International Conference on the Structure of Baryons
at FSU in Tallahassee FL

Exclusive Single Pion Electroproduction off the Proton: Results from CLAS

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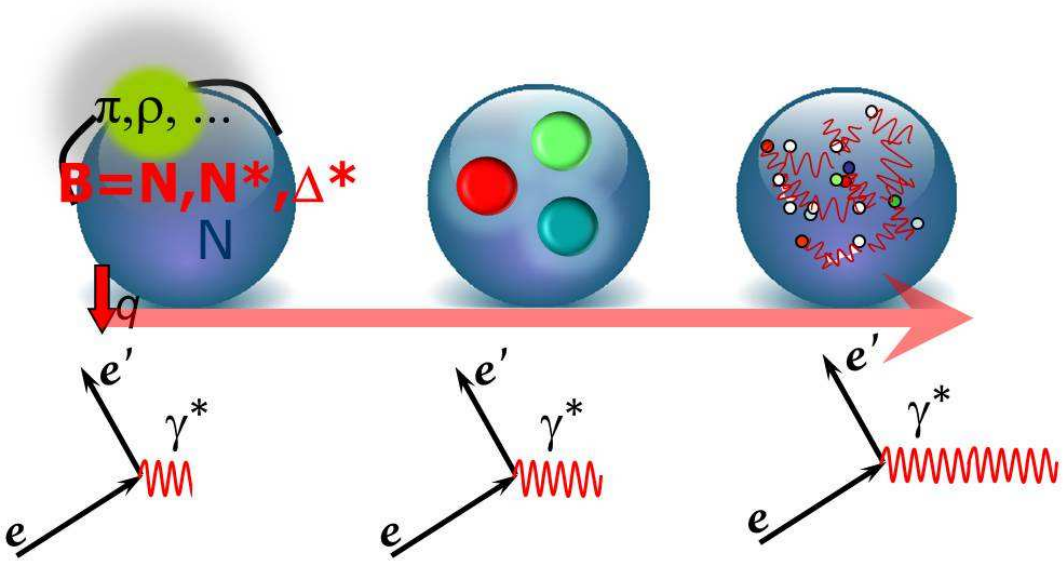
The most challenging problems in Hadron Physics

- Non-purturbative **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 bayrons 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 —— [N. Isgur, V. Burkert (2000)]
- The most fundamental question: " **WHAT ARE THE RELEVANT DEGREE-OF-FREEDOM AT VARYING DISTANCE SCALE ?** "



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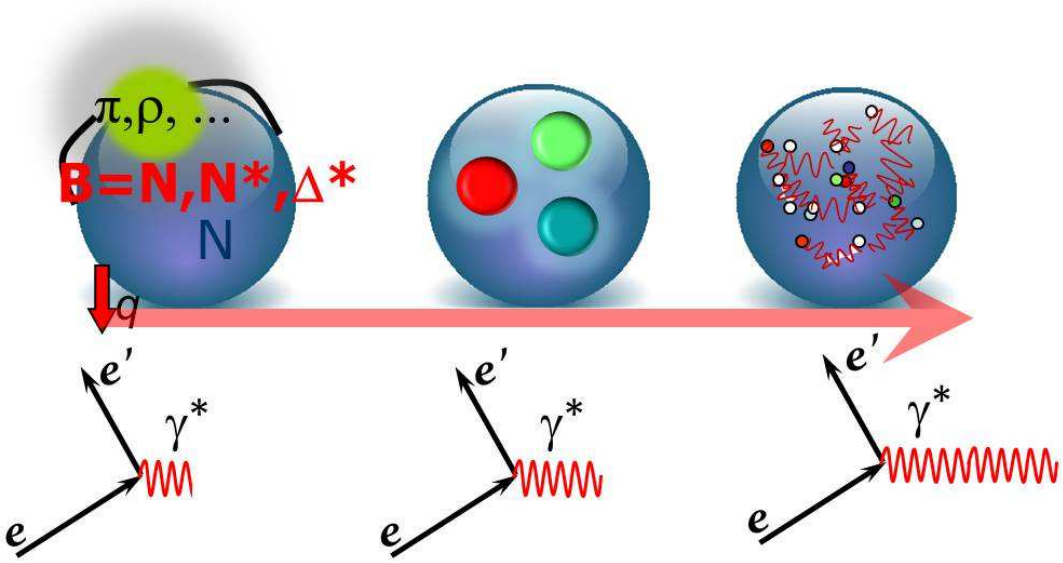

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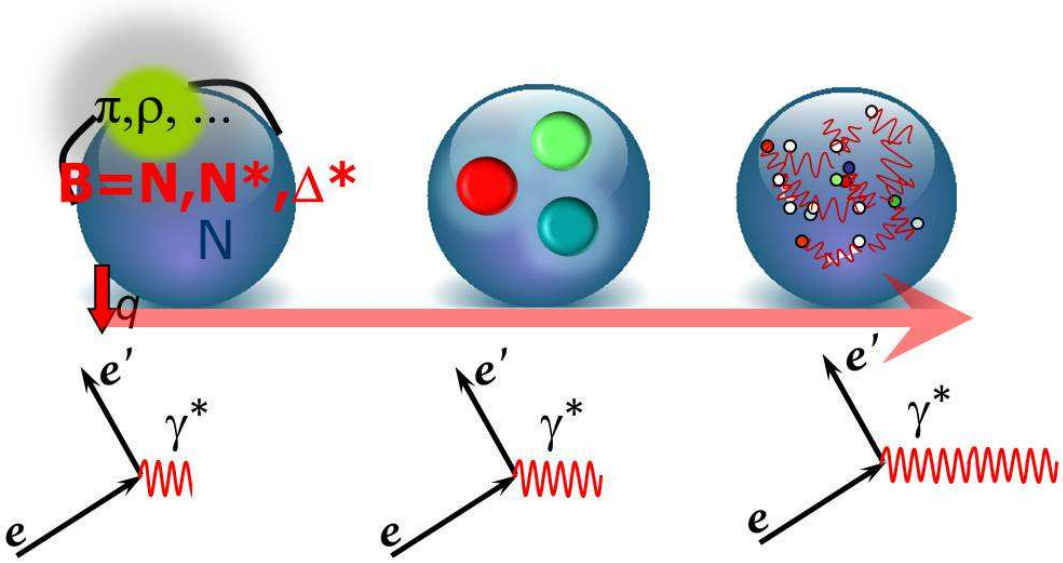

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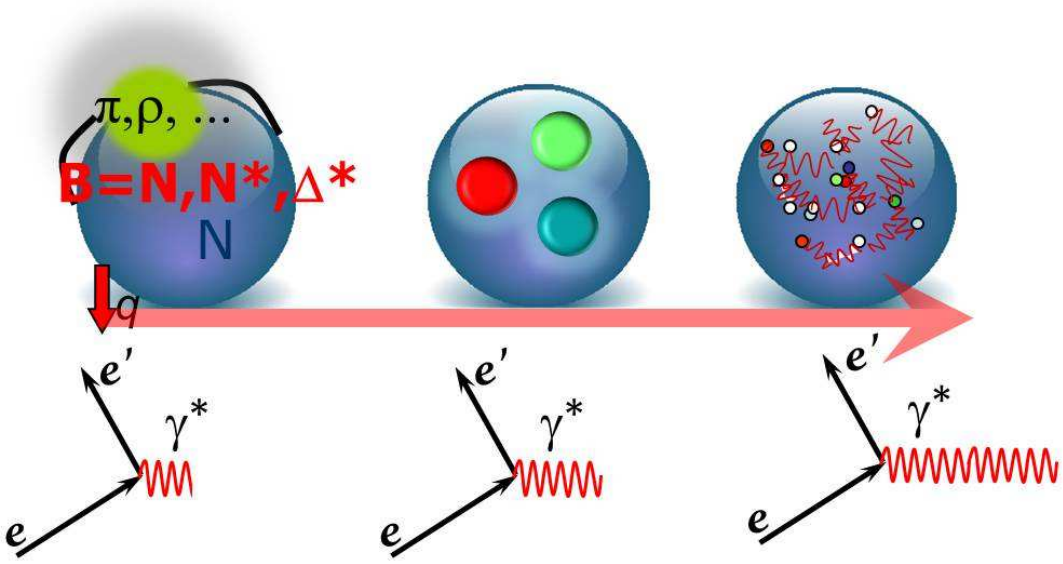

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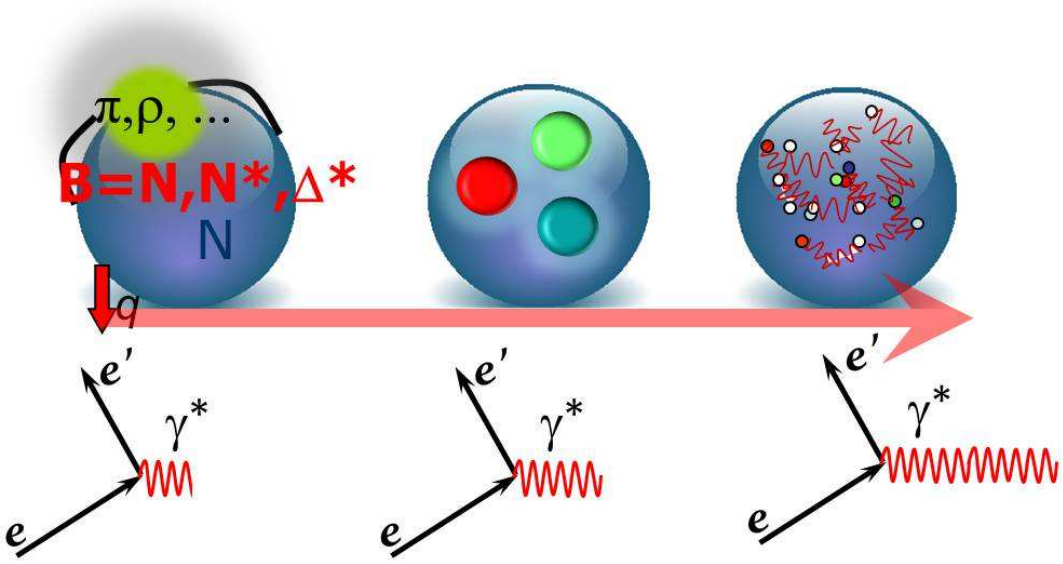


$SU(6) \times O(3)$ Classification of Baryons

- DCSB leads to the presence of massive constituent quarks as effective DOF in hadrons
- Hadrons are viewed as quark-system in an effective potential by gluon field that depend on spins & position of quarks

$SU(6) \otimes O(3)$

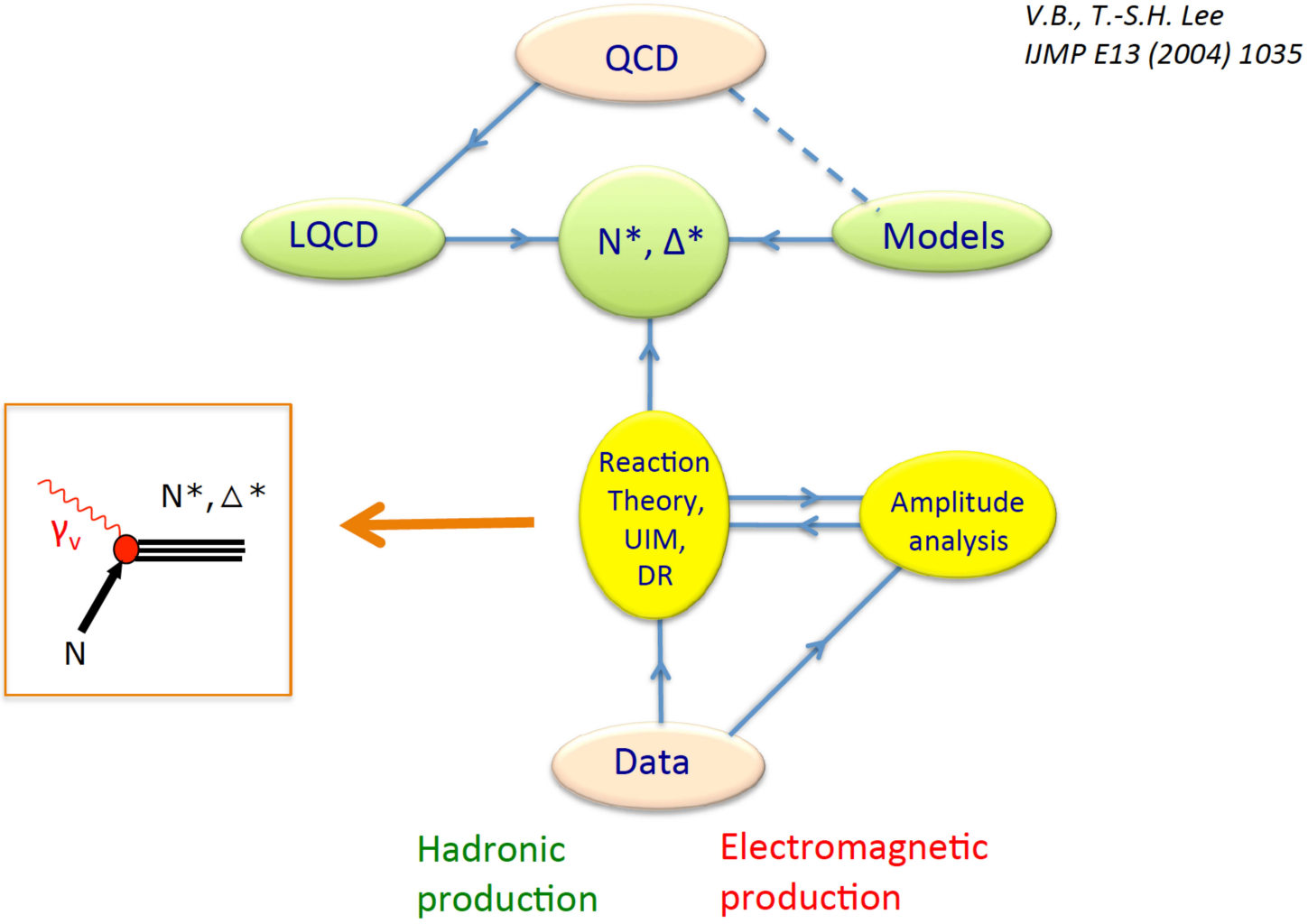
Color	$SU(3)$	$3 \otimes 3 \otimes 3$	$= 10_s + 8_\rho + 8_\lambda + 1_a$
Spin	$SU(2)$	$2 \otimes 2 \otimes 2$	$= 4_s + 2_\rho + 2_\lambda$
Flavor	$SU(3)$	$3 \otimes 3 \otimes 3$	$= 10_s + 8_\rho + 8_\lambda + 1_a$
Spin-flavor	$SU(6)$	$6 \otimes 6 \otimes 6$	$= 56_s + 70_\rho + 70_\lambda + 20_a$
Spatial	$O(3)$	L^P	$= s,\ \rho,\ \lambda,\ a$

** Baryon wavefunction as representation of 3-dimension permutation group:
Symmetric, $\phi_c|SU(6) \otimes O(3)\rangle = \phi_c|N_6, {}^{2S+1}N_3, N, L, J\rangle$

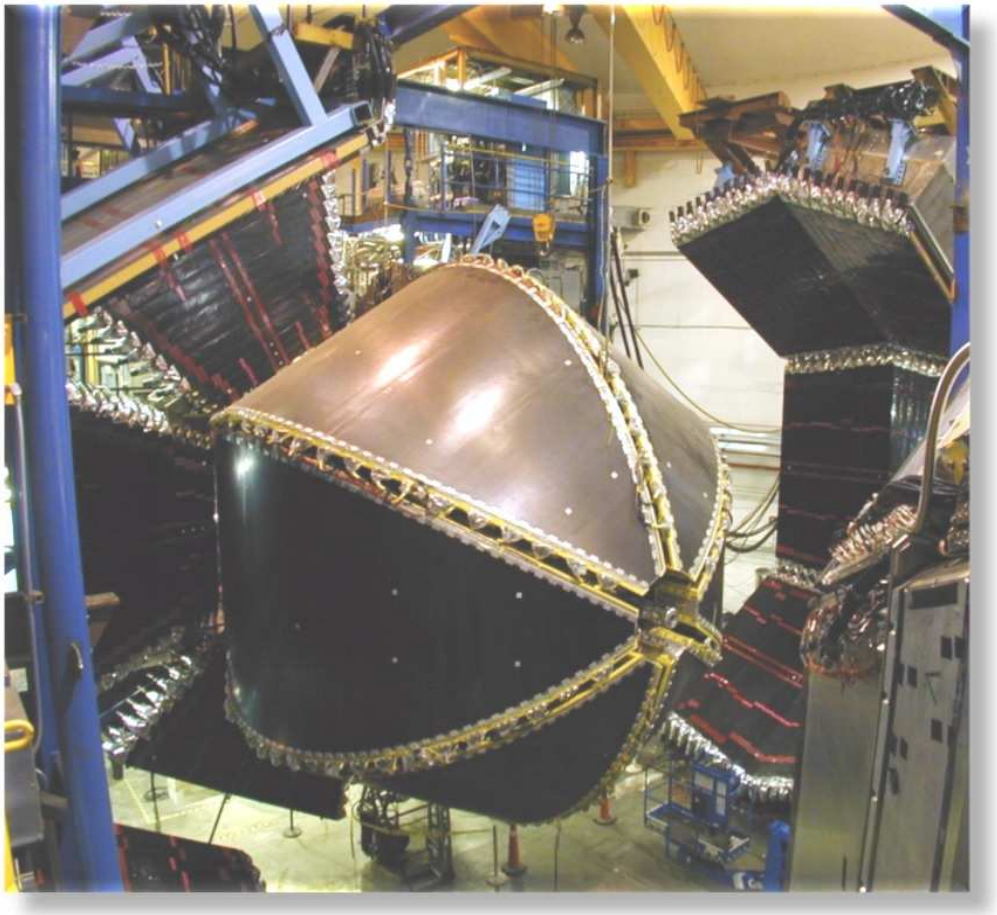
$SU(6) \times O(3)$ Classification of Baryons

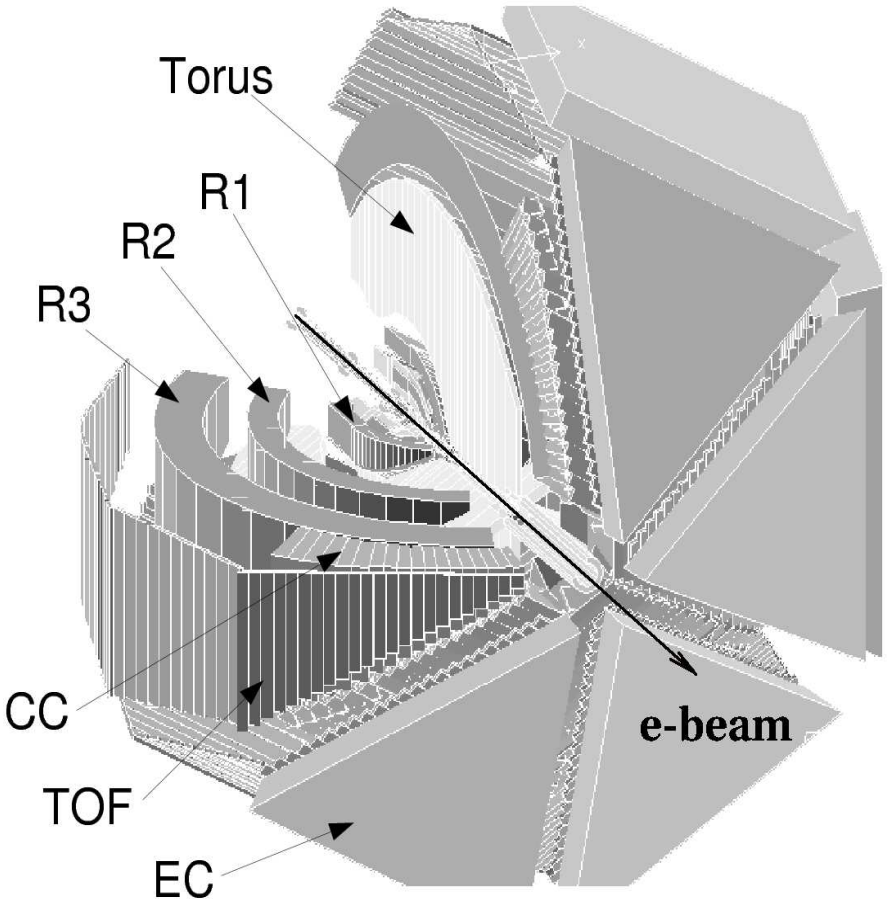
		Status			Status as seen in —						
Particle	J^P	overall	πN	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
N	$1/2^+$	****									
$N(1440)$	$1/2^+$	****	****	****		***				*	***
$N(1520)$	$3/2^-$	****	****	****	***					***	***
$N(1535)$	$1/2^-$	****	****	****	****					**	*
$N(1650)$	$1/2^-$	****	****	***	***			***	**	**	***
$N(1675)$	$5/2^-$	****	****	***	*			*		*	***
$N(1680)$	$5/2^+$	****	****	****	*	**				***	***
$N(1685)$	$?^?$	*									
$N(1700)$	$3/2^-$	***	***	**	*			*	*	*	***
$N(1710)$	$1/2^+$	***	***	***	***		**	***	**	*	**
$N(1720)$	$3/2^+$	****	****	***	***			**	**	**	*
$N(1860)$	$5/2^+$	**	**							*	*
$N(1875)$	$3/2^-$	***	*	***			**	***	**		***
$N(1880)$	$1/2^+$	**	*	*		**		*			
$N(1895)$	$1/2^-$	**	*	**	**			**	*		
$N(1900)$	$3/2^+$	***	**	***	**		**	***	**	*	**
$N(1990)$	$7/2^+$	**	**	**					*		
$N(2000)$	$5/2^+$	**	*	**	**			**	*	**	
$N(2040)$	$3/2^+$	*									
$N(2060)$	$5/2^-$	**	**	**	*				**		
$N(2100)$	$1/2^+$	*									
$N(2150)$	$3/2^-$	**	**	**				**			**
$N(2190)$	$7/2^-$	****	****	***			*	**		*	
$N(2220)$	$9/2^+$	****	****								
$N(2250)$	$9/2^-$	****	****								
$N(2600)$	$11/2^-$	***	***								
$N(2700)$	$13/2^+$	**	**								

Analysis Chain

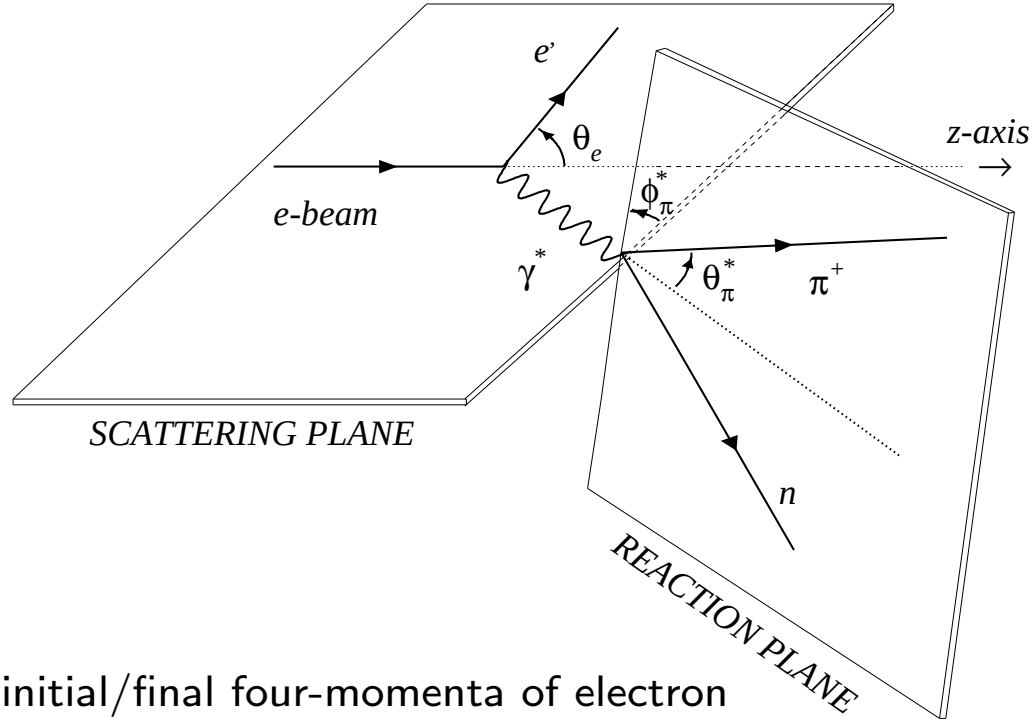


CEBAF Large Acceptance Spectrometer





Reaction



- $k_{i,f}$: the initial/final four-momenta of electron
- $E_{i,f}$: the initial/final energy of electron
- θ_e: the electron scattering angle
- $p_{\gamma,i}$: the virtual photon/target four-momenta
- $W^2 = (p_\gamma + p_i)^2 = M_p^2 + 2M_p\nu - Q^2$
- ν: transferred energy $= E_i - E_f = \frac{p_i \cdot p_\gamma}{M_p}$
- Q^2: virtuality of the exchanged photon $= -(k_i - k_f)^2 = 4E_iE_f \sin^2(\theta_e/2)$
- θ^*_π: the angle between the virtual photon and the hadron (π^+)
- ϕ^*_π: the angle between the electron scattering plane and the hadronic production plane

CLAS single pion data coverage - (published)

Final State	W (GeV)	Q^2 (GeV^2)	Observables
$n\pi^+$	1.1 -1.38	0.16-0.36	$d\sigma/d\Omega$
	1.1 -1.55	0.3 -0.6	$d\sigma/d\Omega$
	1.1 -1.7	**1.7 -4.5**	$d\sigma/d\Omega$, A_B
	1.65-2.0	**1.8 -4.5**	$d\sigma/d\Omega$
$p\pi^0$	1.1 -1.38	0.16-0.36	$d\sigma/d\Omega$
	1.1 -1.68	0.4 -1.8	$d\sigma/d\Omega$, A_B, A_T, A_{BT}
	1.1 -1.39	3.0 -6.0	$d\sigma/d\Omega$

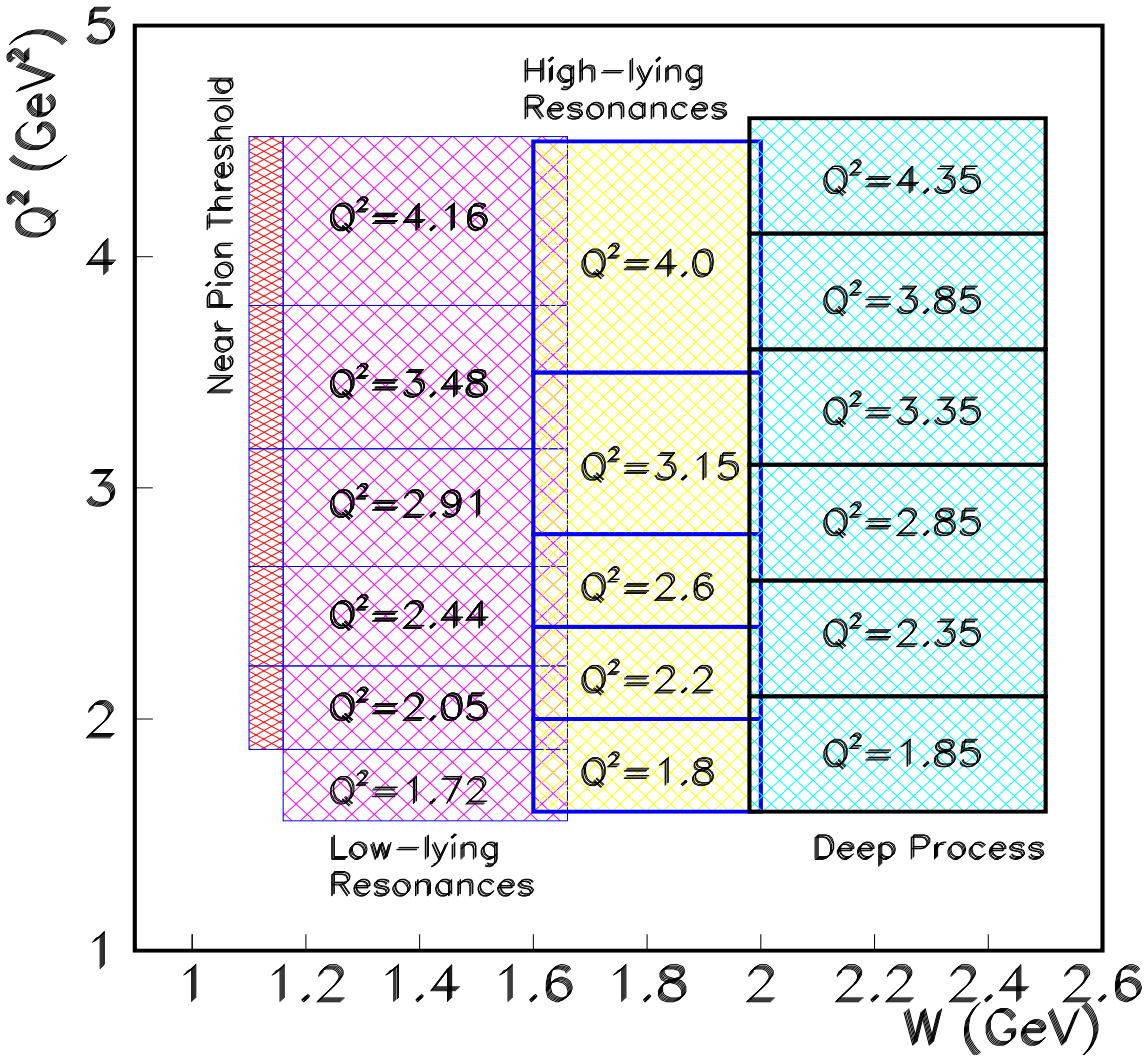
- All CLAS data is available at CLAS-DB
  http://clasweb.jlab.org/physicsdb/

CLAS single pion data coverage for $n\pi^+$

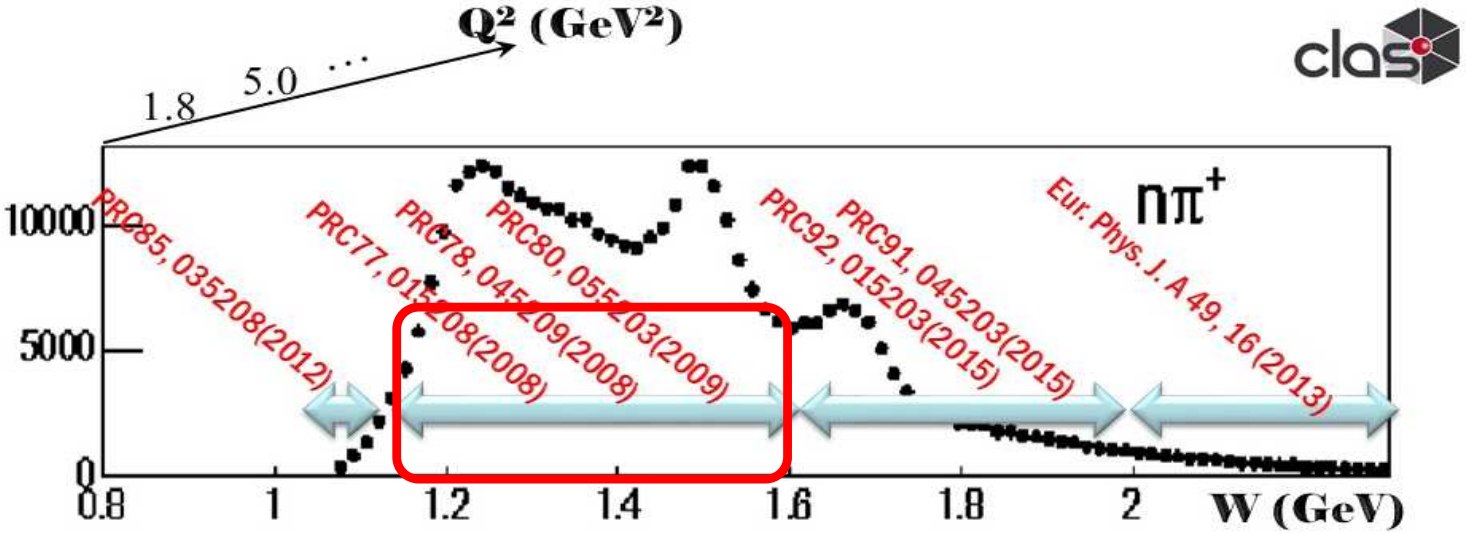
RunGroup	W (GeV)	Q^2 (GeV^2)	Observables	# data
e1-6	1.10 -1.15	1.8 -4.5	$d\sigma/d\Omega$	1800
e1-6	1.1 -1.7	1.7 -4.5	$d\sigma/d\Omega$	50400
			A_{LU}	12600
e1-f	1.65 -2.0	1.8 -4.5	$d\sigma/d\Omega$	32500
e1-6	0.16-0.58 (x_{BJ})	1.6 -4.5	$d\sigma/dt$	140

Kinematic coverage of data, E_0=5.5, 5.75 GeV, $P_e \sim 70\%$

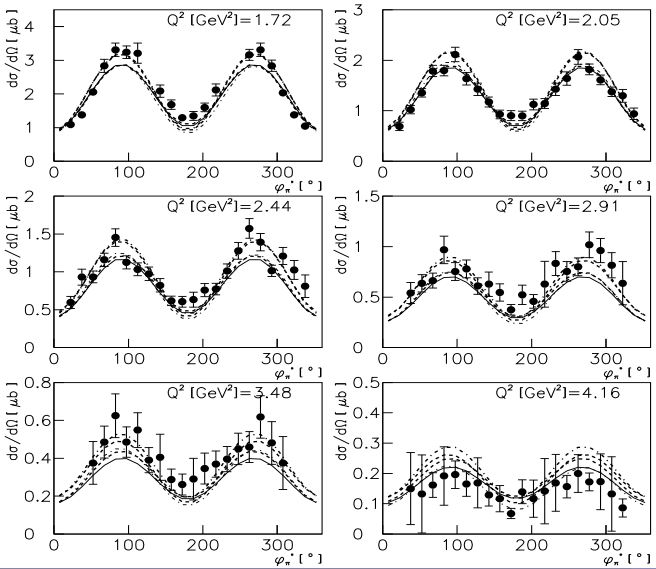
- Overall kinematic range W, Q^2 of all $\gamma^* p \to n\pi^+$ analyses
- From the **near pion threshold** to **Deep Process** regime
- Study of resonances: $\Delta(1232)3/2^+$, $N(1440)1/2^+$, $N(1520)3/2^-$, $N(1535)1/2^-$, $N(1675)5/2^-$, $N(1680)5/2^+$, and $N(1710)1/2^+$

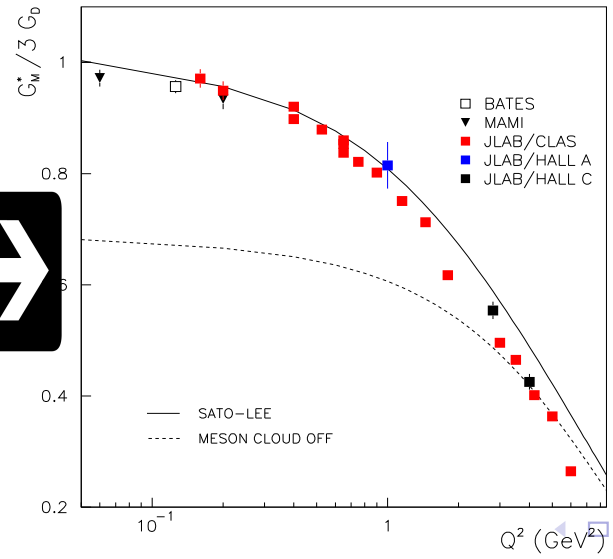


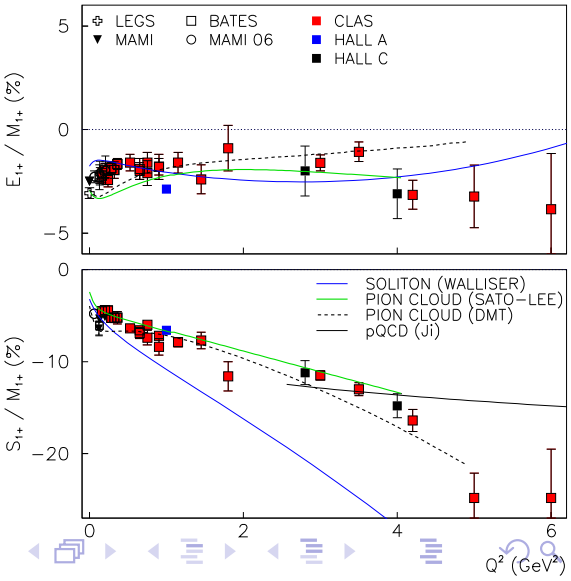
$\vec{e}p \to e'\pi^+ n$ for low lying Δ ($1.15 < W < 1.69$ GeV)



- Transition Form Factors for $\Delta(1232)$ ... sensitive with π^0 data
- Significant meson cloud effect in G_M^* at lower Q^2
- No indication of leading pQCD contribution in $R_{EM} \to +1$







In the analysis

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

  UIM

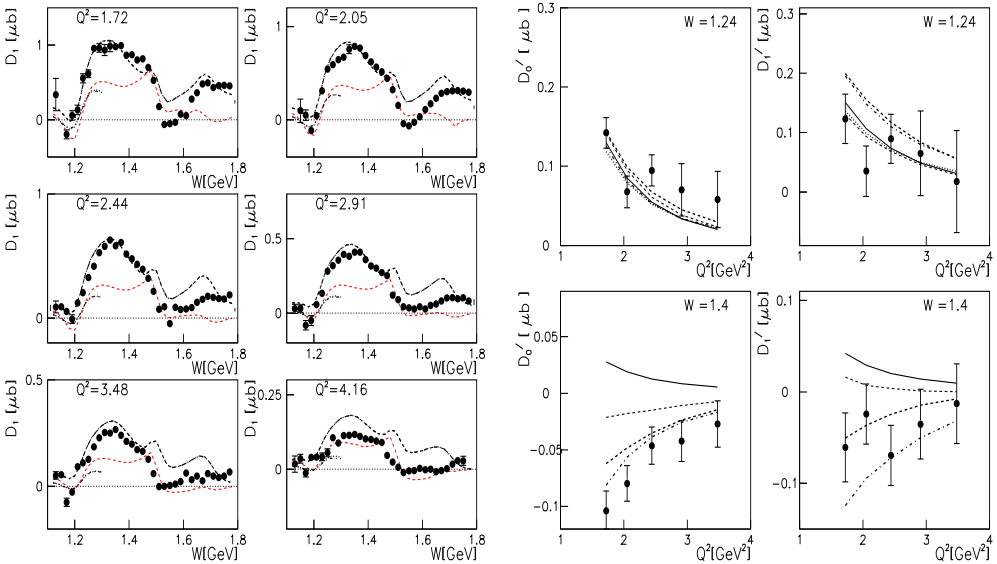
  - BG UIM is built from nucleon exchange in s-, u- and π,ω,ρ exchange in t- channel
  - Unitarization of multipole amplitudes in the K-matrix approximation
  - Resonance contributions are parameterized in the unified BW form with energy dependence

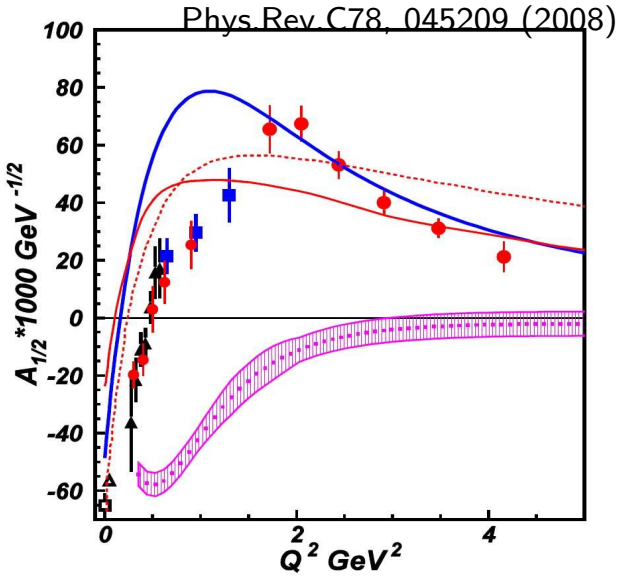
  DR

  - Fixed-t dispersion relation for the invariant amplitude
  - Re-Amplitude to Born-term (s,u, channel nucleon exchange, π exchange in t-
  - Integral Im-Amplitude with the isospin structure
- **Two model-uncertainties**
  1/ BG determination in the UIM and Born term in DR
  2/ A width and mass of resonances from PDG
- **Take into account...**
  1/ All(13) **** and *** states in the 1st,2nd,3rd
  2/ $\Delta(1905)F_{35}$, $\Delta(1950)F_{37}$ in 4th resonance region
- Same BR from PDG2012

$\vec{e}p \to e'\pi^+ n$ for low lying N^* ($1.15 < W < 1.69$ 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*
- Quark core in DSEQCD (thick blue curve), MB cloud contribution (purple band)
- $N\pi$ loops MB, running quark mass (red solid curve)
- $N\sigma$ loops MB, fixed constituent quark mass (red dashed curve) [$\Downarrow$ including single π and 2π data]

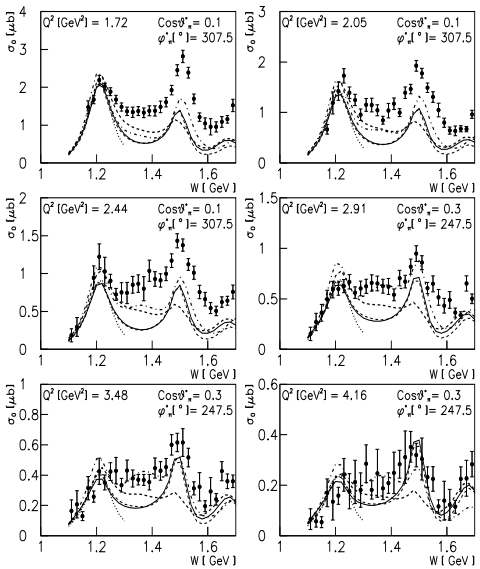


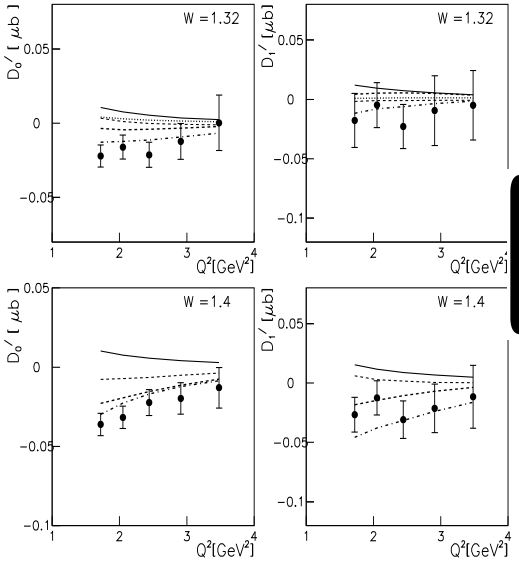


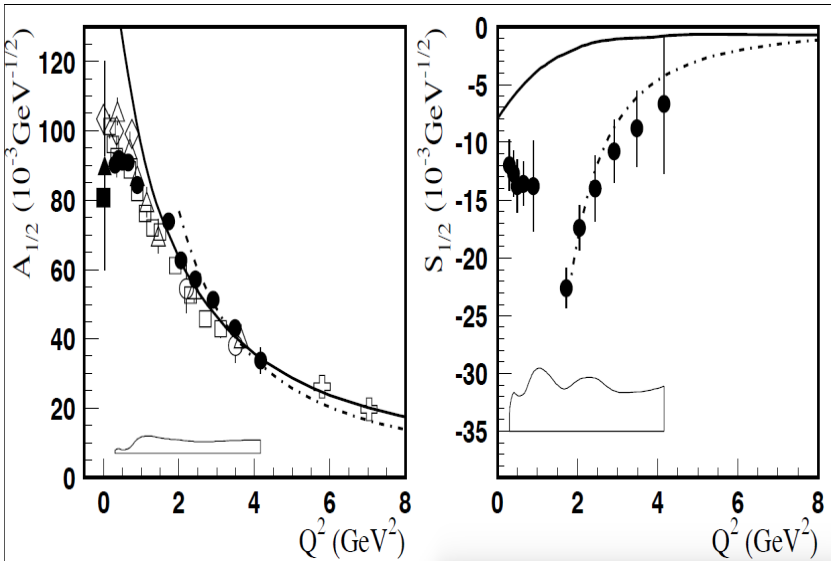
$\vec{e}p \to e'\pi^+ n$ for low lying N^* ($1.15 < W < 1.69$ GeV)

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

[$\Downarrow$ solid: LFRQM, dash-dot: LCSR]

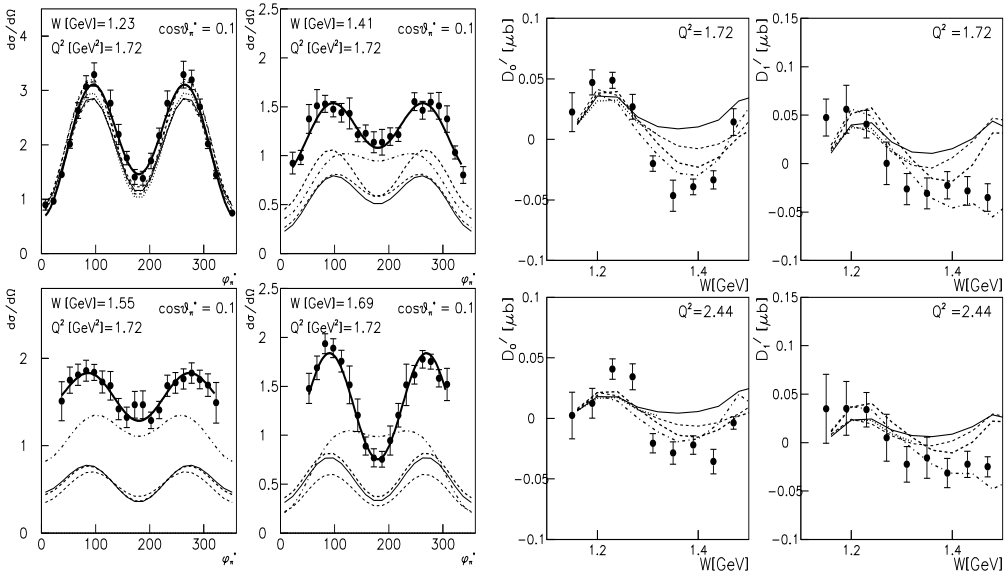




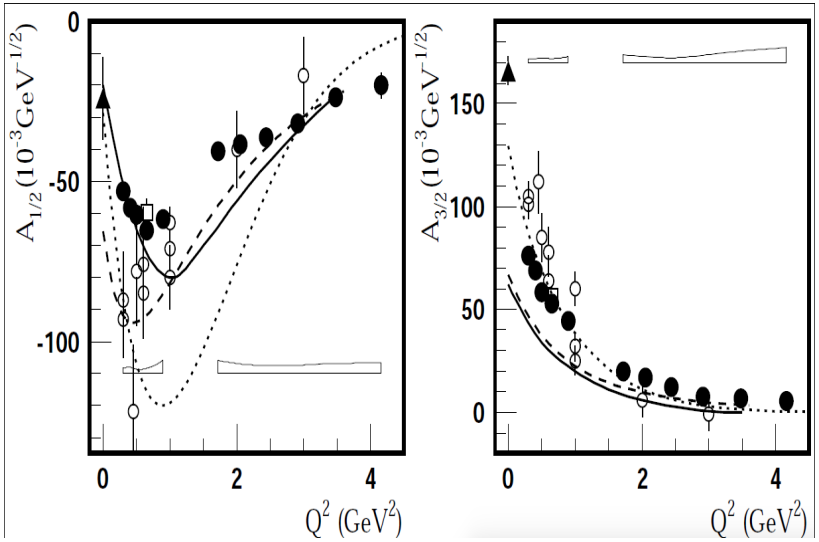


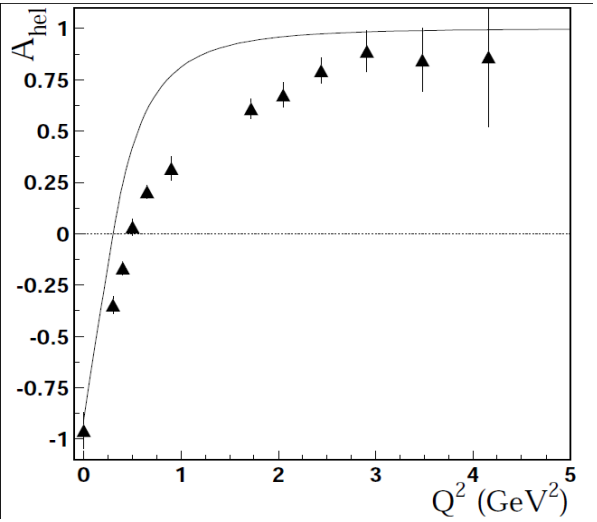
$\vec{e}p \to e'\pi^+ n$ for low lying N^* ($1.15 < W < 1.69$ GeV)

- 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



[▲: RPP(2014), ◯,□: DESY, NINA data]





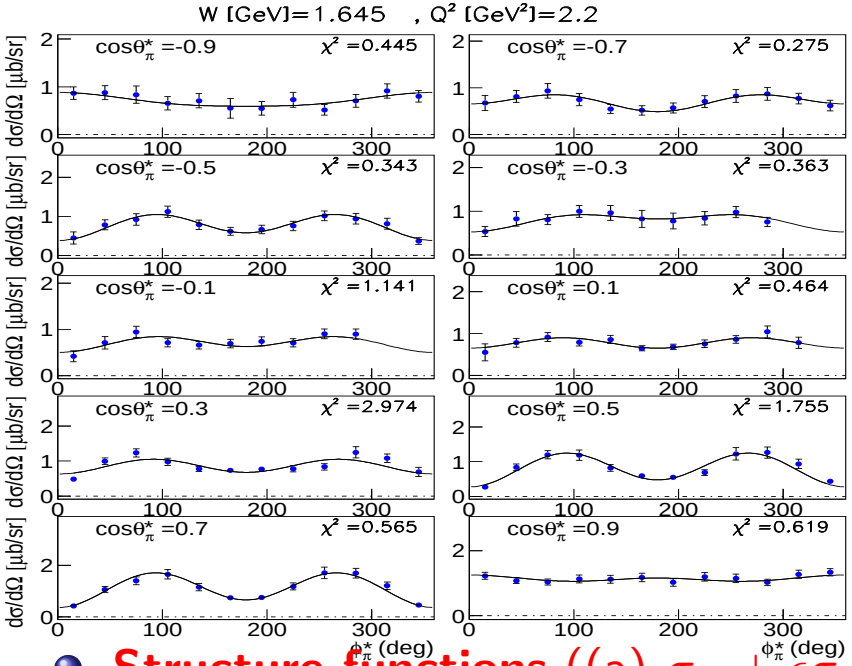
$$\frac{A^{D13}_{1/2}}{A^{D13}_{3/2}} = \frac{-1}{\sqrt{3}}\left(\frac{Q^2}{\alpha} - 1\right)$$

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

- Asymptotic Q^2 behavior of A_{hel} vs. Q^2
  - NRQ 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** for third resonance region



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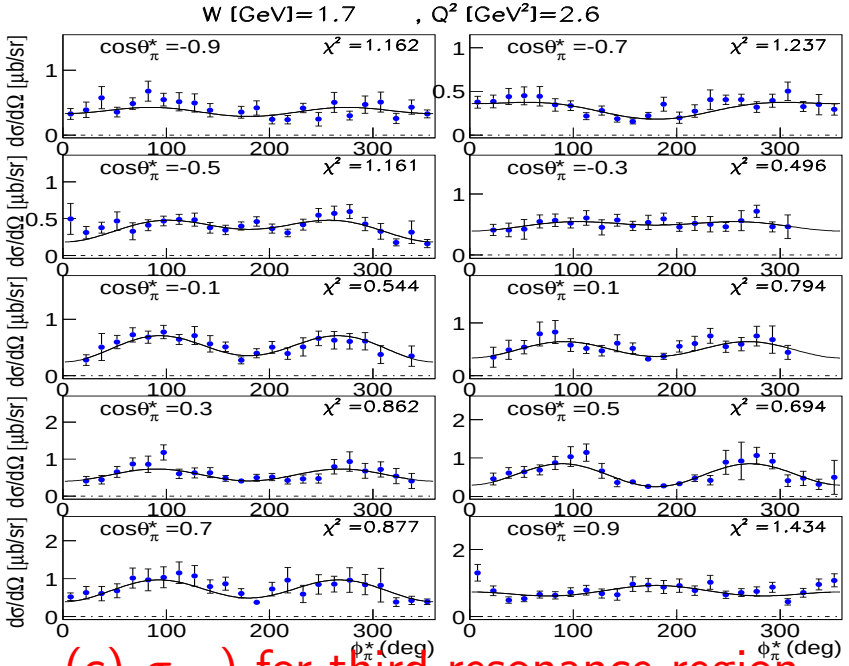
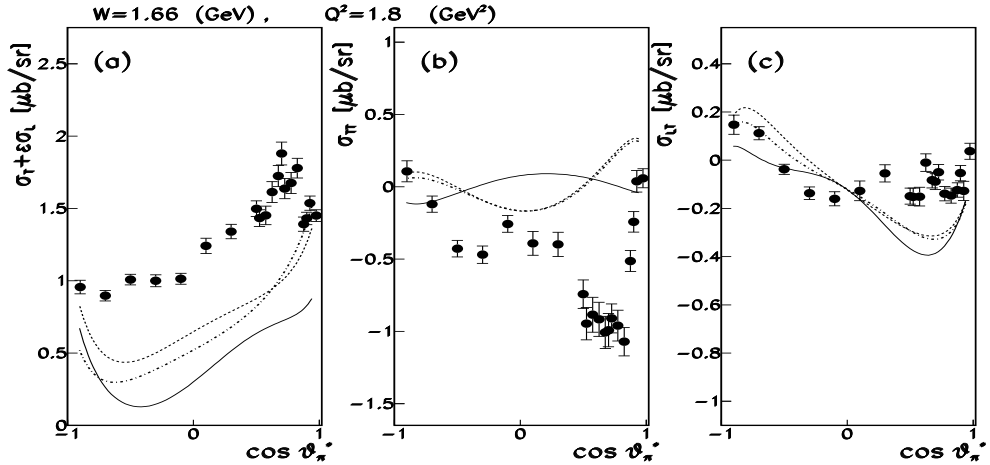
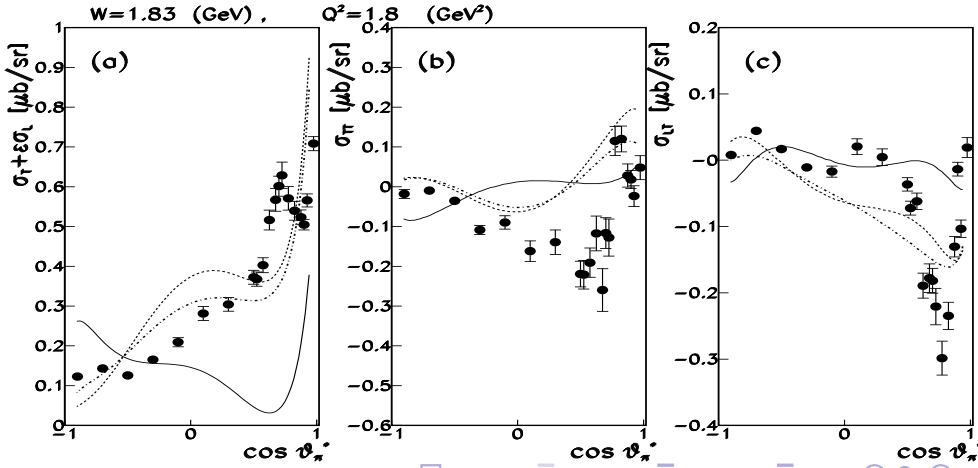


- **Structure functions** ((a) $\sigma_T + \epsilon\sigma_L$, (b) σ_{TT}, (c) σ_{LT}) for third resonance region

  - dash: MAID07, dash-dot: MAID03, dot: DMT





Selection Rules in Symmetric Quark Model

- The first orbital excitation states
  $|70, {}^2 8, 1, 1, J\rangle$ - $S_{11}(1535)(****)$, $D_{13}(1520)(****)$
  $|70, {}^4 8, 1, 1, J\rangle$ - $S_{11}(1650)(****)$, $D_{13}(1700)(***)$, $D_{15}(1675)(****)$

- Moorhouse selection rule (Moorhouse, PRL16, 772 (1966))
  $\gamma + p(|56, {}^2 8; 0, 0, 1/2\rangle) \nleftrightarrow N^*(|70, {}^4 8\rangle)$: vanishing TME for charge operator
  $\gamma + n(|56, {}^2 8; 0, 0, 1/2\rangle) \leftrightarrow N^*(|70, {}^4 8\rangle)$

- Λ selection rule (Zhao, PRD74, 094014 (2006))
  $N^*|70, {}^4 8\rangle \nleftrightarrow K(K^*) + \Lambda$

- Faiman-Hendry selection rule (Faiman,Hendry, PR173, 1720 (1968))
  $\Lambda^*|70, {}^4 8\rangle \nleftrightarrow N(|56, {}^2 8; 0, 0, 1/2\rangle) + \bar{K}$

Moorehouse selection rule must be violated !

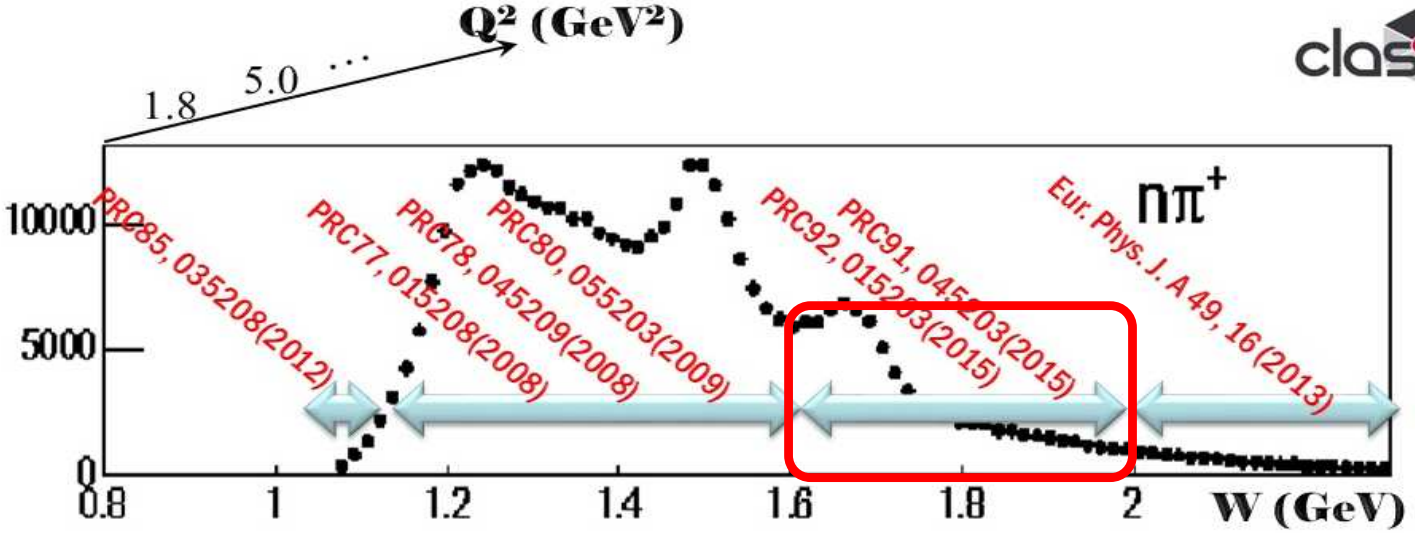
Spin-dependent potential from one-gluon-exchange and $SU(6) \otimes O(3)$ symmetry breaking, interaction H_{hyper} is introducing mass splitting and configuration mixing in $SU(6)$ multiplets

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

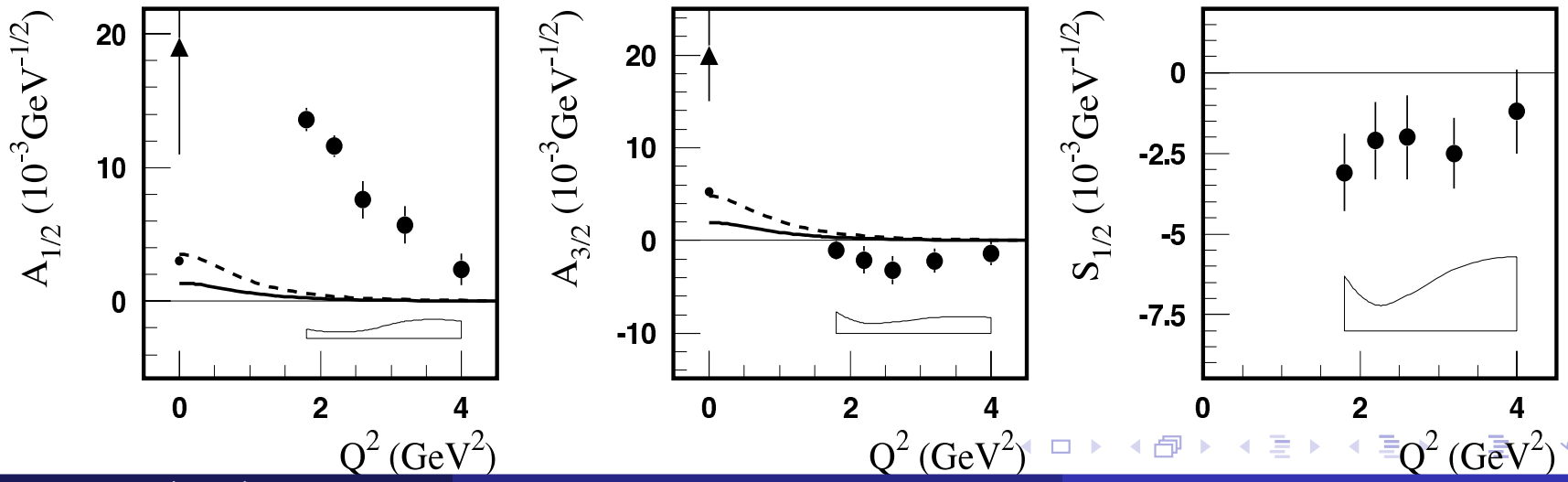
TABLE I. Violations of some SU(6) rules.

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

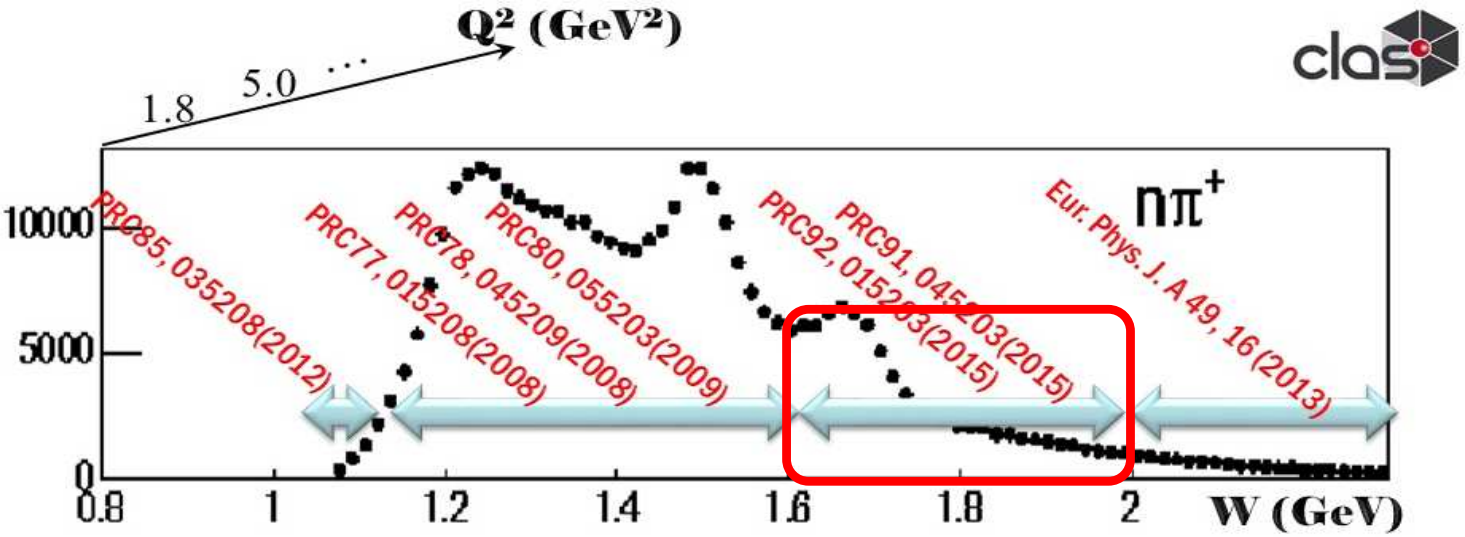
$\vec{e}p \rightarrow e'\pi^+ n$ for high lying N^* ($1.65 < W < 2.0$ GeV)



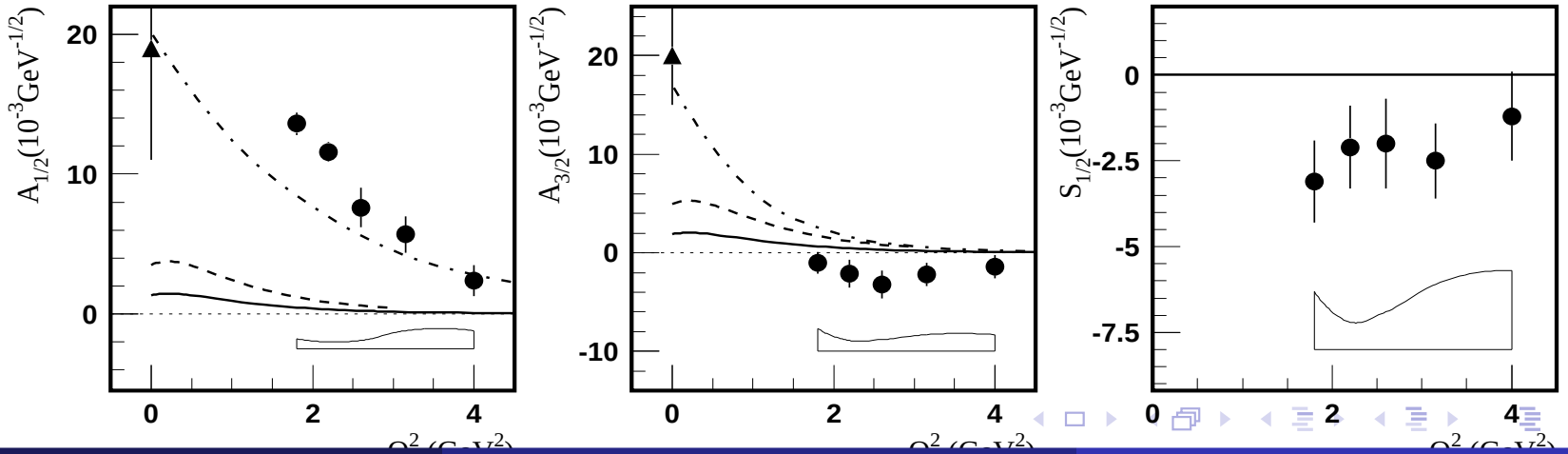
- Transition Form Factors for $N(1675)5/2^-$ (old conv: $D_{15}(1675)$)
- SQTM, Moorhouseselection rule: suppression Transverse Amplitudes
- Solid: M.M.Gianini/E.Santopinto (hQCM)
  dash: D.Merten& U.Loring(2003), Solid-dot(Q^2 =0): I.G.Aznauryan(LFRQ)



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

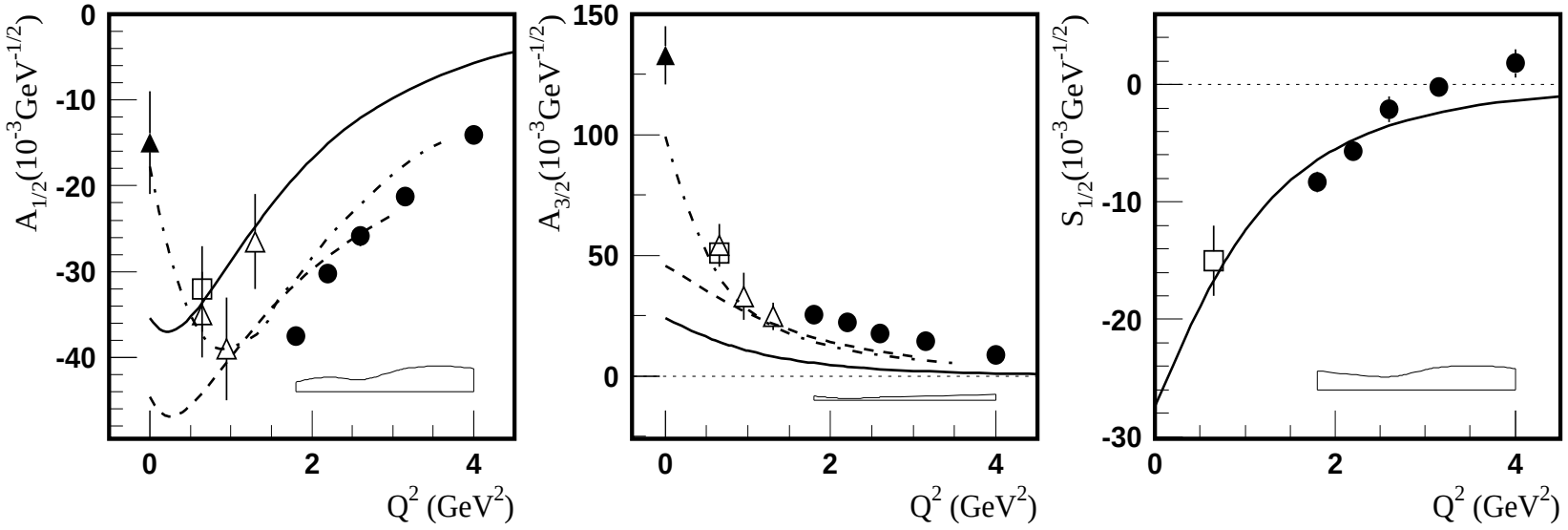


- Non-quark contributions dominance, A strong coupling $A_{1/2}$ for $Q^2 < 4$ GeV^2
- Significant *MB contribution from the dynamical coupled-channel model* *(dash-dot:B.Julia-Diaz,T-S.H.Lee,A.Matsuyama)*
- *A strong suppression of $A_{3/2}$ for $Q^2 > 1.8$ GeV^2*

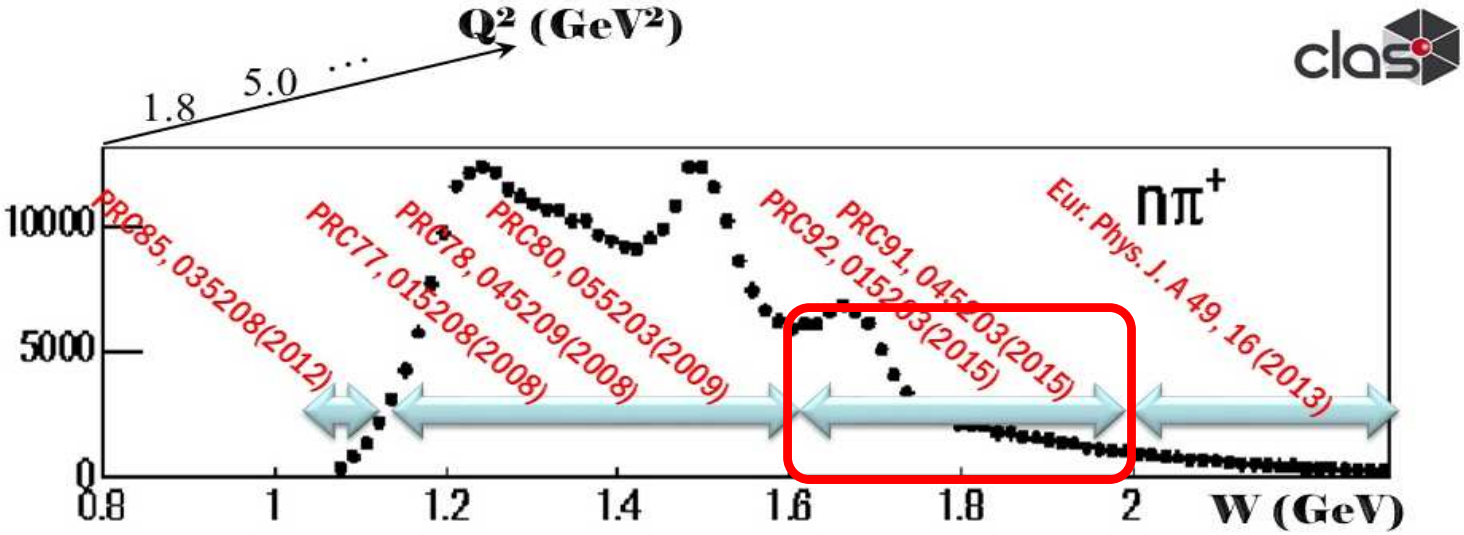


$\vec{e}p \to e'\pi^+ n$ for high lying N^* ($1.65 < W < 2.0$ GeV)

- 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 ?*



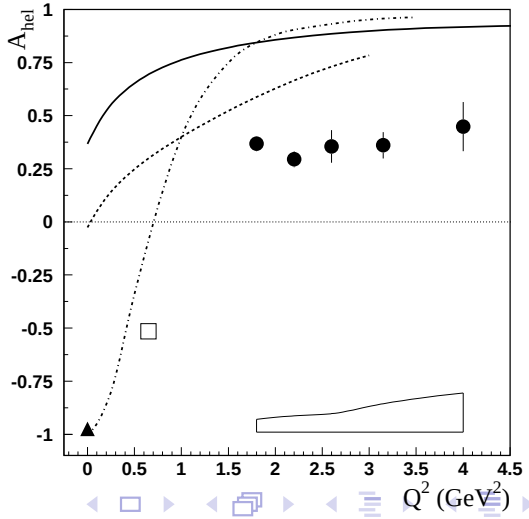
$\vec{e}p \to e'\pi^+ n$ for high lying N^* ($1.65 < W < 2.0$ GeV)



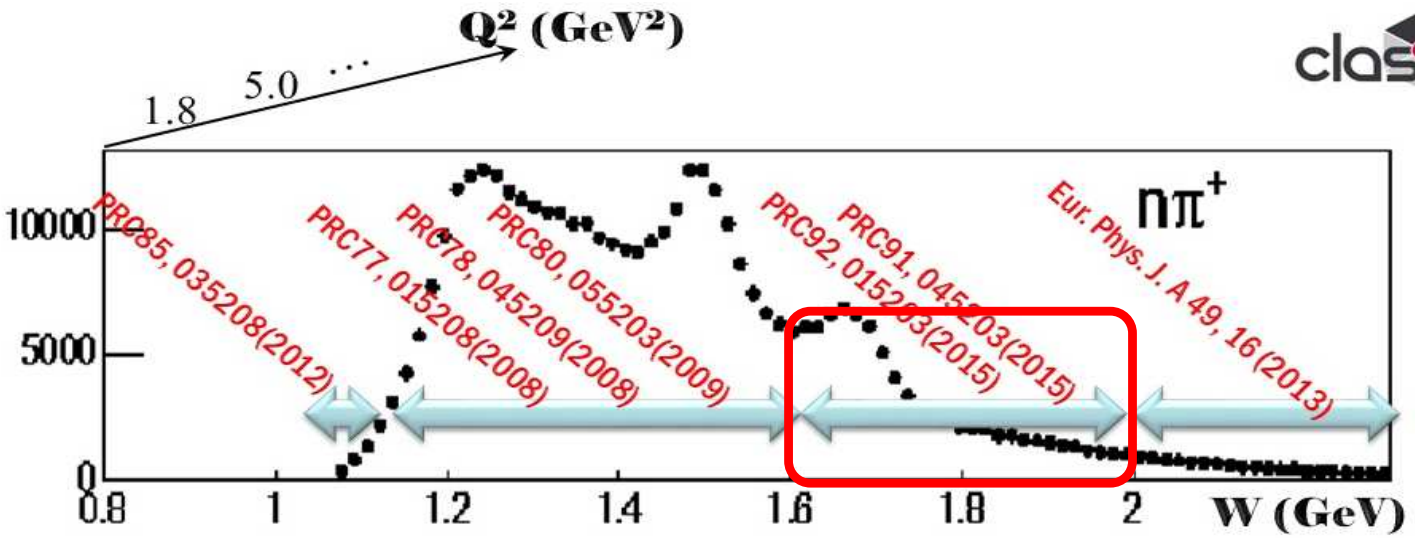
- Helicity asymmetry shows a very slow rise at $Q^2 > 2\text{GeV}^2$
- Interesting of helicity asymmetry $Q^2 > 5$ GeV^2 ?
  $\to$ CLAS12

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

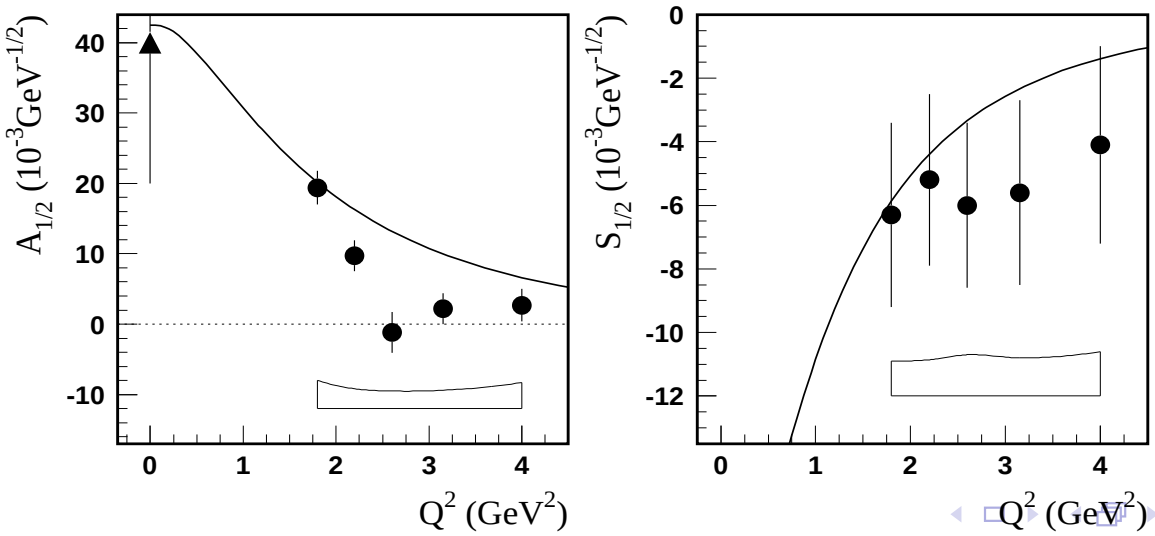
- □ CLAS single-π and 2π electroproduction
- ▲ RPP2014 at $Q^2 = 0$
- Solid: M.M.Gianini/E.Santopinto (hQCM), dash-dot: Z.Lee& F.Close(1990), dash: D.Merten& U.Loring(2003)



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

- **CLAS6 $\rightarrow$ CLAS12 N^* Physics Program**
  - **E12-09-003**, Nucleon Resonance Studies with CLAS12
  - **E12-06-108A**, KY electroproduction with CLAS12
  - **LOI12-15-004**, Search for Hybrid Baryons with CLAS12

Summary

- We have obtained the differential cross-sections/asymmetries using an exclusive single pion electroproduction data for very wide range of kinematics, **near threshold** $< W <$ **DIS** regime, Q^2 =1.6-4.5 GeV^2.
- Precision of single pion data 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 $N(1710)1/2^+$
- Combined analysis with available and future data CLAS12 on all exclusive meson electroproduction channels at $W > 1.2$ GeV at $Q^2 >$ 2 GeV^2 within the framework of coupled channel approaches will improve considerably our knowledge on N^*-state electro-couplings.