# Overview of the N* Program

Ralf W. Gothe for the CLAS Collaboration

UNIVERSITY OF SOUTH CAROLINA

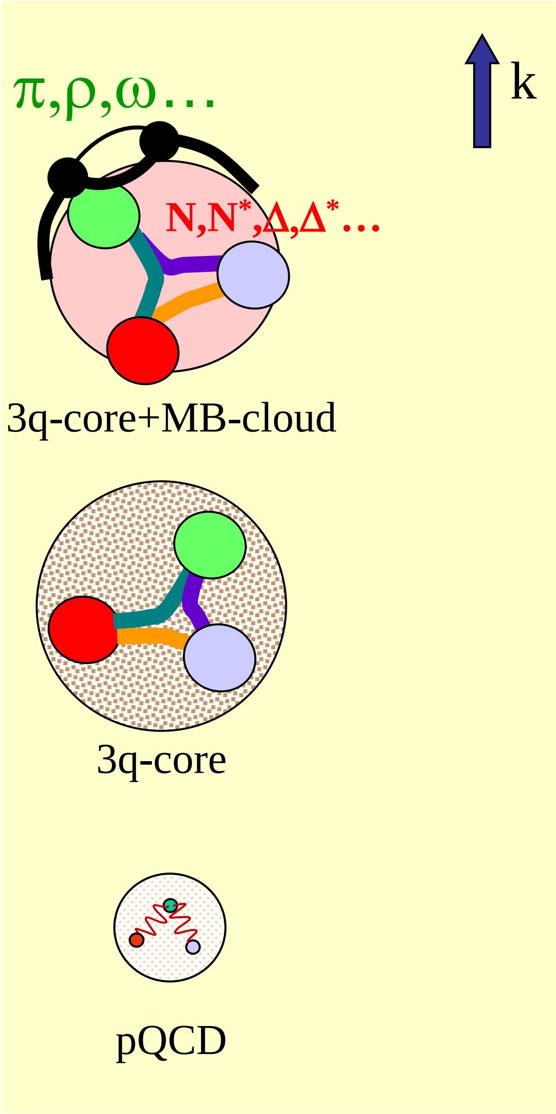
JMU
JAMES MADISON UNIVERSITY

Quark Hadron Duality Workshop: Probing the Transition from Free to Confined Quarks
September 23-25, 2018, James Madison University, Harrisonburg, VA

- **$\gamma_v$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!

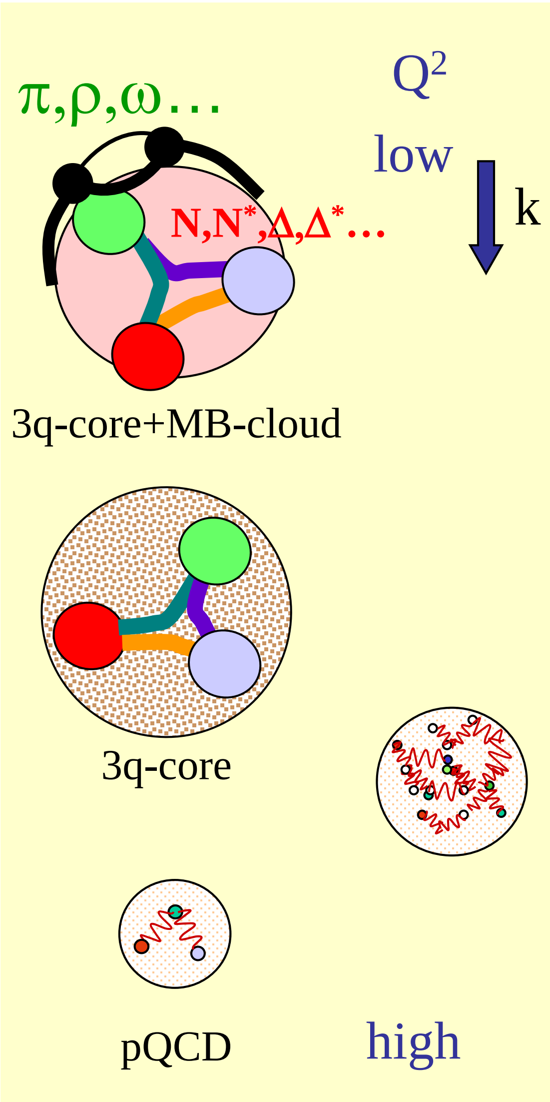
This work is supported in parts by the National Science Foundation under Grant PHY 1812382.

# From Quark Degrees to Meson-Baryon of Freedom




- Study of the distance dependent structure of baryons into the domain where dressed quarks are the dominant active degree of freedom.
- Explore the formation of excited nucleon states in interactions of dressed quarks and their emergence from QCD.

# From Meson-Baryon to Quark Degrees of Freedom

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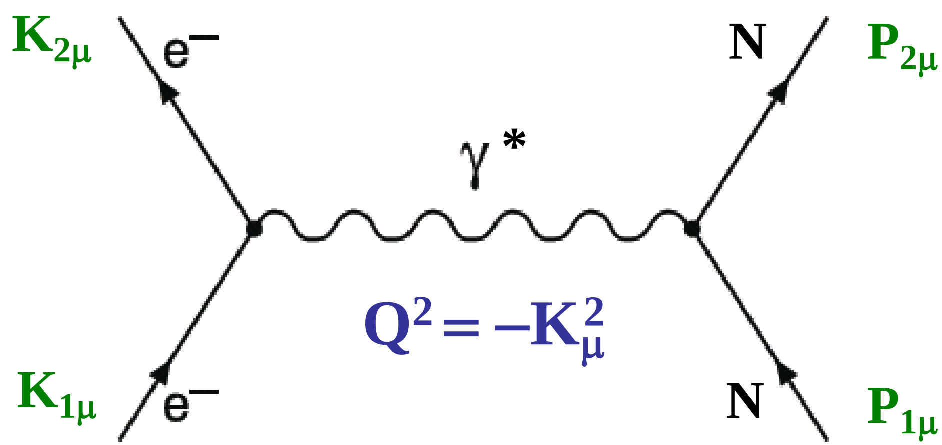
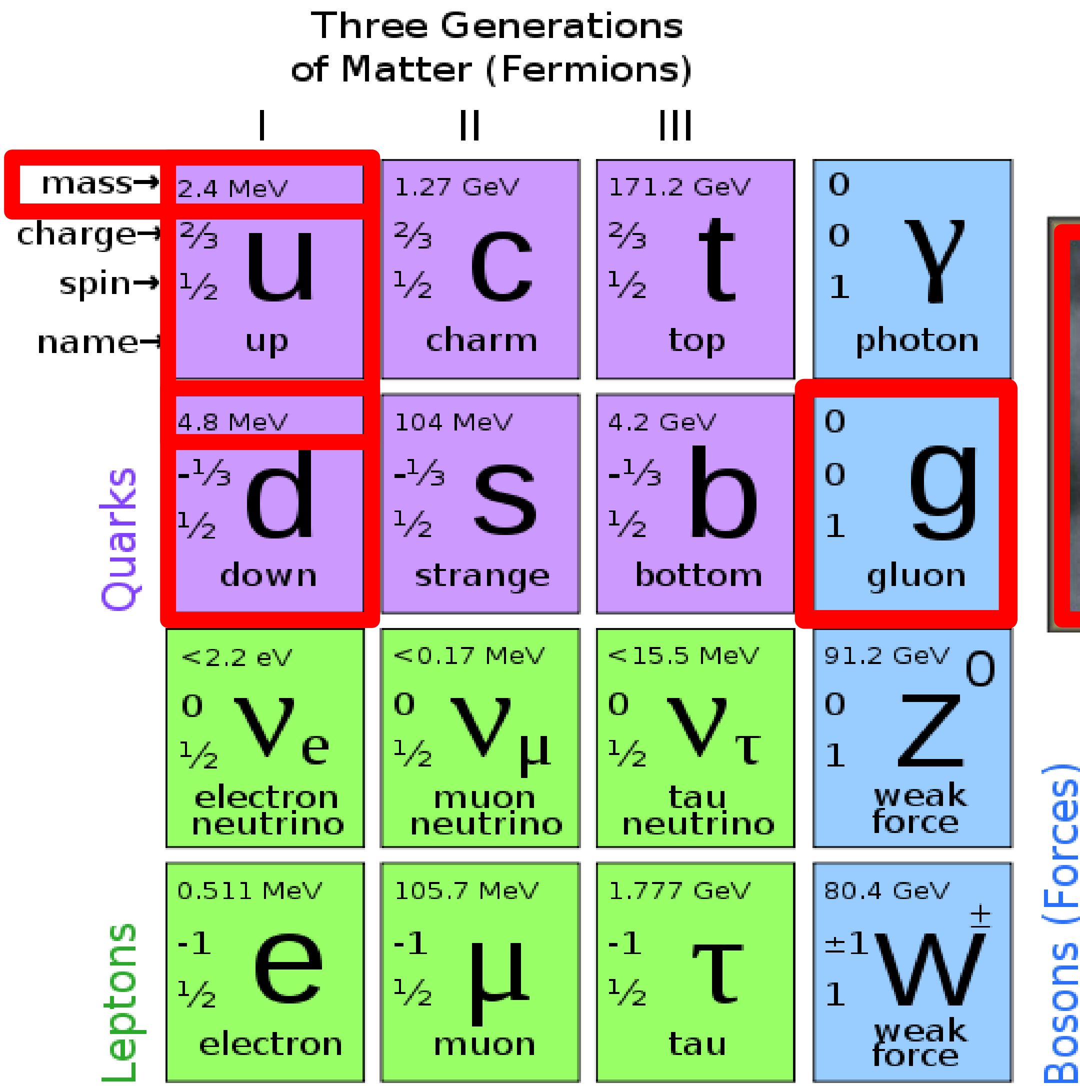
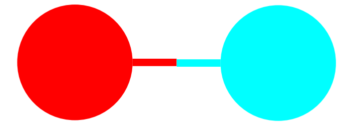
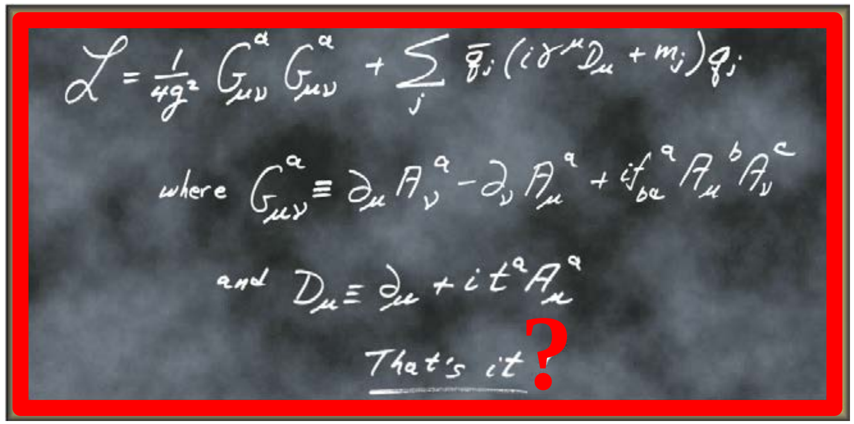


# Spectroscopy

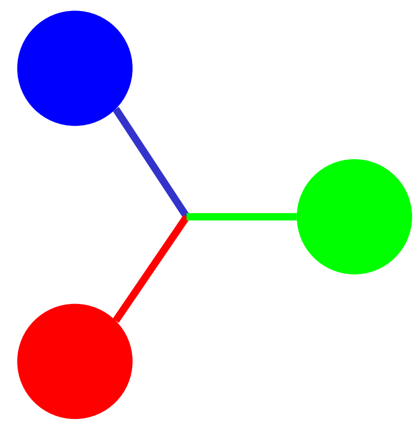
# Build your Mesons and Baryons …






Frank Wilczek, Physics Today, August 2000

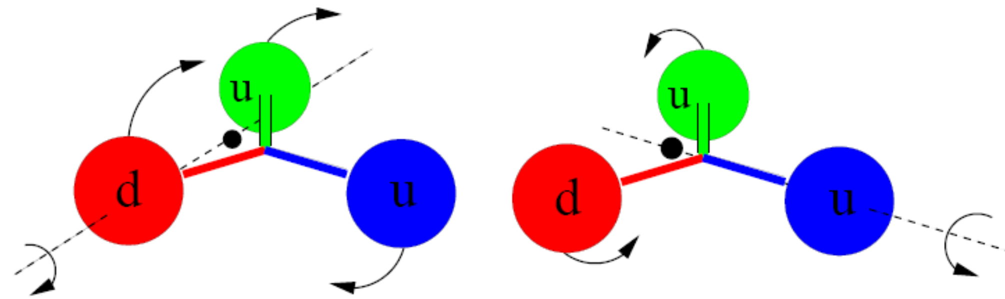


# N and Δ Excited Baryon States …

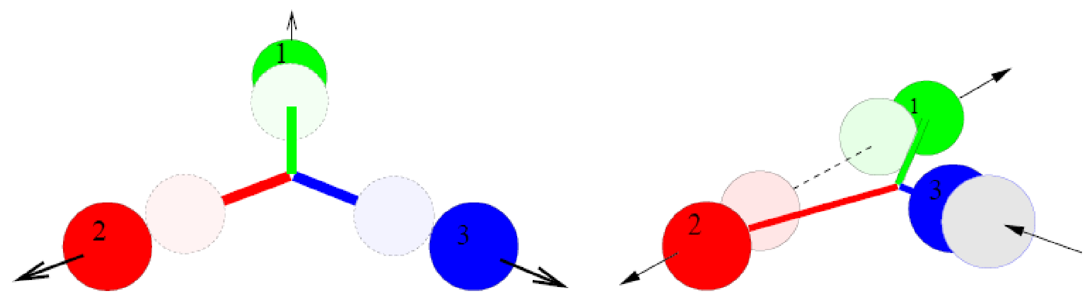
Simon Capstick

- Orbital excitations

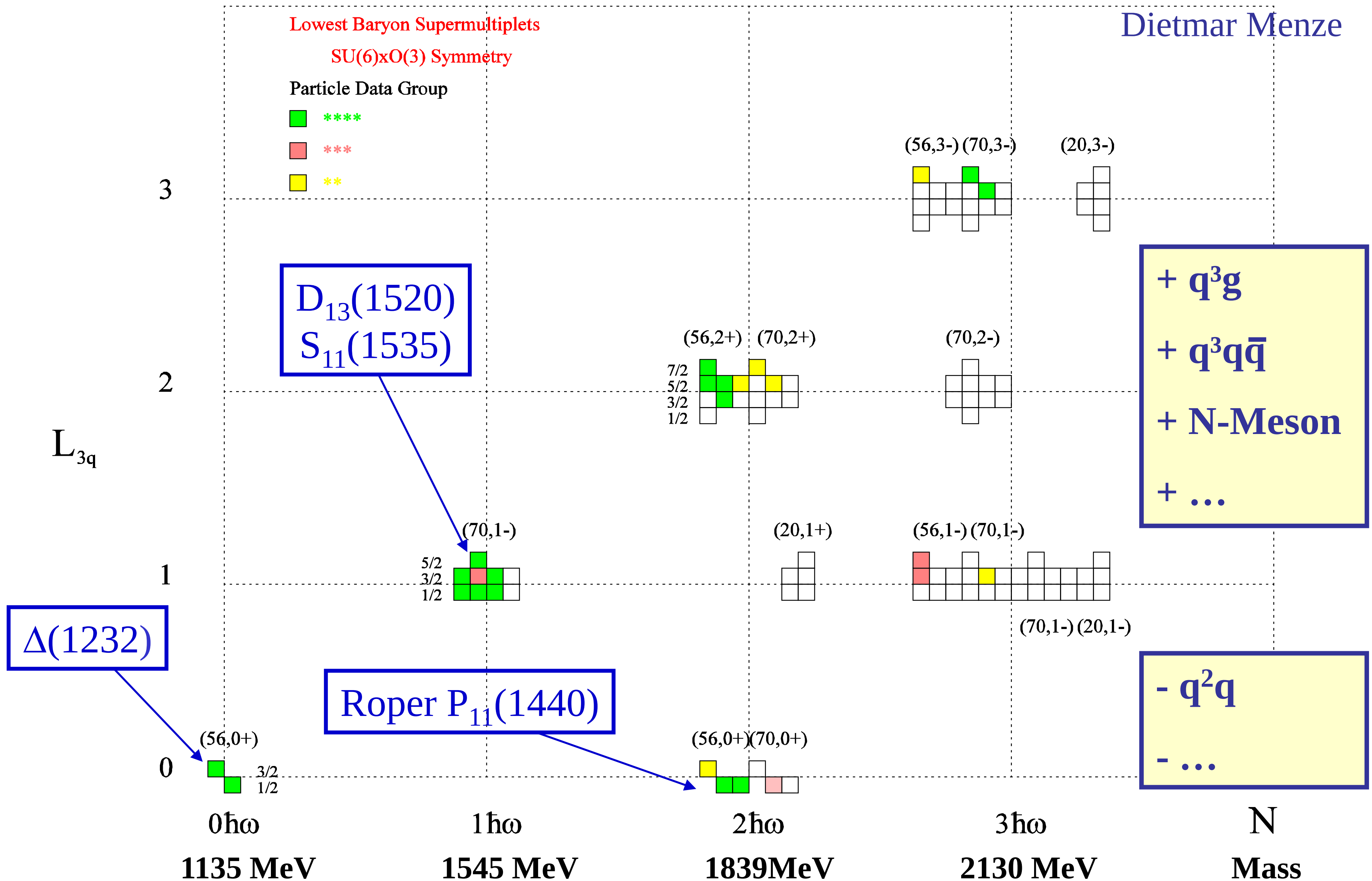
  (two distinct kinds in contrast to mesons)




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

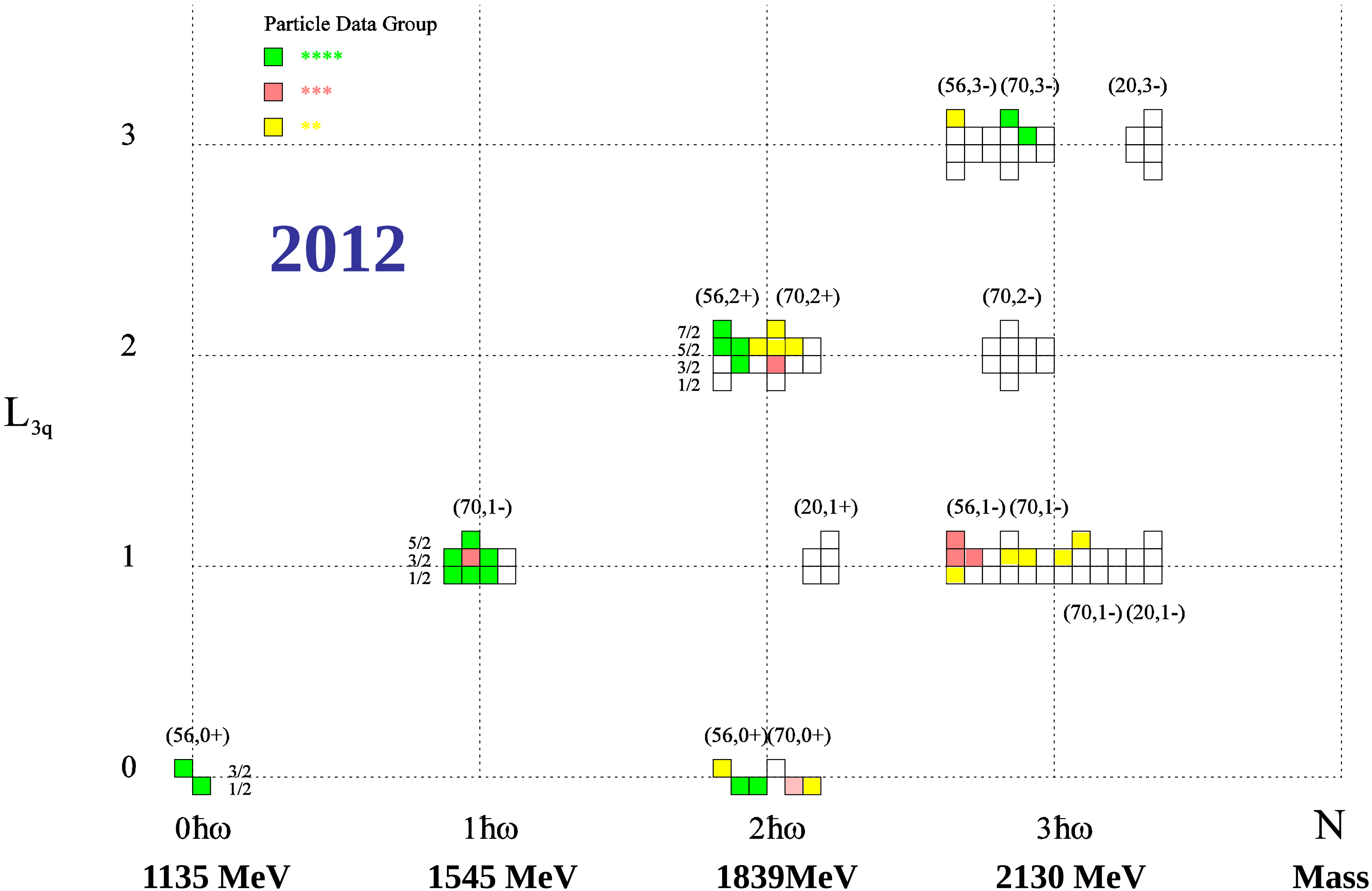


# Quark Model Classification of N*



# Quark Model Classification of N*

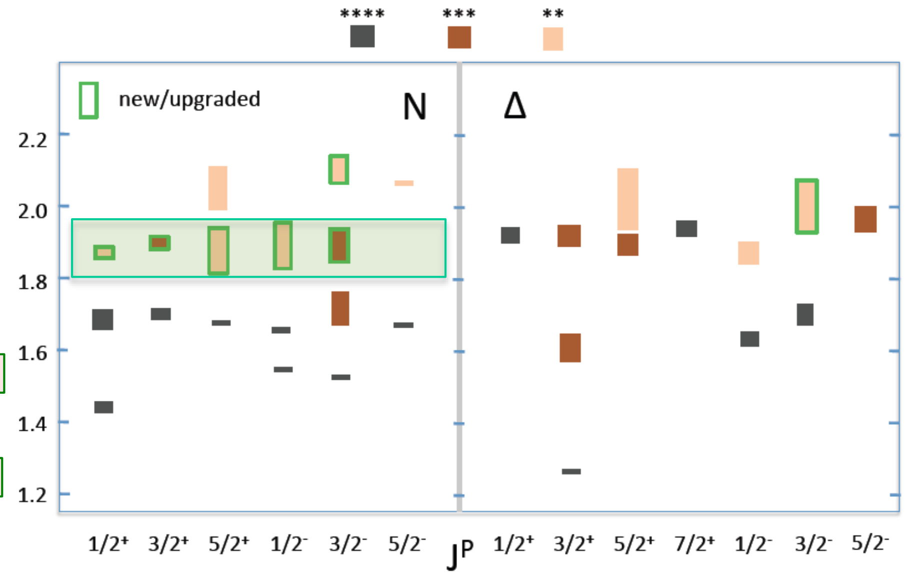
## BnGa energy-dependent coupled-channel PWA of CLAS $K^+\Lambda$ and other data



# N/Δ Spectrum in RPP 2012

| $N^*$ | $J^P$ ($L_{2I,2J}$) | 2010 | 2012 | $\Delta$ | $J^P$ ($L_{2I,2J}$) | 2010 | 2012 |
|---|---|---|---|---|---|---|---|
| $p$ | $1/2^+$ ($P_{11}$) | **** | **** | $\Delta(1232)$ | $3/2^+$ ($P_{33}$) | **** | **** |
| $n$ | $1/2^+$ ($P_{11}$) | **** | **** | $\Delta(1600)$ | $3/2^+$ ($P_{33}$) | *** | *** |
| $N(1440)$ | $1/2^+$ ($P_{11}$) | **** | **** | $\Delta(1620)$ | $1/2^-$ ($S_{31}$) | **** | **** |
| $N(1520)$ | $3/2^-$ ($D_{13}$) | **** | **** | $\Delta(1700)$ | $3/2^-$ ($D_{33}$) | **** | **** |
| $N(1535)$ | $1/2^-$ ($S_{11}$) | **** | **** | $\Delta(1750)$ | $1/2^+$ ($P_{31}$) | * | * |
| $N(1650)$ | $1/2^-$ ($S_{11}$) | **** | **** | $\Delta(1900)$ | $1/2^-$ ($S_{31}$) | ** | ** |
| $N(1675)$ | $5/2^-$ ($D_{15}$) | **** | **** | $\Delta(1905)$ | $5/2^+$ ($F_{35}$) | **** | **** |
| $N(1680)$ | $5/2^+$ ($F_{15}$) | **** | **** | $\Delta(1910)$ | $1/2^+$ ($P_{31}$) | **** | **** |
| $N(1685)$ | | | * | | | | |
| $N(1700)$ | $3/2^-$ ($D_{13}$) | *** | *** | $\Delta(1920)$ | $3/2^+$ ($P_{33}$) | *** | *** |
| $N(1710)$ | $1/2^+$ ($P_{11}$) | *** | *** | $\Delta(1930)$ | $5/2^-$ ($D_{35}$) | *** | *** |
| $N(1720)$ | $3/2^+$ ($P_{13}$) | **** | **** | $\Delta(1940)$ | $3/2^-$ ($D_{33}$) | * | ** |
| $N(1860)$ | $5/2^+$ | | ** | | | | |
| $N(1875)$ | $3/2^-$ | | *** | | | | |
| $N(1880)$ | $1/2^+$ | | ** | | | | |
| $N(1895)$ | $1/2^-$ | | ** | | | | |
| $N(1900)$ | $3/2^+$ ($P_{13}$) | ** | *** | $\Delta(1950)$ | $7/2^+$ ($F_{37}$) | **** | **** |
| $N(1990)$ | $7/2^+$ ($F_{17}$) | ** | ** | $\Delta(2000)$ | $5/2^+$ ($F_{35}$) | ** | ** |
| $N(2000)$ | $5/2^+$ ($F_{15}$) | ** | ** | $\Delta(2150)$ | $1/2^-$ ($S_{31}$) | * | * |
| ~~$N(2080)$~~ | $D_{13}$ | ** | | $\Delta(2200)$ | $7/2^-$ ($G_{37}$) | * | * |
| ~~$N(2090)$~~ | $S_{11}$ | * | | $\Delta(2300)$ | $9/2^+$ ($H_{39}$) | ** | ** |
| $N(2040)$ | $3/2^+$ | | * | | | | |
| $N(2060)$ | $5/2^-$ | | ** | | | | |
| $N(2100)$ | $1/2^+$ ($P_{11}$) | * | * | $\Delta(2350)$ | $5/2^-$ ($D_{35}$) | * | * |
| $N(2120)$ | $3/2^-$ | | ** | | | | |
| $N(2190)$ | $7/2^-$ ($G_{17}$) | **** | **** | $\Delta(2390)$ | $7/2^+$ ($F_{37}$) | * | * |
| ~~$N(2200)$~~ | $D_{15}$ | ** | | $\Delta(2400)$ | $9/2^-$ ($G_{39}$) | ** | ** |
| $N(2220)$ | $9/2^+$ ($H_{19}$) | **** | **** | $\Delta(2420)$ | $11/2^+$ ($H_{3,11}$) | **** | **** |
| $N(2250)$ | $9/2^-$ ($G_{19}$) | **** | **** | $\Delta(2750)$ | $13/2^-$ ($I_{3,13}$) | ** | ** |
| $N(2600)$ | $11/2^-$ ($I_{1,11}$) | *** | *** | $\Delta(2950)$ | $15/2^+$ ($K_{3,15}$) | ** | ** |
| $N(2700)$ | $13/2^+$ ($K_{1,13}$) | ** | ** | | | | |

High-statistics and high-precision photoproduction data from JLAB, MAMI, ELSA, GRAAL

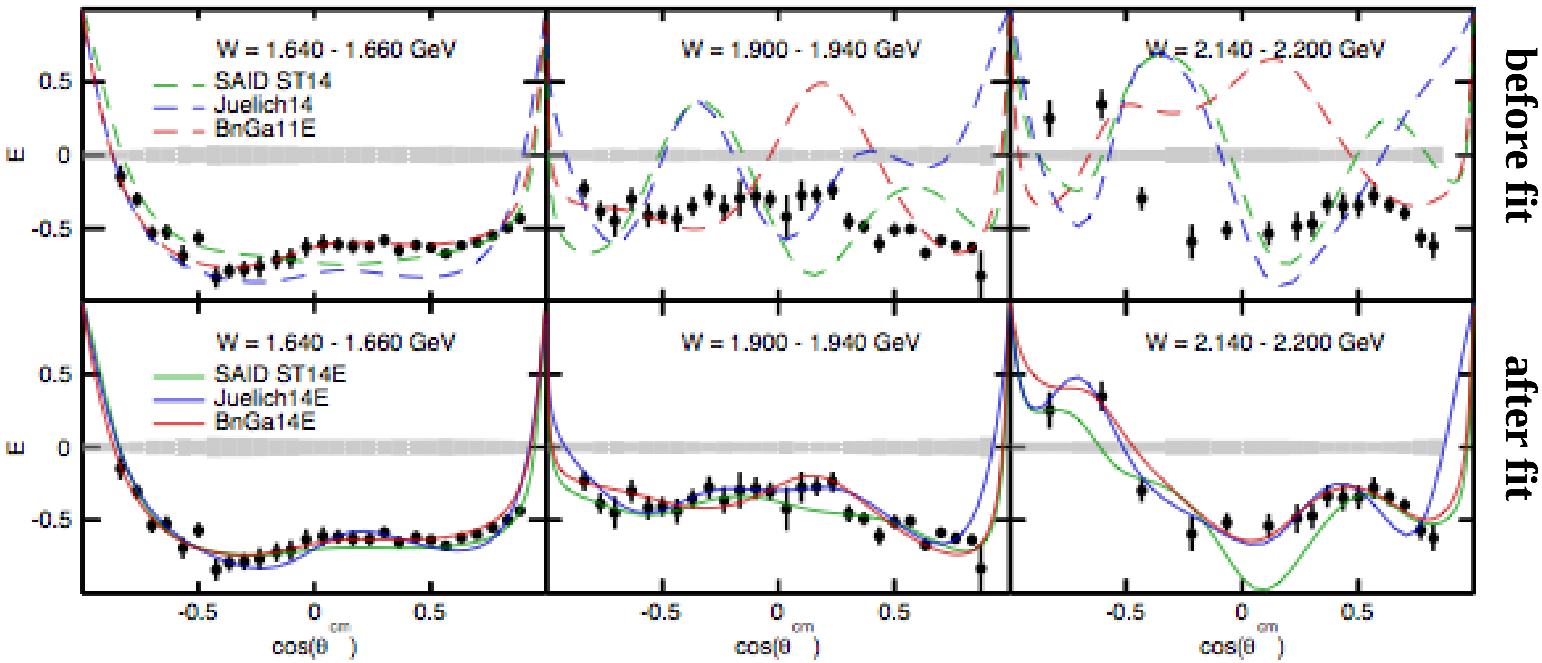



Are we observing parity doublets with the new states or not?

V. Crede & W. Roberts, Rep. Prog. Phys. 76 (2013)

# New FROST Results from $\vec{\gamma}\vec{p}\rightarrow\pi^0 p$

**W = 1.650 GeV** **W = 1.920 GeV** **W = 2.170 GeV**

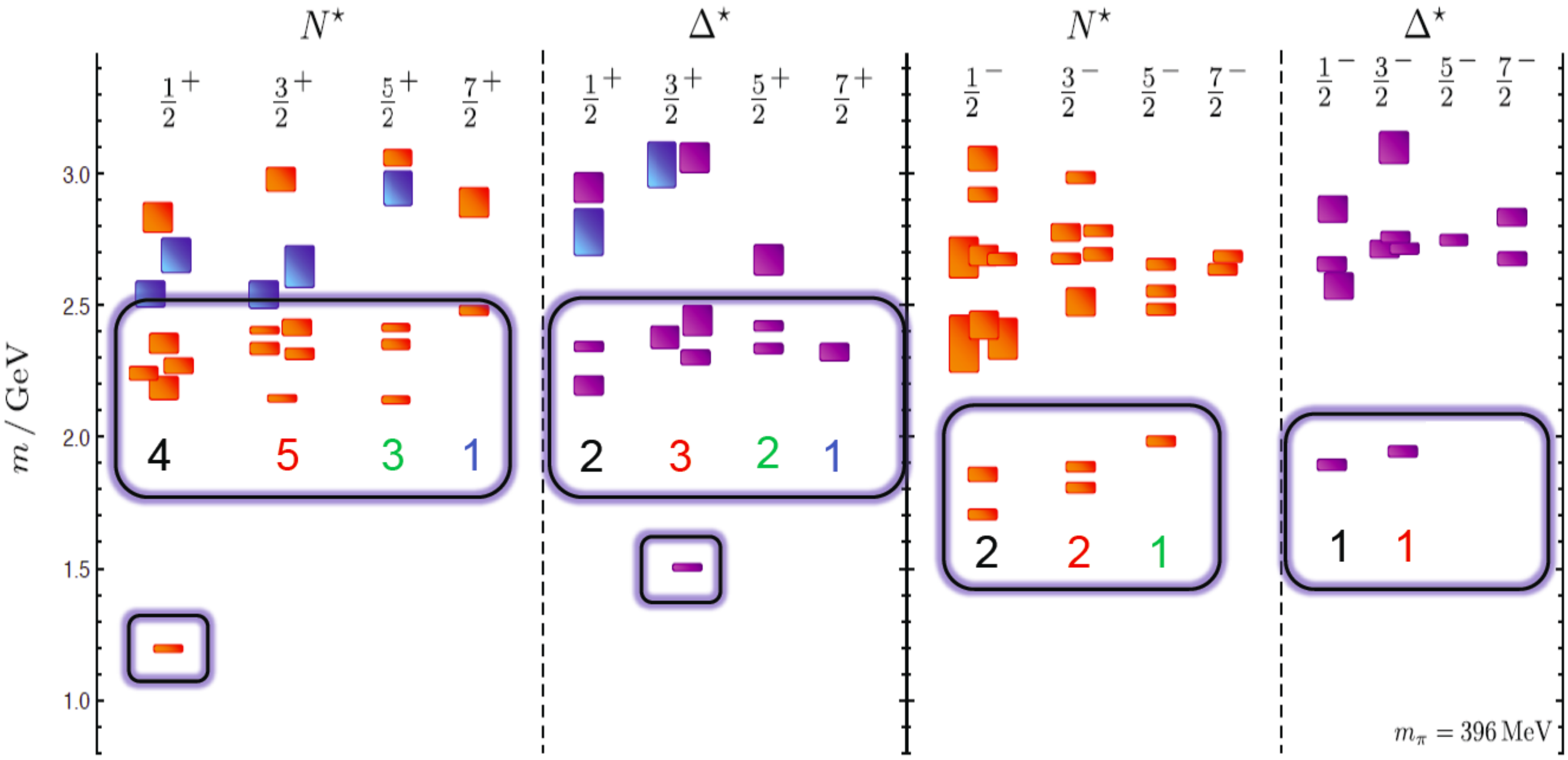



- FROST experiment produced 900 data points of the **double-polarization observable E** in $\pi^+$ photoproduction with circularly polarized beam on longitudinally polarized protons for W = 1240 - 2260 MeV.
- Significant improvements of the description of the data in SAID, Jülich, and BnGa partial-wave analyses after fitting.
- New evidence found in this data for a $\Delta(2200)7/2^-$ resonance (BnGa analysis).

S. Strauch *et al.*, Phys. Lett. B, 750 (2015) 53 and A.V. Anisovich *et al.*, arXiv:1503.05774

# N* Spectrum in LQCD

The strong interaction physics is encoded in the nucleon excitation spectrum that spans the degrees of freedom from meson-baryon and dressed quarks to elementary quarks and gluons.

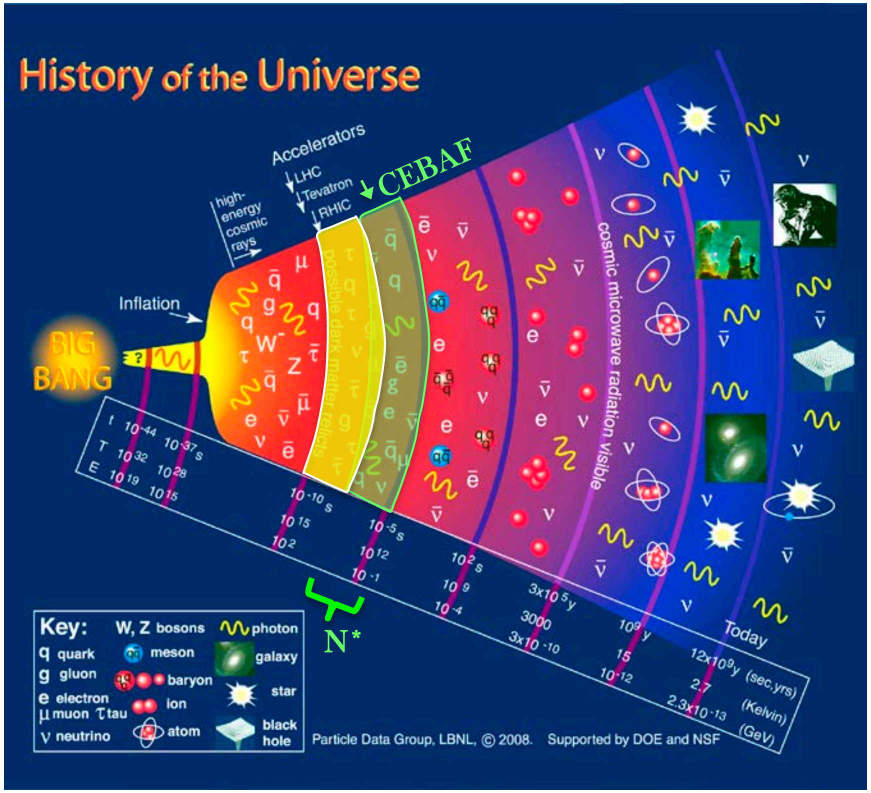


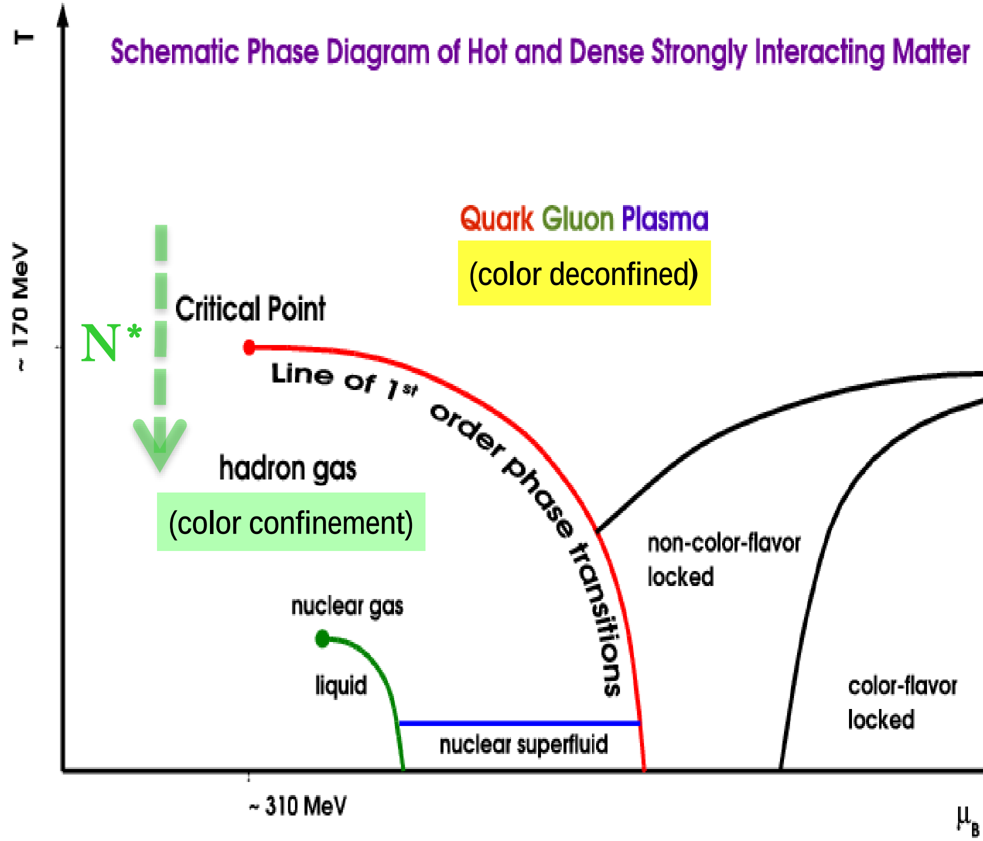

LQCD predicts states with the same quantum numbers as CQMs with underlying SU(6)xO(3) symmetry.

R. Edwards et al. arXiv:1104.5152, 1201.2349

# Evolution of the Early Universe

Volker Burkert



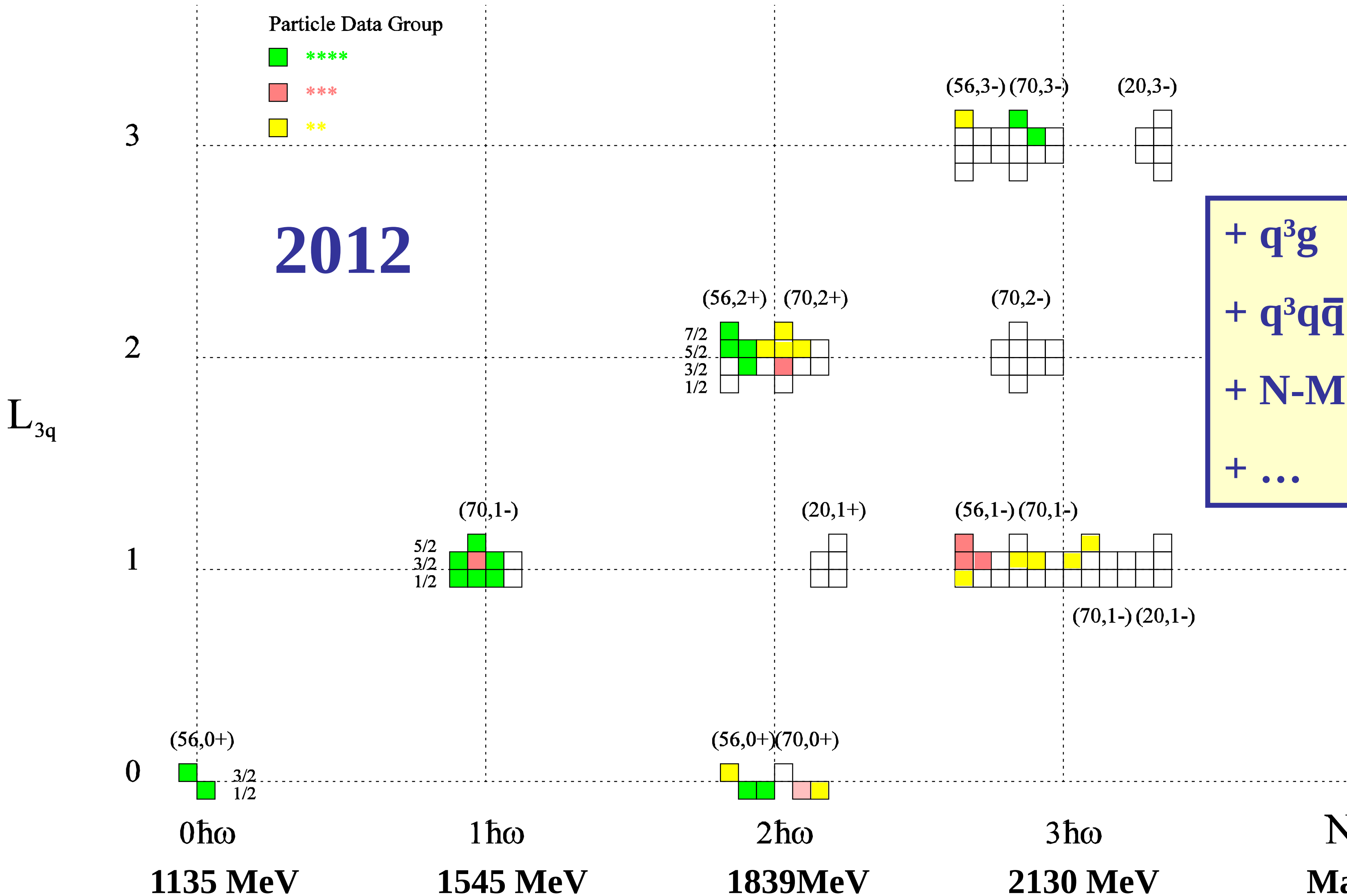




## Dramatic events occur in the microsecond old Universe

- Transition from the QGP to the baryon phase is dominated by excited baryons.
- A quantitative description requires more states than found to date → missing baryons.
- During the transition the quarks acquire dynamical mass and become confinement.

# Quark Model Classification of N*

BnGa energy-dependent coupled-channel PWA of CLAS $K^+\Lambda$ and other data




+ $q^3g$

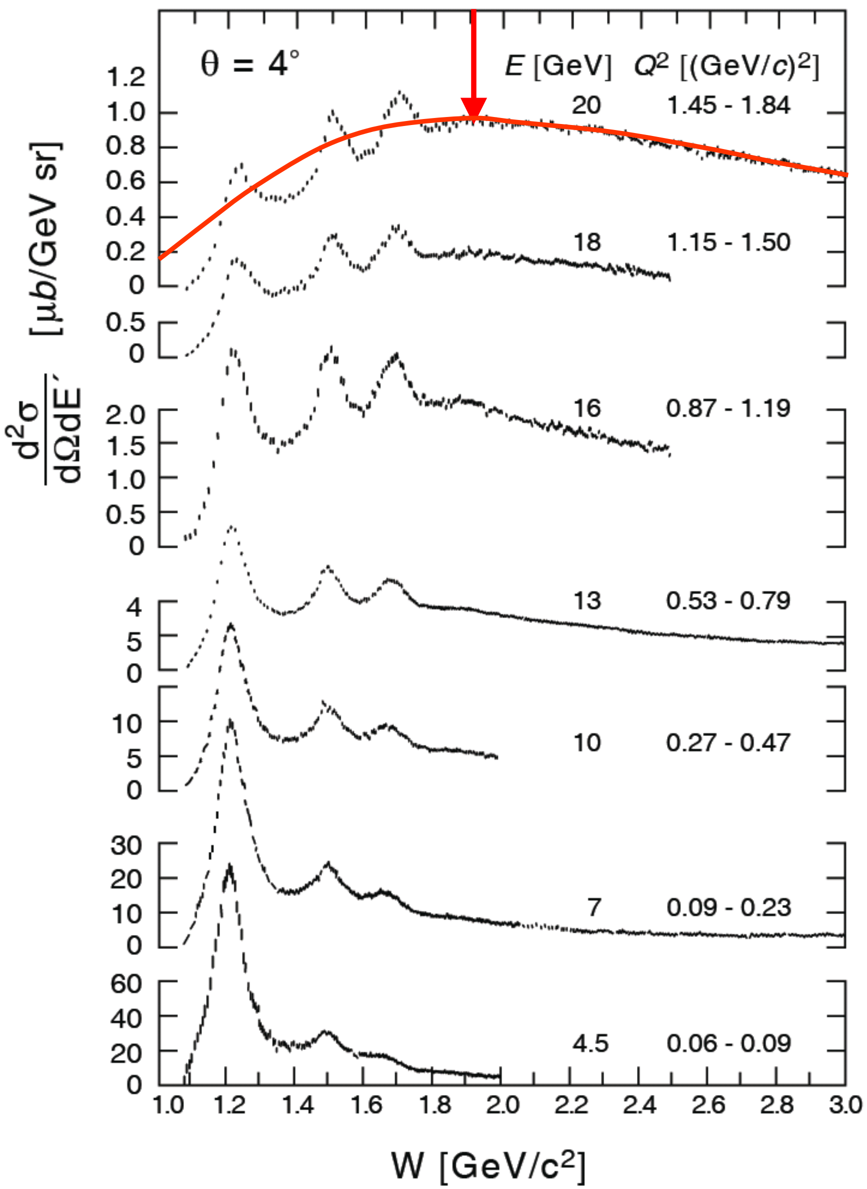
+ $q^3q\bar{q}$

+ N-Meson

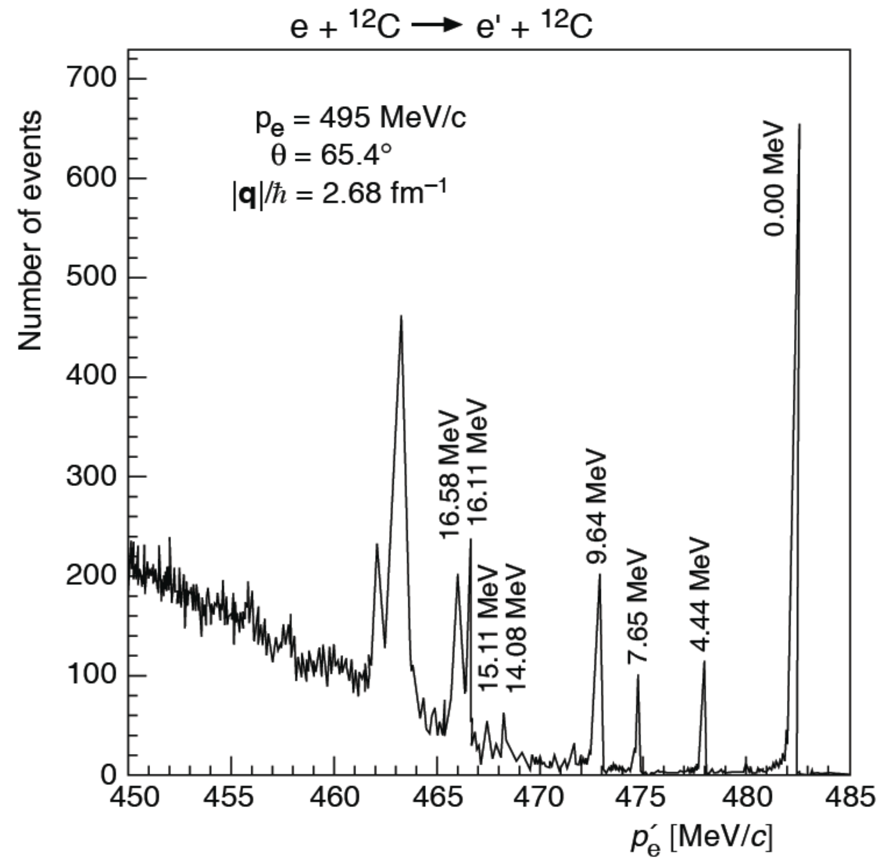
+ …

# Electron Scattering

# Baryon Excitations and Quasi-Elastic Scattering

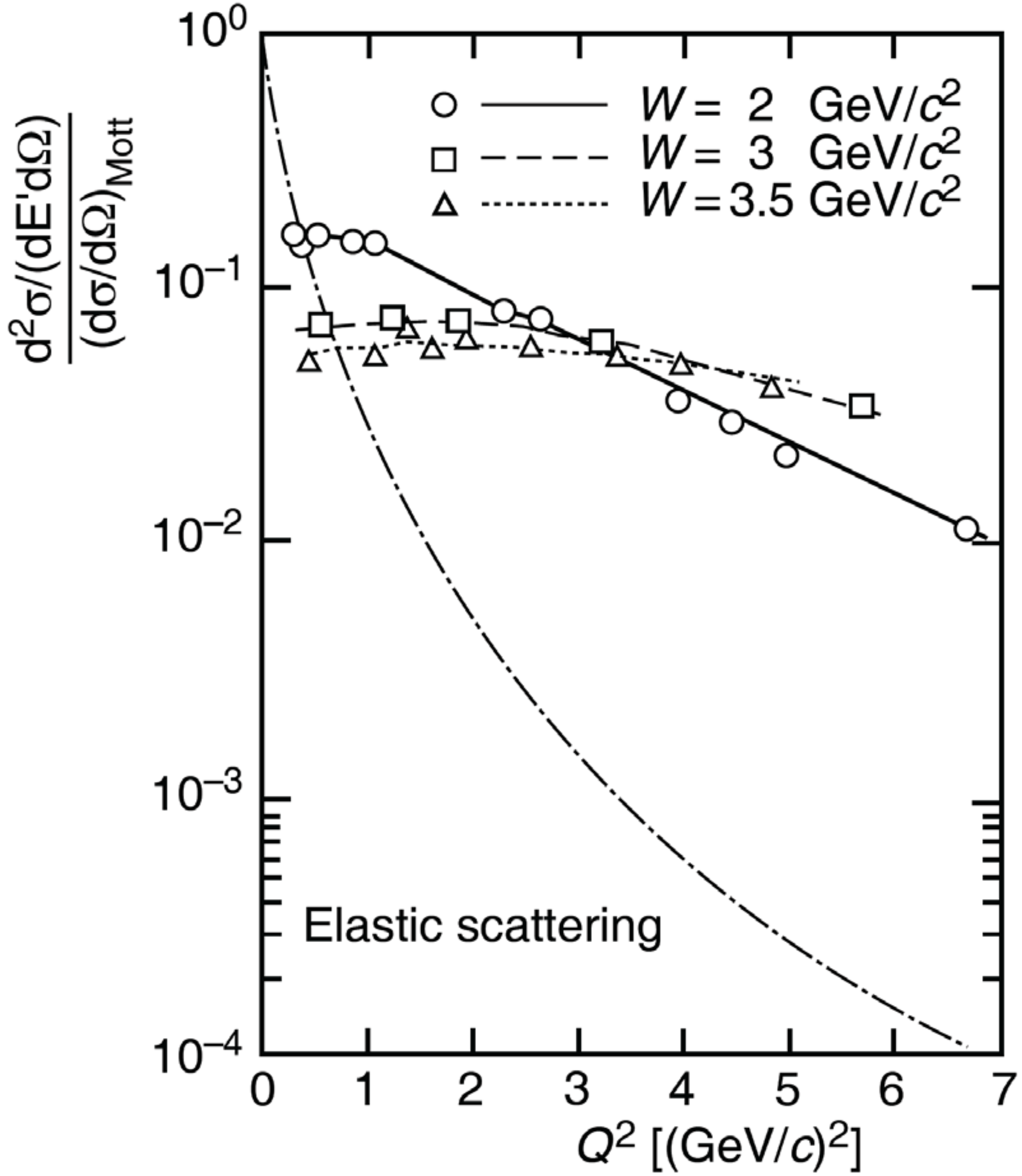



PRL **16** (1970) 1140, PR **D4** (1971) 2901
E.D. Bloom and F.J. Gilman

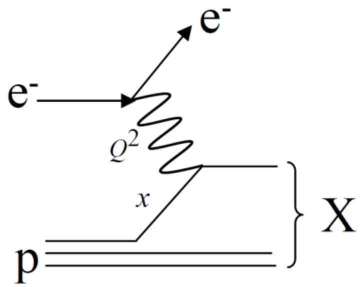


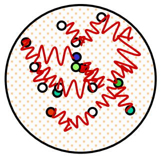

Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

# 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

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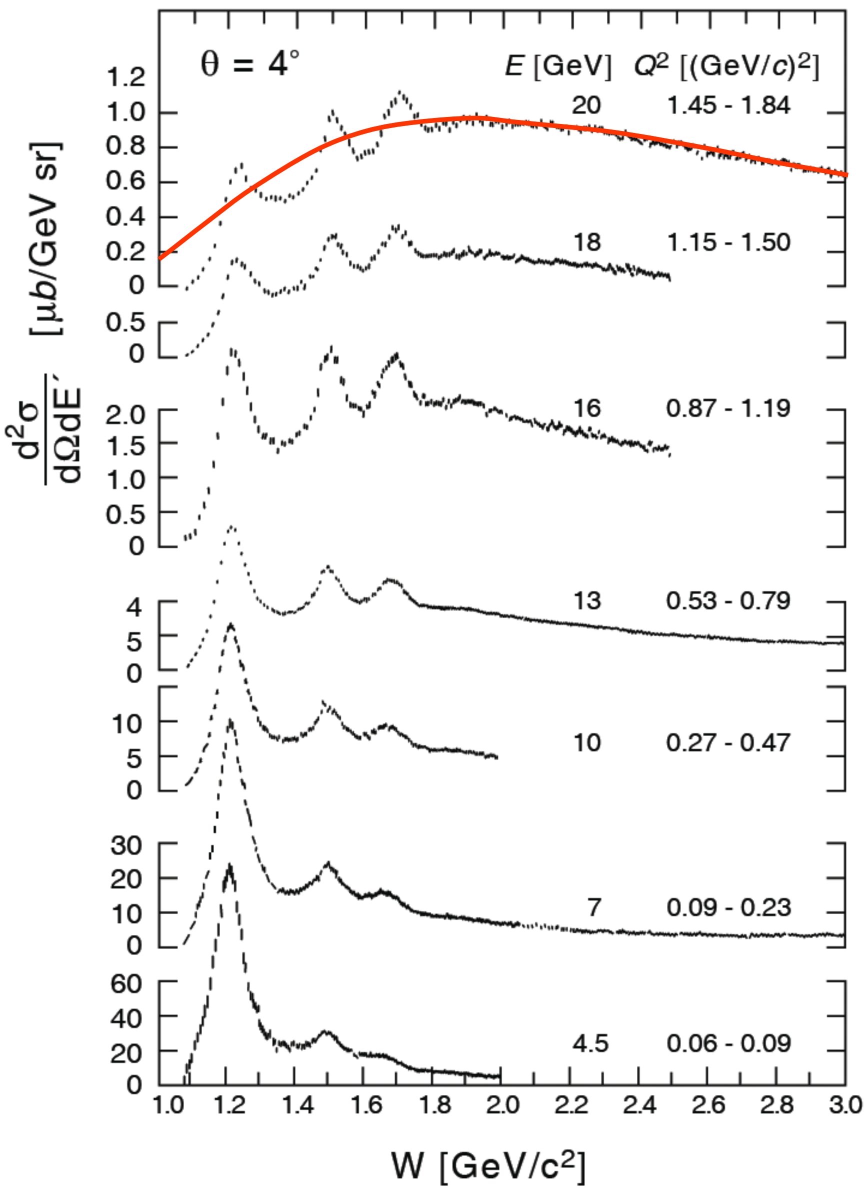
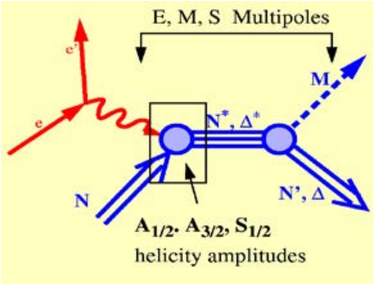
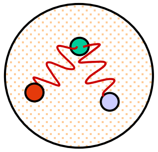



hard and confined



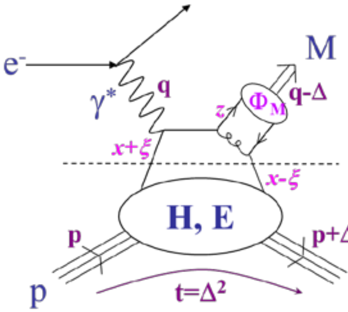



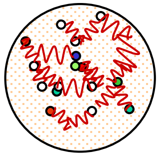
Elastic Form Factors

Transition Form Factors

hard

soft



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

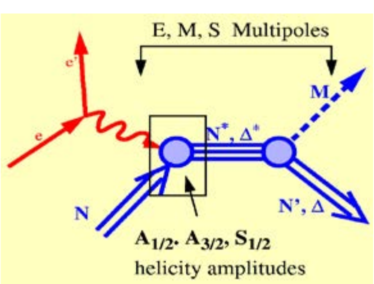
# Structure Analysis of the Baryon

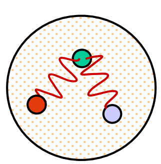
Demolition of a chimney at the "Henninger Brewery" in Frankfurt am Main, Germany, on 2 December 2006

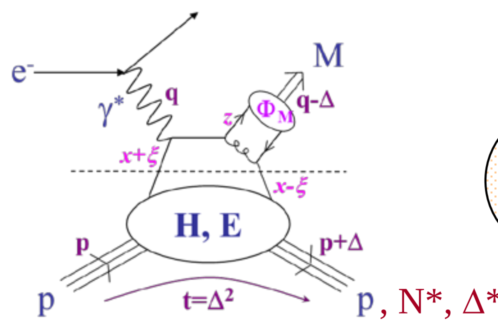
hard and confined

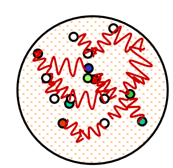
hard and soft

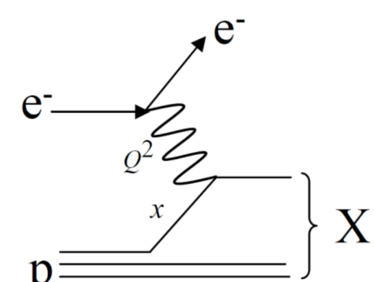
quasi-elastic



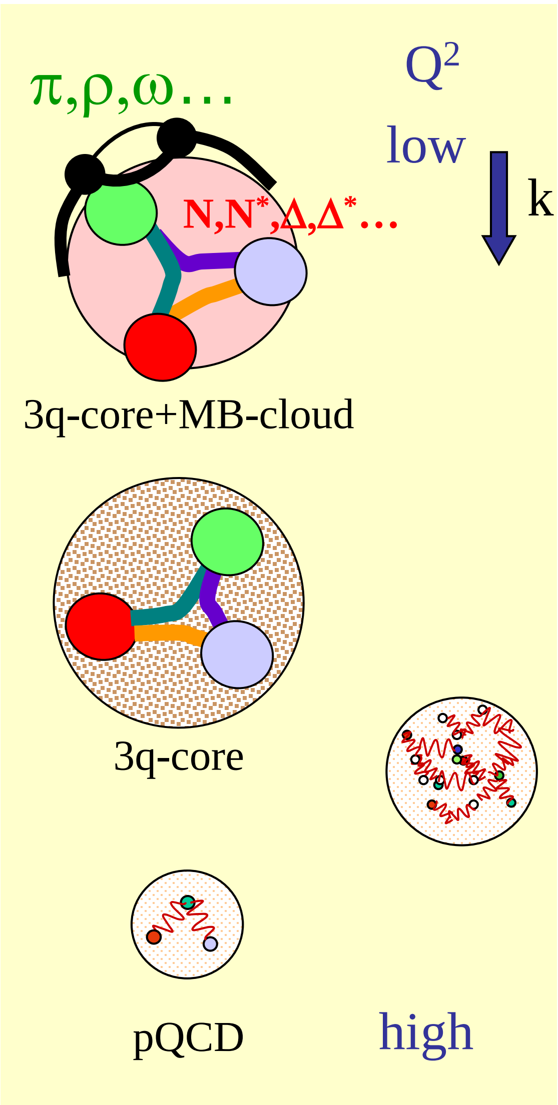




# Transition Form Factors

# Hadron Structure with Electromagnetic Probes

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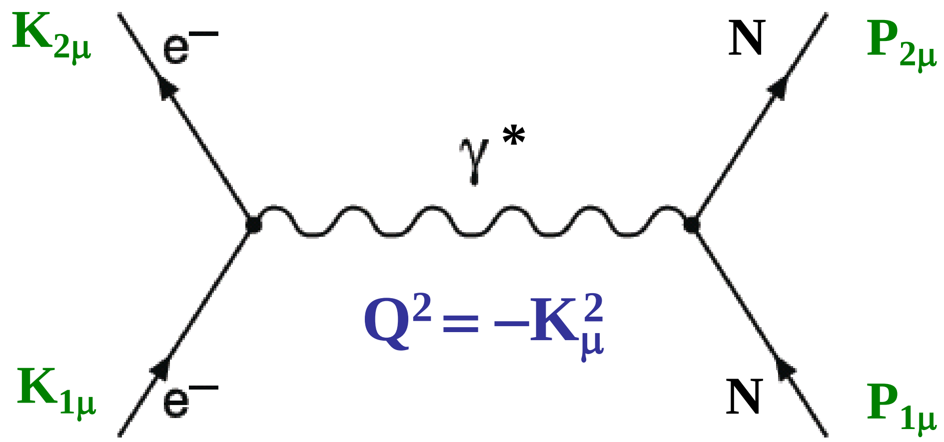
- Explore the formation of excited nucleon states in interactions of dressed quarks and their emergence from QCD.



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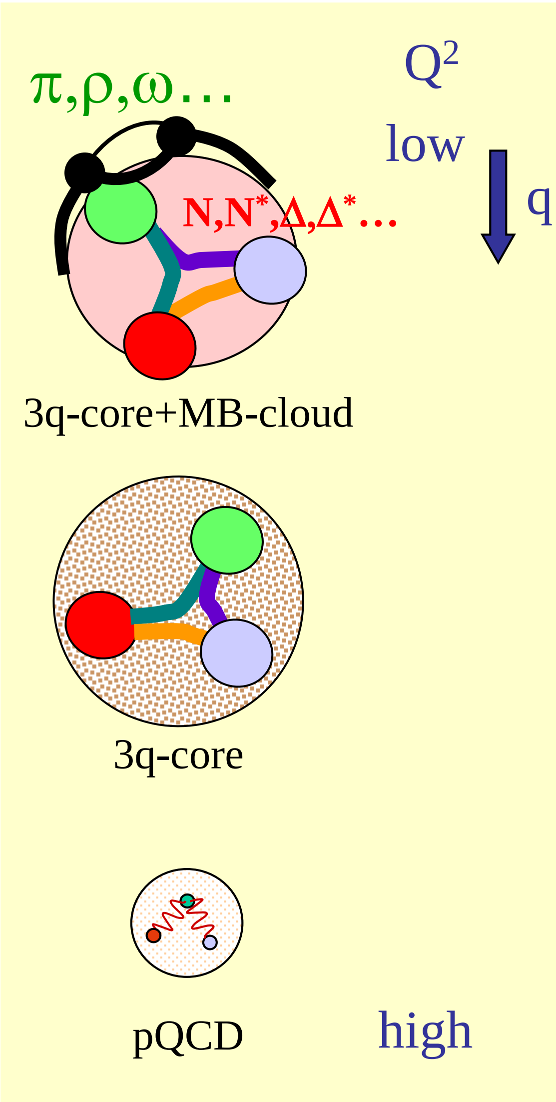


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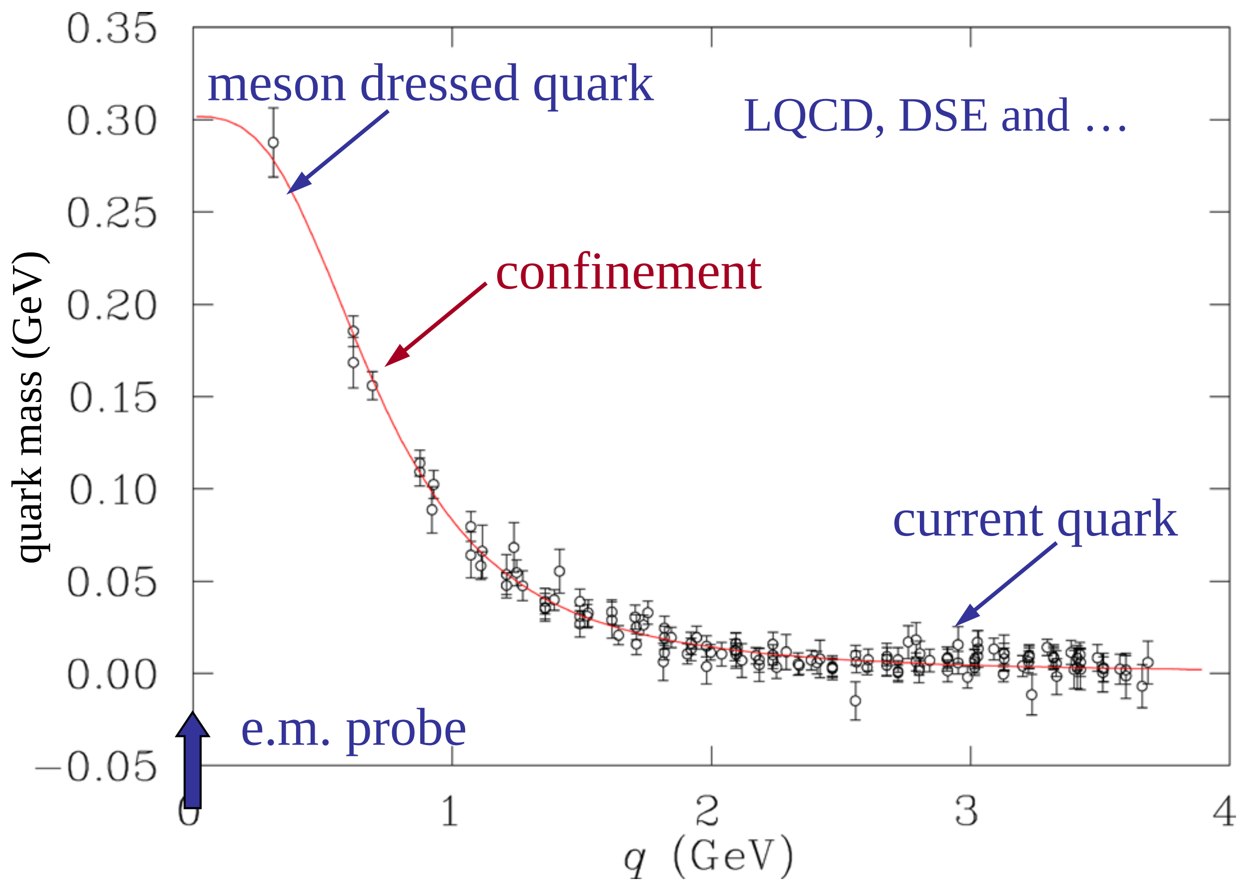
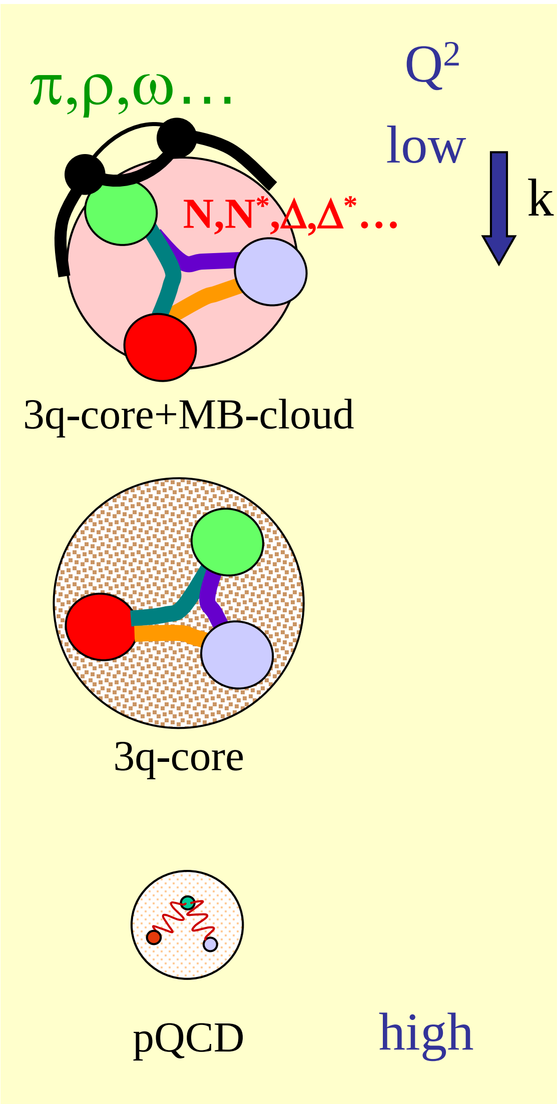
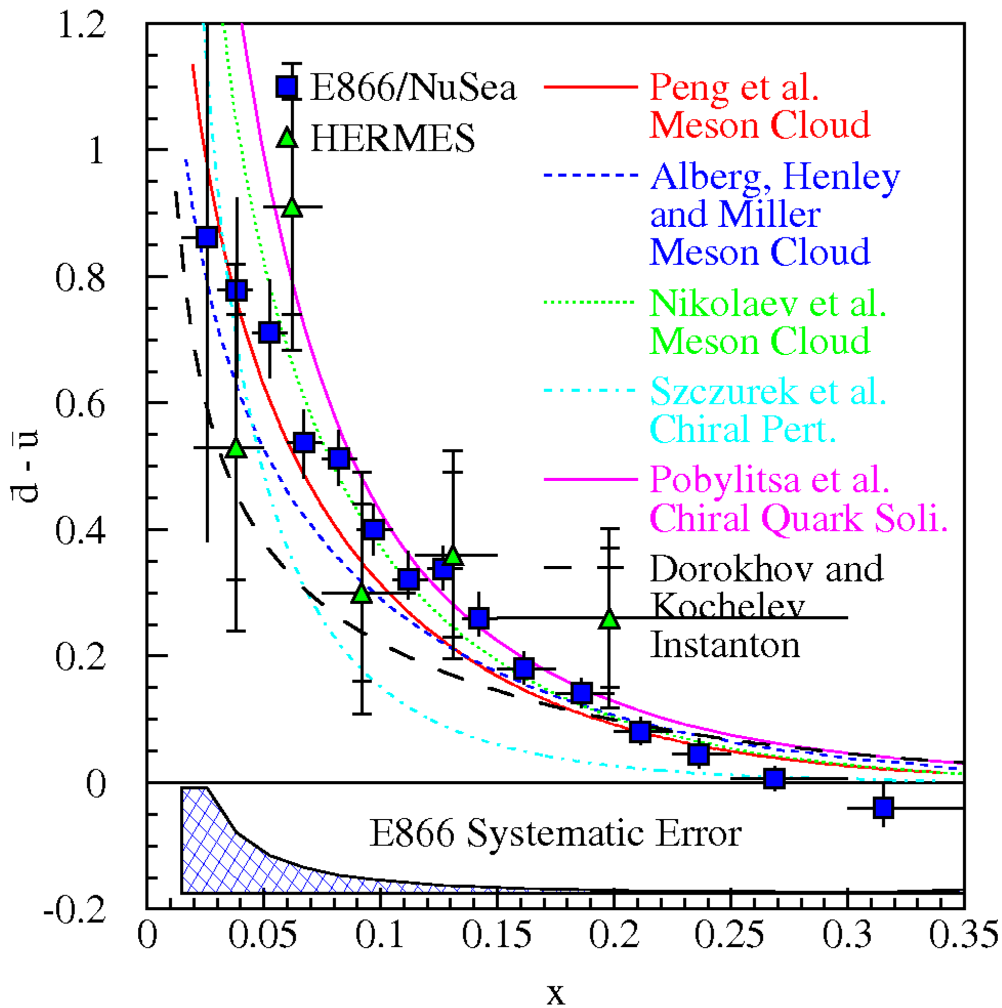


# Hadron Structure with Electromagnetic Probes

Rolf Ent

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

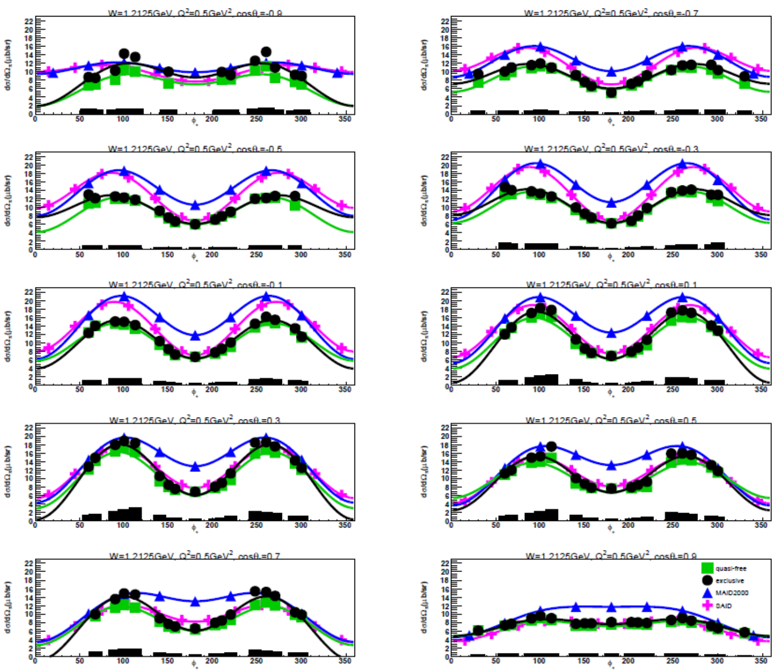


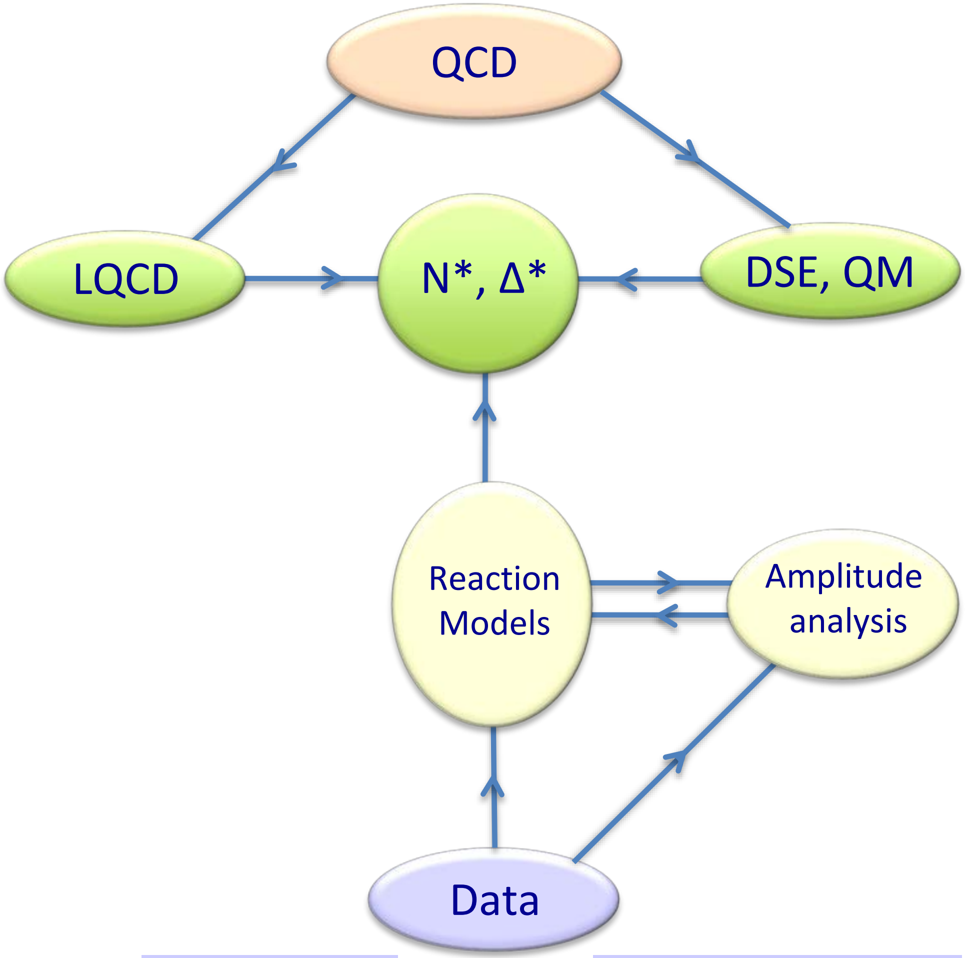
# Data-Driven Data Analyses

## Consistent Results

Single Pion



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



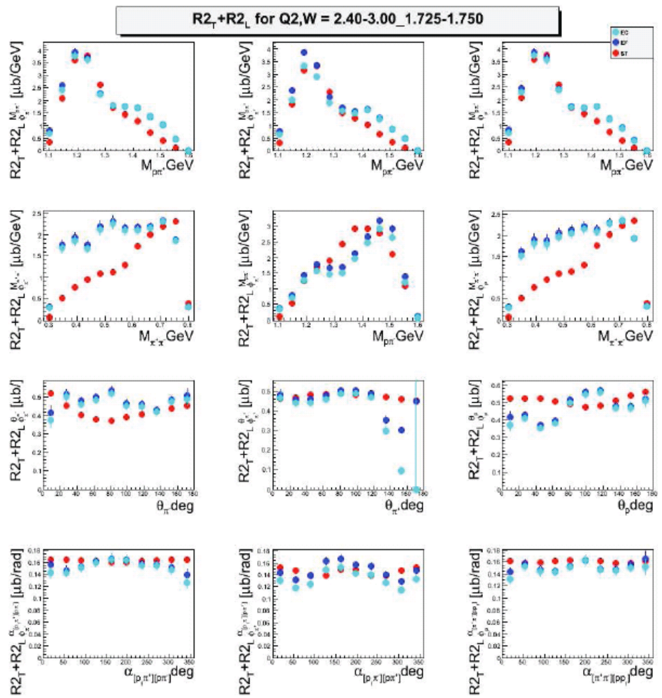

Hadronic production

Electromagnetic production

# Data-Driven Data Analyses

## Consistent Results

Double Pion

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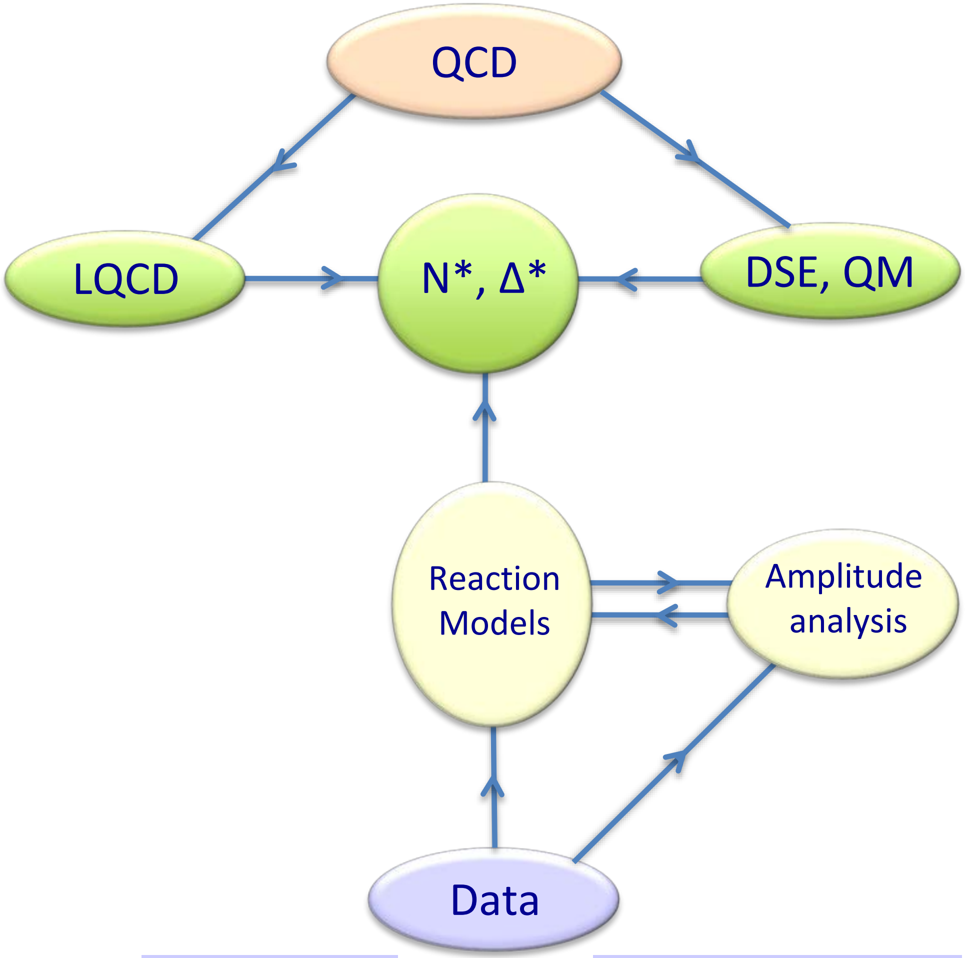



Hadronic production

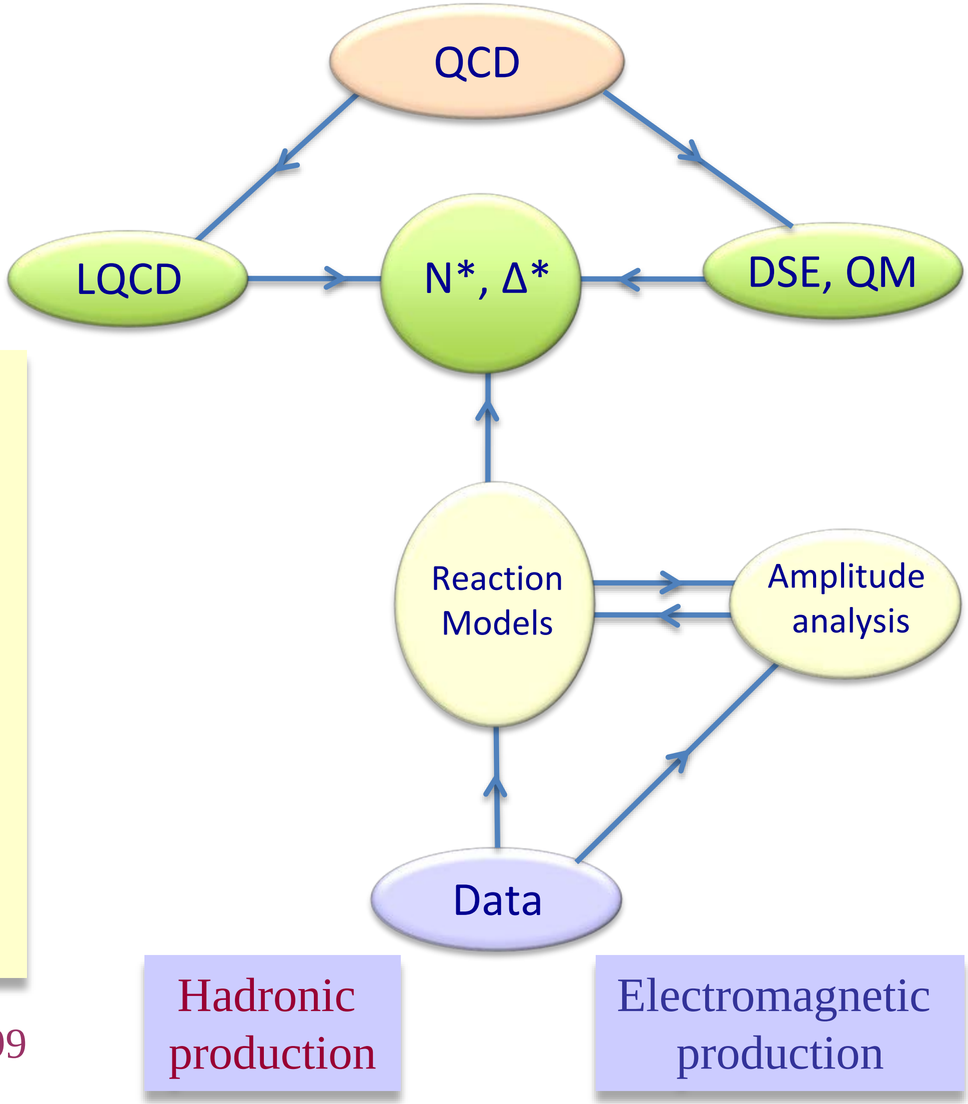
Electromagnetic production

# Data-Driven Data Analyses

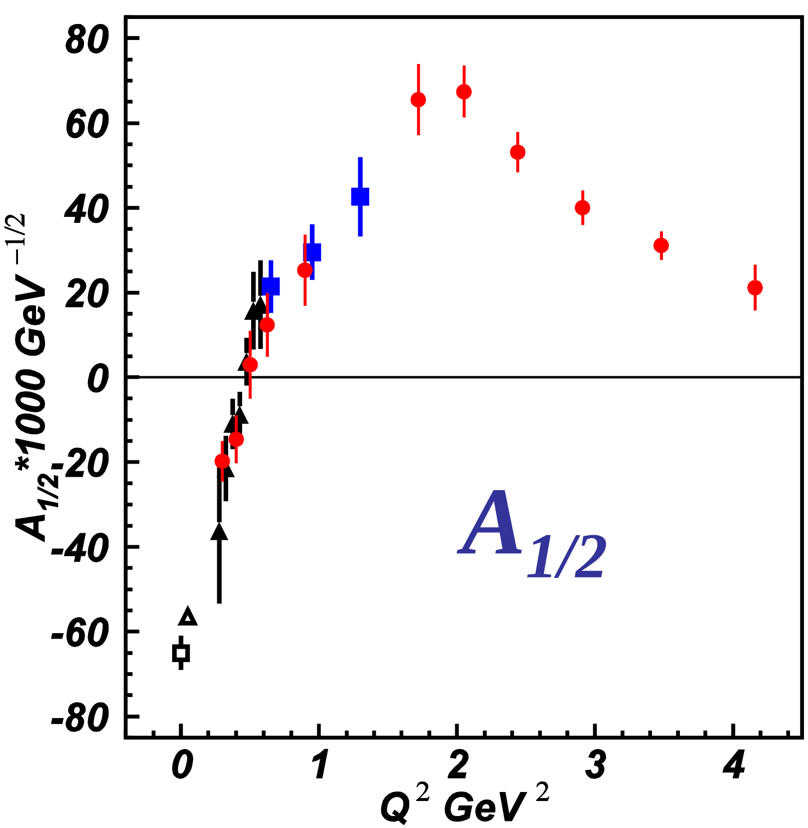
## Consistent Results

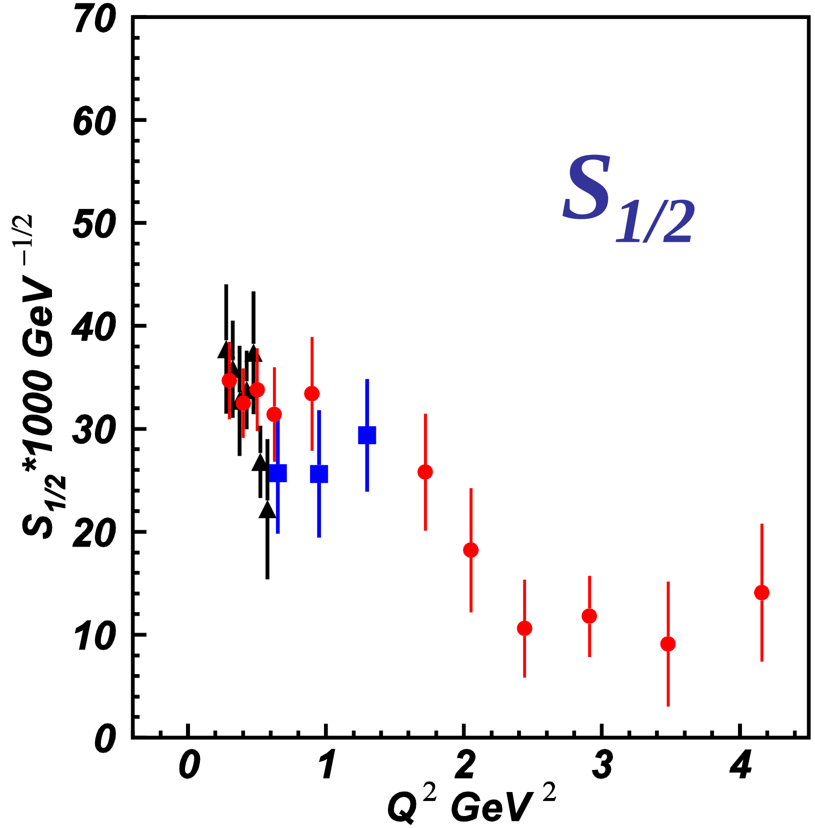
- Single meson production:
  - Unitary Isobar Model (UIM)
  - Fixed-*t* Dispersion Relations (DR)
- Double pion production:
  - Unitarized Isobar Model (JM)
- Coupled-Channel Approaches:
  - EBAC ⇒ Argonne-Osaka
  - JAW ⇒ Jülich-Athens-Washington ⇒ JüBo
  - BoGa ⇒ Bonn-Gatchina

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



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



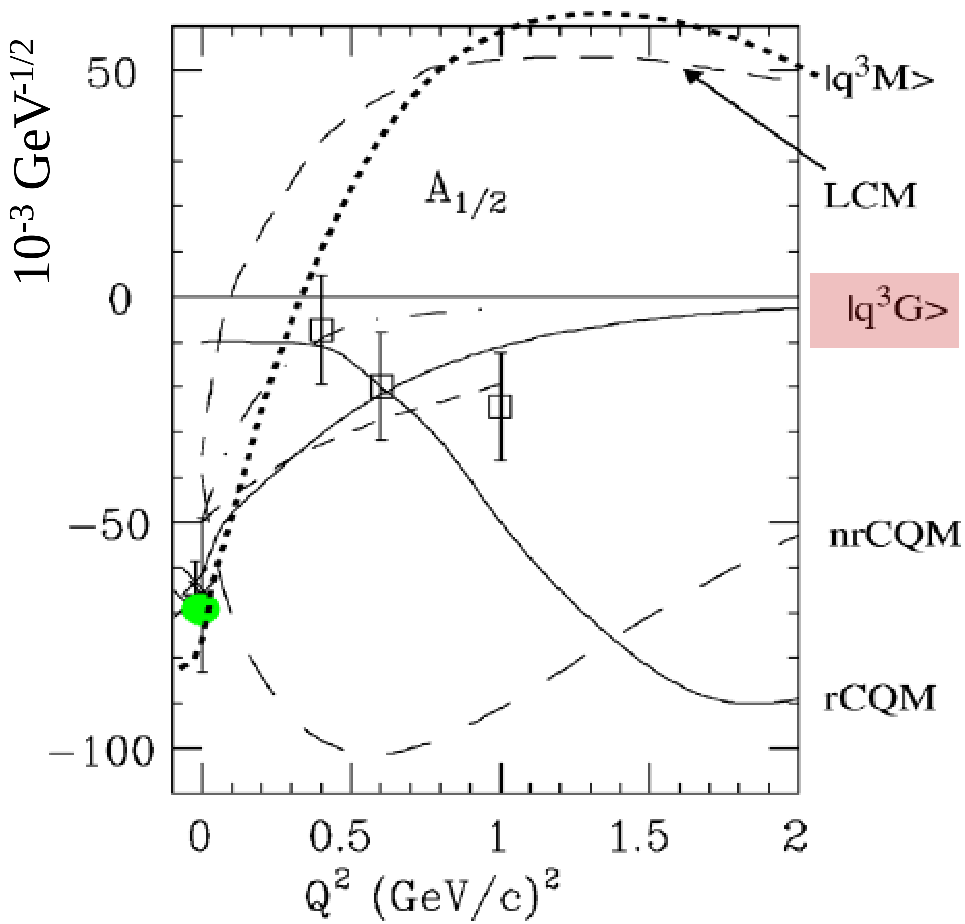




□ PDG ● Nπ (UIM, DR) ▲ Nππ (JM) 2012 ■ Nππ (JM) preliminary

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

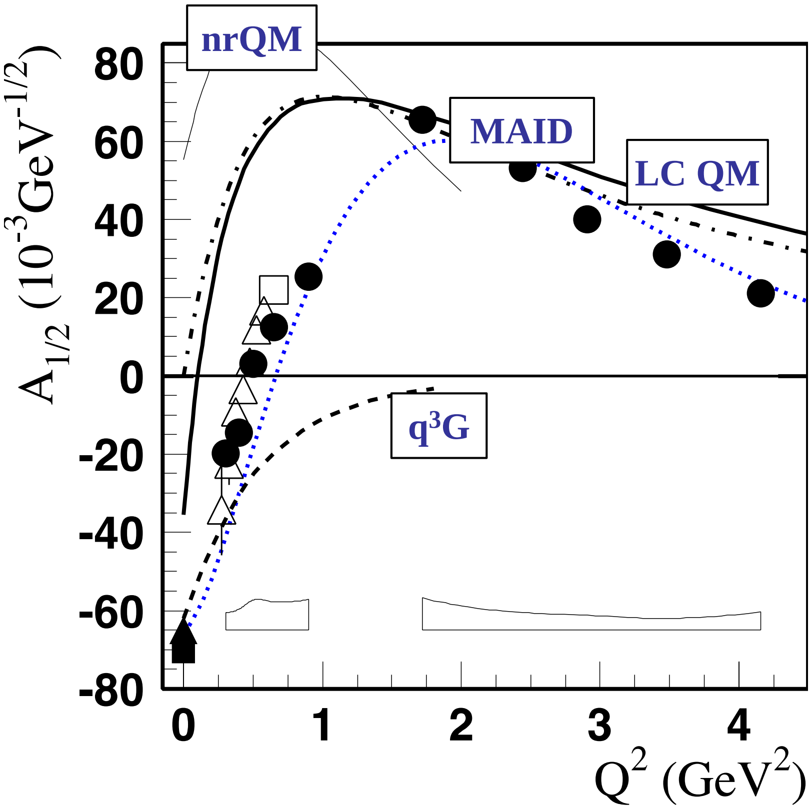
# Electrocouplings of N(1440)$P_{11}$ History




- 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

- $q^2q$
- …

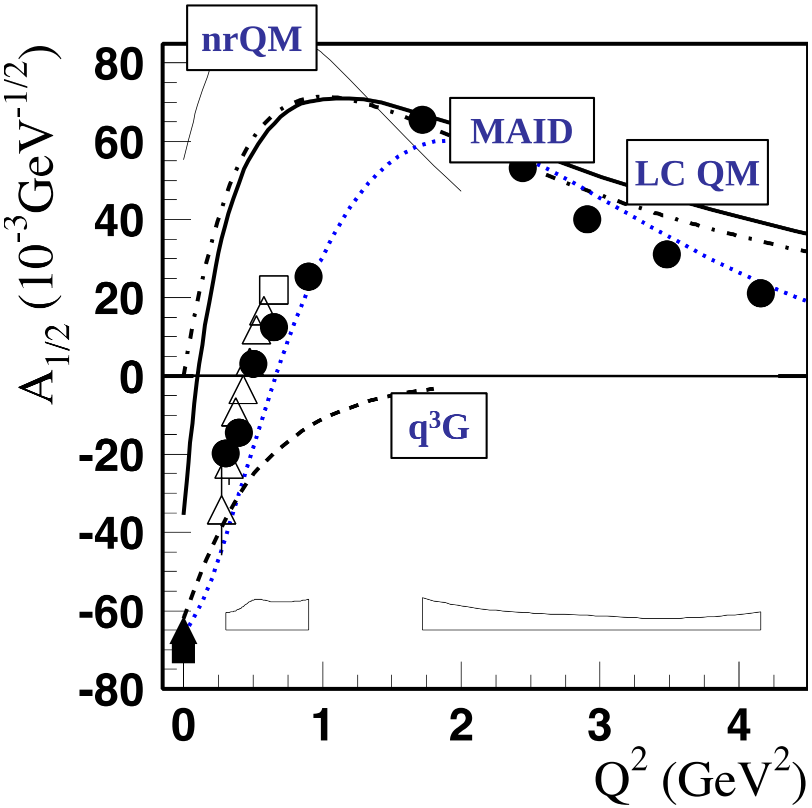
… all have distinctively different $Q^2$ dependencies

- $A_{1/2}$ 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.

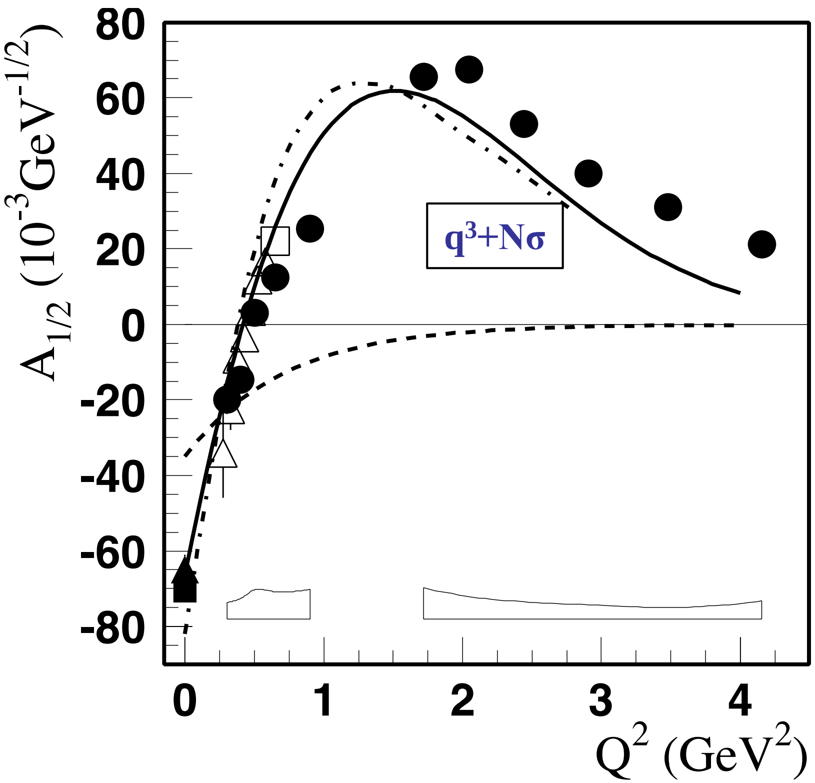
Nick Tyler closes the 1-2 GeV$^2$ gap for single pion production.

# Transition Form Factors and QCD Models

Roper resonance $P_{11}(1440)$




I.T. Obukhovsky

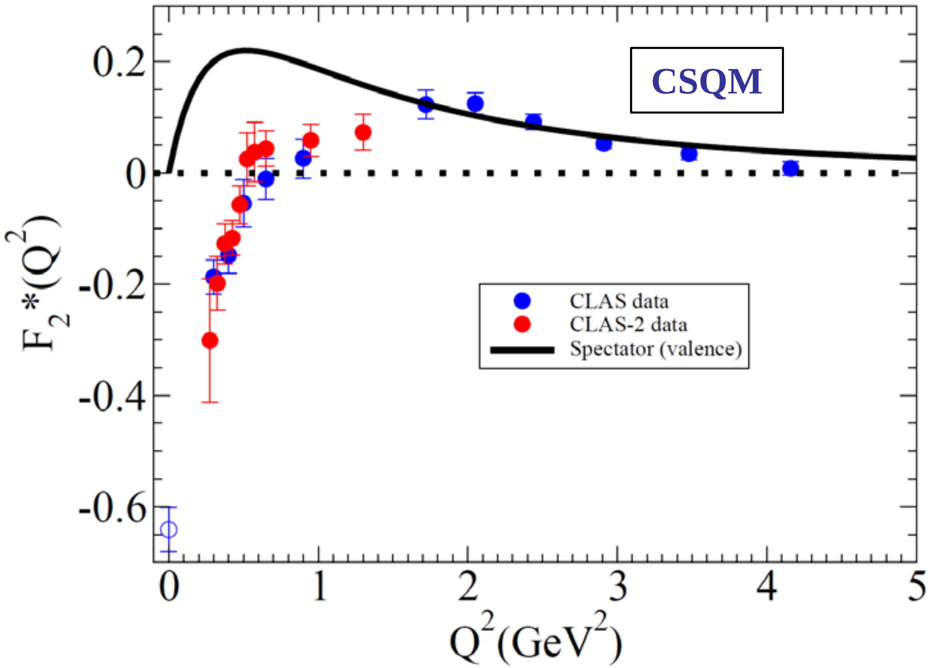


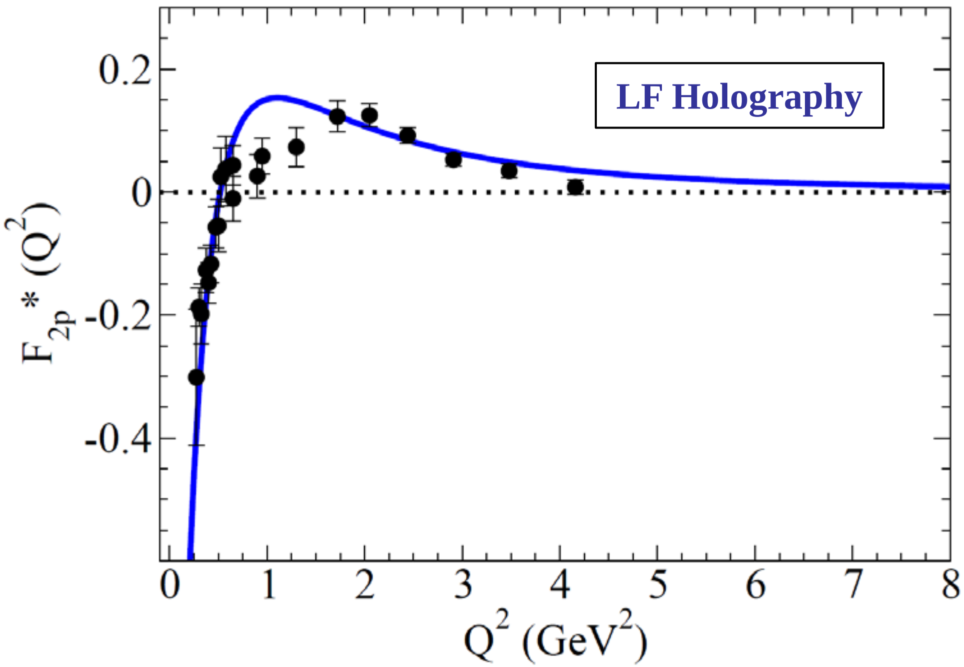

- $A_{1/2}$ has zero-crossing near $Q^2$=0.5 and becomes dominant amplitude at high $Q^2$.
- Consistent with radial excitation at high $Q^2$ and large meson-baryon coupling at small $Q^2$.
- Eliminates gluonic excitation ($q^3G$) as a dominant contribution.

Nick Tyler closes the 1-2 GeV² gap for single pion production.

# Transition Form Factors and QCD Models

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




- $A_{1/2}$ has zero-crossing near $Q^2$=0.5 and becomes dominant amplitude at high $Q^2$.
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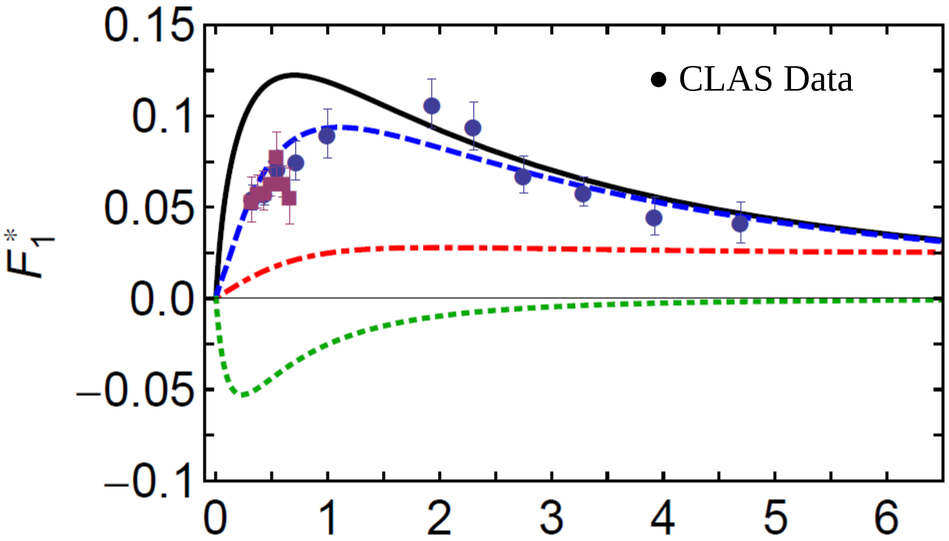
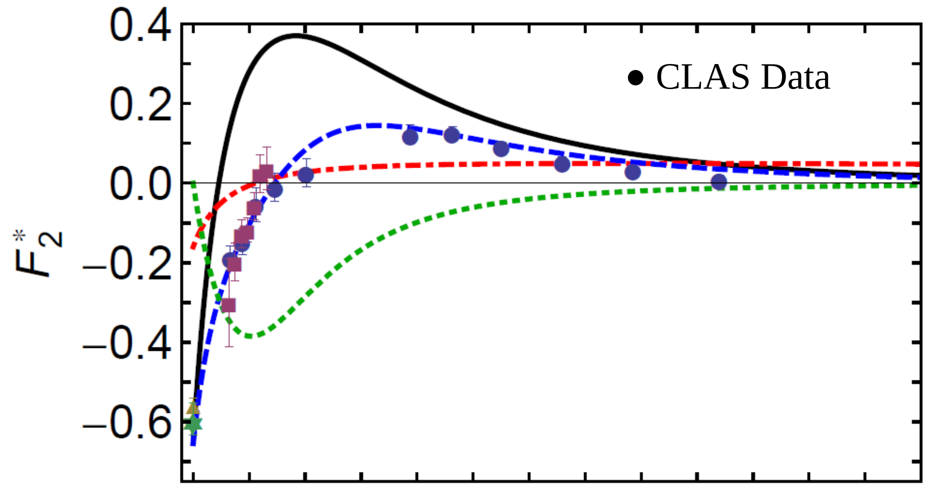
Nick Tyler closes the 1-2 GeV$^2$ gap for single pion production.

# Roper Transition Form Factors in DSE Approach

## $N(1440)P_{11}$

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




$x=Q^2/m_N^2$

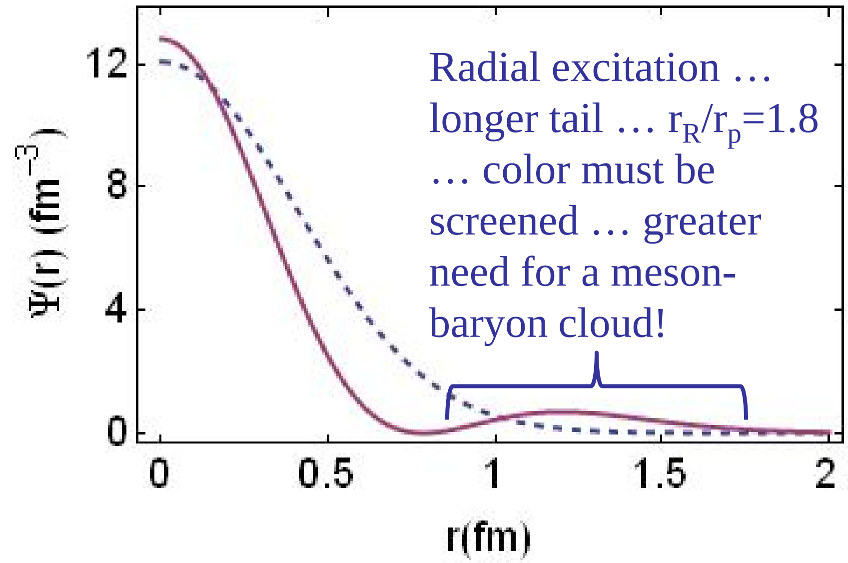
DSE Contact

DSE Realistic

Inferred meson-cloud contribution

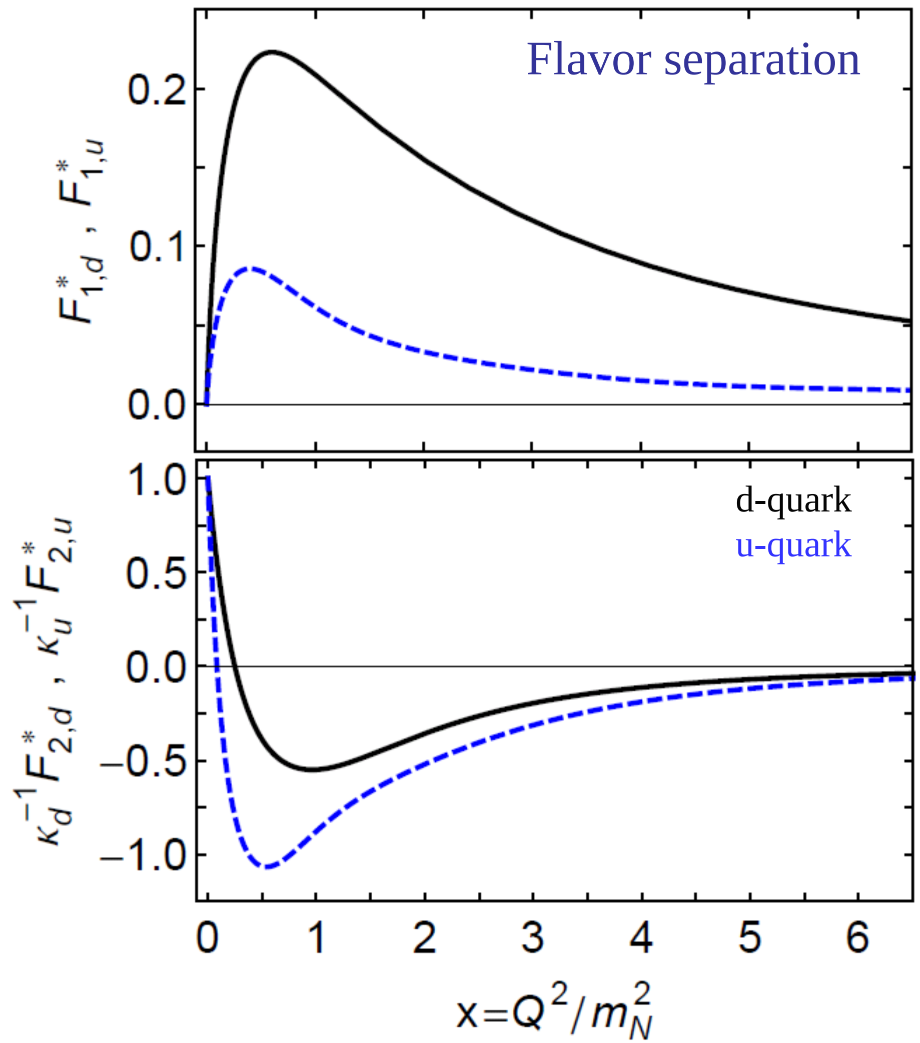
Anticipated complete result

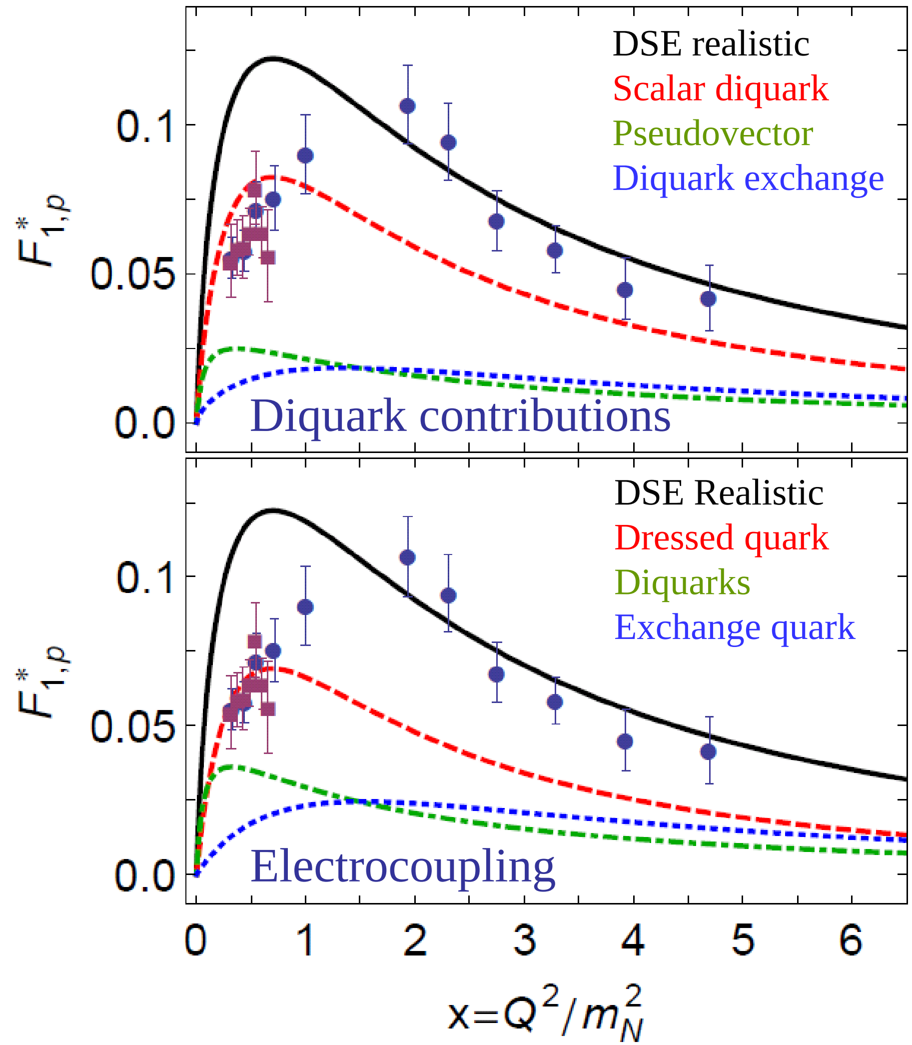
Importantly, the existence of a zero in $F_2$ is not influenced by meson-cloud effects, although its precise location is.



# Roper Transition Form Factors in DSE Approach

**N(1440)$P_{11}$** J. Segovia and C.D. Roberts, arXiv:1607.04405

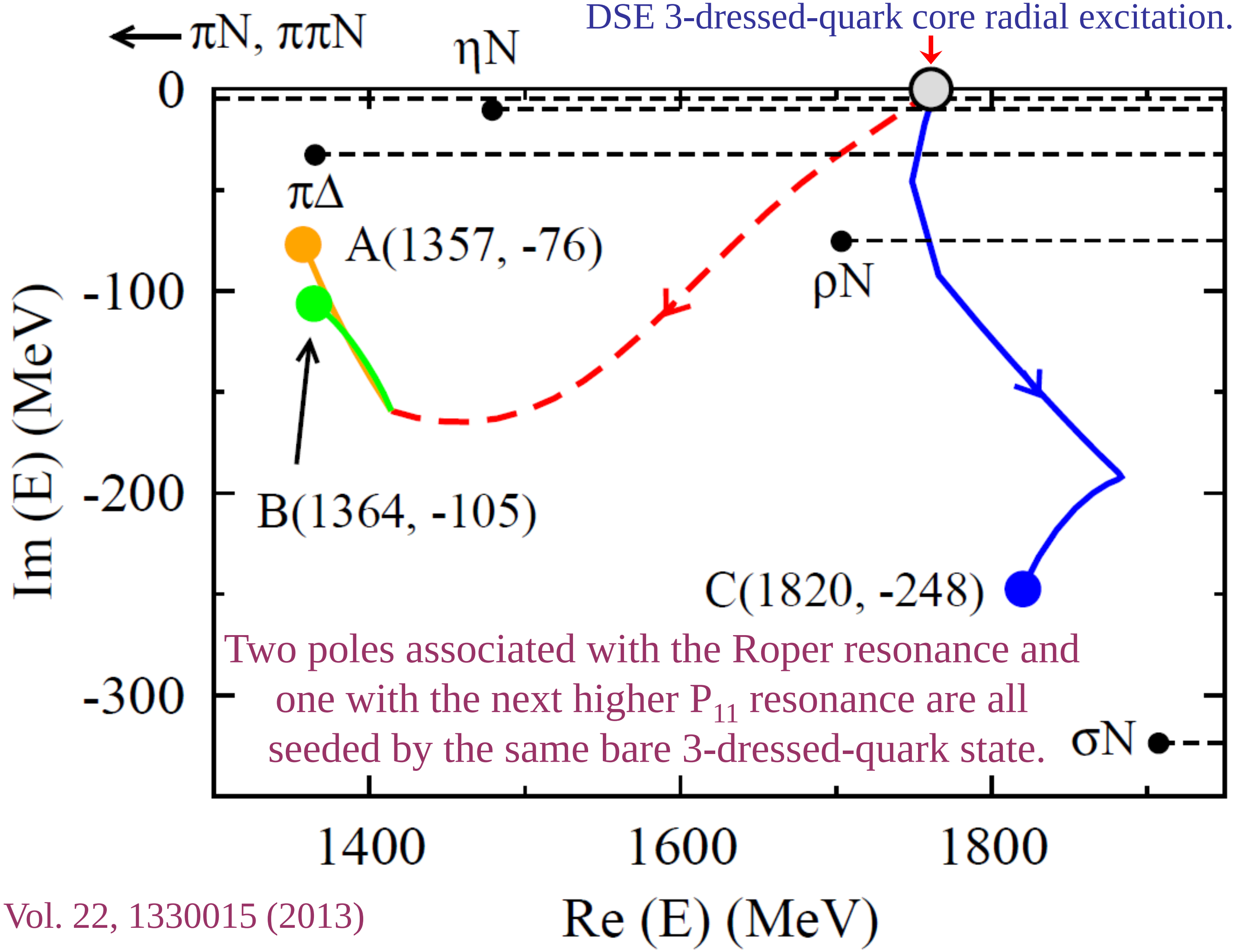


# DSE and EBAC/ANL-Osaka Approaches

… more (π,ππ), (π,πη), and (π,KY) data needed

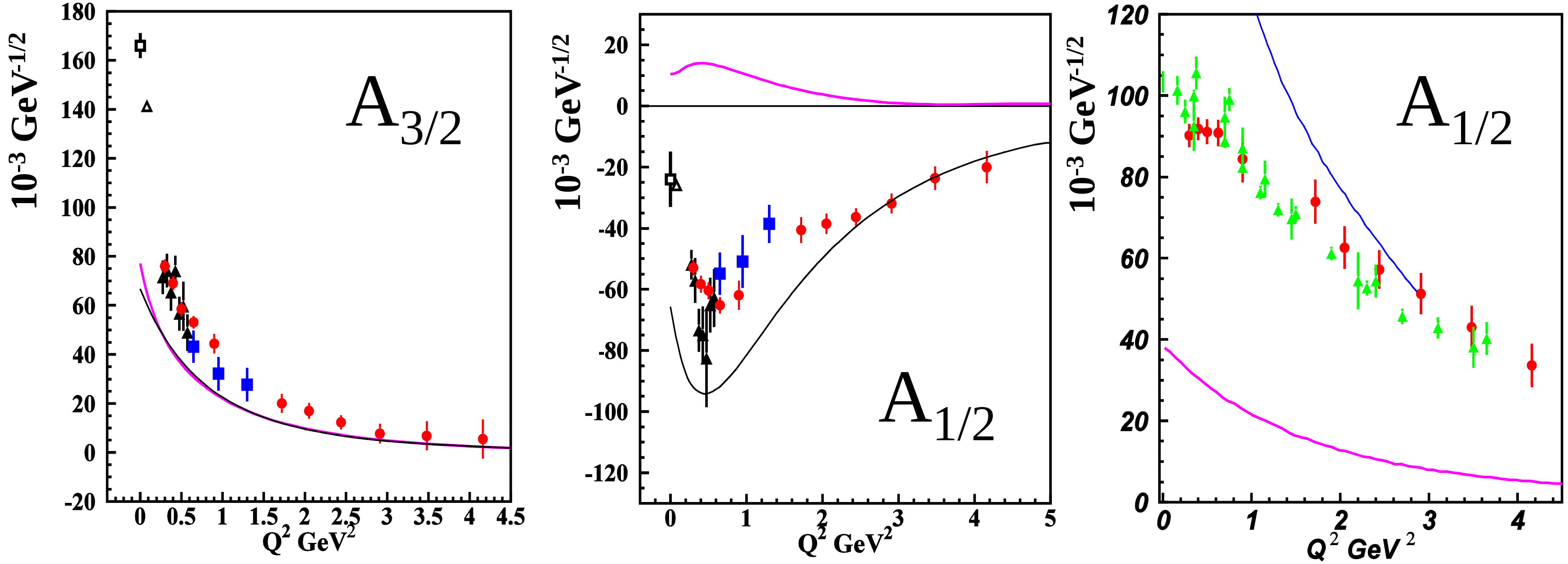
Semi-quantitative agreement with the first DSE 3-dressed-quark core radial excitation.




Two poles associated with the Roper resonance and one with the next higher $P_{11}$ resonance are all seeded by the same bare 3-dressed-quark state.

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

# 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

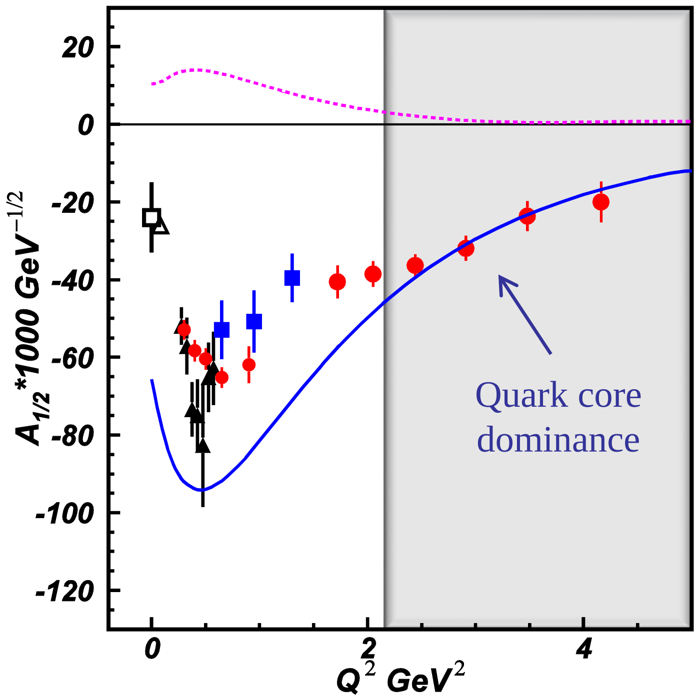
$\pi^+\pi^-p$ 2010

$N\pi$ 2009

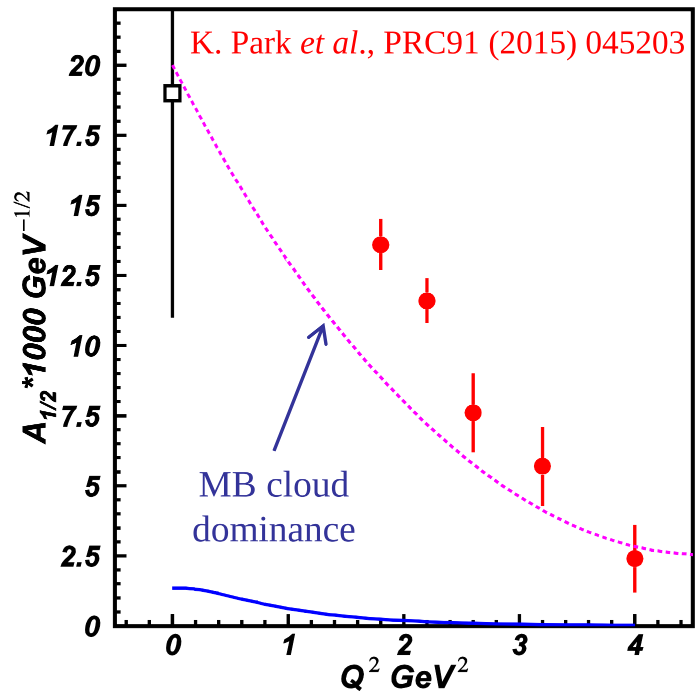
$\eta p$ CLAS/Hall-C

# Interplay between Meson-Baryon Cloud and Quark Core

## N(1520)3/2$^-$




## N(1675)5/2$^-$




Argonne-Osaka MB dressing (absolute values)

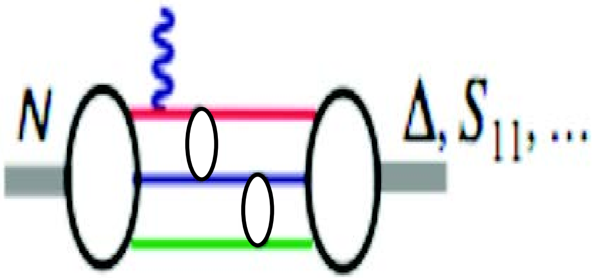
E. Santopinto and M. Giannini, PRC 86 (2012) 065202

The almost direct access to

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

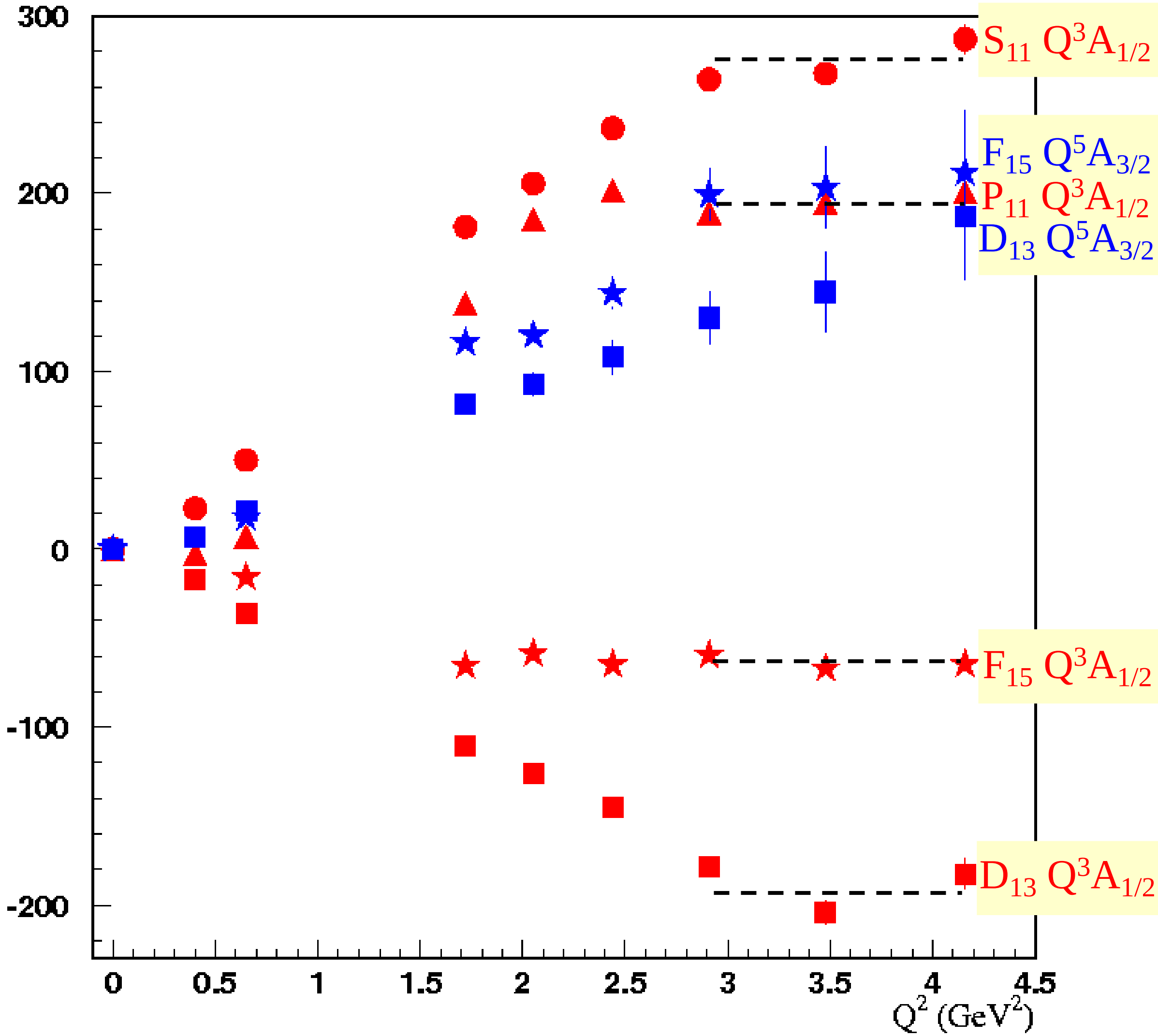
sheds light on the transition from the confined quark to the colorless meson-baryon structure and its dependents on the N* quantum numbers.

# Evidence for the Onset of Precocious Scaling?



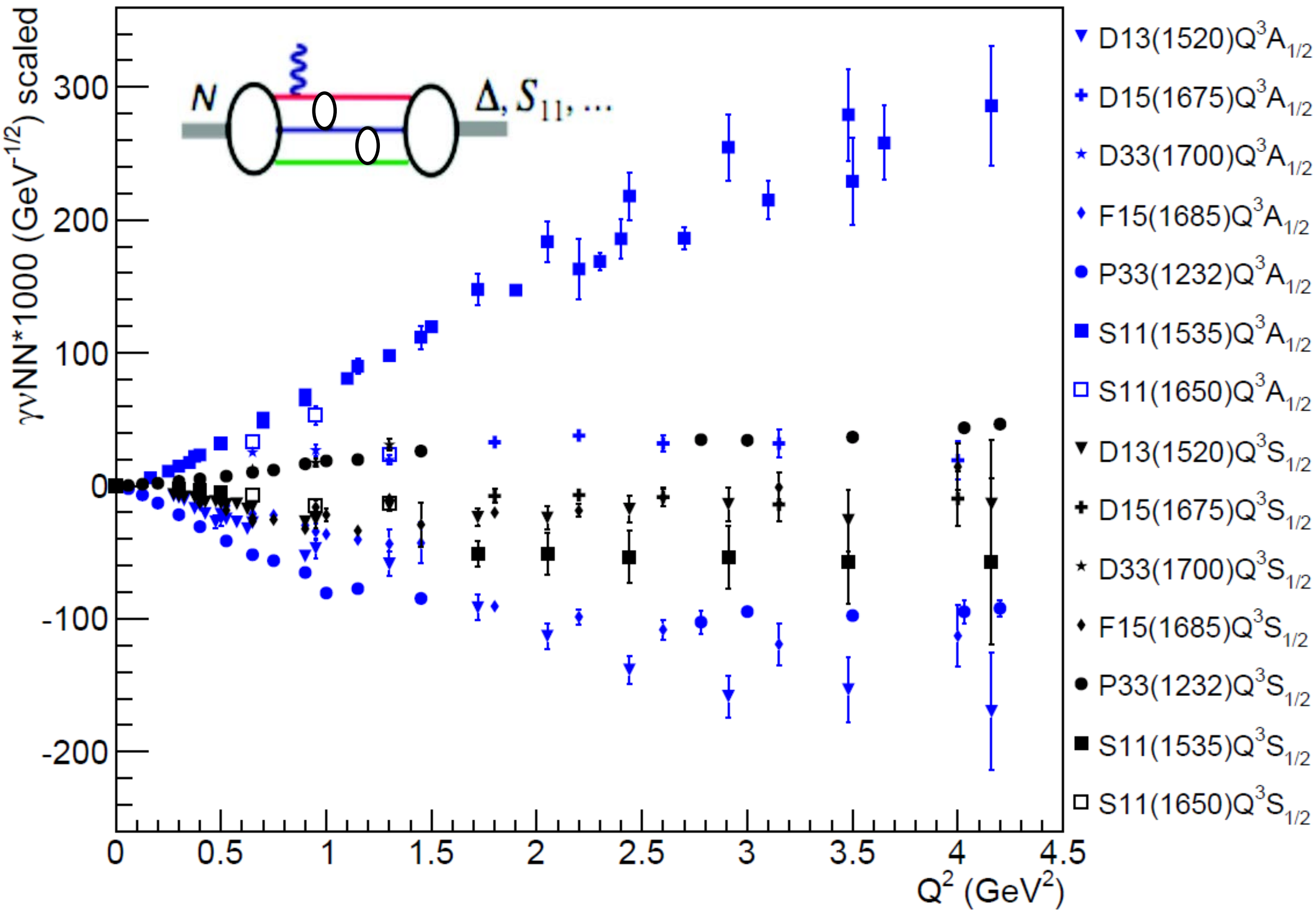

- $A_{1/2} \propto 1/Q^3$
- $A_{3/2} \propto 1/Q^5$

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



# Evidence for the Onset of Precocious Scaling?

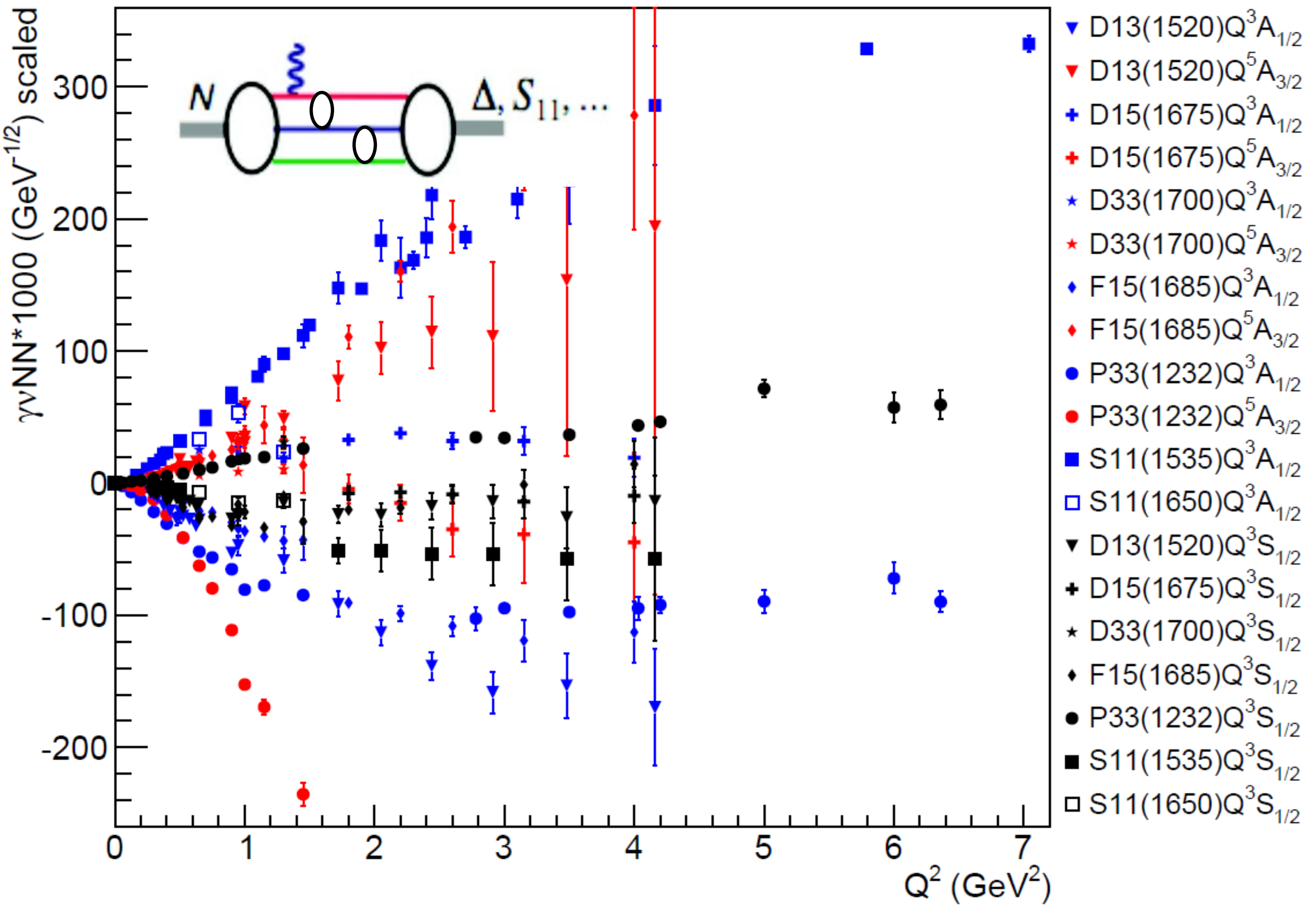
Ye Tian




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

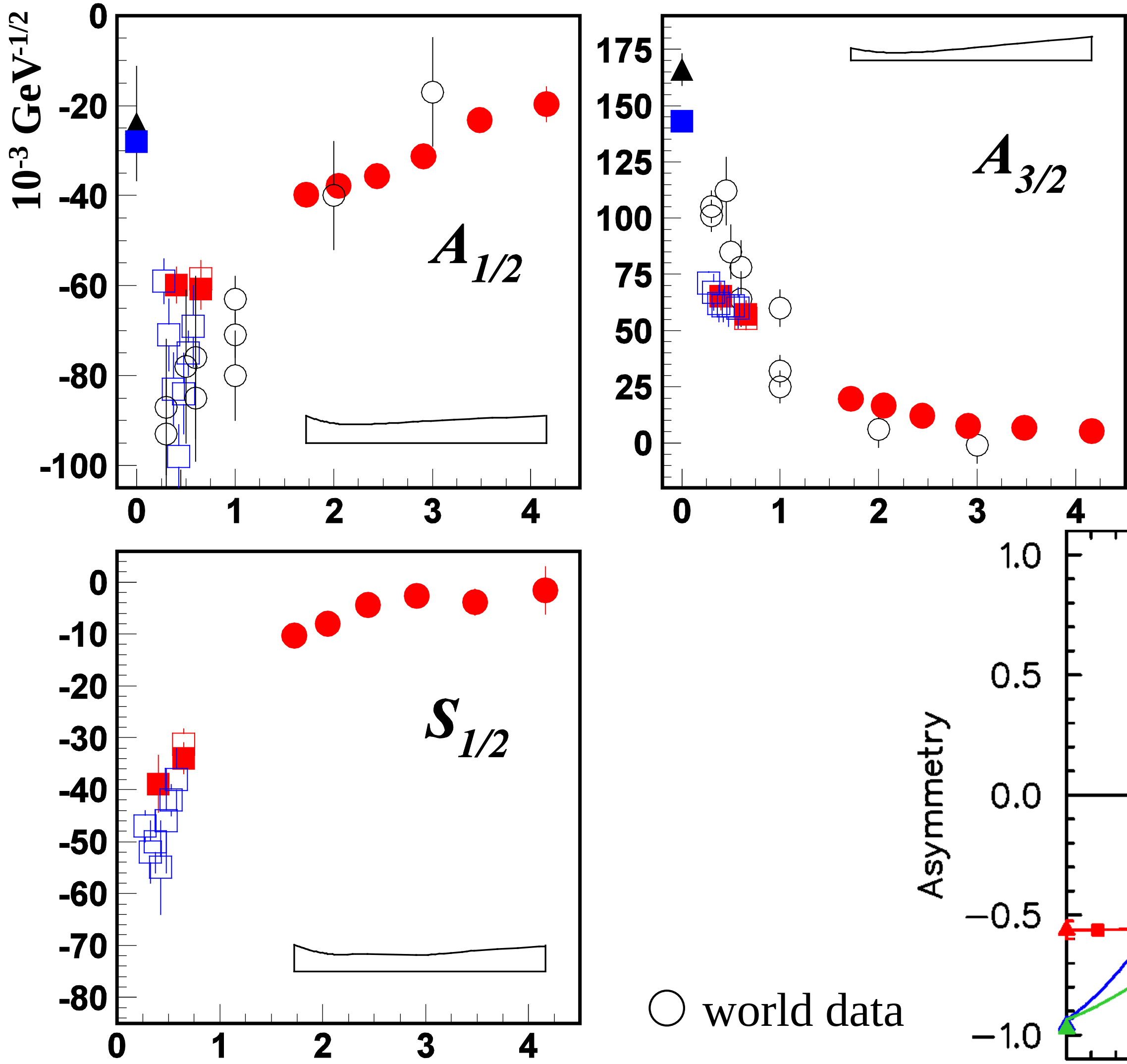
# Evidence for the Onset of Precocious Scaling?

Ye Tian




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

# N(1520)$D_{13}$ Helicity Asymmetry

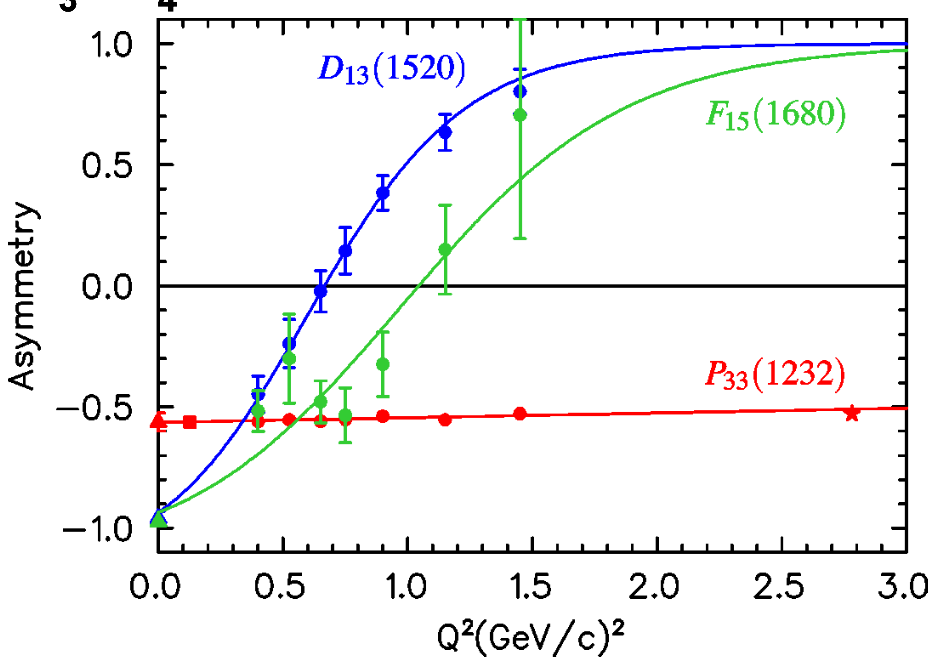



$$A_{hel} = \frac{A_{1/2}^2 - A_{3/2}^2}{A_{1/2}^2 + A_{3/2}^2}$$

L. Tiator

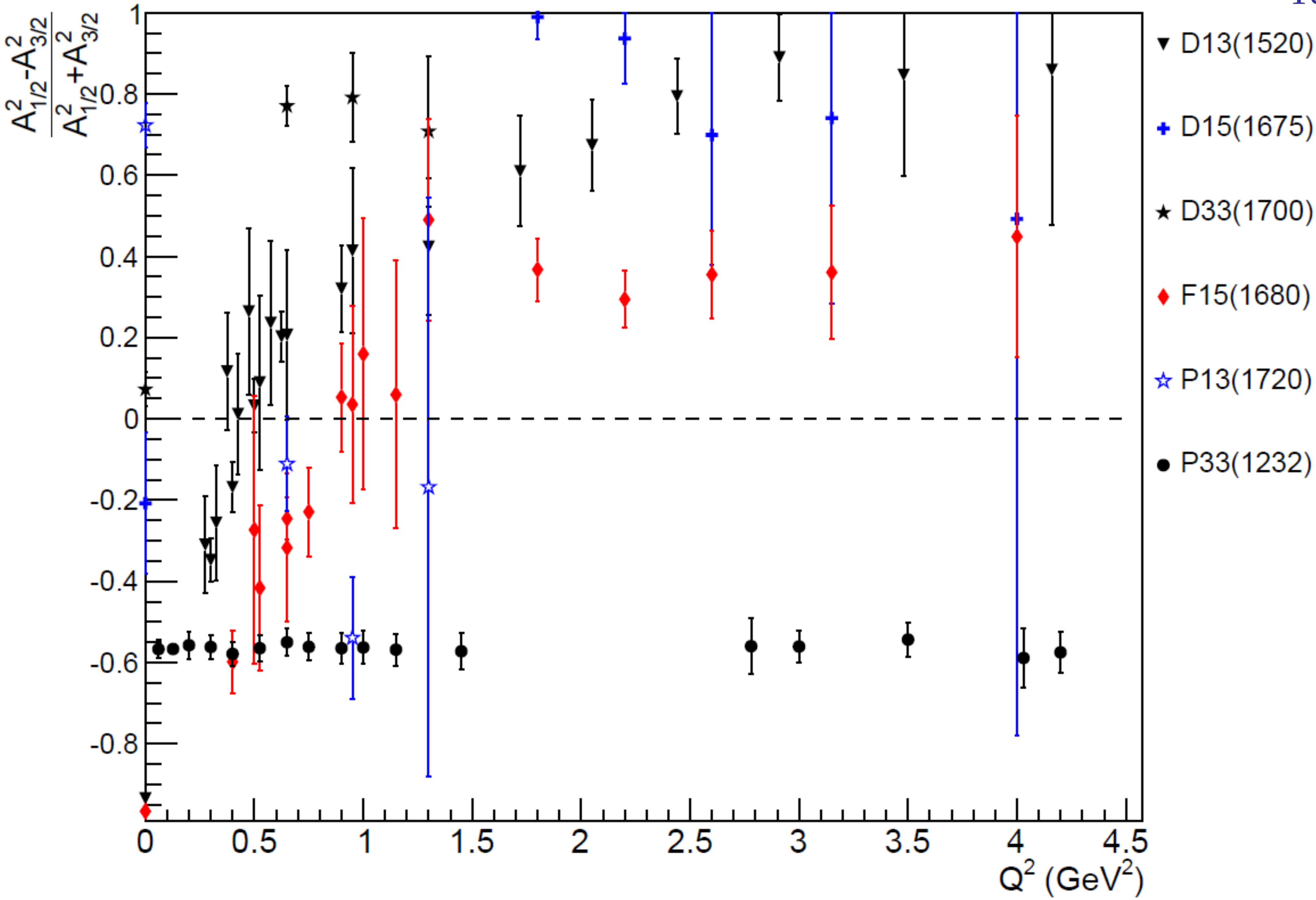
○ world data

▲ PDG estimation ● ■ Nπ (UIM, DR)



# γNN* Helicity Asymmetries

Ye Tian

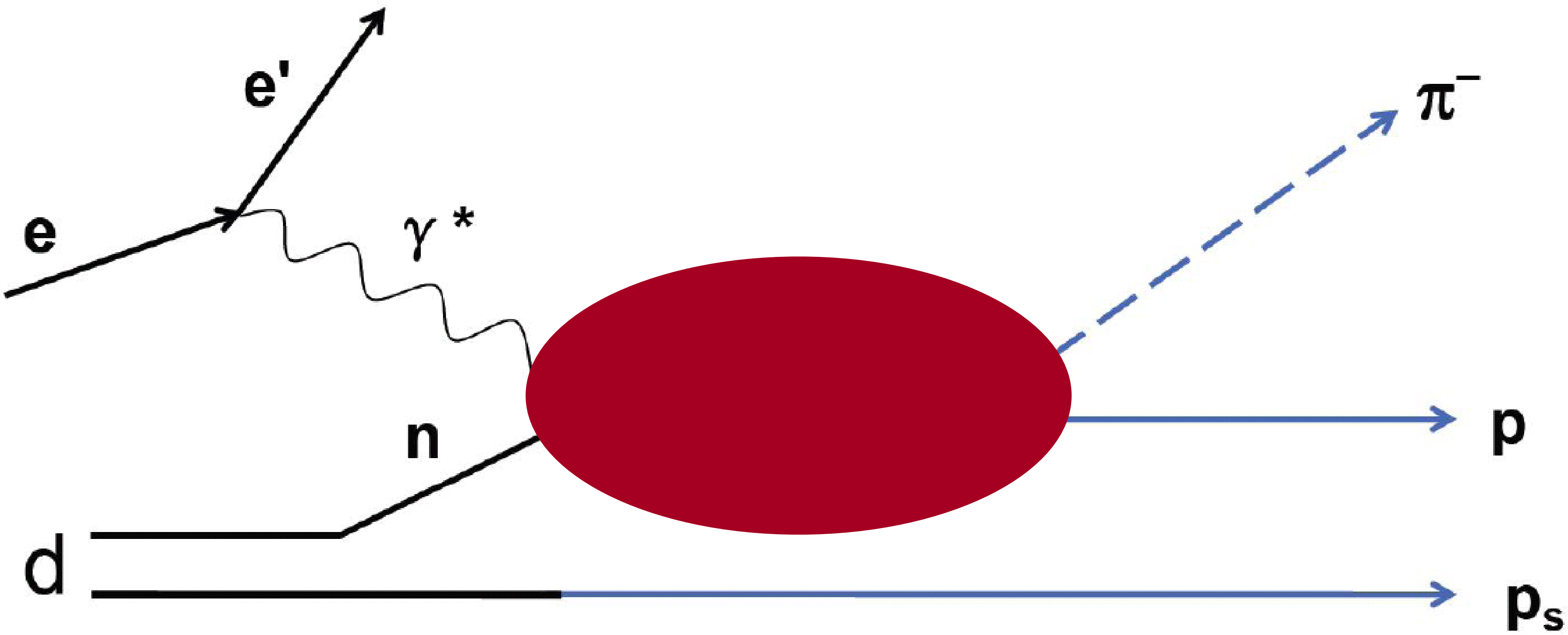



V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)

# New Experimental Results & Approaches

# Single $\pi^-$ Electroproduction off the Deuteron

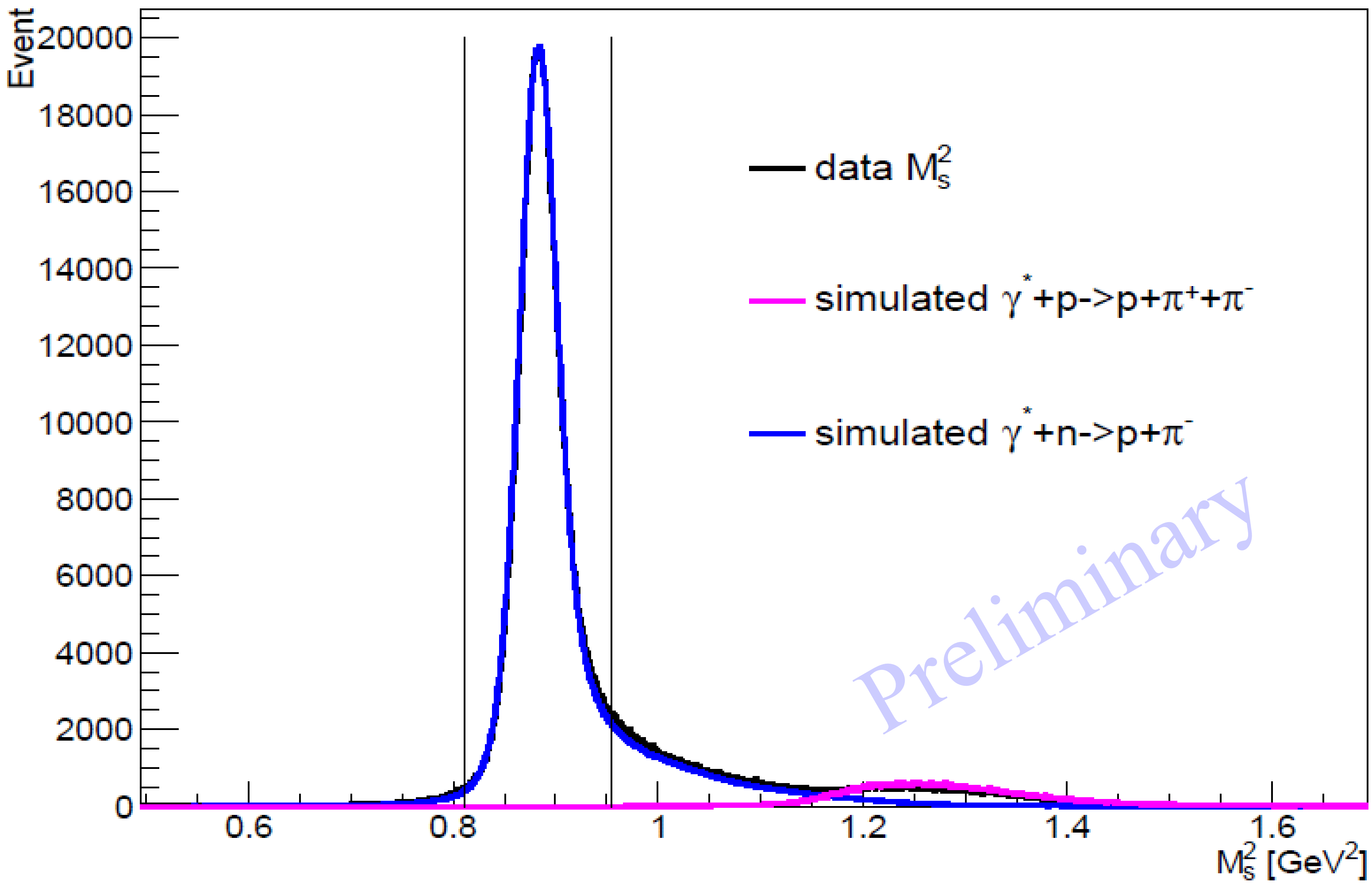
Ye Tian




Exclusive ⇒ Spectator ⇒ Quasi-Free ⇒ FSI

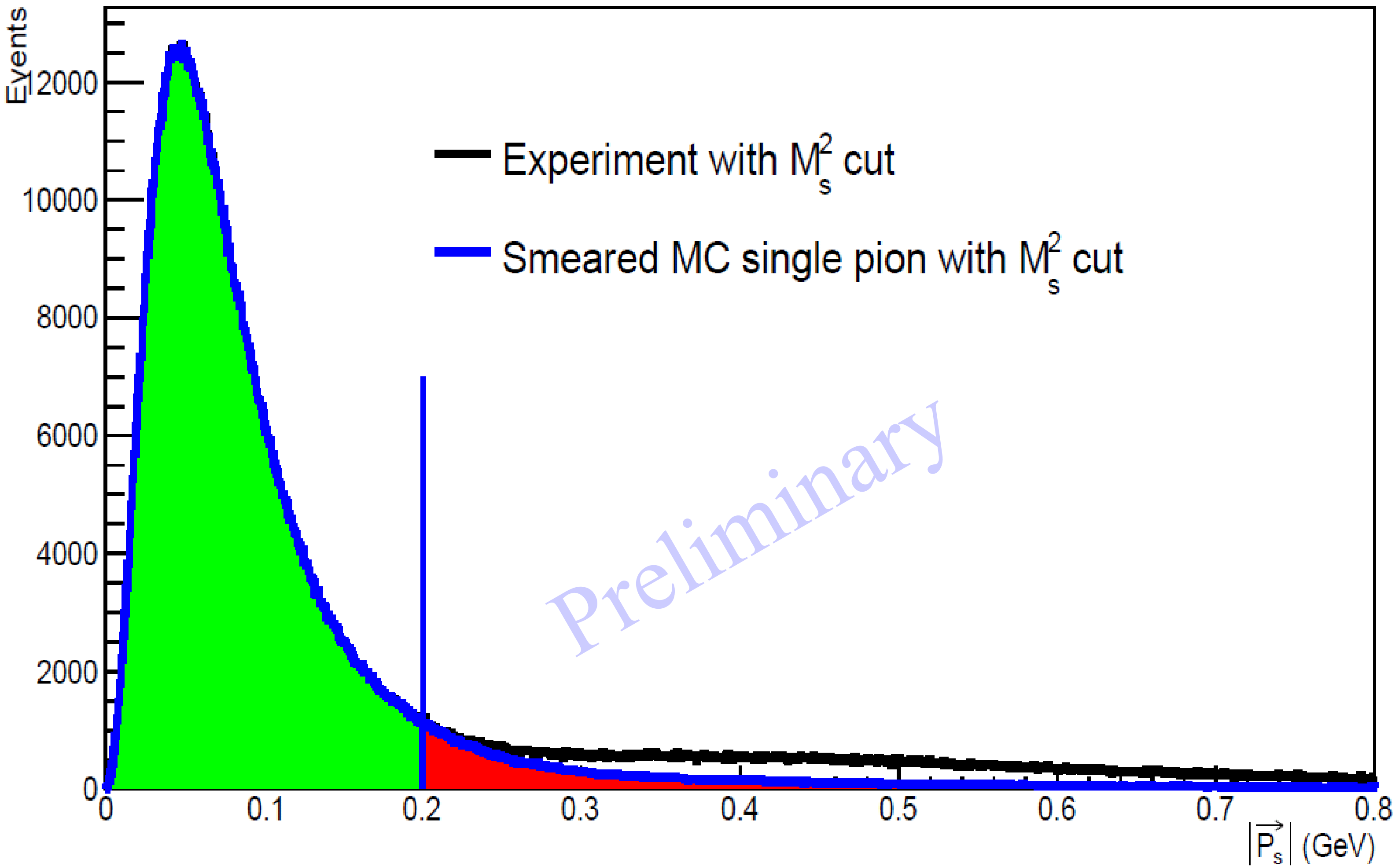
# Single π⁻ Electroproduction off the Deuteron

Ye Tian



# Single $\pi^-$ Electroproduction off the Deuteron

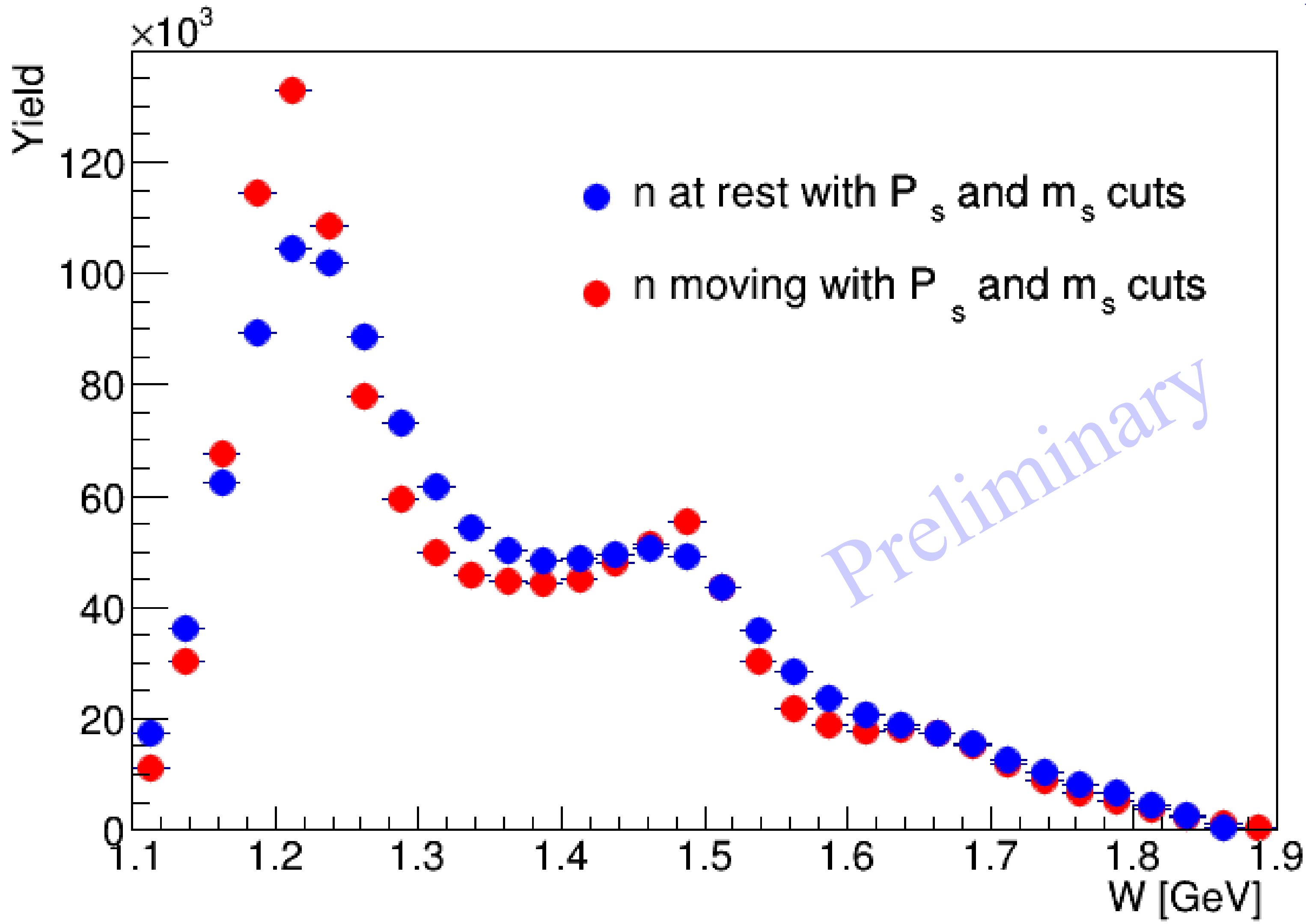
Ye Tian




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 $\pi^-$ Electroproduction off the Deuteron

Ye Tian

W = 1212 MeV

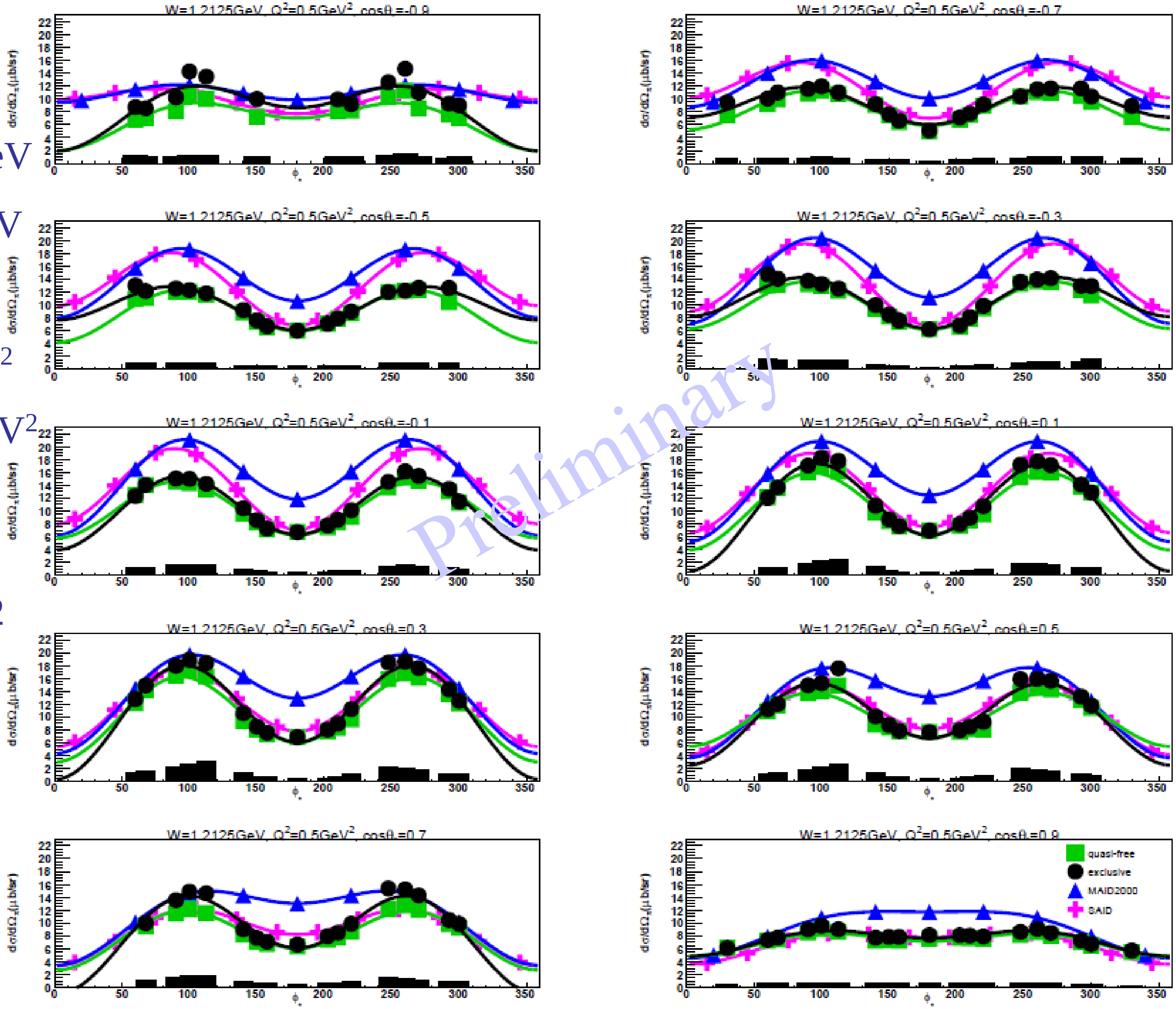
ΔW = 25 MeV

$Q^2 = 0.5\ GeV^2$

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

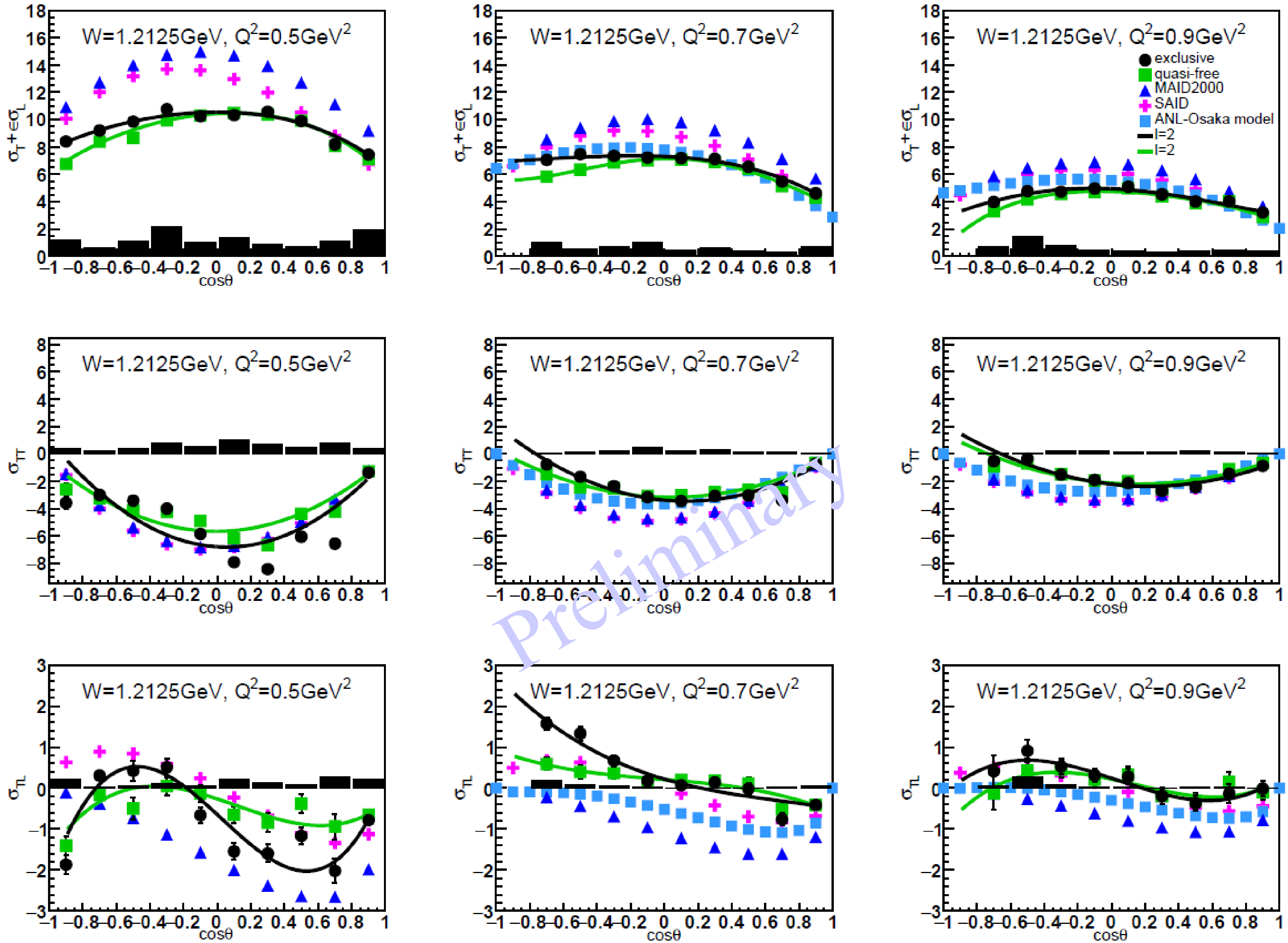
cos(θ) = -0.7
Δcos(θ) = 0.2
cos(θ) = 0.7

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

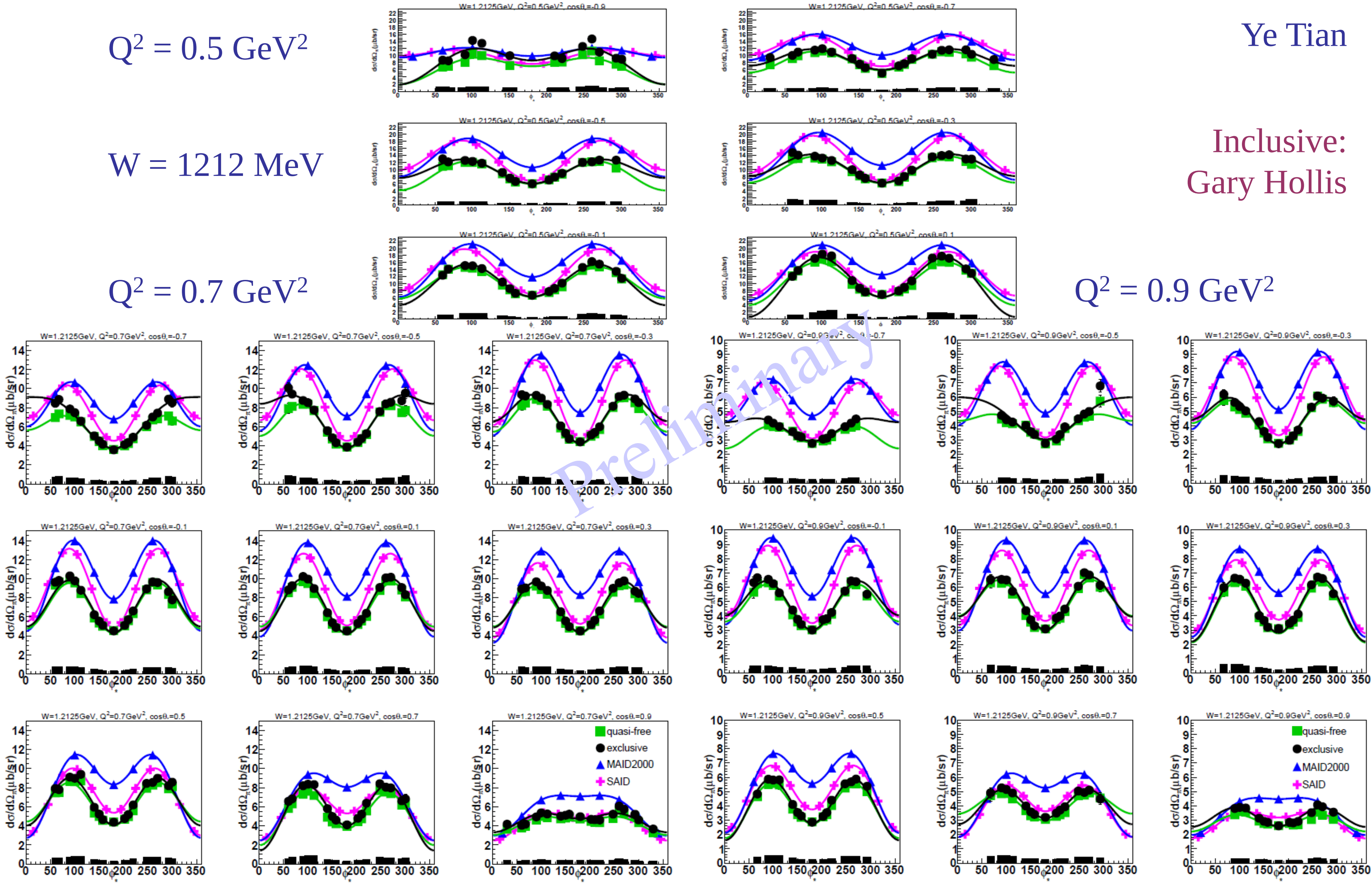


# Single $\pi^-$ Electroproduction off the Deuteron

Ye Tian



# Single π⁻ Electroproduction off the Deuteron



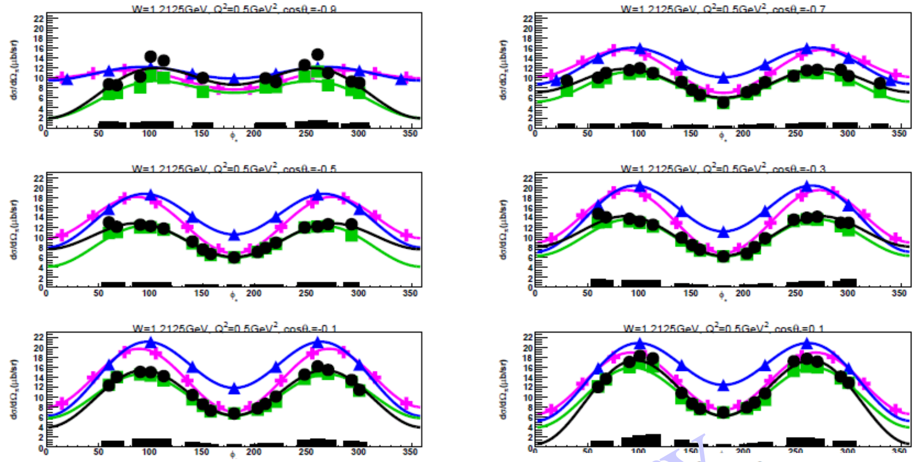
# Single π⁻ Electroproduction off the Deuteron

$Q^2 = 0.5\ GeV^2$

Ye Tian

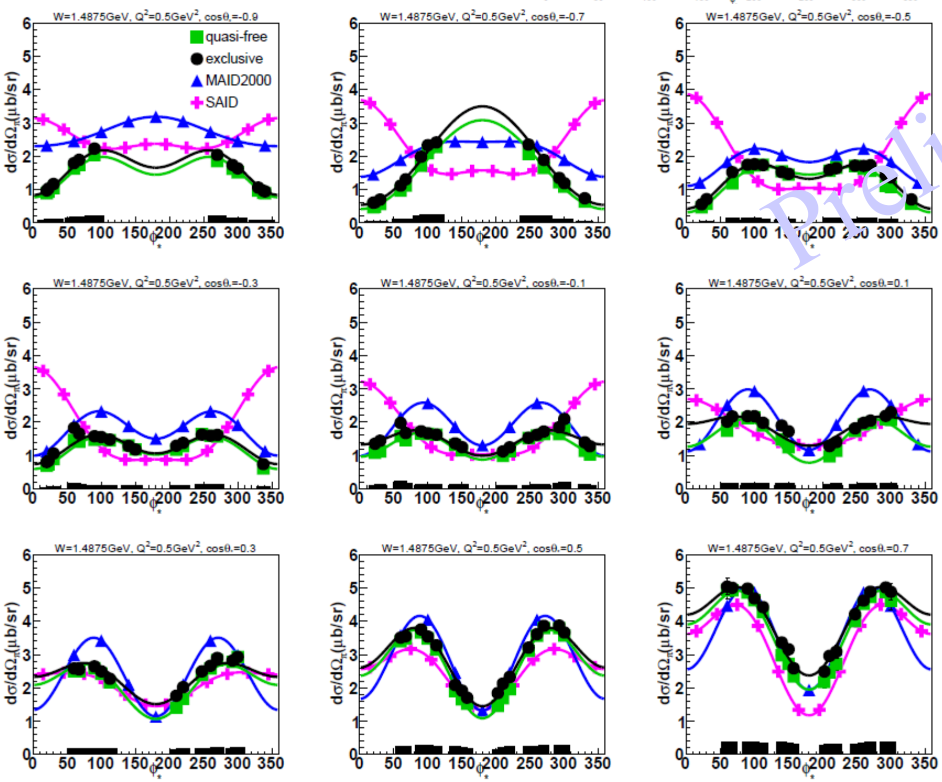
W = 1212 MeV

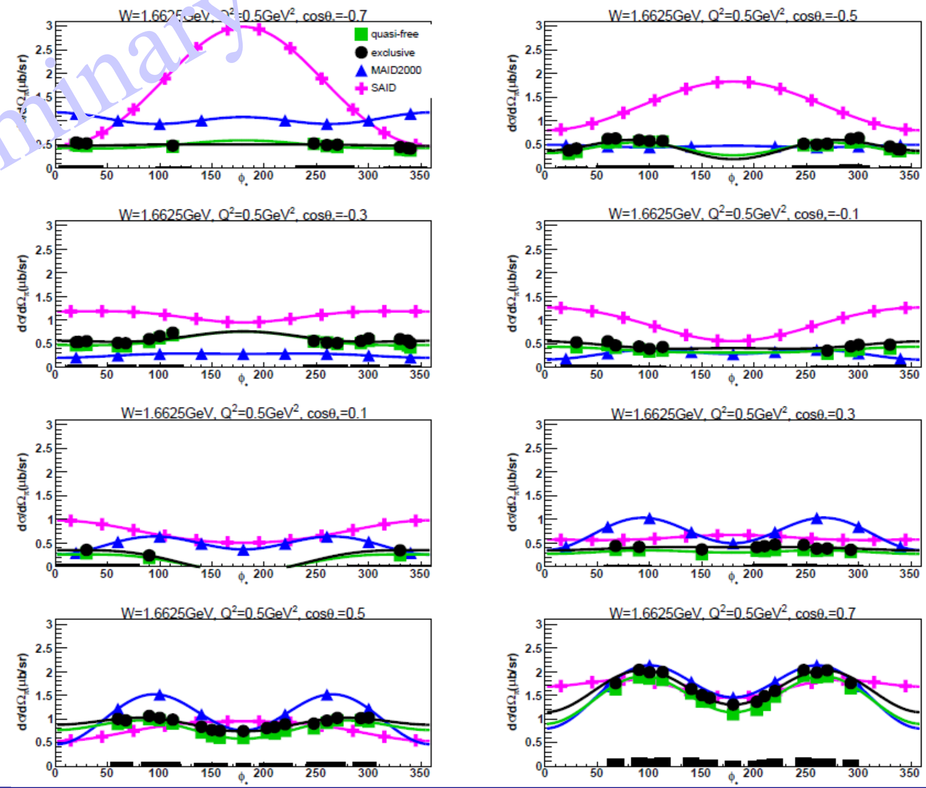
Inclusive:
Gary Hollis



W = 1488 MeV

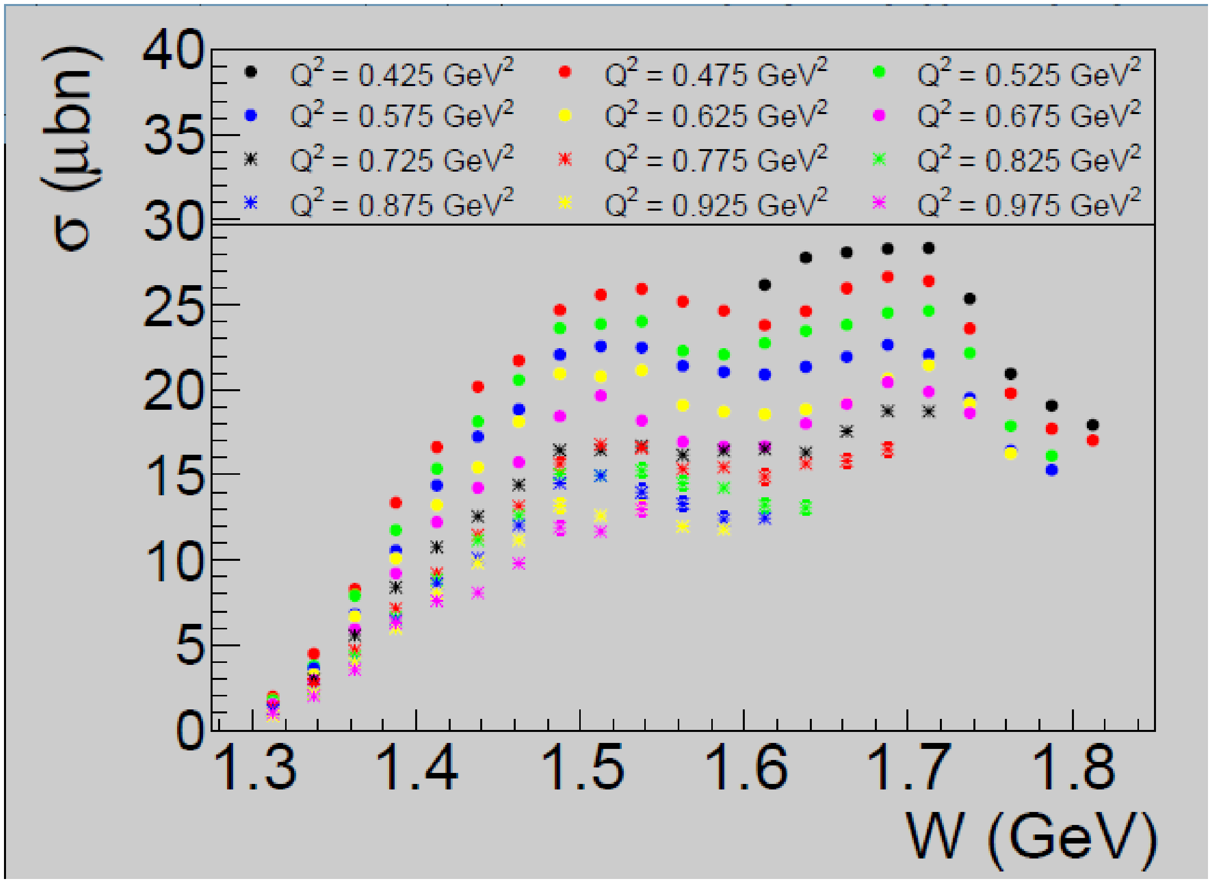
W = 1662 MeV

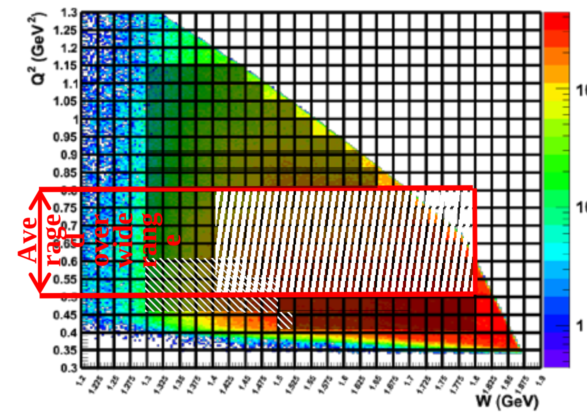


# $N\pi^+\pi^-$ Electroproduction Kinematic Coverage

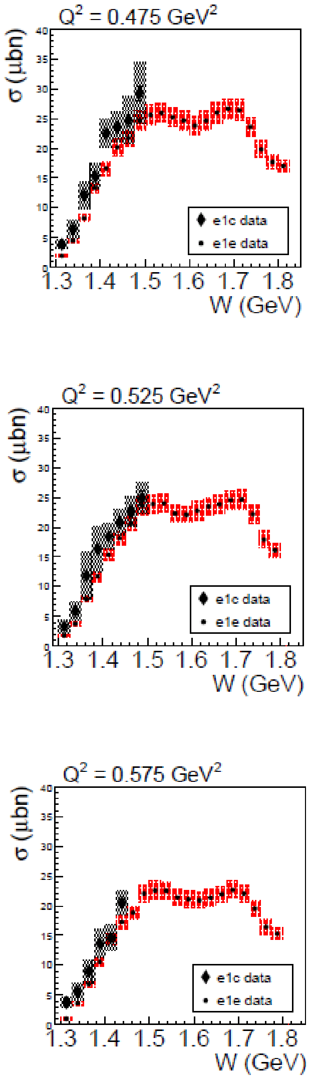
Gleb Fedotov
Phys. Rev. C 98, 025203 (2018)

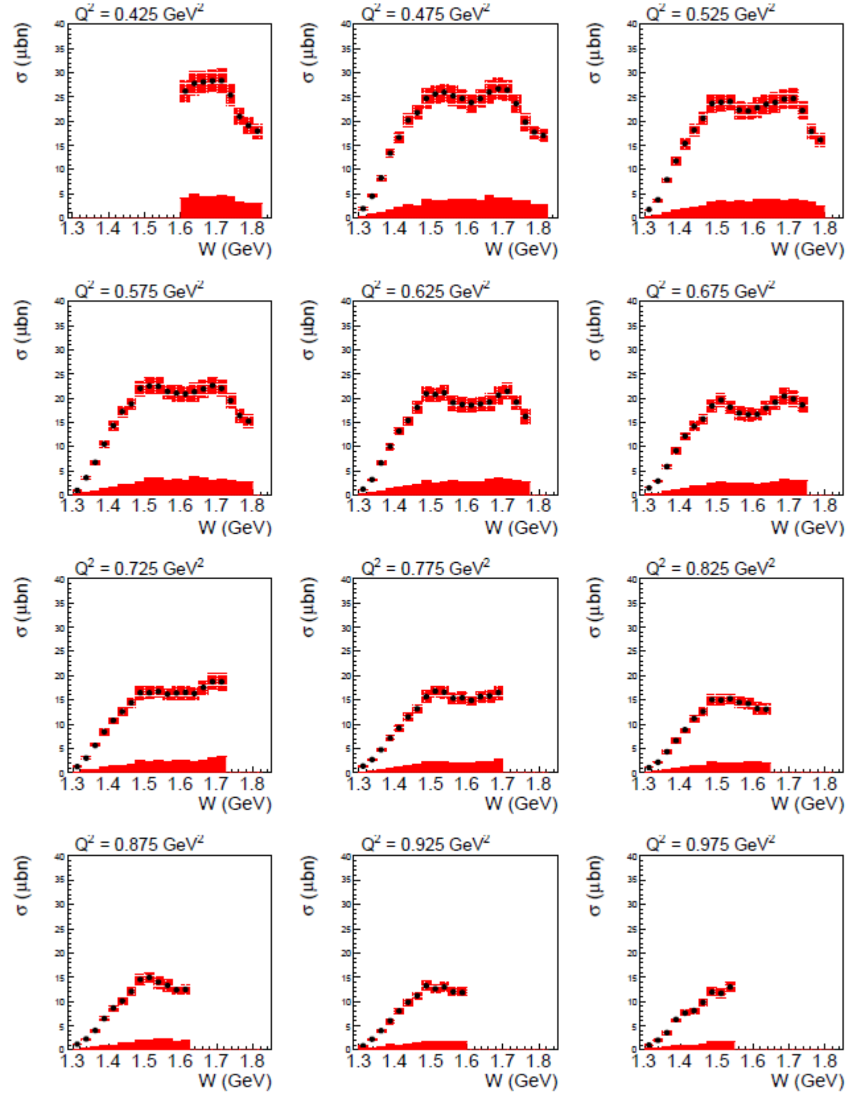



$p\pi^+\pi^-$ event yields over W and $Q^2$. Gray shaded area new e1e data set, hatched area at low $Q^2$ already published e1c data by G. Fedotov *et al.* and hatched area at higher $Q^2$ already published data in one large $Q^2$ bin by M. Ripani *et al.*

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

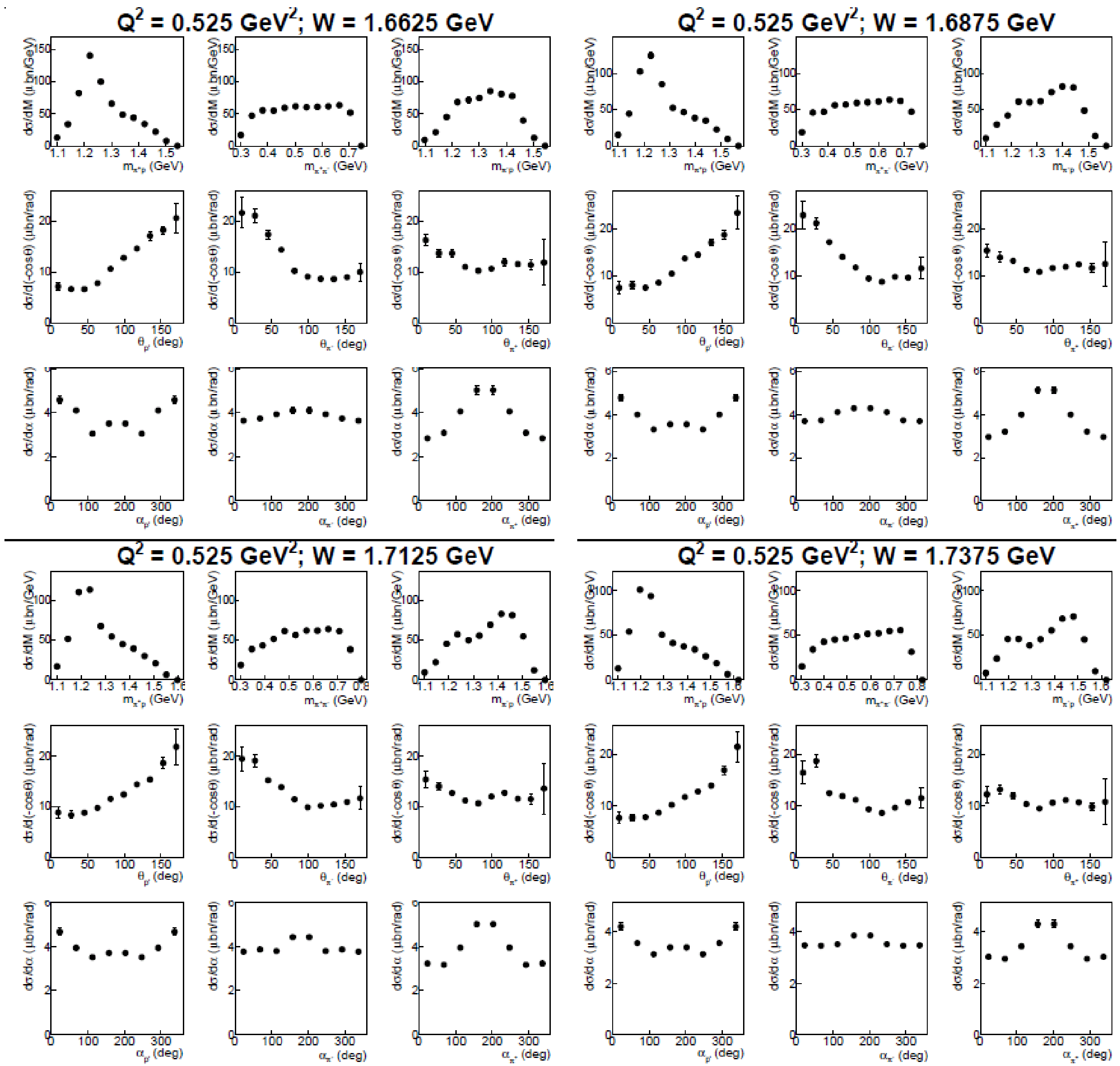



Gleb Fedotov

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

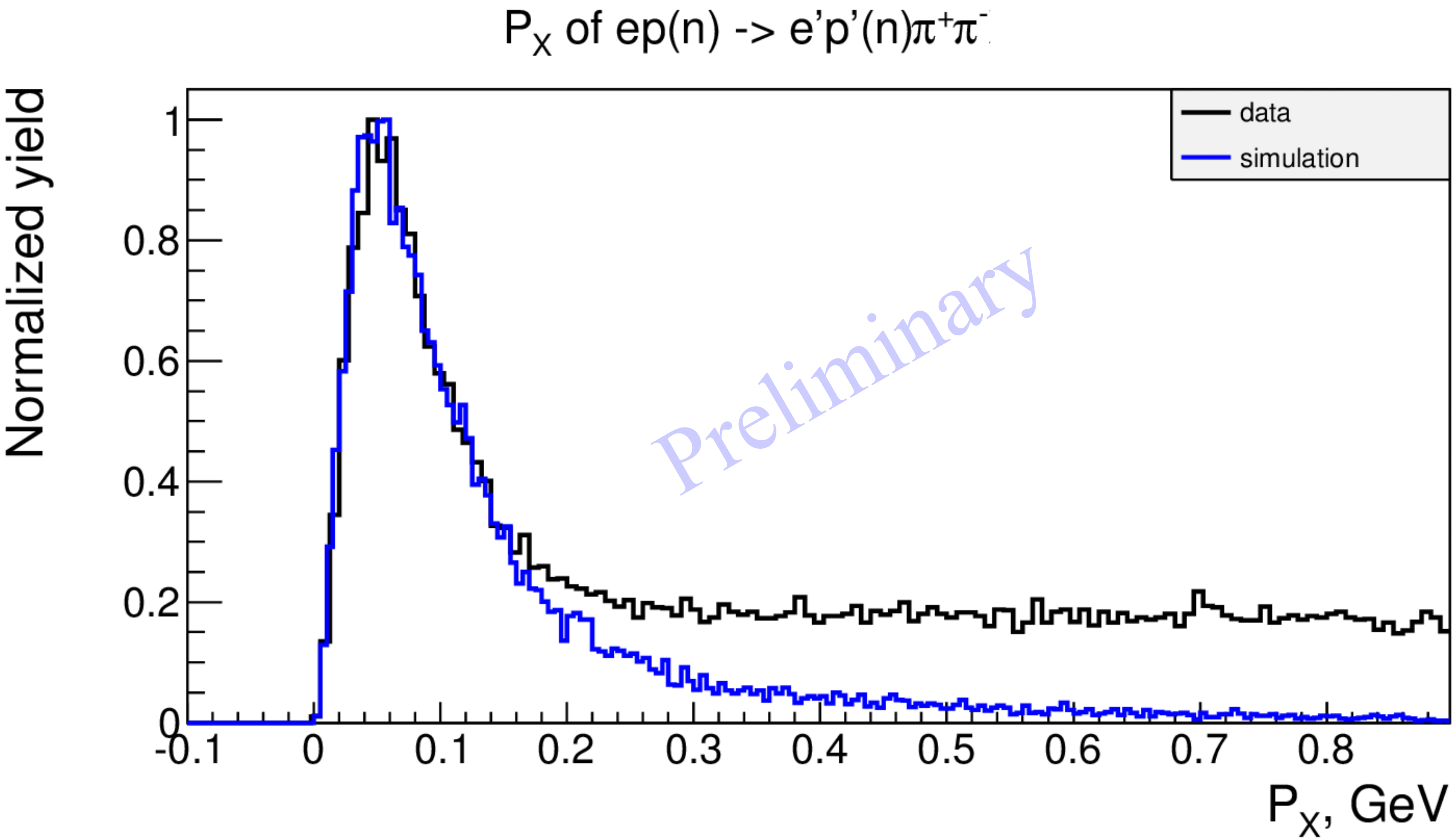
# $N\pi^+\pi^-$ Single-Differential Cross Sections




Gleb Fedotov

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

Iuliia Skorodumina

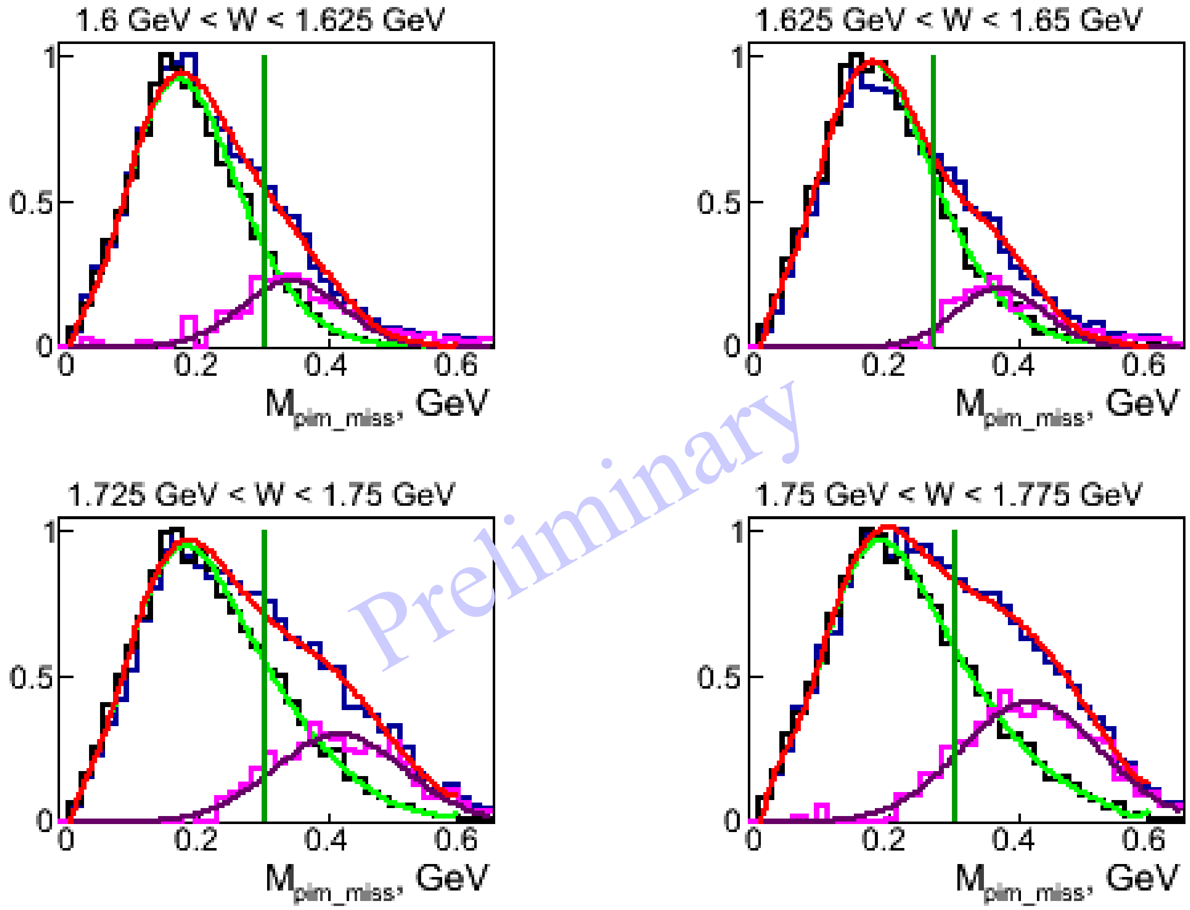


# Effective FSI Correction in $p(n)\pi^+ \pi^-$

Iuliia Skorodumina

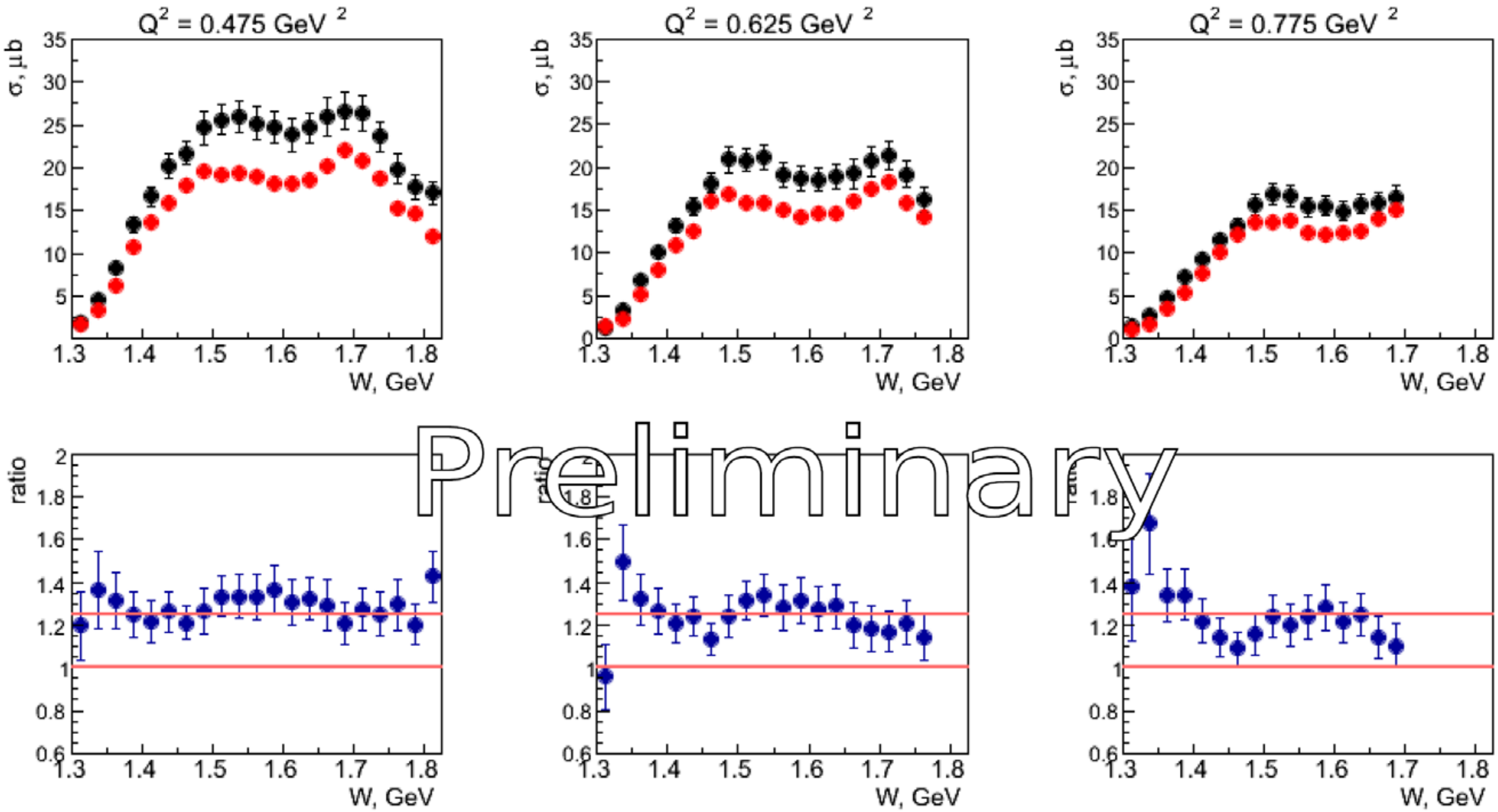
$$\frac{d\sigma_{corrected}}{dW\,dQ^2 d\tau} = \frac{d\sigma_{not\ corrected}}{dW\,dQ^2 d\tau} F_{fsi}(\Delta W, \Delta Q^2)$$

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



# Comparison with Free Proton Cross Section

Iuliia



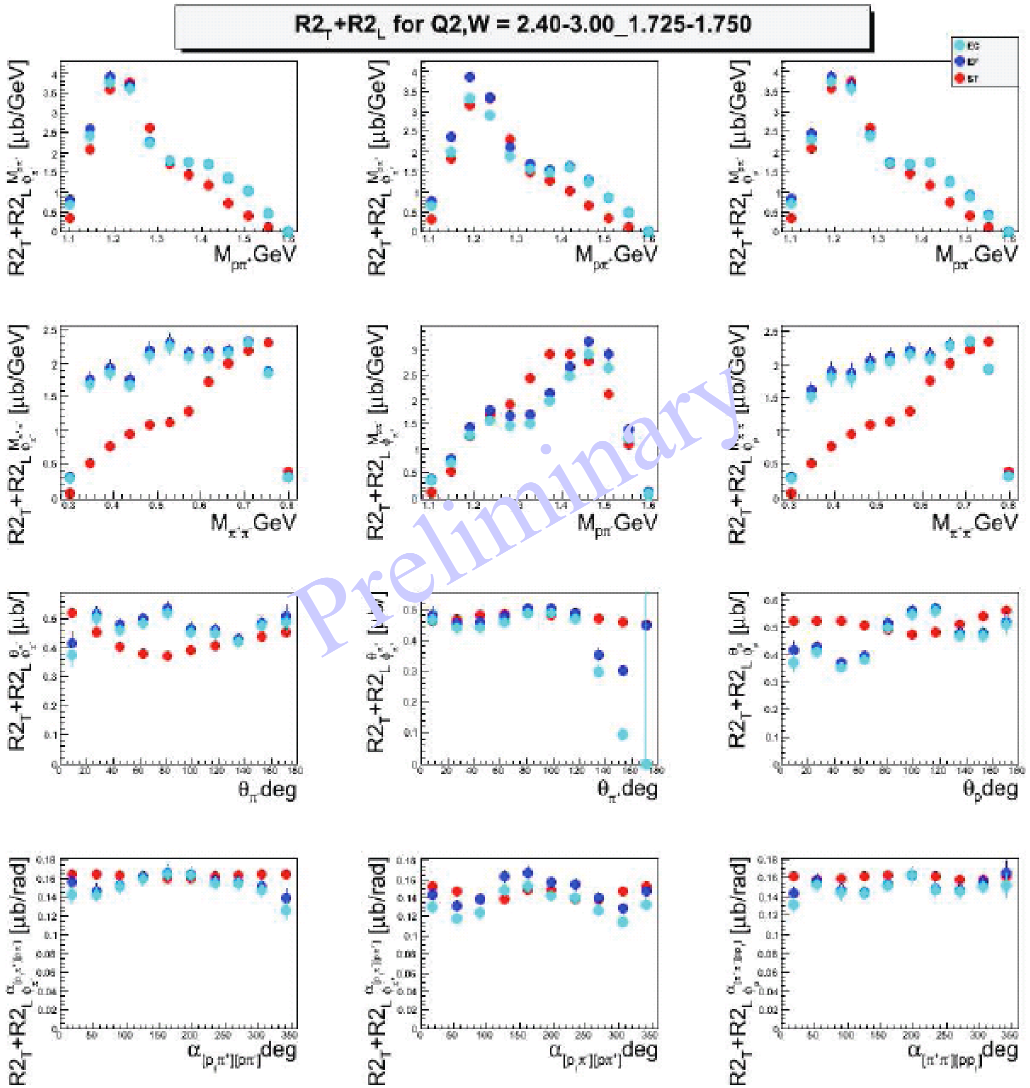

**Black bullets** – free proton cross sections (e1e at $E_{beam}$ = 2.039 GeV)
error bars show both statistical and systematical uncertainties
G. Fedotov under paper review

**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

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

Arjun Trivedi
Evgeny Isupov



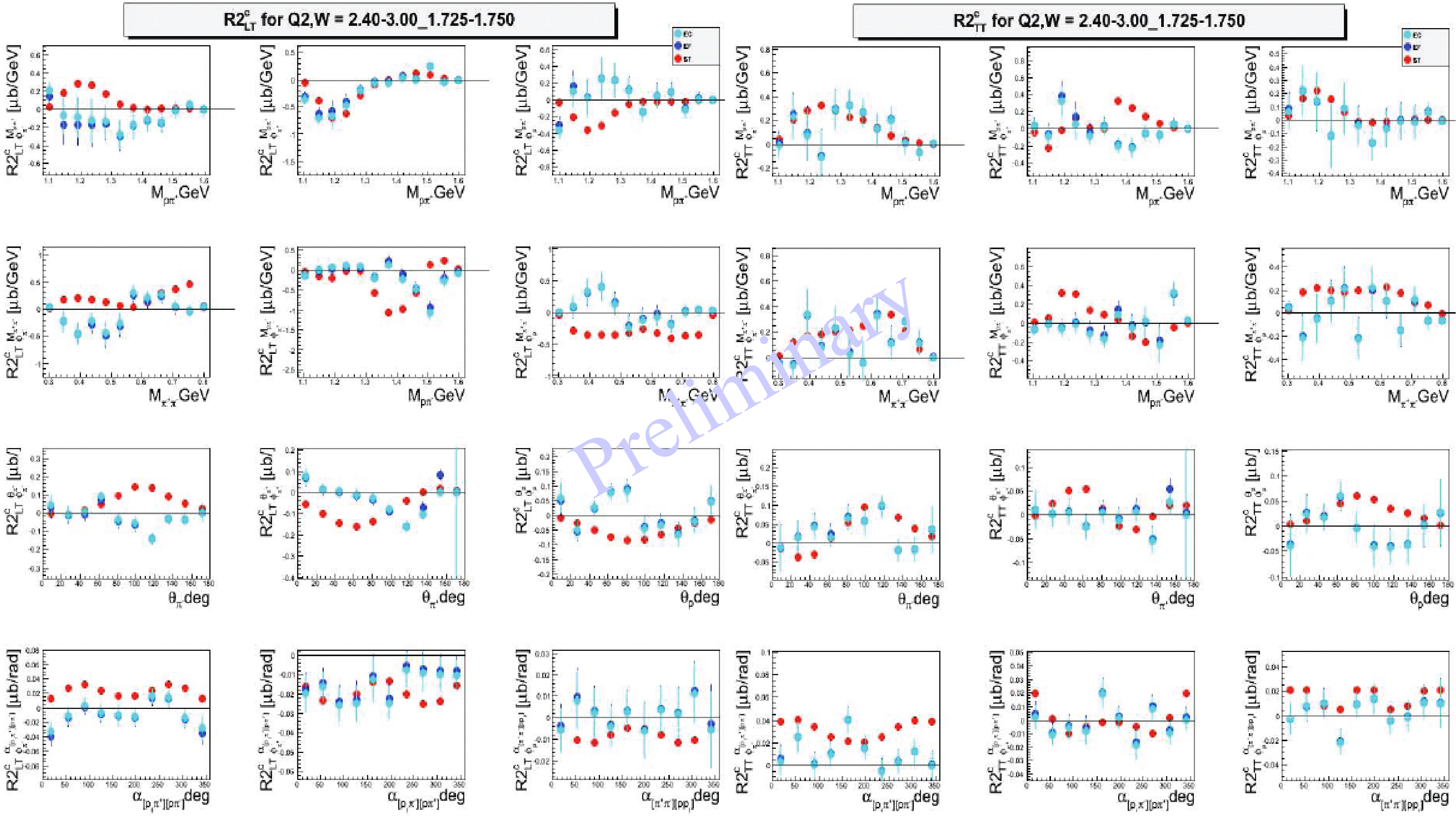

- normalized
- hole filled
- TWOPEG

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

# φ-dependent Nππ Single-Differential Cross Sections

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

Arjun Trivedi



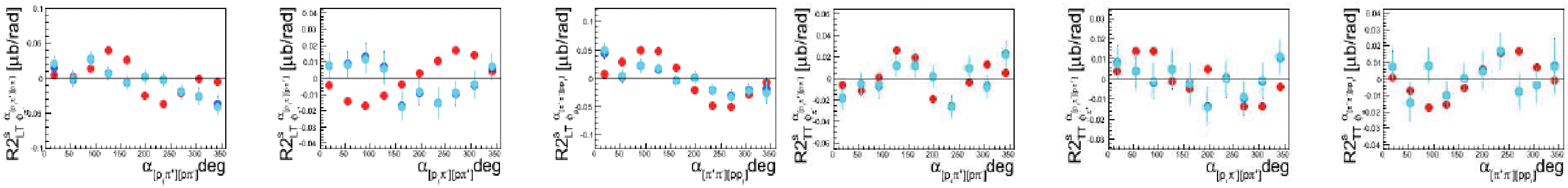

$$\left(\frac{d^2\sigma}{dX_{ij}d\phi_i}\right) = R2_T{}^{X_{ij}} + R2_L{}^{X_{ij}} + \underline{R2_{LT}{}^{c,X_{ij}}\cos\phi_i} + \underline{R2_{TT}{}^{c,X_{ij}}\cos 2\phi_i} + \delta_{X_{ij}\alpha_i}\left(R2_{LT}{}^{s,\alpha_i}\sin\phi_i + R2_{TT}{}^{s,\alpha_i}\sin 2\phi_i\right)$$

# 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.

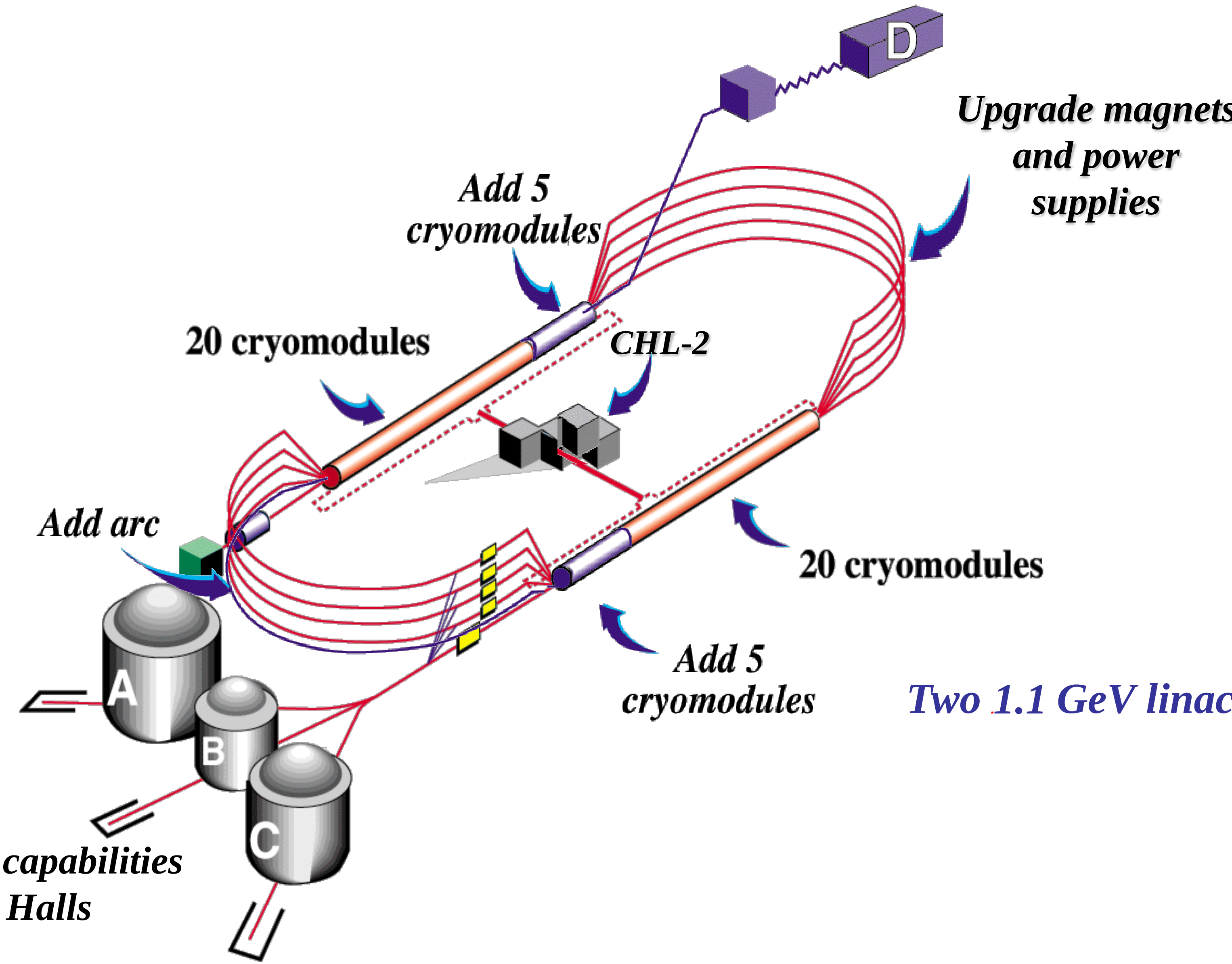
Preliminary



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

# CLAS12

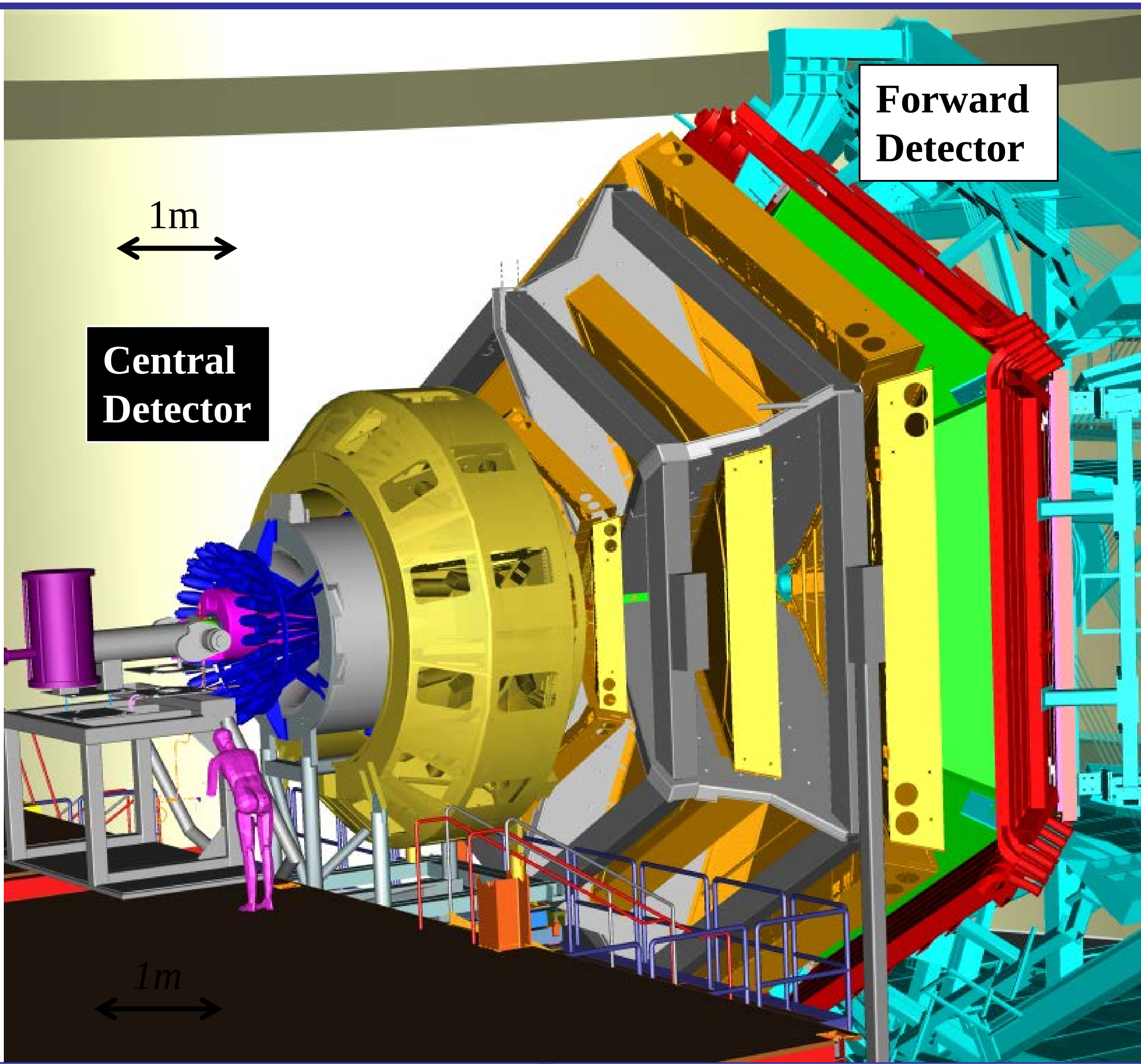
# 12 GeV CEBAF




*Two 1.1 GeV linacs*

*Enhanced capabilities in existing Halls*

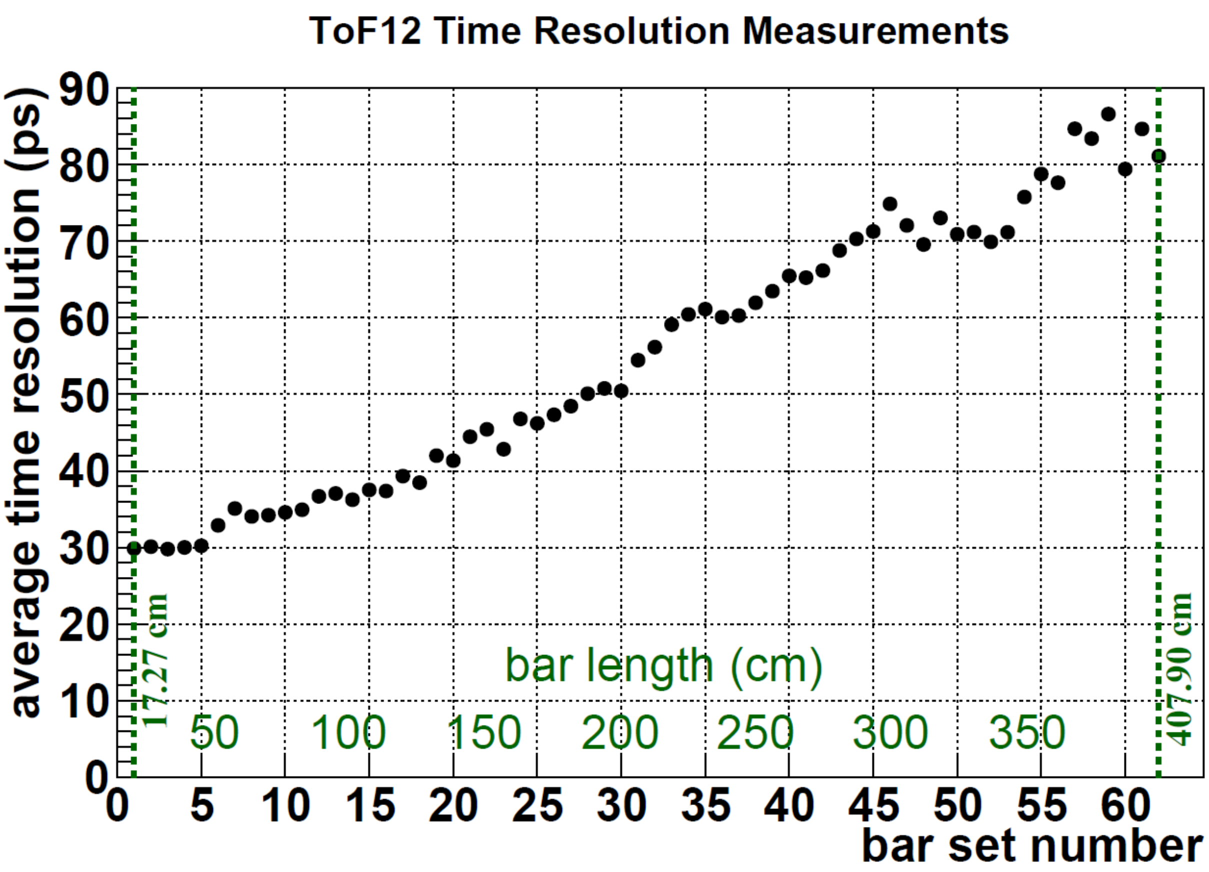
# CLAS12



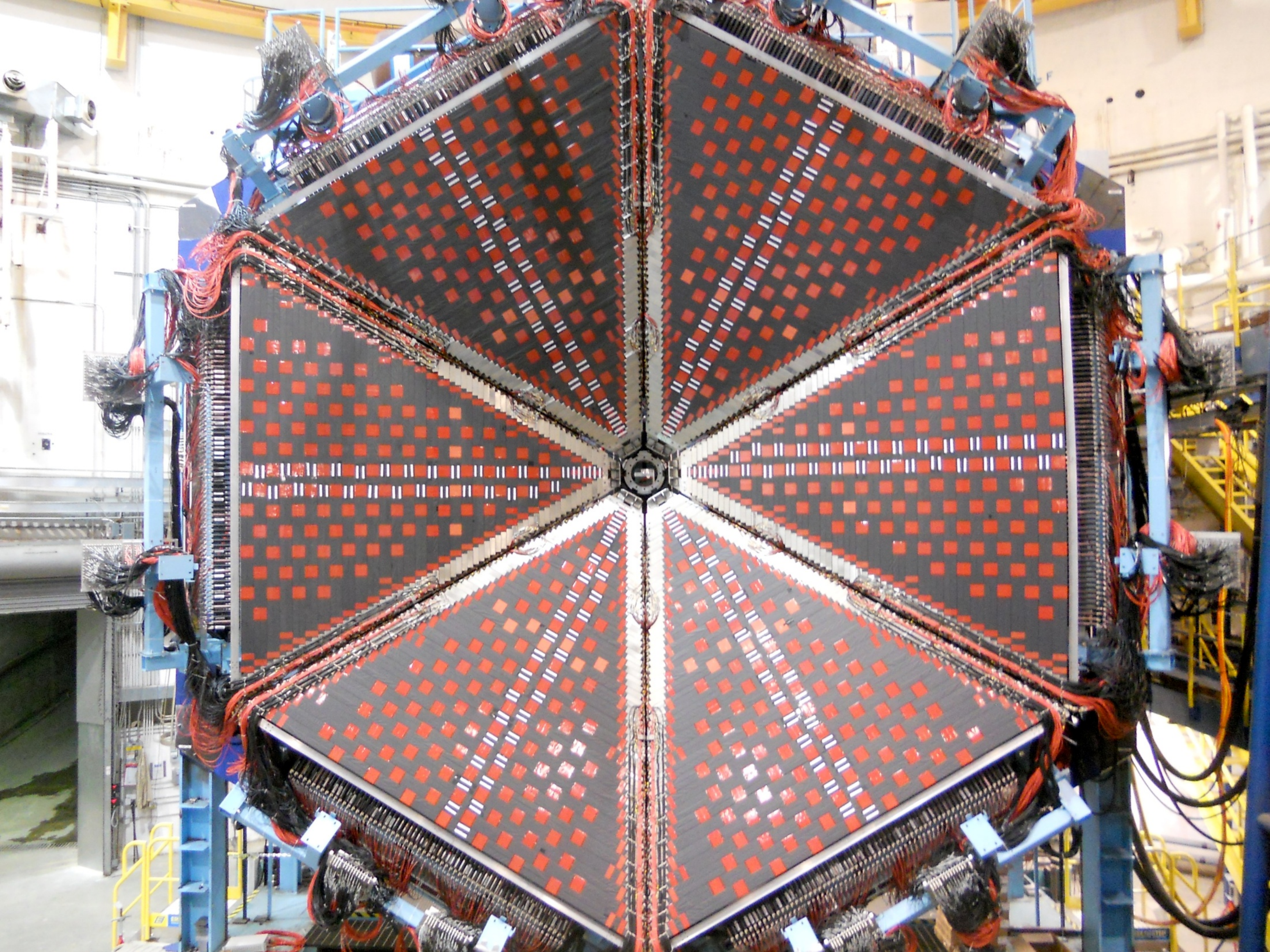

- Luminosity > $10^{35}$ $cm^{-2}s^{-1}$
- Hermeticity
- Polarization

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

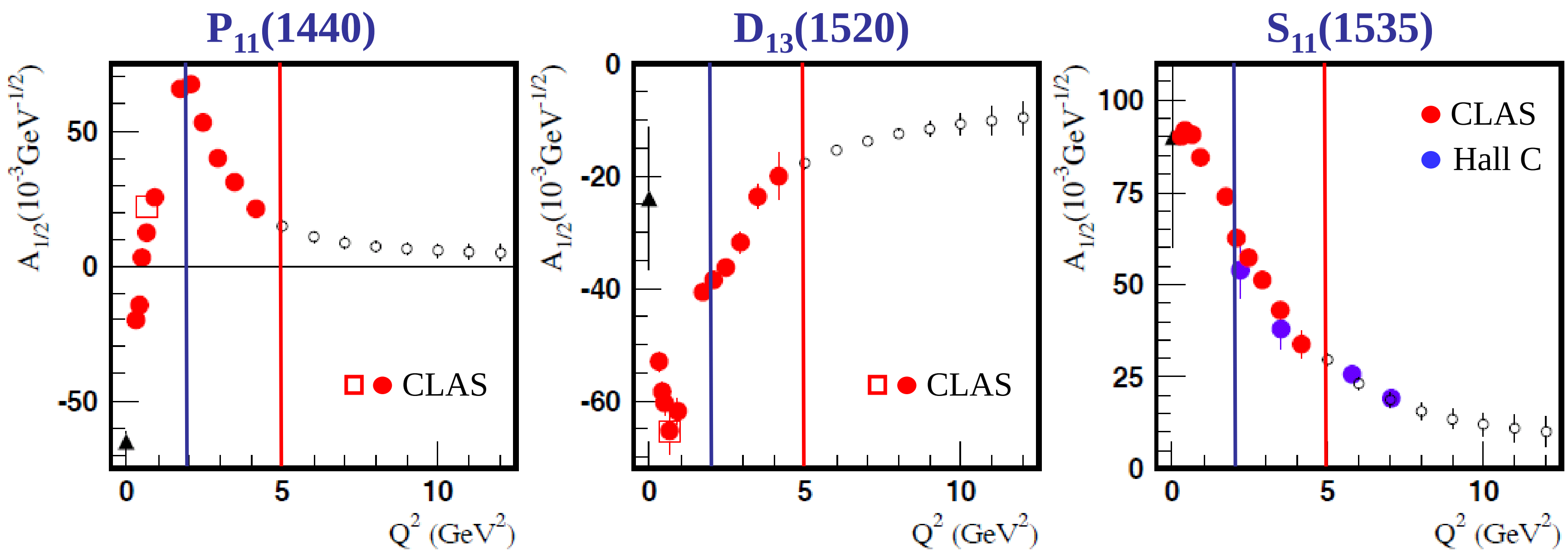
# New Forward Time of Flight Detector for CLAS12







# 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 …**