Exposing EHM using CLAS, CLAS12, and CLAS24 at JLab

Ralf W. Gothe

UNIVERSITY OF SOUTH CAROLINA

ECT* Workshop on Revealing Emergent Mass through Studies of Hadron Spectra and Structure
September 12-16, 2022, Trento, Italy

Jefferson Lab

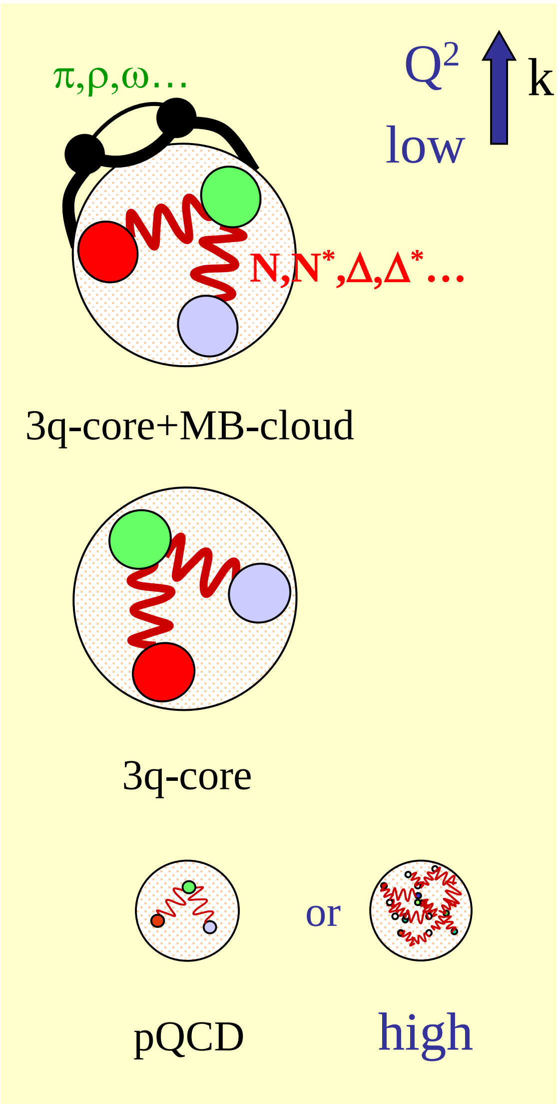
FONDAZIONE BRUNO KESSLER
ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

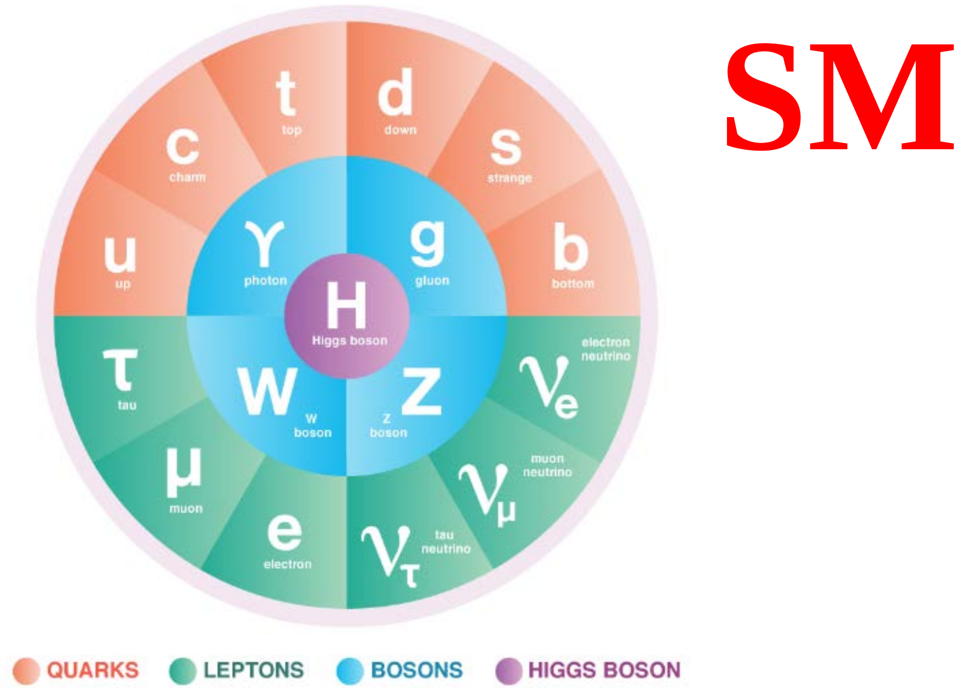
- Why are $\gamma_v NN^*$ electrocouplings interesting? Probing bound valence quarks, baryon wave functions, the emergence of mass, and finally strong QCD.
- What is needed beyond CLAS12? Beam energy and a high acceptance (exclusive), and high-luminosity detector (beam time) with good W resolution.

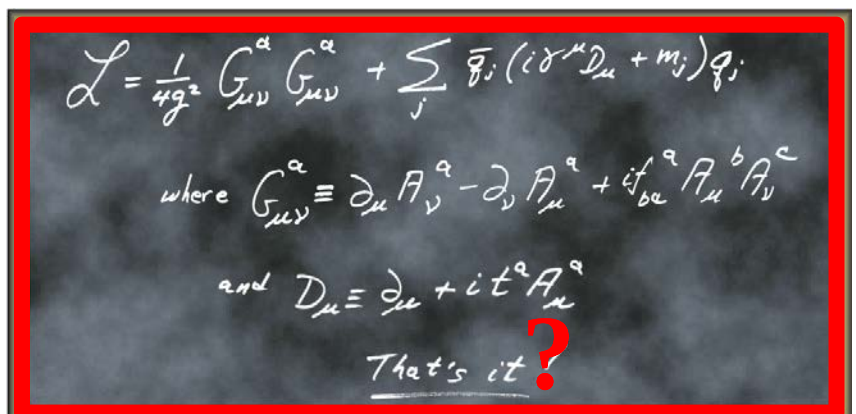
This work is supported in parts by the National Science Foundation under Grant PHY 10011349.

Why are they Interesting?

Emergence of Hadron Mass Traced by Electromagnetic Probes

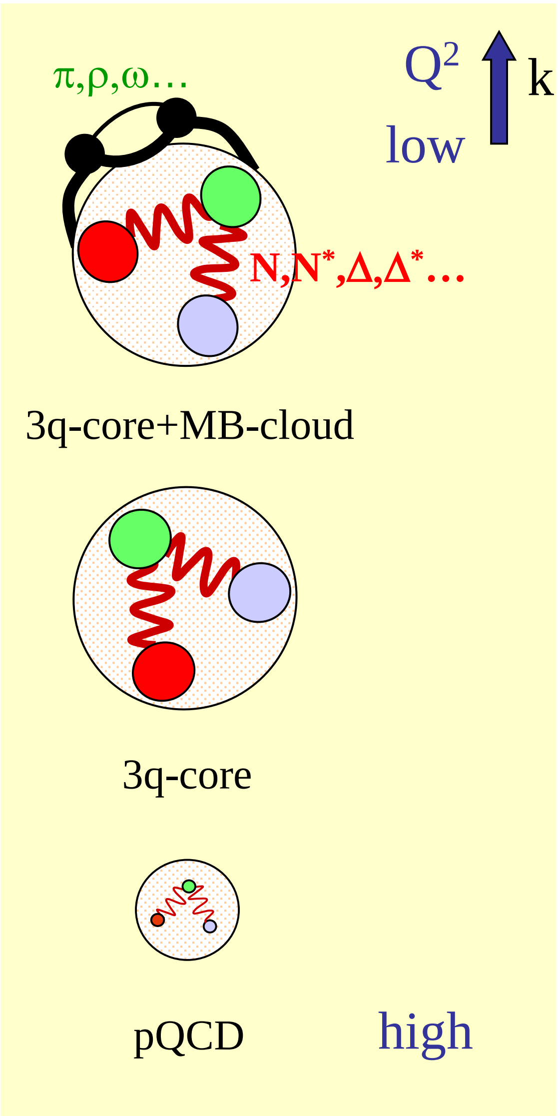




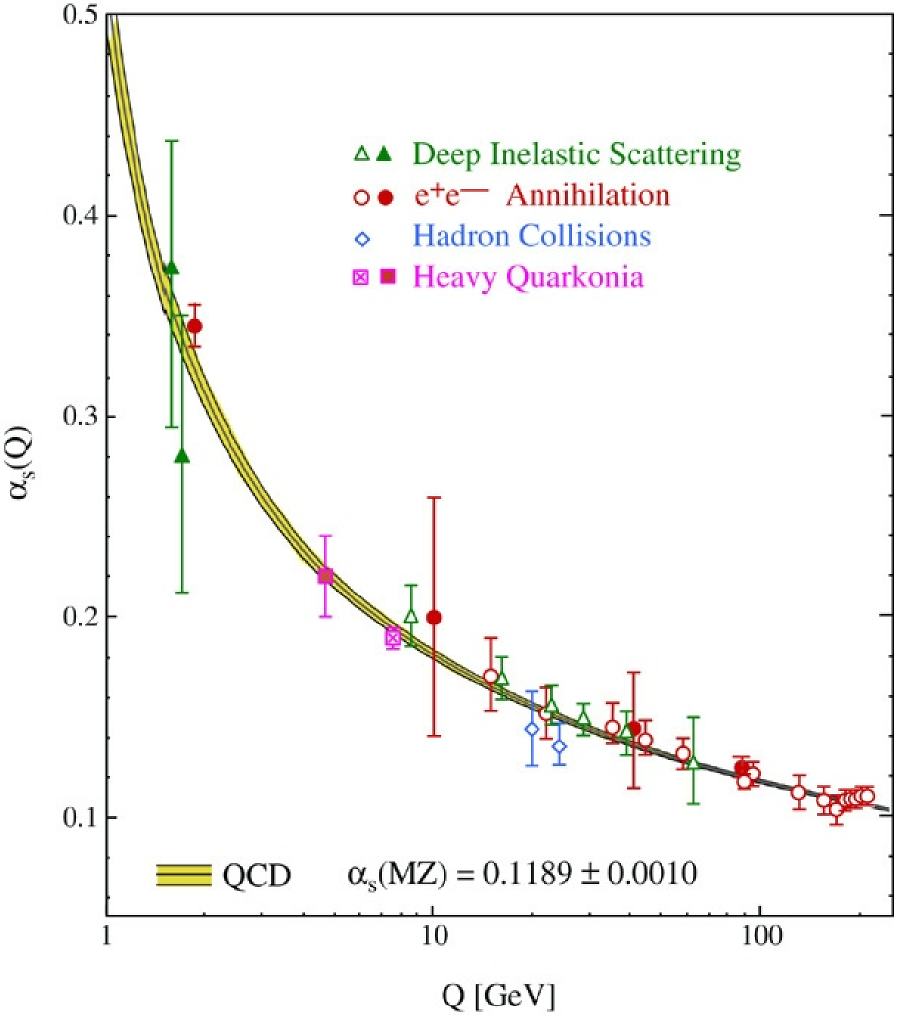


Frank Wilczek, Physics Today, August 2000

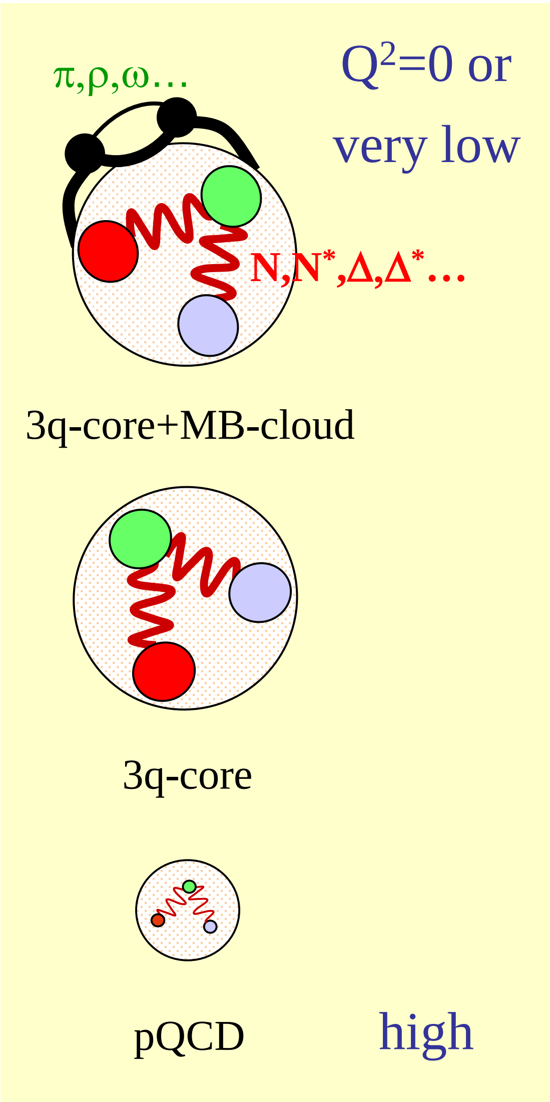
Hadron Structure with Electromagnetic Probes

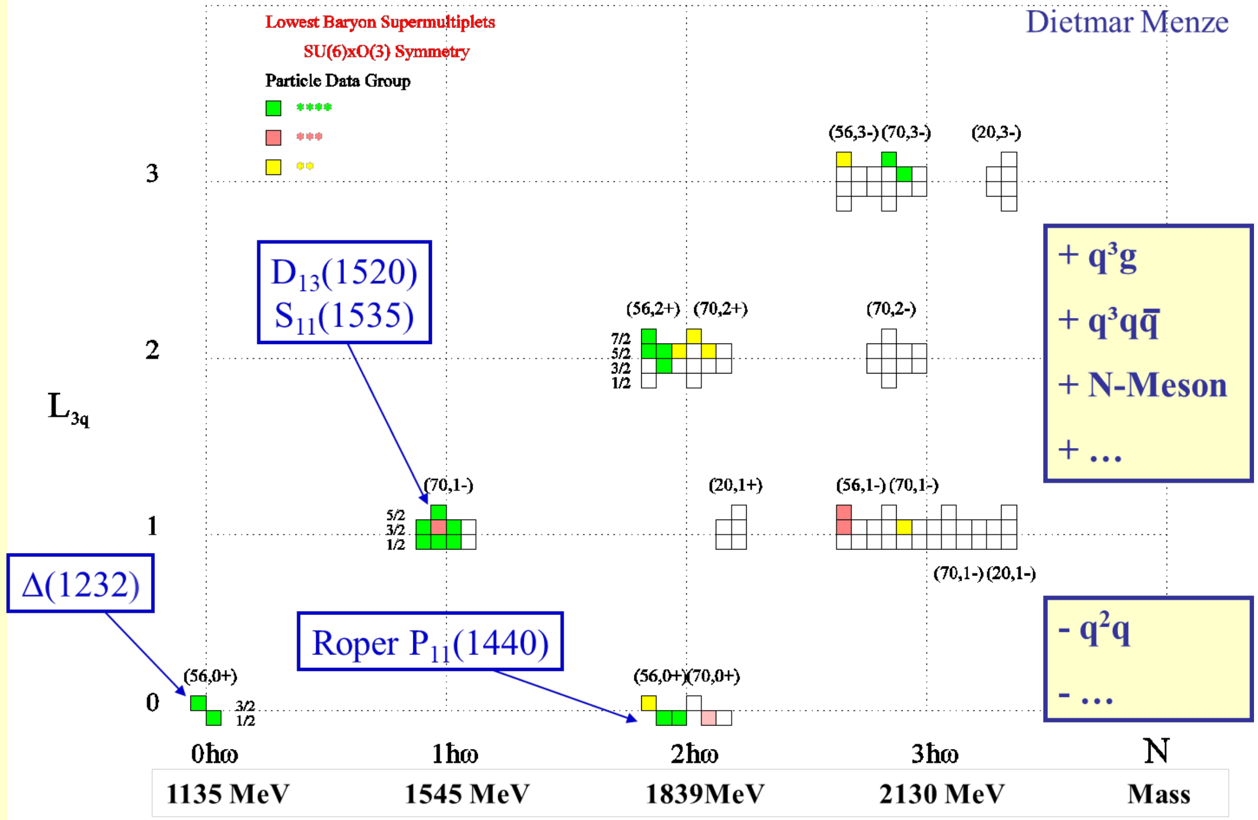


- The SM α_s diverges as Q^2 approaches zero, but confinement and the meson cloud heal this artificial divergence as QCD becomes non-perturbative.



Hadron Spectrum with Electromagnetic Probes

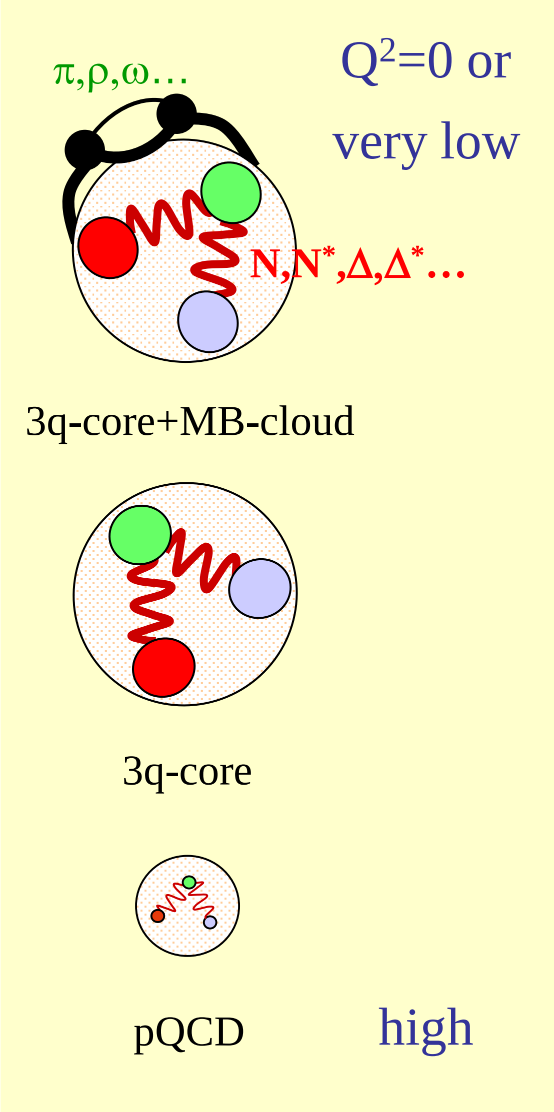


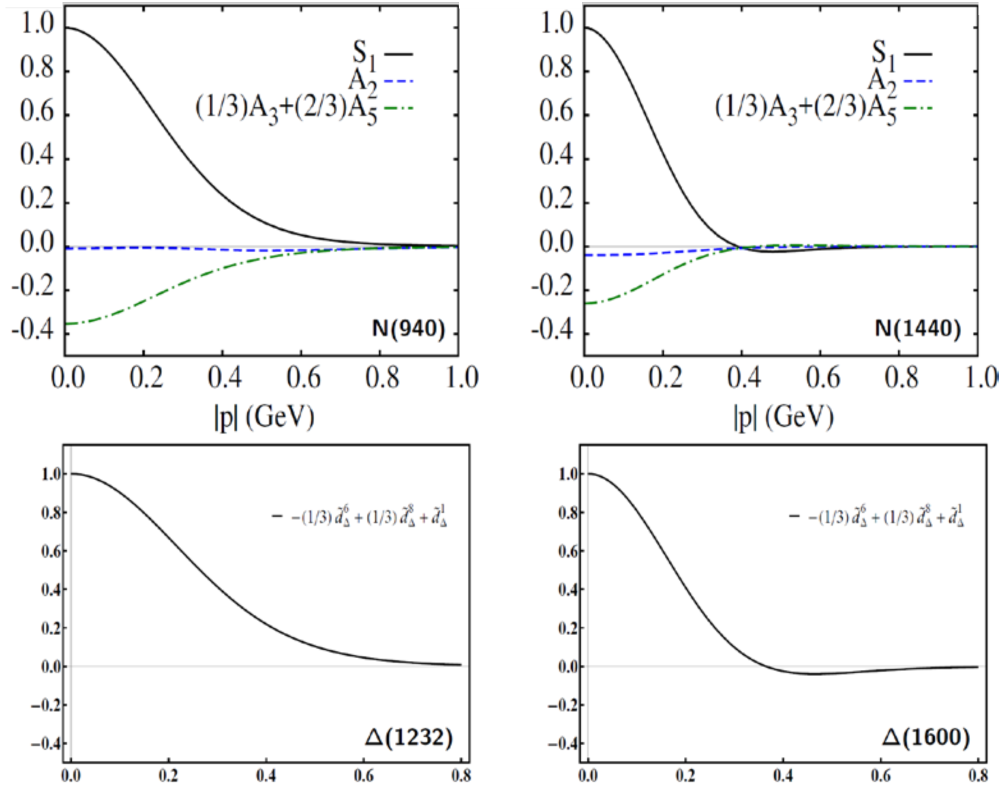


- Study the spectrum of nucleons in the domain where dressed quarks are the major active degree of freedom.
- Explore the formation of excited nucleon states in interactions of fully dressed quarks and their emergence from QCD.

Hadron Spectrum with Electromagnetic Probes

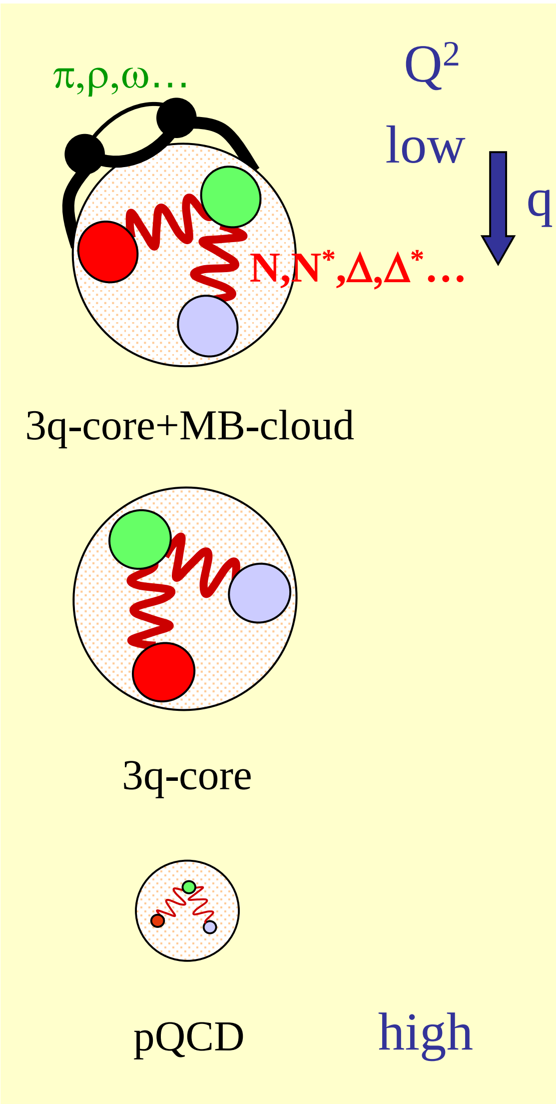
Jorge Segovia





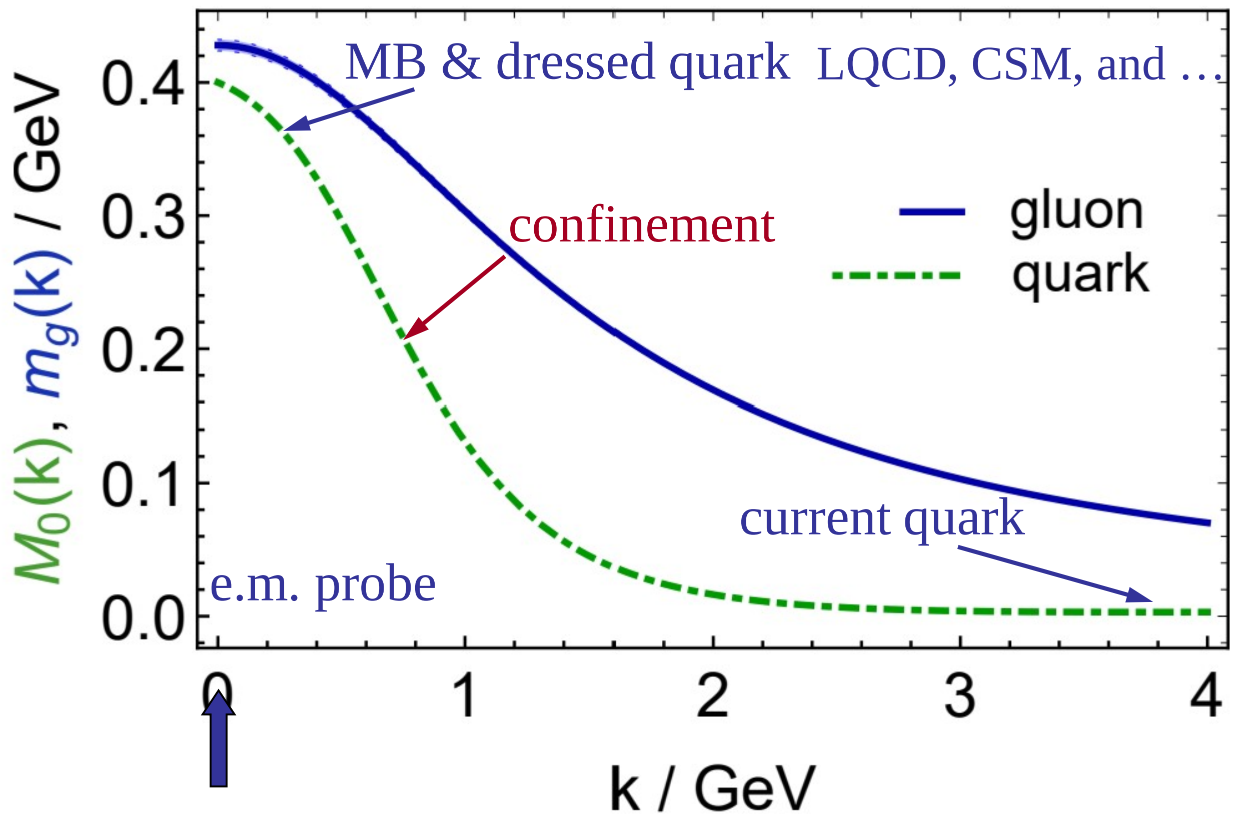
	$N(940)$	$N(1440)$	$\Delta(1232)$	$\Delta(1600)$
scalar	62%	62%	–	–
pseudovector	29%	29%	100%	100%
mixed	9%	9%	–	–
S-wave	0.76	0.85	0.61	0.30
P-wave	0.23	0.14	0.22	0.15
D-wave	0.01	0.01	0.17	0.52
F-wave	–	–	~ 0	0.02

Emergence of Hadron Mass Traced by Electromagnetic Probes

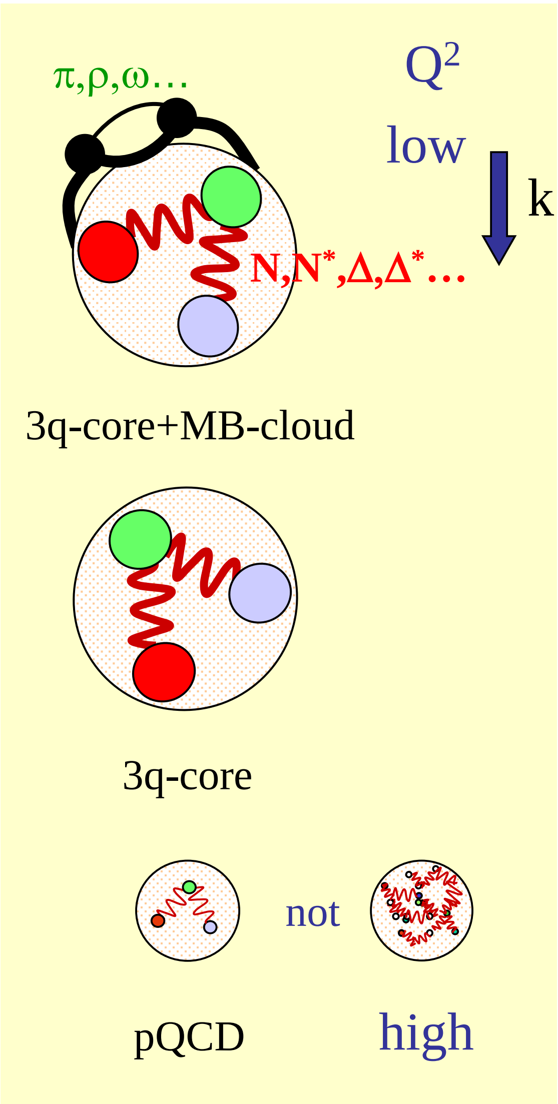


- Study the structure of the nucleon spectrum in the domain where dressed quarks are the major active degree of freedom.

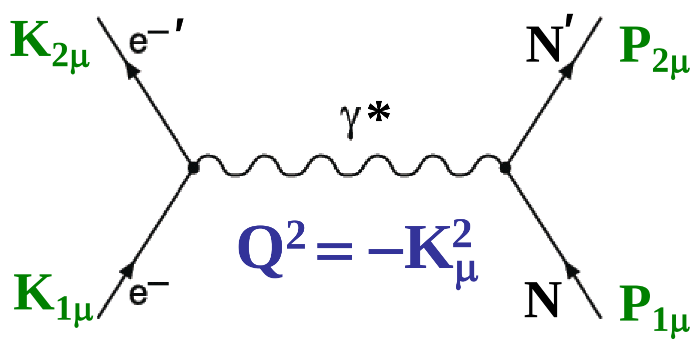
Zhu-Fang Cui et al., Chin. Phys. C **44** (2020) 083102/1-10

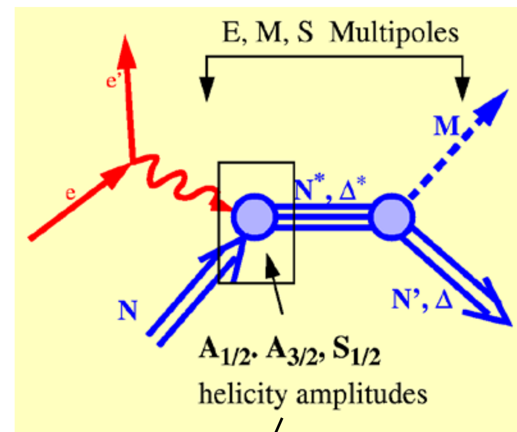


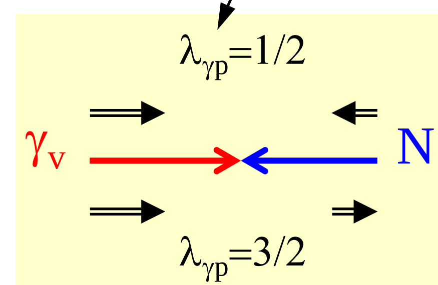
Hadron Structure with Electromagnetic Probes



- 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 at various distance scales and their emergence from QCD.



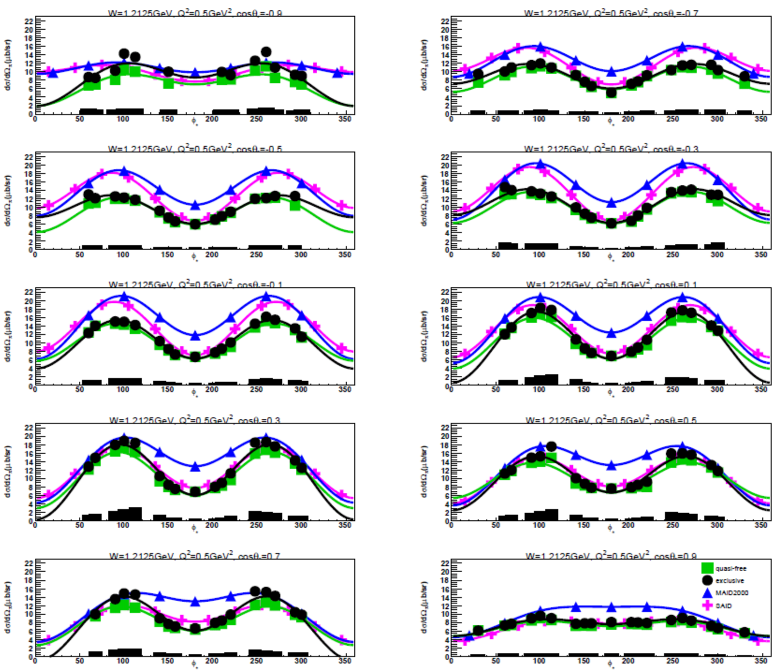




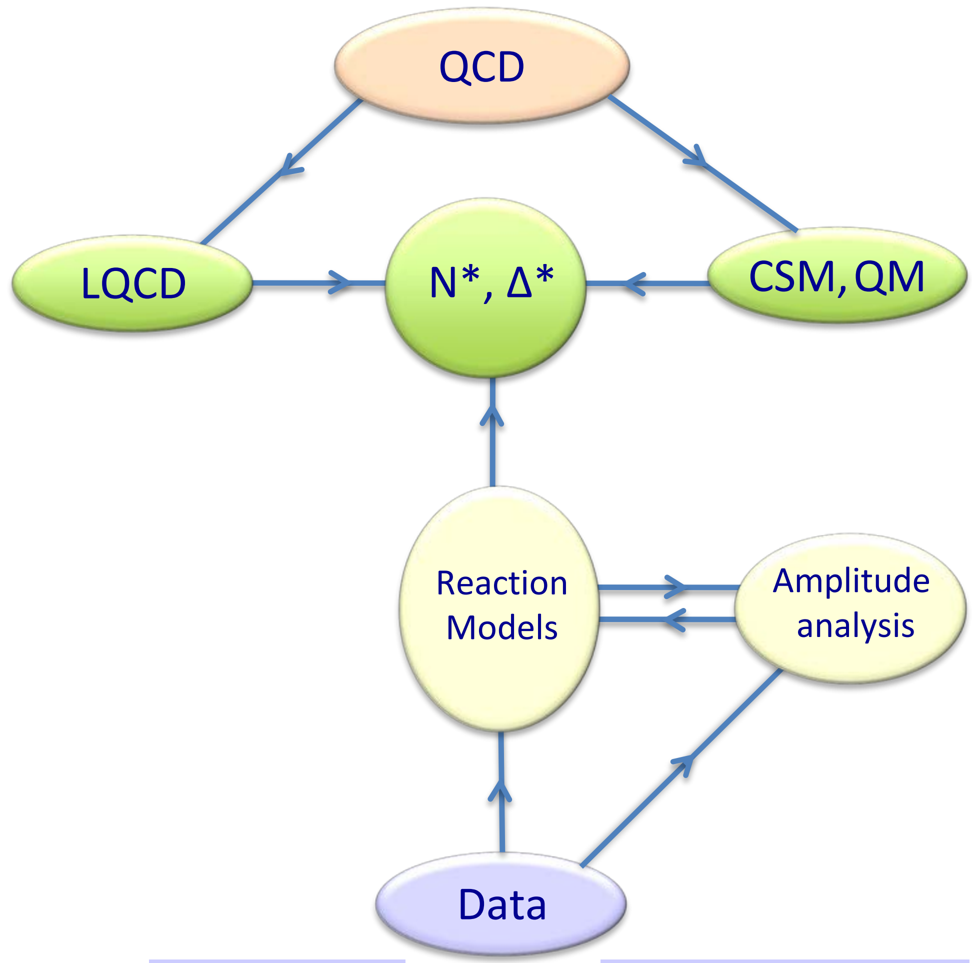
Data-Driven Data Analyses

Consistent Results

Single Pion



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



Hadronic production

Electromagnetic production

Exclusive Single π^- Electroproduction off the Deuteron

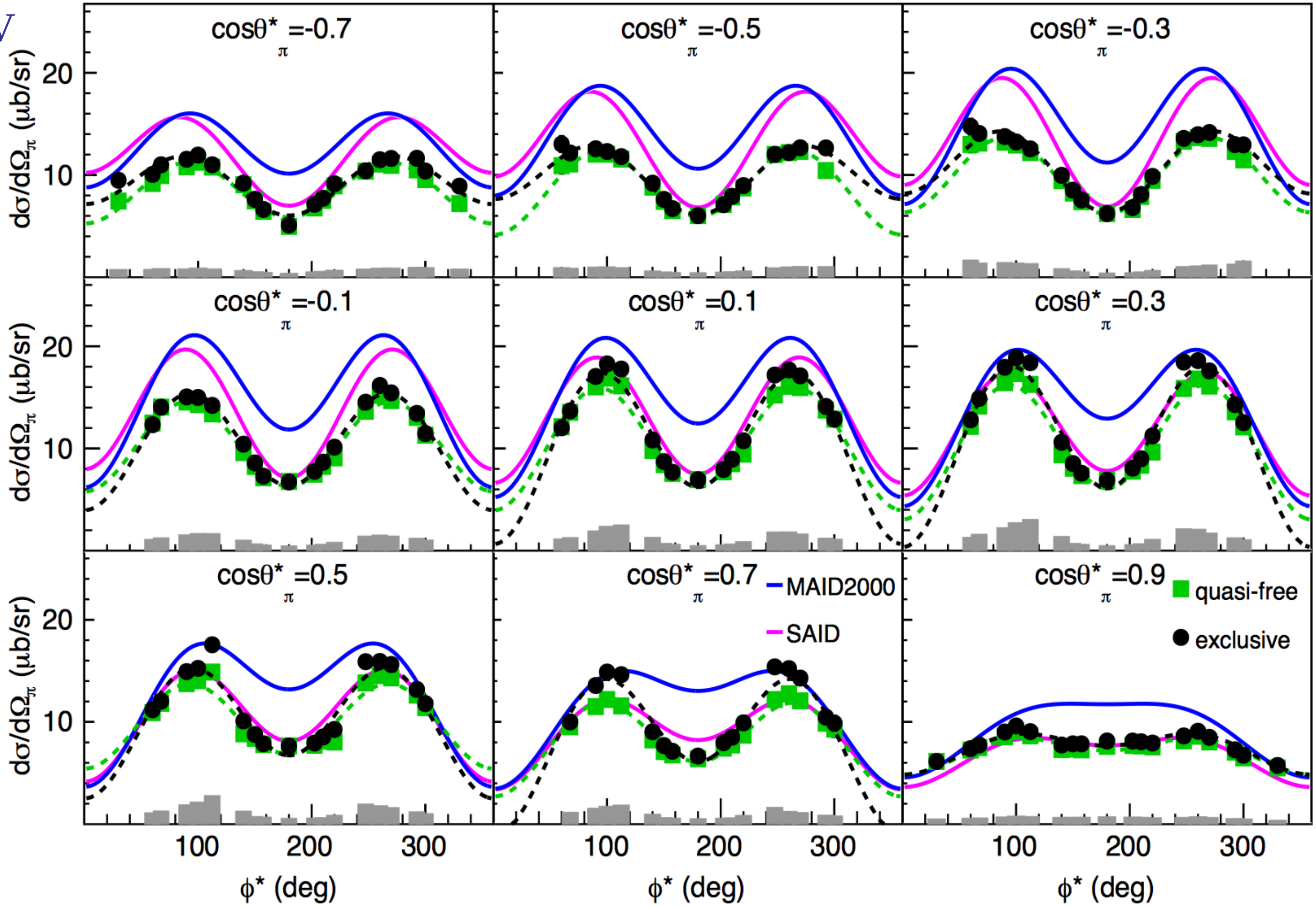
Y. Tian *et al.*, submitted to Phys. Rev C

W = 1.2125 GeV
ΔW = 25 MeV

$Q^2 = 0.5\ GeV^2$
$\Delta Q^2 = 0.2\ GeV^2$

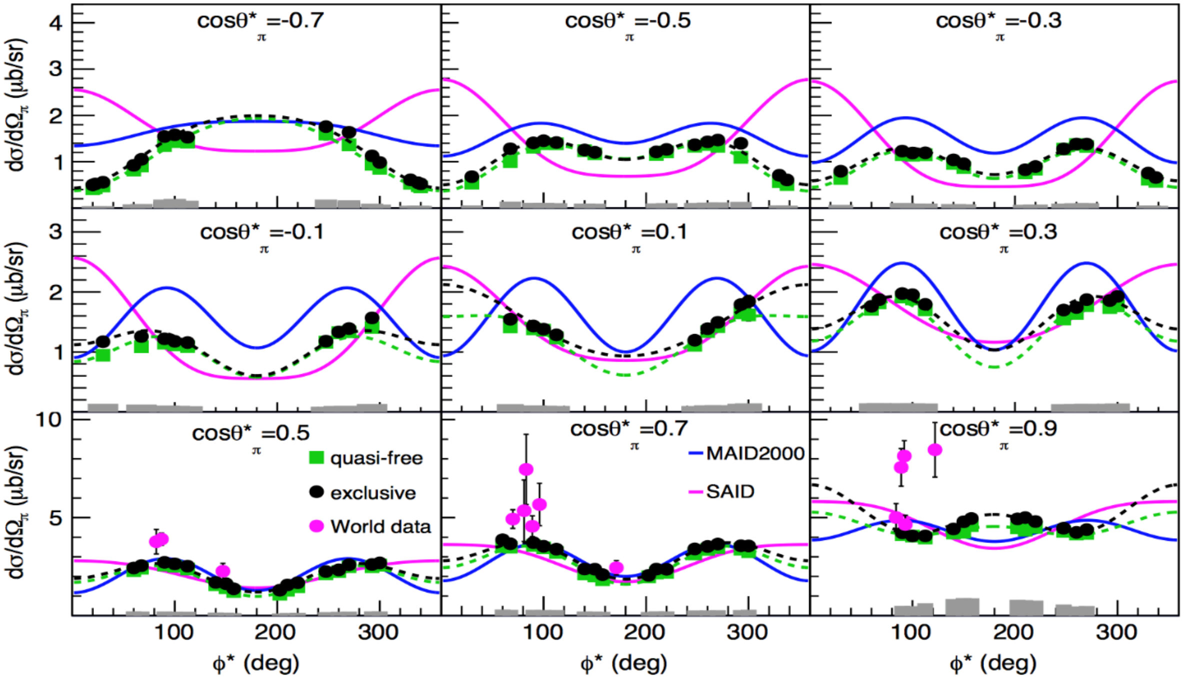
$\cos(\theta) = -0.7$
$\Delta\cos(\theta) = 0.2$
$\cos(\theta) = 0.9$

$\phi = 20^o$
$\Delta\phi = 40^o$
$\phi = 340^o$



Exclusive Single π^- Electroproduction off the Deuteron

Ye Tian

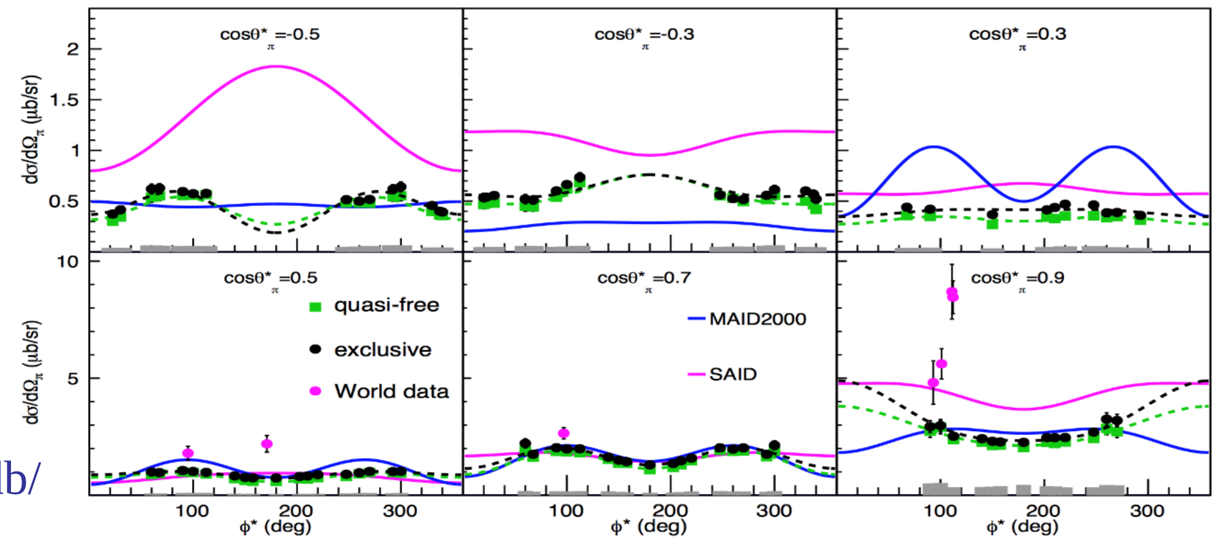


W = 1.5125 GeV

$Q^2 = 0.5$ GeV^2

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

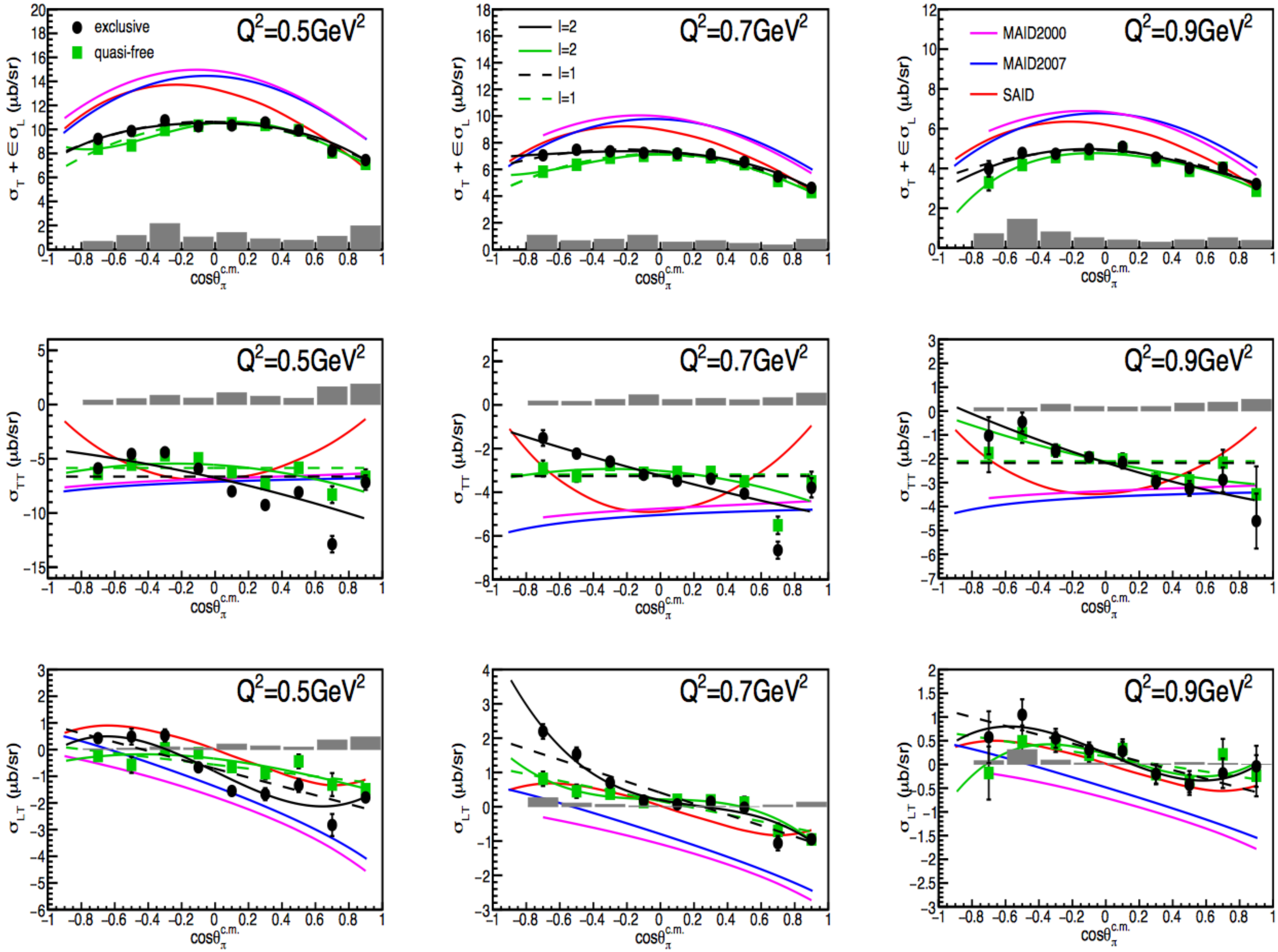
W = 1.6625 GeV



CLAS Database:
https://clasweb.jlab.org/physicsdb/

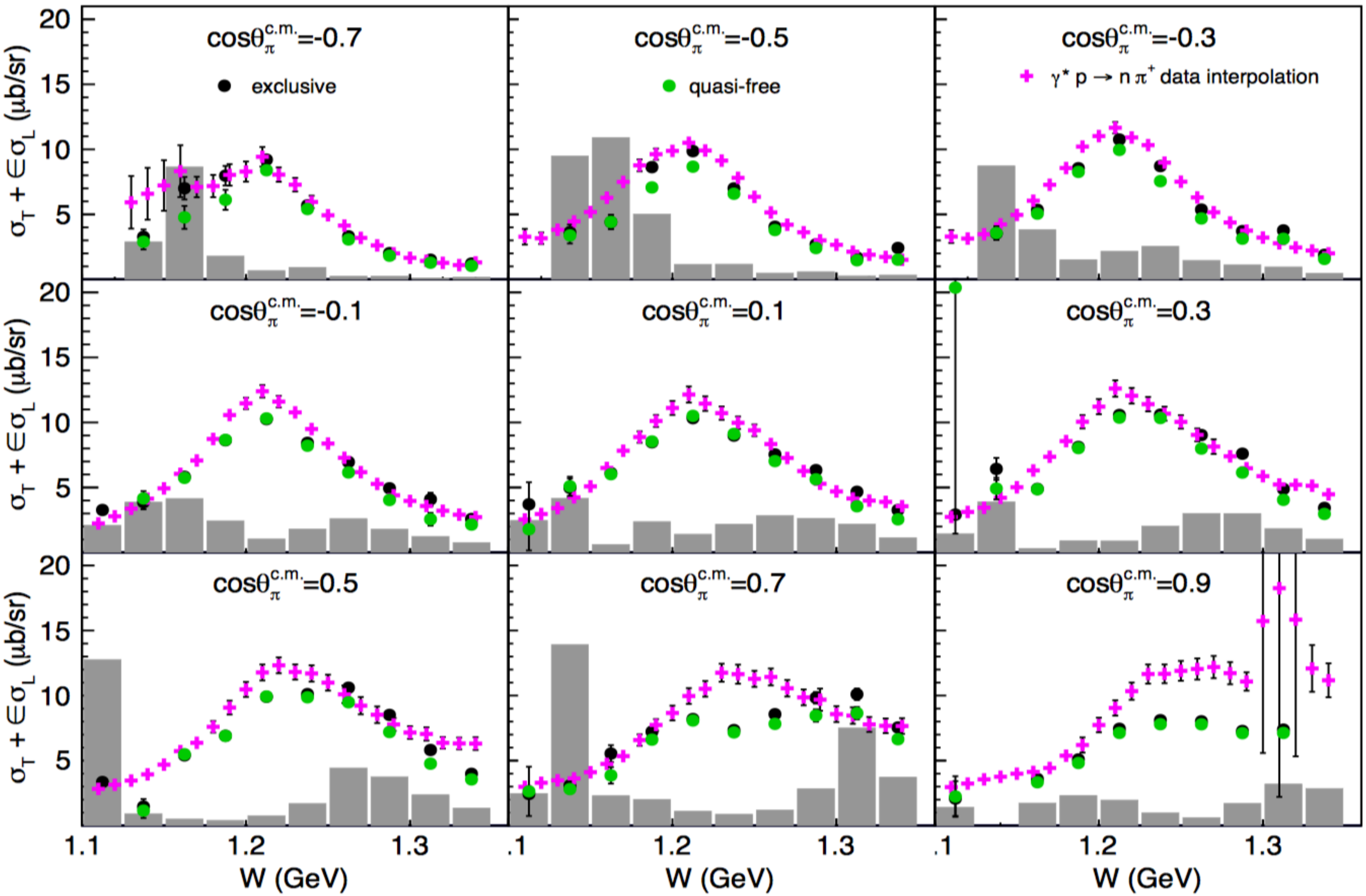
cos θ_π- Dependent Structure Functions @ W=1.2125 GeV

W = 1.2125 GeV   ΔW = 25 MeV   Ye Tian



W-Dependent of the Structure Function $\sigma_T + \varepsilon\sigma_L$

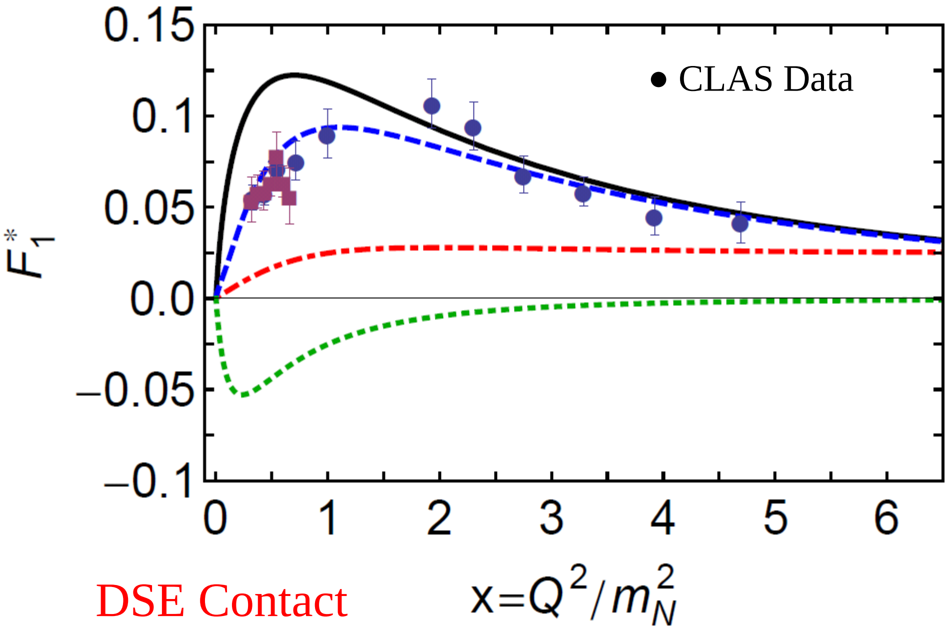
$Q^2 = 0.5$ GeV^2 $\Delta Q^2 = 0.2$ GeV^2 Ye Tian

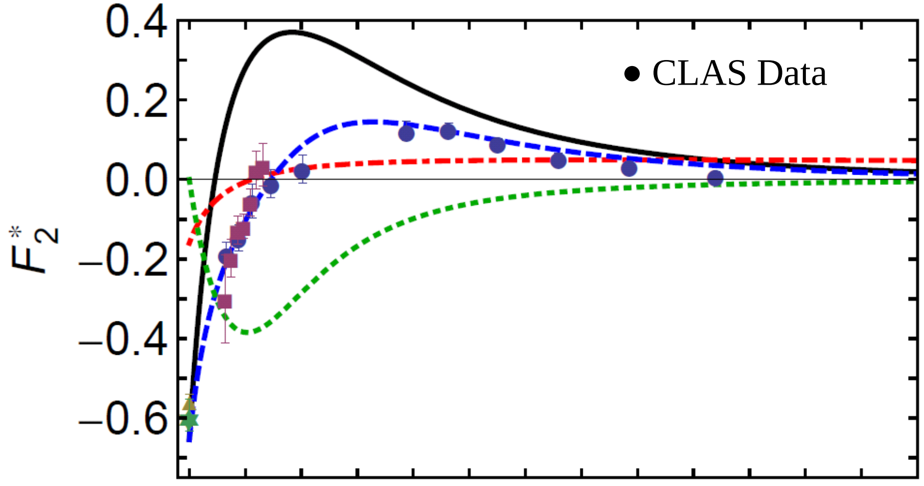


Roper Transition Form Factors in CSM Approach

N(1440)P_{11}

J. Segovia *et al.*, Phys. Rev. Lett. 115, 171801 (2015)



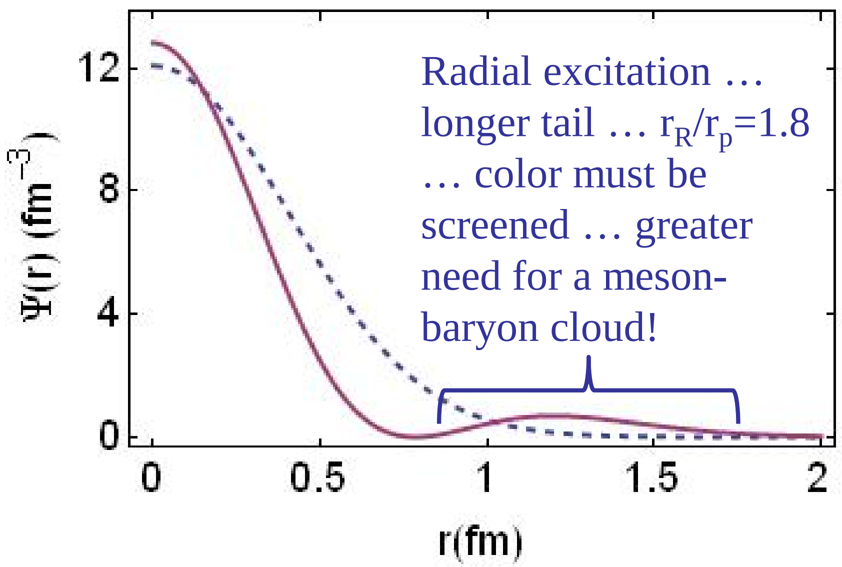


DSE Contact

DSE Realistic

Inferred meson-cloud contribution

Anticipated complete result

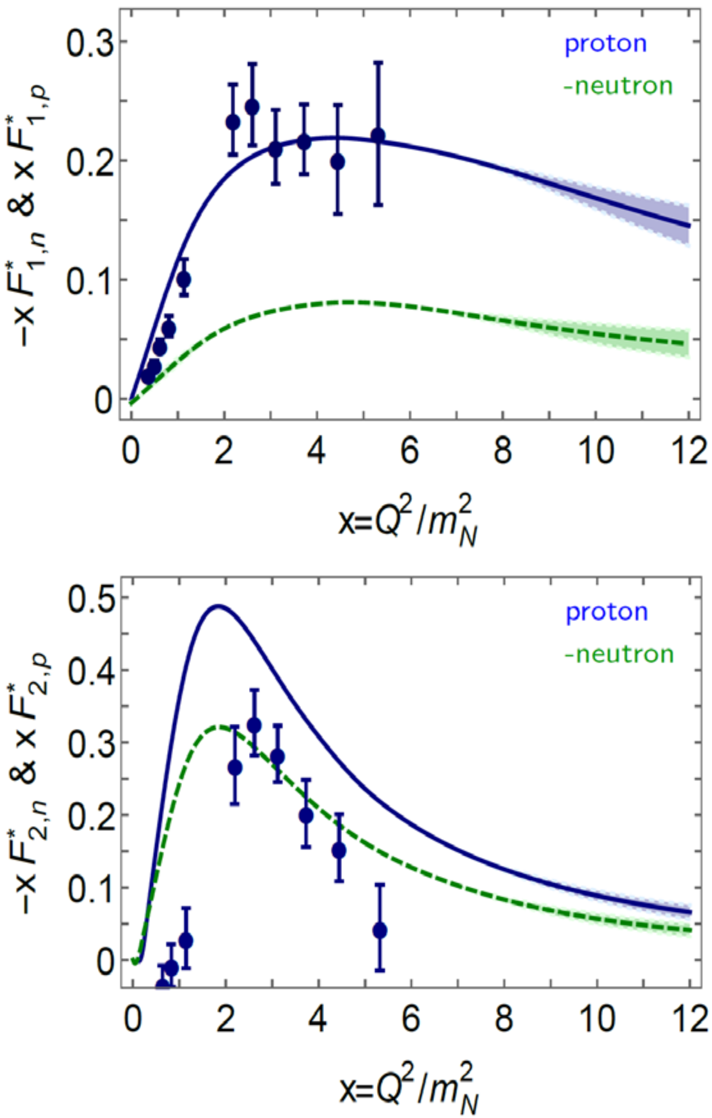


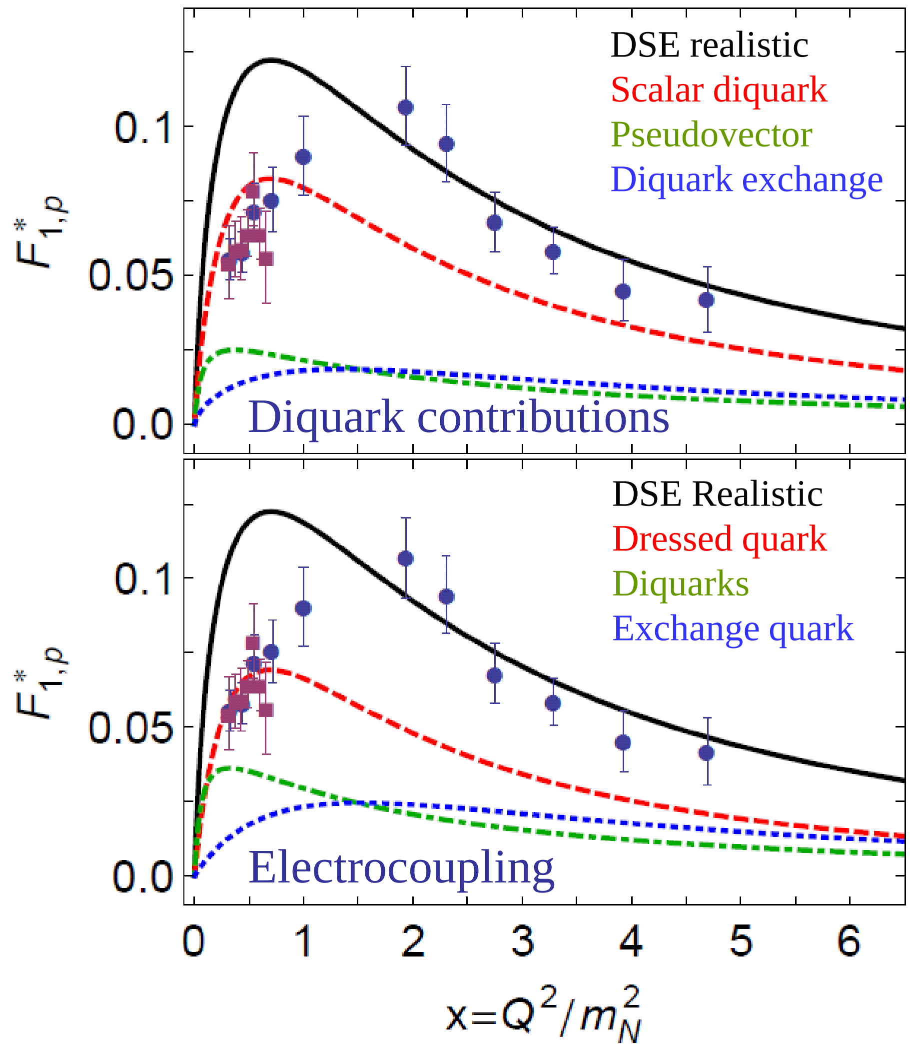
Importantly, the existence of a zero in F_2 is not influenced by meson-cloud effects, although its precise location is.

Roper Transition Form Factors in CSM Approach

N(1440)P_{11}

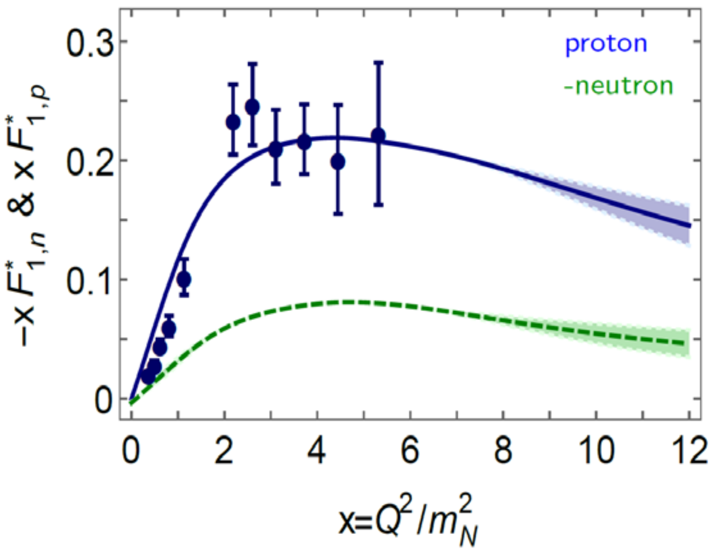
J. Segovia *et al.*, Phys. Rev. C 94, 042201 (2016)

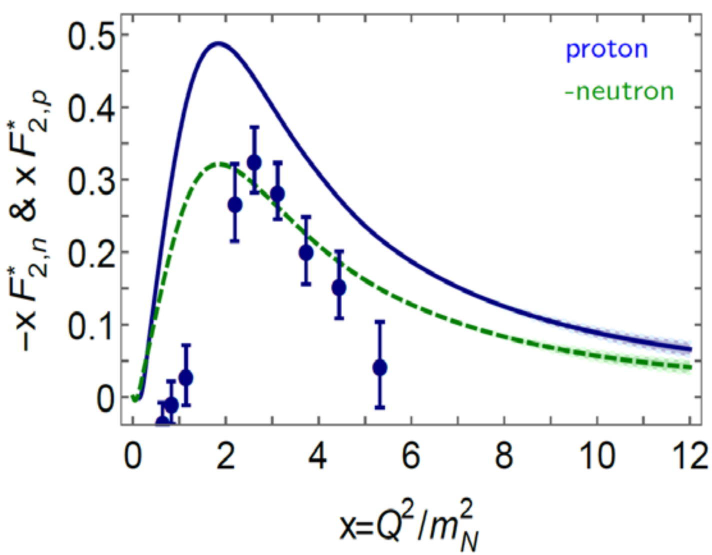




Roper Transition Form Factors in CSM Approach

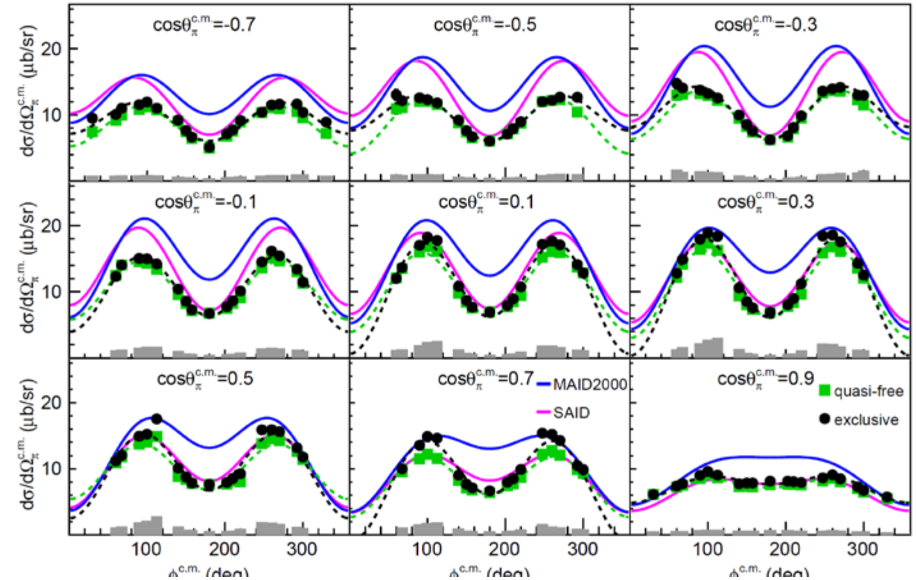
N(1440)P_{11}



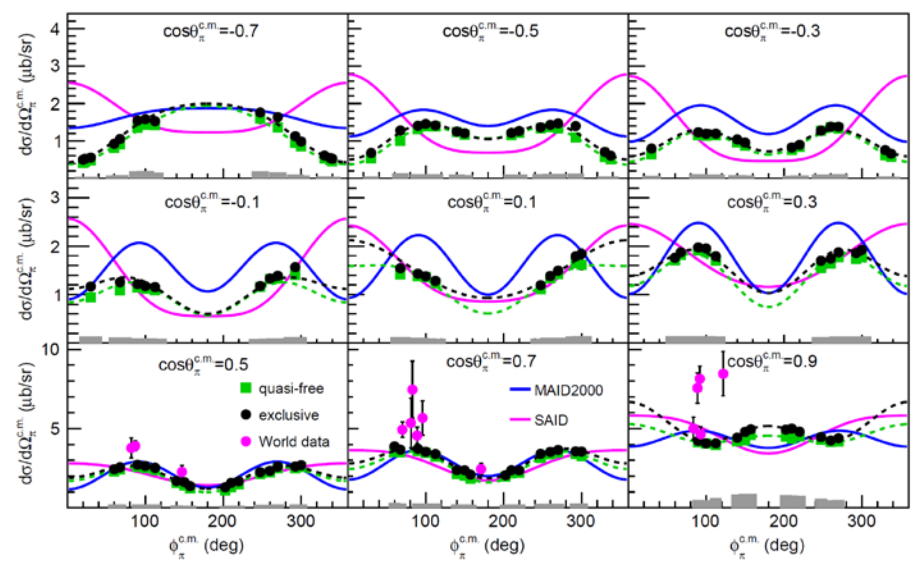


Y. Tian *et al*. submitted to Phys. Rev C

W = 1.2125 GeV



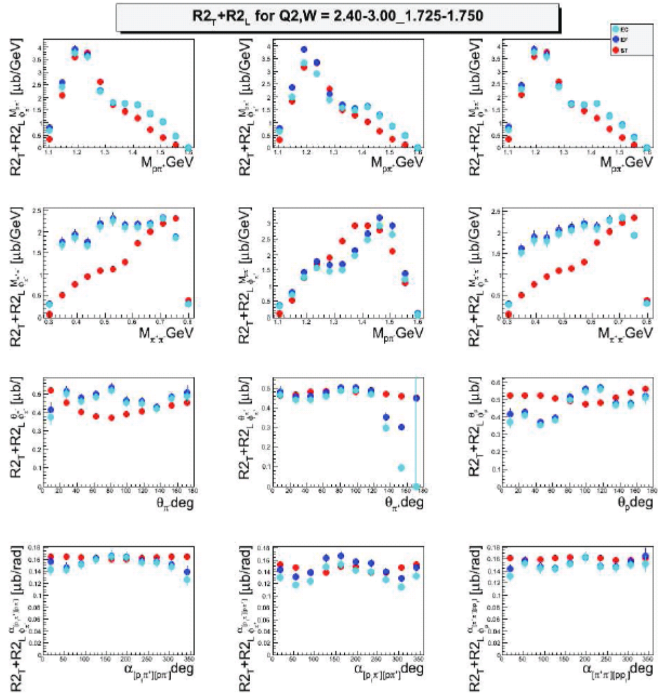
W = 1.5125 GeV



Data-Driven Data Analyses

Consistent Results

Double Pion



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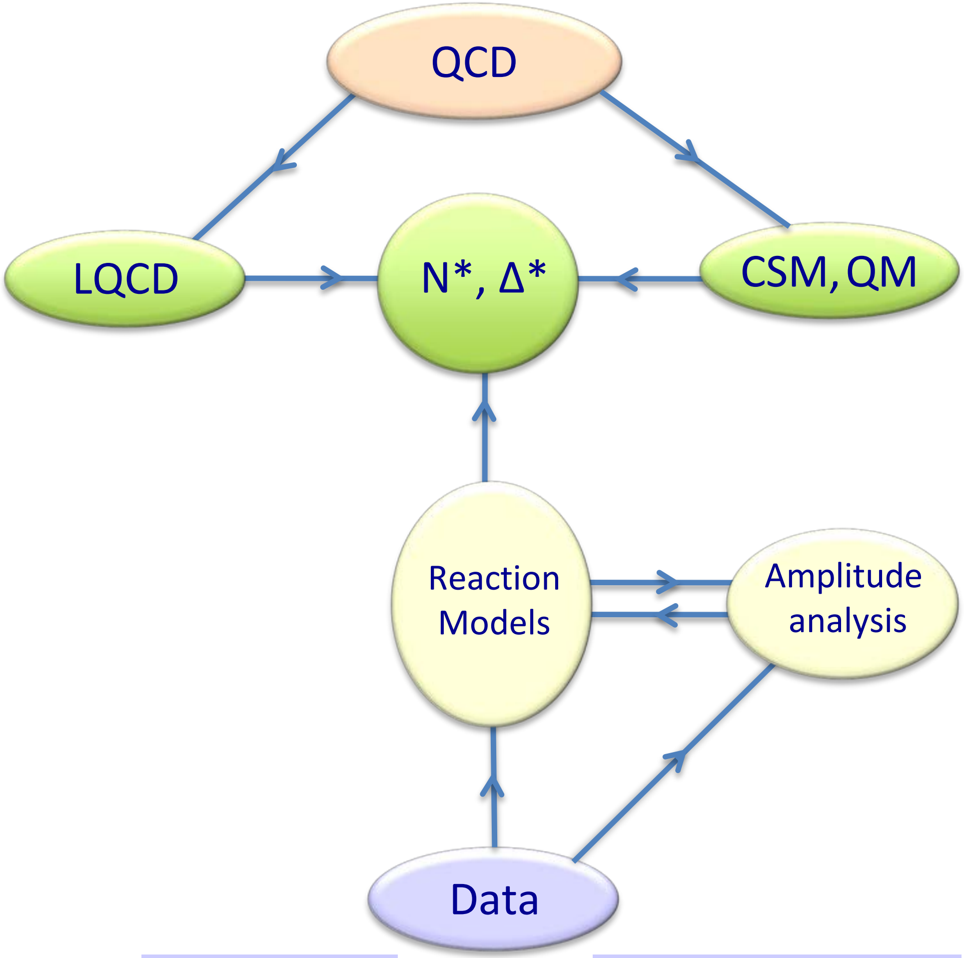


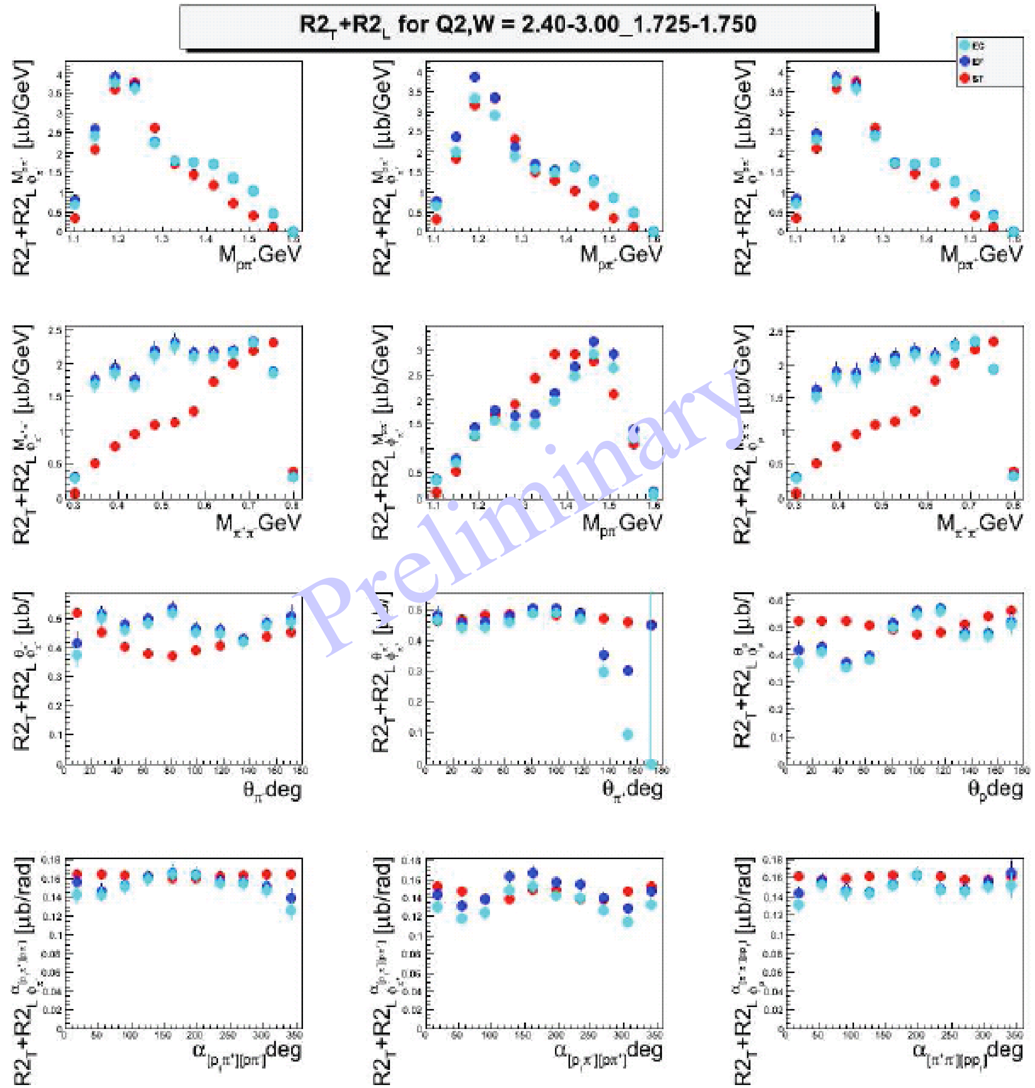
Hadronic production

Electromagnetic production

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



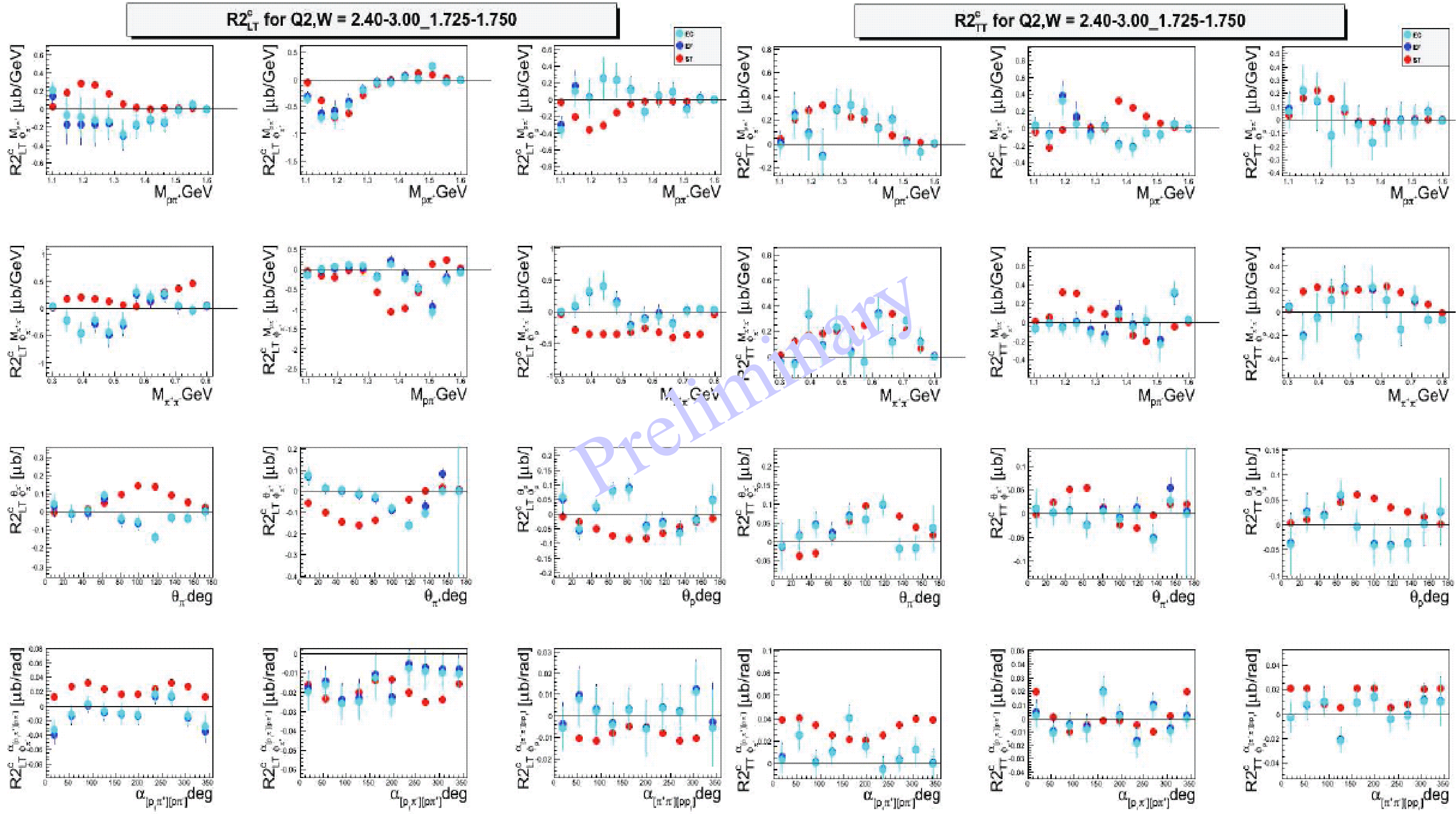
- normalized
- hole filled
- TWOPEG

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

φ-dependent Nππ Single-Differential Cross Sections

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

Arjun Trivedi



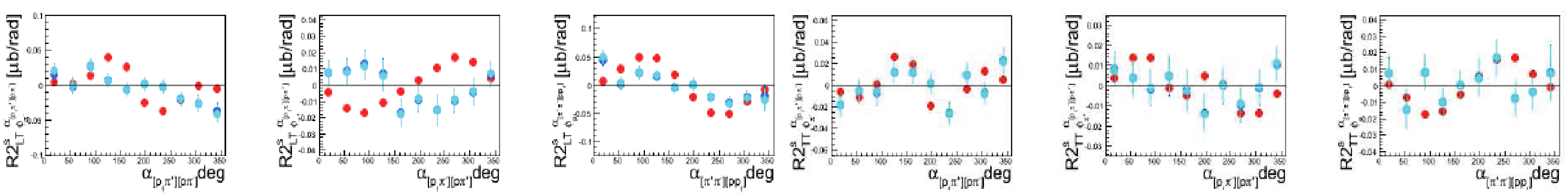
$$\left(\frac{d^2\sigma}{dX_{ij}d\phi_i}\right) = R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}} + \underline{R2_{LT}{}^{c,X_{ij}} \cos\phi_i} + \underline{R2_{TT}{}^{c,X_{ij}} \cos 2\phi_i} + \delta_{X_{ij}\alpha_i}\left(R2_{LT}{}^{s,\alpha_i} \sin\phi_i + R2_{TT}{}^{s,\alpha_i} \sin 2\phi_i\right)$$

φ-dependent Nππ Single-Differential Cross Sections

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

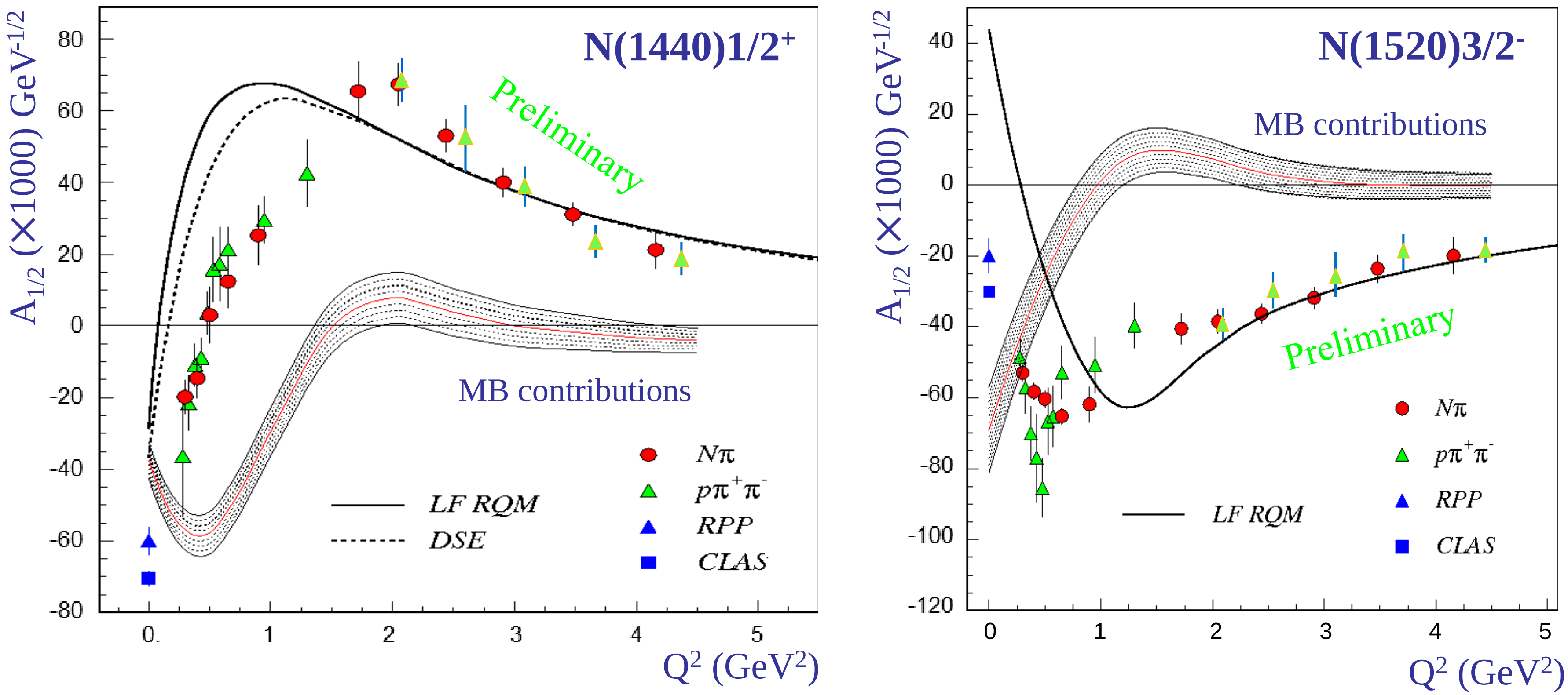
Arjun Trivedi

Chris McLauchlin extracts the beam helicity dependent differential cross sections.



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

N(1440)P_{11} and N(1520)D_{13} Couplings from CLAS



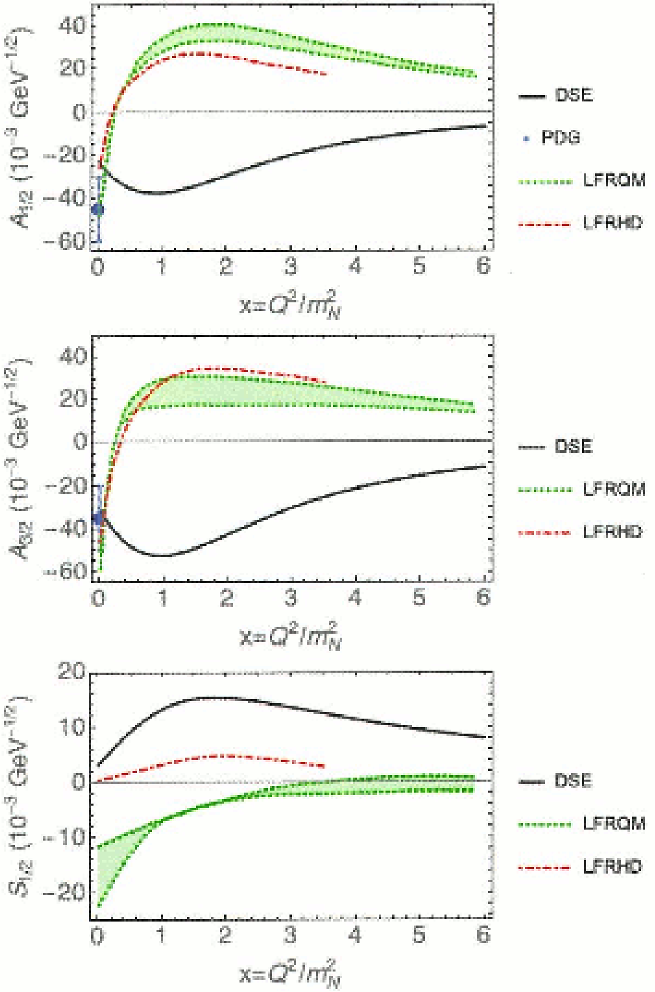
Consistent results obtained in the low-lying resonance region by independent analyses in the exclusive Nπ and $p\pi^+\pi^-$ final-state channels – that have fundamentally different mechanisms for the nonresonant background – underscore the capability of the reaction models to extract reliable resonance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

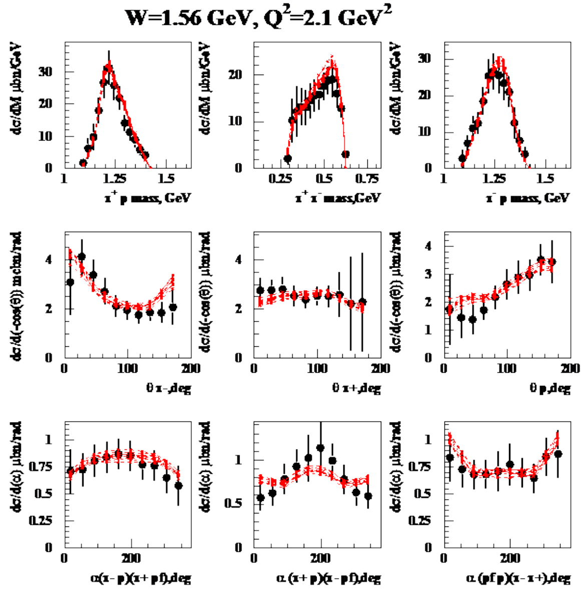
Phys. Rev. C 80, 055203 (2009) 1-22 and Phys. Rev. C 86, 035203 (2012) 1-22

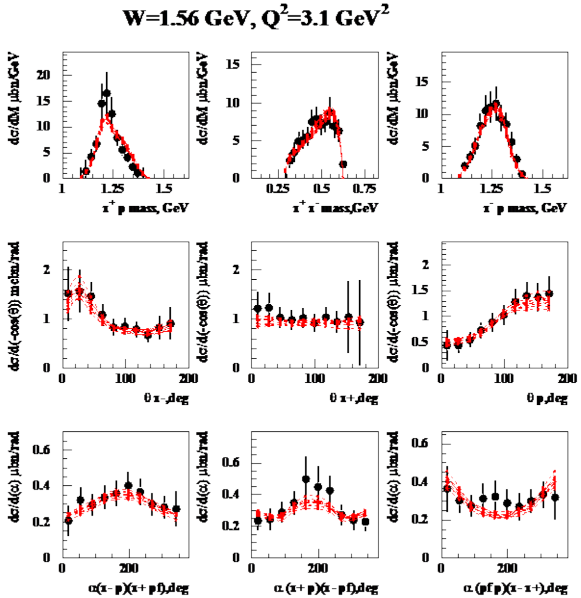
Δ(1600)3/2$^+$ Form Factors in CSM Approach

Arjun Trivedi

CSM predictions of the Δ(1600)3/2$^+$ electrocouplings





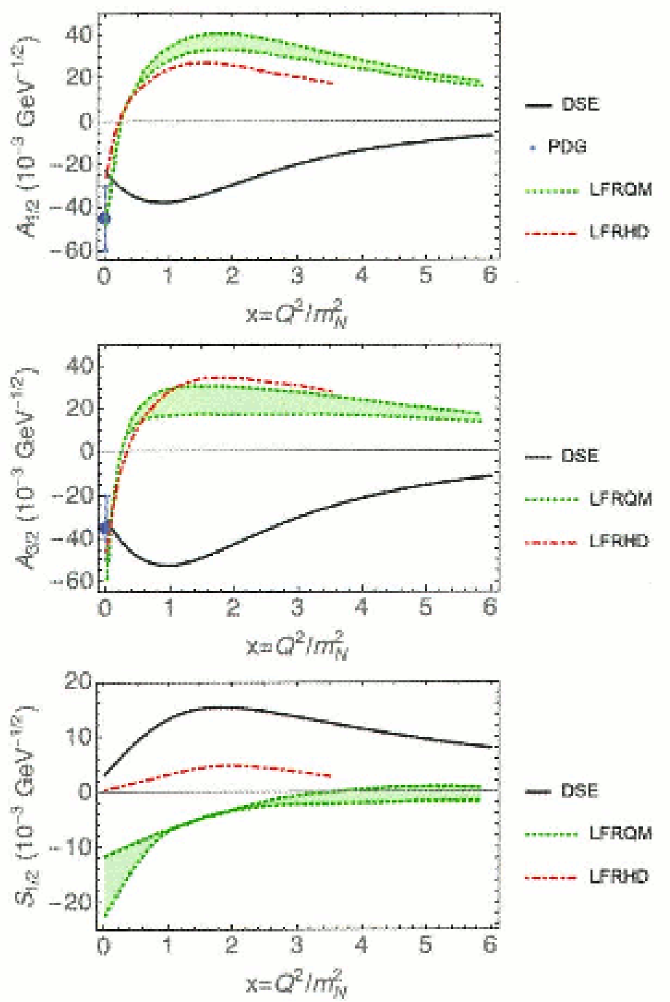


Ya Lu et al., PRD 100, 034001 (2019)

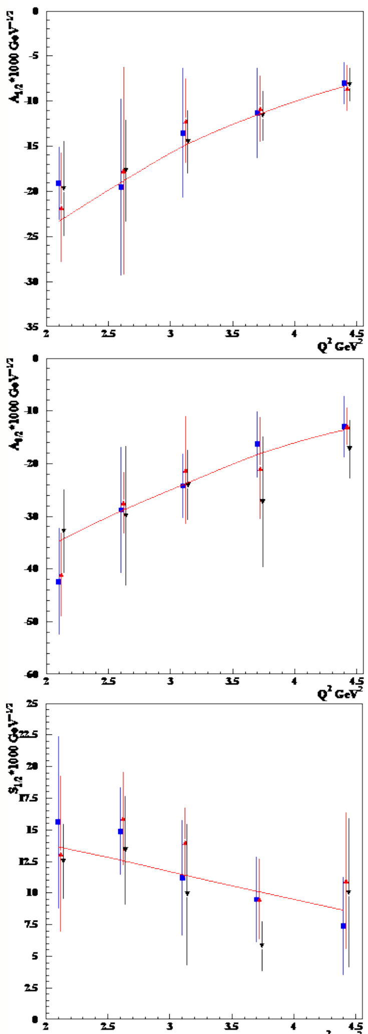
Δ(1600)3/2⁺ Form Factors in CSM Approach

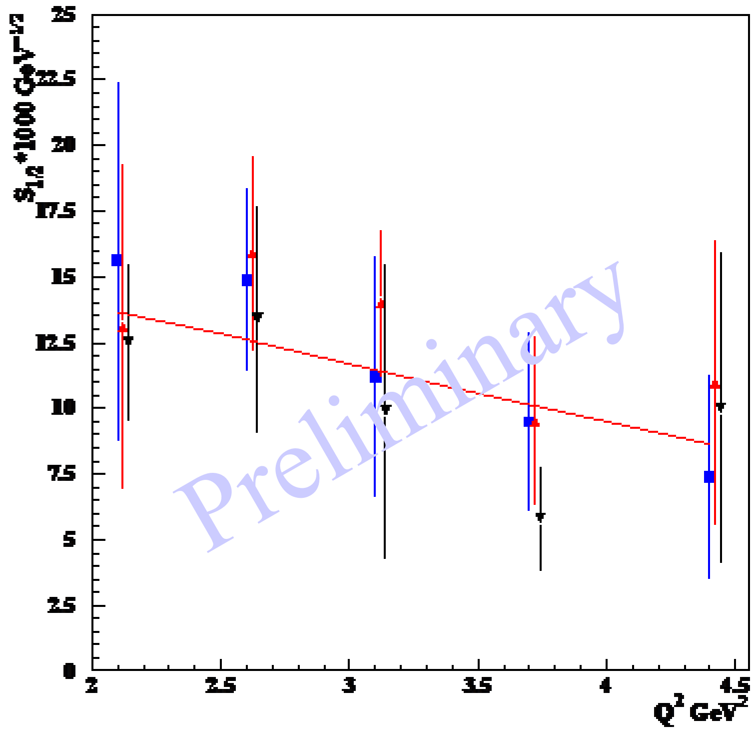
Viktor Mokeev

CSM predictions of the Δ(1600)3/2⁺ electrocouplings



Ya Lu et al., PRD 100, 034001 (2019)

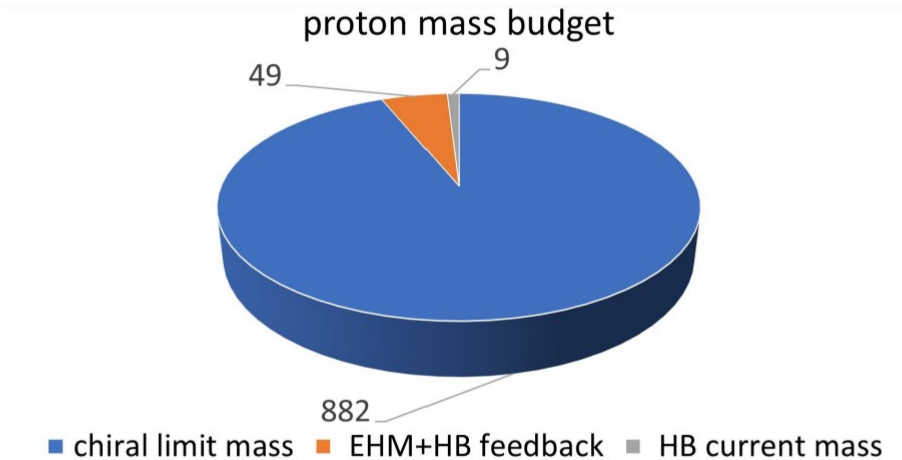


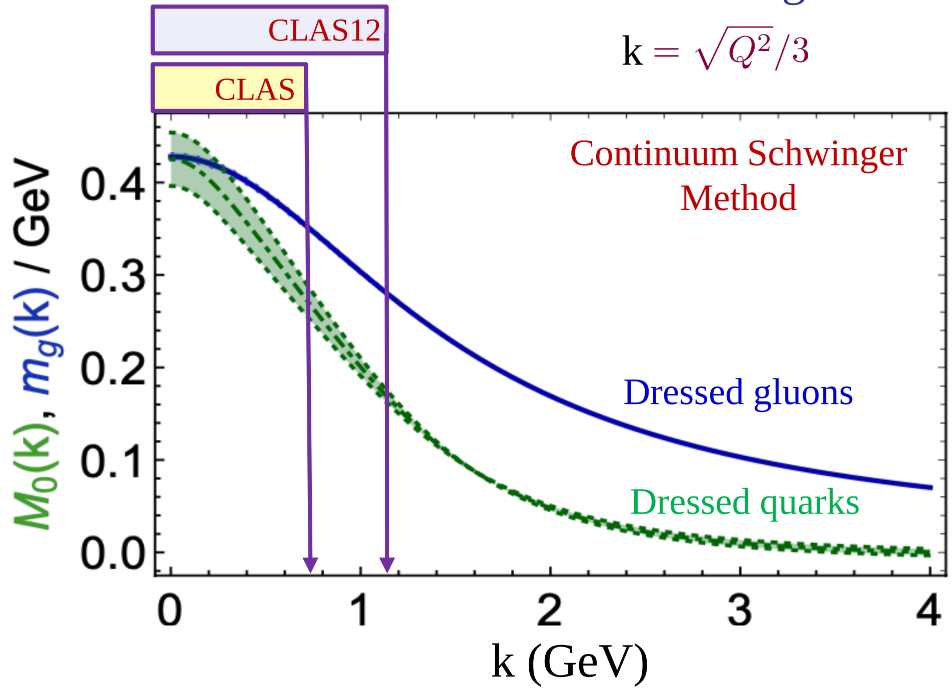


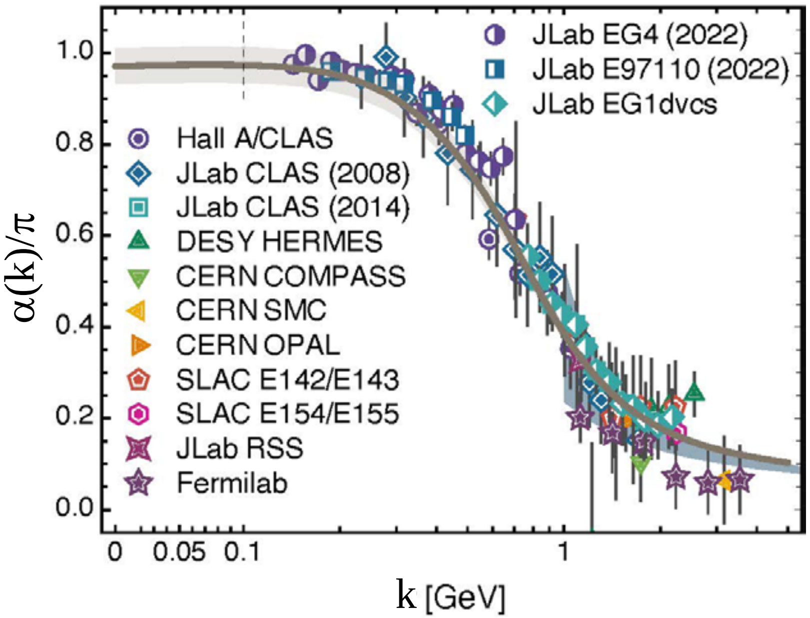
Spring 2022 analysis of Arjun's $\pi^+\pi^-p$ differential cross sections for $2.0\text{GeV}^2<Q^2<5.0\text{GeV}^2$ within three W-intervals, 1.46GeV<W<1.56GeV, 1.51GeV<W<1.61GeV, and 1.56GeV<W<1.66GeV.

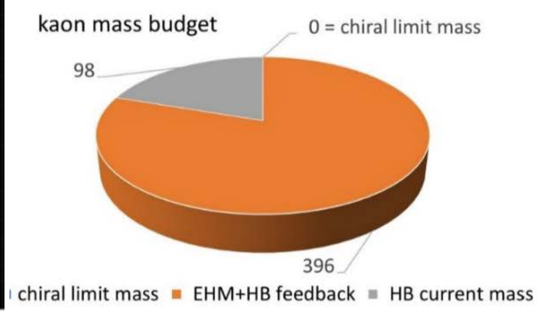
Emergence of Hadron Mass

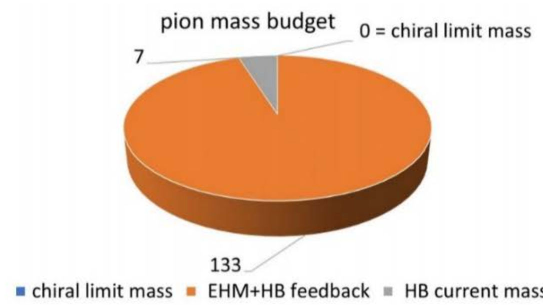
Craig Roberts





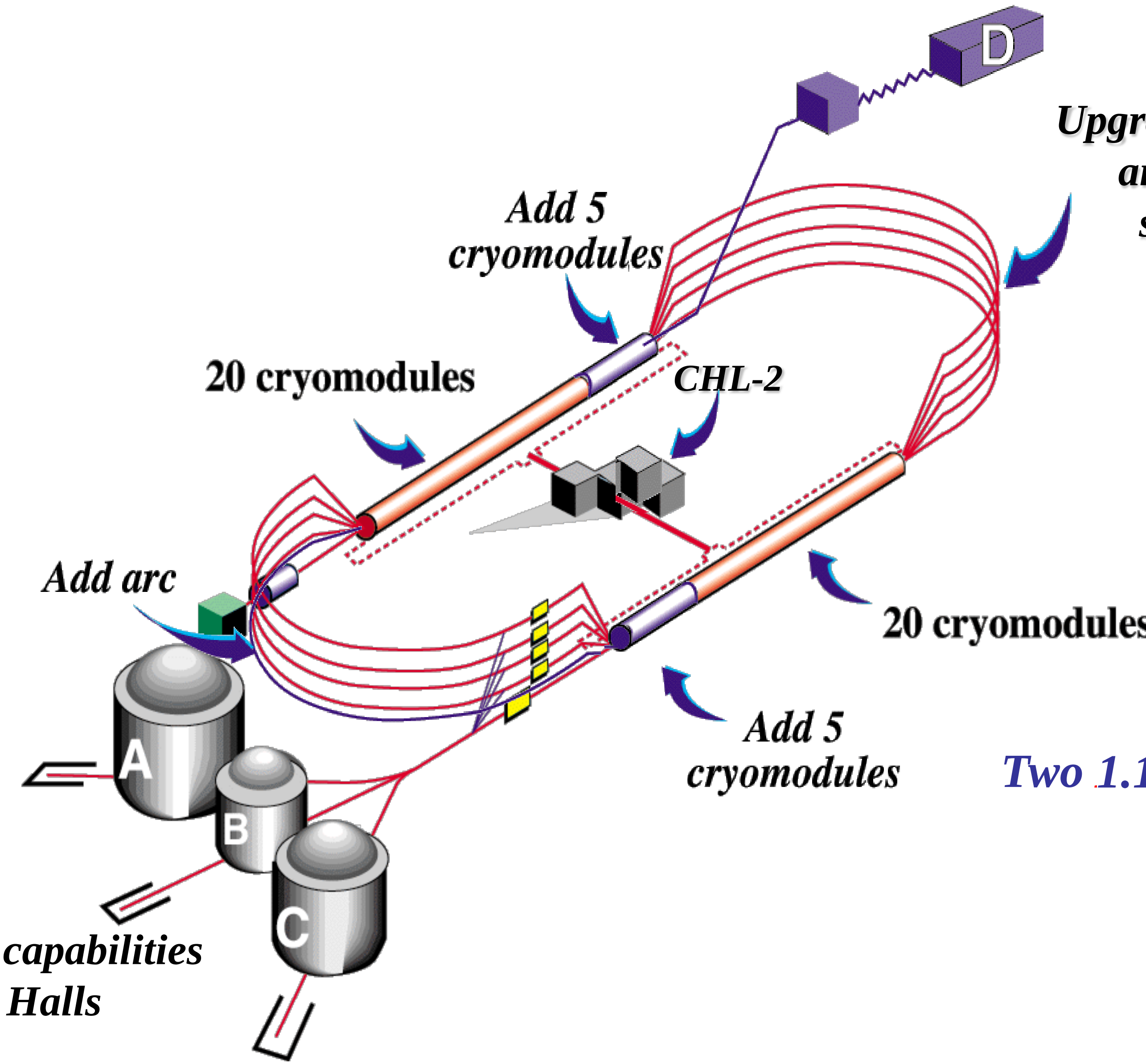






CLAS12

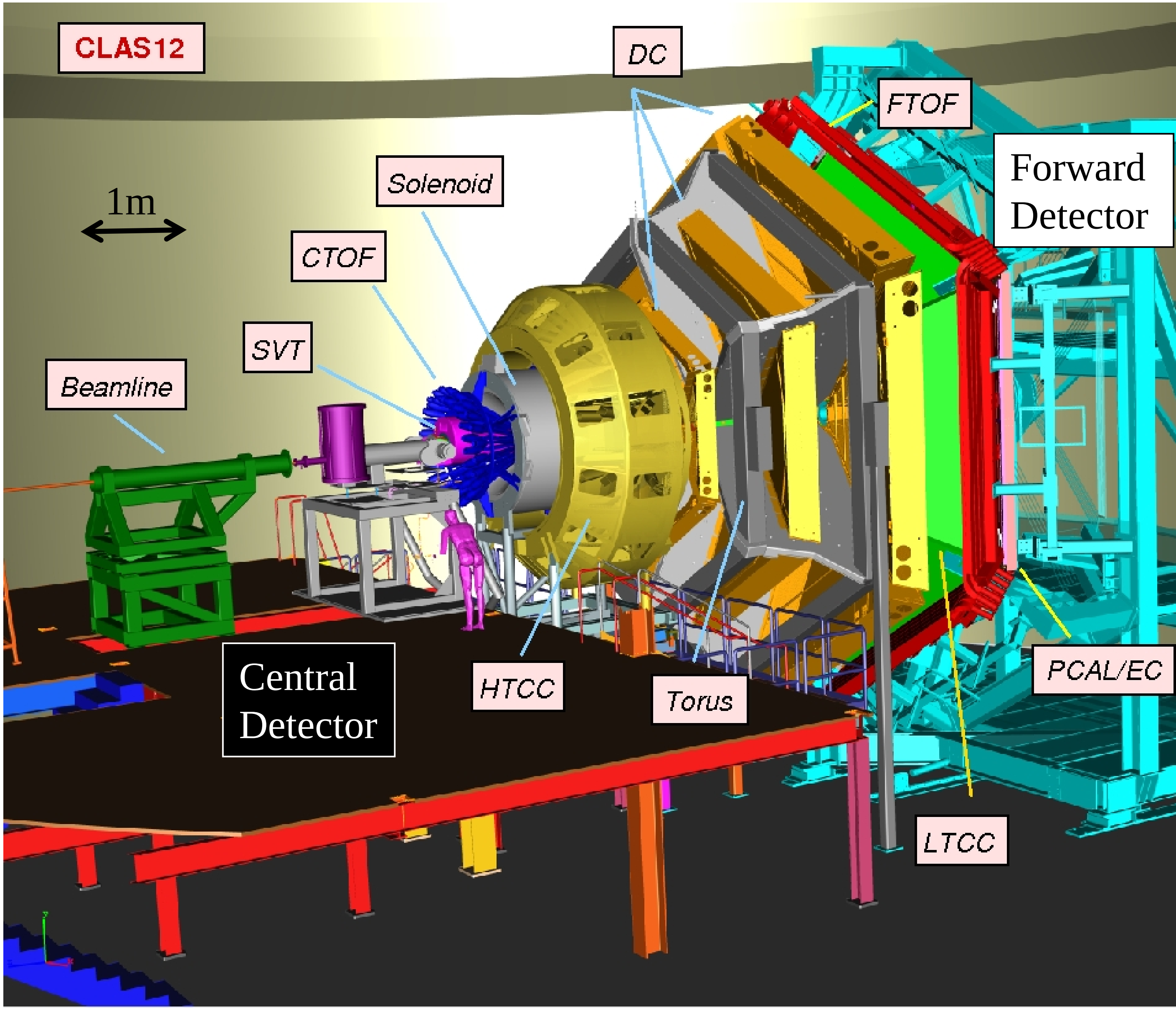
12 GeV CEBAF



Two 1.1 GeV linacs

Enhanced capabilities in existing Halls

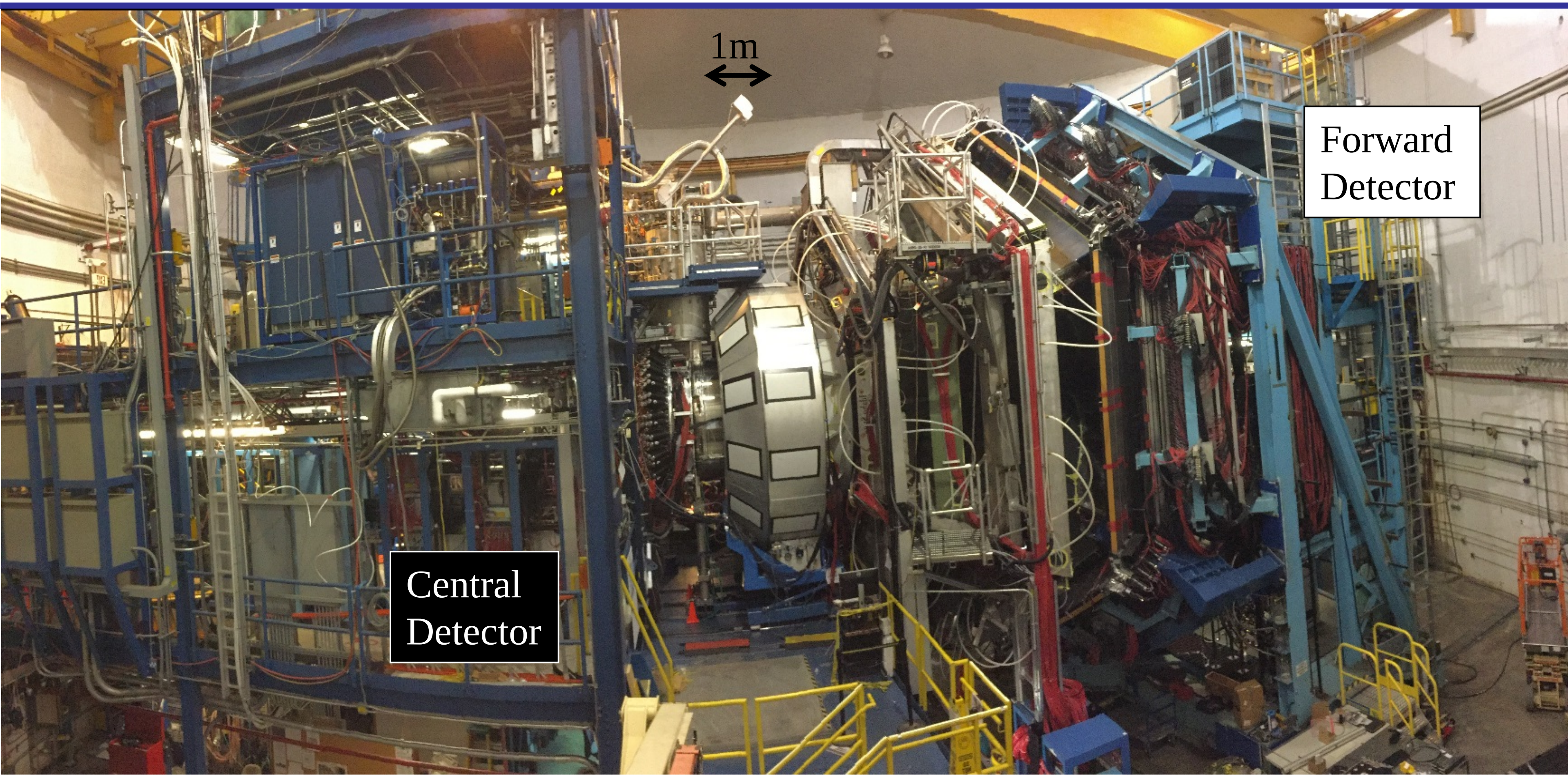
CLAS12



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

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

CLAS12



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- Nucleon Spin Structure
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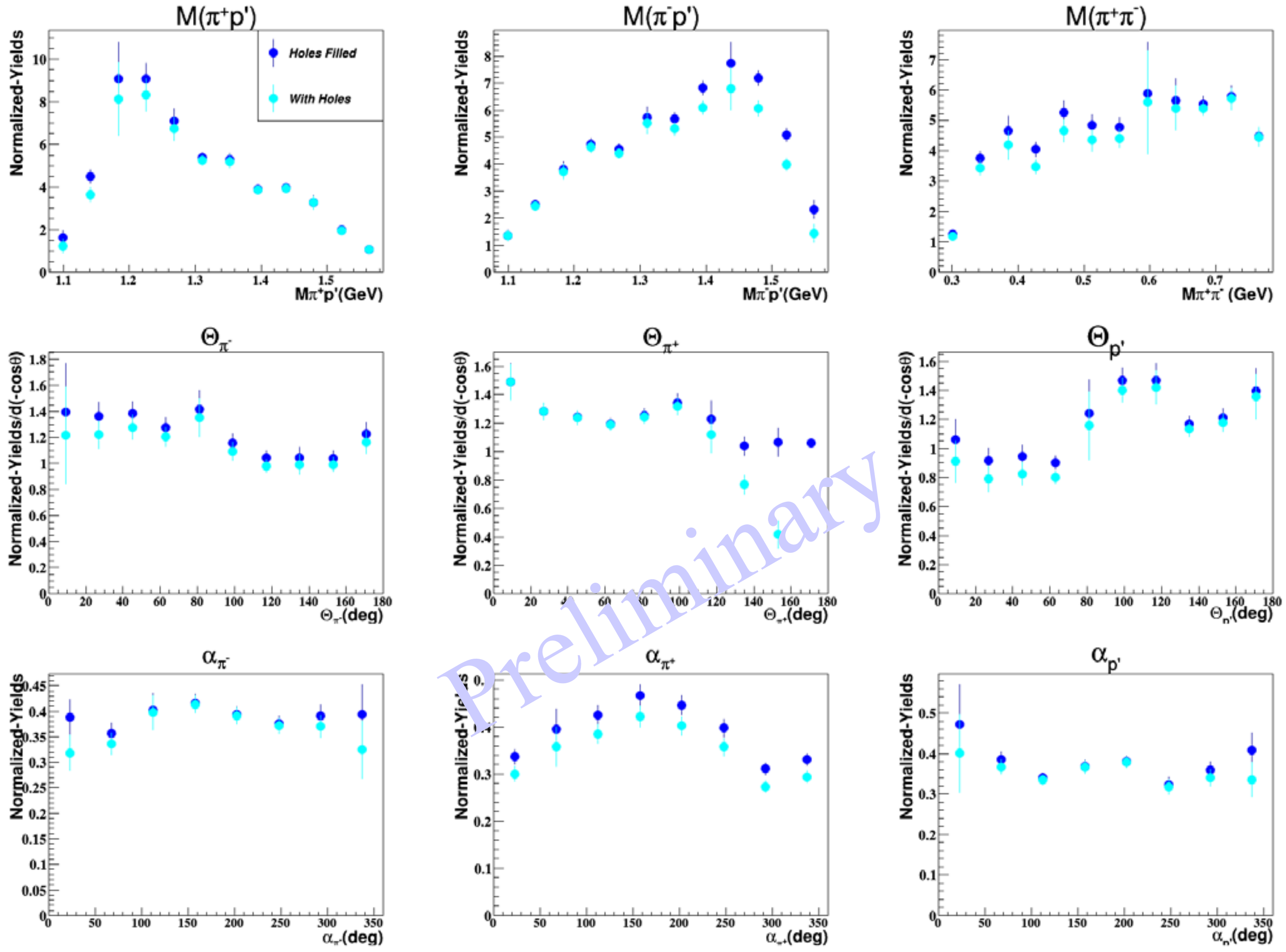
- …

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

Krishna Neupane
CLAS12

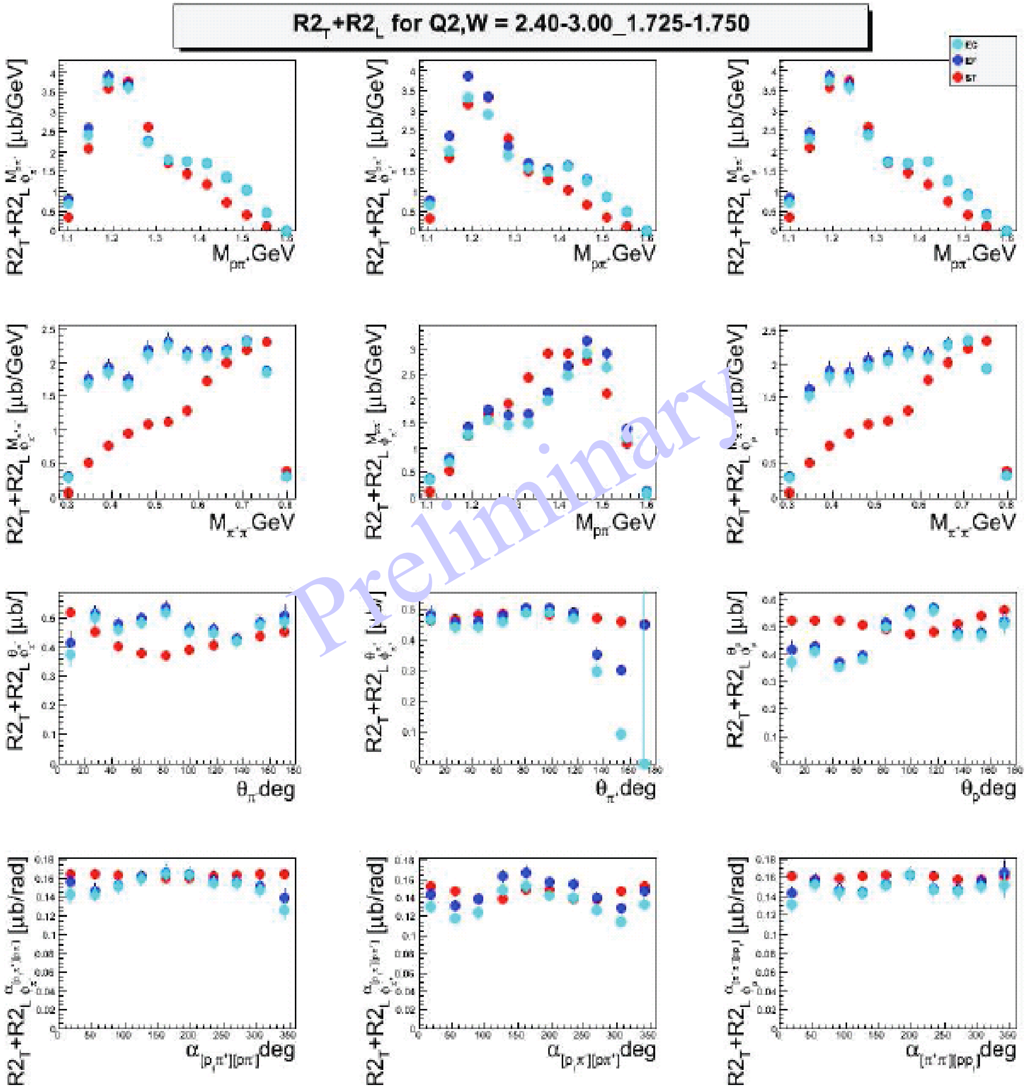


1.725 GeV < W < 1.75 GeV and 3 GeV^2 < Q^2 < 3.5 GeV^2

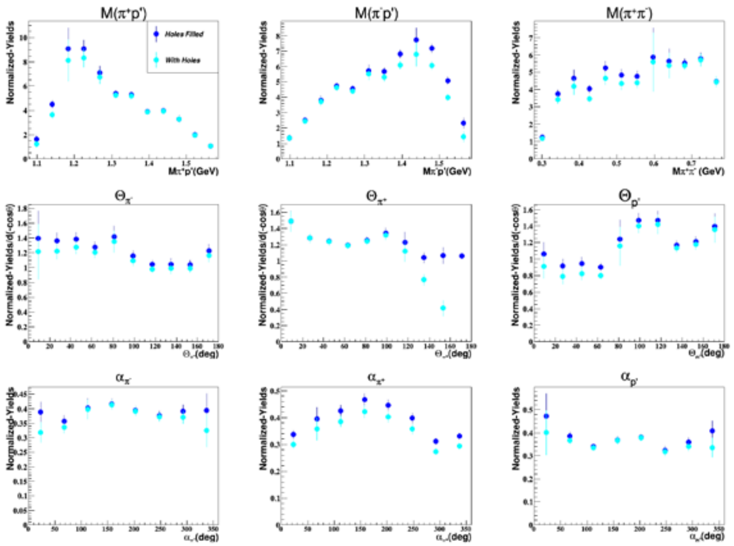
φ-dependent Nππ Single-Differential Cross Sections

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

Arjun Trivedi
Evgeny Isupov



Krishna Neupane
CLAS12



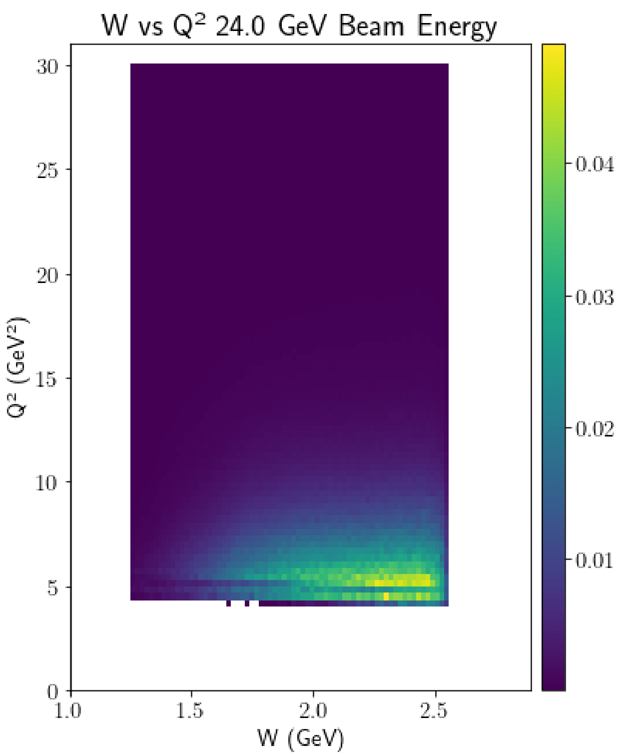
$$\left(\frac{d^2\sigma}{dX_{ij}d\phi_i}\right) = R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}} + R2_{LT}{}^{c,X_{ij}} \cos\phi_i + R2_{TT}{}^{c,X_{ij}} \cos 2\phi_i + \delta_{X_{ij}\alpha_i} \left(R2_{LT}{}^{s,\alpha_i} \sin\phi_i + R2_{TT}{}^{s,\alpha_i} \sin 2\phi_i\right)$$

CLAS20+

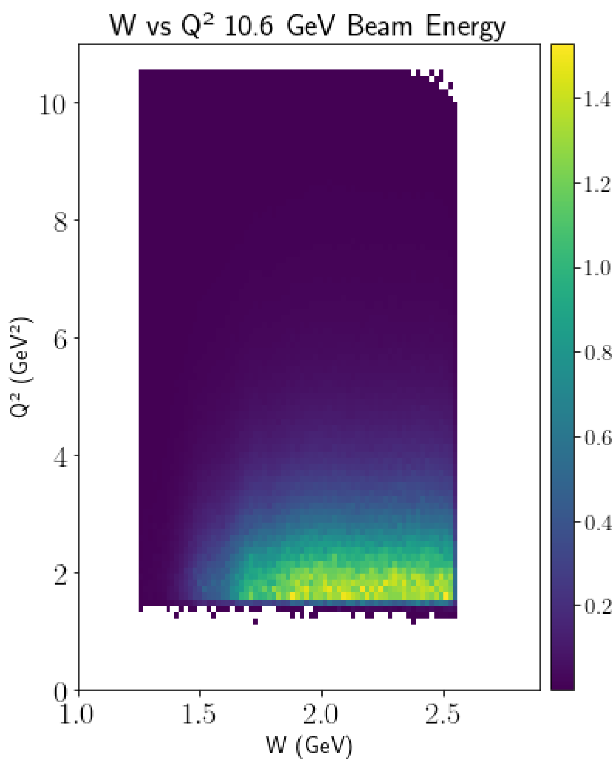
Achievable (W,Q2) Coverage at 24 GeV

Krishna Neupane

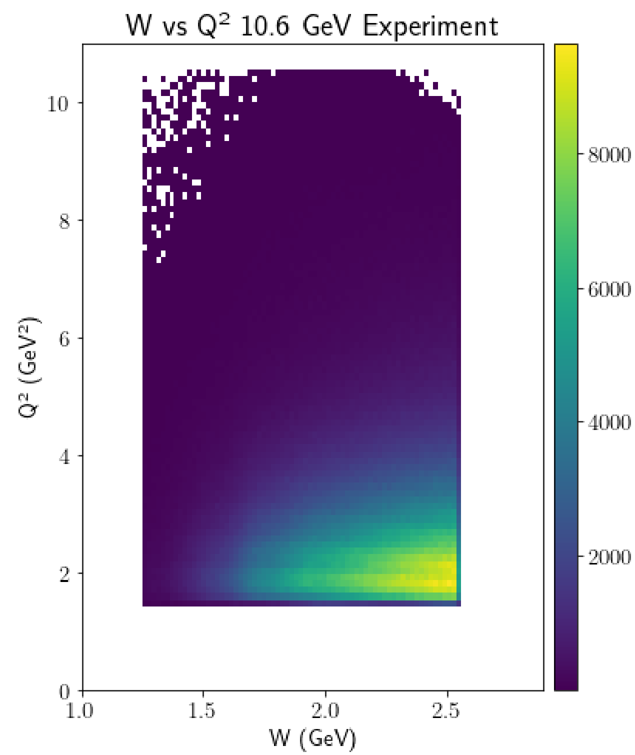
Simulated Reconstructed



Simulated Reconstructed



Measured Reconstructed

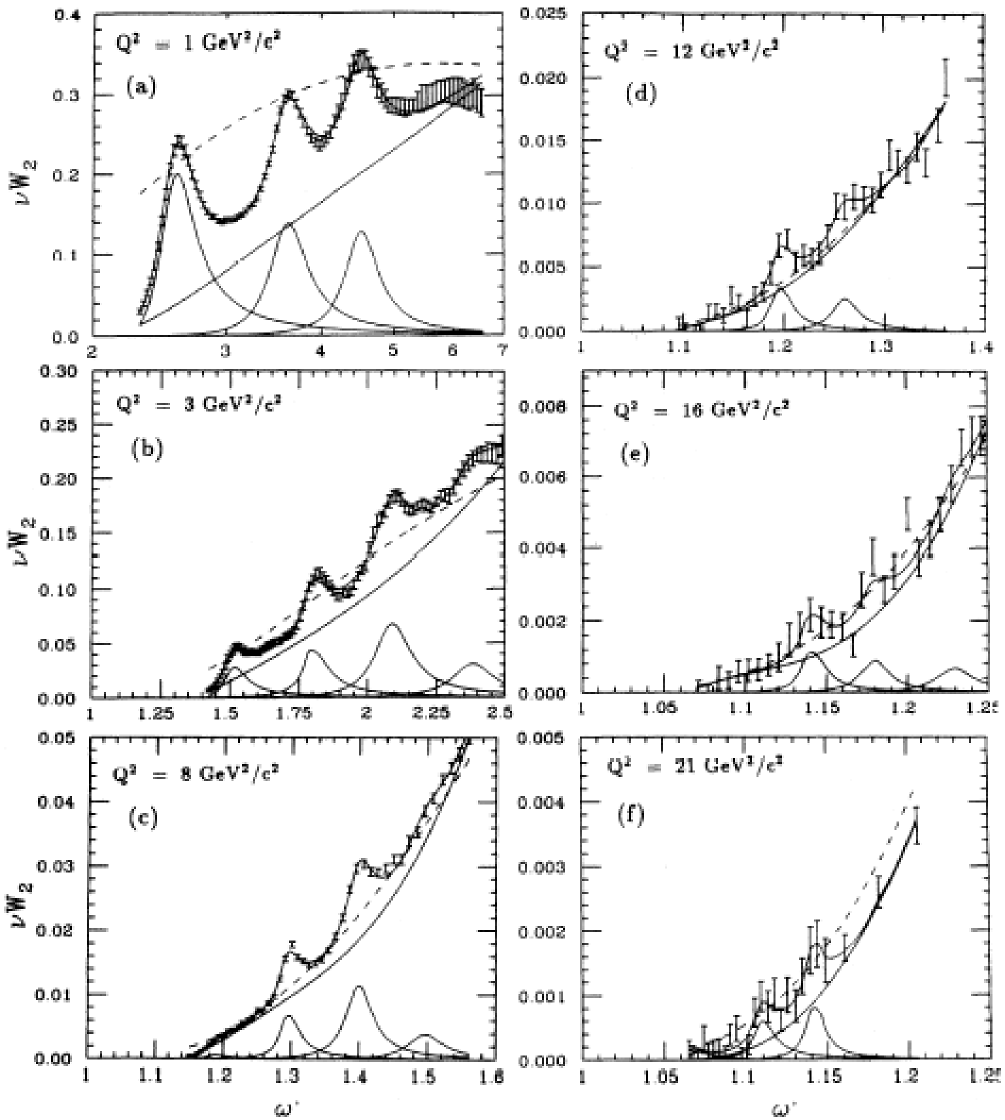


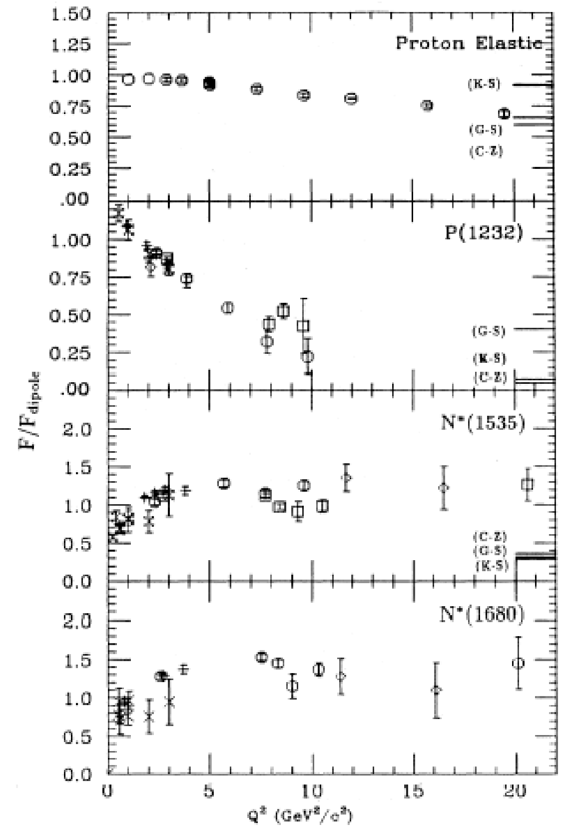
HSG is currently simulating:

- ✓ $p\pi^0, n\pi^+$ Maksim Davydov
- ✓ KY Dan Carman
- ✓ $p\pi^+\pi^-$ Krishna Neupane

- ➢ Comparison to RGA Fall 2018
- ➢ RGA inbending simulation
- ➢ Fully exclusive $p\pi^+\pi^-$

Inclusive Structure Function in the Resonance Region





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

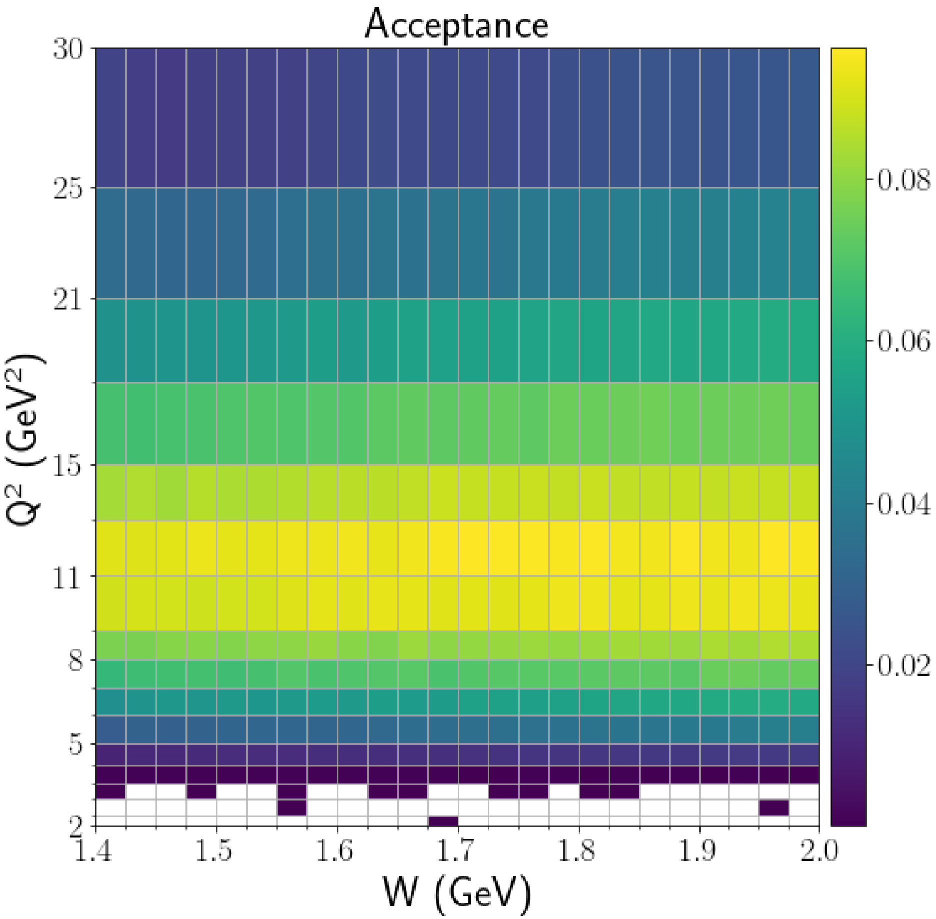
Iuliia Skorodumina

TWOPEG tries to extrapolate cross sections based on inclusive structure functions.

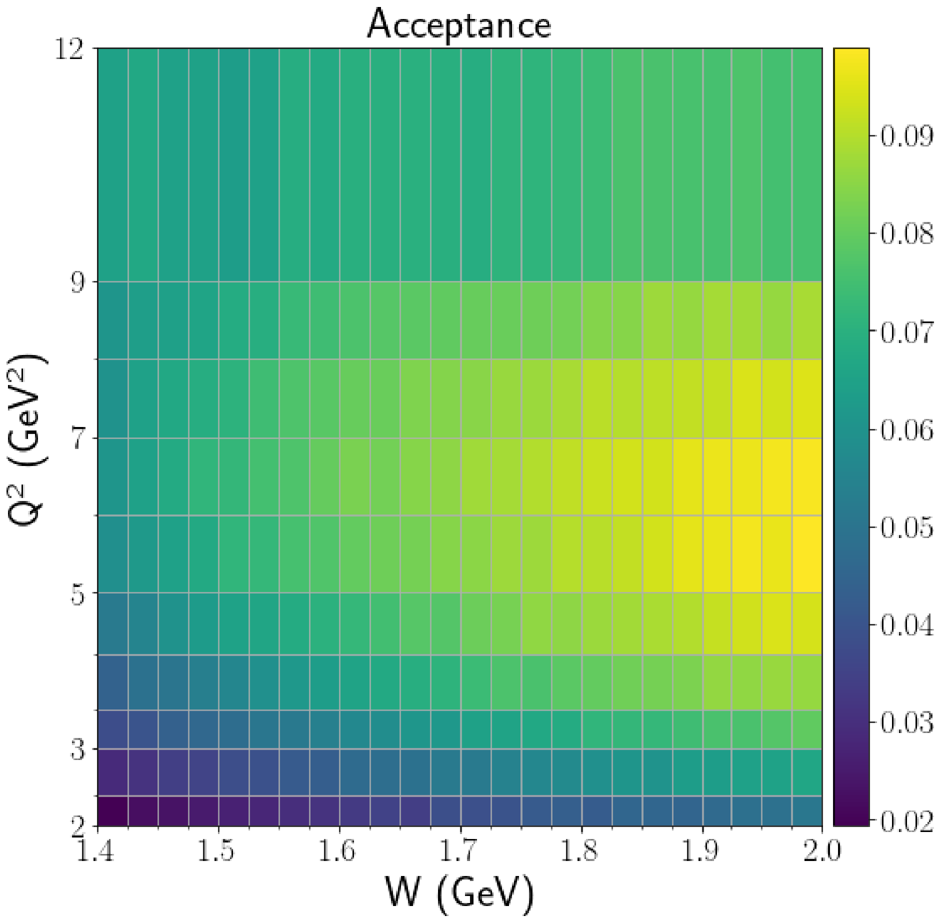
Acceptance for Exclusive $p\pi^+\pi^-$ Final State

Krishna Neupane

Simulated at 24 GeV Beam Energy



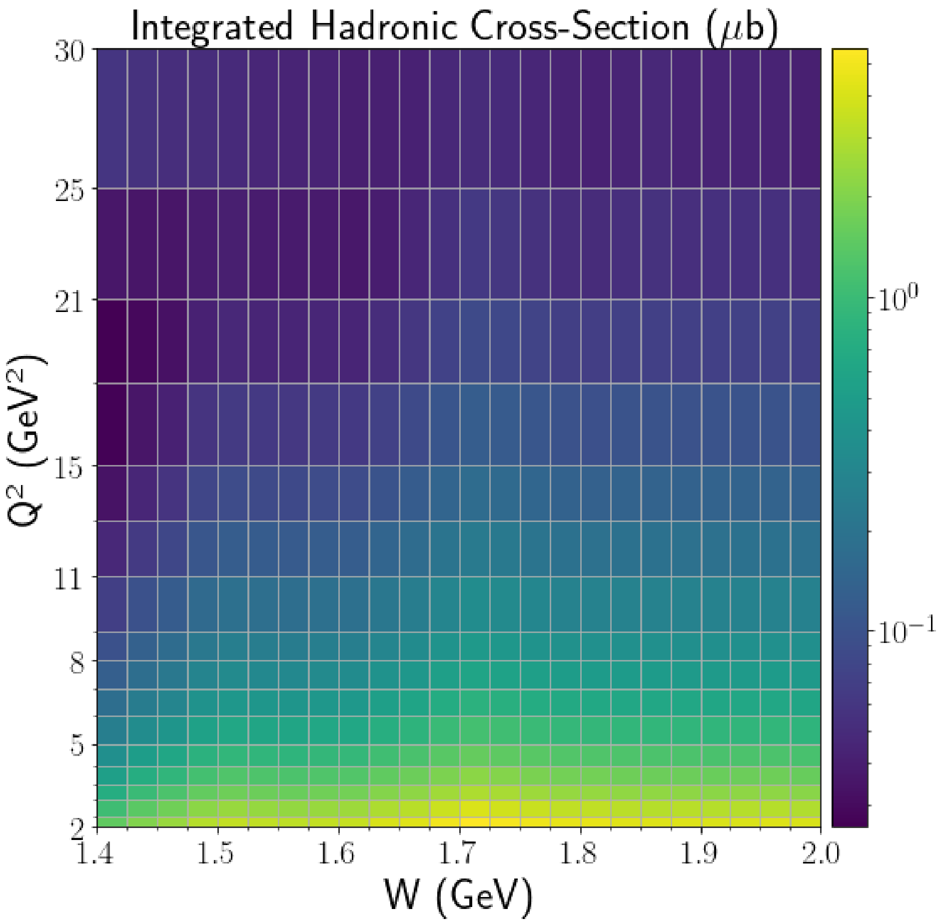
Simulated at 10.6 GeV Beam Energy



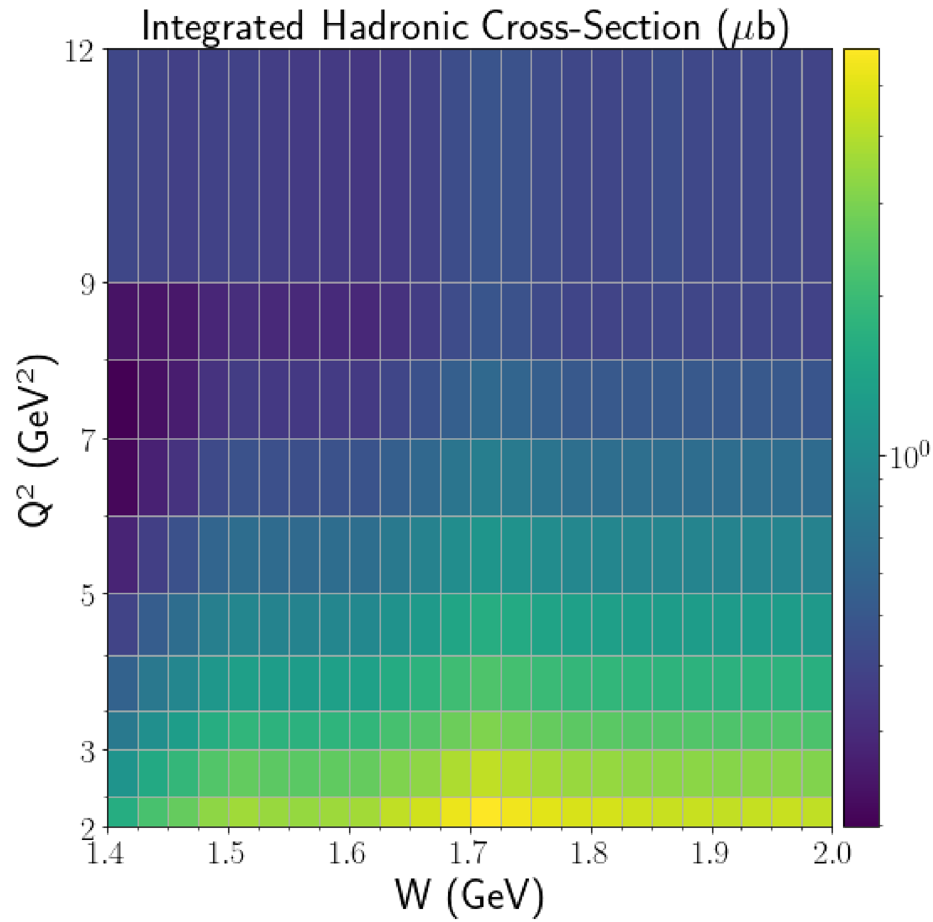
Hadronic Cross Section for Exclusive $p\pi^+\pi^-$ Final State

Krishna Neupane

Simulated at 24 GeV Beam Energy



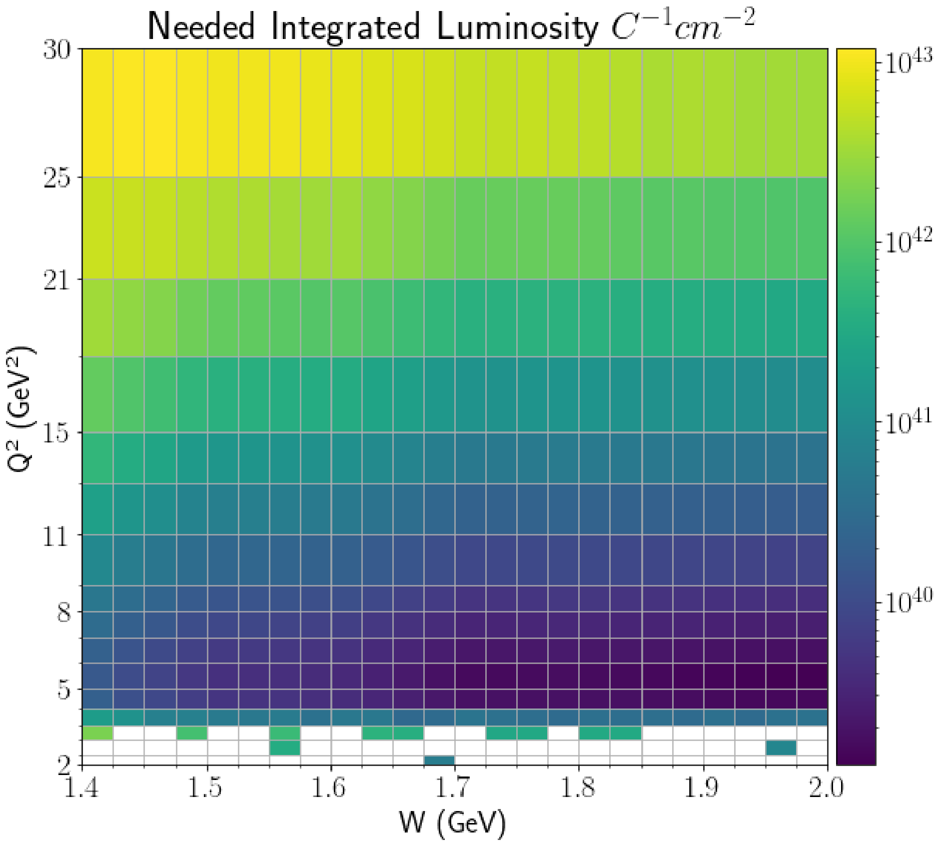
Simulated at 10.6 GeV Beam Energy



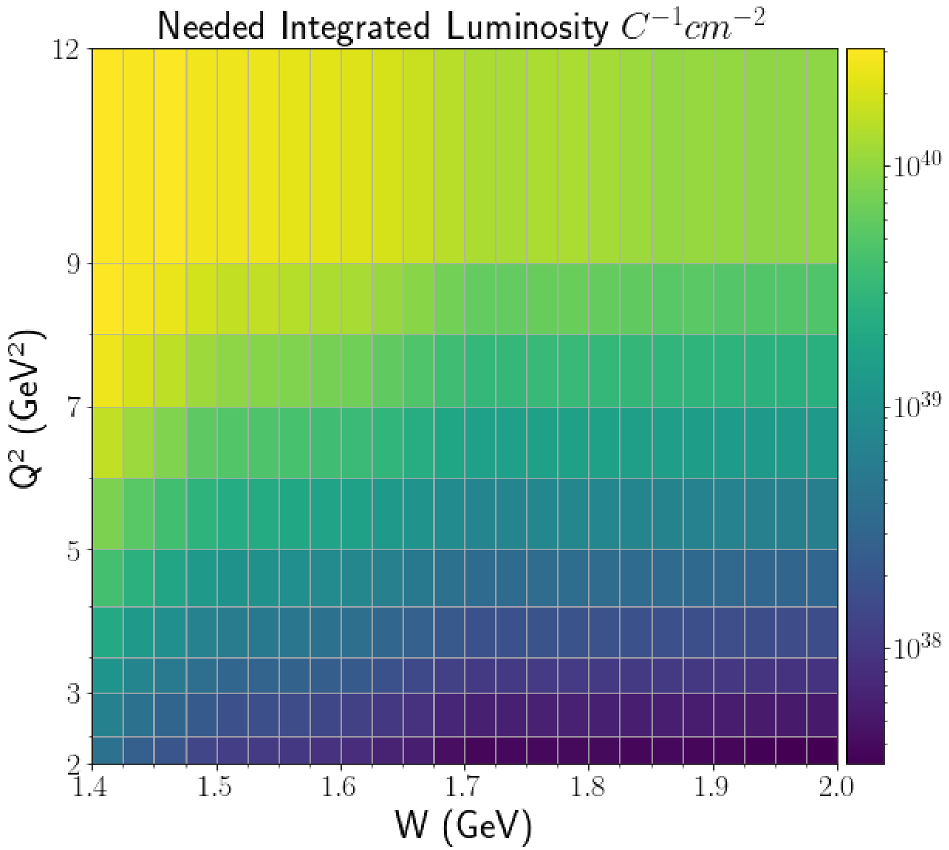
Integrated Luminosity Needs for Exclusive $p\pi^+\pi^-$

Krishna Neupane

Simulated at 24 GeV Beam Energy



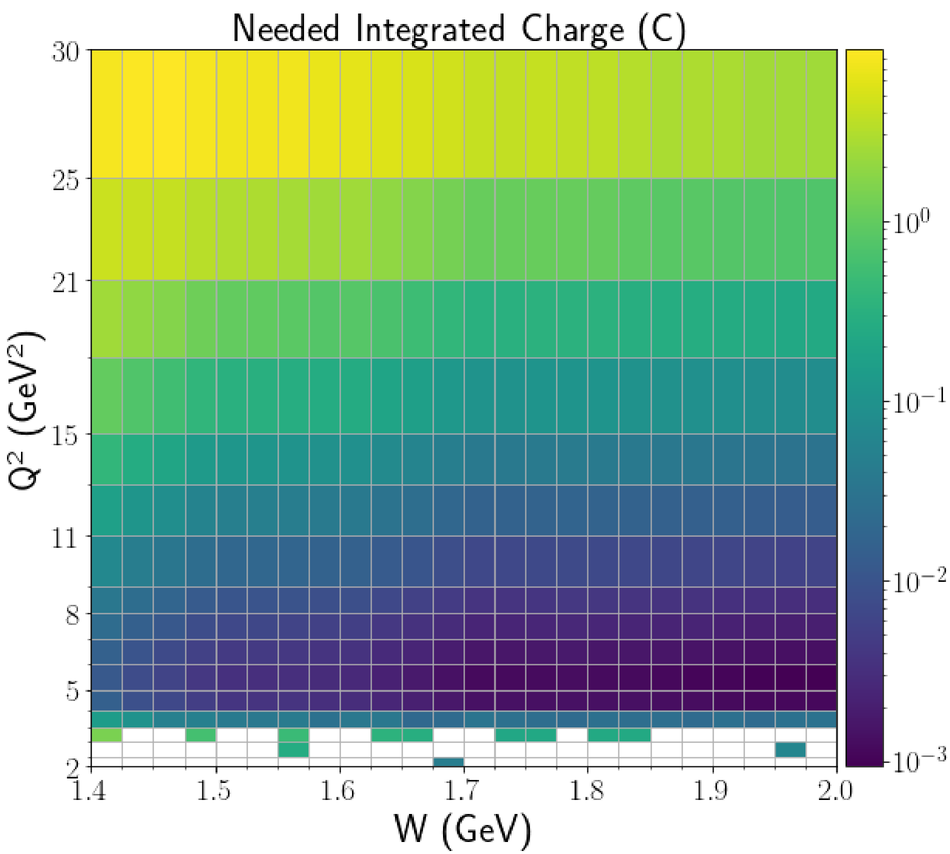
Simulated at 10.6 GeV Beam Energy



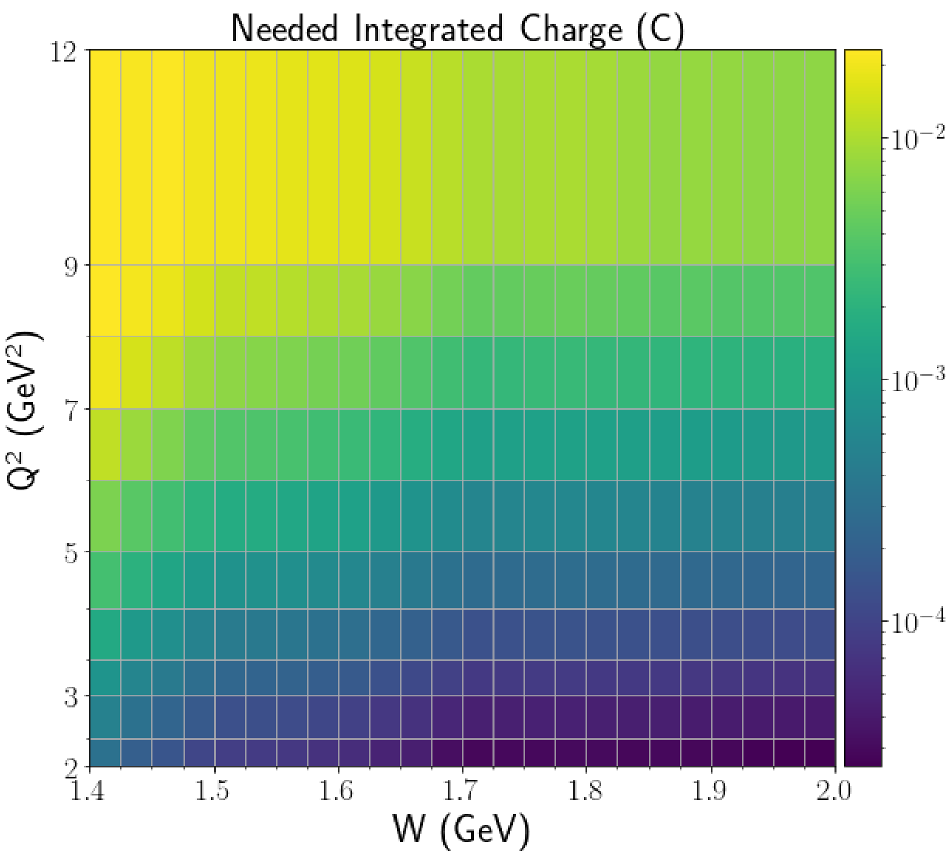
Integrated Charge Needs for Exclusive $p\pi^+\pi^-$

Krishna Neupane

Simulated at 24 GeV Beam Energy



Simulated at 10.6 GeV Beam Energy

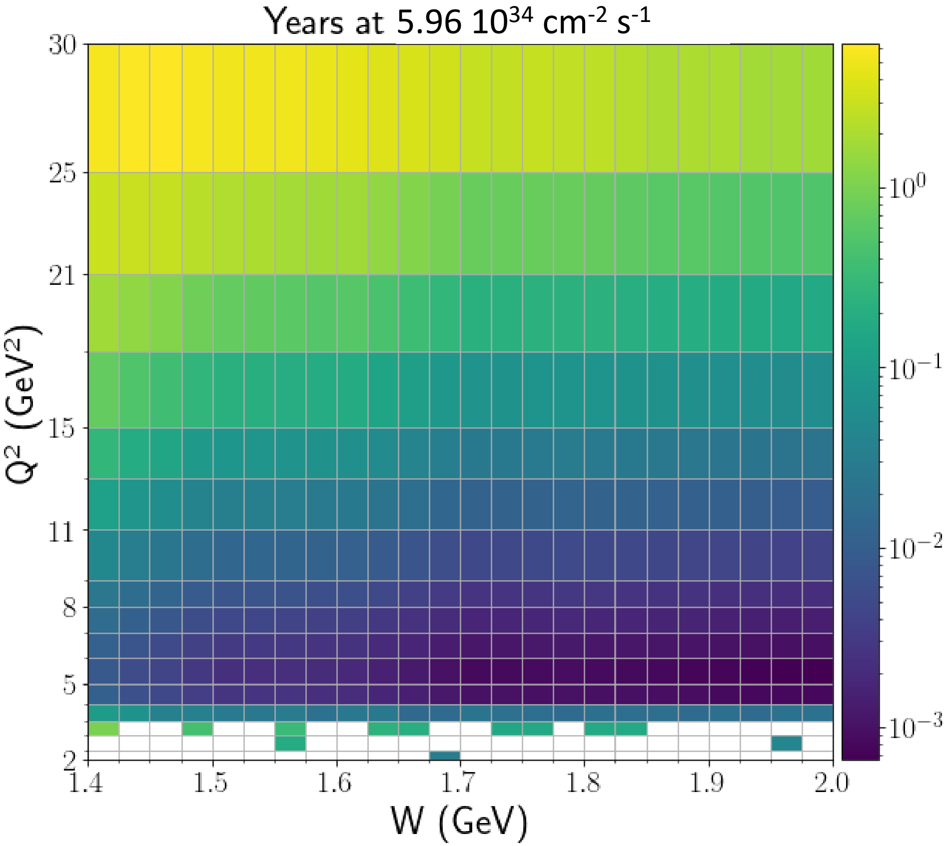


Beam Time Needs for Exclusive $p\pi^+\pi^-$

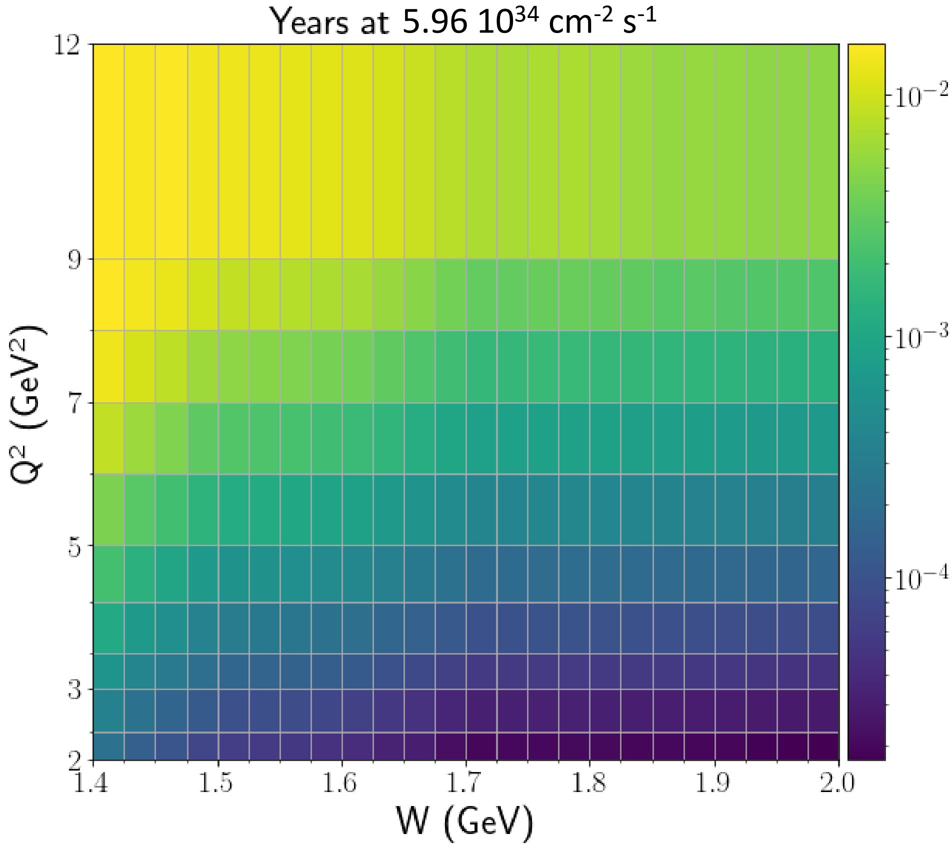
Krishna Neupane

Based on RGA Fall 2018 Luminosity of 5.96 10^{34} cm^{-2} s^{-1} at 45 nA

Simulated at 24 GeV Beam Energy



Simulated at 10.6 GeV Beam Energy



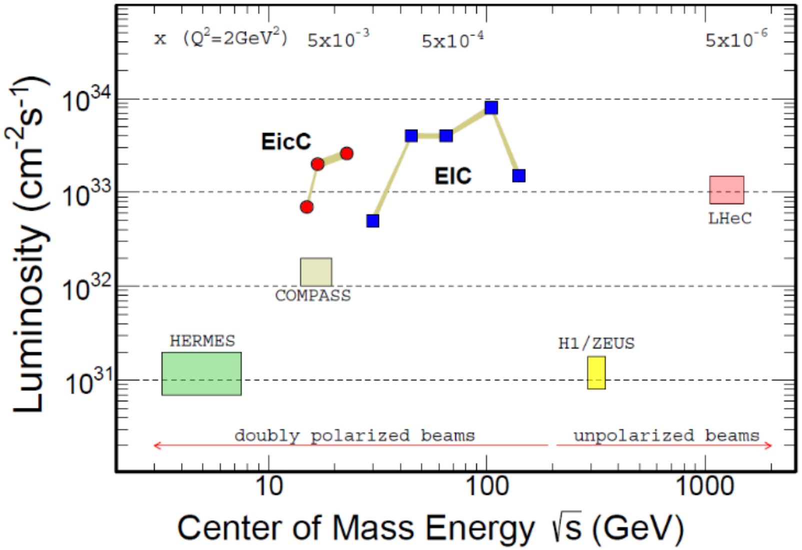
Implementing all analysis cuts (3/2), Golden Run Selection (3), PAC Days (2)

➡ 6 (12) years at 5.96 10^{34} cm^{-2} s^{-1} or 4 (8) month at 10^{36} cm^{-2} s^{-1}

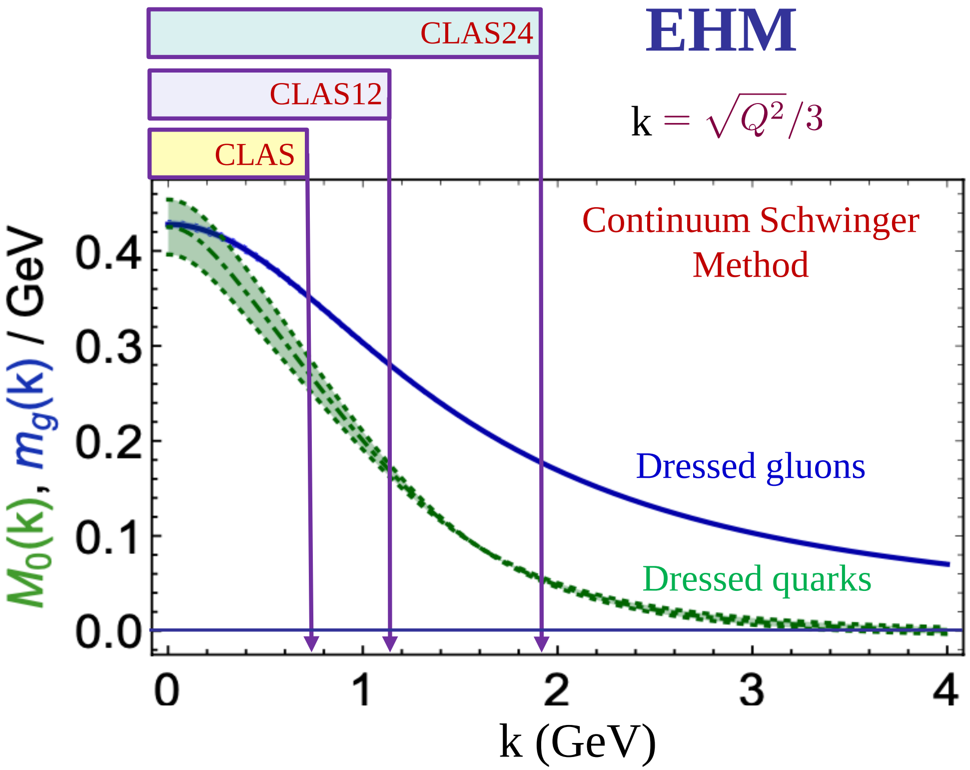
Hadron Structure Needs for CLAS20+

- Beam energy 24 GeV
- Nearly 4π acceptance

- High luminosity detector
- High momentum resolution
- Studies of exclusive reactions



Both EIC and EIcC would need much higher luminosity to carry out this program.



Luminosity "frontier" is the *unique* advantage of JLab.

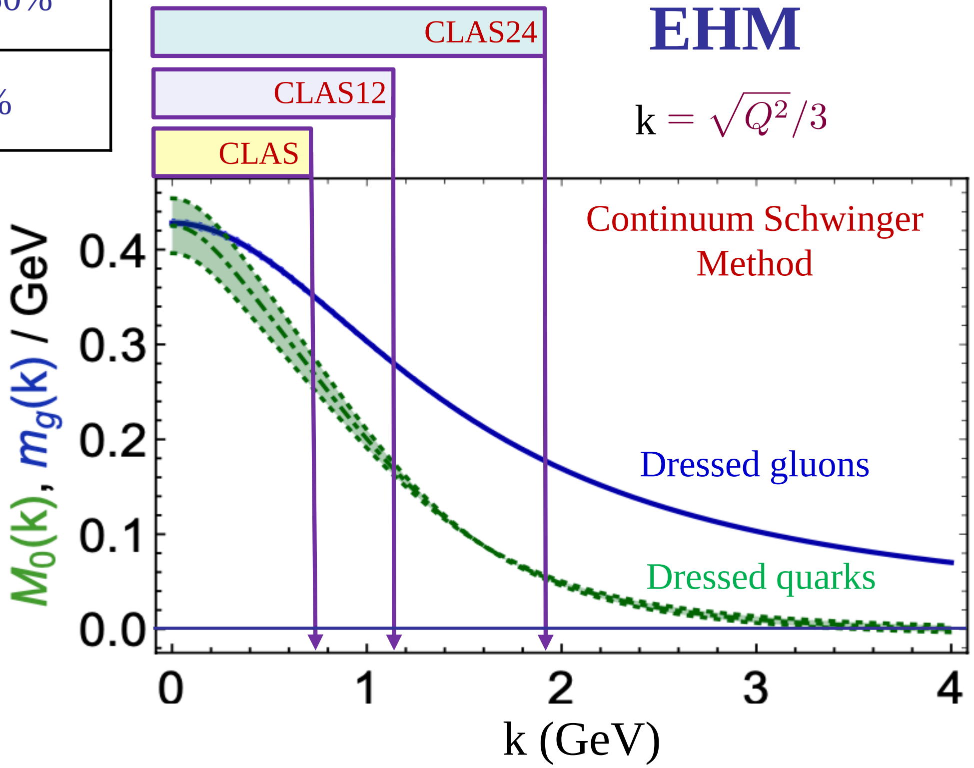
Hadron Structure Needs for CLAS20+

	Q^2-coverage of electrocouplings	Range of quark momenta p	Fraction of dressed quark mass at $p<p_{max}$
CLAS	< 5 GeV^2	< 0.8 GeV	15%-20%
CLAS12	< 12 GeV^2	< 1.2 GeV	40%-50%
CLAS20+	< 35 GeV^2	< 2.0 GeV	80%

- Beam energy 24 GeV
- Nearly 4π acceptance

Increasing knowledge on running dressed quark mass from the results on $\gamma_v pN^*$ electrocouplings.

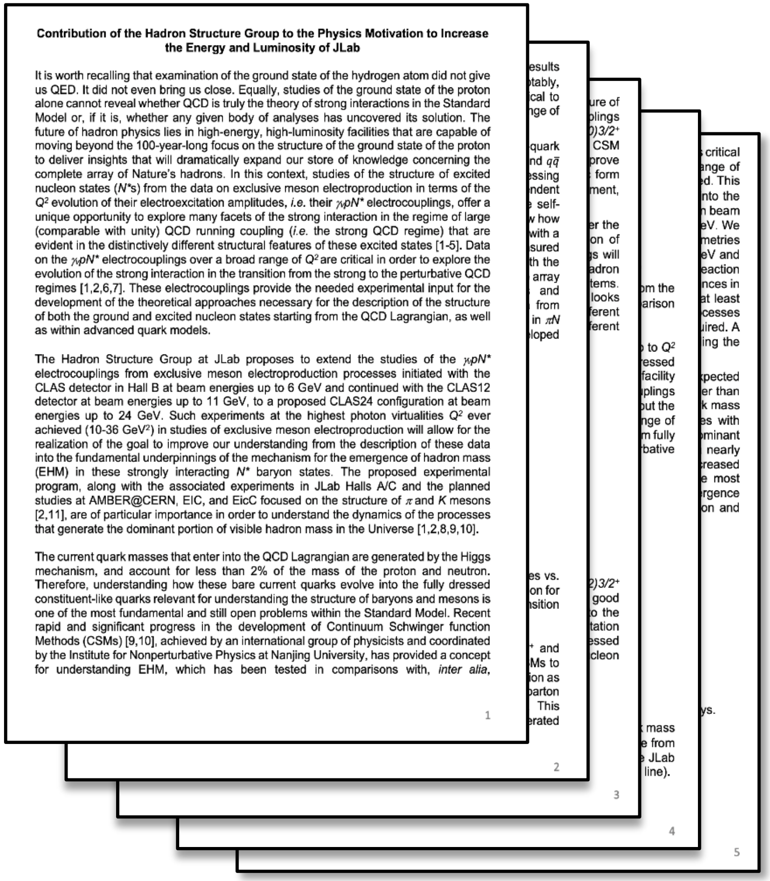
Measured $\gamma_v pN^*$ electrocouplings of most prominent N* states of different structure will provide sound evidence for understanding how the dominant part of the hadron mass and the N* structure itself emerge from QCD and will make CEBAF@20+ GeV the ultimate QCD-facility at the luminosity frontier.



Luminosity "frontier" is the *unique* advantage of JLab.

Hadron Structure with CLAS20+

Hadron Structure Group in Hall B is developing a physics case to support CLAS20+ upgrade.



Contribution of the Hadron Structure Group to the Physics Motivation to Increase the Energy and Luminosity of JLab

It is worth recalling that examination of the ground state of the hydrogen atom did not give us QED. It did not even bring us close. Equally, studies of the ground state of the proton alone cannot reveal whether QCD is truly the theory of strong interactions in the Standard Model or, if it is, whether any given body of analyses has uncovered its solution. The future of hadron physics lies in high-energy, high-luminosity facilities that are capable of moving beyond the 100-year-long focus on the structure of the ground state of the proton to deliver insights that will dramatically expand our store of knowledge concerning the complete array of Nature's hadrons. In this context, studies of the structure of excited nucleon states (N^*s) from the data on exclusive meson electroproduction in terms of the Q^2 evolution of their electroexcitation amplitudes, *i.e.* their $\gamma_v pN^*$ electrocouplings, offer a unique opportunity to explore many facets of the strong interaction in the regime of large (comparable with unity) QCD running coupling (*i.e.* the strong QCD regime) that are evident in the distinctively different structural features of these excited states [1-5]. Data on the $\gamma_v pN^*$ electrocouplings over a broad range of Q^2 are critical in order to explore the evolution of the strong interaction in the transition from the strong to the perturbative QCD regimes [1,2,6,7]. These electrocouplings provide the needed experimental input for the development of the theoretical approaches necessary for the description of the structure of both the ground and excited nucleon states starting from the QCD Lagrangian, as well as within advanced quark models.

The Hadron Structure Group at JLab proposes to extend the studies of the $\gamma_v pN^*$ electrocouplings from exclusive meson electroproduction processes initiated with the CLAS detector in Hall B at beam energies up to 6 GeV and continued with the CLAS12 detector at beam energies up to 11 GeV, to a proposed CLAS24 configuration at beam energies up to 24 GeV. Such experiments at the highest photon virtualities Q^2 ever achieved (10-36 GeV^2) in studies of exclusive meson electroproduction will allow for the realization of the goal to improve our understanding from the description of these data into the fundamental underpinnings of the mechanism for the emergence of hadron mass (EHM) in these strongly interacting N^* baryon states. The proposed experimental program, along with the associated experiments in JLab Halls A/C and the planned studies at AMBER@CERN, EIC, and EicC focused on the structure of π and K mesons [2,11], are of particular importance in order to understand the dynamics of the processes that generate the dominant portion of visible hadron mass in the Universe [1,2,8,9,10].

The current quark masses that enter into the QCD Lagrangian are generated by the Higgs mechanism, and account for less than 2% of the mass of the proton and neutron. Therefore, understanding how these bare current quarks evolve into the fully dressed constituent-like quarks relevant for understanding the structure of baryons and mesons is one of the most fundamental and still open problems within the Standard Model. Recent rapid and significant progress in the development of Continuum Schwinger function Methods (CSMs) [9,10], achieved by an international group of physicists and coordinated by the Institute for Nonperturbative Physics at Nanjing University, has provided a concept for understanding EHM, which has been tested in comparisons with, *inter alia*,

1

List of Participating Institutions:

- Jefferson Lab (Hall B and Theory Division)
- University of Connecticut
- Genova University and INFN of Genova
- Lamar University
- Ohio University
- Skobeltsyn Nuclear Physics Institute and Physics Department at Lomonosov Moscow State University
- University of South Carolina
- INFN Sez di Roma Tor Vergata and Universita di Roma Tor Vergata
- Nanjing University and affiliated institutes
- Tubingen University
- Tomsk State University and Tomsk Polytechnic University
- James Madison University

https://userweb.jlab.org/~carman/clas24