An Experimental Observable to Trace the Mass from pQCD to Strong QCD

Ralf W. Gothe for the CLAS Collaboration

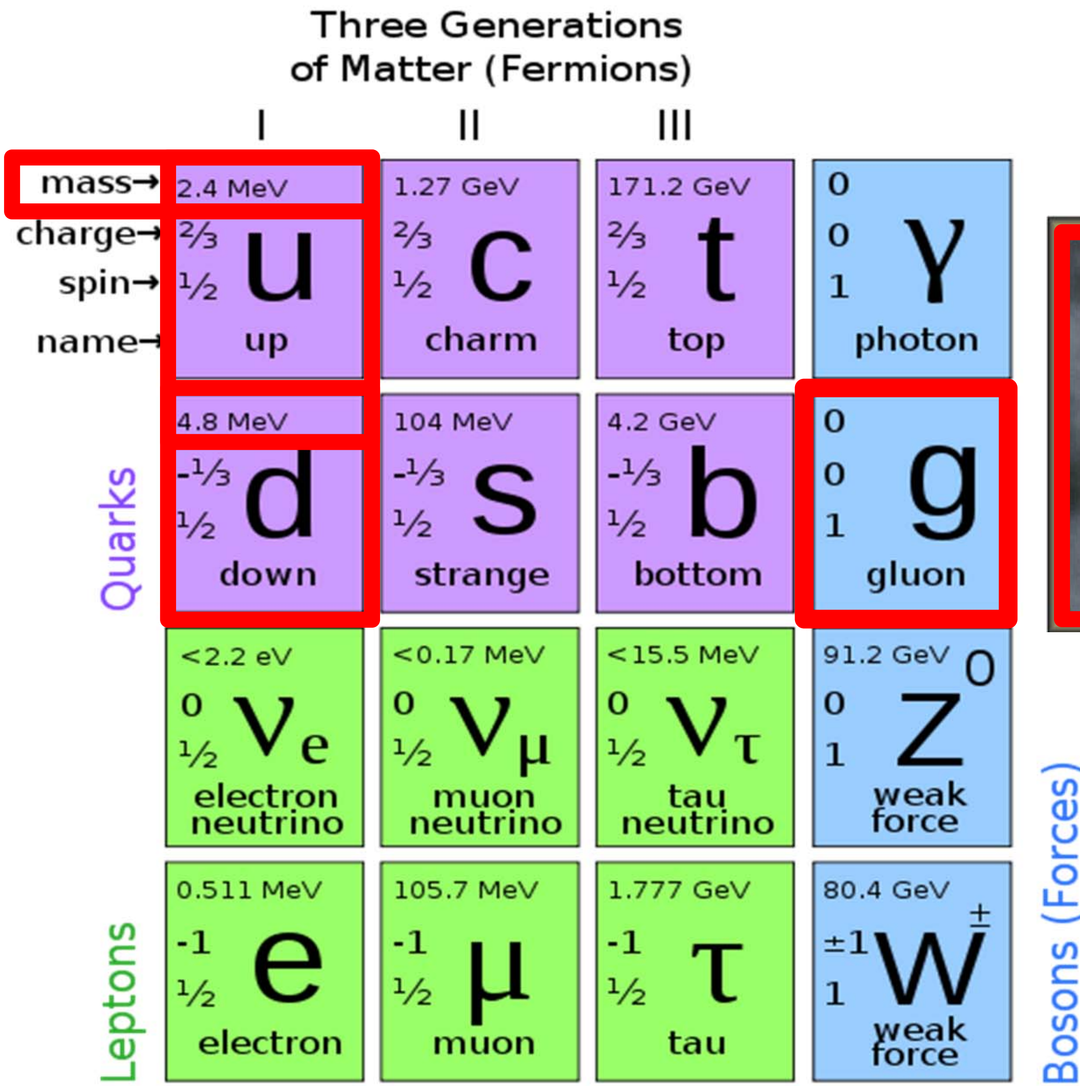
UNIVERSITY OF SOUTH CAROLINA

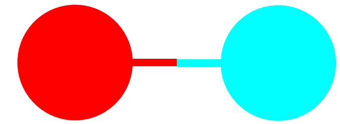
Perceiving the Emergence of Hadron Mass through AMBER@CERN,
March 30 – April 2, 2020, CERN, Geneva, Switzerland

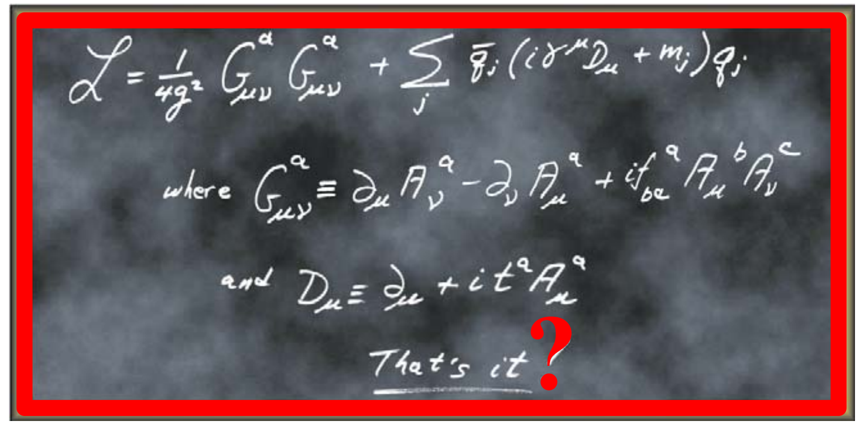
- **Deeply Virtual Lepton Scattering:** Hadronic versus partonic!
- **$\gamma_v NN^*$ Form Factors:** Probing emergent dressing of bound valence quark!
- **Results and Outlook:** New experiments with extended scope and kinematics!

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

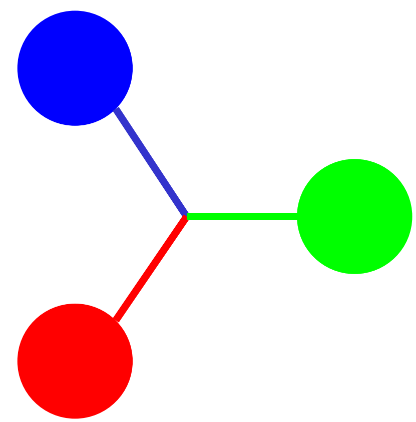
Build your Mesons and Baryons …





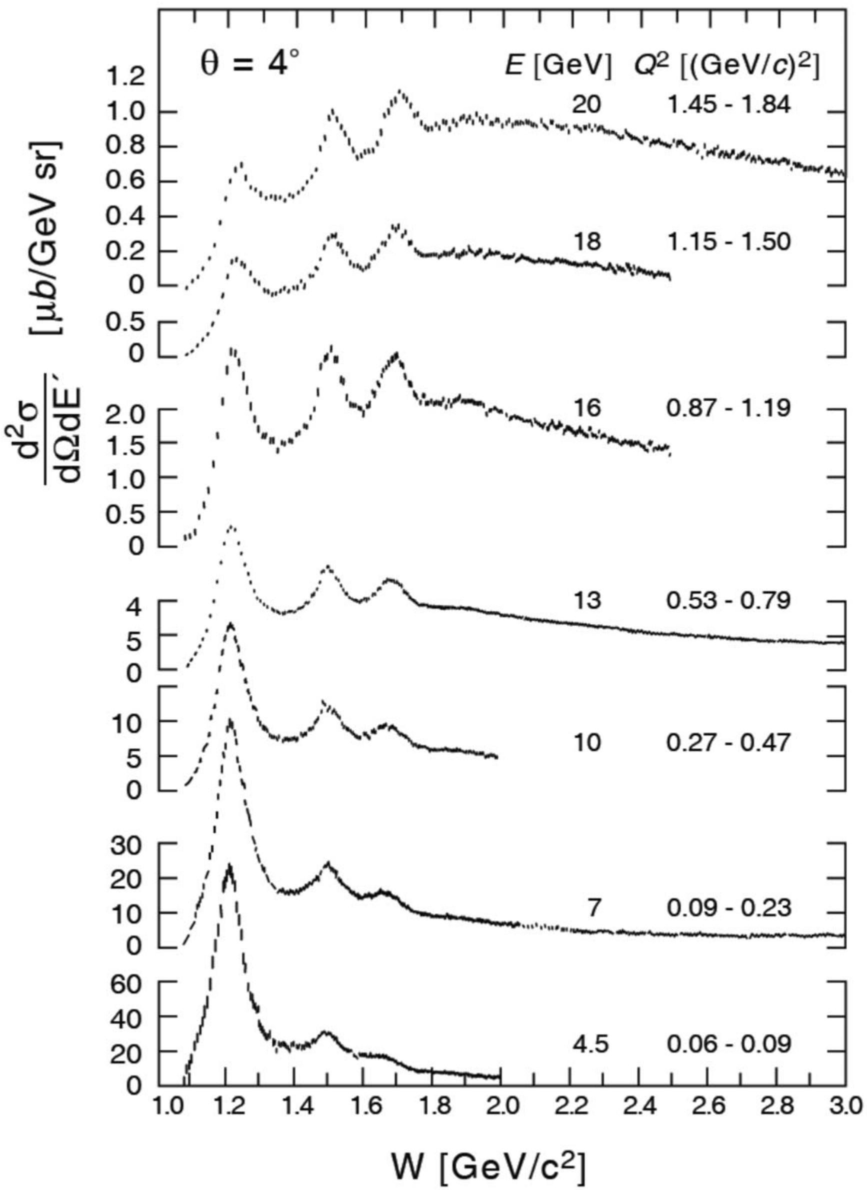


Frank Wilczek, Physics Today, August 2000

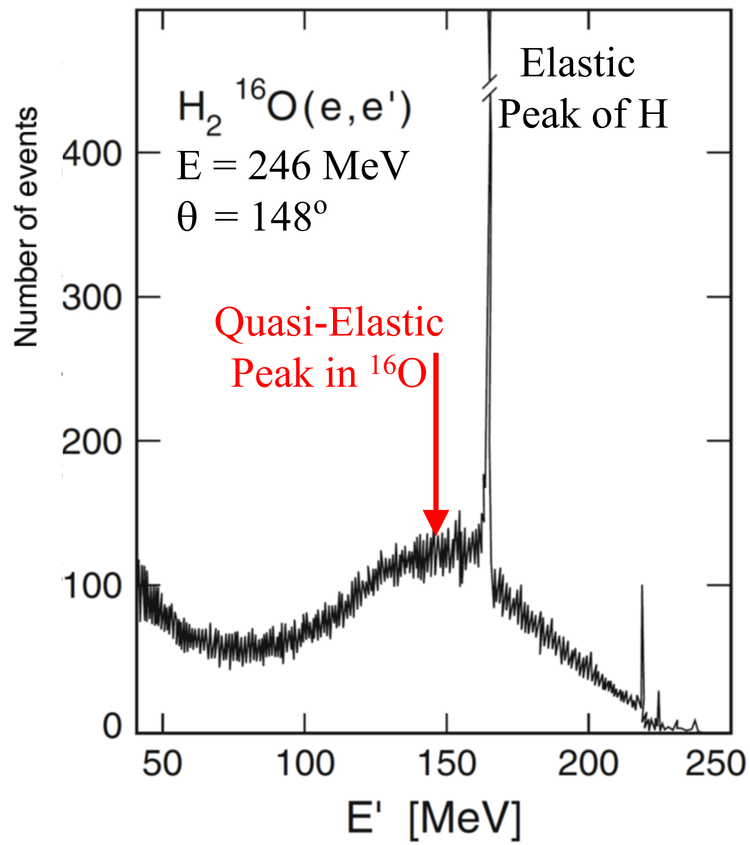


Electron Scattering

Baryon Excitations and Quasi-Elastic Scattering

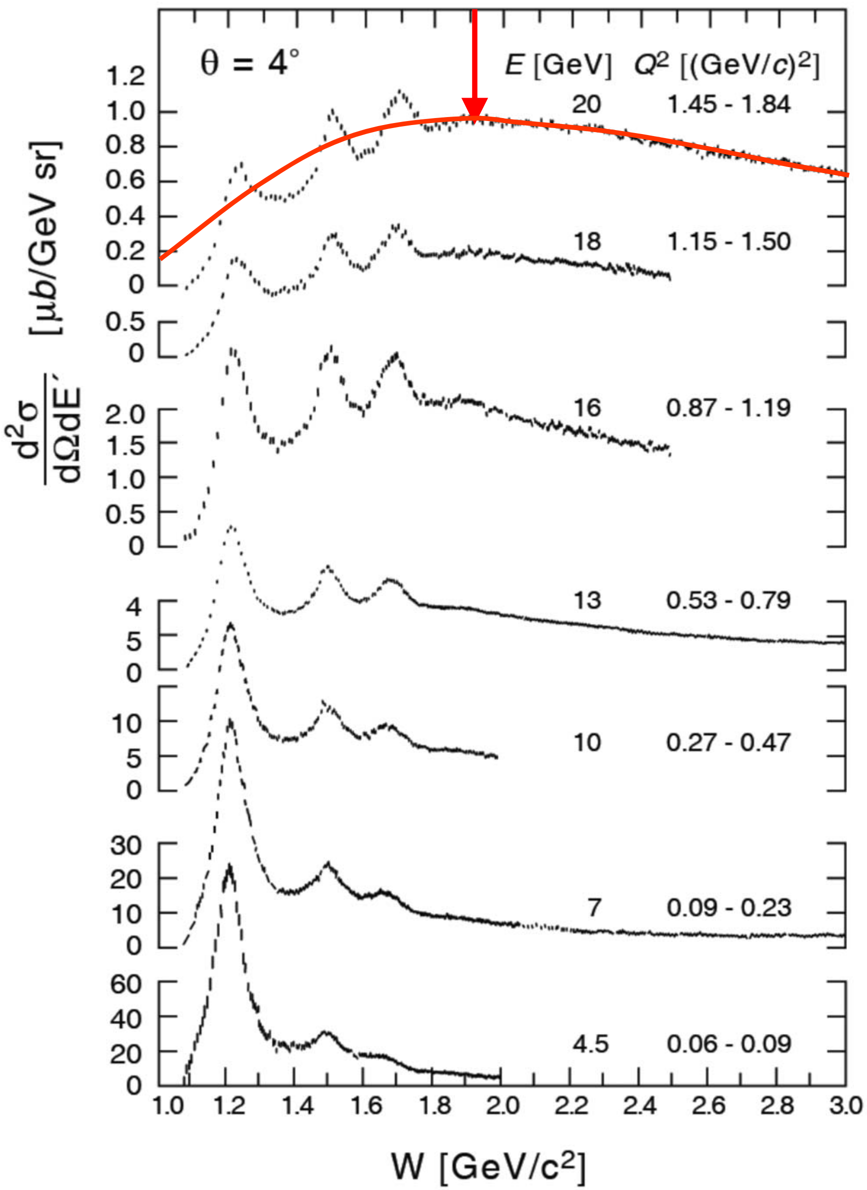


Paticle and Nuclei, Povh et al., MAMI B



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

Baryon Excitations and Quasi-Elastic Scattering



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

W = 1.9 GeV

E' = 17.6 GeV

ν = 2.37 GeV

Q^2 = 1.72 GeV

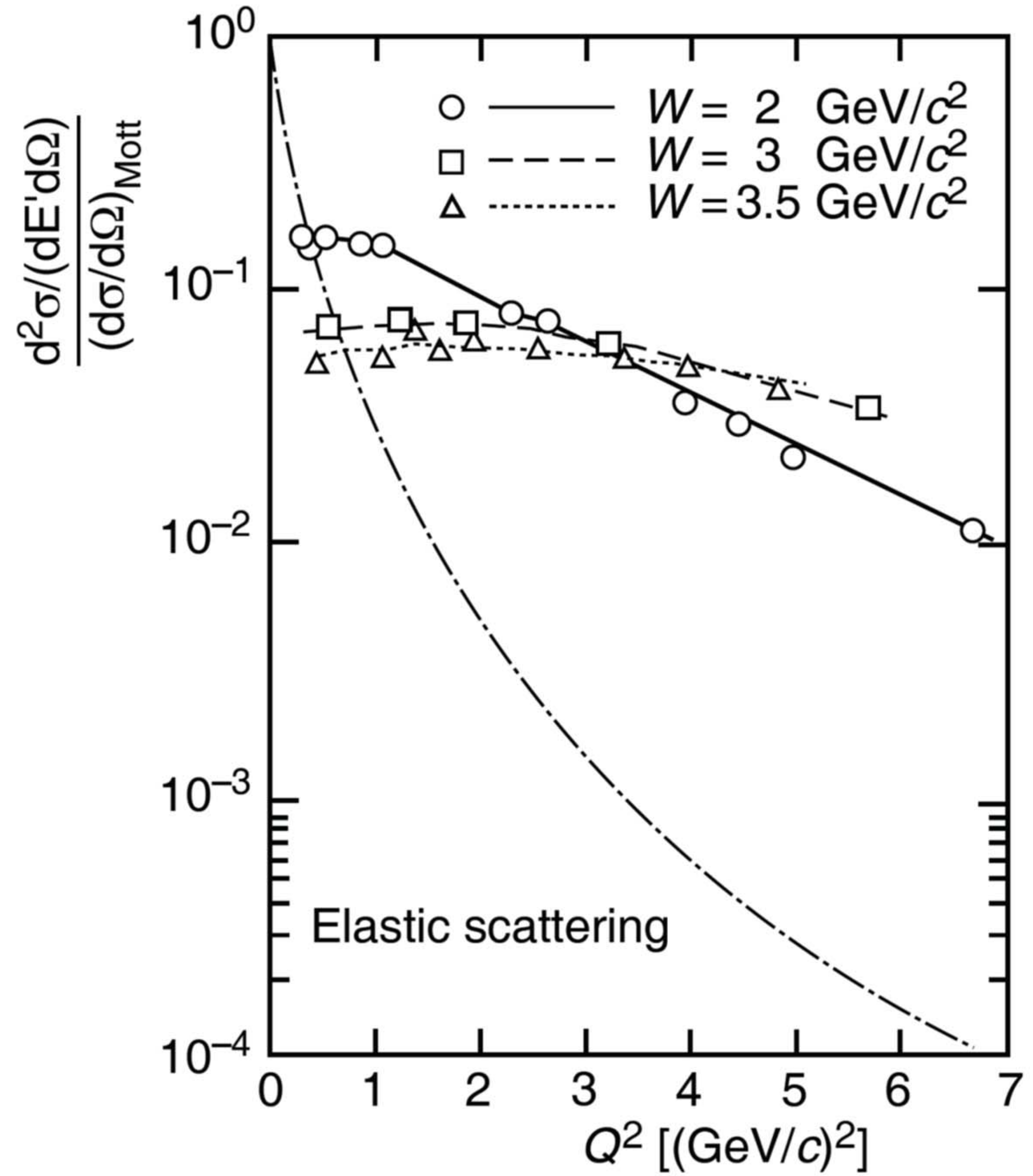
m_q = 0.36 GeV $\quad m_q = Q^2/2\nu$

p_F = 0.67 GeV

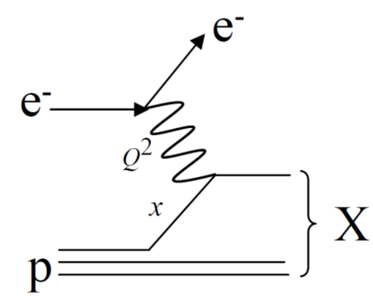
r_F = 0.79 fm $\quad \Delta r_F = \frac{\hbar c}{\Delta p_F} * \sqrt{9\pi/2}$

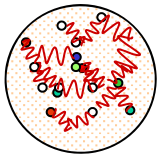
Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Baryon Excitations and Quasi-Elastic Scattering



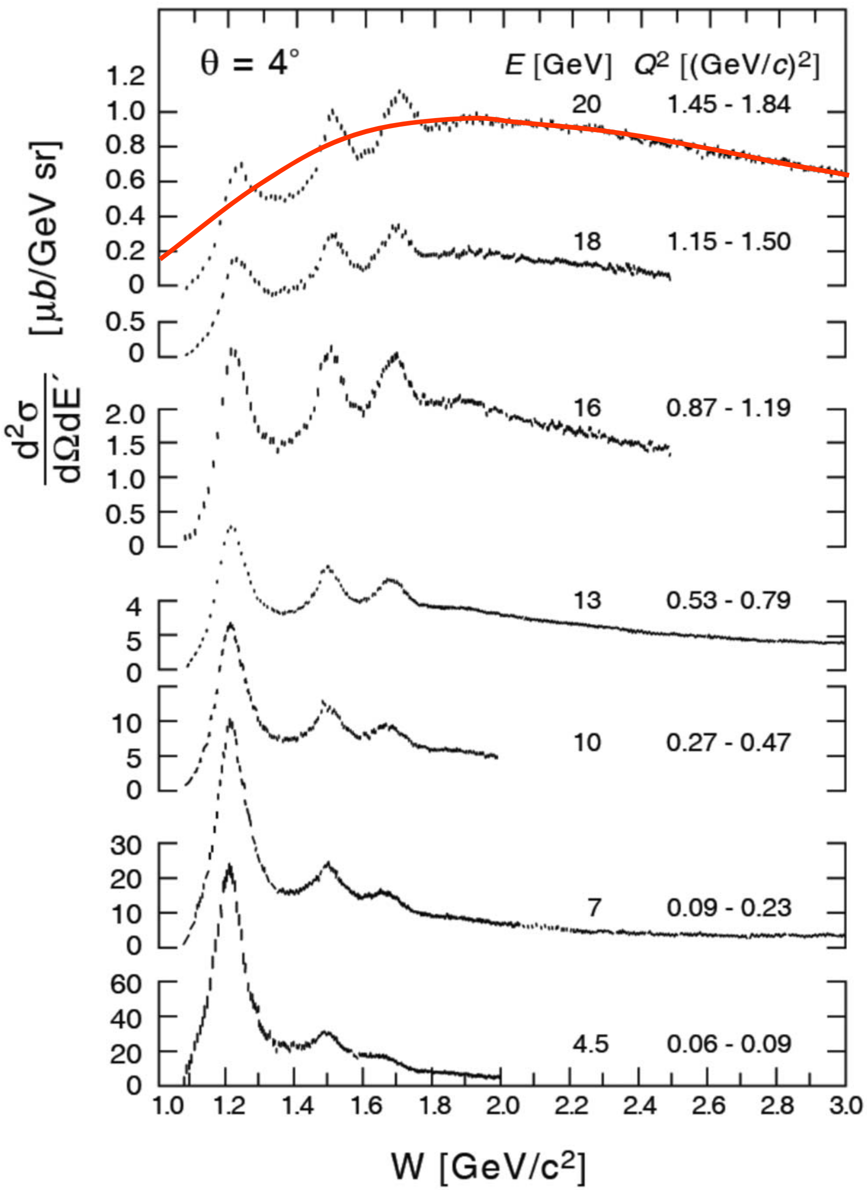
quasi-elastic off
point-like
constituents



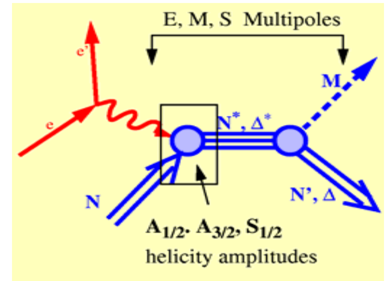


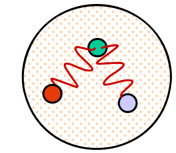
Deep Inelastic Scattering
M. Breidenbach et al.,
Phys. Rev. Lett. **23** (1969) 935

Baryon Excitations and Quasi-Elastic Scattering

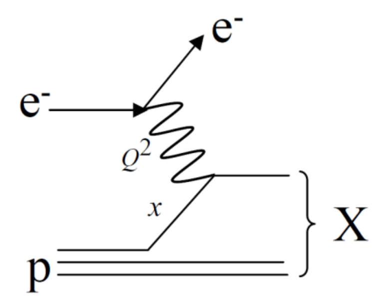


hard and confined



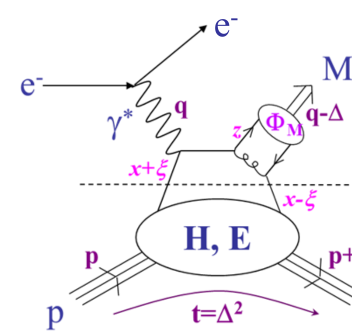


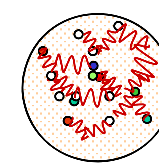
quasi-elastic



hard

soft

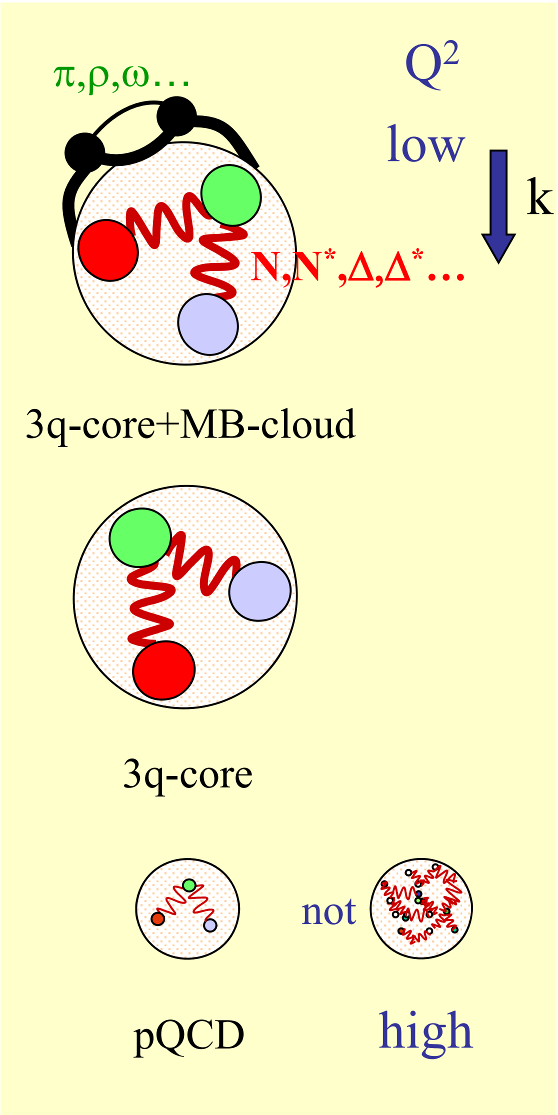




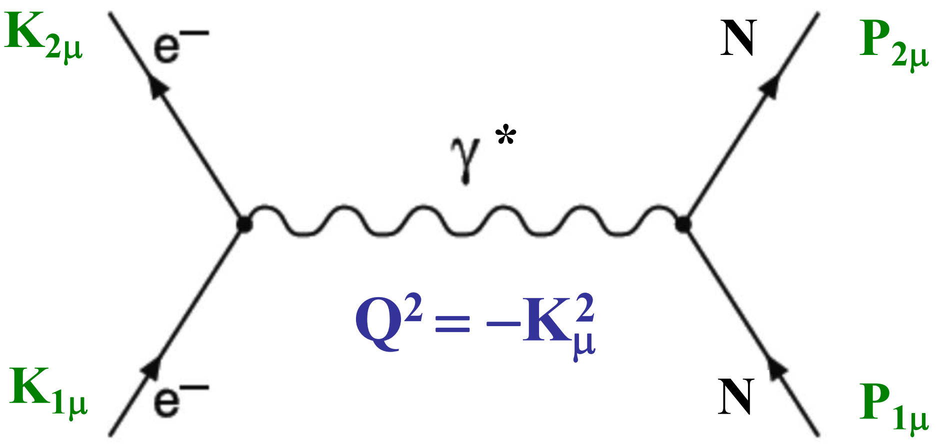
Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Transition Form Factors

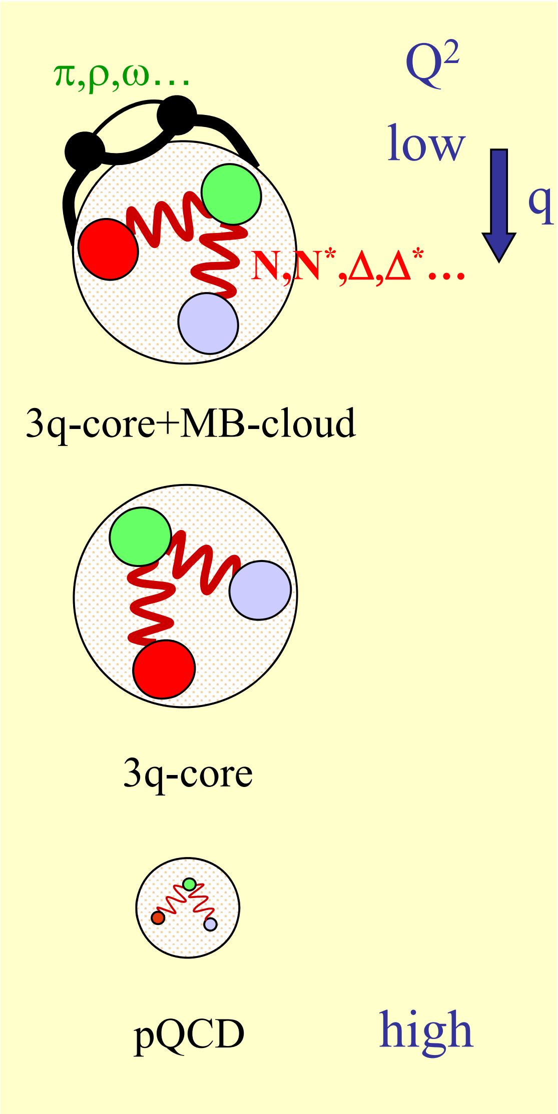
Hadron Structure with Electromagnetic Probes



- 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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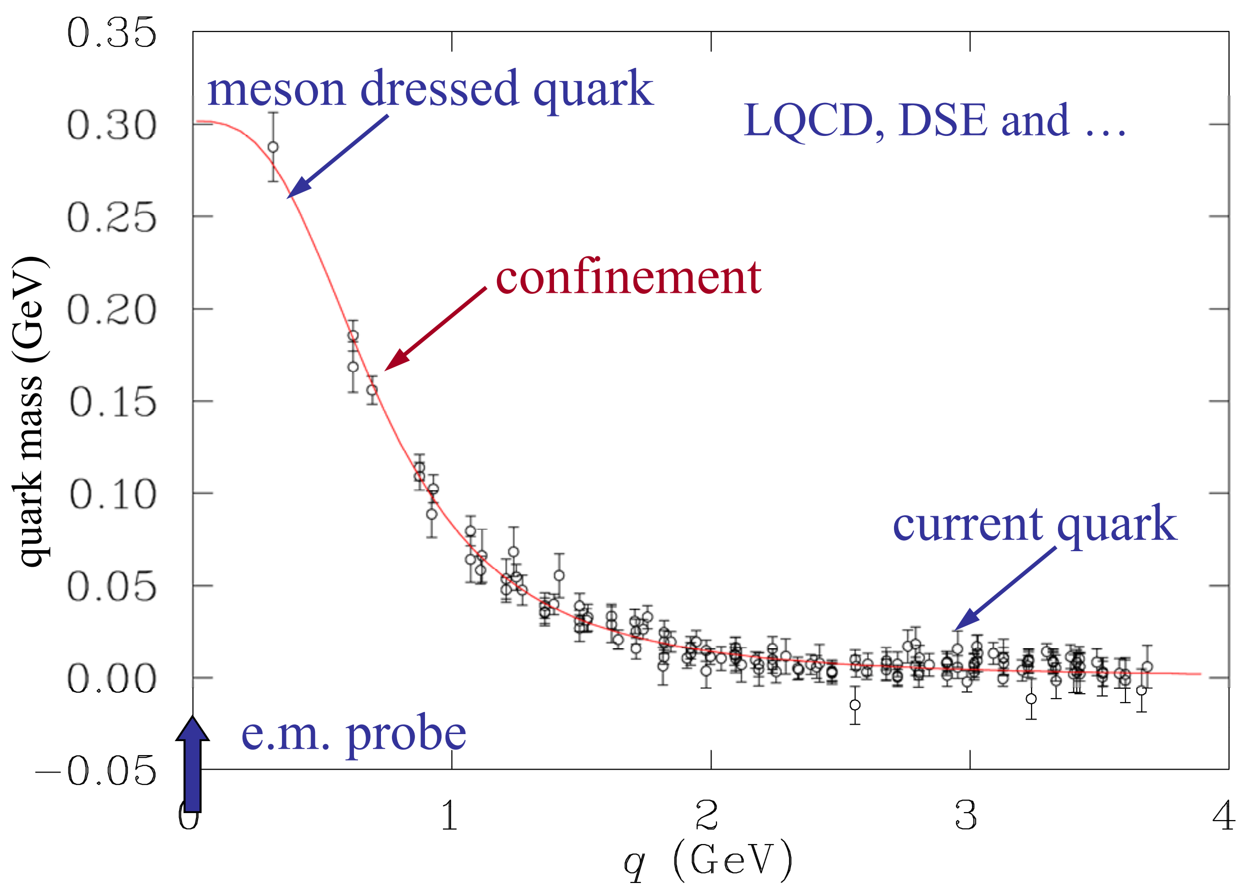
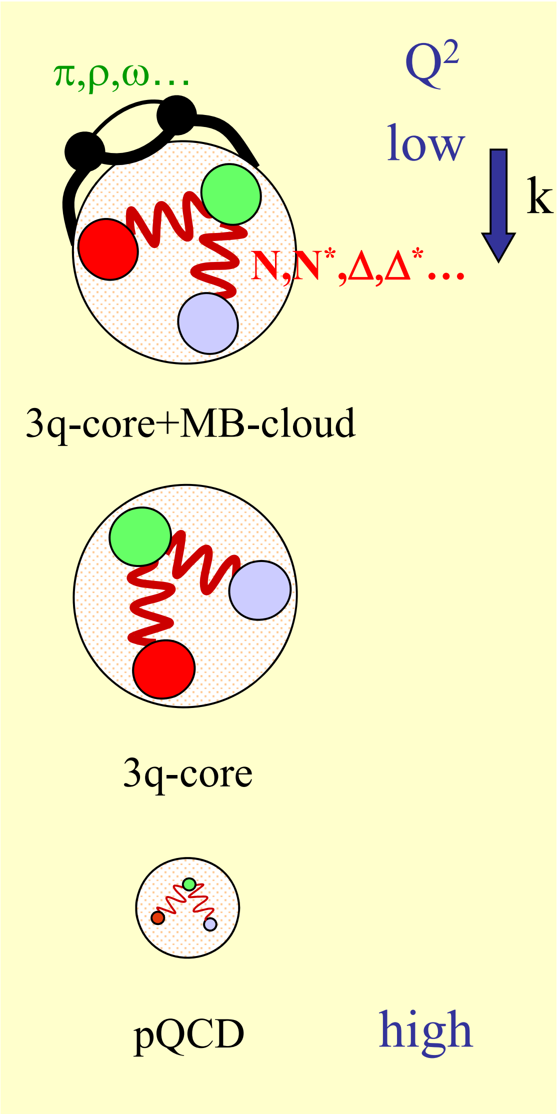
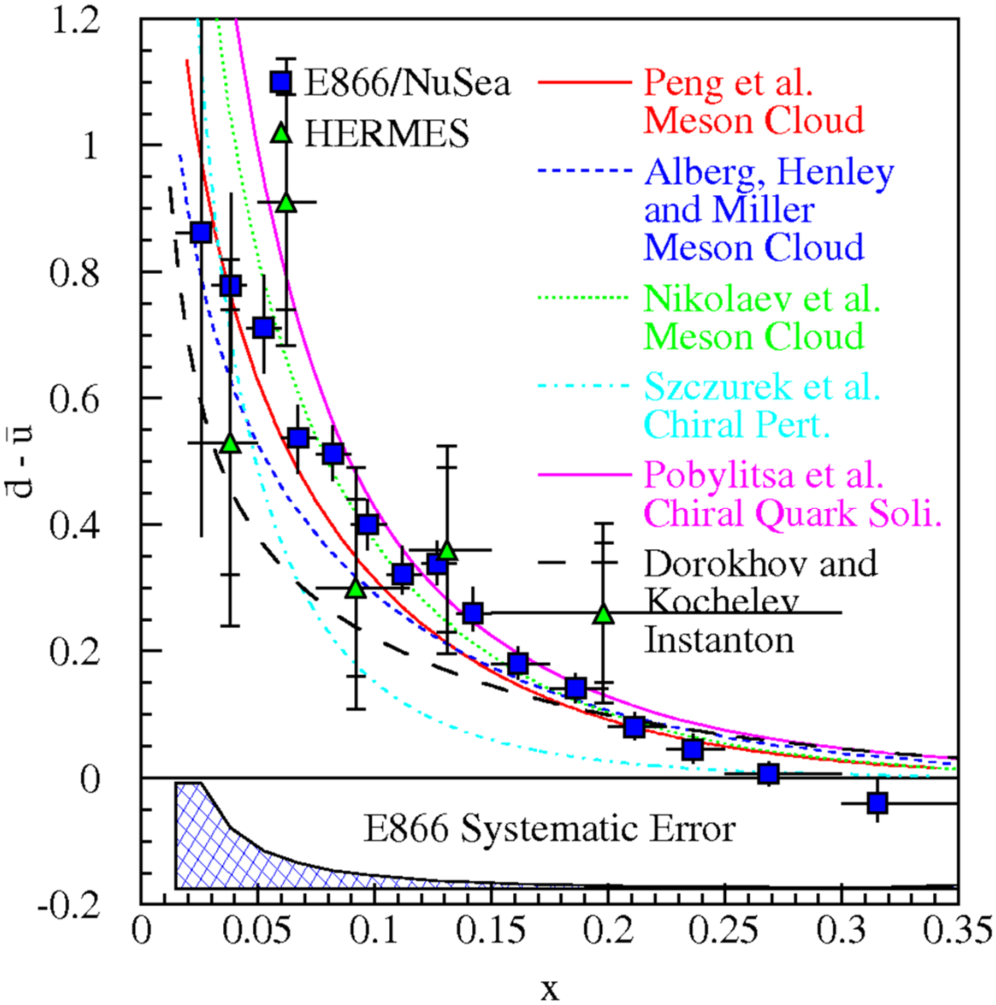


Hadron Structure with Electromagnetic Probes

Rolf Ent



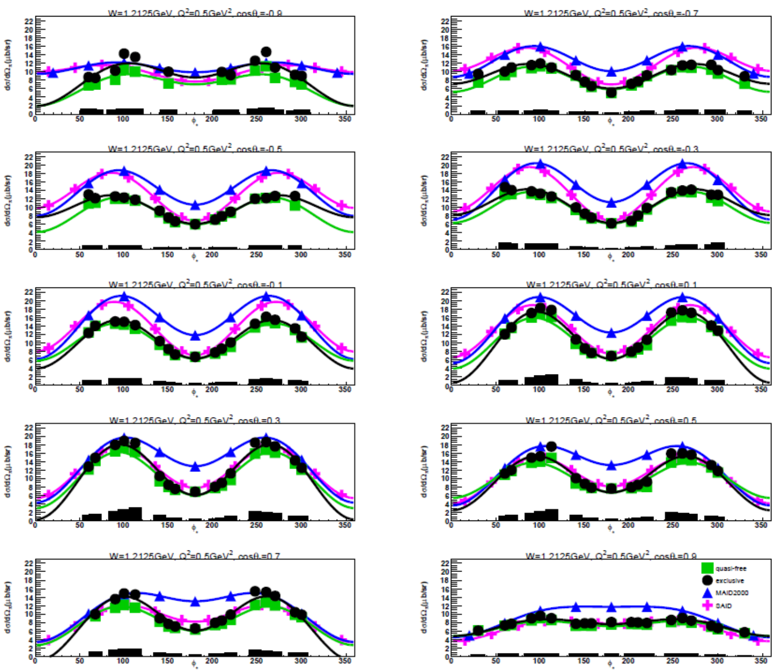
- The pion, or a meson cloud, explains light-quark asymmetry of the sea quarks in the nucleon.



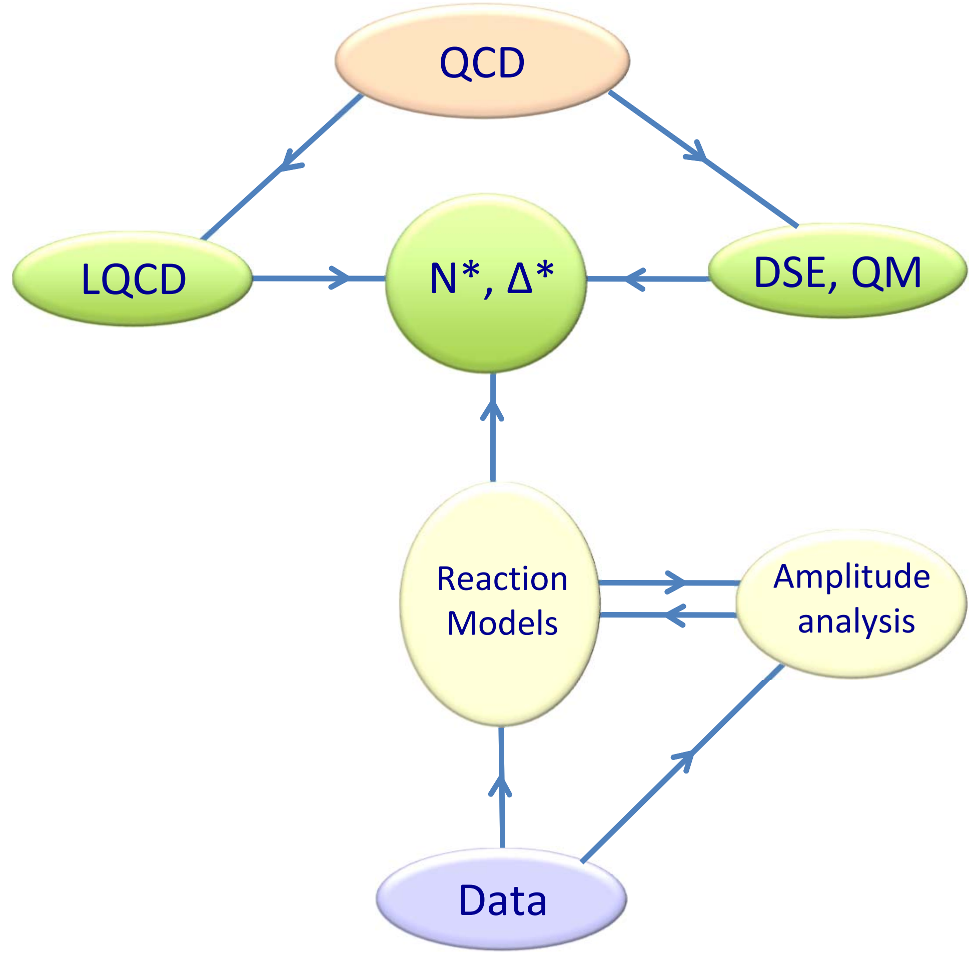
Data-Driven Data Analyses

Consistent Results

Single Pion



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



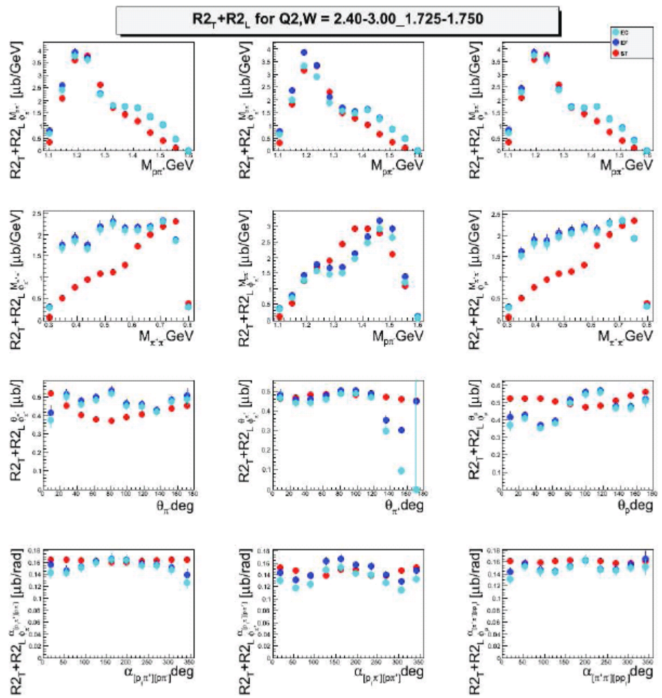
Hadronic production

Electromagnetic production

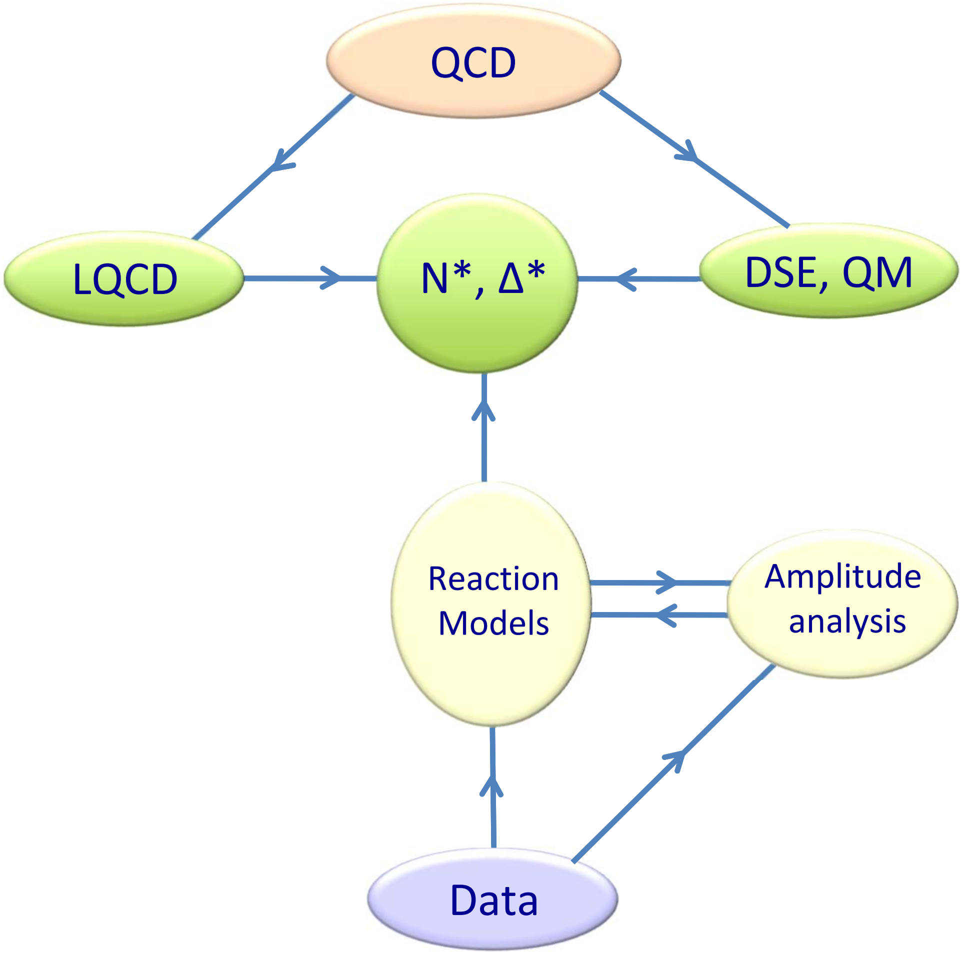
Data-Driven Data Analyses

Consistent Results

Double Pion



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

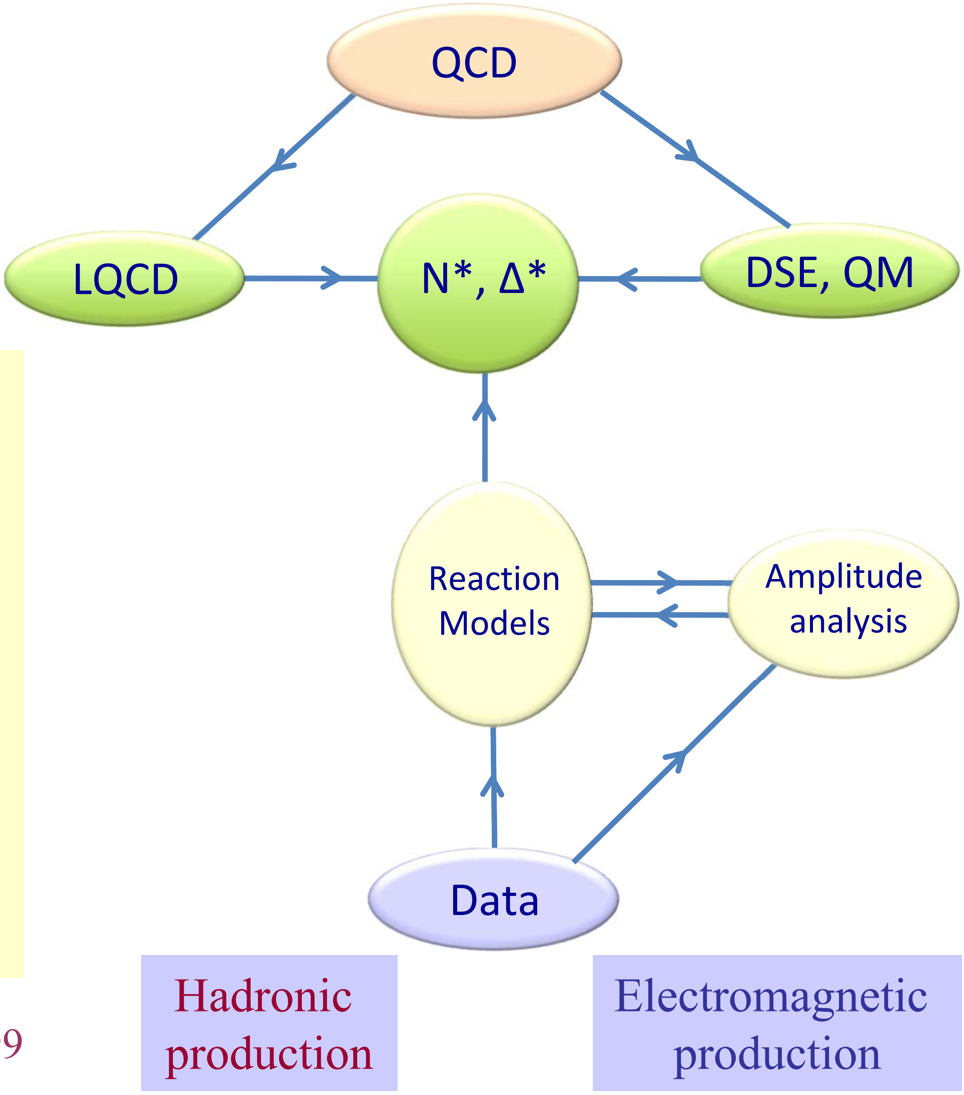


Data-Driven Data Analyses

Consistent Results

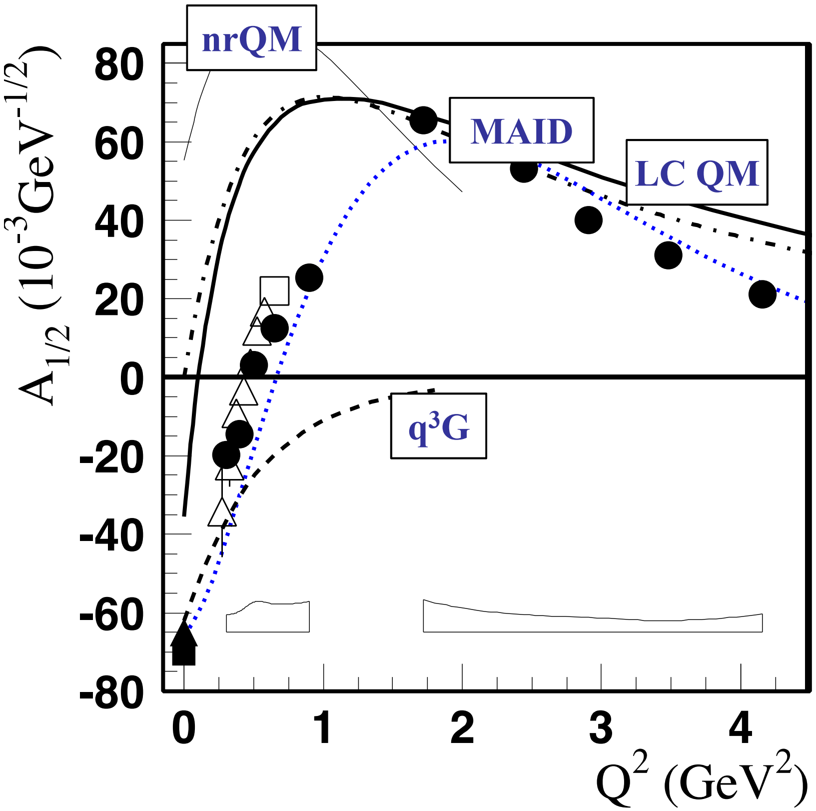
- Single meson production:
  Unitary Isobar Model (UIM)
  Fixed-*t* Dispersion Relations (DR)
- Double pion production:
  Unitarized Isobar Model (JM)
- Coupled-Channel Approaches:
  EBAC ⇒ Argonne-Osaka
  JAW ⇒ Jülich-Athens-Washington ⇒ JüBo
  BoGa ⇒ Bonn-Gatchina

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



Transition Form Factors and QCD Models

Roper resonance $P_{11}(1440)$



PDG 2013 update

+ q^3g
+ $q^3q\bar{q}$
+ N-Meson
+ …

or

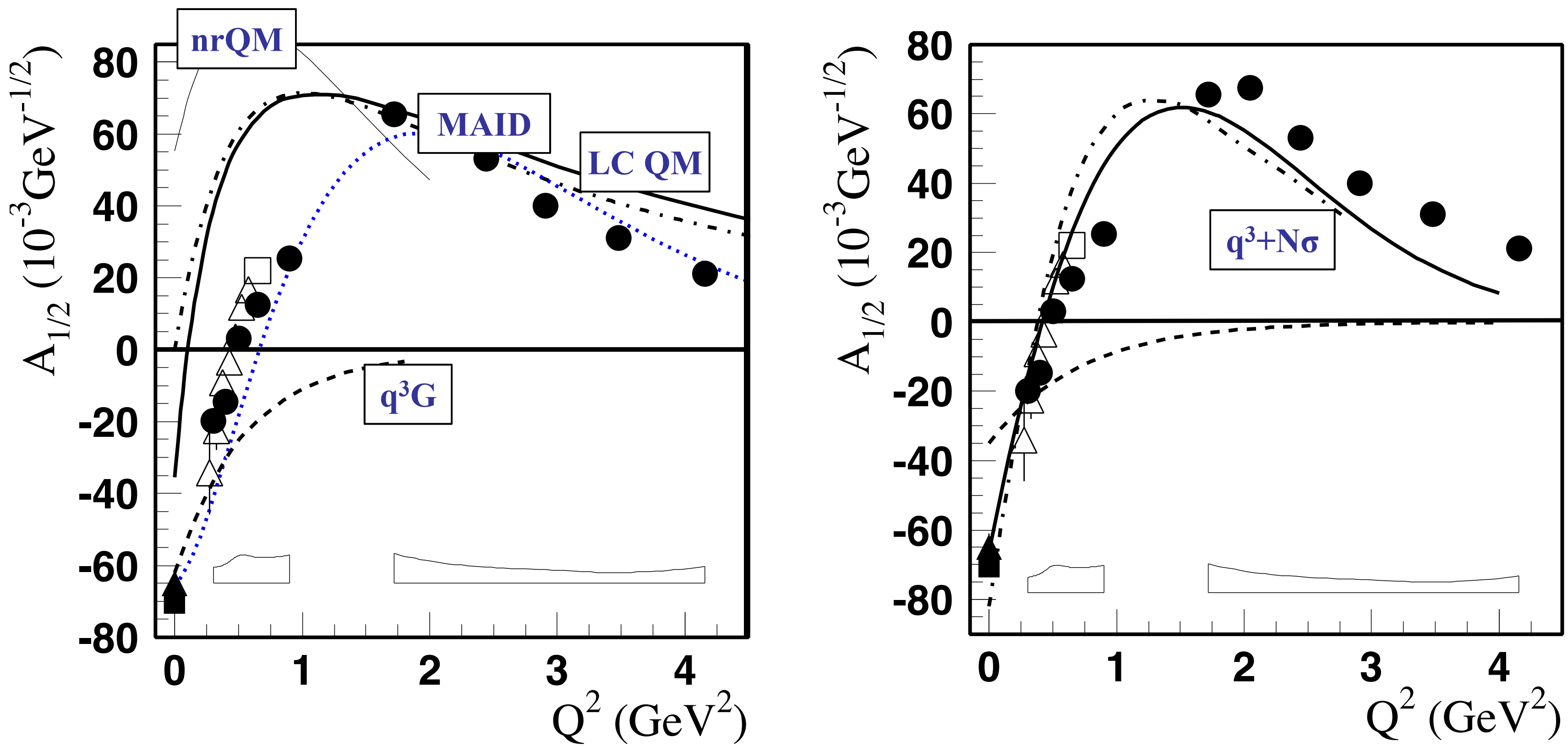
- q^2q
- …

… 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



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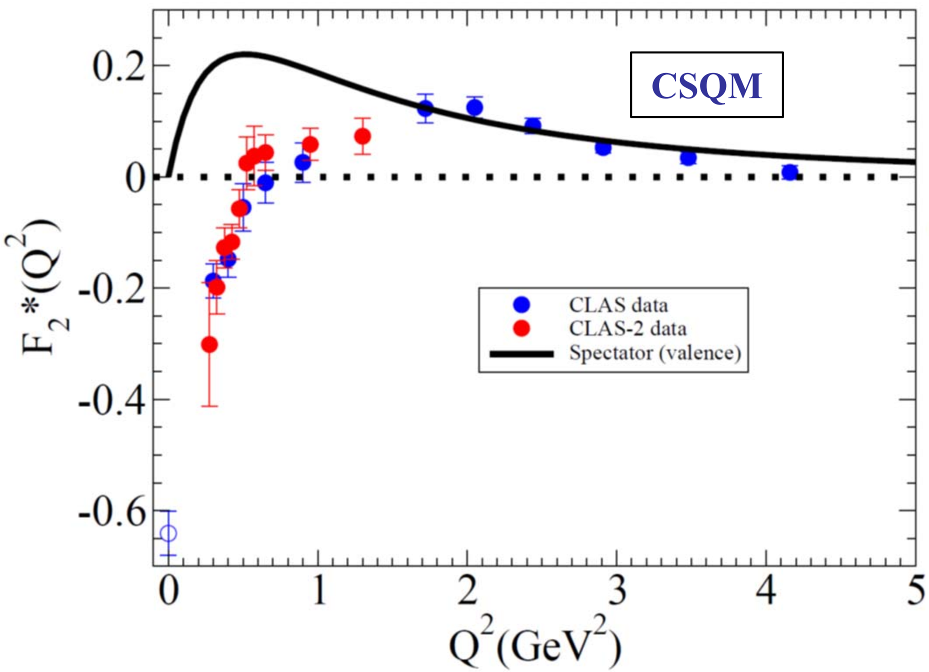
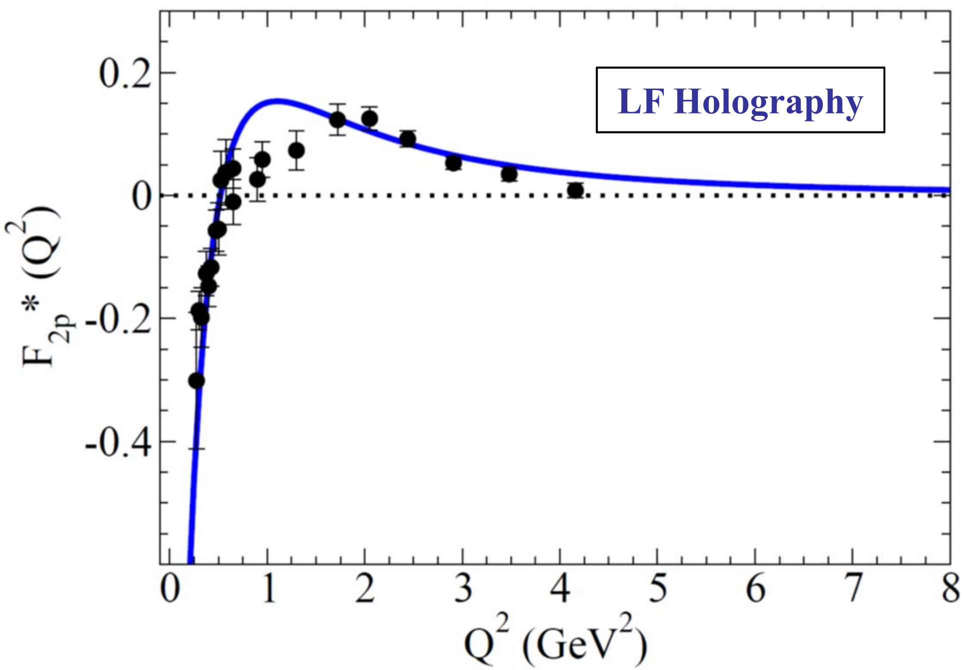
Transition Form Factors and QCD Models

Roper resonance $P_{11}(1440)$

G. Ramalho





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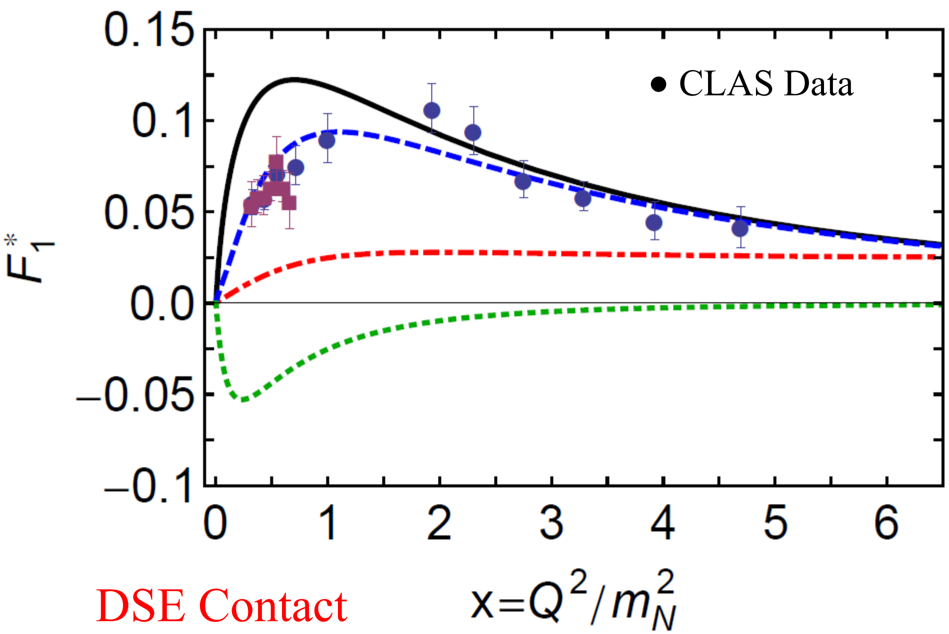
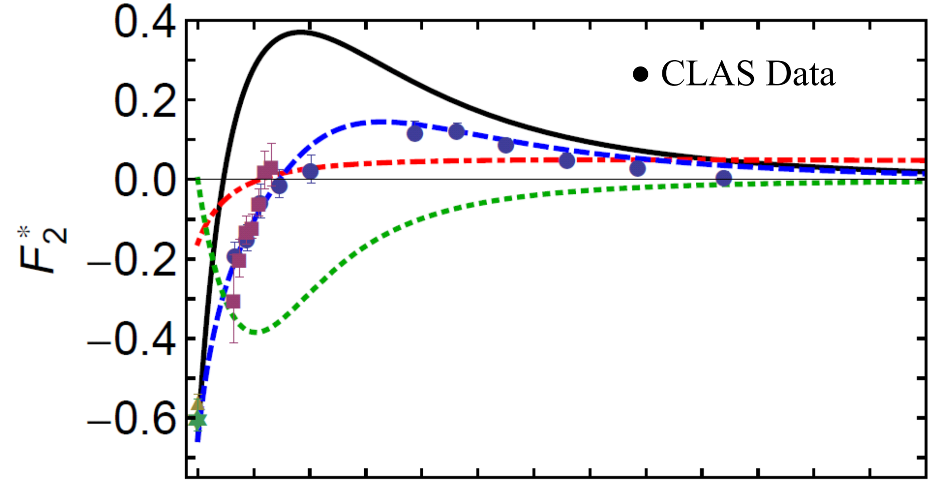
Roper Transition Form Factors in DSE Approach

N(1440)P_{11}

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





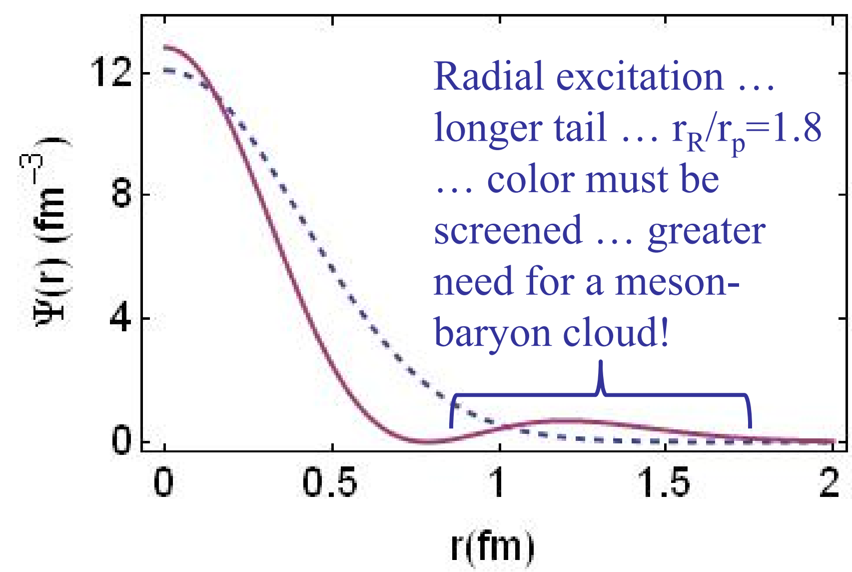
DSE Contact

DSE Realistic

Inferred meson-cloud contribution

Anticipated complete result

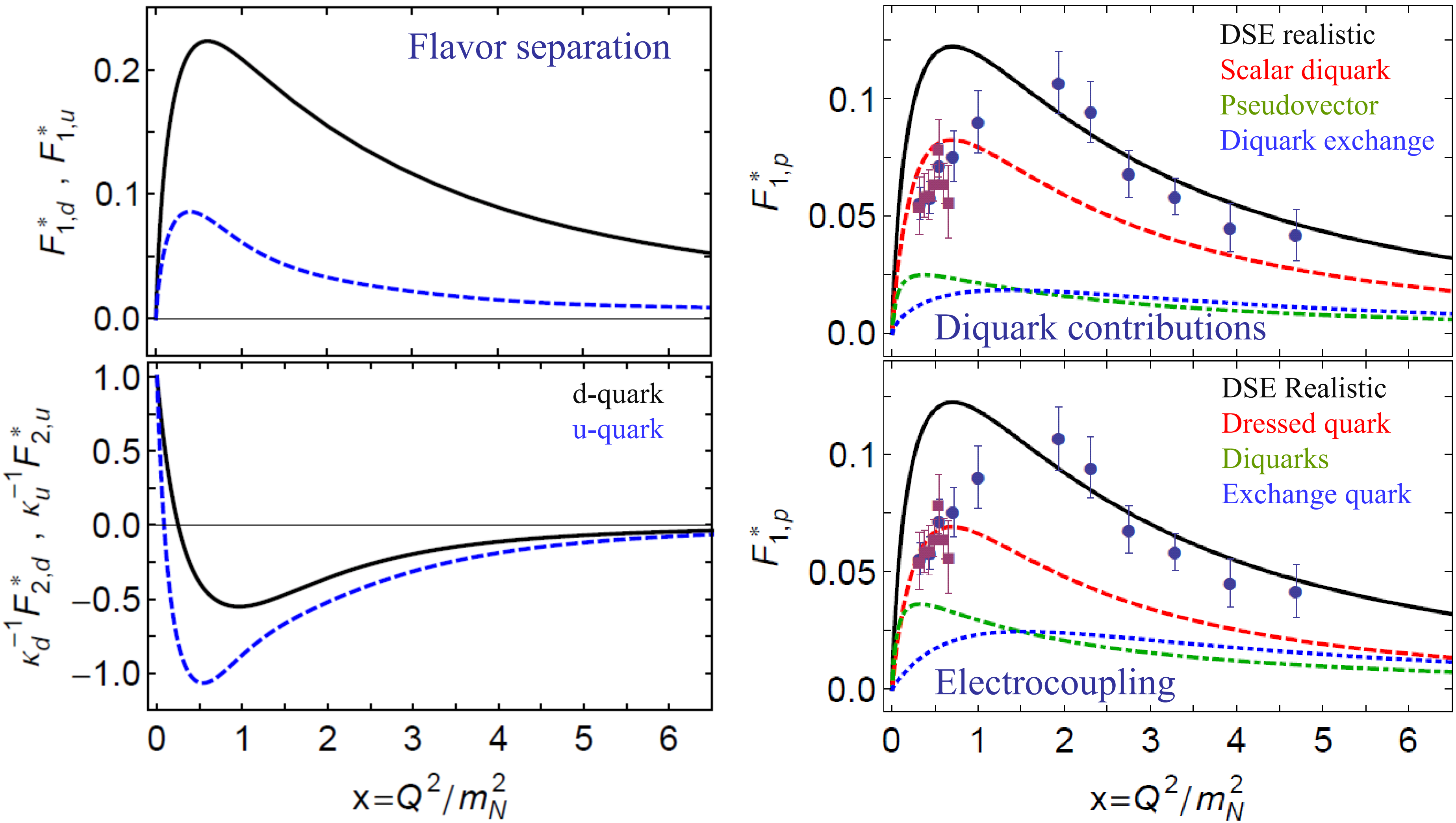
Importantly, the existence of a zero in F_2 is not influenced by meson-cloud effects, although its precise location is.



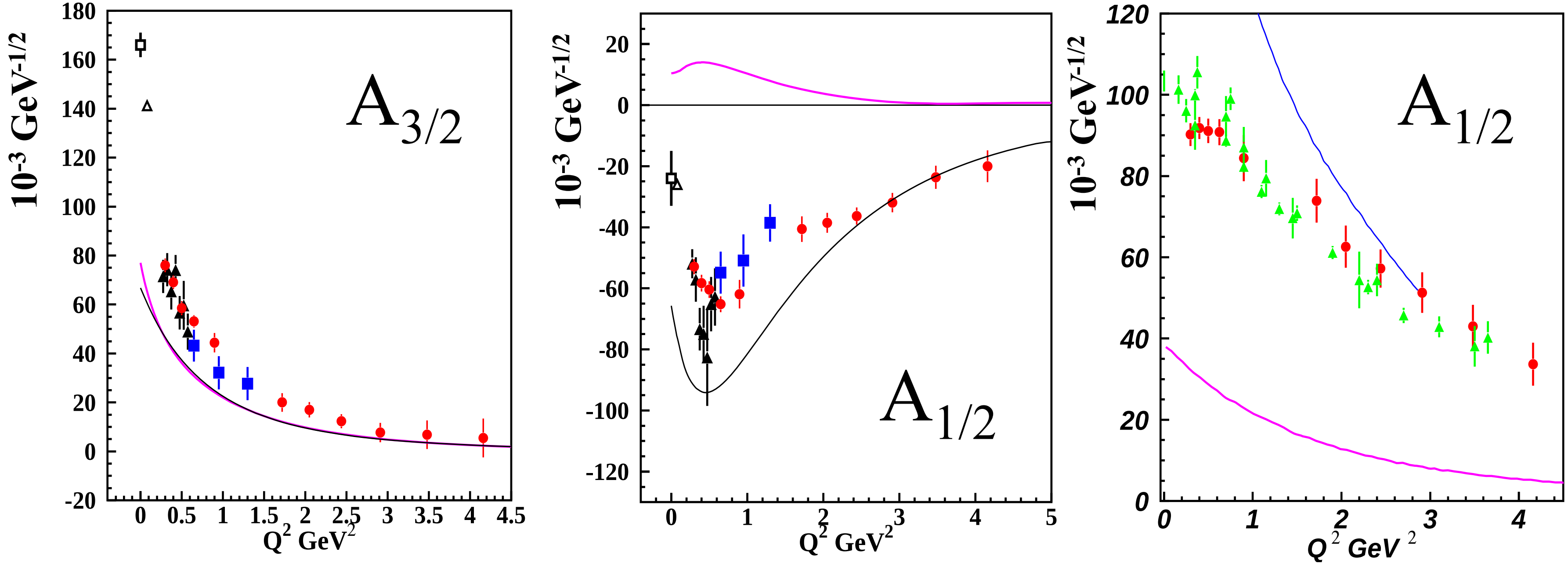
Roper Transition Form Factors in DSE Approach

$N(1440)P_{11}$

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



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



Argonne Osaka / EBAC DCC MB dressing (absolute values)

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

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

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

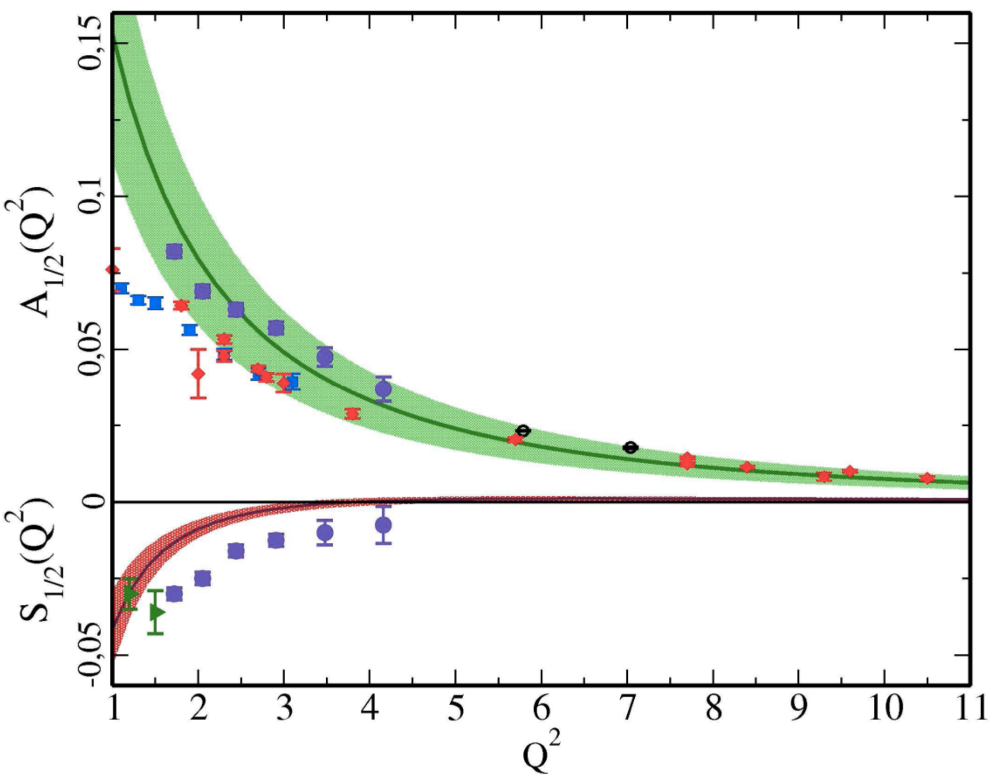
$\pi^+\pi^-p$ 2010

$N\pi$ 2009

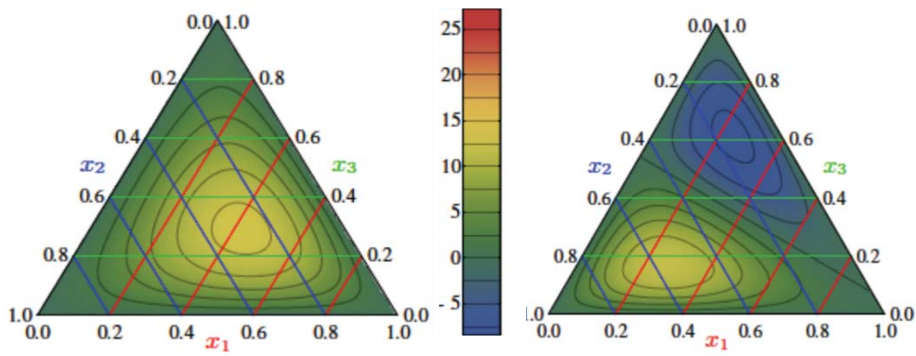
ηp CLAS/Hall-C

LQCD & Light Cone Sum Rule (LCSR) Approach

N(1535)S_{11}



N S_{11}



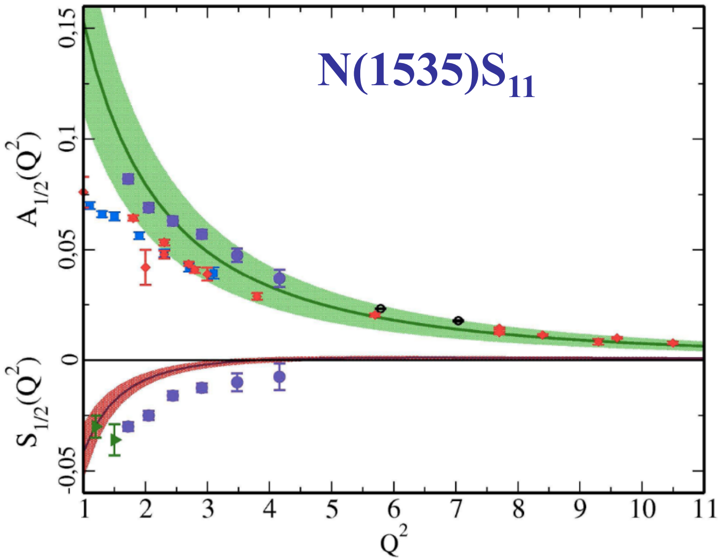
LQCD is used to determine the moments of N* distribution amplitudes (DA) and the N* electrocouplings are determined from the respective DAs within the LCSR framework.

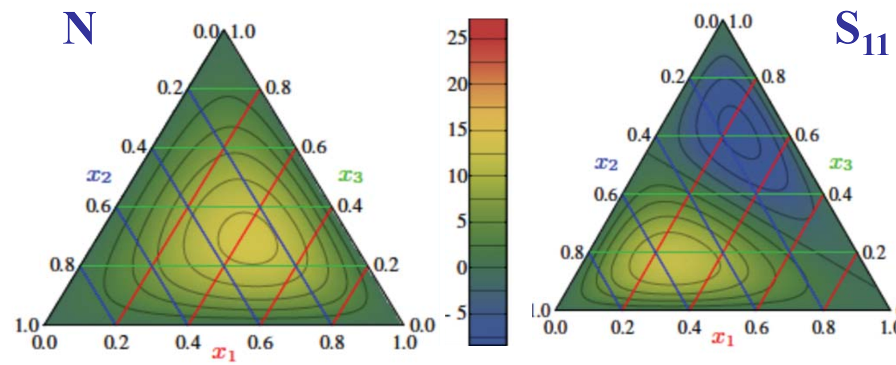
Calculations of N(1535)S_{11} electrocouplings at Q^2 up to 12 GeV^2 are already available and shown by shadowed bands on the plot.

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

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

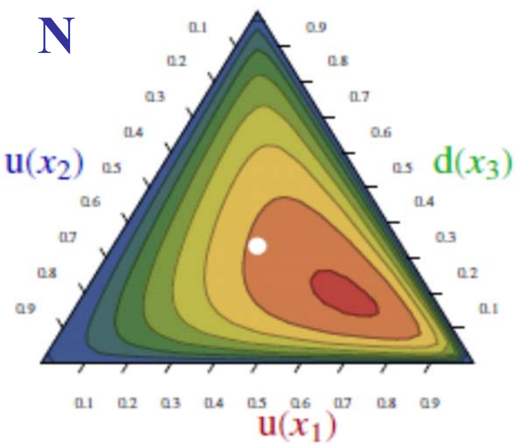
LQCD, LCSR, and DSE Approaches

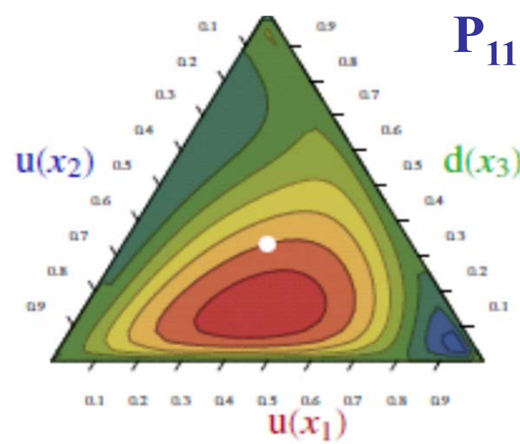




x_i is the momentum fraction of i-th valence quark

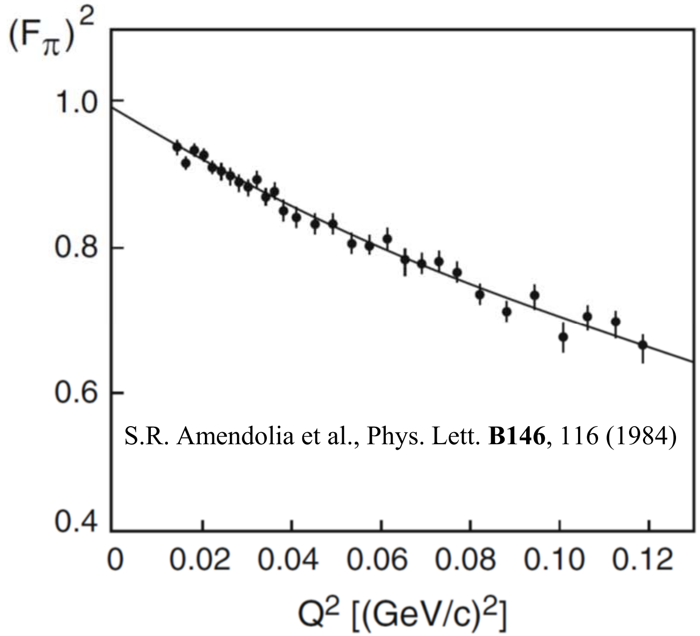
I.V. Anikin *et al.*, Phys. Rev. **D92**, 014018 (2015) and V.M. Braun *et al.*, Phys. Rev. **D89**, 094511 (2014)

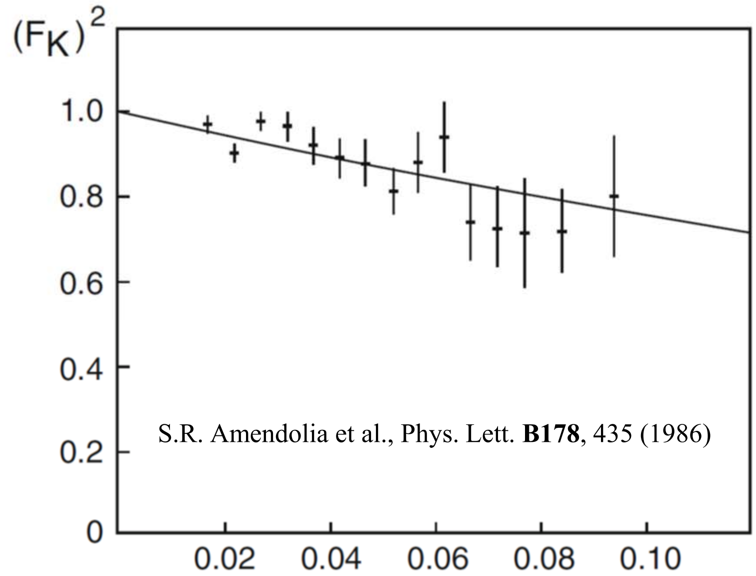




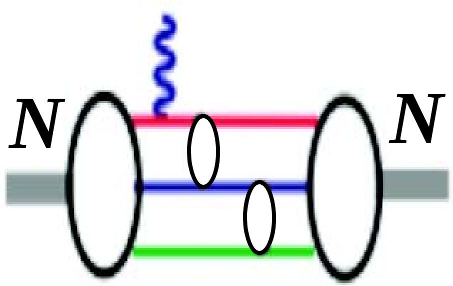
C.D. Roberts and C. Merzag, EPJ Web Conf. **137**, 01017 (2017)

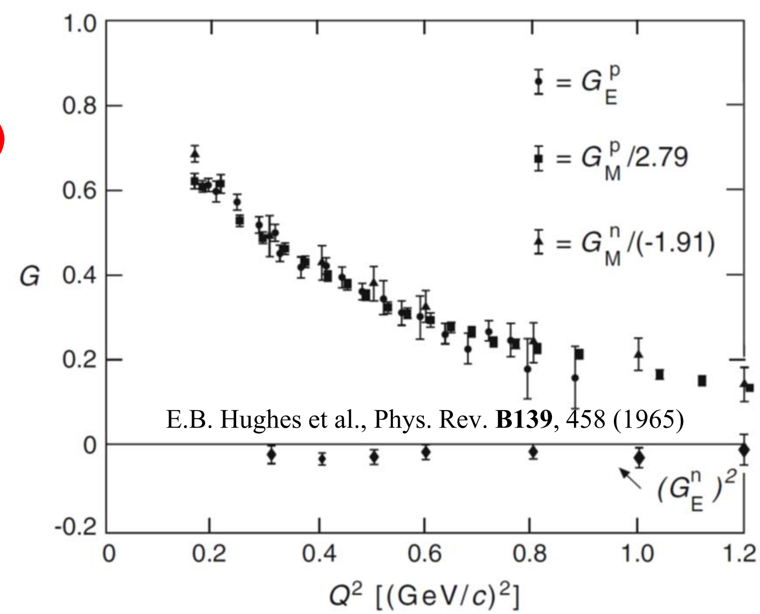
History of Form Factors



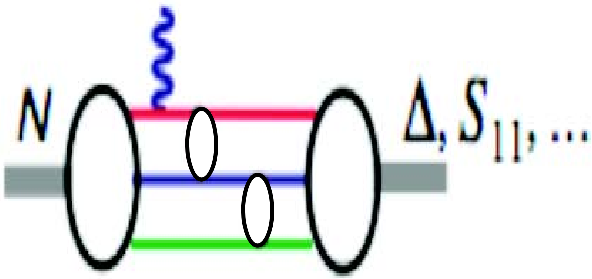


$$F(Q^2) = G_E(Q^2) = \left(1 + Q^2/a^2\hbar^2\right)^{-2}$$

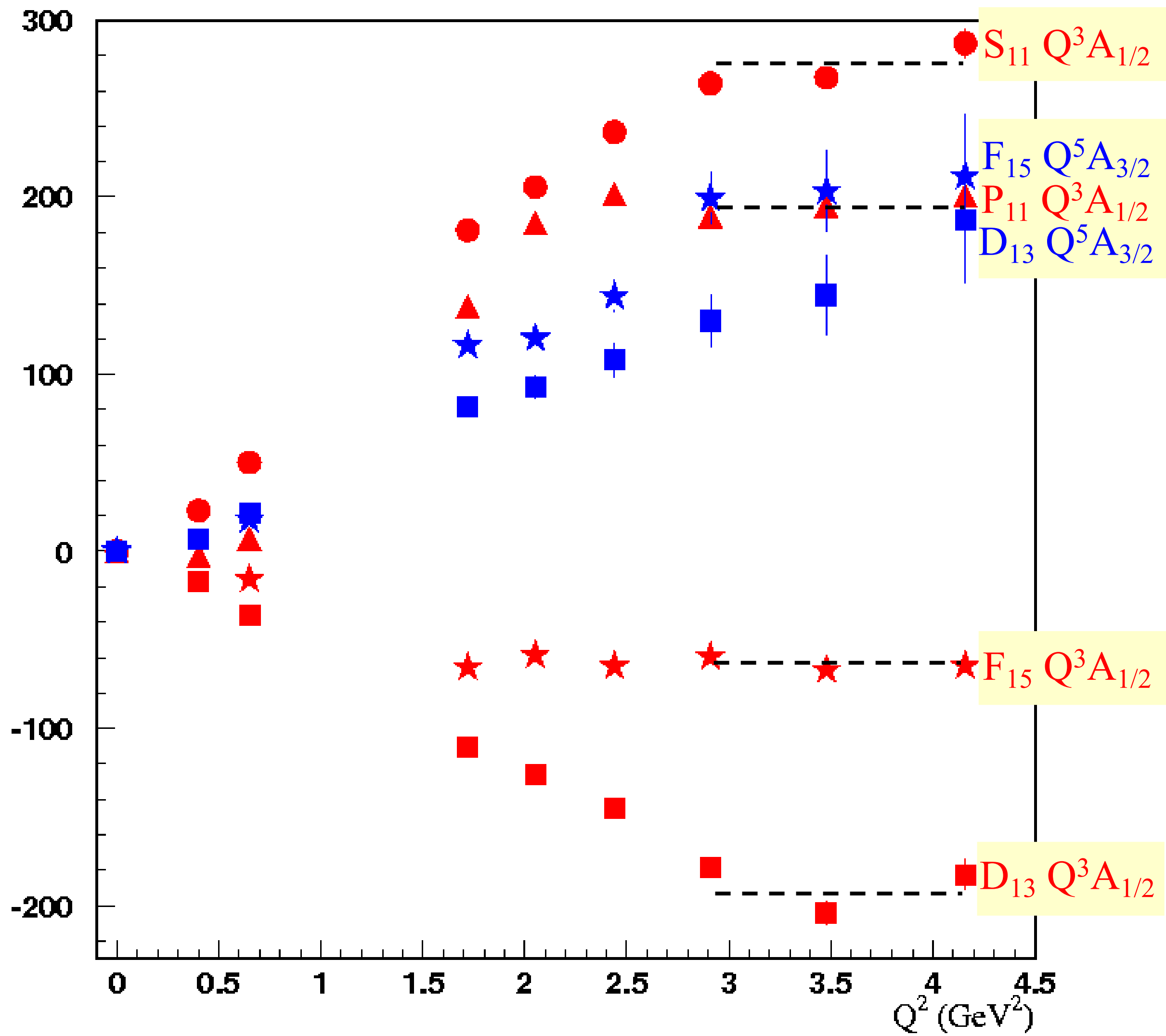




Evidence for the Onset of Precocious Scaling?



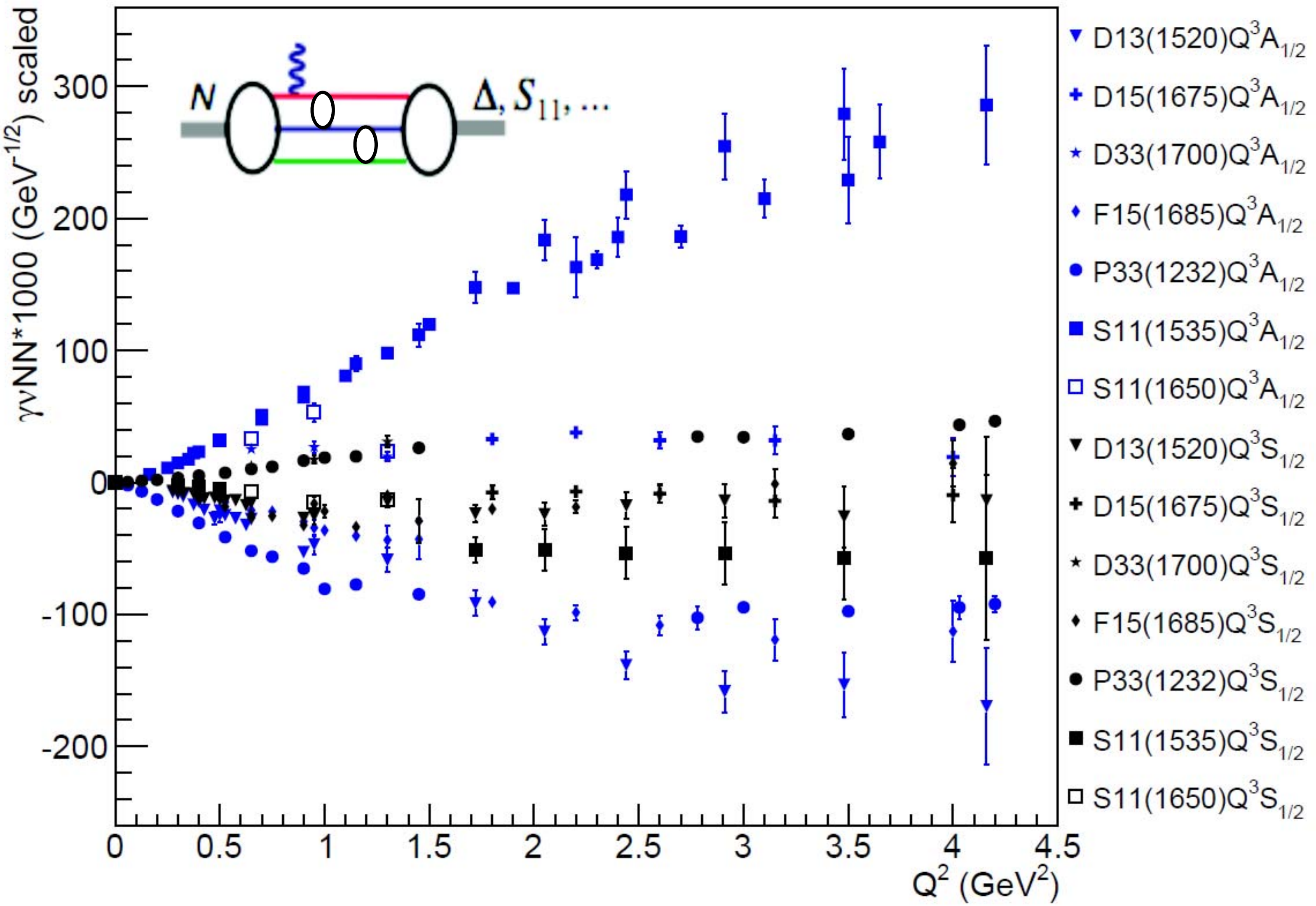
I. G. Aznauryan *et al.*, Phys. Rev. C80, 055203 (2009)



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

Evidence for the Onset of Precocious Scaling?

Ye Tian



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

Evidence for the Onset of Precocious Scaling?

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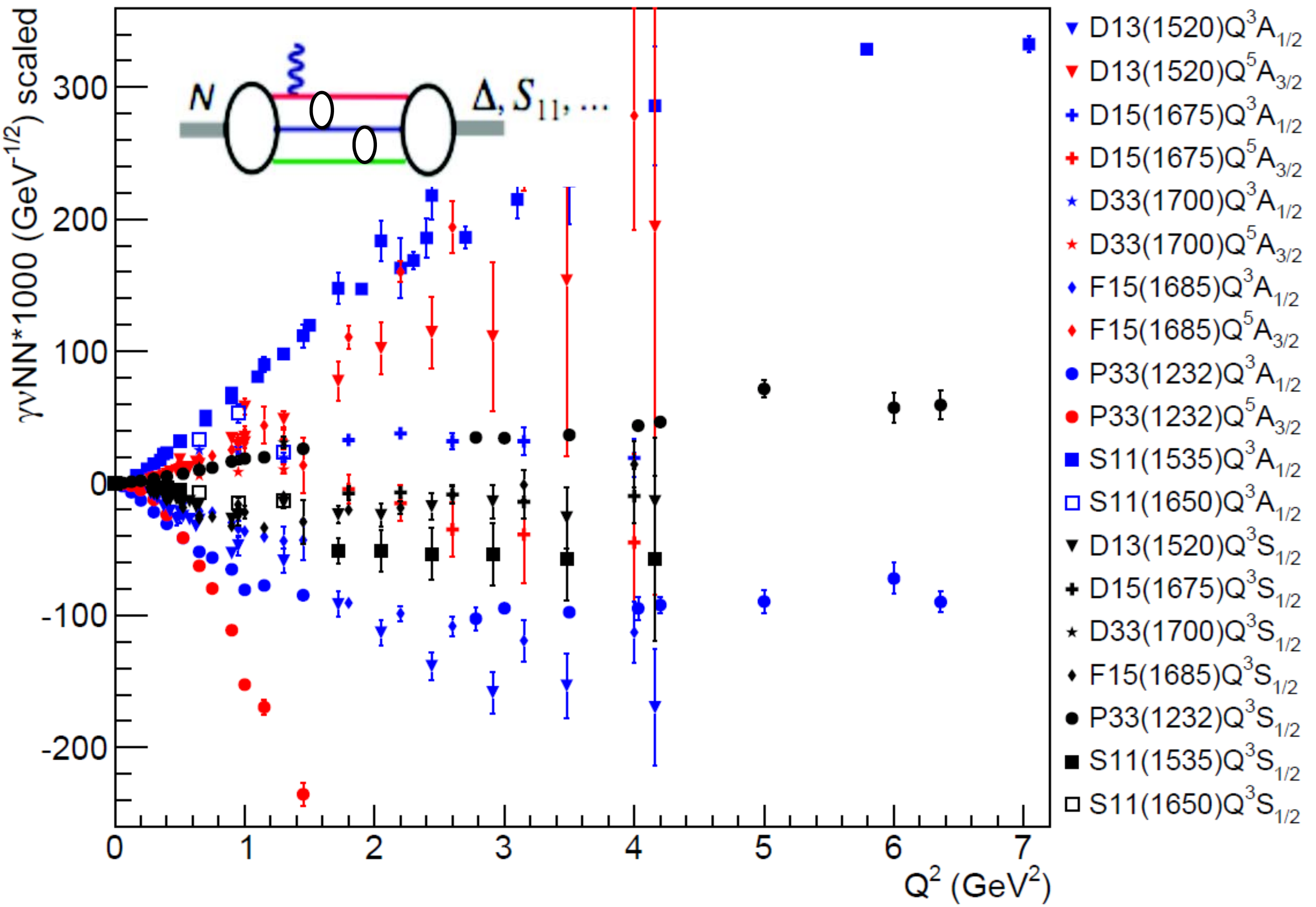
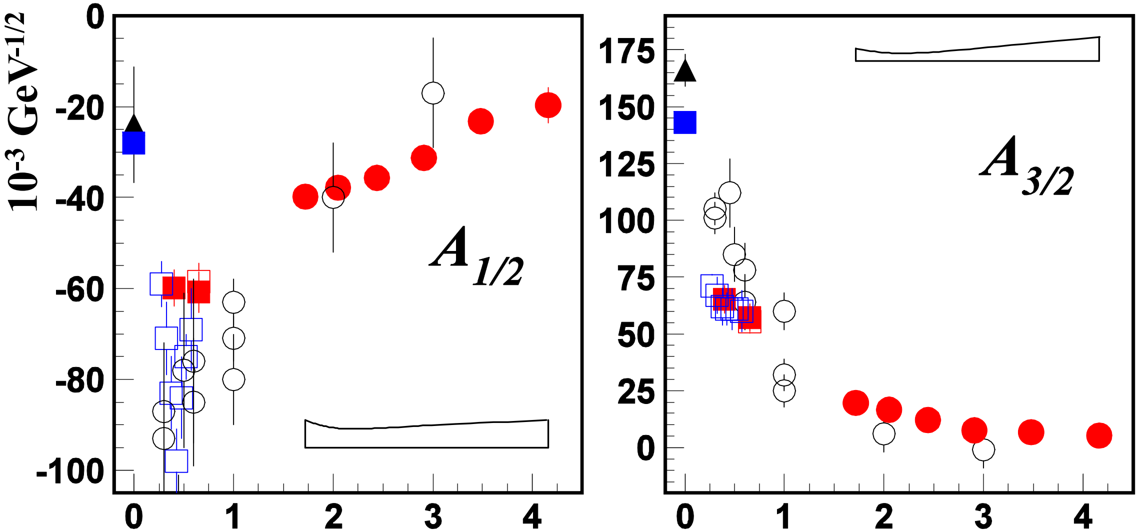
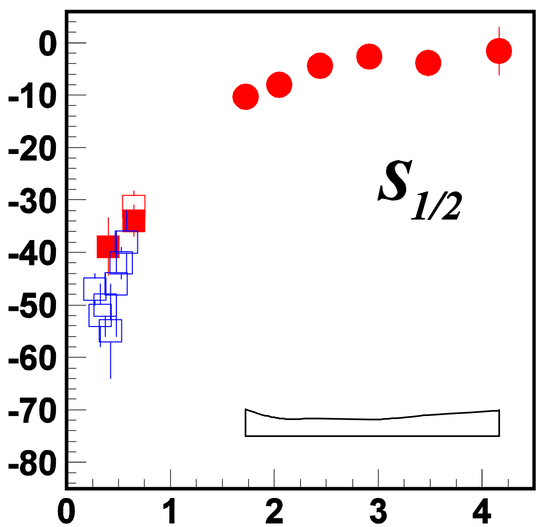


V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)

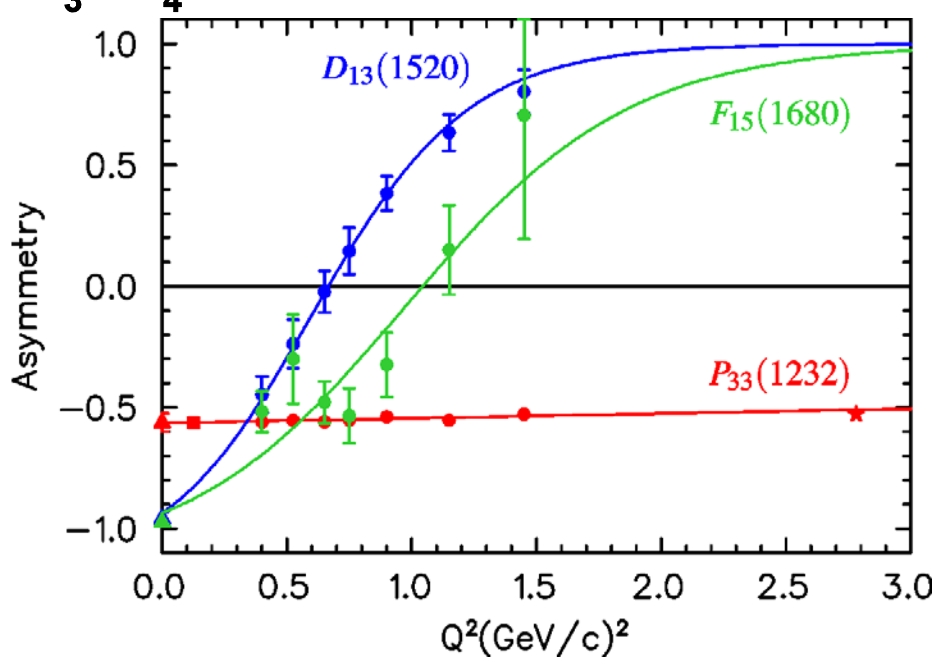
N(1520)D_{13} Helicity Asymmetry





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

L. Tiator

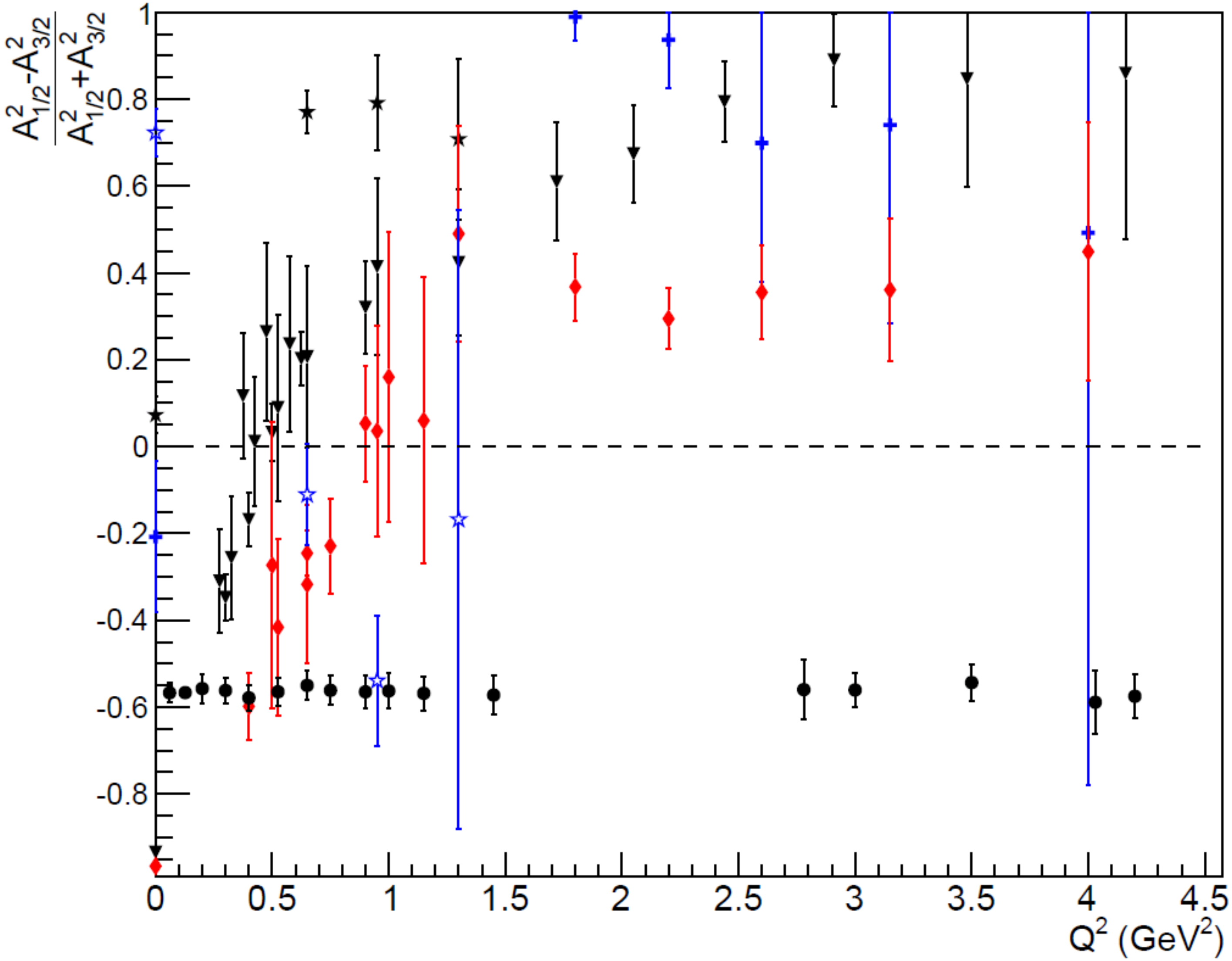


○ world data

▲ PDG estimation ● ■ Nπ (UIM, DR)

γNN* Helicity Asymmetries

Ye Tian

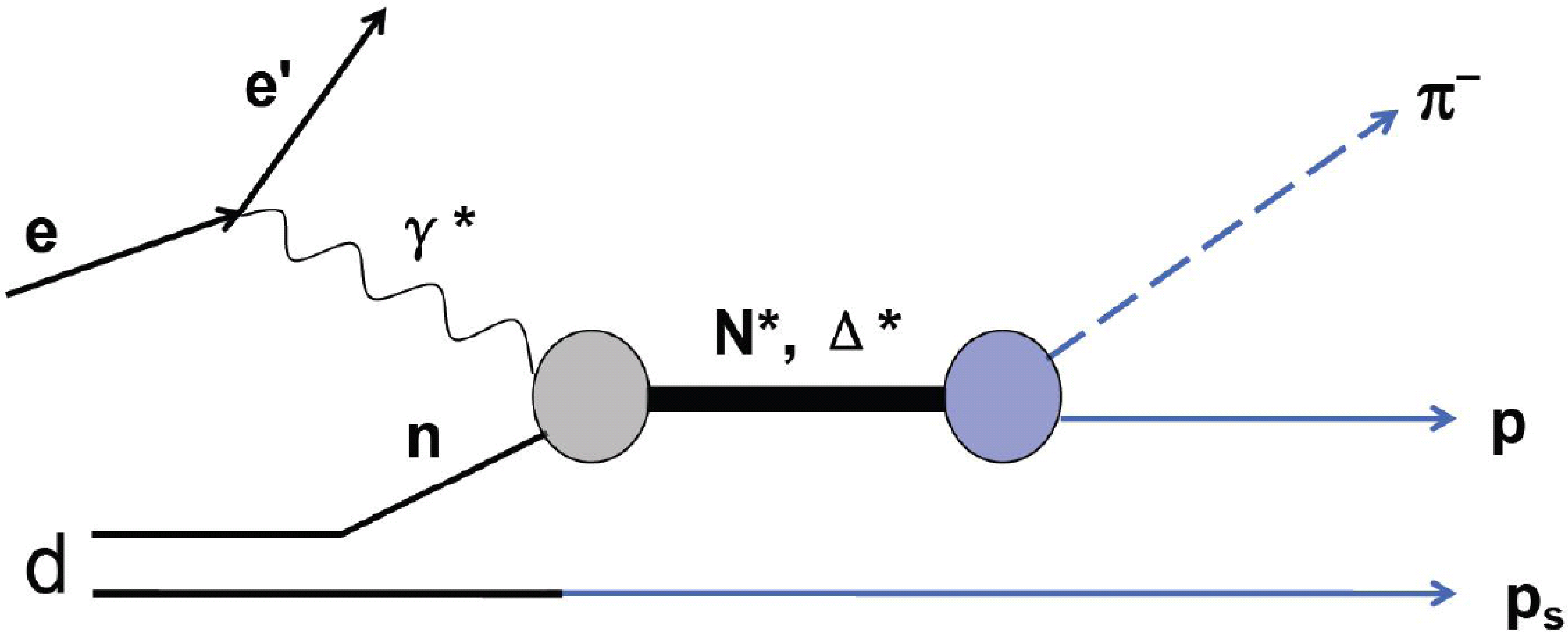


V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)

New Experimental Results & Approaches

Single π^- Electroproduction off the Deuteron

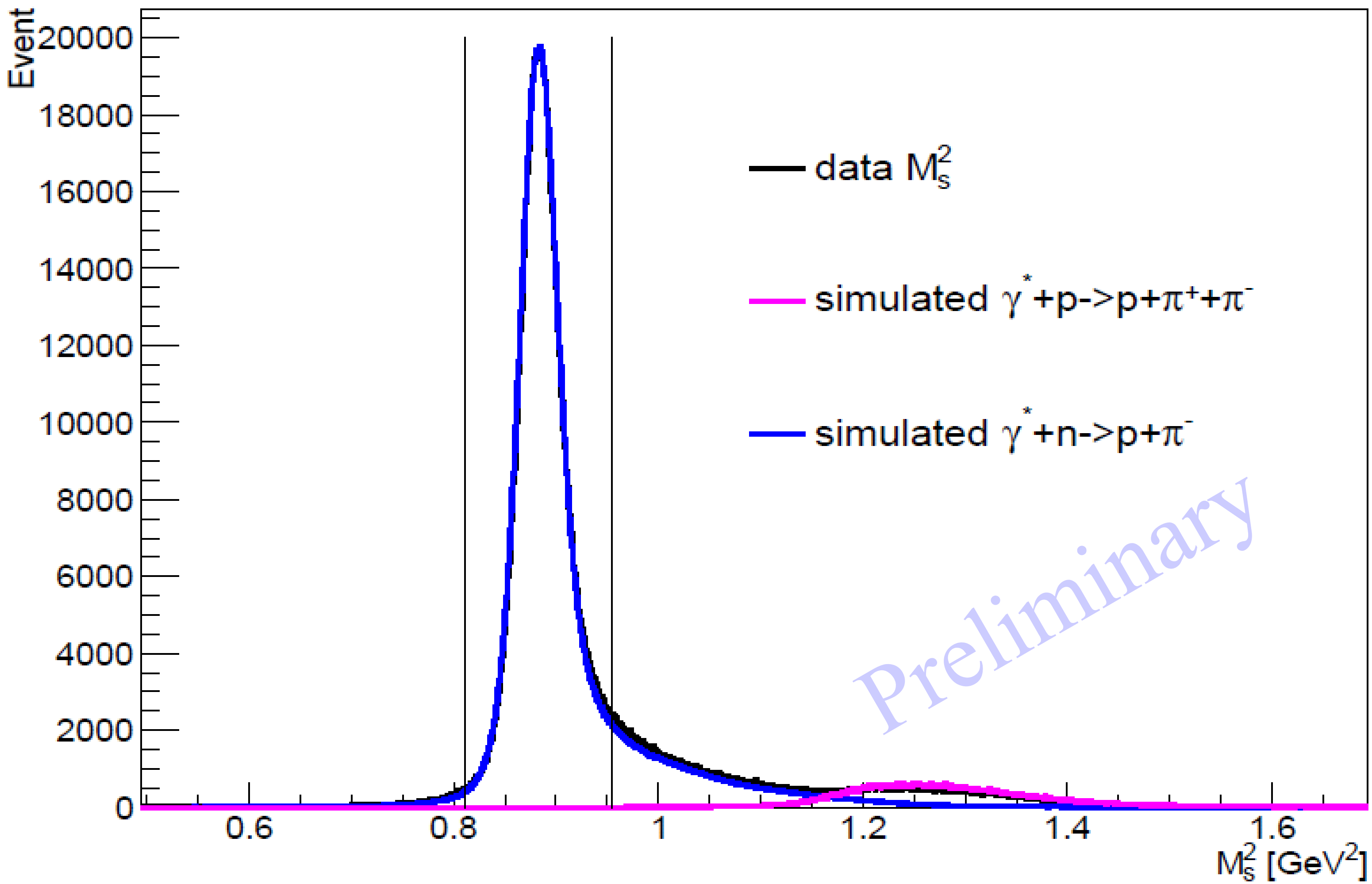
Ye Tian



Exclusive ⇒ Spectator ⇒ Quasi-Free ⇒ FSI

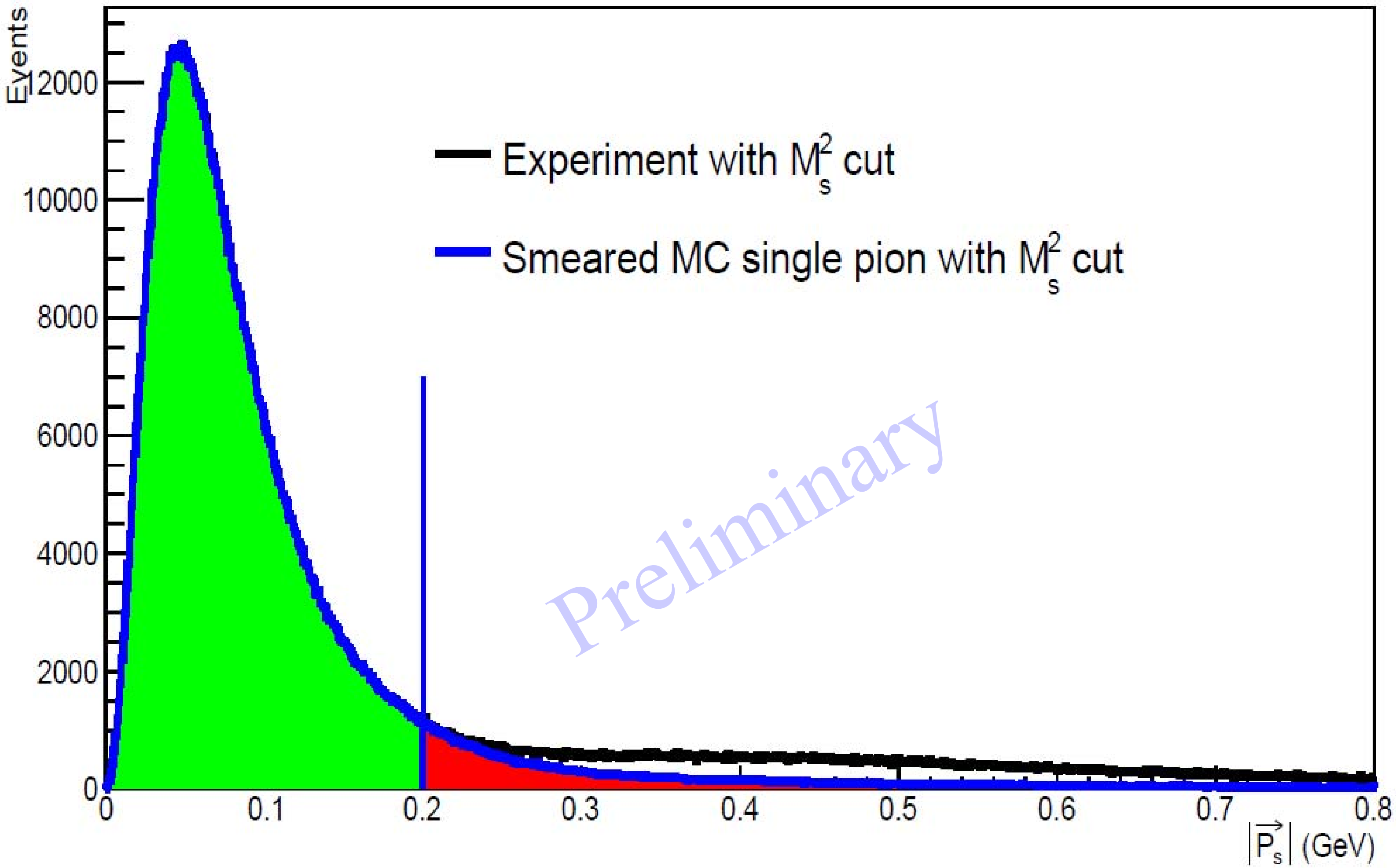
Single π^- Electroproduction off the Deuteron

Ye Tian



Single π^- Electroproduction off the Deuteron

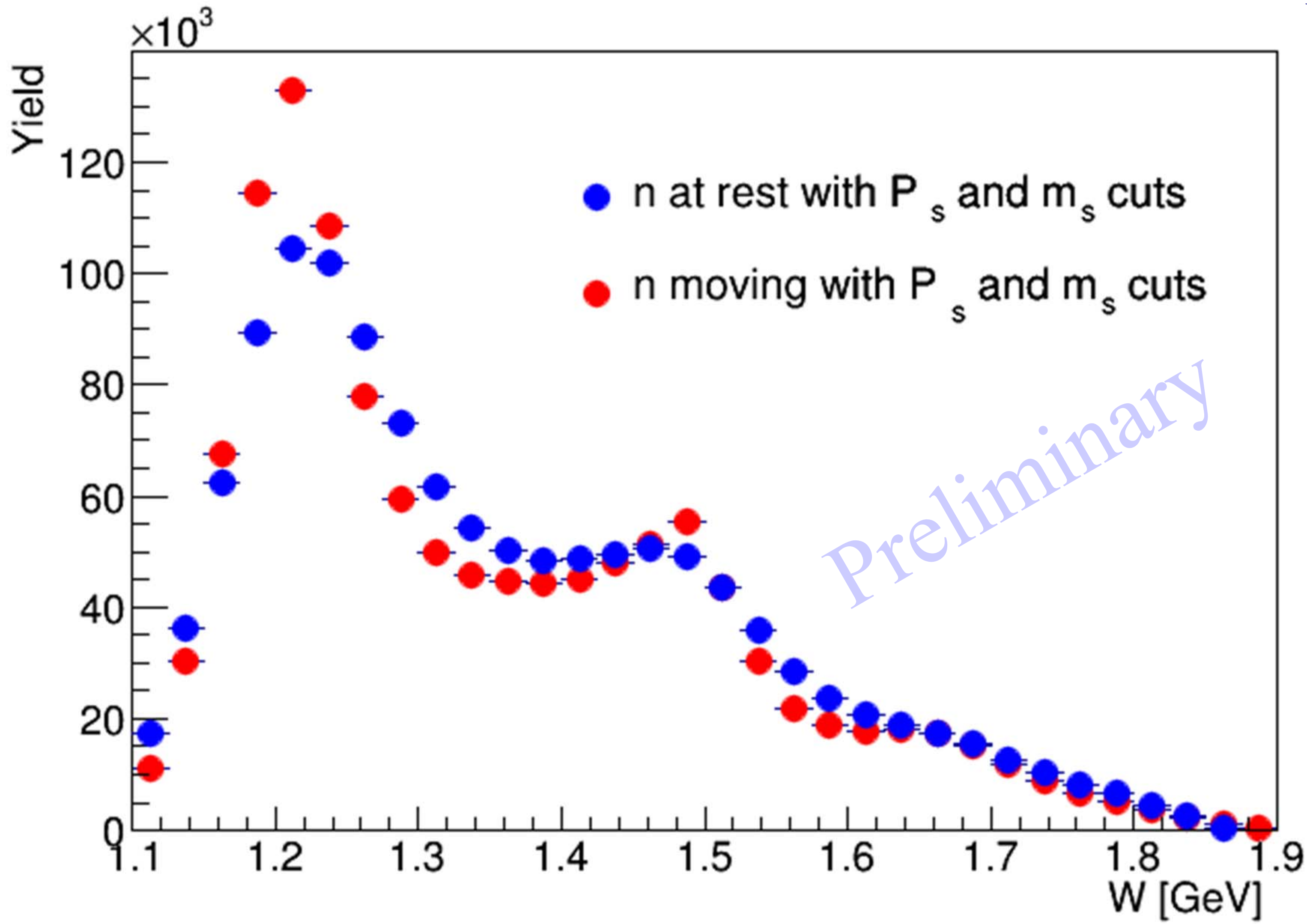
Ye Tian



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

W = 1212 MeV

ΔW = 25 MeV

$Q^2 = 0.5\ GeV^2$

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

cos(θ) = -0.7

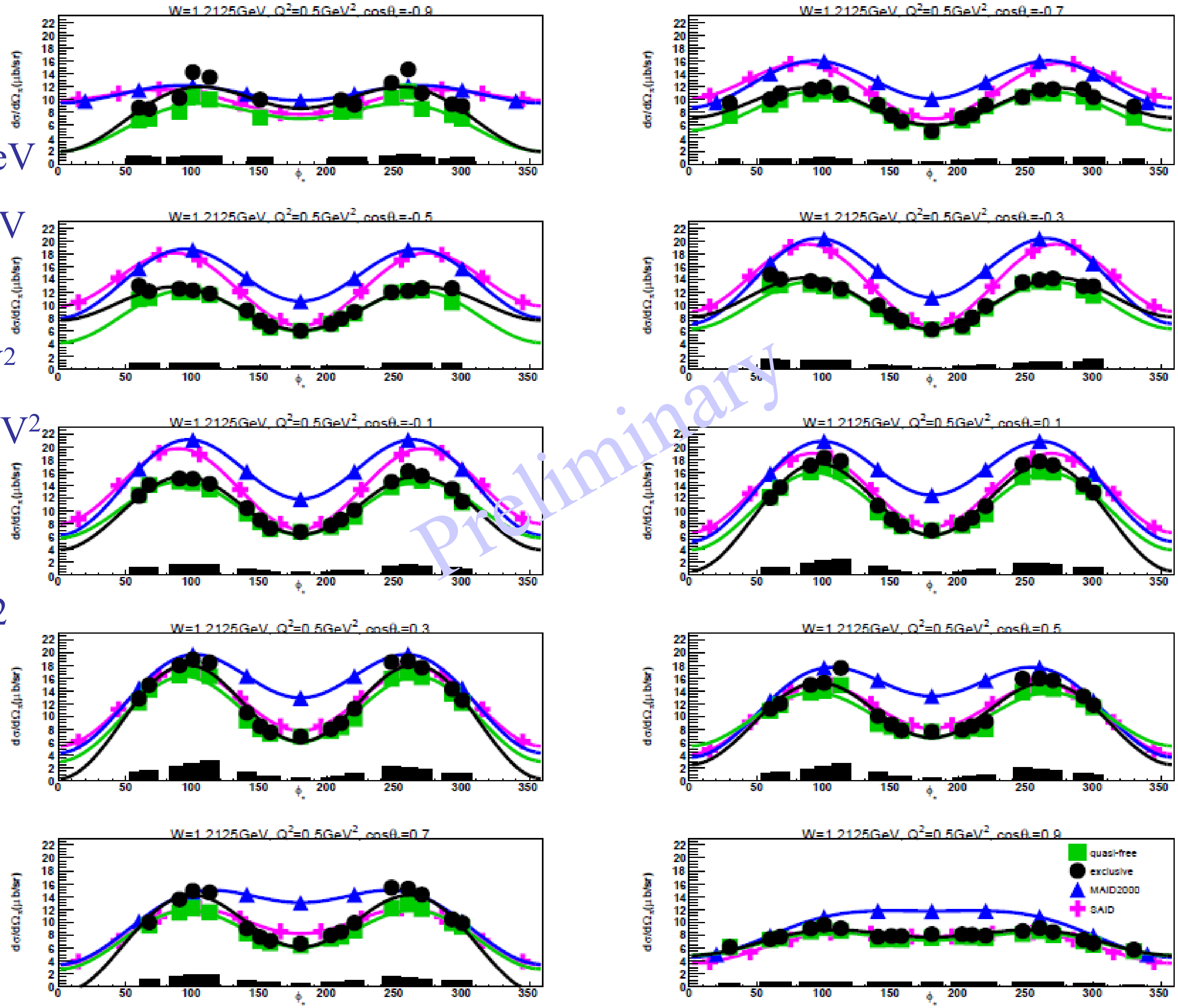
Δcos(θ) = 0.2

cos(θ) = 0.7

$\phi = 20^o$

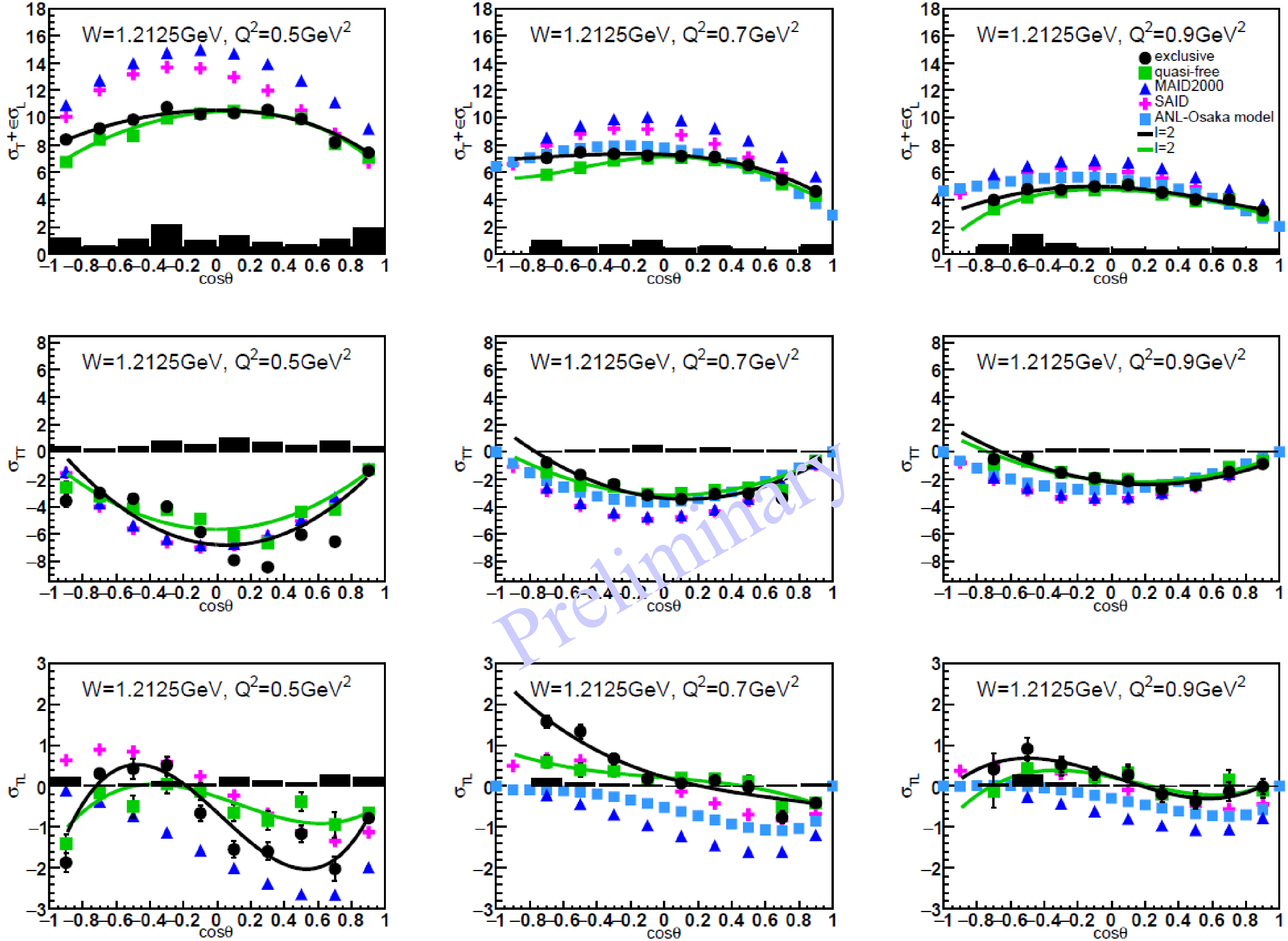
$\Delta\phi = 40^o$

$\phi = 340^o$



Single π⁻ Electroproduction off the Deuteron

Ye Tian



Single π^- Electroproduction off the Deuteron

$Q^2 = 0.5$ GeV^2

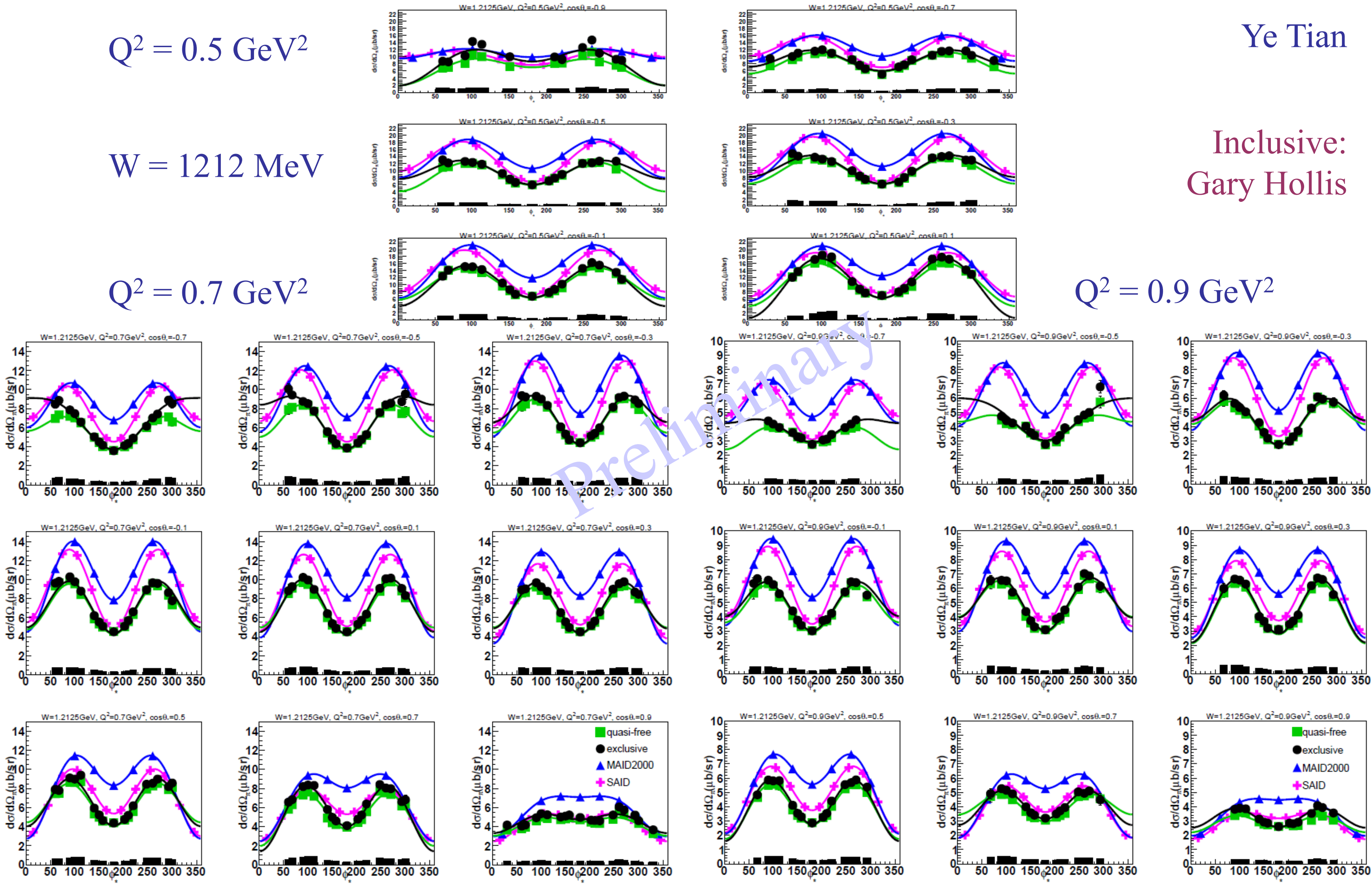
W = 1212 MeV

$Q^2 = 0.7$ GeV^2

$Q^2 = 0.9$ GeV^2

Ye Tian

Inclusive:
Gary Hollis

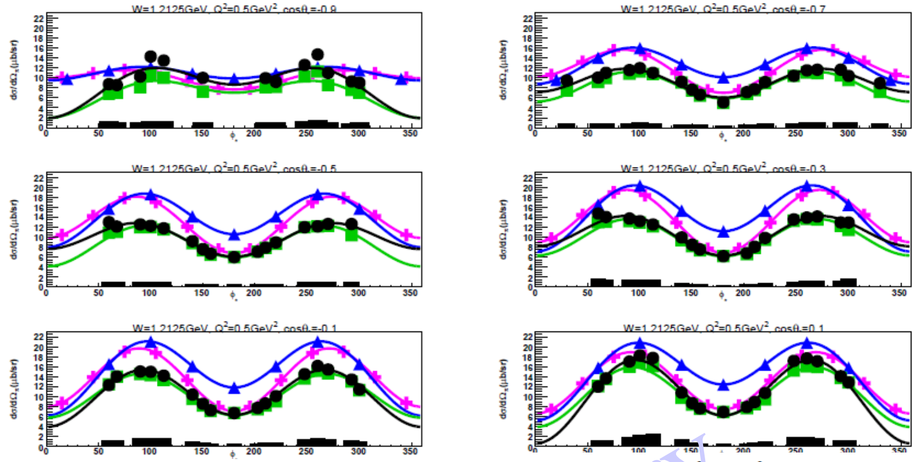


Single π⁻ Electroproduction off the Deuteron

$Q^2 = 0.5$ GeV^2

Ye Tian

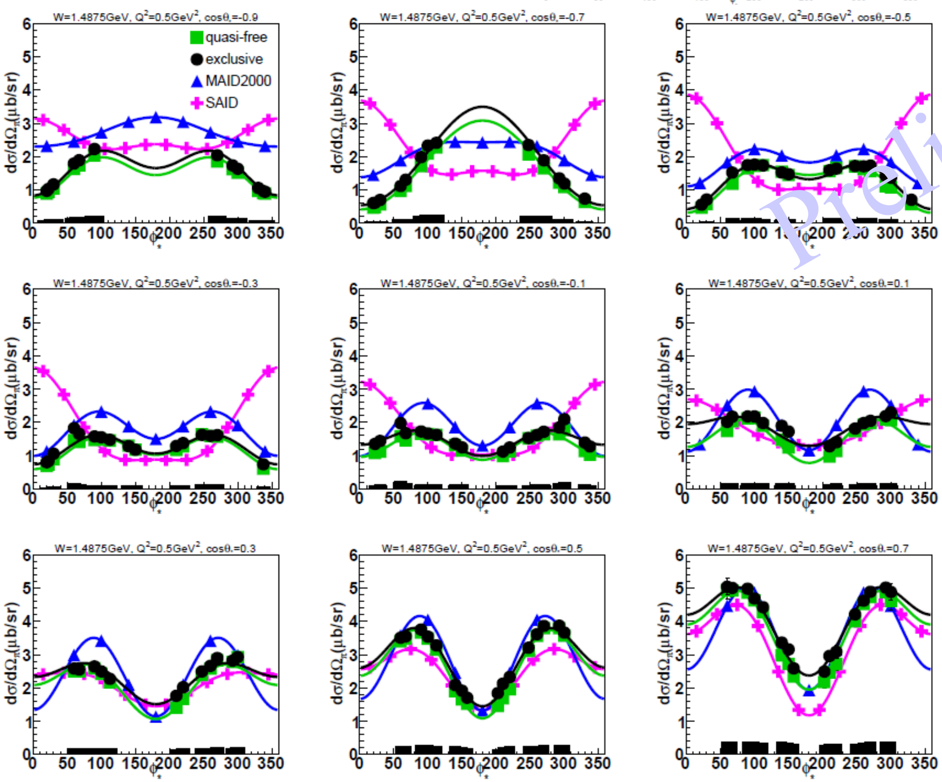
W = 1212 MeV

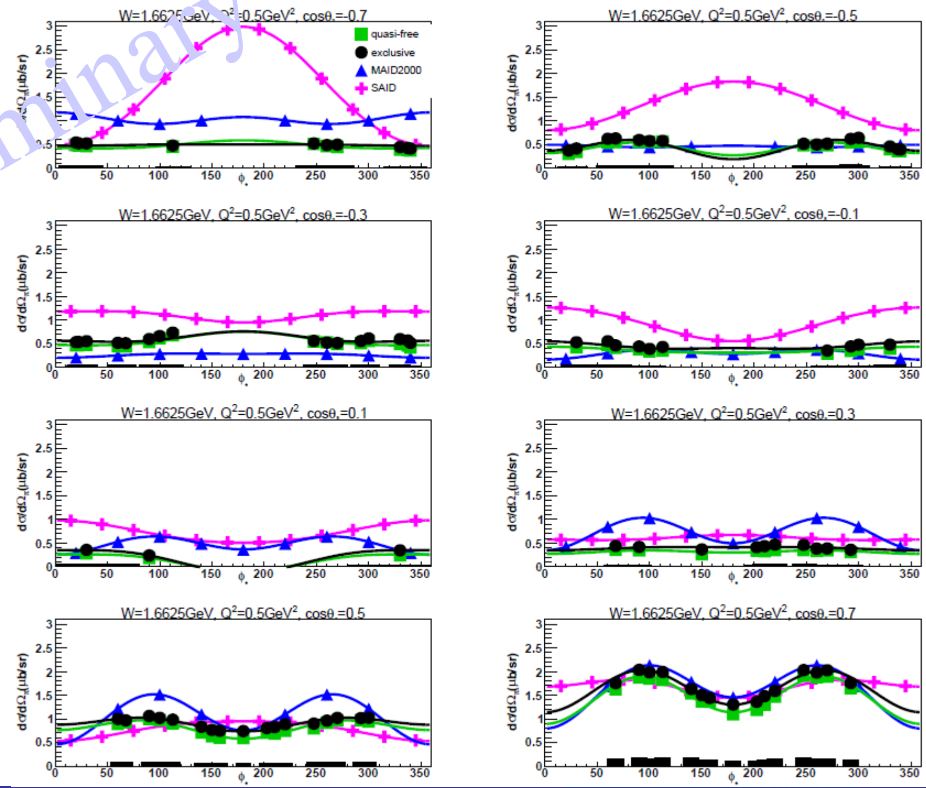


Inclusive:
Gary Hollis

W = 1488 MeV

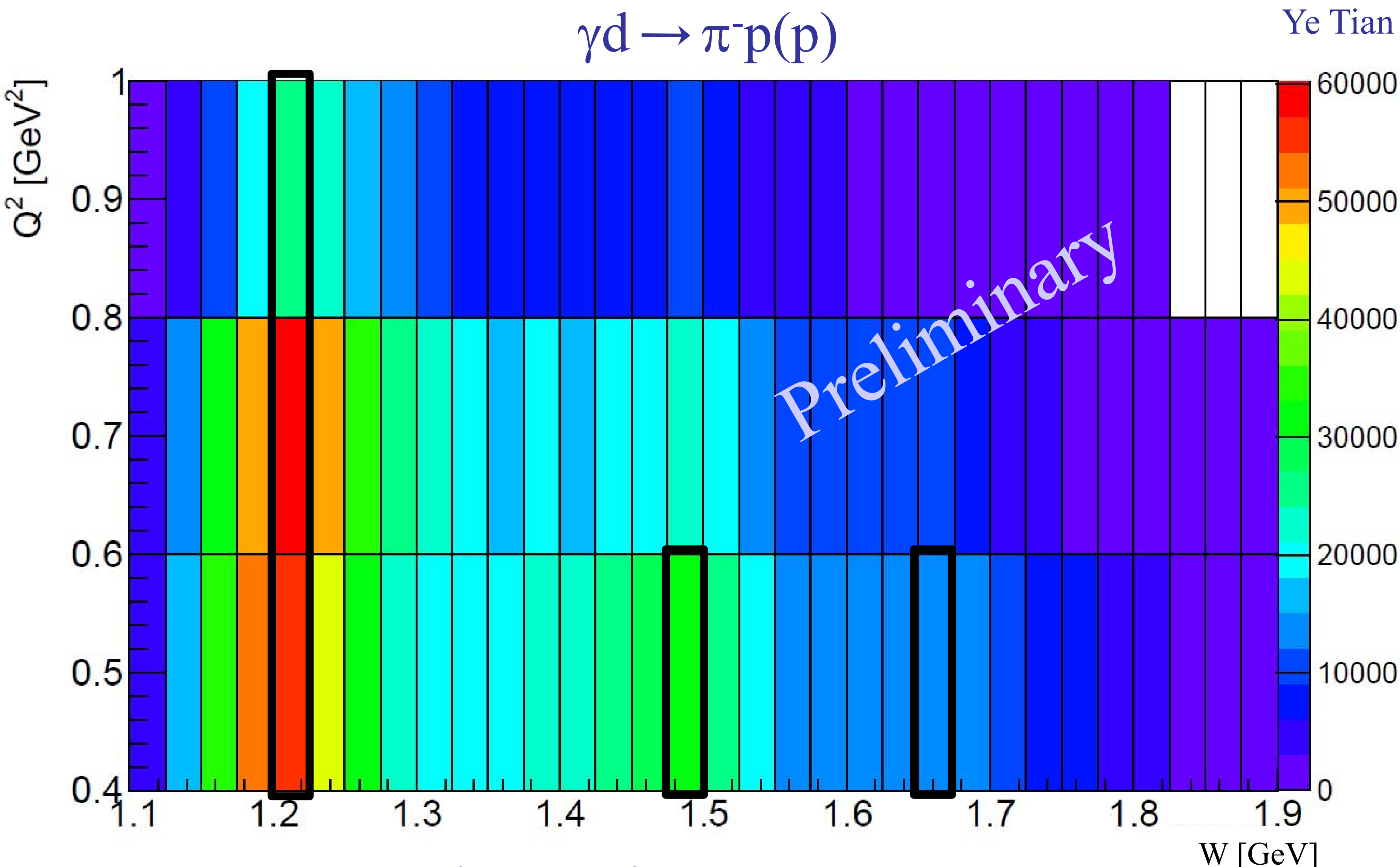
W = 1662 MeV





Single π ⁻ Electroproduction off the Deuteron

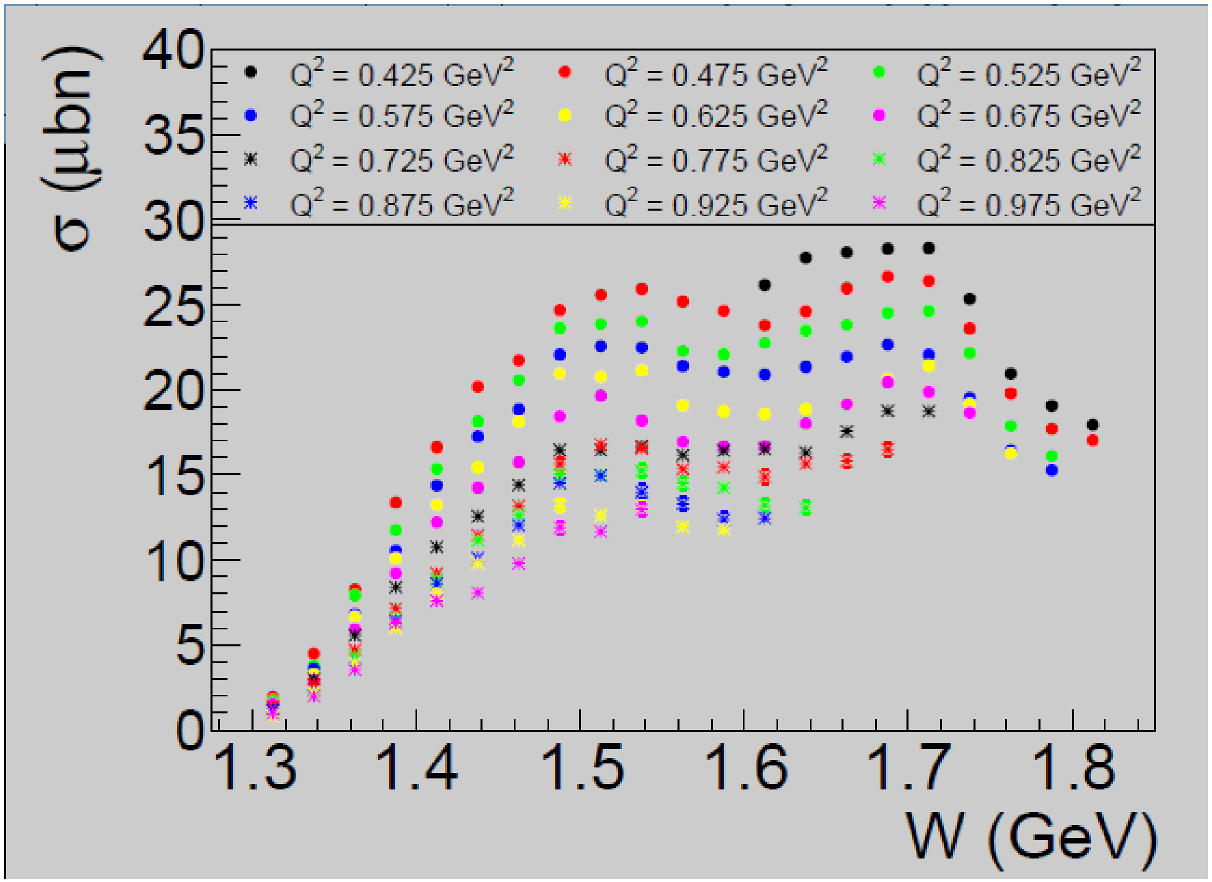
Ye Tian

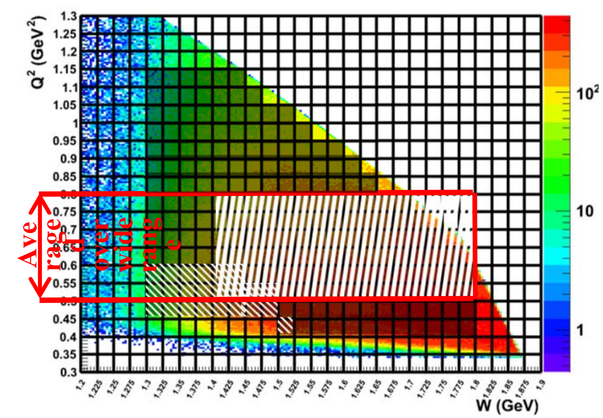


$\Delta Q^2 = 0.2\ GeV^2$ $\Delta W = 25\ MeV$

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

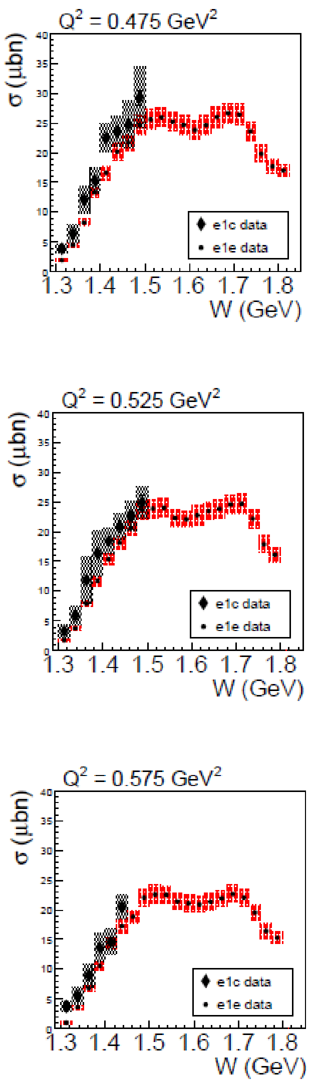
Gleb Fedotov
Phys. Rev. C 98, 025203 (2018)

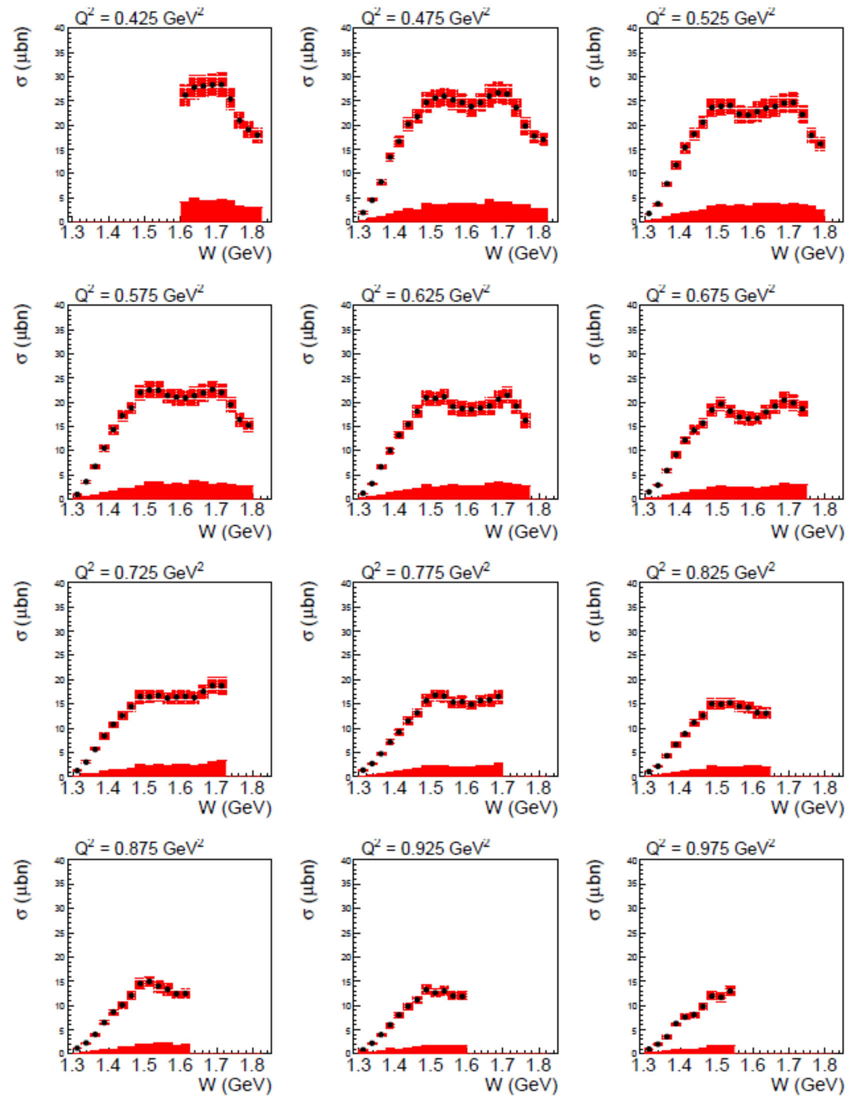




$p\pi^+\pi^-$ event yields over W and Q^2. Gray shaded area new e1e data set, hatched area at low Q^2 already published e1c data by G. Fedotov *et al.* and hatched area at higher Q^2 already published data in one large Q^2 bin by M. Ripani *et al.*

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





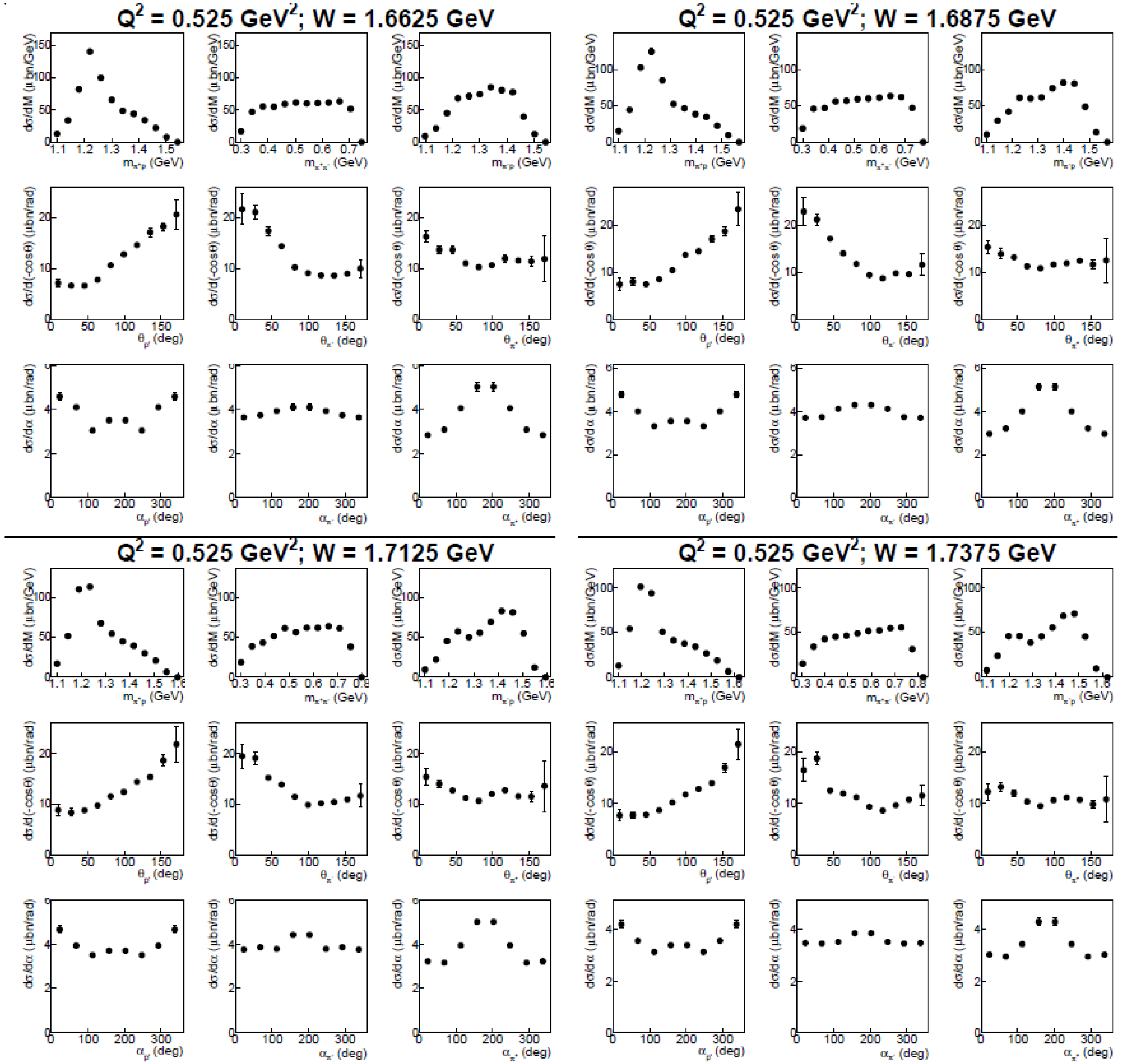
Gleb Fedotov

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.

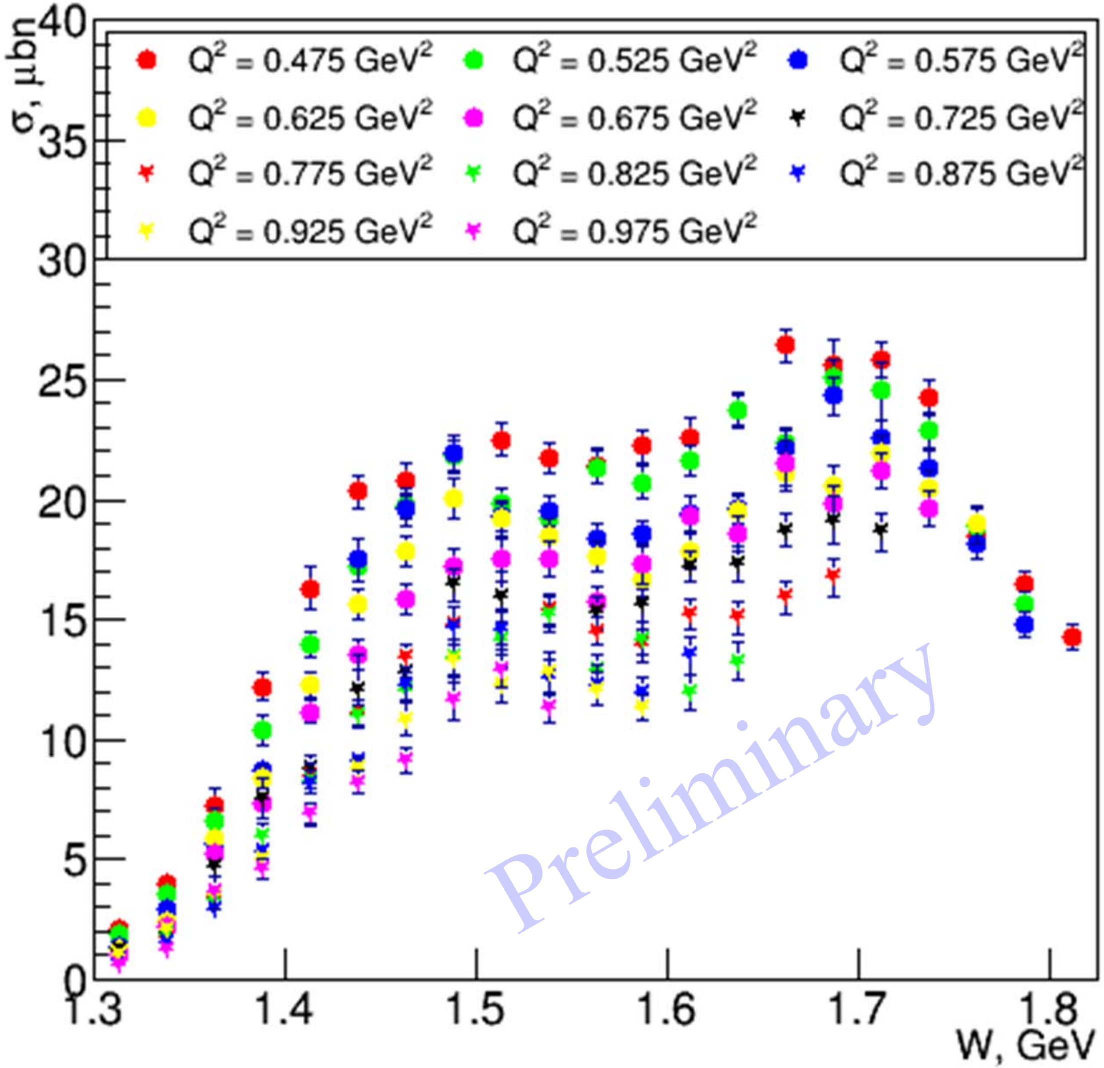
$N\pi^+\pi^-$ Single-Differential Cross Sections

Gleb Fedotov



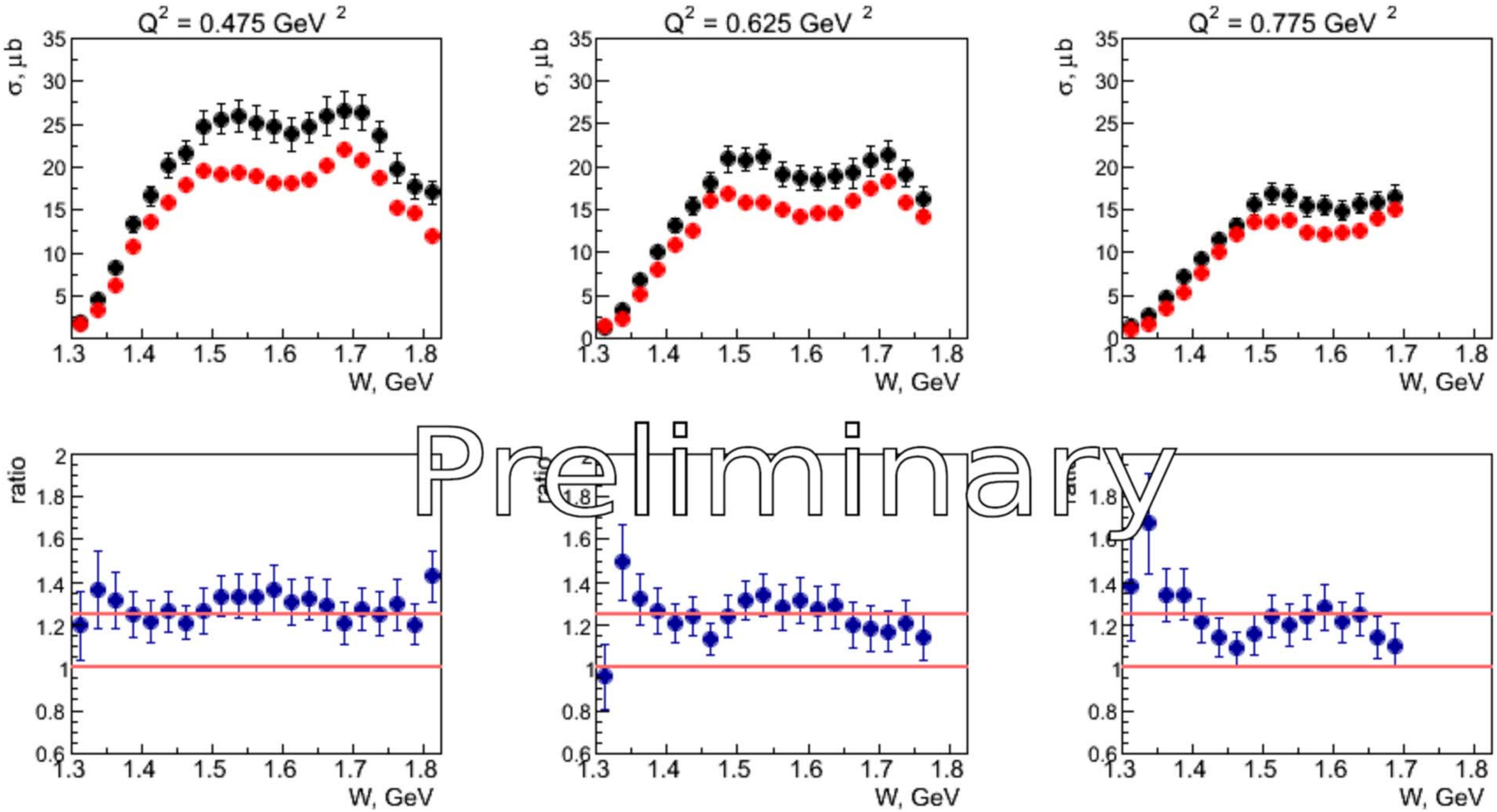
Integrated Cross Section off the Proton in Deuteron

Iuliia Skorodumina



Comparison with Free Proton Cross Section

Iuliia

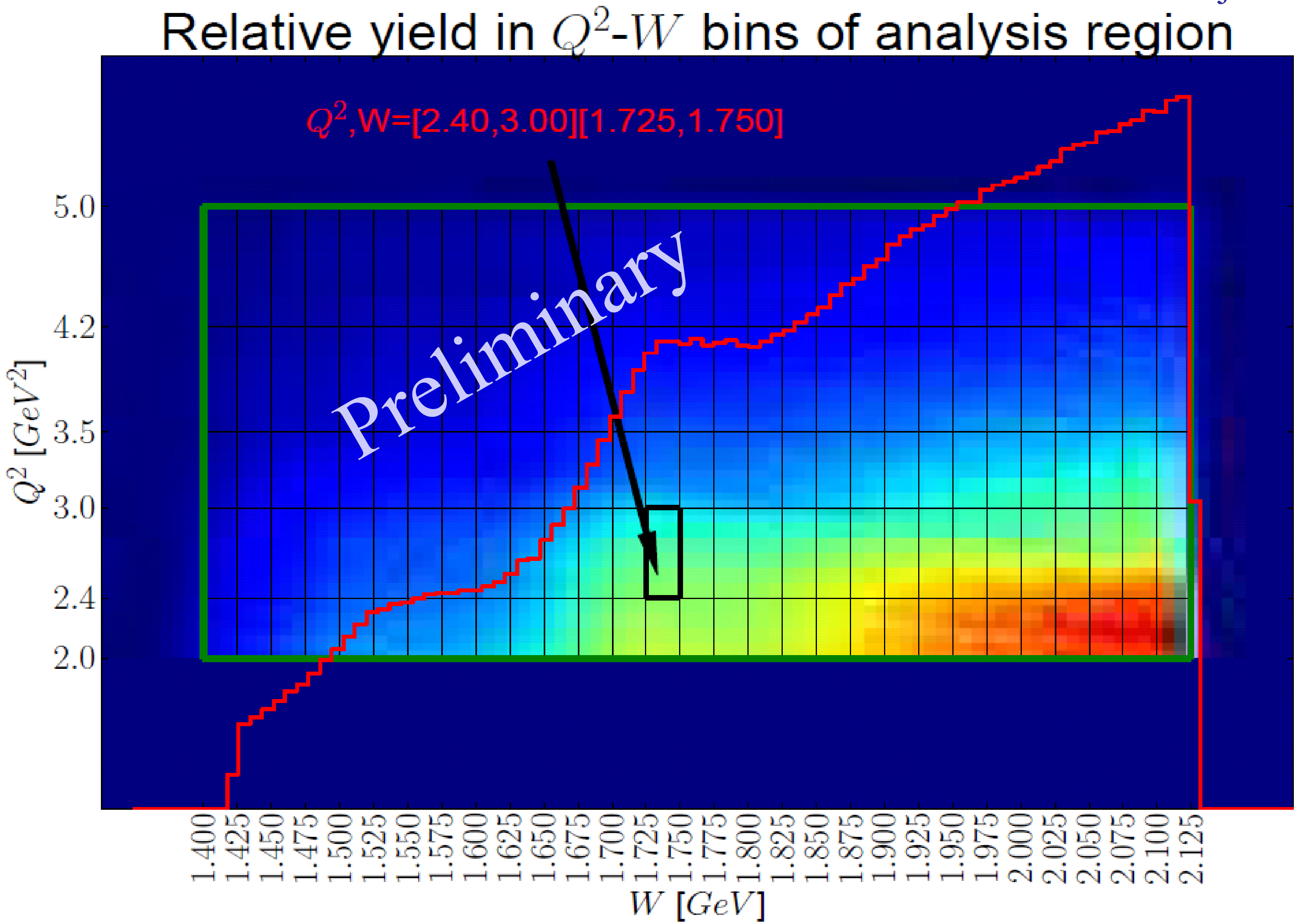


Black bullets – free proton cross sections (e1e at E_{beam} = 2.039 GeV)
error bars show both statistical and systematical uncertainties
G. Fedotov under paper review

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

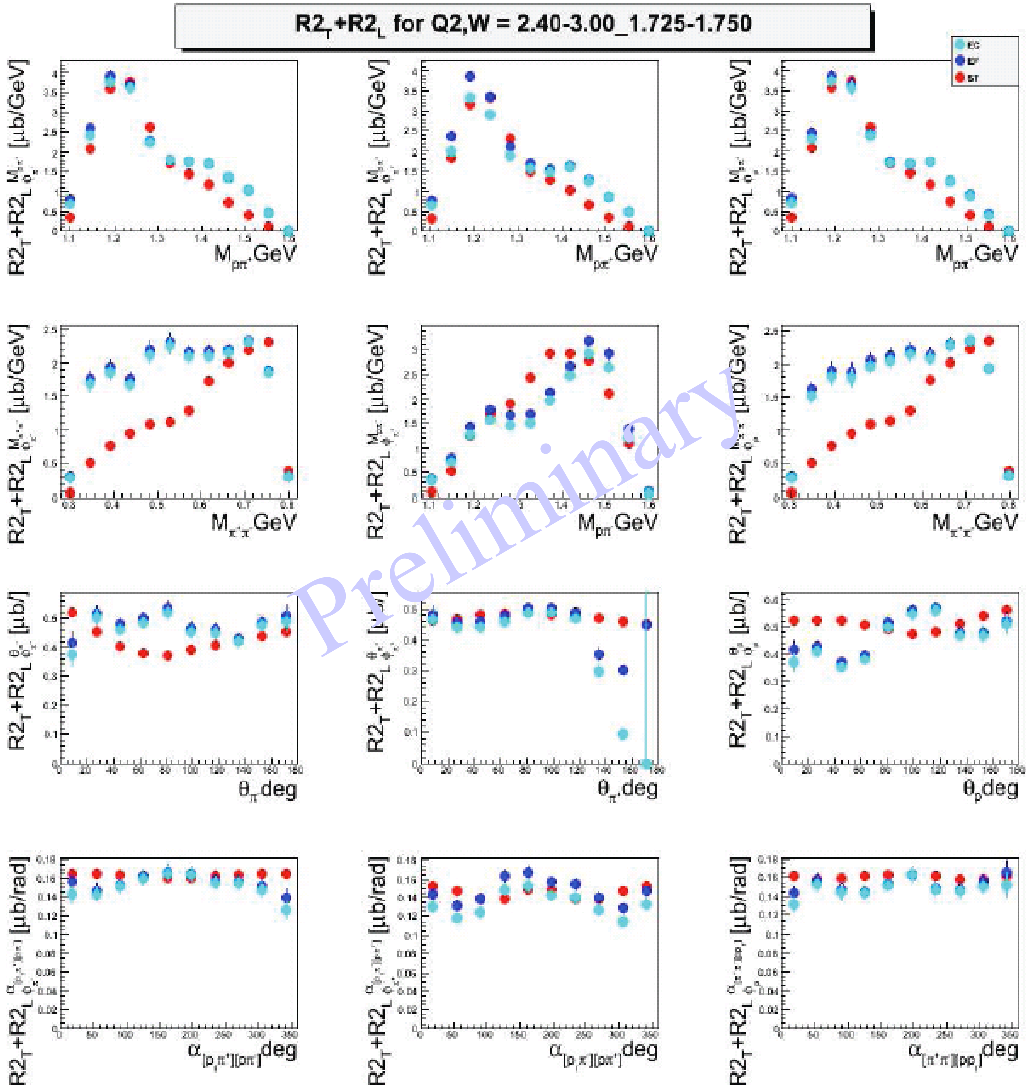
Arjun Trivedi



φ-dependent Nππ Single-Differential Cross Sections

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

Arjun Trivedi
Evgeny Isupov



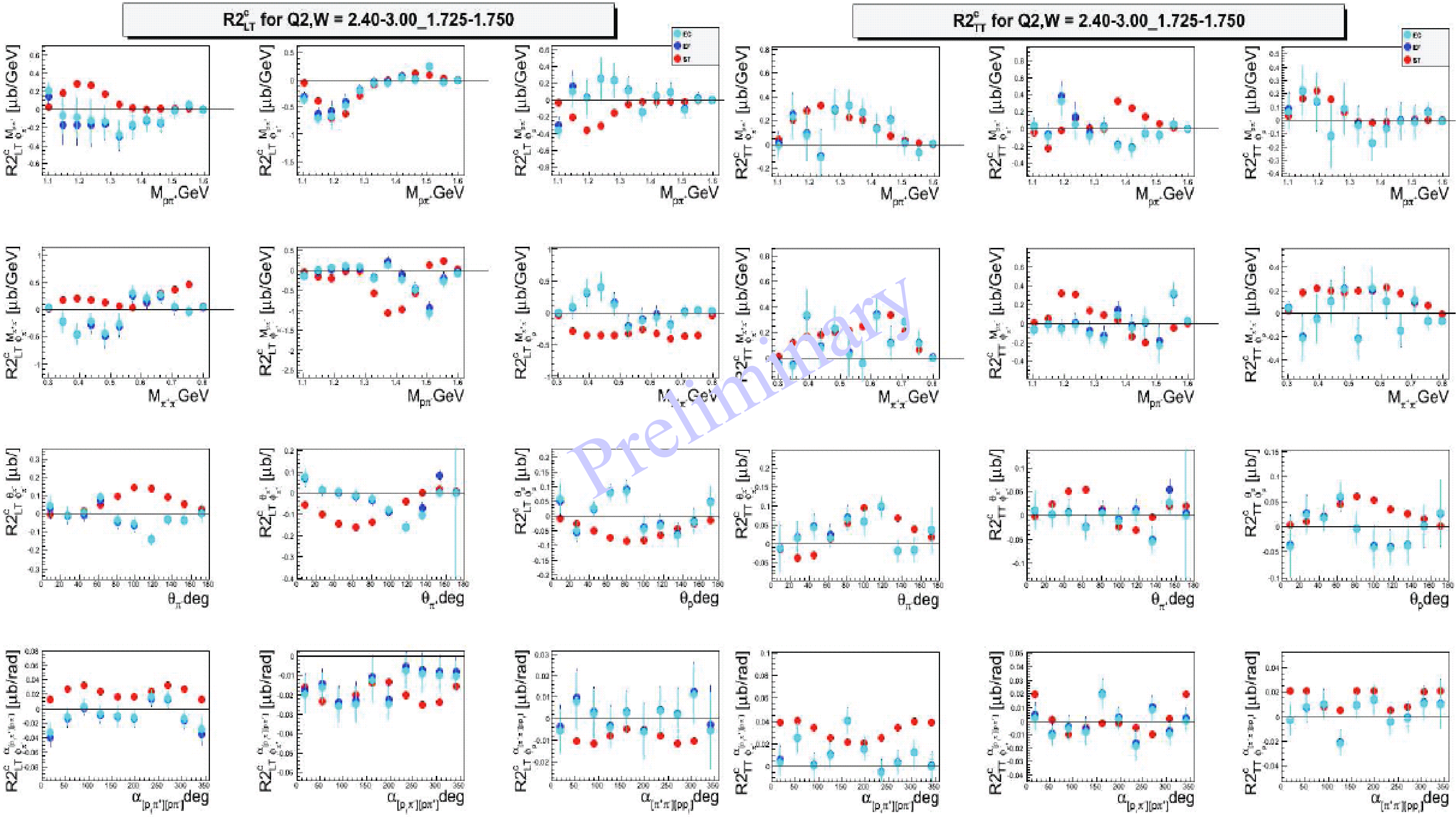
- normalized
- hole filled
- TWOPEG

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

φ-dependent Nππ Single-Differential Cross Sections

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

Arjun Trivedi



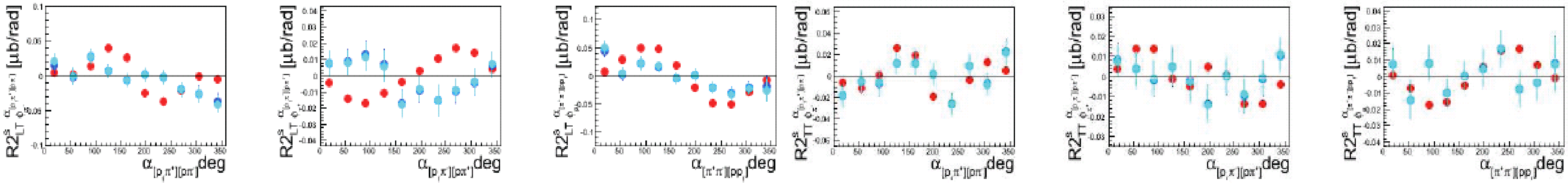
$$\left(\frac{d^2\sigma}{dX_{ij}d\phi_i}\right) = R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}} + \underline{R2_{LT}{}^{c,X_{ij}} \cos\phi_i} + \underline{R2_{TT}{}^{c,X_{ij}} \cos 2\phi_i} + \delta_{X_{ij}\alpha_i}\left(R2_{LT}{}^{s,\alpha_i} \sin\phi_i + R2_{TT}{}^{s,\alpha_i} \sin 2\phi_i\right)$$

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.

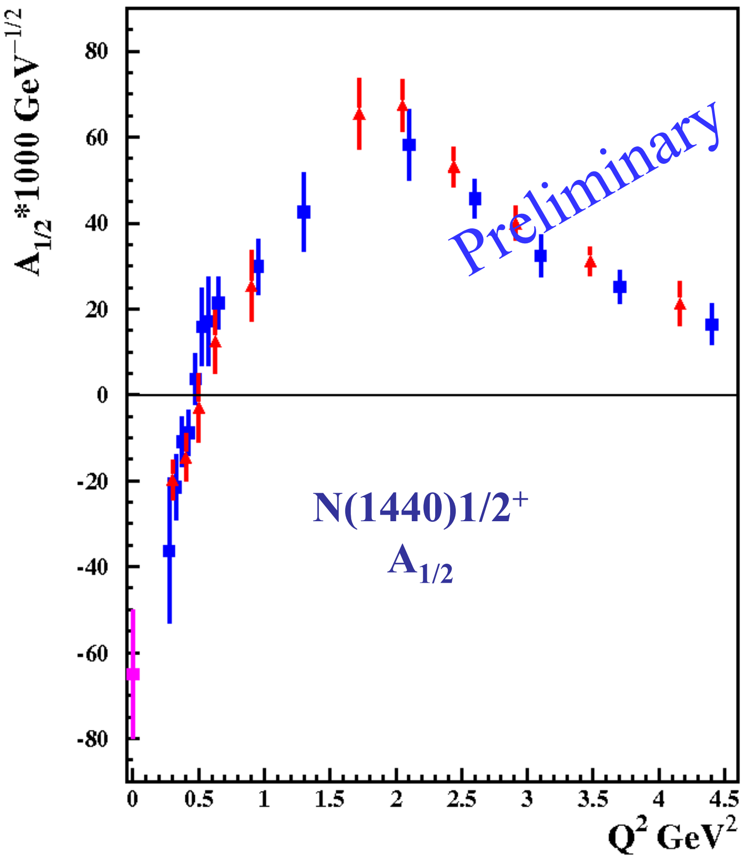
Preliminary



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

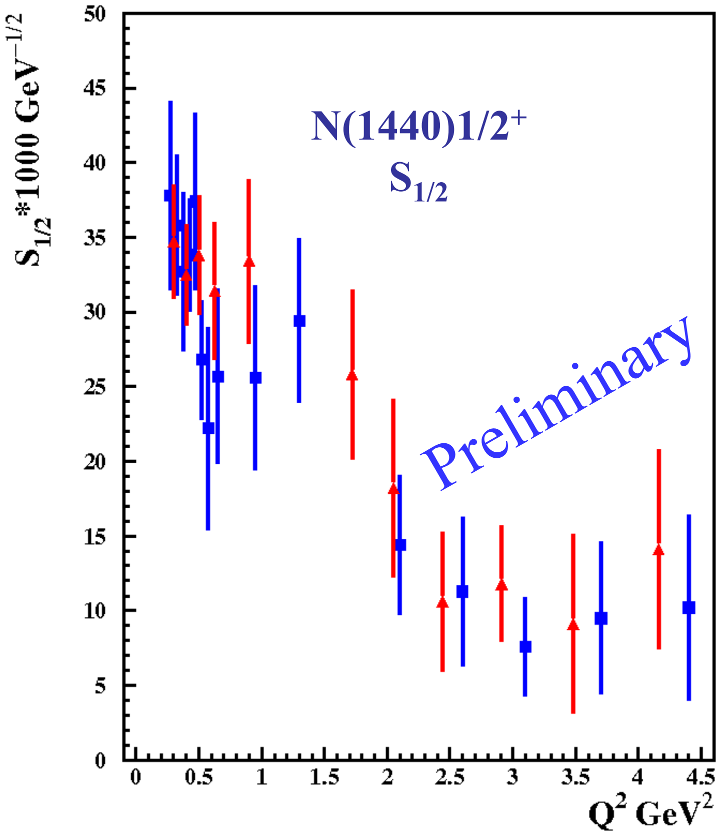
N(1440)1/2⁺ Photo- and Electroexcitation Amplitudes

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

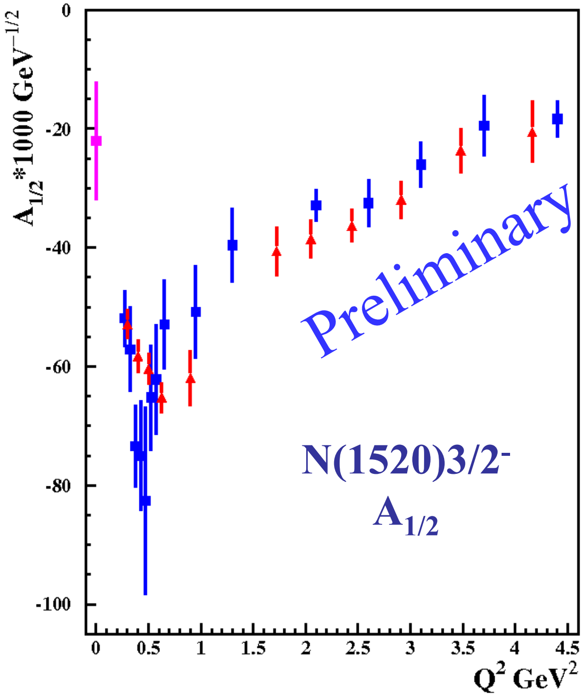


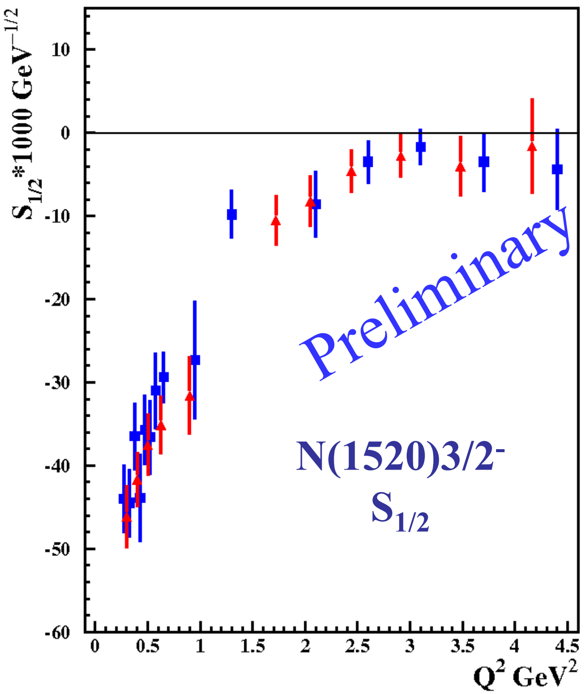
Photocoupling from PDG2018

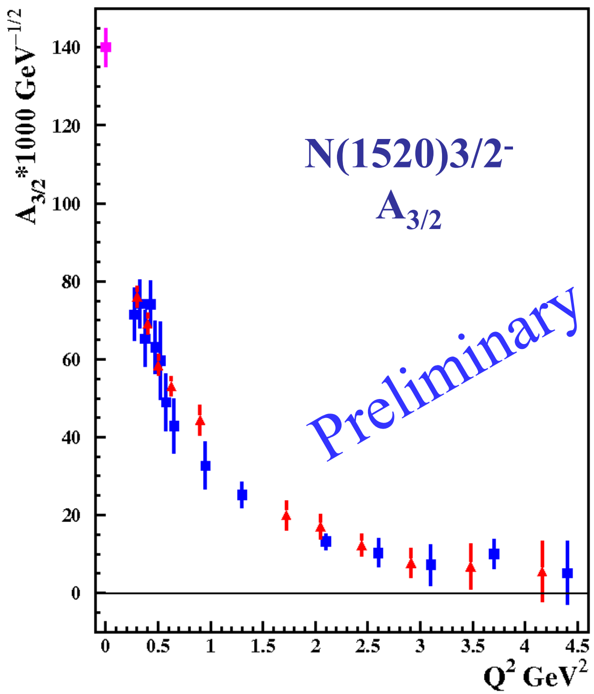
Unpolarized differential cross sections, TT, LT, LT′, beam, target, and beam-target asymmetry data were fit.

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

Viktor Mokeev



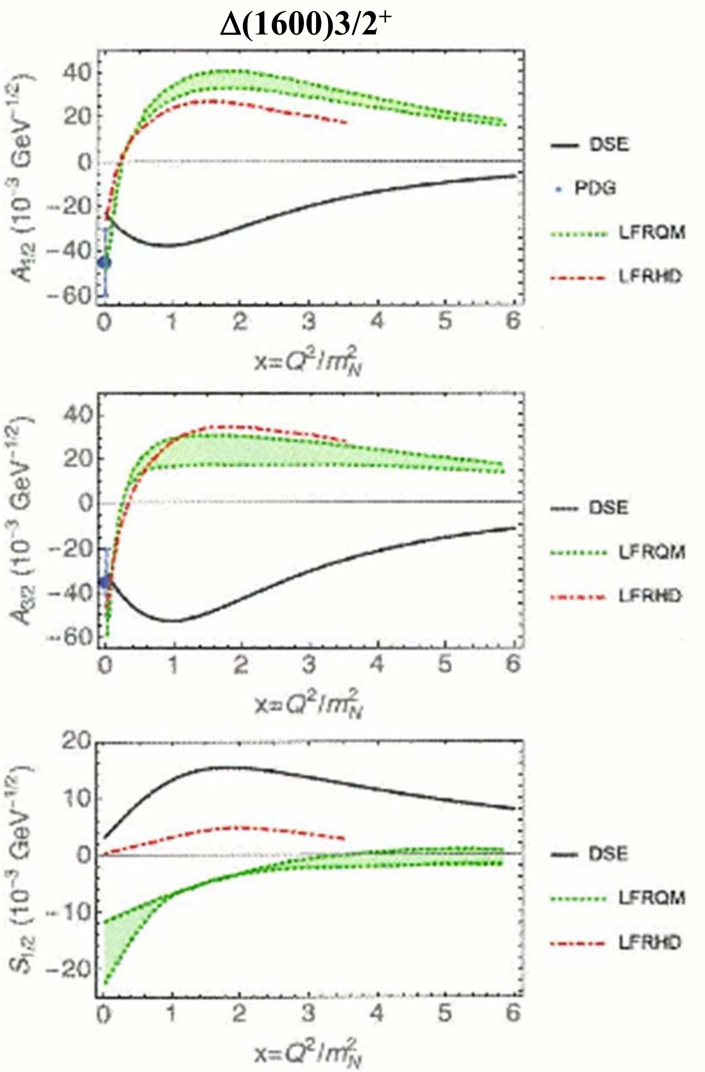




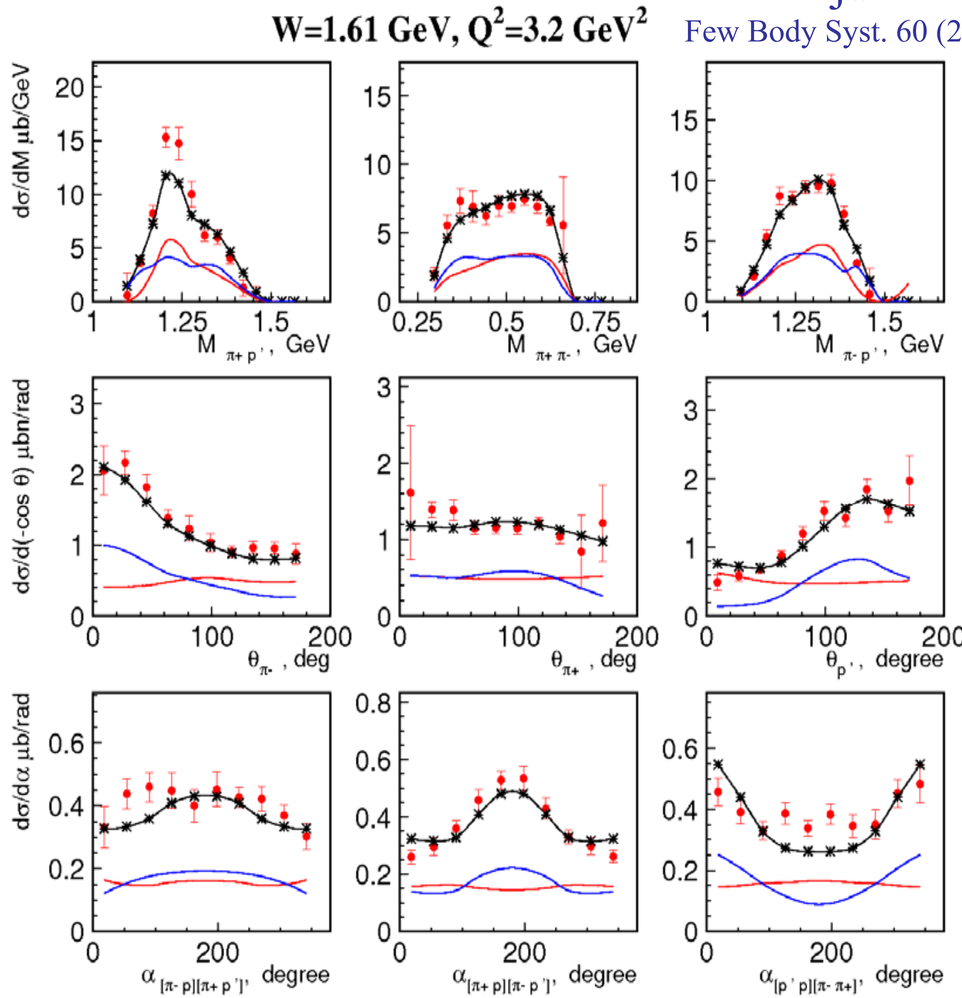
Consistent results on resonance electroexcitation amplitudes from independent studies of two dominant exclusive meson electroproduction channels off proton $N\pi$ and $\pi^+\pi^-p$ strongly support

- 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 $N\pi$ and $\pi^+\pi^-p$ electroproduction off protons.

First Radial Δ-Excitation from Nππ Cross Sections



Arjun Trivedi
Few Body Syst. 60 (2019) 5



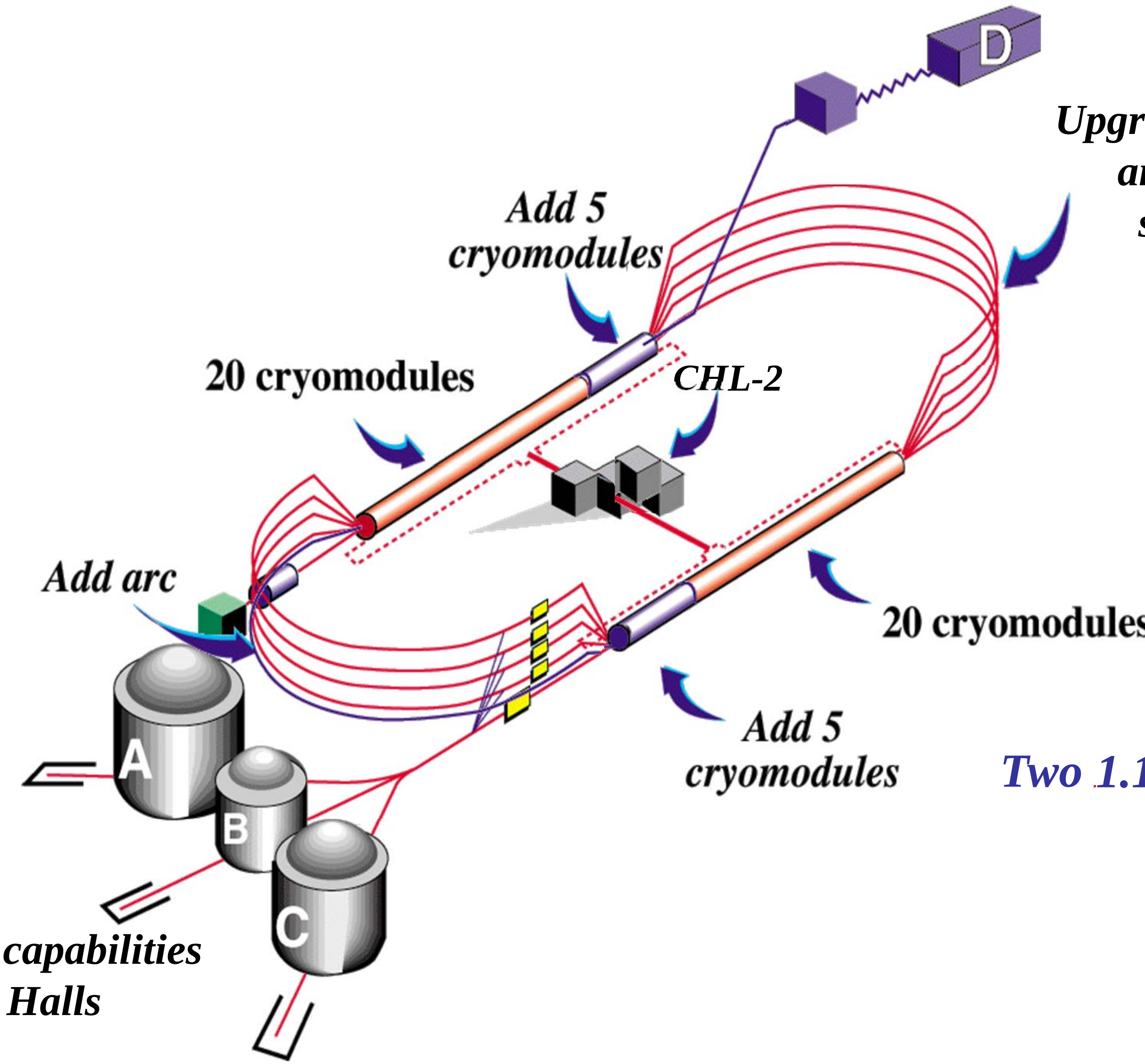
N*
non-resonant contributions

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

Viktor Mokeev (JM19)

CLAS12

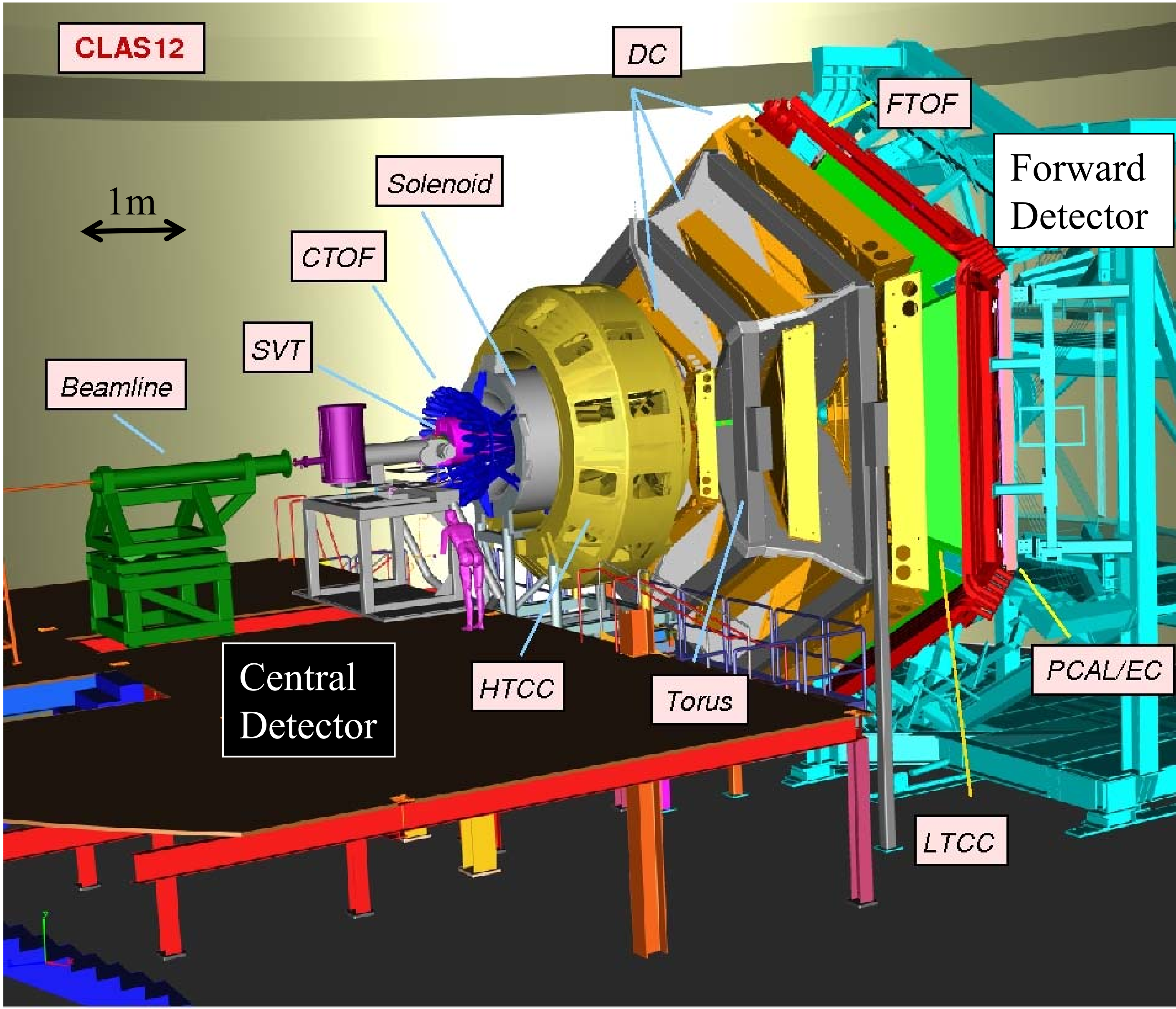
12 GeV CEBAF



Two 1.1 GeV linacs

Enhanced capabilities in existing Halls

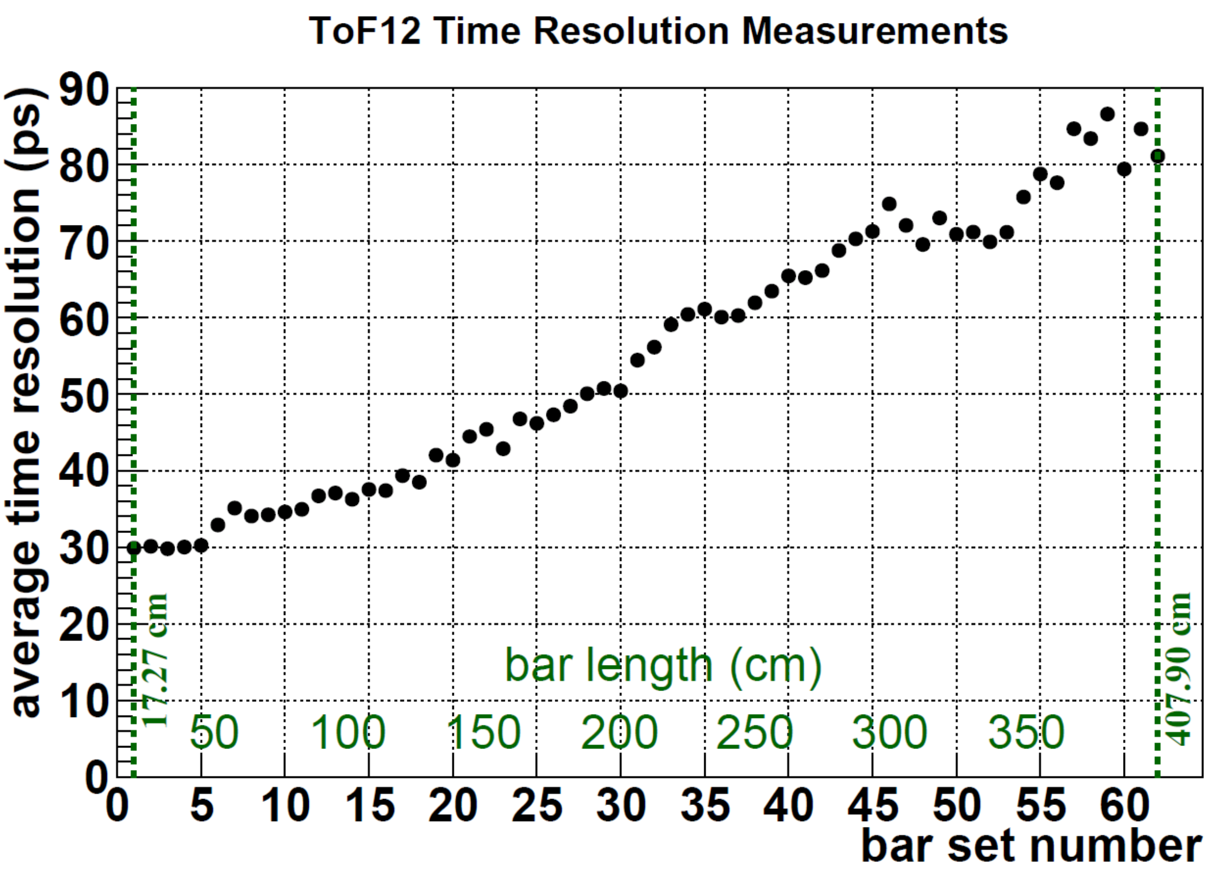
CLAS12

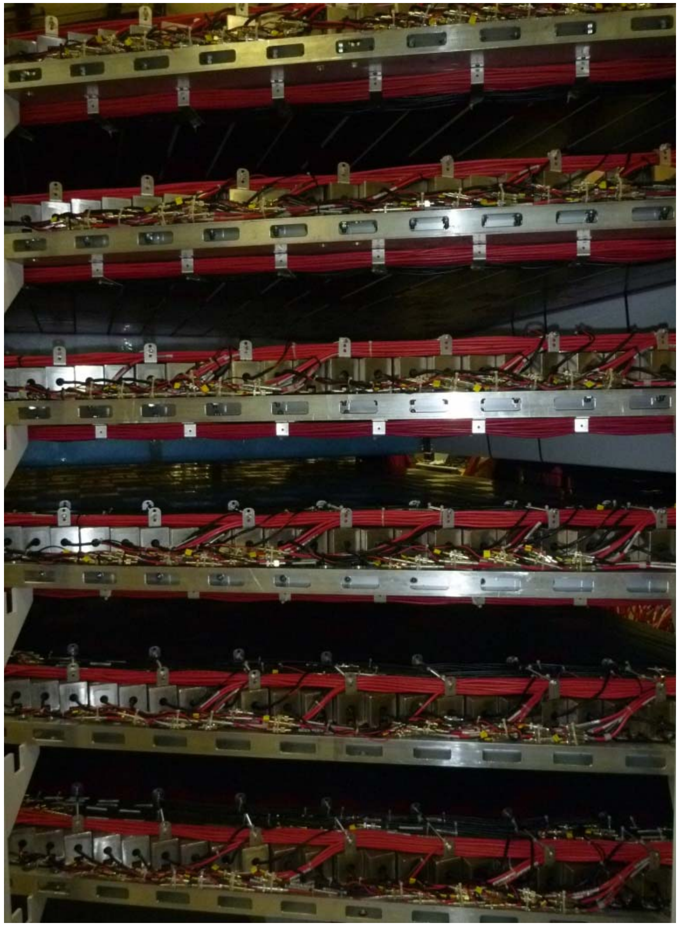


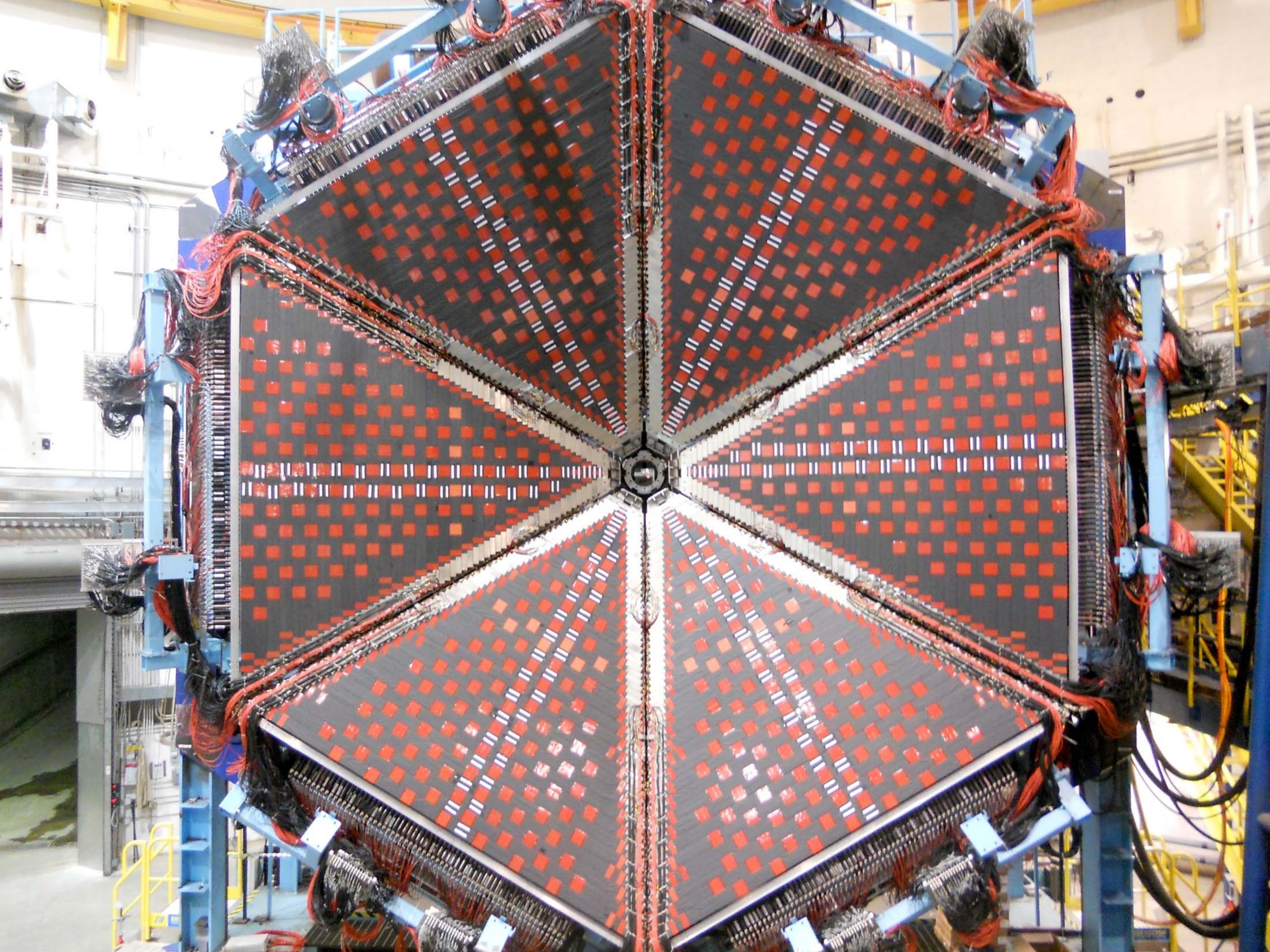
- Luminosity >10^{35} $cm^{-2}s^{-1}$
- Hermeticity
- Polarization

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

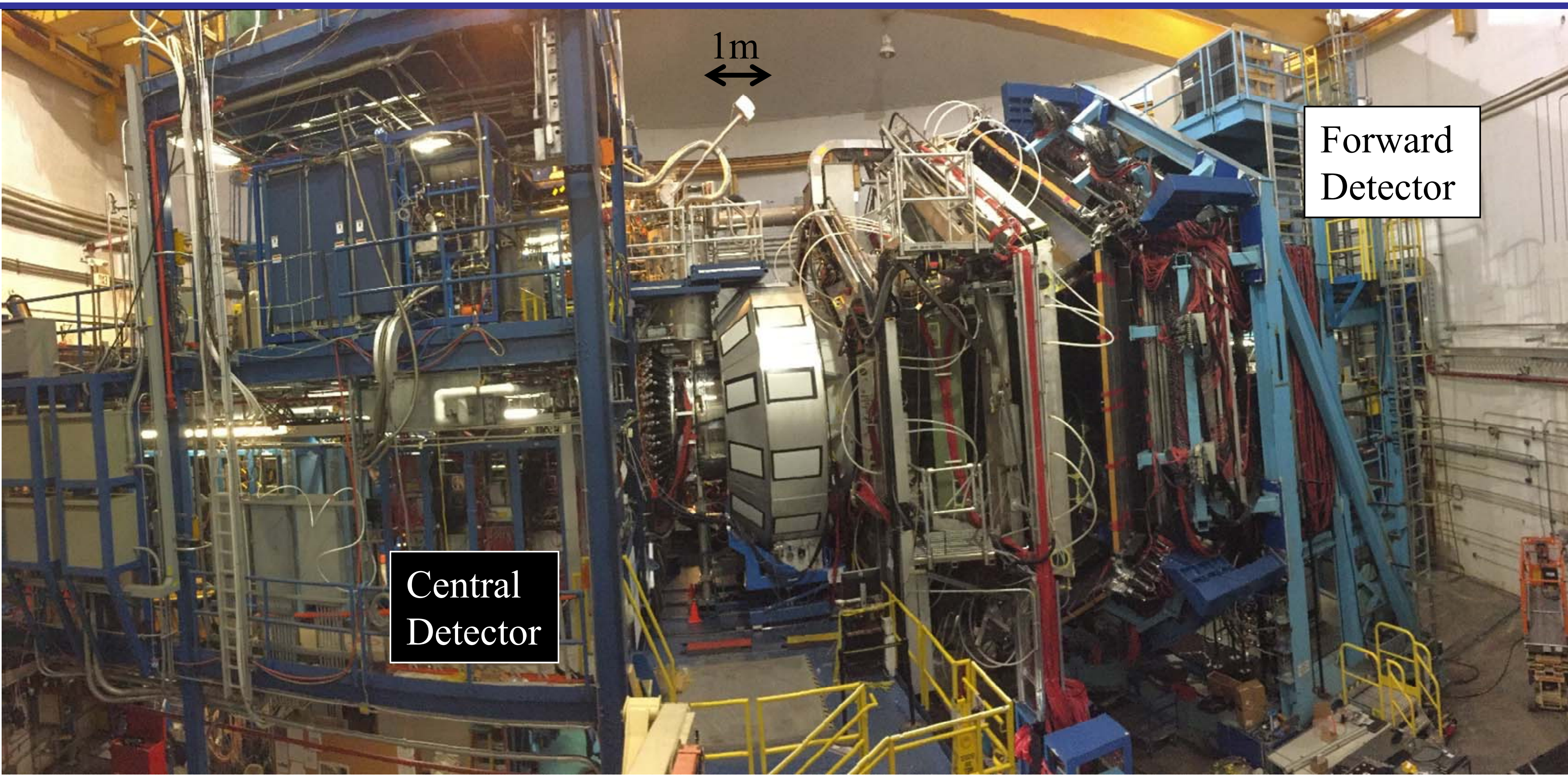
New Forward Time of Flight Detector for CLAS12







CLAS12

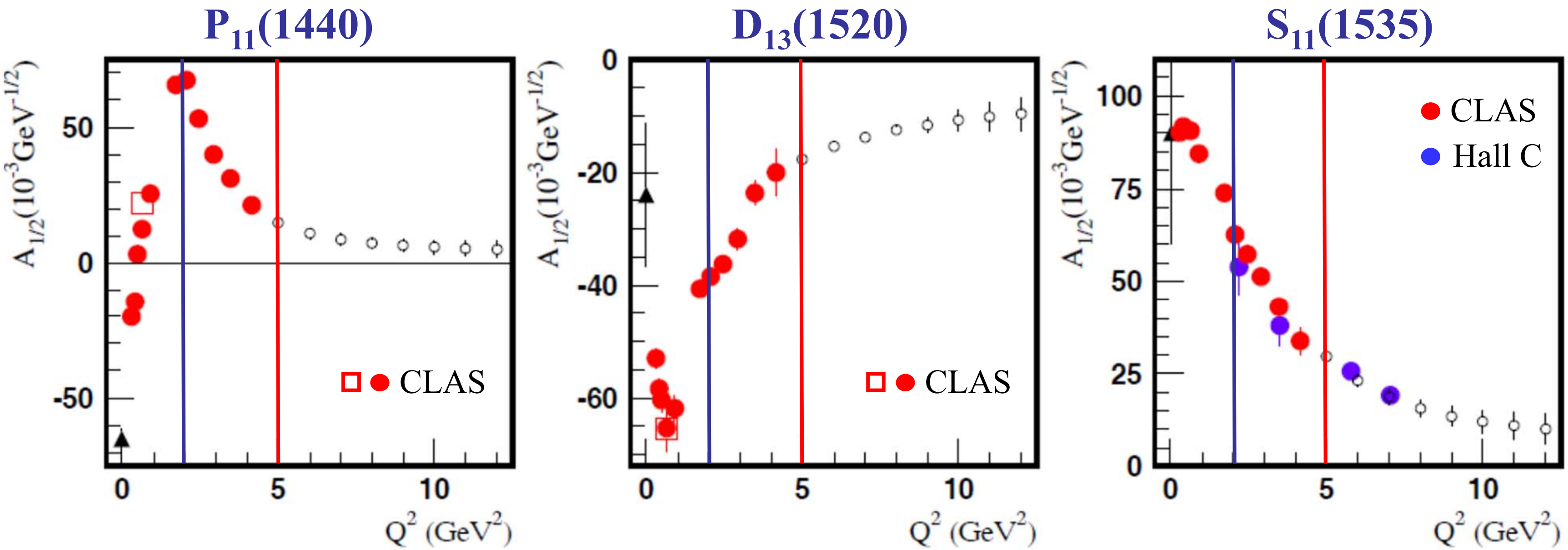


- Luminosity >10^{35} $cm^{-2}s^{-1}$
- Hermeticity
- Polarization

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

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

Anticipated N* Electrocouplings from Combined Analyses of Nπ/Nππ

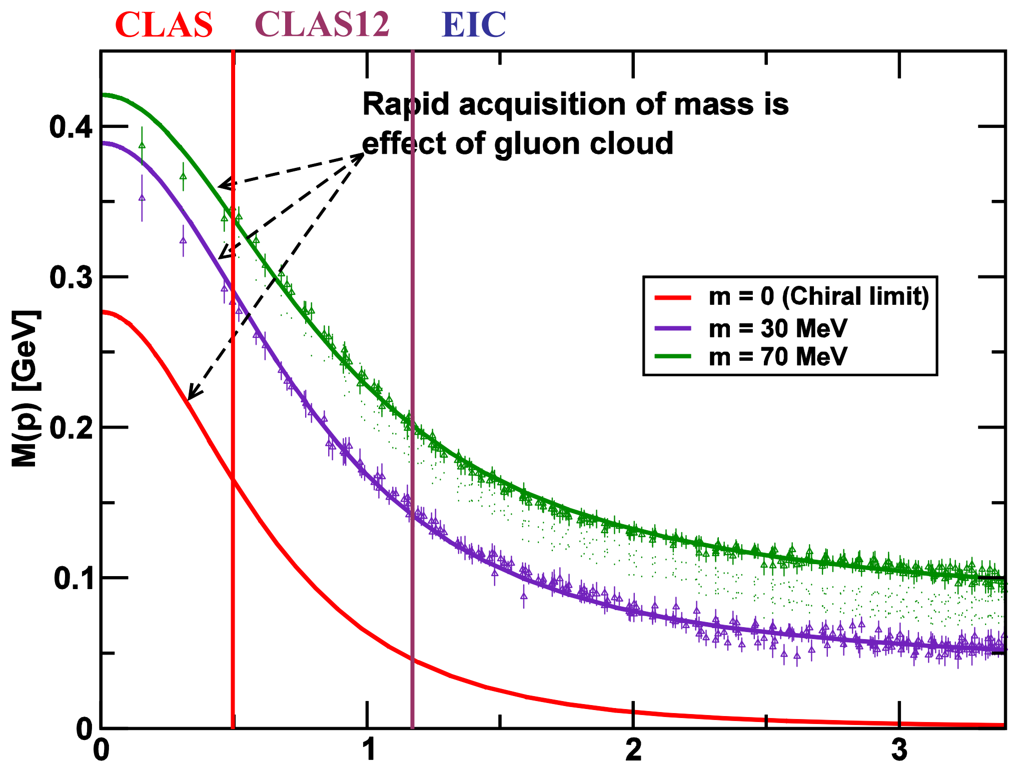


Open circles represent projections and all other markers the available results with the 6-GeV electron beam

- Examples of published and projected results obtained within 60d for three prominent excited proton states from analyses of Nπ and Nππ electroproduction channels. Similar results are expected for many other resonances at higher masses, e.g. $S_{11}(1650)$, $F_{15}(1685)$, $D_{33}(1700)$, $P_{13}(1720)$, …

- The approved CLAS12 experiments E12-09-003 (NM, Nππ) and E12-06-108A (KY) are currently the only experiments that can provide data on $\gamma_v NN^*$ electrocouplings for almost all well established excited proton states at the highest photon virtualities ever achieved in N* studies up to Q^2 of 12 GeV^2, see http://boson.physics.sc.edu/~gothe/research/pub/whitepaper-9-14.pdf.

Dynamical Mass of Light Dressed Quarks



$Q^2 = 2.75\ \text{GeV}^2$ p [GeV] per dressed quark

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

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

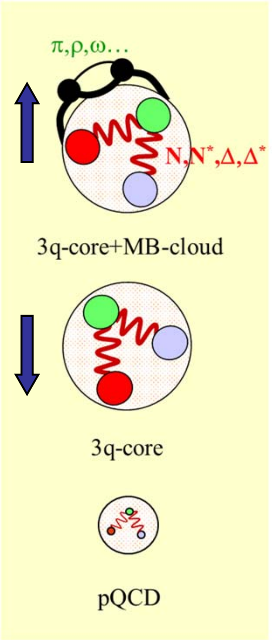
DSE: lines and LQCD: triangles

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

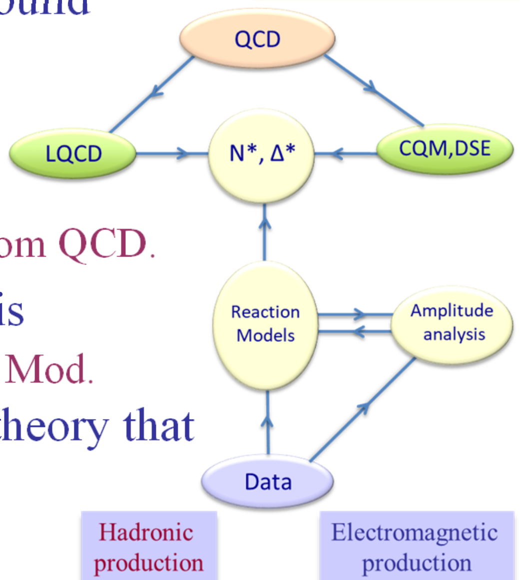
The data on N* electrocouplings at $5\ \text{GeV}^2 < Q^2 < 12\ \text{GeV}^2$ will allow us to chart the momentum evolution of dressed quark mass, and in particular, to explore the transition from dressed to almost bare current quarks as shown above.

Summary

- First high precision photo- and electroproduction data have become available and led to a new wave of significant developments in reaction and QCD-based theories.
- New high precision hadro-, photo-, and electroproduction data off the proton and the neutron will further stabilize coupled channel analyses and expand the validity of reaction models, allowing us to
  - investigate and search for baryon hybrids (E12-16-010) ,
  - establish a repertoire of high precision spectroscopy parameters, and
  - measure light-quark-flavor separated electrocouplings over an extended Q^2-range, both to lower and higher Q^2, for a wide variety of N* states (E12-16-010 A).



- Comparing these results with LQCD, DSE, LCSR, and rCQM will build further insights into
  - the strong interaction of dressed quarks and their confinement,
  - the origin of 98% of nucleon mass, and
  - the emergence of bare quark dressing and dressed quark interactions from QCD.
- A close collaboration of experimentalists and theorists has formed, is growing, and is needed to push these goals, see Review Article Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013) 1-99, that shall lead to a strong QCD theory that describes the strong interaction from current quarks to nuclei.



ECT*2015, INT2016, NSTAR2017, APCTP2018, JLab2019 …