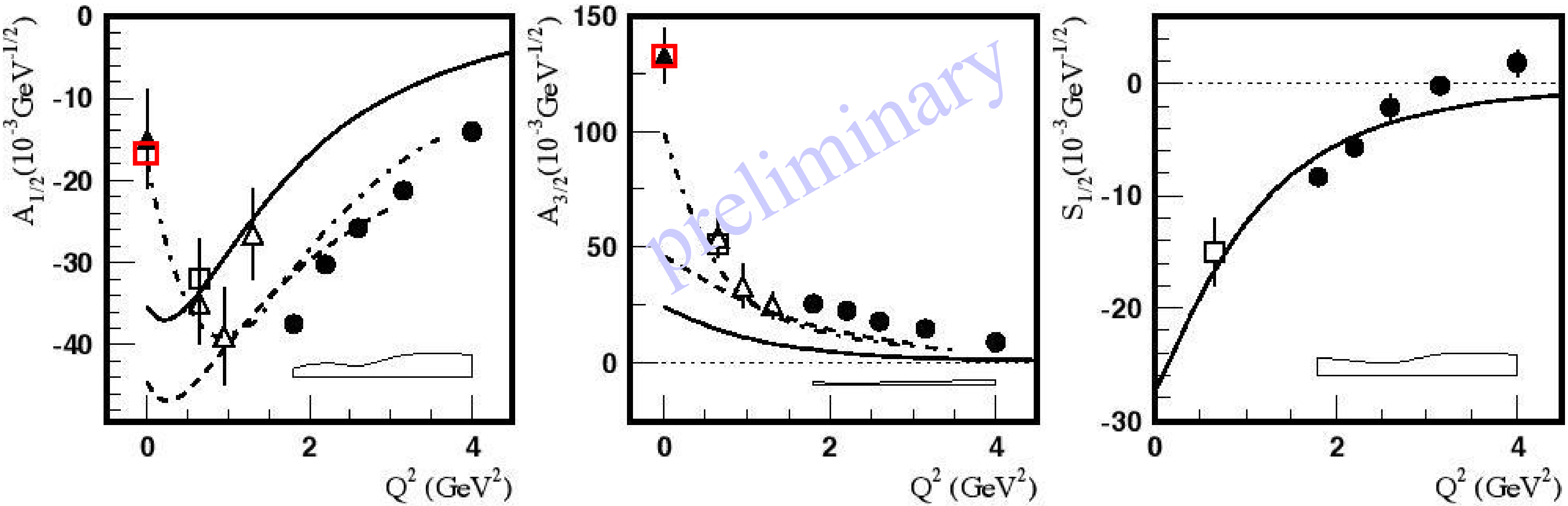


New Experimental Results & Approaches

High-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)

△ $N\pi\pi$: V. Mokeev (JM)

● $N\pi$: I.G. Aznauryan (UIM & DR)

- - - D. Merten, U. Löring et al.

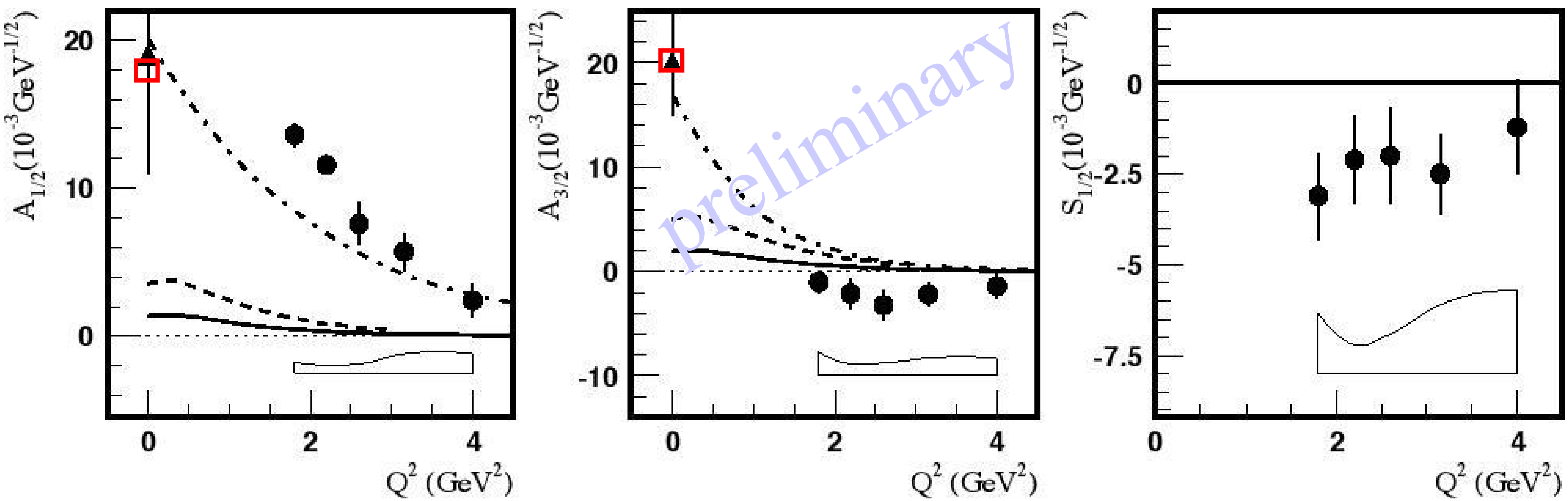
-·-· Z. Lee and F. Close

—— E. Santopinto and M.M. Gianini

High-Lying Resonance Electrocouplings

$N(1675)D_{15}$

Kijun Park



▲ RPP (PDG) Phys. Rev. D 86 (2012)

□ M. Dugger Phys. Rev. C 76 (2007)

● Nπ: I.G. Aznauryan (UIM & DR)

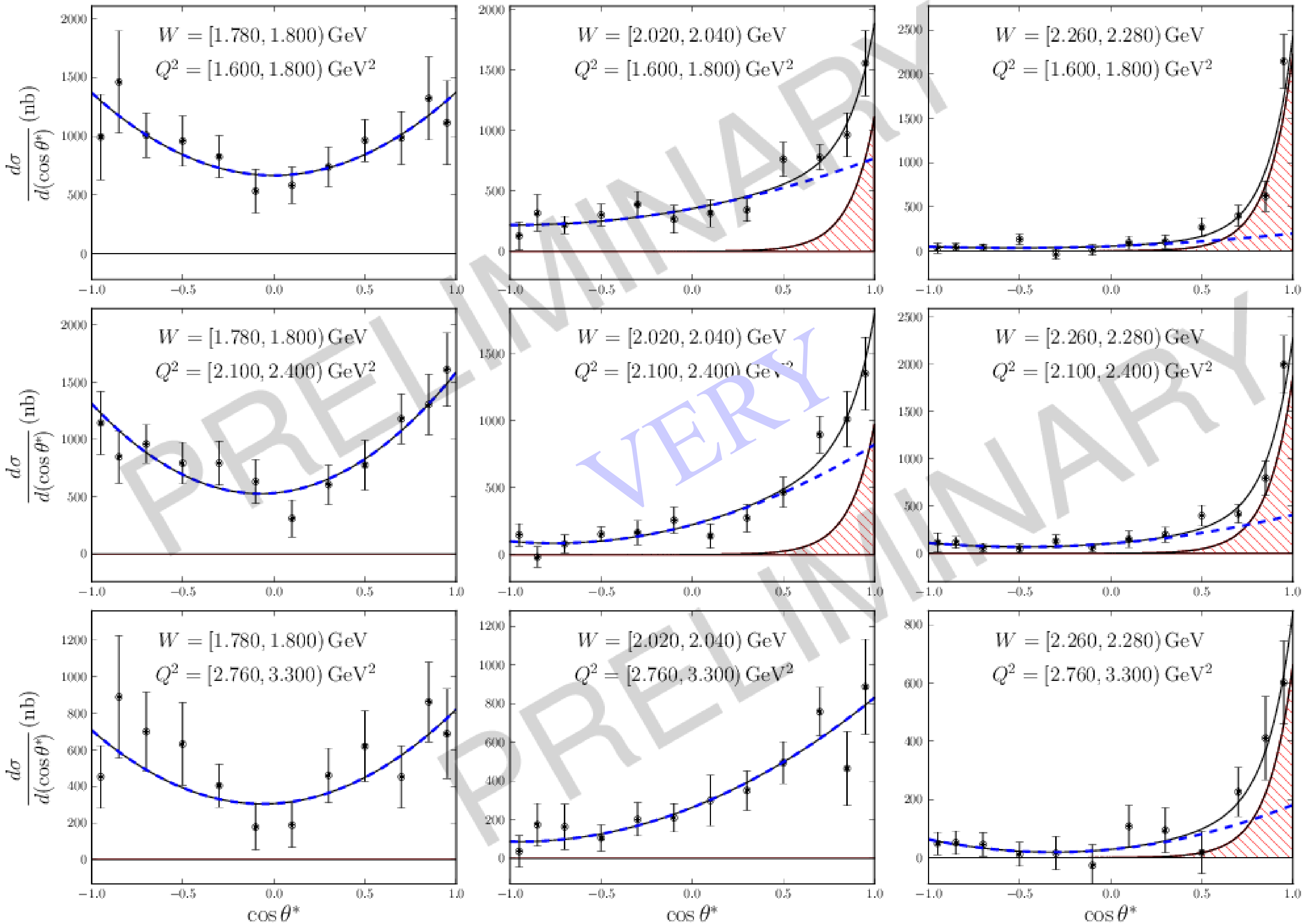
- - - D. Merten, U. Löring et al.

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

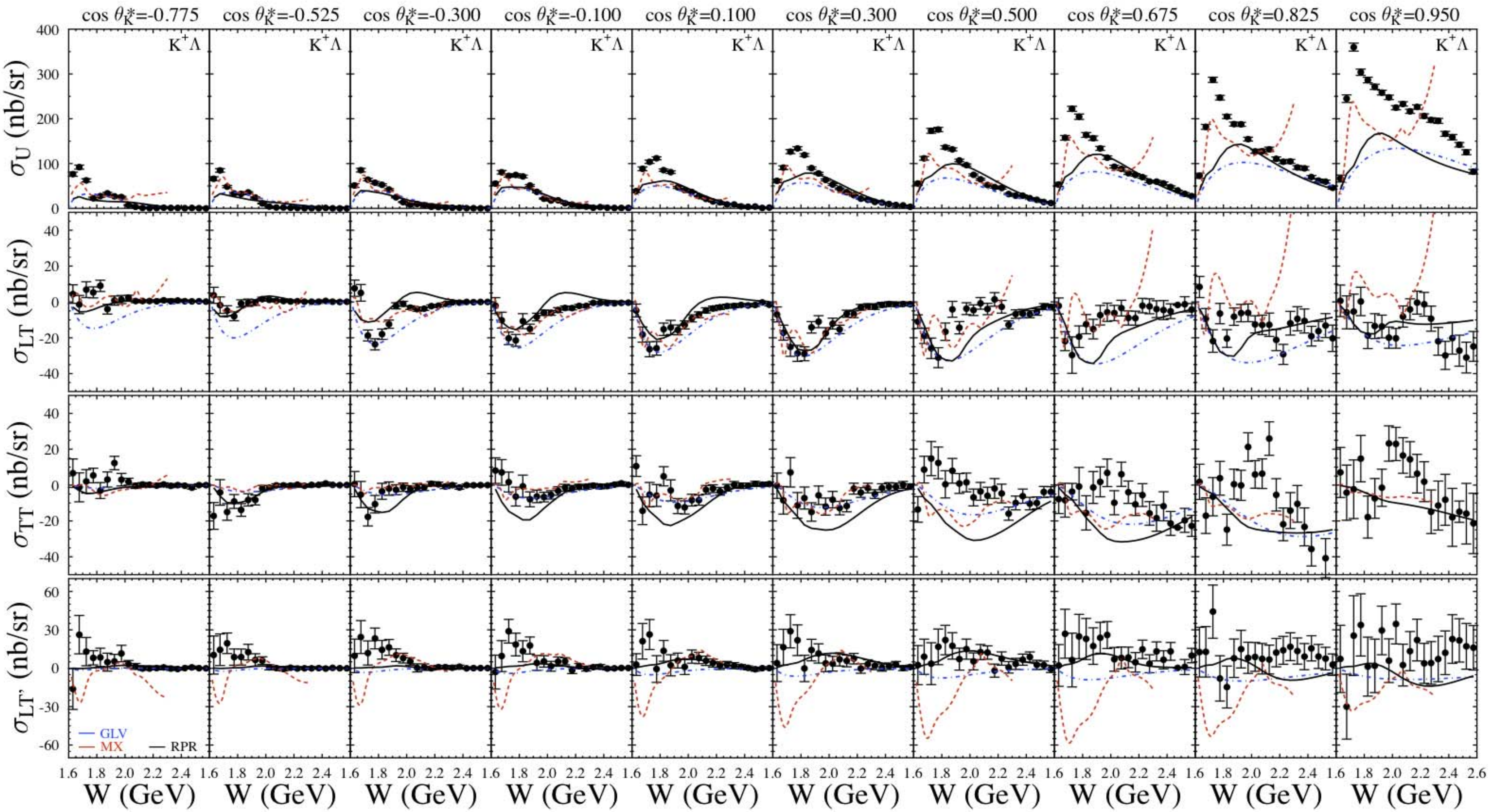
—— E. Santopinto and M.M. Gianini

High-Lying Resonances in ω Electroproduction

Evan Phelps



$K^+\Lambda$ Structure Functions

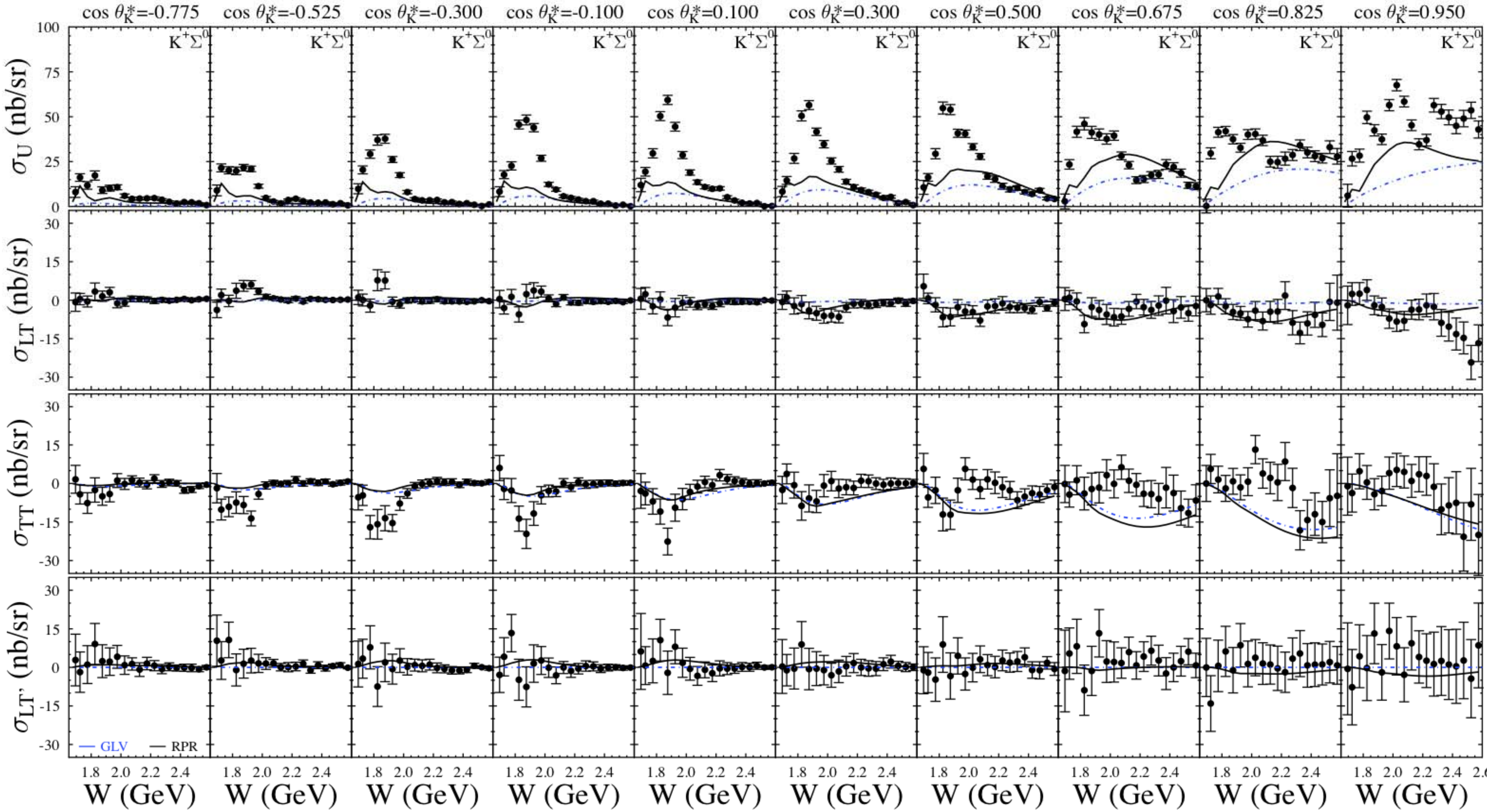


[Carman et al., PRC 87, 025204 (2013)]

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



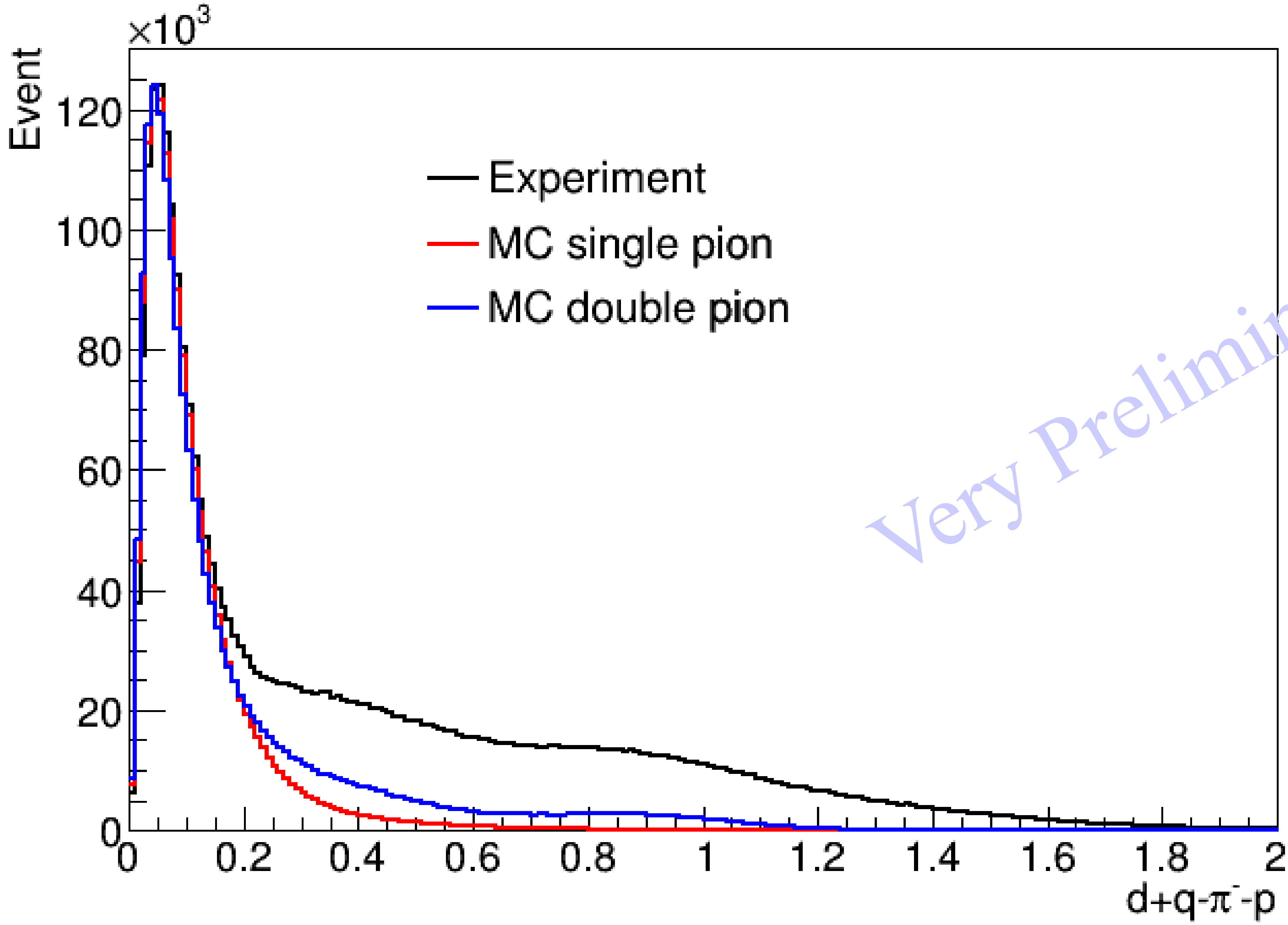
[Carman et al., PRC 87, 025204 (2013)]

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

CLAS12 experiment E12-06-108A

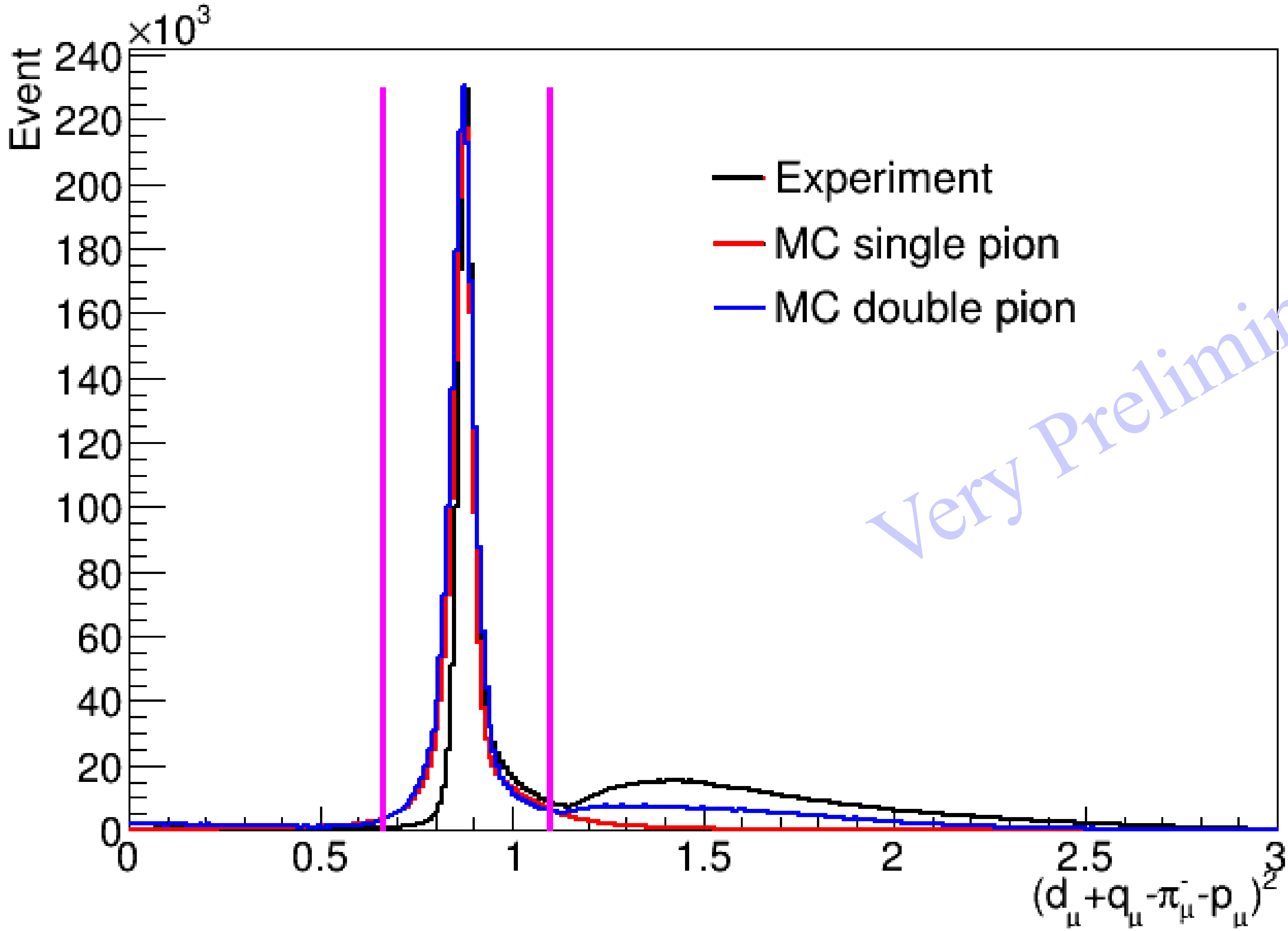
Single π Electroproduction off the Deuteron

Ye Tian



Single π Electroproduction off the Deuteron

Ye Tian



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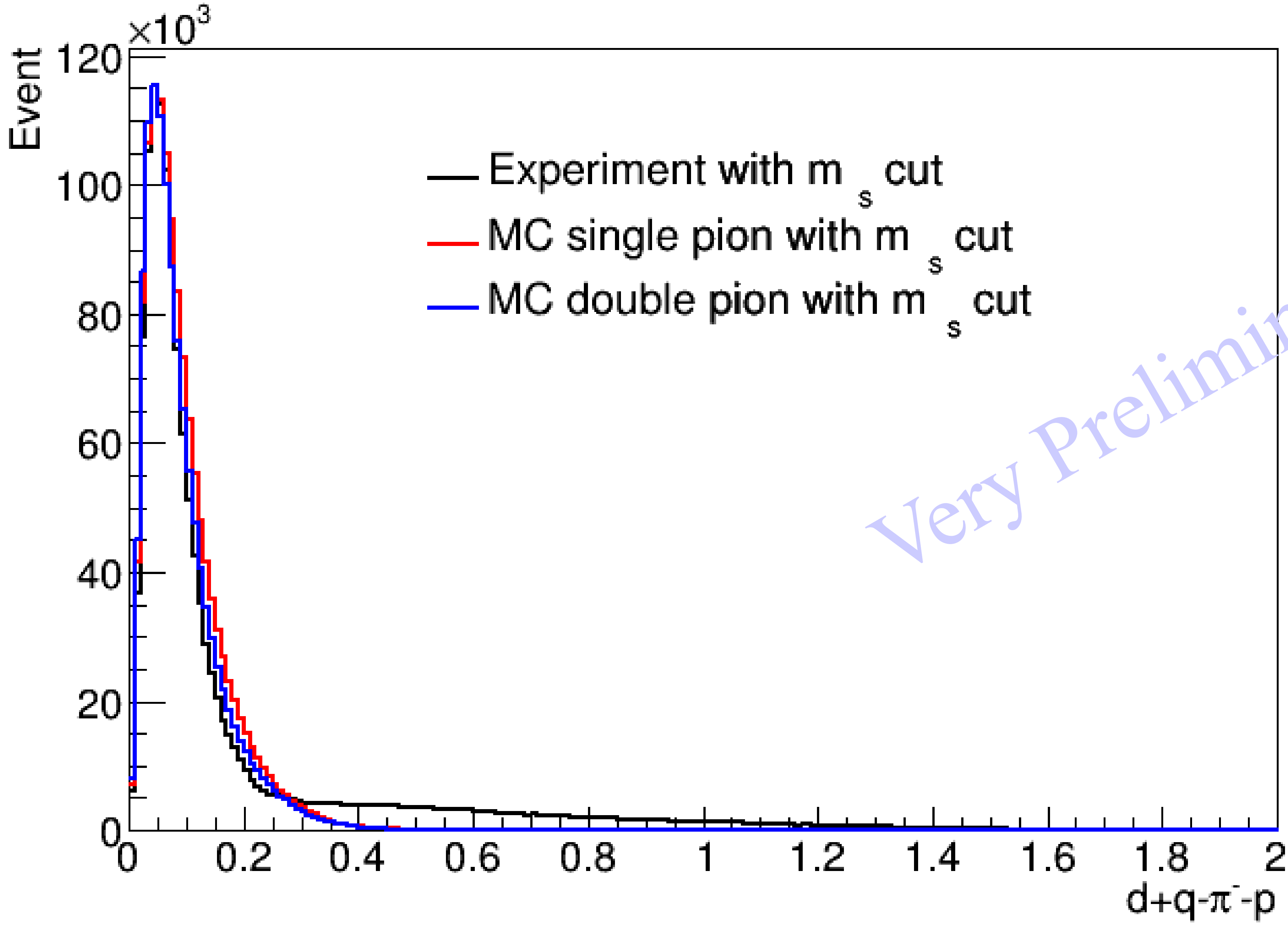

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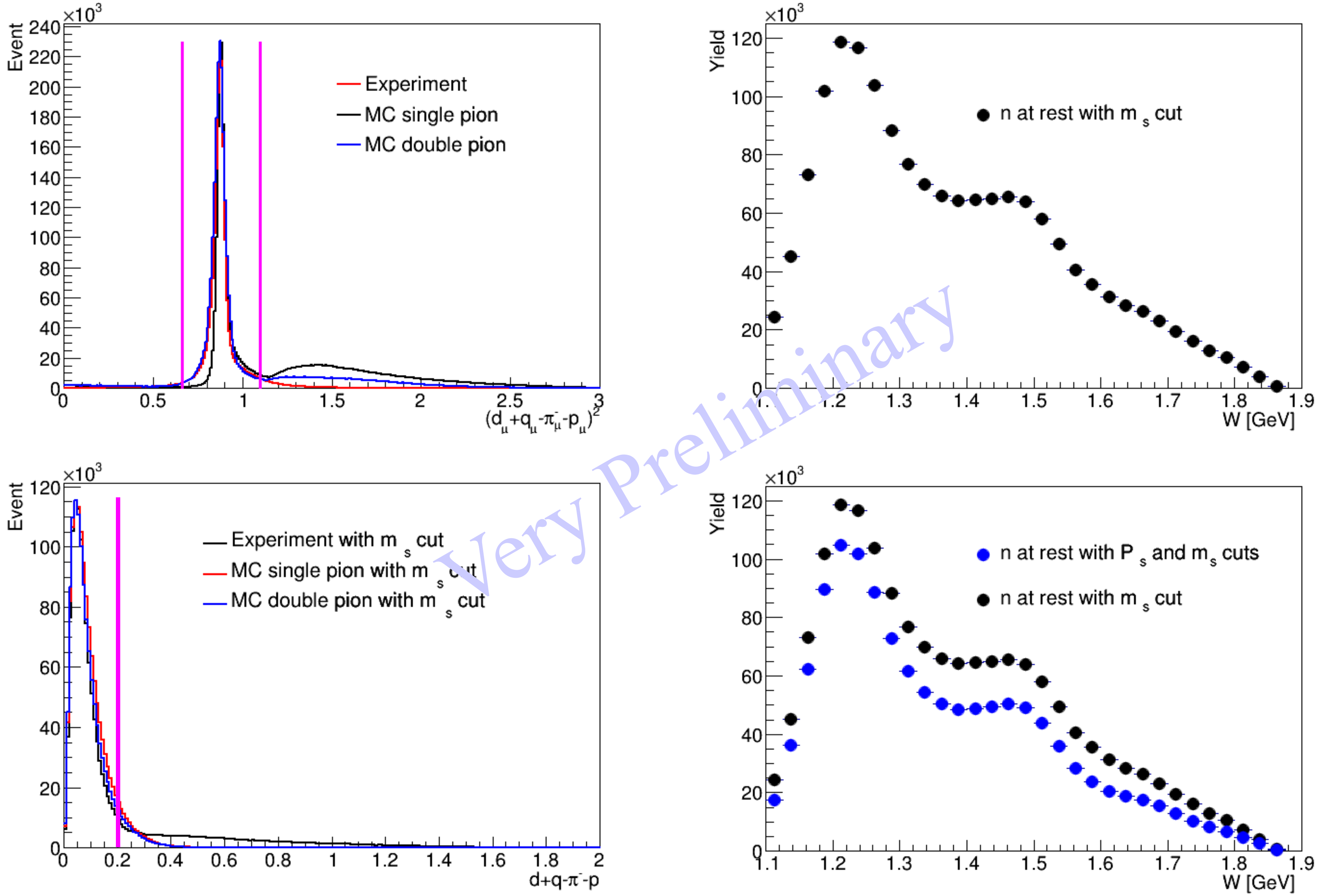

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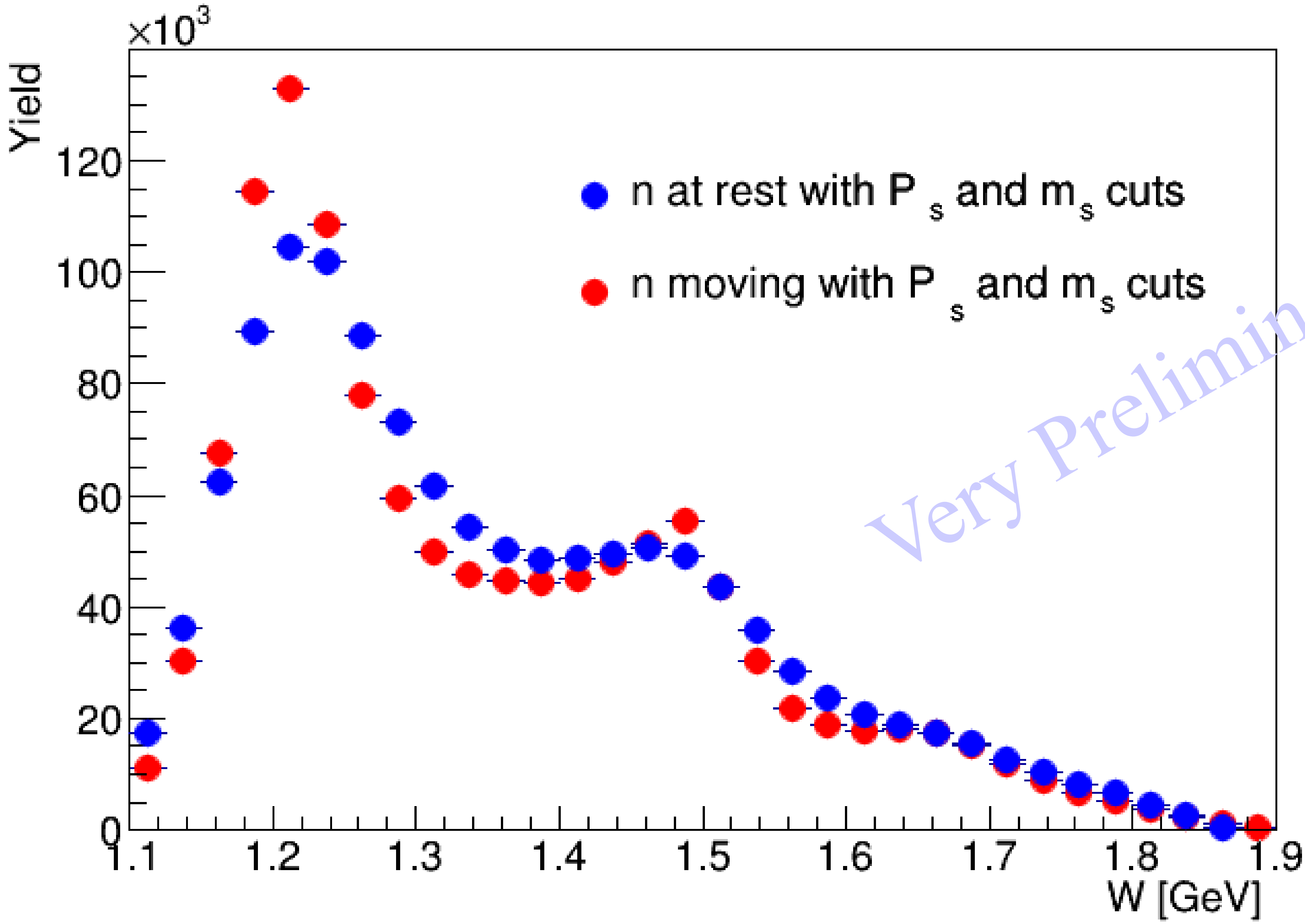

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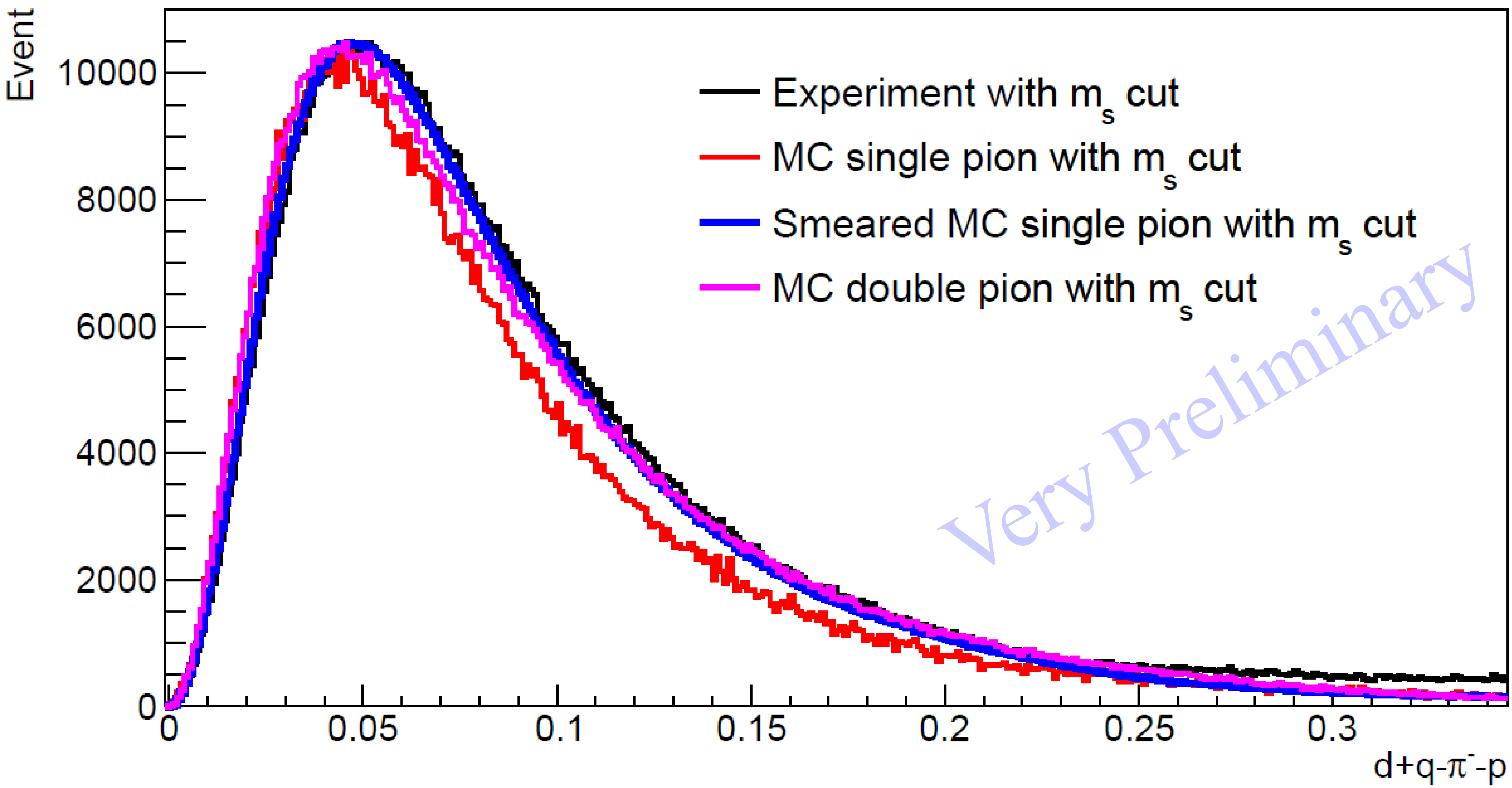


Below a missing momentum of 0.2 GeV the **measured data** coincides with the resolution **smeared theoretical Fermi momentum distribution**.

FSI for $\gamma\, n \rightarrow \pi^- p$

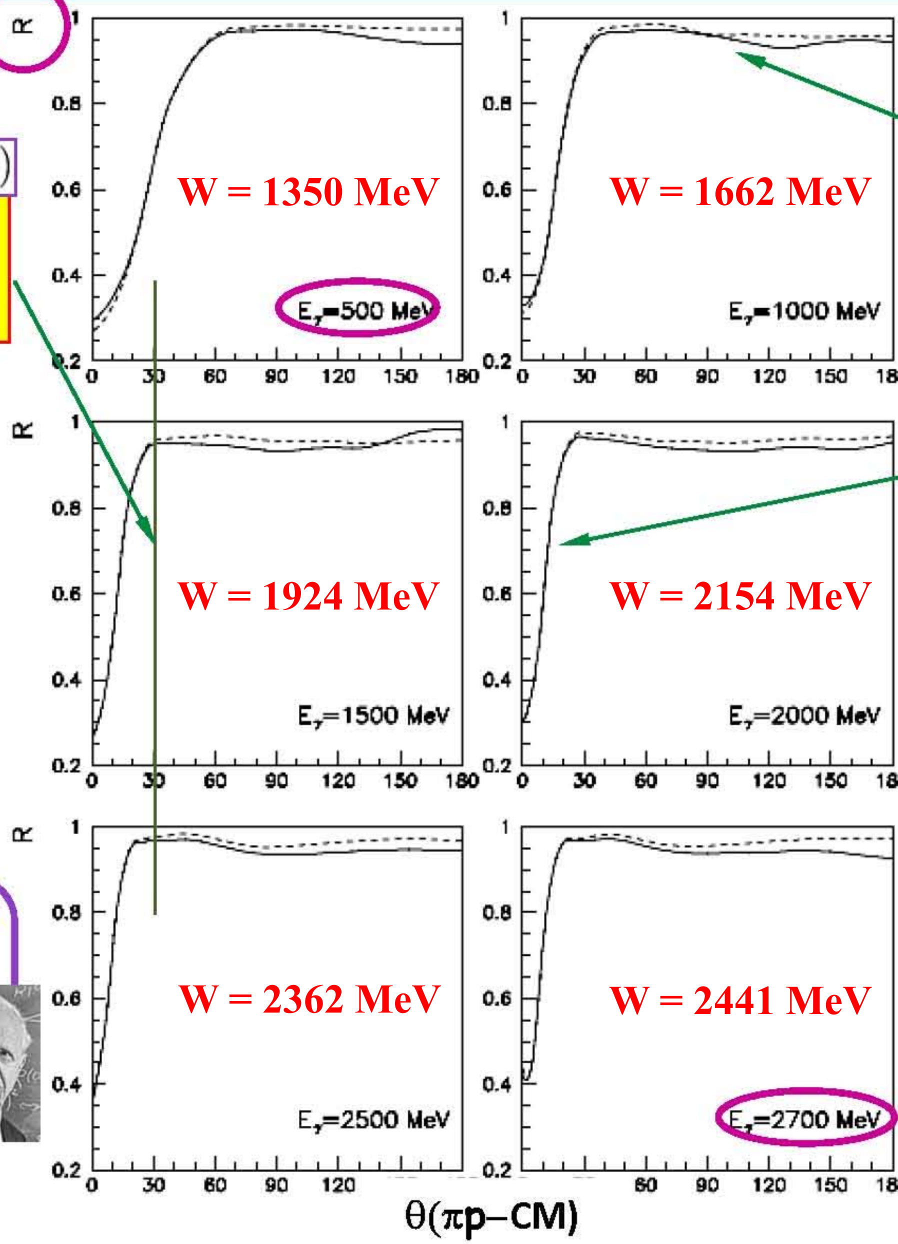
[V. Tarasov, A. Kudryavtsev, W. Briscoe, H. Gao, IS, Phys Rev C **84**, 035203 (2011)]

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

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

CLAS data:
E > 1 GeV
θ > 32 deg

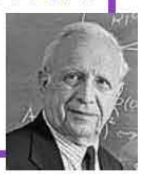
- There is no large sensitivity to cuts.



- For **CLAS** data
  - The **FSI** correction factor **R < 1.**
  - The behavior is smooth vs. **θ.**
  - The effect **Δσ/σ ≤ 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.

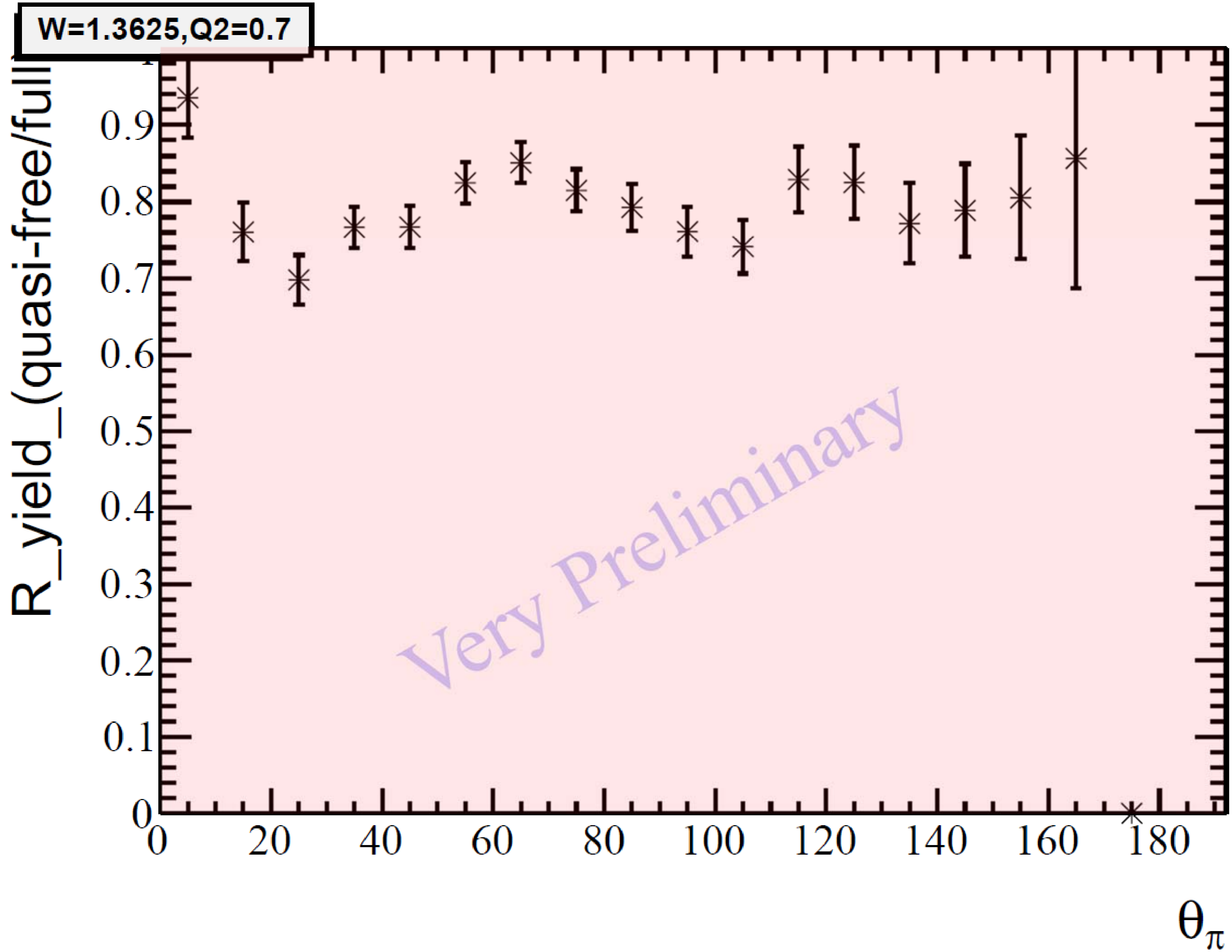
- Our estimation of the **Glauber FSI** corrections gives the value of **5**%.
- **Previous** estimations gave the order of **15-30**%.



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

Single π Electroproduction off the Deuteron

Ye Tian

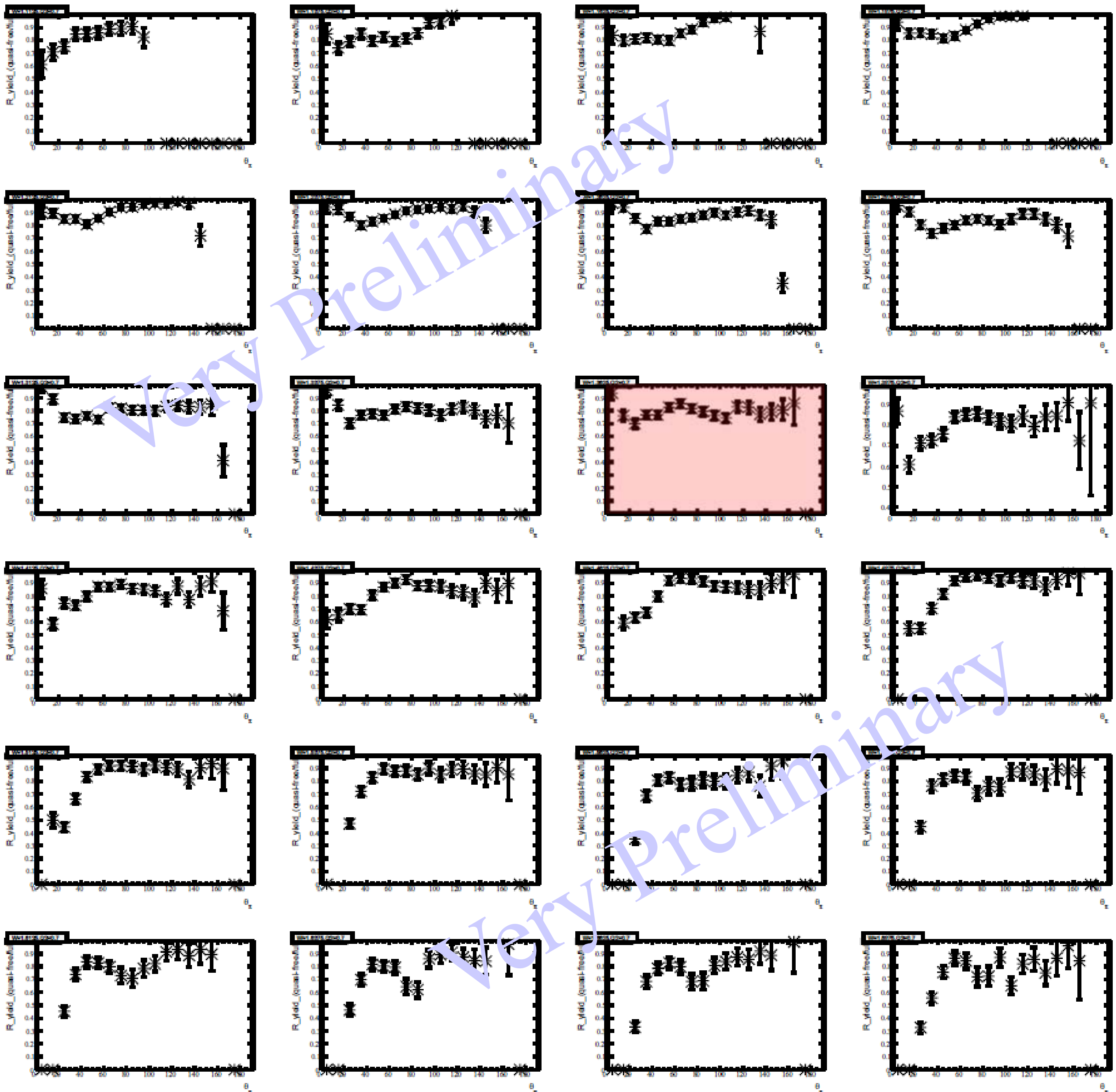


Single π Electroproduction off the Deuteron

W = 1125 MeV

ΔW = 25 MeV

Ye Tian



$Q^2 = 0.7\ GeV^2$

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

W = 1685 MeV

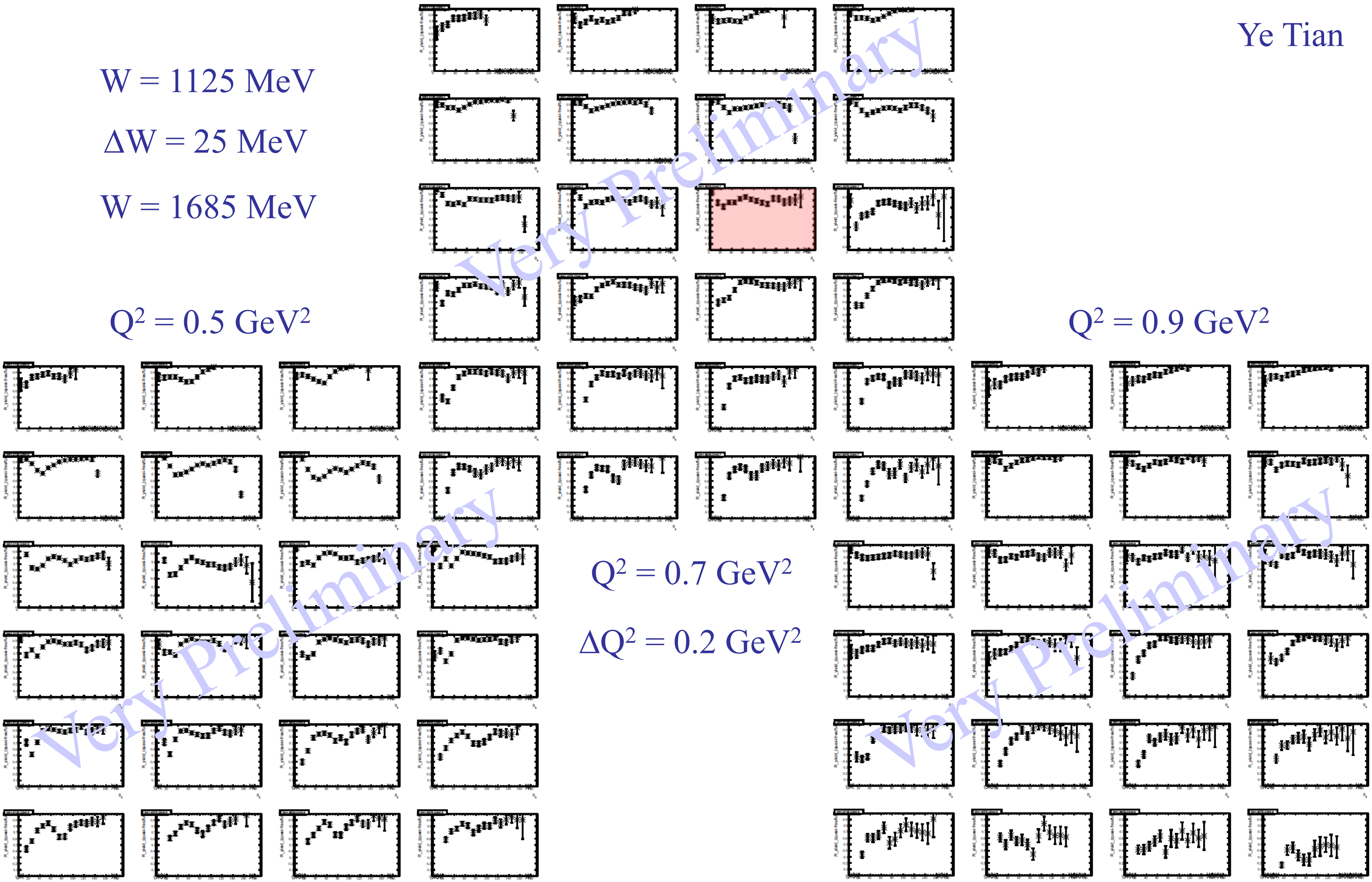
Single π Electroproduction off the Deuteron

Ye Tian

W = 1125 MeV

ΔW = 25 MeV

W = 1685 MeV



$Q^2 = 0.5\ GeV^2$

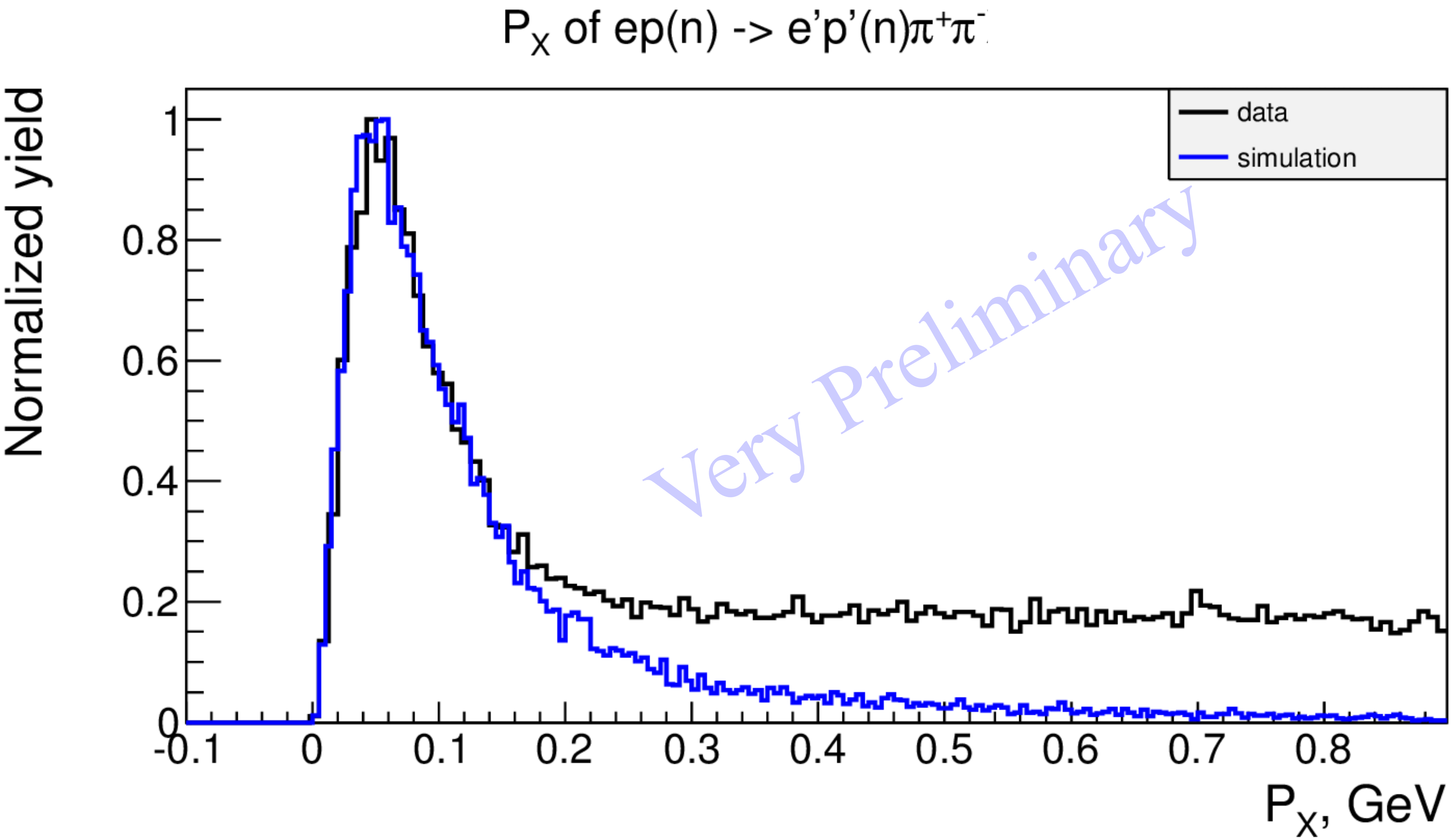
$Q^2 = 0.7\ GeV^2$

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

$Q^2 = 0.9\ GeV^2$

Double π Electroproduction off the Deuteron

Iuliia Skorodomina



Double π Electroproduction off the Deuteron

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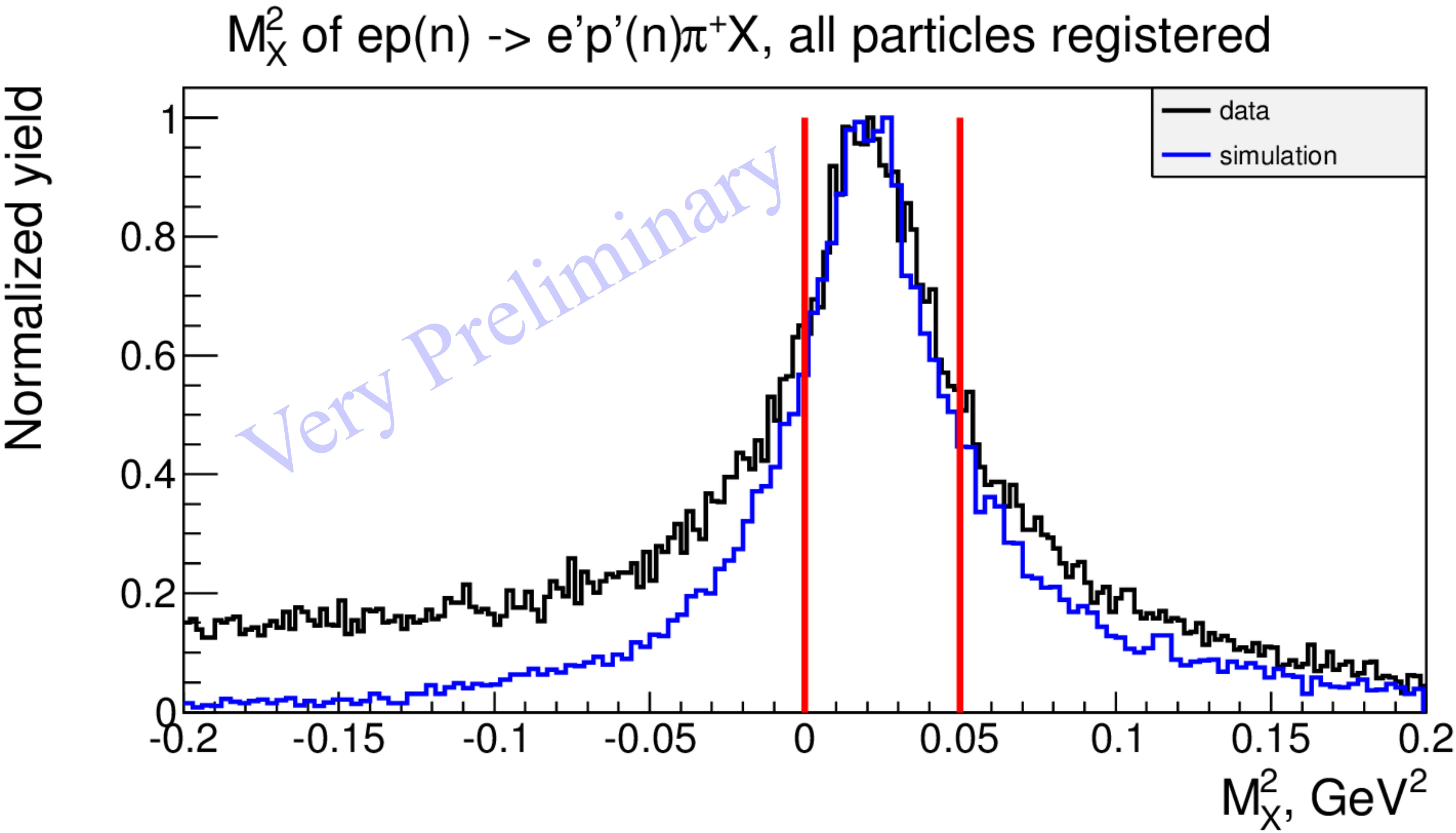

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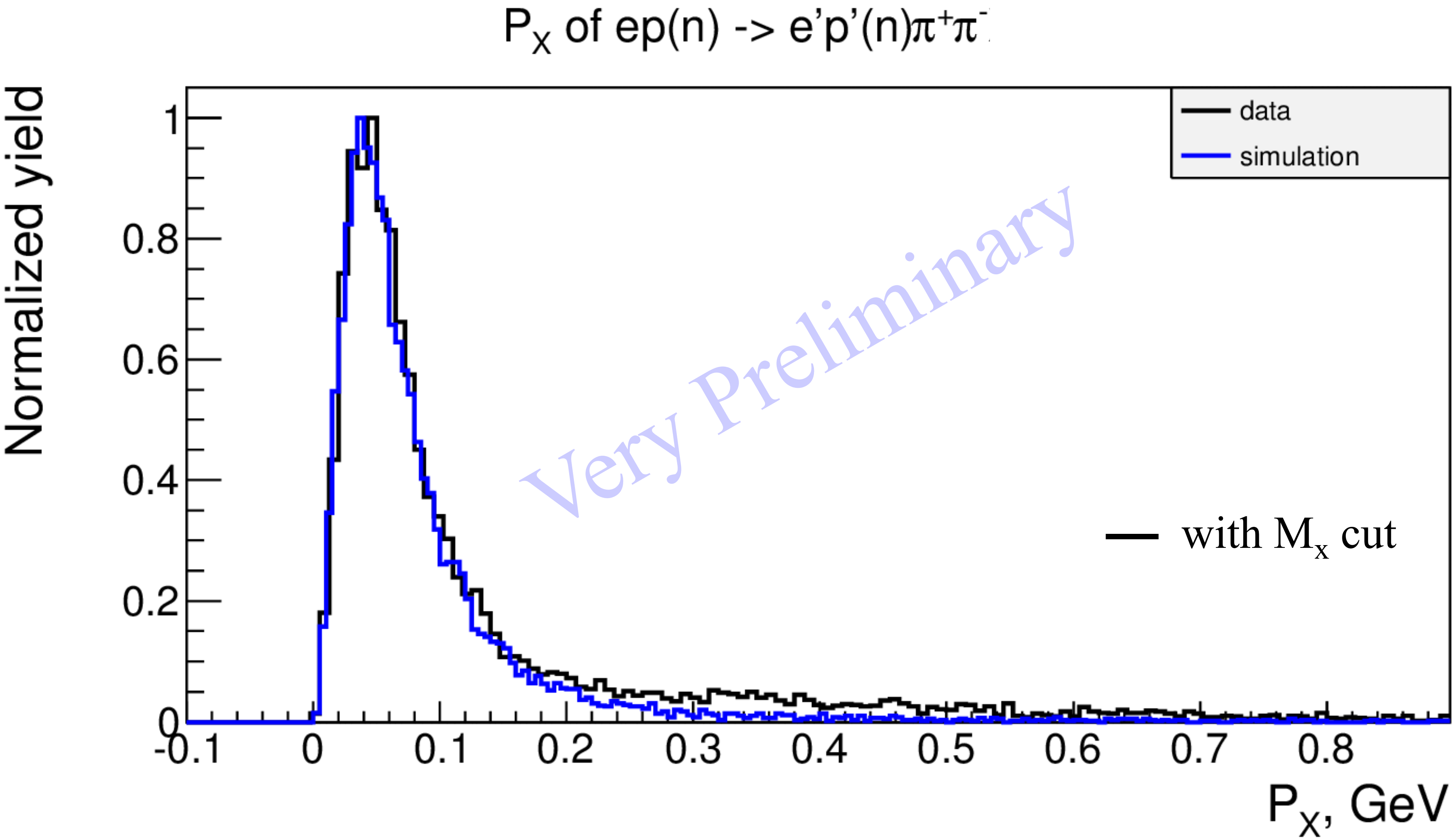
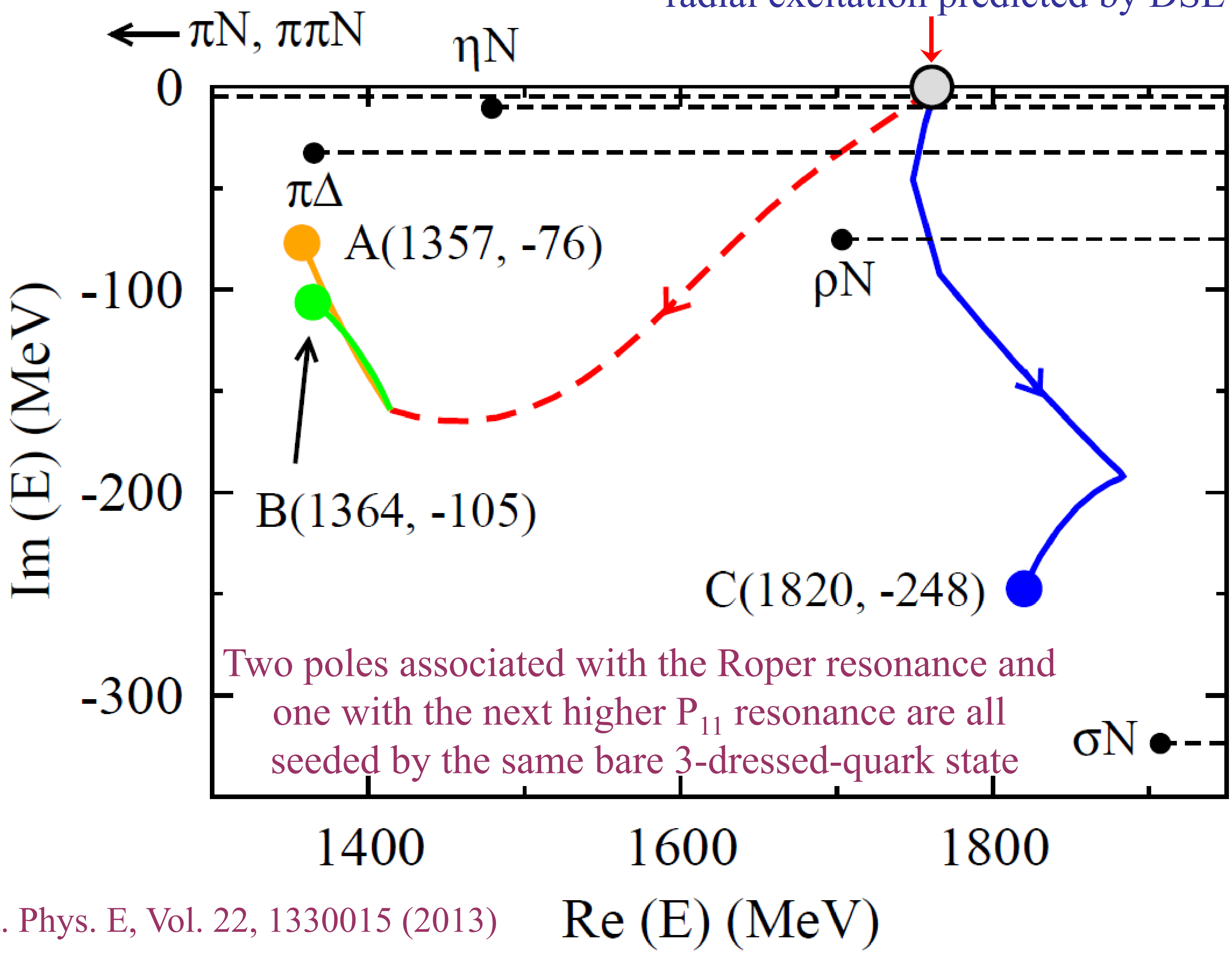


QCD-Based Models and Theory?

DSE and EBAC Approaches

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



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

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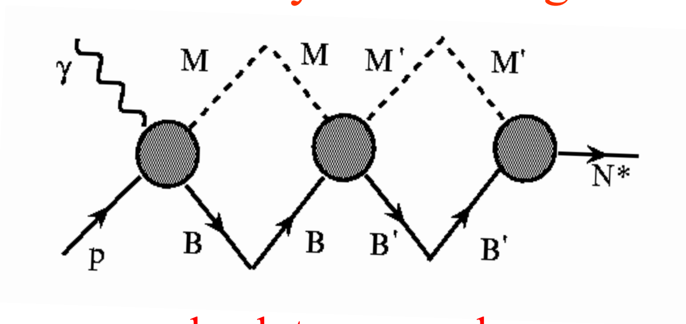
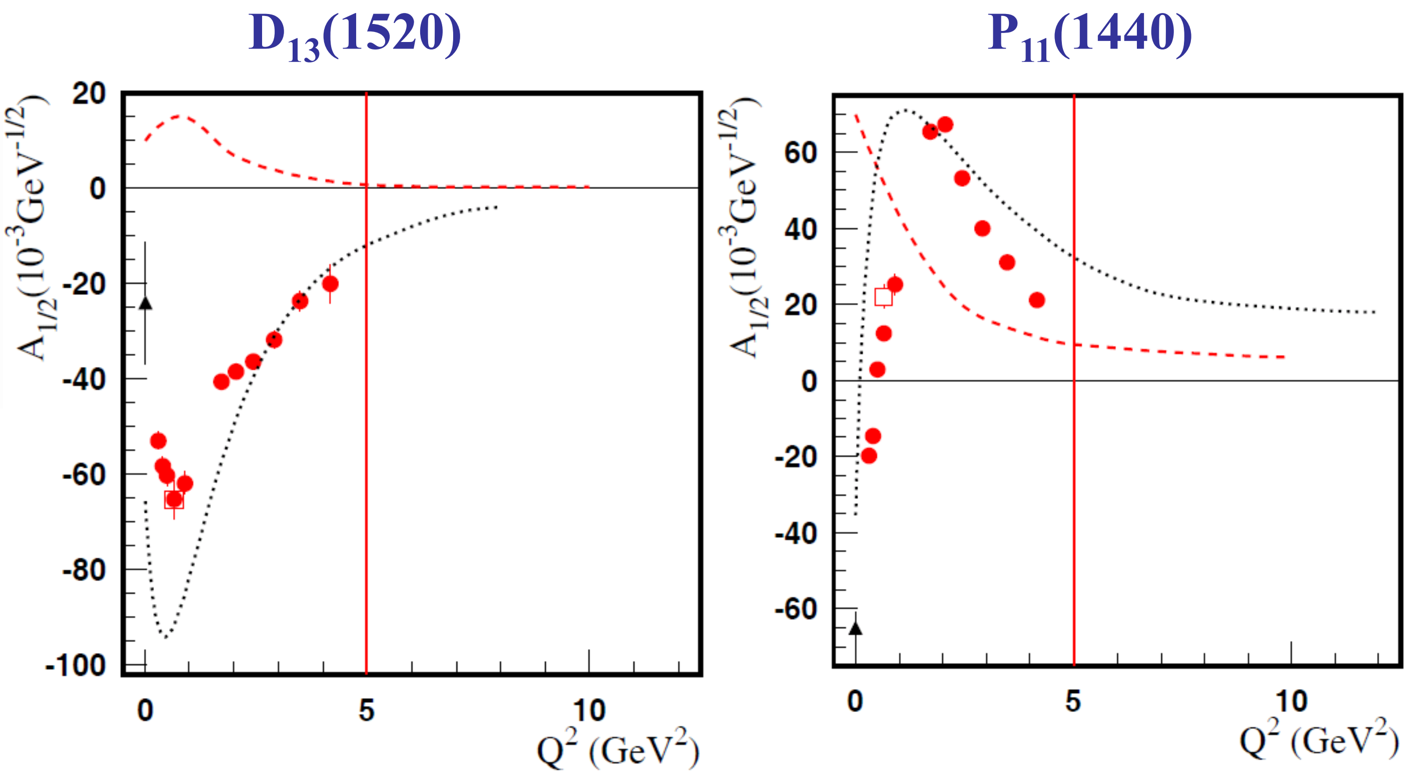
Progress in Experiment and Phenomenology

Meson-Baryon Dressing



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

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

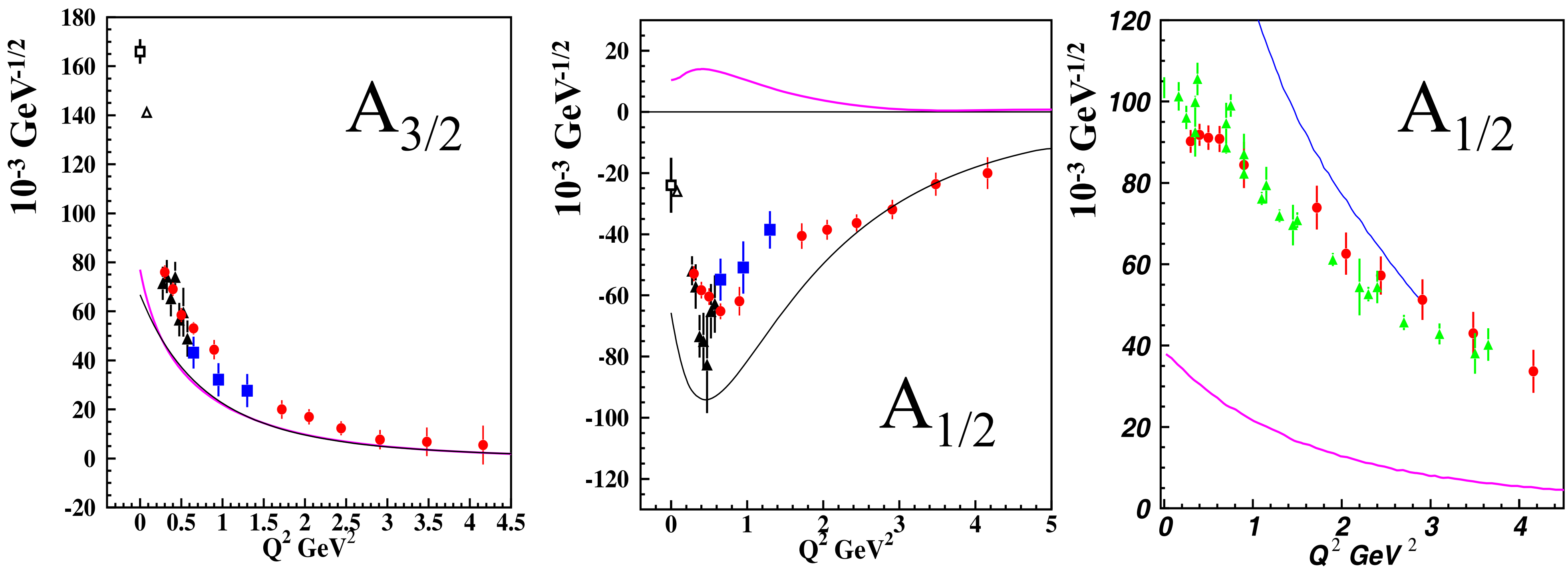


CLAS: Nπ and Nπ/Nππ combined (Phys. Rev. C80, 055203, 2009)

➢ 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 this experiment ($Q^2 > 5$ GeV^2) will afford for the first time direct access to the non-perturbative strong interaction among dressed quarks, their emergence from QCD, and the subsequent N* formation.

Electrocouplings of N(1520)D_{13} and N(1535)S_{11}



Argonne Osaka / EBAC DCC MB dressing (absolute values)

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

S. Capstick, B.D. Keister (rCQM) PRD51, 3598 (1995)

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

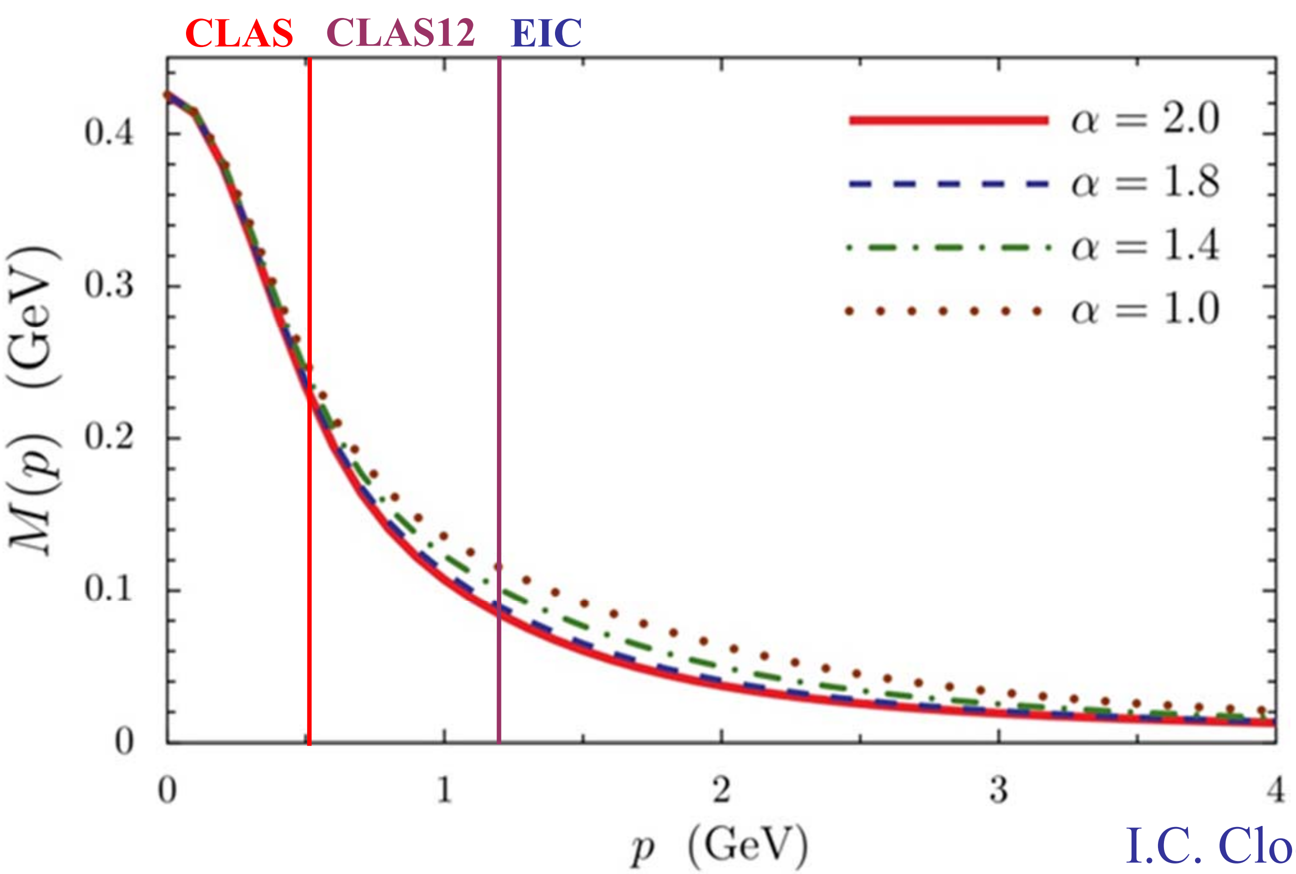
$\pi^+\pi^-p$ 2010

$N\pi$ 2009

ηp CLAS/Hall-C

Dyson-Schwinger Equation (DSE) Approach

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



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

Impact of a modified momentum dependence of the dressed-quark propagator.

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

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

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

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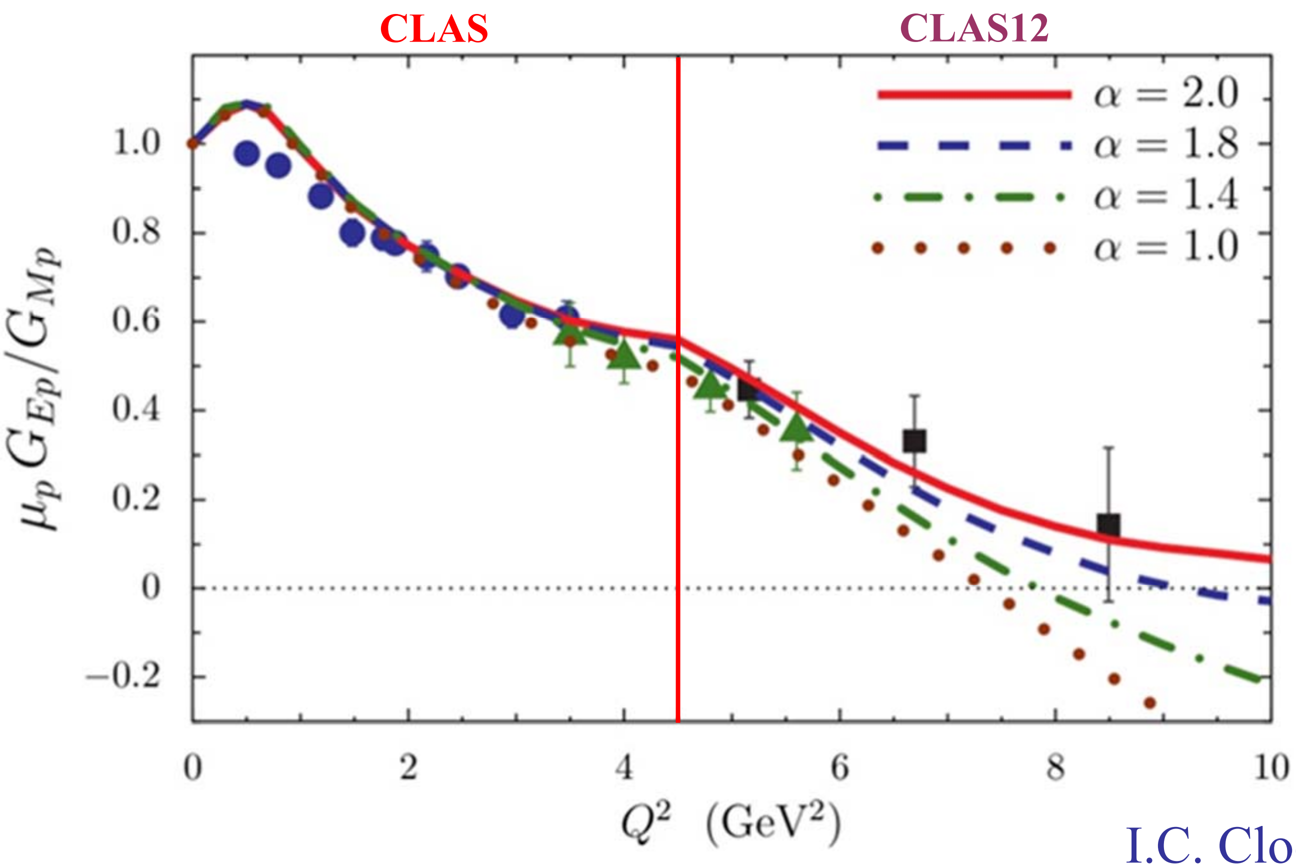

N* electrocouplings can be determined by applying Bethe-Salpeter / Faddeev equations to 3 dressed quarks while the properties and interactions are derived from QCD.

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

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

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

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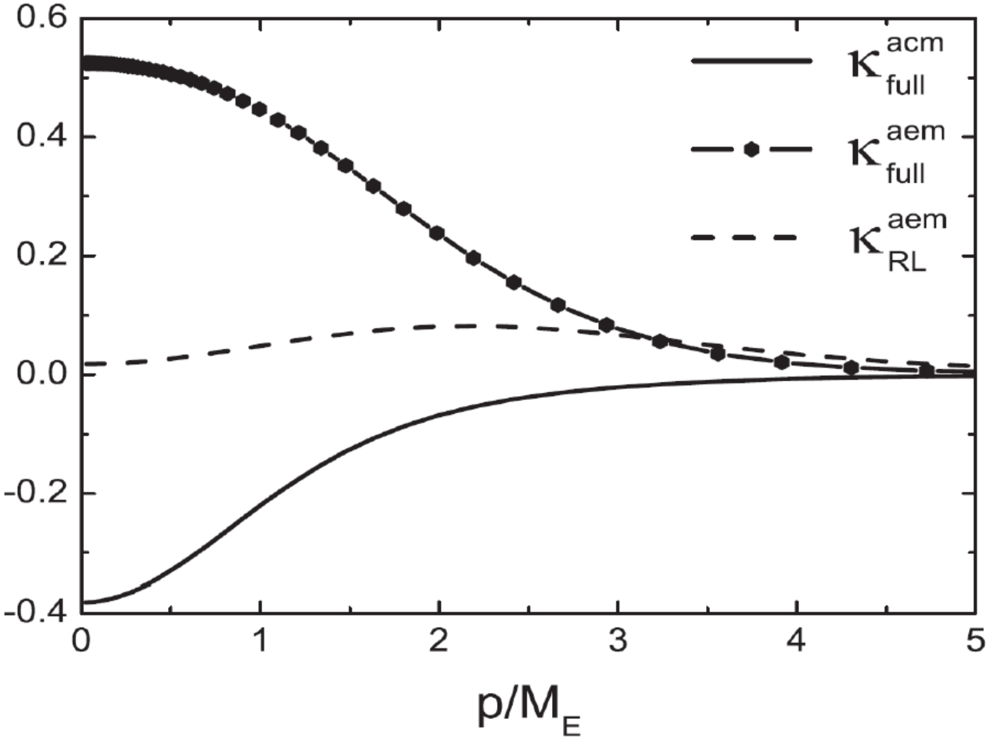
Anomalous Magnetic Moment in DSE Approach



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

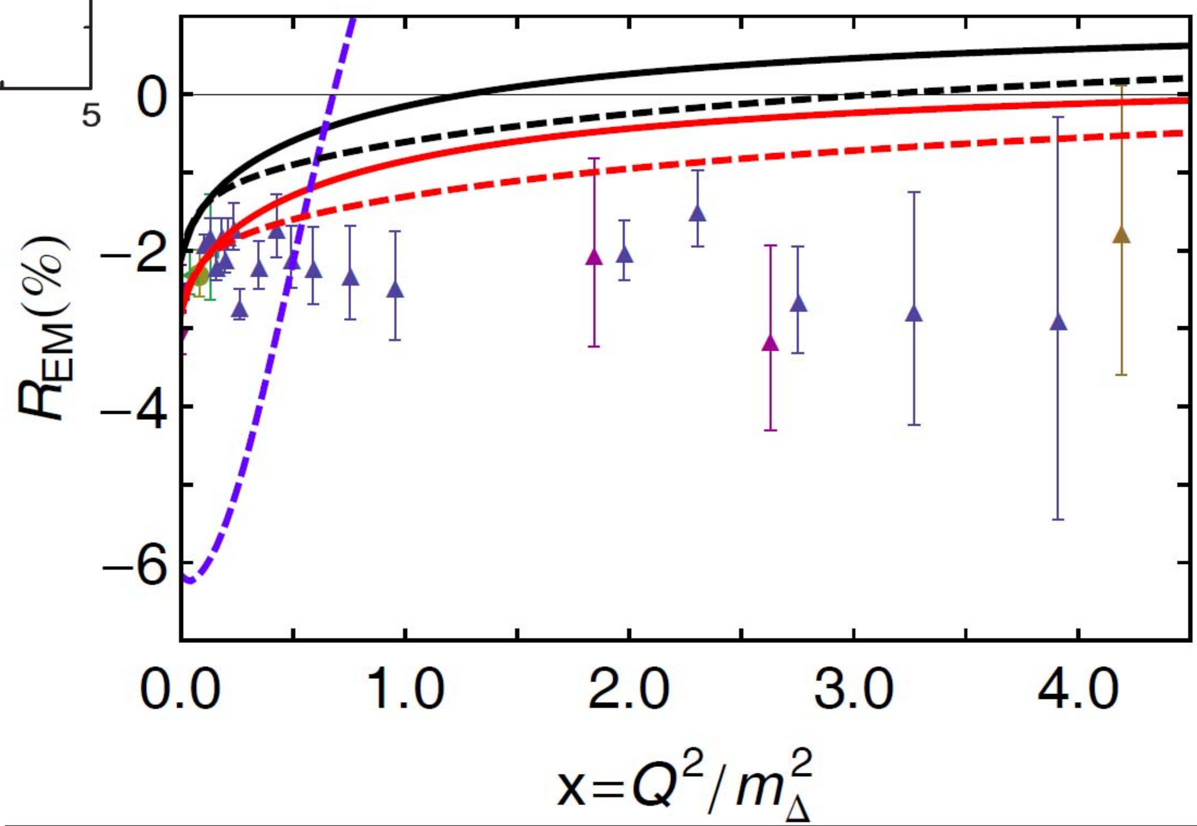
J. Segovia

contact interaction

sophisticated interaction

with momentum dependent κ

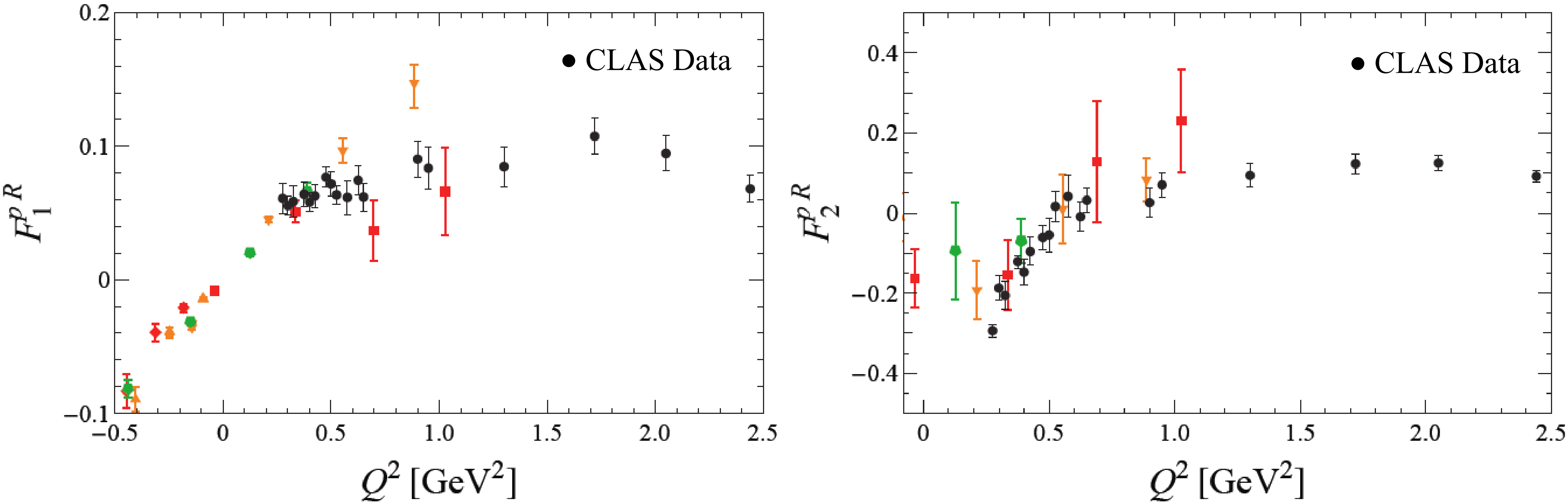
renormalized at real photon point



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

Roper Transition Form Factors in LQCD

$p(1440)P_{11}$ Huey-Wen Lin and S.D. Cohen



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

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

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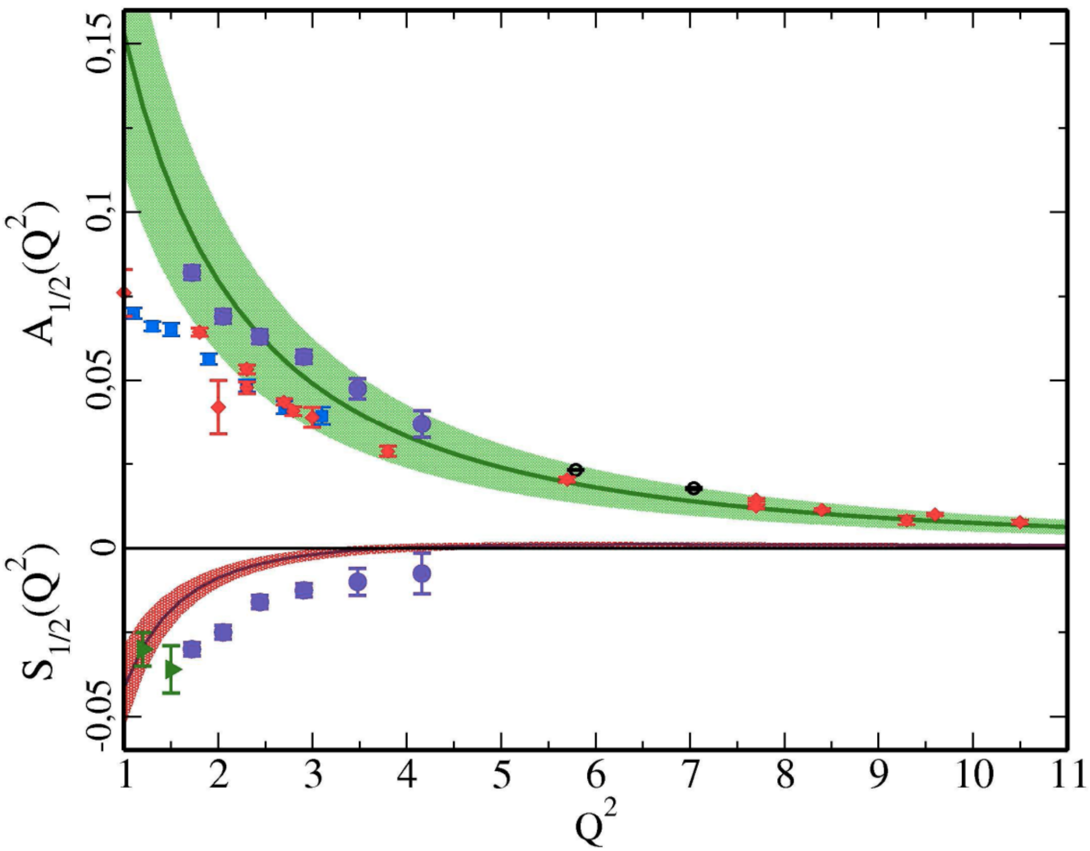
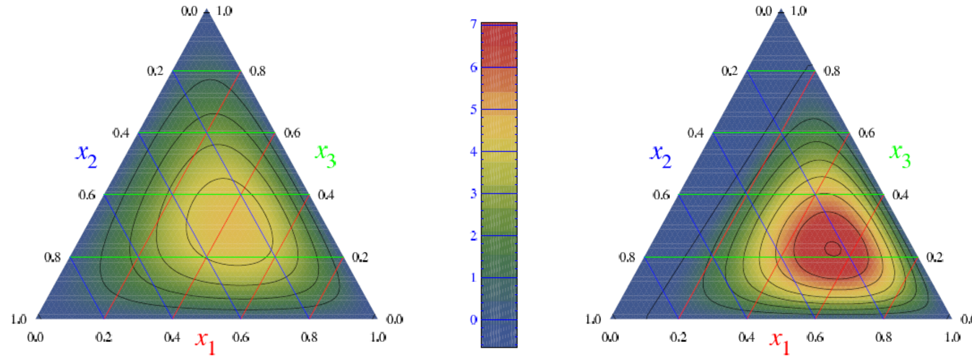
LQCD & Light Cone Sum Rule (LCSR) Approach

$N(1535)S_{11}$



N S_{11}



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

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

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

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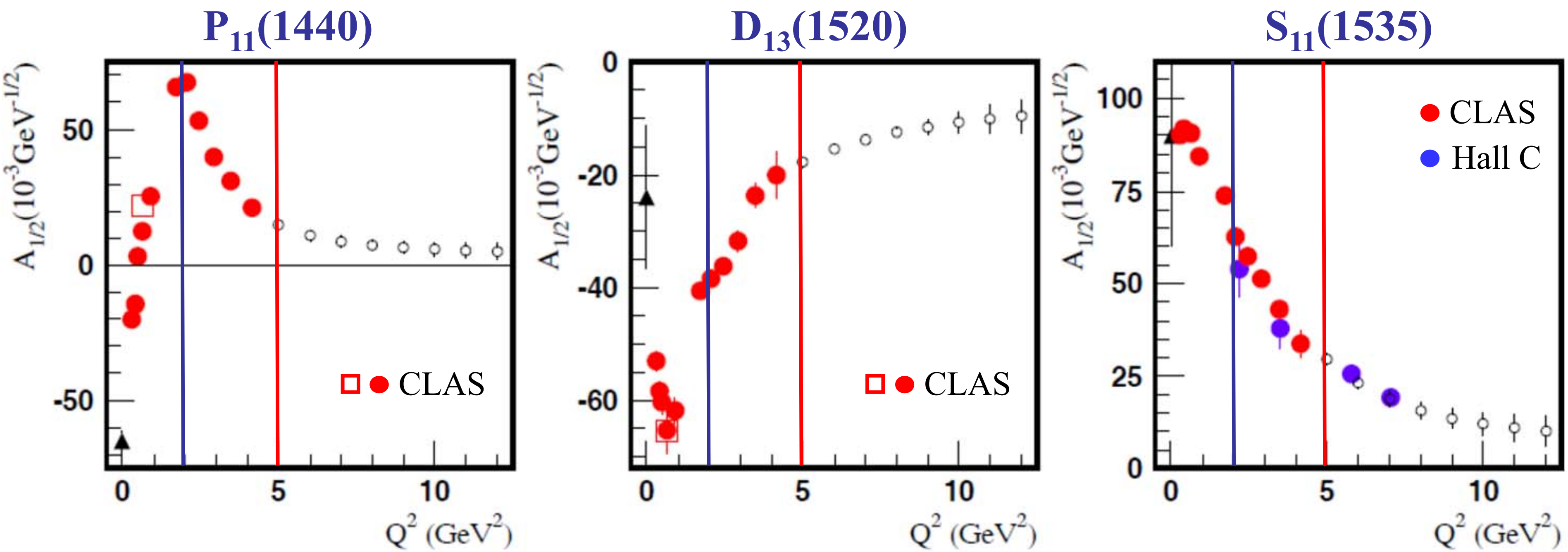
Anticipated N* Electrocouplings from Combined Analyses of Nπ/Nππ



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 $\gamma_v NN^*$ 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.

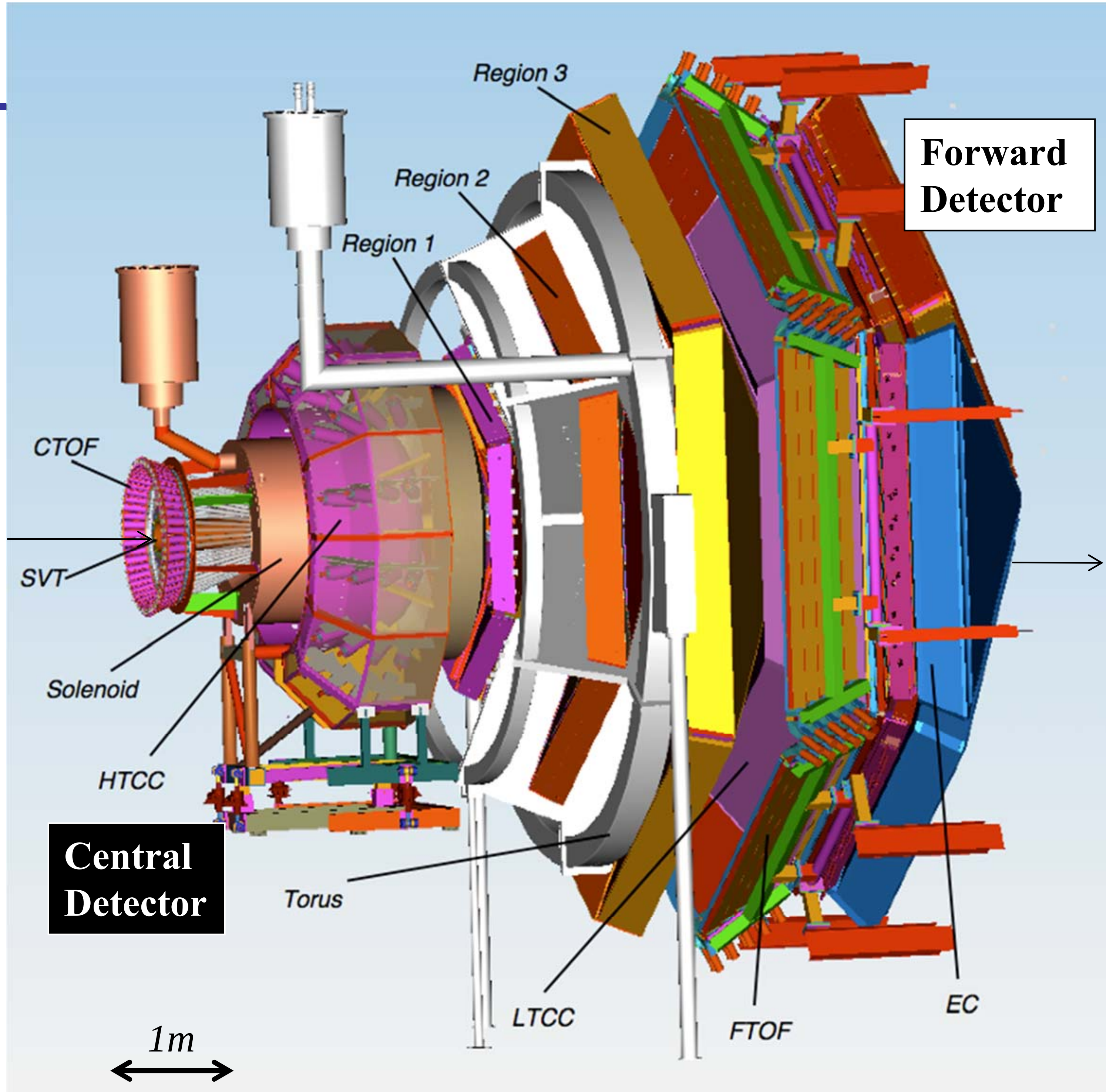
Summary

- We will measure and determine the electrocouplings $A_{1/2}$, $A_{3/2}$, $S_{1/2}$ as a function of Q^2 for prominent nucleon and Δ states,
  - see our Proposal http://www.physics.sc.edu/~gothe/research/pub/nstar12-12-08.pdf.
- Comparing our results with DSE, LQCD, LCSR, and rCQM will gain insight into
  - the strong interaction of dressed quarks and their confinement in baryons,
  - the dependence of the light quark mass on momentum transfer, thereby shedding light on dynamical chiral-symmetry breaking, and
  - the emergence of bare quark dressing and dressed quark interactions from QCD.
- This unique opportunity to understand origin of 98% of nucleon mass is also an experimental and theoretical challenge. A wide international collaboration is needed for:
  - the development of reaction models that will account for hard quark/parton contributions at high Q^2 and
  - the theoretical interpretation on N* electrocouplings, see our Review Article Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013) 1-99.
- Any constructive criticism, help, or participation is always most welcomed, contact:
  - Viktor Mokeev mokeev@jlab.org or Ralf Gothe gothe@sc.edu.

E12-09-003

… and more?

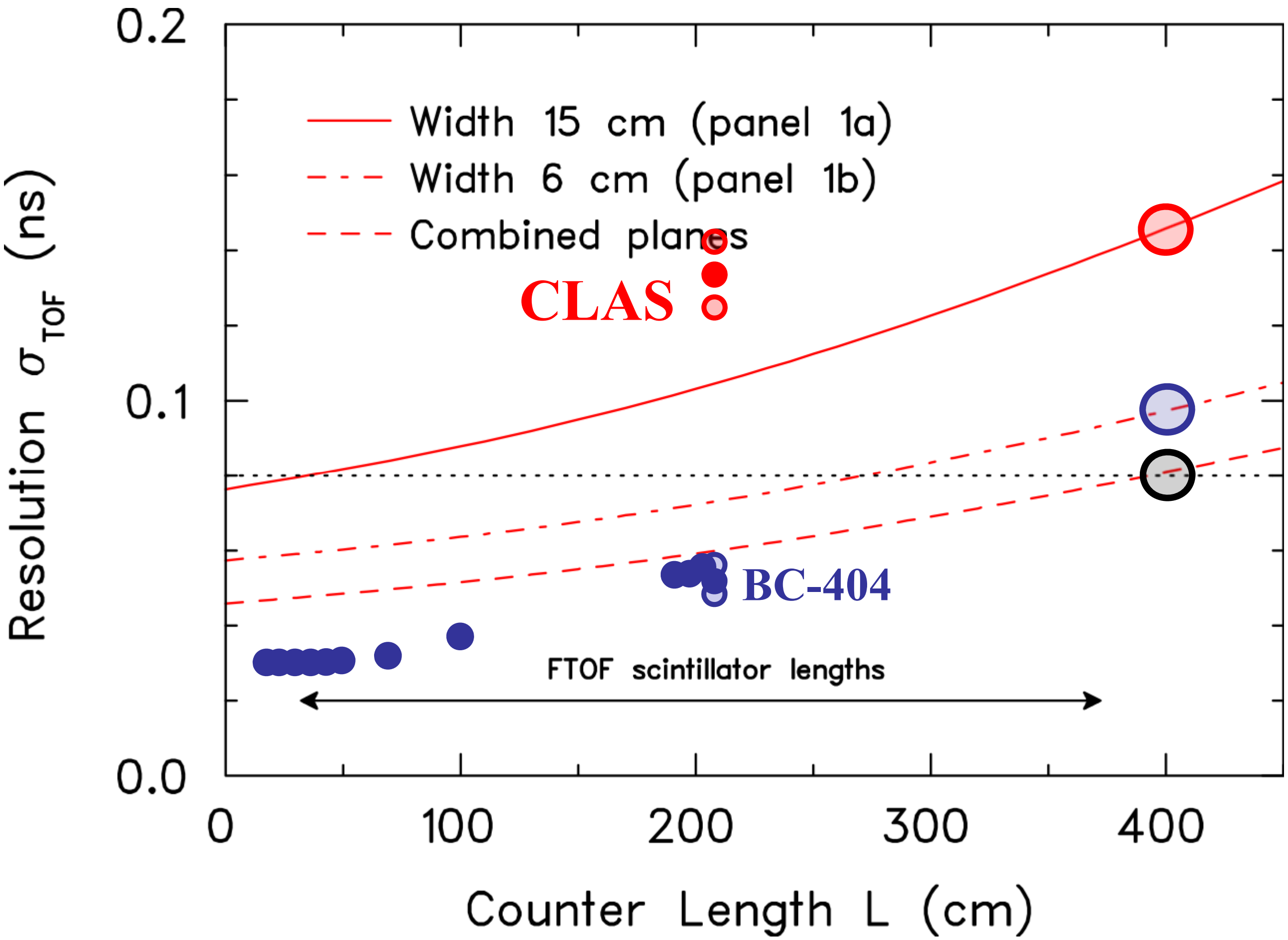
CLAS12

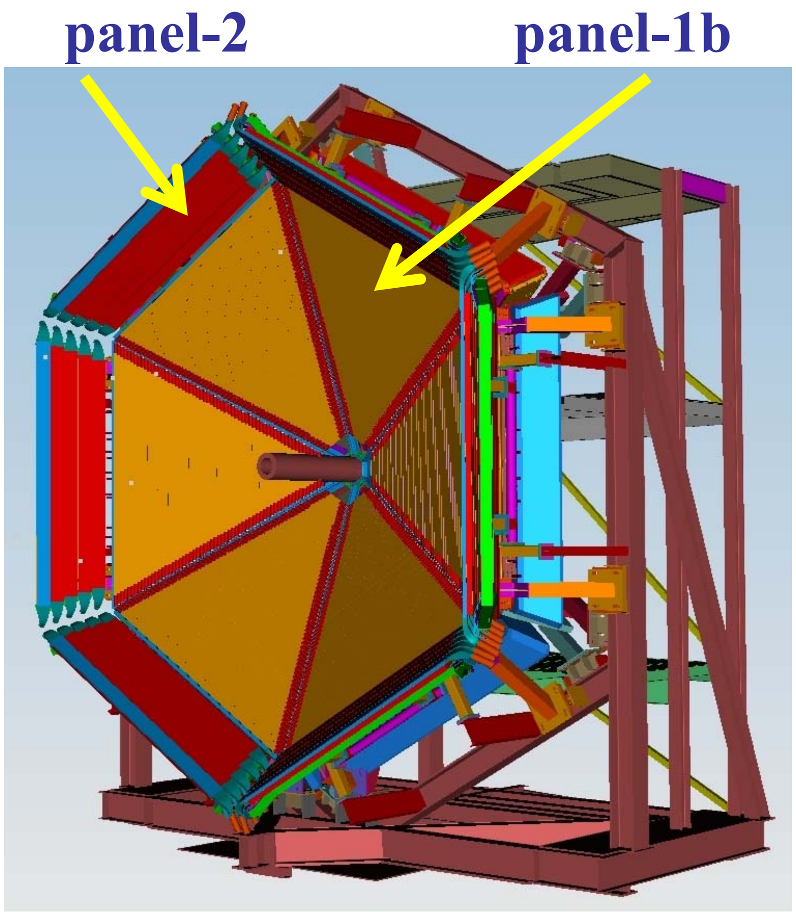


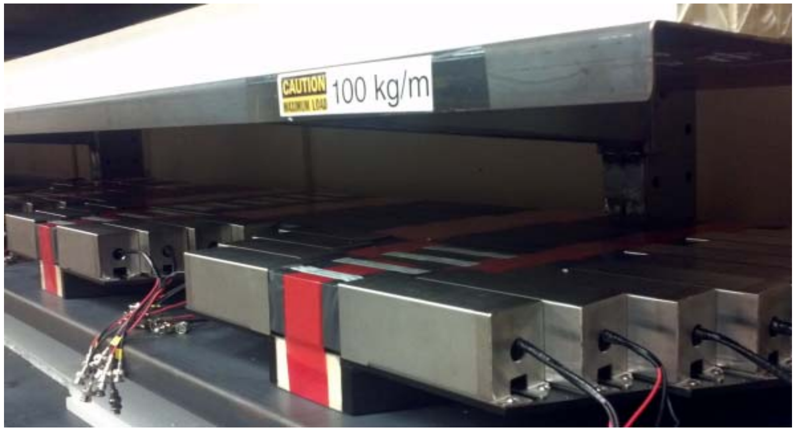
- Luminosity > 10^{35} $cm^{-2}s^{-1}$
- Hermeticity
- Polarization

- 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

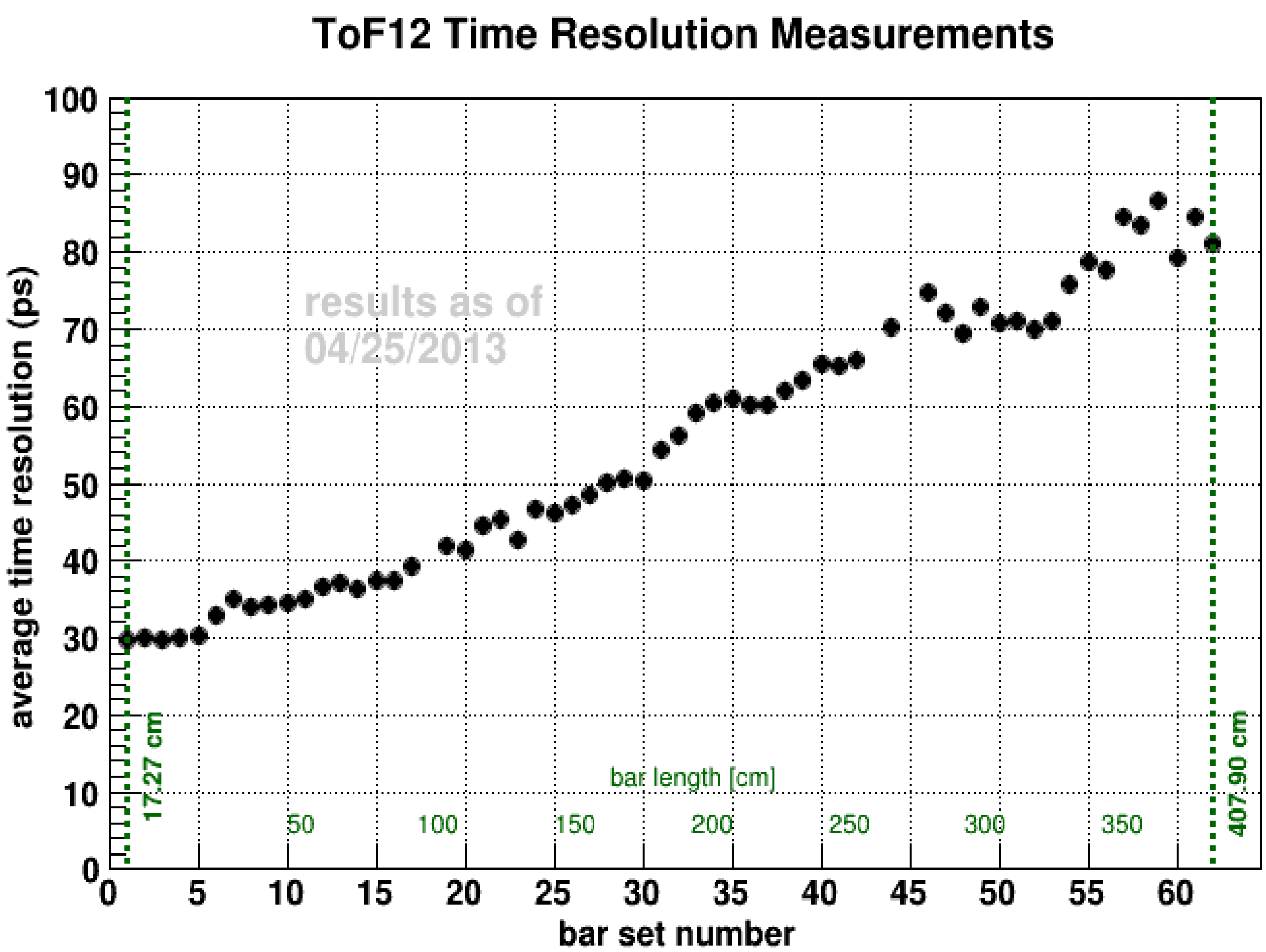


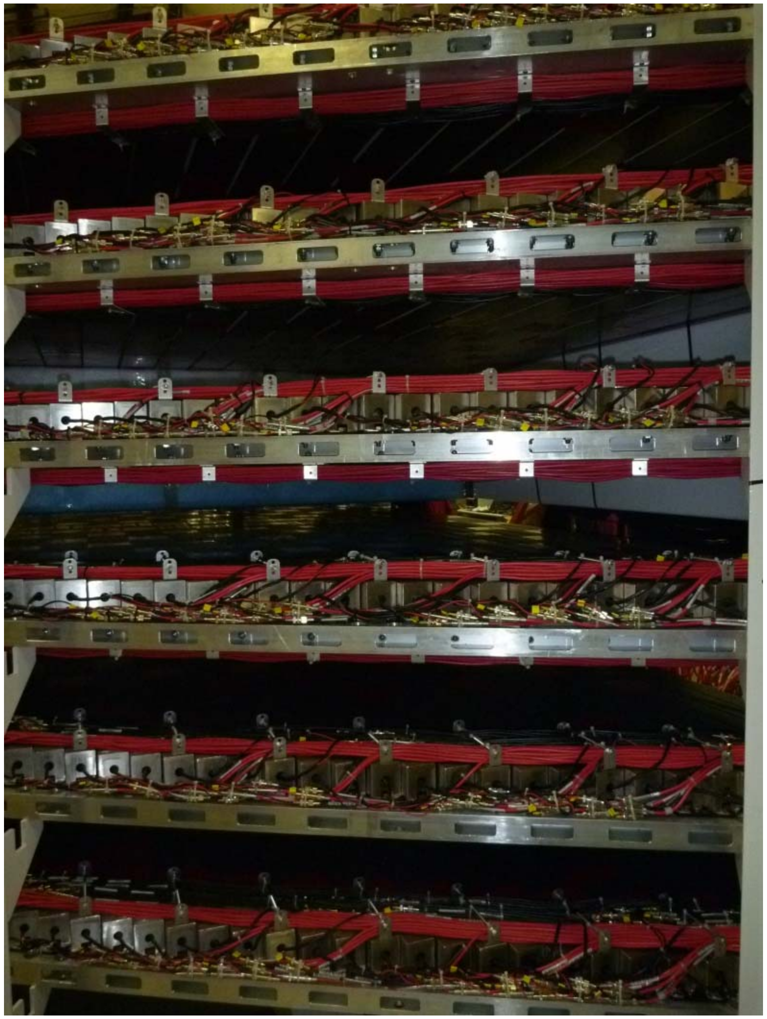


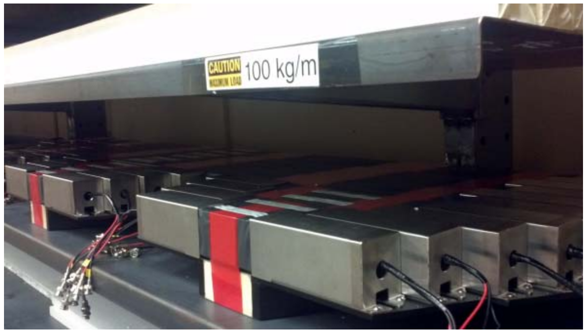


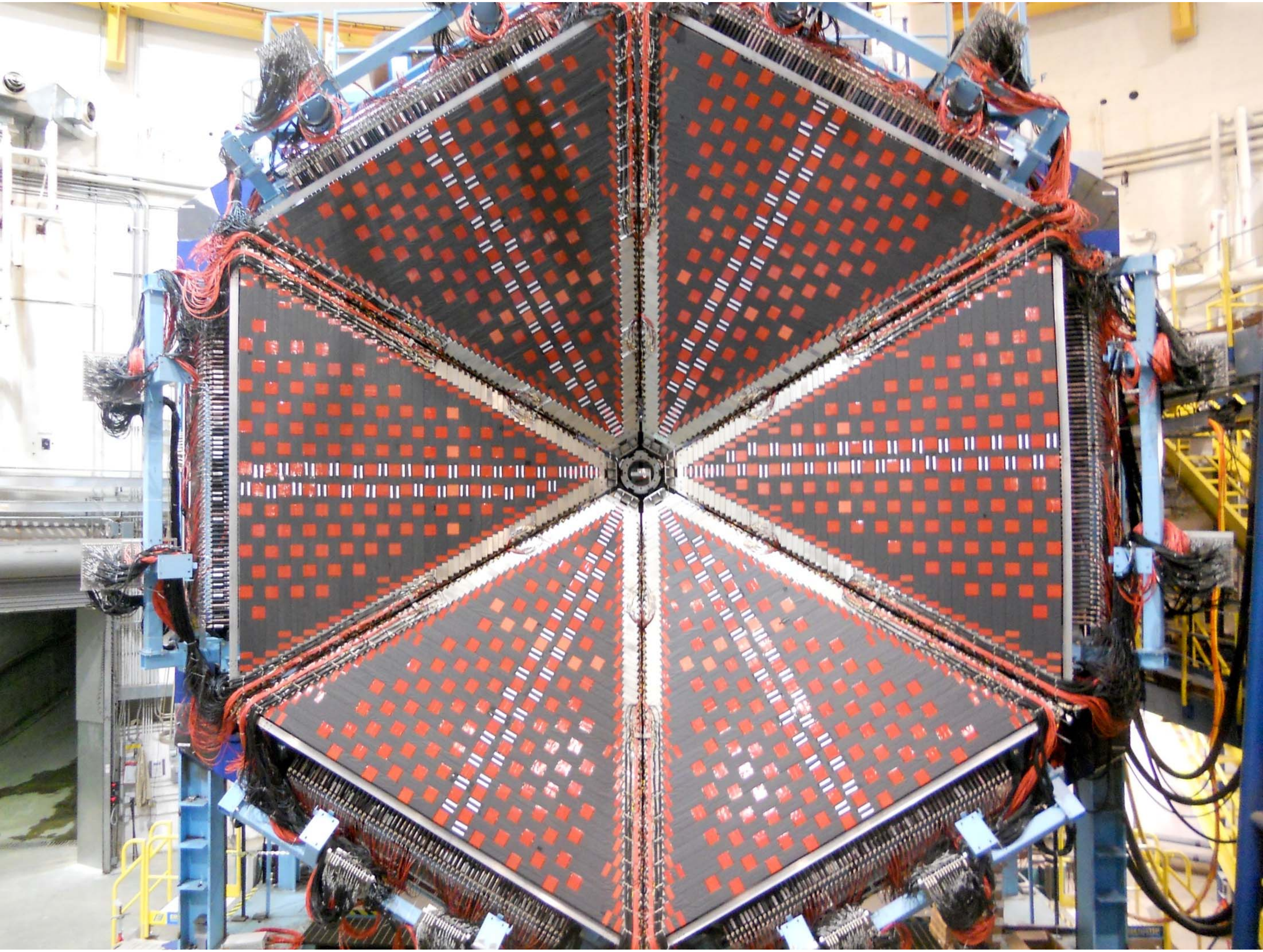
World-record time resolution of 48 ns averaged over the full length of 210 cm

New Forward Time of Flight Detector for CLAS12









Nucleon Resonances: From Photoproduction to High Photon Virtualities

ECT* Workshop 2015, October 12-16, Trento, Italy

- Experimental Results, Current Projects, and Future Developments
- Phenomenological Analysis Approaches
- Dynamical Coupled Channel Analyses
- N* Spectrum and Structure from Lattice QCD
- N* Physics from Dyson-Schwinger Equations
- Light-Front Sum Rules and Quark Distribution Amplitudes
- Quark-Hadron Duality
- Holographic and Light-Front QCD
- QCD-Based Constituent Quark Models