

# Extracting Resonance Parameters from Exclusive Electroproduction off Protons at CLAS

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August 23, 2017

NoSTAR 2017

The 11th International Workshop on the Physics of Excited Nucleons

August 20 – 23, 2017

at the University of South Carolina, Columbia, SC

# Overview

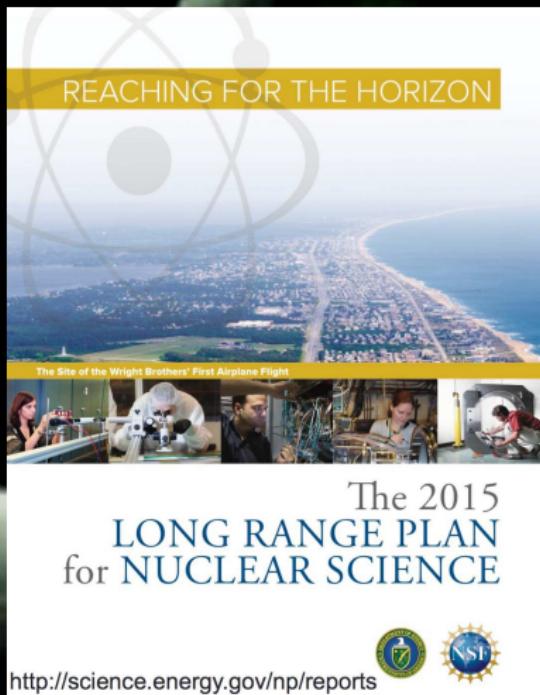
1 Introduction

2 Physics Result Highlight !

3 New Interesting Results !

4 Summary

# Long Range Plan 2015 ( 21<sup>st</sup> Century Nuclear Science )



REACHING FOR THE HORIZON

The Site of the Wright Brothers' First Airplane Flight



The 2015  
LONG RANGE PLAN  
for NUCLEAR SCIENCE

<http://science.energy.gov/np/reports>

1. **Fully utilize programs at existing & under construction facilities (JLab12, RHIC, NSCL, FRIB,...)**
  - (a) How did visible matter come into being and how does it evolve ?
  - (b) How does subatomic matter organize itself and what phenomena emerge ?
  - (c) Do we understand the fundamental interactions that are basic to the structure of matter ?



How to approach ?

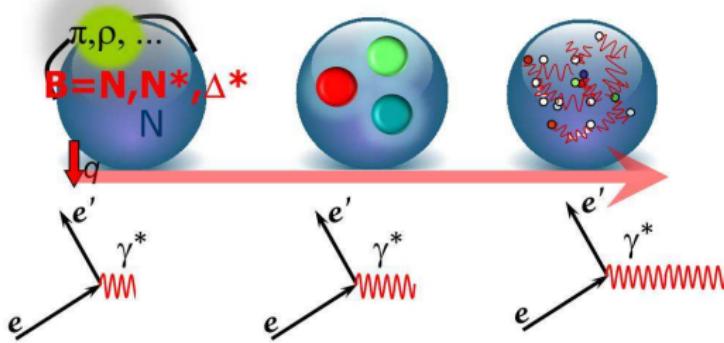
Public Lecture by, C. Robert, Monday

# The most challenging problems in Hadron Physics

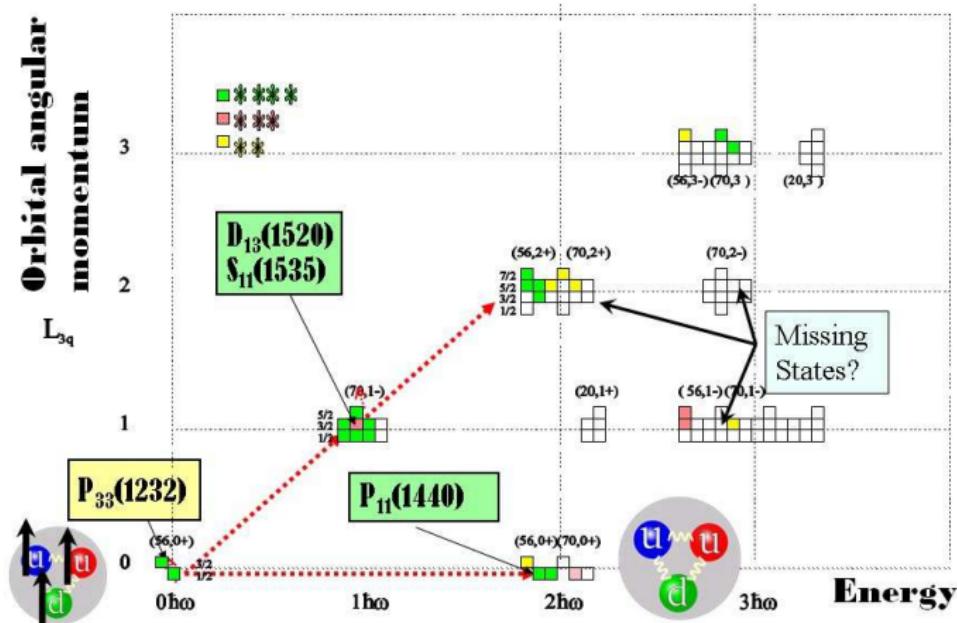
- Non-perturbative **DCSB** generates more than 98% of **dress quark masses** as well as **dynamical structure** although, Higgs mechanism < 2% in  $N$ ,  $N^*$  masses
- Quark-gluon **confinement** in baryons emerges from QCD; dressed quarks, meson-baryon cloud, dressed gluon,...
- Study of the excited states of the nucleon is important step in the development of a fundamental understanding of strong interaction; QGP → Hadrons
- The most fundamental question: “ **WHAT ARE THE RELEVANT DEGREE-OF-FREEDOM AT VARYING DISTANCE SCALE ?** ”

Talk by, V. Moekv, C. Robert, Sunday, P1

Talk by V. Burkert, Sunday, P1

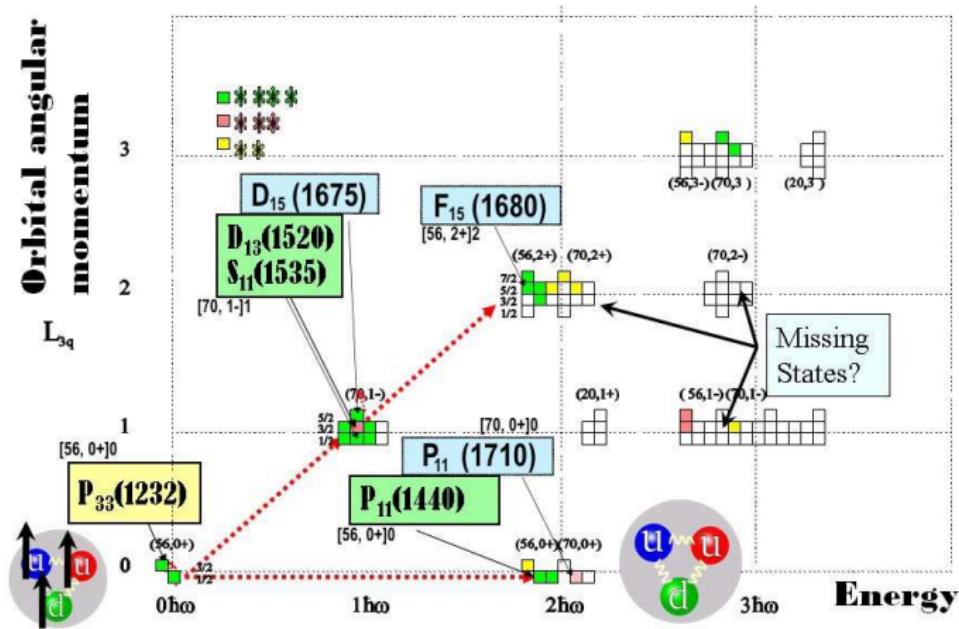


# $SU(6) \times O(3)$ Classification of Baryons



- There are questions about underlying DoF of some well known state...but still many open questions.. related with QCD, FT, CQM, LQCD ...
- Effective degrees of freedom / Transition charge densities / Running quark mass → Nature of States

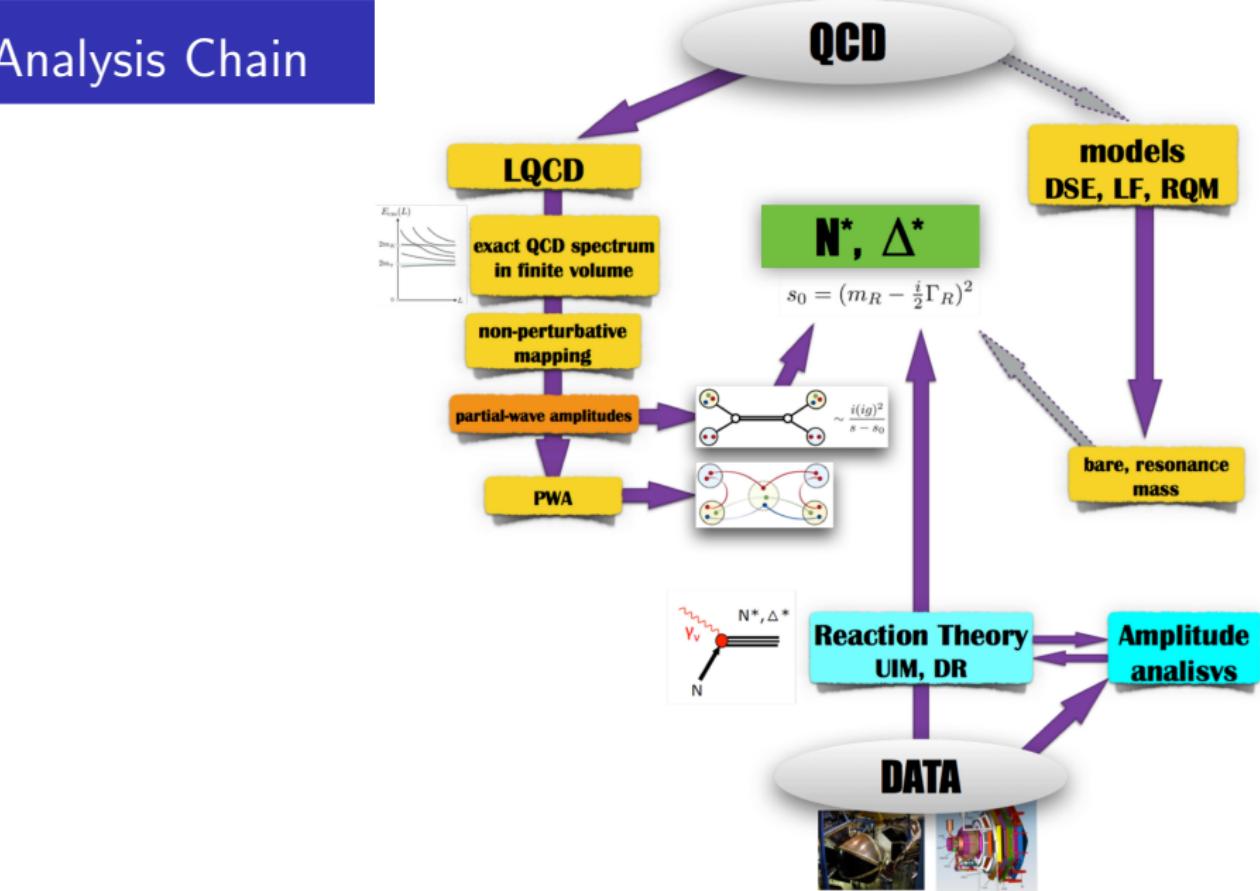
## $SU(6) \times O(3)$ Classification of Baryons



- There are questions about underlying DoF of some well known state...but still many open questions.. related with QCD, FT, CQM, LQCD ...
  - Effective degrees of freedom / Transition charge densities / Running quark mass → Nature of States

# Analysis Chain

QCD



Modified the original flowchart

Credit to R. Briceno

# Analysis Approaches and CLAS data analyses

- **UIM, DR** for  $\pi^+n$  and  $\pi^0p$  - [Speaker: [K. Park, N. Markov](#)]
  - I. G. Aznauryan, Phys. Rev. **C67**, 015209 (2003).
  - I. G. Aznauryan *et al.*, CLAS Coll., Phys. Rev. **C80**, 055203 (2009).
  - I. G. Aznauryan *et al.*, CLAS Coll., Phys. Rev. **C91**, 045203 (2015).
- Extension of **UIM, DR, Data fit** for  $\eta p$ ,  $\omega p$  - [Speaker: [E. Phelps](#)]
  - I. G. Aznauryan, Phys. Rev. **C68**, 065204 (2003).
  - H. Denizli *et al.*, CLAS Coll., Phys. Rev. **C76**, 015204 (2007).
- **JM-MB** model, Data fit for  $\pi^+\pi^-p$  - [Speaker: [A. Trivedi, G. Fedotov](#)]
  - V. I. Mokeev, V. D. Burkert *et al.*, Phys. Rev. **C80**, 045212 (2009).
  - V. I. Mokeev *et al.*, CLAS Coll., Phys. Rev. **C86**, 035203 (2012).
  - V. I. Mokeev, V. D. Burkert *et al.*, Phys. Rev. **C93**, 054016 (2016).

Overview:  $NN^*$  Electrocoupling Extraction from CLAS data

Talk by V. Mokeev, Tuesday, P5

Global coupled-channel analyses for exclusive  $\gamma N$ ,  $\pi N$ ,  $\pi\pi N$ ,  $K\Lambda$ ,  $K\Sigma$

Talk by H. Kamano [ANL-Osaka], Monday, P3

Talk by M. Doering [Juli-Bonn], Tuesday, P5

# Analysis Approaches

- Two different approaches: **UIM, DR**

## **UIM**

- BG UIM is built from nucleon exchange in  $s$ -,  $u$ - and  $\pi, \omega, \rho$  exchange in  $t$ - channel
- Unitarization of multipole amplitudes in the  $K$ -matrix approximation
- Resonance contributions are parameterized in the unified BW form with energy dependence

## **DR**

- Fixed- $t$  dispersion relation for the invariant amplitude
- Re-Amplitude to Born-term (nucleon exchange in  $s$ -,  $u$ -,  $\pi$  exchange in  $t$ -channel)
- Integral  $Im$ -Amplitude with the isospin structure

- **Two model-uncertainties**

- BG determination in the UIM and Born term in DR
- A width and mass of resonances from PDG

- **Take into account...**

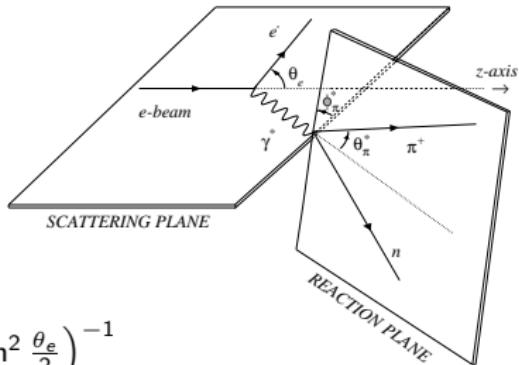
- All(13) \*\*\*\* and \*\*\* states in the  $1^{st}, 2^{nd}, 3^{rd}$
- $\Delta(1905)F_{35}, \Delta(1950)F_{37}$  in  $4^{th}$  resonance region

- Same BR from PDG2012

# Data Analyses, $\vec{e}p \rightarrow e'\pi N$ , $\vec{e}p \rightarrow e'\pi\pi N$

- assume: one photon exchange approximation

$$\frac{d^5\sigma}{dE_f d\Omega_e d\Omega_\pi^*} = \Gamma_\nu \cdot \frac{d^2\sigma}{d\Omega_\pi^*}$$



where,

$$\Gamma_\nu: \text{virtual photon flux: } \frac{\alpha}{2\pi^2 Q^2} \frac{(W^2 - M_p^2) E_f}{2M_p E_e} \frac{1}{1-\epsilon},$$

$$\epsilon: \text{virtual photon polarization: } \left(1 + 2 \left(1 + \frac{\nu^2}{Q^2}\right) \tan^2 \frac{\theta_e}{2}\right)^{-1}$$

$$\frac{d^2\sigma}{d\Omega_\pi^*} = \frac{p_\pi^*}{k_\pi^*} \left( \sigma_0 + h \sqrt{2\epsilon(1-\epsilon)} \sigma'_{LT} \sin \theta_\pi^* \sin \phi_\pi^* \right)$$

$$\sigma_0 = \sigma_U + \epsilon \sigma_{TT} \sin^2 \theta_\pi^* \cos 2\phi_\pi^* + \sqrt{2\epsilon(1+\epsilon)} \sigma_{LT} \sin \theta_\pi^* \cos \phi_\pi^*$$

where,

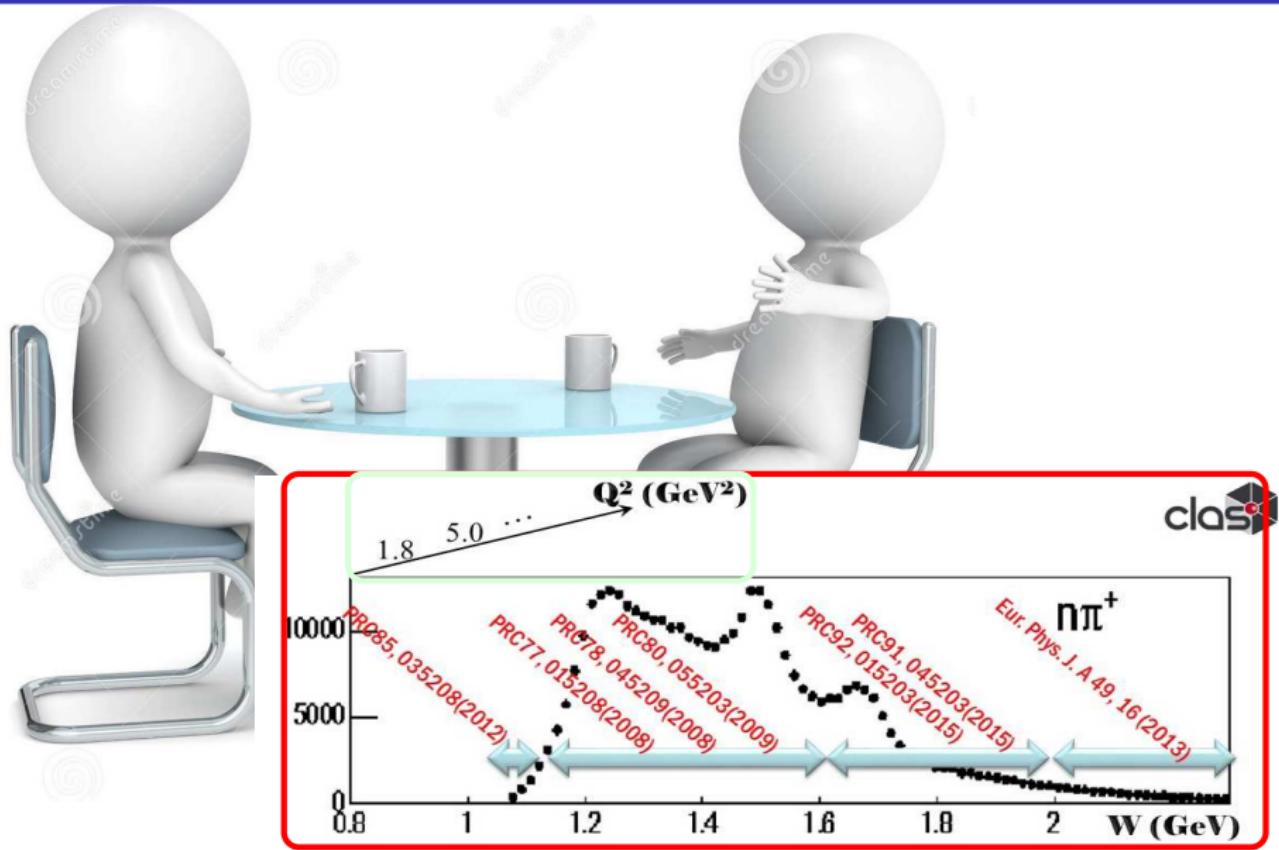
$h$ : beam helicity state

$\sigma_0$ : unpolarized cross-section

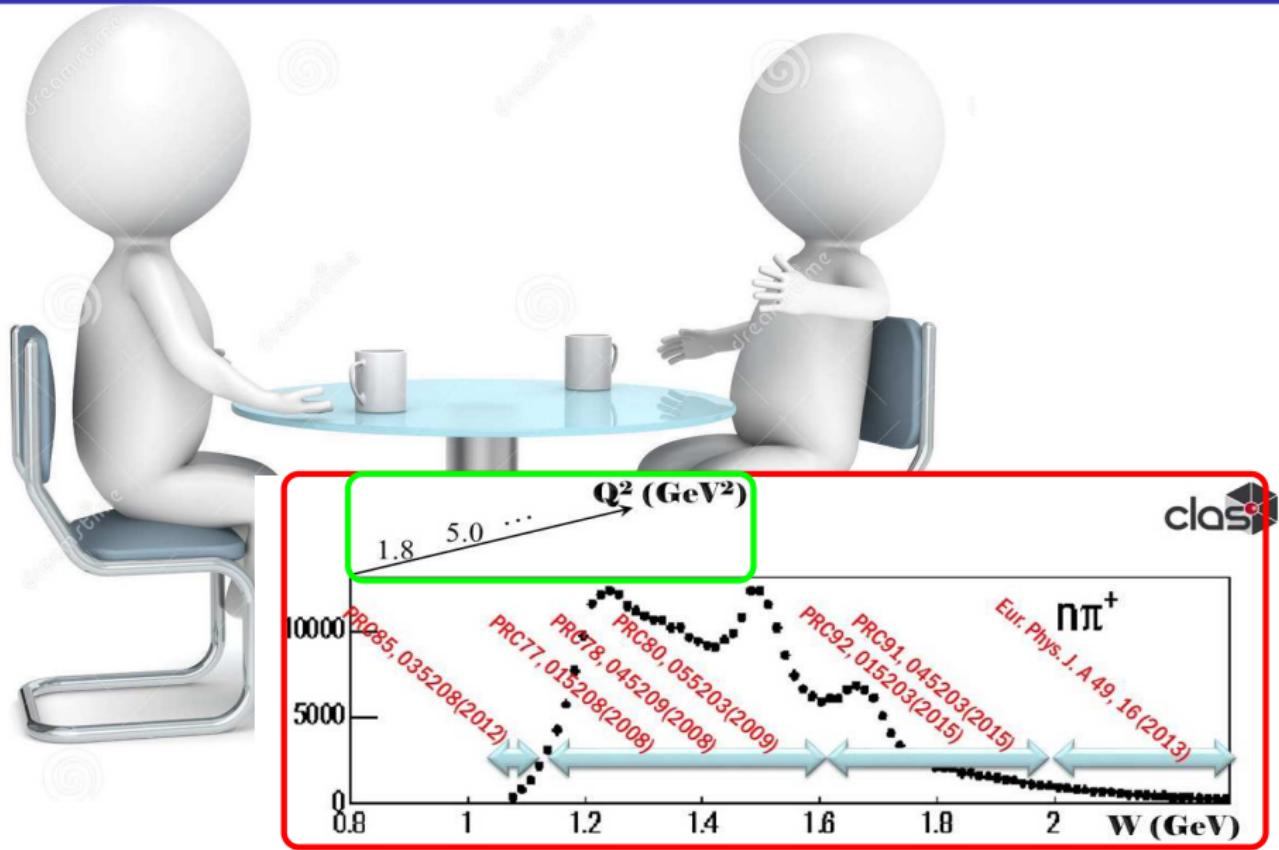
$$\sigma_U = \sigma_T + \epsilon \sigma_L$$

Kinematics is completely defined by five variables ( $Q^2$ ,  $W$ ,  $\theta_\pi^*$ ,  $\phi_\pi^*$ , and  $\phi_e$ )

Let me briefly talk about the highlighted results ...

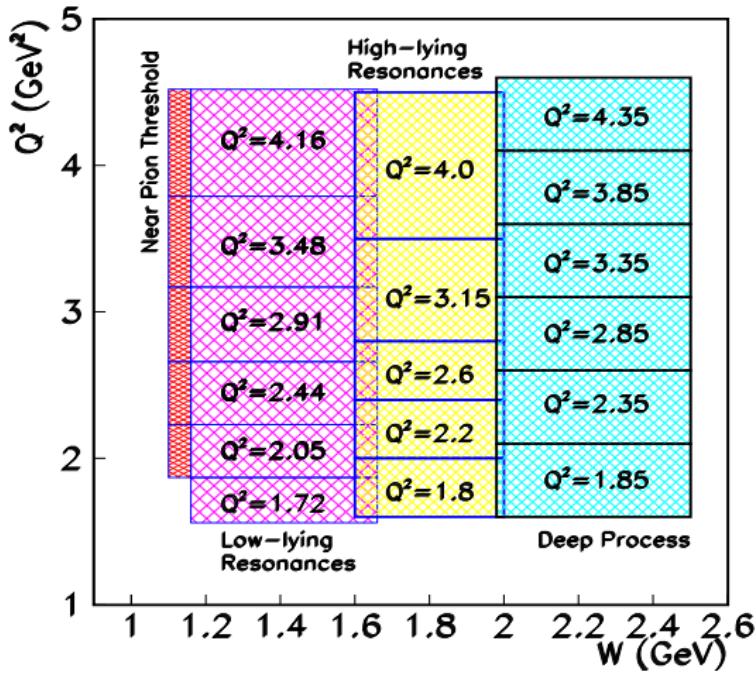


Let me briefly talk about the highlighted results ...



In particular,  $ep \rightarrow e'\pi^+n$

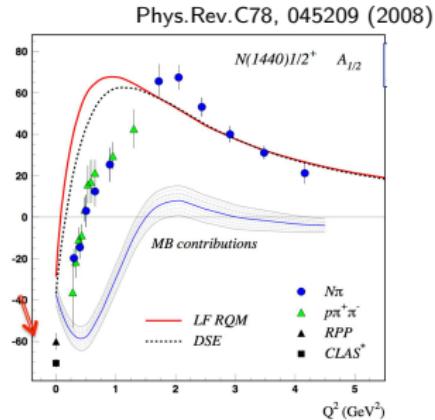
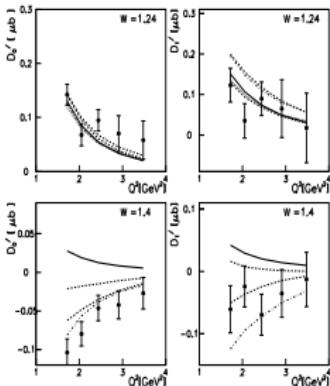
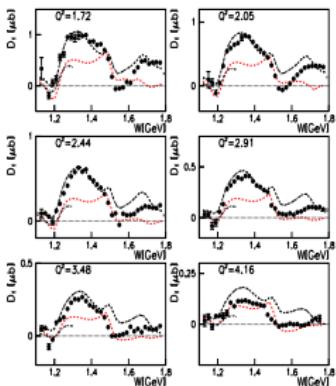
- Kinematic range  $W$ (excitation),  $Q^2$ (resolution) of  $\gamma^* p \rightarrow n\pi^+$   
→ From the near pion threshold to Deep Process regime



# $\vec{e}p \rightarrow e'\pi^+n$ for low lying $N^*$ ( $W = 1.15 - 1.69$ GeV)

- Transition Form Factors for  $N(1440)1/2^+$  (old conv:  $P_{11}(1440)$ )
- $A_{1/2}$  shows a sign change in  $Q^2 \sim 0.8$  GeV $^2$
- $S_{1/2}$  is large at low  $Q^2$  and drop off smoothly with increasing  $Q^2$
- A complex interplay btw inner core of quarks in the first radial excitation and external MB cloud
- LF RQM (thick red curve), Quark core in DSEQCD (thick dashed curve) MB cloud contribution (shaded band)

Talk by V. Burkert, Tuesday, D3; J. Segovia, Tuesday, P6; H. Kamano, Monday, P3; ...

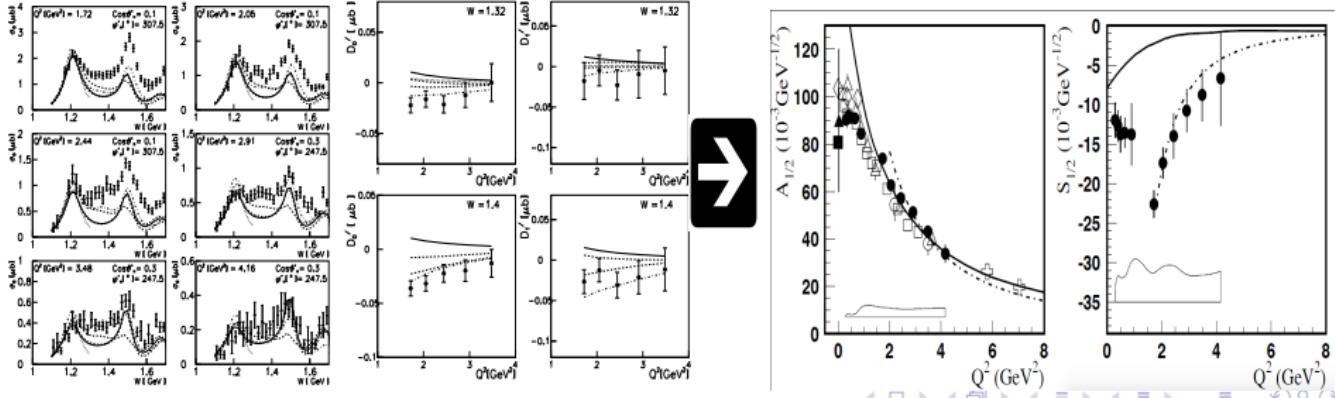


# $\vec{e}p \rightarrow e'\pi^+n$ for low lying $N^*$ ( $W = 1.15 - 1.69$ GeV)

- Transition Form Factors for  $N(1535)1/2^-$  (old conv:  $S_{11}(1535)$ )
- $\beta_{N\eta}^{PDG} = 0.45 - 0.60 \rightarrow \beta_{N\pi}^{PDG} = 0.485$  &  $\beta_{N\eta}^{PDG} = 0.460$ , excellent agreement
- Sensitive to long. as well (strong interference  $S_{11}-P_{11}$ )
- Previously Opposite sign of  $S_{1/2}$  !
  - Impossible to change in quark model (LFRQM failed for  $S_{1/2}$  !)
  - Combined with the difficulties in the description of
    - large width of  $S_{11}(1535) \rightarrow \eta N$
    - large  $S_{11}(1535) \rightarrow \phi N, \Lambda K$  couplings
  - It shows that 3q picture for  $S_{11}(1535)$  should be complemented ! [I.Aznuryan]

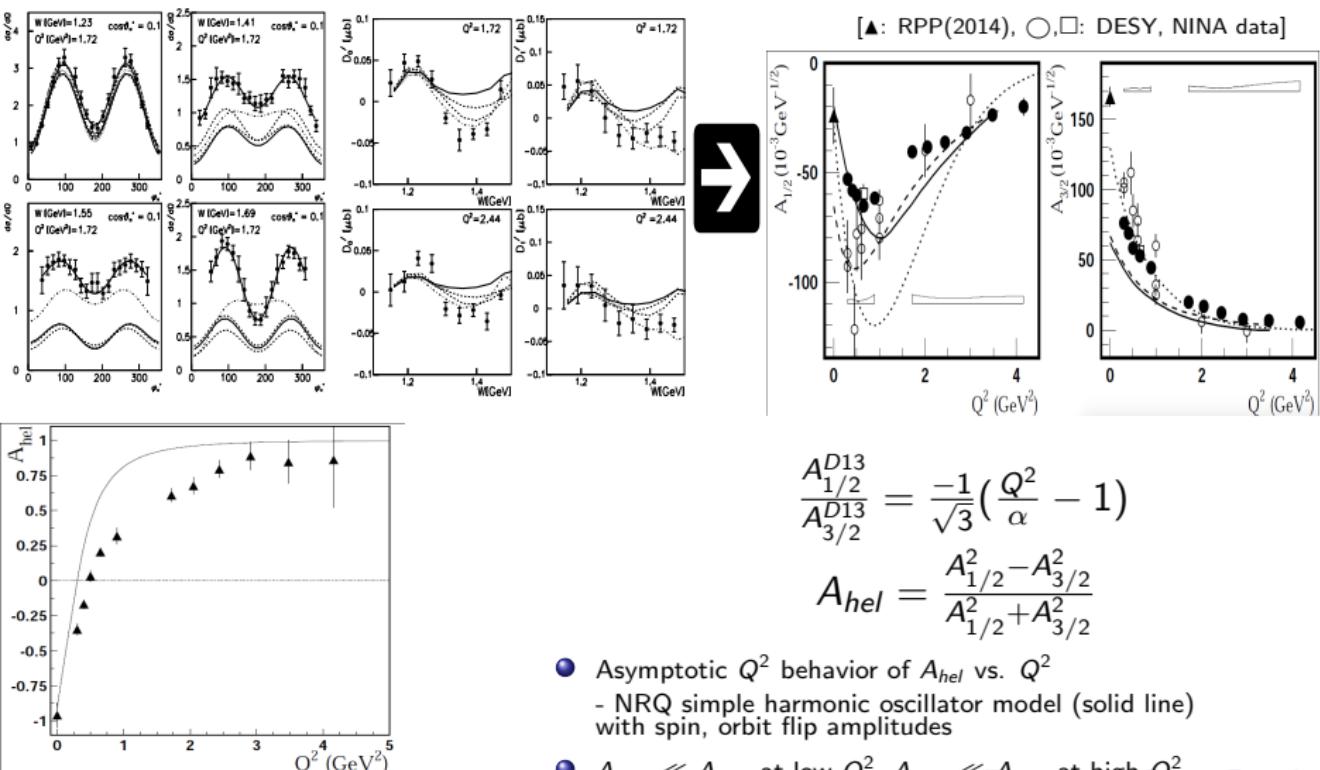
Talk by G. Ramalho, Tuesday, D3;...

[ ↓ solid: LFRQM, dash-dot: LCSR ]



# $\vec{e}p \rightarrow e'\pi^+n$ for low lying $N^*$ ( $W = 1.15 - 1.69$ GeV)

- Transition Form Factors for  $N(1520)3/2^-$  (old conv:  $D_{13}(1520)$ )
- $A_{1/2}$  is large at high  $Q^2$ ,  $A_{3/2}$  is small at high  $Q^2$

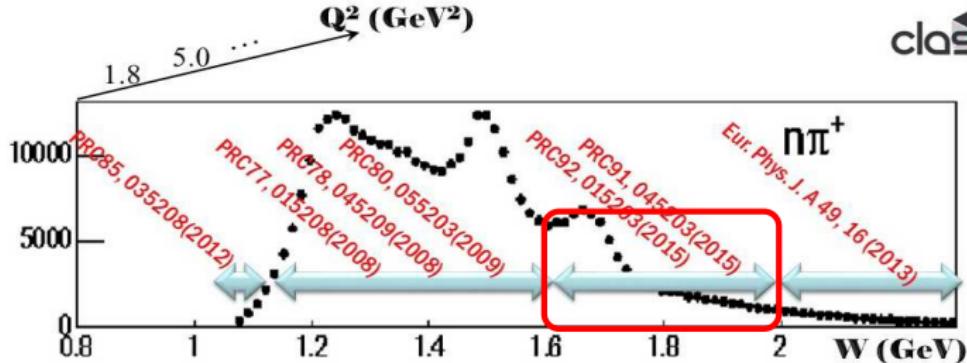


$$\frac{A_{1/2}^{D_{13}}}{A_{3/2}^{D_{13}}} = \frac{-1}{\sqrt{3}} \left( \frac{Q^2}{\alpha} - 1 \right)$$

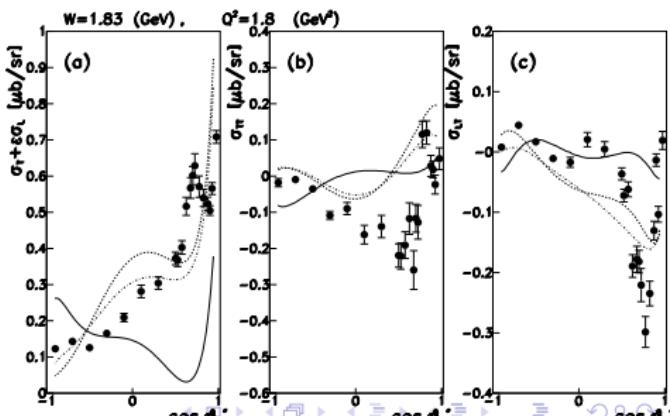
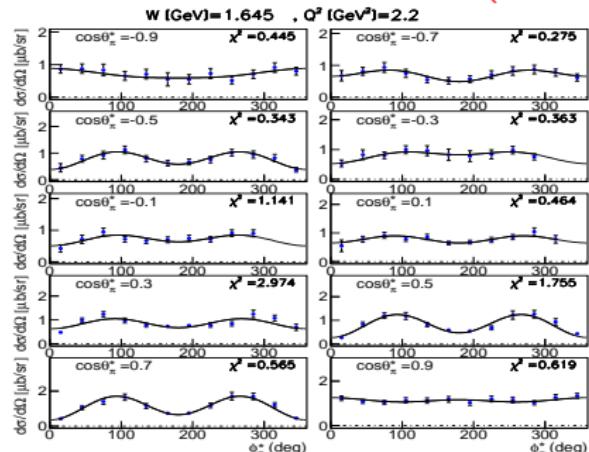
$$A_{hel} = \frac{A_{1/2}^2 - A_{3/2}^2}{A_{1/2}^2 + A_{3/2}^2}$$

- Asymptotic  $Q^2$  behavior of  $A_{hel}$  vs.  $Q^2$ 
  - NRQCD simple harmonic oscillator model (solid line) with spin, orbit flip amplitudes
- $A_{1/2} \ll A_{3/2}$  at low  $Q^2$ ,  $A_{3/2} \ll A_{1/2}$  at high  $Q^2$

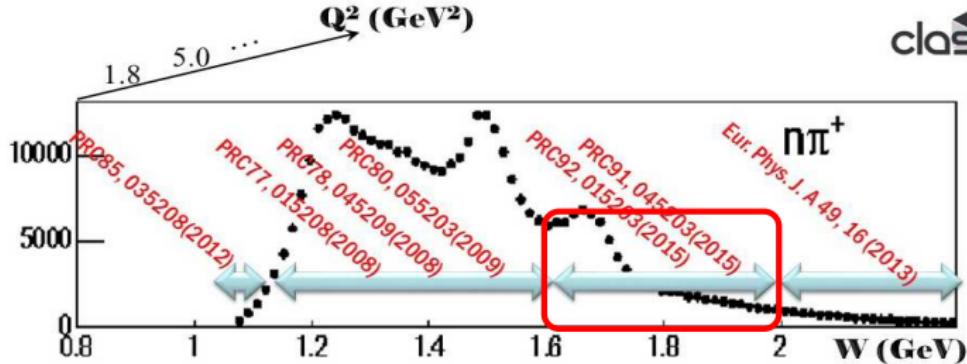
# $\vec{e}p \rightarrow e'\pi^+ n$ for high lying $N^*$ ( $1.65 < W < 2.0$ GeV)



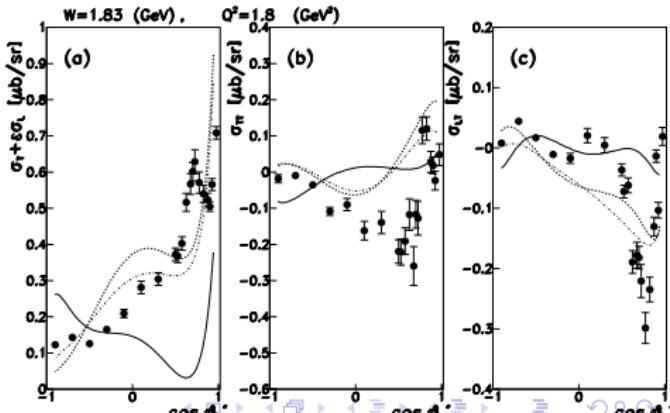
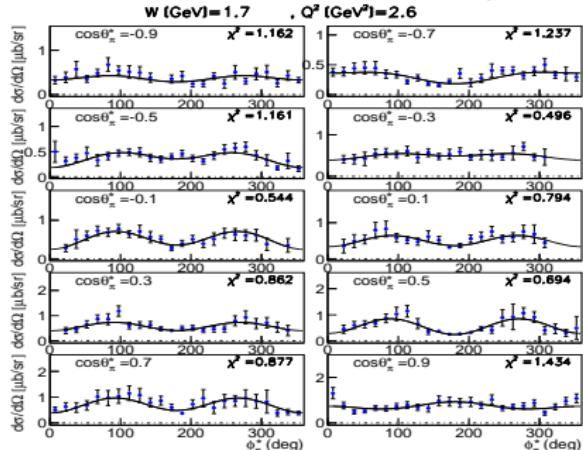
- differential cross-sections (12 bins of  $\phi^*$ ) for third resonance region



# $\vec{e}p \rightarrow e'\pi^+ n$ for high lying $N^*$ ( $1.65 < W < 2.0$ GeV)



- differential cross-sections (24 bins of  $\phi^*$ ) for third resonance region



# Moorhouse selection rule must be violated !

Spin-dependent potential from one-gluon-exchange and  $SU(6) \otimes O(3)$  symmetry breaking, color hyperfine interaction  $H_{hyper}$  is introducing mass splitting and configuration mixing in  $SU(6)$  multiplets

Isgur, Karl, PRL 41, 1269 (1978).

$$H_{hyper} = \frac{2\alpha_s}{3m_i m_j} \left[ \frac{8\pi}{3} S_i \cdot S_j \delta^3(r_{ij}) + \frac{1}{r_{ij}^3} \left( \frac{3(S_i \cdot r_{ij})(S_j \cdot r_{ij})}{r_{ij}^2} - S_i \cdot S_j \right) \right]$$

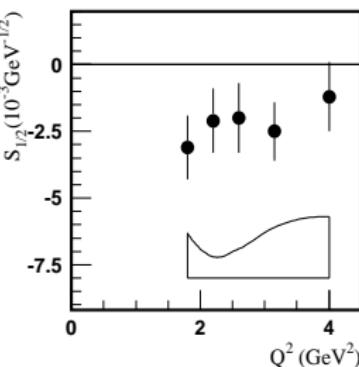
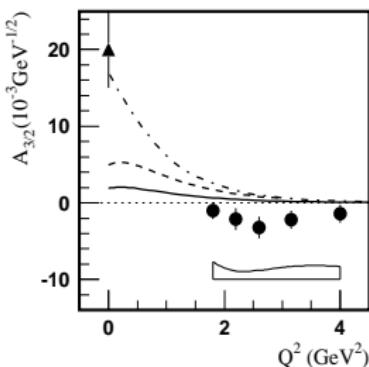
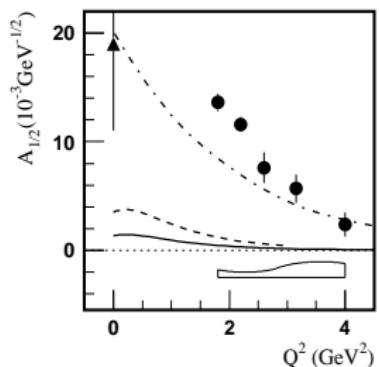
TABLE I. Violations of some SU(6) rules.

Quantity	SU(6) (Relative values)	This calculation (Relative values)	Experiment (Various units)
$A_{3/2}^- n (D_{15} \rightarrow n \gamma)$	$-\alpha$	$-\alpha$	$-60 \pm 33^a$
$A_{1/2}^- n (D_{15} \rightarrow n \gamma)$	$-0.71\alpha$	$-0.71\alpha$	$-33 \pm 25^a$
$A_{3/2}^+ p (D_{15} \rightarrow p \gamma)$	0	$+0.31\alpha$	$+20 \pm 13^a$
$A_{1/2}^+ p (D_{15} \rightarrow p \gamma)$	0	$+0.22\alpha$	$+19 \pm 14^a$
$A (D_{15} \rightarrow KN)$	$\beta$	$\beta$	$+0.41 \pm 0.03^b$
$A (D_{05} \rightarrow \bar{K}N)$	0	$-0.28\beta$	$-0.09 \pm 0.04^c$
$\langle \sum e_i r_i^2 \rangle_p$	$\gamma$	$\gamma$	$+0.82 \pm 0.02^d$
$\langle \sum e_i r_i^2 \rangle_n$	0	$-0.16\gamma$	$-0.12 \pm 0.01^e$

[R. G. Moorhouse, Phys. Rev. Lett. 16, 771 (1966)]

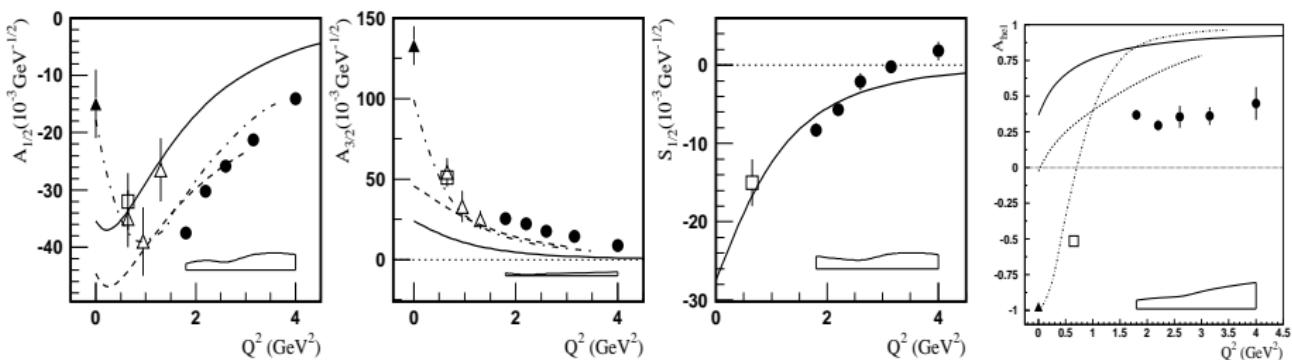
# $\vec{e}p \rightarrow e'\pi^+n$ for high lying $N^*$ ( $W = 1.65 - 2.0$ GeV)

- Transition Form Factors for  $N(1675)5/2^-$  (old conv:  $D_{15}(1675)$ )
- SQTM, Moorhouse selection rule: suppression Transverse Amplitudes
  - Solid: M. M. Gianini/E. Santopinto (hQCM)
  - dash: D.Merten& U.Loring(2003)
- Non-quark contributions dominance, A strong coupling  $A_{1/2}$  for  $Q^2 < 4$  GeV $^2$
- Significant *MB* contribution from the dynamical coupled-channel model
  - (dash-dot: B. Julia-Diaz, T-S. H. Lee, A. Matsuyama)
- A strong suppression of  $A_{3/2}$  for  $Q^2 > 1.8$  GeV $^2$



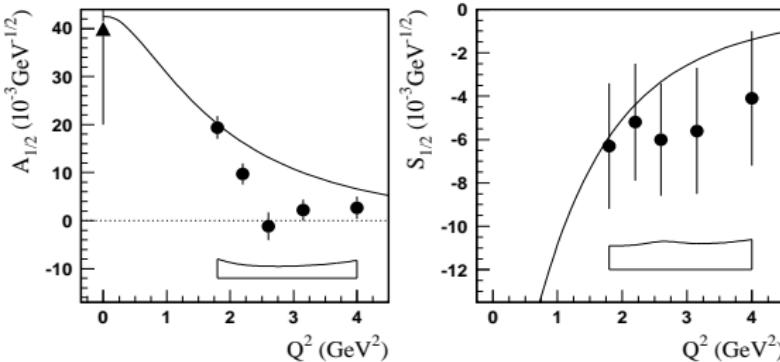
# $\vec{e}p \rightarrow e'\pi^+n$ for high lying $N^*$ ( $W = 1.65 - 2.0$ GeV)

- Transition Form Factors for  $N(1680)5/2^+$  (old conv:  $F_{15}(1680)$ )
  - ▲ RPP(PDG:2014), △ V.Mokeev& I.G.Aznauryan(2013), □ I.G.Aznauryan(2005)
  - Solid: M.M.Gianini/E.Santopinto (hQCM), dash-dot: Z.Lee& F.Close(1990), dash: D.Merten& U.Loring(2003)
- All models estimates amplitudes larger  $A_{1/2}$  ( lower  $A_{3/2}$  ) than data
- $MB$  contribution should be taken into account ?



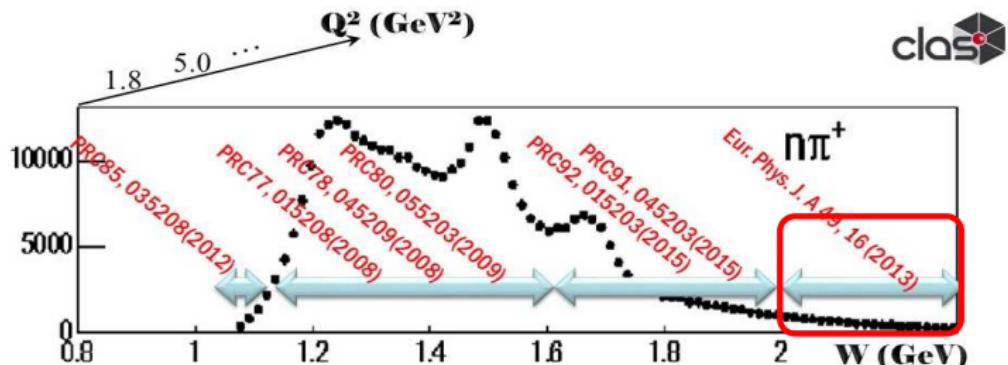
# $\vec{e}p \rightarrow e'\pi^+ n$ for high lying $N^*$ ( $W = 1.65 - 2.0$ GeV)

- Transition Form Factors for  $N(1710)1/2^+$  (old conv:  $P_{11}(1710)$ )
- Finite size of  $A_{1/2}$  for  $Q^2 < 2.5$  GeV $^2$
- Finite size and negative of  $S_{1/2}$  for all given  $Q^2$  GeV $^2$



Solid: M.M.Gianini  
E.Santopinto (hQCM)

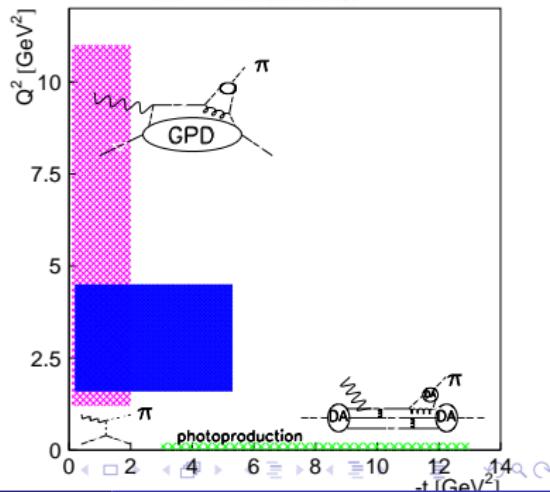
# Deep Inelastic Scattering Regime ( $W > 2.0$ GeV)



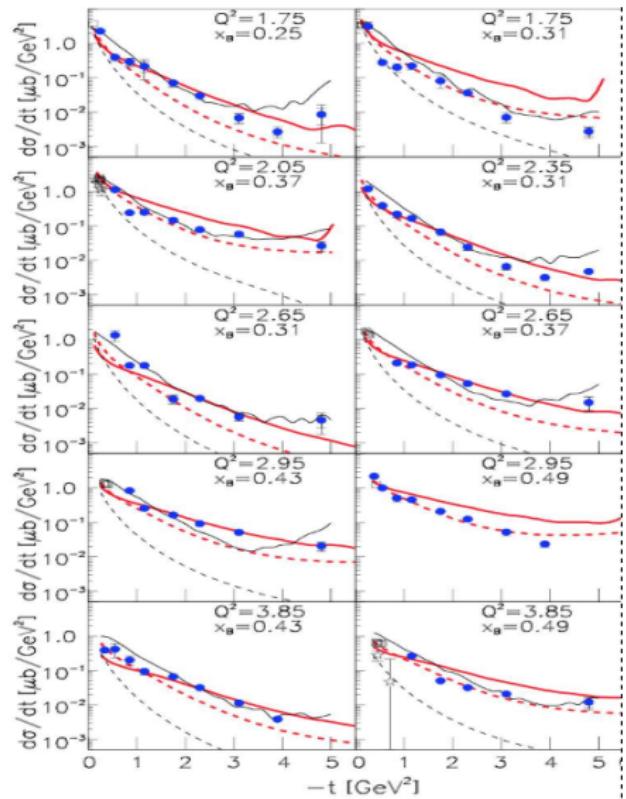
- Transition between hadronic and partonic picture of strong interaction
- GPD
  - Correlations of longitudinal momentum fraction with transverse spatial position
- DVMP:  $N(e, e' NM)$ ,  $M = \pi, \rho, \phi, \dots$ 
  - Connection to the transversity GPD

Blue box →

[K.Park, et al., Eur. Phys. J. A49 16, (2013)]

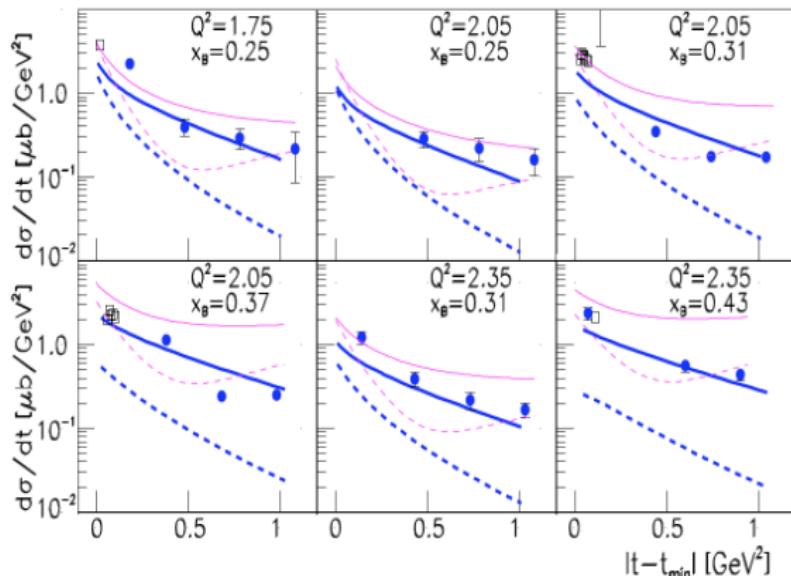


# Hard Exclusive Forward, Large-angle $\gamma^* p \rightarrow n\pi^+$

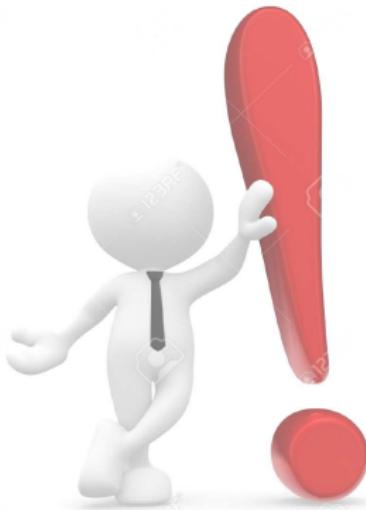


- Solid ( $d\sigma/dt$ ), dashed curves ( $d\sigma_L/dt$ )
- Red curves: J. M. Laget, Regge-model
- Blue curves: M. Kaskulov, Hybrid (hadron-parton) model

# Hard Exclusive Forward, Large angle $\gamma^* p \rightarrow n\pi^+$

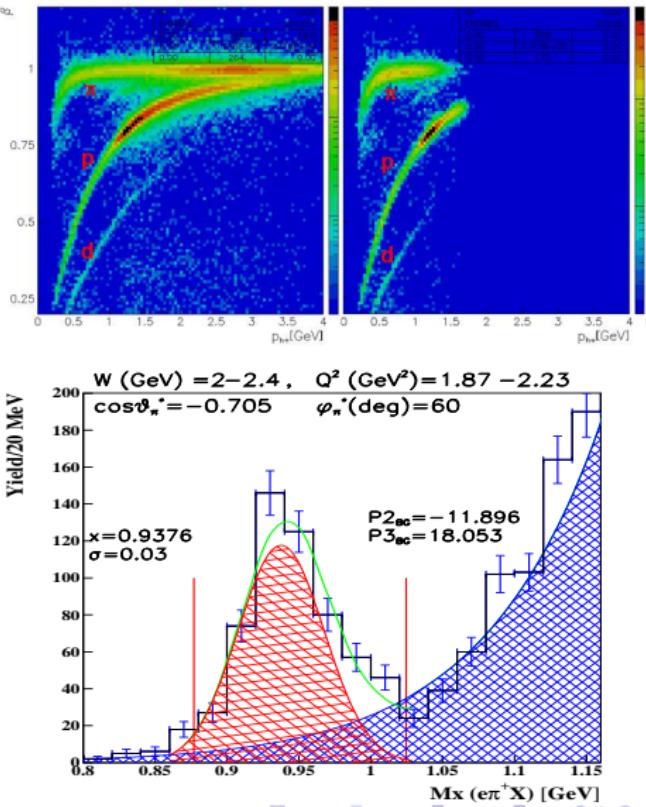
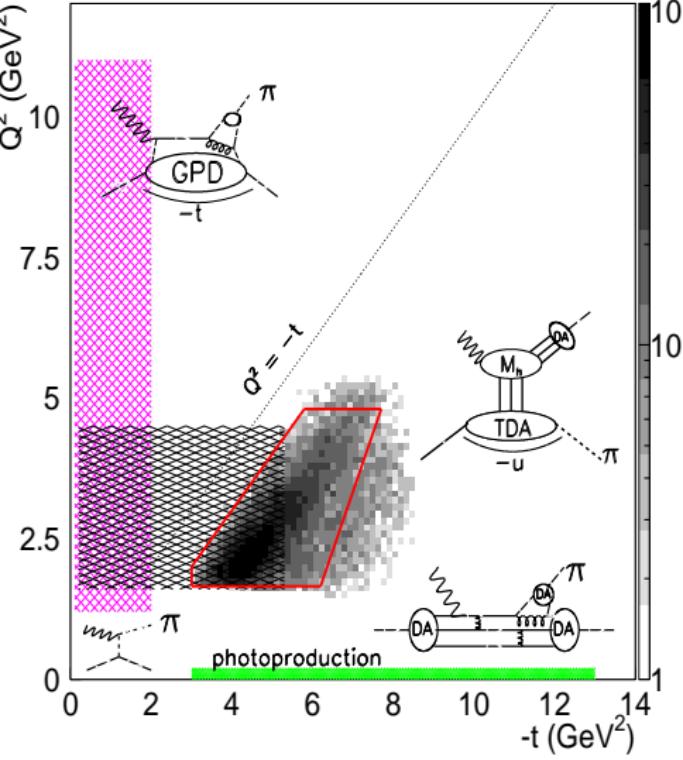


- Solid ( $d\sigma/dt$ ), dashed curves ( $d\sigma_L/dt$ )
- Magenta curves: M. Kaskulov, Duality model
  - Transverse: resonance excitation
  - Longitudinal:  $t$ -channel meson exchange
- Blue curves: G-K : Transversity of GPDs
  - Partonic model (handbag diagram) (But w/o adjusting Jlab kinematics)

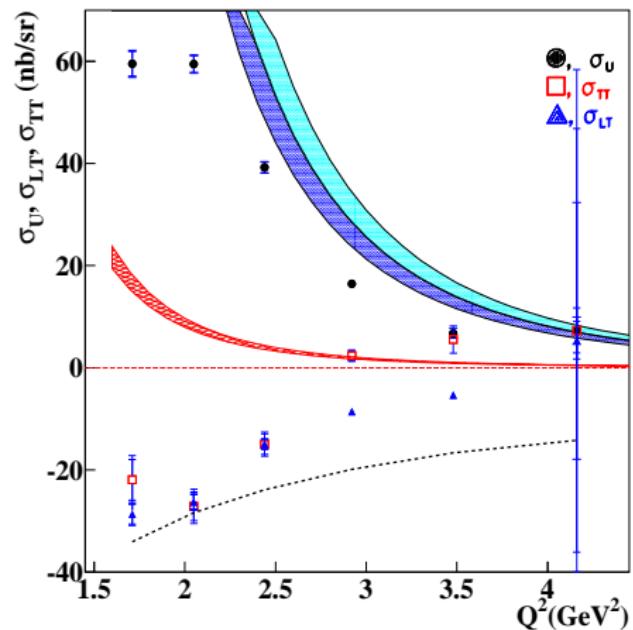


New upcoming results 2017 !!!  
**under CLAS<sup>6</sup> Paper Review**

# Hard Exclusive Backward angle $\gamma^* p \rightarrow n\pi^+$



# Structure functions vs. $\pi N$ -TDA calculation



- $\sigma_T + \epsilon\sigma_L$  ( $\bullet$ ),  $\sigma_{TT}$  ( $\square$ ), and  $\sigma_{LT}$  ( $\blacktriangle$ )
- A recent theoretical calculation as a function of  $\xi \simeq Q^2/(Q^2 + 2W^2)$
- Nucleon to meson TDAs provide new information about correlation of partons inside hadrons
- Curves : the contribution of  $\pi N$ -TDA model  
Red band: BLW NNLO<sup>a</sup>, dark blue band: COZ<sup>b</sup>, and light blue band: KS<sup>c</sup>
- Theoretical understanding is growing up: spectral representation for  $\pi N$  TDA based on quadruple distributions; factorized Ansatz for quadruple distributions with input at  $\xi = 1$ .
- Open questions: proof of factorization theorems, interpretation in the impact parameter space, analytic properties of the amplitude

<sup>a</sup>A. Lenz, et al., Phys.Rev. D79, 093007, (2009).

<sup>b</sup>V.L Chernyak, et al., Z. Phys. C42, 583 (1989)..

<sup>c</sup>I.D. King et al., Nucl. Phys. B279, 785, (1987).

# Summary

- Extraction of the transition form factor should be carried out through the differential cross-sections/asymmetries measurements for near full angles and large kinematics  $W$ ,  $Q^2$
- Precision data for  $\gamma^* p \rightarrow n\pi^+$  from CLAS allows to extract the helicity amplitudes for various resonance states,  $N(1440)1/2^+$ ,  $N(1520)3/2^-$ ,  $N(1535)1/2^-$ ,  $N(1675)5/2^-$ ,  $N(1680)5/2^+$ , and  $N(1710)1/2^+$
- Coupled-channel analysis (including  $\pi N$ ,  $\pi\pi N$ ,  $KY$ , ...) is crucial in particular high  $W$  and this will improve considerably our knowledge on  $N^*$ -state electro-couplings.

**§§ Full Mass Spectrum with  $Q^2$  evolution and  
Coupled-Channel Analyses help us to map out nucleon  
structure in terms of the effective degree of freedom §§**