New Opportunities in Nucleon Resonances

Ralf W. Gothe for the CLAS Collaboration

UNIVERSITY OF SOUTH CAROLINA

Teleworkshop on Strong QCD from Hadron Structure Experiments
June 7-10, 2021, Nanjing University, China

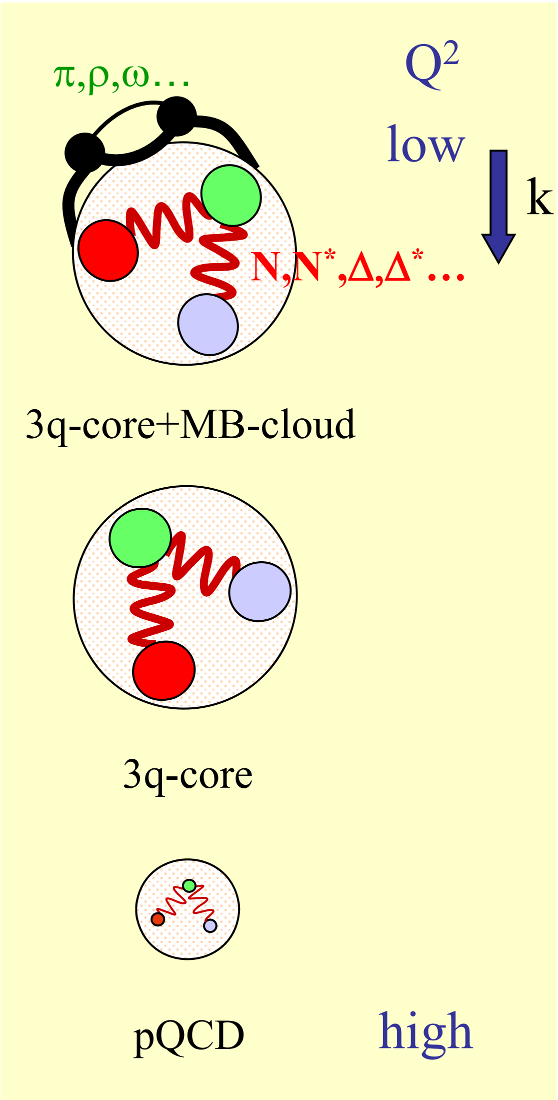
南京大學 NANJING UNIVERSITY | 非微扰物理研究所 Institute for Nonperturbative Physics | apctp asia pacific center for theoretical physics

- **Virtual Lepton Scattering:** Hadronic versus partonic perspective!
- **$\gamma_v NN^*$ Form Factors:** Probing emergent dressing of bound valence quark!
- **Status Quo and Outlook:** New results with extended scope and kinematics!

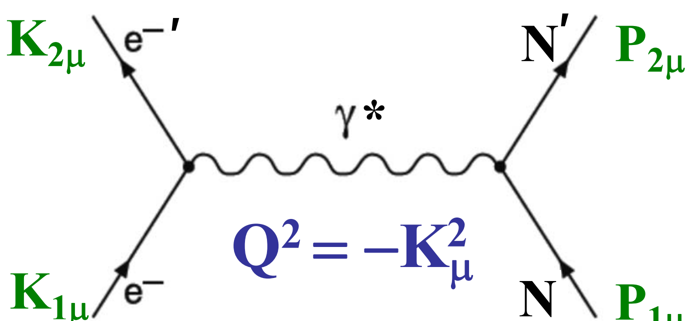
This work is supported in parts by the National Science Foundation under Grant PHY 1812382.

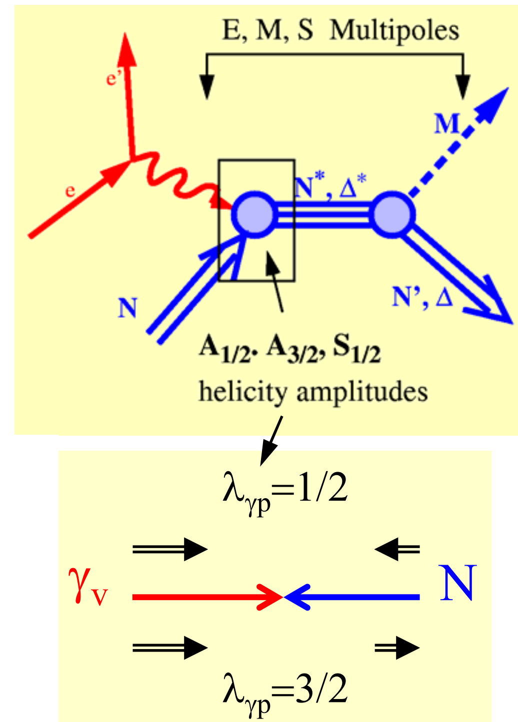
Electron Scattering

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.





Structure Analysis of the Baryon

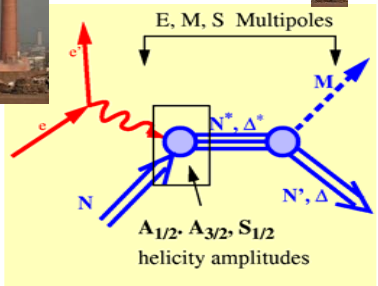
Demolition of a chimney at the "Henninger Brewery" in Frankfurt am Main, Germany, on 2 December 2006

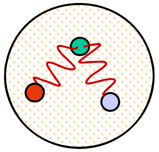
hard and confined

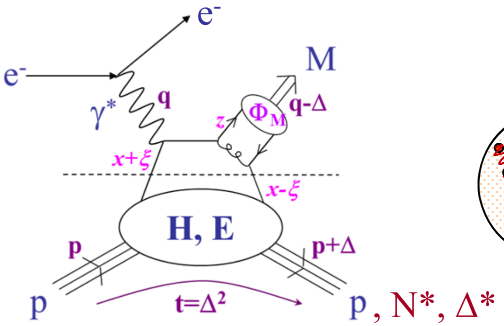
…

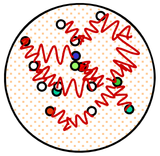
hard and soft

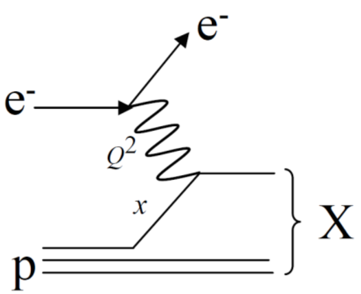
hard and quasi-elastic





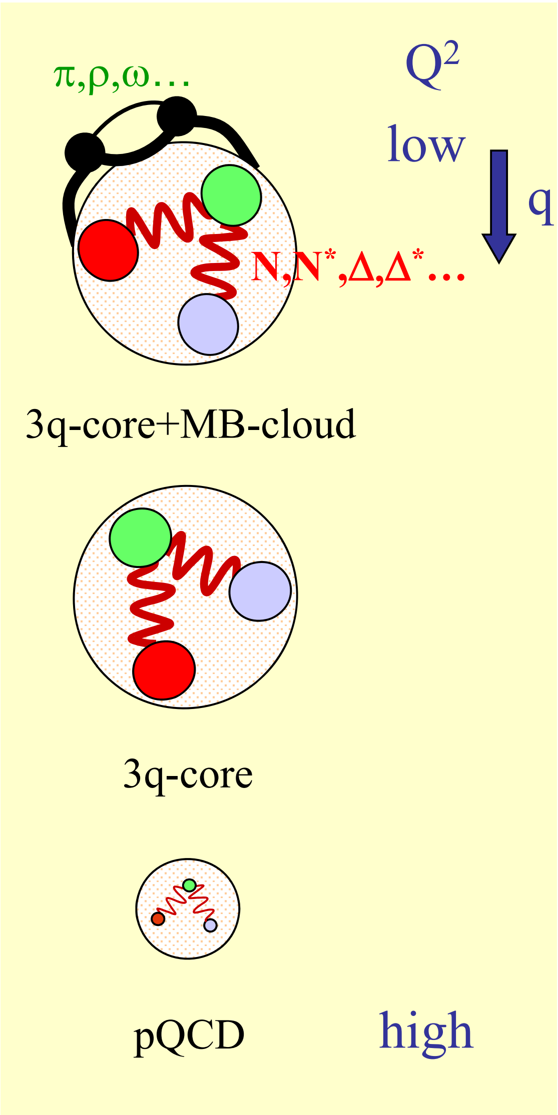






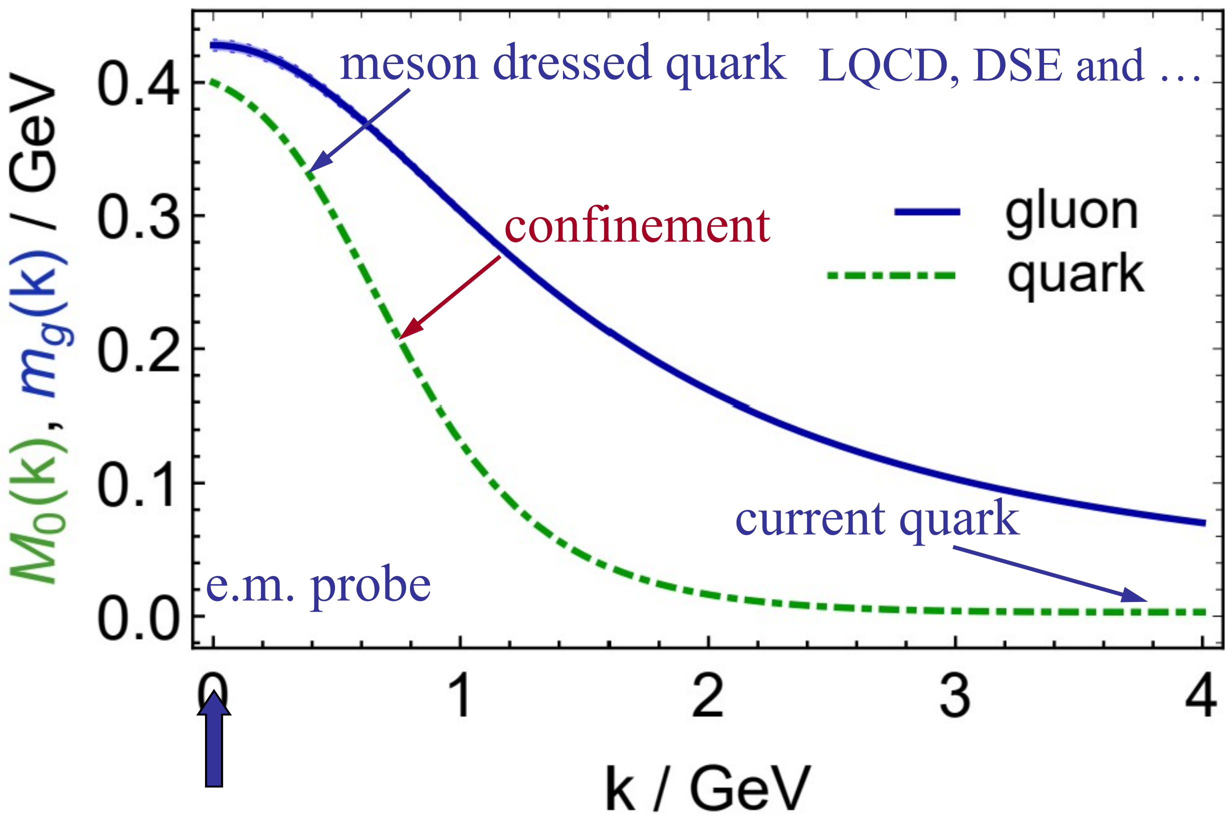
Transition Form Factors

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.

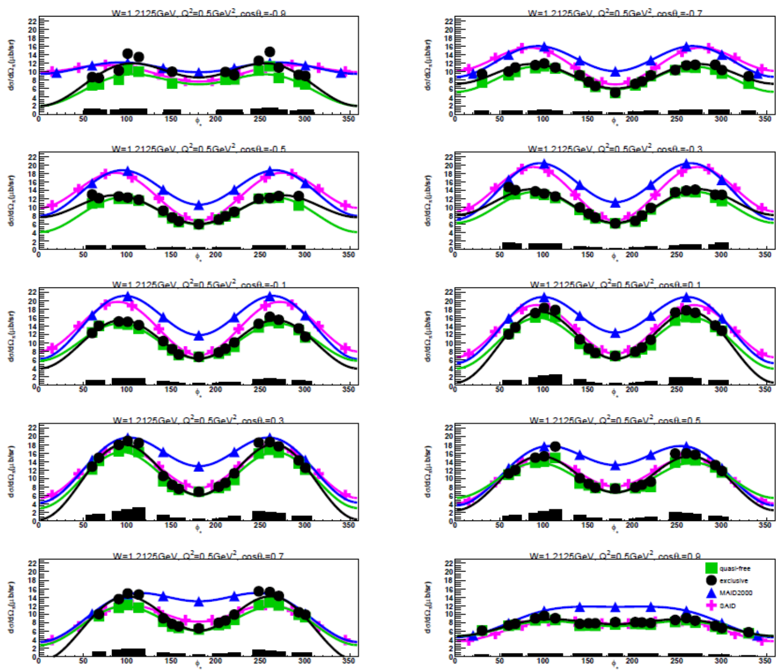
Zhu-Fang Cui et al., Chin. Phys. C **44** (2020) 083102/1-10



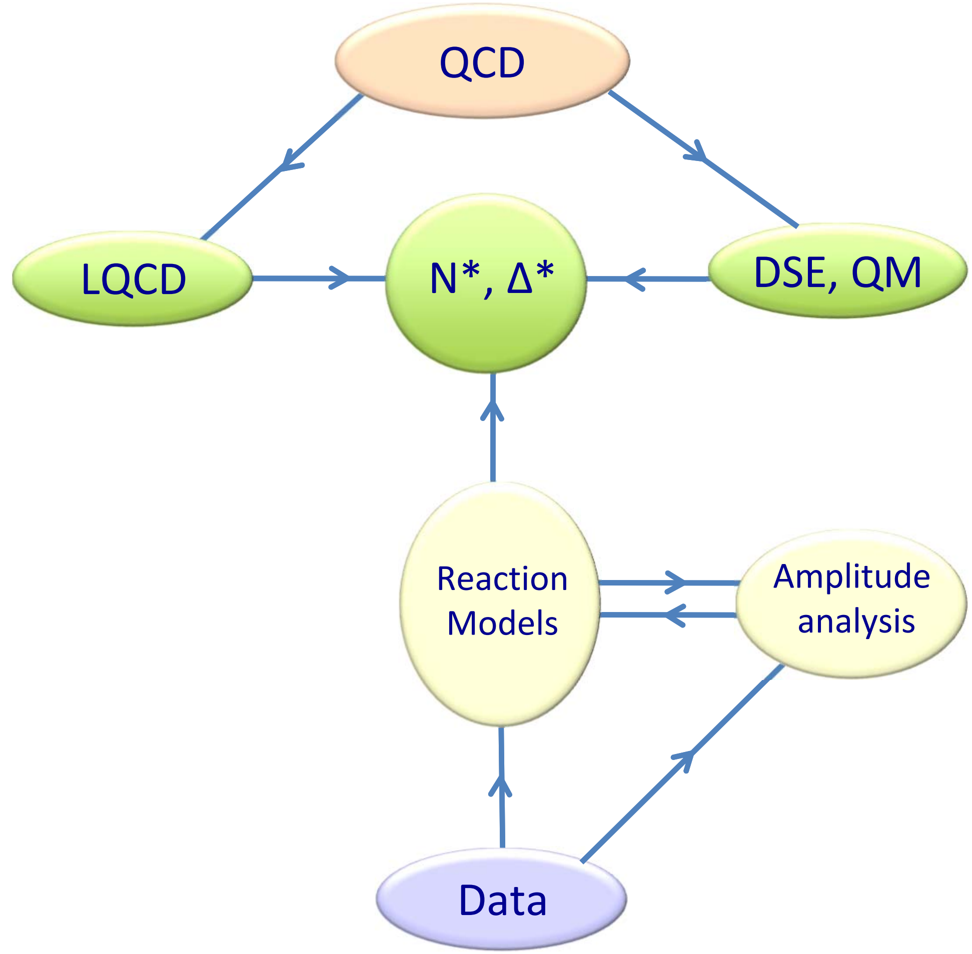
Data-Driven Data Analyses

Consistent Results

Single Pion



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



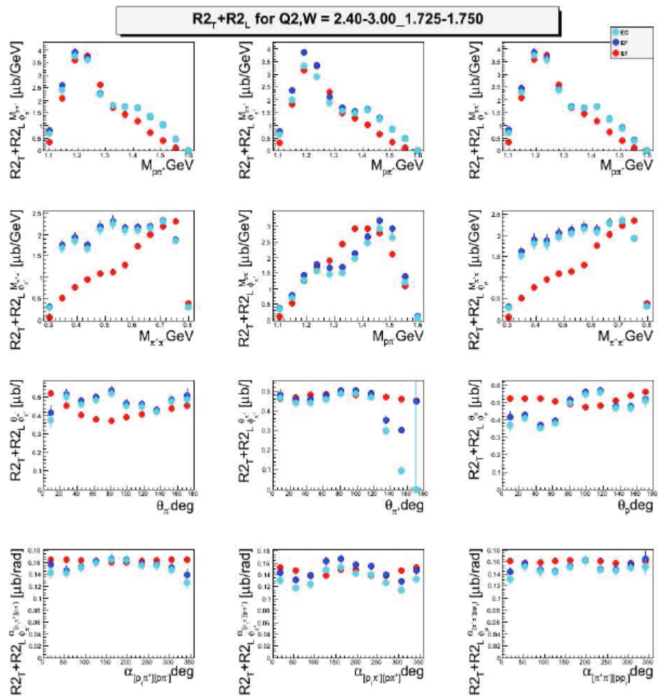
Hadronic production

Electromagnetic production

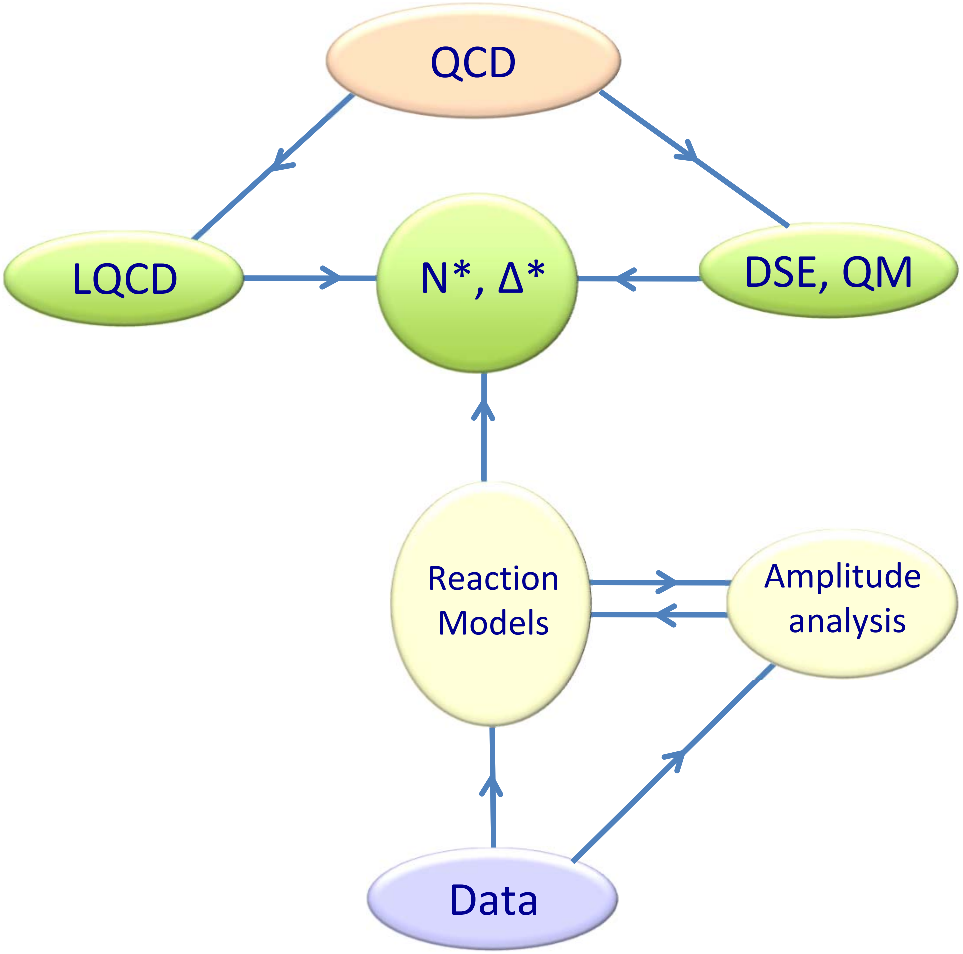
Data-Driven Data Analyses

Consistent Results

Double Pion



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



Hadronic production

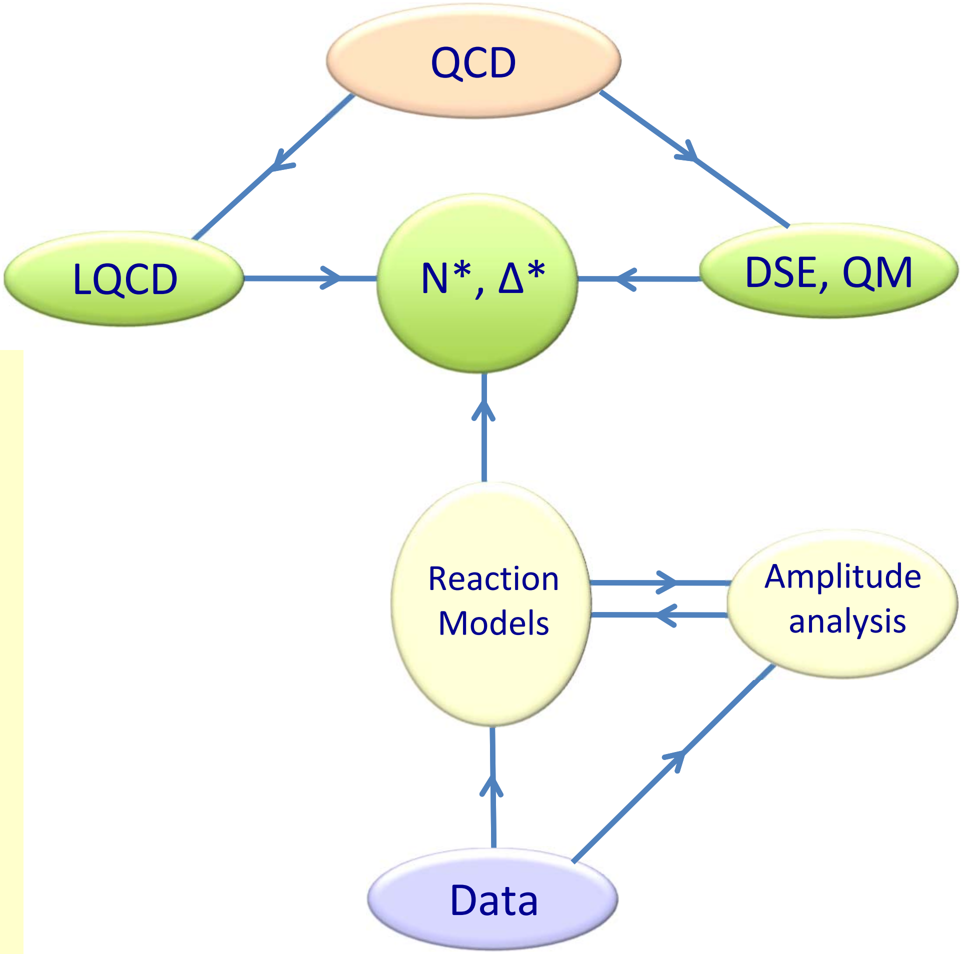
Electromagnetic production

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

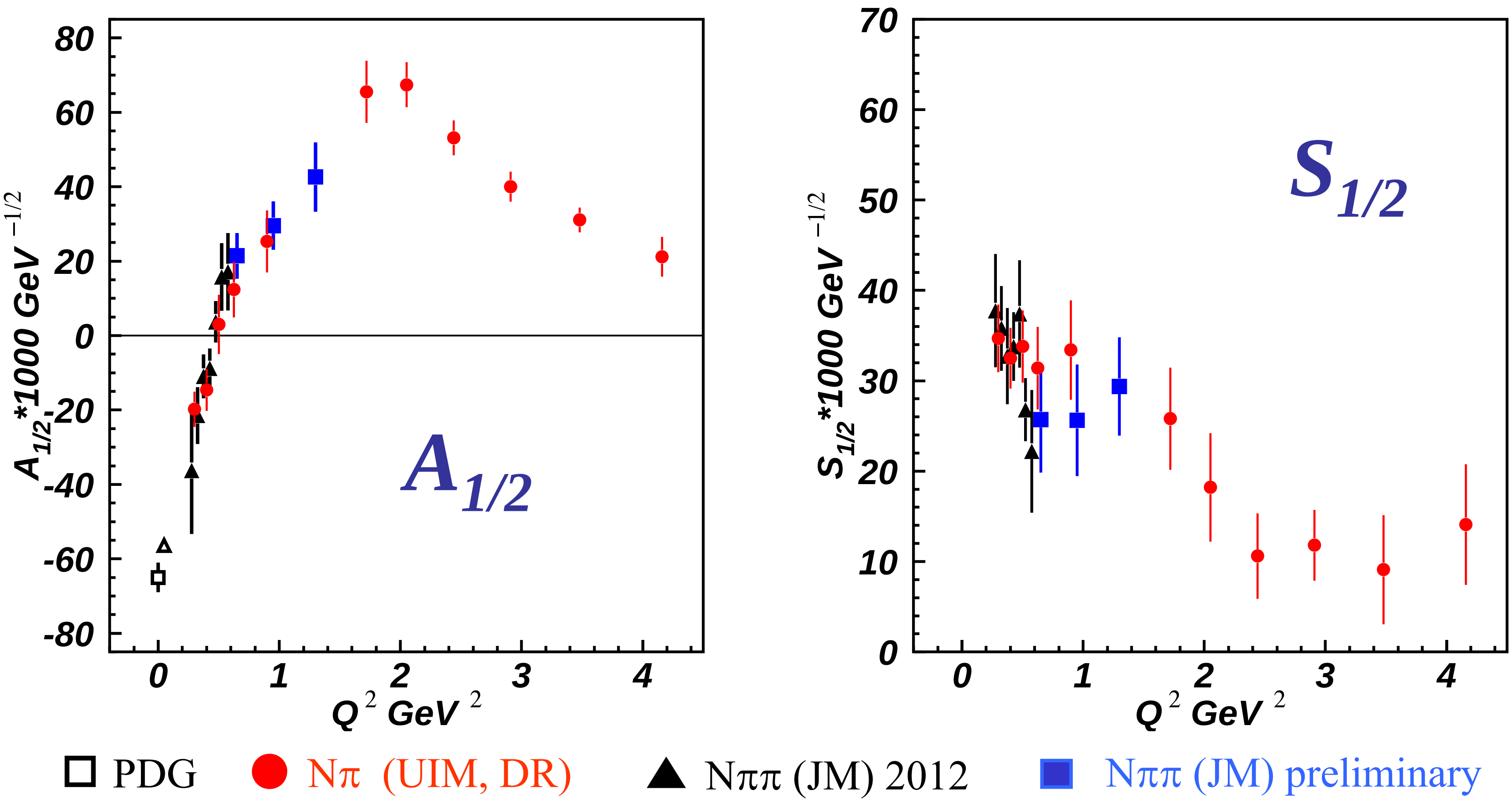
Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013) 1-99



Hadronic production

Electromagnetic production

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



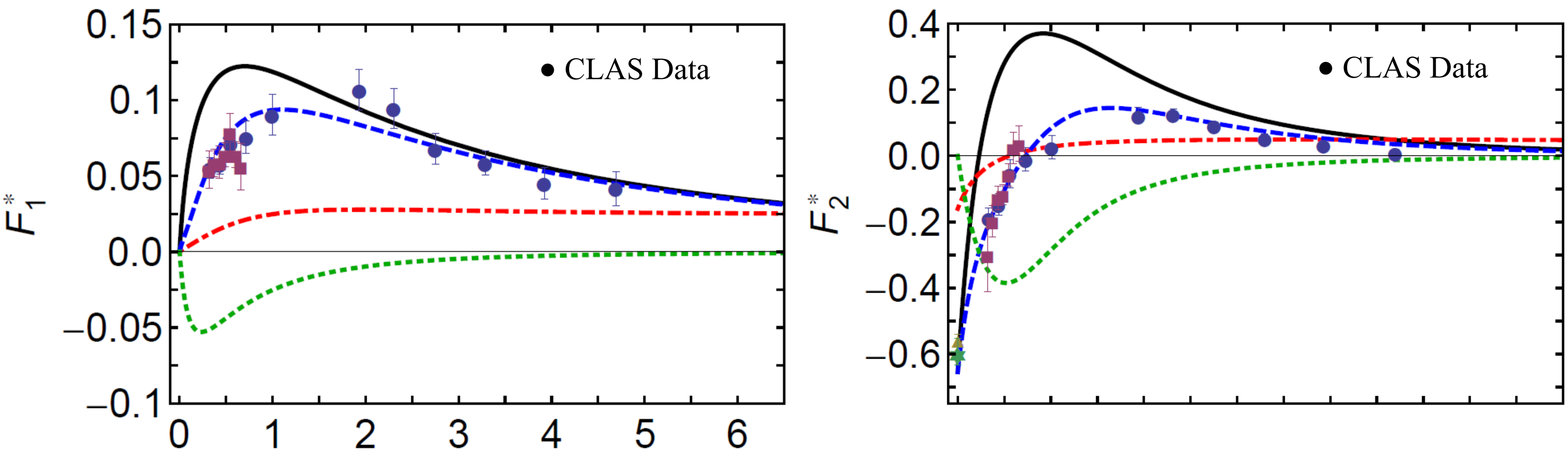
Consistent results obtained in the low-lying resonance region by independent analyses in the exclusive Nπ and $p\pi^+\pi^-$ final-state channels – that have fundamentally different mechanisms for the nonresonant background – underscore the capability of the reaction models to extract reliable resonance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

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

Roper Transition Form Factors in DSE Approach

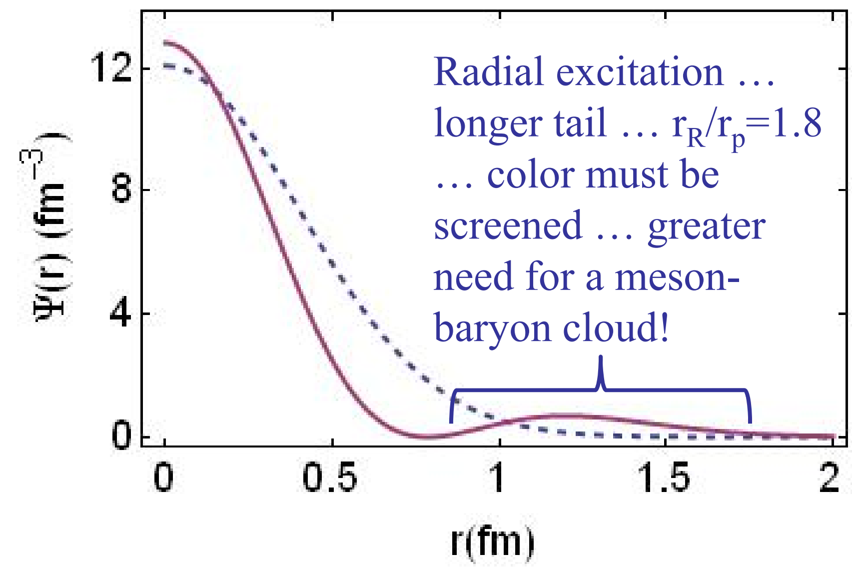
N(1440)P_{11}

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



$x = Q^2/m_N^2$

DSE Contact
DSE Realistic
Inferred meson-cloud contribution
Anticipated complete result

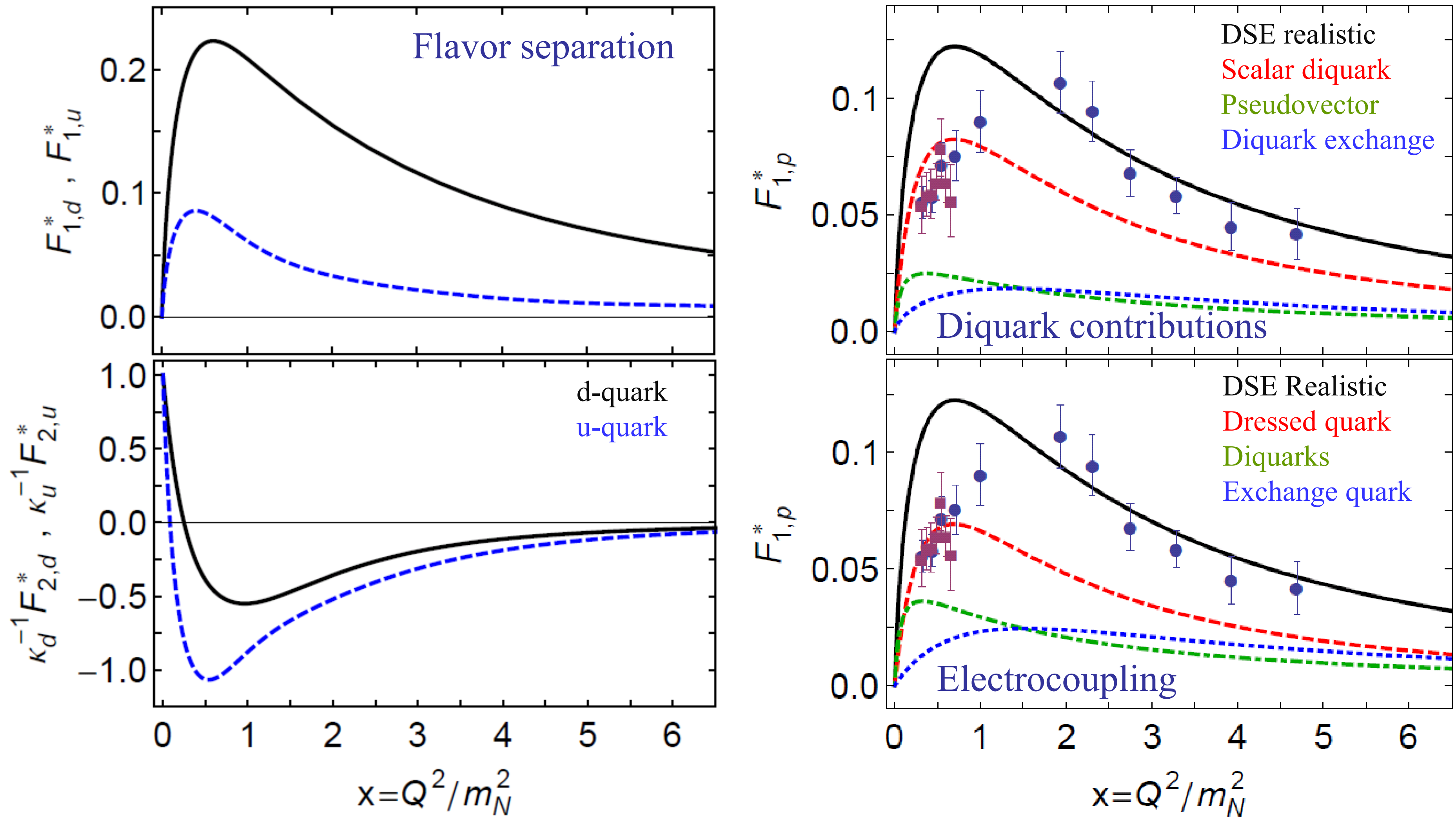


Importantly, the existence of a zero in F_2 is not influenced by meson-cloud effects, although its precise location is.

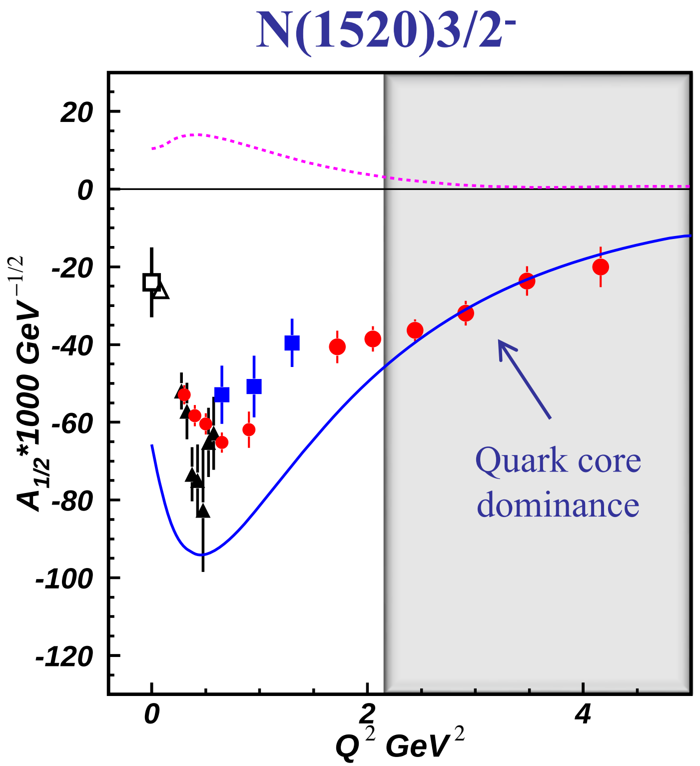
Roper Transition Form Factors in DSE Approach

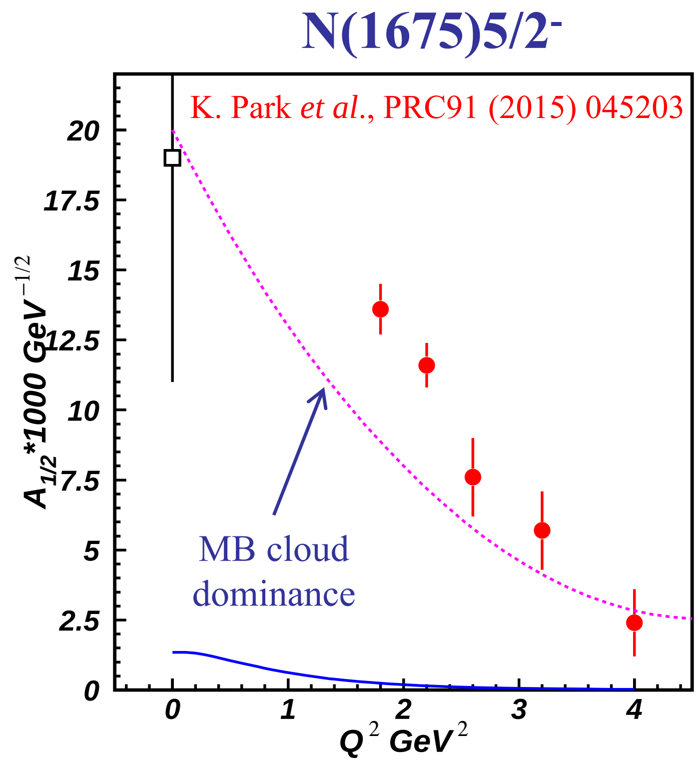
$N(1440)P_{11}$

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



Interplay between Meson-Baryon Cloud and Quark Core





Argonne-Osaka MB dressing (absolute values)

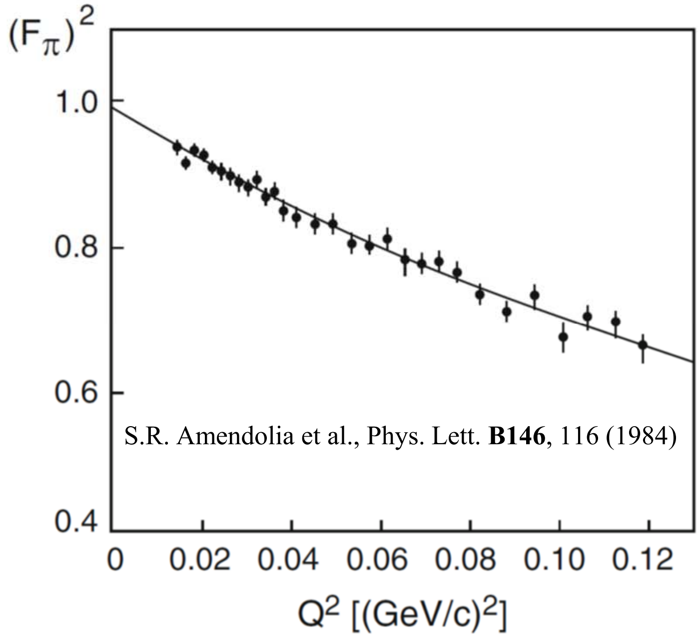
E. Santopinto and M. Giannini, PRC 86 (2012) 065202

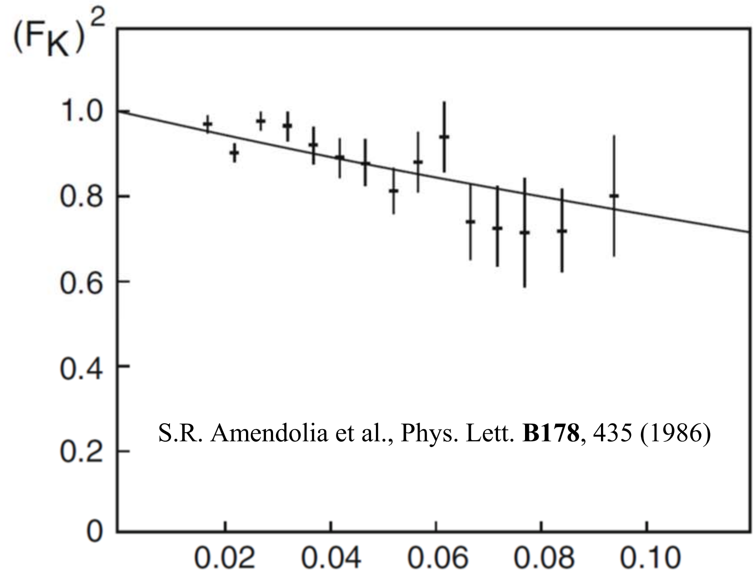
The almost direct access to

- quark core from the data on $N(1520)3/2^-$
- meson-baryon cloud from the data on $N(1675)5/2^-$

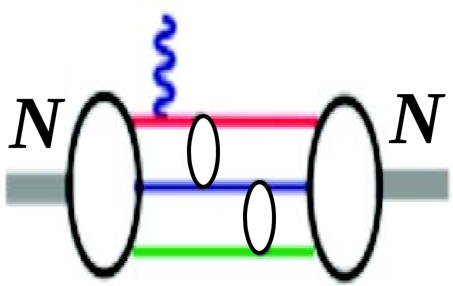
sheds light on the transition from the confined quark to the colorless meson-baryon structure and its dependents on the N* quantum numbers.

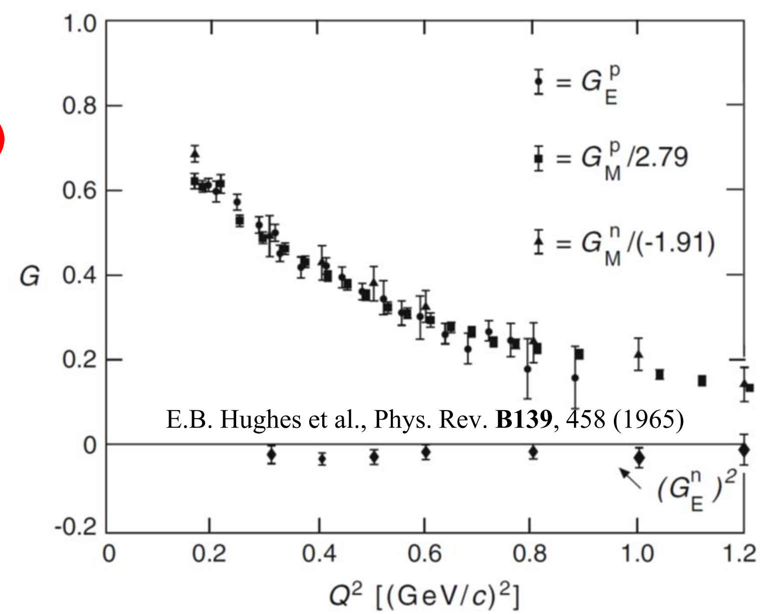
History of Form Factors



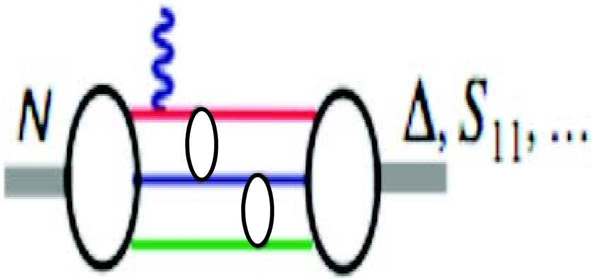


$$F(Q^2) = G_E(Q^2) = \left(1 + Q^2/a^2\hbar^2\right)^{-2}$$

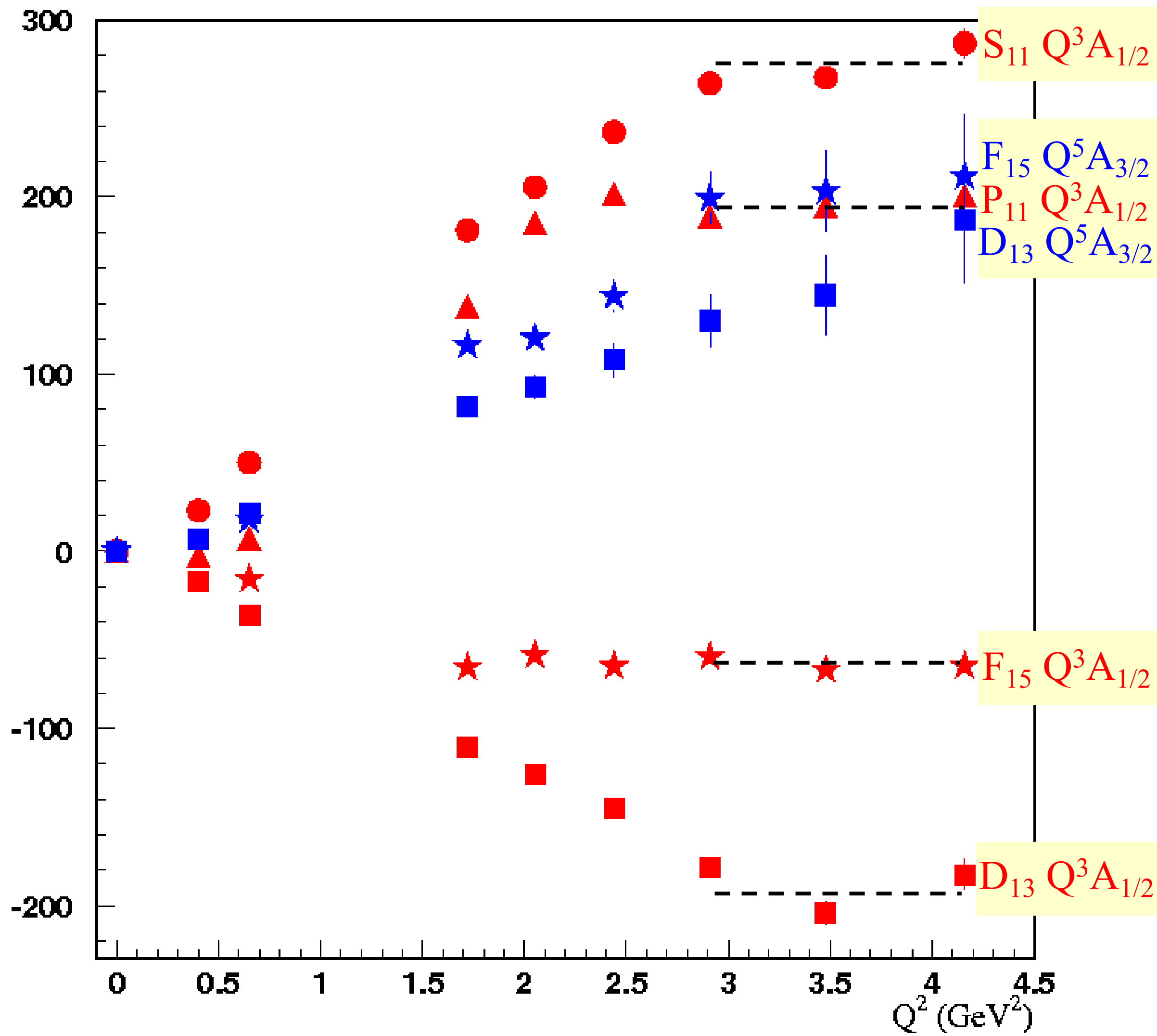




Evidence for the Onset of Precocious Scaling?



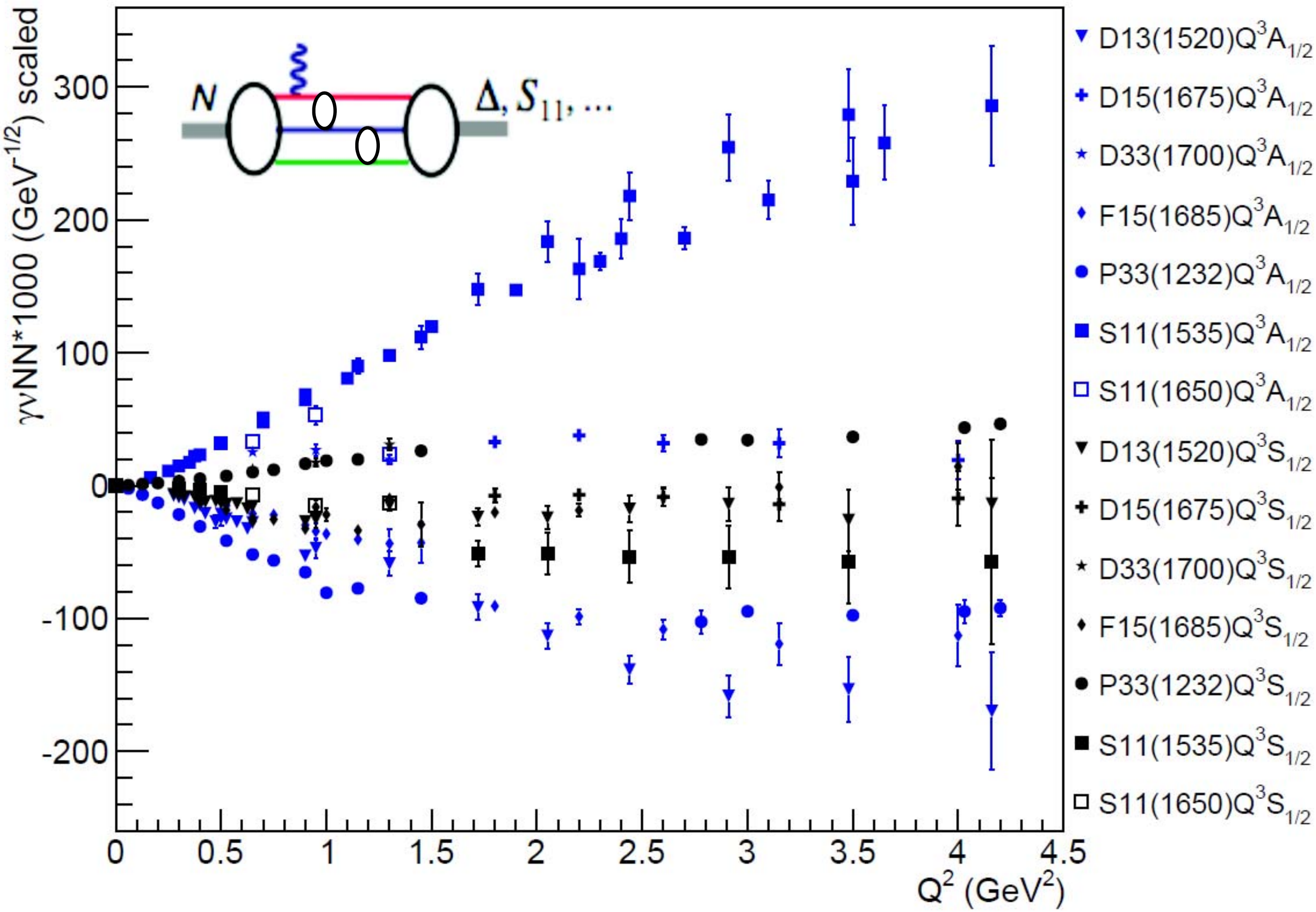
I. G. Aznauryan *et al.*, Phys. Rev. C80, 055203 (2009)



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

Evidence for the Onset of Precocious Scaling?

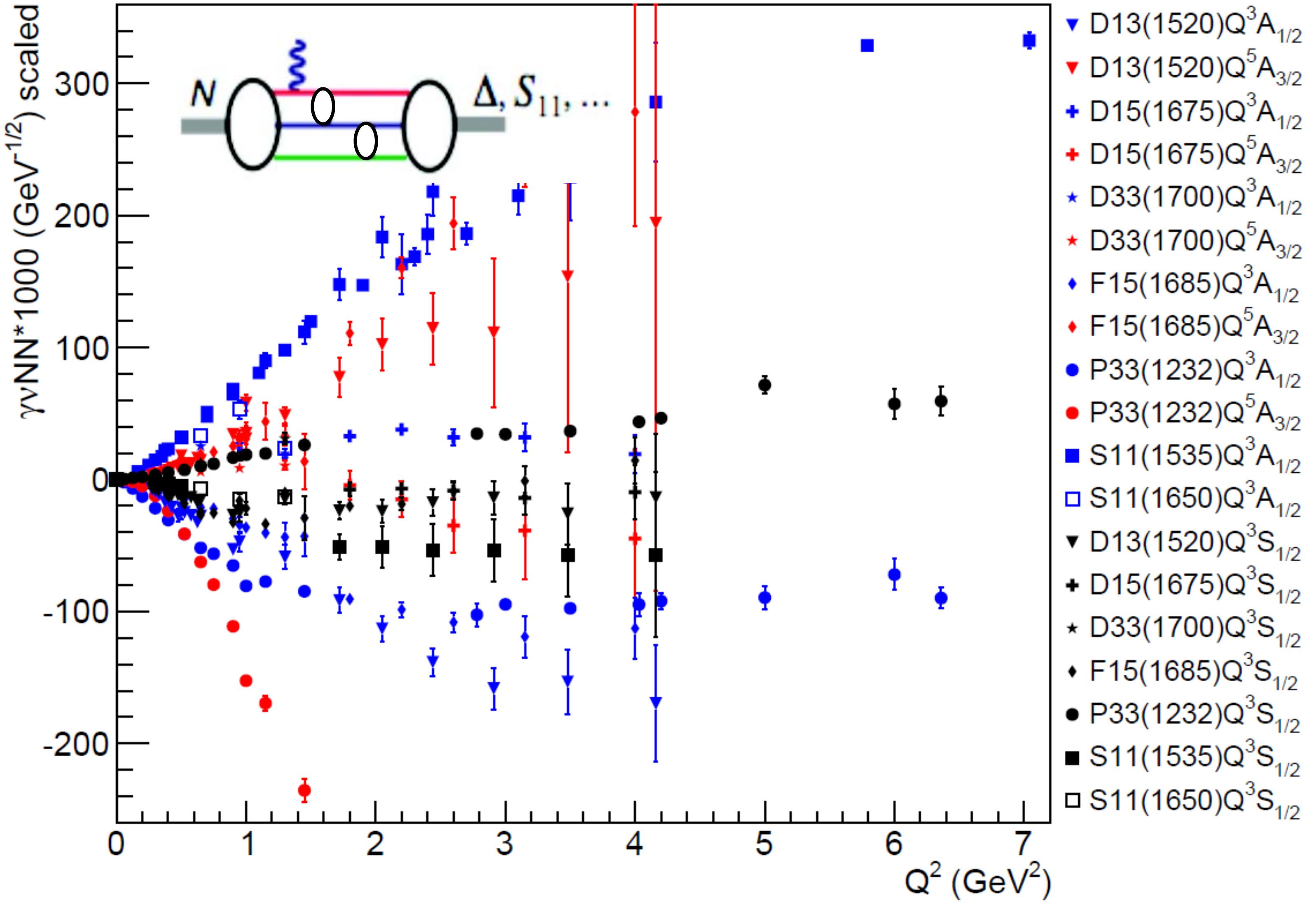
Ye Tian



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

Evidence for the Onset of Precocious Scaling?

Ye Tian

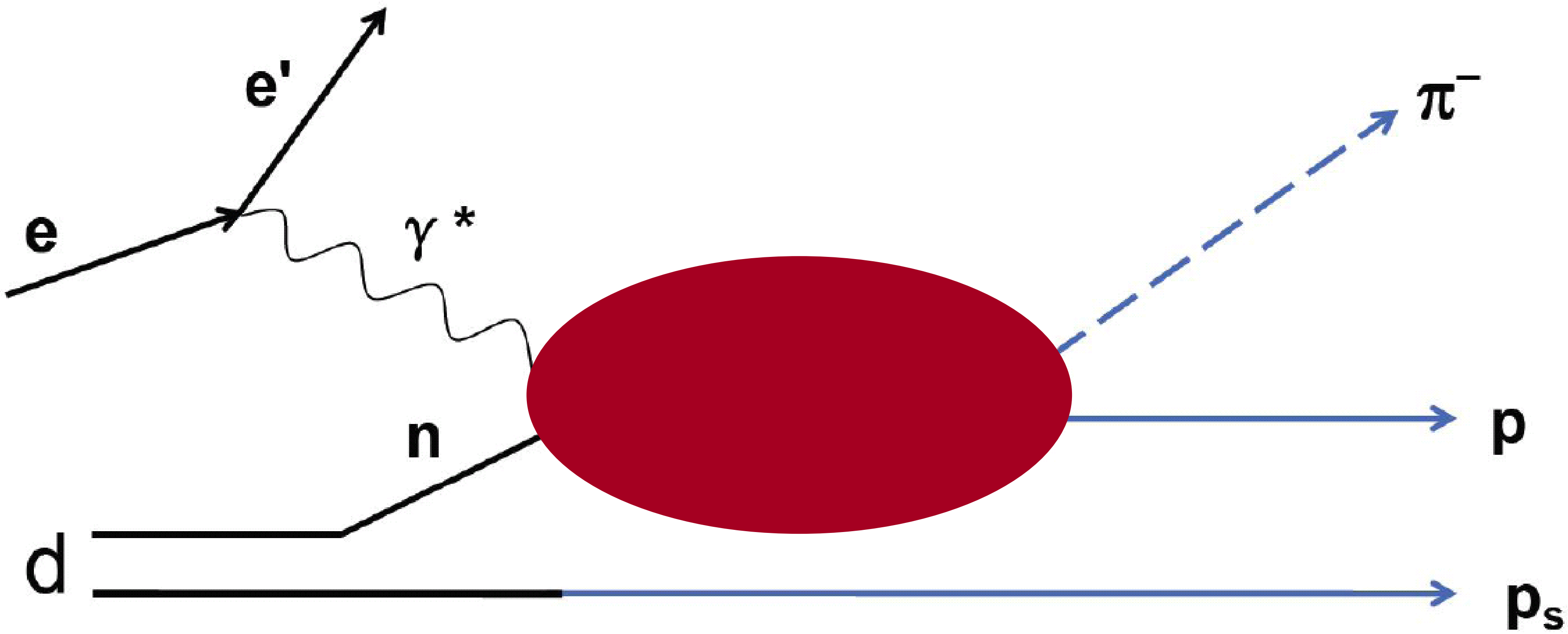


V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)

New Experimental Approaches & Results

Exclusive Single π⁻ Electroproduction off the Deuteron

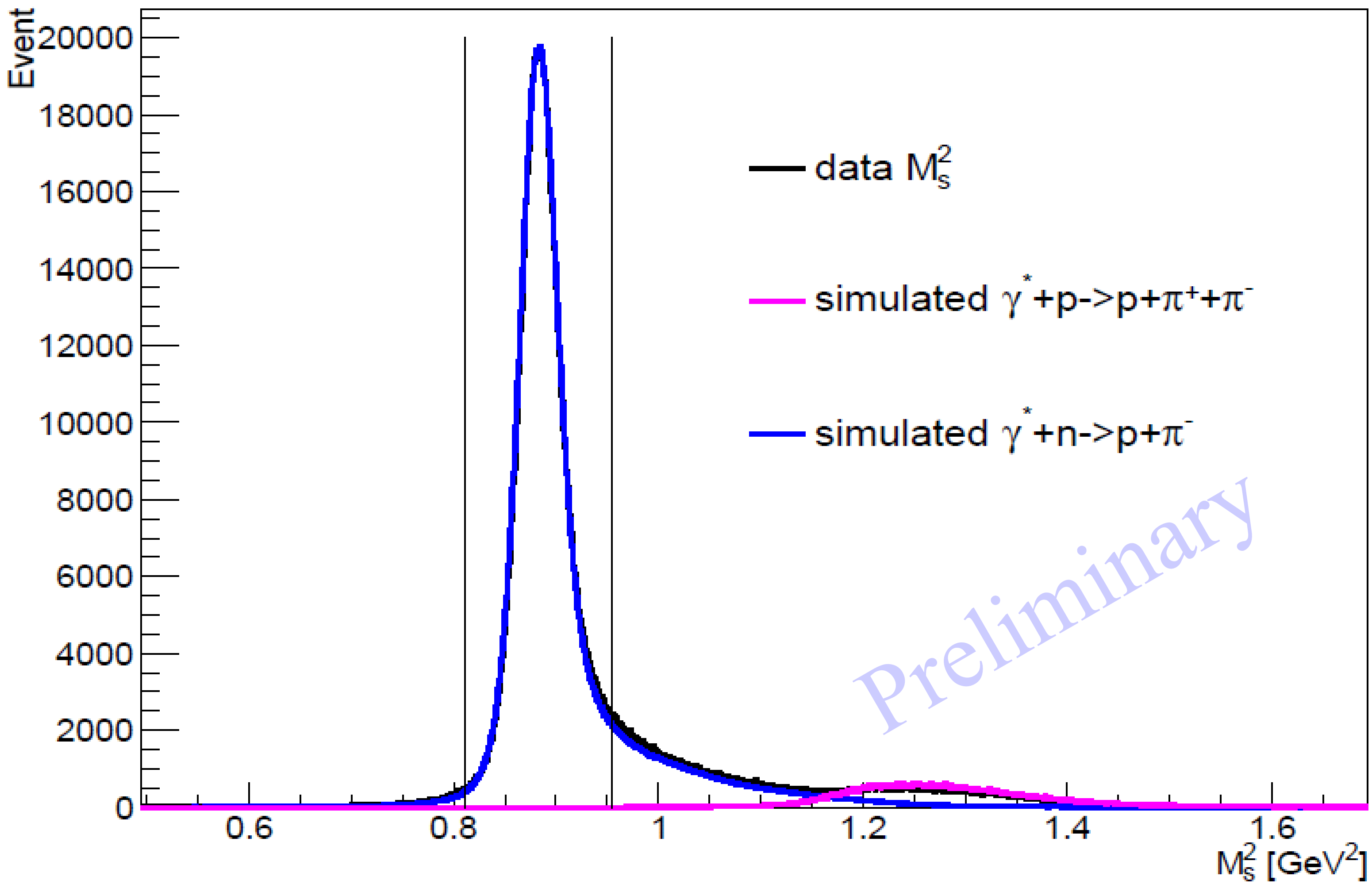
Ye Tian



Exclusive ⇒ Spectator ⇒ Quasi-Free ⇒ FSI

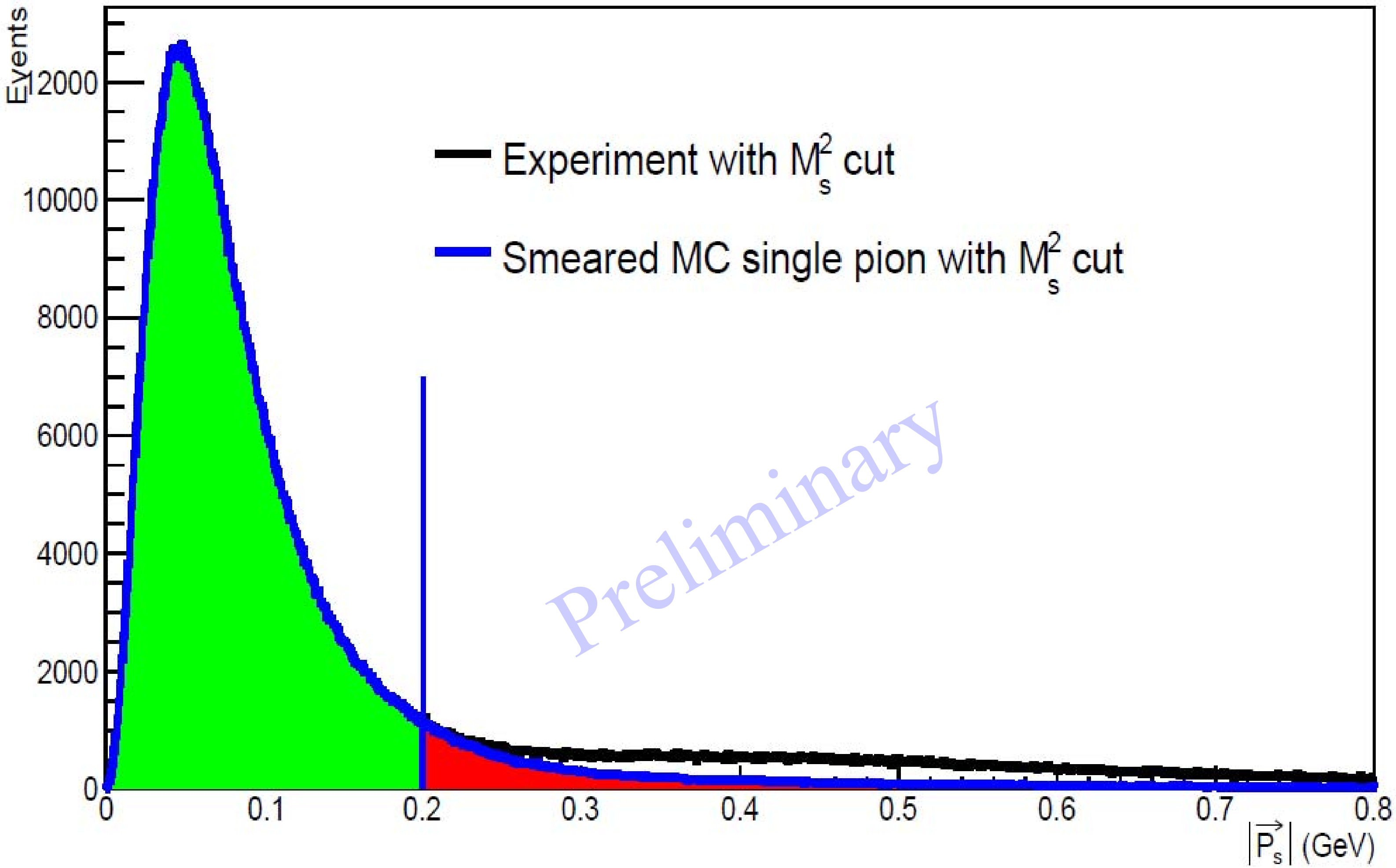
Exclusive Single π^- Electroproduction off the Deuteron

Ye Tian



Exclusive Single π⁻ Electroproduction off the Deuteron

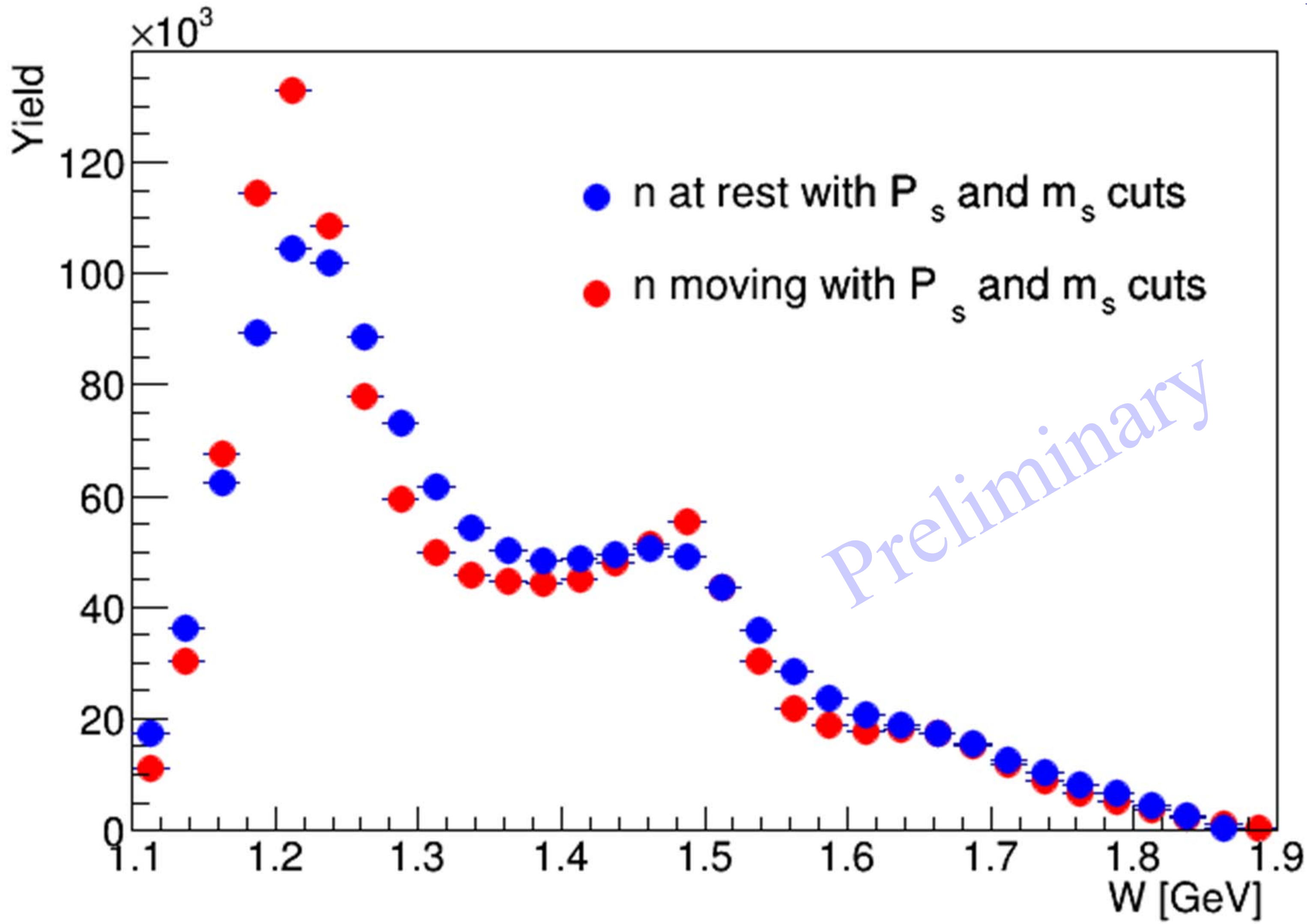
Ye Tian



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

Exclusive Single π^- Electroproduction off the Deuteron

Ye Tian



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

Exclusive Single π^- Electroproduction off the Deuteron

Ye Tian

W = 1212 MeV

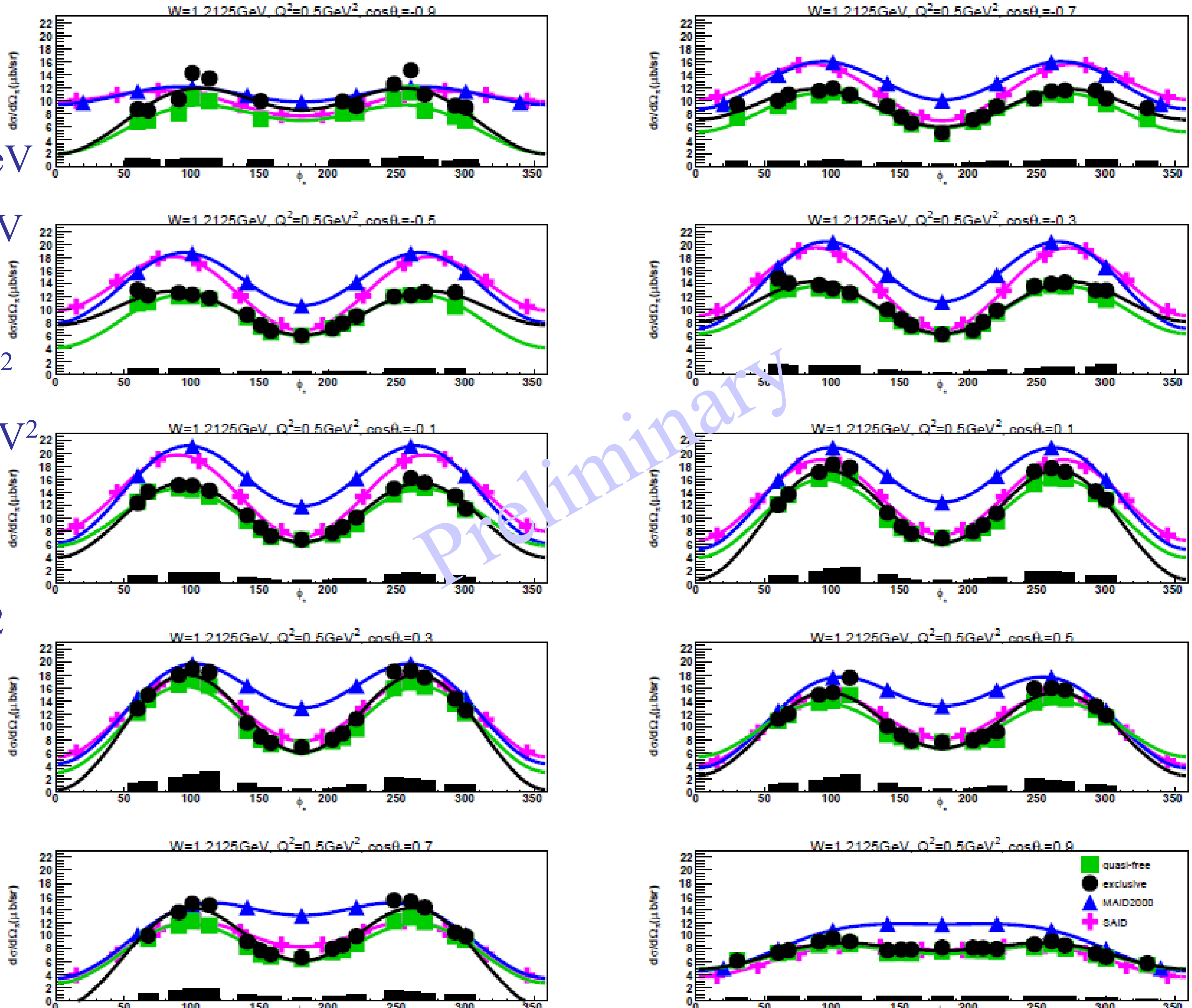
ΔW = 25 MeV

$Q^2 = 0.5\ GeV^2$

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

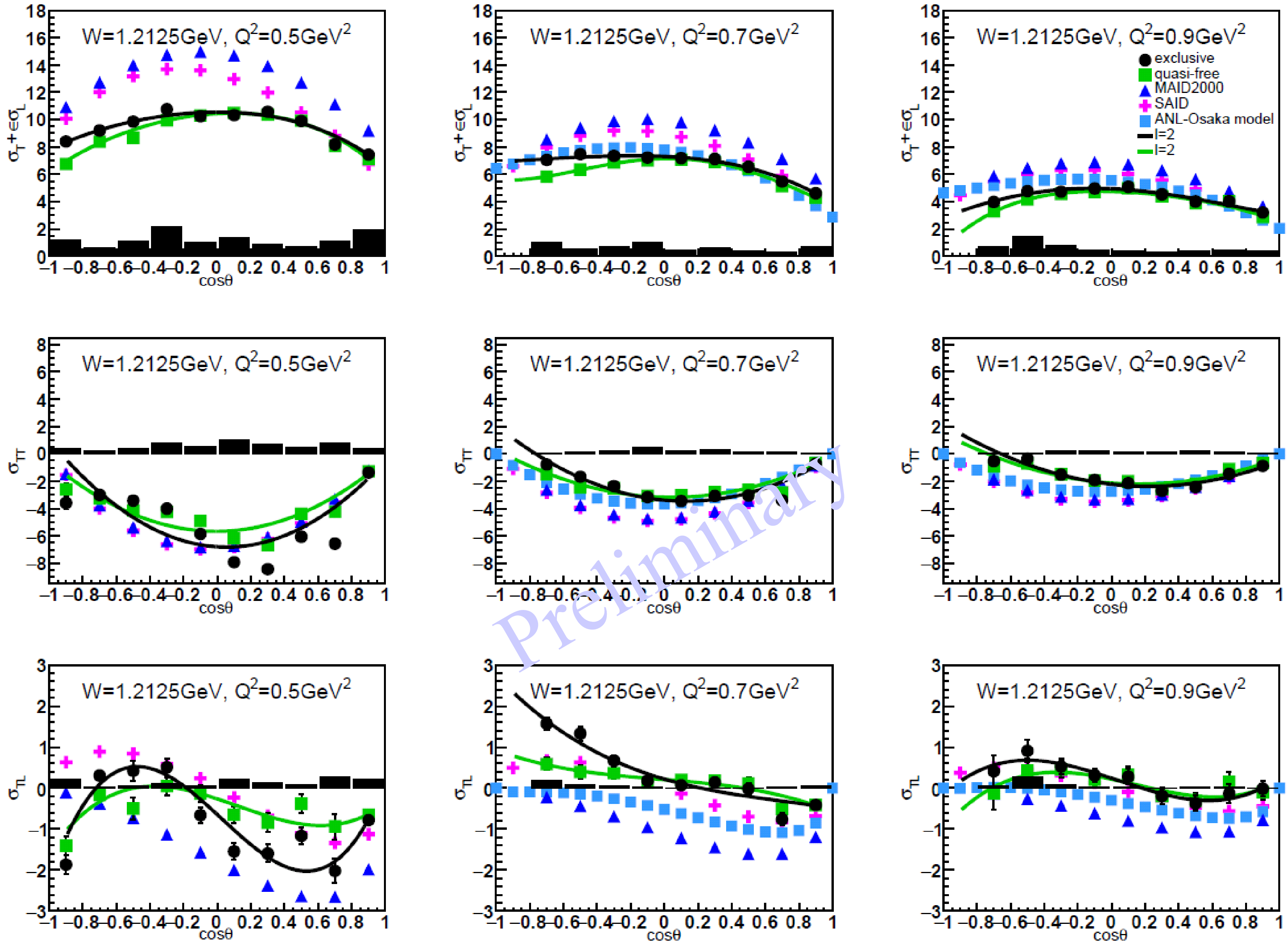
cos(θ) = -0.7
Δcos(θ) = 0.2
cos(θ) = 0.7

φ = 20°
Δφ = 40°
φ = 340°



Exclusive Single π⁻ Electroproduction off the Deuteron

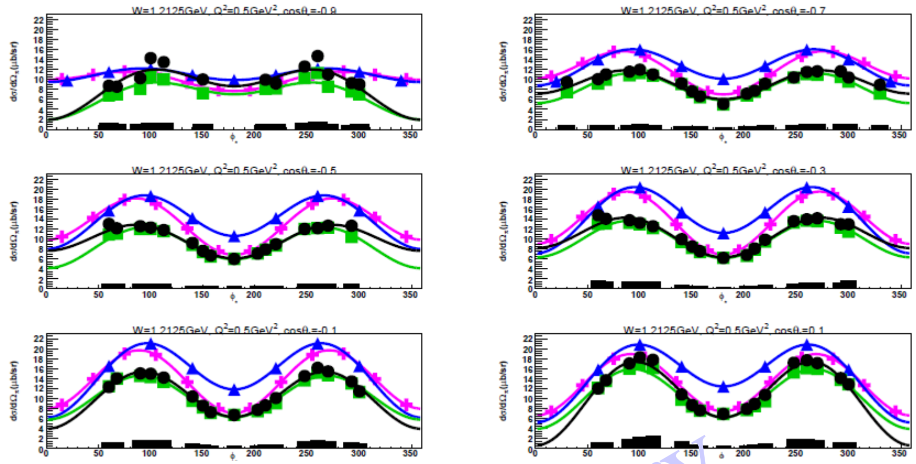
Ye Tian



Exclusive Single π^- Electroproduction off the Deuteron

$Q^2 = 0.5$ GeV^2

W = 1212 MeV

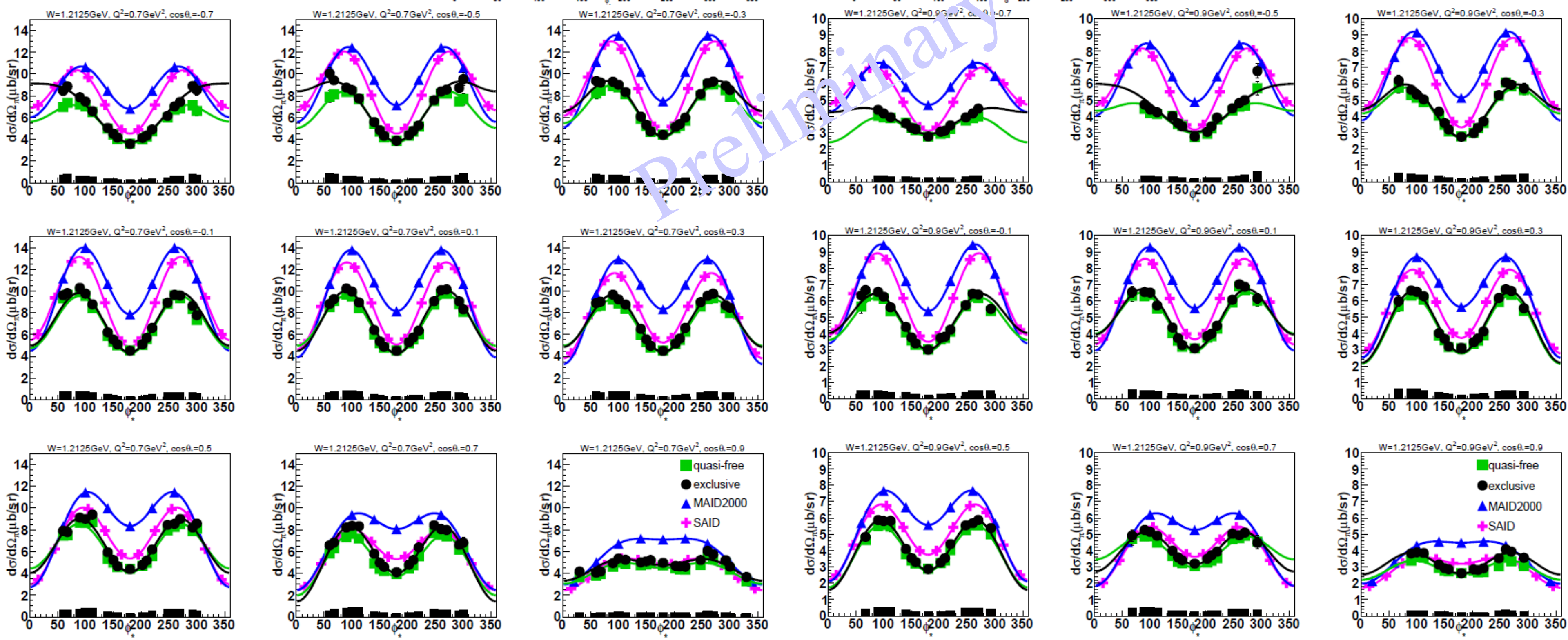


Ye Tian

Inclusive:
Gary Hollis

$Q^2 = 0.7$ GeV^2

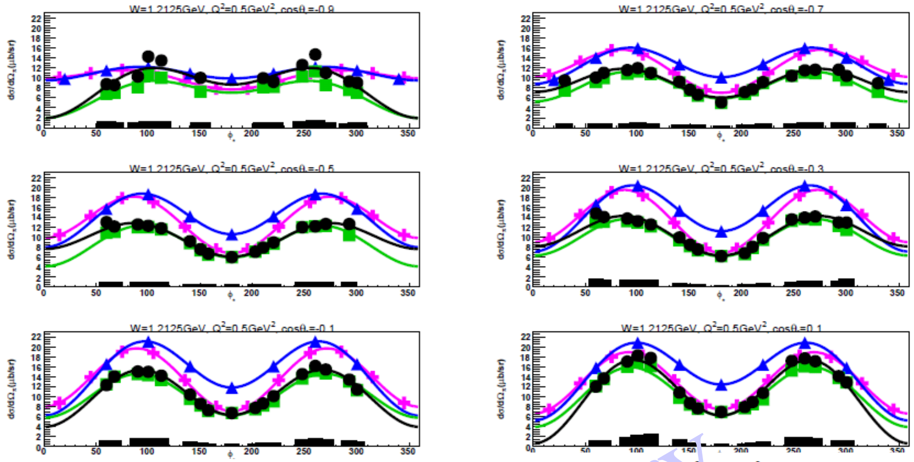
$Q^2 = 0.9$ GeV^2



Exclusive Single π^- Electroproduction off the Deuteron

$Q^2 = 0.5\ GeV^2$

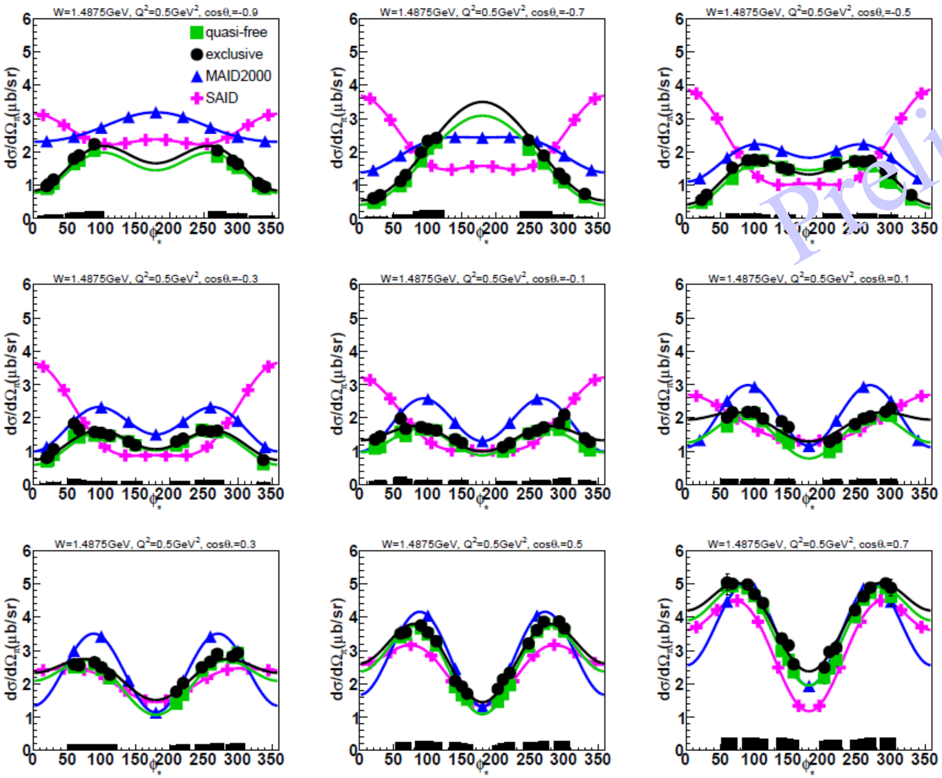
W = 1212 MeV



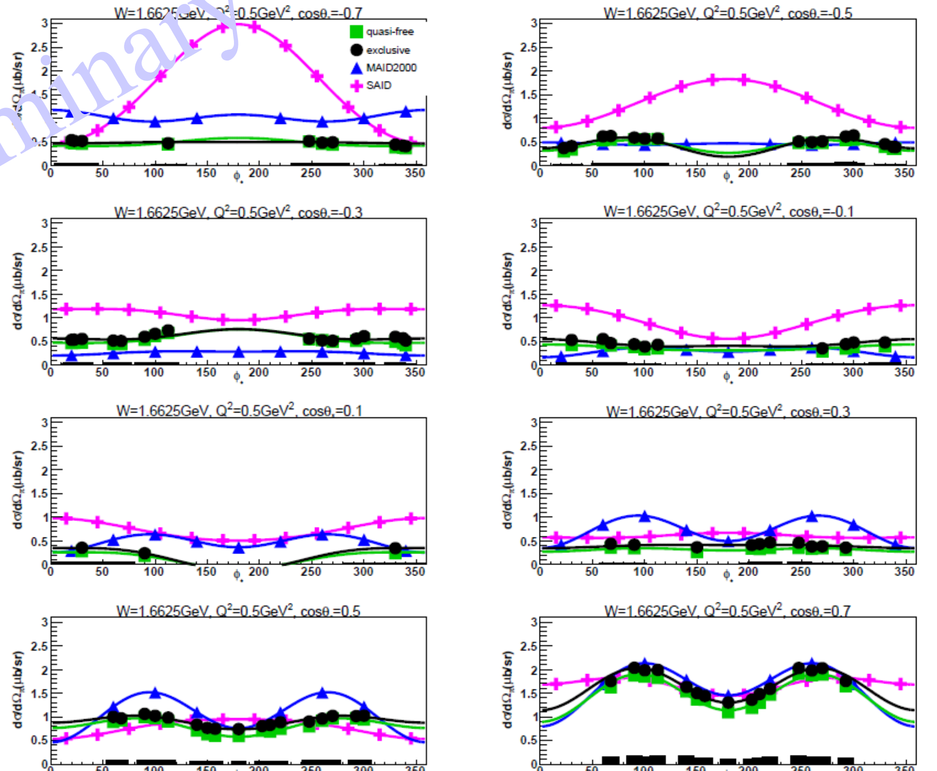
Ye Tian

Inclusive:
Gary Hollis

W = 1488 MeV



W = 1662 MeV

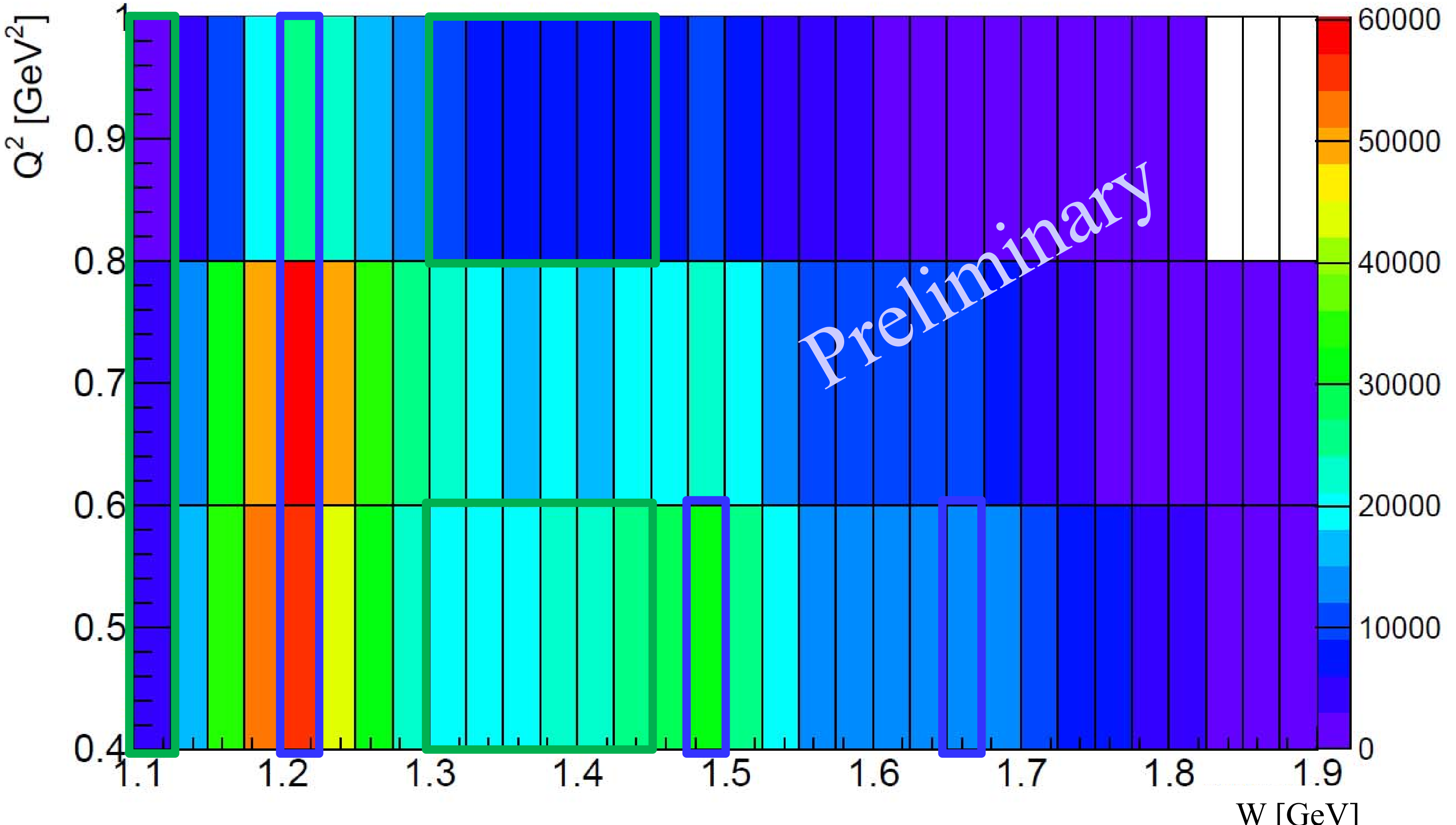


Single π ⁻ Electroproduction off the Deuteron

Ye Tian

Gary Hollis

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



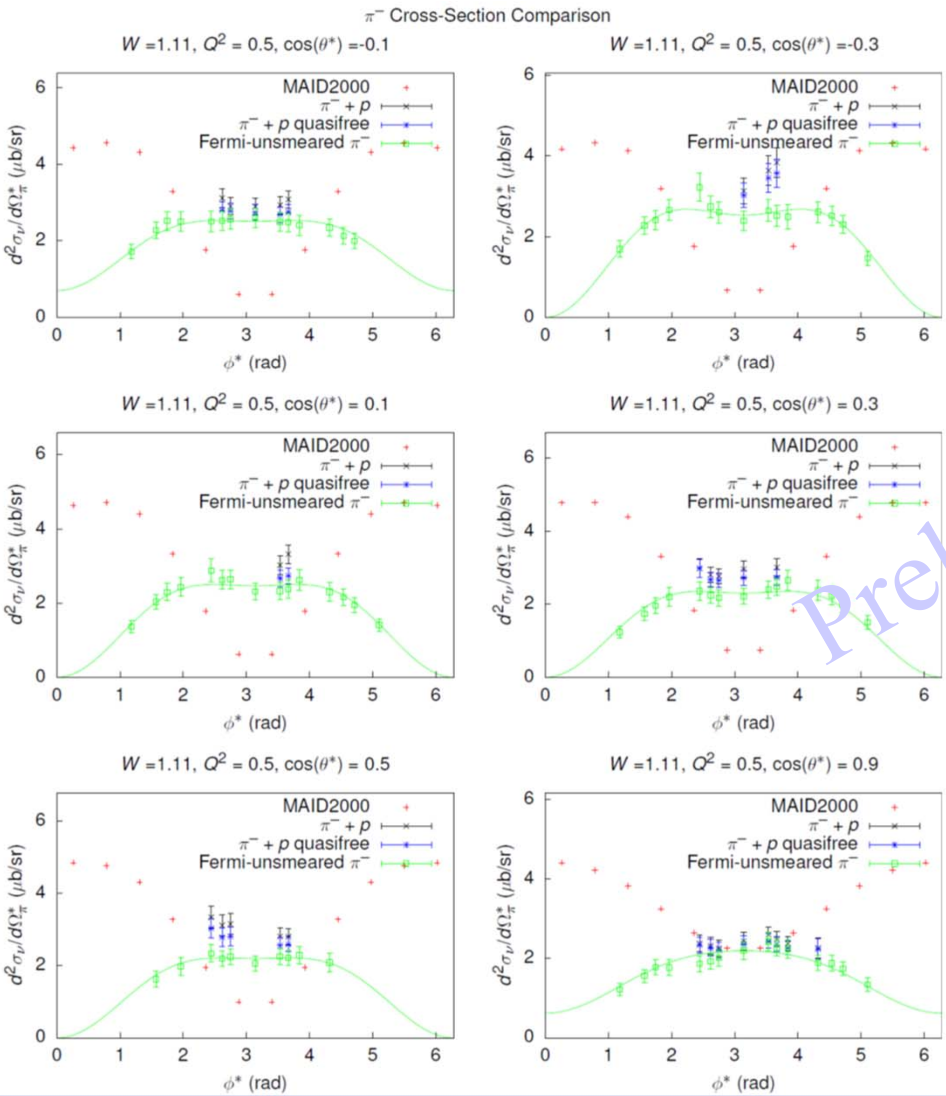
$\Delta Q^2 = 0.2\ GeV^2$ $\Delta W = 25\ MeV$

Single π^- Electroproduction off the Bound Neutron

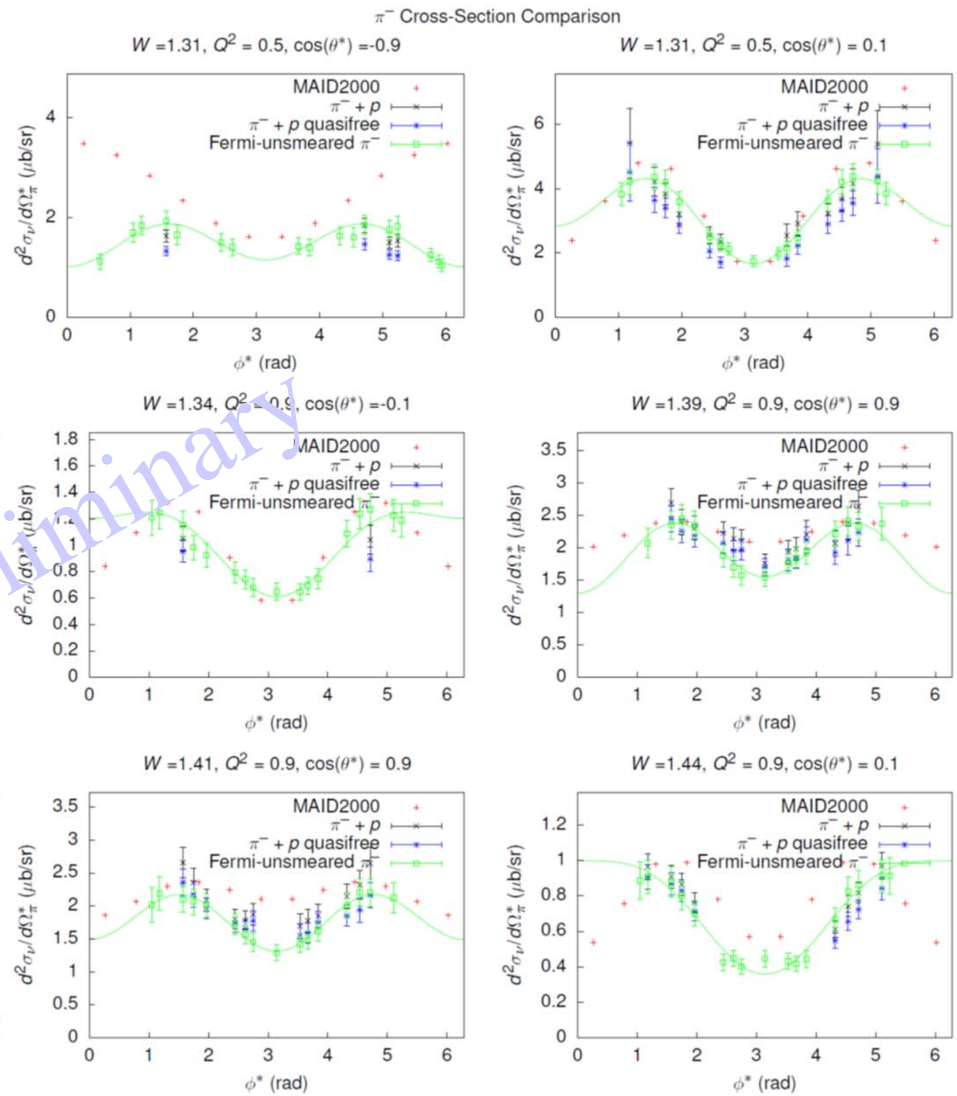
Ye Tian

Gary Hollis

W = 1.11 GeV $Q^2 = 0.5\ GeV^2$



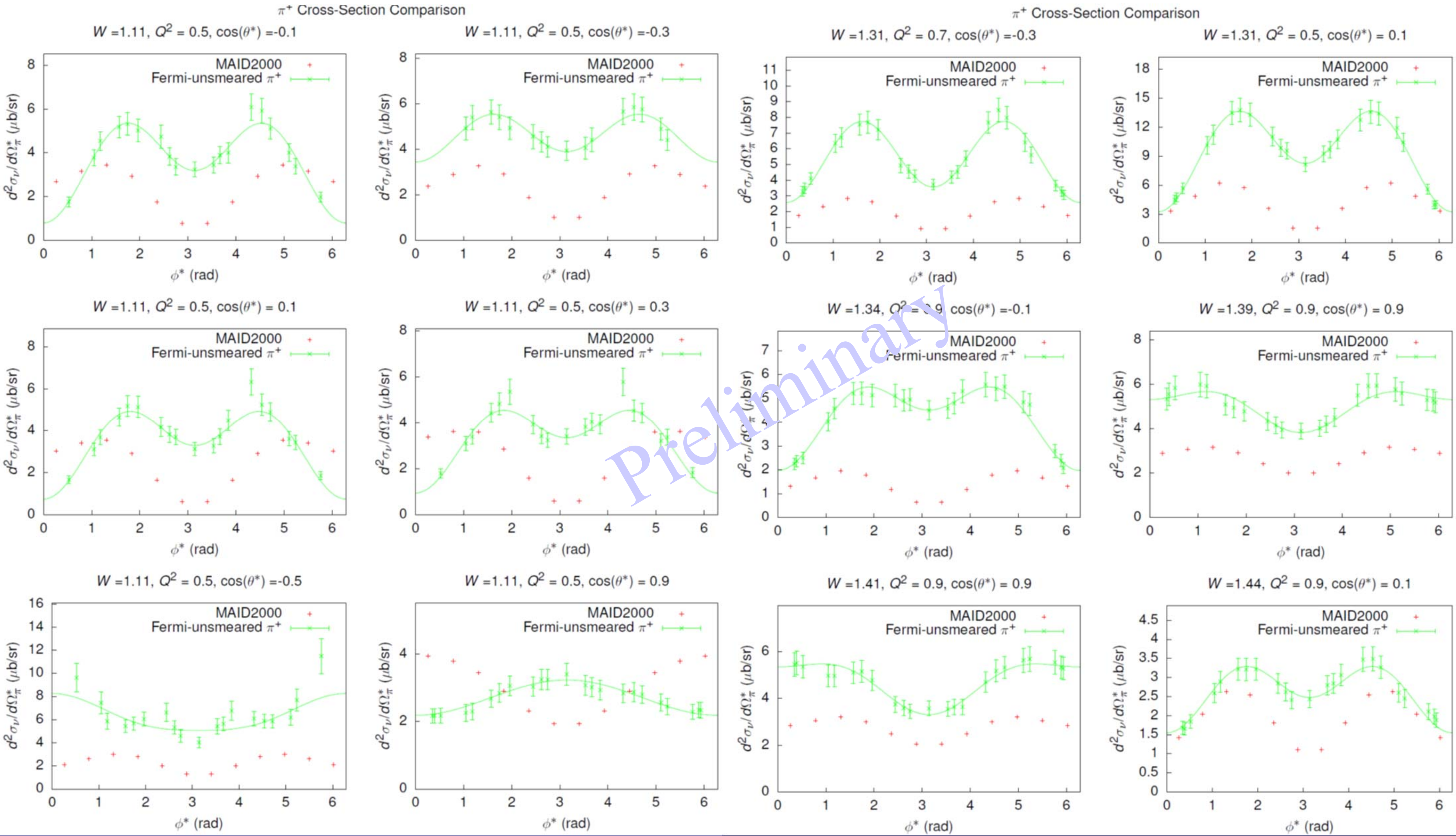
W = 1.31-1.44 GeV $Q^2 = 0.5\text{-}0.9\ GeV^2$



Single π^+ Electroproduction off the Bound Proton

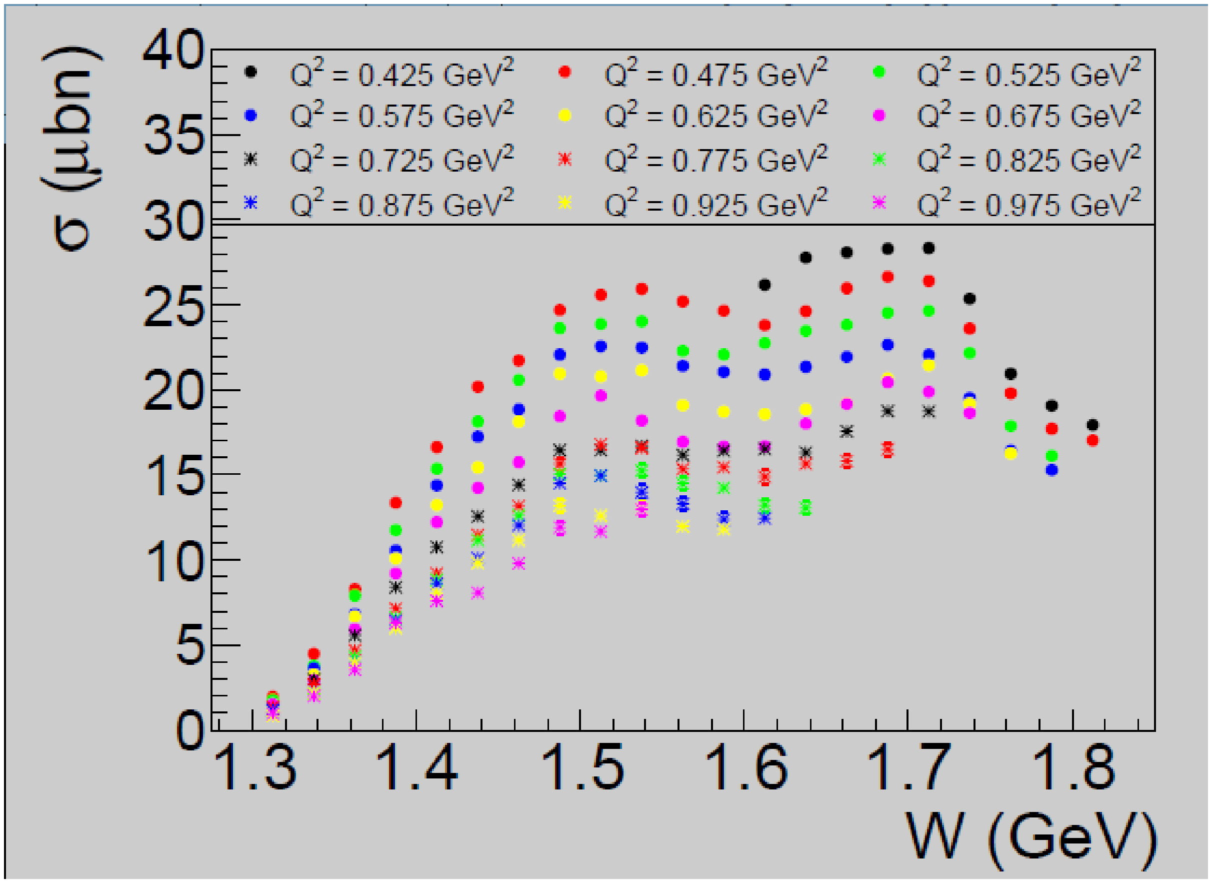
Ye Tian
Gary Hollis

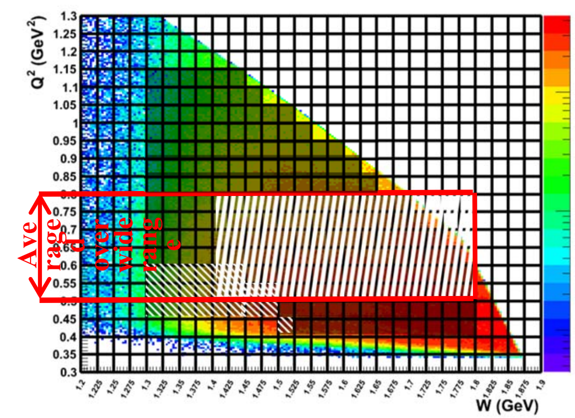
$W = 1.11$ GeV $Q^2 = 0.5$ GeV^2 $W = 1.31\text{-}1.44$ GeV $Q^2 = 0.5\text{-}0.9$ GeV^2



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

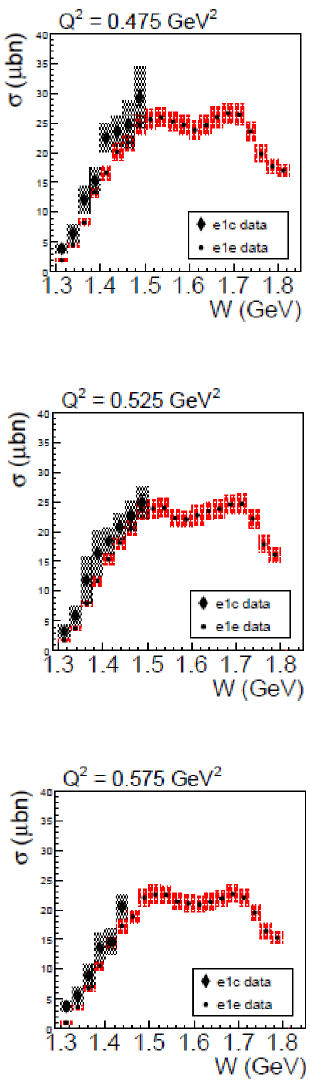
Gleb Fedotov
Phys. Rev. C 98, 025203 (2018)

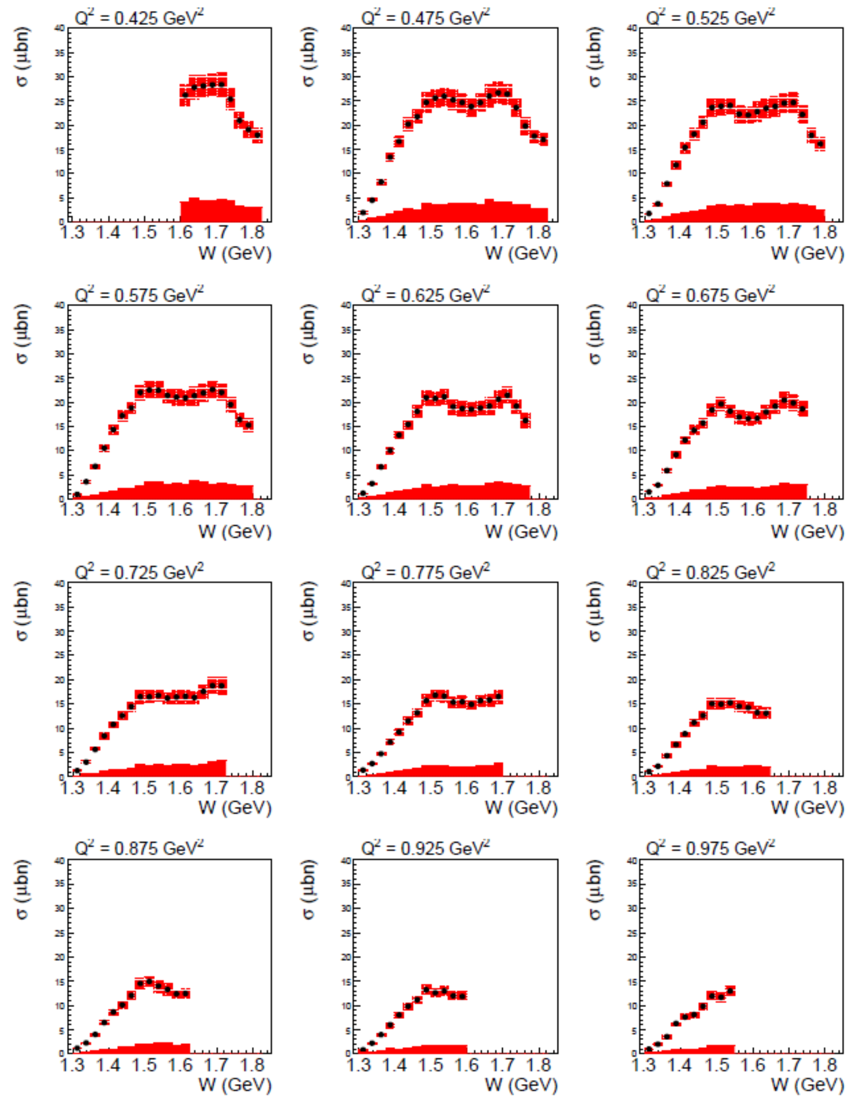




$p\pi^+\pi^-$ event yields over W and Q^2. Gray shaded area new e1e data set, hatched area at low Q^2 already published e1c data by G. Fedotov *et al.* and hatched area at higher Q^2 already published data in one large Q^2 bin by M. Ripani *et al.*

Integrated $N\pi^+\pi^-$ Cross Sections





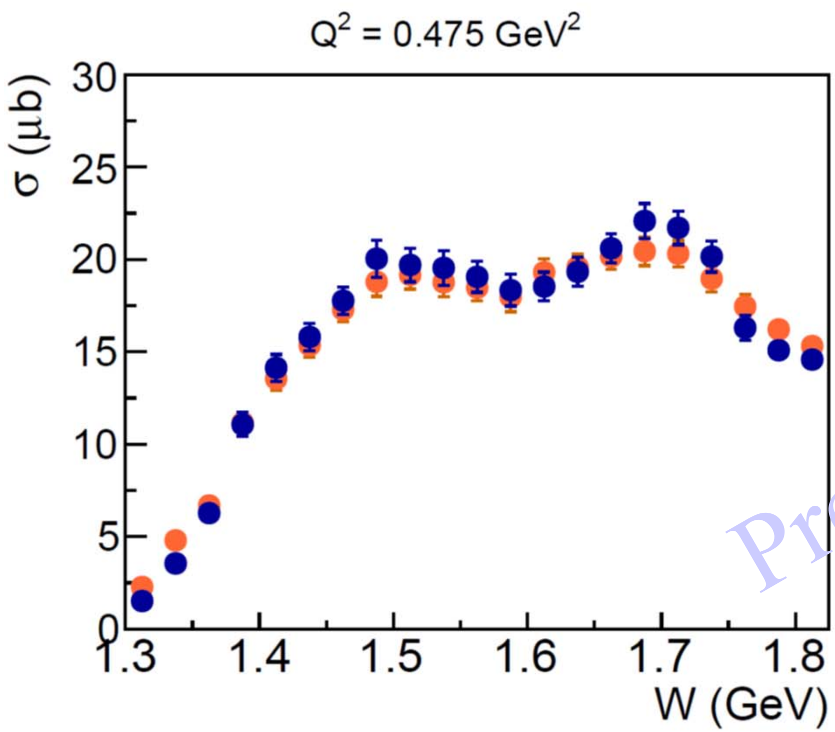
Gleb Fedotov

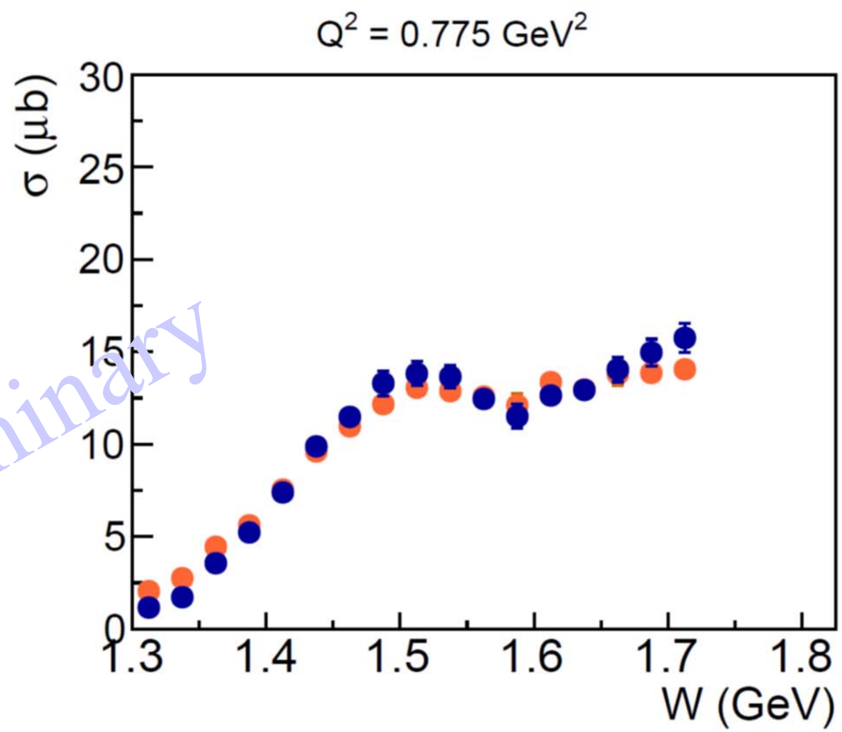
Bound Proton:
I. Skorodumina

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

Unfolding Fermi Smearing via Event Generator

Iuliia Skorodumina



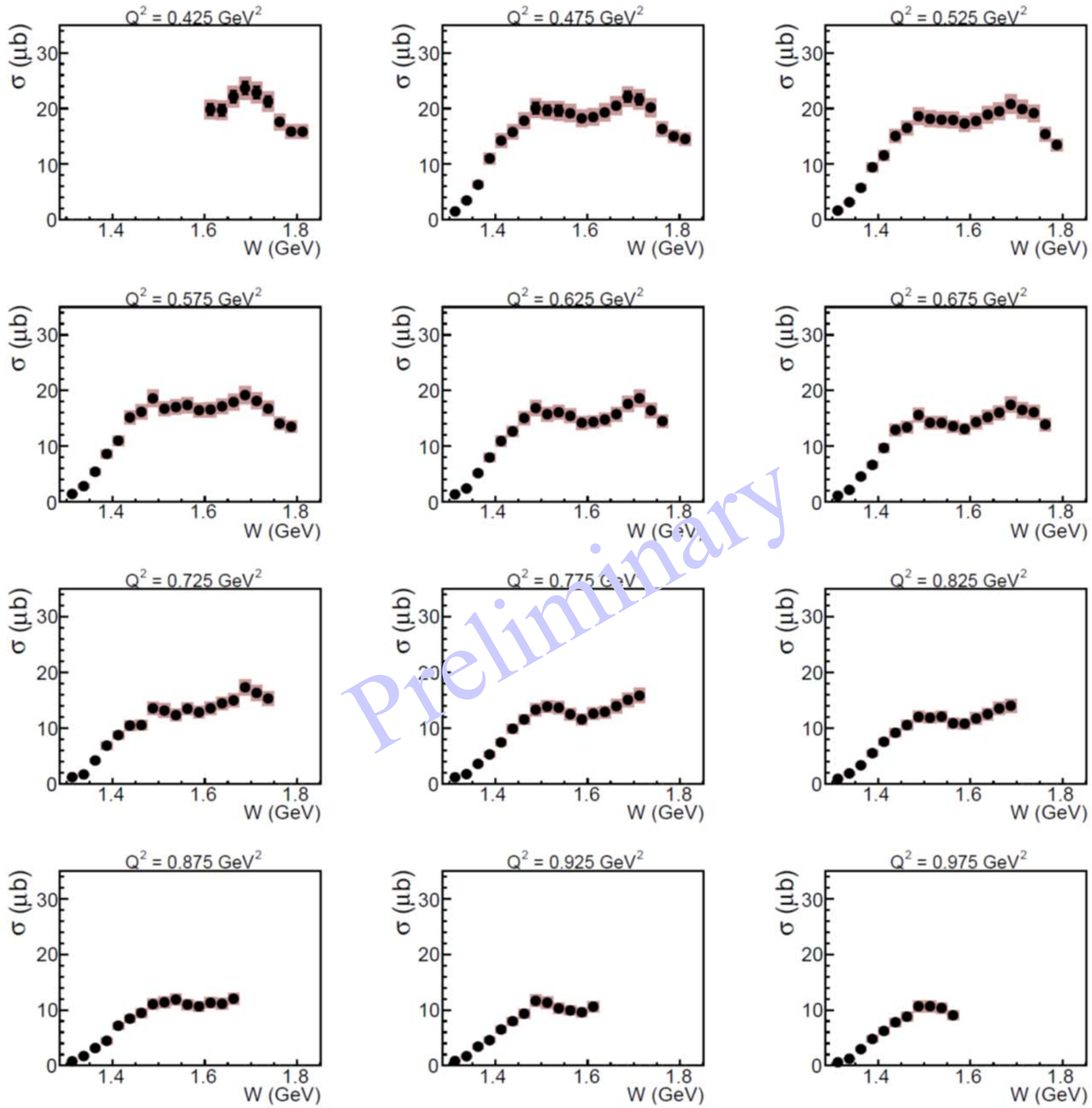


Blue bullets – integrated cross section with Fermi correction

Red bullets – integrated cross Section without Fermi correction

π^- missing topology

Integrated Cross Section off the Proton in Deuteron



Iuliia Skorodumina

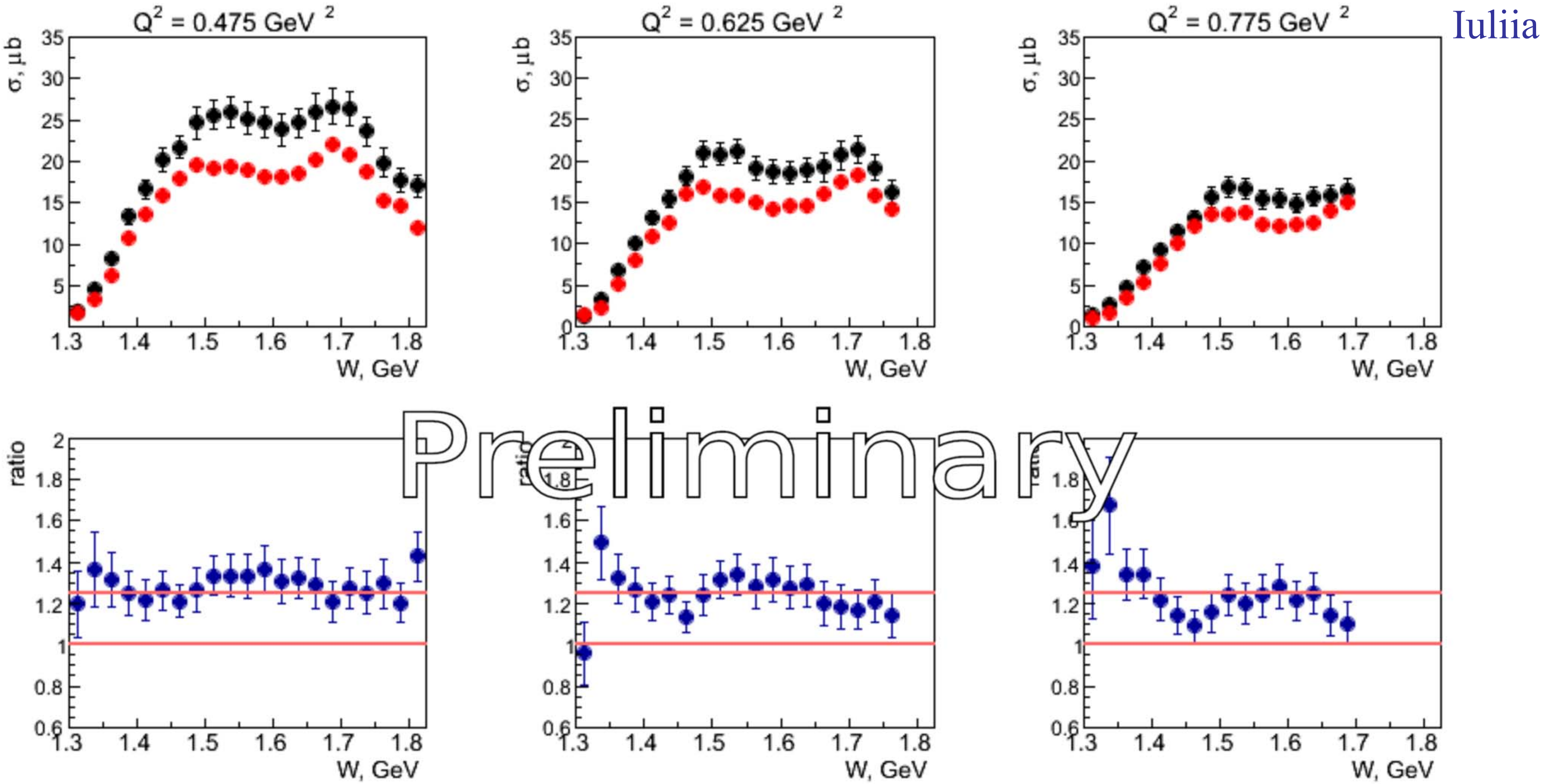
Black symbols – extracted integral cross sections.

Error bars correspond to the combination of the statistical and model dependence uncertainties.

Pink shadowed areas correspond to the total uncertainty, which is the combination of the statistical, model dependence, and systematic uncertainties.

$$\sigma_v^{int}(W,Q^2) = \int \frac{d^5\sigma_v}{d^5\tau} \mathrm{d}M_{h_1h_2}\mathrm{d}M_{h_2h_3}\mathrm{d}\Omega_{h_1}\mathrm{d}\alpha_{h_1}$$

Comparison with Free Proton Cross Section



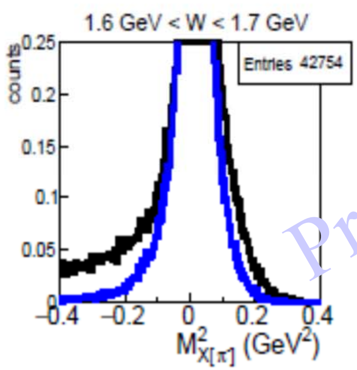
Black bullets – free proton cross sections (e1e at E_{beam} = 2.039 GeV)
error bars show both statistical and systematical uncertainties
G. Fedotov under paper review

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

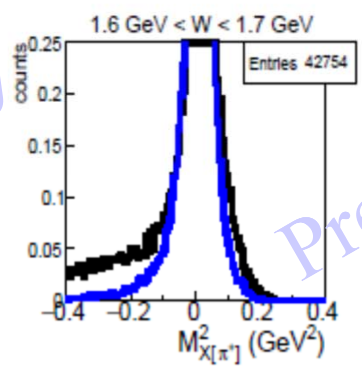
Isolating FSI of Various Final Hadrons

Iuliia Skorodumina

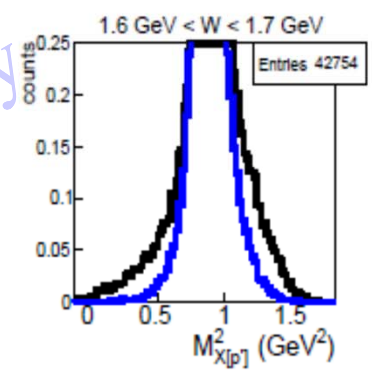
- The quantity $P_{\mu X}$ incorporates information on FSI of each hadron type (p, π^+, and π^-).
- The quantity M^2_X absorbs only information on FSI of each of the two registered final hadrons, while the information the unregistered hadron is not used in the calculation of M^2_X.
- This remarkable feature offers the opportunity of isolating FSI contributions from various pairs of final hadrons considering the missing masses related to the corresponding third hadron.



$M^2_{X[\pi-]}$ isolates pn and π^+n FSI



$M^2_{X[\pi+]}$ isolates pn and π^-n FSI



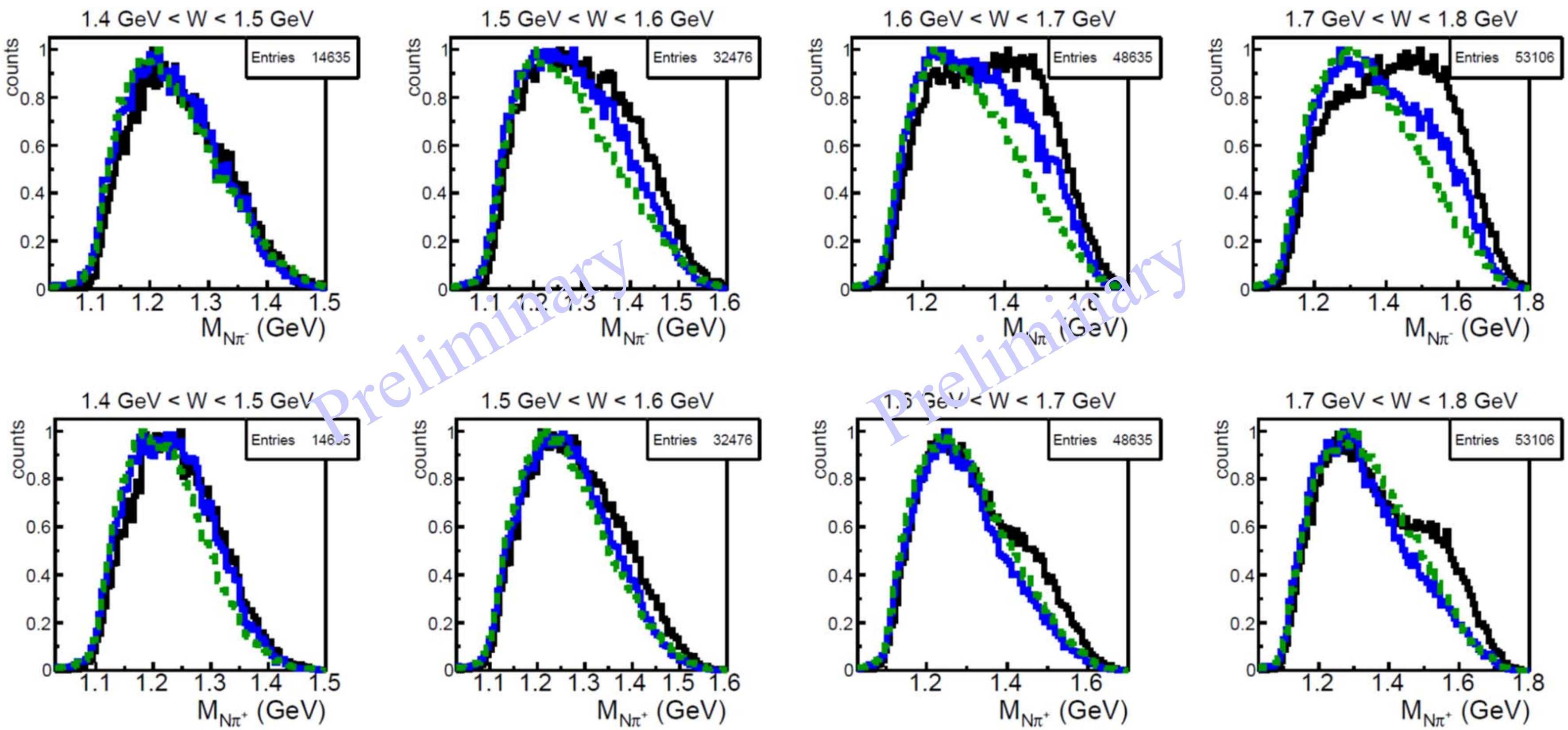
$M^2_{X[p']}$ isolates π^+n and π^-n FSI

Preliminary

Preliminary

Resonance Formation in Pion-Neutron Formation

Iuliia Skorodumina



Black curve – data.

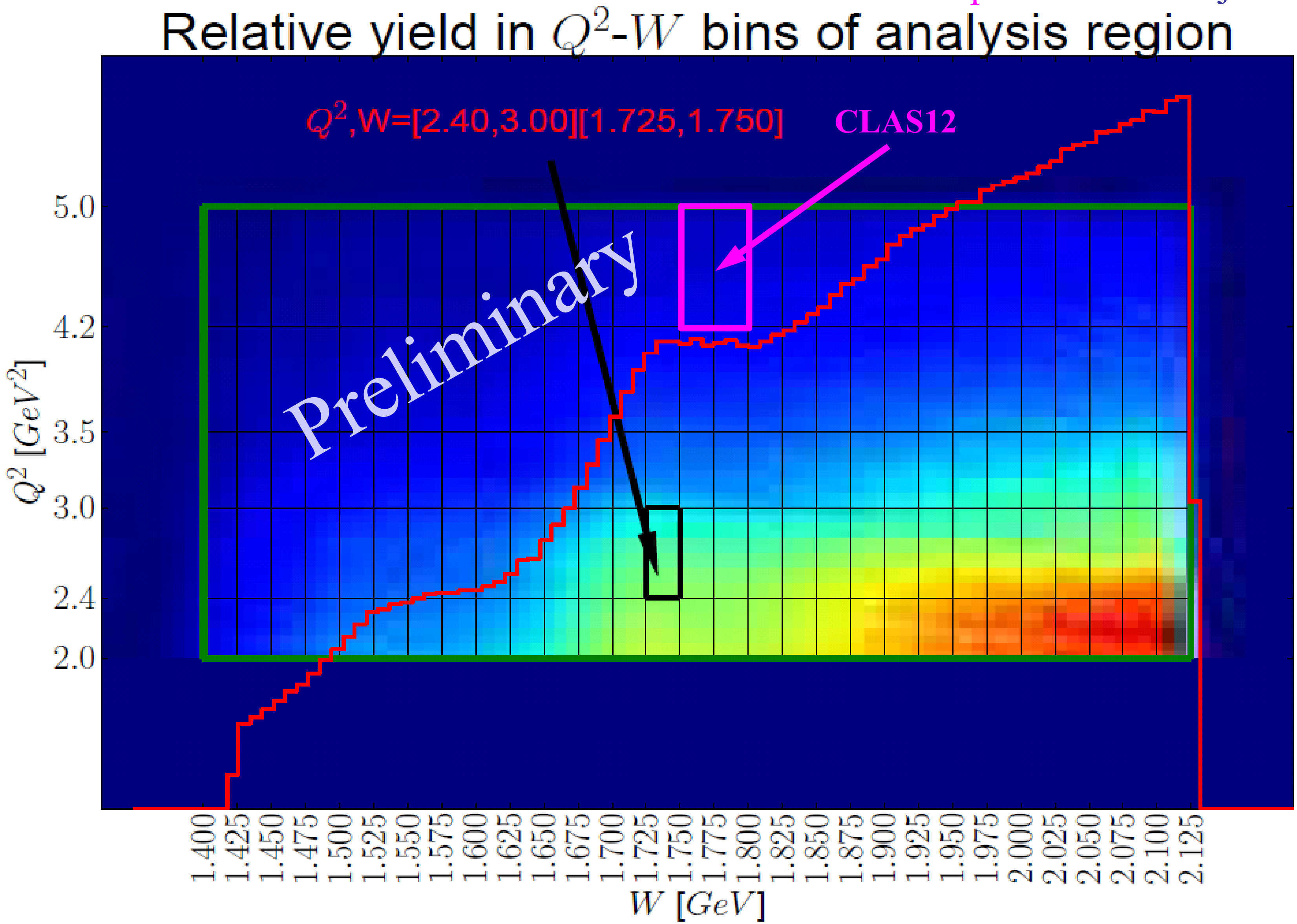
Blue curve – regular simulation (FSI not included).

Green curve – simulation with phase-space distributions of kinematic variables.

φ-dependent Nππ Single-Differential Cross Sections

Krishna Neupane

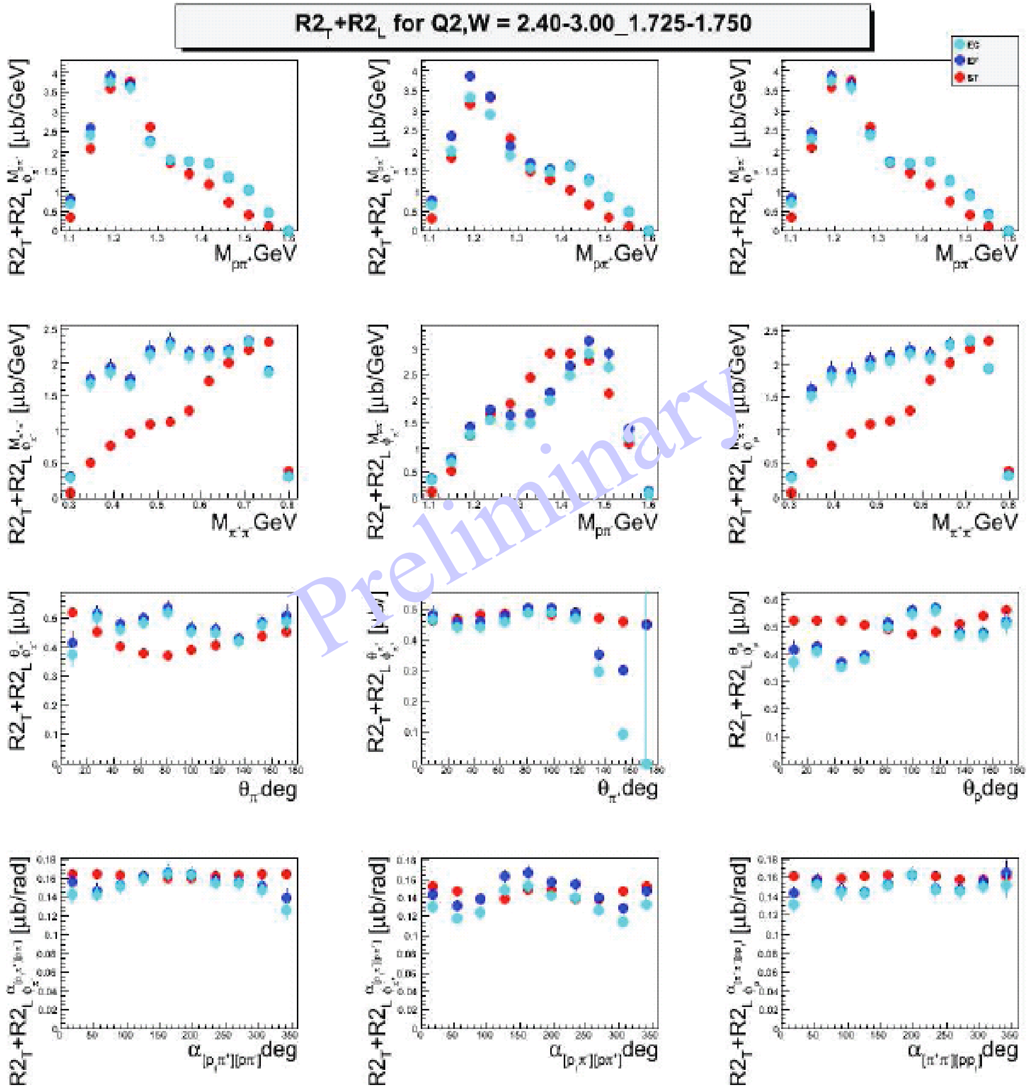
Arjun Trivedi



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

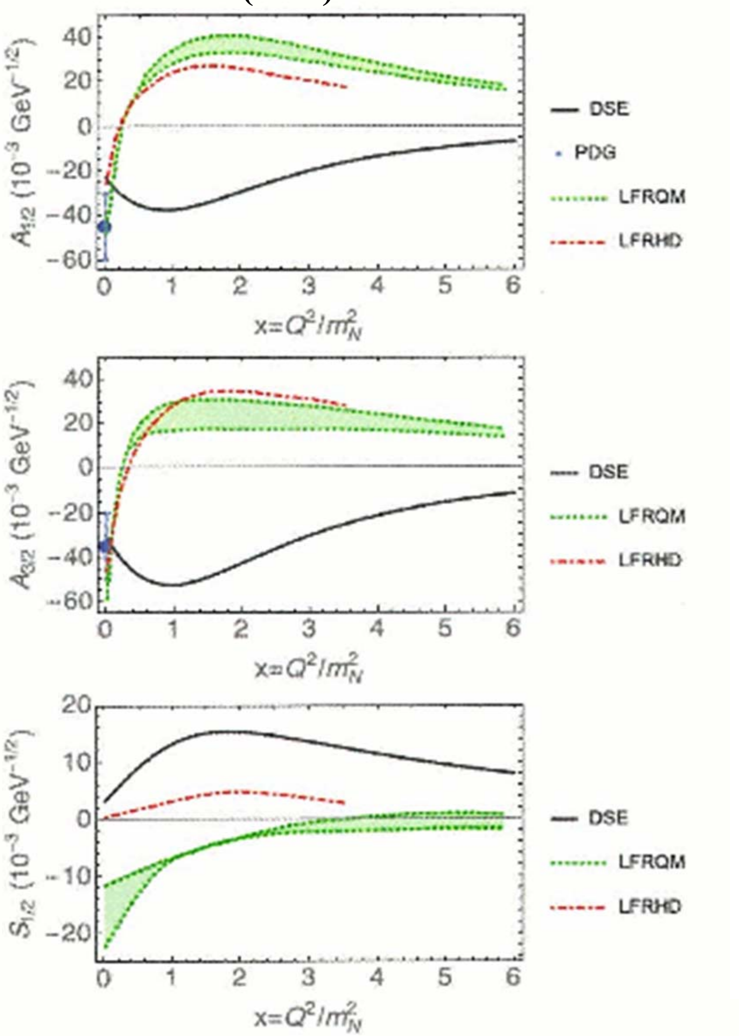


- normalized
- hole filled
- TWOPEG

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

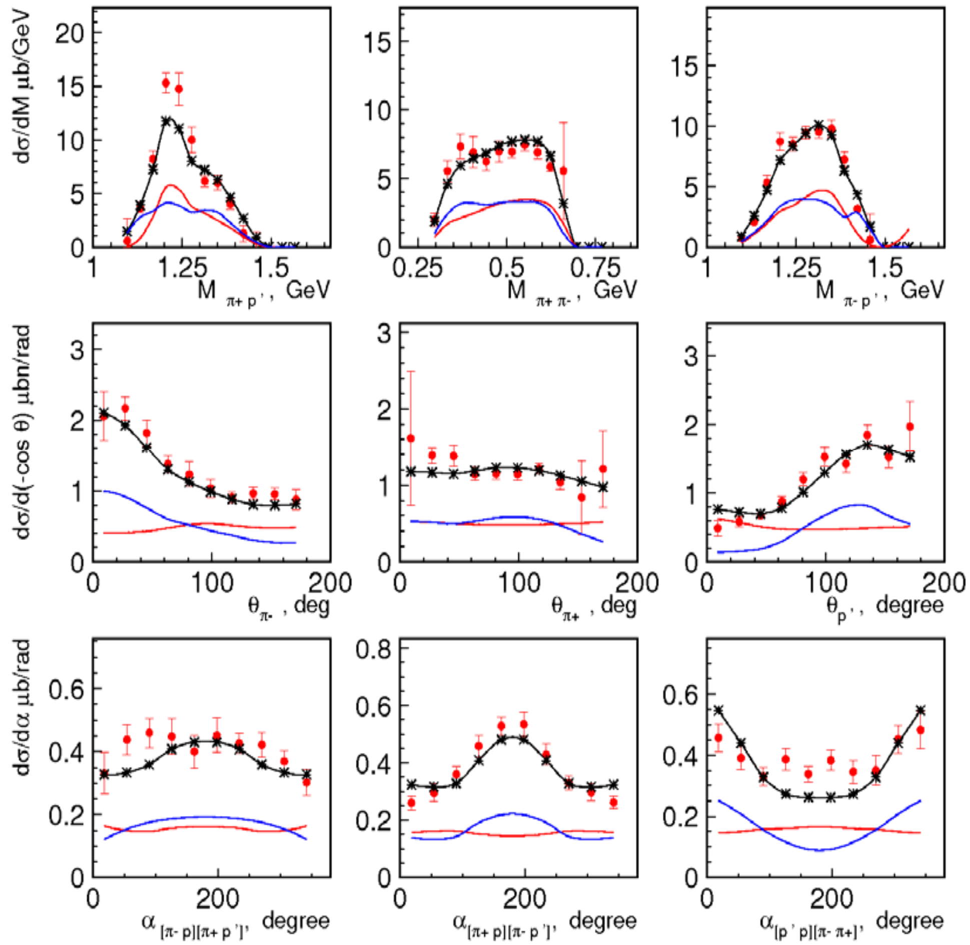
First Radial Δ-Excitation from Nππ Cross Sections

Δ(1600)3/2⁺



Arjun Trivedi
Few Body Syst. 60 (2019) 5

W=1.61 GeV, Q^2=3.2 GeV^2



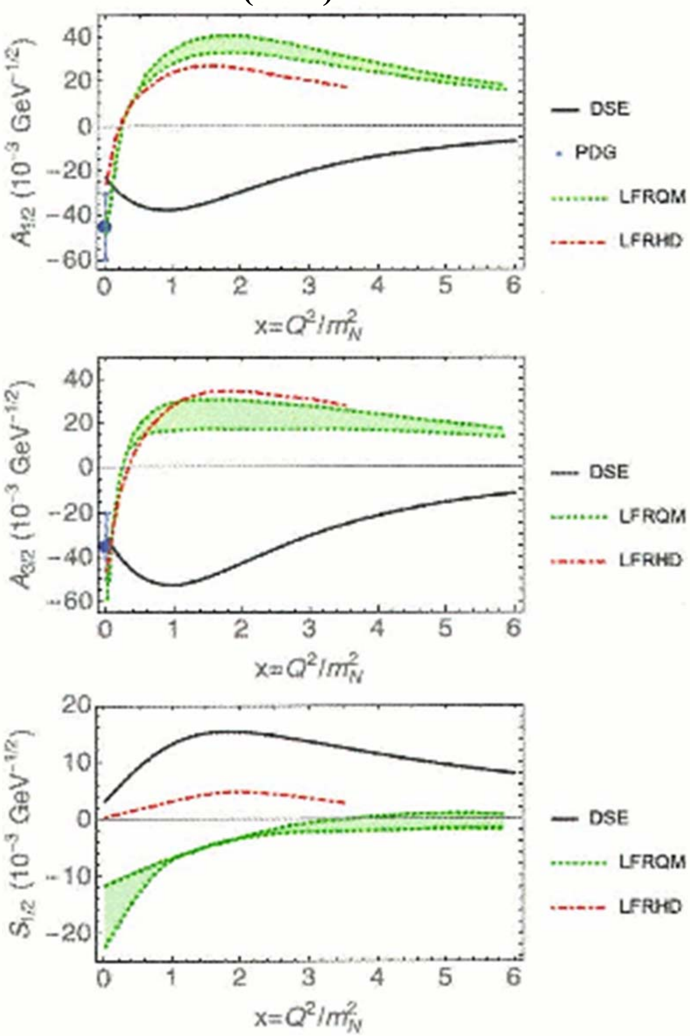
Ya Lu *et al.*, arXiv:1904.03205 [nucl-th]

Viktor Mokeev (JM19)

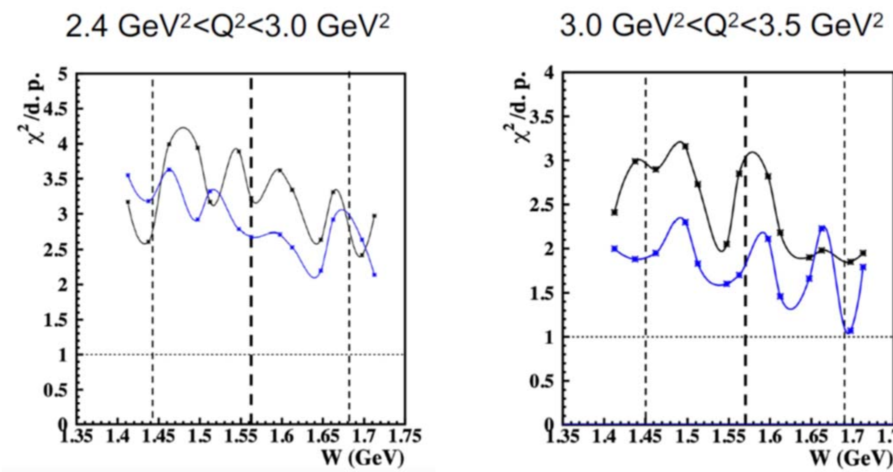
N*
non-resonant contributions

First Radial Δ-Excitation from Nππ Cross Sections

Δ(1600)3/2⁺



Arjun Trivedi
Few Body Syst. 60 (2019) 5



Thick dashed line stands for Δ(1600)3/2⁺ mass, the interval between thin dashed lines corresponds to the resonance width

Δ(1600)3/2⁺ contribution is replaced by the non-resonant processes

Δ(1600)3/2⁺ resonance is included with electro-couplings predicted within continuum QCD

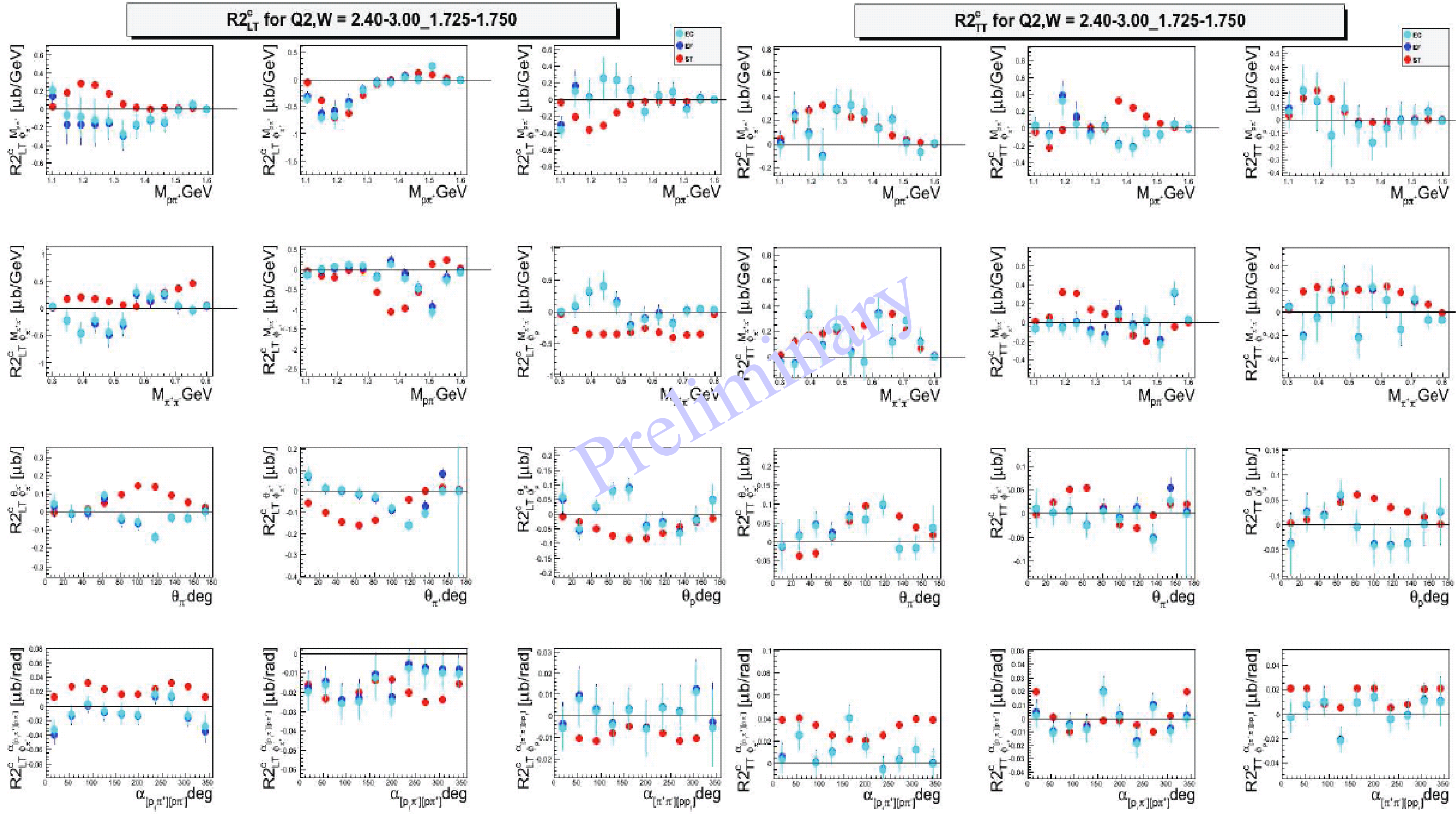
Ya Lu *et al.*, arXiv:1904.03205 [nucl-th]

Viktor Mokeev (JM19)

φ-dependent Nππ Single-Differential Cross Sections

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

Arjun Trivedi



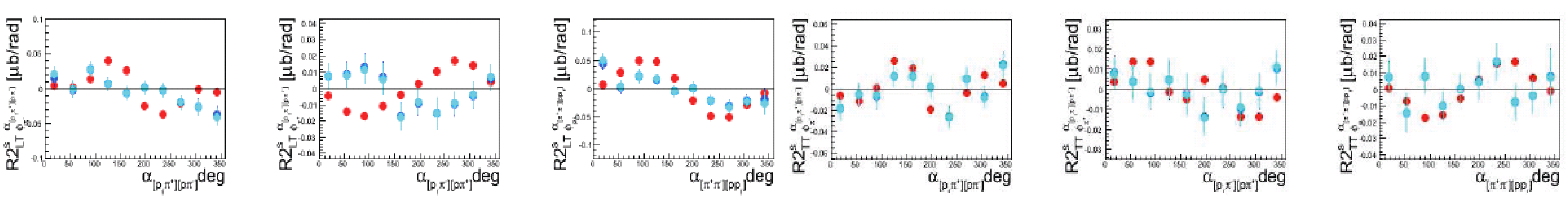
$$\left(\frac{d^2\sigma}{dX_{ij}\,d\phi_i}\right) = R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}} + \underline{R2_{LT}{}^{c,X_{ij}} \cos\phi_i} + \underline{R2_{TT}{}^{c,X_{ij}} \cos 2\phi_i} + \delta_{X_{ij}\alpha_i}\left(R2_{LT}{}^{s,\alpha_i} \sin\phi_i + R2_{TT}{}^{s,\alpha_i} \sin 2\phi_i\right)$$

φ-dependent Nππ Single-Differential Cross Sections

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

Arjun Trivedi

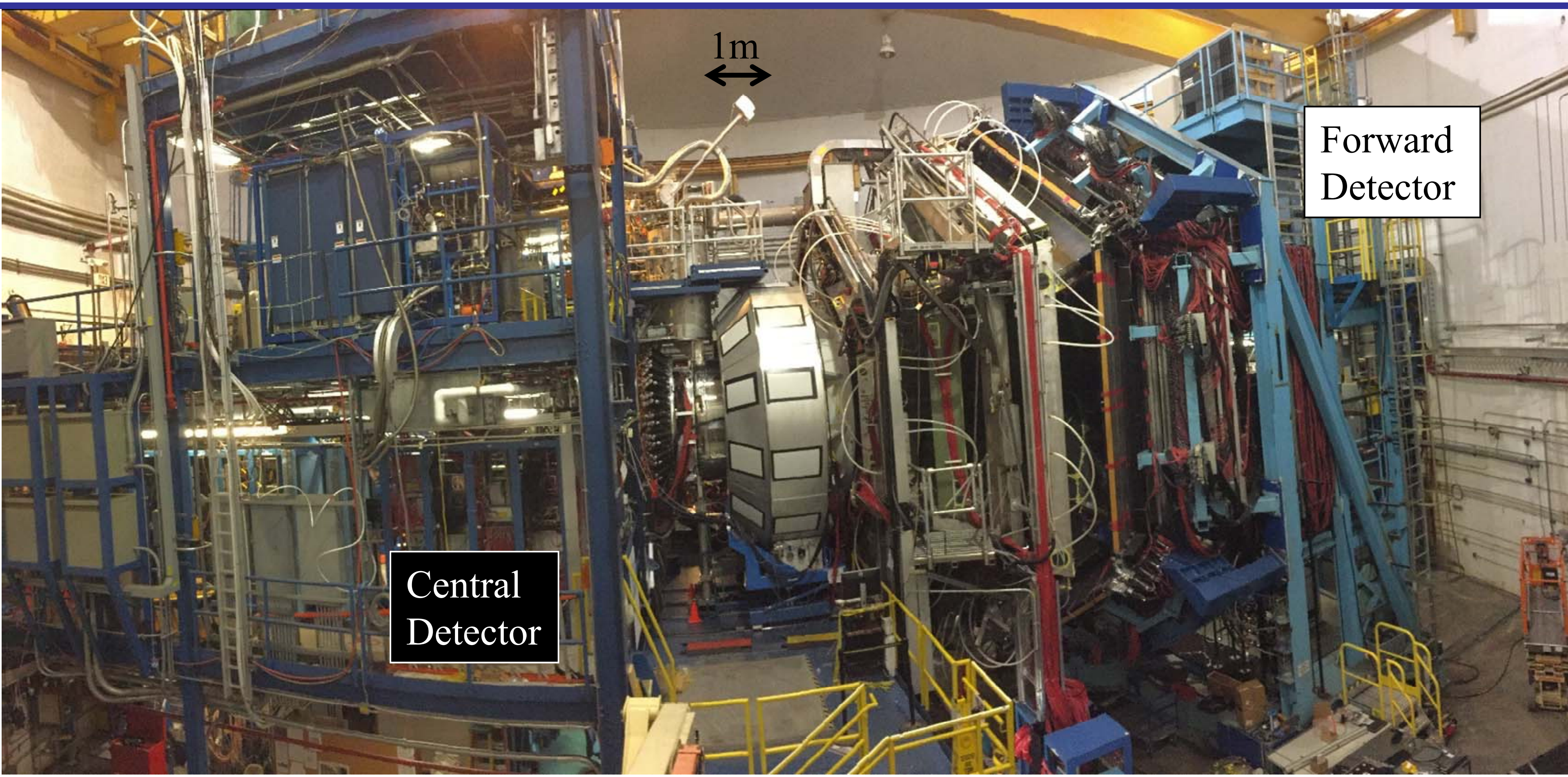
Chris McLauchlin extracts the beam helicity dependent differential cross sections.



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

CLAS12

CLAS12

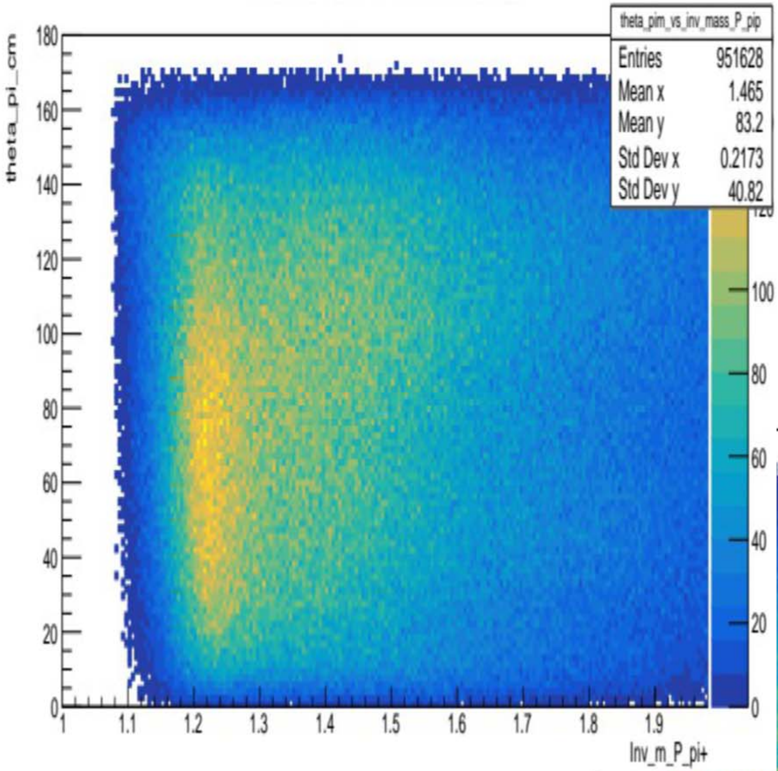


- Luminosity >10^{35} $cm^{-2}s^{-1}$
- Hermeticity
- Polarization
- Baryon Spectroscopy
- Elastic Form Factors
- N → N* Form Factors
- GPDs and TMDs
- DIS and SIDIS
- Nucleon Spin Structure
- Color Transparency
- …

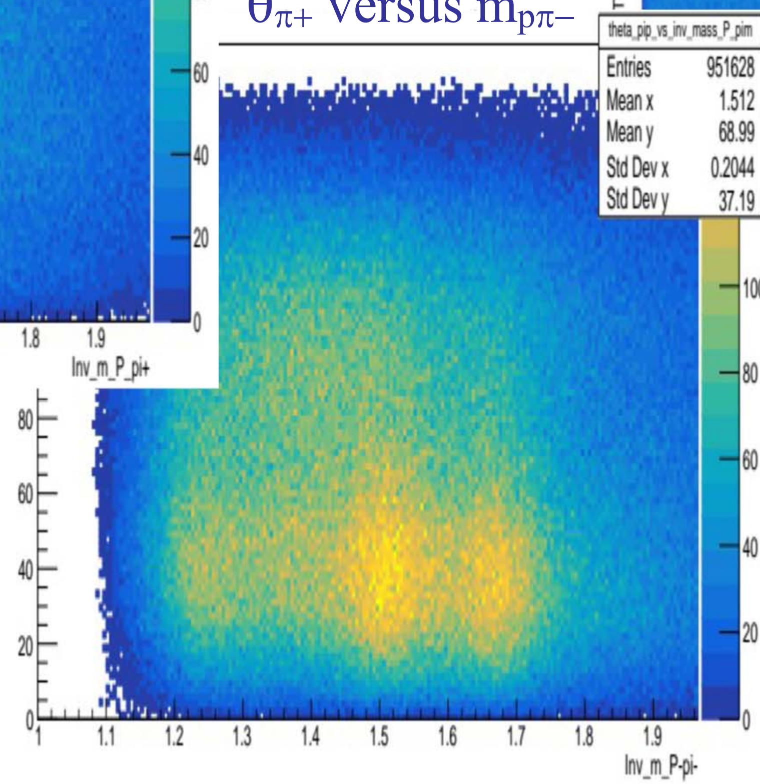
Preliminary RGA CLAS12 Data Analysis: $p\pi^+\pi^-$

10.6 GeV

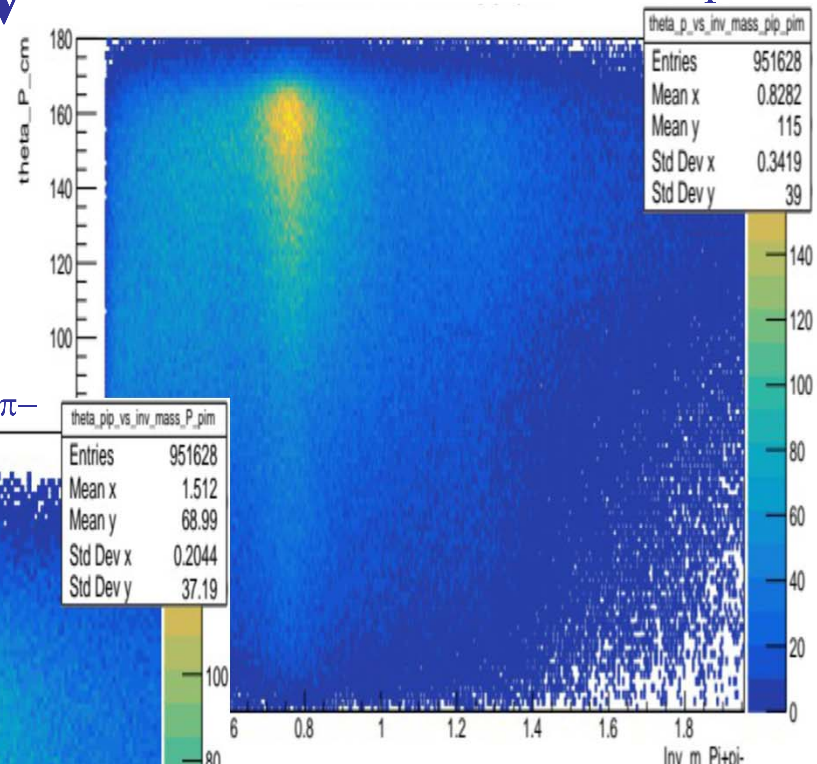
Krishna Neupane



$\theta_{\pi-}$ versus $m_{p\pi+}$



$\theta_{\pi+}$ versus $m_{p\pi-}$

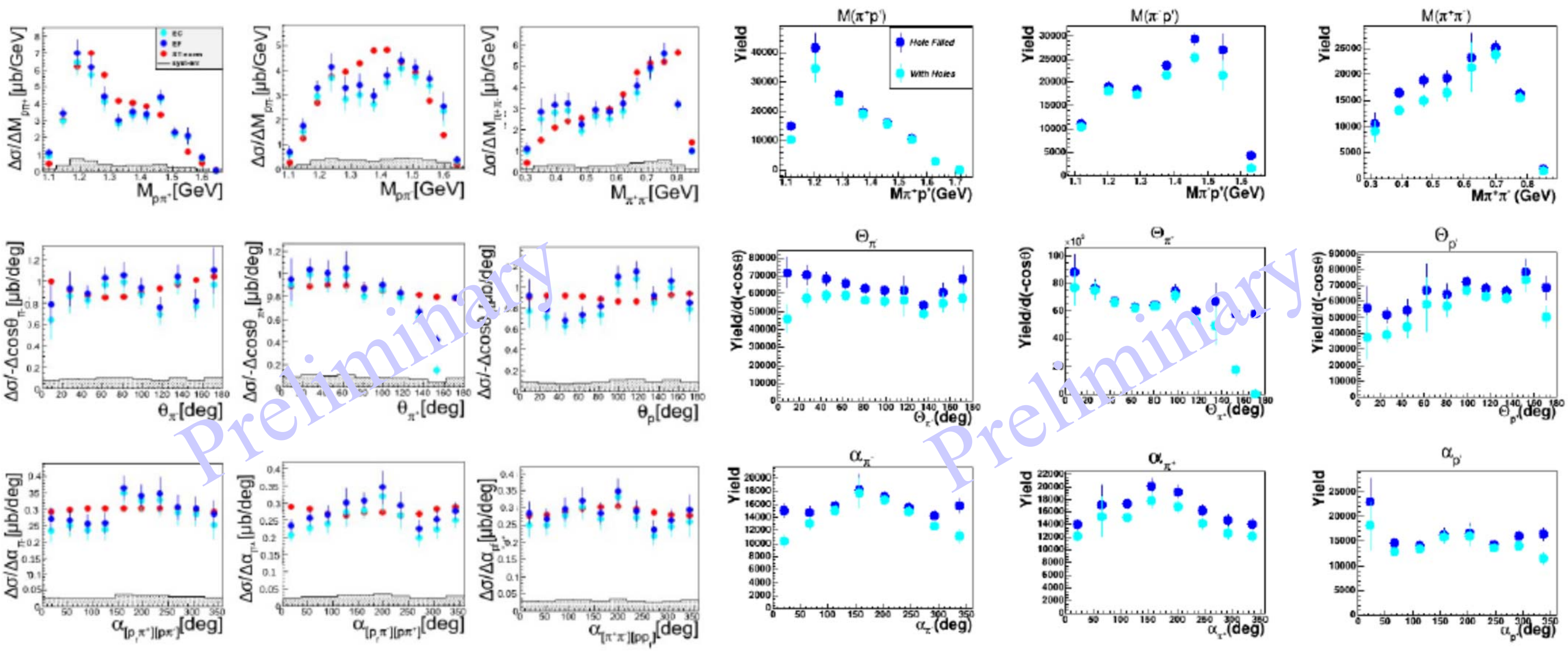


θ_p versus $m_{\pi+\pi-}$

Preliminary RGA CLAS12 Data Analysis: $p\pi^+\pi^-$

Arjun Trivedi CLAS	Krishna Neupane CLAS12

● TWOPEG ● hole filled ● normalized

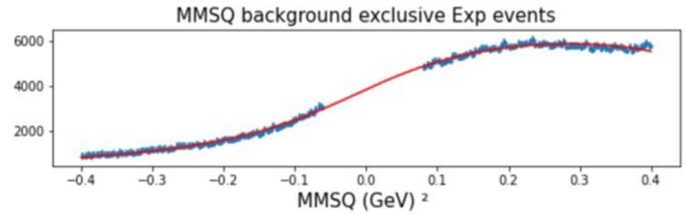


1.75 GeV < W < 1.8 GeV and 4 GeV^2 < Q^2 < 5 GeV^2

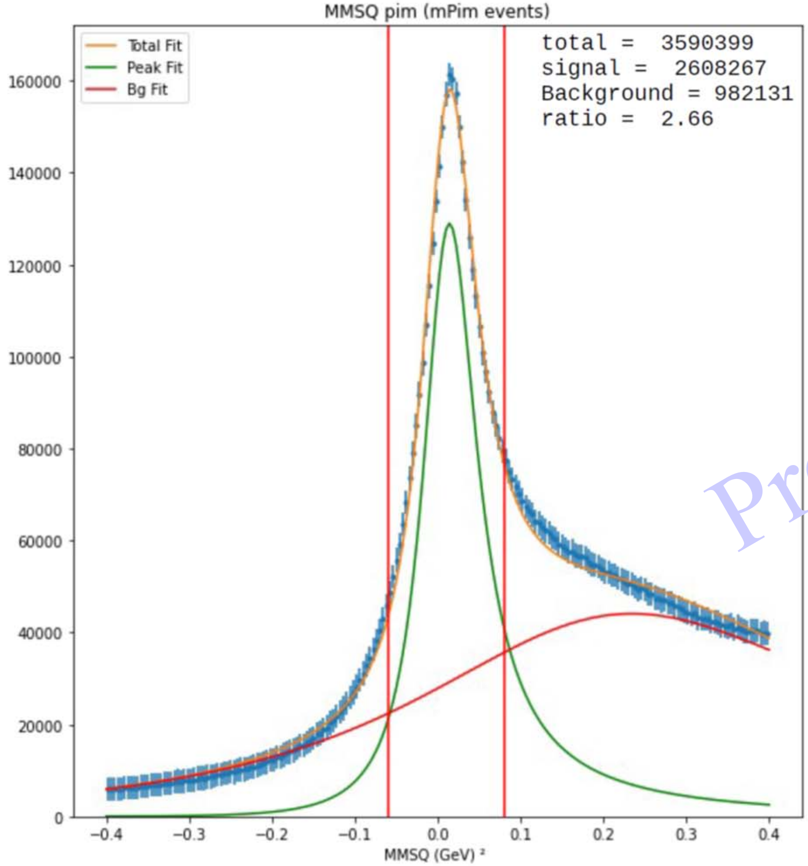
Single Particle Efficiency: Experiment

Krishna Neupane

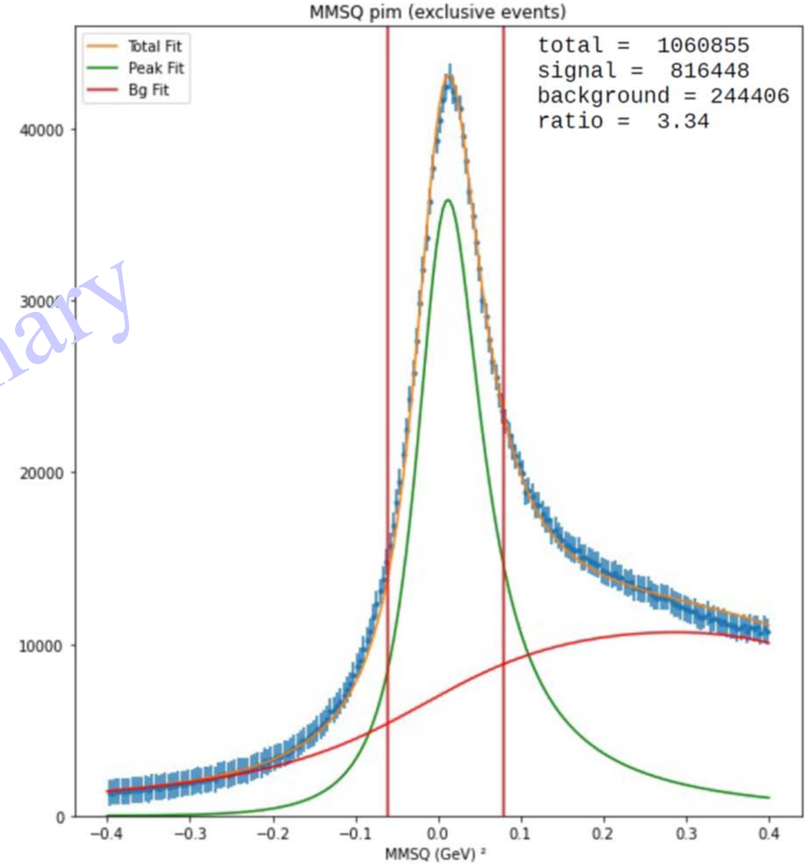
10.6 GeV



ε_{π^-}=31.3%



Preliminary

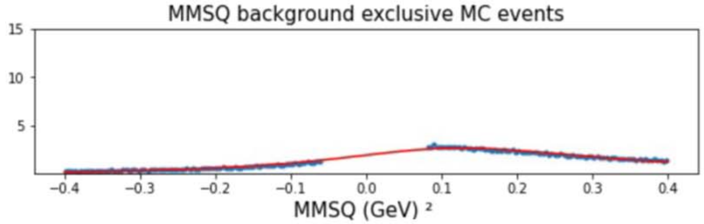


Single Particle Efficiency: Simulation

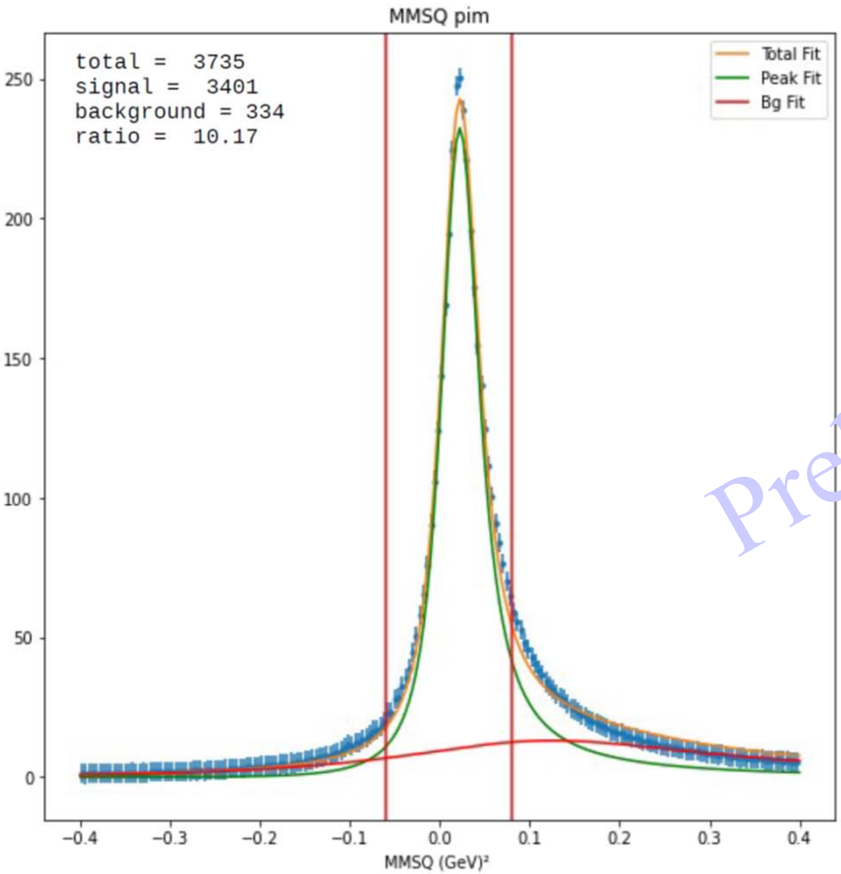
Efficiency Correction Factor = 87.7%

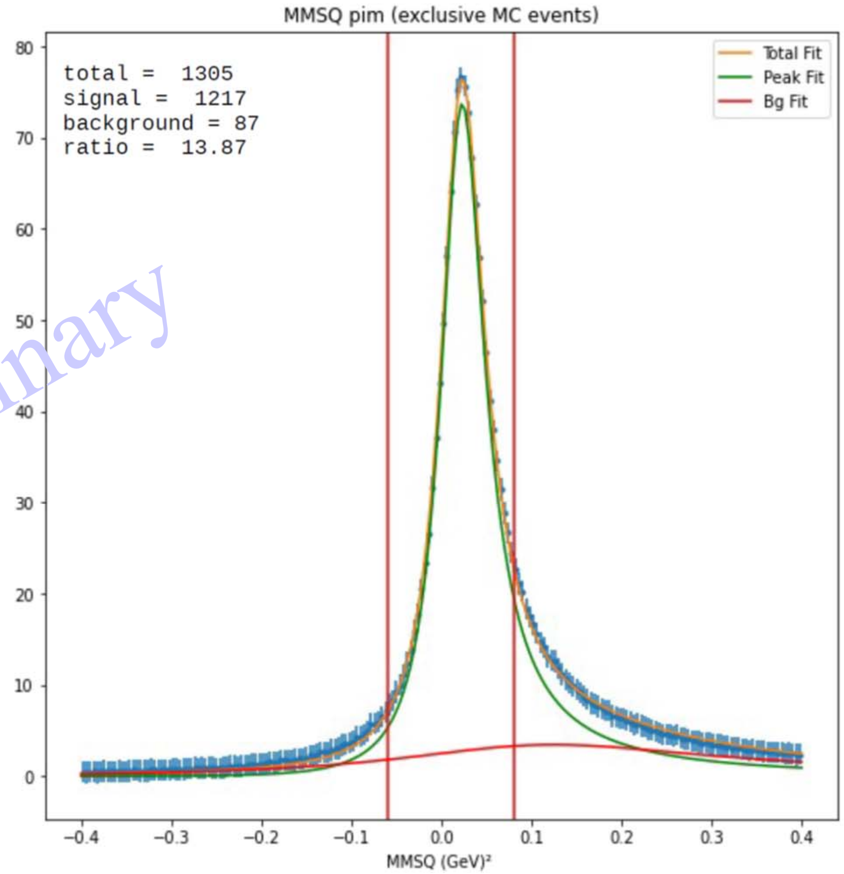
Krishna Neupane

10.6 GeV



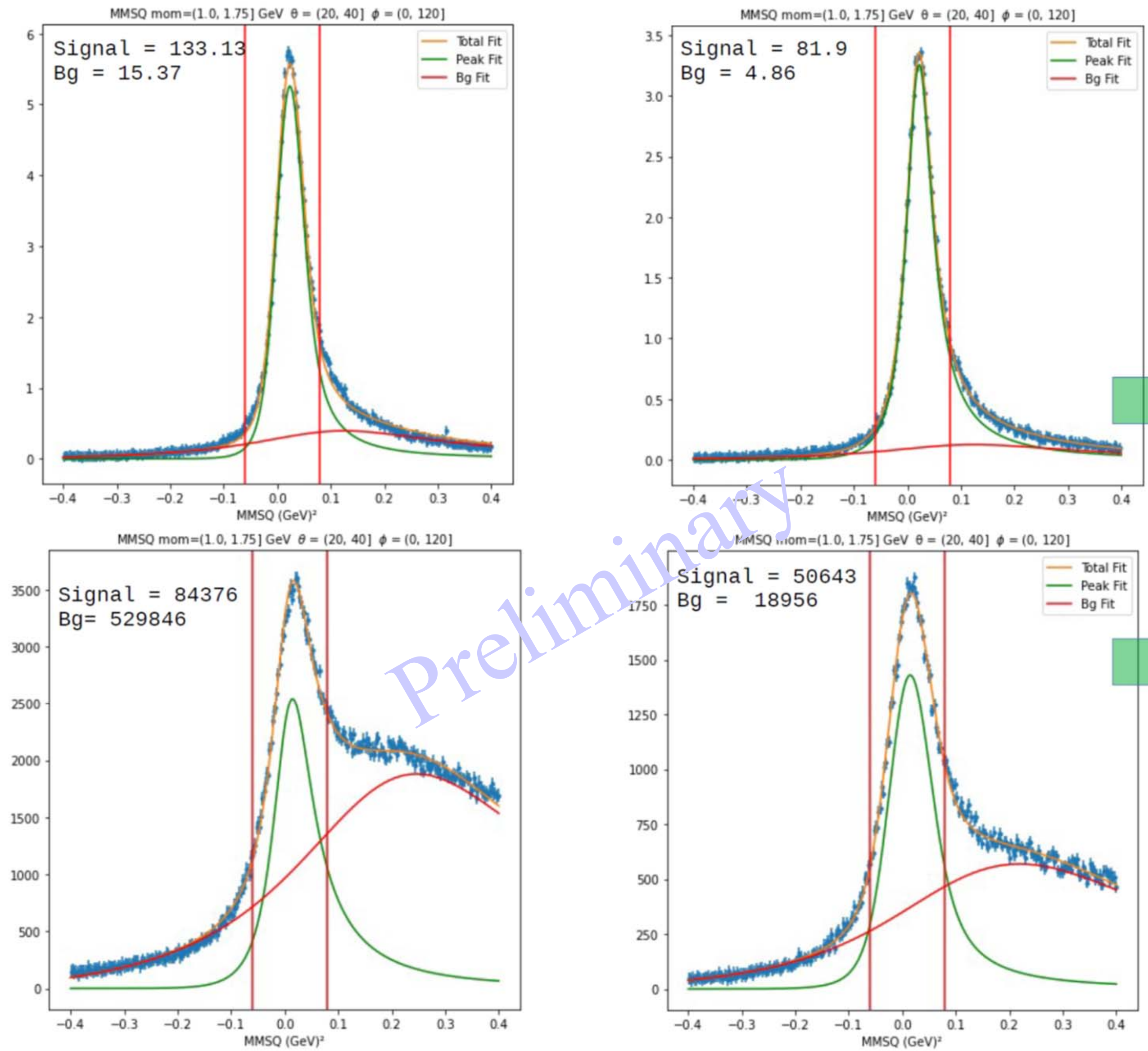
ε_{π^-}=35.7%





Single Particle Efficiency

Krishna Neupane



π^- **mom** (4 bins)
$\theta_{\pi-}$ (3 bins)
$\varphi_{\pi-}$ (3 bins)

Simulation

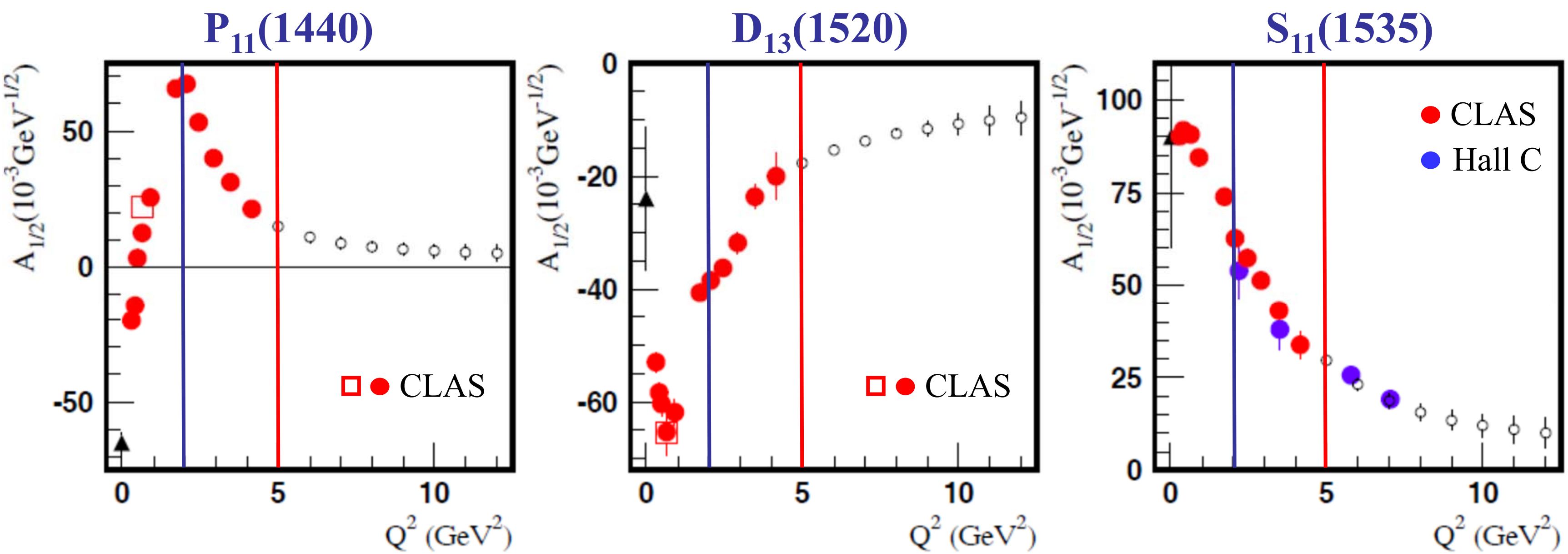
ε_{π^-}=61.1%

Experiment

ε_{π^-}=60.0%

Efficiency Correction Factor = **98.1%**

Anticipated N* Electrocouplings from Combined Analyses of Nπ/Nππ

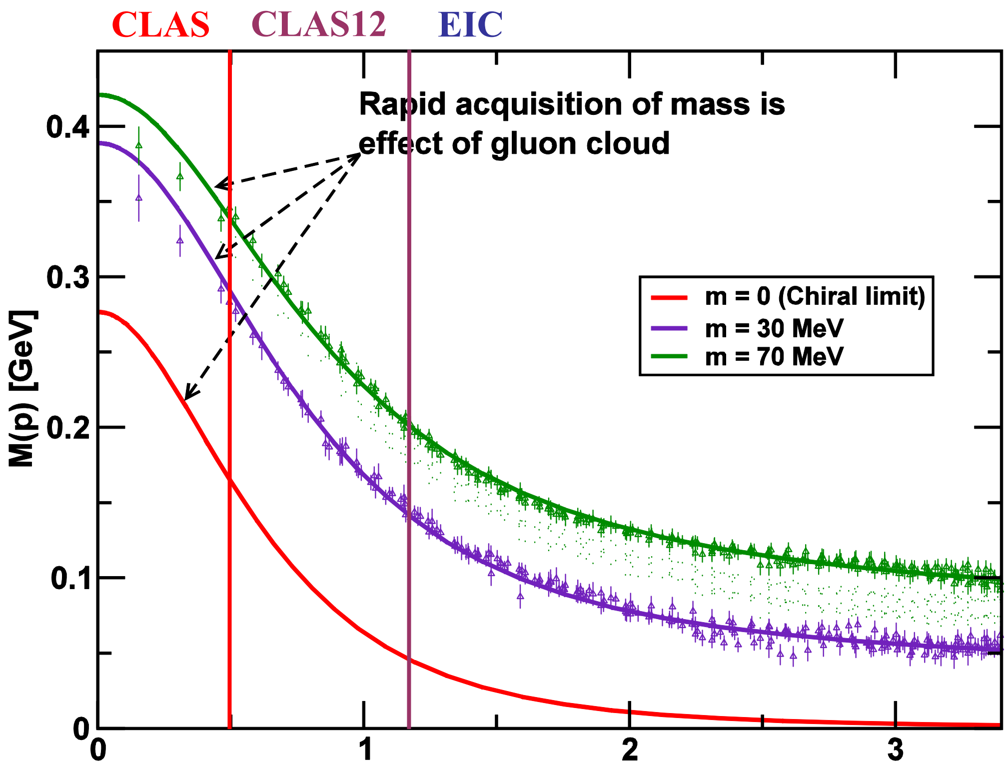


Open circles represent projections and all other markers the available results with the 6-GeV electron beam

- 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, see http://boson.physics.sc.edu/~gothe/research/pub/whitepaper-9-14.pdf.

Dynamical Mass of Light Dressed Quarks



$Q^2 = 2.75\ GeV^2$

DSE and LQCD predict the dynamical generation of the momentum dependent dressed quark mass that comes from the gluon dressing of the current quark propagator.

These dynamical contributions account for more than 98% of the dressed light quark mass.

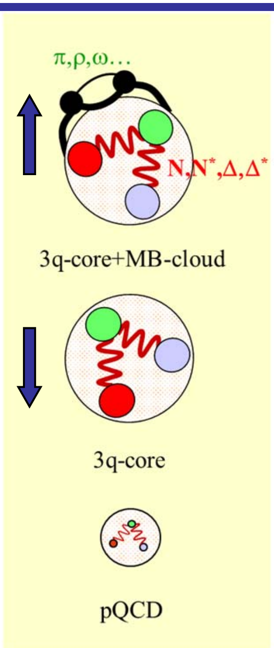
DSE: lines and LQCD: triangles

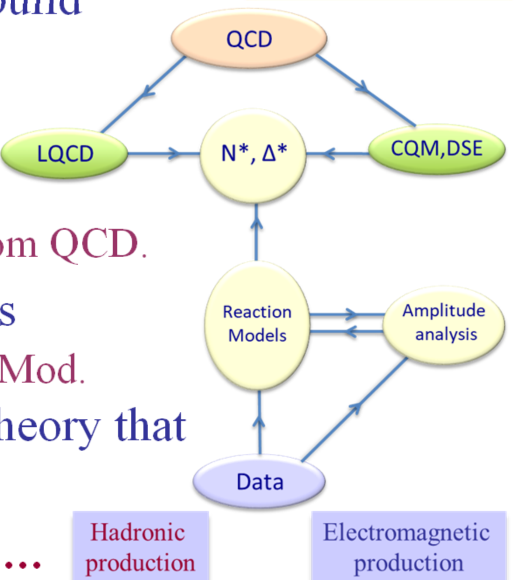
$Q^2 = 12\ GeV^2 = (p \text{ times number of quarks})^2 = 12\ GeV^2 \rightarrow p = 1.15\ GeV$

The data on N* electrocouplings at $5\ GeV^2 < Q^2 < 12\ GeV^2$ will allow us to chart the momentum evolution of dressed quark mass, and in particular, to explore the transition from dressed to almost bare current quarks as shown above.

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 further 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, APCTP2018, JLab2019, sQCD 2021 …