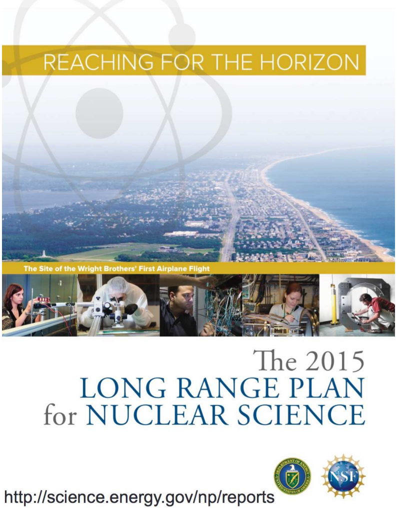
Extracting Resonance Parameters from $\gamma^* p \rightarrow n\pi^+$ at CLAS

Kijun Park

Nov. 13-18, 2016

Overview

Long Range Plan 2015



1. **Fully utilize programs at existing & under construction facilities (JLab12, RHIC, NSCL, FRIB,...)**
2. Sustain a targeted program in fundamental symmetries & neutrino research
3. Invest in a ton-scale neutrino-less double beta decay experiment
4. Construct a high-energy high-luminosity polarized **EIC** with highest priority following the completion of FRIB
5. Invest in mid- and small-scale projects at universities and laboratories

21^{st} Century Nuclear Science: LRP2015

1. How did visible matter come into being and how does it evolve ?

2. How does subatomic matter organize itself and what phenomena emerge ?

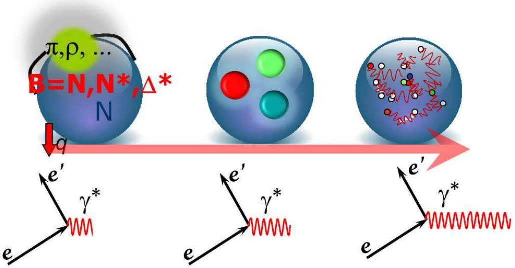
3. Are the fundamental interactions that are basic to the structure of matter fully understood ?

4. How can the knowledge and technical progress provided by nuclear physics best be used to benefit society ?

How can we approach these questions ?

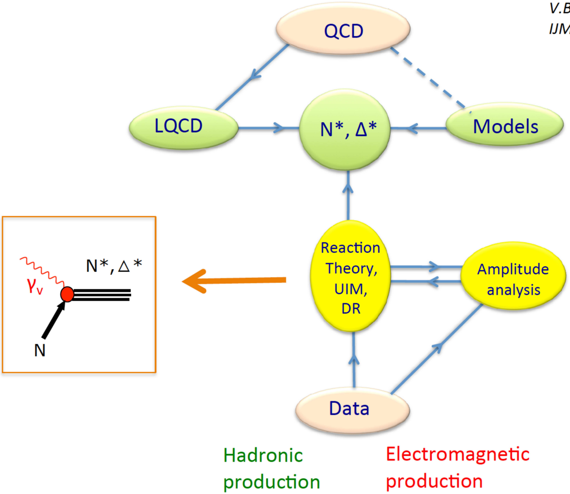
The most challenging problems in Hadron Physics

- 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 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 ?** "

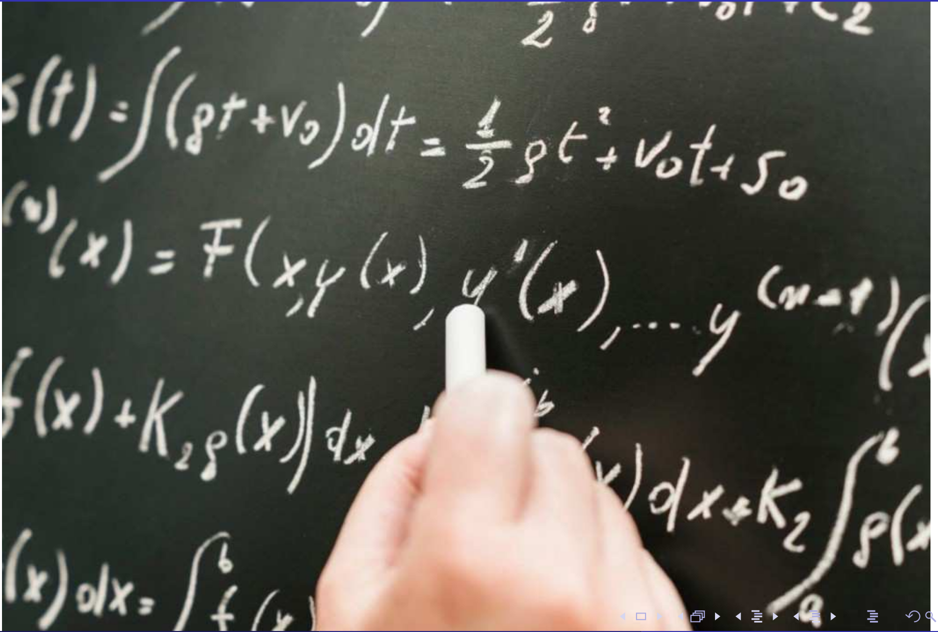


Analysis Chain

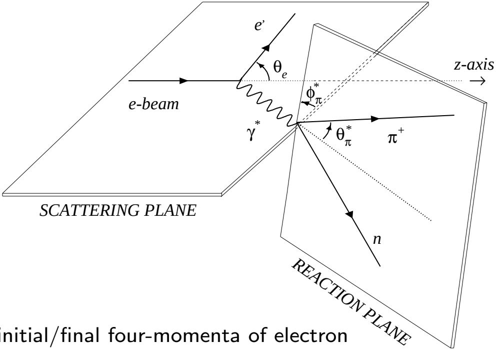
V.B., T.-S.H. Lee
IJMP E13 (2004) 1035



Let me talk a little bit about kinematics



Reaction, $\vec{e}p \rightarrow e'\pi^+ n$



- $k_{i,f}$: 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

Formalism, $\vec{e}p \rightarrow e'\pi^+ n$

- 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,

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

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

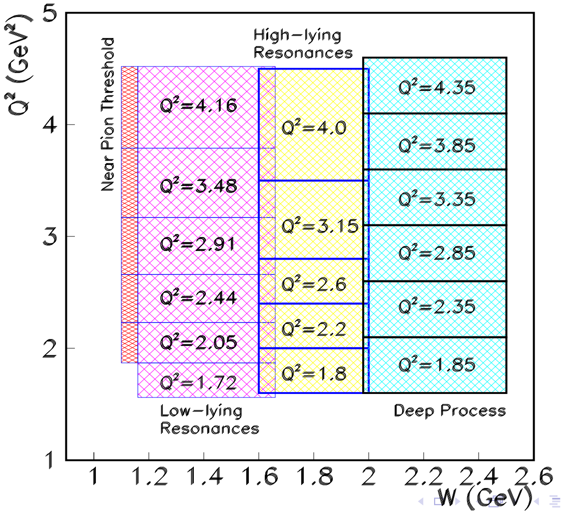
$$\frac{d^2\sigma}{d\Omega^*_\pi} = \frac{p^*_\pi}{k^*_\pi}\left(\sigma_0 + h\sqrt{2\epsilon(1-\epsilon)}\sigma'_{LT}\sin\theta^*_\pi \sin\phi^*_\pi\right)$$

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

where,
h: beam helicity state
σ_0: unpolarized cross-section
$\sigma_U = \sigma_T + \epsilon\sigma_L$
Kinematics is completely defined by five variables (Q^2, W, θ^*_π, ϕ^*_π, and ϕ_e)

Kinematic coverage, E_0=5.49, 5.75 GeV, $P_e \sim 70\%$

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



Let me talk about the highlighted results briefly...

In the analysis

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

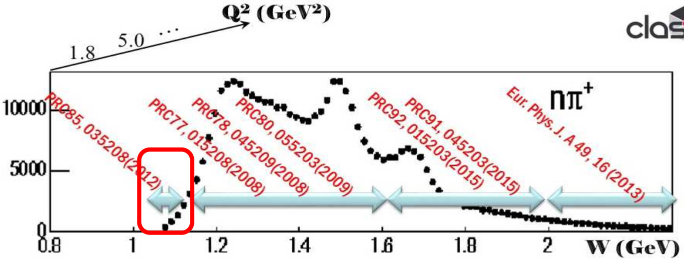
  UIM

  - 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

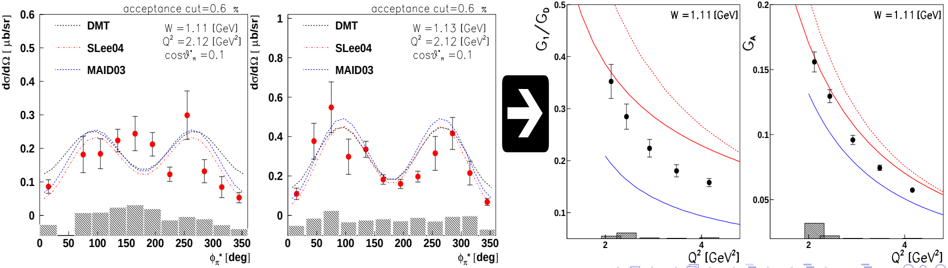
  - Fixed-*t* dispersion relation for the invariant amplitude
  - *Re*-Amplitude to Born-term (nucleon exchange in *s*-,*u*-, π exchange in *t*-channel)
  - Integral *Im*-Amplitude with the isospin structure
- **Two model-uncertainties**
  1/ BG determination in the UIM and Born term in DR
  2/ A width 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

Near threshold ($W < 1.15$ 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

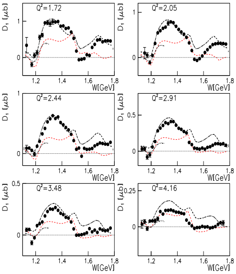
[red solid: LCSR+FF, dash: pure LCSR, blue solid: MAID07 ⇓]

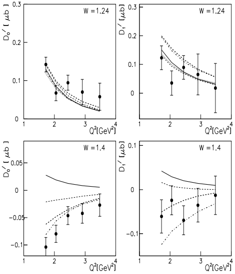


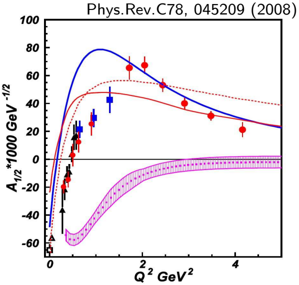
$\vec{e}p \to e'\pi^+ n$ for low lying N^* ($W = 1.15 - 1.69$ GeV)

- 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***
- 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]



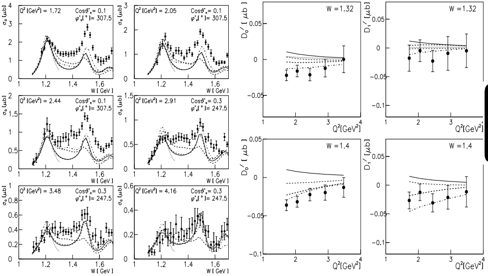


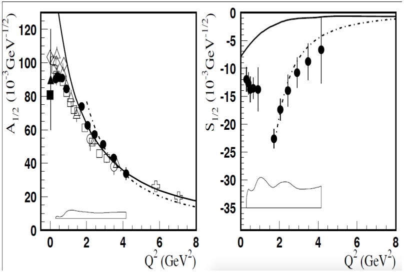


$\vec{e}p \to e'\pi^+ n$ for low lying N^* ($W = 1.15 - 1.69$ GeV)

- 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
- Sensitive to long. as well (strong interference S_{11}-P_{11})
- Previously 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]

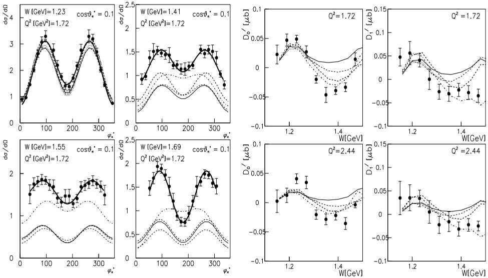
[$\Downarrow$ solid: LFRQM, dash-dot: LCSR]



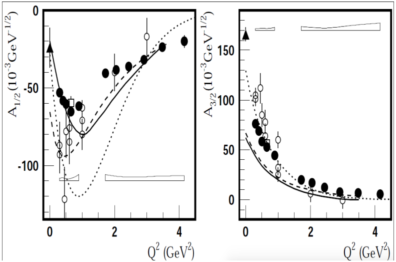


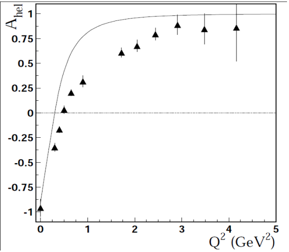
$\vec{e}p \to e'\pi^+ n$ for low lying N^* ($W = 1.15 - 1.69$ GeV)

- 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



[▲: RPP(2014), ○,□: DESY, NINA data]





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

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

- 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

Selection Rules in Symmetric Quark Model

- The first orbital excitation states
  $|70, {}^28, 1, 1, J\rangle$ - $S_{11}(1535)$(****), $D_{13}(1520)$(****)
  $|70, {}^48, 1, 1, J\rangle$ - $S_{11}(1650)$(****), $D_{13}(1700)$(***), $D_{15}(1675)$(****)

- **Moorhouse selection rule** (Moorhouse, PRL16, 772 (1966))
  $\gamma + p(|56, {}^28; 0, 0, 1/2\rangle) \not\leftrightarrow N^*(|70, {}^48\rangle)$: vanishing TME for charge operator
  $\gamma + n(|56, {}^28; 0, 0, 1/2\rangle) \leftrightarrow N^*(|70, {}^48\rangle)$

- Λ selection rule (Zhao, PRD74, 094014 (2006))
  $N^*|70, {}^48\rangle \not\leftrightarrow K(K^*) + \Lambda$

- Faiman-Hendry selection rule (Faiman,Hendry, PR173, 1720 (1968))
  $\Lambda^*|70, {}^48\rangle \not\leftrightarrow N(|56, {}^28; 0, 0, 1/2\rangle) + \bar{K}$

Moorhouse 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

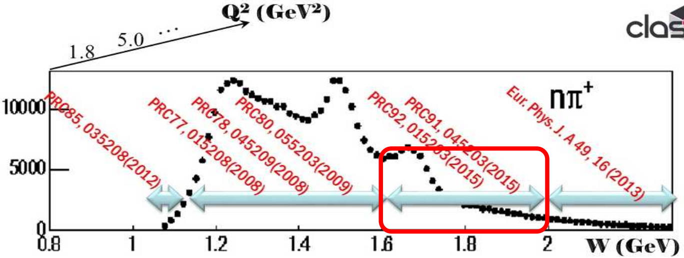
$$H_{hyper} = \frac{2\alpha_s}{3m_i m_j}\left[\frac{8\pi}{3} S_i \cdot S_j \delta^3(r_{ij}) + \frac{1}{r_{ij}^3}\left(\frac{3(S_i \cdot r_{ij})(S_j \cdot r_{ij})}{r_{ij}^2} - S_i \cdot S_j\right)\right]$$

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

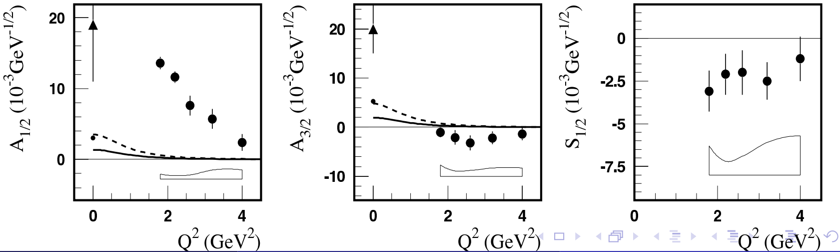
Quantity	SU(6) (Relative values)	This calculation (Relative values)	Experiment (Various units)
$A_{3/2}^{n}(D_{15} \to n\gamma)$	$-\alpha$	$-\alpha$	-60 ± 33 [a]
$A_{1/2}^{n}(D_{15} \to n\gamma)$	-0.71α	-0.71α	-33 ± 25 [a]
$A_{3/2}^{p}(D_{15} \to p\gamma)$	0	$+0.31\alpha$	$+20 \pm 13$ [a]
$A_{1/2}^{p}(D_{15} \to p\gamma)$	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]

[Reference:Isgur, Karl, PRL 41, 1269 (1978).]

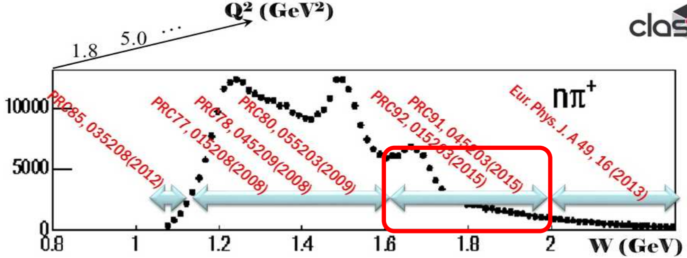
$\vec{e}p \to e'\pi^+ n$ for high lying N^* ($W = 1.65 - 2.0$ GeV)



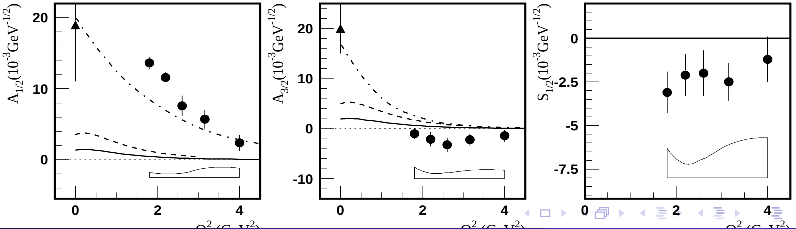
- Transition Form Factors for $N(1675)5/2^-$ (old conv: $D_{15}(1675)$)
- SQTM, Moorhouse selection rule: suppression Transverse Amplitudes
- Solid: M.M.Gianini/E.Santopinto (hQCM)
  dash: D.Merten& U.Loring(2003), Solid-dot(Q^2 =0): I.G.Aznauryan(LFRQ)



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

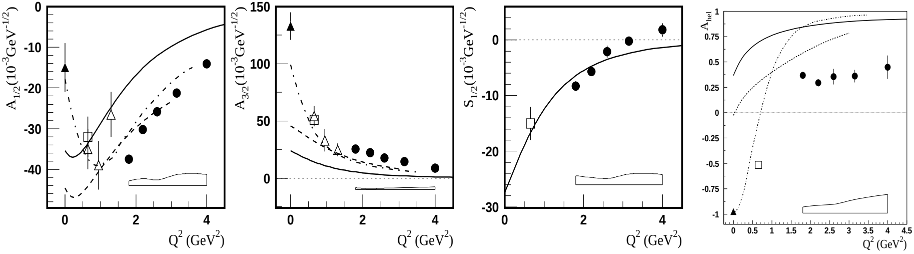


- Non-quark contributions dominance, A strong coupling $A_{1/2}$ for $Q^2 < 4$ GeV^2
- Significant *MB contribution from the dynamical coupled-channel model (dash-dot:B.Julia-Diaz,T-S.H.Lee,A.Matsuyama)*
- *A strong suppression of $A_{3/2}$ for $Q^2 > 1.8$ GeV^2*



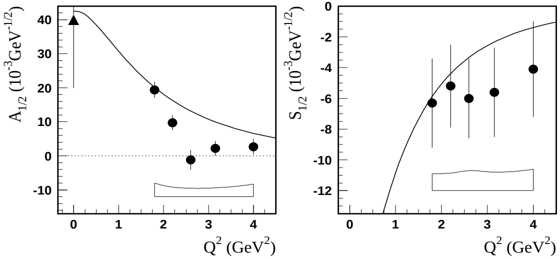
$\vec{e}p \rightarrow e'\pi^+ n$ for high lying N^* ($W = 1.65 - 2.0$ GeV)

- 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 ?



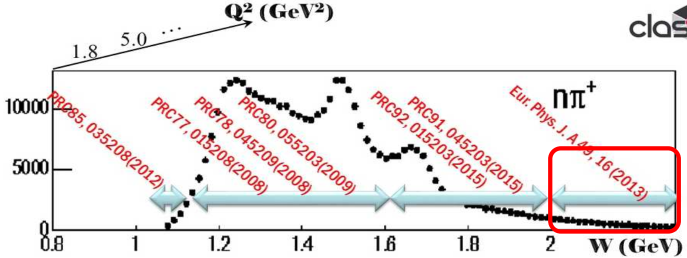
$\vec{e}p \rightarrow e'\pi^+ n$ for high lying N^* ($W = 1.65 - 2.0$ GeV)

- 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



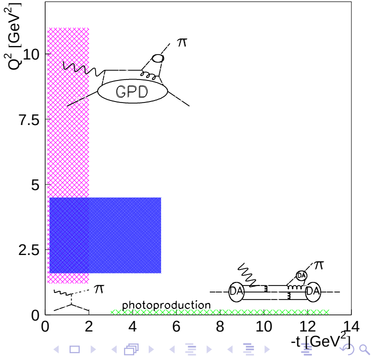
Solid: M.M.Gianini
E.Santopinto (hQCM)

Deep Inelastic Process ($W > 2.0$ GeV)

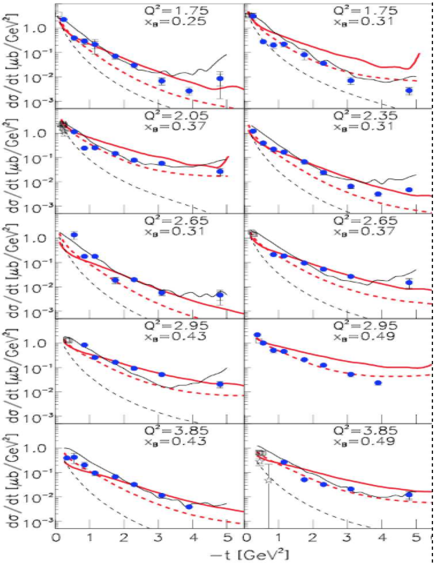


- Transition between hadronic and partonic picture of strong interaction
- GPD
  $\rightarrow$ Correlations of longitudinal momentum fraction with transverse spatial position
- DVMP: $N(e, e'NM)$, $M = \pi$, ρ, ϕ, ...
  $\rightarrow$ Connection to the transversity GPD
- Kinematic variables $\rightarrow$ x_{BJ}, Q^2 and $-t$

Blue box $\rightarrow$
[K.Park, *et al.*, Eur. Phys. J. A49 16, (2013)]

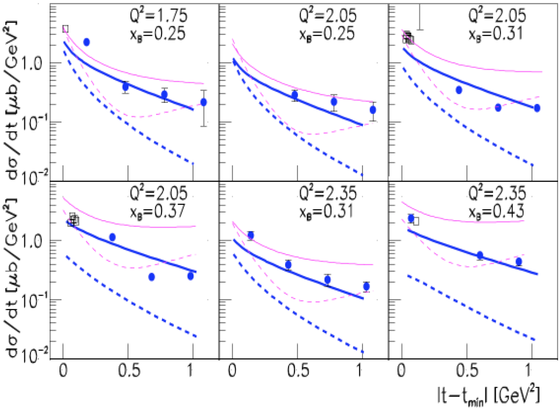


Hard exclusive forward,large-angled $\gamma^* p \rightarrow n\pi^+$

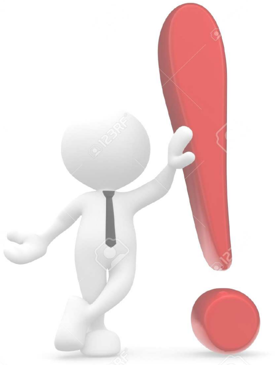


- Solid ($d\sigma/dt$), dashed curves ($d\sigma_L/dt$)
- Red curves: J. M. Laget, Regge-model
- Blue curves: M. Kaskulov, Hybrid (hadron-parton) model

Hard exclusive forward, large-angled $\gamma^* p \to n\pi^+$



- 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)

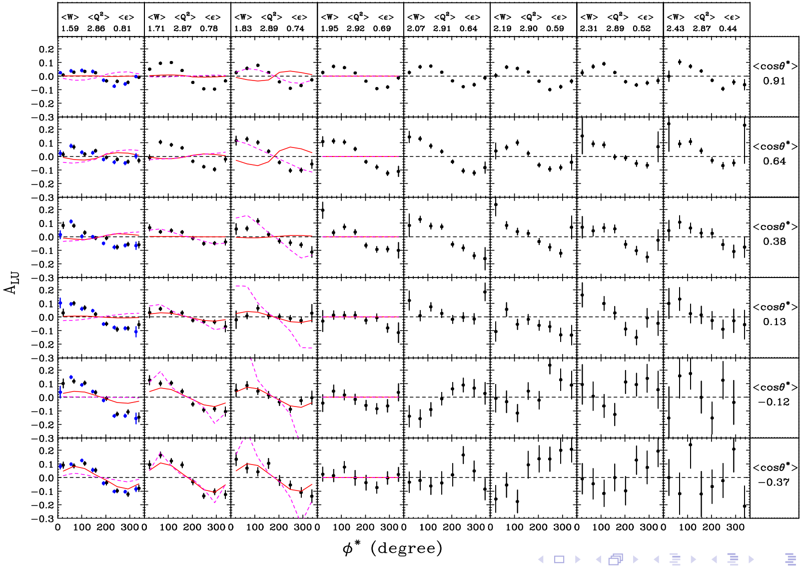


New upcoming results 2017 !!!

under CLAS^6 Analysis Review !

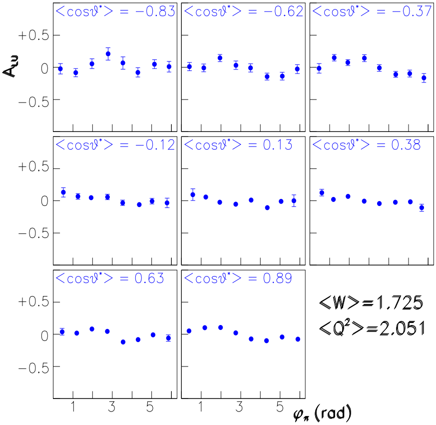
$\vec{e}p \to e'\pi^+ n$, A_{LU} for $W = 1.6 - 2.4$ GeV

Curves: solid-MAID2007, dashed-JANR, Blue: Phys. Rev. C**77** 015208, (2008), Black points: current work **P. Bosted/K. Park**

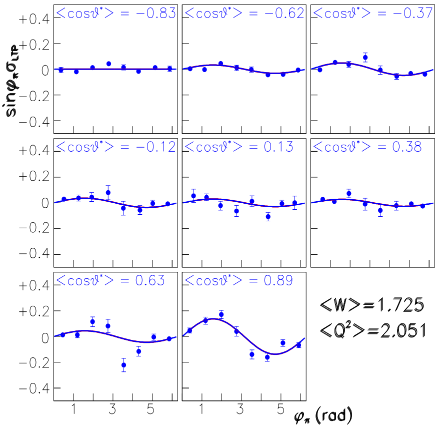


A_{LU}, $\sigma_{LT'}$ for $W = 1.68 - 2.03$ GeV, **PRELIMINARY**

A_{LU}



$\sin\phi^* \sigma_{LTP}$

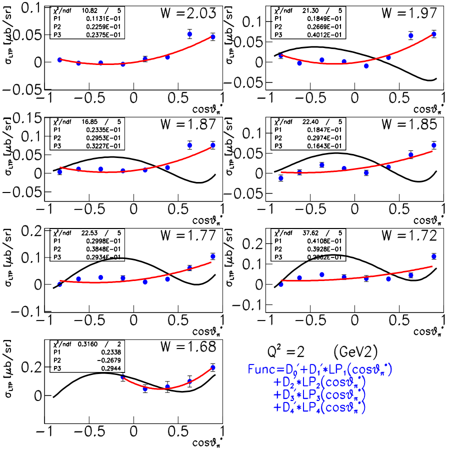


Blue curves: $\sin\phi^*$ fit

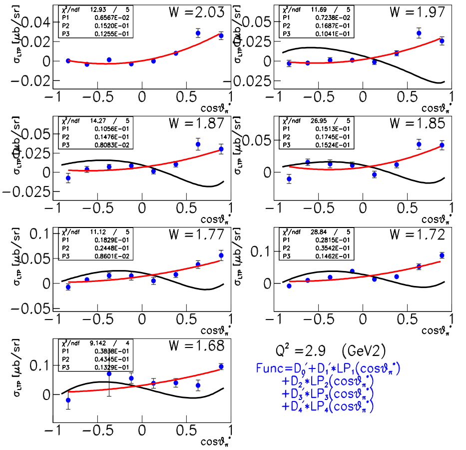
$\sigma_{LT'}$ vs. $\cos\theta_\pi^*$, MAID2007, **PRELIMINARY**

Red curves: Legendre fit, Black curves: MAID2007

$Q^2 = 2.0$ GeV^2



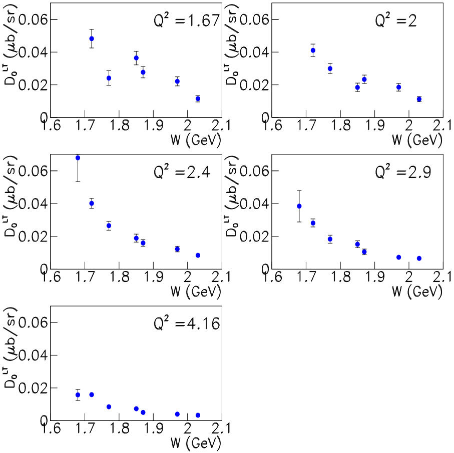
$Q^2 = 2.90$ GeV^2



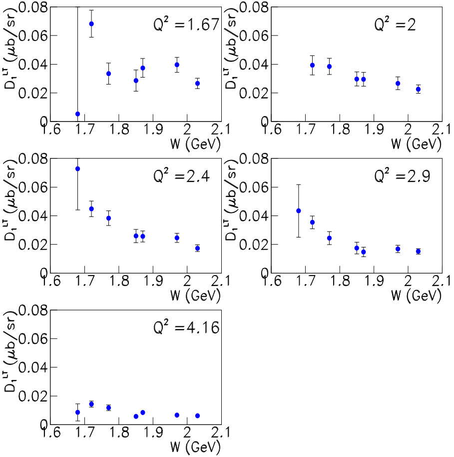
Moments $D^{LT'}$ vs. W, **PRELIMINARY**

Observation: interesting behavior above $W > 1.8$ GeV

Moments $D_0^{LT'}$



Moments $D_1^{LT'}$



Summary

- Extraction of the transition form factor have been carried out through the differential cross-sections/asymmetries measurements for $\gamma^* p \to n\pi^+$ data for nearly full range of kinematics, **near threshold** $< W <$ **DIS** regime, Q^2 =1.6-4.5 GeV^2.

- Precision data for $\gamma^* p \to n\pi^+$ from CLAS allows to extract the helicity amplitudes for various reonance 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 $p\pi^0$,$p\pi^+\pi^-$,...$K\Lambda$, $K\Sigma$...) is crucial in particular high W and this will improve considerably our knowledge on N^*-state electro-couplings.

  $\rightarrow$ Coupled-Channel Analysis and A Full Mass Spectrum data help us to map out nucleon structure with an effective degree of freedom.