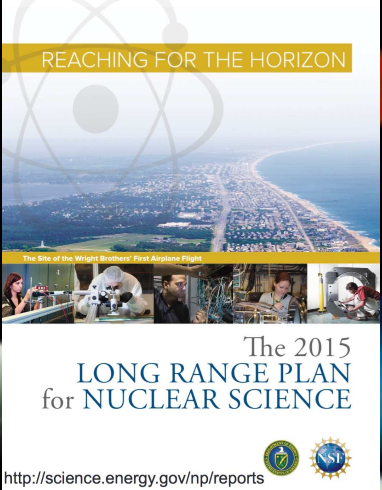
Recent Results of the Exclusive Single Pion Electroproduction off the Proton from CLAS

KIJUN PARK

July 1-4, 2018

Overview

Long Range Plan 2015 (21^{st} Century Nuclear Science)



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 ?

Present one of the many efforts

This Talk !

The most challenging problems in Hadron Physics

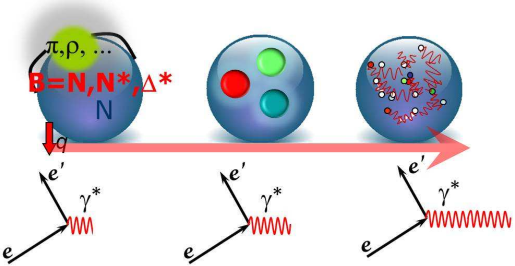
- Non-perturbative **DCSB** generates more than 98% of **dress quark masses** as well as **dynamical structure** although, Higgs mechanism $< 2\%$ in N, N^* masses
- Quark-gluon **confinement** in bayrons emerges from QCD; dressed quarks, meson-baryon cloud, dressed gluon,...

Talk by, C. Robert, V. Mokeev

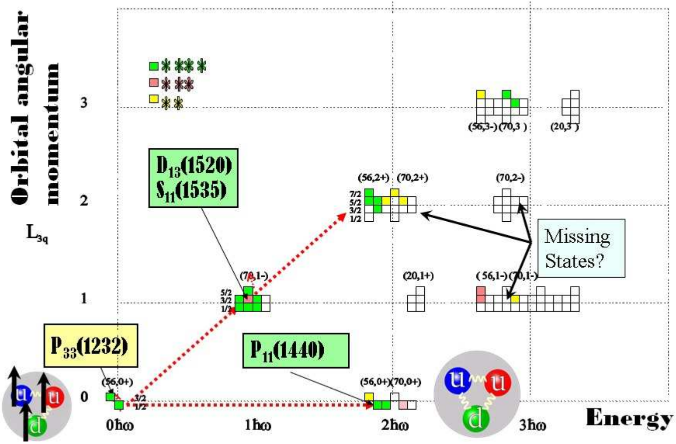
- Study of the excited states of the nucleon is important step in the development of a fundamental understanding of strong interaction; QGP $\rightarrow$ Hadrons

Talk by V. Mokeev

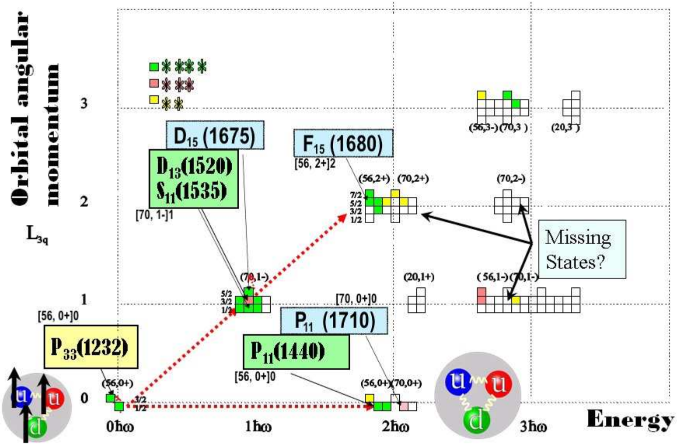
- The most fundamental question: " **WHAT ARE THE RELEVANT DEGREE-OF-FREEDOM AT VARYING DISTANCE SCALE ?** "



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

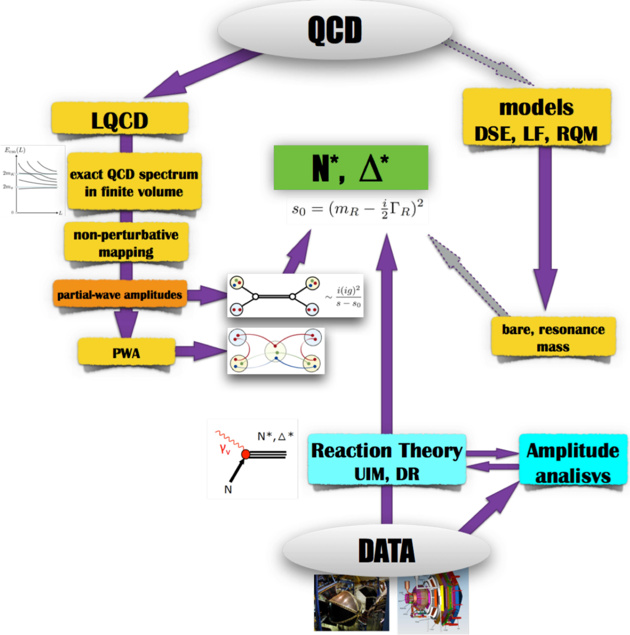


- There are questions about underlying DoF of some well known state...but still many open questions.. related with QCD, FT, CQM, LQCD ...
- Effective degrees of freedom / Transition charge densities / Running quark mass → **Nature of States**



- 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 $\rightarrow$ **Nature of States**

Analysis Chain



Modified the original flowchart

Credit to R. Briceno

Analysis Approaches and CLAS data analyses

- **UIM**, **DR** for $\pi^+ n$ and $\pi^0 p$

  I. G. Aznauryan, Phys. Rev. C**67**, 015209 (2003).
  I. G. Aznauryan *et al.*, CLAS Coll., Phys. Rev. C**80**, 055203 (2009).
  I. G. Aznauryan *et al.*, CLAS Coll., Phys. Rev. C**91**, 045203 (2015).

- Extension of **UIM**, **DR**, **Data fit** for ηp, ωp

  I. G. Aznauryan, Phys. Rev. C**68**, 065204 (2003).
  H. Denizli *et al.*, CLAS Coll., Phys. Rev. C**76**, 015204 (2007).

- **JM-MB** model, Data fit for $\pi^+ \pi^- p$

  V. I. Mokeev, V. D. Burkert *et al.*, Phys. Rev. C**80**, 045212 (2009).
  V. I. Mokeev *et al.*, CLAS Coll., Phys. Rev. C**86**, 035203 (2012).
  V. I. Mokeev, V. D. Burkert *et al.*, Phys. Rev. C**93**, 054016 (2016).

Overview: NN^* Electrocoupling Extraction from CLAS data

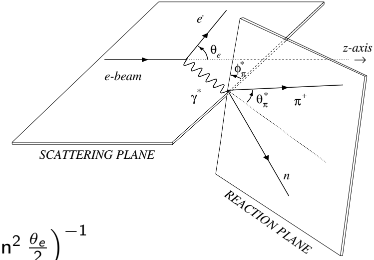
Talk by V. Mokeev

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

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

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

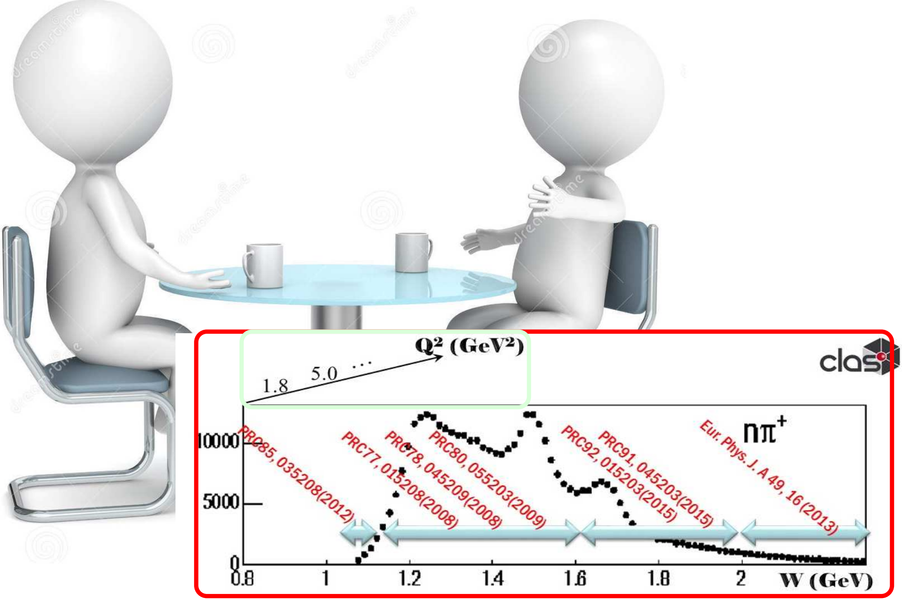
ϵ: virtual photon polarization: $\left(1 + 2\left(1 + \frac{\nu^2}{Q^2}\right)\tan^2\frac{\theta_e}{2}\right)^{-1}$

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

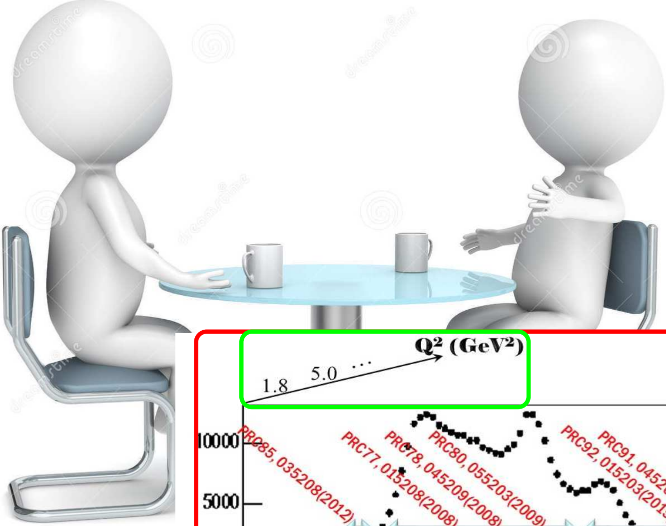
$$\sigma_0 = \sigma_U + \epsilon\sigma_{TT}\sin^2\theta_\pi^*\cos 2\phi_\pi^* + \sqrt{2\epsilon(1+\epsilon)}\sigma_{LT}\sin\theta_\pi^*\cos\phi_\pi^*$$

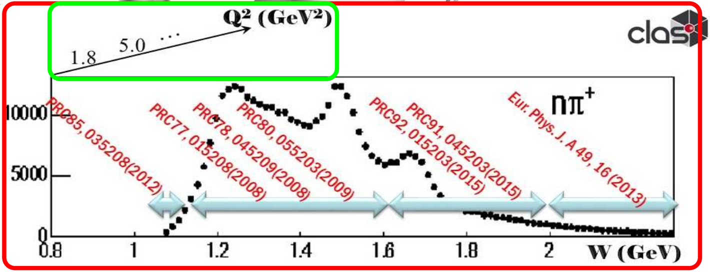
where,
h: beam helicity state
σ_0: unpolarized cross-section
$\sigma_U = \sigma_T + \epsilon\sigma_L$
Kinematics is completely defined by five variables (Q^2, W, θ_π^*, ϕ_π^*, and ϕ_e)

Let me briefly talk about the highlighted results ...



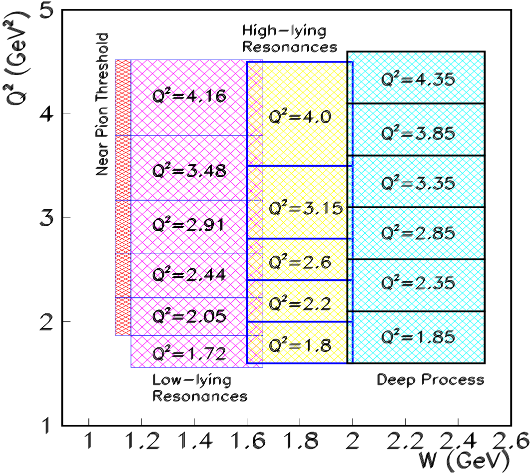
Let me briefly talk about the highlighted results ...



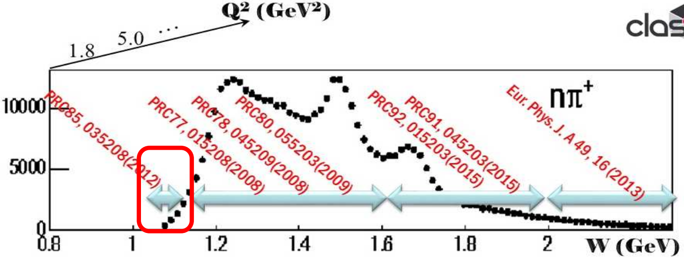


In particular, $ep \to e'\pi^+ n$

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

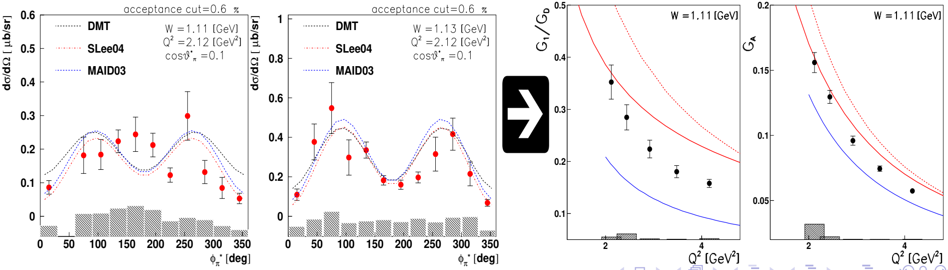


Near threshold ($W < 1.15$ GeV)



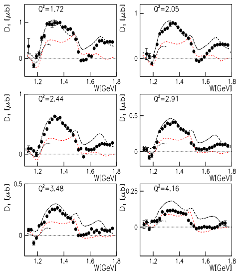
- Generalized form factor (G_1) and Axial Form Factor (G_A) near pion threshold
- Multipole fit & LCSR, Both showed consistent results in lowest W

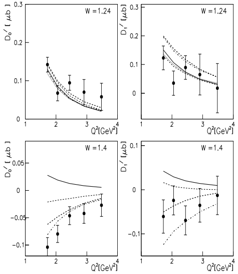
[red solid: LCSR+FF, dash: pure LCSR, blue solid: MAID07 ⇓]



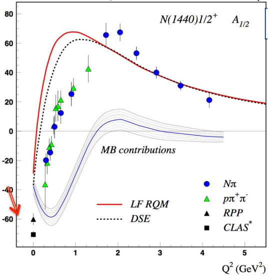
$\vec{e}p \rightarrow e'\pi^+n$ for low lying N^* ($W = 1.15 - 1.69$ GeV)

- 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)





Phys.Rev.C78, 045209 (2008)



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

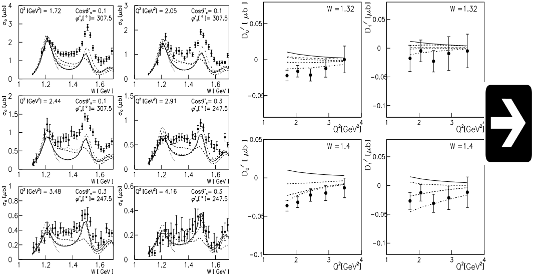
- Transition Form Factors for $N(1535)1/2^-$ (old conv: $S_{11}(1535)$)
- $\beta^{PDG}_{N\eta} = 0.45 - 0.60 \to \beta^{PDG}_{N\pi} = 0.485$ & $\beta^{PDG}_{N\eta} = 0.460$, excellent agreement
- Sensitive to long. as well (strong interference S_{11}-P_{11})
- Previously Opposite sign of $S_{1/2}$!

  $\to$ Impossible to change in quark model (LFRQM failed for $S_{1/2}$!)

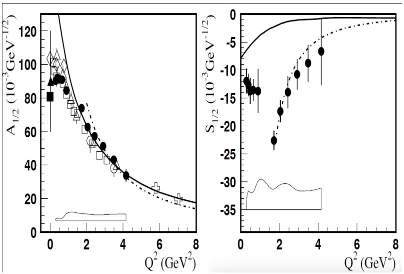
  $\to$ Combined with the difficulties in the description of
  (1) large width of $S_{11}(1535) \to \eta N$
  (2) large $S_{11}(1535) \to \phi N$, ΛK couplings

  $\to$ It shows that $3q$ picture for $S_{11}(1535)$ should be complemented ! [I.Aznuryan]

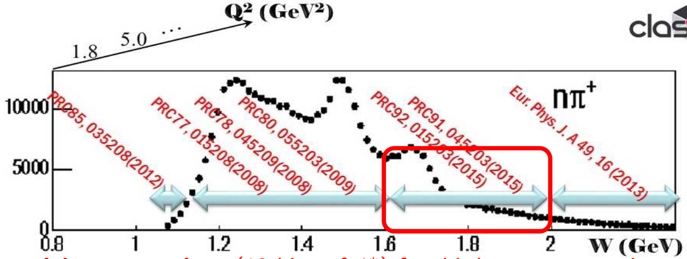
...



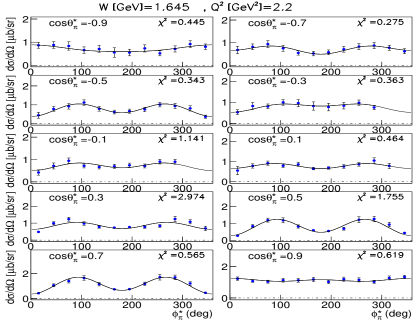
[⇓ solid: LFRQM, dash-dot: LCSR]

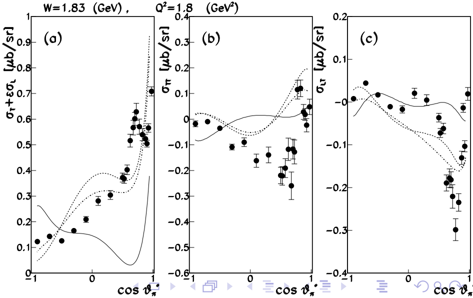


$\vec{e}p \to e'\pi^+ n$ for high lying N^* $(1.65 < W < 2.0$ GeV$)$

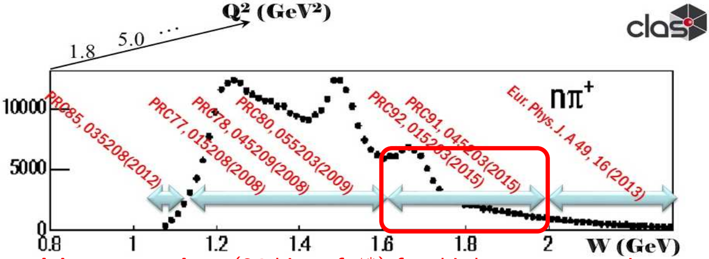


- **differential cross-sections** (12 bins of ϕ^*) for third resonance region

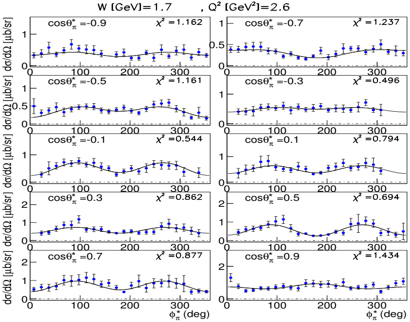


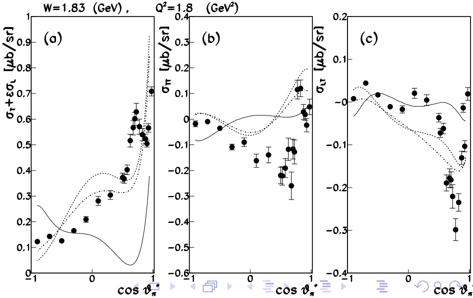


$\vec{e}p \rightarrow e'\pi^+ n$ for high lying N^* ($1.65 < W < 2.0$ GeV)



- **differential cross-sections** (24 bins of ϕ^*) for third resonance region





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))
  $\gamma + p(|56, {}^2 8; 0, 0, 1/2\rangle) \not\leftrightarrow N^*(|70, {}^4 8\rangle)$: 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))
  $N^*|70, {}^4 8\rangle \not\leftrightarrow K(K^*) + \Lambda$

- Faiman-Hendry selection rule (Faiman,Hendry, PR173, 1720 (1968))
  $\Lambda^*|70, {}^4 8\rangle \not\leftrightarrow N(|56, {}^2 8; 0, 0, 1/2\rangle) + \bar{K}$

Moorhouse selection rule must be violated !

Spin-dependent potential from one-gluon-exchange and $SU(6) \otimes O(3)$ symmetry breaking, color hyperfine interaction H_{hyper} is introducing mass splitting and configuration mixing in $SU(6)$ multiplets Isgur, Karl, PRL 41, 1269 (1978).

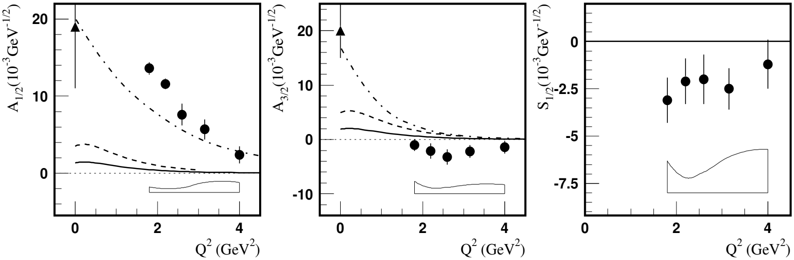
$$H_{hyper} = \frac{2\alpha_s}{3m_i m_j}\left[\frac{8\pi}{3} S_i \cdot S_j \delta^3(r_{ij}) + \frac{1}{r_{ij}^3}\left(\frac{3(S_i \cdot r_{ij})(S_j \cdot r_{ij})}{r_{ij}^2} - S_i \cdot S_j\right)\right]$$

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

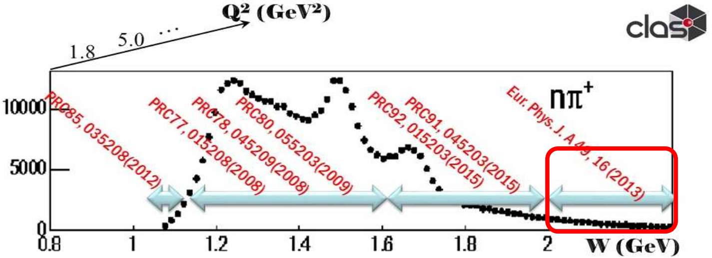
Quantity	SU(6) (Relative values)	This calculation (Relative values)	Experiment (Various units)
$A_{3/2}^{n}(D_{15}\to n\gamma)$	$-\alpha$	$-\alpha$	-60 ± 33 [a]
$A_{1/2}^{n}(D_{15}\to n\gamma)$	-0.71α	-0.71α	-33 ± 25 [a]
$A_{3/2}^{p}(D_{15}\to p\gamma)$	0	$+0.31\alpha$	$+20\pm13$ [a]
$A_{1/2}^{p}(D_{15}\to p\gamma)$	0	$+0.22\alpha$	$+19\pm14$ [a]
$A(D_{15}\to KN)$	β	β	$+0.41\pm0.03$ [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	$+0.82\pm0.02$ [d]
$\langle\sum e_i r_i^2\rangle_n$	0	-0.16γ	-0.12 ± 0.01 [e]

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

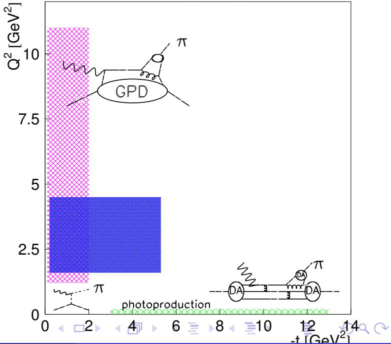
- Transition Form Factors for $N(1675)5/2^-$ (old conv: $D_{15}(1675)$)
- SQTM, Moorhouse selection rule: suppression Transverse Amplitudes
  $\to$ Solid: M. M. Gianini/E. Santopinto (hQCM)
  $\to$ dash: D.Merten& U.Loring(2003)
- Non-quark contributions dominance, A strong coupling $A_{1/2}$ for $Q^2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



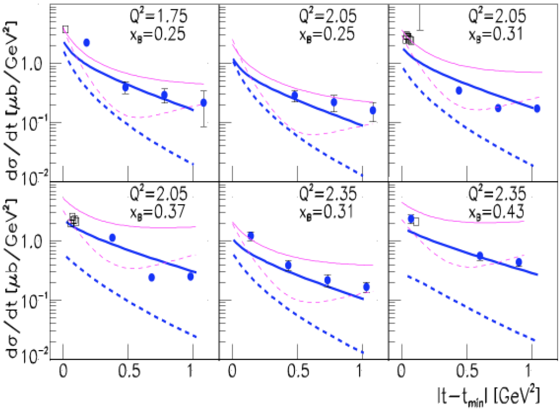
Deep Inelastic Scattering Regime ($W > 2.0$ GeV)



- Transition between hadronic and partonic picture of strong interaction
- GPD
  $\rightarrow$ Correlations of longitudinal momentum fraction with transverse spatial position
- DVMP: $N(e, e'NM)$, $M = \pi, \rho, \phi, \ldots$
  $\rightarrow$ Connection to the transversity GPD
  Blue box $\rightarrow$
  [K.Park, *et al.*, Eur. Phys. J. A49 16, (2013)]

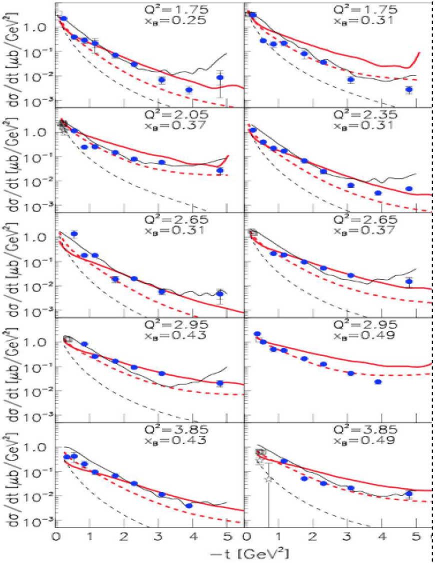


Hard Exclusive Forward, Large angle $\gamma^* p \to n\pi^+$



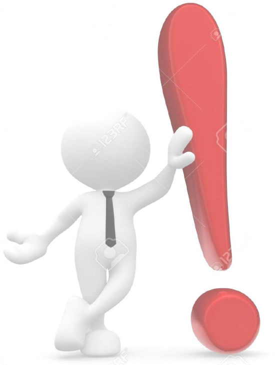
- Solid ($d\sigma/dt$), dashed curves ($d\sigma_L/dt$)
- Magenta curves:
  M. Kaskulov, Duality model
  $\to$ Transverse: resonance excitation
  $\to$ Longitudinal: t-channel meson exchange
- Blue curves: G-K : Transversity of GPDs
  $\to$ Partonic model (handbag diagram) (But w/o adjusting Jlab kinematics)

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



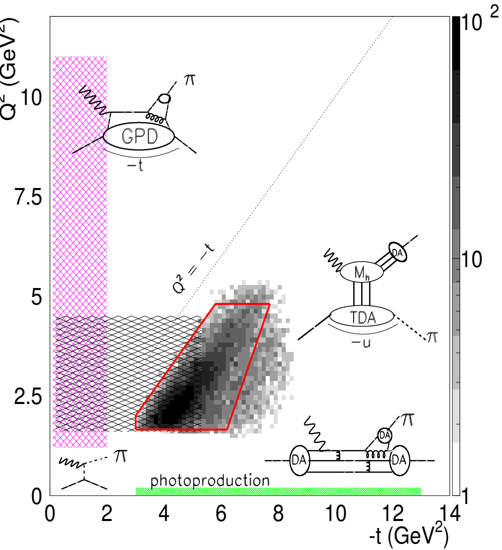
- Solid ($d\sigma/dt$), dashed curves ($d\sigma_L/dt$)
- Red curves: J. M. Laget, Regge-model
- Blue curves: M. Kaskulov, Hybrid (hadron-parton) model

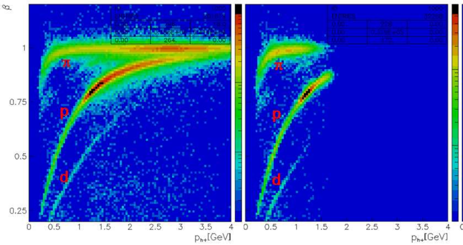
** Hybrid: The partonic part of production mechanism is described by DIS quark knock out reaction is followed by string

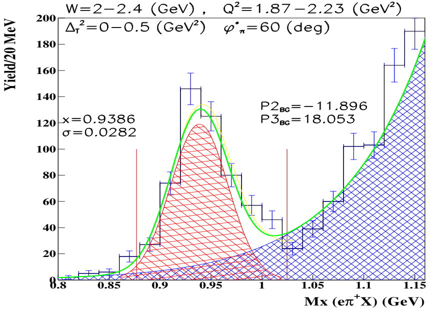


New Results 2018 !!!
& Upcoming New Results 2019 !!!

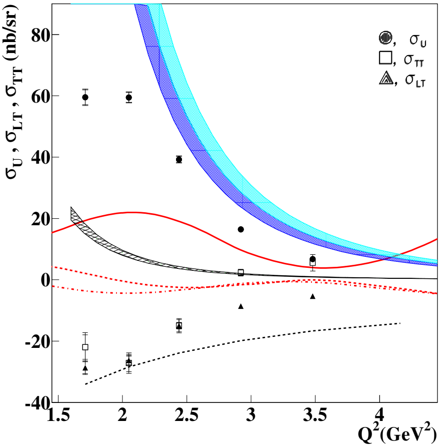
Hard Exclusive Backward angle $\gamma^* p \to n\pi^+$







Structure functions vs. πN-TDA calculation



[K.Park, *et al.*, Phys. Lett. B 780, 340 (2018)]

- $\sigma_T + \epsilon\sigma_L$ (●), σ_{TT} (□), and σ_{LT} (▲)
- 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 πN-TDA model
  Red band: BLW NNLO [a], dark blue band: COZ [b], and light blue band: KS [c]
- Nucleon pole exchange in u-channel contribution is determinant for smaller ξ (D-term GPDs)
- Theoretical understanding is growing up: spectral representation for πN 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

---

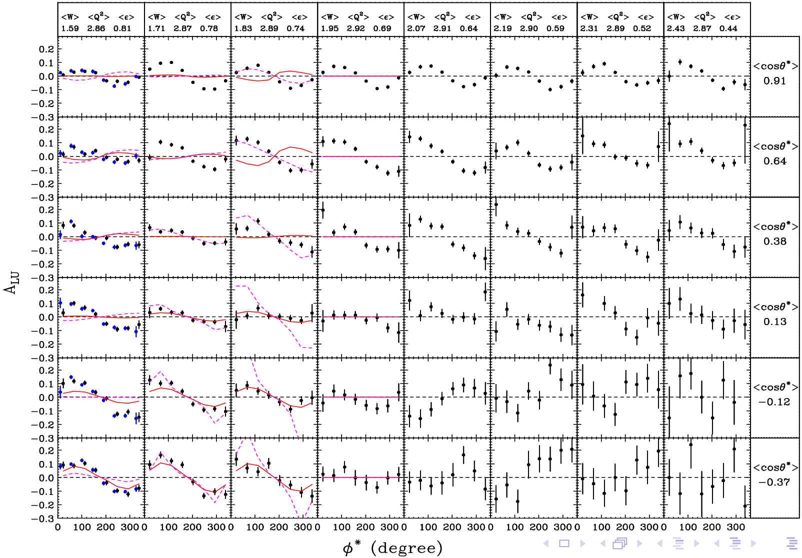
[a] A. Lenz, et al., Phys.Rev. D79, 093007, (2009)

[b] V.L. Chernyak, et al., Z. Phys. C42, 583 (1989).

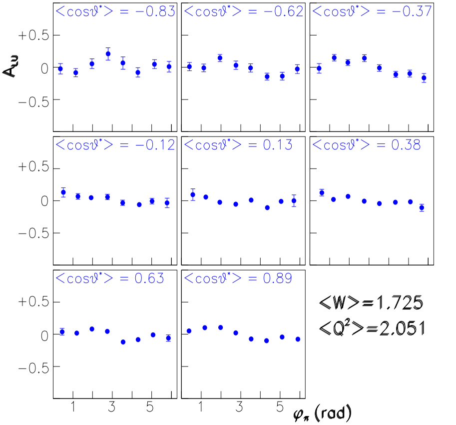
[c] I.D. King et al., Nucl. Phys. B279, 785, (1987)

$\vec{e}p \rightarrow e'\pi^+ n$, A_{LU} for high W, **PRELIMINARY**

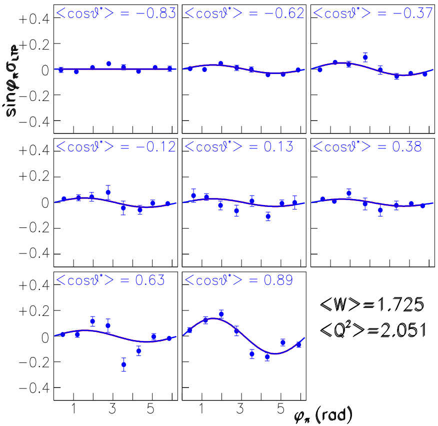
Curves: solid-MAID2007, dashed-JANR, **Blue: Phys. Rev. C77 015208, (2008)**, Black points: current work **K. Park & P. Bosted 2018**



A_{LU}



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

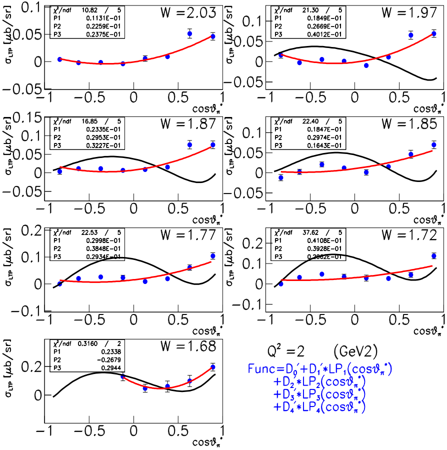


Blue curves: $\sin\phi^*$ fit

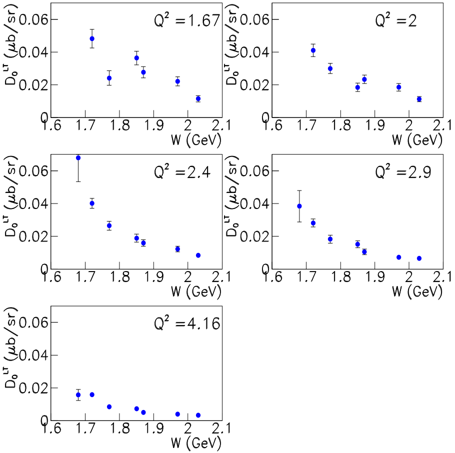
$\sigma_{LT'}$ vs. $\cos\theta^*_\pi$, MAID2007, **PRELIMINARY**

Red curves: Legendre fit, Black curves: MAID2007

$Q^2 = 2.0$ GeV^2



Moments $D_0^{LT'}$



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 $N(1710)1/2^+$, Near Threshold (GFF, G_A), and DIS...
- Coupled-channel analysis (including πN, $\pi\pi N$, 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** §§

BACKUP

Analysis Approaches

- 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**

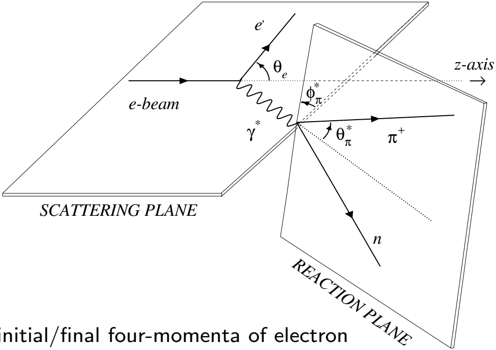
  → BG determination in the UIM and Born term in DR
  → A width and mass of resonances from PDG

- **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

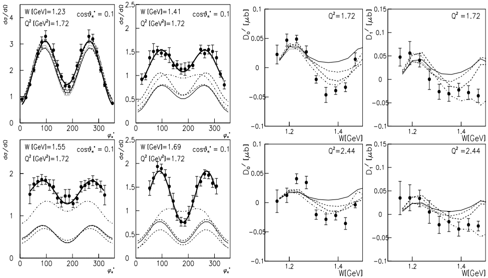
Reaction, $\vec{e}p \to e'\pi^+ n$ - SKIP



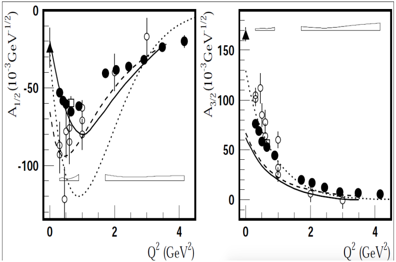
- $k_{i,f}$: the initial/final four-momenta of electron
- $E_{i,f}$: the initial/final energy of electron
- θ_e: the electron scattering angle
- $p_{\gamma,i}$: the virtual photon/target four-momenta
- $W^2 = (p_\gamma + p_i)^2 = M_p^2 + 2M_p\nu - Q^2$
- ν: transferred energy $= E_i - E_f = \frac{p_i \cdot p_\gamma}{M_p}$
- 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

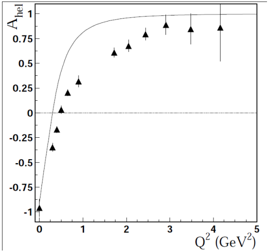
$\vec{e}p \rightarrow e'\pi^+ n$ for low lying N^* ($W = 1.15 - 1.69$ GeV)

- 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



[▲: RPP(2014), ○,□: DESY, NINA data]





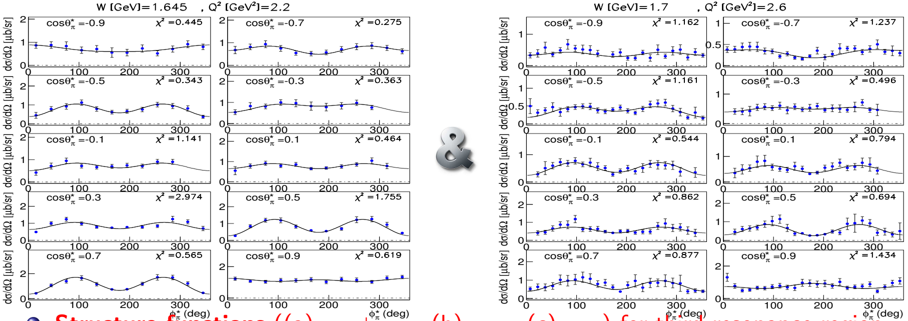
$$\frac{A_{1/2}^{D13}}{A_{3/2}^{D13}} = \frac{-1}{\sqrt{3}}\left(\frac{Q^2}{\alpha} - 1\right)$$

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

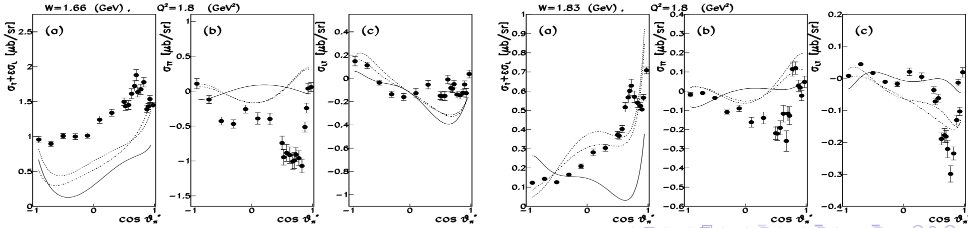
- Asymptotic Q^2 behavior of A_{hel} vs. Q^2
  - NRQ simple harmonic oscillator model (solid line) with spin, orbit flip amplitudes
- $A_{1/2} \ll A_{3/2}$ at low Q^2, $A_{3/2} \ll A_{1/2}$ at high Q^2

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

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

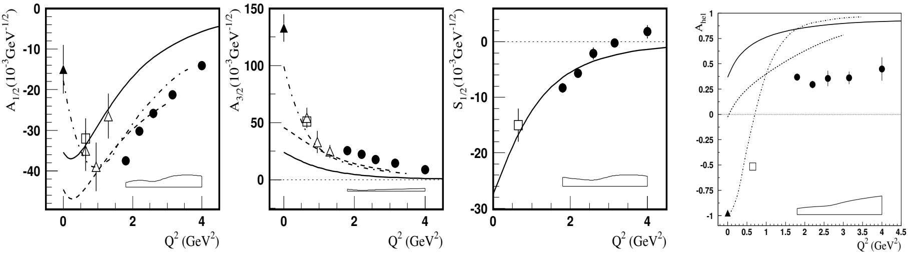


- **Structure functions** ((a) $\sigma_T + \epsilon\sigma_L$, (b) σ_{TT}, (c) σ_{LT}) for third resonance region
  - dash: MAID07, dash-dot: MAID03, dot: DMT

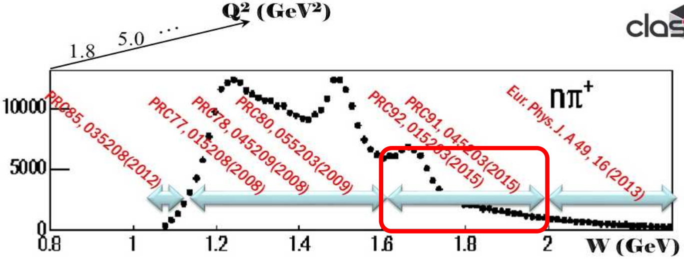


$\vec{e}p \rightarrow e'\pi^+ n$ for high lying N^* ($W = 1.65 - 2.0$ GeV)

- Transition Form Factors for $N(1680)5/2^+$ (old conv: $F_{15}(1680)$)
  $\rightarrow$ ▲ RPP(PDG:2014), △ V. Mokeev& I.G.Aznauryan(2013), □ I.G.Aznauryan(2005)
  $\rightarrow$ 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 ?

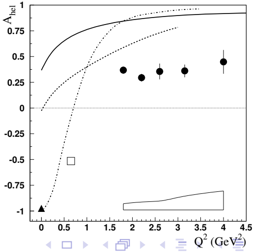


$\vec{e}p \to e'\pi^+ n$ for high lying N^* ($W = 1.65 - 2.0$ GeV)



- 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

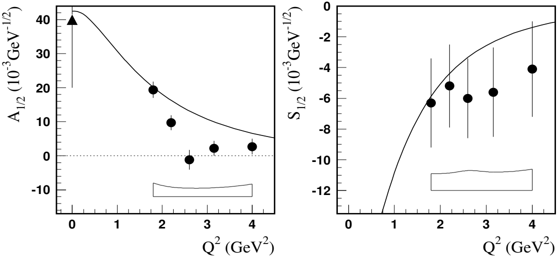
$$A_{hel} = \frac{A_{1/2}^2 - A_{3/2}^2}{A_{1/2}^2 + A_{3/2}^2}$$



- □ 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)

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

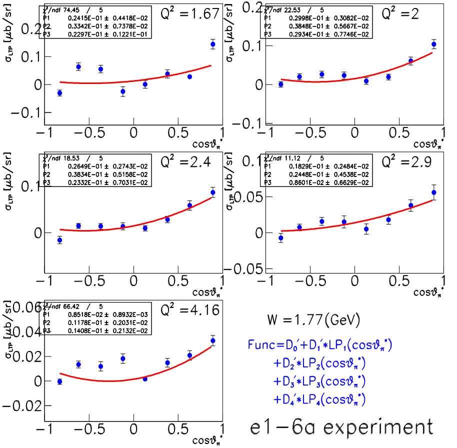


Solid: M.M. Gianini
E. Santopinto (hQCM)

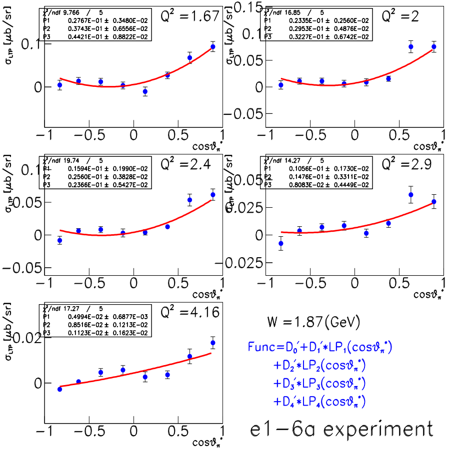
$\sigma_{LT'}$ vs. $\cos\theta^*_\pi$ PRELIMINARY

Red curves: Legendre fit

W = 1.77 GeV



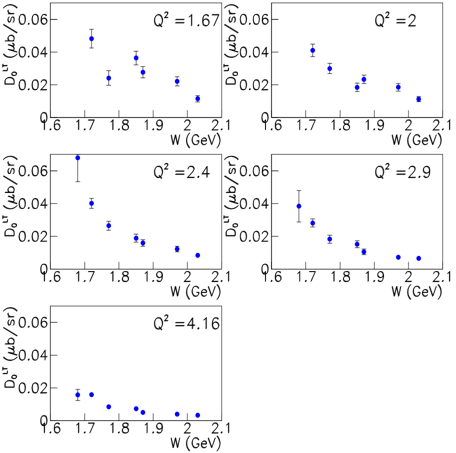
W = 1.87 GeV



Moments $D^{LT'}$ vs. W, Q^2 PRELIMINARY

Observation: interesting behavior above $W > 1.8$ GeV

Moments $D_0^{LT'}$



Moments $D_1^{LT'}$