Electroexcitation of Nucleon Resonances

in Pion Electroproduction:

towards high Q^2

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- **Unitary Isobar Model**
- **Dispersion Relations**

  - **Low $Q^2 \Longrightarrow$ high Q^2**

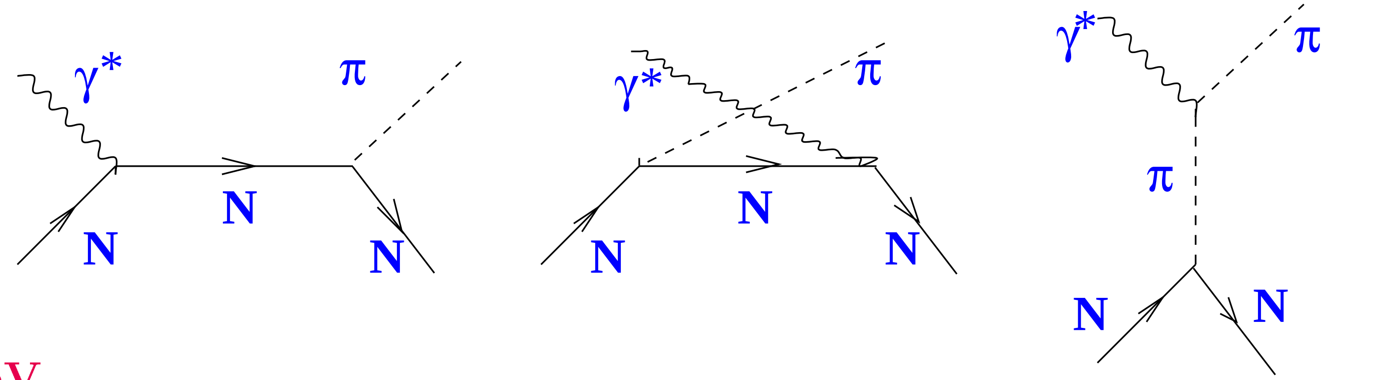
- **Results extracted from CLAS data**

Dispersion Relations

- **Dispersion relations for invariant amplitudes at fixed t:**

$$\mathrm{Re}B_i(s,t,Q^2) = \textit{Born term} + \frac{1}{\pi}\int\limits_{W_{thr}}^{\infty} \mathrm{Im}B_i(s',t,Q^2)\left(\frac{1}{s'-s} \pm \frac{1}{s'-u}\right) ds'$$

- **Born term: Q^2 evolution of all form factors is known**



- $\int\limits_{W_{thr}}^{2\ \mathrm{GeV}} \rightarrow \mathrm{Im} \rightarrow\ P_{33}(1232) + \text{other resonances}(B-W)$

- $\int\limits_{2\ \mathrm{GeV}}^{\infty} \rightarrow\ \mathrm{Regge-poles}$

Dispersion Relations in the $P_{33}(1232)$ resonance region

- The $P_{33}(1232)$ resonance

  ▷ This is an isolated resonance

  ▷ The corresponding πN amplitude is elastic up to $W \simeq 1.5$ GeV and is known with great accuracy

  ▷ Watson theorem: $\mathrm{Im}M(W,Q^2) = h^*_{\pi N} M(W,Q^2)$

  ▷ Dispersion relations for the multipoles $M^{(3/2)}_{1+}$, $E^{(3/2)}_{1+}$, $S^{(3/2)}_{1+}$ turn into singular integral equations:

$$M(W,Q^2) = M^B(W,Q^2) + \frac{1}{\pi}\int\limits_{W_{thr}}^{\infty} \frac{h^*_{\pi N} M(W',Q^2)}{W'-W-i\varepsilon} dW' + \mathit{nonsing.\ part}$$

- **Nonresonance multipoles in the $P_{33}(1232)$ resonance region:**
  - ▷ **We find their real parts by DR**
  - ▷ **For imaginary parts we use the Watson theorem**

So, the $P_{33}(1232)$ resonance region can be investigated by DR in very accurate way

Dispersion Relations above the $P_{33}(1232)$ resonance region

- In the integrands because of fixed t, at $s' < s$ we can turn out in unphysical region; this can cause two kinds of uncertainties in the large $P_{33}(1232)$ contribution:

  (I) $s' < s \Longrightarrow \cos\theta' > \cos\theta$

  $\Longrightarrow$ possible divergence of partial-wave expansion

  $\triangleright$ With increasing Q^2, this problem becomes less important because at given $s, s', \cos\theta$, we have:

  $$\cos\theta'(\text{large } Q^2) < \cos\theta'(Q^2 = 0)$$

(II) At large energies and large angles, $|t|$ is large:

in the integrands

$$s' < s \Longrightarrow u' = 2m_N^2 + m_\pi^2 - s' + (|t| - Q^2) \longrightarrow M_\Delta^2 \Longrightarrow$$

u channel $P_{33}(1232)$ contribution can become important

▷ **This problem becomes more important at large Q^2:**

$$u'(Q^2 \geq 1 \text{ GeV}^2, W = 1.5 \text{ GeV}) \approx u'(Q^2 = 0, W = 1.7 \text{ GeV})$$

- **At $W < 1.7$ GeV, the integrals $\int\limits_{2\text{ GeV}}^{\infty}$ are small;**

  at higher energies their role becomes important

- **The energy region of applicability of DR was checked using SAID multipoles:** *I.A. Phys.Rev.* **C67** *015209(2003)*

- **The conclusion is:**

(I) DR can be used at small Q^2 up to W=1.7 GeV

(II) DR can be used at $Q^2 \geq 1$ GeV^2 up to W=1.5 GeV

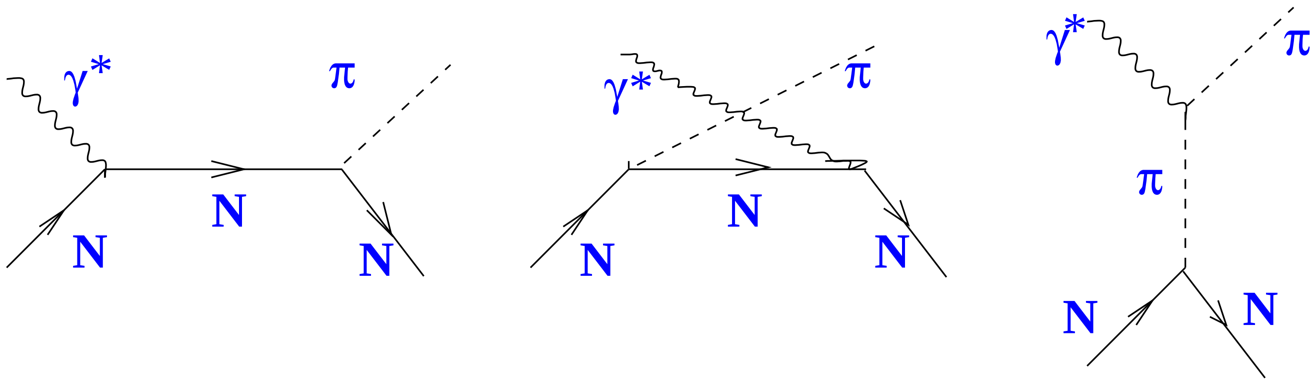
- **At $Q^2 = 0.4,\ 0.65$ GeV^2, DR were successfully used for the analysis of CLAS data on π^0, π^+ cross sections and polarized beam asymmetries at $W < 1.7$ GeV:**

  I.Aznauryan, et al.,Phys. Rev. **C71** *015201 (2005)*

Unitary Isobar Model

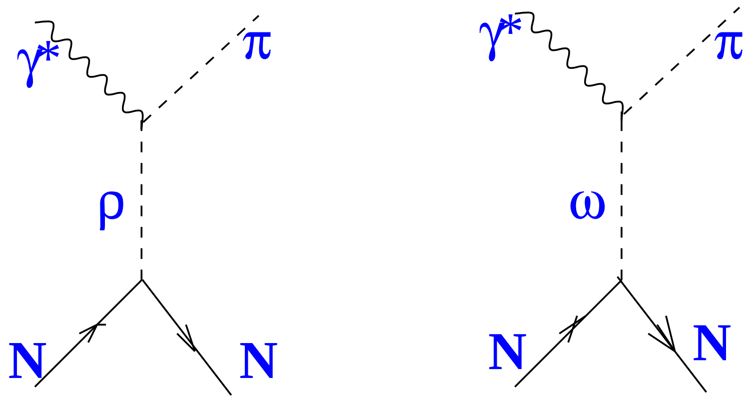
- **Unitary Isobar Model is based on the Effective-Lagrangian approach which was originally used to describe photoproduction amplitude at threshold:**

Born term with PV πNN coupling



- **Later, the approach was extended to the $P_{33}(1232)$ resonance region in the number of works and to higher energies by** *D.Drechsel, L.Tiator et al., NP A645 (1999) 145*:

- **t channel ρ and ω contributions were added to Born term**



- **mixed $PV - PS$ πNN coupling was introduced**

- **mult. ampl. were unitarized in K-matrix approximation**

- **Such approach is justified at small energies (the $P_{33}(1232)$ resonance region) and small Q^2:**
  - $*$ $|t|$ **is small**
  - $*$ $\frac{1}{|t-m_{mes}^2|} \sim \frac{1}{m_{mes}^2} \Longrightarrow$ **t-channel exchanges by mesons with lowest masses are dominant**
- **With increasing energies or Q^2, $|t|$ becomes large, and some modifications can be needed**
- **Continued to 2 GeV, the background=Born term+ $\rho+\omega$ contradicts to data.**

- **We linked the low energy background to Regge poles:**

  Vanderhaegen, Gidal, Laget, NP **A627** *645 (1997); PR* **C57** *1454 (1998)*

- **At $Q^2 = 0$, this allowed us to obtain good description of SAID multipole amplitudes up to $W = 2$ GeV with a unified Breit-Wigner parametrization for the resonances**

- **We have compared multipoles of UIM and DR at $W \leq 1.5$ GeV and $Q^2 \leq 4$ GeV^2: they turned out very close to each other**

- **Recently, a multipole analysis of π^0 electroproduction at $\mathbf{Q^2 = 1\ GeV^2}$ was performed, based on HALL A polarization measurements at $\mathbf{1.17 \leq W \leq 1.35\ GeV}$:**

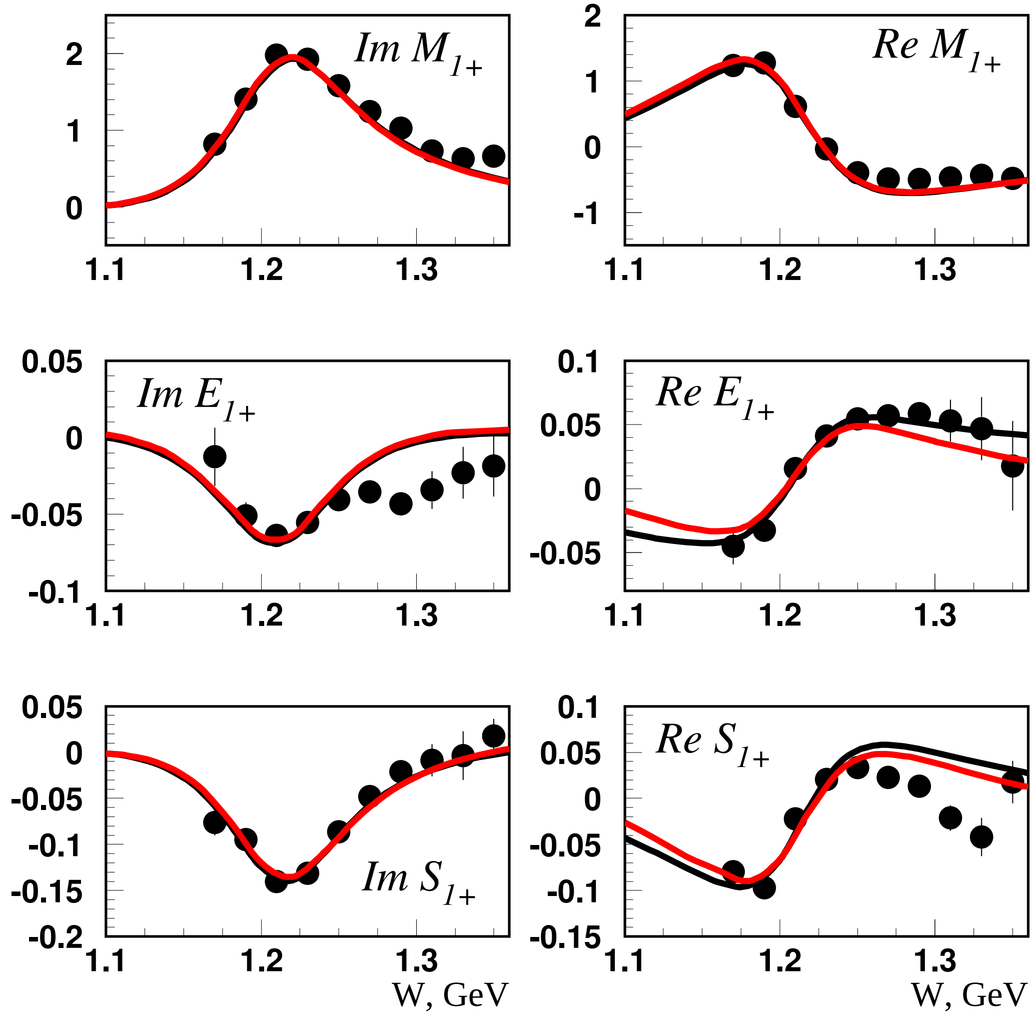
  J.Kelly et al., nucl-ex/0505024

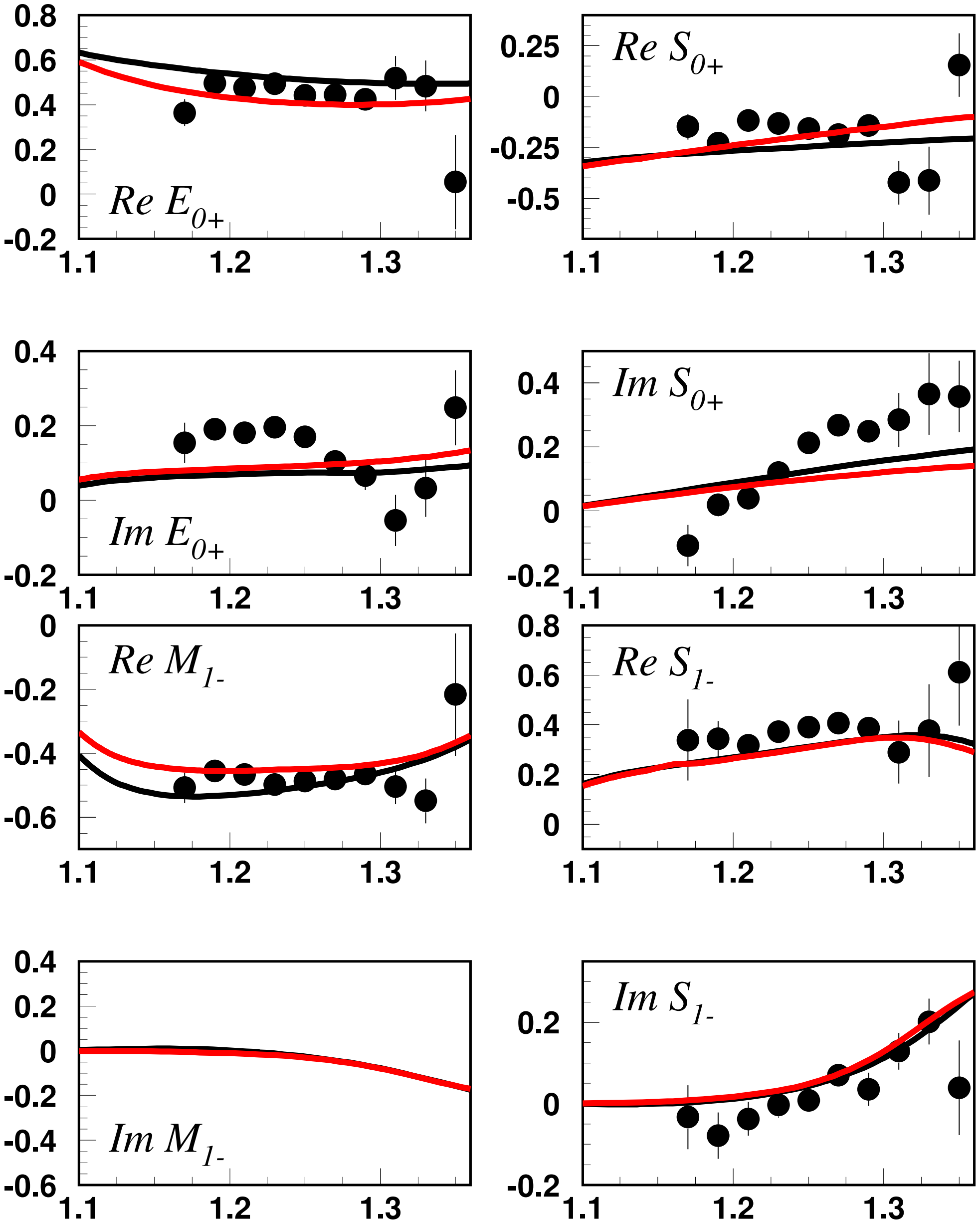
- **Multipoles of both approaches: UIM and DR, are very close to HALL A multipoles. So we conclude:**

UIM can be used without significant modifications

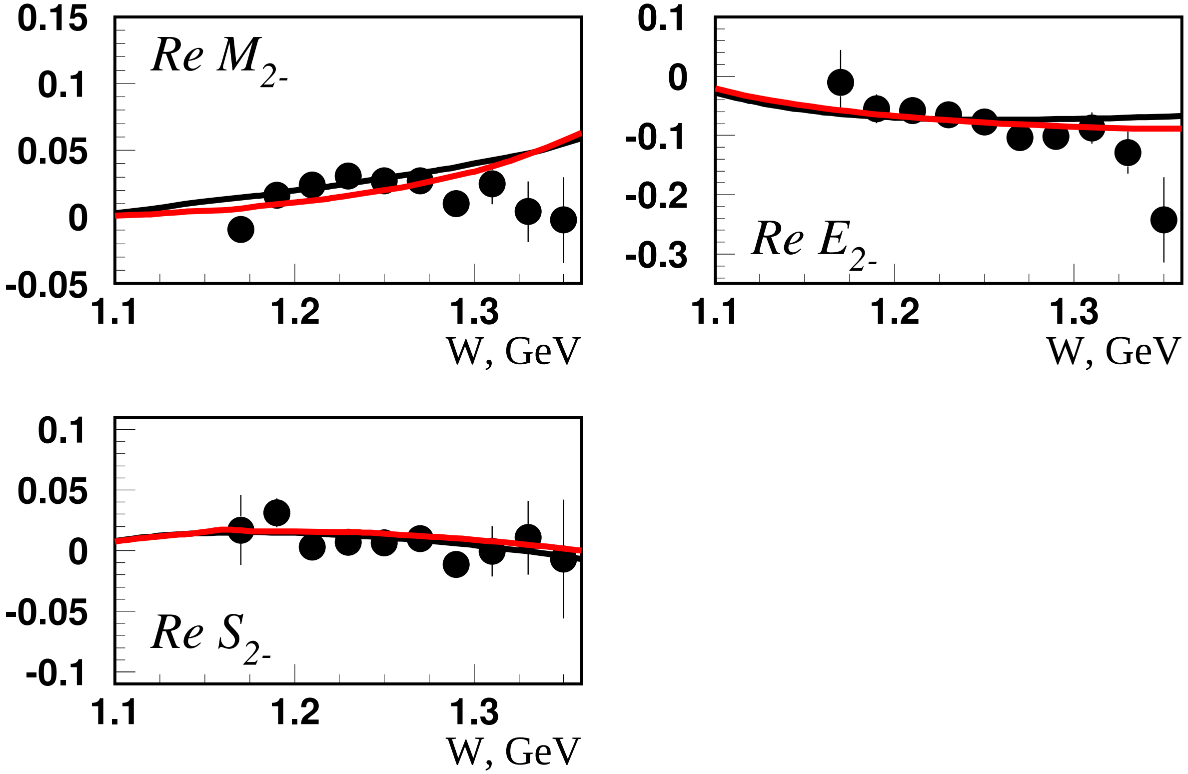
at $\mathbf{Q^2 \leq 4\ GeV^2}$

- **Comparison of HALL A multipole amplitudes at $Q^2 = 1\ \mathrm{GeV}^2$ with DR and UIM results**





Re E_{0+}
Re S_{0+}
Im E_{0+}
Im S_{0+}
Re M_{1-}
Re S_{1-}
Im M_{1-}
Im S_{1-}
0.8
0.6
0.4
0.2
0
-0.2
0.25
-0.25
-0.5
-0.4
-0.6
1.1
1.2
1.3



Re M_{2-}
Re E_{2-}
Re S_{2-}
W, GeV
W, GeV
W, GeV

Resonances

- **First resonance region**
  - $\triangleright$ $[\mathbf{56}, \mathbf{0}^+]$: $\mathbf{P_{33}(1232)}$
- **Second resonance region**
  - $\triangleright$ $[\mathbf{56}, \mathbf{0}^+]_\mathbf{r}$: $\mathbf{P_{11}(1440)}$
  - $\triangleright$ $[\mathbf{70}, \mathbf{1}^-]$: $\mathbf{D_{13}(1520)},\ \mathbf{S_{11}(1535)}$
- **Third resonance region**
  - $\triangleright$ $[\mathbf{56}, \mathbf{0}^+]_\mathbf{r}$: $\mathbf{P_{33}(1600)}$
  - $\triangleright$ $[\mathbf{70}, \mathbf{1}^-]$: $\mathbf{S_{11}(1650)},\ \mathbf{S_{31}(1620)}, \mathbf{D_{15}(1675)},\ \mathbf{D_{13}(1700)},\ \mathbf{D_{33}(1700)}$
  - $\triangleright$ $[\mathbf{56}, \mathbf{2}^+]$: $\mathbf{F_{15}(1680)},\ \mathbf{P_{13}(1720)}$

Data

- **The most complete data set we have at $\mathbf{Q^2 = 0.4}$ and $\mathbf{0.65\ GeV^2}$ from Hall B (the CLAS Collaboration)**

  $*$ π^0, π^+ **differential cross sections:** $W = 1.1 - 1.68\ GeV$

  $*$ $\mathbf{p(\vec{e}, e'p)\pi^0}$ **and** $\mathbf{p(\vec{e}, e'n)\pi^+}$ **longitudinal beam asymmetry (first measurements):** $W = 1.1 - 1.66\ GeV$

- **From the analysis of this data set the amplitudes of the $\gamma \mathbf{p} \rightarrow \mathbf{P_{33}(1232)},\ \mathbf{P_{11}(1440)},\ \mathbf{D_{13}(1520)},\ \mathbf{S_{11}(1535)}$ were found:** *I.Aznauryan, et al.,Phys. Rev.* **C71** *015201 (2005)*

- **At $\mathbf{Q^2 = 0.65\ (GeV/c)^2}$, we performed combined analysis of CLAS and world data on single pion and CLAS data on double charged pion electroproduction in II and III resonance regions:** *Aznauryan, Burkert, Mokeev, et al., hep-ph/0508057, to appear in PRC*

- **Successful description of these major contributions to meson electroproduction with common N^* photocouplings is very important, as it confirms the reliability of background description and resonance/background separation in both channels**

- I will present also preliminary results for the transitions

  $\gamma p \to \mathbf{P_{11}(1440)},\ \mathbf{D_{13}(1520)},\ \mathbf{S_{11}(1535)},\ \mathbf{F_{15}(1680)}$

  obtained from CLAS π^+ data on the cross sections and longitudinally polarized beam asymmetry at

  $\mathbf{Q^2 = 1.72,\ 2.05,\ 2.44,\ 2.91,\ 3.48\ GeV^2}$

Data (continued)

- π^0 **differential cross sections:**

  $\ast$ **Hall B (the CLAS Collaboration)**

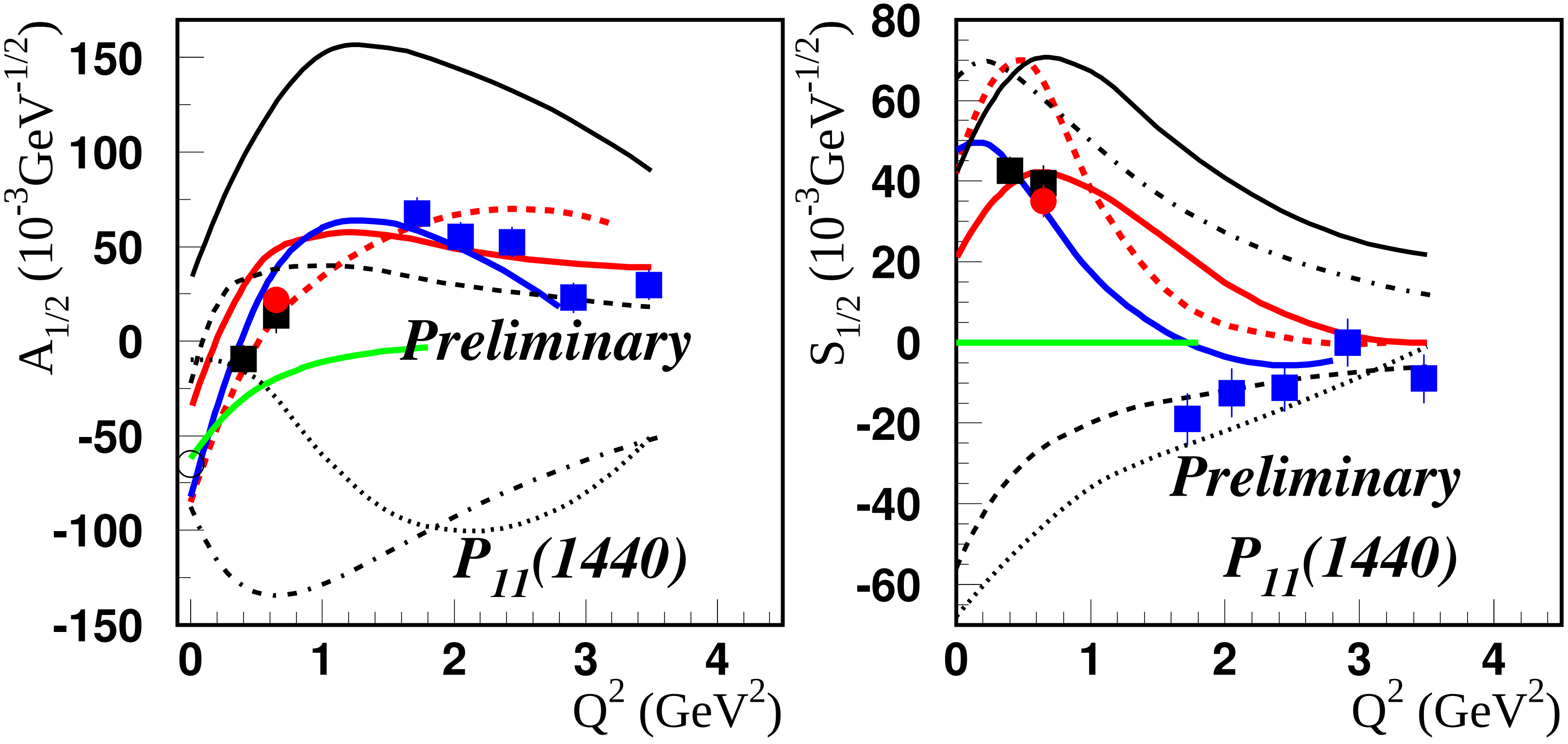
  $Q^2 = 0.4,\ 0.52,\ 0.65,\ 0.75,\ 0.9,\ 1.15, 1.45,\ 1.8\, GeV^2$

  $\ast$ **Hall B (the CLAS Collaboration) Preliminary**

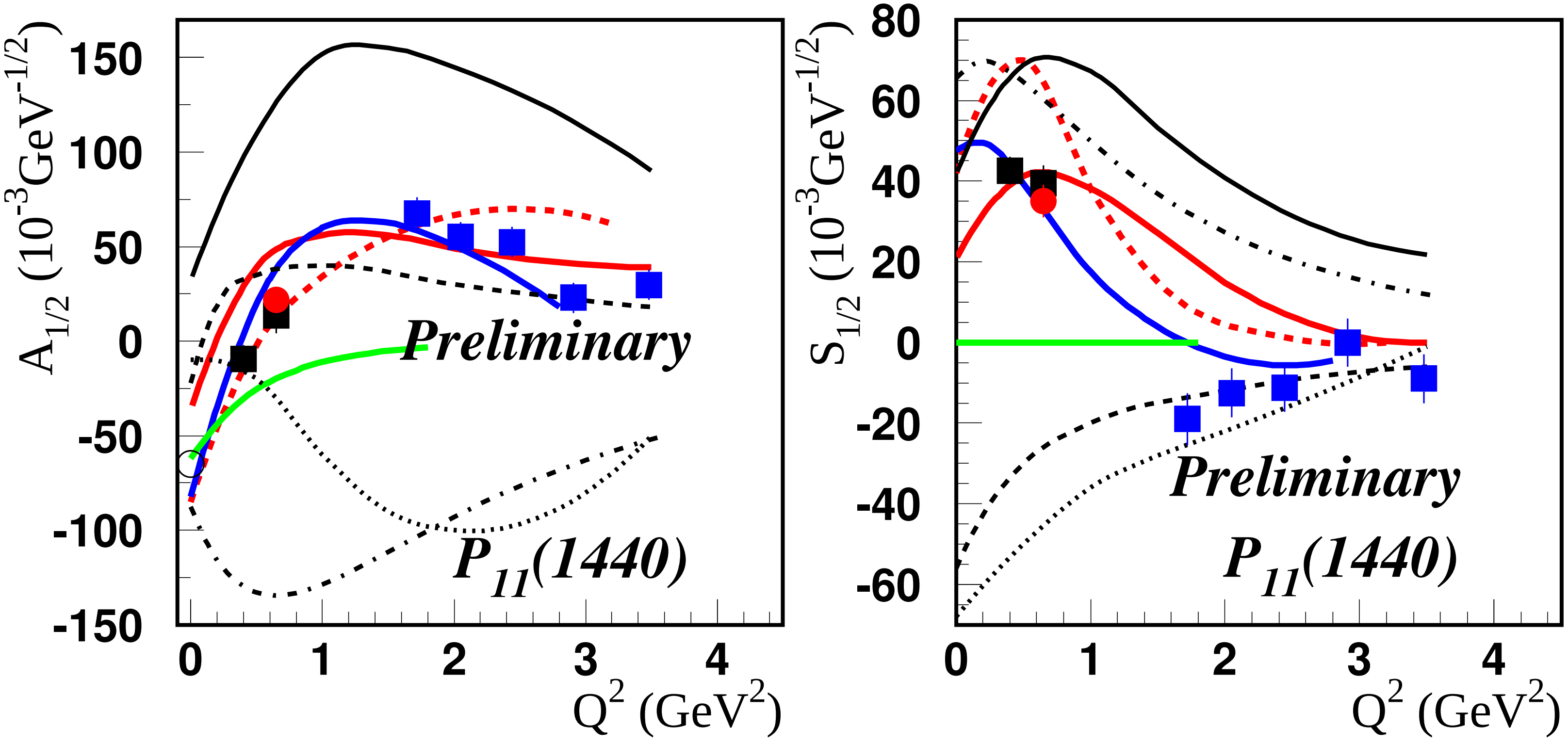
  $Q^2 = 2.15,\ 2.4,\ 3.0,\ 3.5,\ 4.2, 5\, GeV^2$

  $\ast$ **Hall C:** $Q^2 = 2.8,\ 4\, GeV^2$

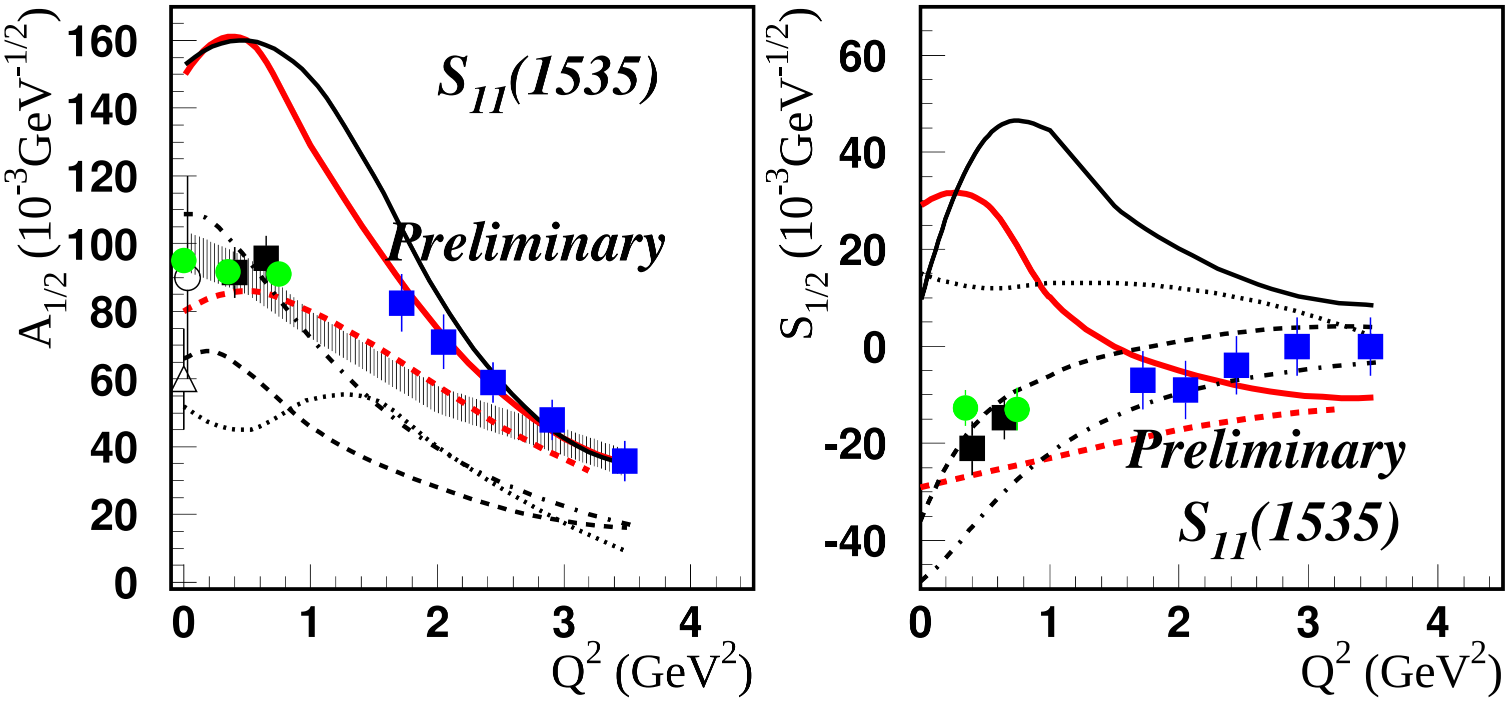
- **This data allow to extract the $\gamma\mathbf{N} \rightarrow \mathbf{P_{33}(1232)}$ transition amplitudes from $\mathbf{Q^2 = 0}$ to $\mathbf{Q^2 = 5\ GeV^2}$**



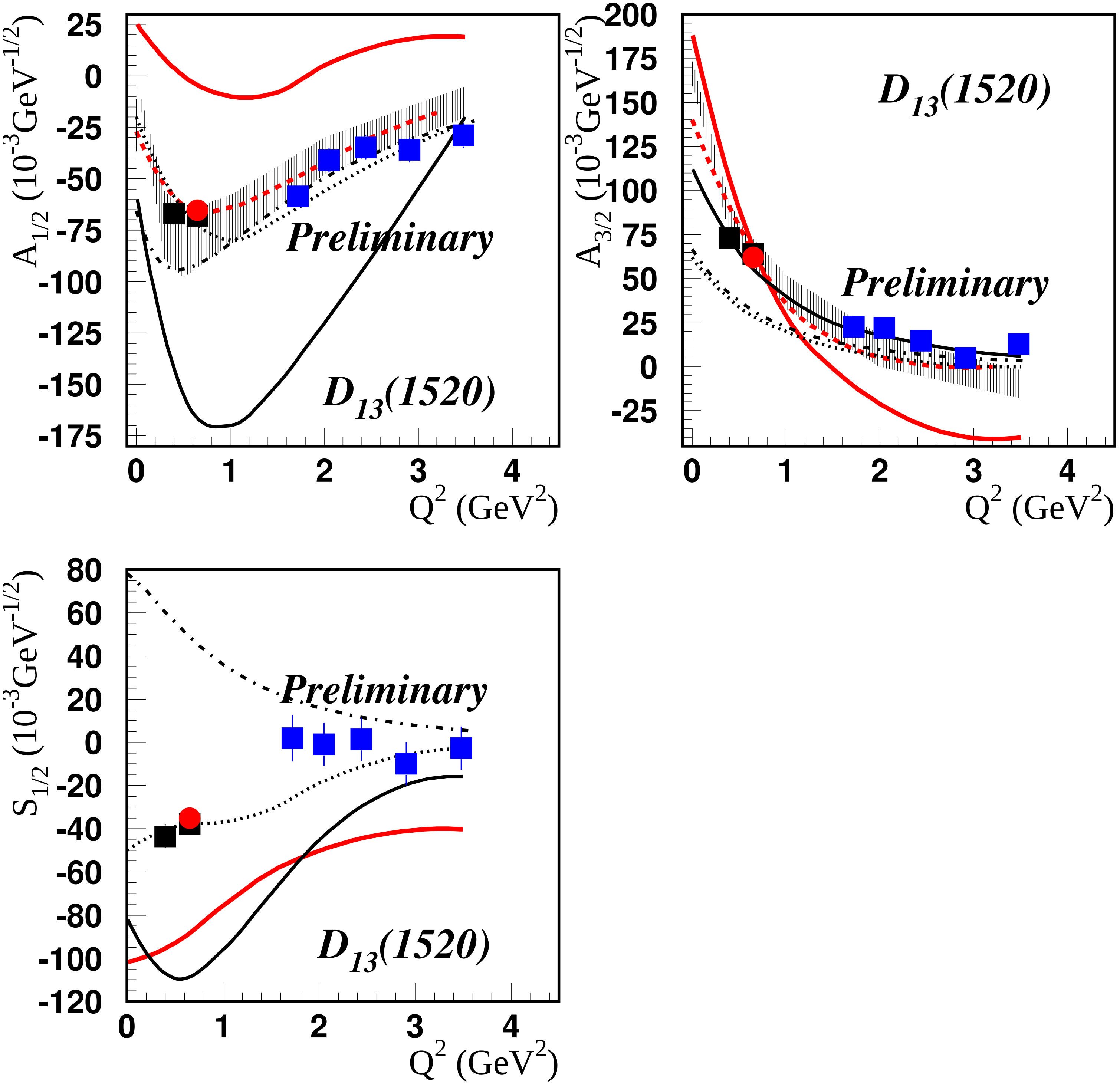
- **Black boxes: from CLAS π^0, π^+ data**
- **Red point: from CLAS single and double pion data**
- **Blue boxes: preliminary results from CLAS π^+ data**



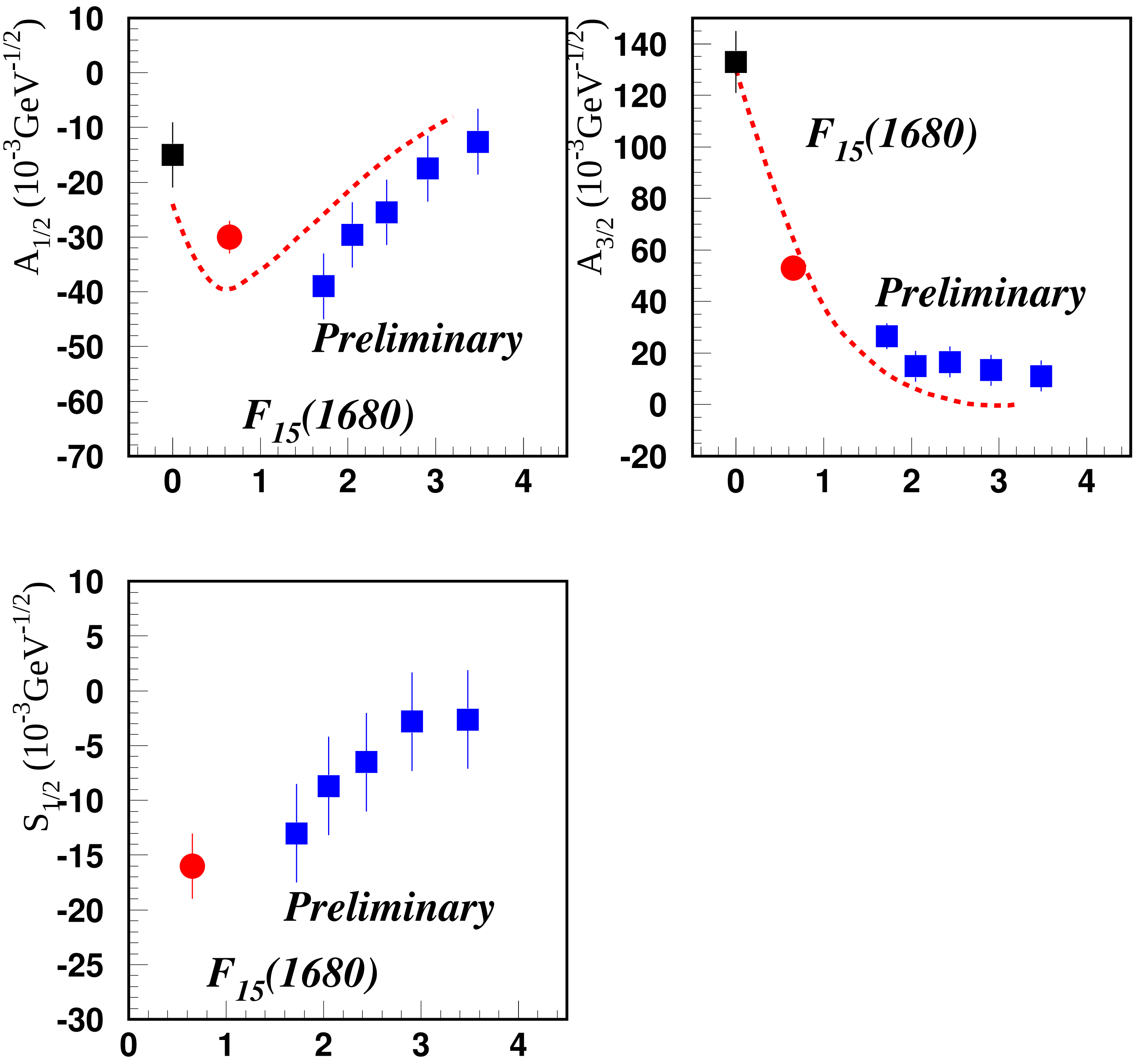
- **blue curves: quark model with $q\bar{q}$ cloud**, *Cano, Gonzales*
- **red curves: Light-front RQM**, *Capstick, Keister*
- **green curves: Roper as a q^3G hybrid state**, *Burkert, Li*



- **Black boxes: from CLAS π^0, π^+ data**
- **Green bullets: our analysis of CLAS and world η data**
- **Blue boxes: preliminary results from CLAS π^+ data**



$A_{1/2}$ $(10^{-3}GeV^{-1/2})$
Preliminary
$D_{13}(1520)$
Q^2 (GeV^2)
$A_{3/2}$ $(10^{-3}GeV^{-1/2})$
Preliminary
$D_{13}(1520)$
Q^2 (GeV^2)
$S_{1/2}$ $(10^{-3}GeV^{-1/2})$
Preliminary
$D_{13}(1520)$
Q^2 (GeV^2)



$A_{1/2}$ $(10^{-3}GeV^{-1/2})$
F15(1680)
Preliminary
$A_{3/2}$ $(10^{-3}GeV^{-1/2})$
F15(1680)
Preliminary
$S_{1/2}$ $(10^{-3}GeV^{-1/2})$
Preliminary
F15(1680)

- **Predictions of quark model with $q\bar{q}$ cloud:** *Cano, Gonzales, PL B431, 270 (1998)*, **are close to our results for Roper**

- **Predictions of light-front relativistic quark model:** *Capstick, Keister, PR D51, 3598 (1995)*, **are also close to the results for Roper; however, they disagree with the results for $S_{11}(1535)$ and $D_{13}(1520)$**

- **Roper as a q^3G hybrid state:** *Li, Burkert, PR D46, 70 (1992)*, **is ruled out due to strong longitudinal response at low Q^2 and large transverse amplitude at high Q^2**

Summary of the results for

$\gamma p \rightarrow P_{11}(1440),\ D_{13}(1520),\ S_{11}(1535),\ F_{15}(1680)$

- For the first time transverse and longitudinal amplitudes for the transition $\gamma N \rightarrow$ Roper are obtained in wide Q^2 region: $Q^2 = 0 \div 4\ GeV^2$
- For the first time definite results are obtained for the longitudinal amplitudes of the transitions $\gamma N \rightarrow D_{13}(1520),\ S_{11}(1535),\ F_{15}(1680)$; and also accurate results are obtained for their transverse amplitudes

Summary of the results for

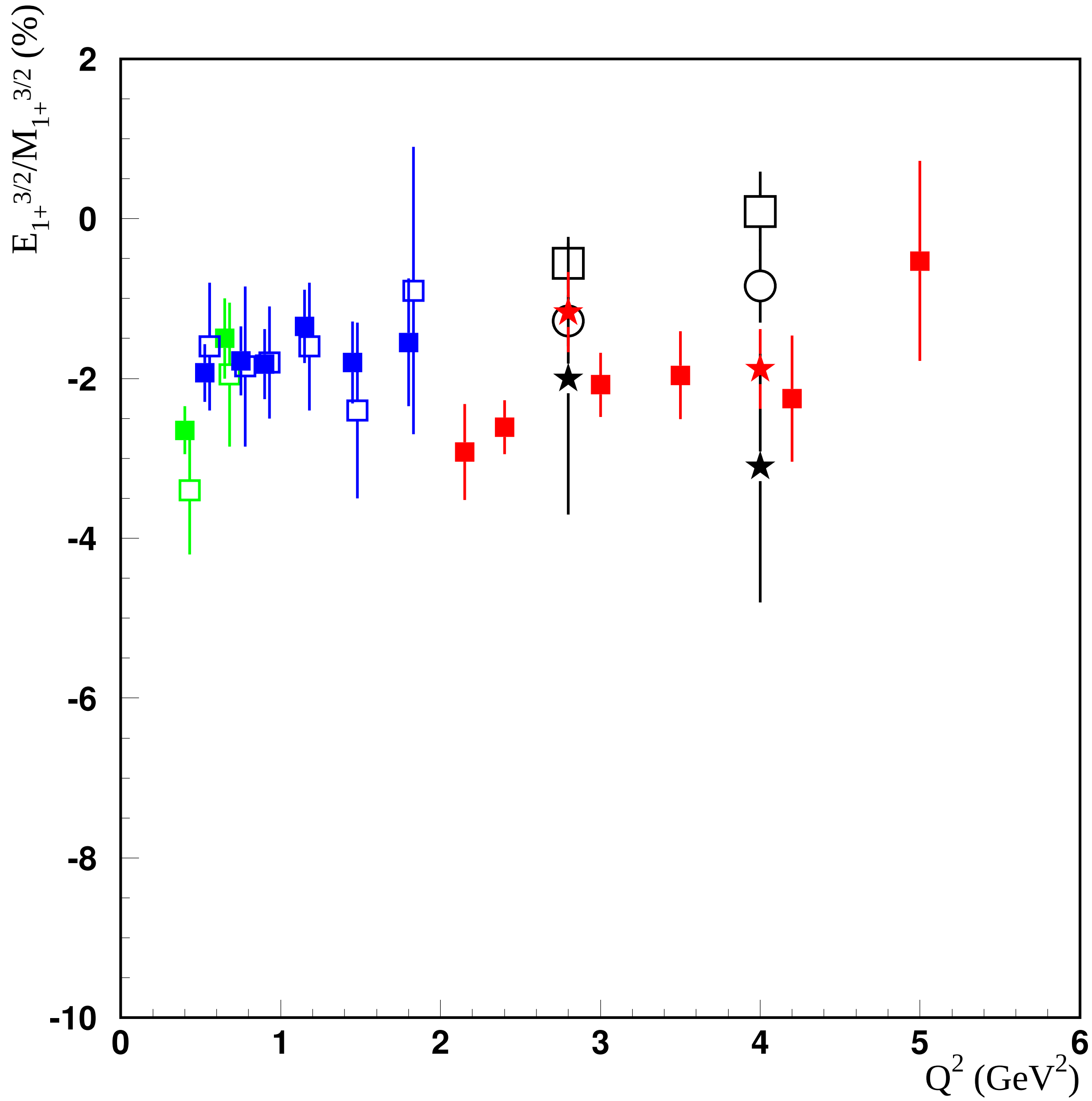
$\gamma \mathrm{p} \rightarrow \mathrm{P}_{11}(1440),\ \mathrm{D}_{13}(1520),\ \mathrm{S}_{11}(1535),\ \mathrm{F}_{15}(1680)$

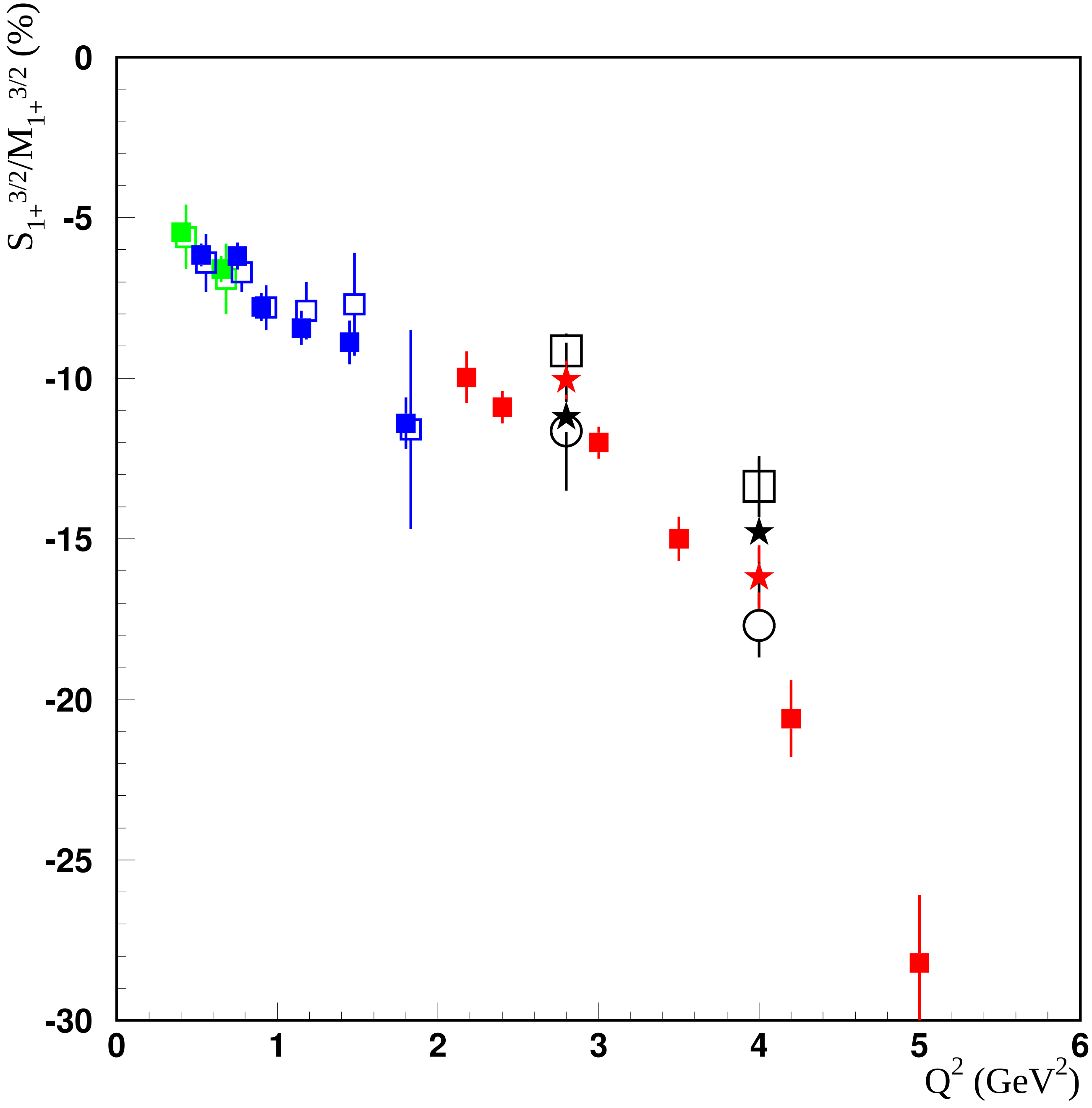
- **The amplitudes for all transitions extracted from the π, 2π, and η electroproduction are in good agreement with each other**

- **None of quark models gives simultaneously good description of the $\gamma \mathrm{N} \rightarrow \mathrm{P}_{11}(1440),\ \mathrm{D}_{13}(1520),\ \mathrm{S}_{11}(1535)$ transition amplitudes**

Q^2 evolution of the ratios $E_{1+}^{3/2}/M_{1+}^{3/2}$ and $S_{1+}^{3/2}/M_{1+}^{3/2}$

for the $\gamma N \to P_{33}(1232)$ transition





$S_{1+}^{3/2}/M_{1+}^{3/2}$ (%)
0
-5
-10
-15
-20
-25
-30
0
1
2
3
4
5
6
Q^2 (GeV^2)

- Information on the Q^2- evolution of the ratios $E_{1+}^{(3/2)}/M_{1+}^{(3/2)}$, $S_{1+}^{(3/2)}/M_{1+}^{(3/2)}$ is very interesting for understanding of the mechanisms and the scale of transition to pQCD regime, because the transition from soft to hard mechanisms is characterized by a striking change in the behaviour of $E_{1+}^{3/2}/M_{1+}^{3/2}$, $S_{1+}^{3/2}/M_{1+}^{3/2}$:

    ▷ The conservation of quark helicities in the pQCD regime leads to the asymptotic relations

$$E_{1+}^{3/2}/M_{1+}^{3/2} = 1,\ S_{1+}^{3/2}/M_{1+}^{3/2} = \mathrm{const}$$

    ▷ In contrast with this at $Q^2 = 0$ we have strong suppression of $E_{1+}^{(3/2)}$ and $S_{1+}^{(3/2)}$:

$$E_{1+}^{3/2}/M_{1+}^{3/2} \cong 0,\ S_{1+}^{3/2}/M_{1+}^{3/2} \cong 0$$

Summary for Q^2 evolution ...

- At $Q^2 < 5$ GeV^2 there is no indication of approaching the pQCD regime in the ratios $E_{1+}^{3/2}/M_{1+}^{3/2}$ and $S_{1+}^{3/2}/M_{1+}^{3/2}$
- None of soft approaches gives simultaneously satisfactory description of $E_{1+}^{3/2}/M_{1+}^{3/2}$ and $S_{1+}^{3/2}/M_{1+}^{3/2}$