Can Transition Formfactors Reveal Diquark Correlations?

Ralf W. Gothe for the CLAS Collaboration

UNIVERSITY OF SOUTH CAROLINA

ECT*

Diquark Correlations in Hadron Physics: Origin, Impact and Evidence
September 23-27, 2019, ECT*, Trento, Italy

- **$\gamma_v NN^*$ Experiments:** The best access to the baryon and quark structure?
- **Analysis and New Results:** Exclusive, quasi-free, and final state interaction!
- **Outlook:** New experiments with extended scope and kinematics!

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

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Diquark Correlations in Hadron Physics: Origin, Impact and Evidence
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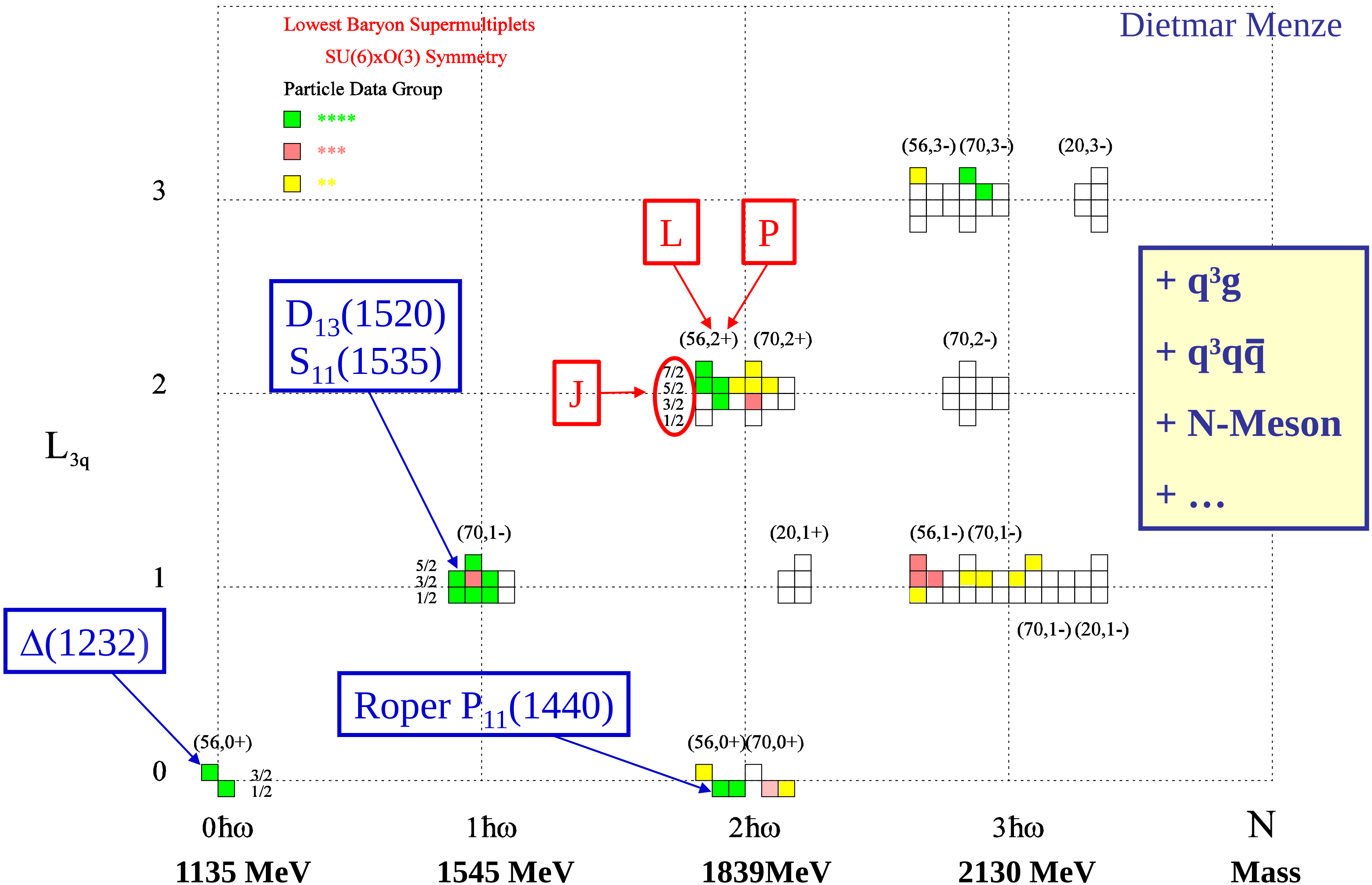
- **Are dressed quarks fictious model creatures?** Do we have evidence that they exist?
- **Why are quarks in DIS pointlike?** What is the difference between a large-x valence quark and a dressed quark?
- **When does (precocious) scaling set in?** What does it mean?

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

Spectroscopy

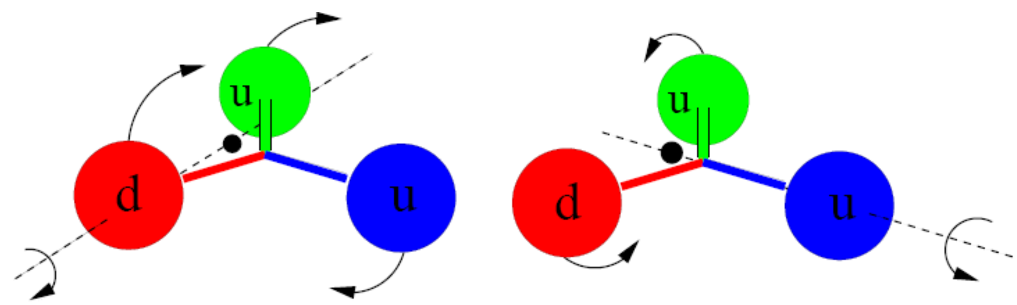
Quark Model Classification of N*



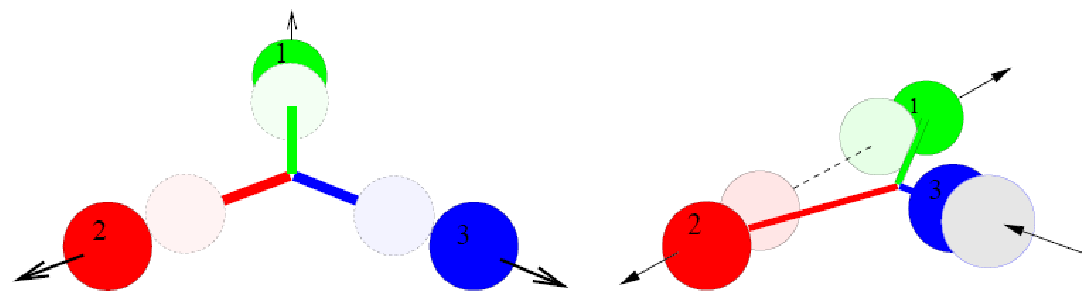
N and Δ Excited Baryon States …

Simon Capstick

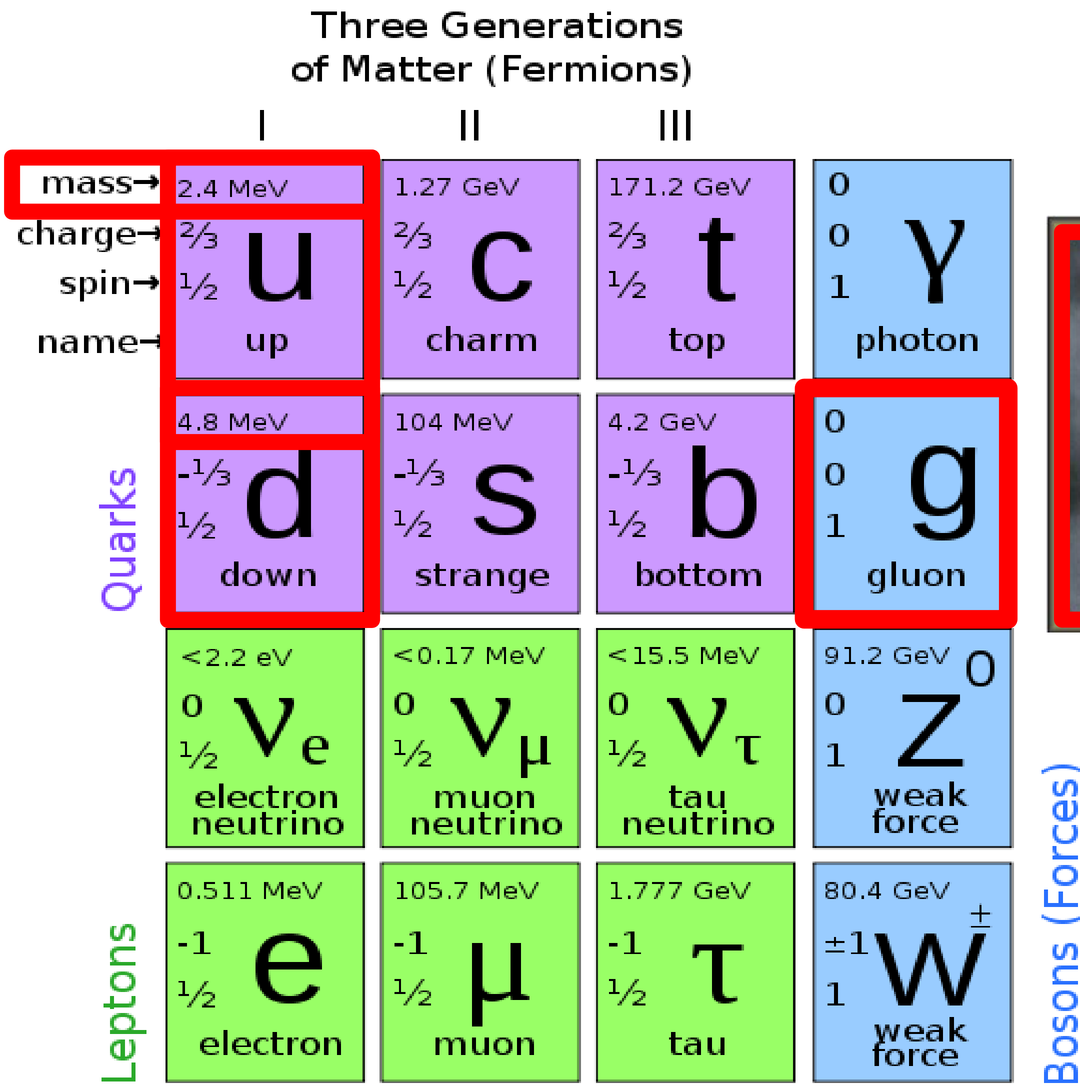
- Orbital excitations (two distinct kinds in contrast to mesons)

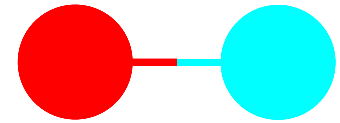


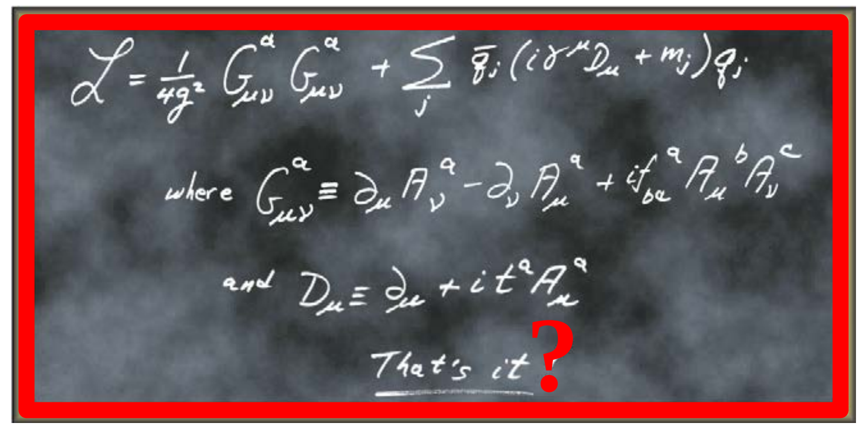
- Radial excitations (also two kinds in contrast to mesons)



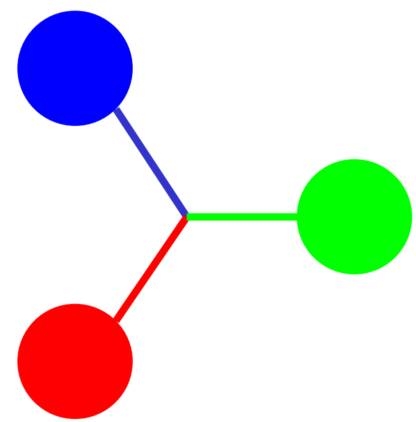
Build your Mesons and Baryons …





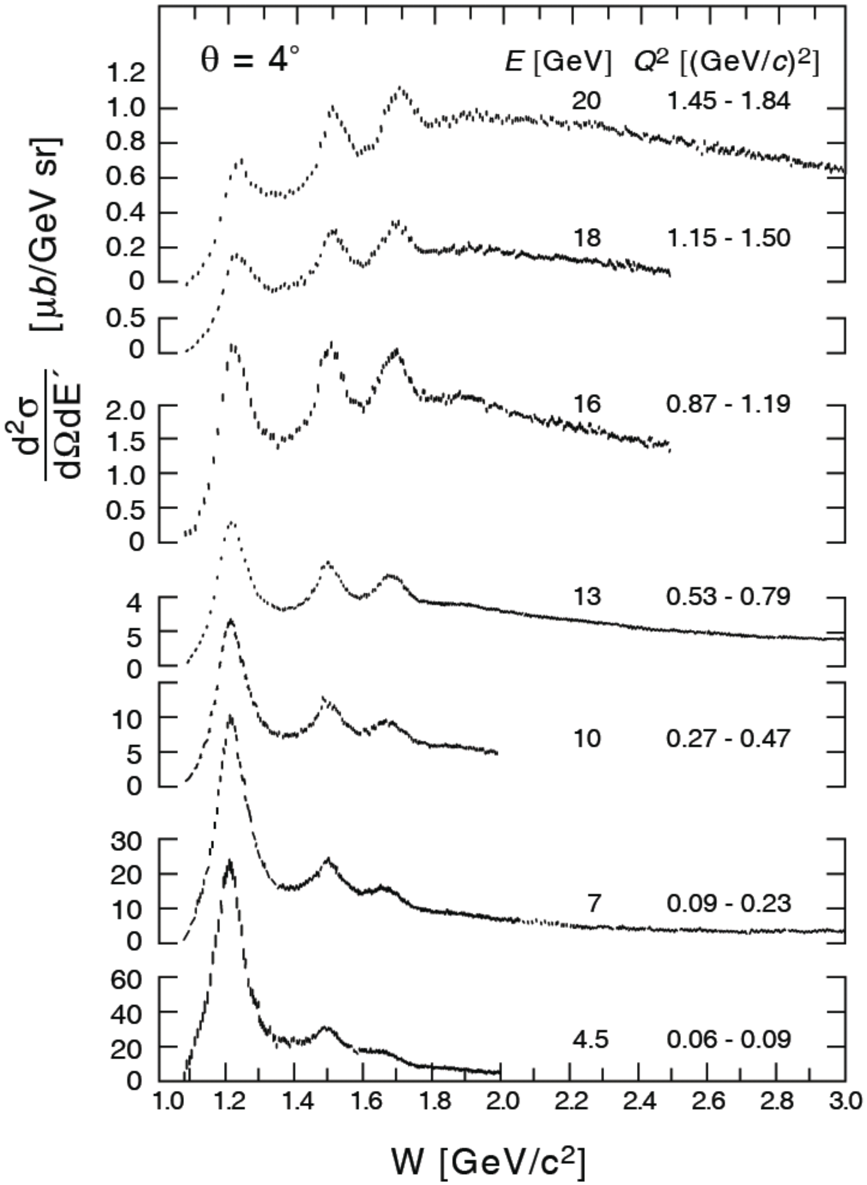


Frank Wilczek, Physics Today, August 2000

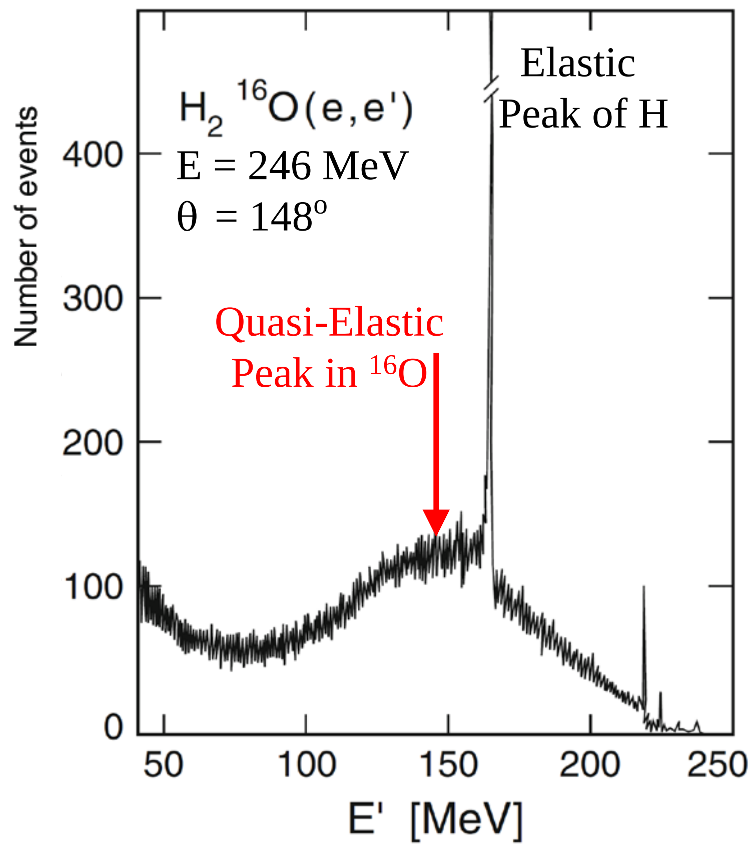


Electron Scattering

Baryon Excitations and Quasi-Elastic Scattering

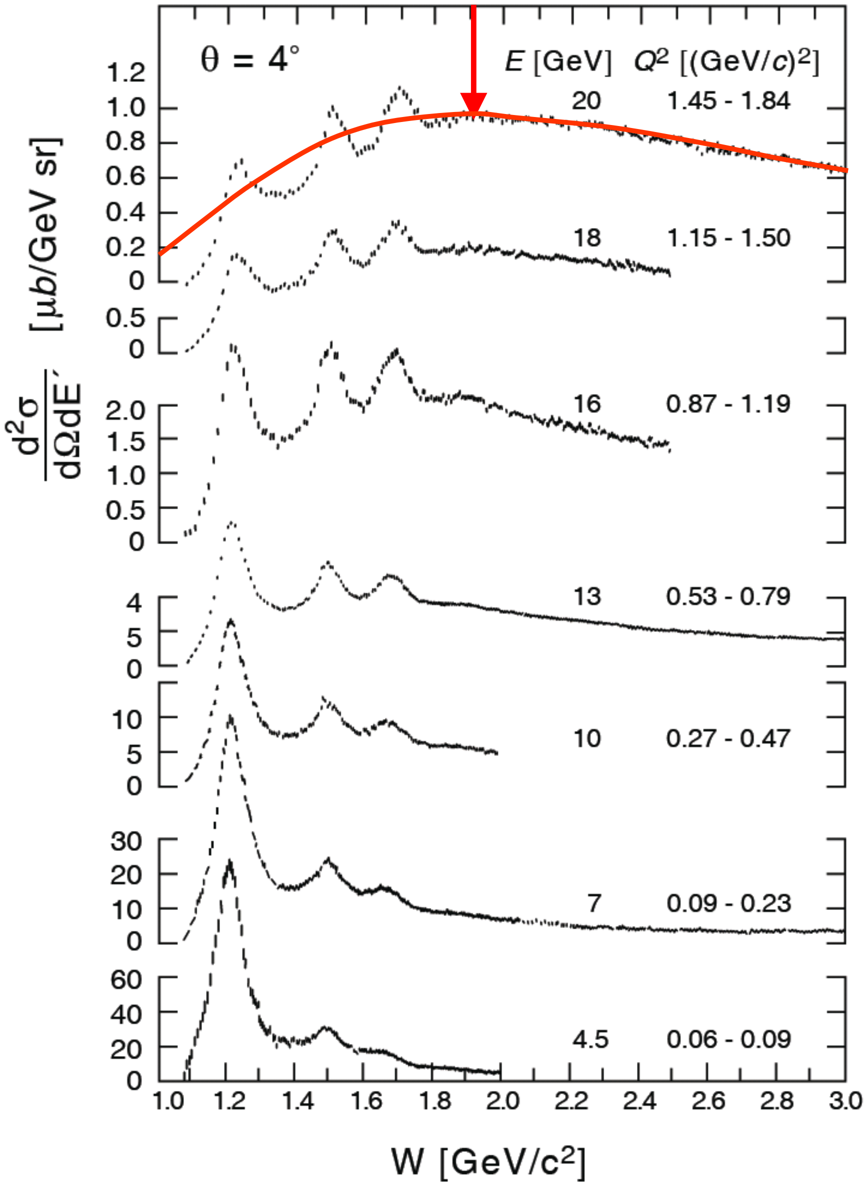


Paticle and Nuclei, Povh et al., MAMI B

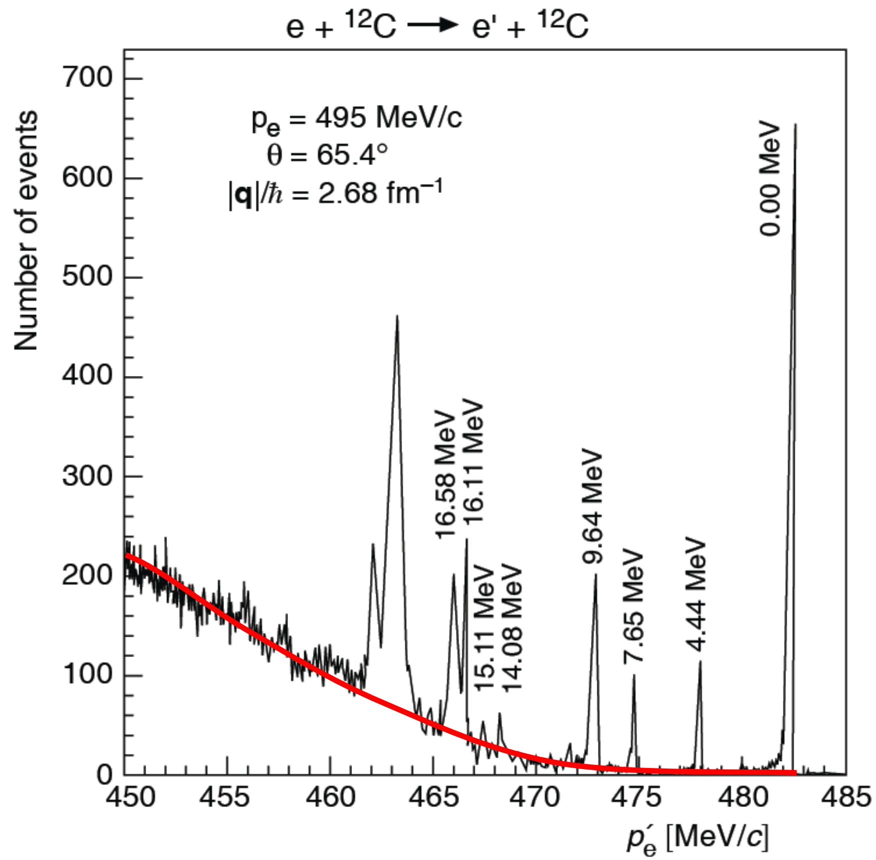


Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Quark-Hadron Duality

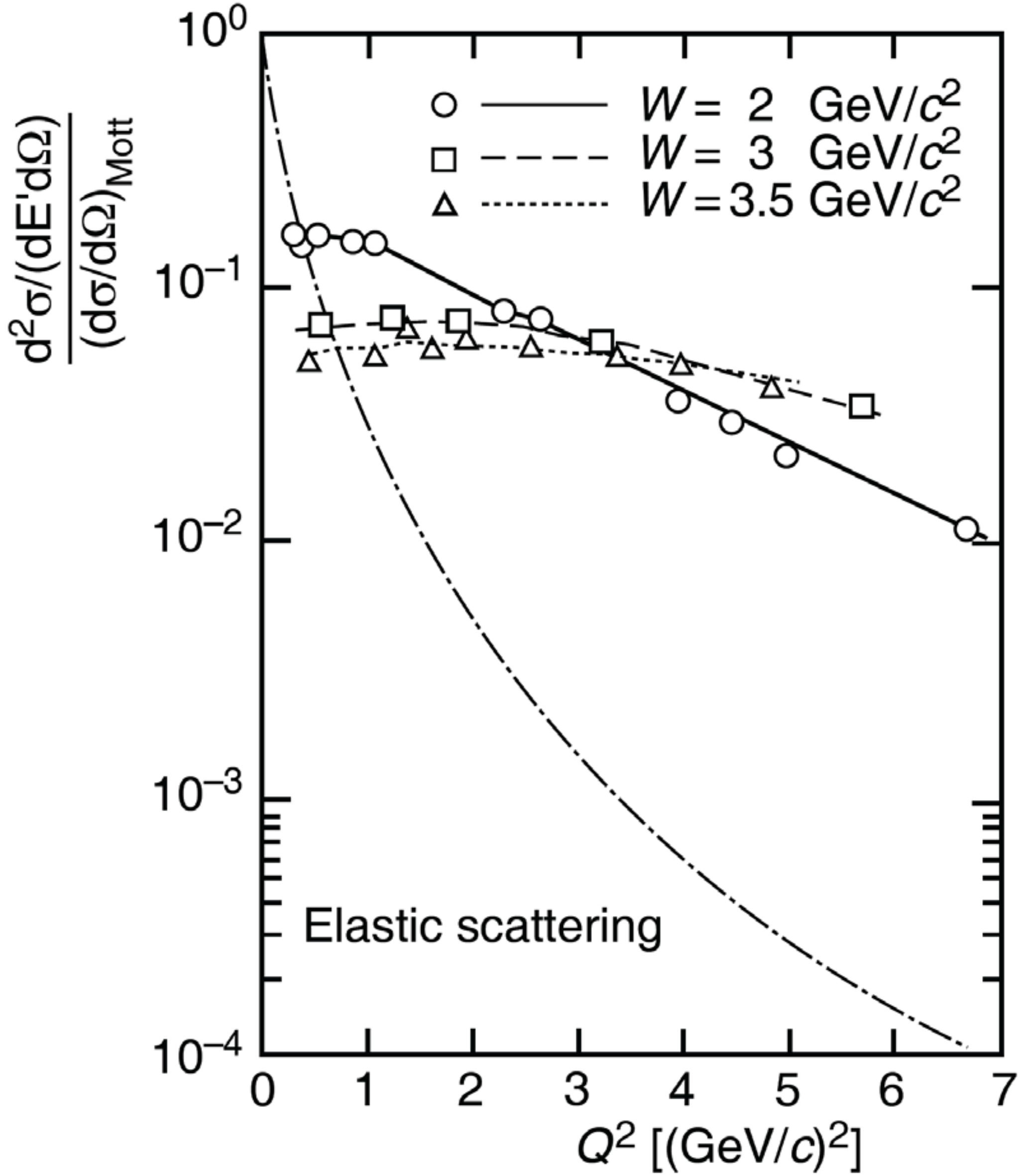


PRL **16** (1970) 1140, PR **D4** (1971) 2901
E.D. Bloom and F.J. Gilman

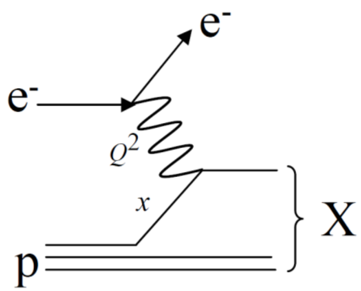


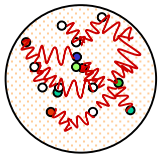
Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Baryon Excitations and Quasi-Elastic Scattering



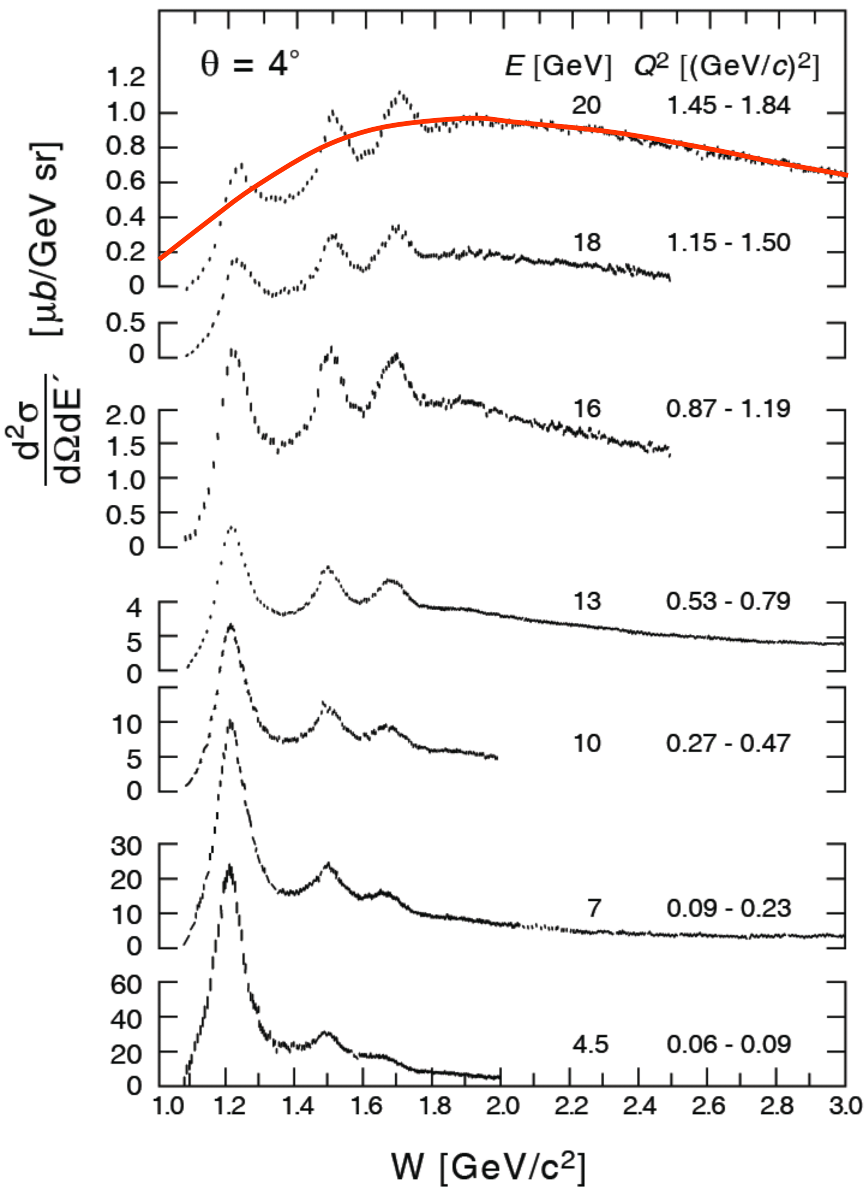
quasi-elastic off
point-like
constituents



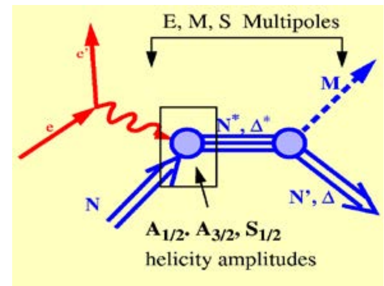


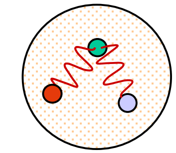
Deep Inelastic Scattering
M. Breidenbach et al.,
Phys. Rev. Lett. **23** (1969) 935

Baryon Excitations and Quasi-Elastic Scattering

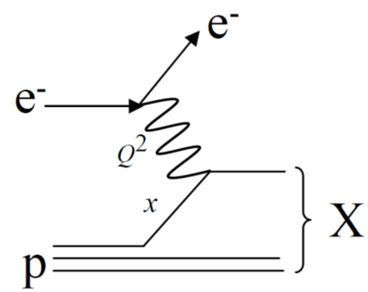


hard and confined



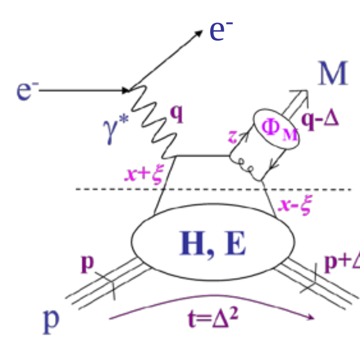


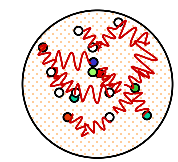
quasi-elastic



hard

soft

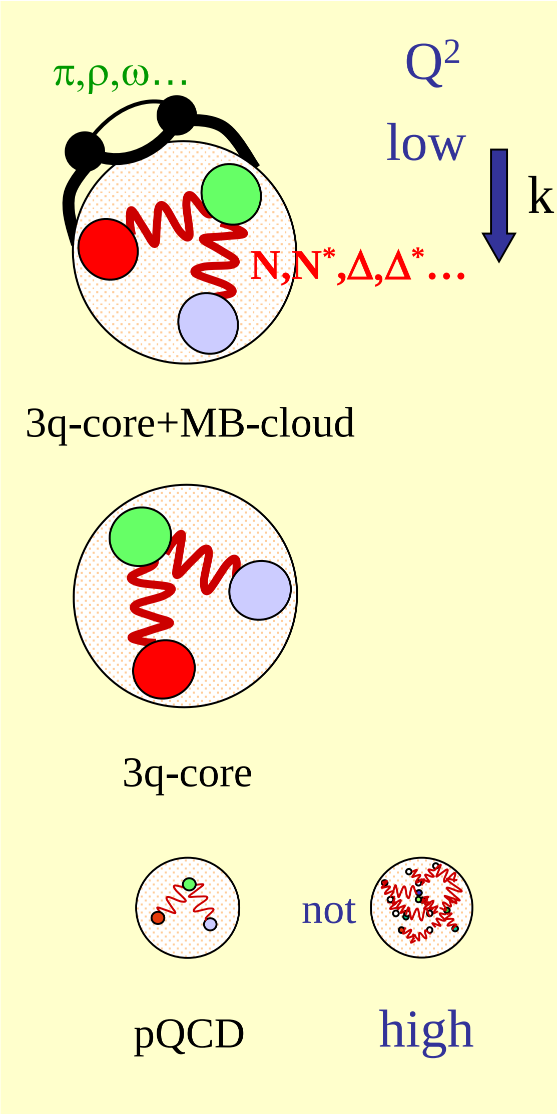




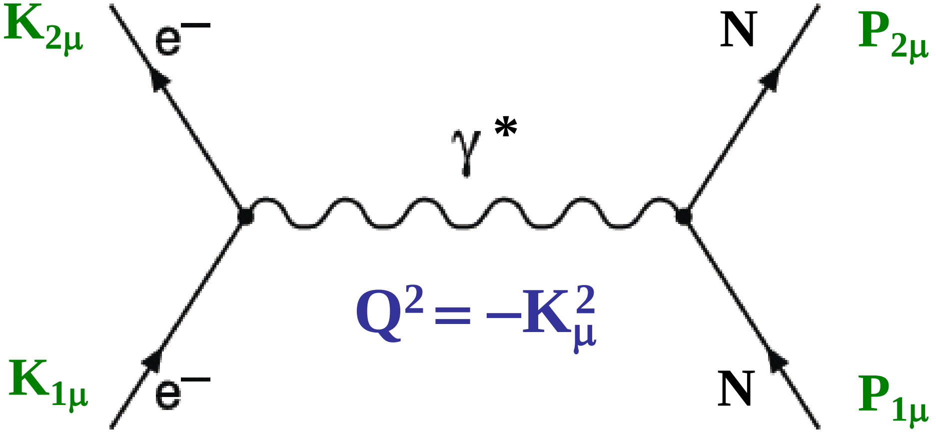
Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Transition Form Factors

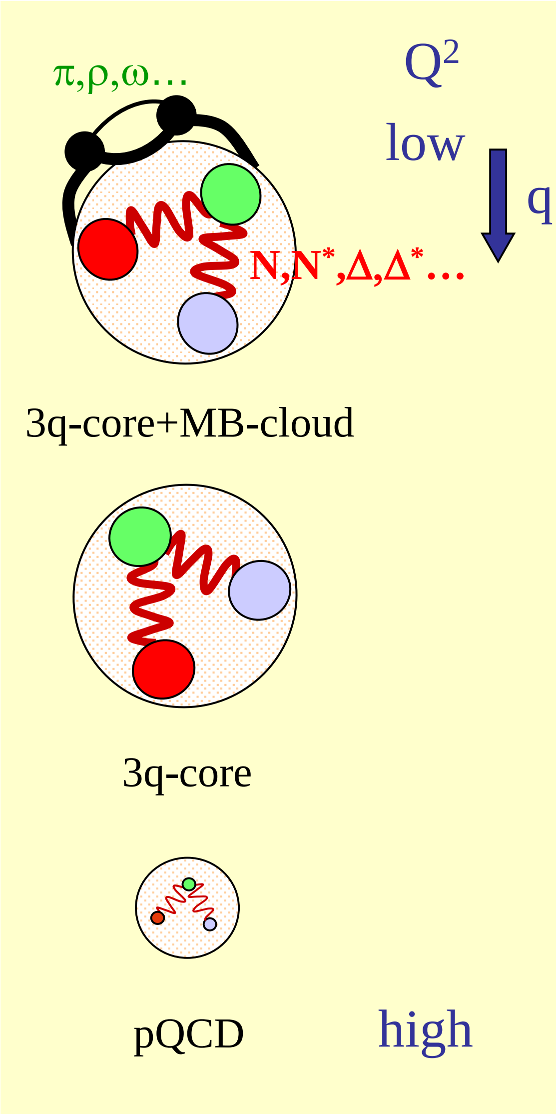
Hadron Structure with Electromagnetic Probes



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



Hadron Structure with Electromagnetic Probes



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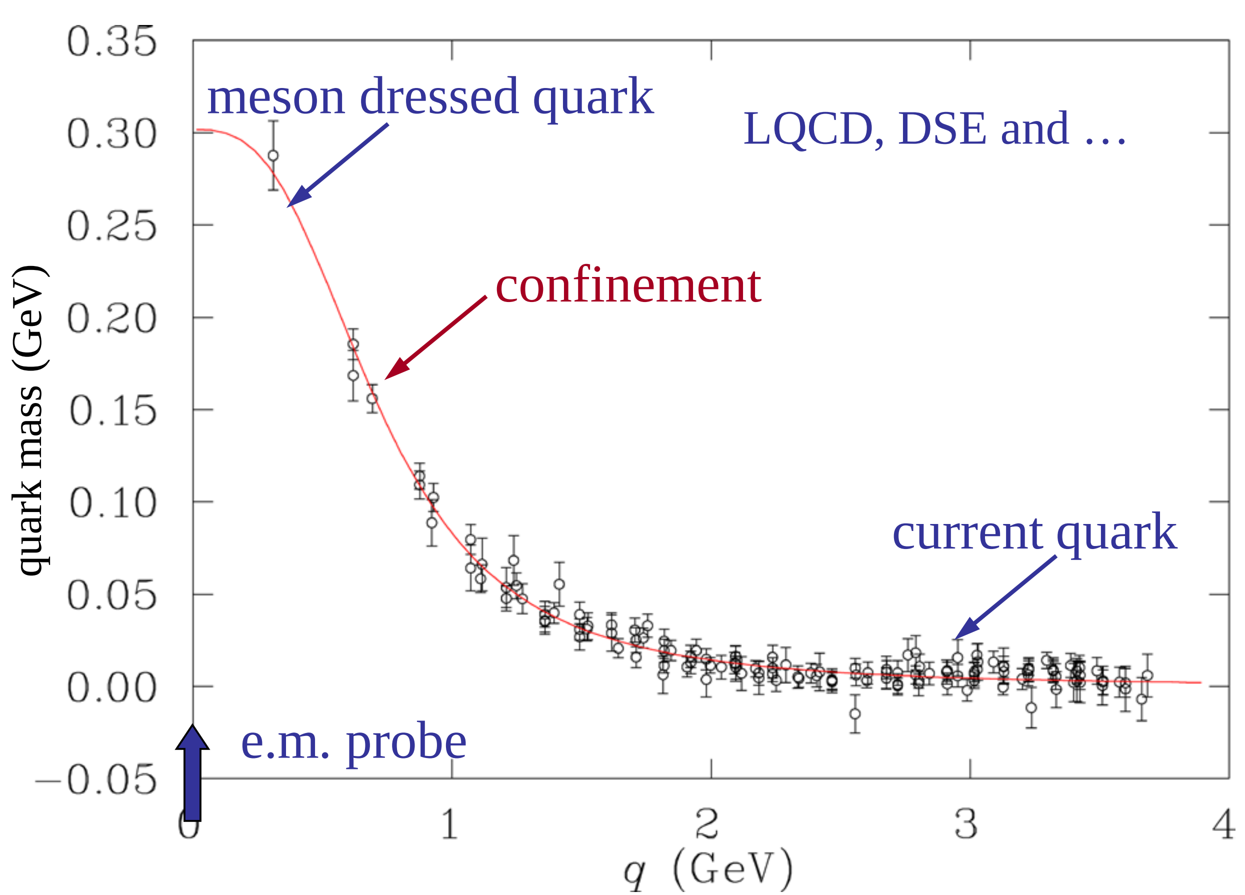
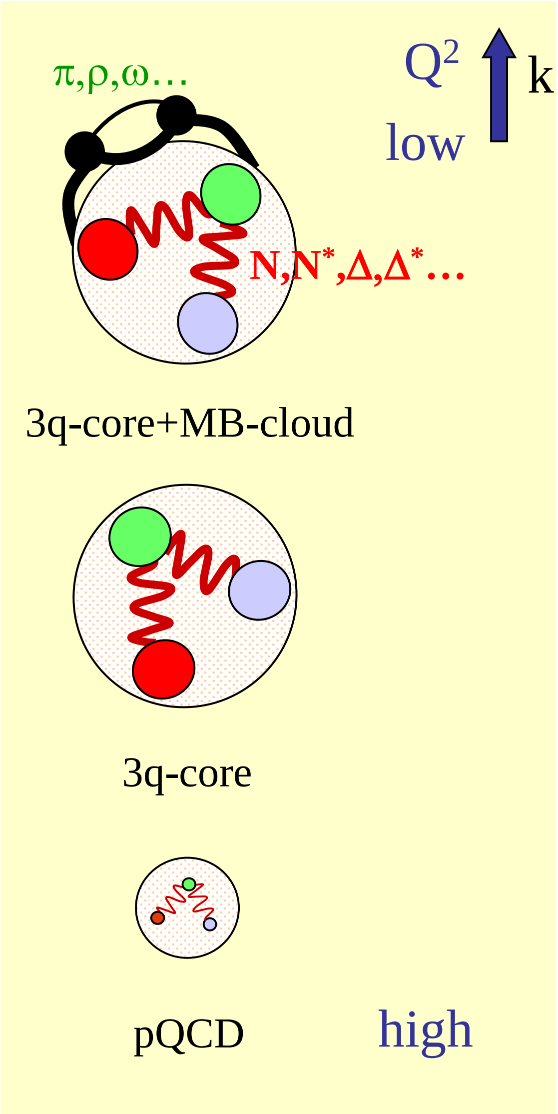
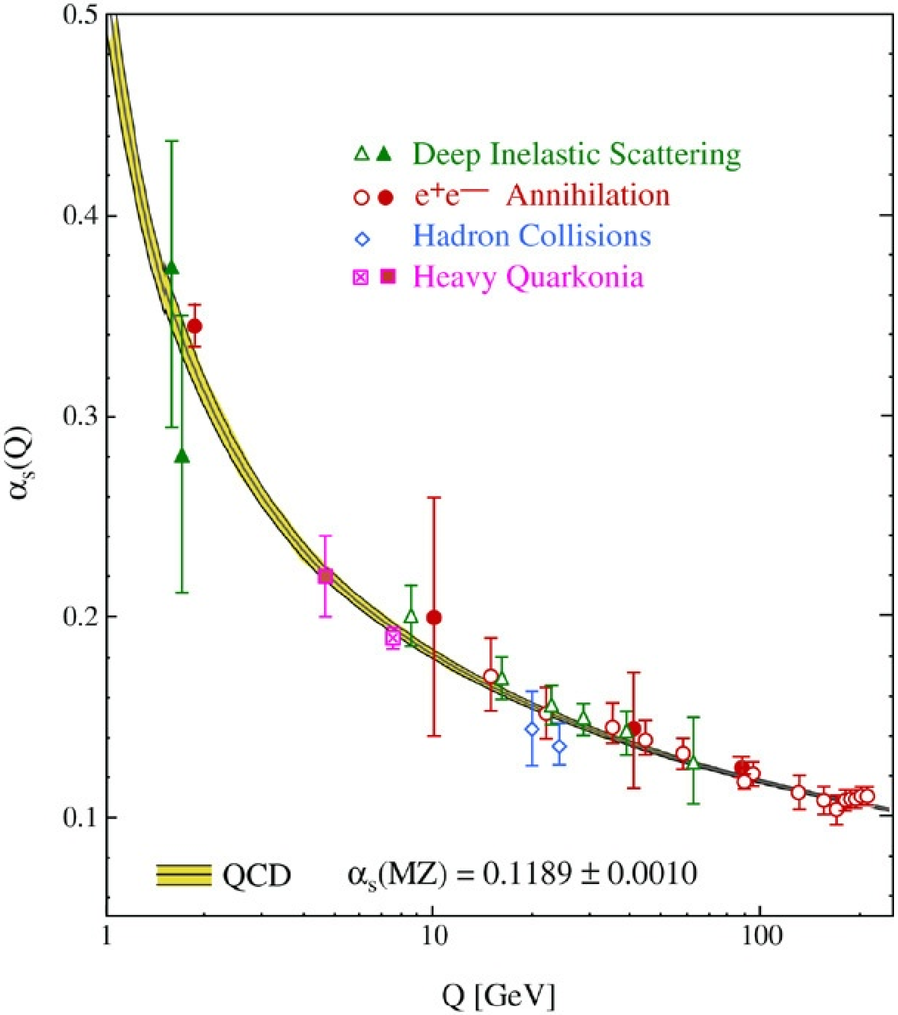


Hadron Structure with Electromagnetic Probes

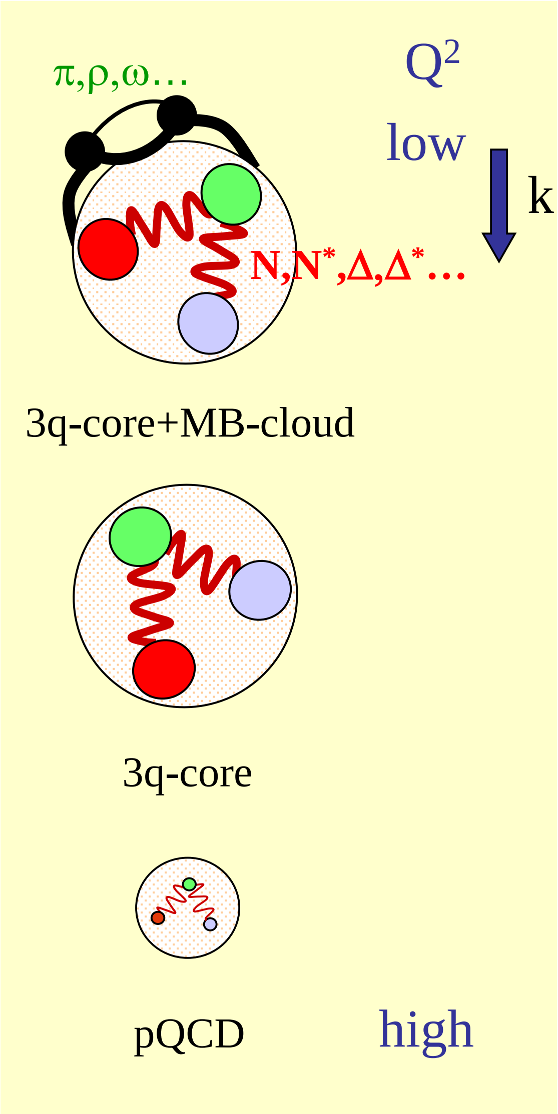


- The SM α_s diverges as Q^2 approaches zero, but confinement and the meson cloud heal this artificial divergence as QCD becomes non-perturbative.

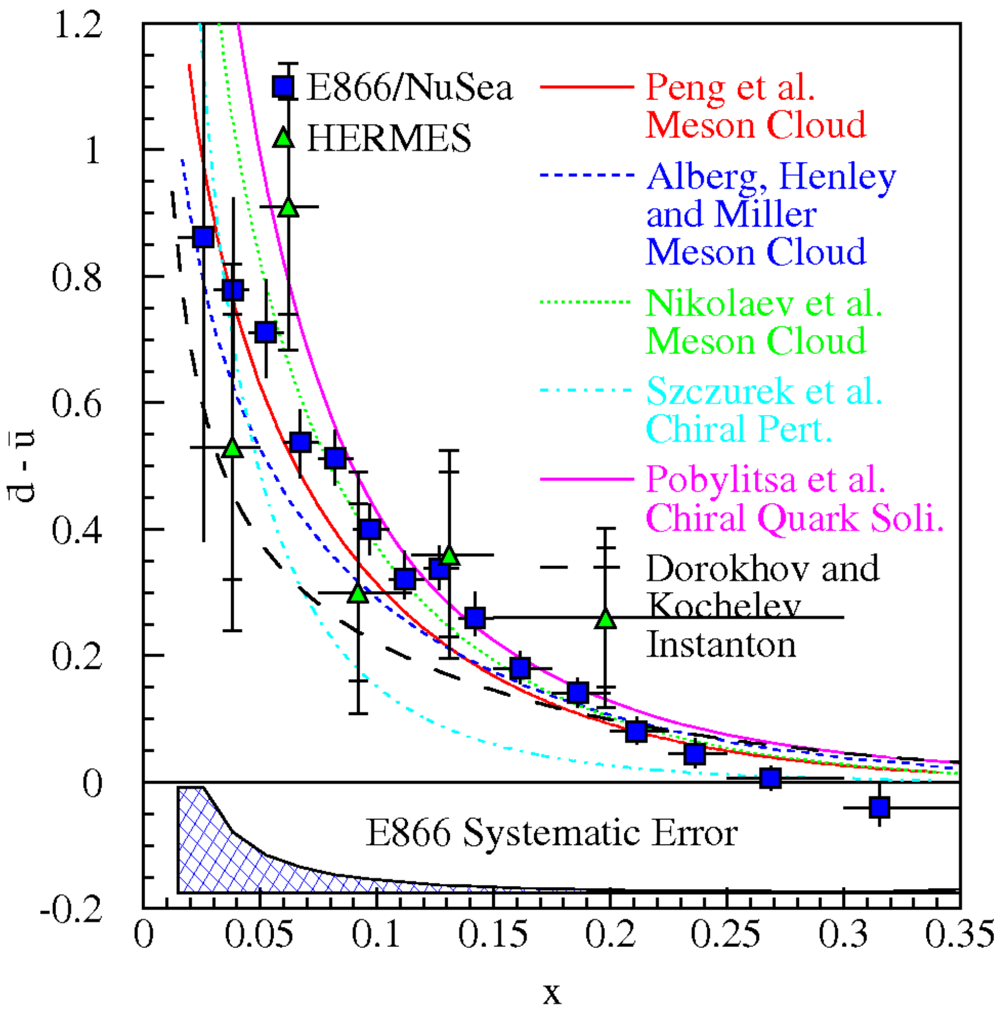


Hadron Structure with Electromagnetic Probes

Rolf Ent



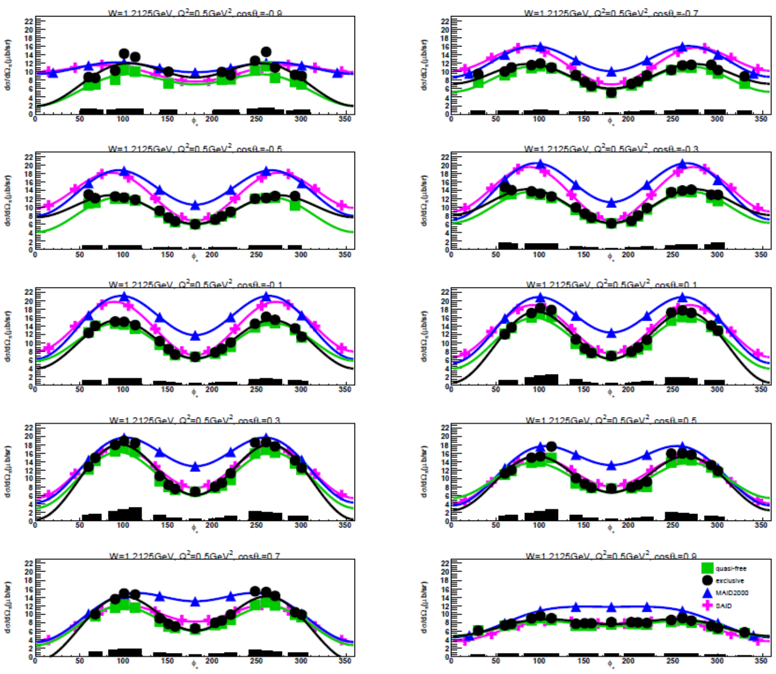
- The pion, or a meson cloud, explains light-quark asymmetry of the sea quarks in the nucleon.



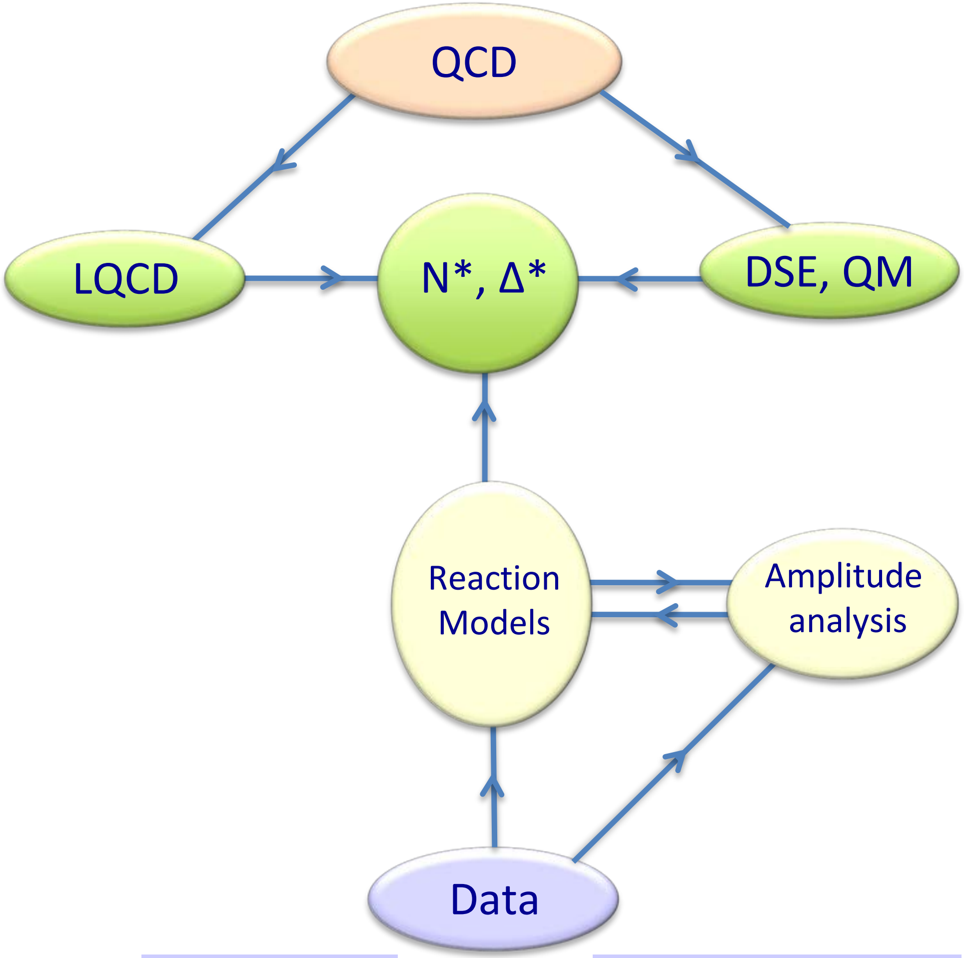
Data-Driven Data Analyses

Consistent Results

Single Pion



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



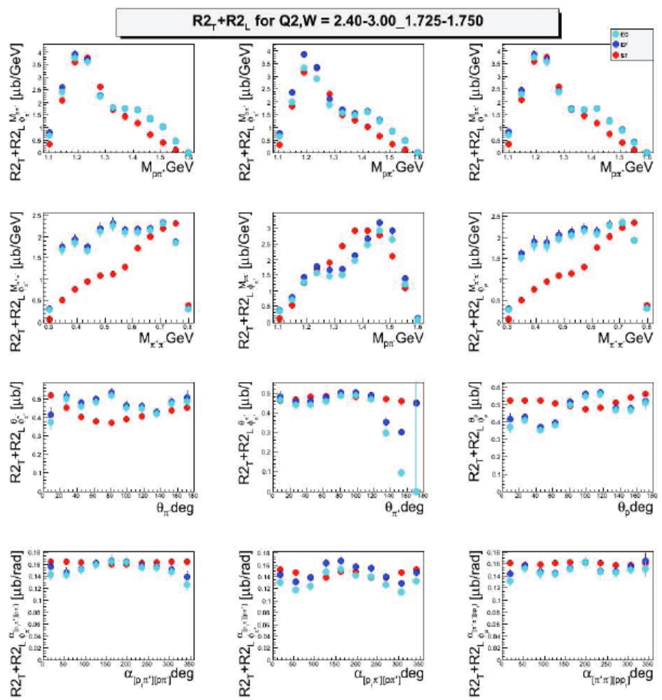
Hadronic production

Electromagnetic production

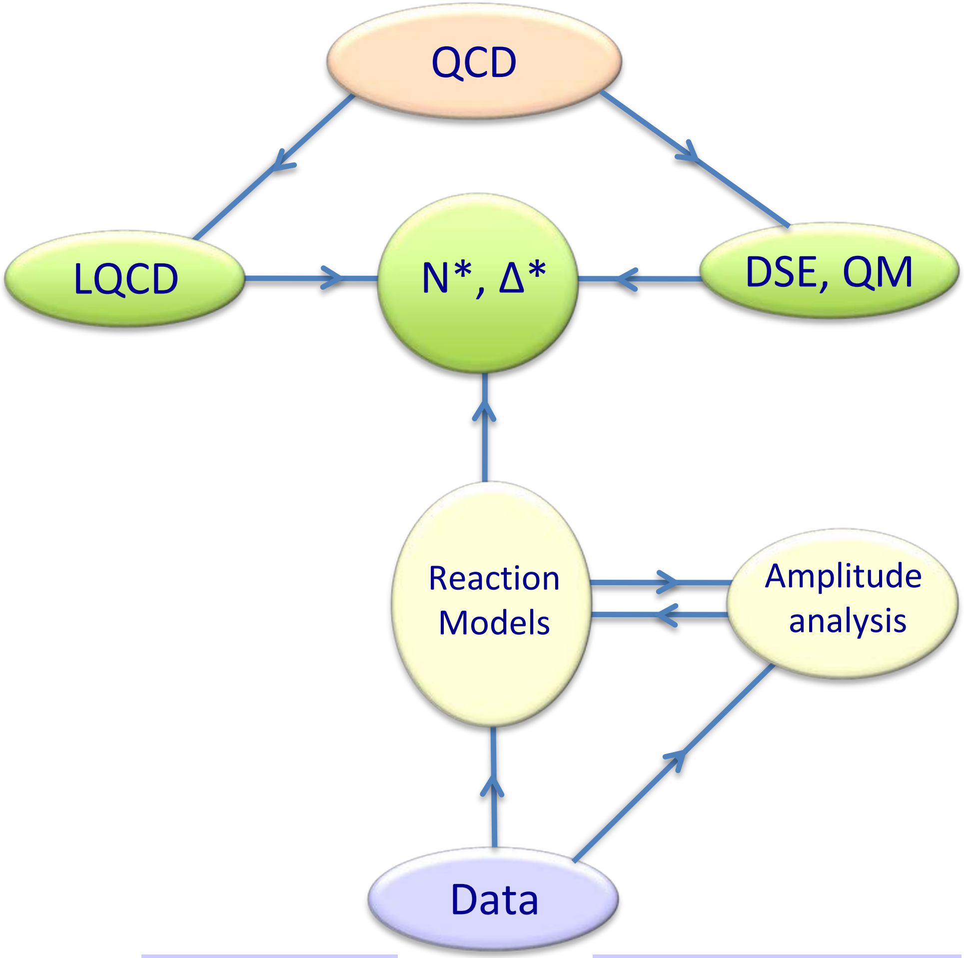
Data-Driven Data Analyses

Consistent Results

Double Pion



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



Hadronic production

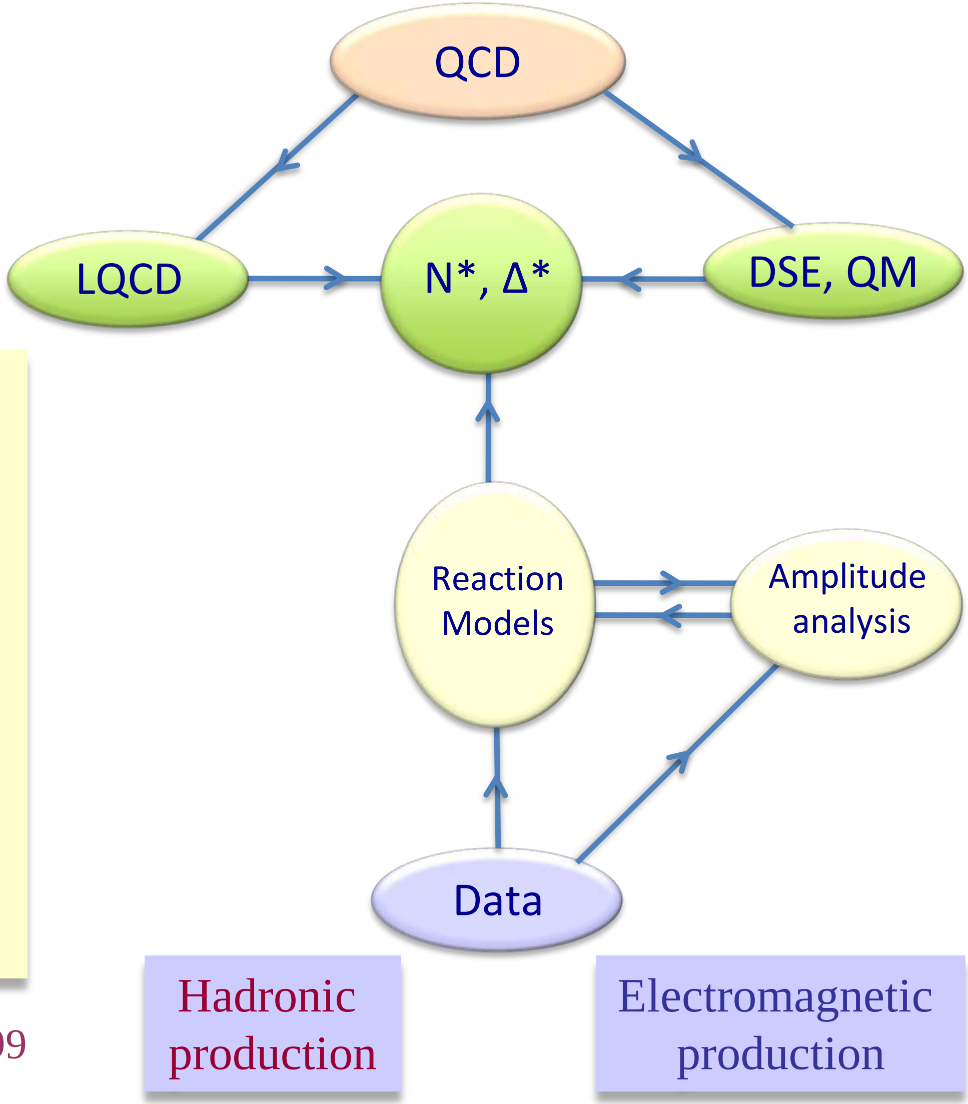
Electromagnetic production

Data-Driven Data Analyses

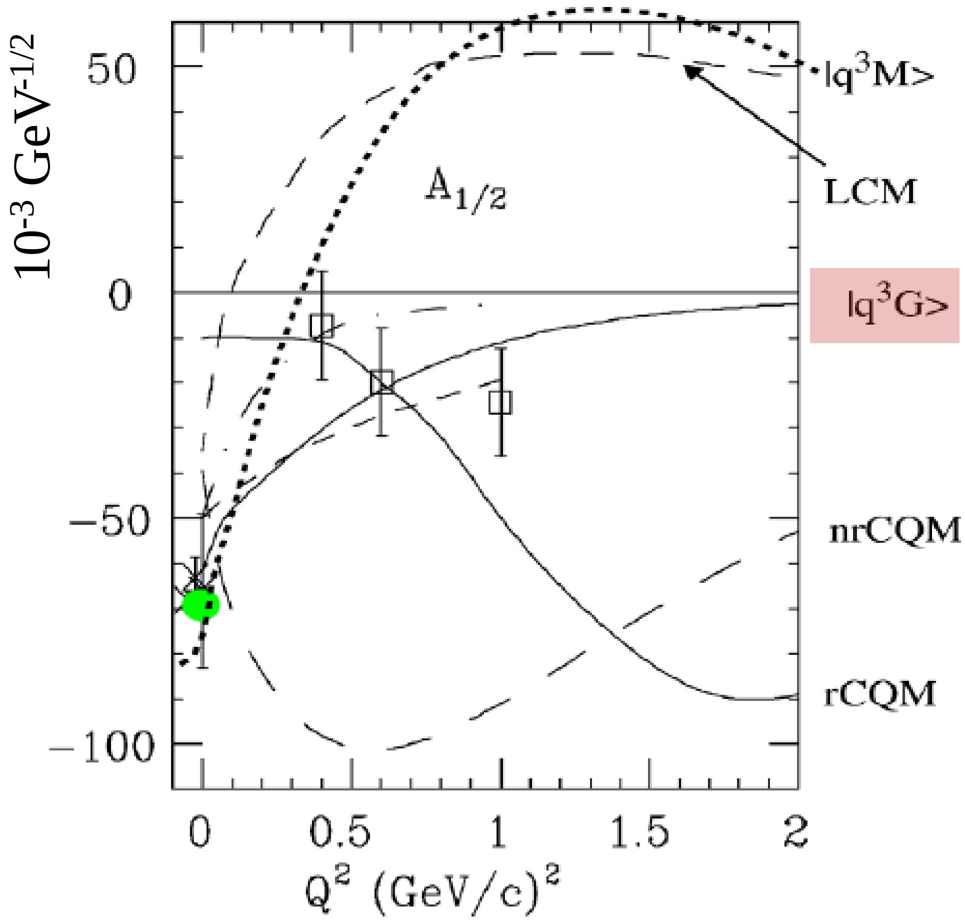
Consistent Results

- 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



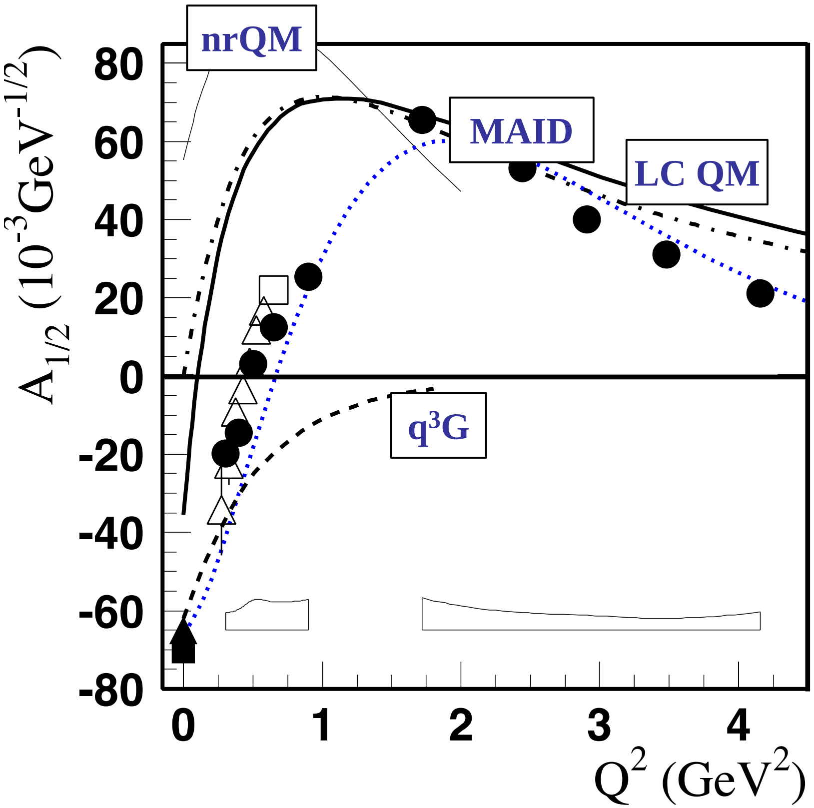
Electrocouplings of N(1440)P_{11} History



- Lowest mass hybrid baryon should be $J^P = 1/2^+$ as Roper.
- In 2002 Roper $A_{1/2}$ results were consistent with a hybrid state.

Transition Form Factors and QCD Models

Roper resonance $P_{11}(1440)$



PDG 2013 update

+ q^3g

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

+ N-Meson

+ …

or

- q^2q

- …

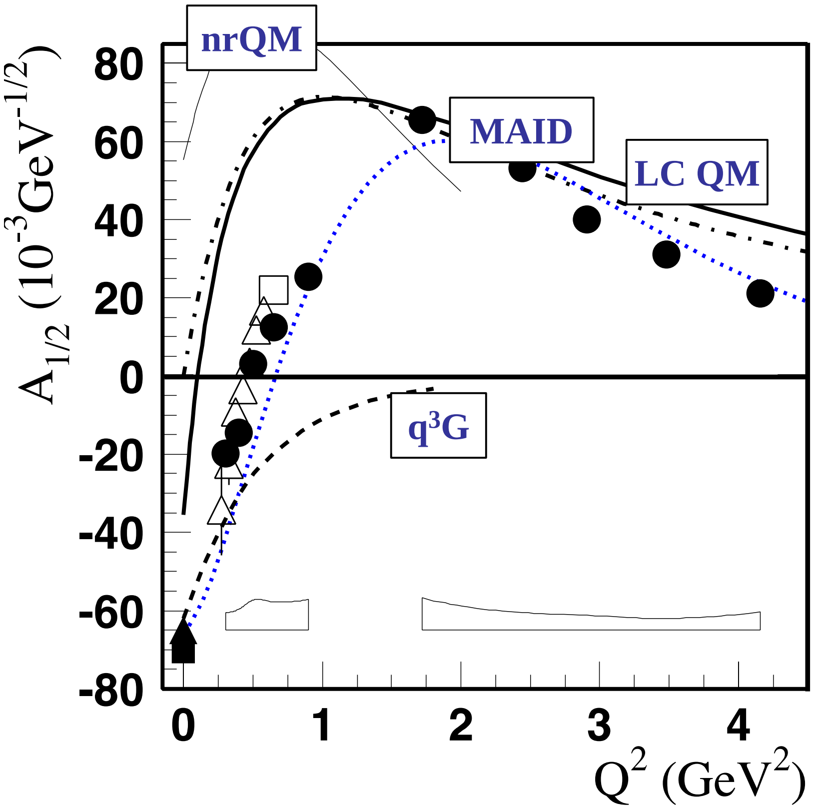
… all have distinctively different Q^2 dependencies

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

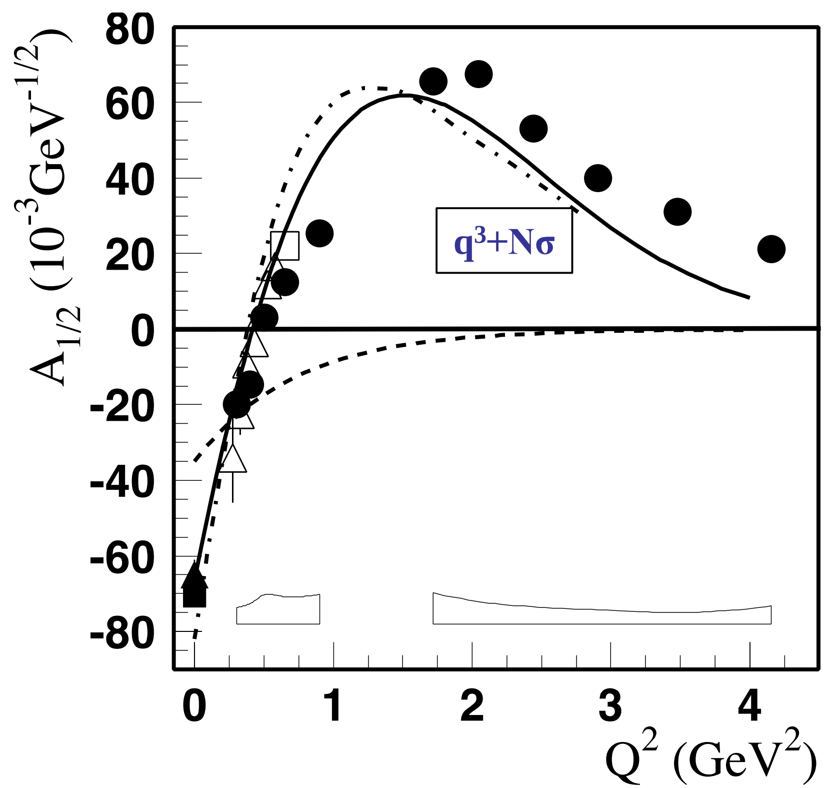
Nick Tyler closes the 1-2 GeV^2 gap for single pion production.

Transition Form Factors and QCD Models

Roper resonance $P_{11}(1440)$



I.T. Obukhovsky



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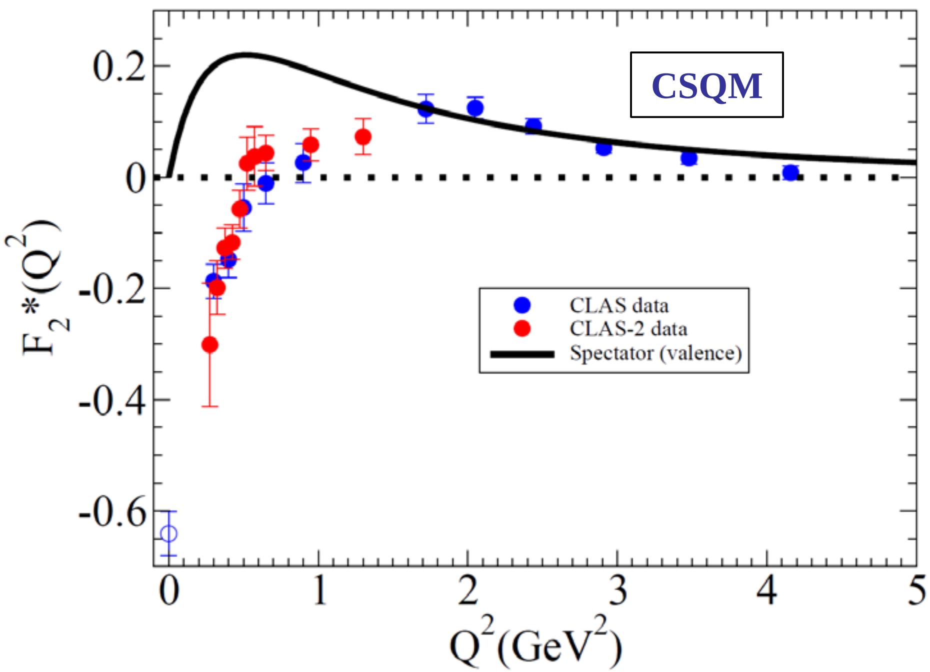
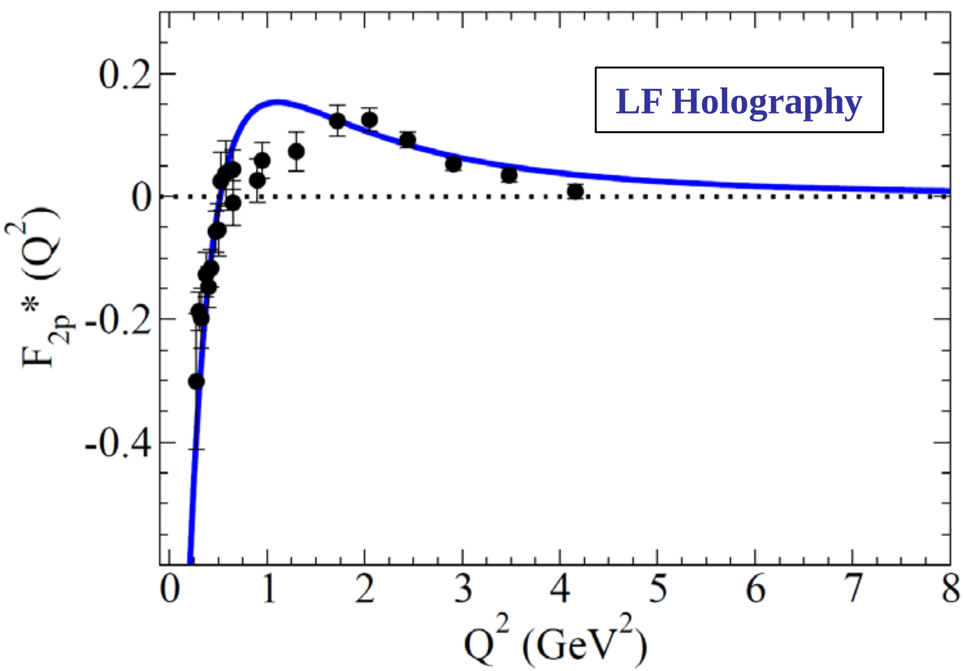
Transition Form Factors and QCD Models

Roper resonance $P_{11}(1440)$ G. Ramalho





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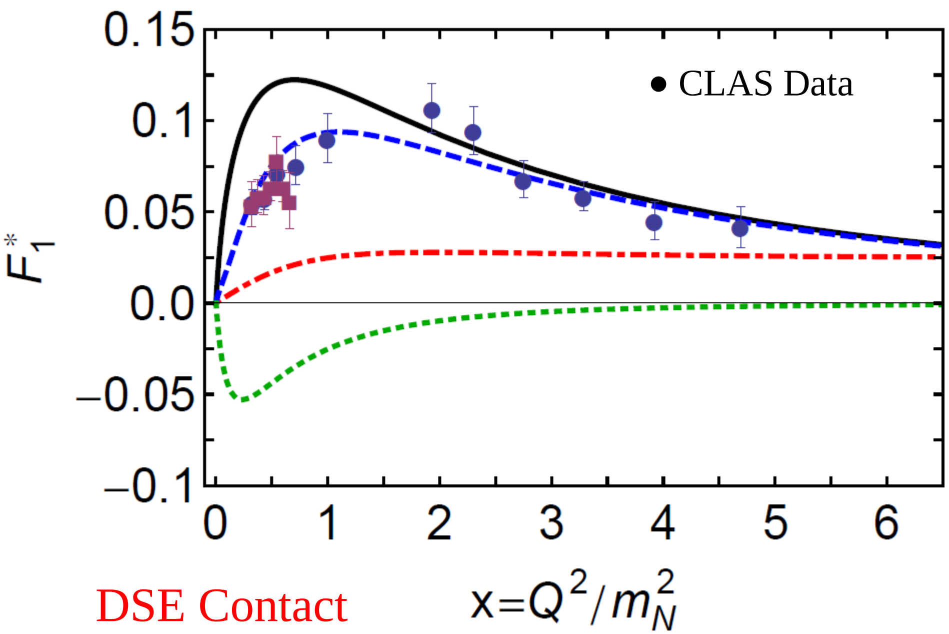
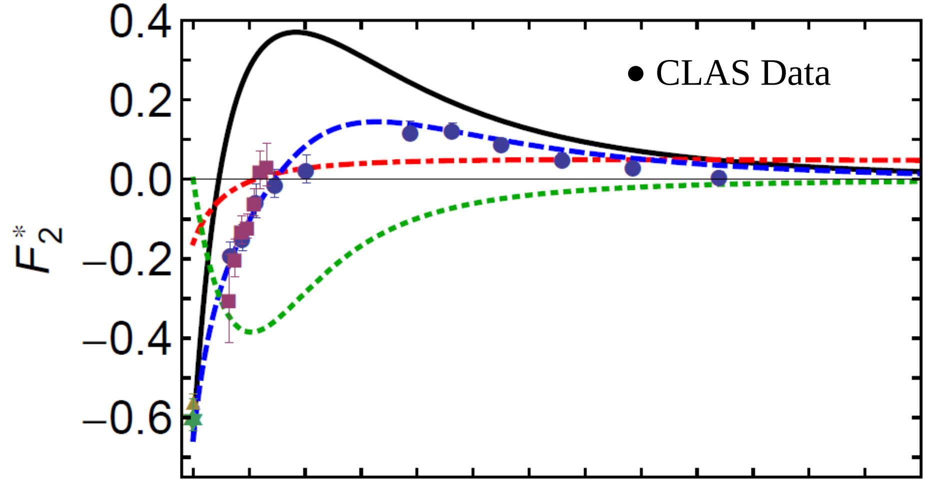
Roper Transition Form Factors in DSE Approach

N(1440)P_{11}

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





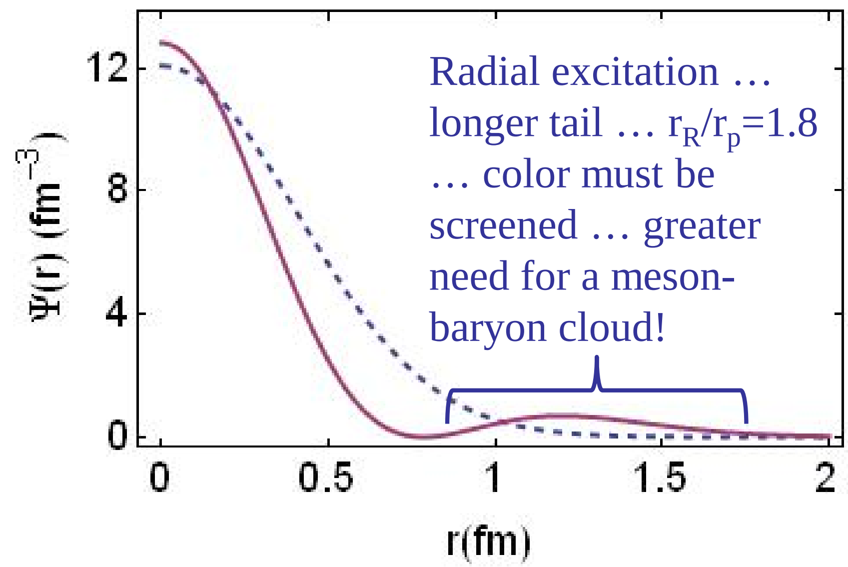
DSE Contact

DSE Realistic

Inferred meson-cloud contribution

Anticipated complete result

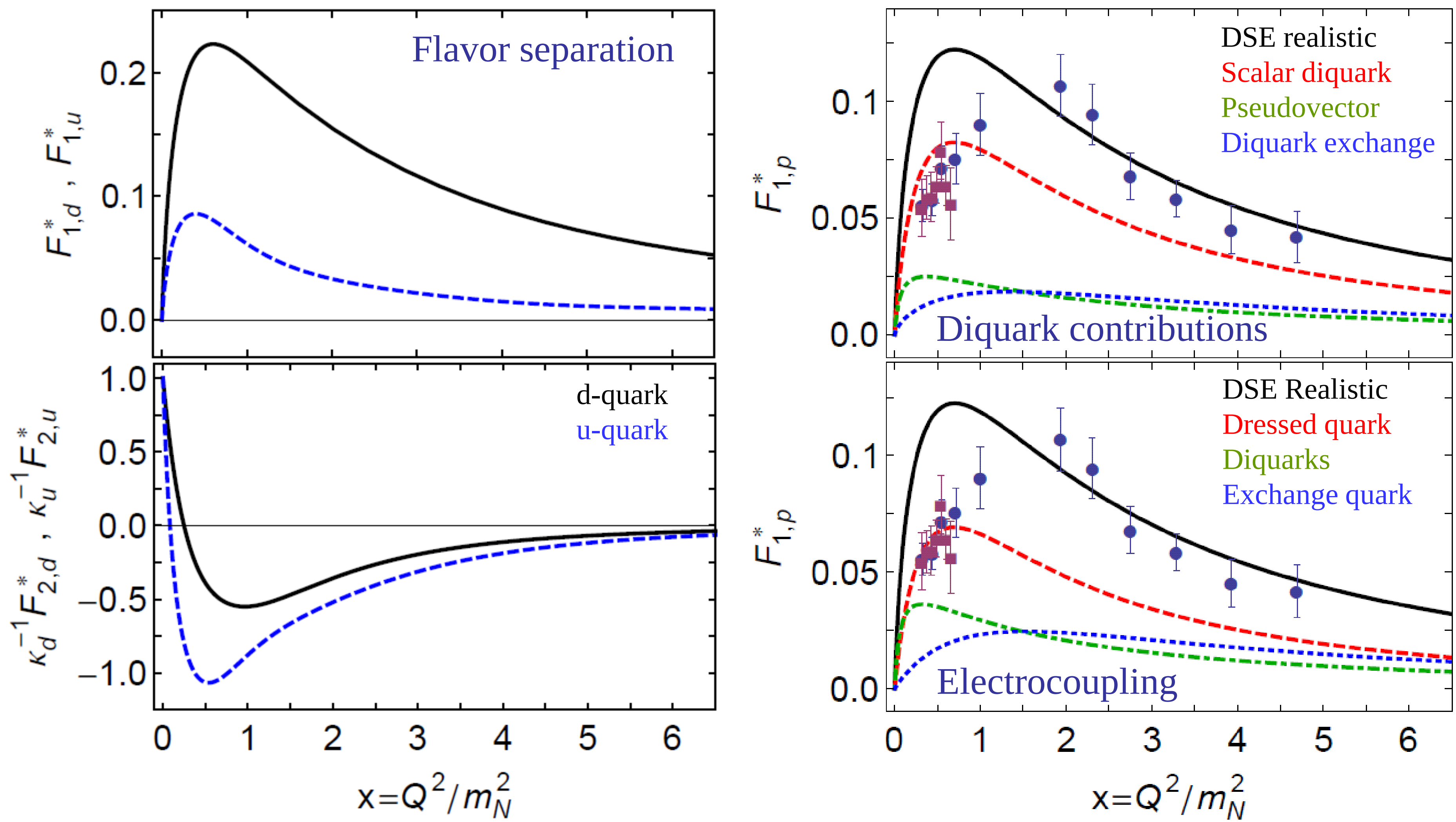
Importantly, the existence of a zero in F_2 is not influenced by meson-cloud effects, although its precise location is.



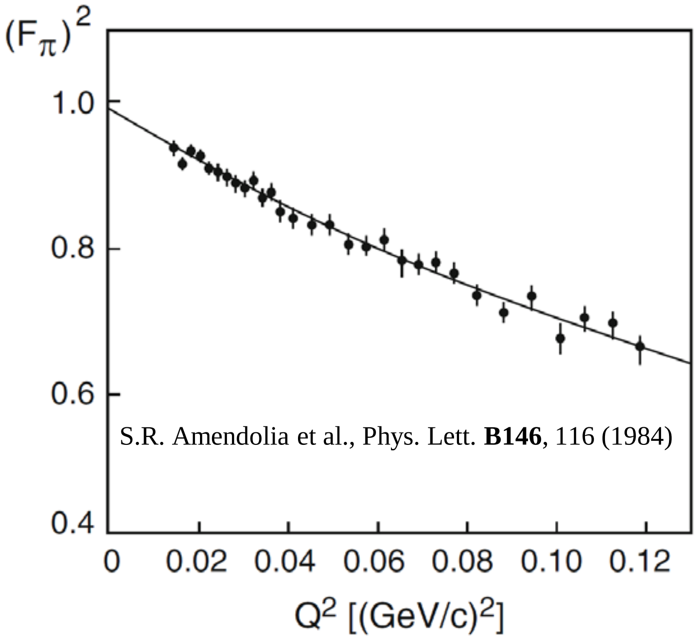
Roper Transition Form Factors in DSE Approach

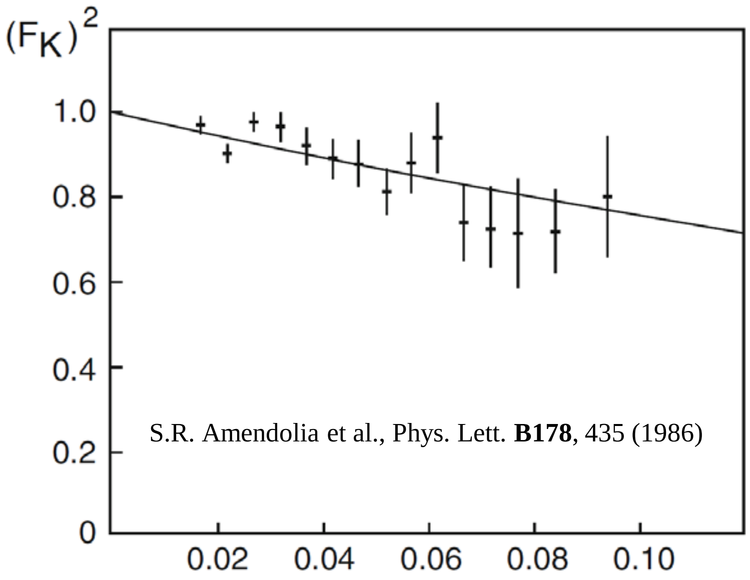
N(1440)P_{11}

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

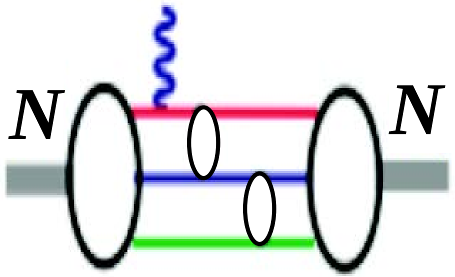


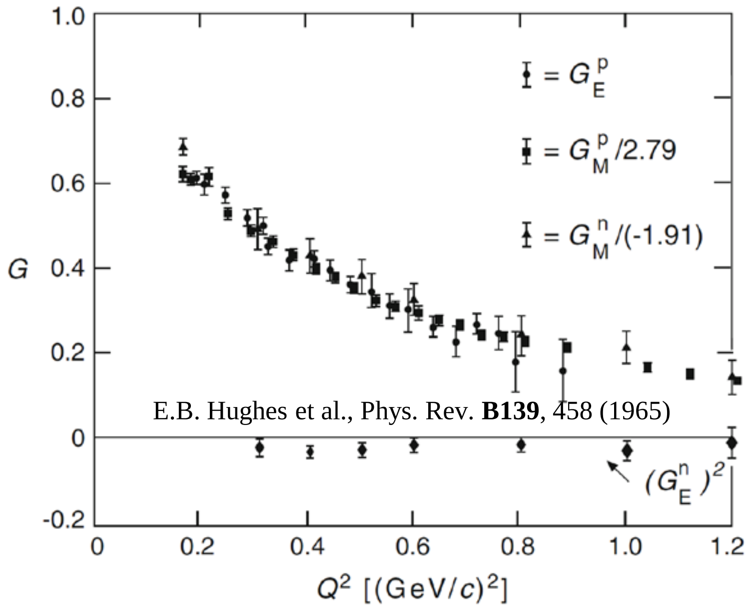
History of Form Factors



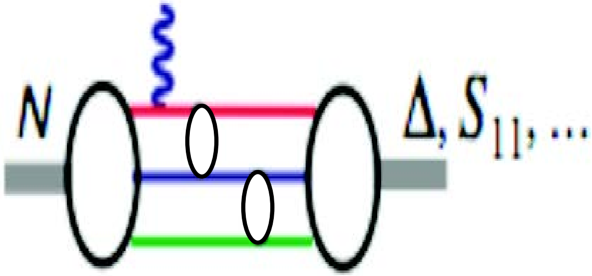


$$F(Q^2) = G_E(Q^2) = \left(1 + Q^2/a^2\hbar^2\right)^{-2}$$



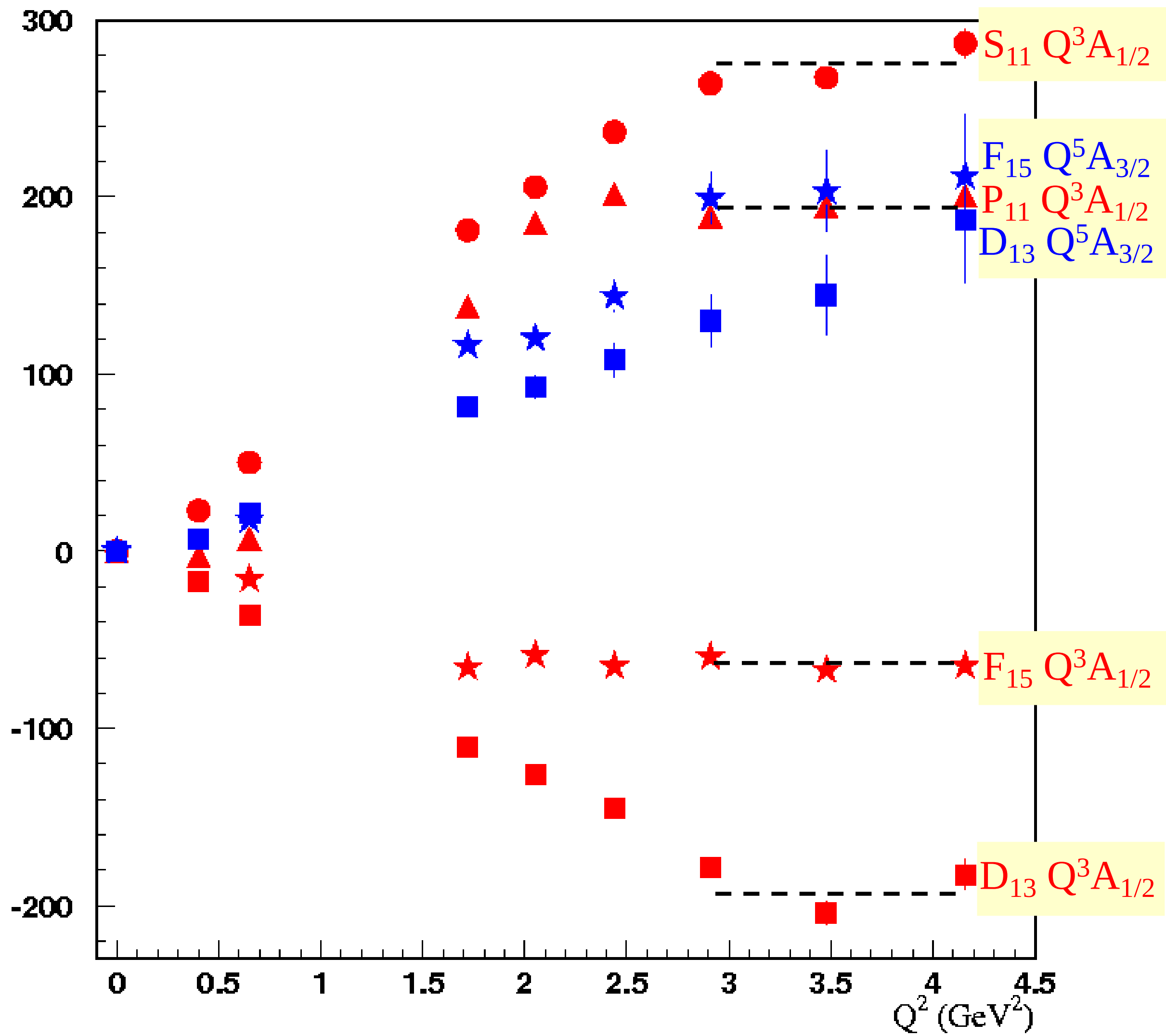


Evidence for the Onset of Precocious Scaling?



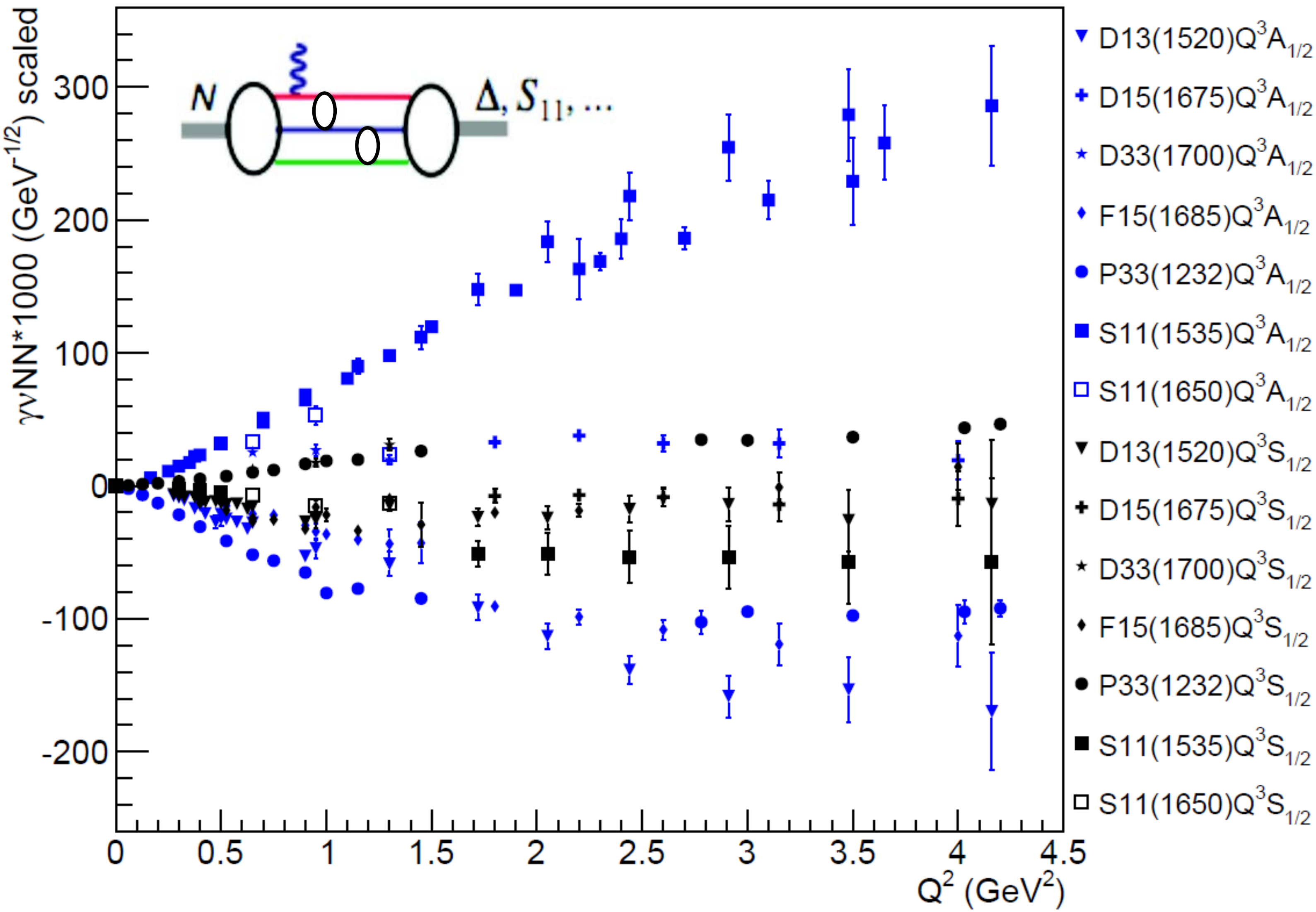
- $A_{1/2}$ α $1/Q^3$
- $A_{3/2}$ α $1/Q^5$

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



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?

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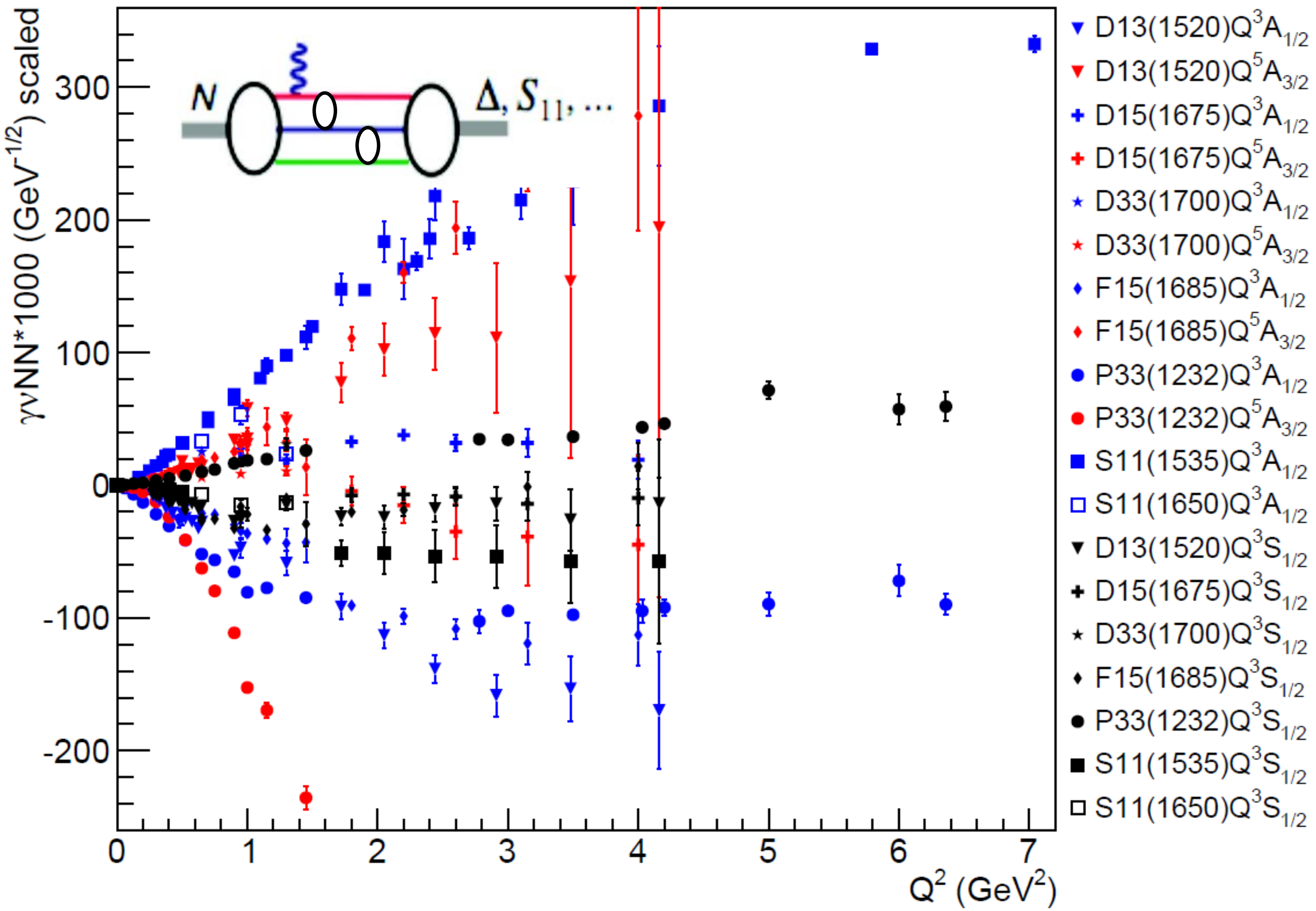
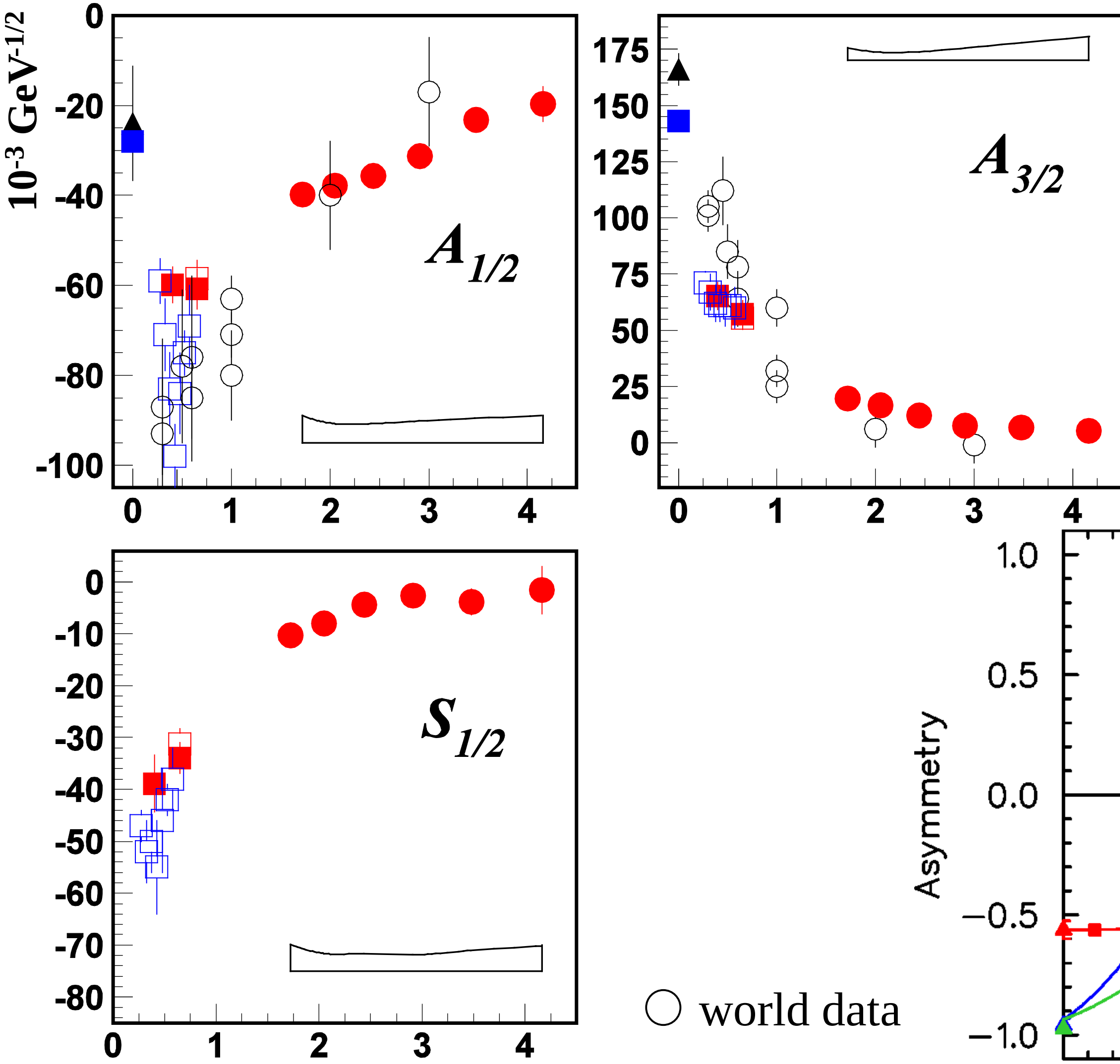


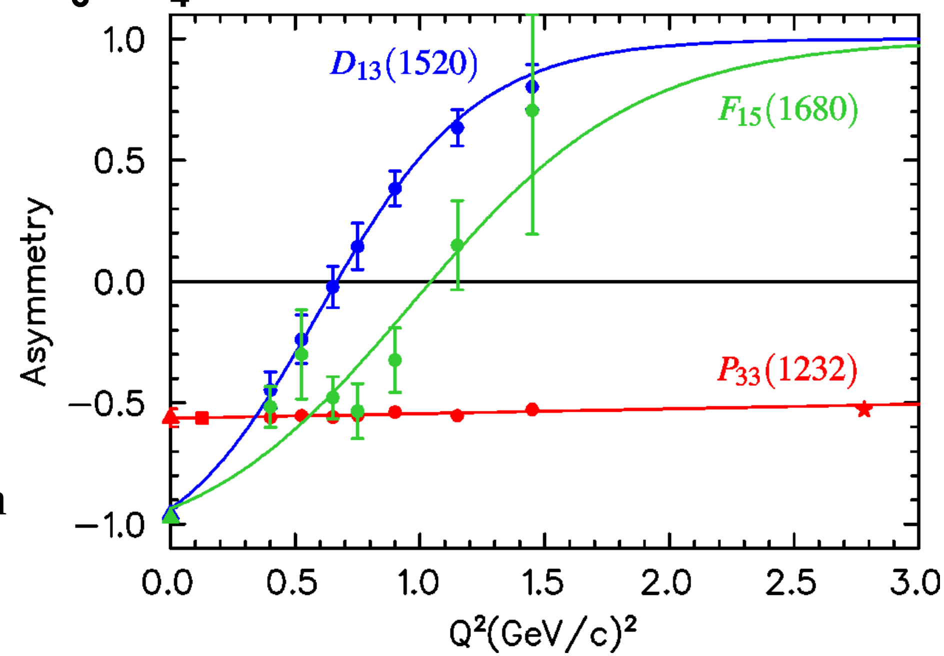
V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)

N(1520)D_{13} Helicity Asymmetry



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

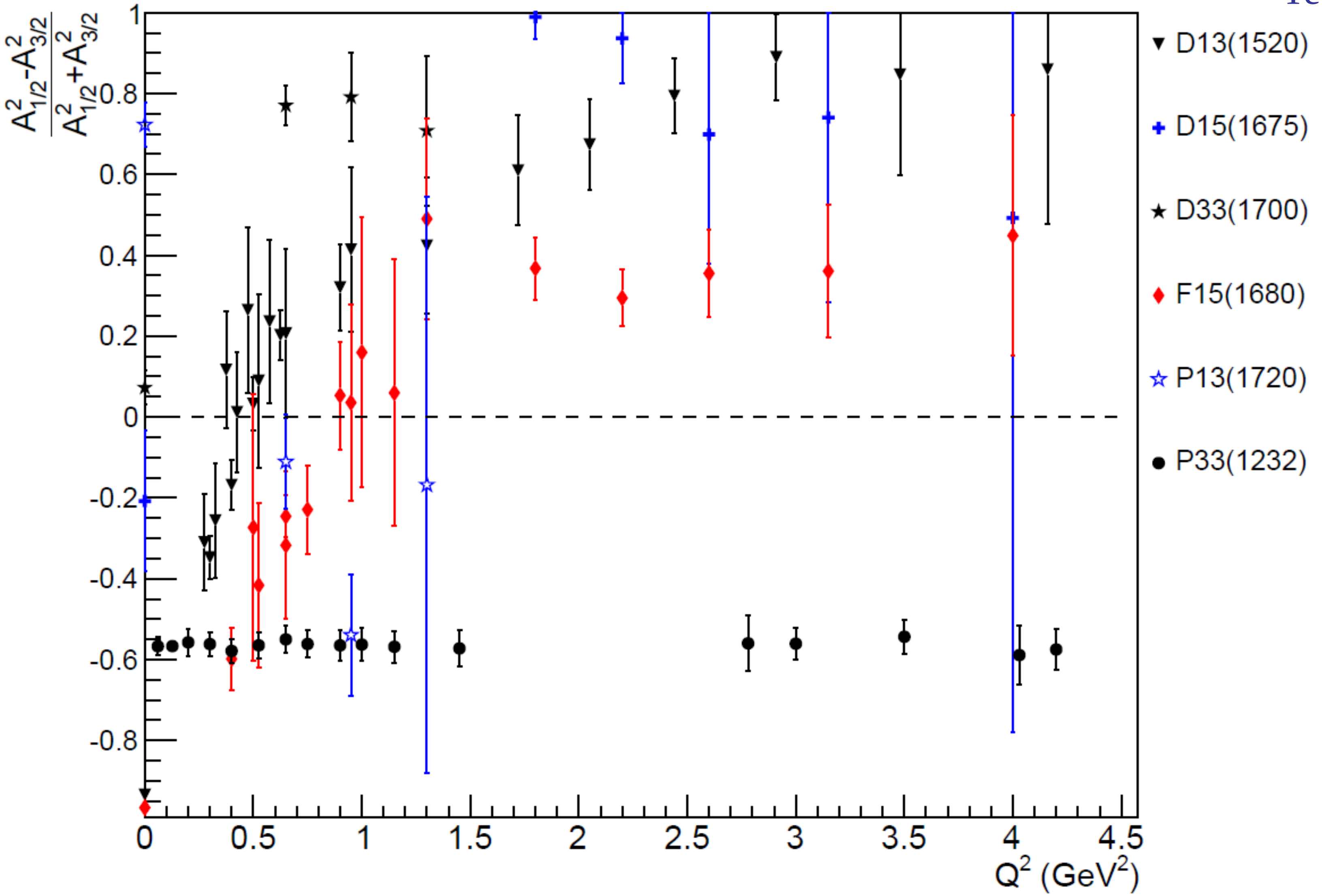
L. Tiator



▲ PDG estimation ● ■ Nπ (UIM, DR)

γNN* Helicity Asymmetries

Ye Tian

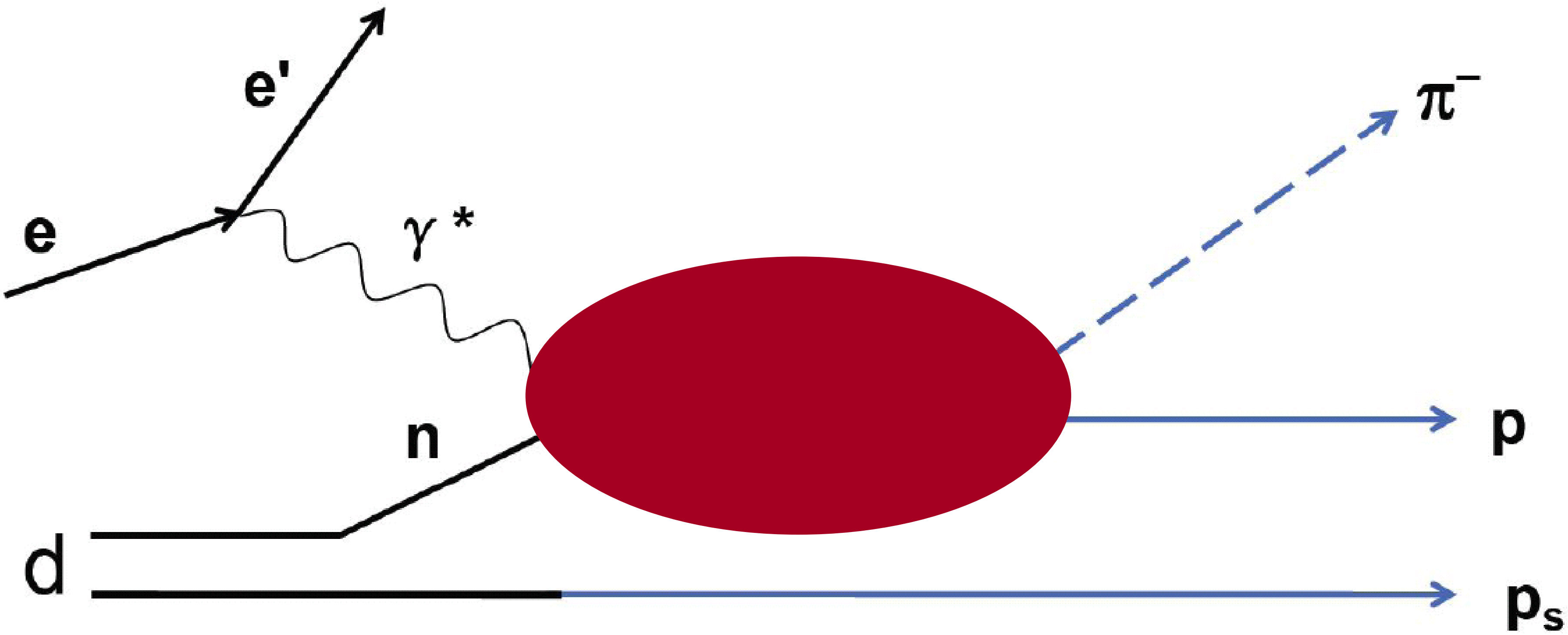


V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)

New Experimental Results & Approaches

Single π^- Electroproduction off the Deuteron

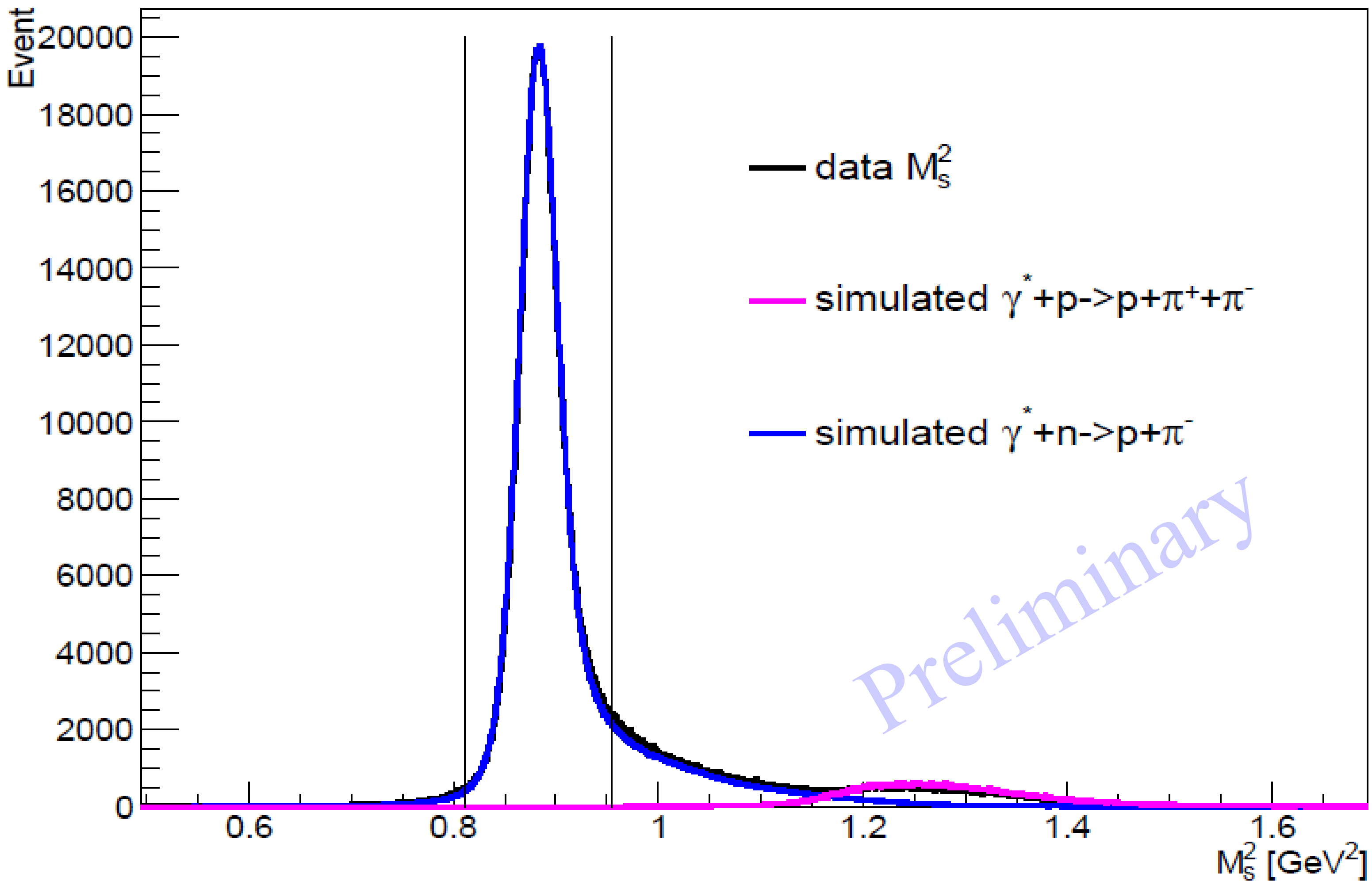
Ye Tian



Exclusive ⇒ Spectator ⇒ Quasi-Free ⇒ FSI

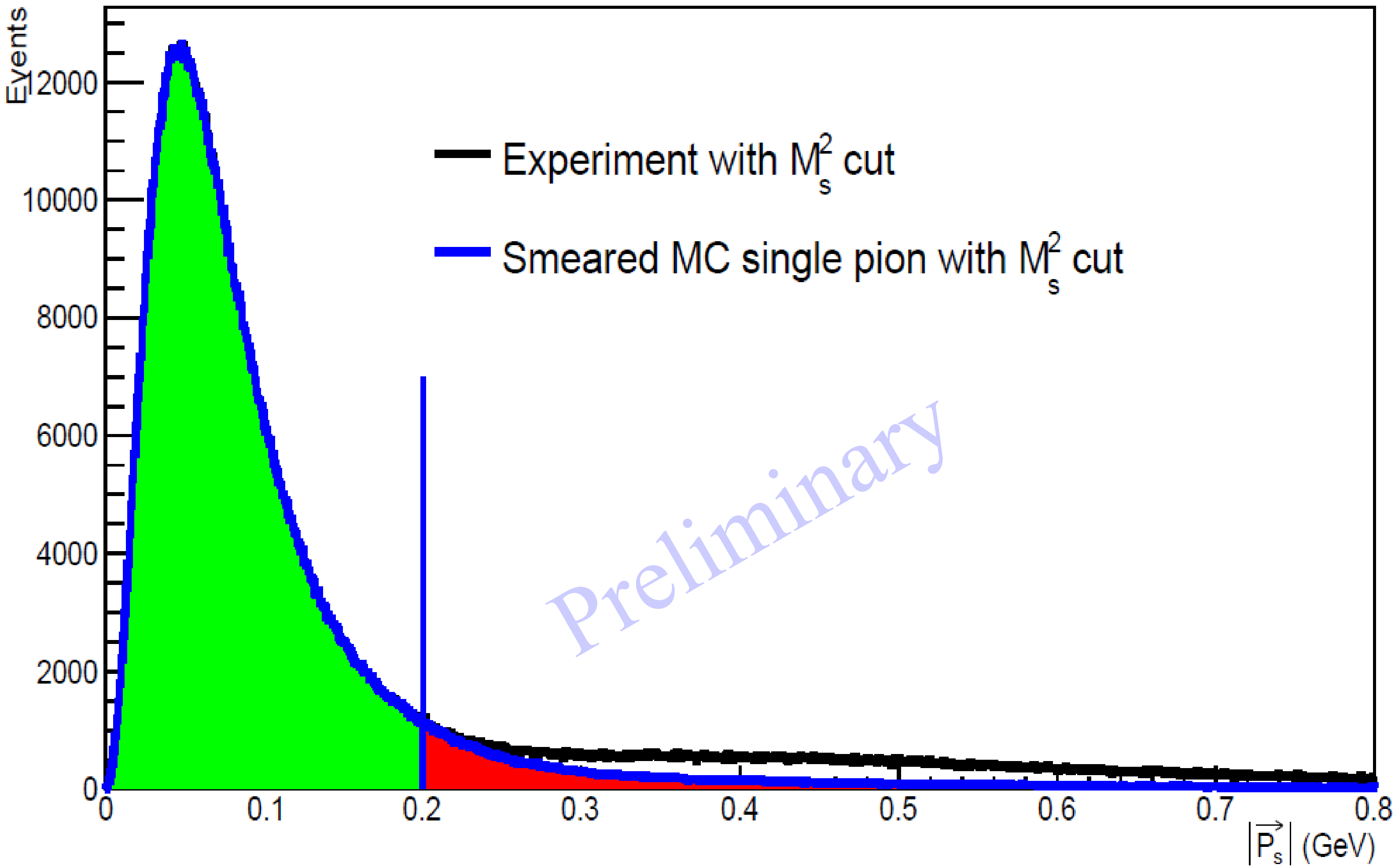
Single π^- Electroproduction off the Deuteron

Ye Tian



Single π⁻ Electroproduction off the Deuteron

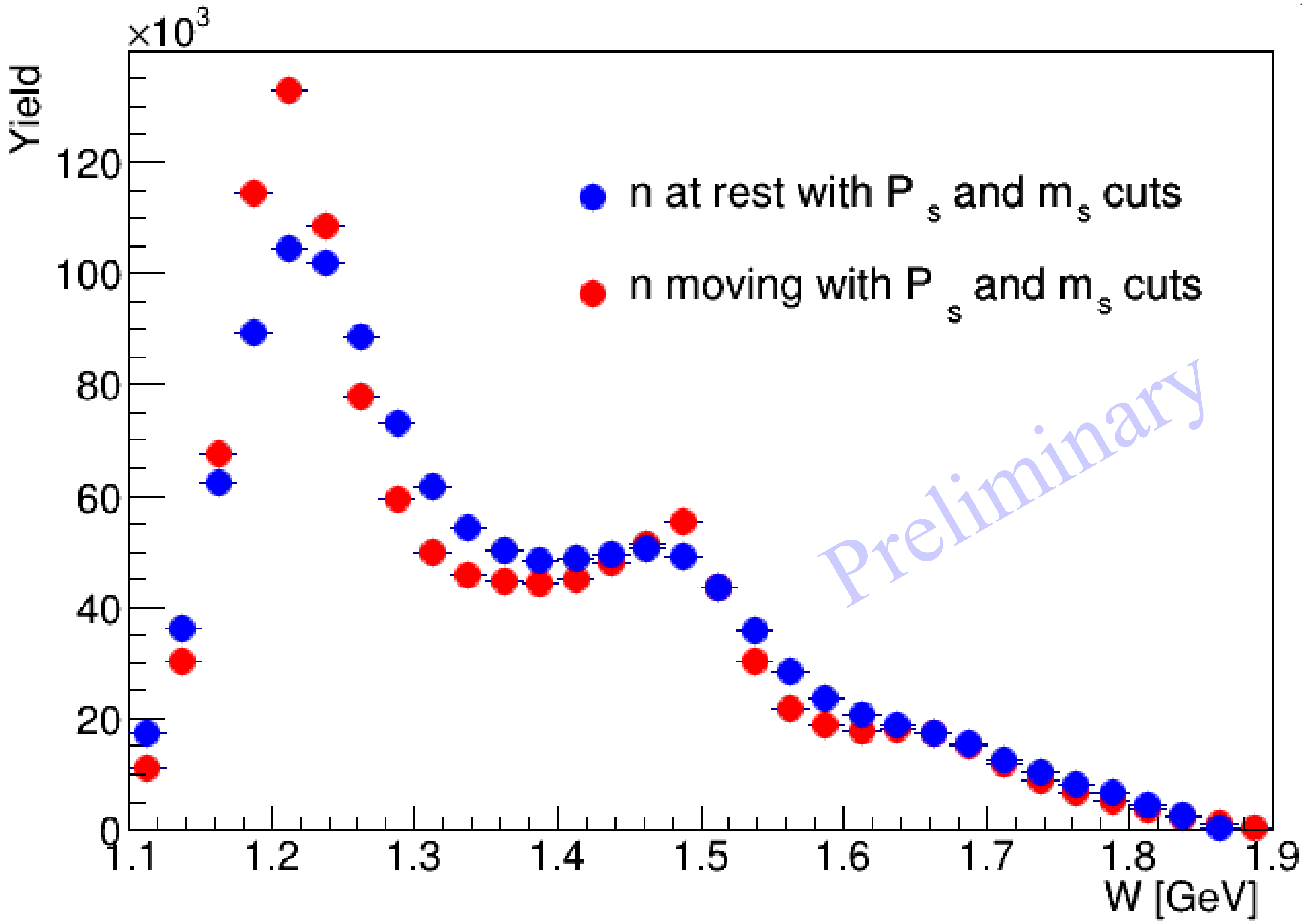
Ye Tian



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

Single π⁻ Electroproduction off the Deuteron

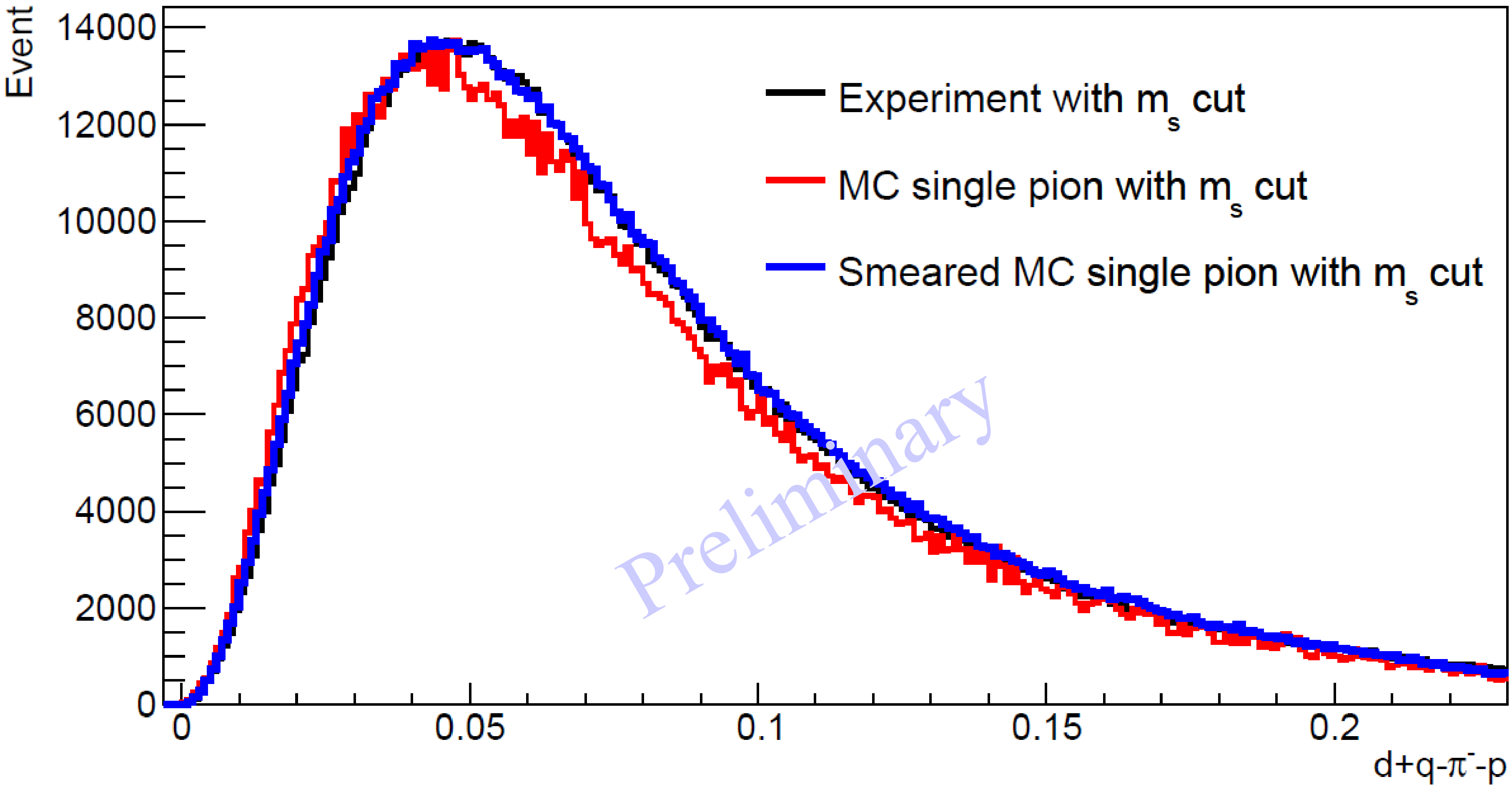
Ye Tian



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

Single π⁻ Electroproduction off the Deuteron

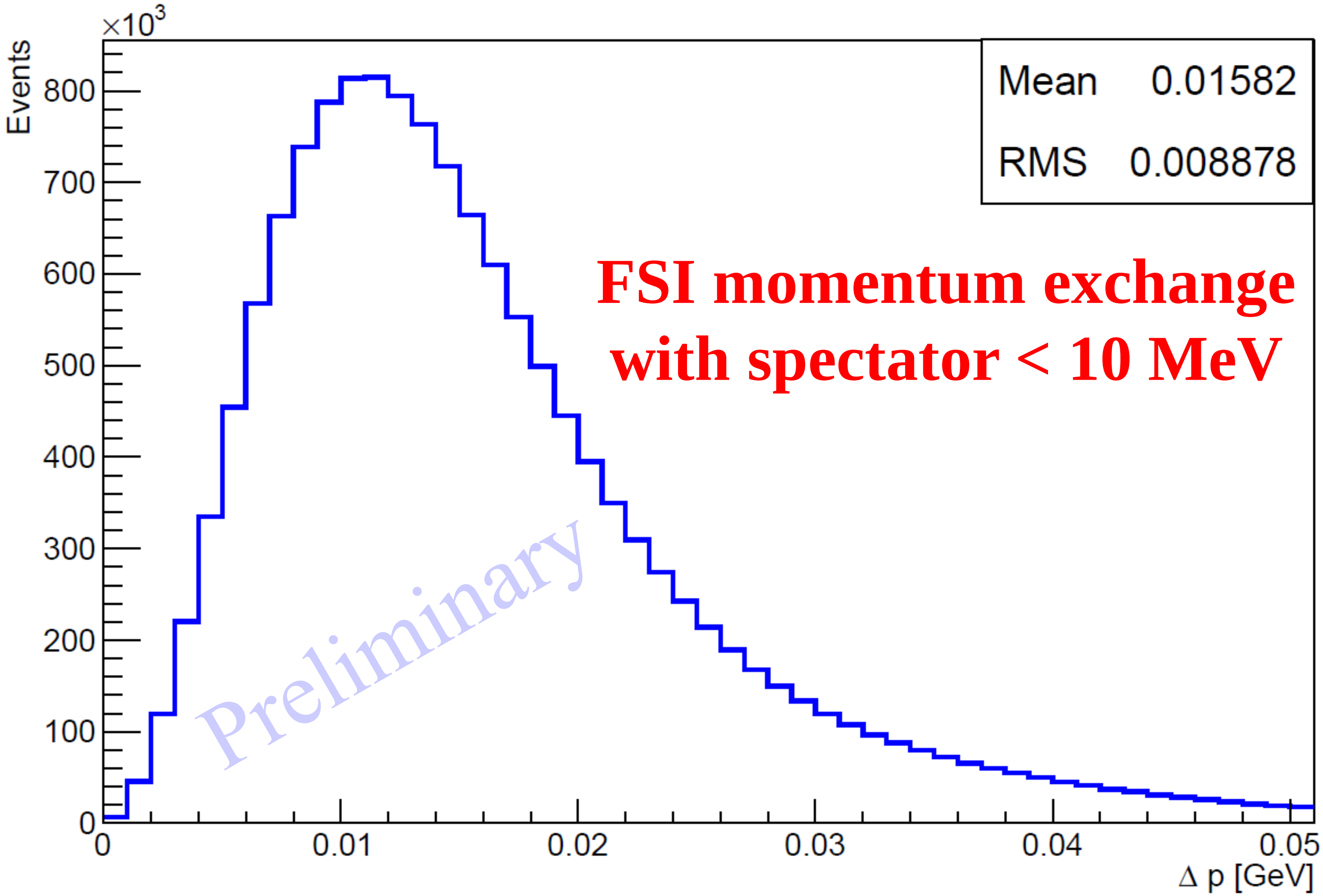
Ye Tian



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

Single π⁻ Electroproduction off the Deuteron

Ye Tian



Momentum resolution with CLAS of the reconstructed missing momentum of the second proton.

Single π^- Electroproduction off the Deuteron

Ye Tian

W = 1212 MeV

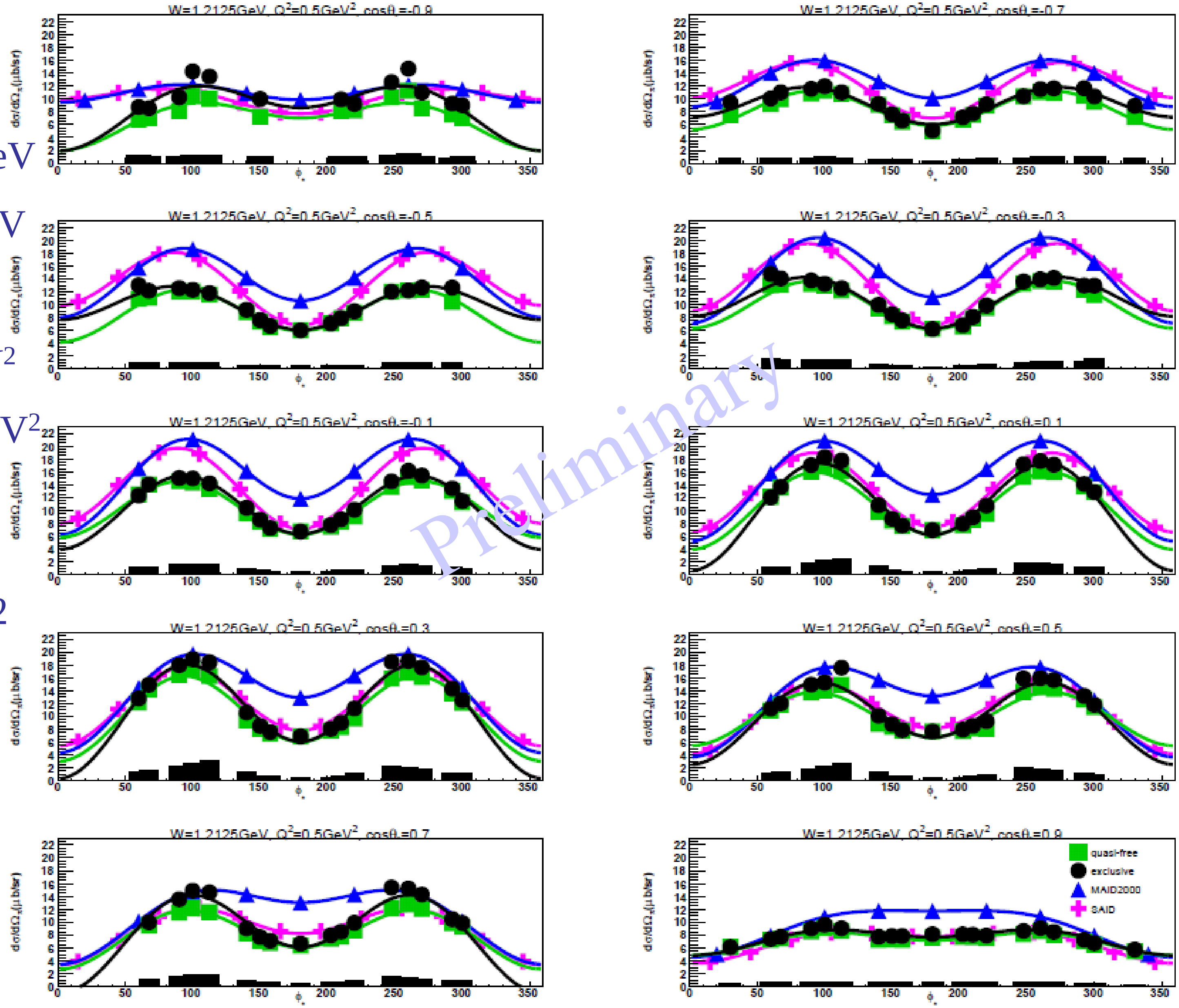
ΔW = 25 MeV

$Q^2 = 0.5\ GeV^2$

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

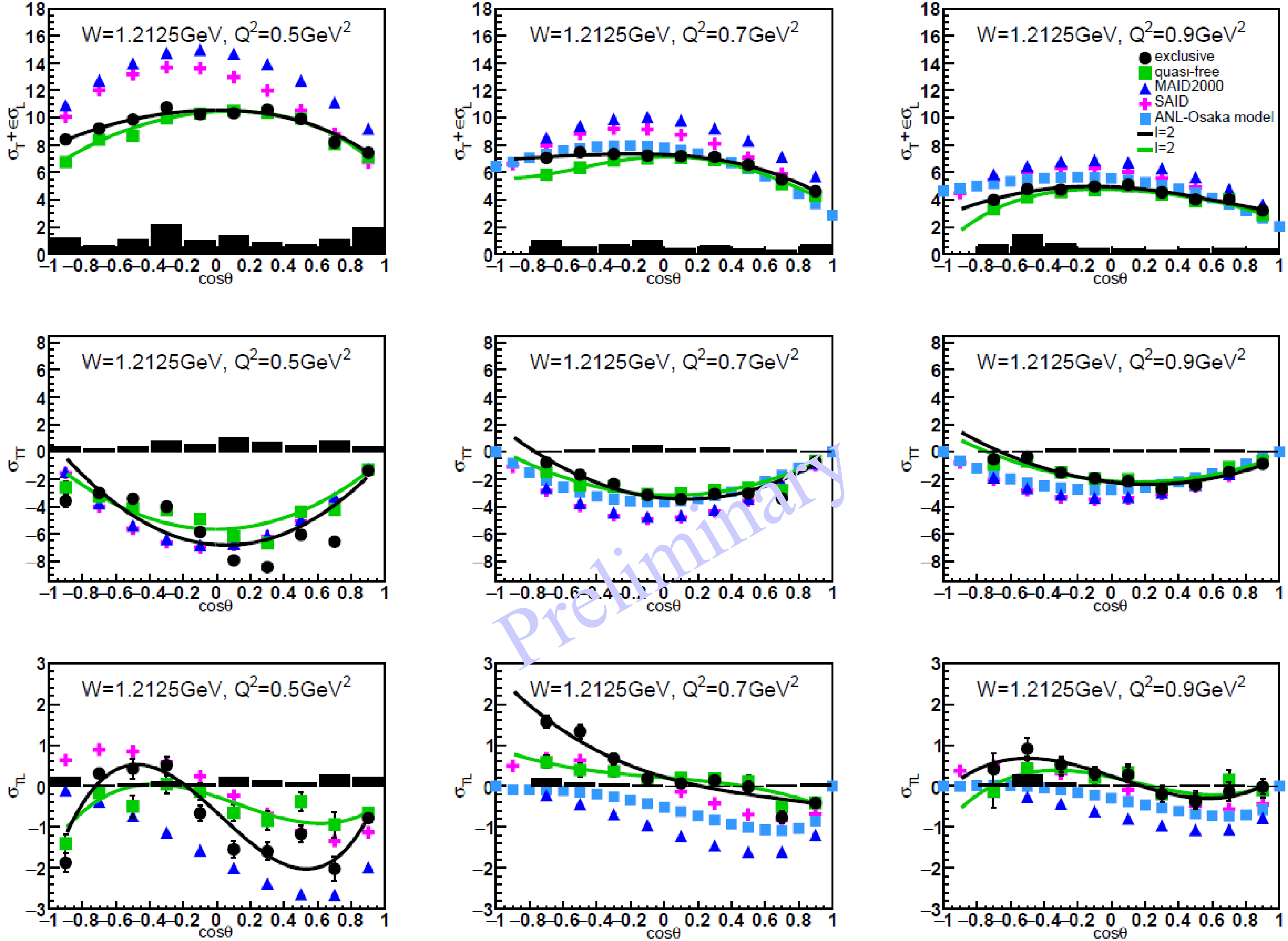
cos(θ) = -0.7
Δcos(θ) = 0.2
cos(θ) = 0.7

ϕ = 20°
Δϕ = 40°
ϕ = 340°



Single π^- Electroproduction off the Deuteron

Ye Tian



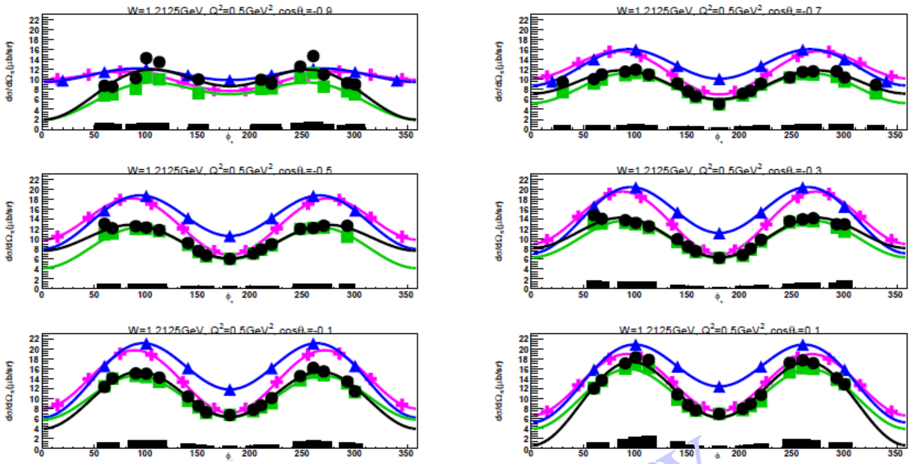
Single π^- Electroproduction off the Deuteron

$Q^2 = 0.5\ GeV^2$

$W = 1212\ MeV$

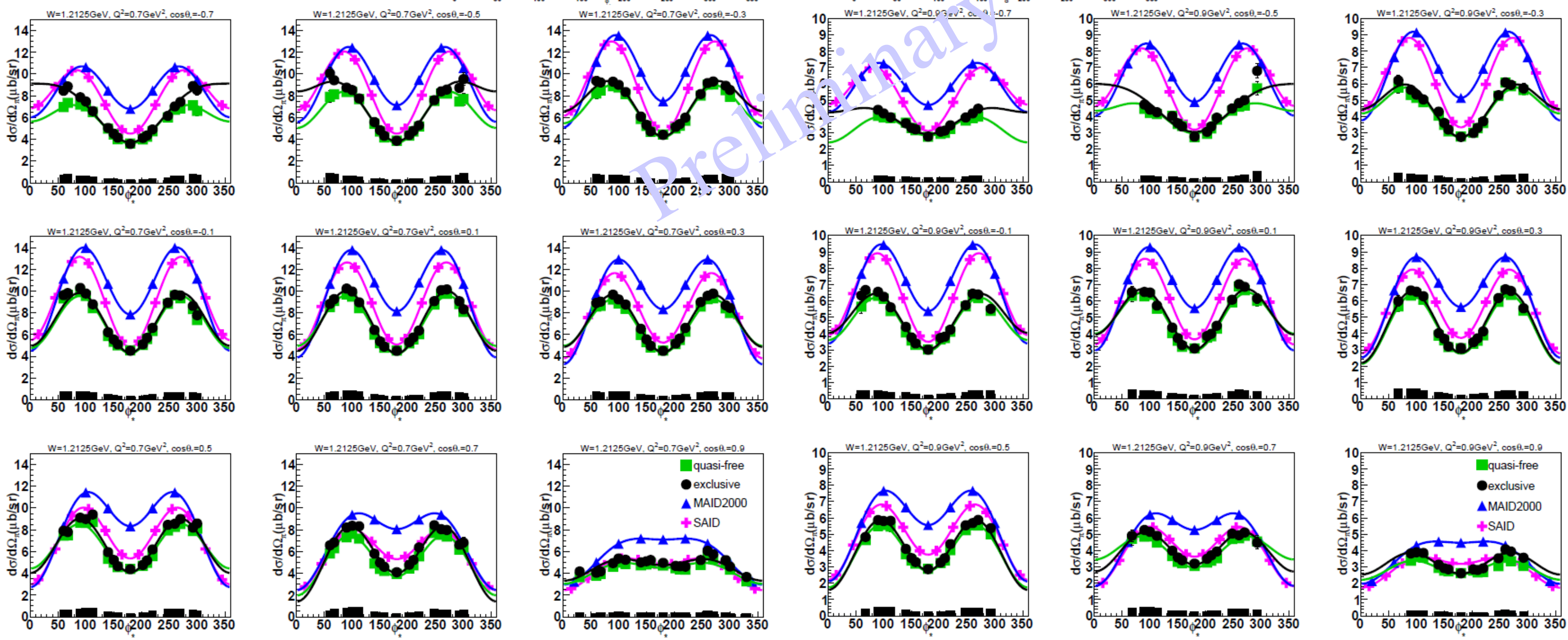
Ye Tian

Inclusive:
Gary Hollis



$Q^2 = 0.7\ GeV^2$

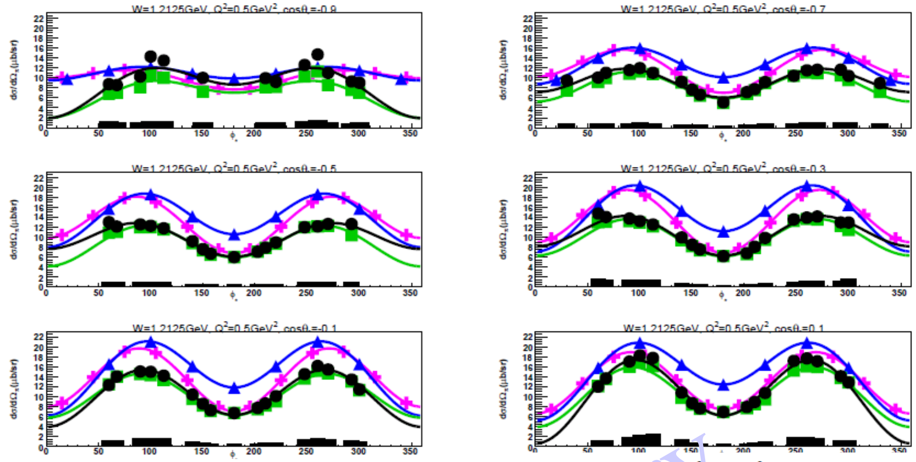
$Q^2 = 0.9\ GeV^2$



Single π^- Electroproduction off the Deuteron

$Q^2 = 0.5\ GeV^2$

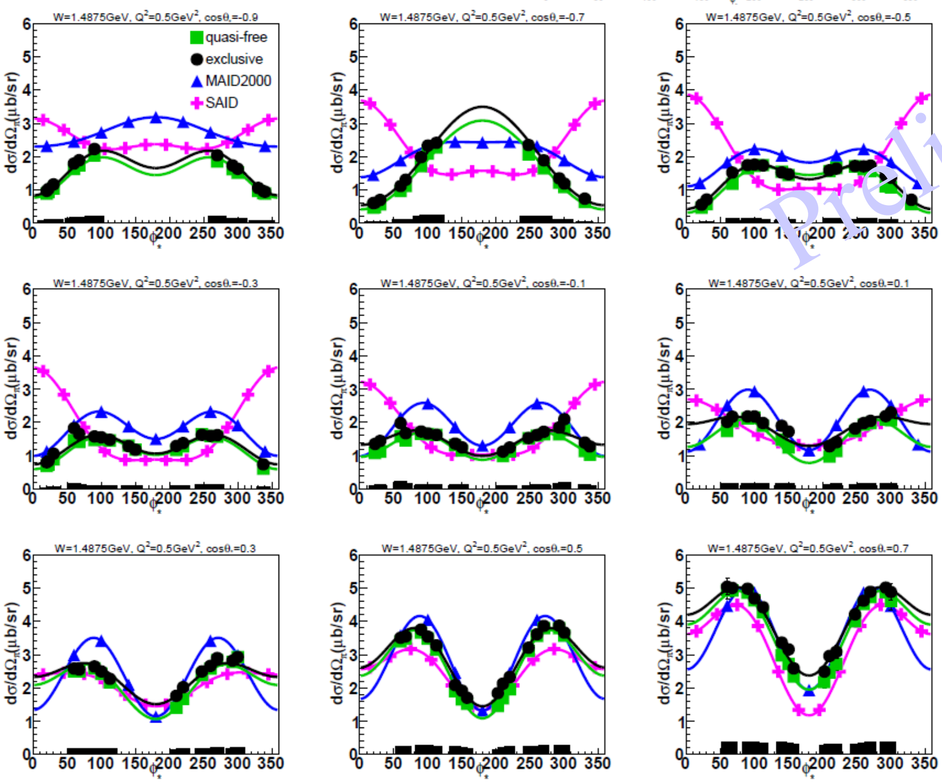
W = 1212 MeV



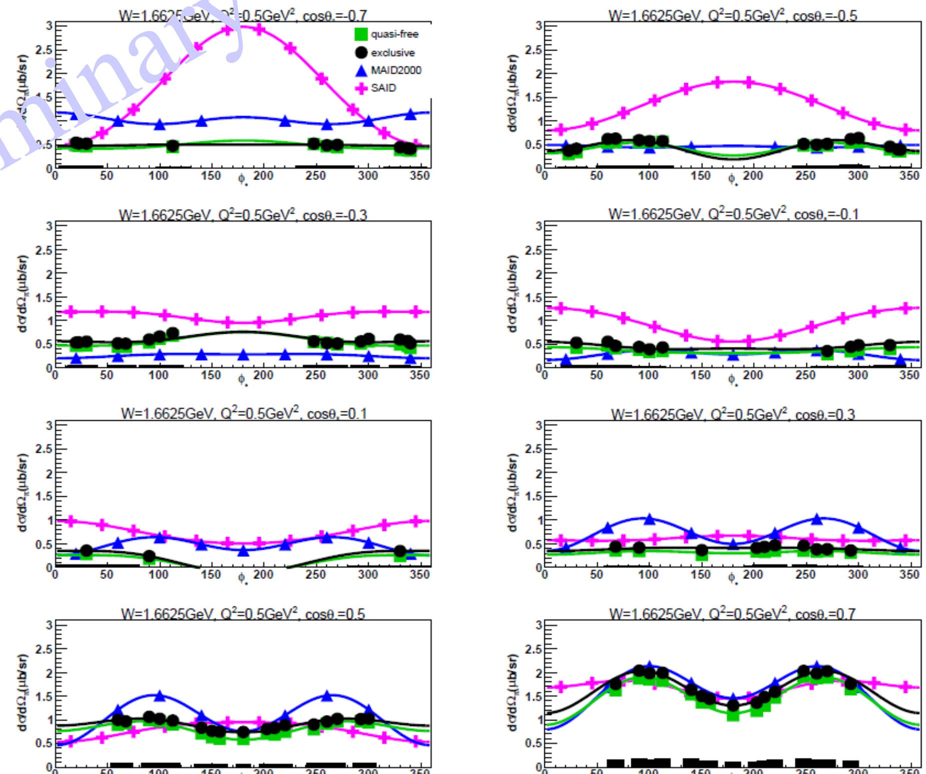
Ye Tian

Inclusive:
Gary Hollis

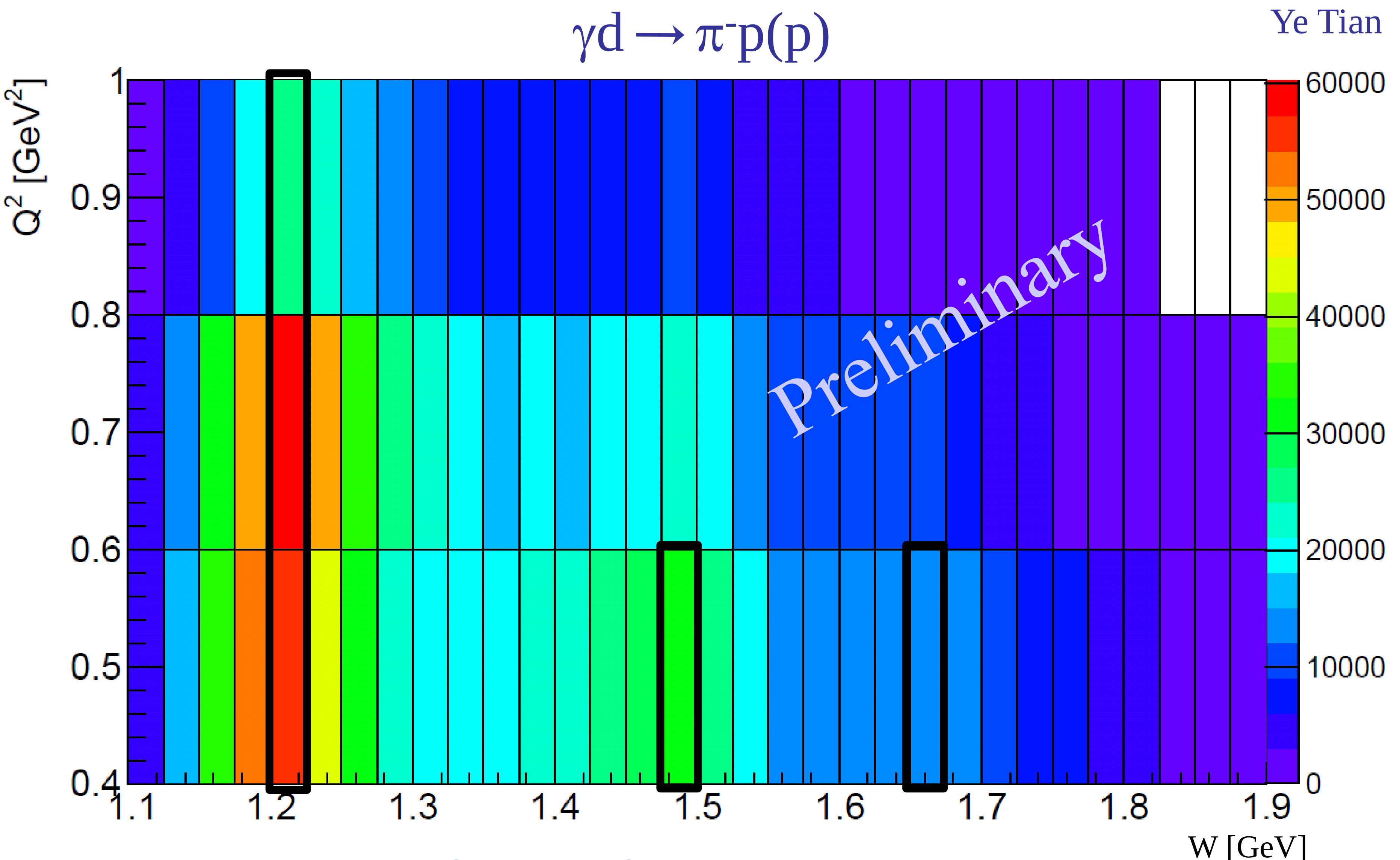
W = 1488 MeV



W = 1662 MeV



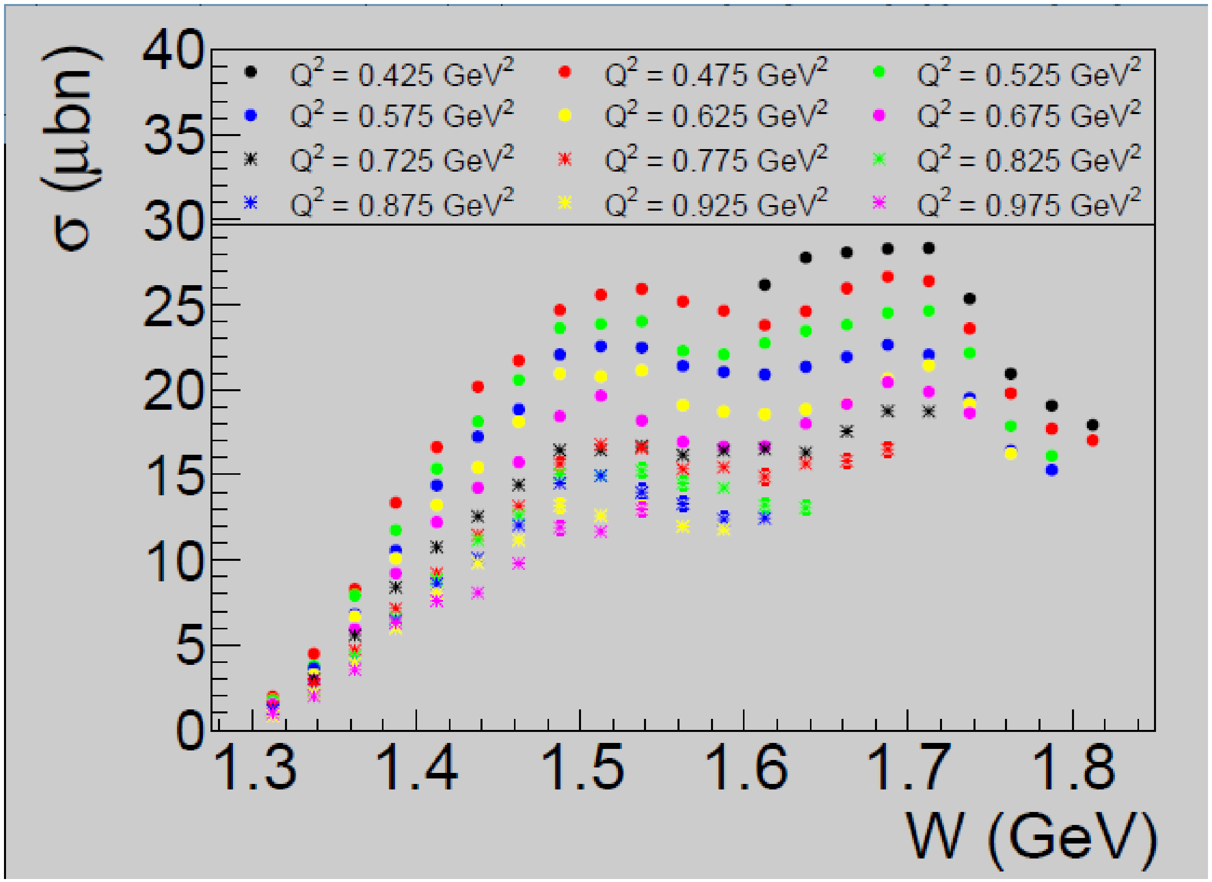
Single π⁻ Electroproduction off the Deuteron

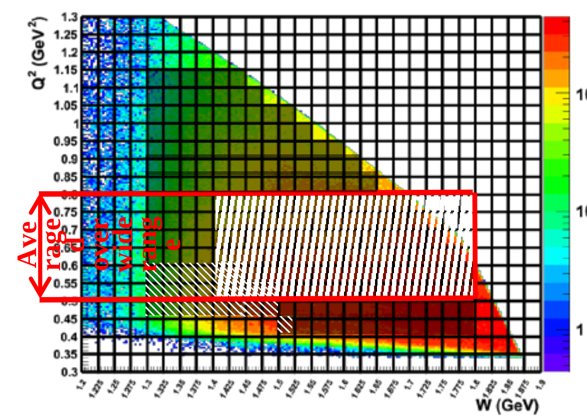


$\Delta Q^2 = 0.2\ GeV^2$ $\Delta W = 25\ MeV$

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

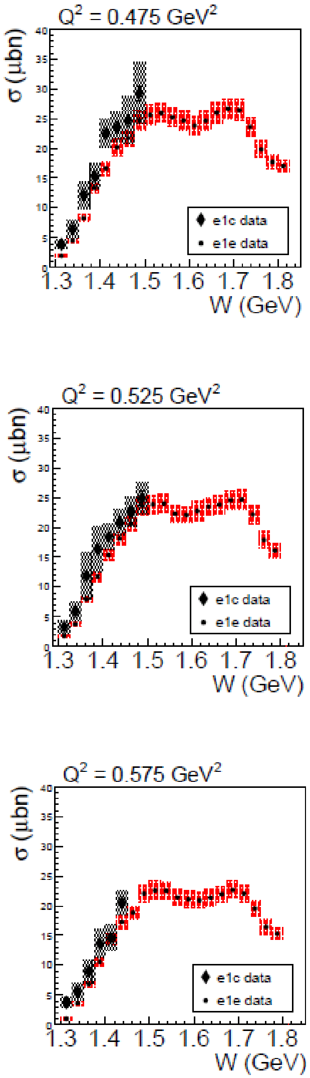
Gleb Fedotov
Phys. Rev. C 98, 025203 (2018)

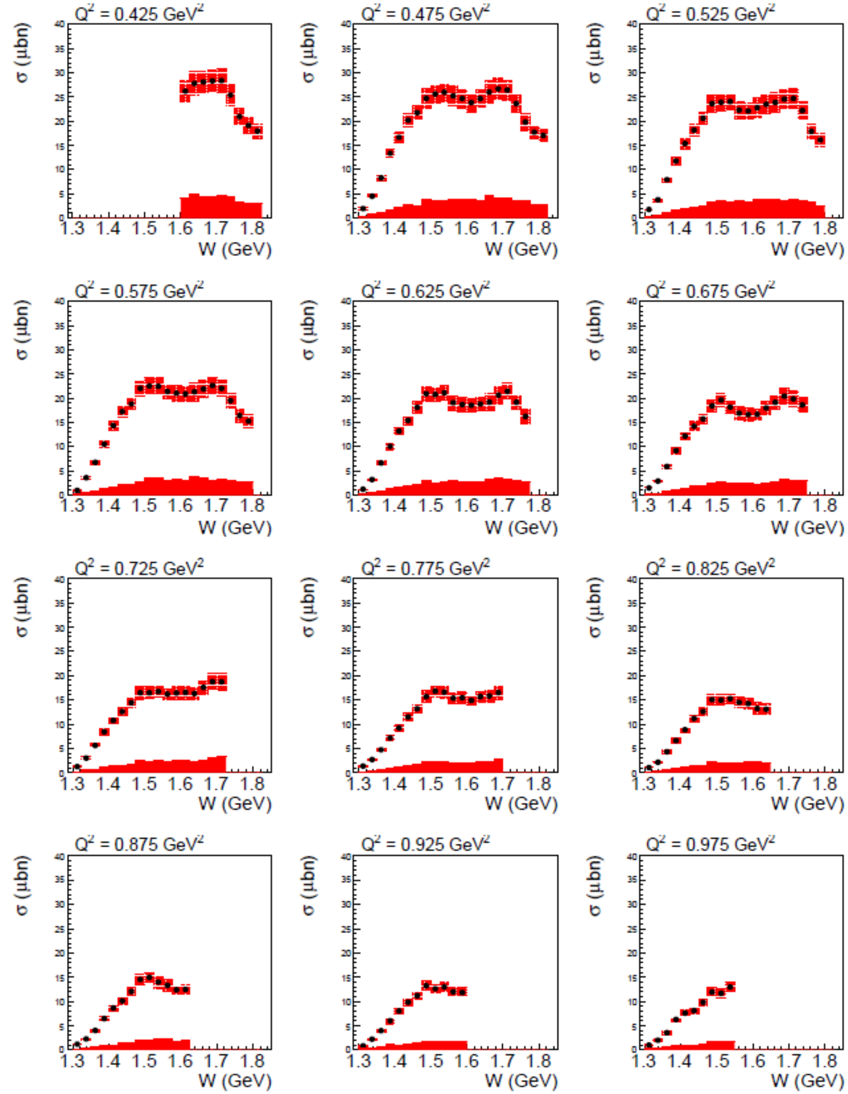




$p\pi^+\pi^-$ event yields over W and Q^2. Gray shaded area new e1e data set, hatched area at low Q^2 already published e1c data by G. Fedotov *et al.* and hatched area at higher Q^2 already published data in one large Q^2 bin by M. Ripani *et al.*

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





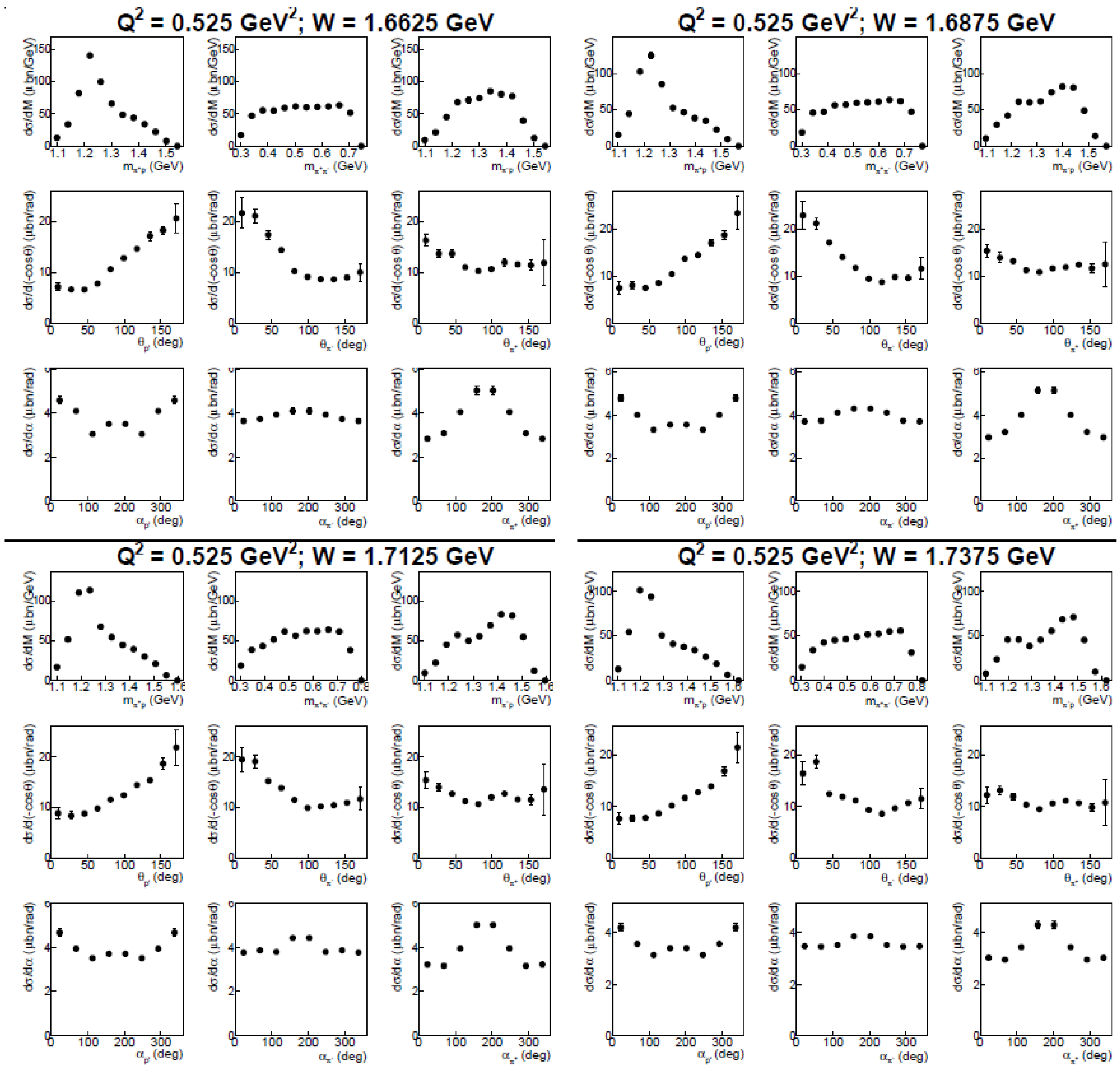
Gleb Fedotov

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.

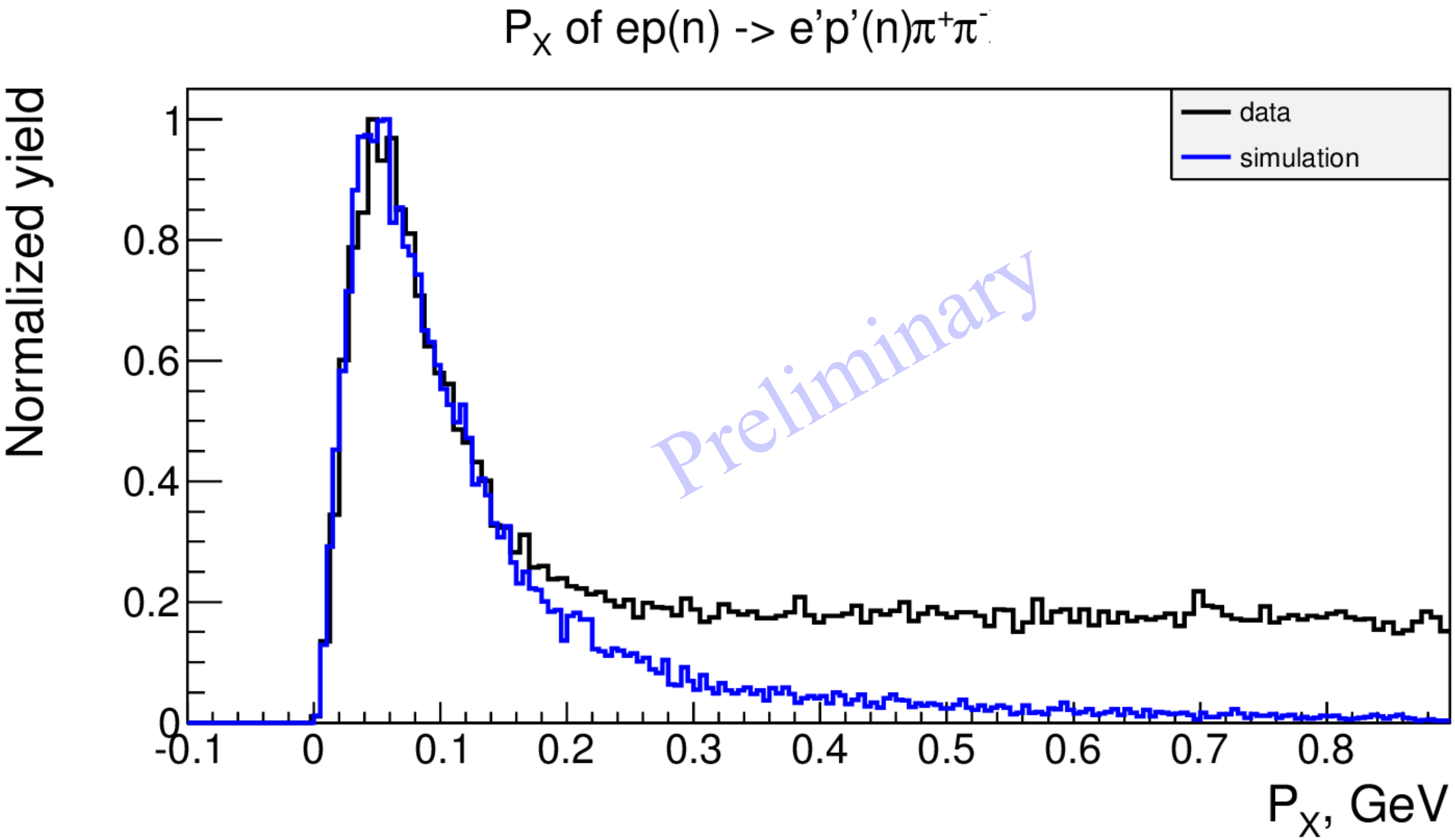
$N\pi^+\pi^-$ Single-Differential Cross Sections

Gleb Fedotov



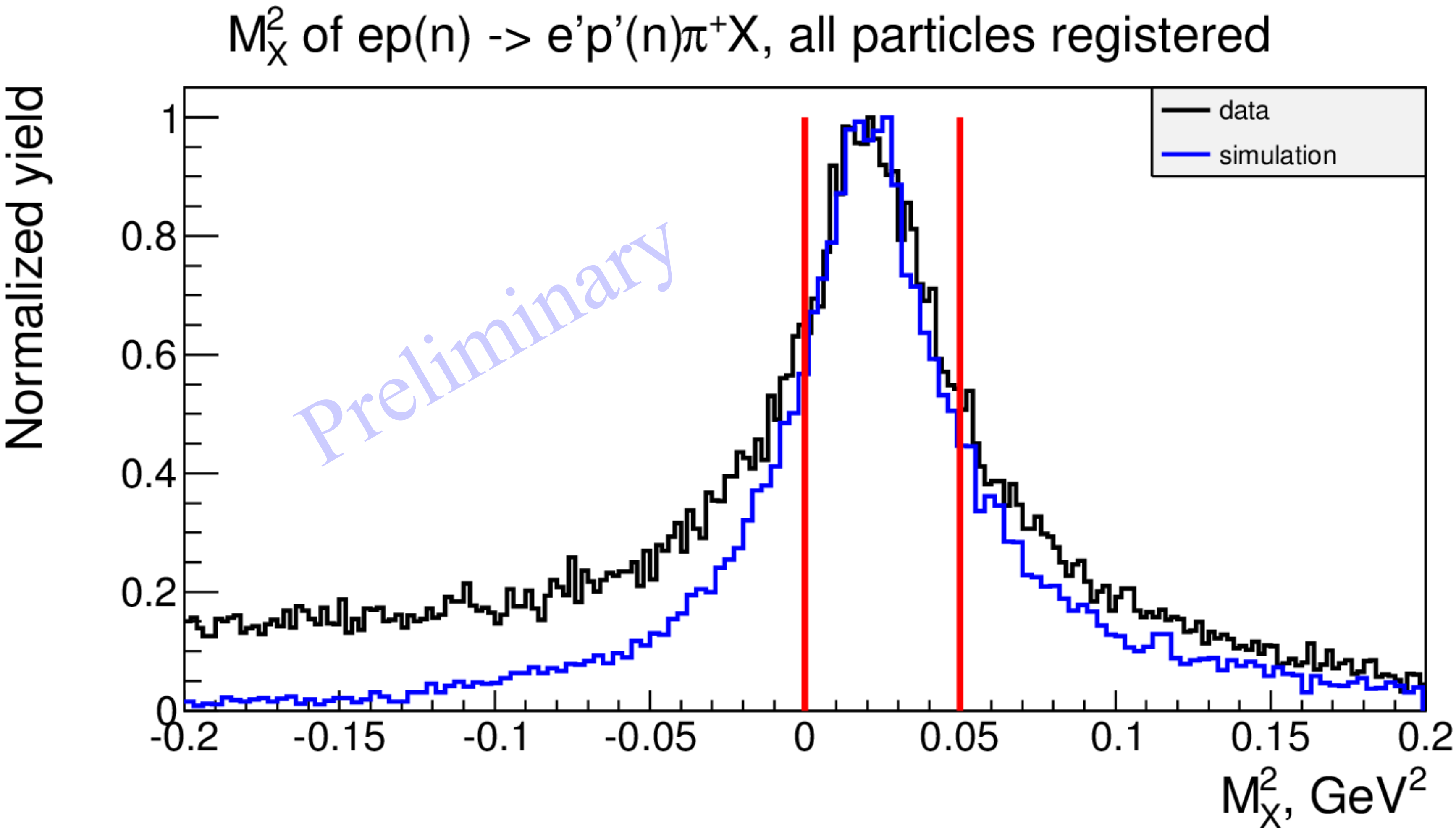
Exclusive $\pi^+\pi^-$ Electroproduction off the Deuteron

Iuliia Skorodumina



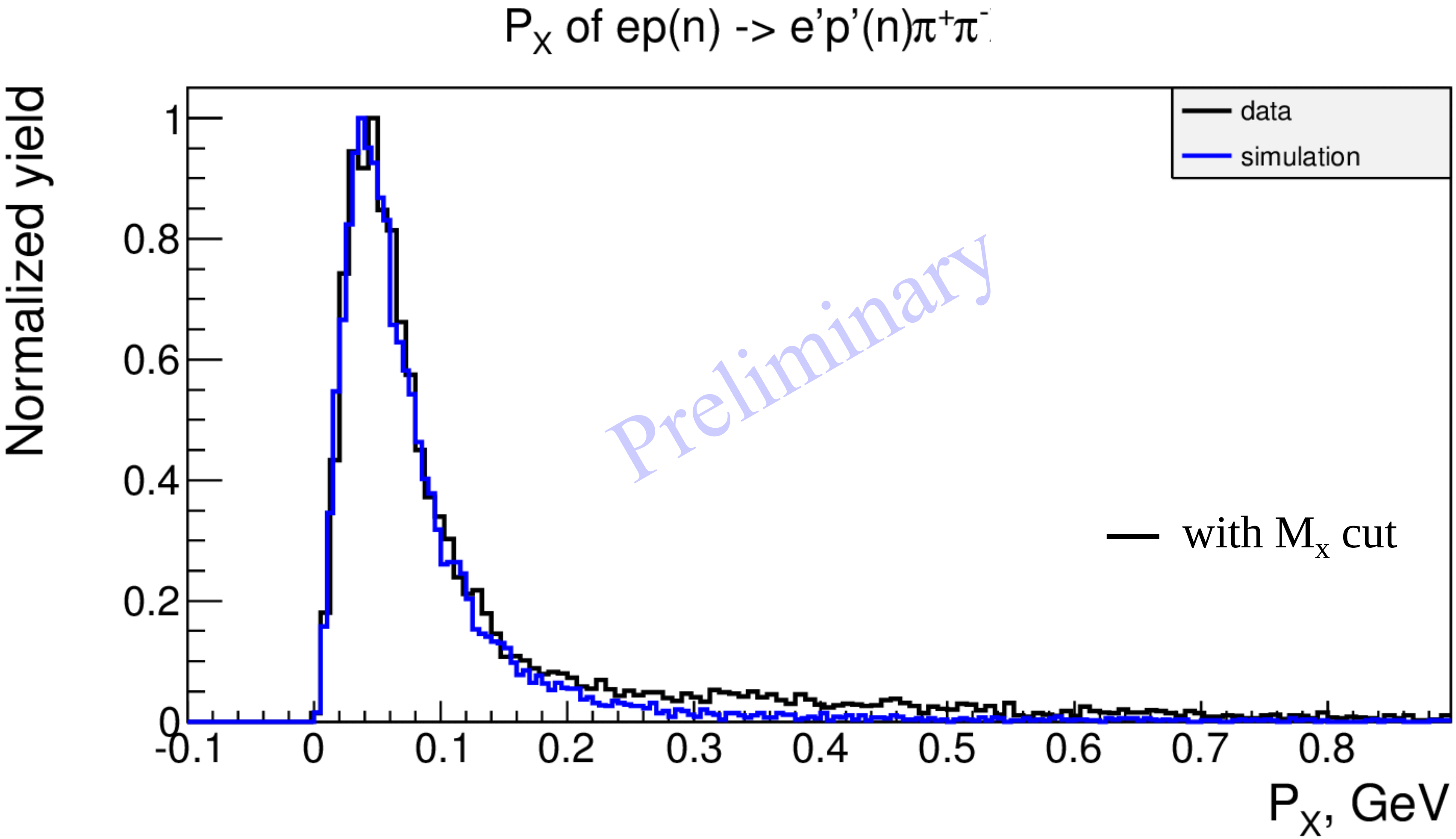
Exclusive $\pi^+\pi^-$ Electroproduction off the Deuteron

Iuliia Skorodumina



Exclusive $\pi^+\pi^-$ Electroproduction off the Deuteron

Iuliia Skorodumina

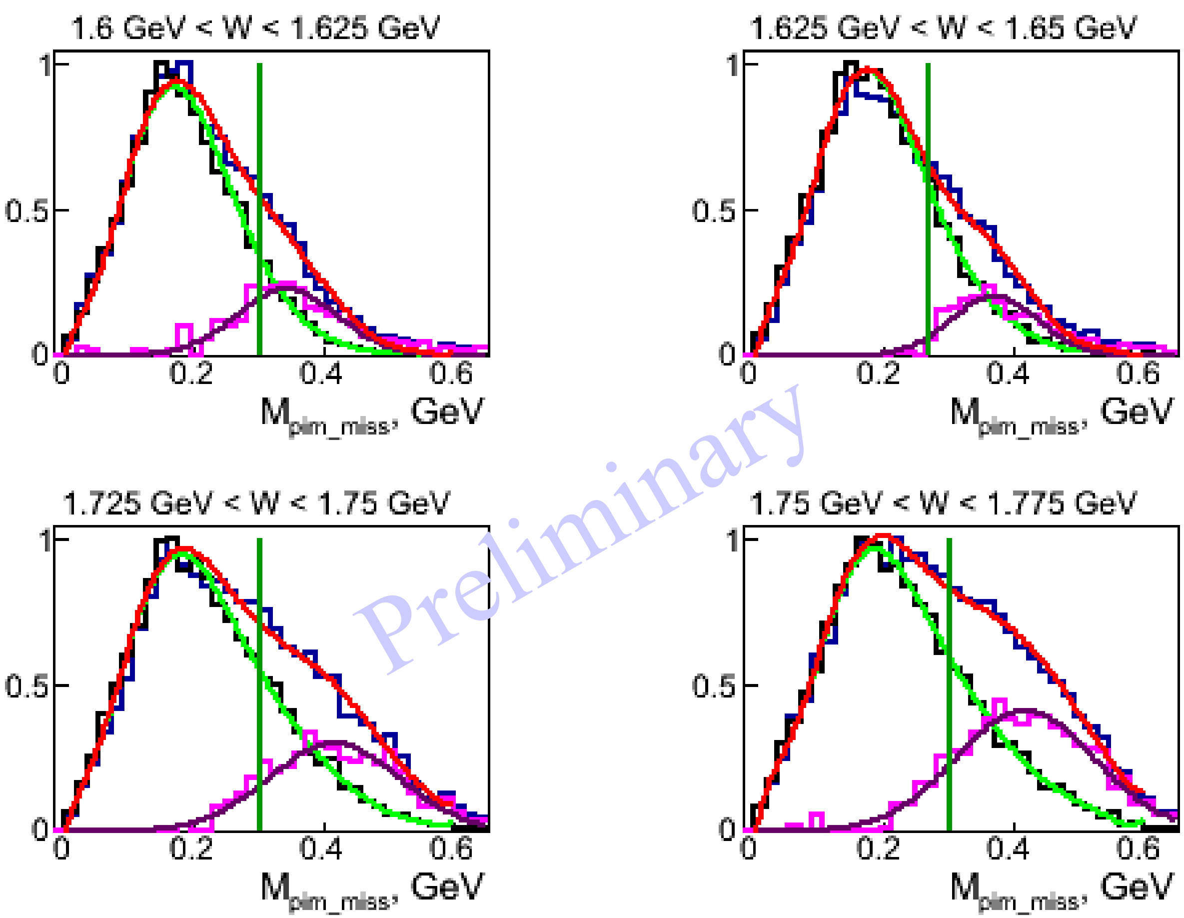


Effective FSI Correction in $p(n)\pi^+(\pi^-)$

Iuliia Skorodumina

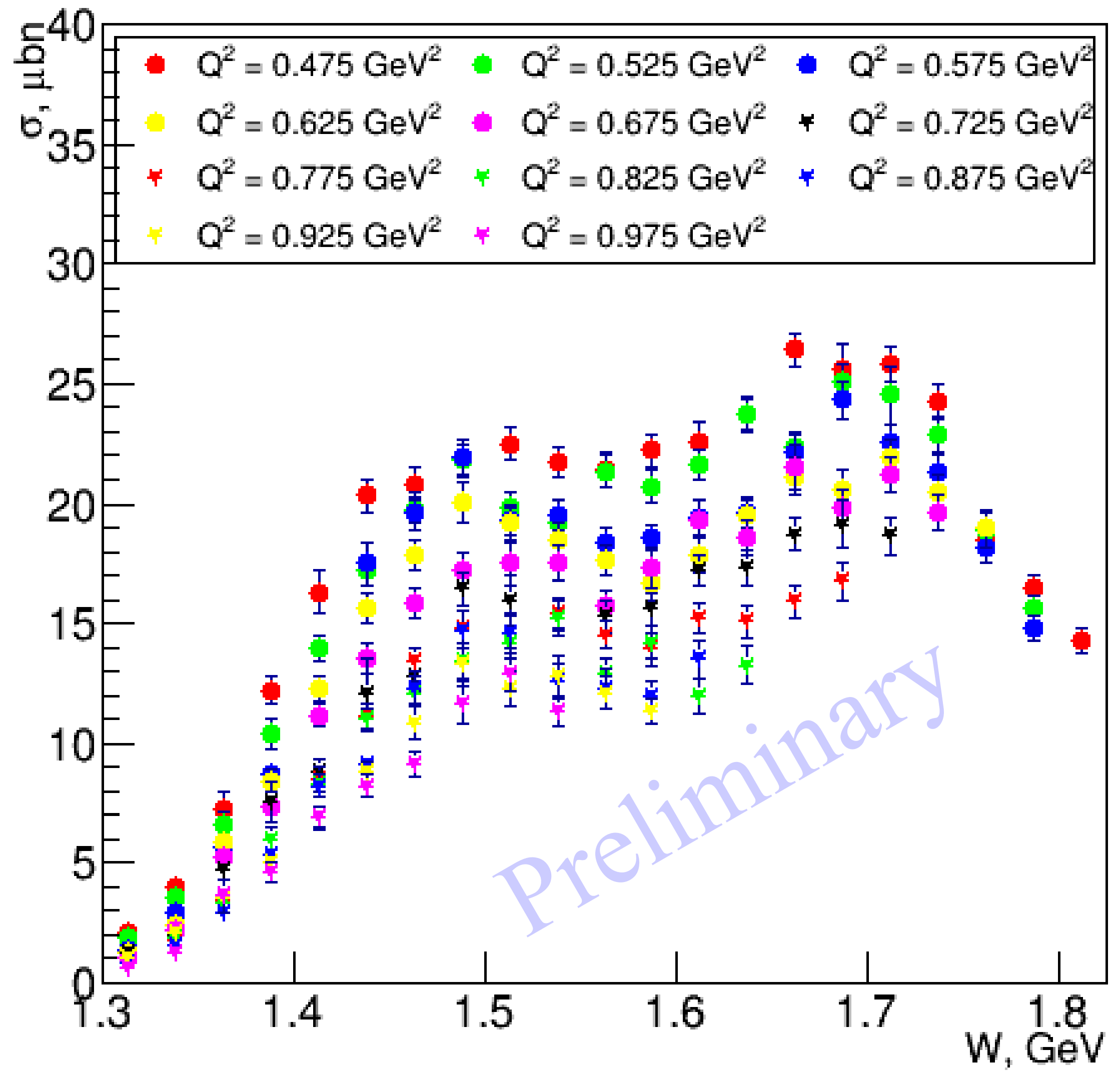
$$\frac{d\sigma_{corrected}}{dW\,dQ^2 d\tau} = \frac{d\sigma_{not\ corrected}}{dW\,dQ^2 d\tau} F_{fsi}(\Delta W, \Delta Q^2)$$

$$F_{fsi}(\Delta W, \Delta Q^2) = \frac{Area\ under\ green}{Area\ under\ red}$$



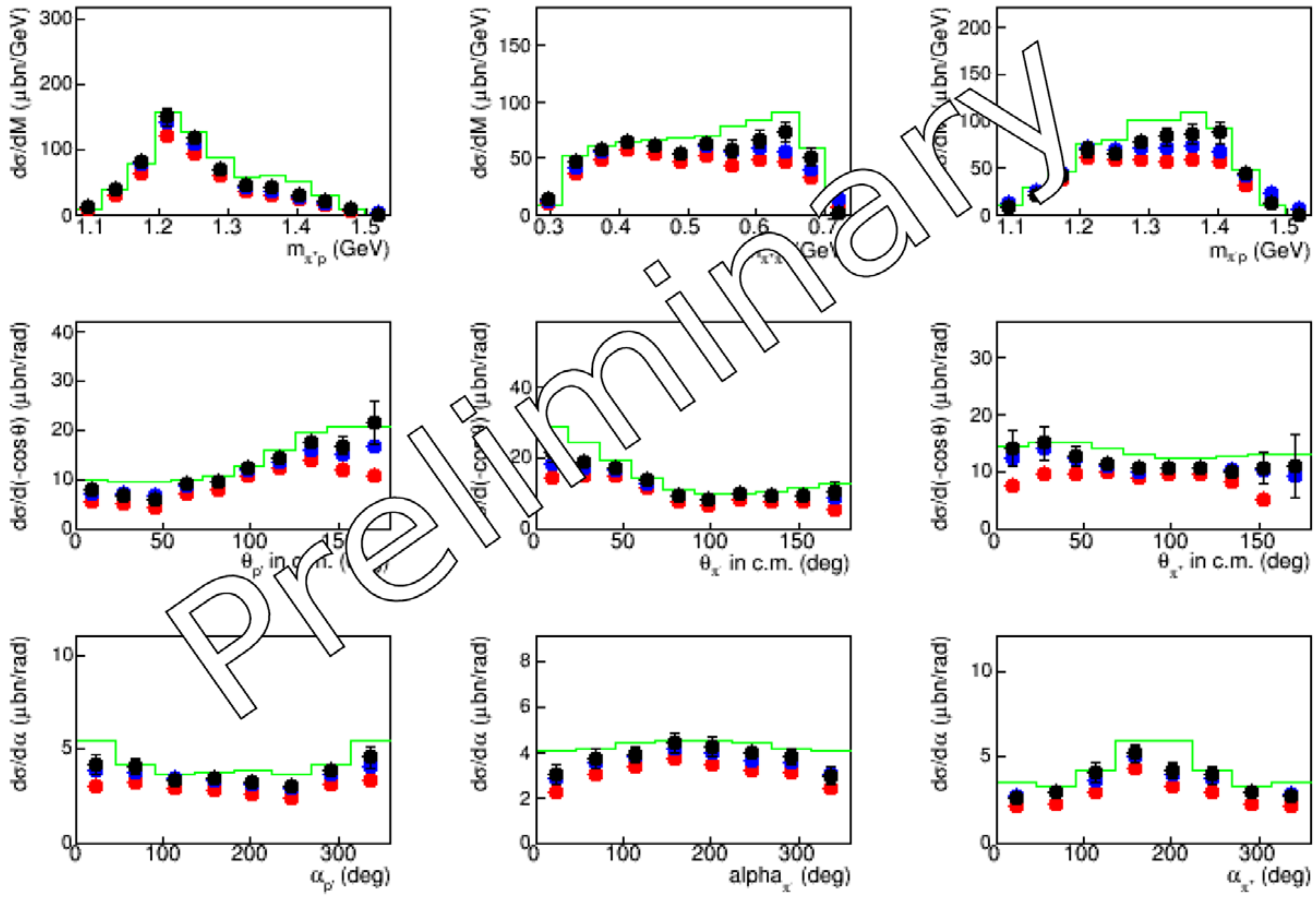
Integrated Cross Section off the Proton in Deuteron

Iuliia Skorodumina



Comparison with Free Proton Cross Section

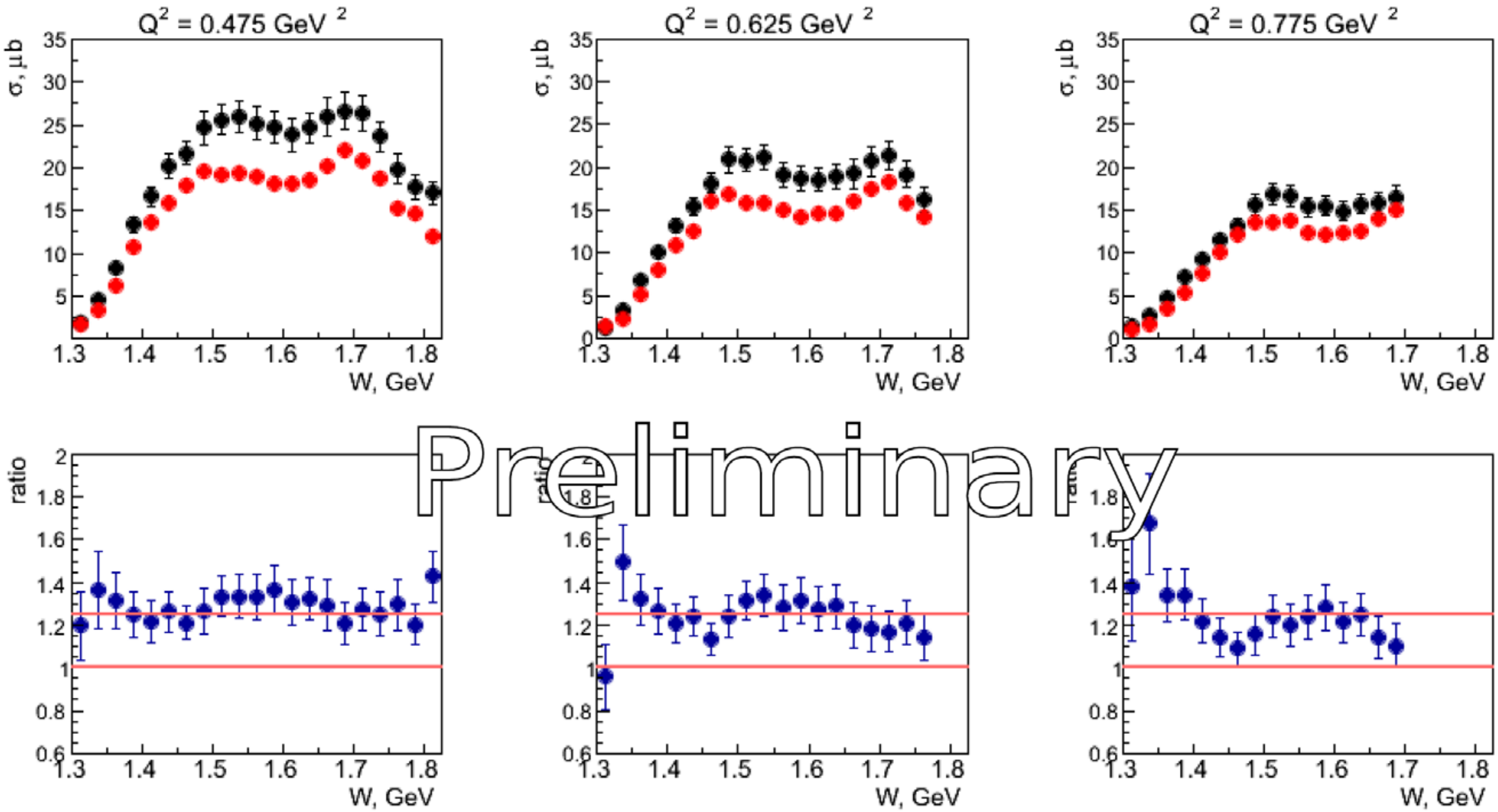
Iuliia



Red – empty cells are NOT filled **Blue** – empty cells are filled
Black – Fermi correction is applied **Green Curve** – TWOPEG off free proton

Comparison with Free Proton Cross Section

Iuliia

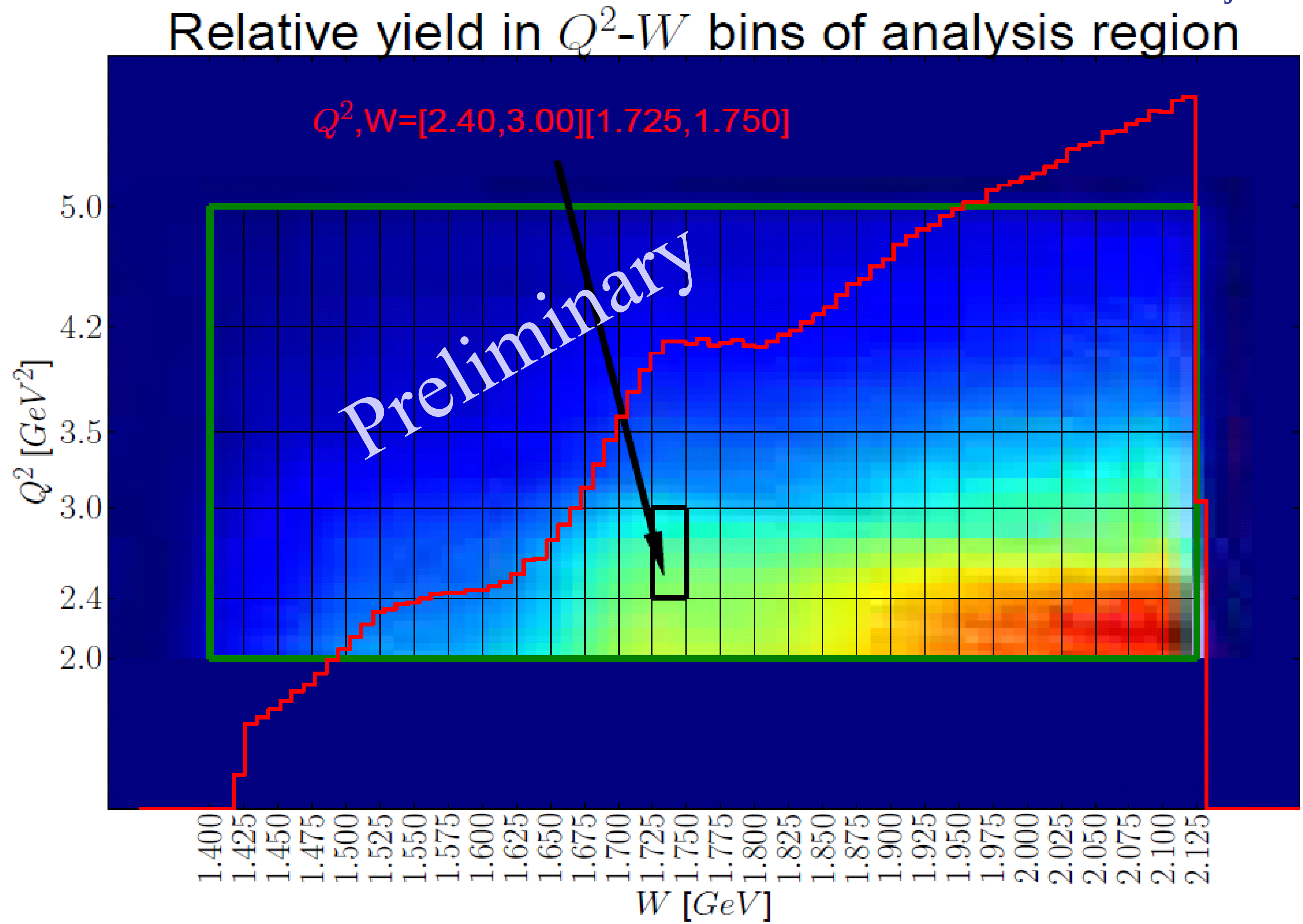


Black bullets – free proton cross sections (e1e at E_{beam} = 2.039 GeV)
error bars show both statistical and systematical uncertainties
G. Fedotov under paper review

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

φ-dependent Nππ Single-Differential Cross Sections

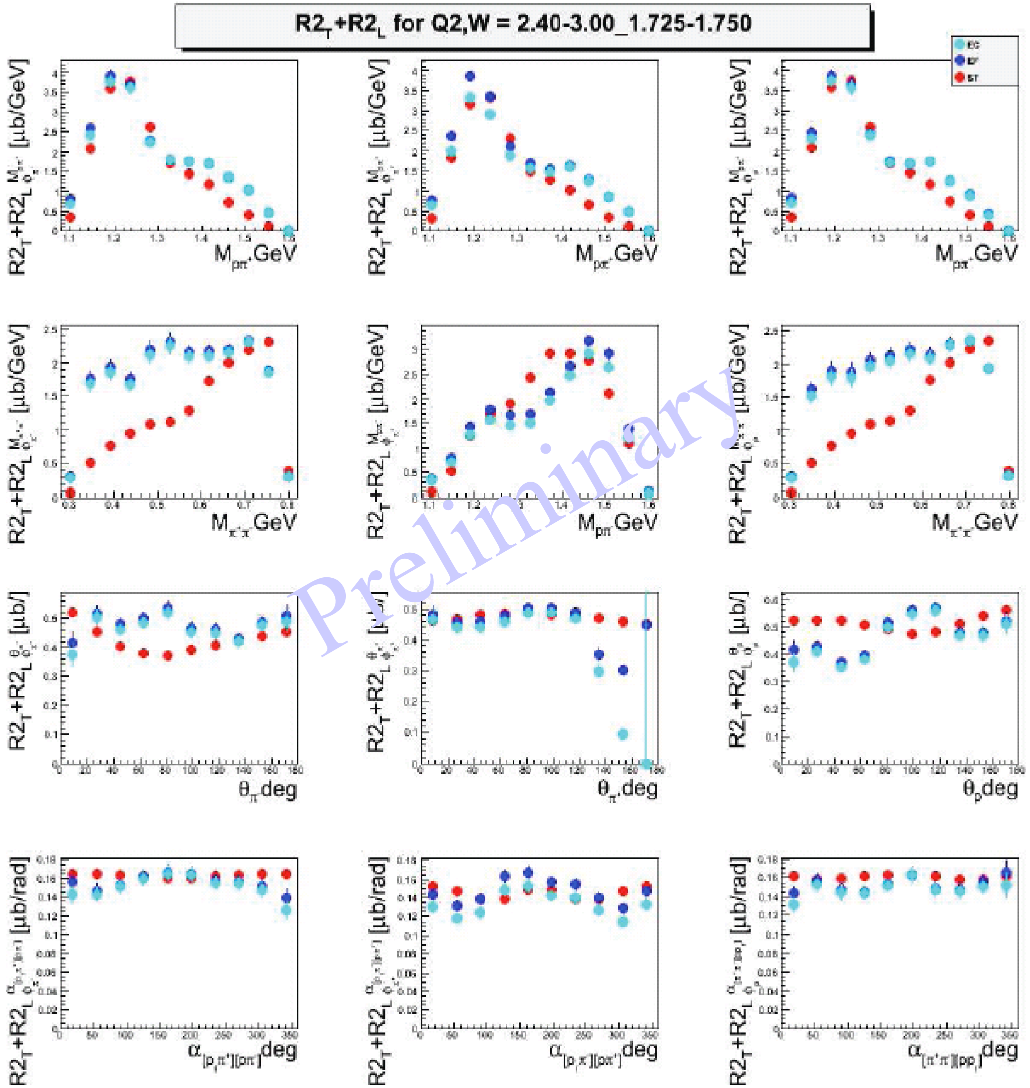
Arjun Trivedi



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



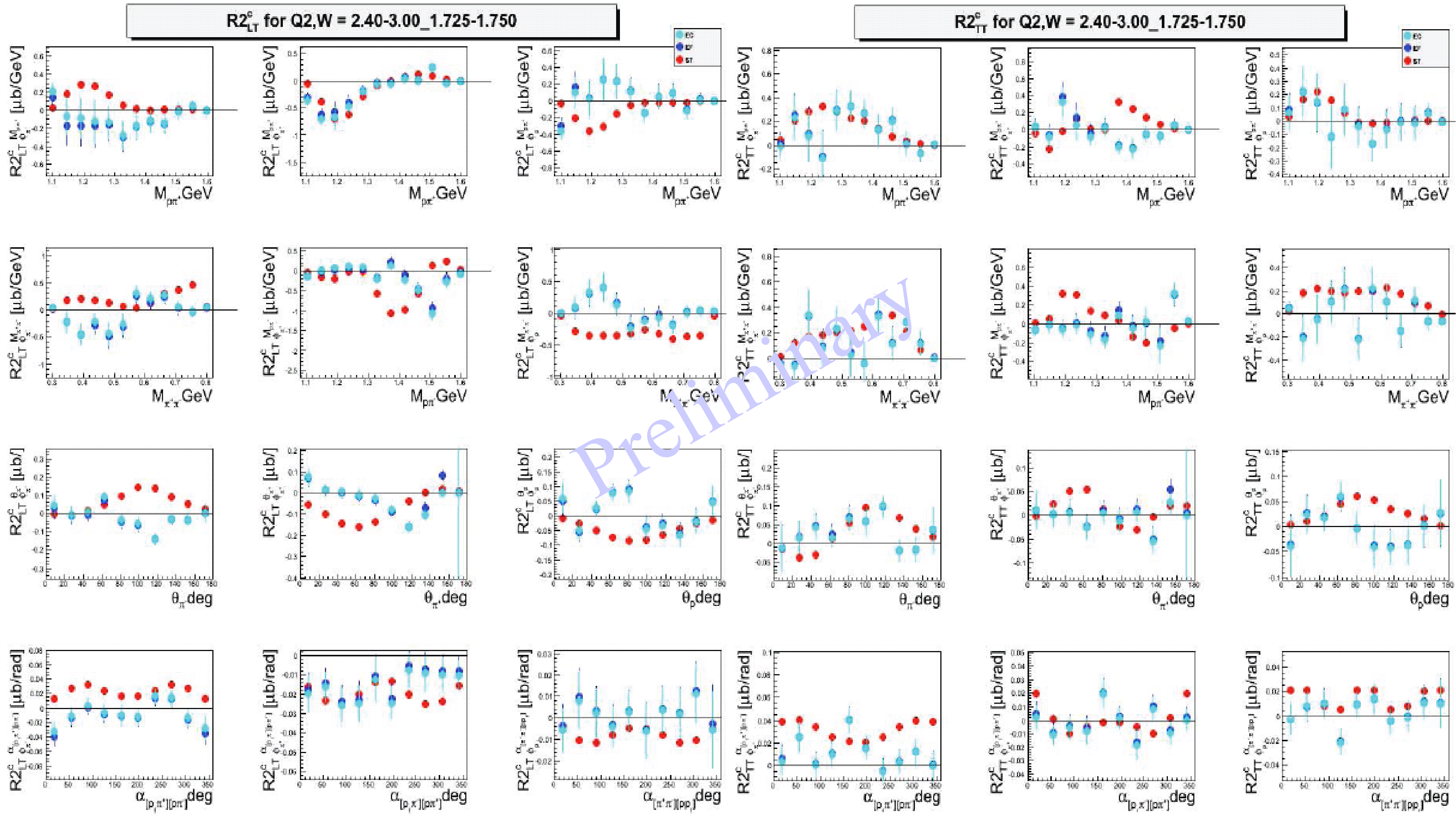
- normalized
- hole filled
- TWOPEG

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

φ-dependent Nππ Single-Differential Cross Sections

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

Arjun Trivedi



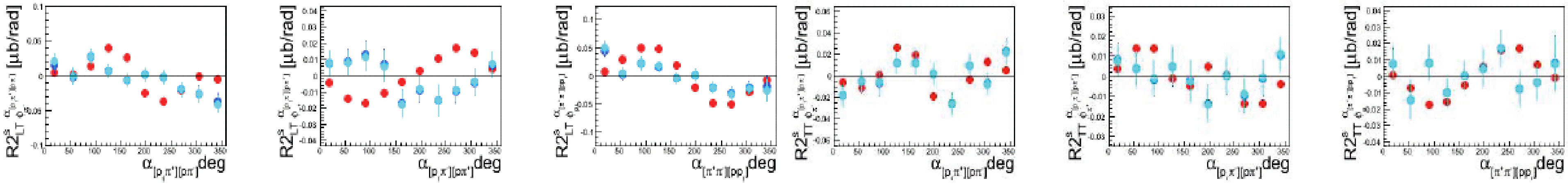
$$\left(\frac{d^2\sigma}{dX_{ij}\,d\phi_i}\right) = R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}} + \underline{R2_{LT}{}^{c,X_{ij}}\cos\phi_i} + \underline{R2_{TT}{}^{c,X_{ij}}\cos 2\phi_i} + \delta_{X_{ij}\alpha_i}\left(R2_{LT}{}^{s,\alpha_i}\sin\phi_i + R2_{TT}{}^{s,\alpha_i}\sin 2\phi_i\right)$$

φ-dependent Nππ Single-Differential Cross Sections

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

Arjun Trivedi

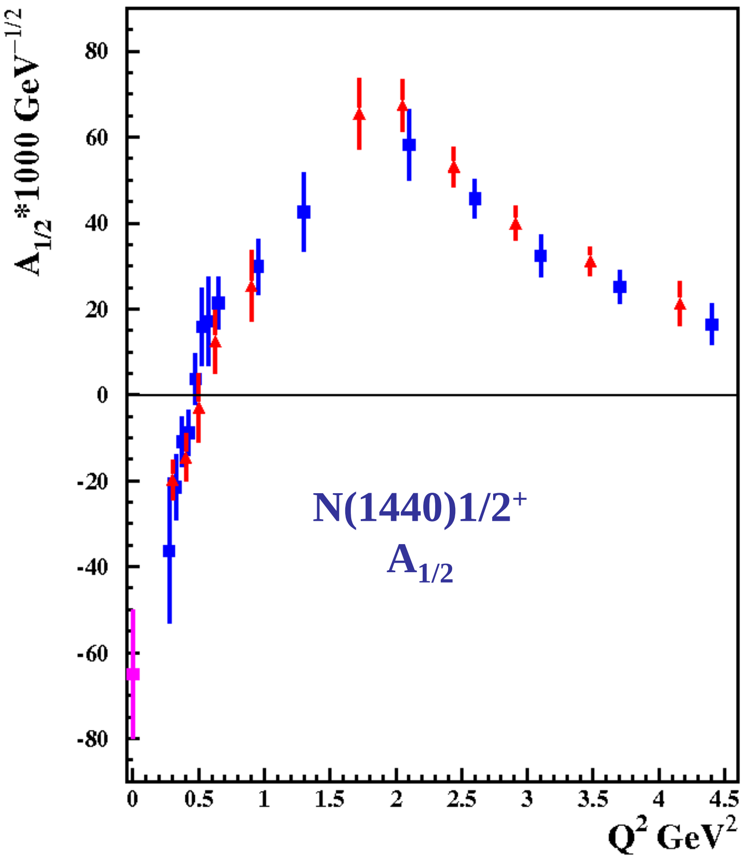
Chris McLauchlin extracts the beam helicity dependent differential cross sections.



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

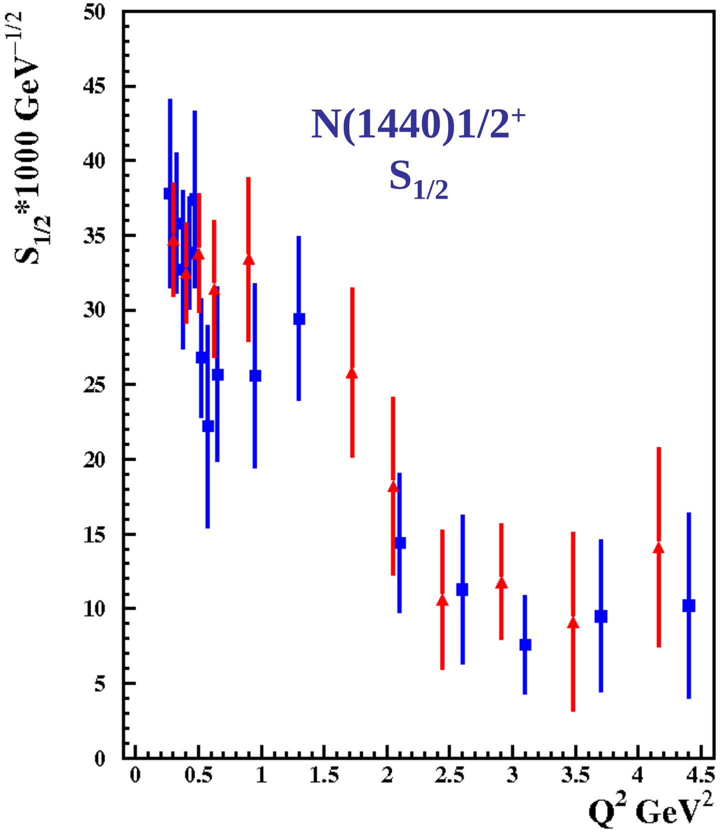
N(1440)1/2$^+$ Photo- and Electroexcitation Amplitudes

Viktor Mokeev



From Nπ electroproduction off protons: Combined Unitary Isobar and Dispersion Relation Approach (Inna Aznauryan)

From $\pi^+\pi^-p$ electroproduction off protons: Data driven JM meson-baryon model

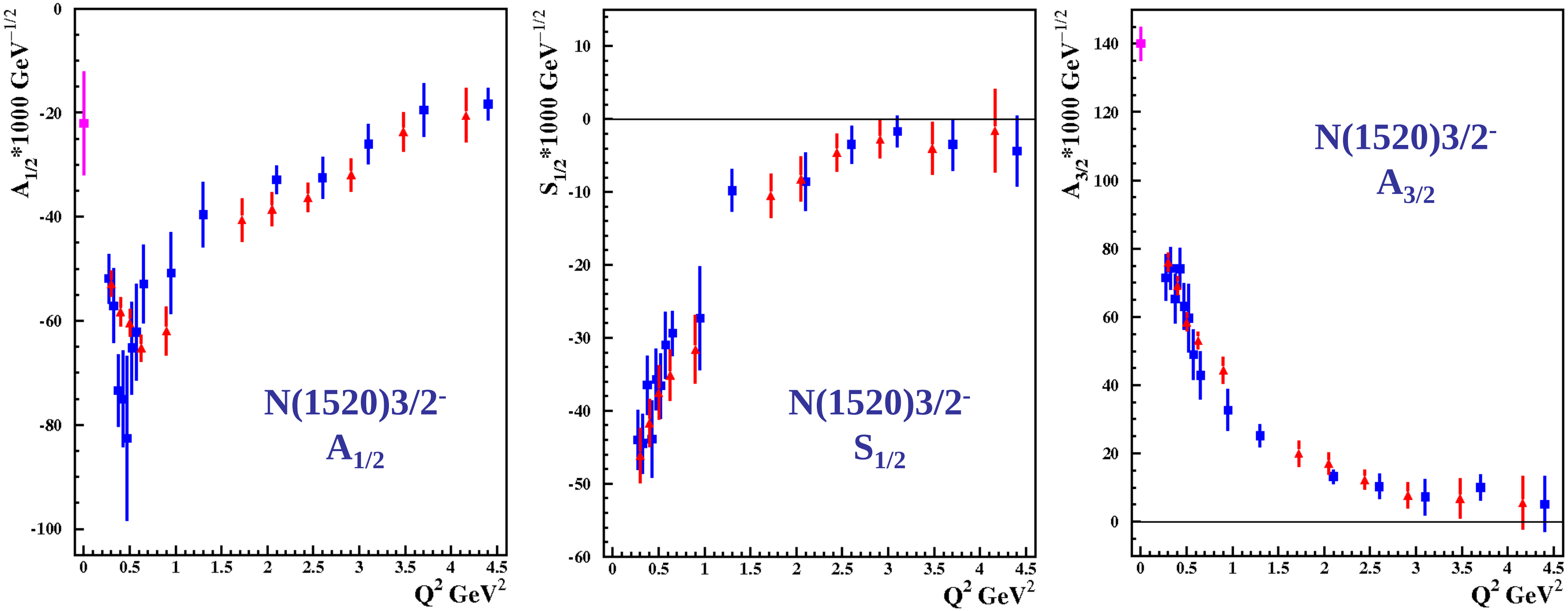


Photocoupling from PDG2018

Unpolarized differential cross sections, TT, LT, LT′, beam, target, and beam-target asymmetry data were fit.

N(1520)3/2$^-$ Photo- and Electroexcitation Amplitudes

Viktor Mokeev

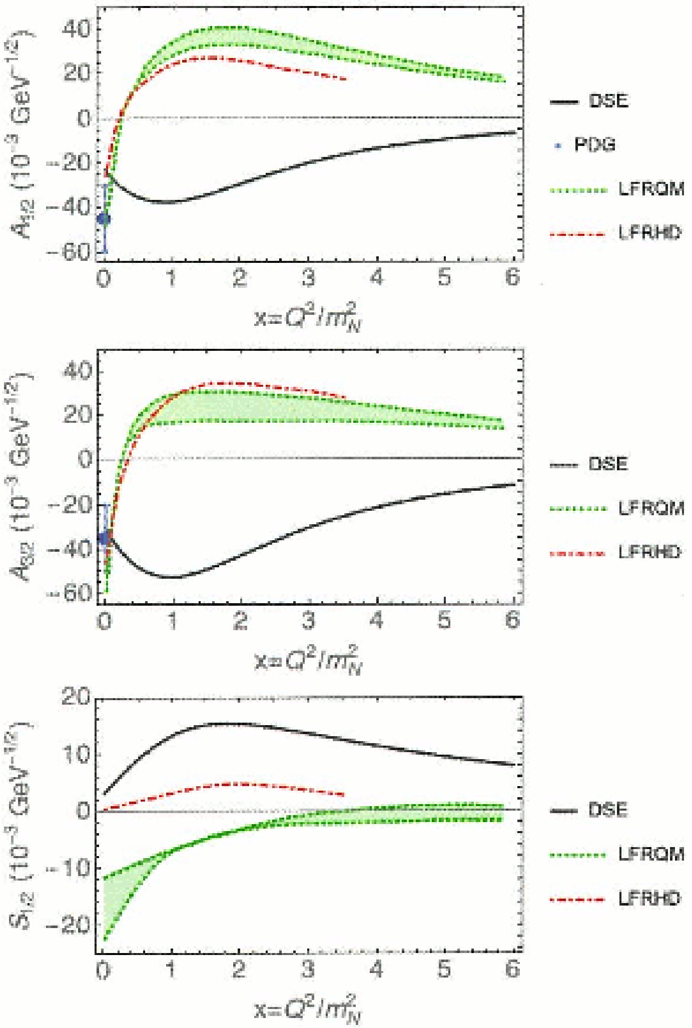


Consistent results on resonance electroexcitation amplitudes from independent studies of two dominant exclusive meson electroproduction channels off proton Nπ and $\pi^+\pi^-p$ strongly support

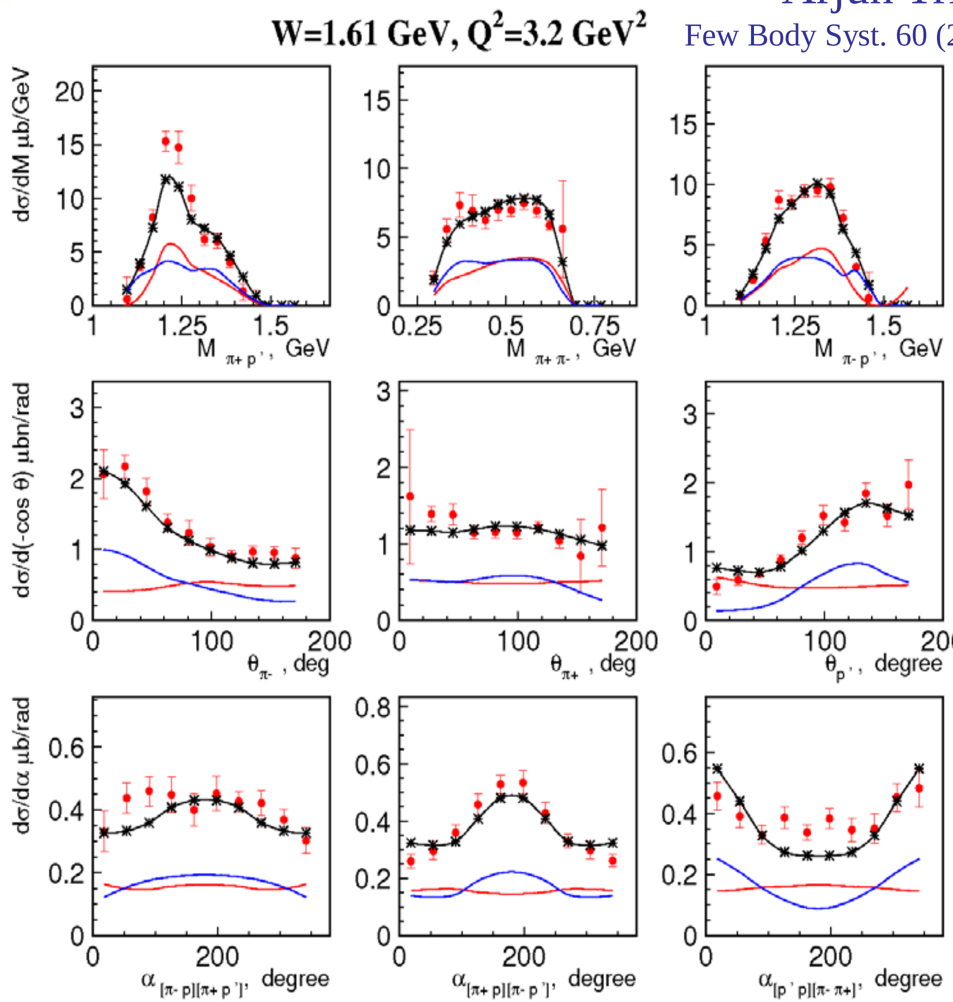
- a credible extraction of these quantities and
- the capability of the reaction models developed by CLAS collaboration to reliably extract nucleon resonance electroexcitation amplitudes from independent studies of the exclusive Nπ and $\pi^+\pi^-p$ electroproduction off protons.

First Radial Δ-Excitation from Nππ Cross Sections

Δ(1600)3/2⁺



Arjun Trivedi
Few Body Syst. 60 (2019) 5



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

Viktor Mokeev (JM19)

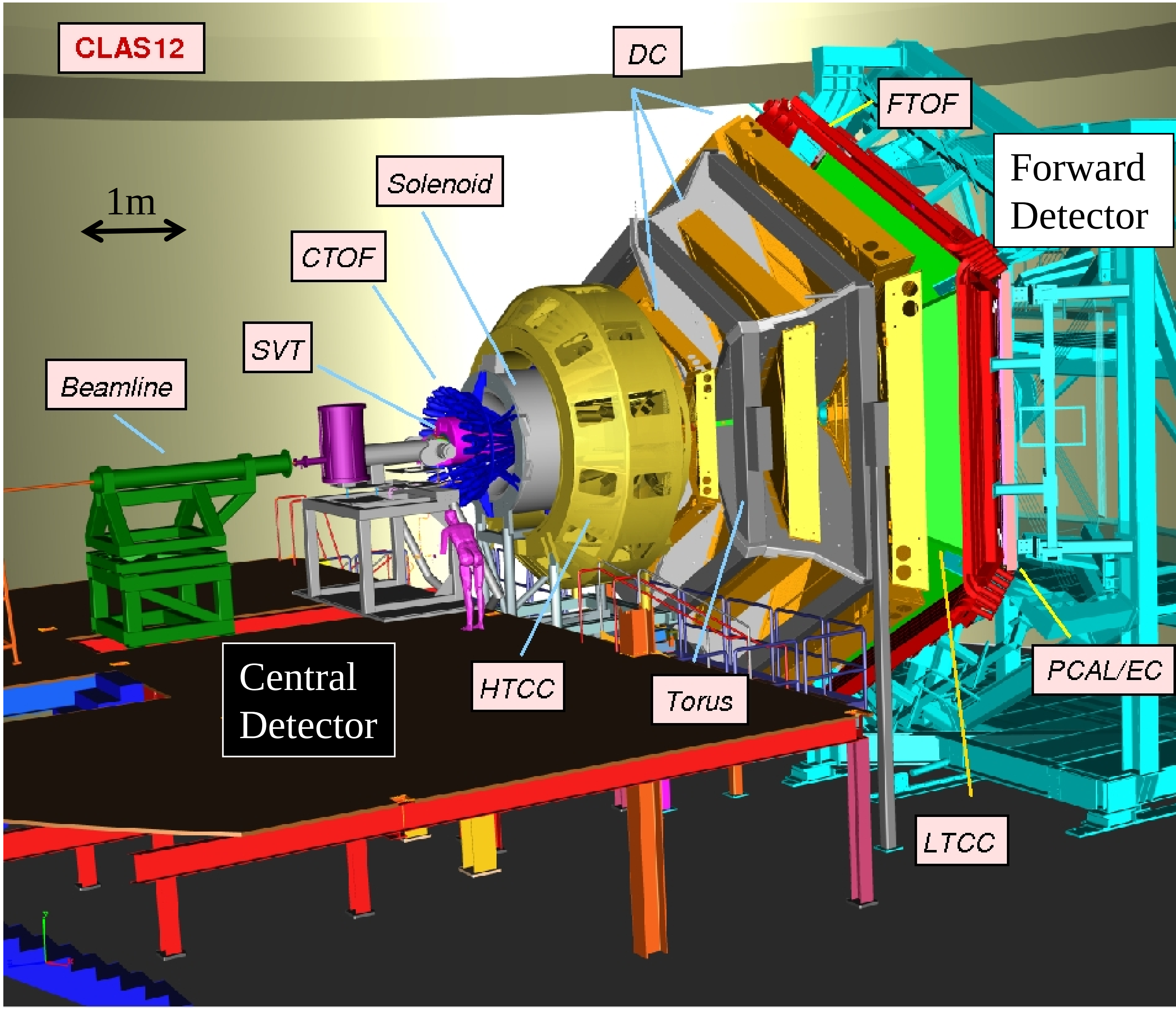
N*
non-resonant contributions

CLAS12

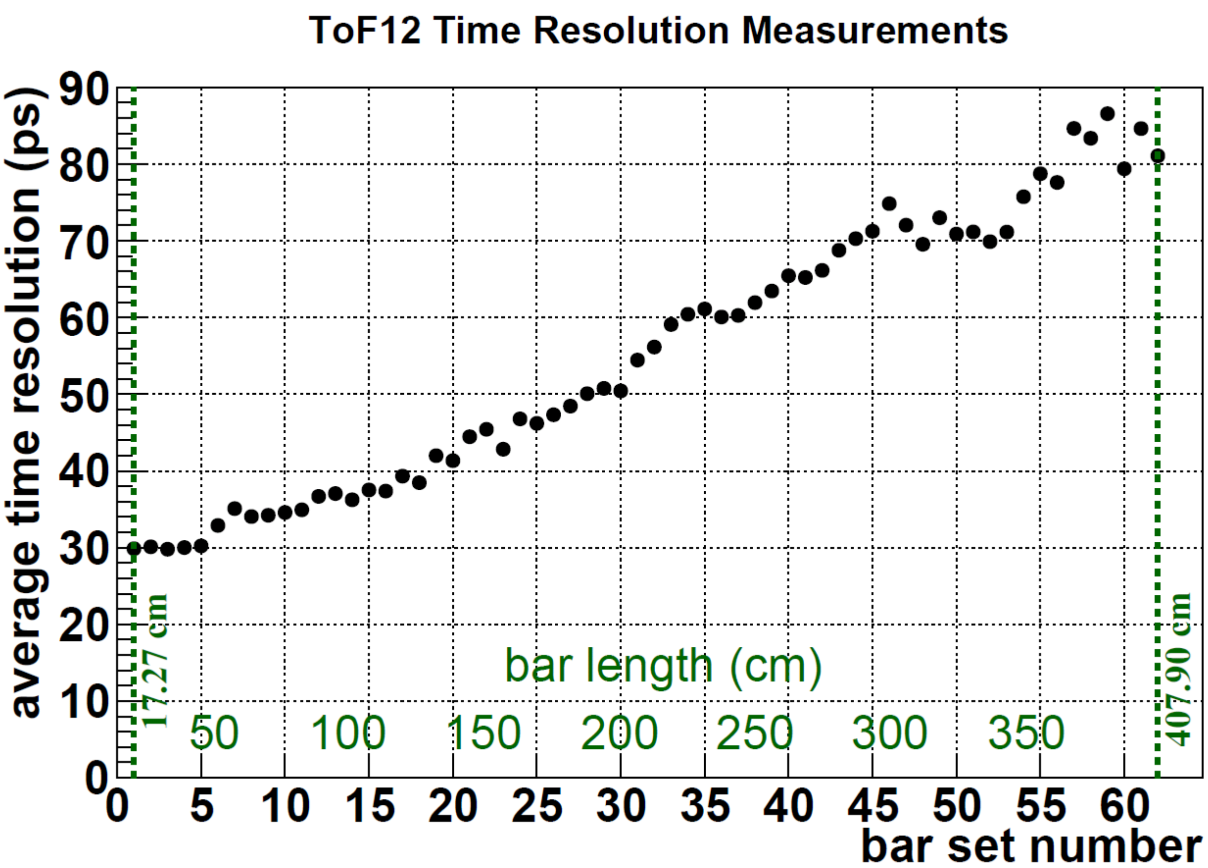
CLAS12

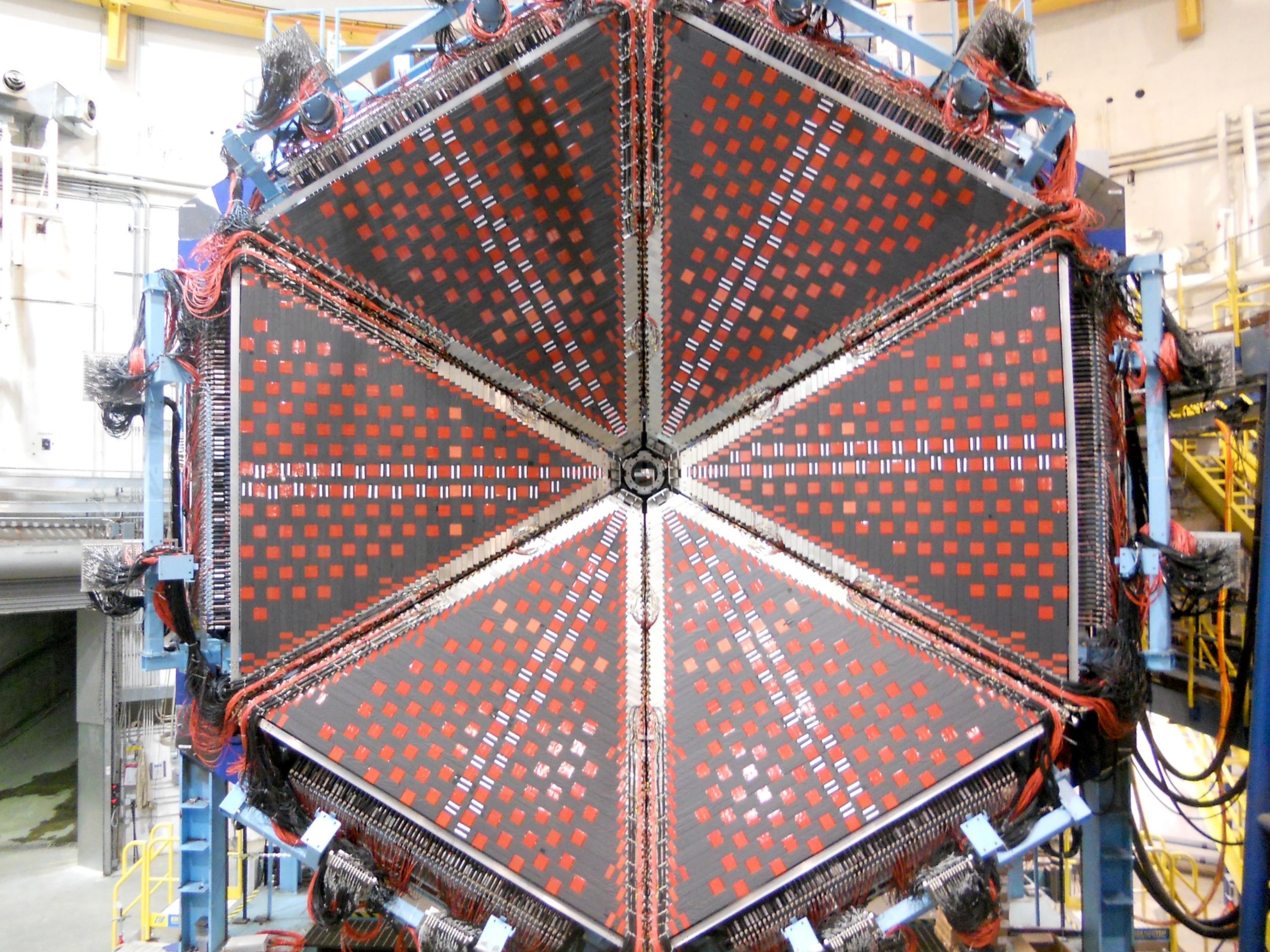
- Luminosity $>10^{35}\,cm^{-2}s^{-1}$
- Hermeticity
- Polarization

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

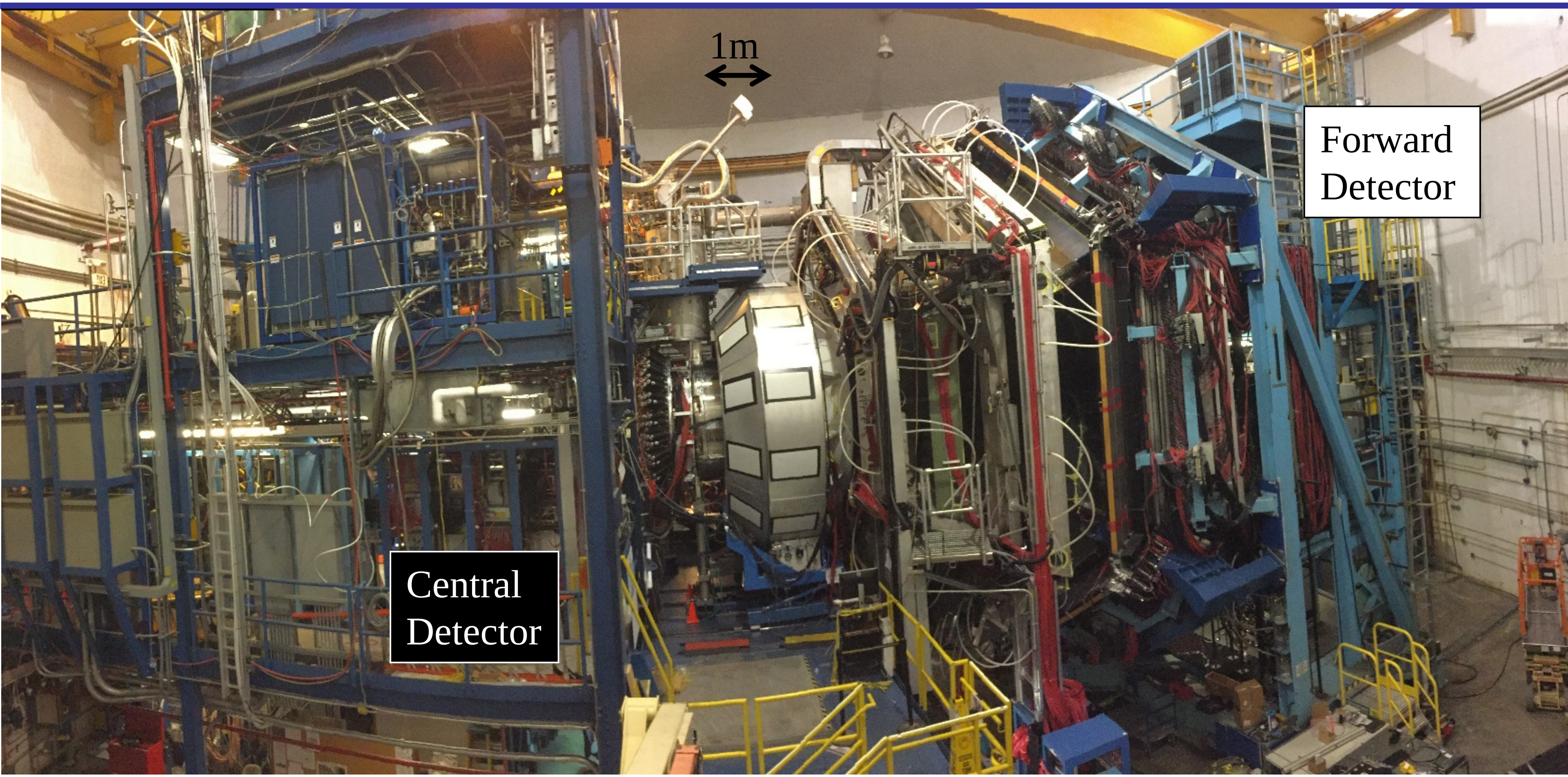


New Forward Time of Flight Detector for CLAS12





CLAS12



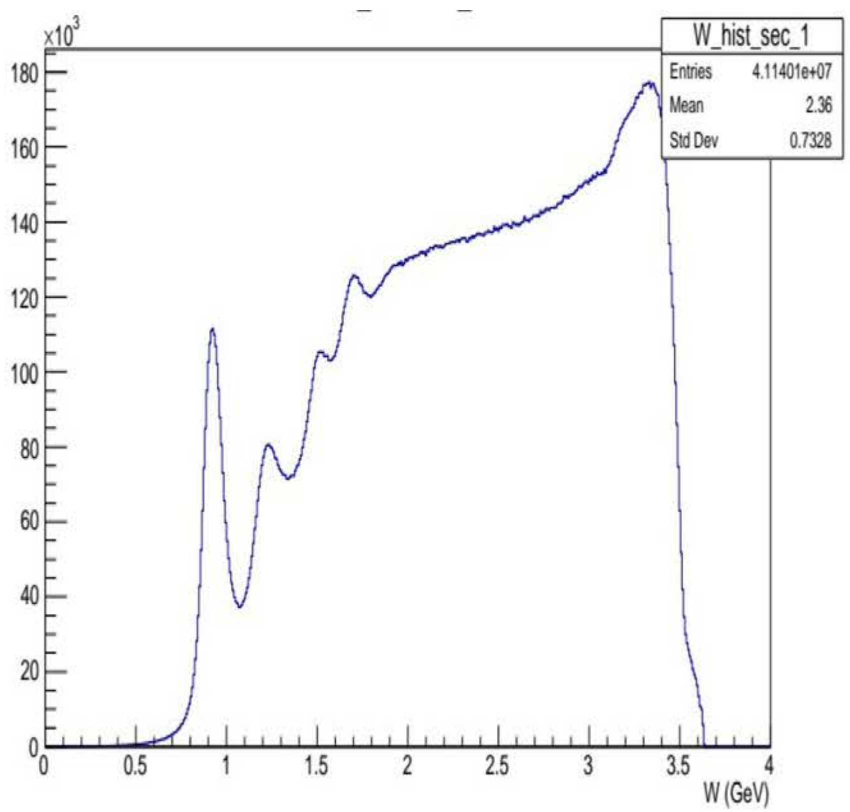
- Luminosity $>10^{35}\ cm^{-2}s^{-1}$
- Hermeticity
- Polarization

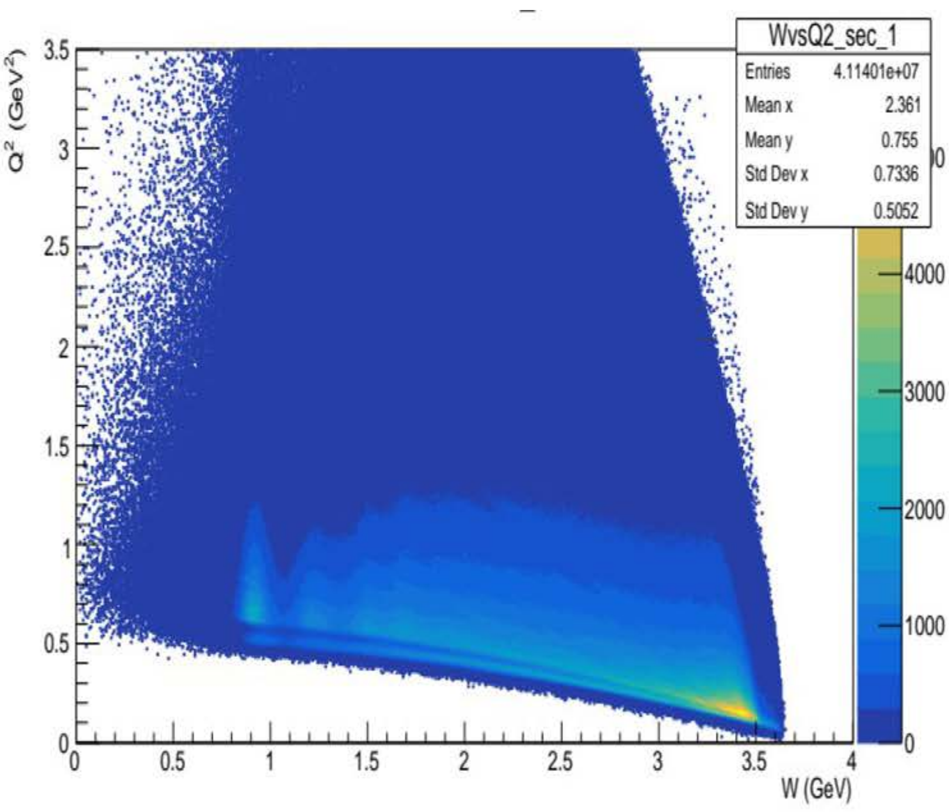
- Baryon Spectroscopy
- Elastic Form Factors
- N → N* Form Factors

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

Preliminary RGA/K CLAS12 Data Analysis

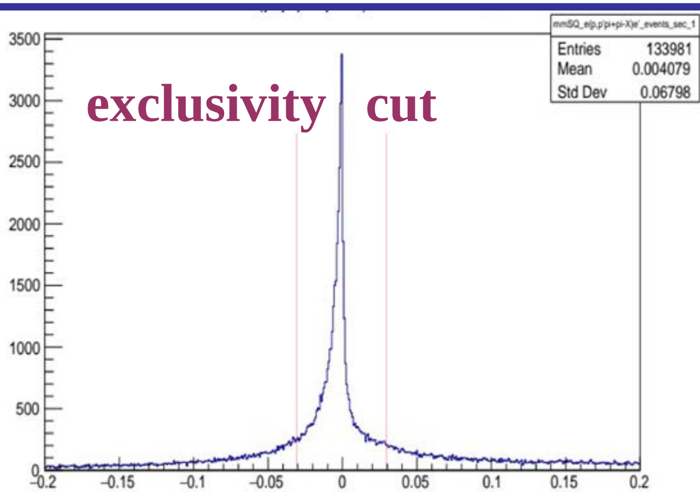
Krishna Neupane



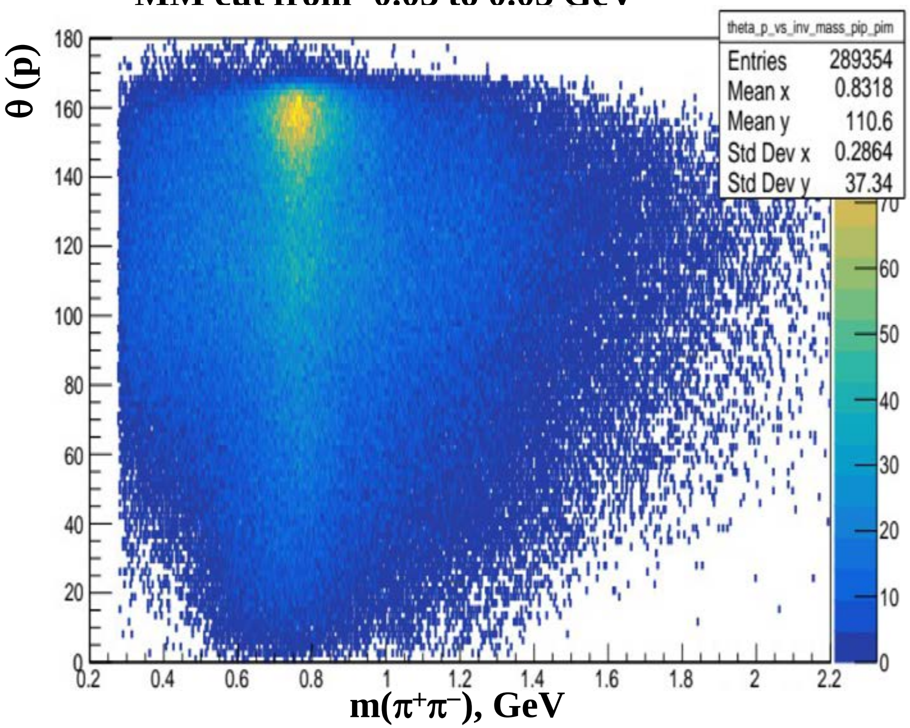


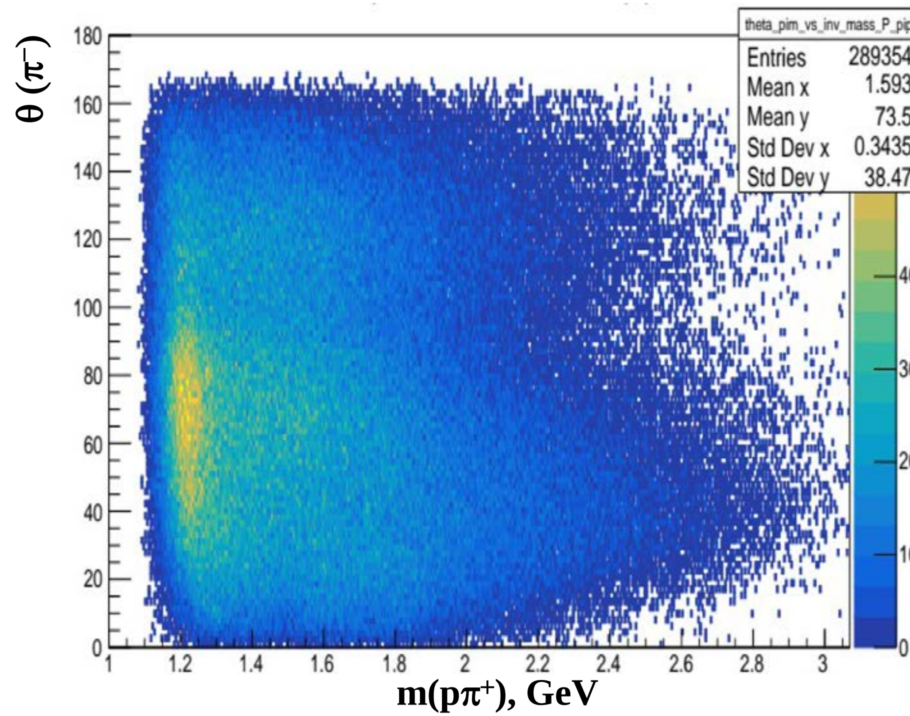
Preliminary RGA/K CLAS12 Data Analysis: $p\pi^+\pi^-$

Krishna Neupane

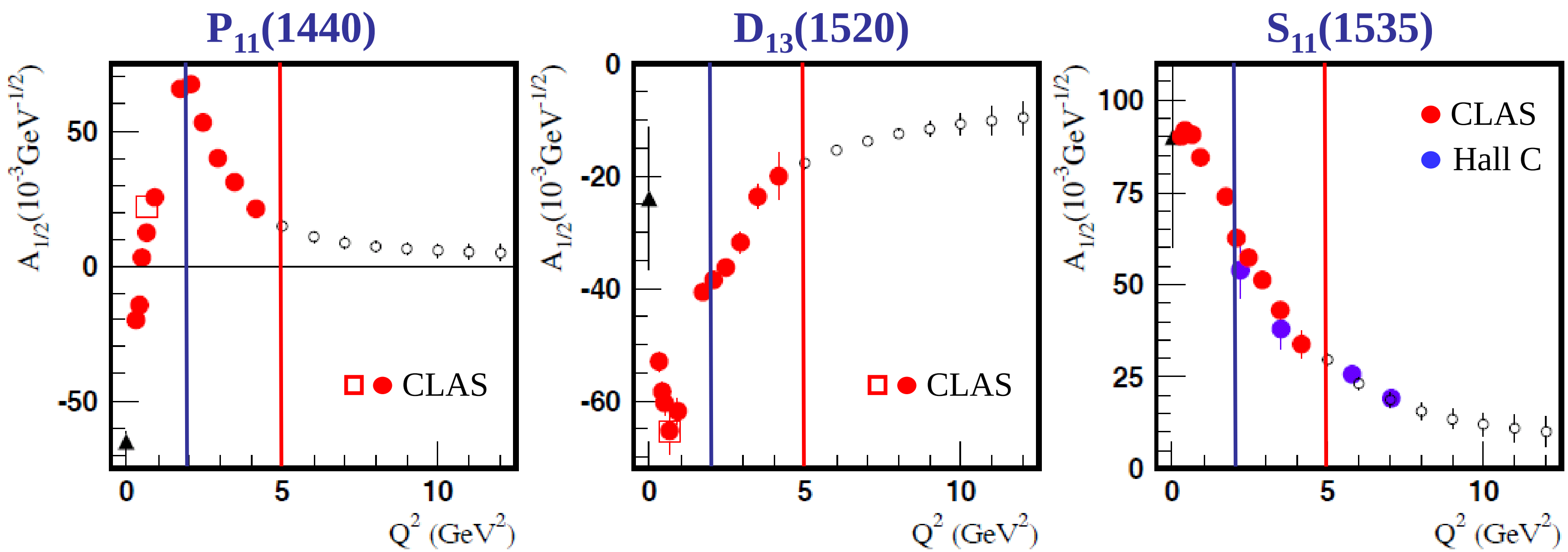


MM cut from -0.03 to 0.03 GeV





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.

Summary

- First high precision photo- and electroproduction data have become available and led to a new wave of significant developments in reaction and QCD-based theories.
- New high precision hadro-, photo-, and electroproduction data off the proton and the neutron will stabilize coupled channel analyses and expand the validity of reaction models, allowing us to
  - investigate and search for baryon hybrids (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 …