Exclusive Single Pion 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,...

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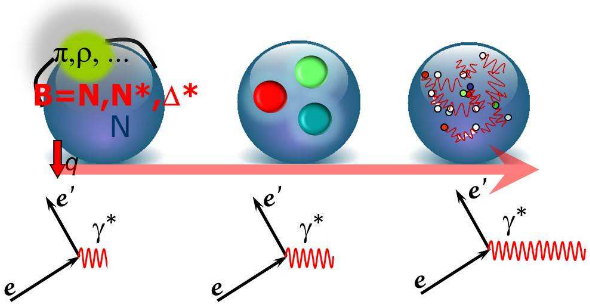
- Study of the excited states of the nucleon is important step in the development of a fundamental understanding of strong interaction

[N. Isgur, V. Burkert (2000)]

- The most fundamental question: " **WHAT ARE THE RELEVANT DEGREE-OF-FREEDOM AT VARYING DISTANCE SCALE ?** "



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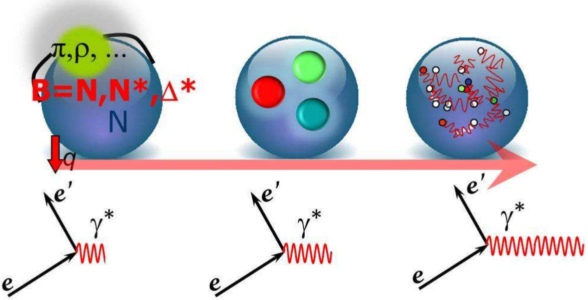

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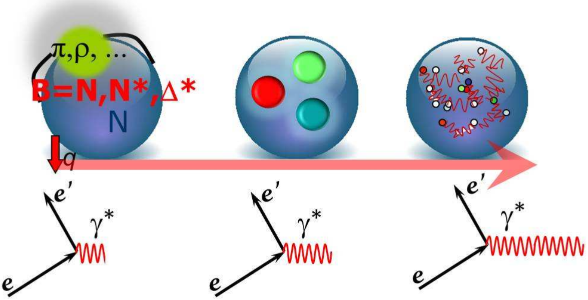
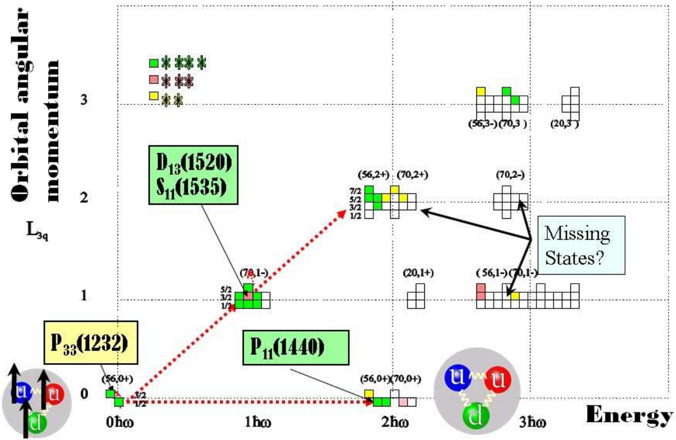


$SU(6) \times O(3)$ Classification of Baryons

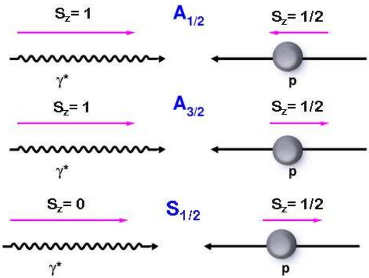


- There are questions about underlying DoF of some well known state...but still many open questions.. related with QCD, FT, CQM, LQCD ...

Photo-coupling Amplitudes

Spin combination

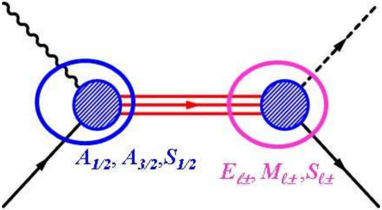
- Transverse
- Longitudinal



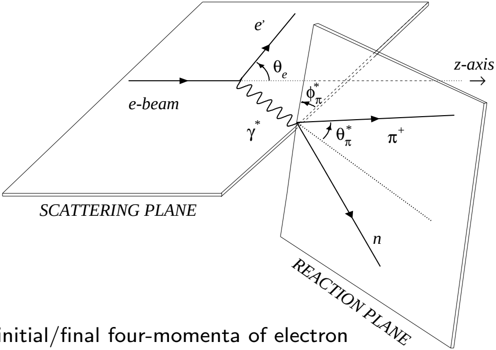
Multipole Amplitudes

- $E_{l\pm}$, $M_{l\pm}$, and $S_{l\pm}$

  $\rightarrow$ l: the orbital angular momentum in $N\pi$ system
  $\rightarrow$ $\pm$ sign: spin of proton couples to the orbital momentum

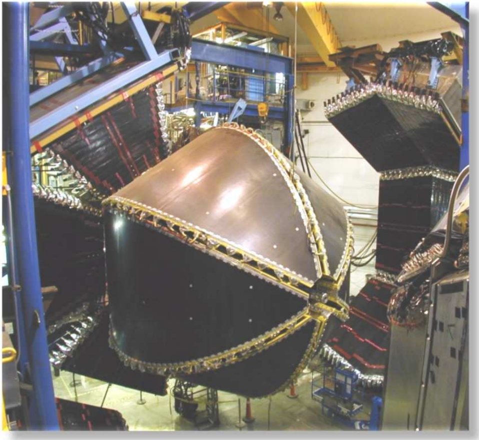


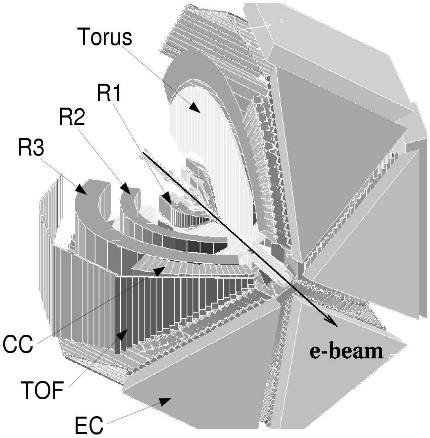
Reaction



- $k_{i,f}$: 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

CEBAF Large Acceptance Spectrometer





CLAS single pion data coverage

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/`

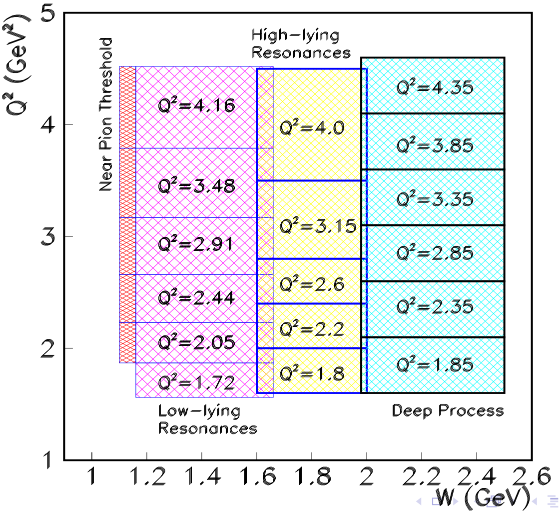
[** $K\Lambda$, $K\Sigma$ see talk by D. Carman, 2π see talk by V. Mokeev]

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	$d\sigma/d\Omega$, (A_{LU})	50400 (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

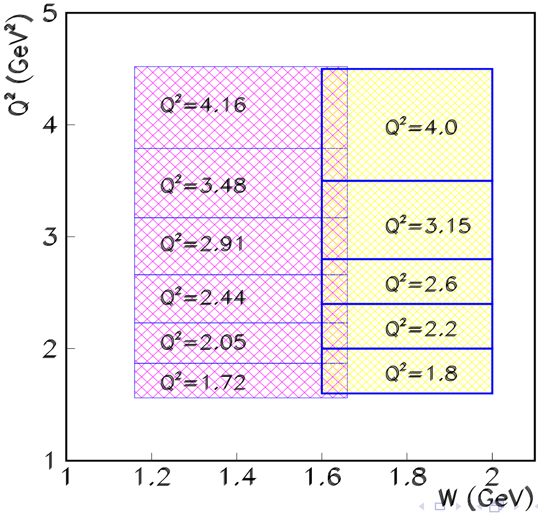
Kinematic coverage of data, E_0=5.5, 5.75 GeV, $P_e \sim 70\%$

- Overall kinematic range W, Q^2 of all $\gamma^* p \to n\pi^+$ analyses
- From the **near pion threshold** to **Deep Process** regime

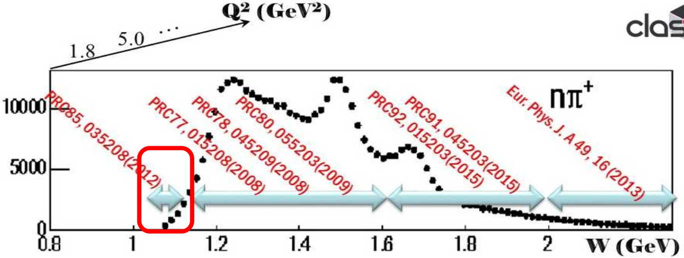


Kinematic coverage of data

- Kinematic range W, Q^2 of N^* analyses
- ($\Delta(1232)3/2^+$), $N(1440)1/2^+$, $N(1520)3/2^-$, $N(1535)1/2^-$, $N(1675)5/2^-$, $N(1680)5/2^+$, and $N(1710)1/2^+$

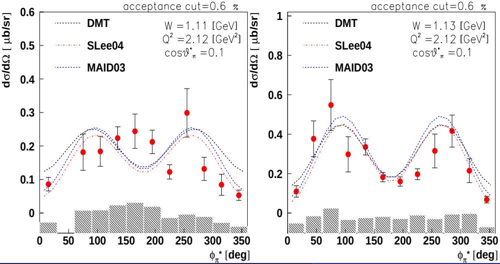


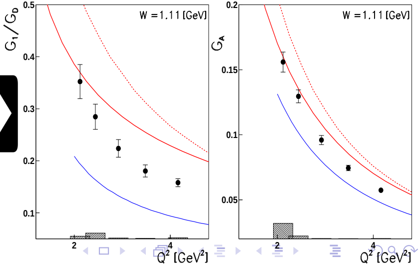
$\vec{e}p \to e'\pi^+ n$ near pion threshold ($1.1 < W < 1.15$ GeV)



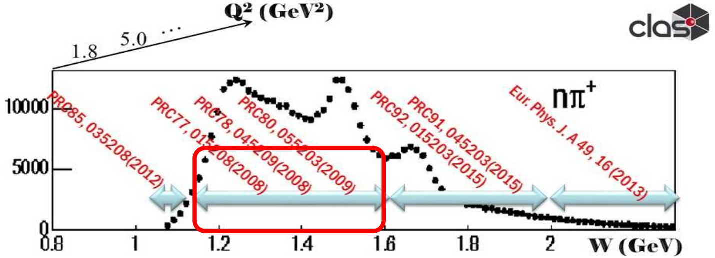
- Generalized form factor (G_1) and Axial Form Factor (G_A) near pion threshold
- Multipole fit vs. LCSR, Both are consistent result in lowest W
- Transverse s-wave multipole (E_{0+}) is dominated

[red solid: LCSR+FF, dash: pure LCSR, blue solid: MAID07 ⇓]

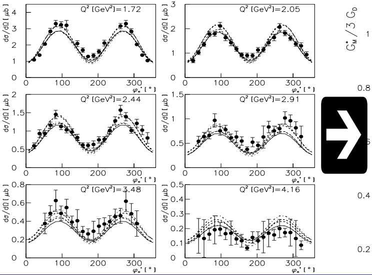


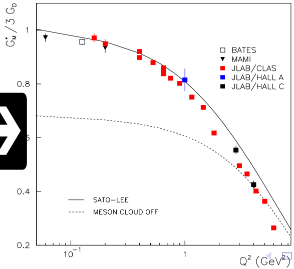


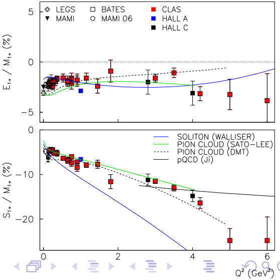
$\vec{e}p \rightarrow e'\pi^+ n$ for low lying Δ ($1.15 < W < 1.69$ GeV)



- 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 $R_{EM} \rightarrow +1$







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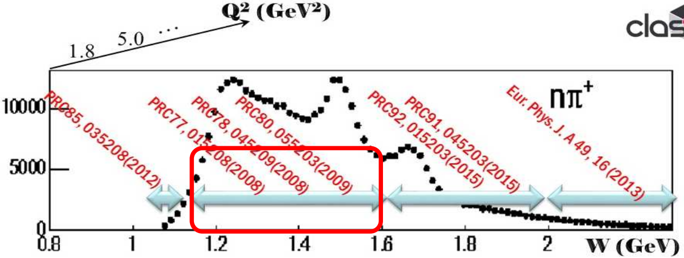
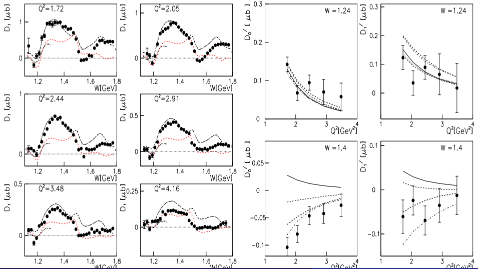
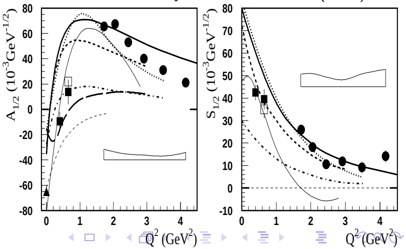
$\vec{e}p \to e'\pi^+n$ for low lying N^* $(1.15 < W < 1.69\ \mathrm{GeV})$



- Transition Form Factors for $N(1440)1/2^+$ (old conv: $P_{11}(1440)$)
- $A_{1/2}$ shows a sign change in $Q^2 \sim 0.8\ \mathrm{GeV}^2$
- $S_{1/2}$ is large at low Q^2 and drop off smoothly with increasing Q^2



Phys.Rev.C78, 045209 (2008)



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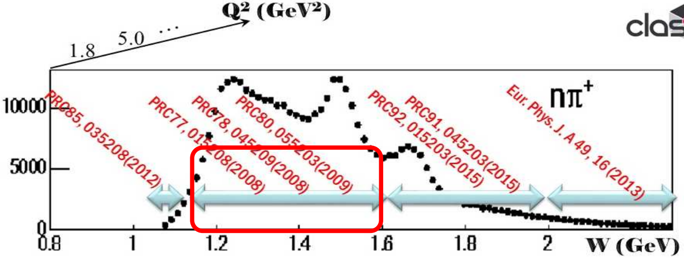
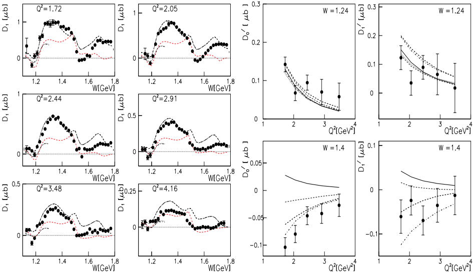
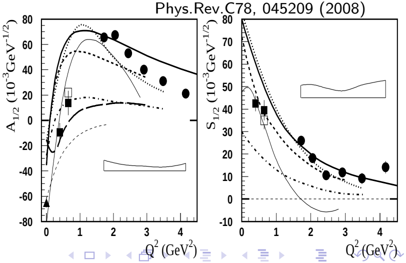


- NR-Quark VM(thin-solid)/Rule out a hybrid baryon model(gluon Excite)
- LFRQ model needs a *MB interaction at large distance*
- **A complex interplay btw inner core of quarks in the first radial excitation and external** *MB cloud*





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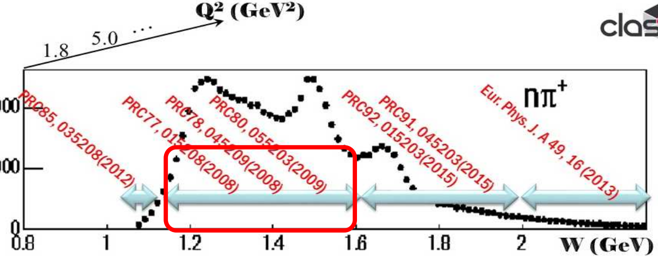
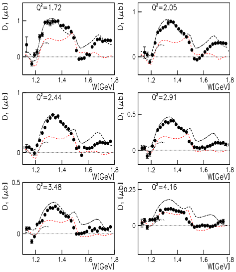
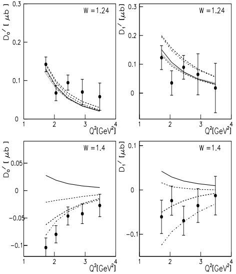
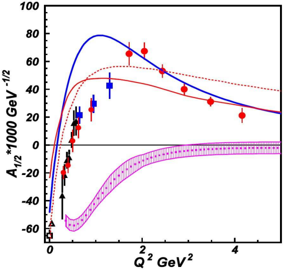


- Quark core in DSEQCD (thick blue curve), MB cloud contribution (purple band)
- $N\pi$ loops MB, running quark mass (red solid curve)
- $N\sigma$ loops MB, fixed constituent quark mass (red dashed curve)

[$\Downarrow$ including single π and 2π data]







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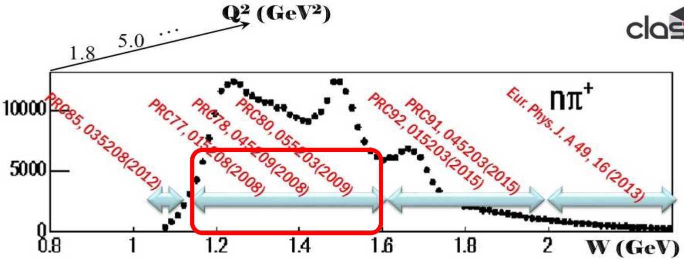
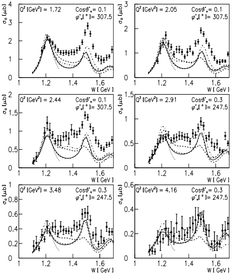
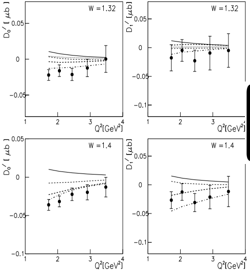
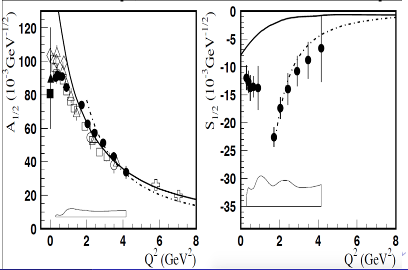


- Transition Form Factors for $N(1535)1/2^-$ (old conv: $S_{11}(1535)$)
- $\beta^{PDG}_{N\eta} = 0.45 - 0.60 \rightarrow \beta^{PDG}_{N\pi} = 0.485$ & $\beta^{PDG}_{N\eta} = 0.460$, excellent agreement $N\pi$, $N\eta$
- Sensitive to long. as well (strong interference S_{11}-P_{11})





[⇓ solid: LFRQM, dash-dot: LCSR]



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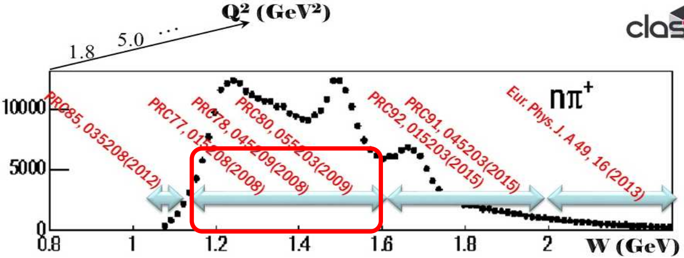
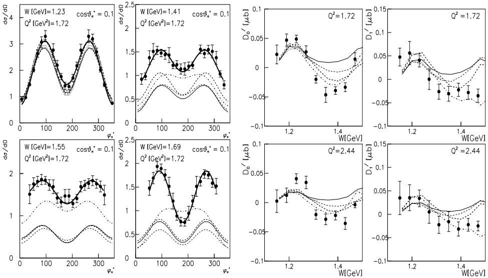
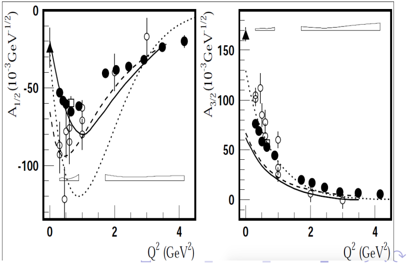


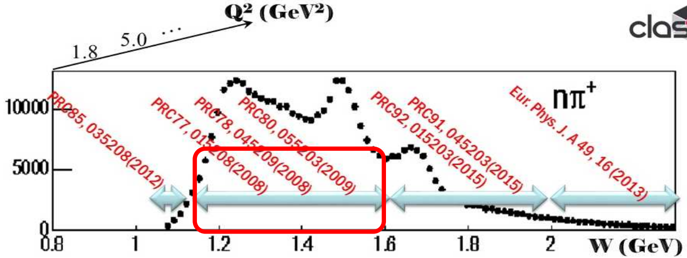
- Transition Form Factors for $N(1520)3/2^-$ (old conv: $D_{13}(1520)$)
- $A_{1/2}$ is large at high Q^2, $A_{3/2}$ is small at high Q^2



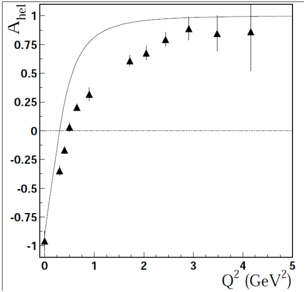
[▲: RPP(2014), ○,□: DESY, NINA data]



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



- Helicity Asymmetry for $N(1520)3/2^-$ (old conv: $D_{13}(1520)$)

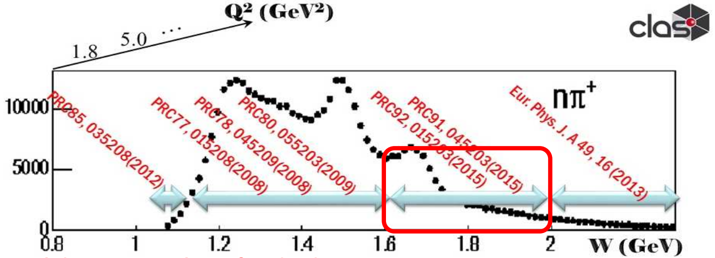


$$\frac{A_{1/2}^{D13}}{A_{3/2}^{D13}} = \frac{-1}{\sqrt{3}}\left(\frac{Q^2}{\alpha} - 1\right)$$

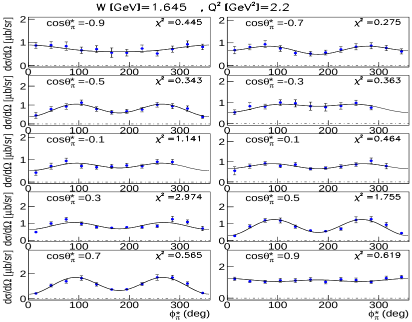
$$A_{hel} = \frac{A_{1/2}^2 - A_{3/2}^2}{A_{1/2}^2 + A_{3/2}^2}$$

- Asymptotic Q^2 behavior of A_{hel} vs. Q^2
  - 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^* $(1.65 < W < 2.0\ \mathrm{GeV})$



- **differential cross-sections** for third resonance region



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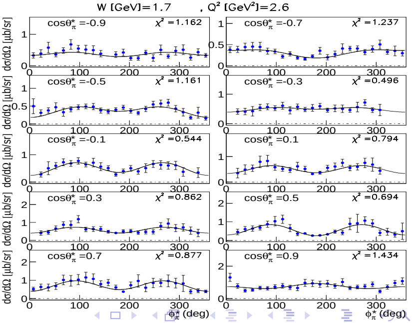

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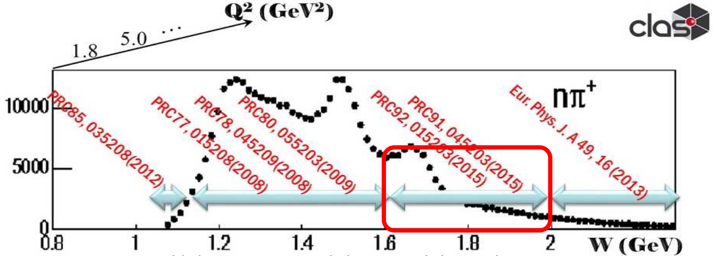
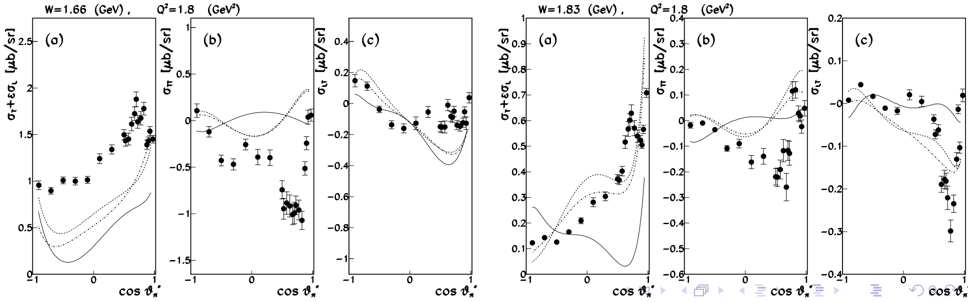


- **structure functions** ((a) $\sigma_T + \epsilon\sigma_L$, (b) σ_{TT}, (c) σ_{LT}) for third resonance region
  - dash: MAID07, dash-dot: MAID03, dot: DMT



In the analysis

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

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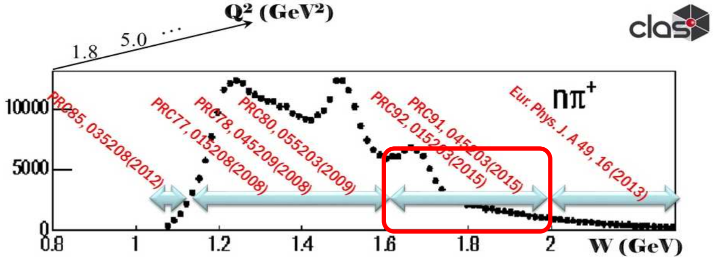
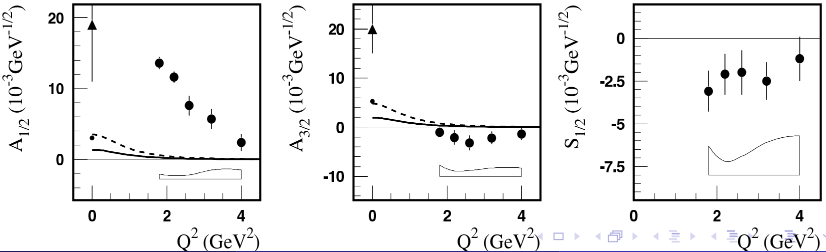
  - Fixed-t dispersion relation for the invariant amplitude
  - *Re*-Amplitude to Born-term (s,u, channel nucleon exchange, π exchange in t-
  - Integral *Im*-Amplitude with the isospin structure
- **Two model-uncertainties**
  1/ BG determination in the UIM and Born term in DR
  2/ A width and mass of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

$\vec{e}p \to e'\pi^+ n$ 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)



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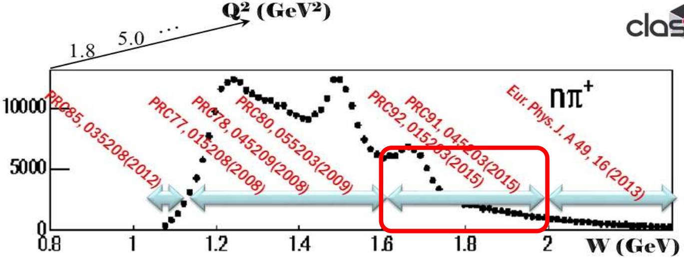
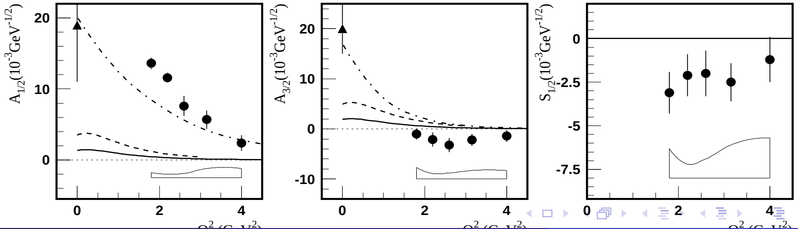
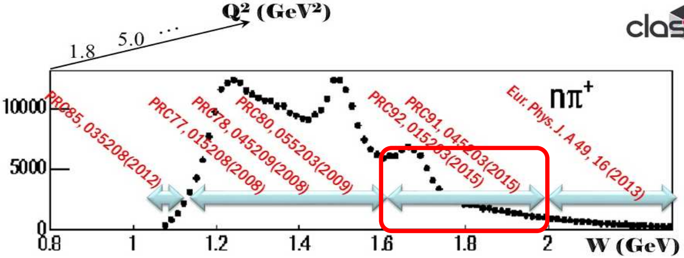


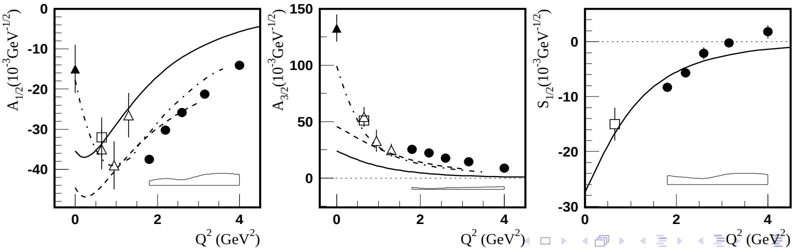
- Non-quark contributions dominance, A strong coupling $A_{1/2}$ for $Q^2 < 4$ GeV^2
- Significant *MB contribution from the dynamical coupled-channel model* *(dash-dot:B.Julia-Diaz,T-S.H.Lee,A.Matsuyama)*
- *A strong suppression of* $A_{3/2}$ *for* $Q^2 > 1.8$ GeV^2



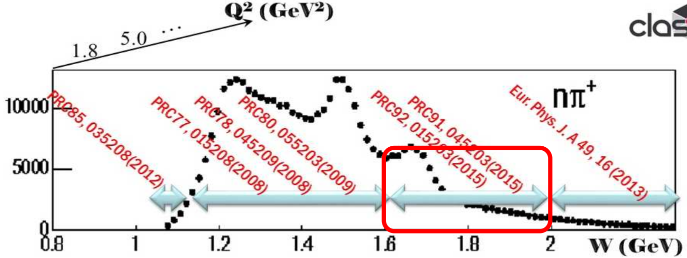
$\vec{e}p \rightarrow e'\pi^+ n$ for high lying N^* ($1.65 < W < 2.0$ GeV)



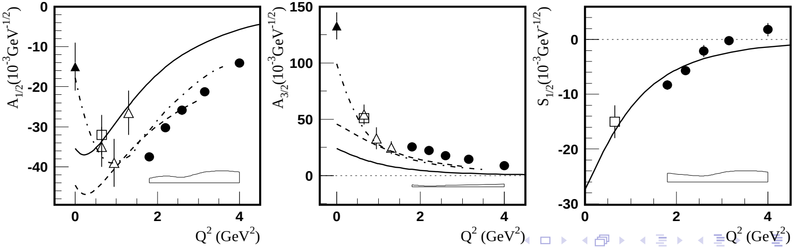
- Transition Form Factors for $N(1680)5/2^+$ (old conv: $F_{15}(1680)$)
- ▲ RPP(PDG:2014), △ V.Mokeev& I.G.Aznauryan(2013), □ I.G.Aznauryan(2005)
- Solid: M.M.Gianini/E.Santopinto (hQCM), dash-dot: Z.Lee& F.Close(1990), dash: D.Merten& U.Loring(2003)



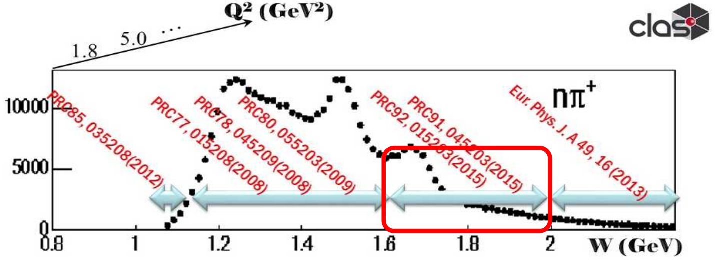
$\vec{e}p \to e'\pi^+ n$ for high lying N^* ($1.65 < W < 2.0$ GeV)



- Transition Form Factors for $N(1680)5/2^+$ (old conv: $F_{15}(1680)$)
- All models estimates amplitudes larger $A_{1/2}$ (lower $A_{3/2}$) than data
- *MB contribution should be taken into account ?*



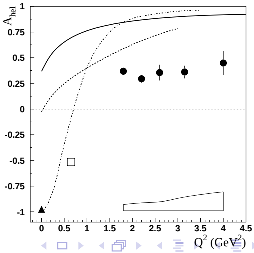
$\vec{e}p \to e'\pi^+ n$ for high lying N^* $(1.65 < W < 2.0$ GeV$)$



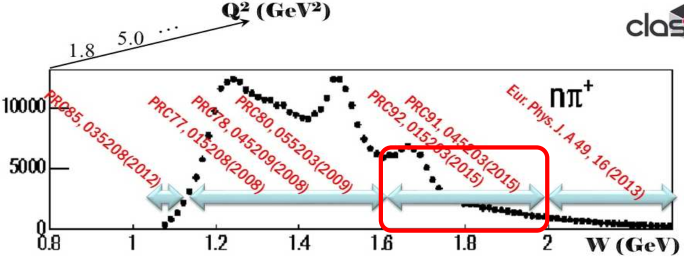
- Helicity asymmetry shows a very slow rise at $Q^2 > 2\text{GeV}^2$
- Interesting of helicity asymmetry $Q^2 > 5$ GeV^2 ? $\to$ CLAS12

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

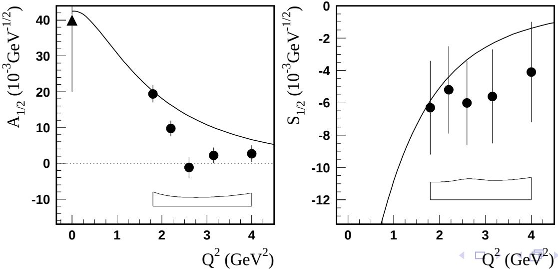
- □ CLAS single-π and 2π electroproduction
- ▲ RPP2014 at $Q^2 = 0$
- Solid: M.M.Gianini/E.Santopinto (hQCM), dash-dot: Z.Lee& F.Close(1990), dash: D.Merten& U.Loring(2003)



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



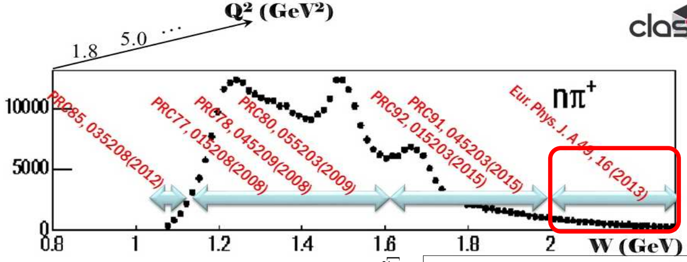
- Transition Form Factors for $N(1710)1/2^+$ (old conv: $P_{11}(1710)$)
- Finite size of $A_{1/2}$ for $Q^2 < 2.5$ GeV^2
- Finite size and negative of $S_{1/2}$ for all given Q^2 GeV^2



Solid: M.M.Gianini

E.Santopinto (hQCM)

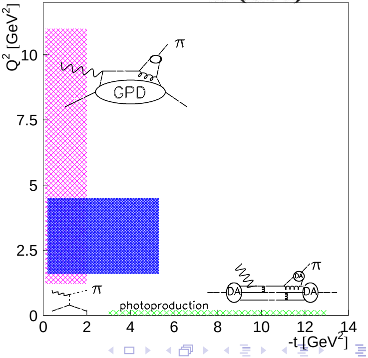
$\vec{e}p \to e'\pi^+ n$ for Deep Process ($W > 2.0$ GeV)



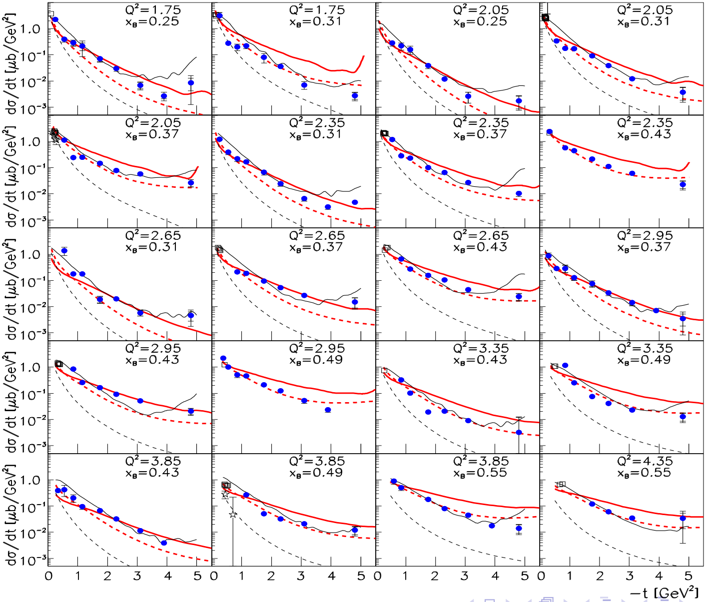
- Transition between hadronic and partonic picture of strong interaction
- Connection to the transversity GPD
- Kinematic variables $\to x_{BJ}$, Q^2 and $-t$

Blue box $\to$

Note that $-t$: the momentum transfer to the nucleon, $t = (p_N - p'_N)^2$

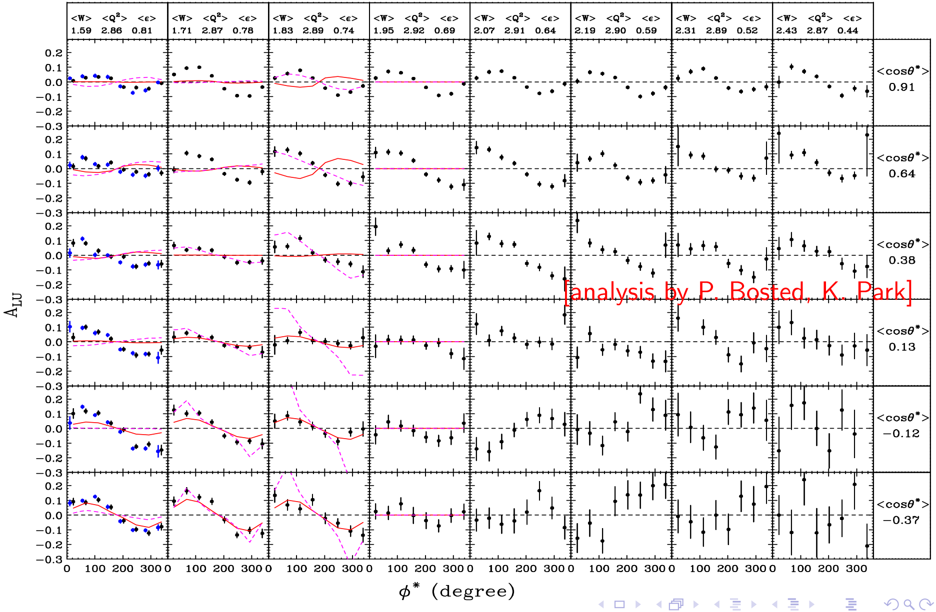


$\vec{e}p \to e'\pi^+ n$ for Deep Process ($W > 2.0$ GeV)



More single pion data are coming from CLAS6!

$\vec{e}p \rightarrow e'\pi^+ n$, beam asymmetry $(A_{LU})^{PRELIMINARY}$ e1-6, eg1b



$\vec{e}p \rightarrow e'\pi^0 p$ for (low Q^2)

E_0 =2 GeV, W =1.1-1.8 GeV, Q^2=0.4-1.0 GeV^2 [analysis by N. Markov]

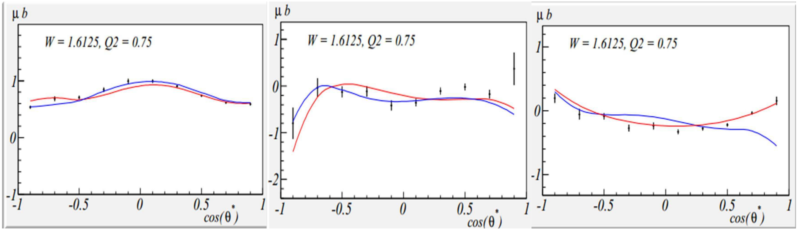


Figure: (**PRELIMINARY**) $\sigma_T + \epsilon\sigma_L$, σ_{TT}, and σ_{LT}, red(MAID07), blue(SAID08) curves

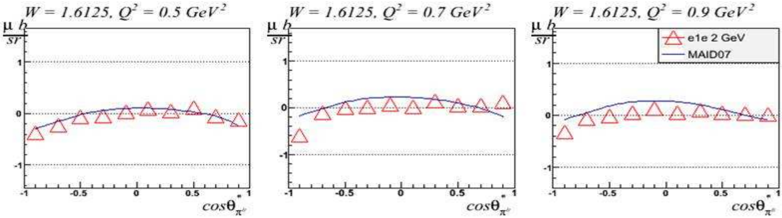
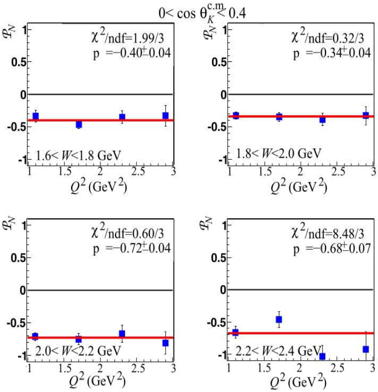


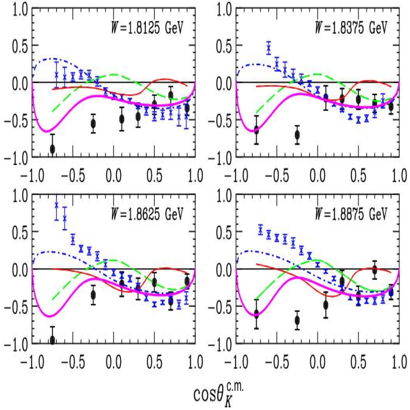
Figure: (**PRELIMINARY**) $\sigma_{LT'}$ blue(MAID07) curve

- **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

LOI12-15-004, + Additional interesting aspect

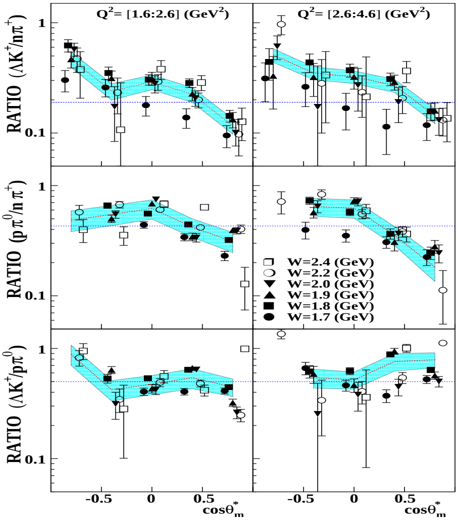
- Understanding of physics between $Q^2 = 0$ and $Q^2 > 0$ GeV^2
- Already saw in some resonance states in previous presentation
- Another example $K^+\Lambda$ induced polarization [Phy.Rev.C**90**, 035202 (2014).]





LOI12-15-004, + Additional interesting aspect

- Hadronization in high energy by color flux-tube model
- Strangeness suppression factor shows consistent with high energy results
  - [Phys.Rev.Lett.**113**, 152004 (2014).]
- Q^2 independence is universal down to phton point ?



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 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.