Transition Form Factors Probing the Bound Three Quark Structure at 30+GeV^2

Ralf W. Gothe

UNIVERSITY OF SOUTH CAROLINA

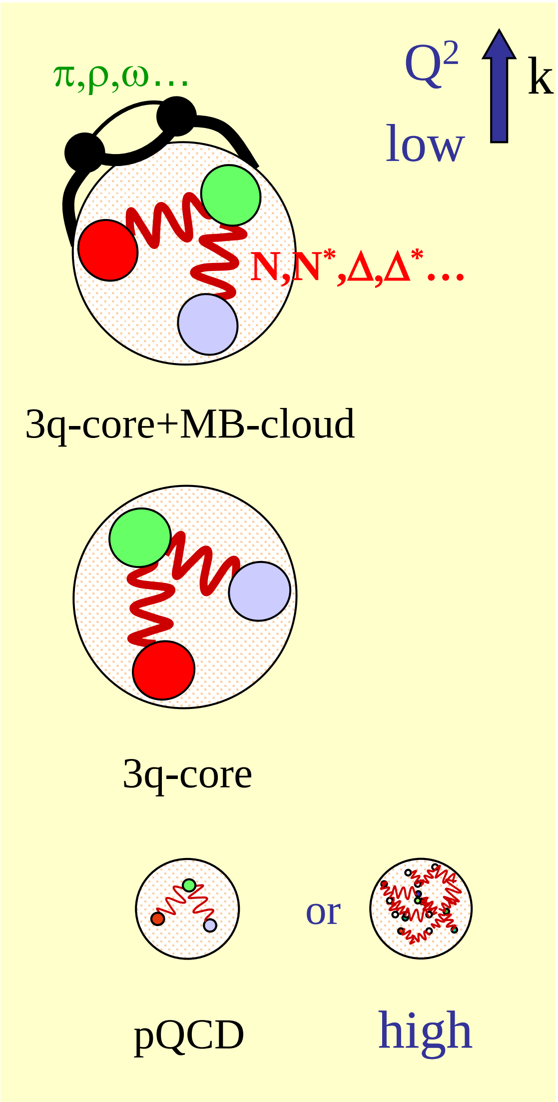
Science at the Luminosity Frontier: Jefferson Lab at 22 GeV Workshop
January 23-25, 2023, Jefferson Lab, Newports News, VA

- Why are γ_vNN* 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.

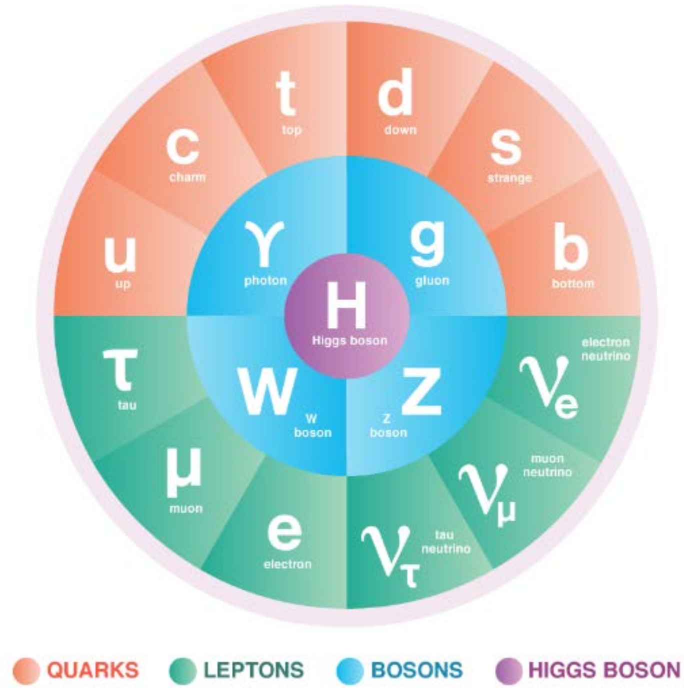
This work is supported in parts by the National Science Foundation under Grant PHY 10011349.

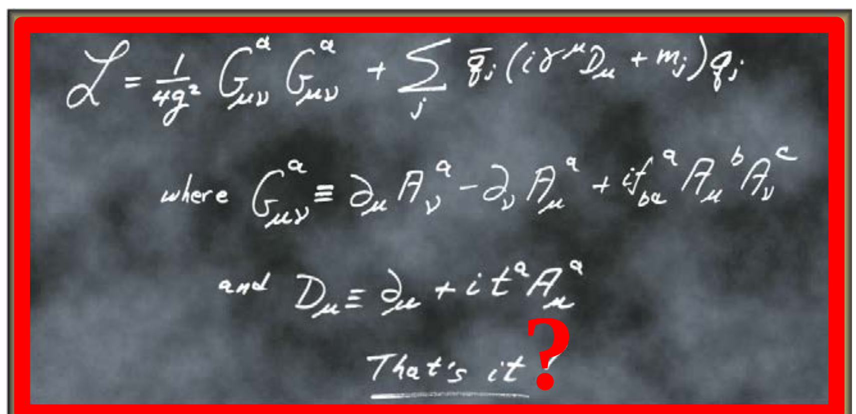
Why are they Interesting?

Emergence of Hadron Mass Traced by Electromagnetic Probes



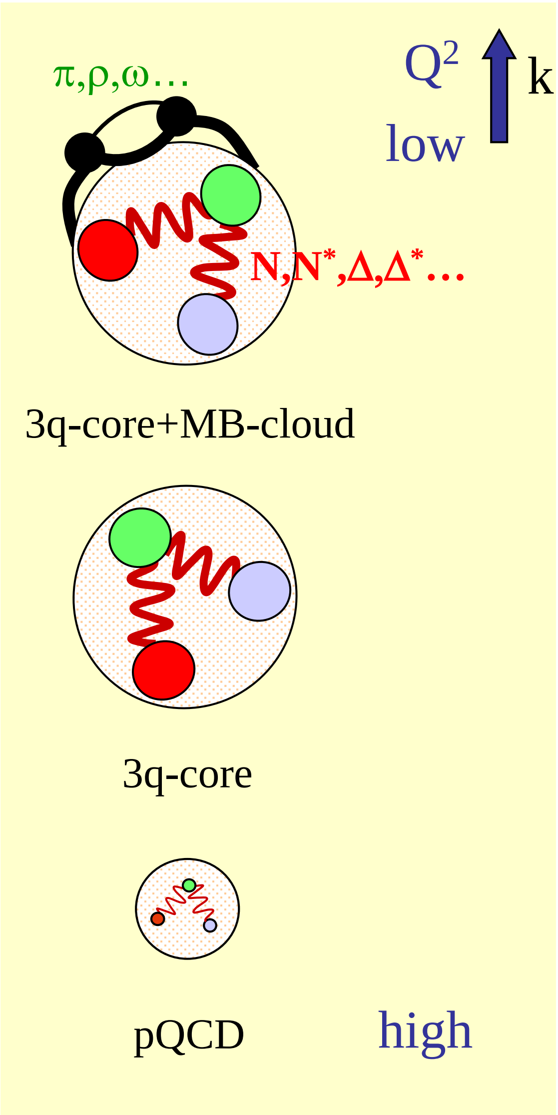
SM



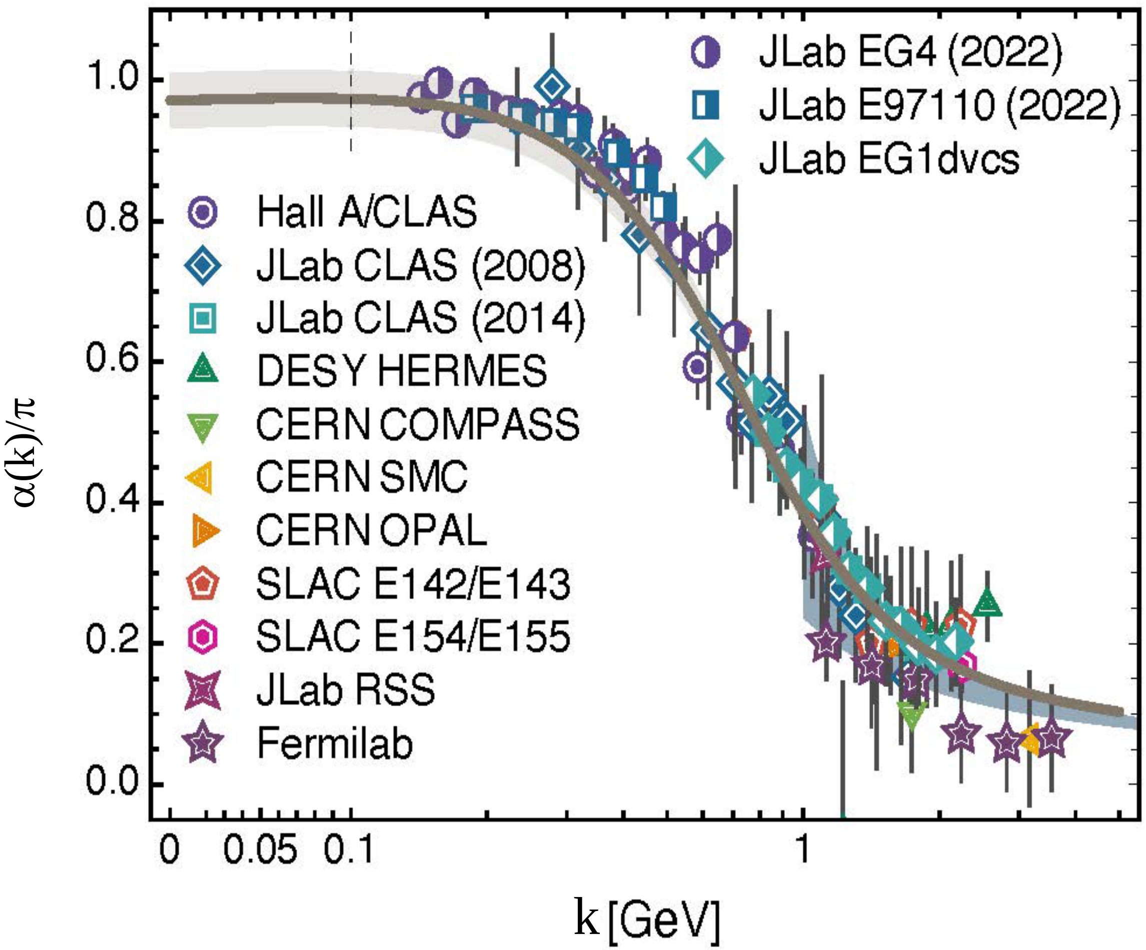


Frank Wilczek, Physics Today, August 2000

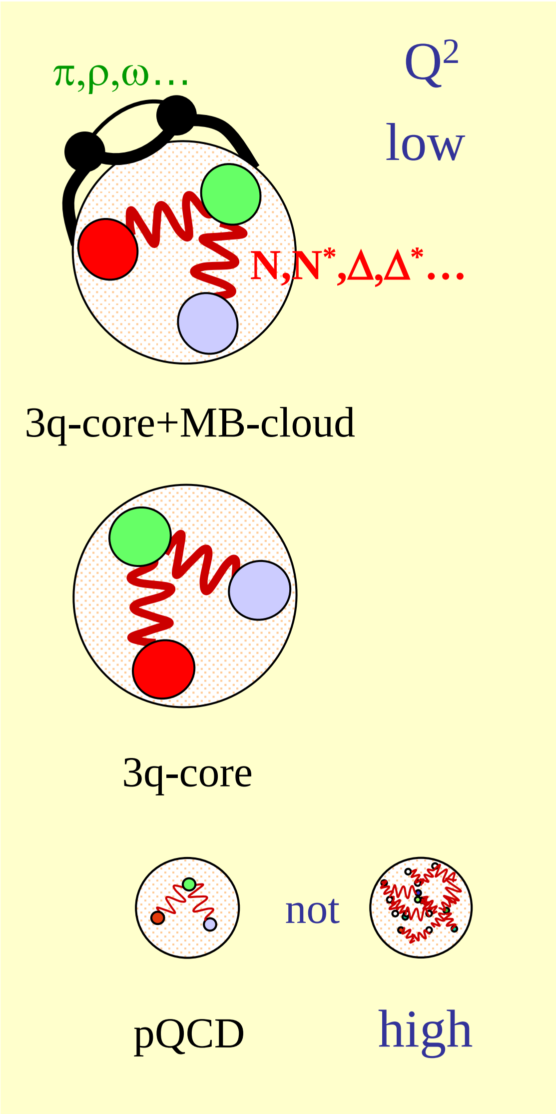
Hadron Structure with Electromagnetic Probes



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

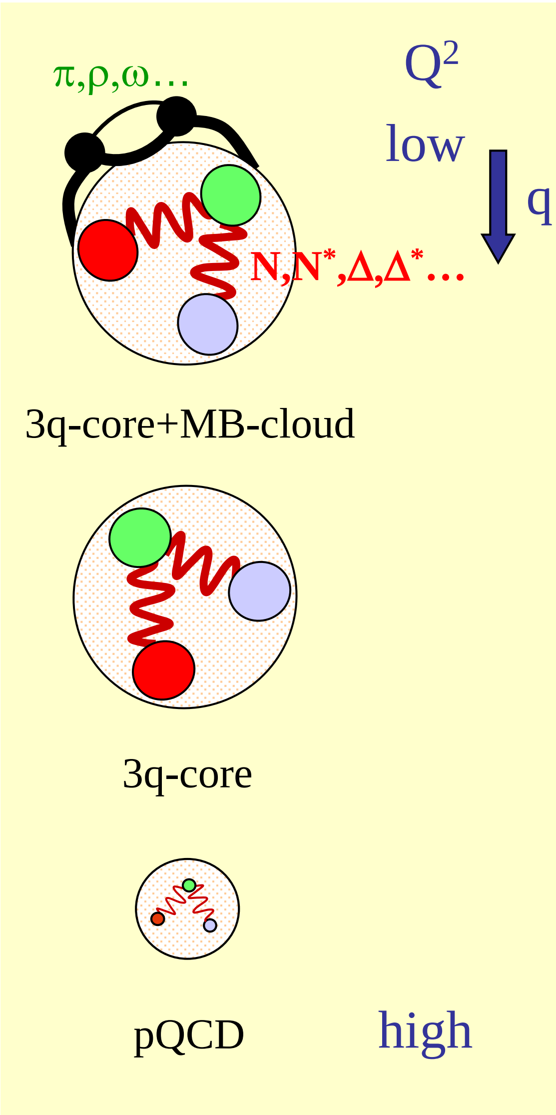


Hadron Structure with Electromagnetic Probes



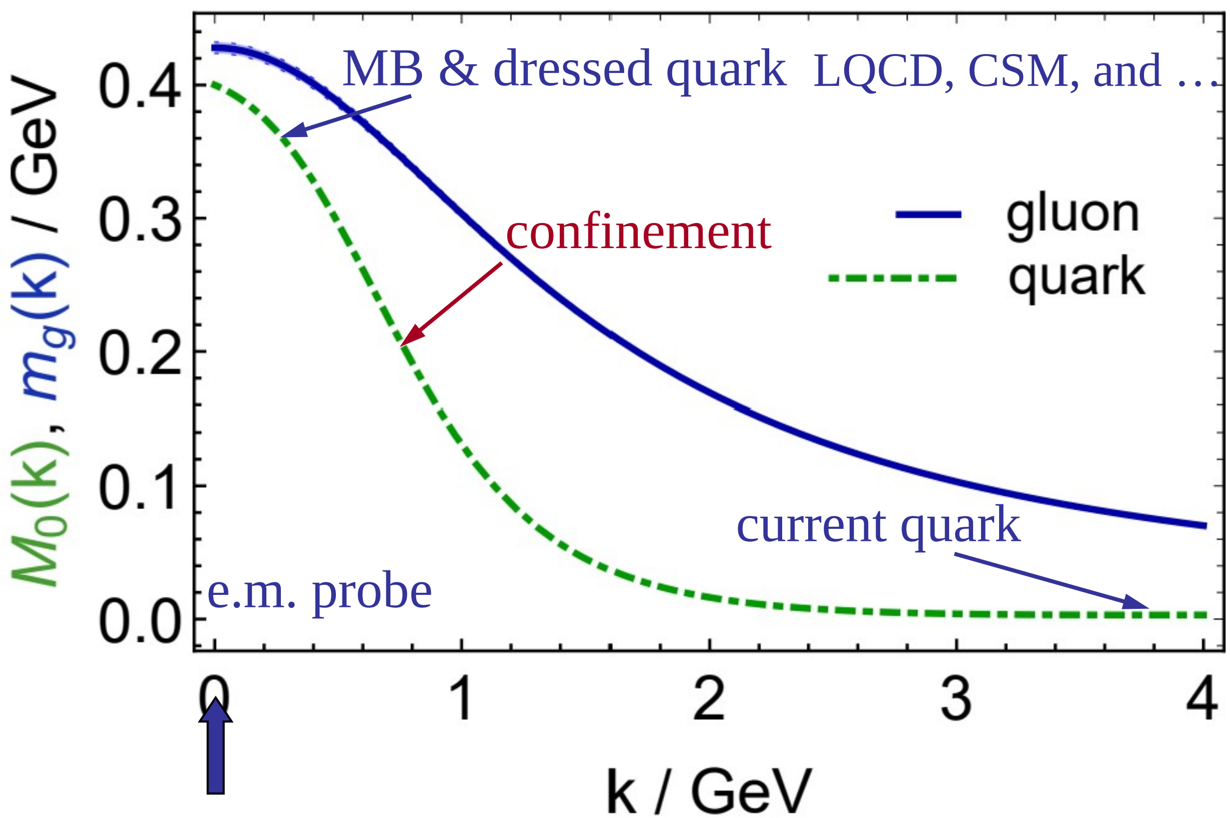
- Study the structure of the nucleon spectrum in the domain where most of the mass is generated by the strong field.

Emergence of Hadron Mass Traced by Electromagnetic Probes



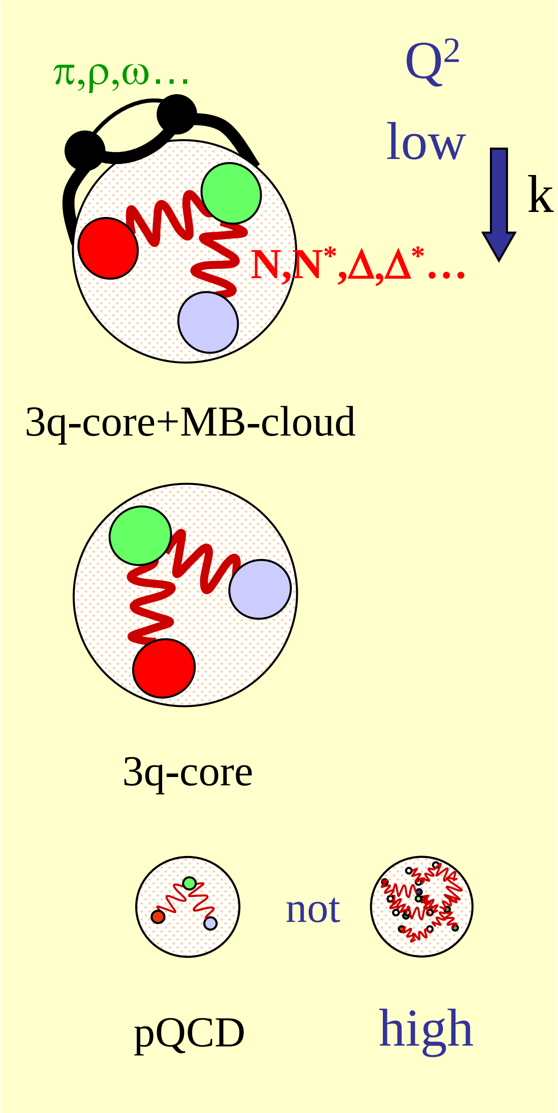
- Study the structure of the nucleon spectrum in the domain where most of the mass is generated by the strong field and dressed quarks are the major active degree of freedom.

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

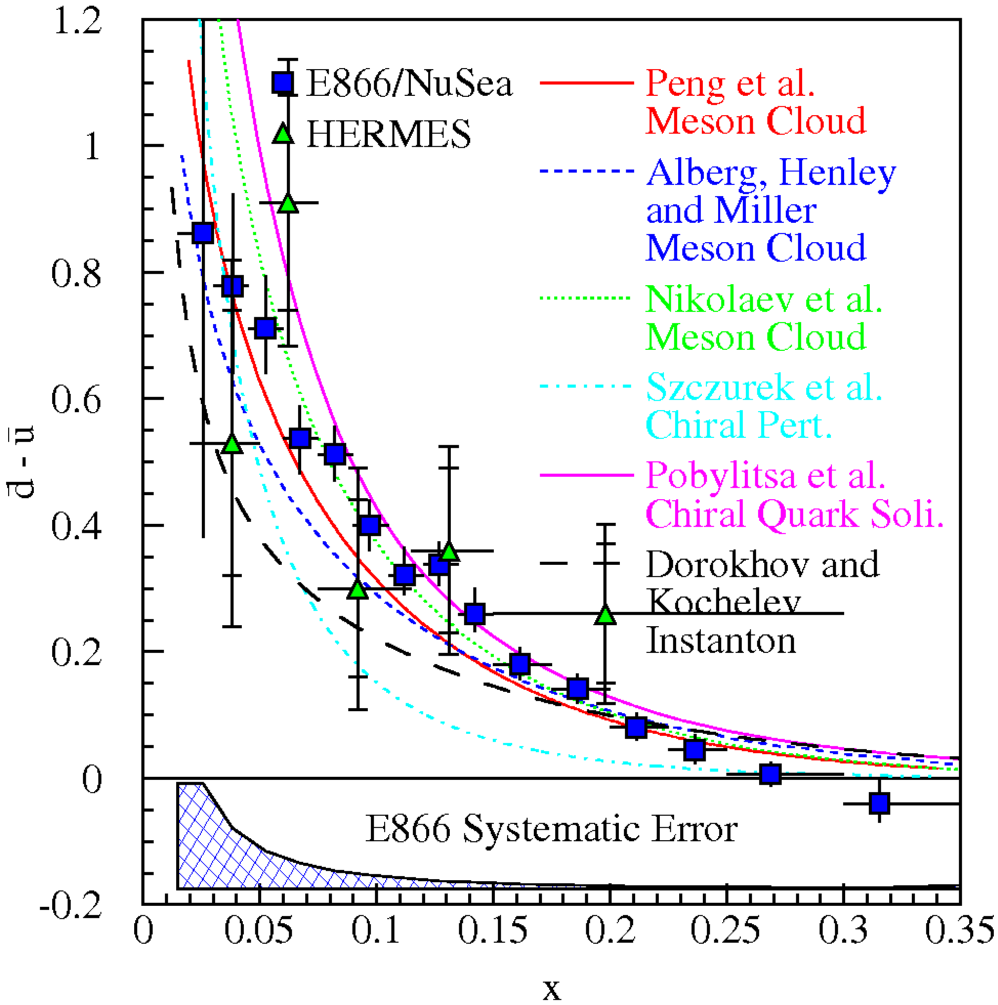


Hadron Structure with Electromagnetic Probes

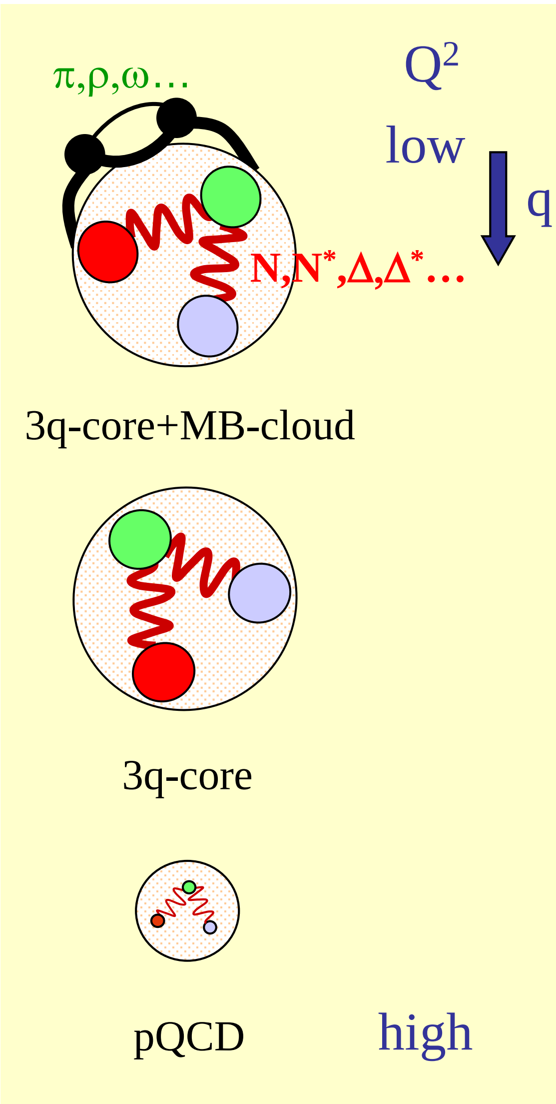
Rolf Ent



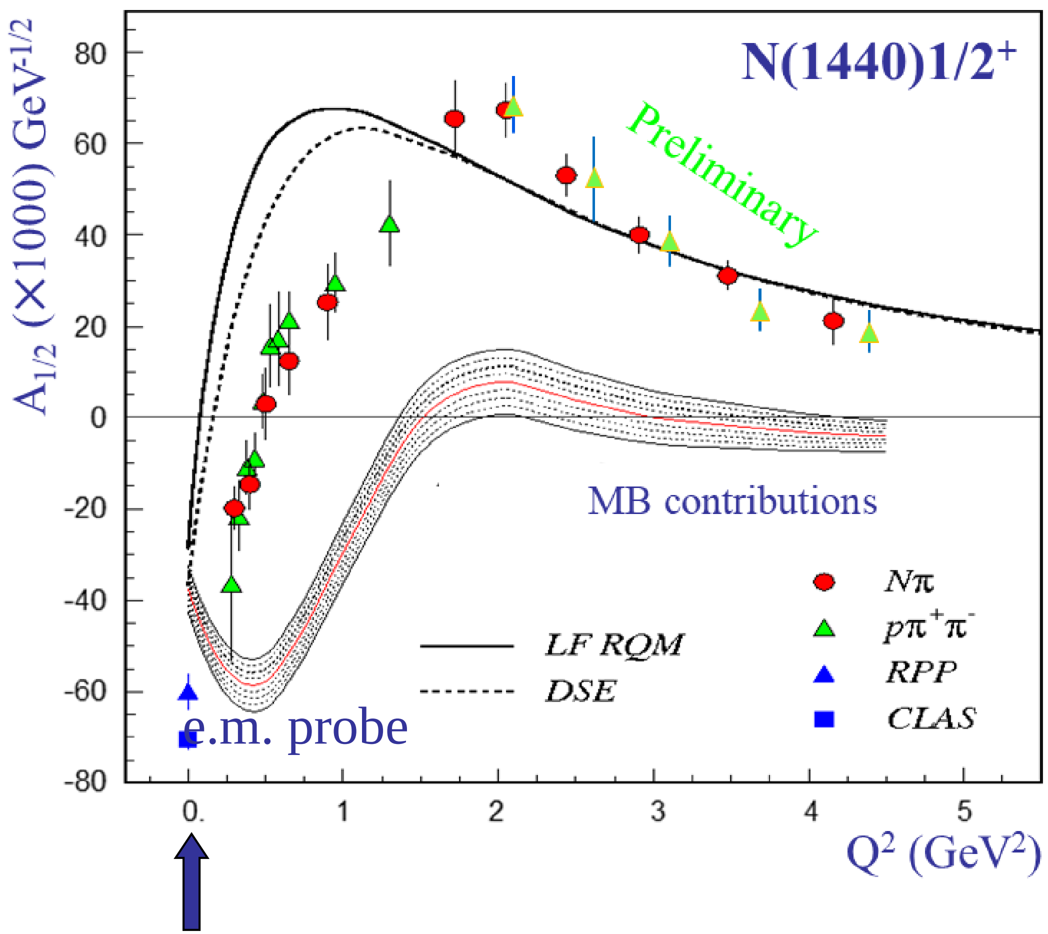
- The pion, or a meson cloud, explains light-quark asymmetry of the sea quarks in the nucleon.



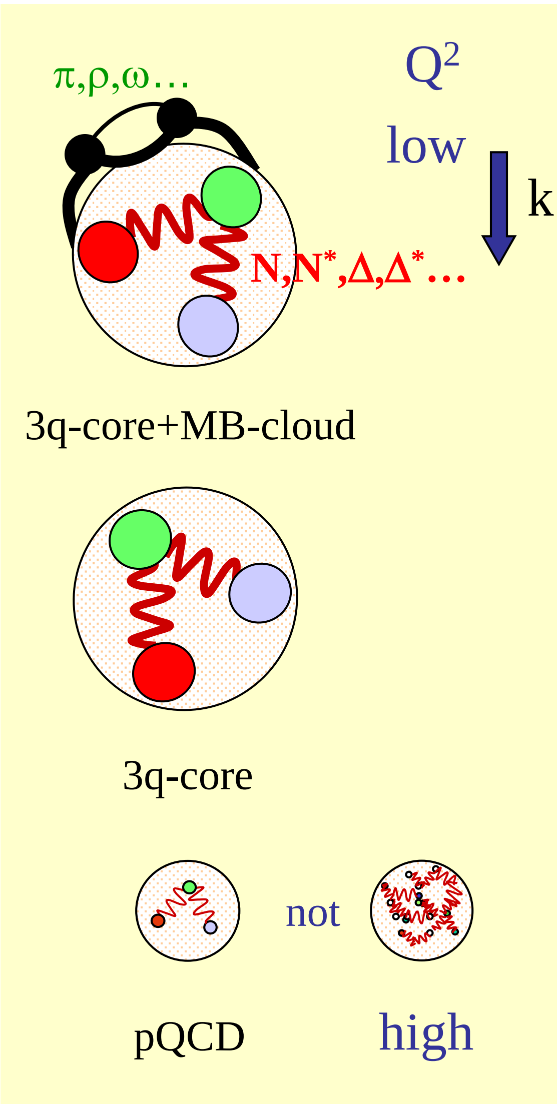
Emergence of Hadron Mass Traced by Electromagnetic Probes



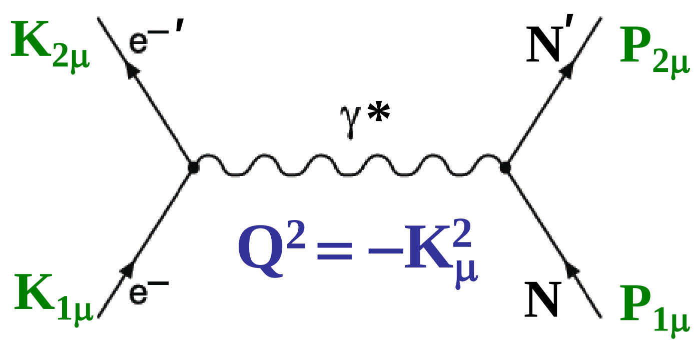
- Study the structure of the nucleon spectrum in the domain where dressed quarks are the major active degree of freedom.

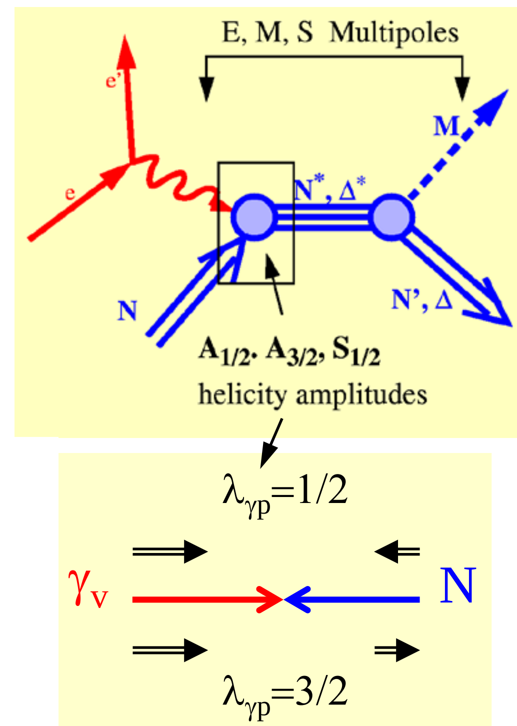


Hadron Structure with Electromagnetic Probes



- 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.

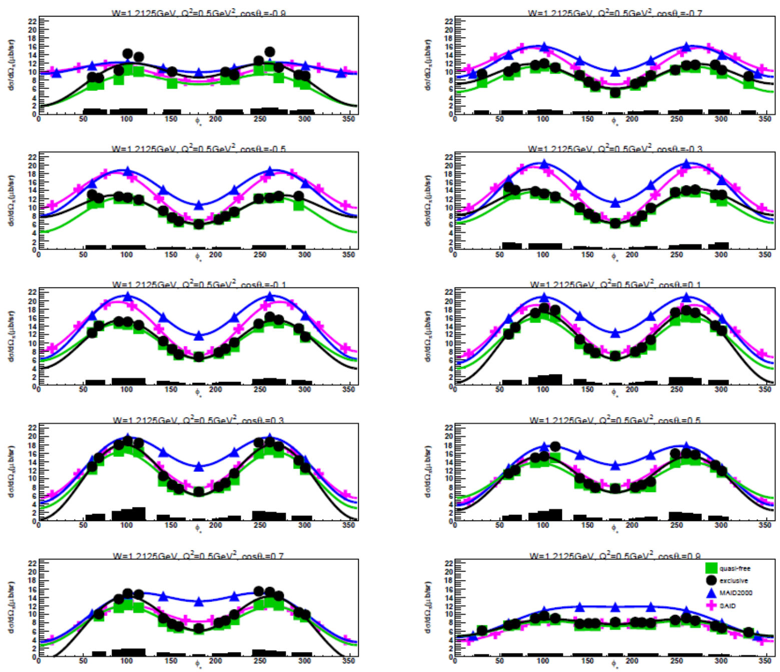




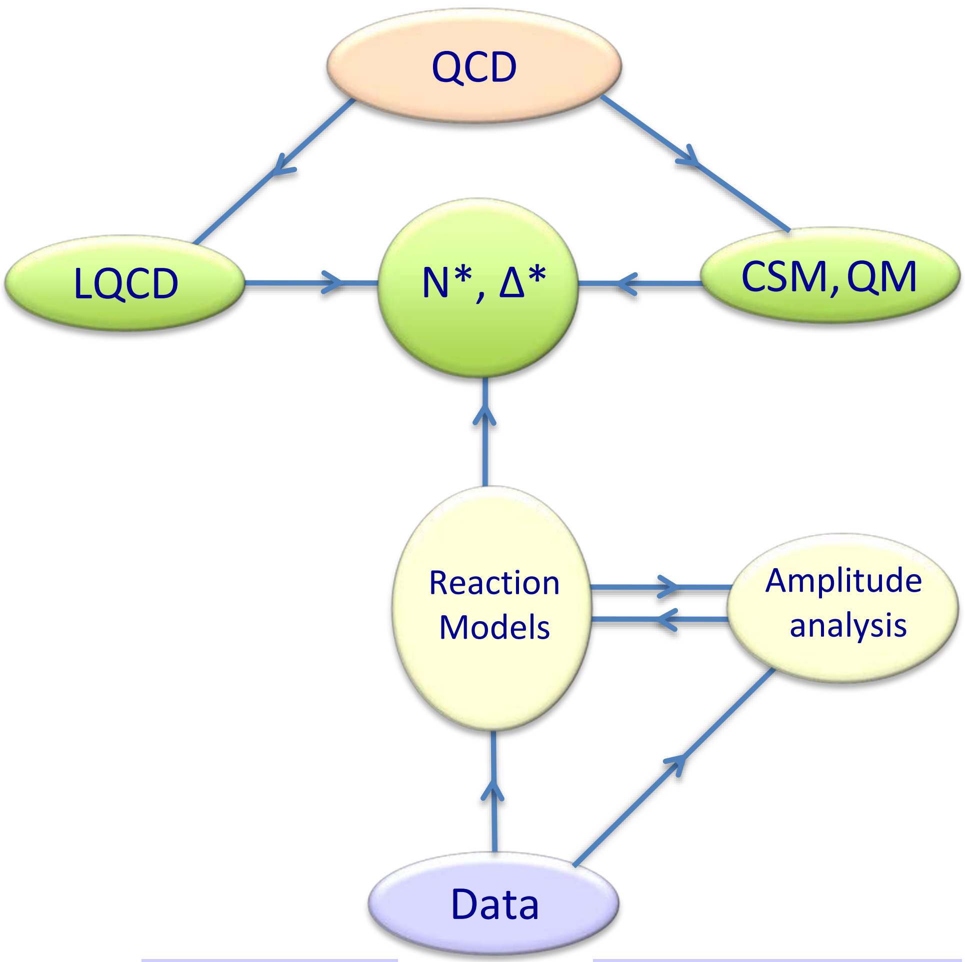
Data-Driven Data Analyses

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.*, Phys. Rev. **C 107**, 015201 (2023) 26

W = 1.2125 GeV

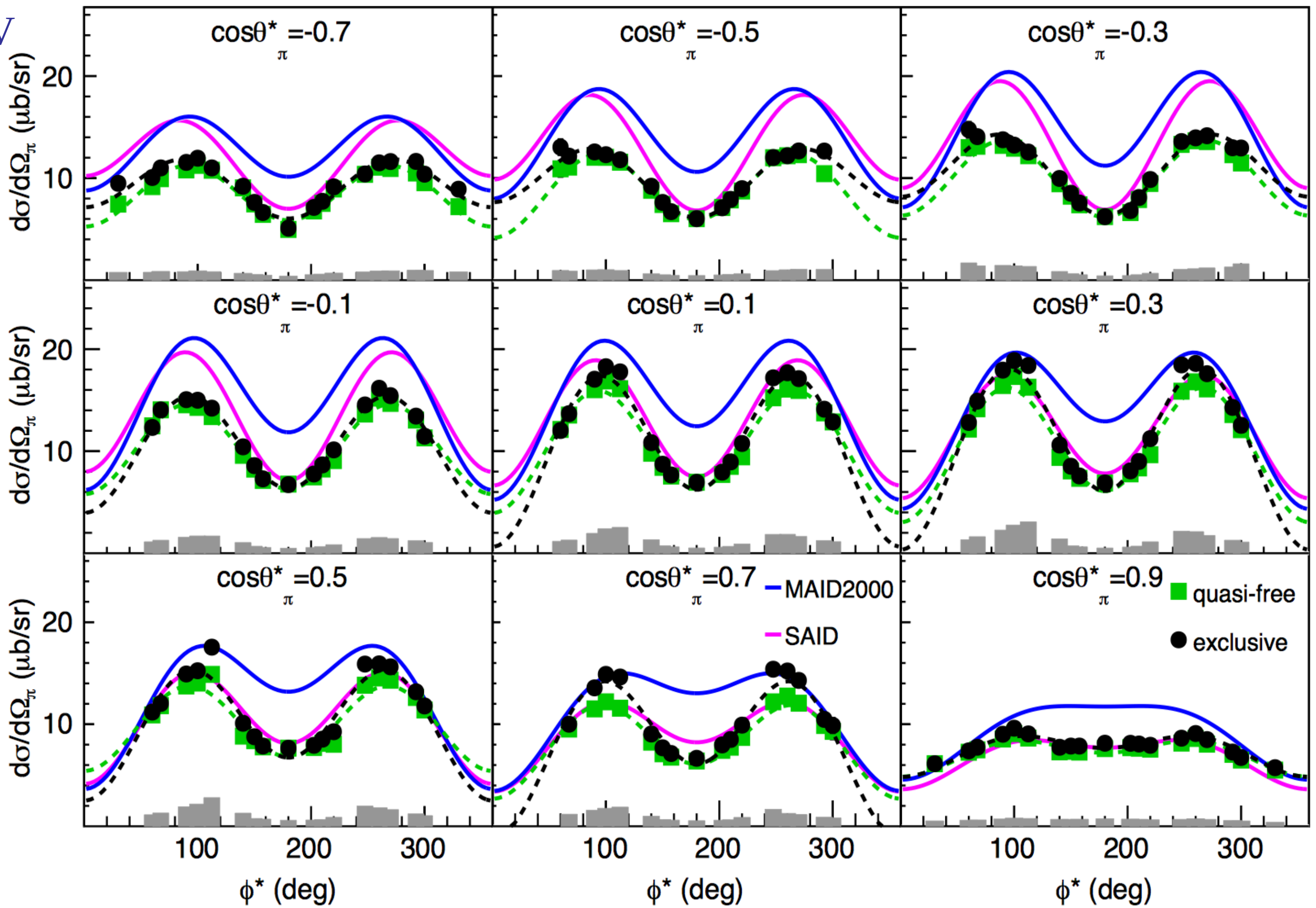
ΔW = 25 MeV

Q^2 = 0.5 GeV^2

ΔQ^2 = 0.2 GeV^2

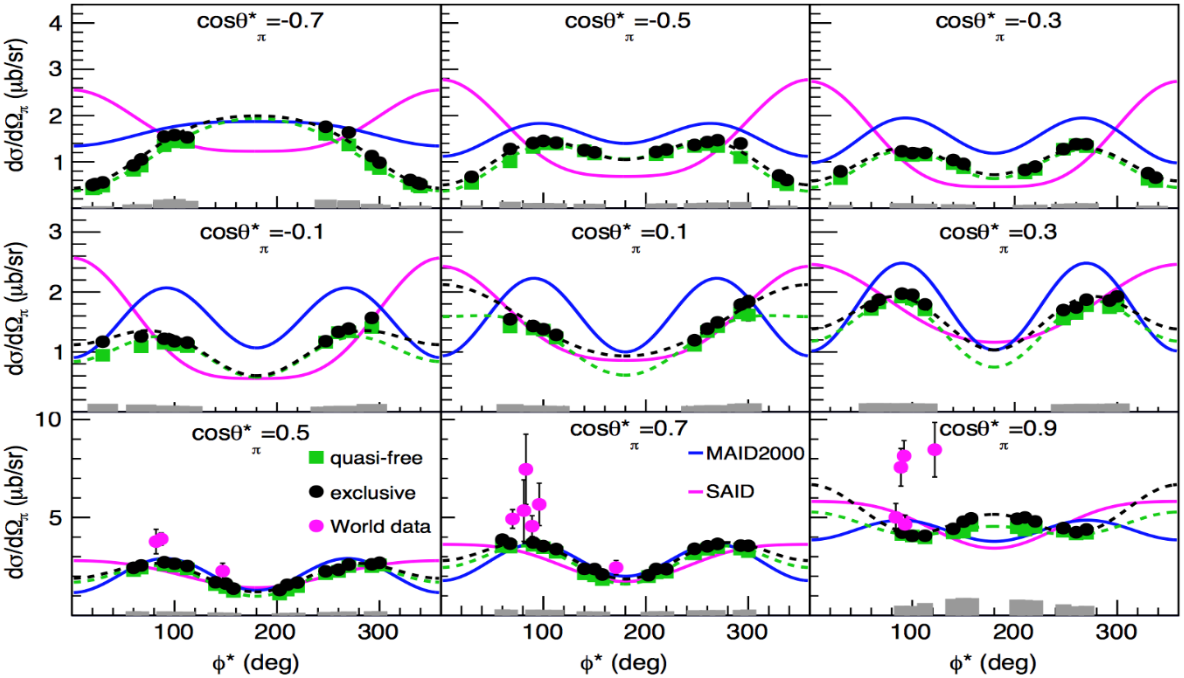
cos(θ) = -0.7
Δcos(θ) = 0.2
cos(θ) = 0.9

ϕ = 20°
Δϕ = 40°
ϕ = 340°



Exclusive Single π ⁻ Electroproduction off the Deuteron

Ye Tian

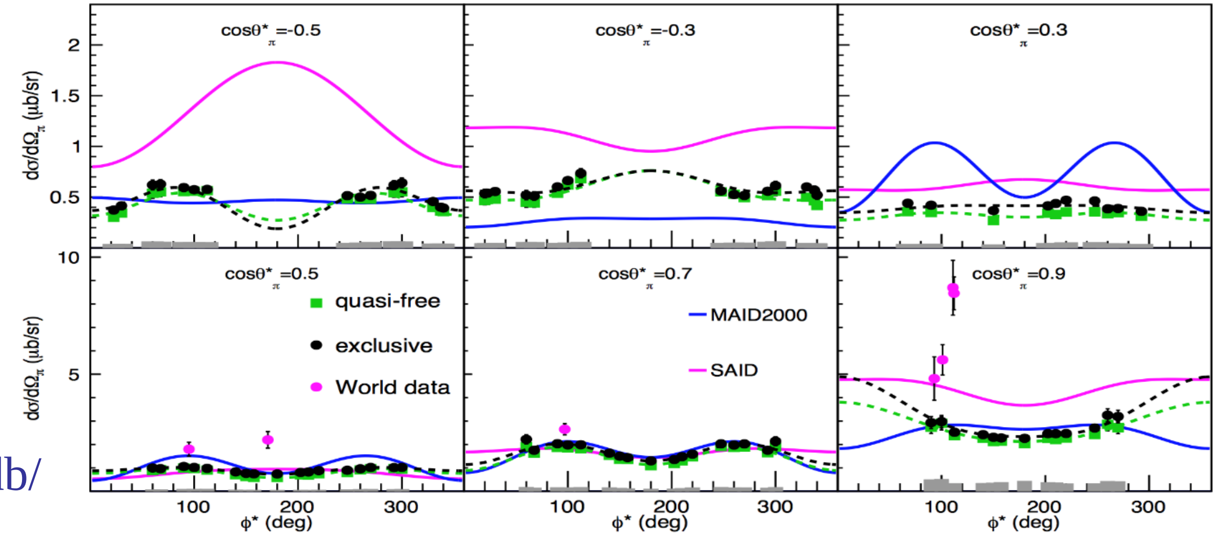


W = 1.5125 GeV

$Q^2 = 0.5\ GeV^2$

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

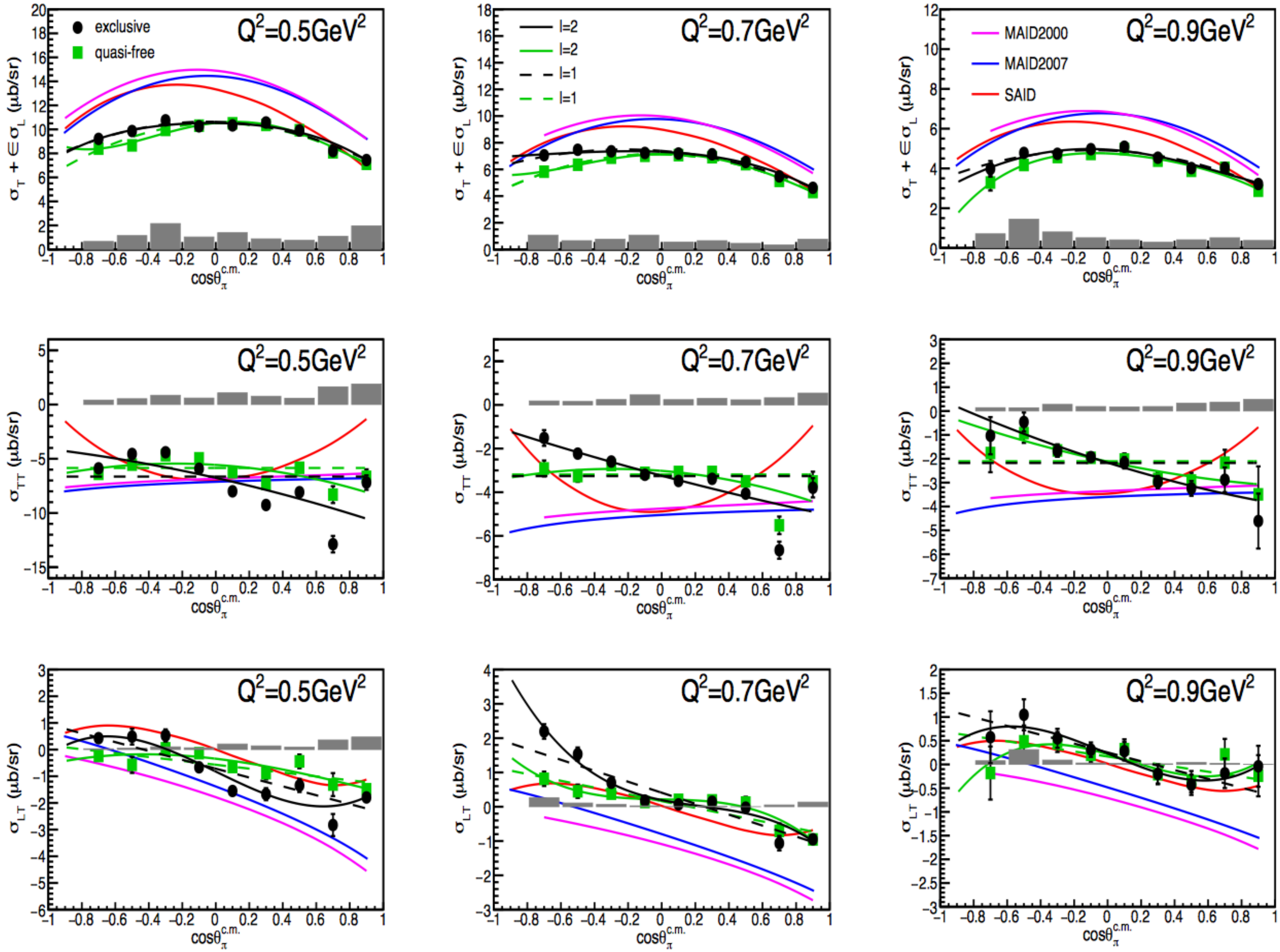
W = 1.6625 GeV



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

cos θ_π- Dependent Structure Functions @ W=1.2125 GeV

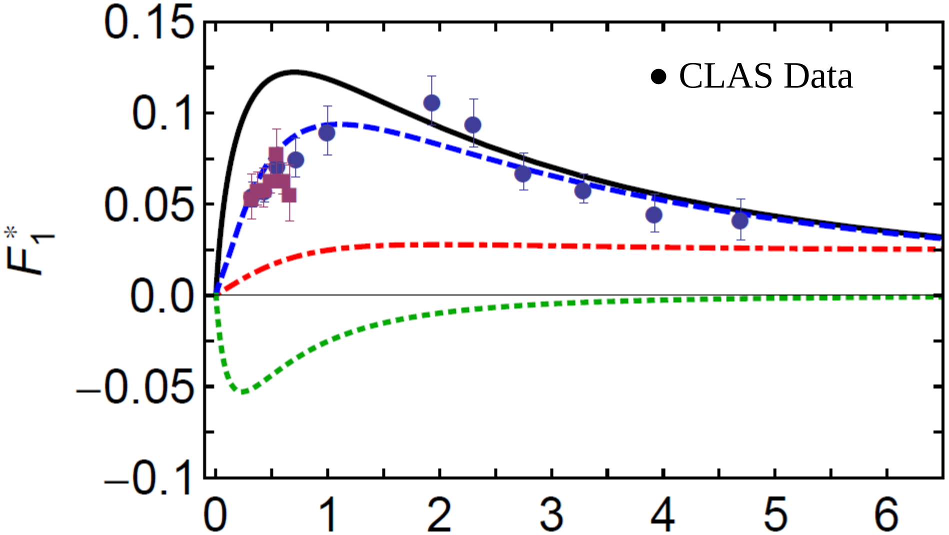
W = 1.2125 GeV   ΔW = 25 MeV   Ye Tian

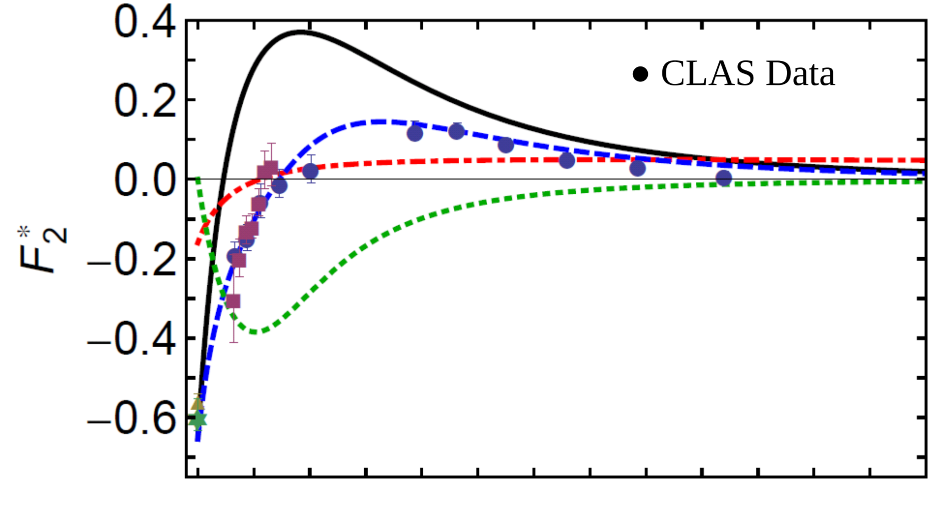


Roper Transition Form Factors in CSM Approach

$N(1440)P_{11}$

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





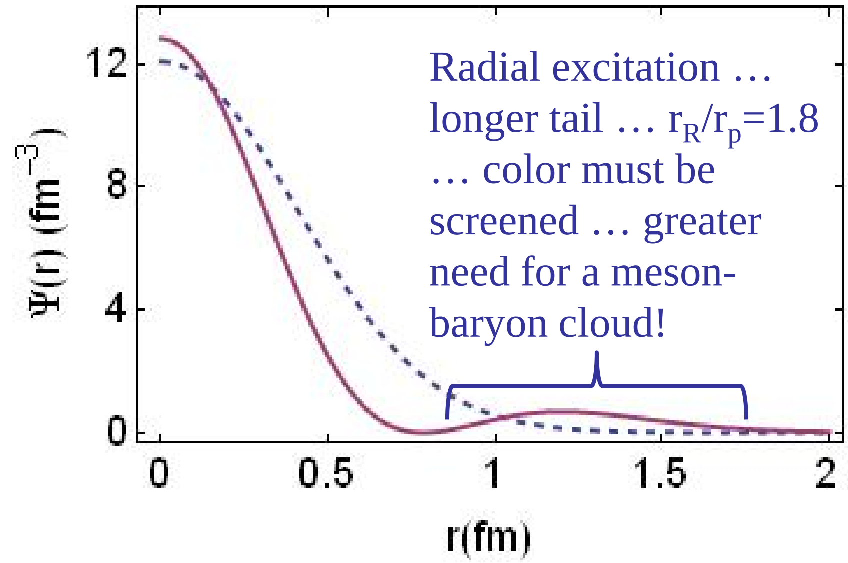
$x = Q^2/m_N^2$

DSE Contact

DSE Realistic

Inferred meson-cloud contribution

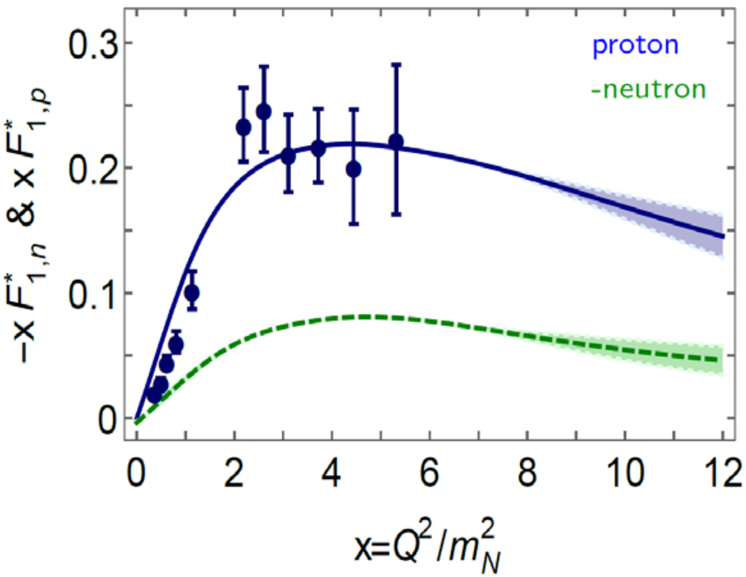
Anticipated complete result



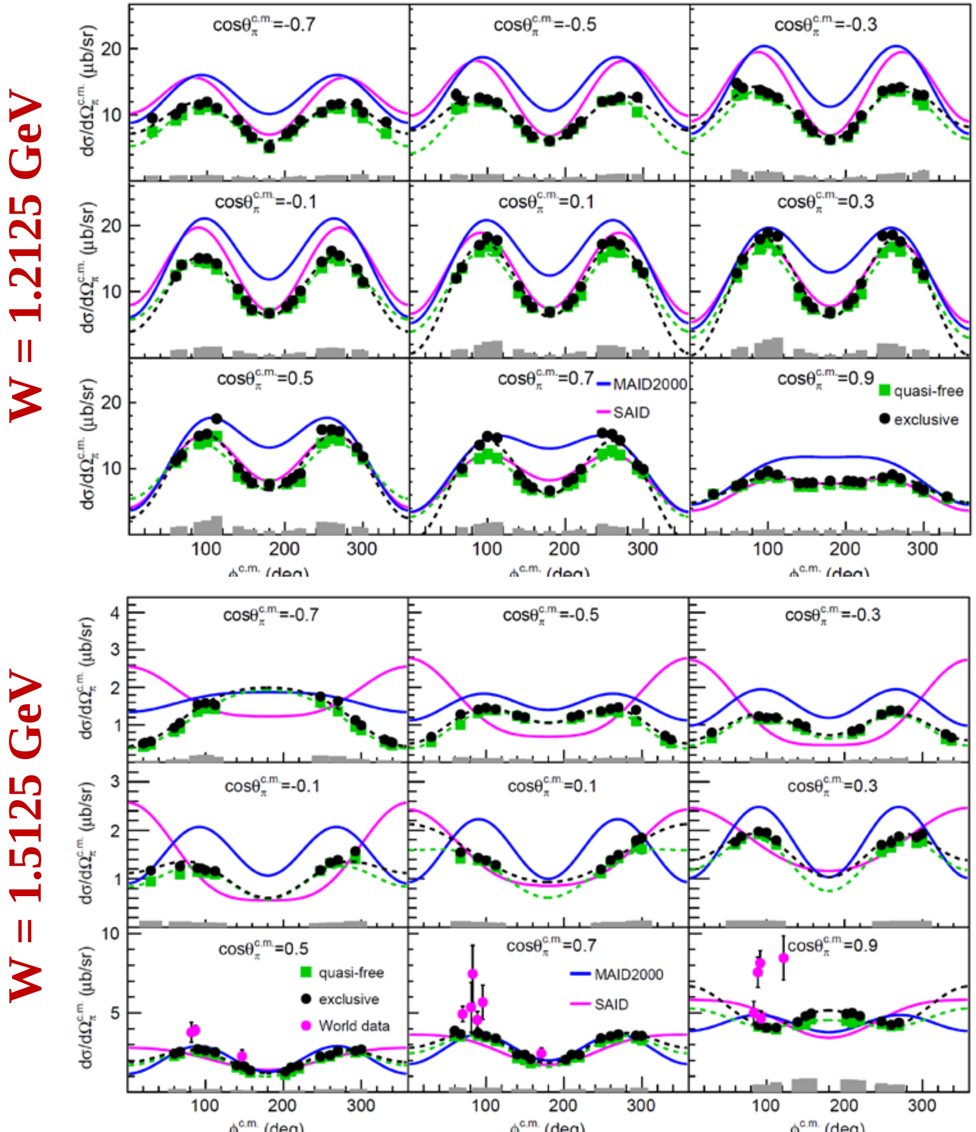
Importantly, the existence of a zero in F_2 is not influenced by meson-cloud effects, although its precise location is.

Roper Transition Form Factors in CSM Approach

$N(1440)P_{11}$



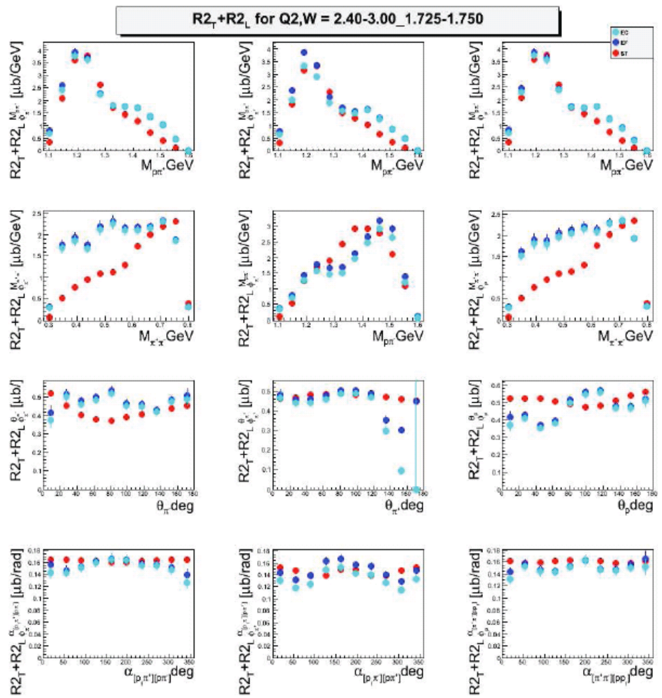
Y. Tian *et al*. submitted to Phys. Rev C



Data-Driven Data Analyses

Consistent Results

Double Pion



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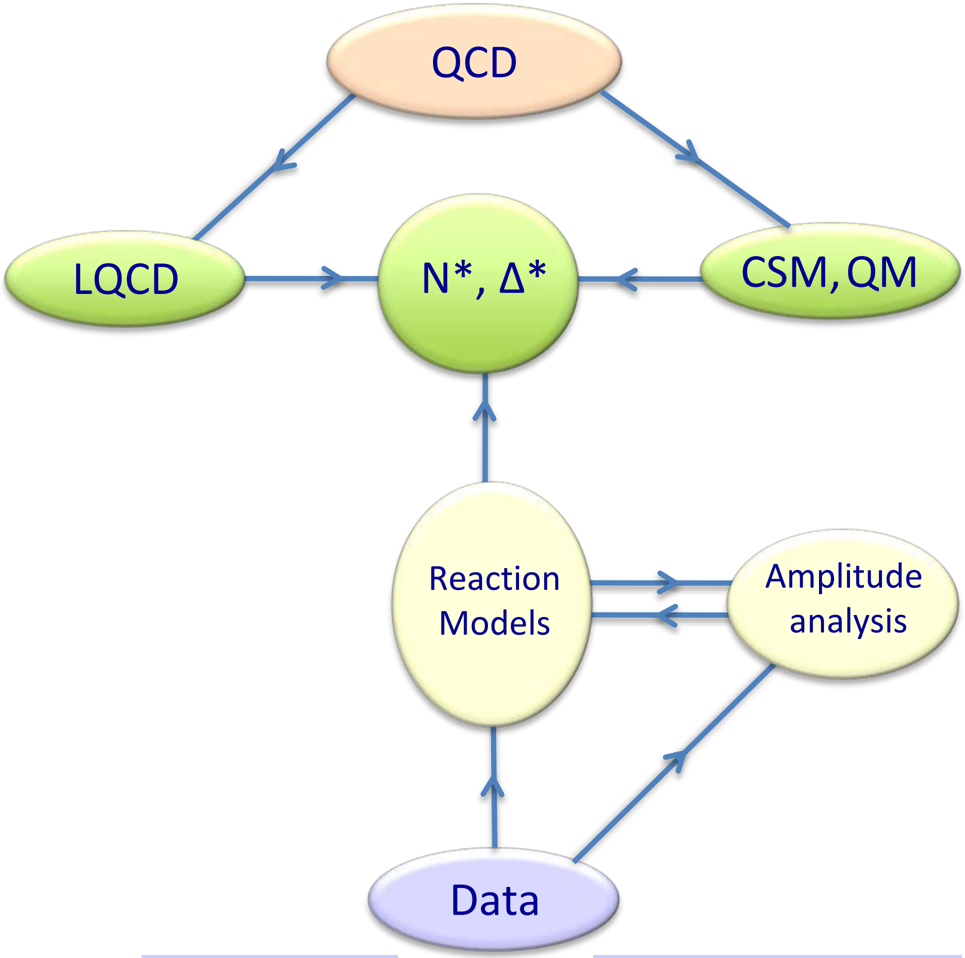


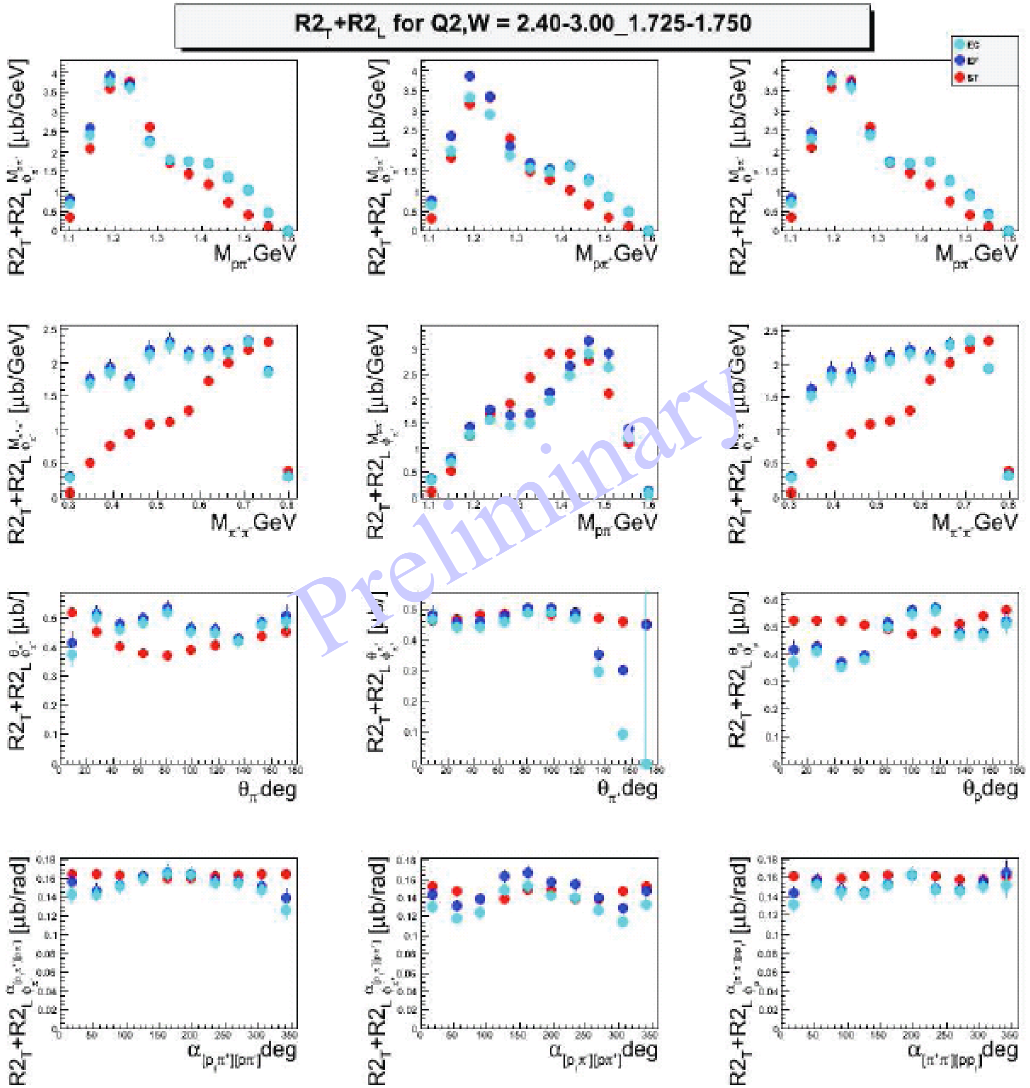
Hadronic production

Electromagnetic production

φ-independent 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



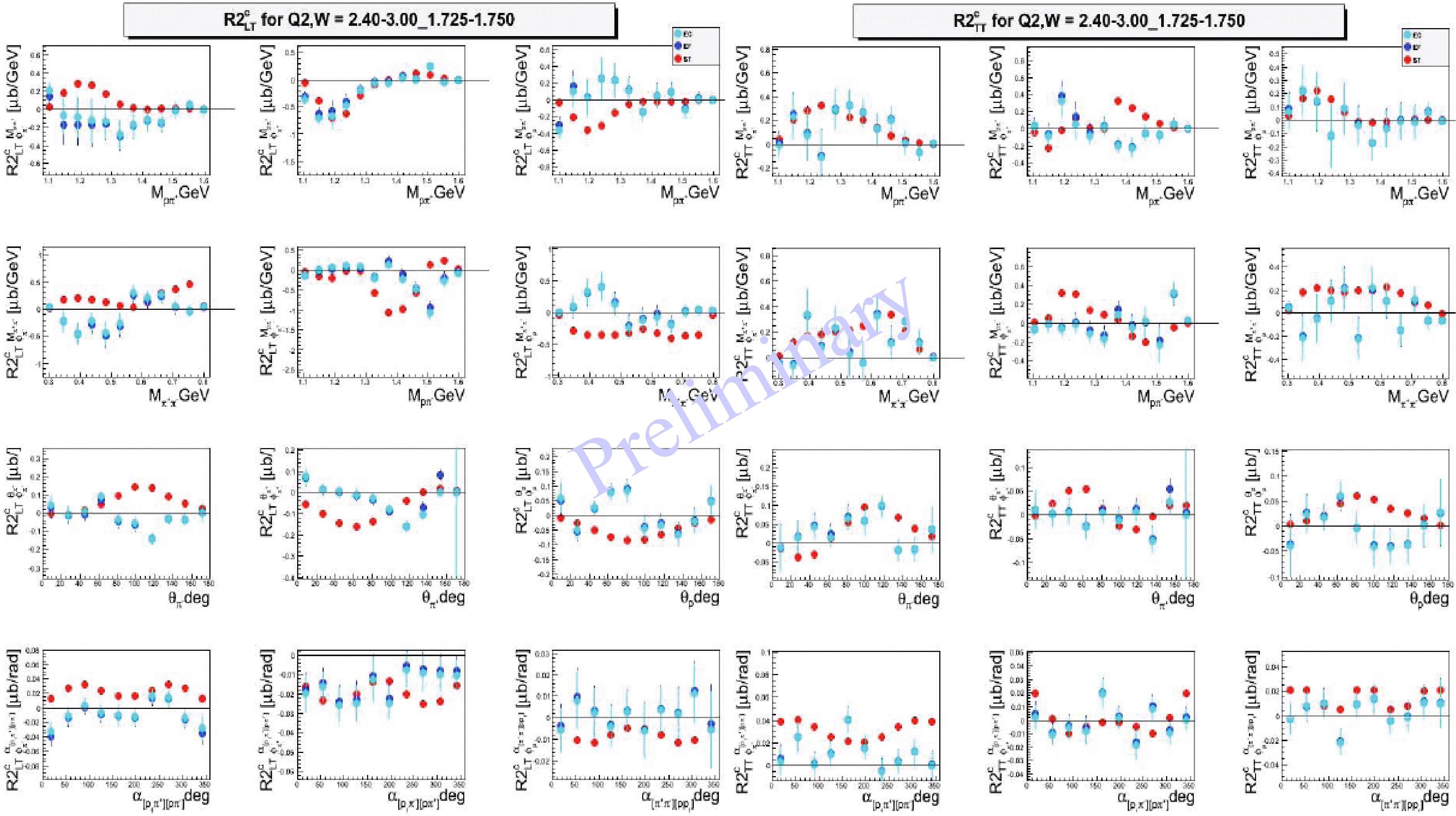
- normalized
- hole filled
- TWOPEG

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

φ-dependent Nππ Single-Differential Cross Sections

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

Arjun Trivedi



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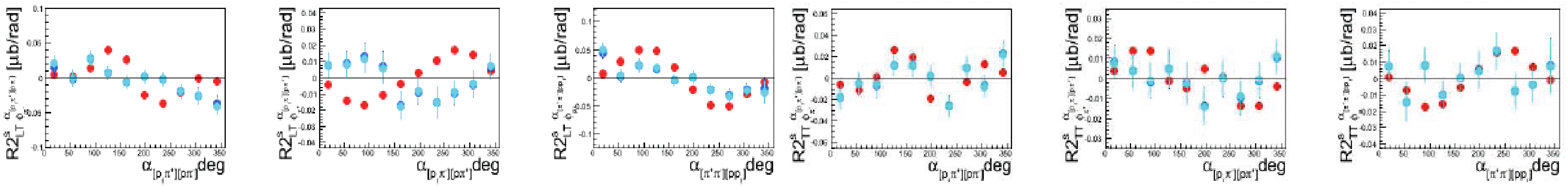
φ-dependent Nππ Single-Differential Cross Sections

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

Arjun Trivedi

Chris McLauchlin extracts the beam helicity dependent differential cross sections.

Preliminary



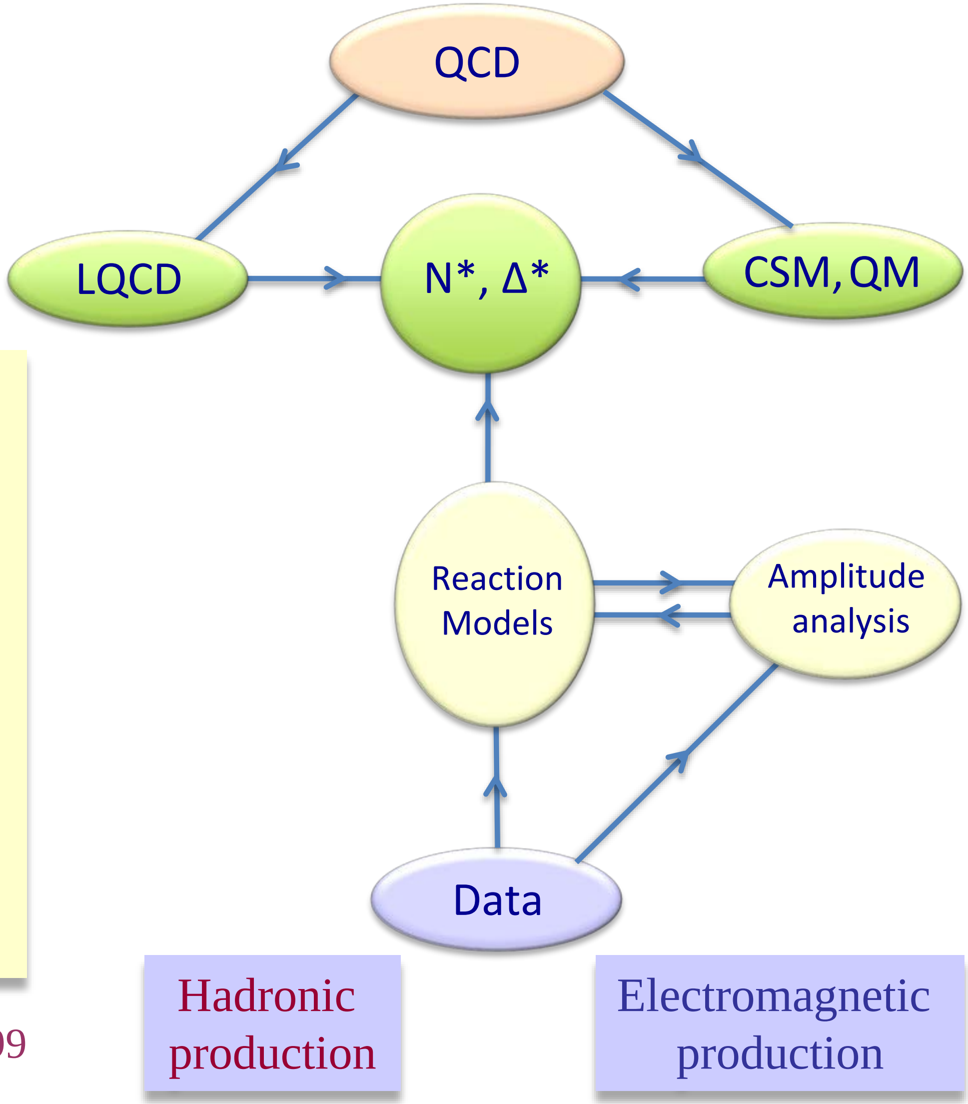
$$\left(\frac{d^2\sigma}{dX_{ij}\,d\phi_i}\right) = R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}} + R2_{LT}{}^{c,X_{ij}} \cos\phi_i + R2_{TT}{}^{c,X_{ij}} \cos 2\phi_i + \delta_{X_{ij}\alpha_i} \left(\underline{R2_{LT}{}^{s,\alpha_i} \sin\phi_i} + \underline{R2_{TT}{}^{s,\alpha_i} \sin 2\phi_i}\right)$$

Data-Driven Data Analyses

Consistent Results

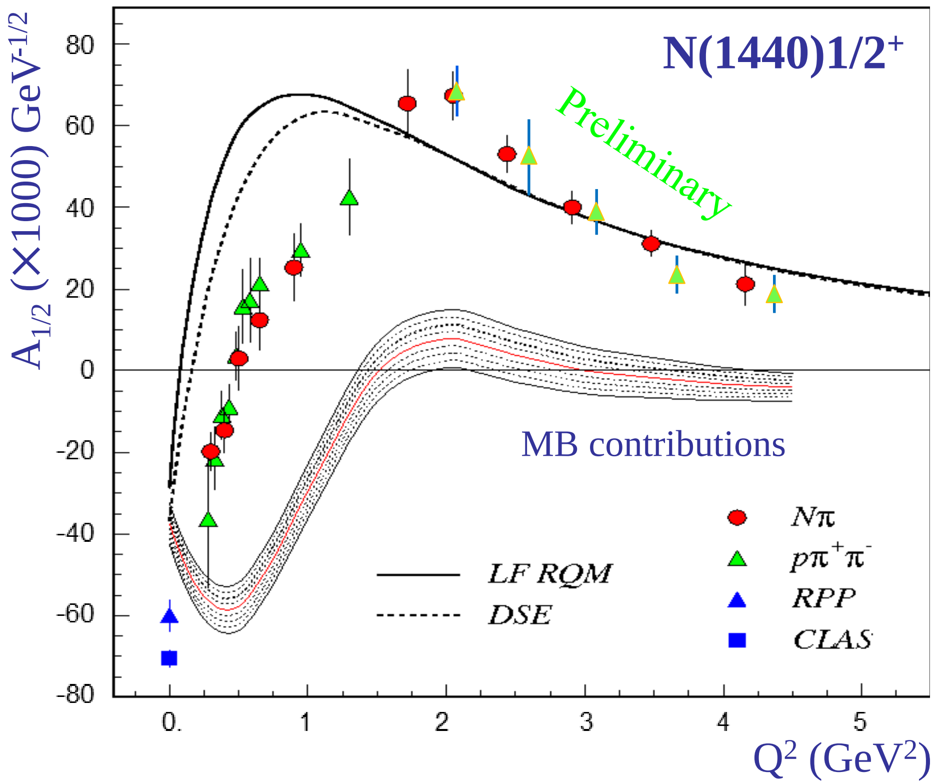
- Single meson production:
  - Unitary Isobar Model (UIM)
  - Fixed-*t* Dispersion Relations (DR)
- Double pion production:
  - Unitarized Isobar Model (JM)
- Coupled-Channel Approaches:
  - EBAC ⇒ Argonne-Osaka
  - JAW ⇒ Jülich-Athens-Washington ⇒ JüBo
  - BoGa ⇒ Bonn-Gatchina

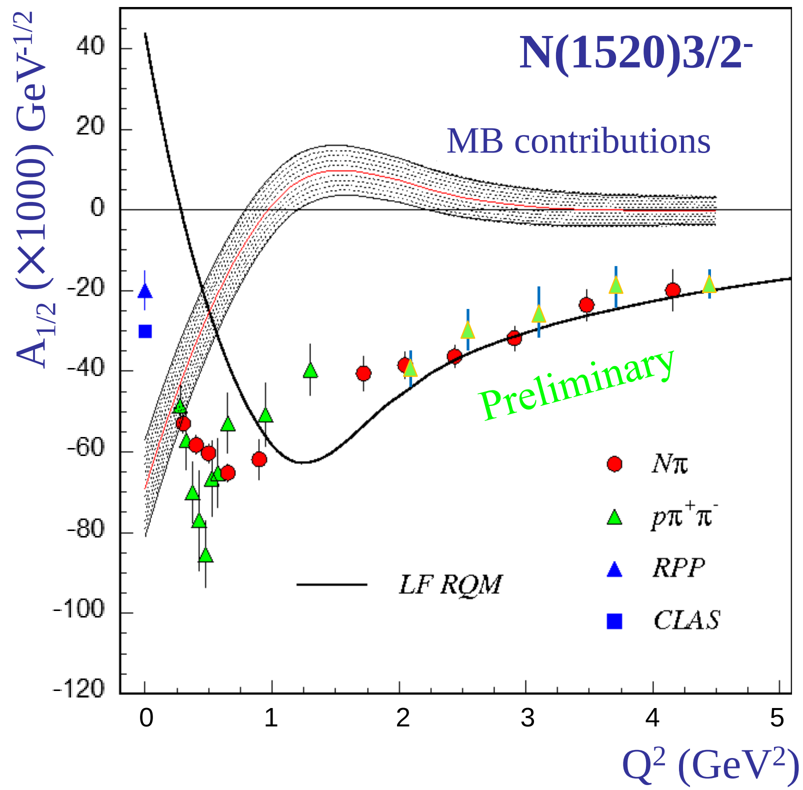
Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013) 1-99



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

Viktor Mokeev



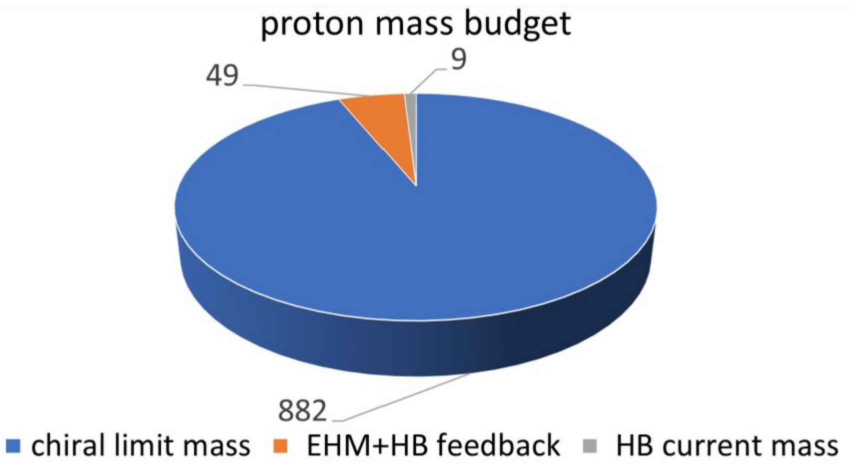


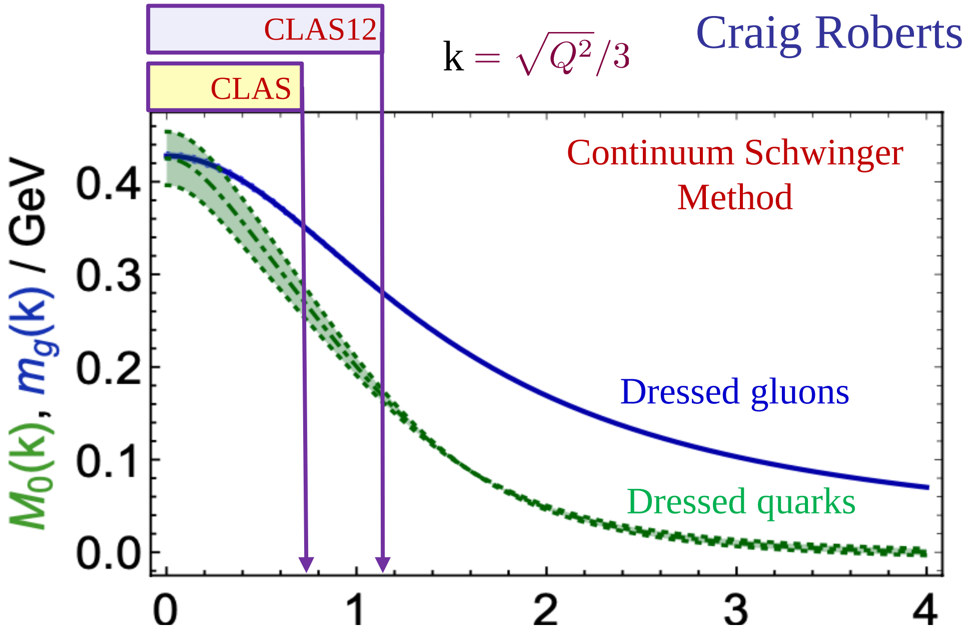
Consistent results obtained in the low-lying resonance region by independent analyses in the exclusive Nπ and $p\pi^+\pi^-$ final-state channels – that have fundamentally different mechanisms for the nonresonant background – underscore the capability of the reaction models to extract reliable resonance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

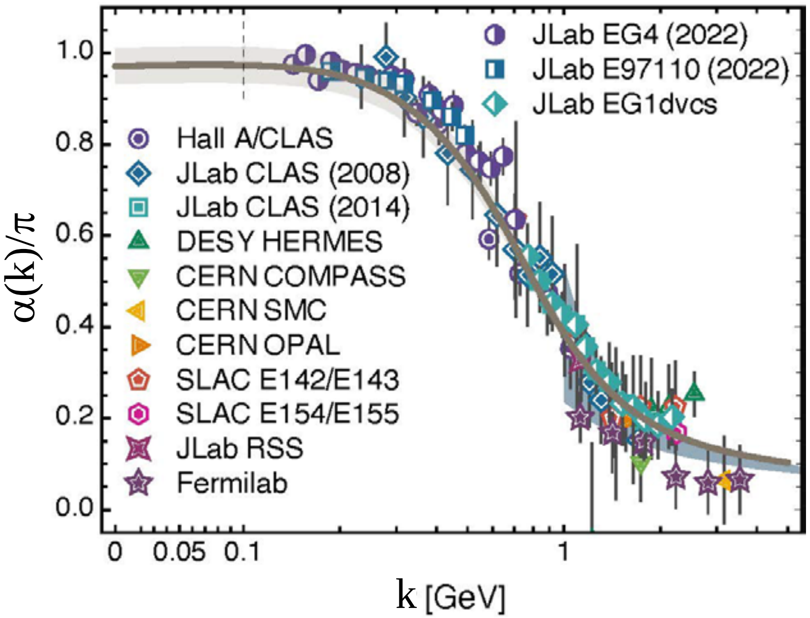
Phys. Rev. C 80, 055203 (2009) 1-22 and Phys. Rev. C 86, 035203 (2012) 1-22

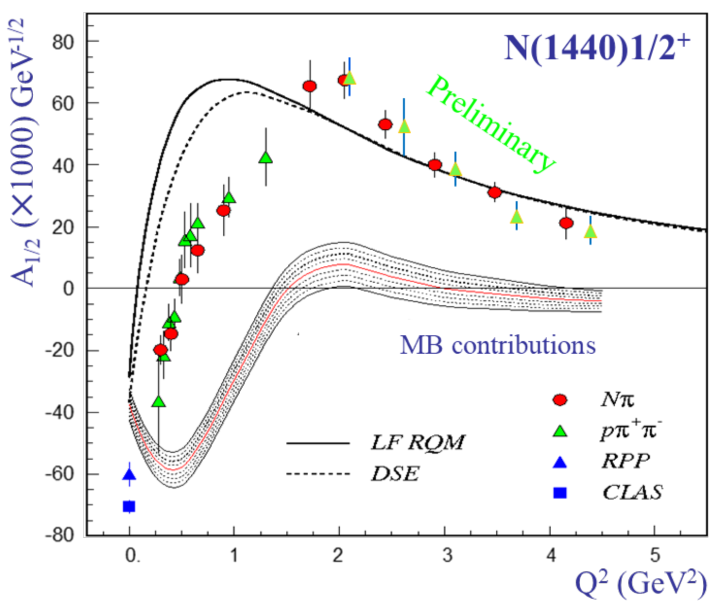
Emergence of Hadron Mass

Craig Roberts

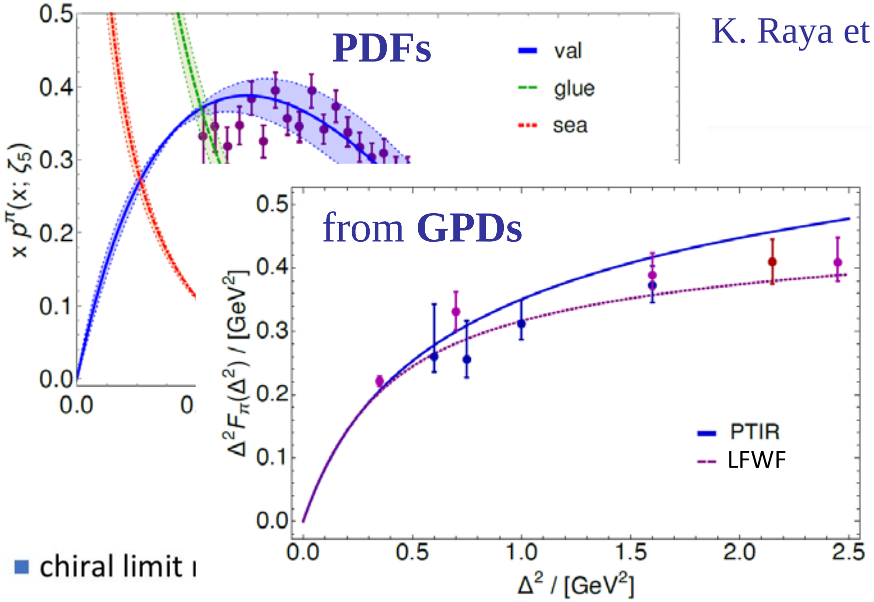






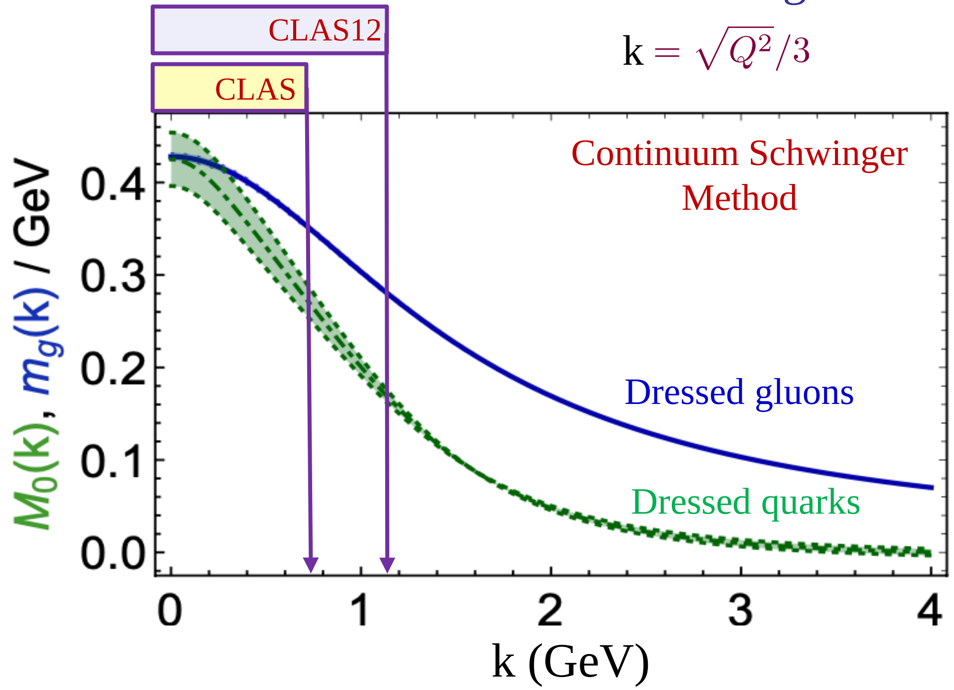


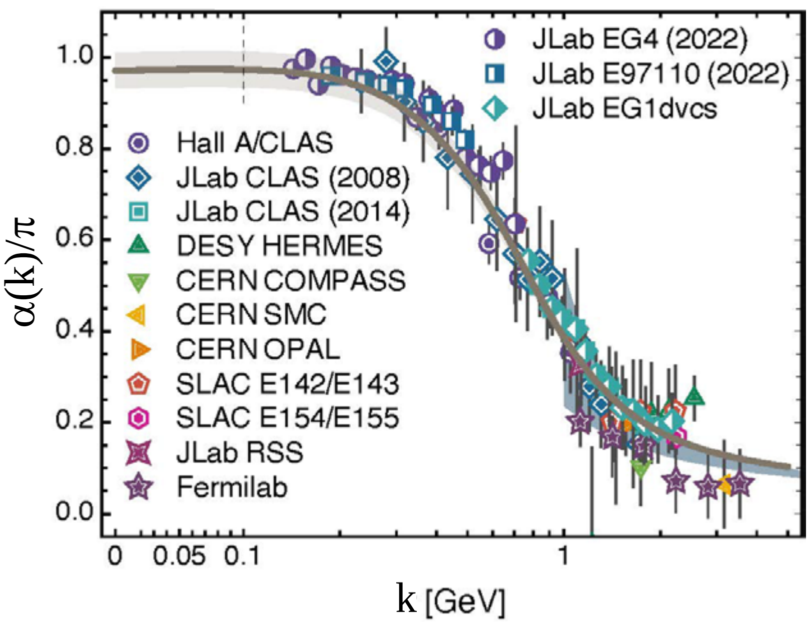
Emergence of Hadron Mass

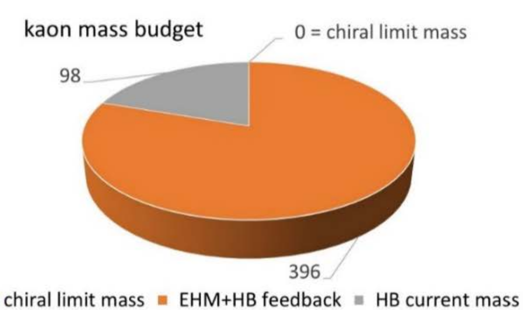


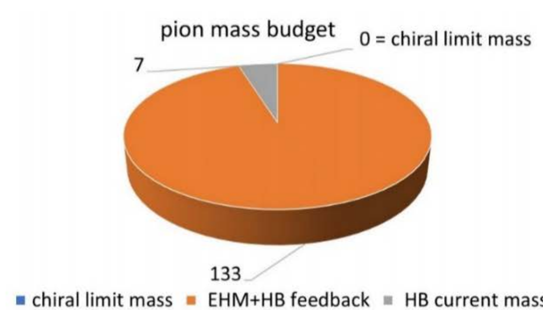
K. Raya et al 2022 Chinese Phys. C 46 013105

Craig Roberts



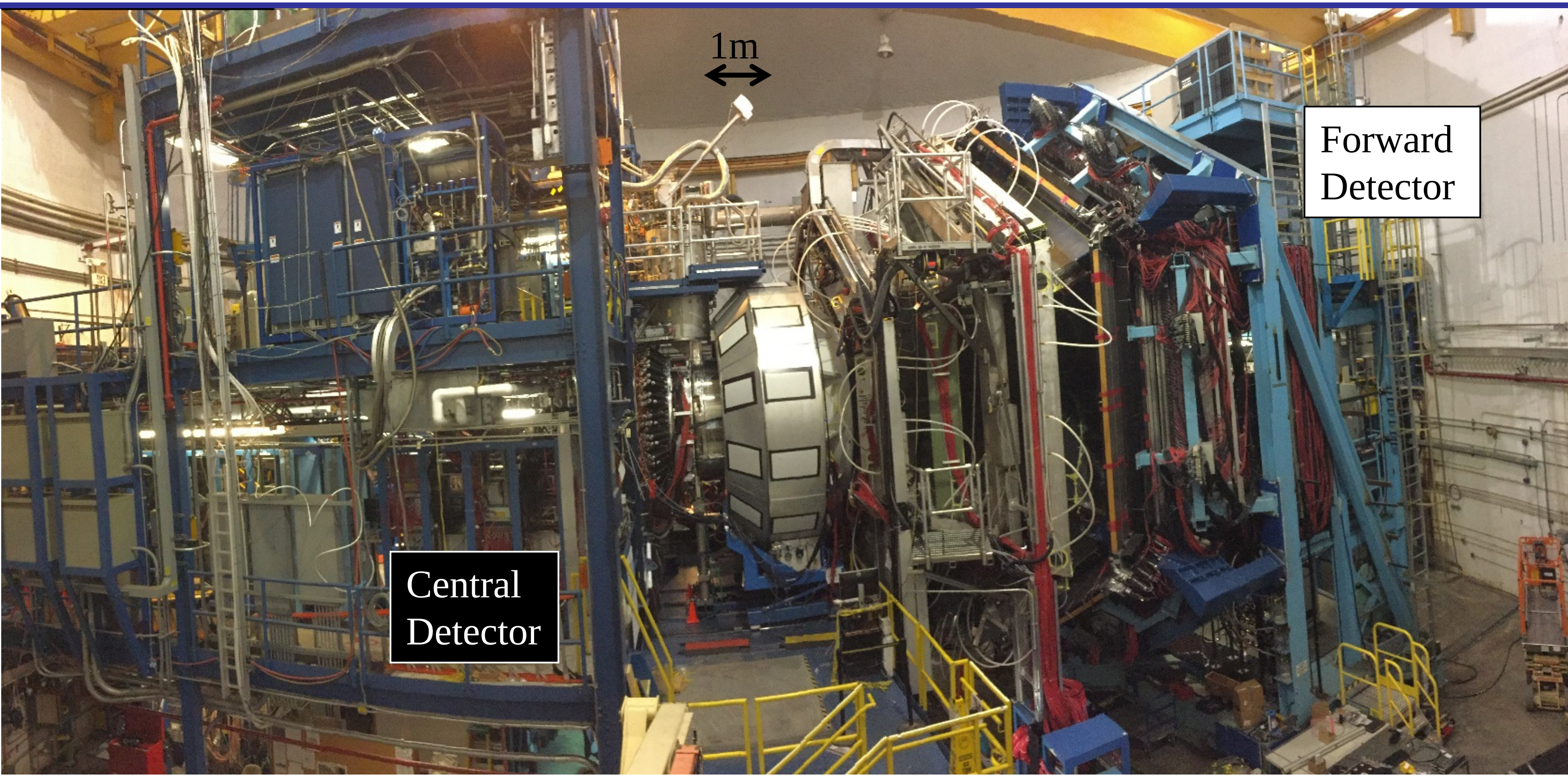






CLAS12

CLAS12



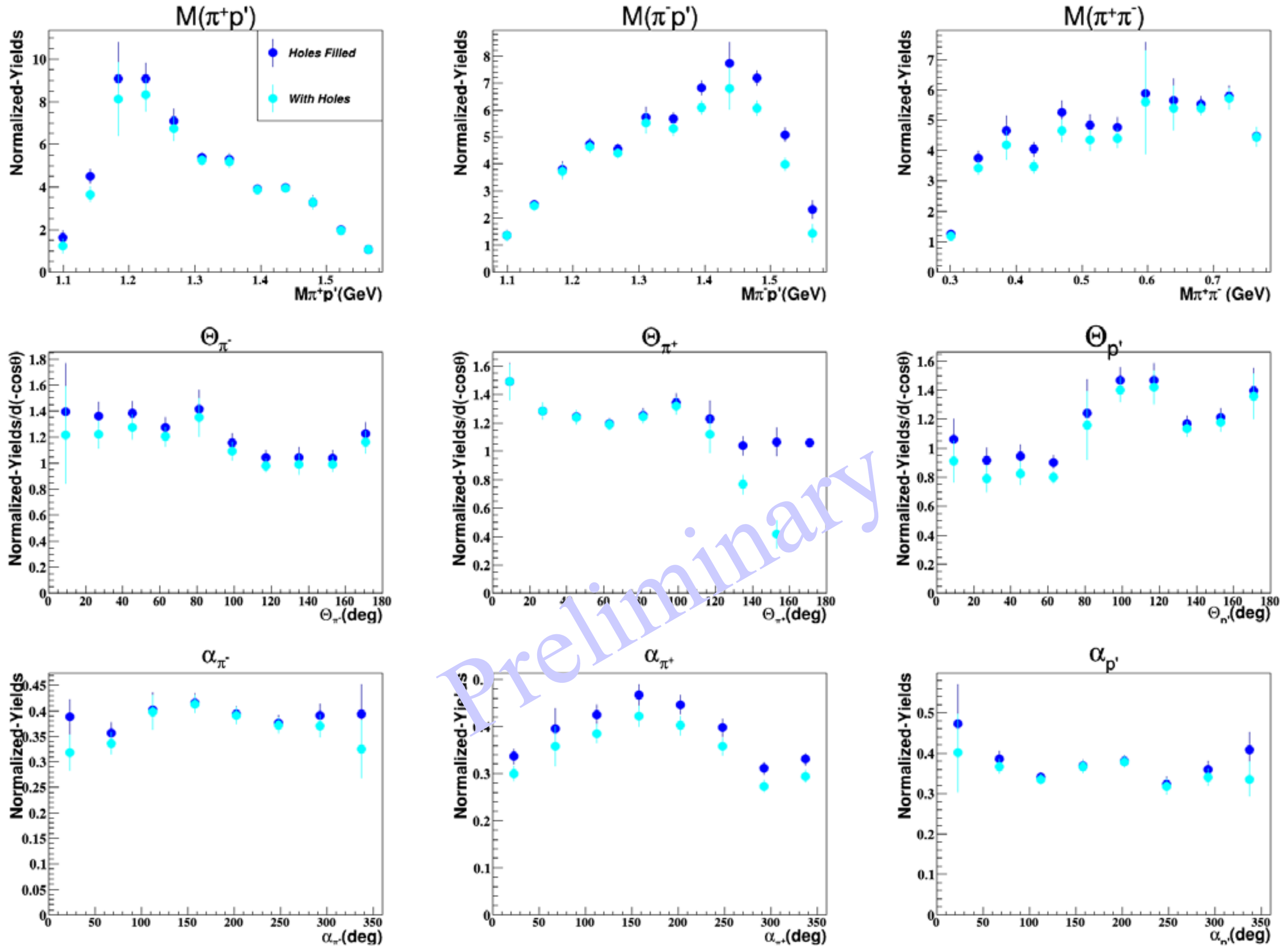
- Luminosity $>10^{35}\,cm^{-2}s^{-1}$
- Hermeticity
- Polarization

- Baryon Spectroscopy
- Elastic Form Factors
- $N \rightarrow N^*$ Form Factors

- GPDs and TMDs
- DIS and SIDIS
- Nucleon Spin Structure
- Color Transparency
- …

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

Krishna Neupane
CLAS12

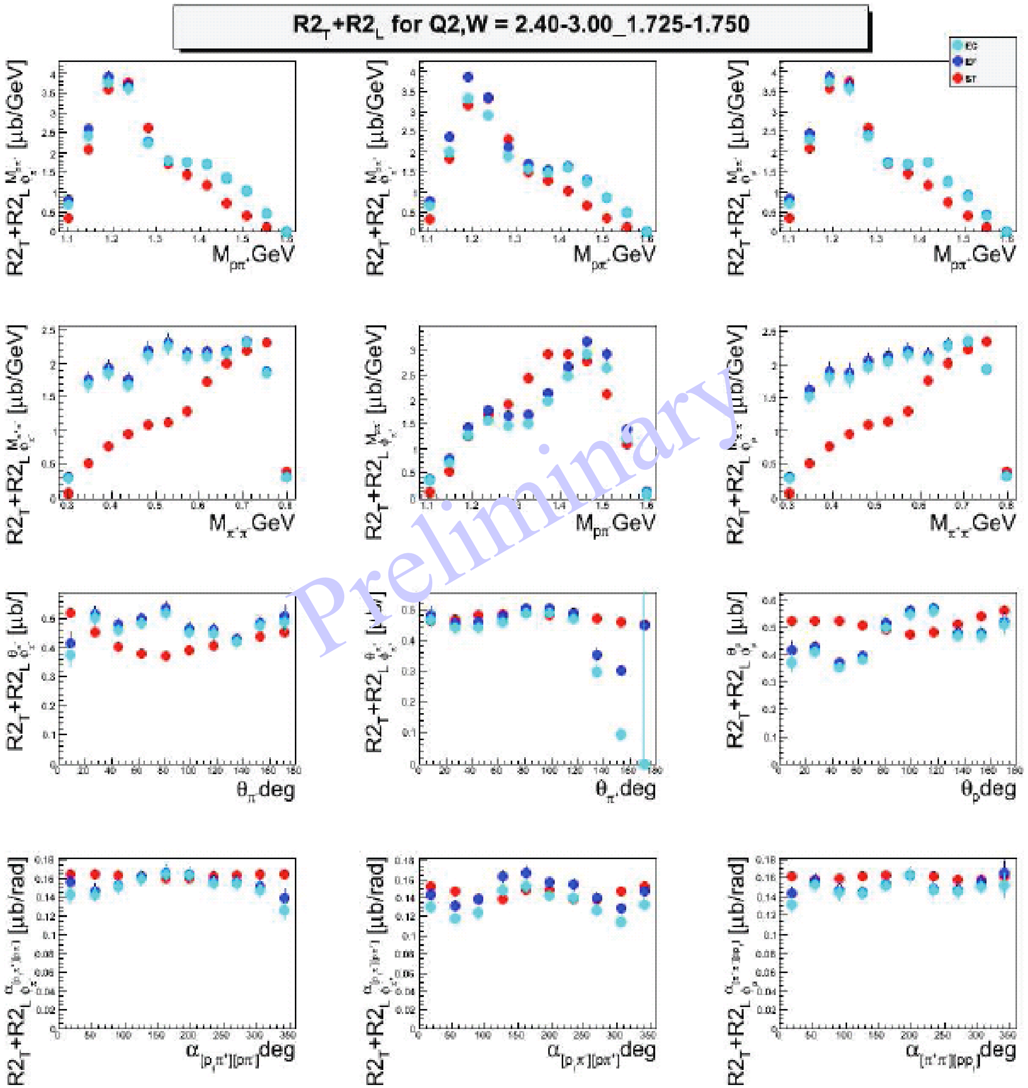


$1.725\ \text{GeV} < W < 1.75\ \text{GeV}$ and $3\ \text{GeV}^2 < Q^2 < 3.5\ \text{GeV}^2$

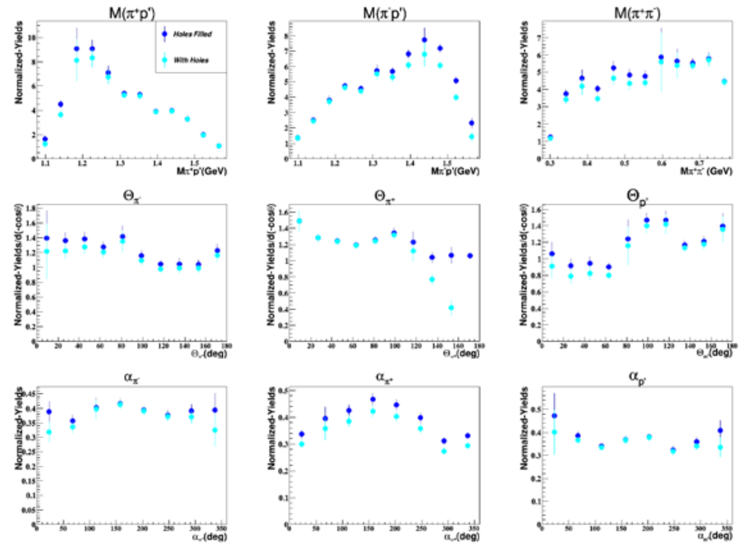
φ-dependent Nππ Single-Differential Cross Sections

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

Arjun Trivedi
Evgeny Isupov



Krishna Neupane
CLAS12



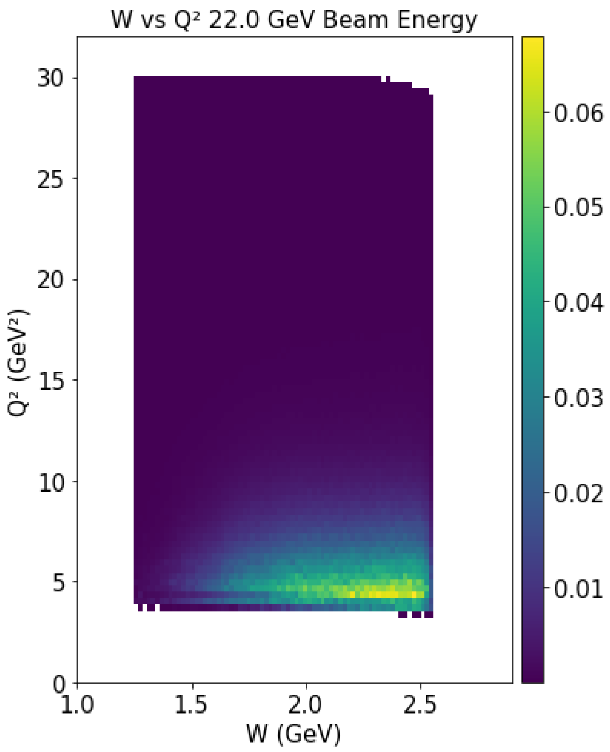
$$\left(\frac{d^2\sigma}{dX_{ij}\,d\phi_i}\right) = R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}} + R2_{LT}{}^{c,X_{ij}}\cos\phi_i + R2_{TT}{}^{c,X_{ij}}\cos 2\phi_i + \delta_{X_{ij}\alpha_i}\left(R2_{LT}{}^{s,\alpha_i}\sin\phi_i + R2_{TT}{}^{s,\alpha_i}\sin 2\phi_i\right)$$

CLAS22

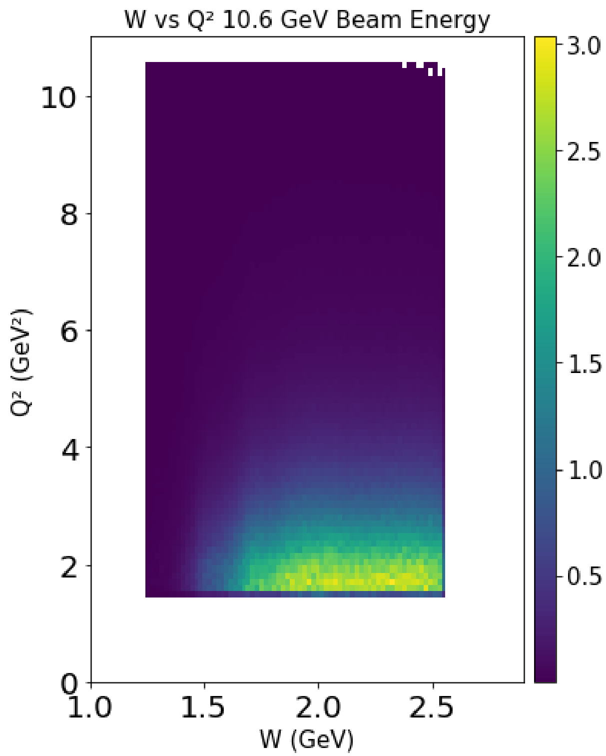
Achievable (W,Q2) Coverage at 22 GeV

Krishna Neupane

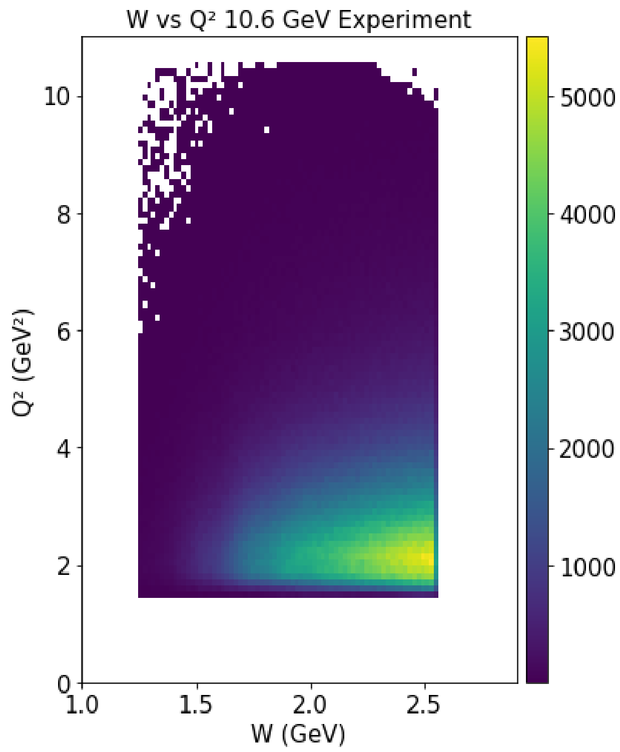
Simulated Reconstructed



Simulated Reconstructed



Measured Reconstructed

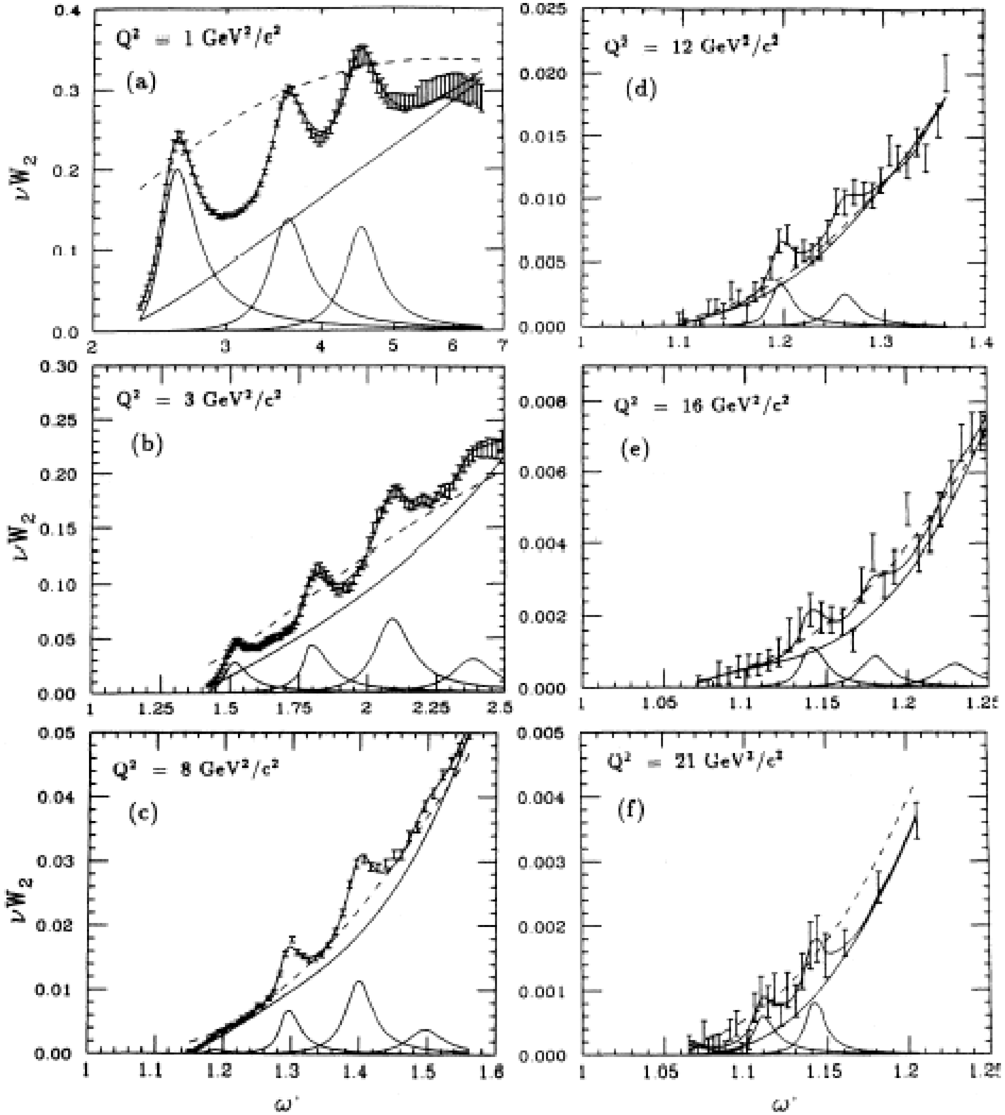


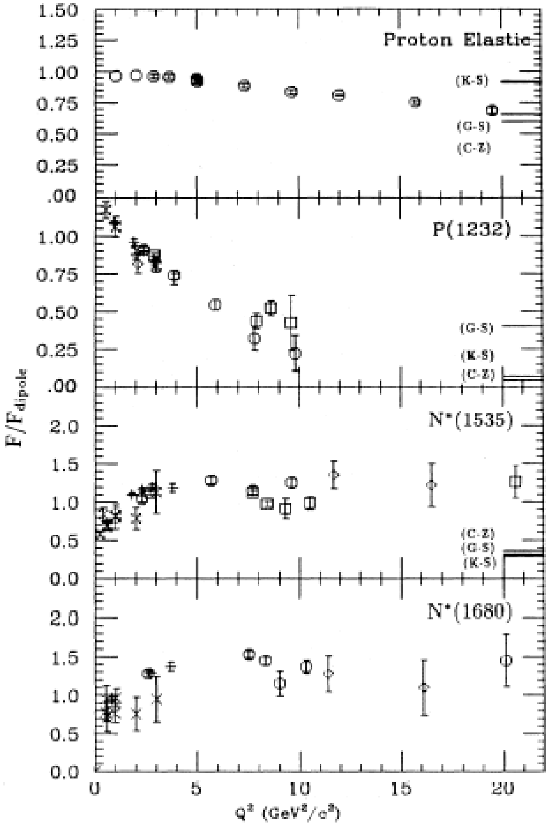
HSG is currently simulating:

- ✓ $p\pi^0, n\pi^+$ 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.

TWOPEG Formfactor Extrapolation to 30 GeV^2

Iuliia Skorodumina

$$\frac{d^5\sigma}{d^5\tau}(Q^2) = \frac{d^5\sigma}{d^5\tau}(0.65\ GeV^2) * \frac{F^2(Q^2)}{F^2(0.65\ GeV^2)}$$ with $F(Q^2) = \frac{1}{\left(1+\frac{Q^2}{0.7\ GeV^2}\right)}$

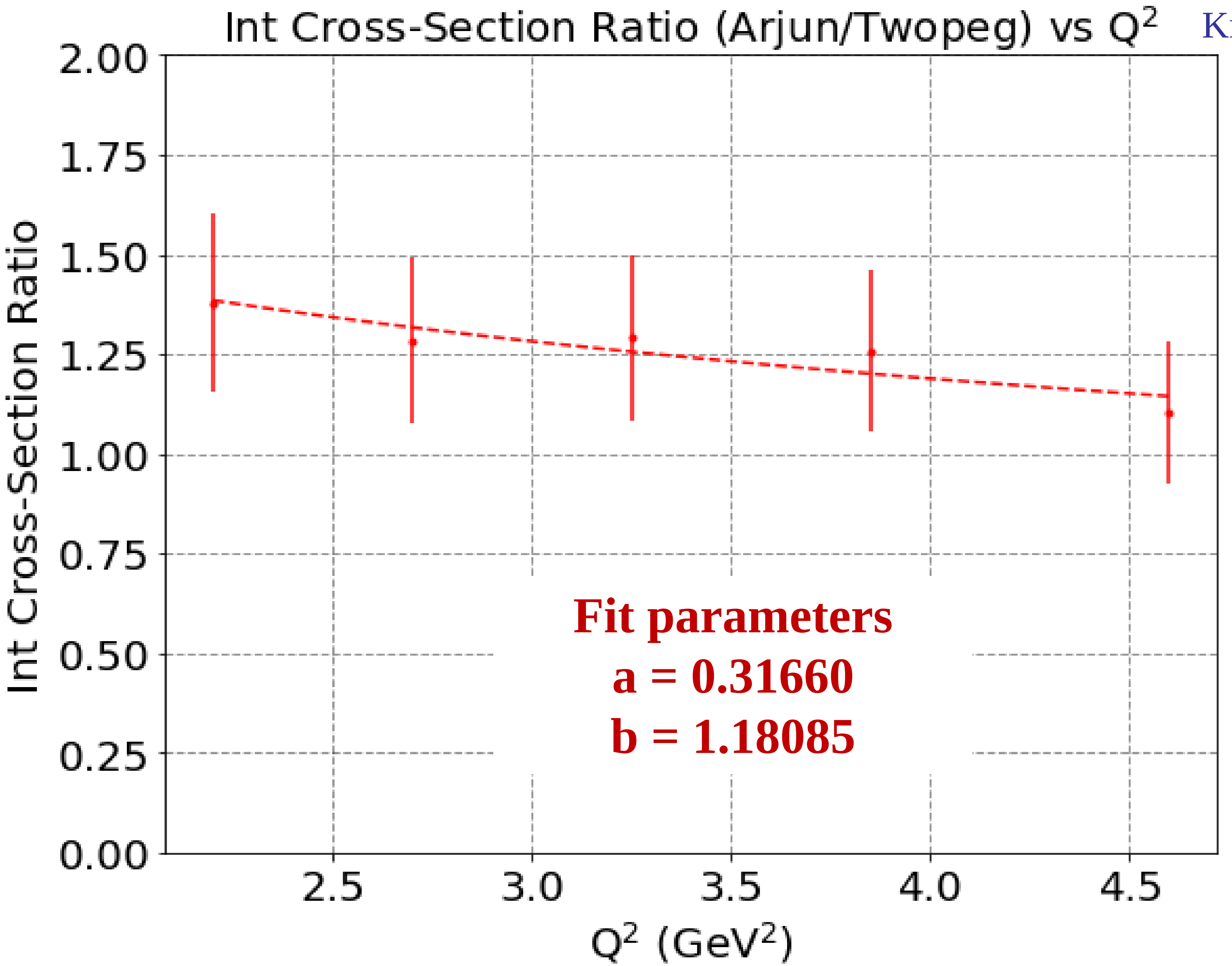
point like	monopole	dipole
$F(Q^2) = 1$	$F(Q^2) = \left(1+\frac{Q^2}{0.7\ GeV^2}\right)^{-1}$	$F(Q^2) = \left(1+\frac{Q^2}{0.7\ GeV^2}\right)^{-2}$
DIS	background	resonance excitation

⚠ inclusive, semi-inclusive, exlusive:
each channel has a different Q^2 dependence ⚠

$$\frac{d^5\sigma}{d^5\tau}(Q^2) = \frac{d^5\sigma}{d^5\tau}(0.65\ GeV^2) * \frac{F^2(Q^2)}{F^2(0.65\ GeV^2)} * \frac{\left(F^2(Q^2)\right)^a}{\left(F^2(0.65\ GeV^2)\right)^b}$$

Formfactor Extrapolation to 30 GeV^2

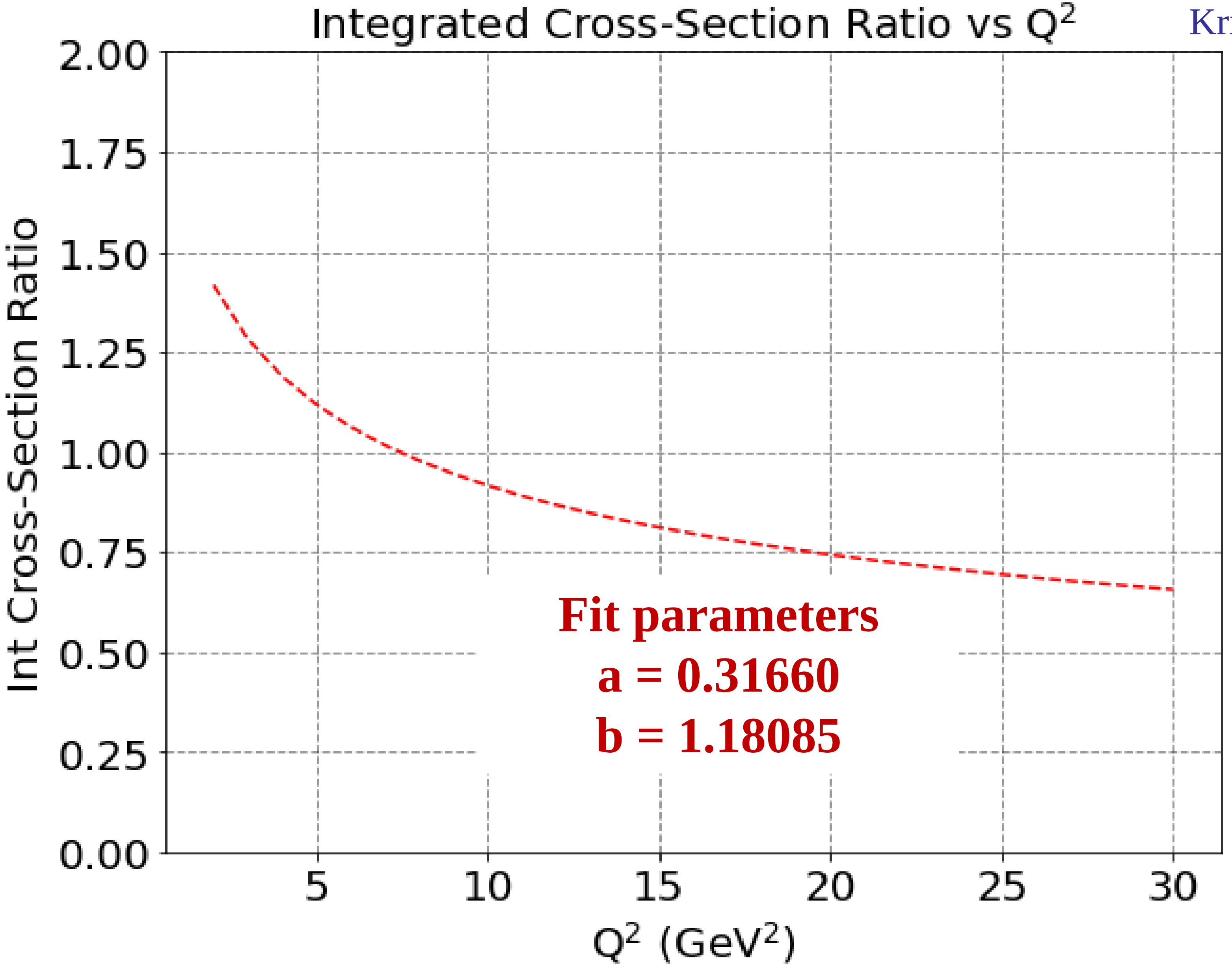
Krishna Neupane



Fit parameters
a = 0.31660
b = 1.18085

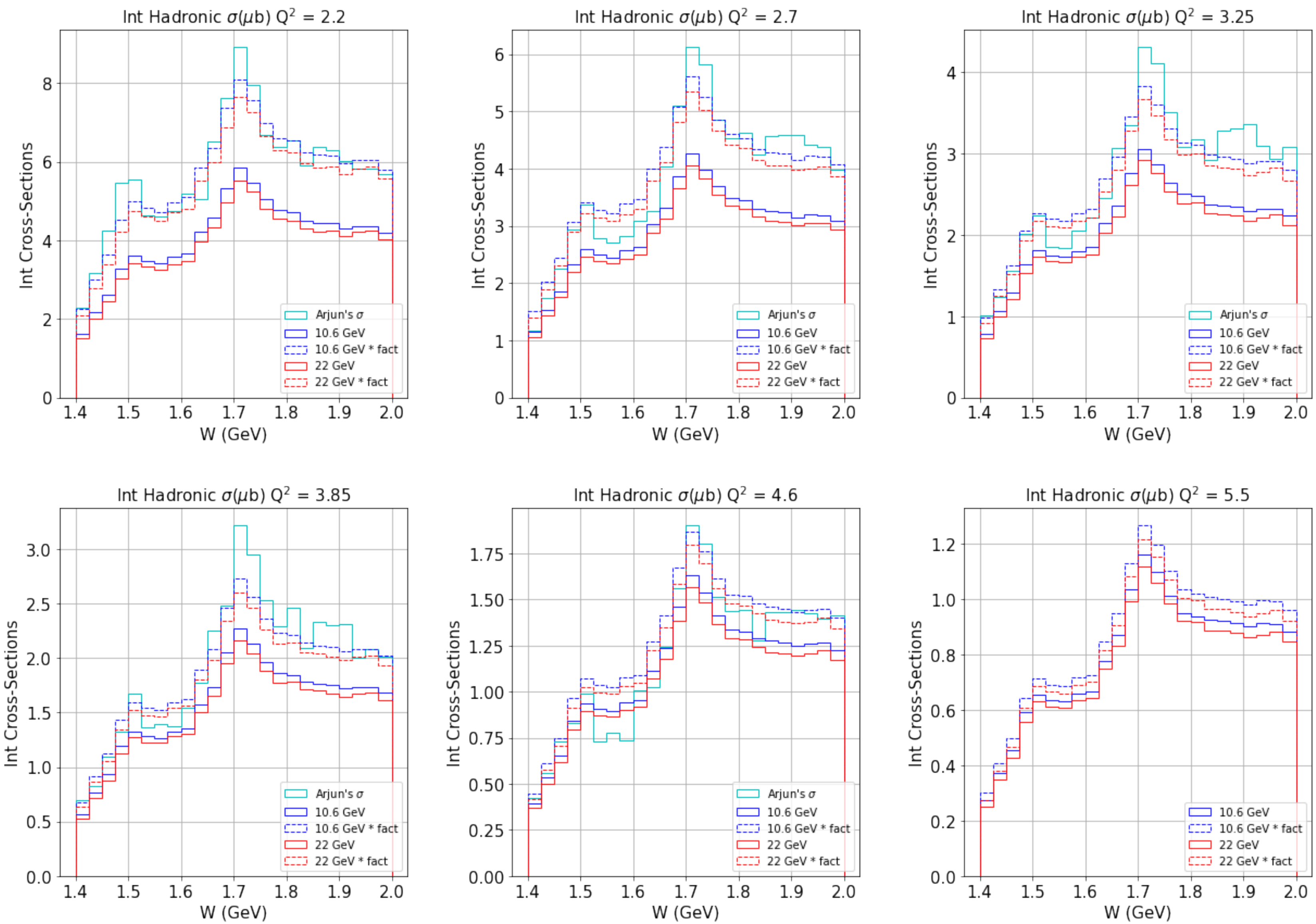
Formfactor Extrapolation to 30 GeV^2

Krishna Neupane



Formfactor Extrapolation to 30 GeV^2

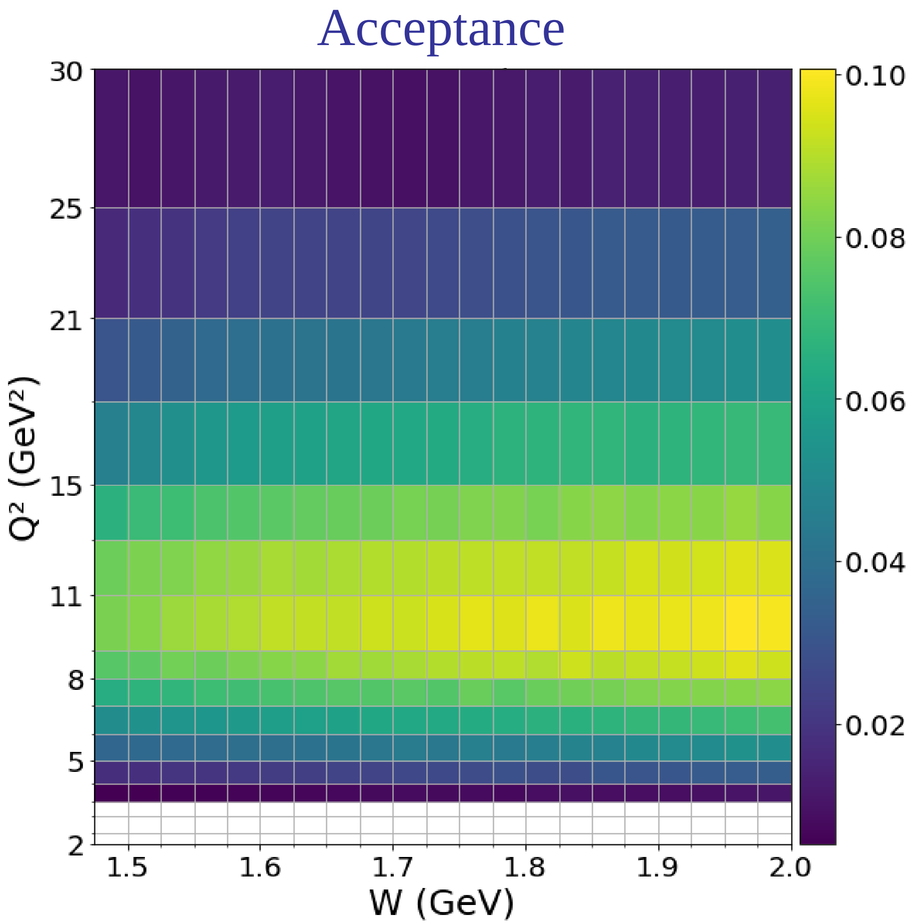
Krishna Neupane



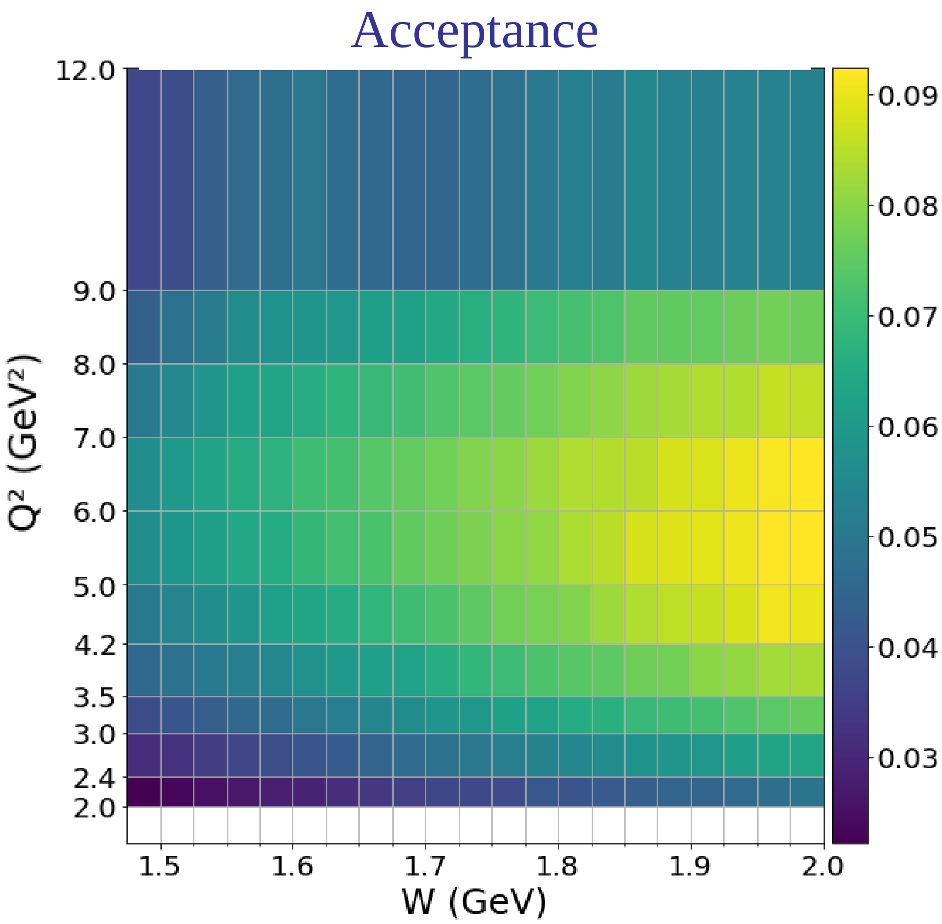
Acceptance for Exclusive $p\pi^+\pi^-$ Final State

Alexis Osmond & Krishna Neupane

Simulated at 22 GeV Beam Energy



Simulated at 10.6 GeV Beam Energy

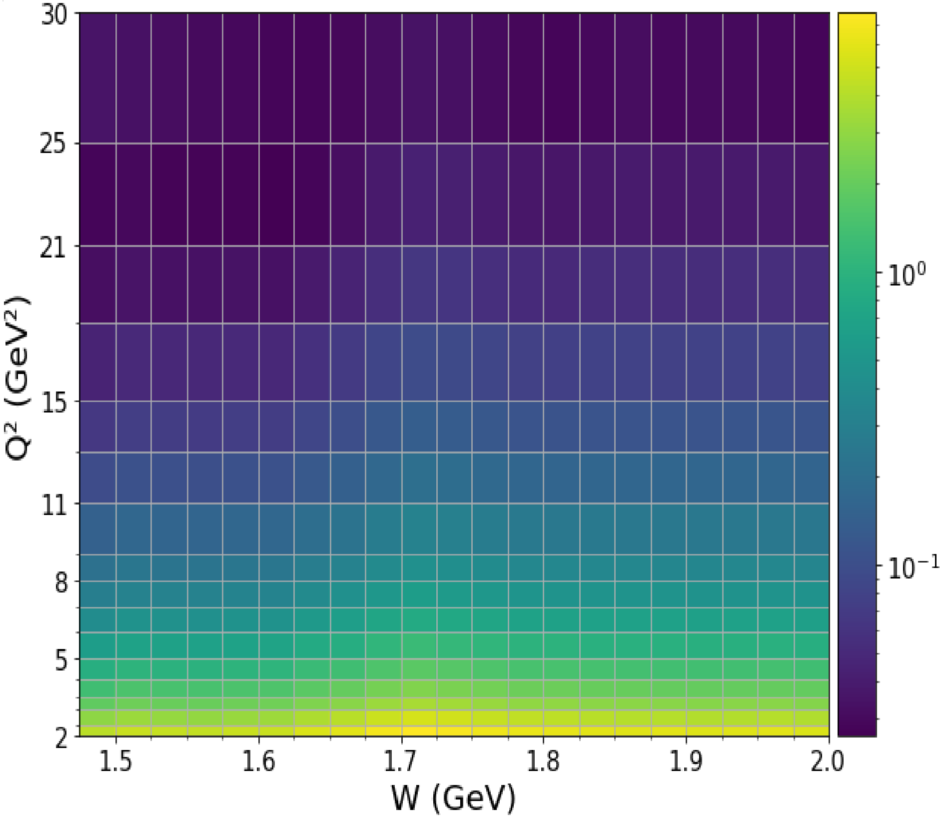


Hadronic Cross Section for Exclusive $p\pi^+\pi^-$ Final State

Alexis Osmond & Krishna Neupane

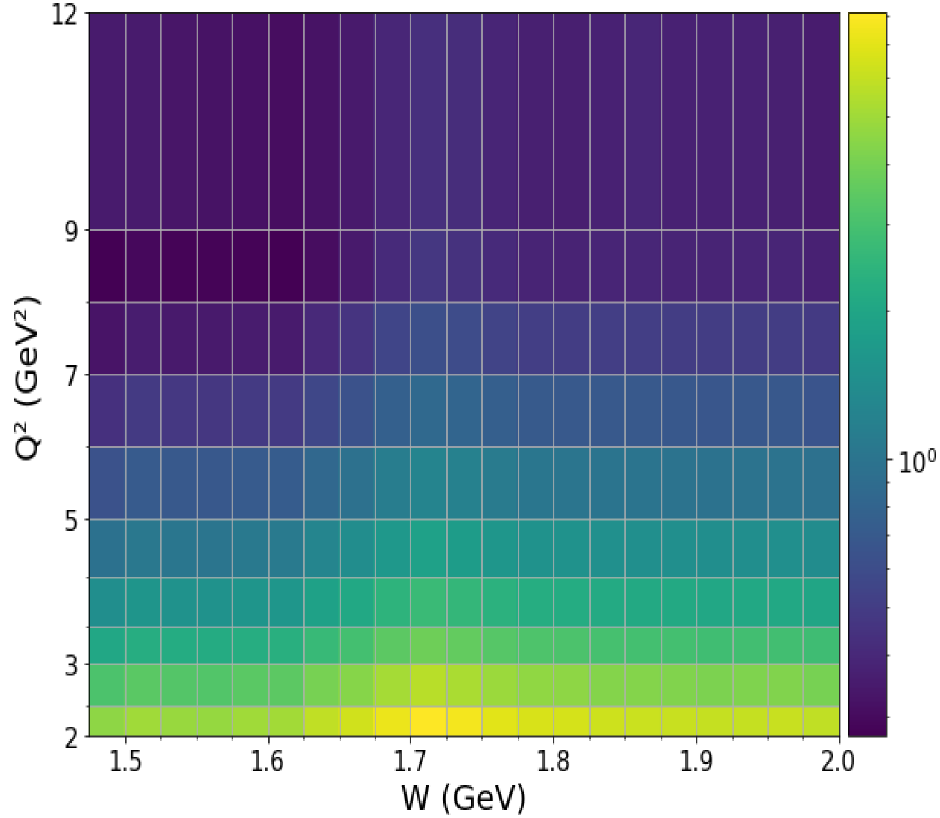
Simulated at 22 GeV Beam Energy

Integrated Hadronic Cross Section (μb)



Simulated at 10.6 GeV Beam Energy

Integrated Hadronic Cross Section (μb)

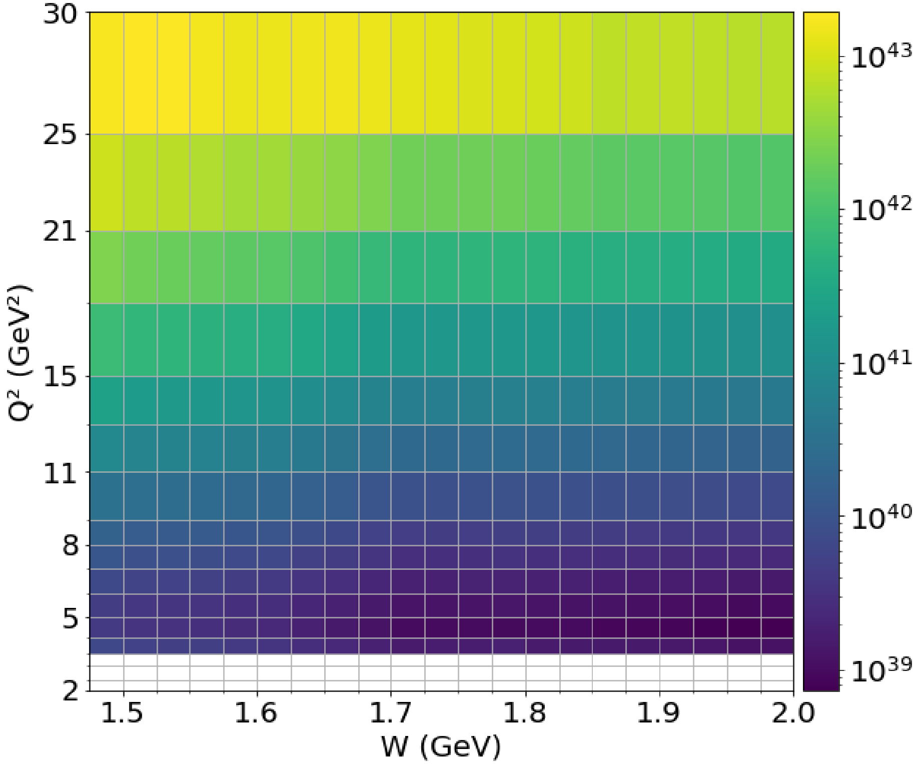


Integrated Luminosity Needs for Exclusive $p\pi^+\pi^-$

Alexis Osmond & Krishna Neupane

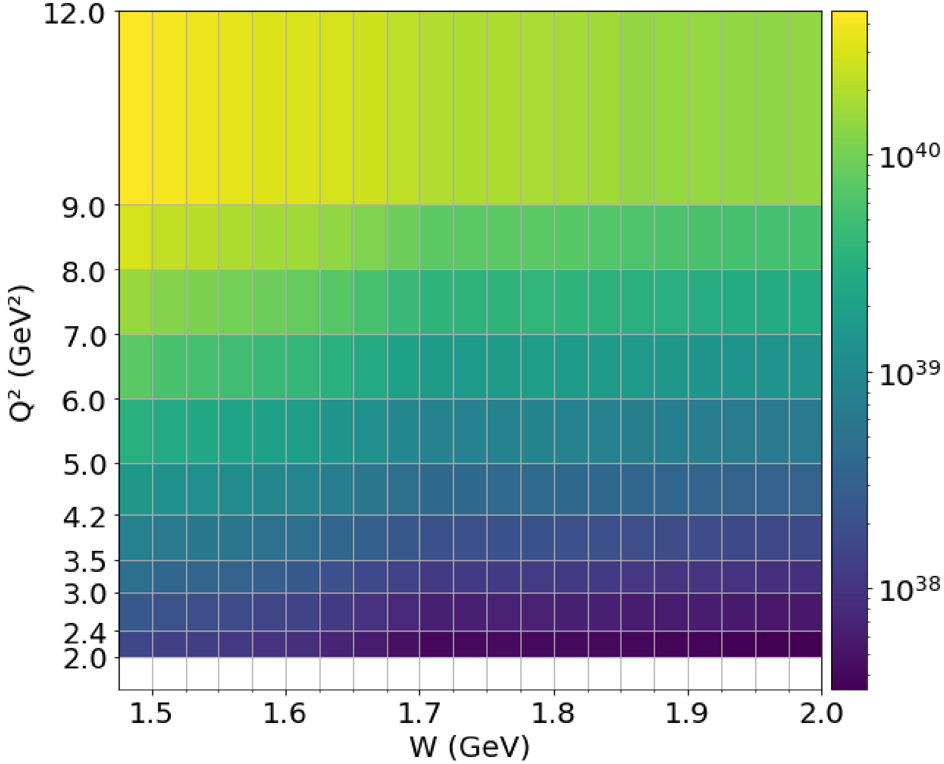
Simulated at 22 GeV Beam Energy

Needed Integrated Luminosity (cm^{-2})



Simulated at 10.6 GeV Beam Energy

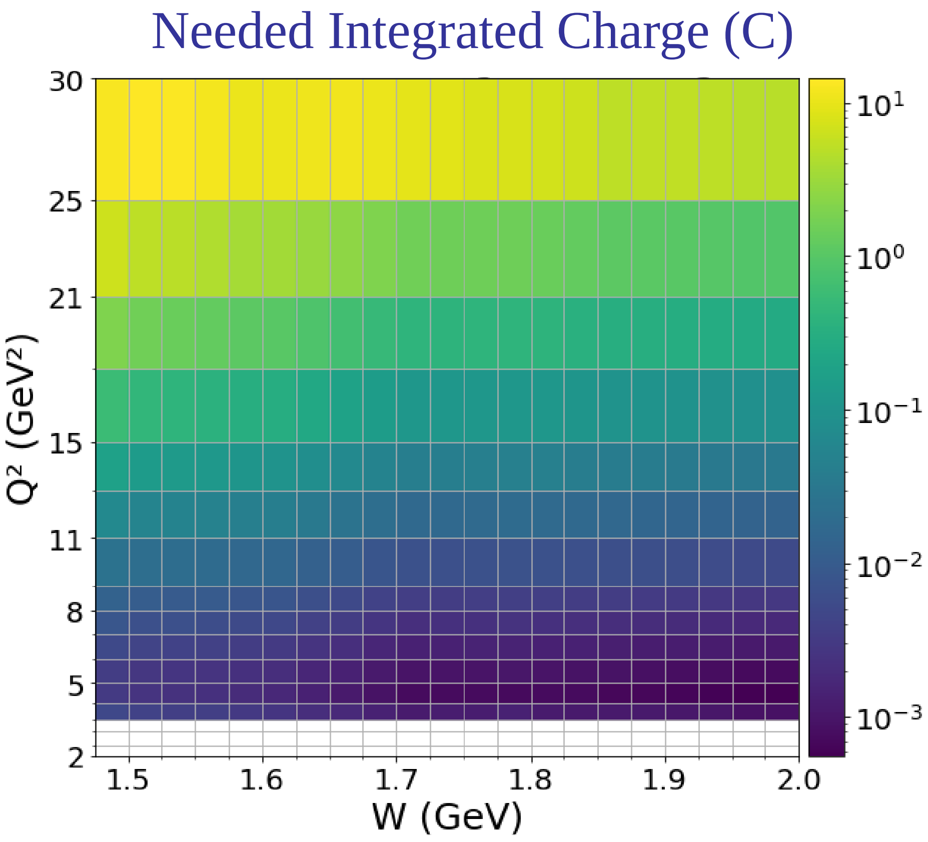
Needed Integrated Luminosity (cm^{-2})



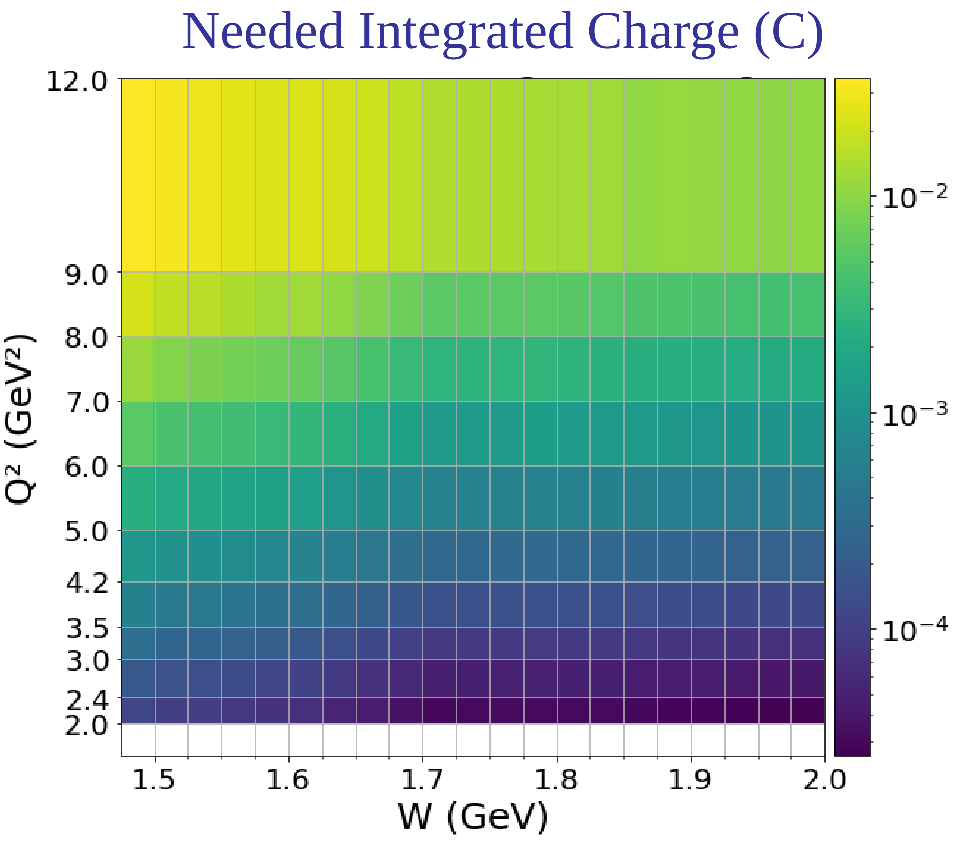
Integrated Charge Needs for Exclusive $p\pi^+\pi^-$

Alexis Osmond & Krishna Neupane

Simulated at 22 GeV Beam Energy



Simulated at 10.6 GeV Beam Energy



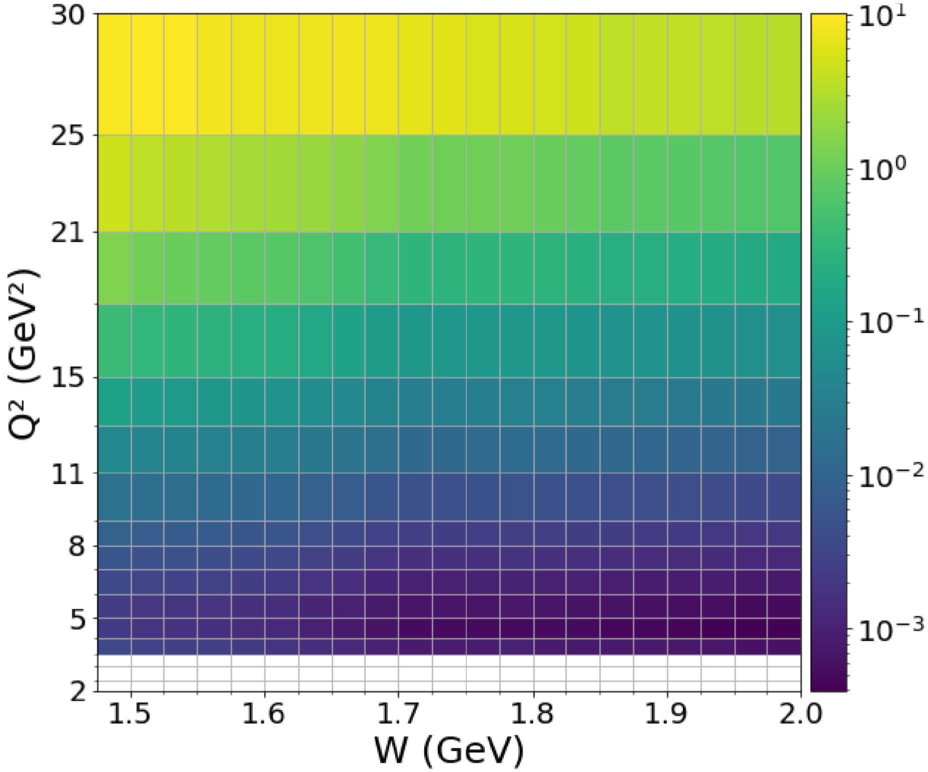
Beam Time Needs for Exclusive $p\pi^+\pi^-$

Alexis Osmond & Krishna Neupane

Based on RGA Fall 2018 Luminosity of 5.96 10^{34} cm^{-2} s^{-1} at 45 nA and 5 cm LH_2

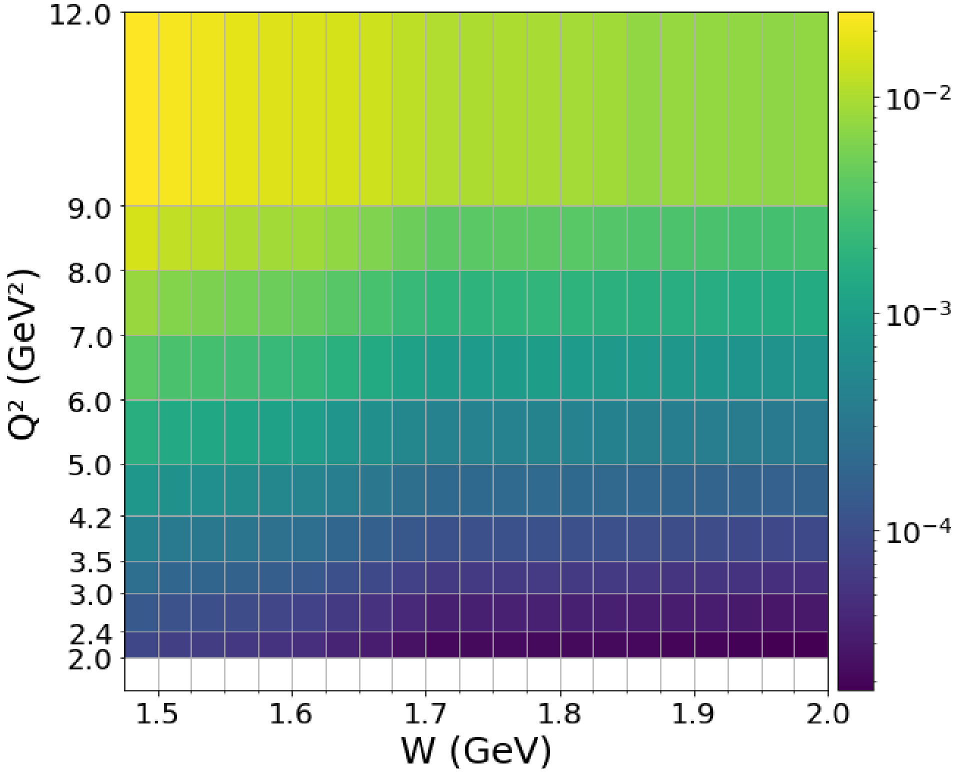
Simulated at 22 GeV Beam Energy

Needed Years at 5.96 10^{34} (cm^{-2} s^{-1})



Simulated at 10.6 GeV Beam Energy

Needed Years at 5.96 10^{34} (cm^{-2} s^{-1})



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

➡ 8 (16) years at 5.96 10^{34} cm^{-2} s^{-1} or 11 (22) month at 5 10^{35} cm^{-2} s^{-1}

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

Alexis Osmond & Krishna Neupane

Based on RGA Fall 2018 Luminosity of 5.96 10^{34} cm^{-2} s^{-1} at 45 nA and 5 cm LH_2

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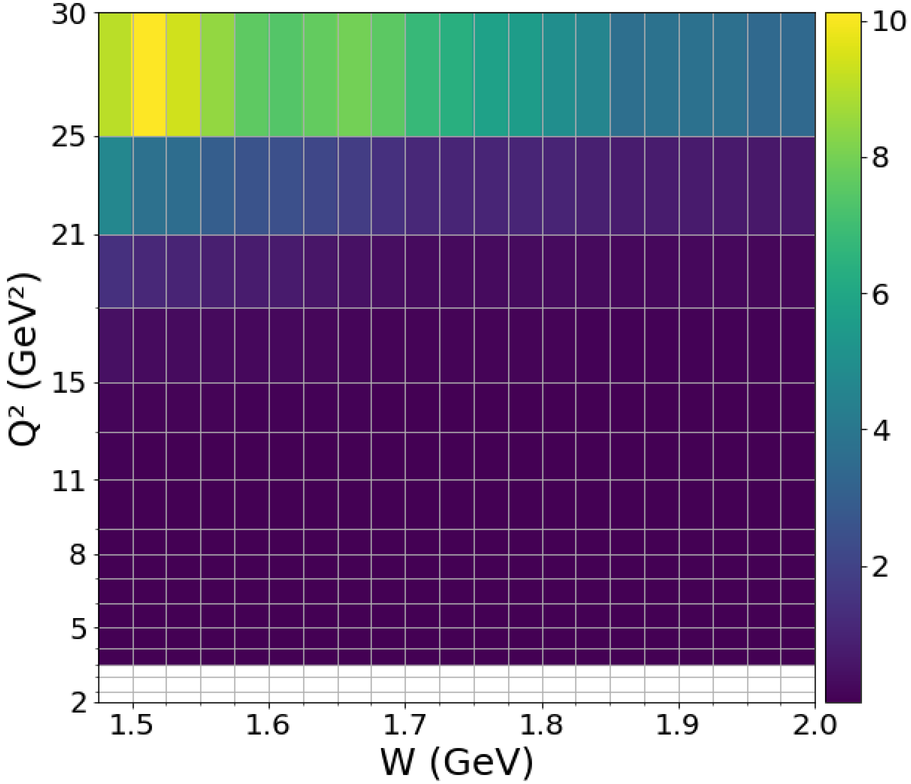
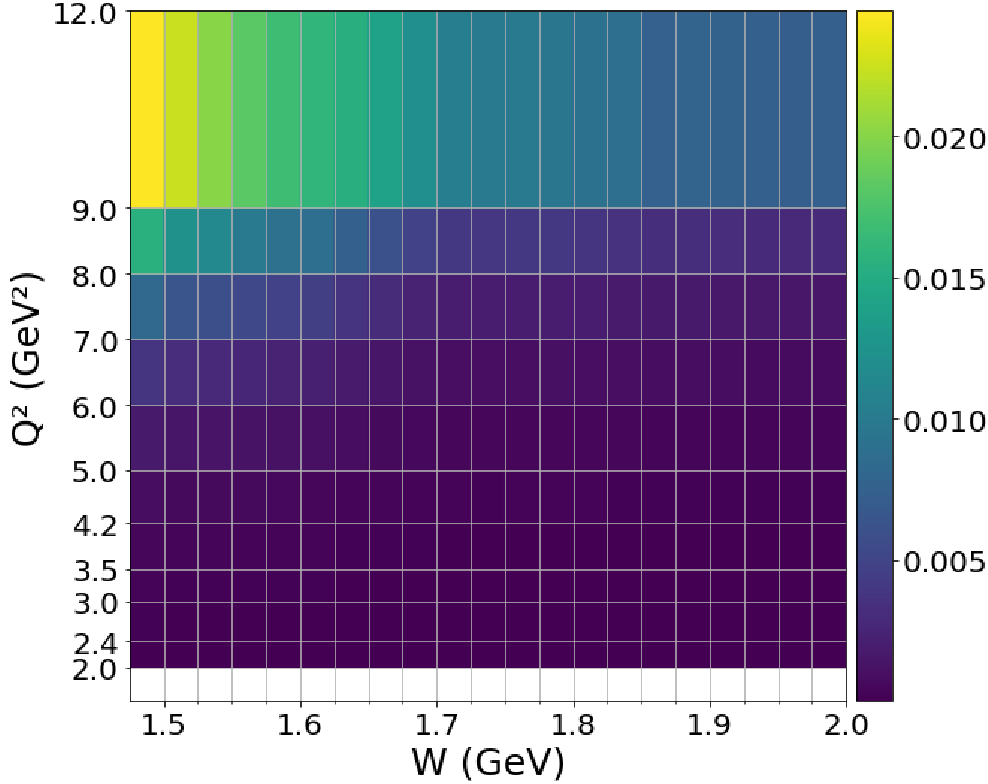
Needed Years at 5.96 10^{34} (cm^{-2} s^{-1})



Simulated at 10.6 GeV Beam Energy

Needed Years at 5.96 10^{34} (cm^{-2} s^{-1})



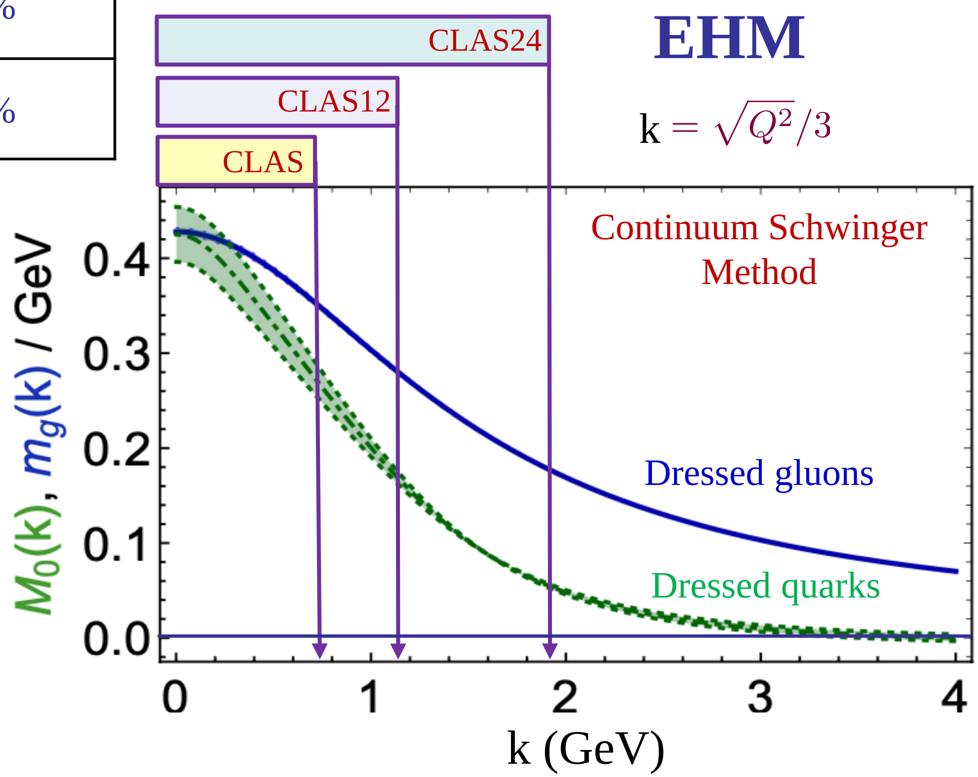
Implementing all analysis cuts (3/2), Golden Run Selection (3), PAC Days (2)

➡ 8 (16) years at 5.96 10^{34} cm^{-2} s^{-1} or 11 (22) month at 5 10^{35} cm^{-2} s^{-1}

Hadron Structure Needs for CLAS20+

	Q^2-coverage of electrocouplings	Range of quark momenta k	Fraction of dressed quark mass at $k<k_{max}$
CLAS	< 5 GeV^2	< 0.8 GeV	30%
CLAS12	< 12 GeV^2	< 1.2 GeV	50%
$CLAS20^+$	< 35 GeV^2	< 2.0 GeV	90%

- Beam energy 22 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.

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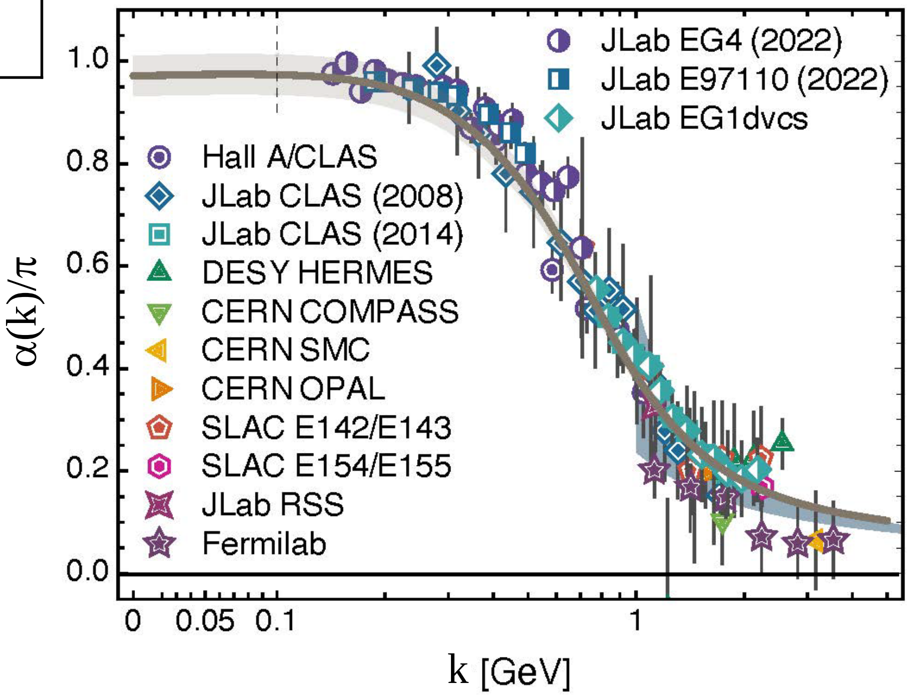
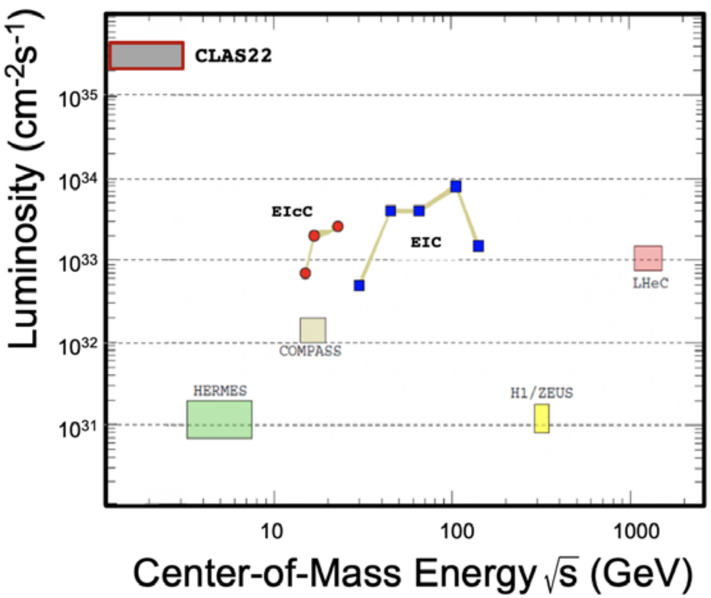


Luminosity "frontier" is the *unique* advantage of JLab.

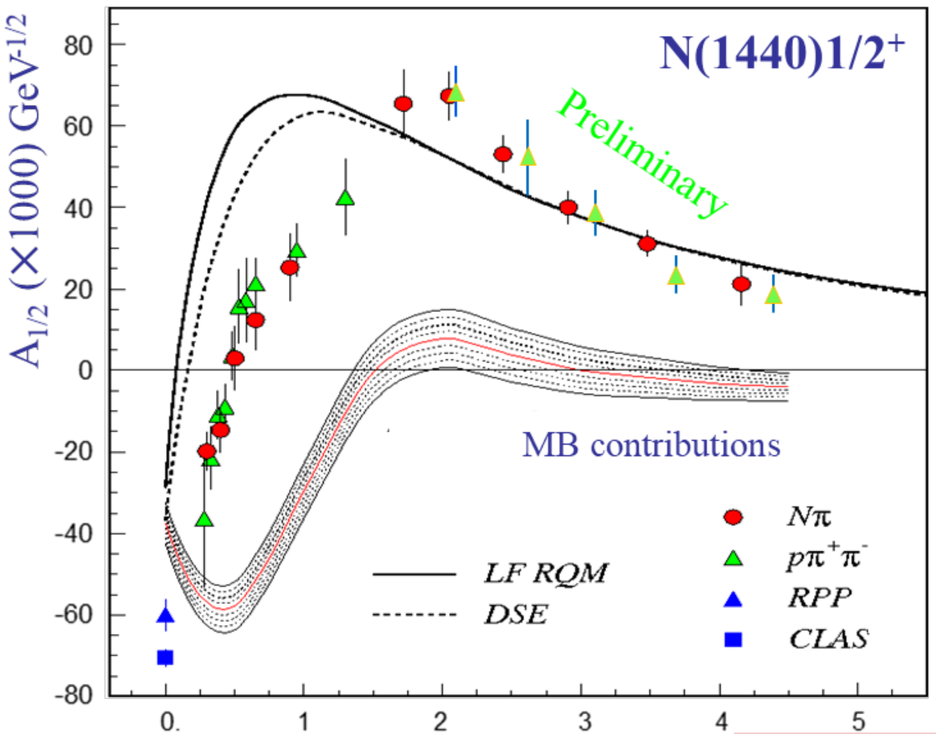
Hadron Structure Needs for CLAS20+

- Beam energy 22 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.



Extend up to 35 GeV^2

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

$\gamma_v pN^*$ and EHM

particles

MDPI

Review

Preprint no. JLAB-PHY-23-3744, NJU-INP 069/23

Nucleon Resonance Electroexcitation Amplitudes and Emergent Hadron Mass

e-Print: 2301.07777

Daniel S. Carman [1,†], Ralf W. Gothe [2,†], Victor I. Mokeev [1,†], and Craig D. Roberts [3,4,†] *

Abstract: Understanding the strong interaction dynamics that govern the emergence of hadron mass (EHM) represents a challenging open problem in the Standard Model. In this paper we describe new opportunities for gaining insight into EHM from results on nucleon resonance (N^*) electroexcitation amplitudes (*i.e.* $\gamma_v pN^*$ electrocouplings) in the mass range up to 1.8 GeV for virtual photon four-momentum squared (*i.e.* photon virtualities Q^2) up to 7.5 GeV^2 available from exclusive meson electroproduction data acquired during the 6-GeV era of experiments at Jefferson Laboratory (JLab). These results, combined with achievements in the use of continuum Schwinger function methods (CSMs), offer new opportunities for charting the momentum dependence of the dressed quark mass from results on the Q^2-evolution of the $\gamma_v pN^*$ electrocouplings. This mass function is one of the three pillars of EHM and its behavior expresses influences of the other two, *viz.* the running gluon mass and momentum-dependent effective charge. A successful description of the $\Delta(1232)3/2^+$ and $N(1440)1/2^+$ electrocouplings has been achieved using CSMs with, in both cases, common momentum-dependent mass functions for the dressed quarks, for the gluons, and the same momentum-dependent strong coupling. The properties of these functions have been inferred from nonperturbative studies of QCD and confirmed, *e.g.*, in the description of nucleon and pion elastic electromagnetic form factors. Parameter-free CSM predictions for the electrocouplings of the $\Delta(1600)3/2^+$ became available in 2019. The experimental results obtained in the first half of 2022 have confirmed the CSM predictions. We also discuss prospects for these studies during the 12-GeV era at JLab using the CLAS12 detector, with experiments that are currently in progress, and canvass the physics motivation for continued studies in this area with a possible increase of the JLab electron beam energy up to 22 GeV. Such an upgrade would finally enable mapping of the dressed quark mass over the full range of distances (*i.e.* quark momenta) where the dominant part of hadron mass and N^* structure emerge in the transition from the strongly coupled to perturbative QCD regimes.

check for updates

Citation: Carman, D.S.; Gothe, R.W.; Mokeev, V.I.; and Roberts, C.D. Nucleon Resonance Electroexcitation and Emergent Hadron Mass. *Particles* **2023**, *1*, 1–23. https://doi.org/

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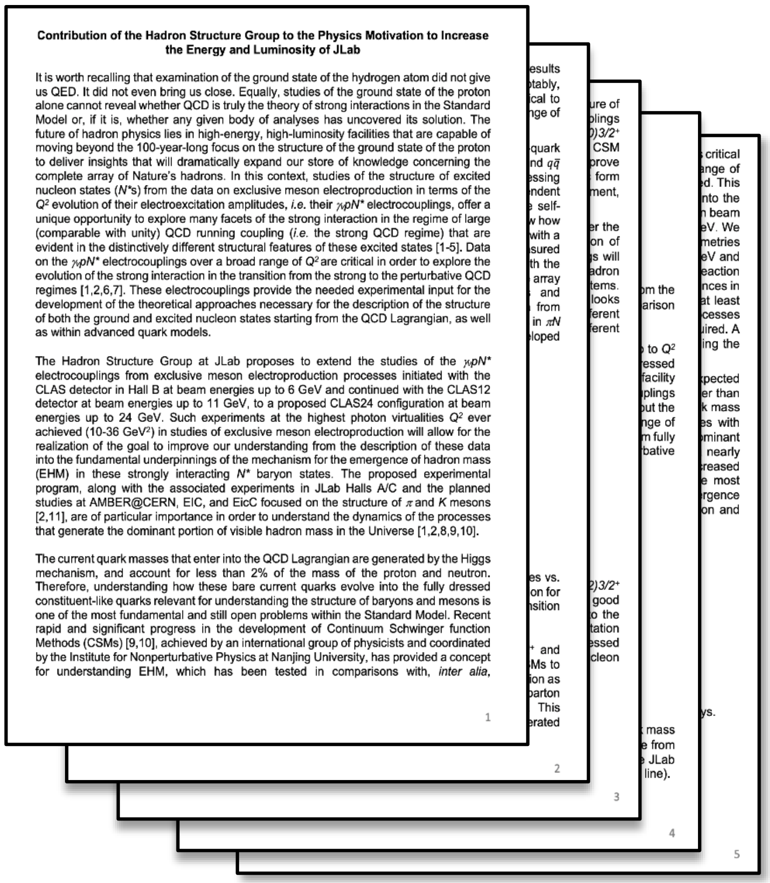
Accepted:
Published:

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