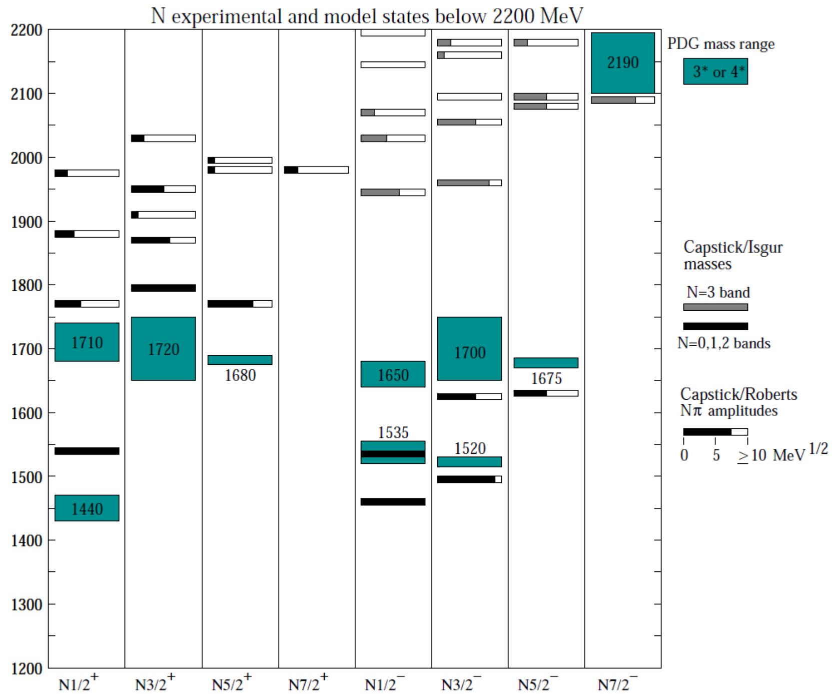
Pion electro-production in the 1^{st} and 2^{nd} resonance regions

S. Širca, U. of Ljubljana, Slovenia

Bled | September 16, 2008

Motivation

- Understand (****, ***) baryon spectra: masses, widths, form-factors

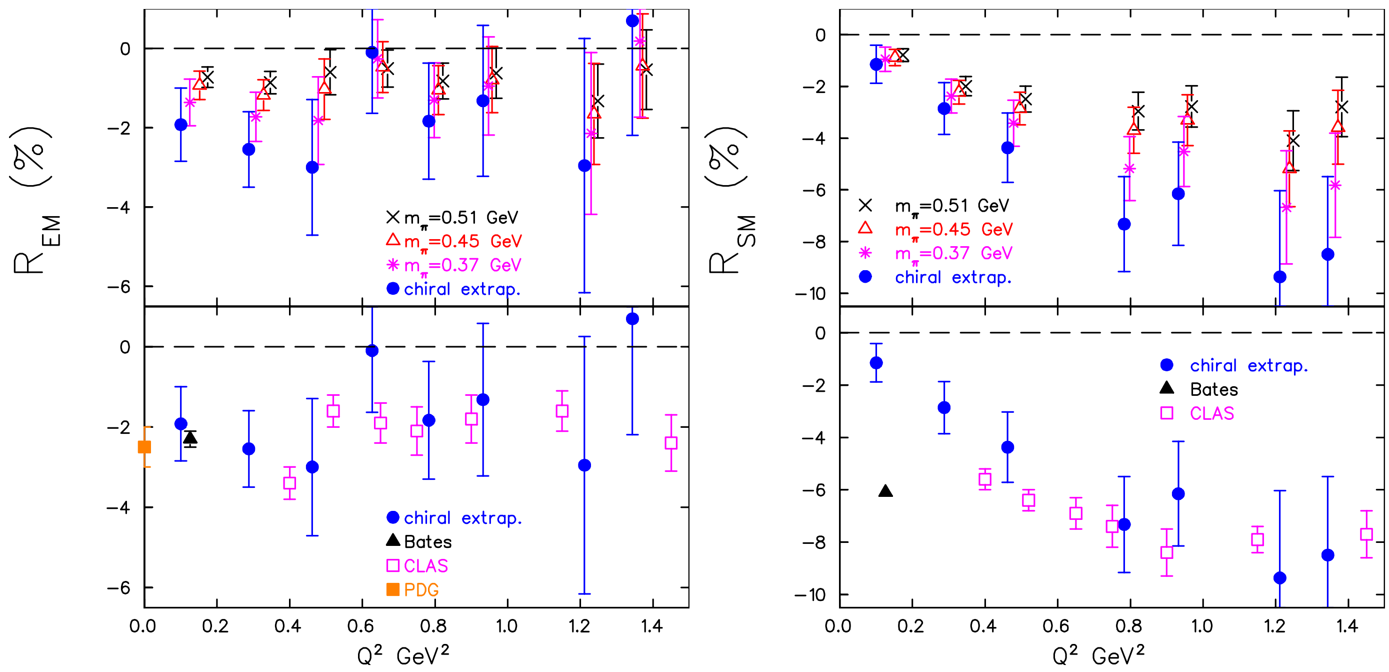


- Understand structure of resonances, related to
  — confinement
  — chiral symmetry of QCD (meson cloud)
- Distinguish structure from reaction mechanisms, compare to models
- Current focus of “overall” phenomenological analyses is above $\approx$ 1.7 GeV

Key issues with $P_{33}(1232)$

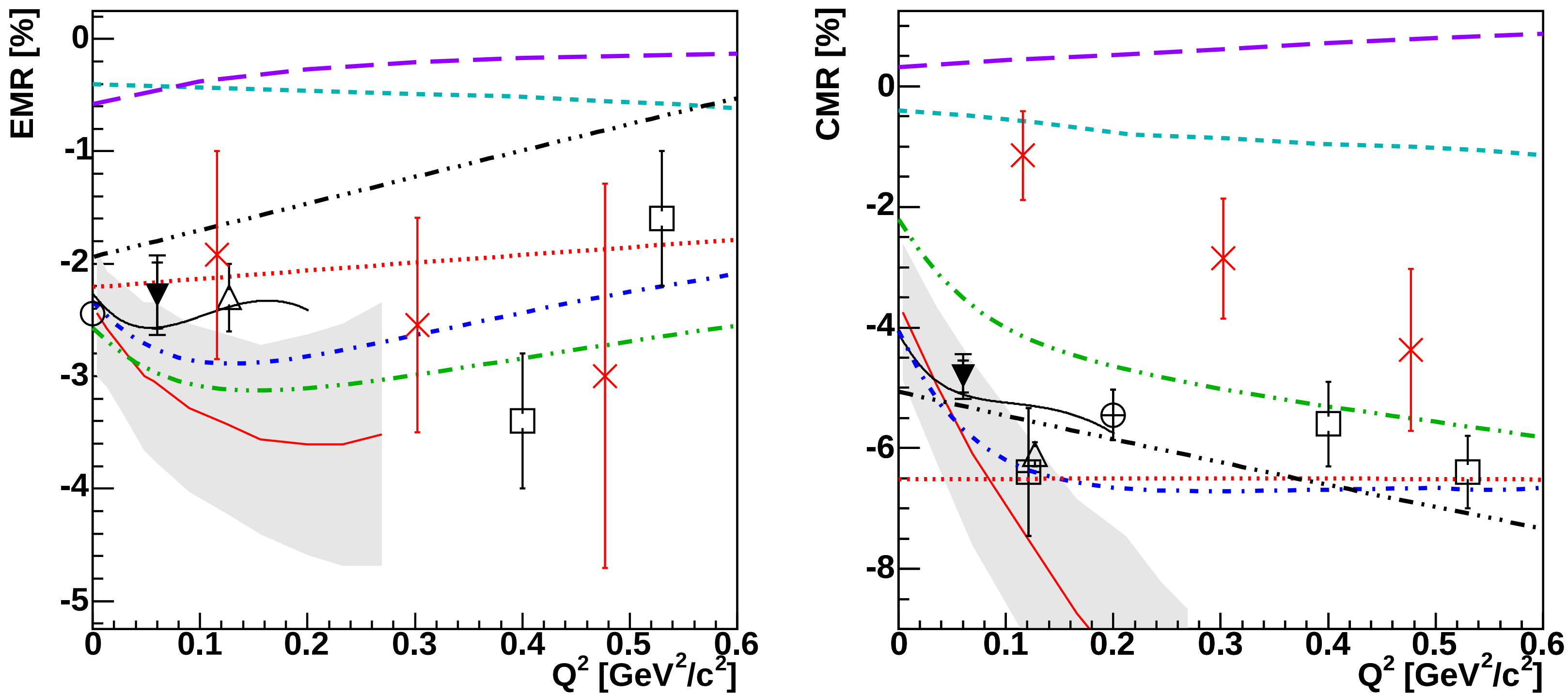
- Textbooks say mostly OK, but...
- EMR/CMR at low Q^2: situtation unclear (both theory and exp)
- Discrepancies at $Q^2 \approx 1$
- Transition to pQCD (EMR$\rightarrow$ 1, CMR$\rightarrow$const) not established
- Calculation of reaction amplitudes on the Lattice in its infancy

Alexandrou++ PRL 94 (2005) 021601



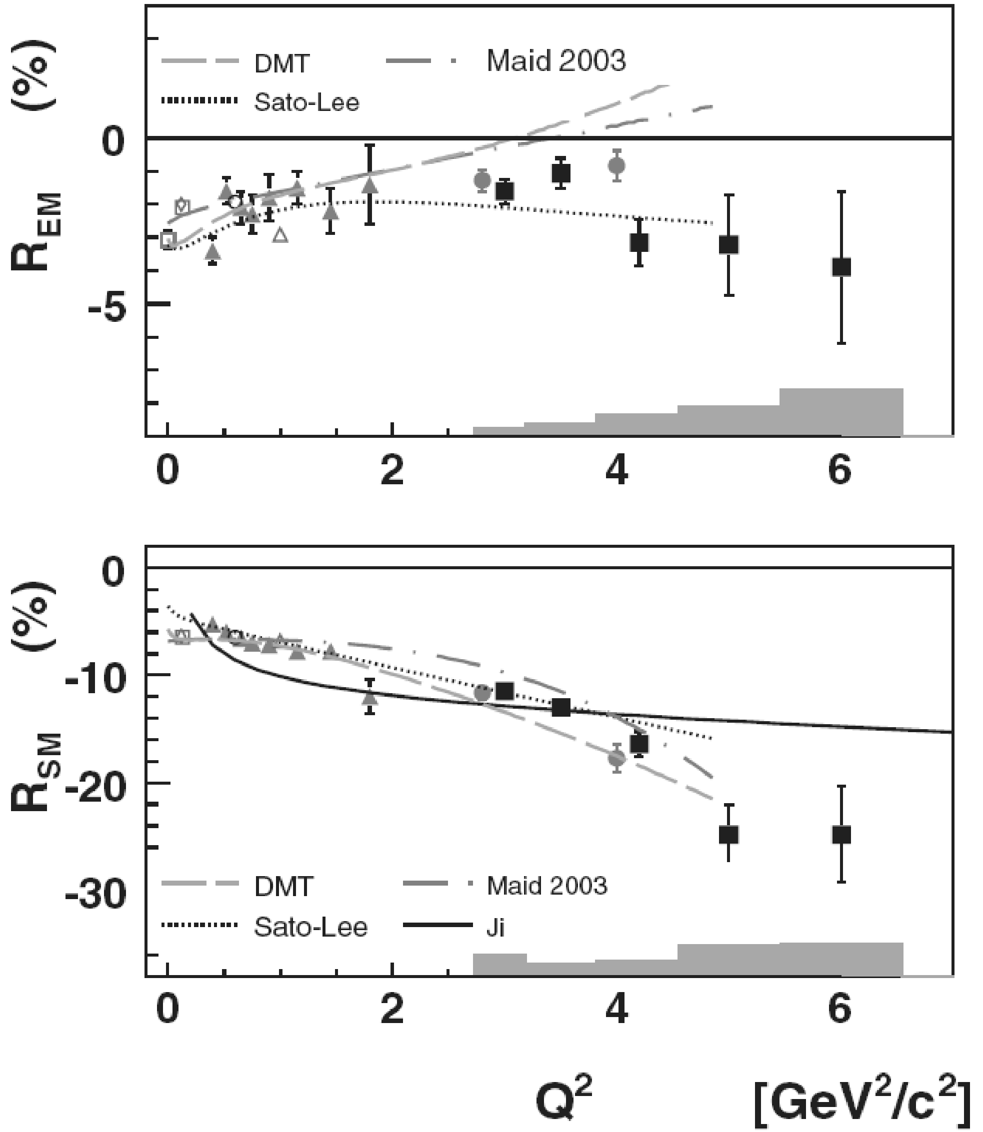
$\mathrm{N} \rightarrow \Delta(1232)$ **transition** **low** Q^2

$\mathrm{EMR} = E_{1+}^{3/2}/M_{1+}^{3/2}$ $\mathrm{CMR} = S_{1+}^{3/2}/M_{1+}^{3/2}$



- pion-cloud physics at low Q^2: MIT-Bates, A1/Mainz
- stringent constraints on models, both quark and baryon sector
- experimentally, tremendous advantage in polarization DOFs
- transition to pQCD at very high Q^2: JLab (?)

N → Δ(1232) transition



Ungaro++ PRL **97** (2006) 112003

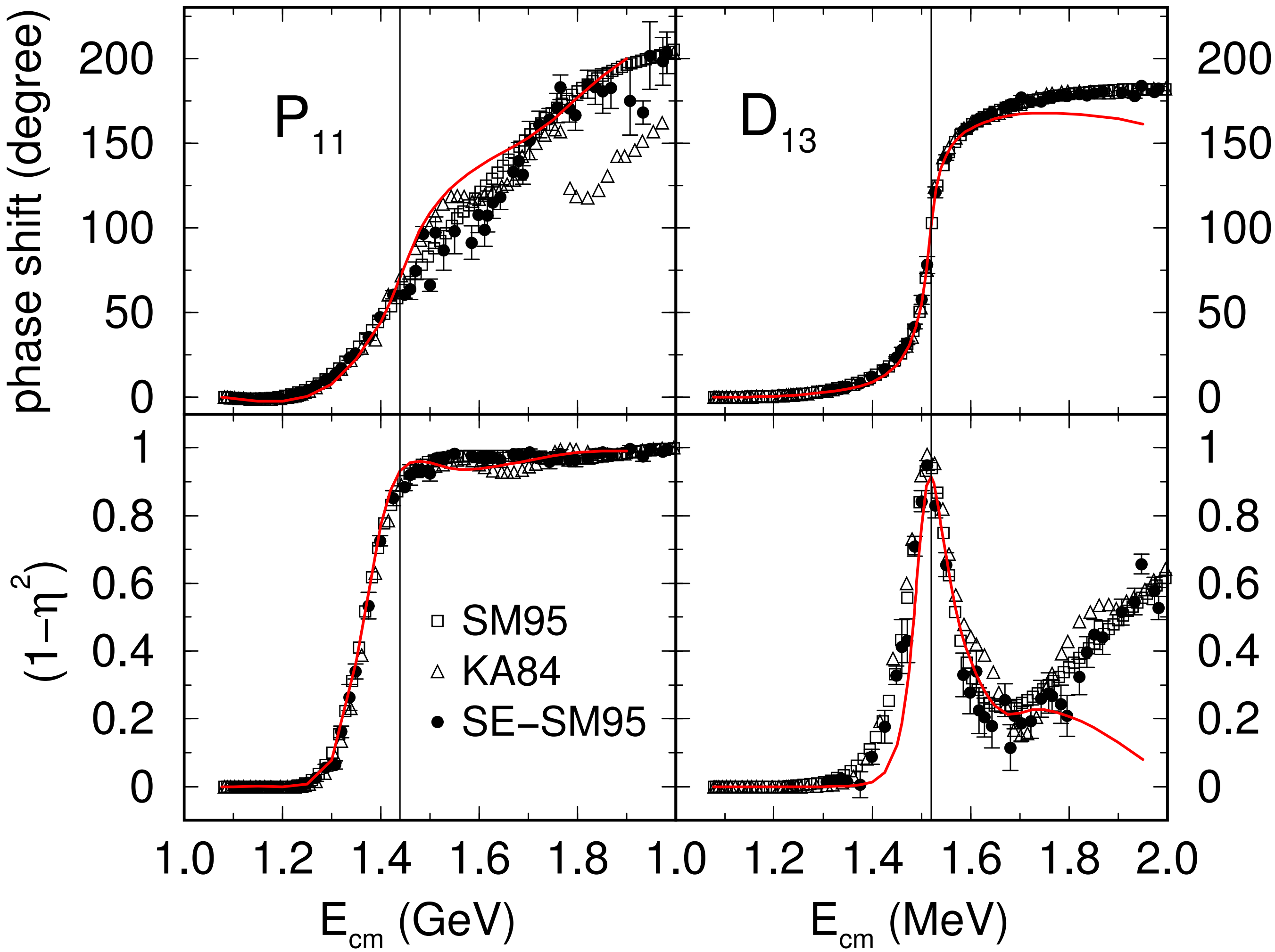
Key issues with $P_{11}(1440)$ ... and $S_{11}(1535)$

- Large width of Roper
- Atypical behaviour of $\mathrm{Im}T_{\pi N}$ in P11
- Inconsistent M, Γ (πN XS ... 1470, 350 MeV), ($|dT/dW|$) ... 1375, 180 MeV for the Roper
- Large width of $S_{11}(1535) \to \eta N$ at threshold
- Level ordering (parity inversion) of $P_{11}(1440)$ wrt. $S_{11}(1535)$

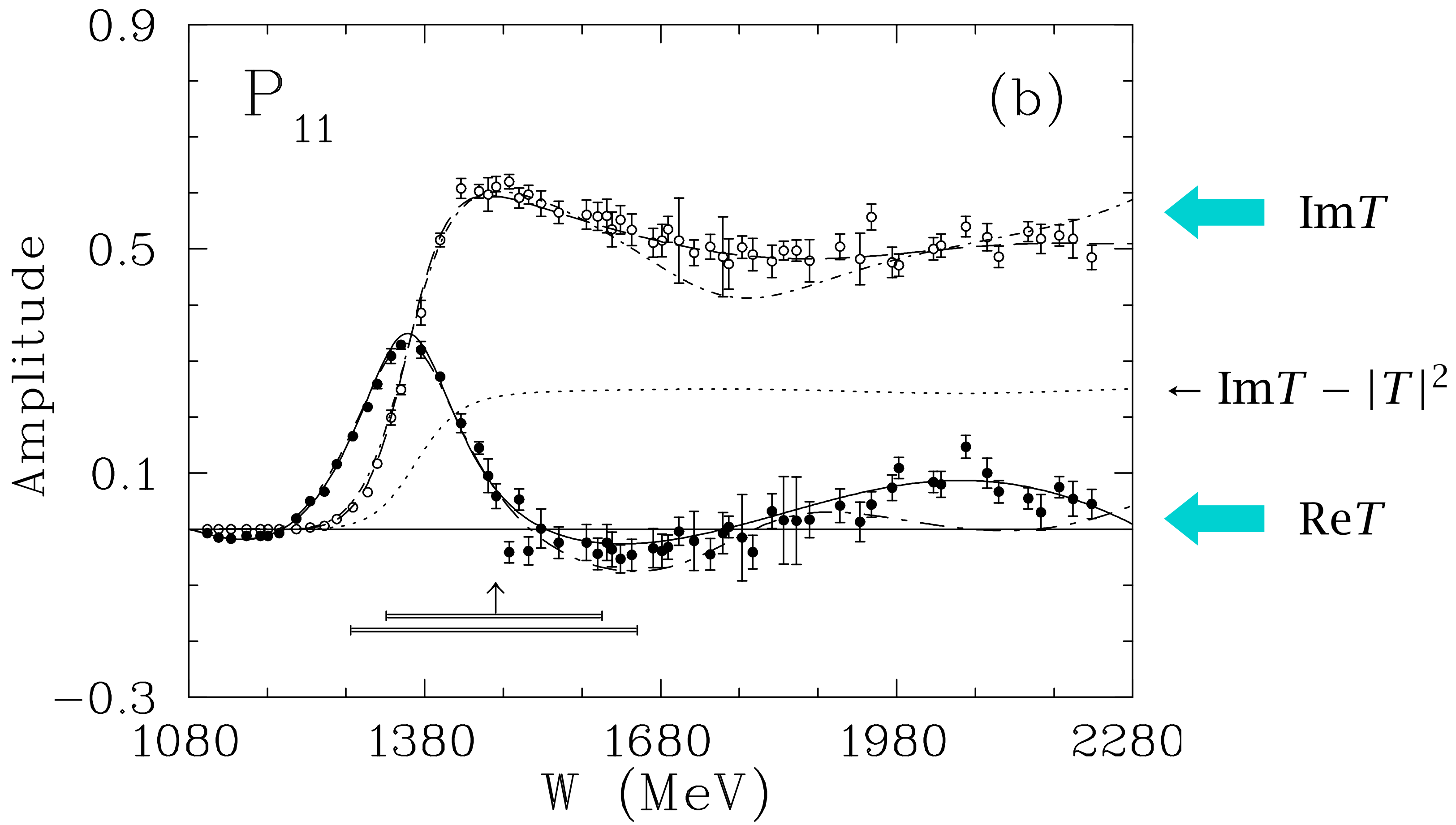
× Hard to reconcile in 3q picture (OZI-violating):

- Large $S_{11}(1535) \to \phi N$ coupling in near-threshold $pp \to pp\phi$, $\pi^- p \to n\phi$
  Xie++ PRC **77** (2008) 015206
- Large $S_{11}(1535) \to \Lambda N$ coupling in $\Psi \to p\bar{p}$, $\bar{p}\Lambda K^+$
  Liu++ PRL **96** (2006) 042202

SAID PWA of πN scattering in P_{11} channel



SAID PWA of πN scattering in P_{11} channel

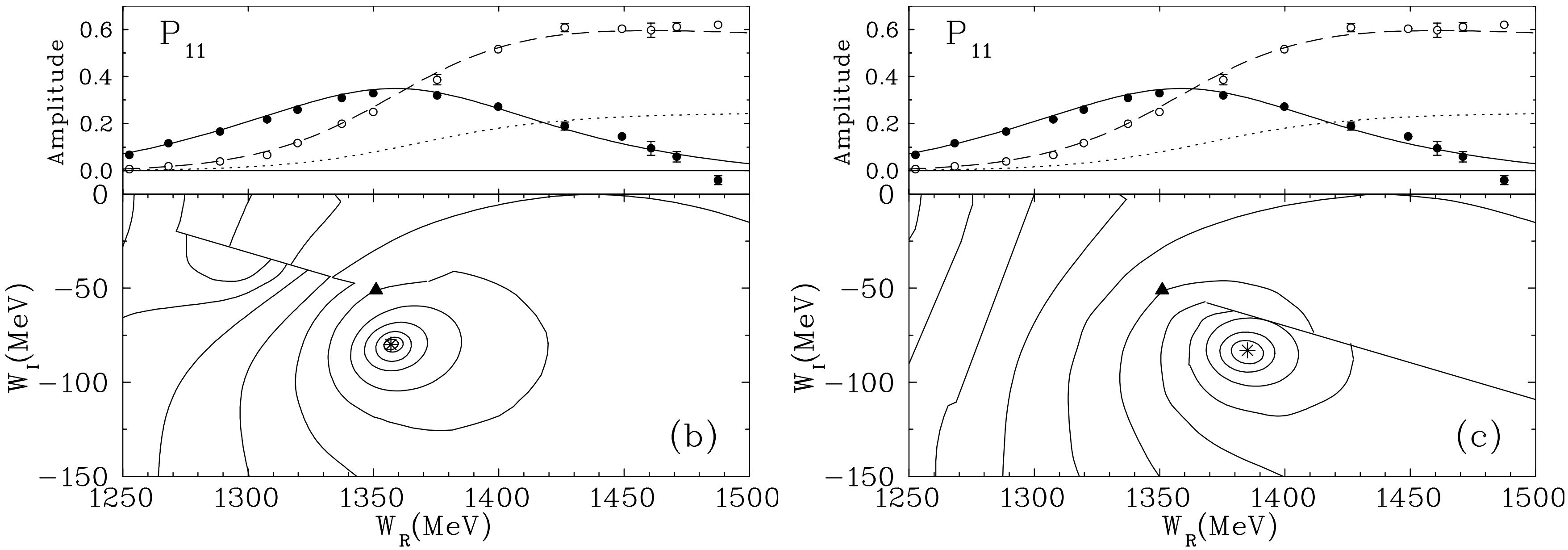


SAID FA02 $M_{\rm BW} = (1468 \pm 4.5)$ MeV, $\Gamma/2 = (180 \pm 13)$ MeV

$M_{\rm pole} = 1357 - i\,80$ MeV (I RS)

$1385 - i\,83$ MeV (II RS)

Roper pole-ology



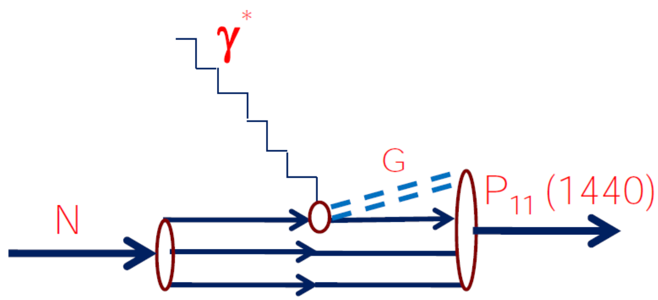
Arndt++ PRC **52** (1995) 2120, **69** (2004) 035213

- single BW with two poles on different Riemann sheets
- doublet ?

Roper in quark models

- Spherically symmetric SU(6)
  Radial excitation ("breathing mode") of proton $(1s)^3 \longrightarrow (1s)^2(2s)^1$
  Sizeable monopole strength (C0 / $S^p_{1/2}$ / S_{1-}) + dipole (M1 / $A^p_{1/2}$ / M_{1-})

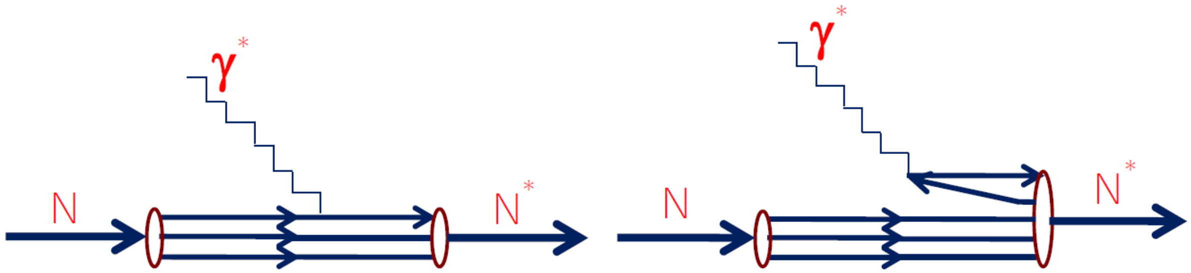
- Hybrid models
  Gluonic partner of proton (q^3g)
  Li, Burkert, Li PRD **46** (1992) 70



  Same quantum numbers as (q^3), indistinguishable by spectroscopy alone
  Equal radial WF ⇒ C0 suppressed, no "breathing", M1 dominates
  Roper mass through QCD sum rules
  in pQCD (asymptotic electroproduction rate off (q^3g) vs. (q^3))

- Constituent, semi-relativistic, relativistic QM and QM with meson DOFs
  Extensive studies with varying success
  Mostly limited to masses and photo-couplings

Additional $q\bar{q}$ components



- $\approx$ 30% admixture of $qqqq\bar{q}$ components in the Roper $\Rightarrow \Gamma(\text{theory}) = \Gamma(\text{exp})$

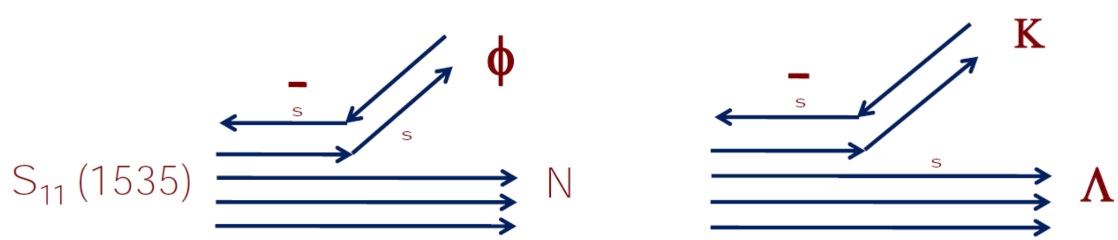
  Li, Riska PRC **74** (2006) 015202

- Lowest 5q configuration in $S_{11}(1535)$ is $qqqs\bar{s}$

  $\Rightarrow$ correct $P_{11}(1440)$ wrt. $S_{11}(1535)$ mass ordering

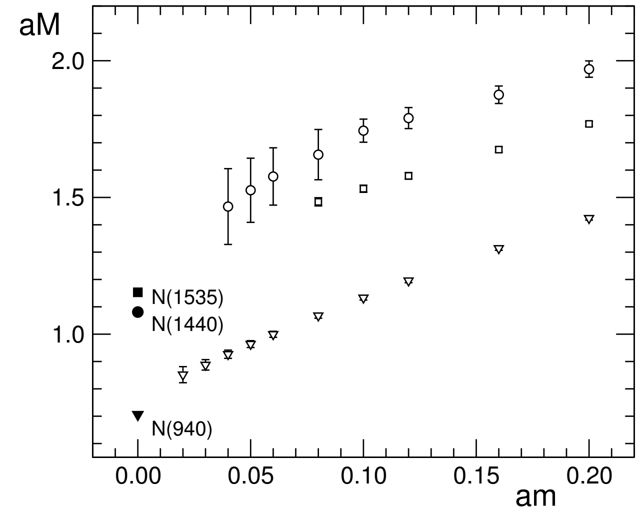
  $\Rightarrow$ large $S_{11}(1535) \to \phi N$, ΛK couplings without OZI violation

  An, Zou nucl-th/0802.3996



$P_{11}(1440)$ and $S_{11}(1535)$ on the Lattice

- close to CL, effects of CSB important
- level ordering should change with m_q
  Heavy q: 1st radial above 1st orbital exc
  CL: reversed levels

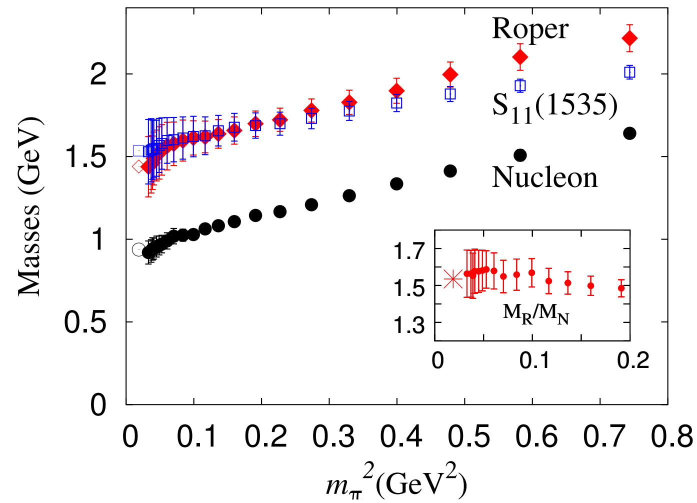


Bern-Graz-Regensburg / PRD **70** (2004) 054502

"... do not attempt a chiral extrapolation of our data ... numbers seem to approach the experimental data reasonably well"

"... the Roper's leading Fock component is a 3-quark state"

Kentucky / PLB **605** (2005) 137



"...+ and – parity excited states of the nucleon tend to cross over as the quark masses are taken to the chiral limit. Both results at the physical pion mass agree with the exp values ... seen for the first time in a lattice QCD calculation"

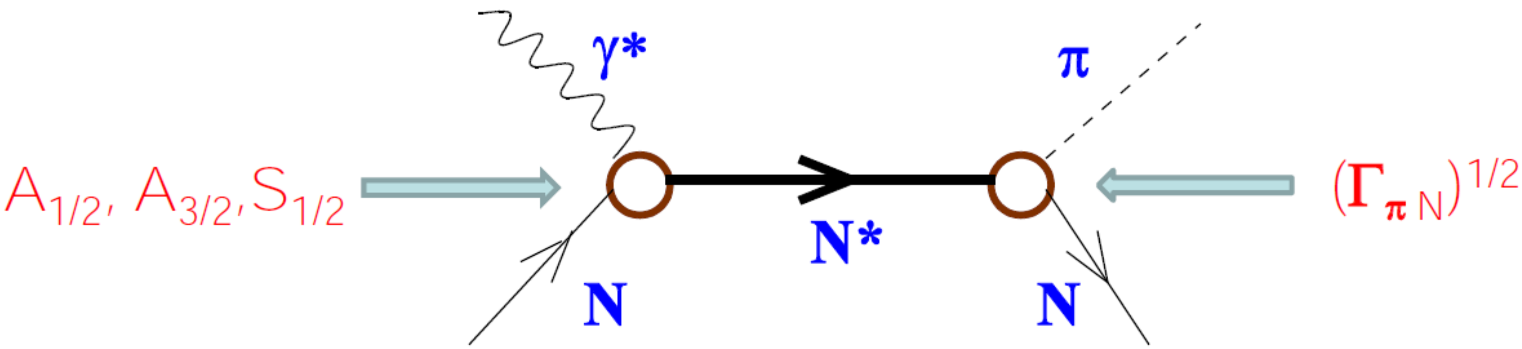
"...a successful description of the Roper resonance depends not so much on the use of the dynamical quarks, but that most of the essential physics is captured by using light quarks to ensure the correct chiral behavior"

Formalism for $p(\vec{e}, e'p)\pi$

Tremendous simplification when only beam is polarized:

$$\frac{d\sigma}{d\Omega} = \sigma_T + \varepsilon\sigma_L + \sqrt{2\varepsilon(\varepsilon+1)}\,\sigma_{LT}\cos\phi + \varepsilon\sigma_{TT}\cos 2\phi + h\sqrt{2\varepsilon(1-\varepsilon)}\,\sigma_{LT'}\sin\phi$$

Separate strong and EM vertex:



With sufficient angular coverage: extract Legendre moments

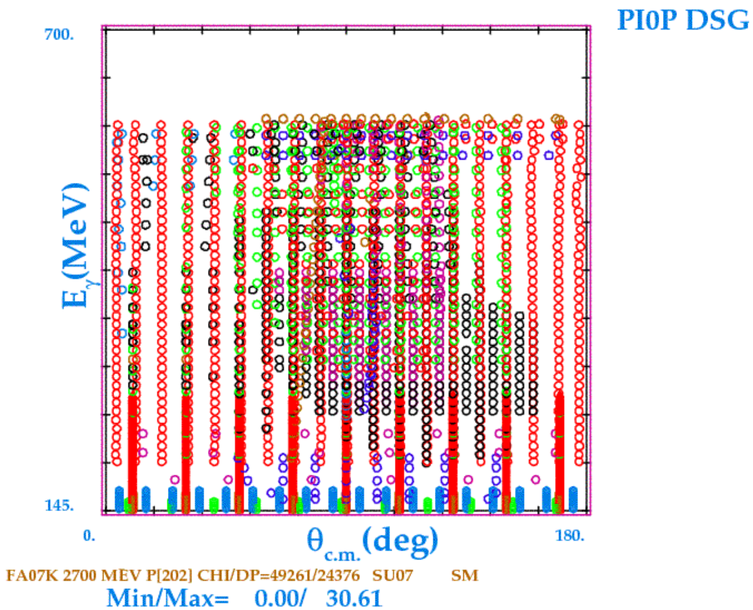
$$\sigma_\alpha(W, \cos\theta) = \sum_l D_l(W) P_l(\cos\theta)$$

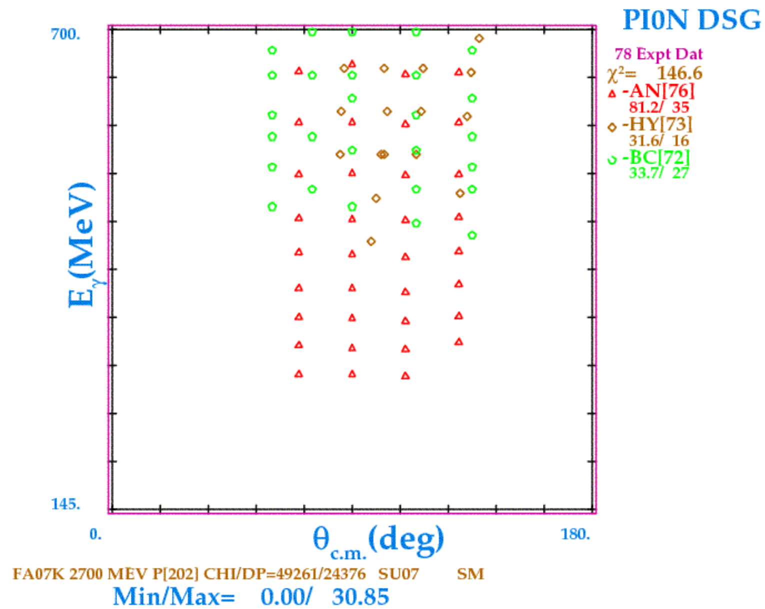
→ still “easy”

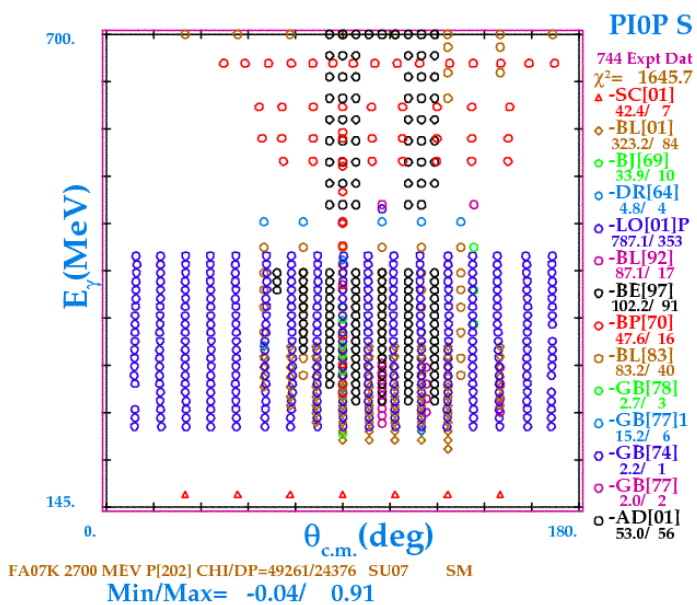
→ typical for CLAS (Hall B @ JLab)

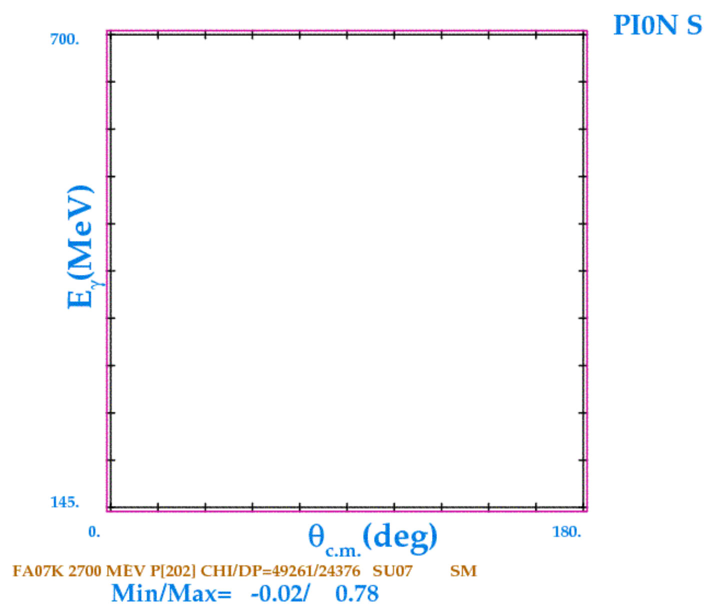
Available data (photoproduction)

example: $d\sigma$, Σ









Phenomenology: extraction of resonance parameters

Ideal case:

1 At given energy E, perform complete/over-complete measurements at all angles θ, i.e. 8 observables for pseudo-scalar photo-production $\mathrm{d}\sigma$, single-pol Σ, T, P, double-pol G, H, E, F

2 Extract amplitudes $F_{\lambda_\mathrm{f}\lambda_\gamma\lambda_\mathrm{i}}(E,\theta)$

3 Project out partial-wave amplitudes $f_{[LS]J}(E)$ from $F_{\lambda_\mathrm{f}\lambda_\gamma\lambda_\mathrm{i}}(E,\theta)$

4 Extract resonance poles and residues from $f_{[LS]J}(E)$

- speed-plot method (Höhler)
- time-delay method (Wigner)
- analytic continuation to complex E plane
  - — dispersion relations
  - — isobar and/or K-matrix equations
  - — dynamical scattering equations

$\times$ Electro-production: more observables, more multipoles

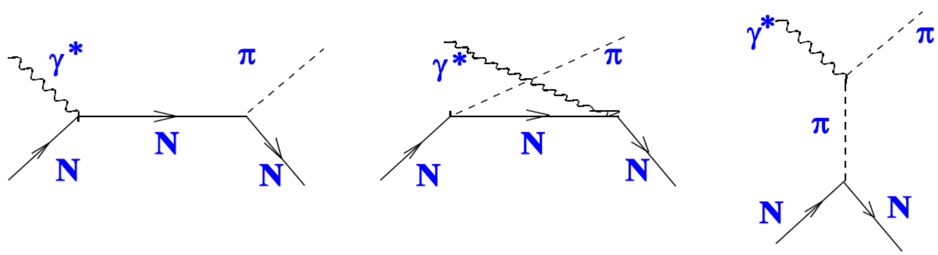
Dispersion relations

1 Build **Im** parts of amplitudes from s-channel resonance contributions with Breit-Wigner parameterization; include all ****, ***, ** resonances

2 Use fixed-t dispersion relations to find **Re** parts
There are 18 amplitudes $B_i^{(+,-,0)}(s,t,Q^2)$ for $\gamma^\star \mathrm{N} \to \mathrm{N}\pi$

$$\mathrm{Re}\, B_i(s,t,Q^2) = \textbf{Born} + \frac{1}{\pi}\int_{\mathrm{thr}}^{\infty} \mathrm{Im}\, B_i(s,t,Q^2) \left(\frac{1}{s'-s} \pm \frac{1}{s'-u} \right) \mathrm{d}s'$$

Born =

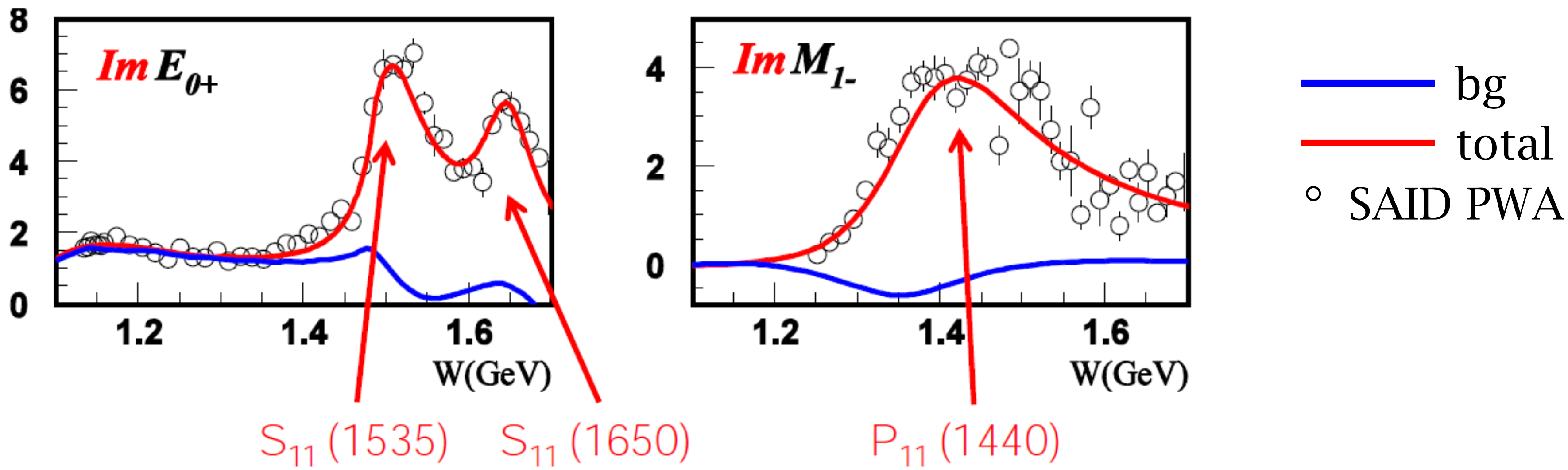


3 Constraint: Fermi-Watson theorem

× Example: $P_{33}(1232)$, $\mathcal{M} \in \{M_{1+}^{3/2}, E_{1+}^{3/2}, S_{1+}^{3/2}\}$
Integral equations for $\mathcal{M}$, particular + homogeneous solution
particular sol: magnitude fixed by Born terms
homogeneous sol: shapes fixed by DR, weight fitted to data

Advantage of dispersion relations

- **Im** of amplitudes determined mainly by resonance contributions



- **Re** parts of amplitudes can contain large non-resonant contributions fixed by DR

× Example: **Im** parts of amplitudes in $P_{33}(1232)$ region can generate non-resonant multipoles $E_{0+}^{(0)}$, $E_{0+}^{(1/2)}$, $E_{0+}^{(3/2)}$, $S_{0+}^{(0)}$, $S_{0+}^{(1/2)}$, $S_{0+}^{(3/2)}$
— Re parts fixed by DR
— Im parts fixed by Fermi-Watson with phenomenological $\delta_{0+}^{(1/2)}$, $\delta_{0+}^{(3/2)}$

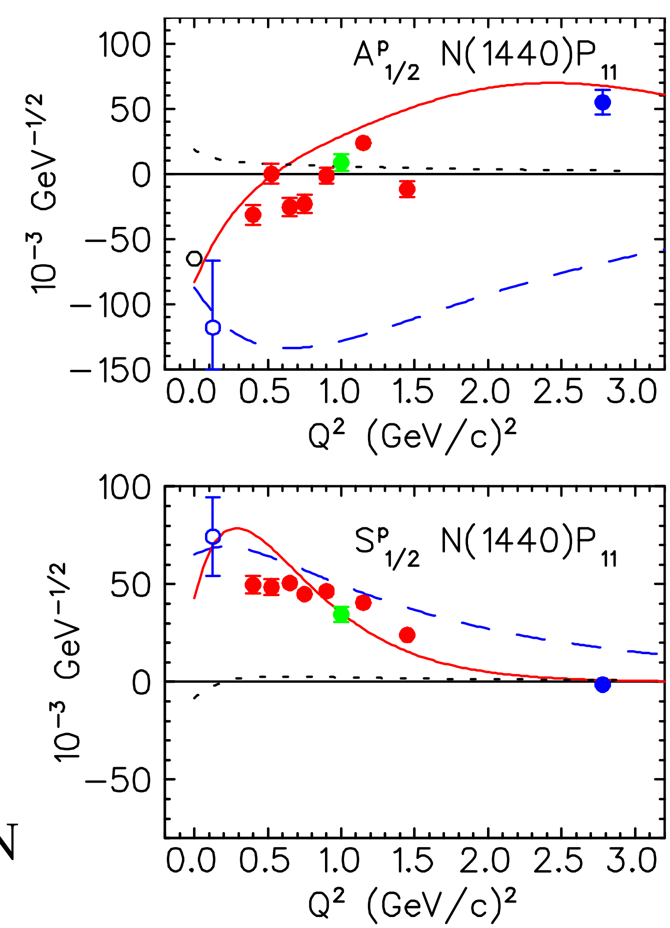
Unitary Isobar Models, Dynamical Models

All used in the past for N → Δ, uncertainties ↑↑ beyond Δ

MAID — Mainz unitary isobar model

- effective $\mathcal{L}$, adjustable parameters
- resonances in BW forms
- backgrounds are Born terms, ρ-, ω-exch
- total amplitudes unitarized
- attempt to incorporate all EP data into "super-global" fits
  ⇒ Need XS, single-, and double-pol observables to stabilize fits

MAID2003 w/o CLAS (2003) data

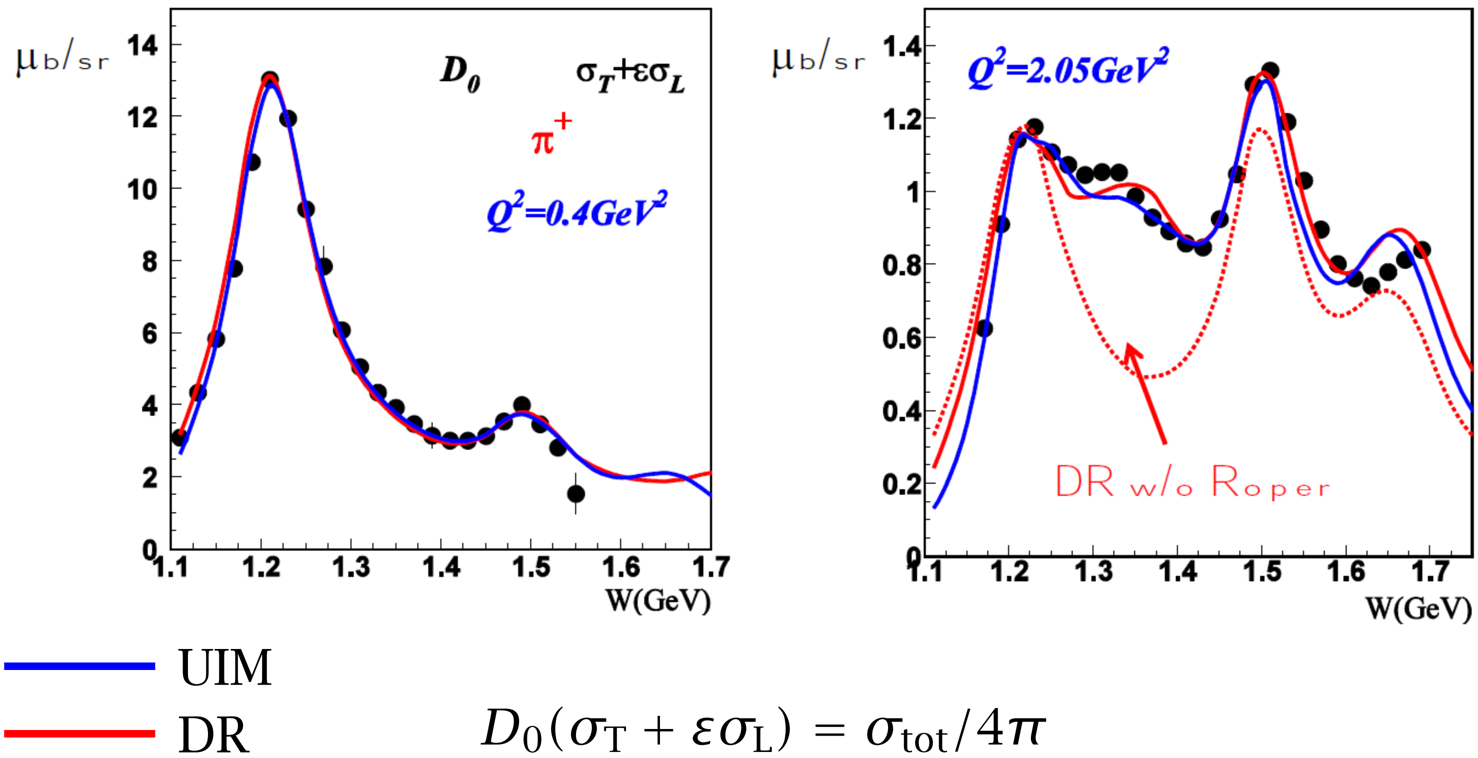


DMT — Dubna-Mainz-Taipei dynamical model

- Include πN FSI such that unitarity preserved
- $t_{\gamma\pi} = t^{\mathrm{B}}_{\gamma\pi} + t^{\mathrm{R}}_{\gamma\pi} = v_{\gamma\pi}\, g_0\, t_{\pi\mathrm{N}}$
- $t_{\pi\mathrm{N}}$ fitted to πN (SAID), $v_{\gamma\pi}$ fitted to γN → πN

SL — Sato-Lee

Example result: Q^2-dependence of D_0

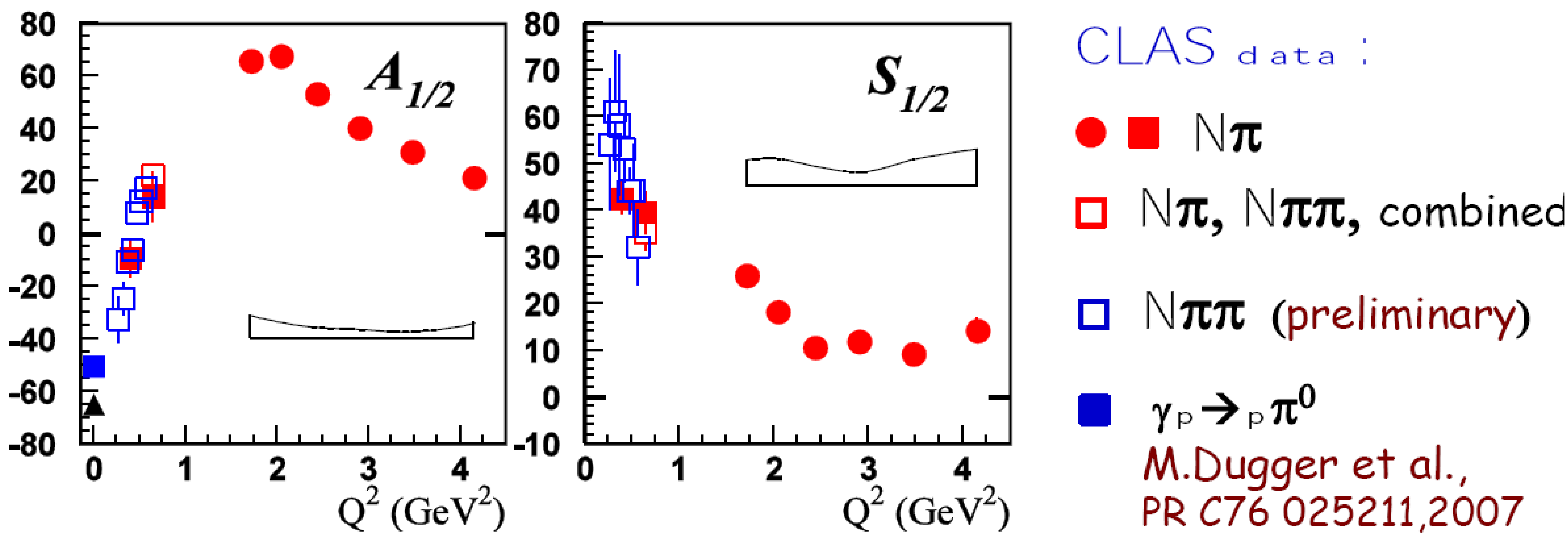


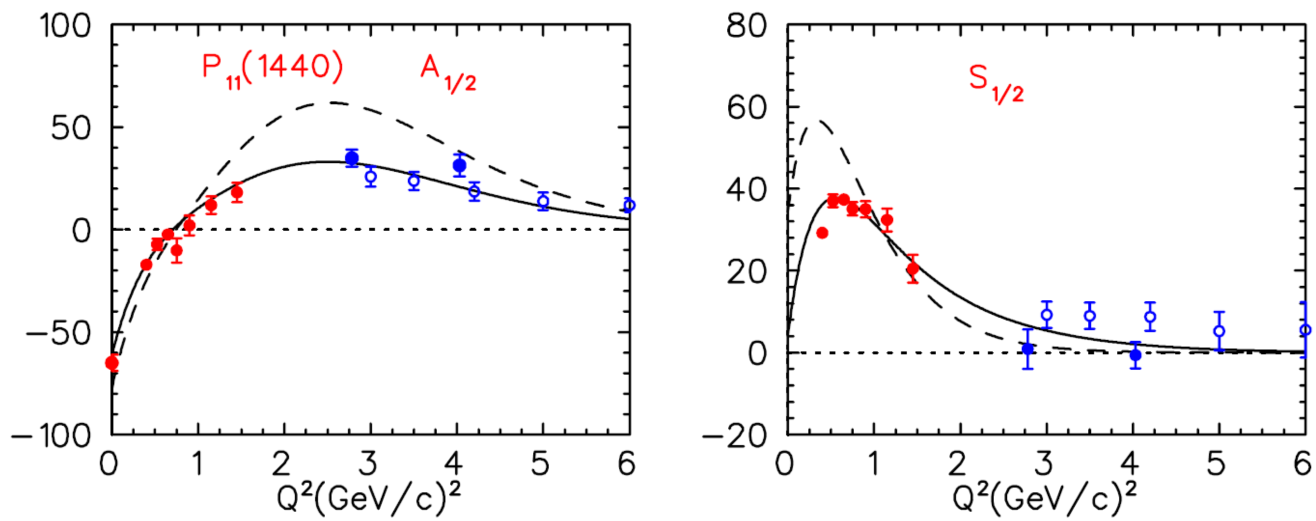
$$D_0(\sigma_\mathrm{T} + \varepsilon\sigma_\mathrm{L}) = \sigma_\mathrm{tot}/4\pi$$

- For Q^2 large, $P_{11}(1440)$, $S_{11}(1535)$, $D_{13}(1520)$ become more dominant w.r.t. P_{33}
- Similar: slow Q^2 decrease of $D_{0,1,2}(\sigma_\mathrm{T} + \varepsilon\sigma_\mathrm{L})$

  $\Leftarrow$ due to slow fall-off of $A_{1/2}$ of the P_{11}, S_{11}, D_{13}

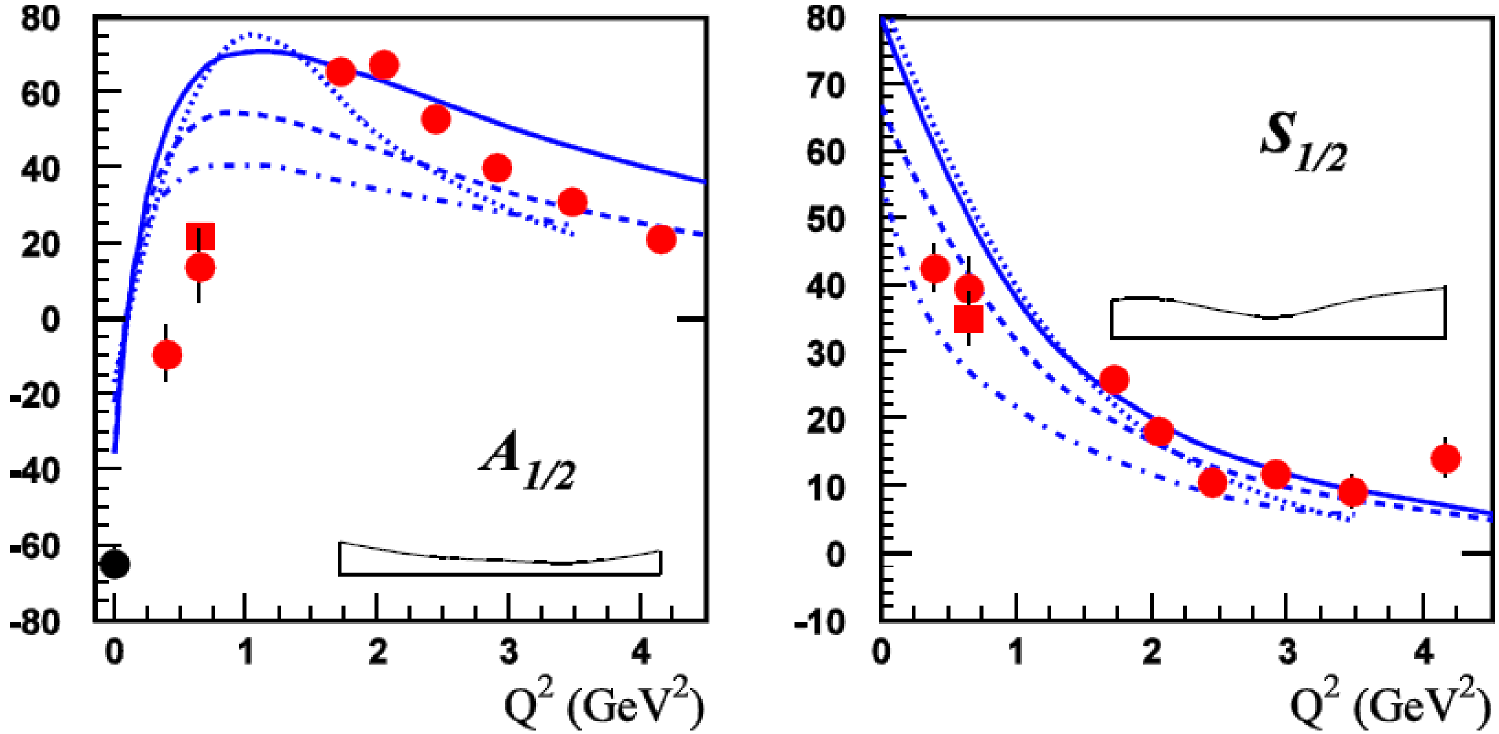
Helicity amplitudes for $\gamma^* p \to P_{11}(1440)$





MAID 2007 “Super-global” fits, Drechsel++ EPJA **34** (2007) 69

$P_{11}(1440)$ as a 3q state



Weber PRC **41** (1990) 2783

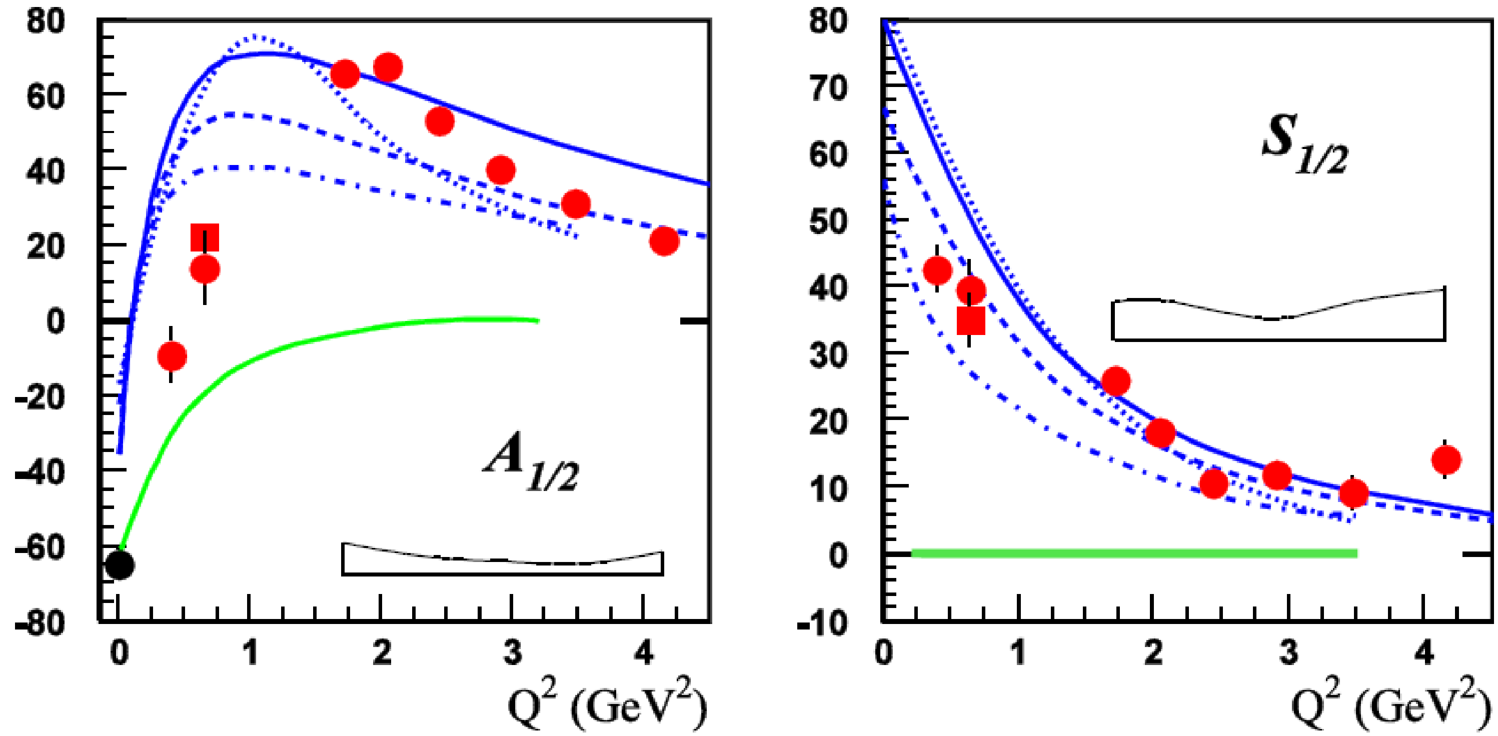
Capstick, Keister PRD **51** (1995) 3598

Pace, Simula PLB **397** (1997) 13

Aznauryan PRC **76** (2007) 025212

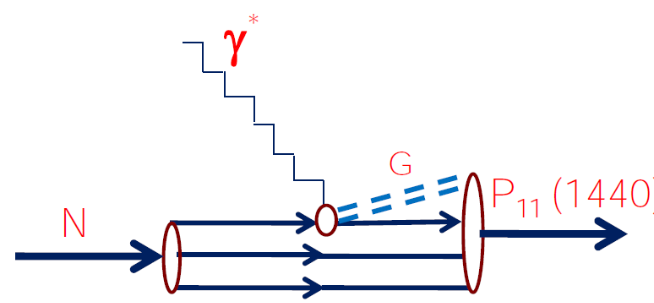
- All LF RQM: sign change of $A_{1/2}$, magnitude of $S_{1/2}$
- Solid evidence in favour of $P_{11}(1440)$ as first radial excitation of 3q ground state
- All fail to describe $A_{1/2}$ at low Q^2

$P_{11}(1440)$ as a q^3g hybrid state

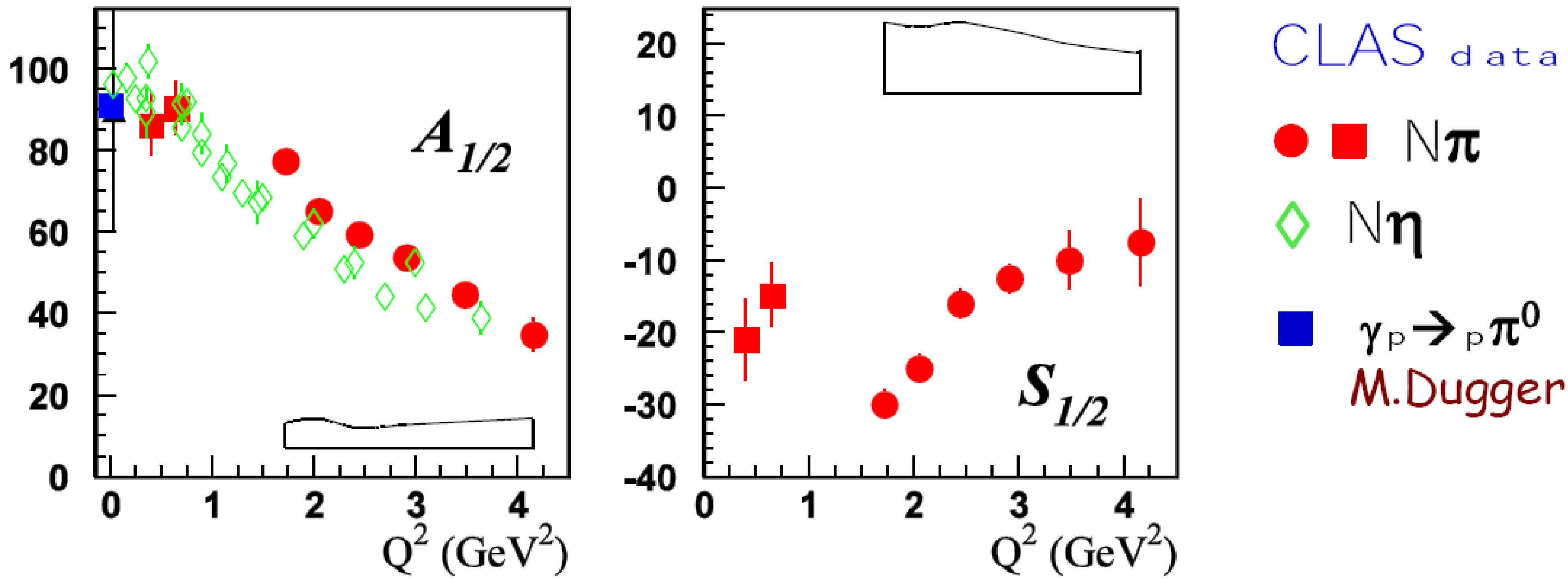


Li, Burkert, Li, PRD **46** (1992) 70

- Suppression of $S_{1/2}$ due to form of $\gamma^\star q \to qg$ vertex
- Hybrid q^3g picture **ruled out**



Helicity amplitudes for $\gamma^* p \to S_{11}(1535)$

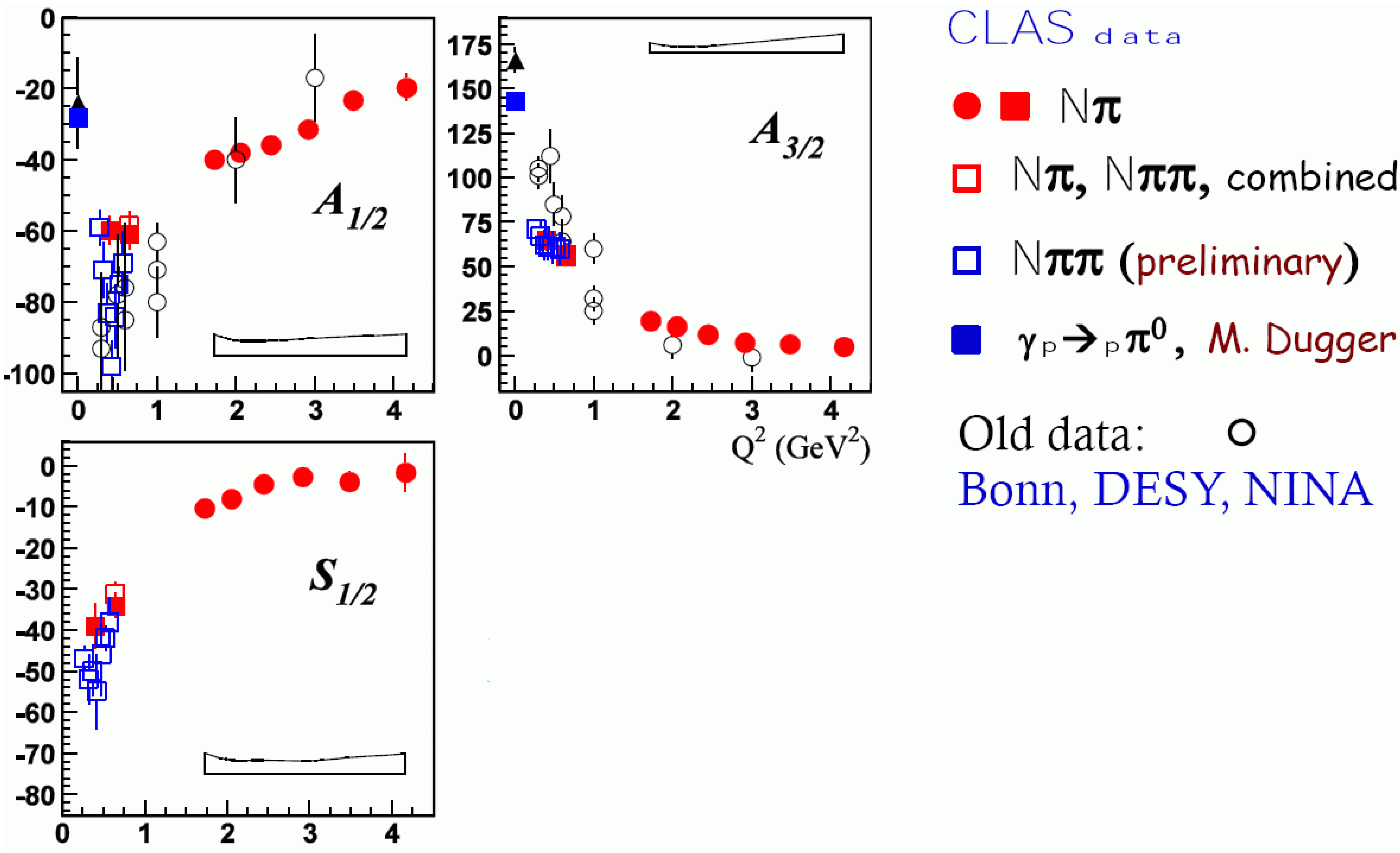


- First measurement of $S_{1/2}$ in Nπ

× Hard to extract $S_{1/2}$ in η electroproduction

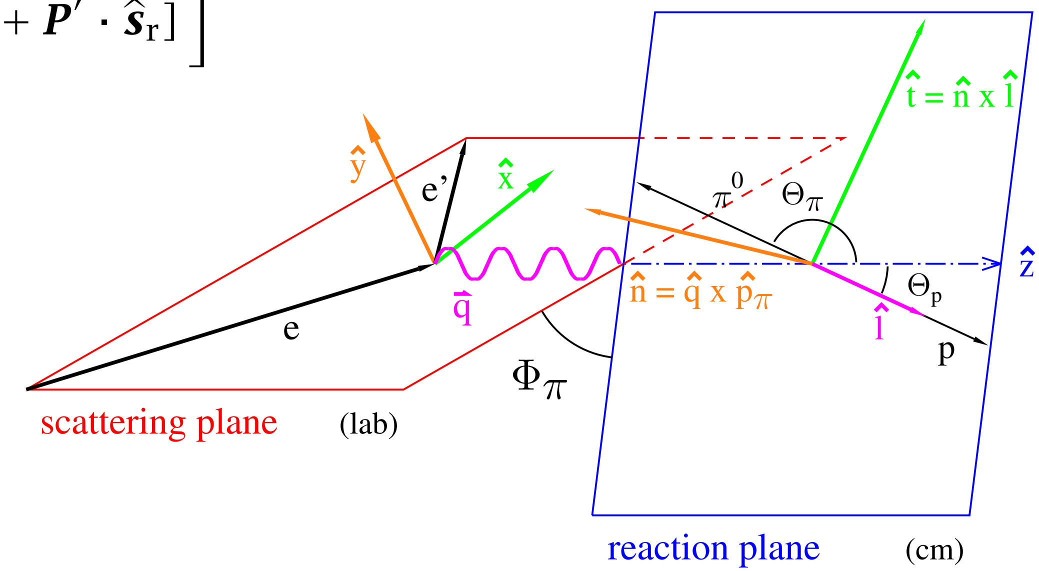
- Slow fall-off of $A_{1/2}$ seen in η production confirmed by π data
- Results for $A_{1/2}$ from η and π production ≈ agree with $\beta_{\pi N} = 0.45$, $\beta_{\eta N} = 0.52$
  (PDG: $\beta_{\pi N} = 0.35 - 0.55$, $\beta_{\eta N} = 0.45 - 0.60$)

Helicity amplitudes for $\gamma^* p \rightarrow D_{13}(1520)$



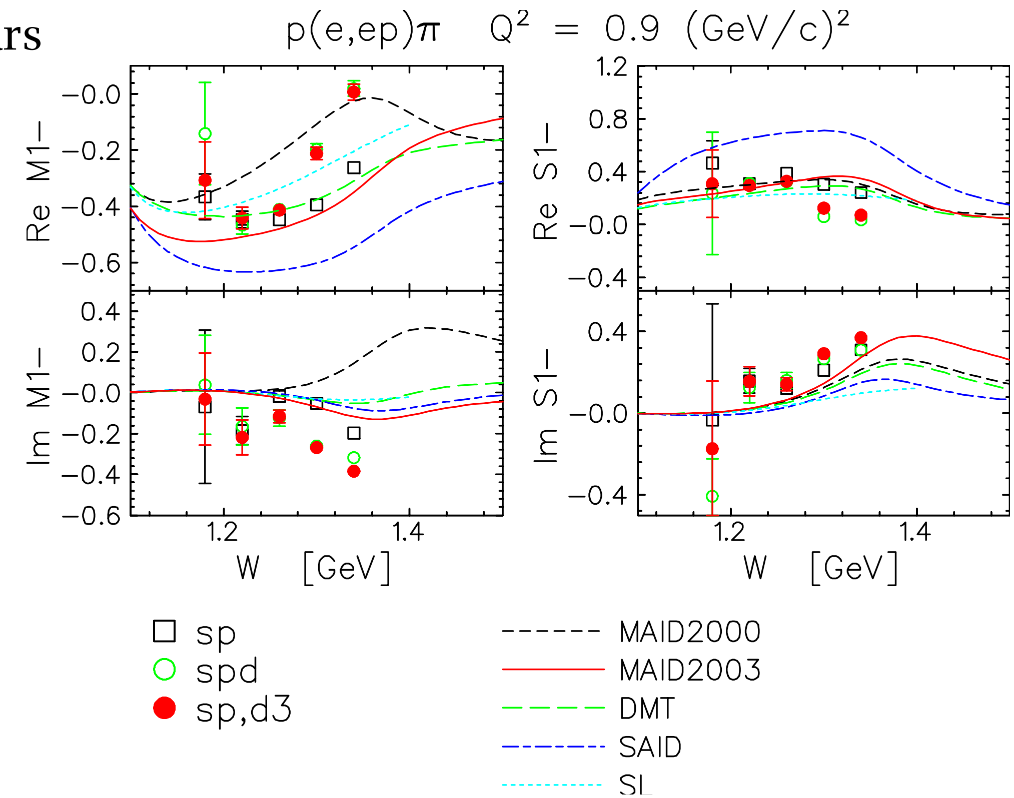
Much harder: $\mathrm{p}(\vec{\mathrm{e}}, \mathrm{e}'\vec{\mathrm{p}})\pi$

$$\frac{d\sigma}{dE'_e\, d\Omega_e\, d\Omega_p^\star} = \frac{\sigma_0}{2}\left[1 + \boldsymbol{P}\cdot\hat{\boldsymbol{s}}_r + h[A_e + \boldsymbol{P}'\cdot\hat{\boldsymbol{s}}_r]\right]$$

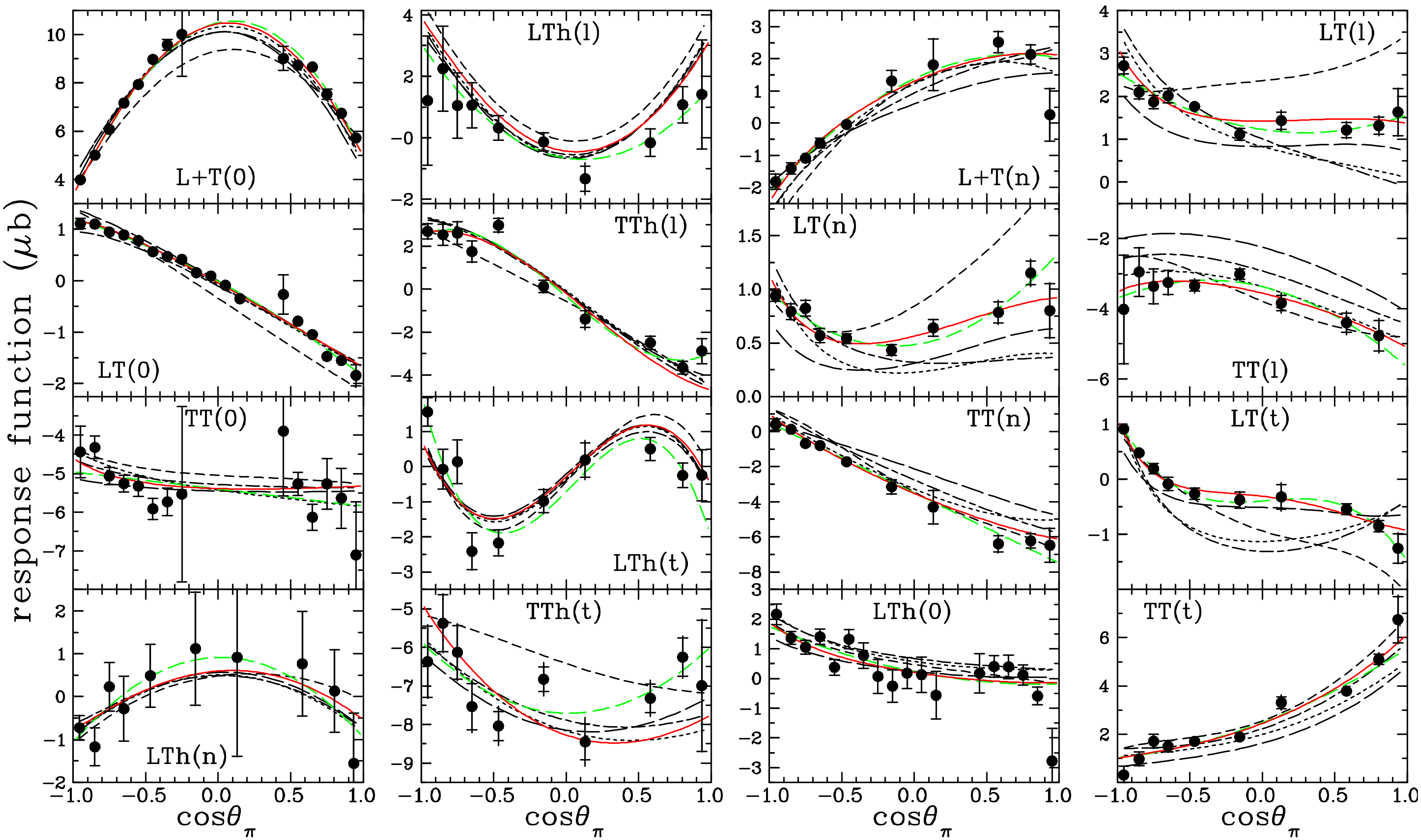


$$\begin{aligned}\frac{d\sigma}{dE'_e\, d\Omega_e\, d\Omega_p^\star} = \Gamma_v \frac{|\boldsymbol{p}_p^\star|\, W}{K_\gamma M_p} \Big[&(R_T + R_T^n S_n) + 2\varepsilon_L^\star (R_L + R_L^n S_n) \\ &+\sqrt{\varepsilon_L^\star (1+\varepsilon)}\,[\,(R_{LT} + R_{LT}^n S_n)\cos\phi + (R_{LT}^l S_l + R_{LT}^t S_t)\sin\phi\,] \\ &+\varepsilon\,[\,(R_{TT} + R_{TT}^n S_n)\cos 2\phi + (R_{TT}^l S_l + R_{TT}^t S_t)\sin 2\phi\,] \\ &+h\sqrt{\varepsilon_L^\star (1-\varepsilon)}\,[\,(R'_{LT} + R'^n_{LT} S_n)\sin\phi + (R'^l_{LT} S_l + R'^t_{LT} S_t)\cos\phi\,] \\ &+h\sqrt{1-\varepsilon^2}\,[\,R'^l_{TT} S_l + R'^t_{TT} S_t\,]\Big]\end{aligned}$$

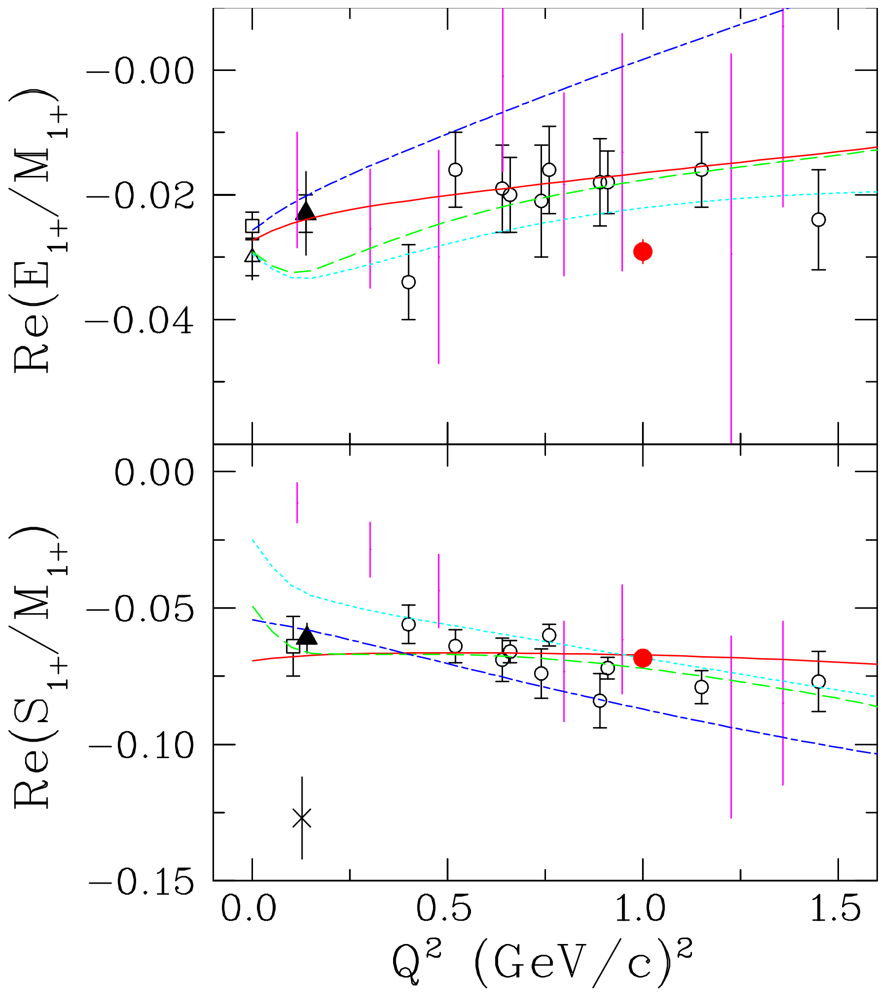
- Angular distributions of recoil polarization components
- Billinear combinations of transition multipoles (magnitudes and phases)
- Different observables, different billinears



- $Q^2 = (1.0 \pm 0.2)\ (\mathrm{GeV/c})^2$
  $W = (1.23 \pm 0.02)\ \mathrm{GeV}$
- large Q^2
  $\Rightarrow$ large out-of-plane acceptance
- 14 independent responses
  2 Rosenbluth combinations
  $\Rightarrow$ multipole analysis up to $l = 1$
- $l \leq 1$ truncation too severe
- M_{1+} dominance picture inadequate
- 1− ("Roper") multipoles out of range



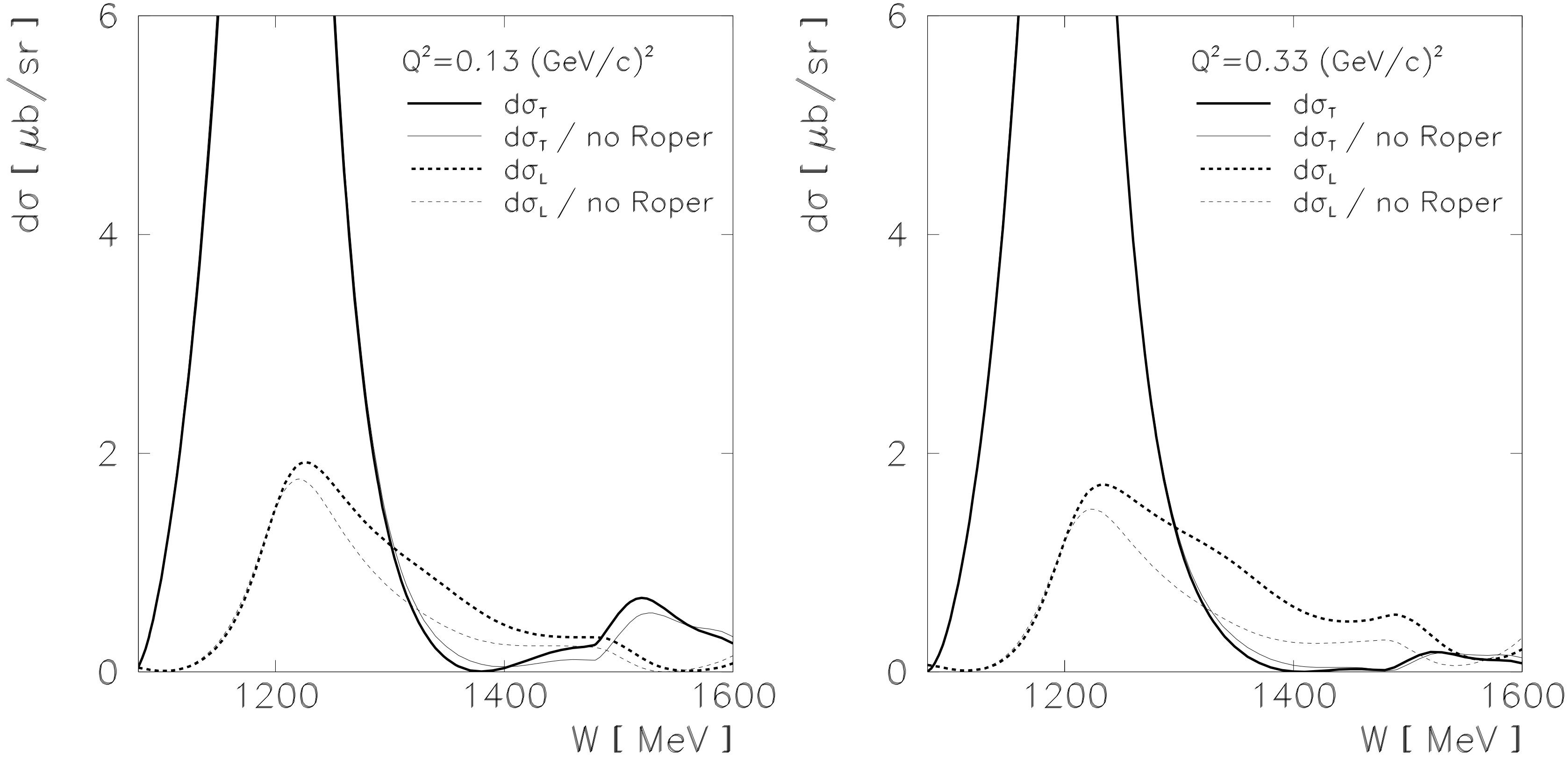
Kelly++ PRL **95** (2005) 102001, PRC **75** (2007) 025201



Kelly++ PRL **95** (2005) 102001

$N \to \Delta(1232)$ vs. $N \to N^\star(1440)$

XS is not the way to go... rates in Roper at least $\sim 10\times$ smaller



Amplification Through Interference

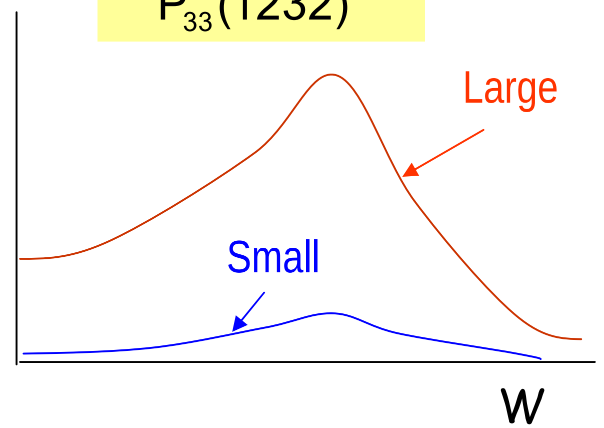
- Real LT Response

$$\sigma_{LT} \propto \mathrm{Re}(L^{*}T)$$
$$= \mathrm{Re}(L)\mathrm{Re}(T) + \mathrm{Im}(L)\mathrm{Im}(T)$$

Amplify small resonant multipole by interference with large resonant multipole

$\mathrm{Im}(S_{1+})$ $\mathrm{Im}(M_{1+})$

$P_{33}(1232)$



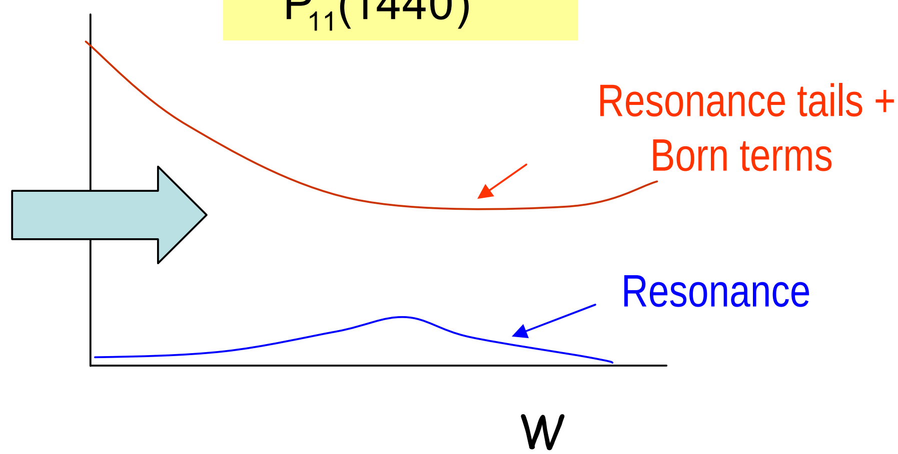
- Imaginary LT Response

$$\sigma'_{LT} \propto \mathrm{Im}(L^{*}T)$$
$$= \mathrm{Re}(L)\mathrm{Im}(T) - \mathrm{Im}(L)\mathrm{Re}(T)$$

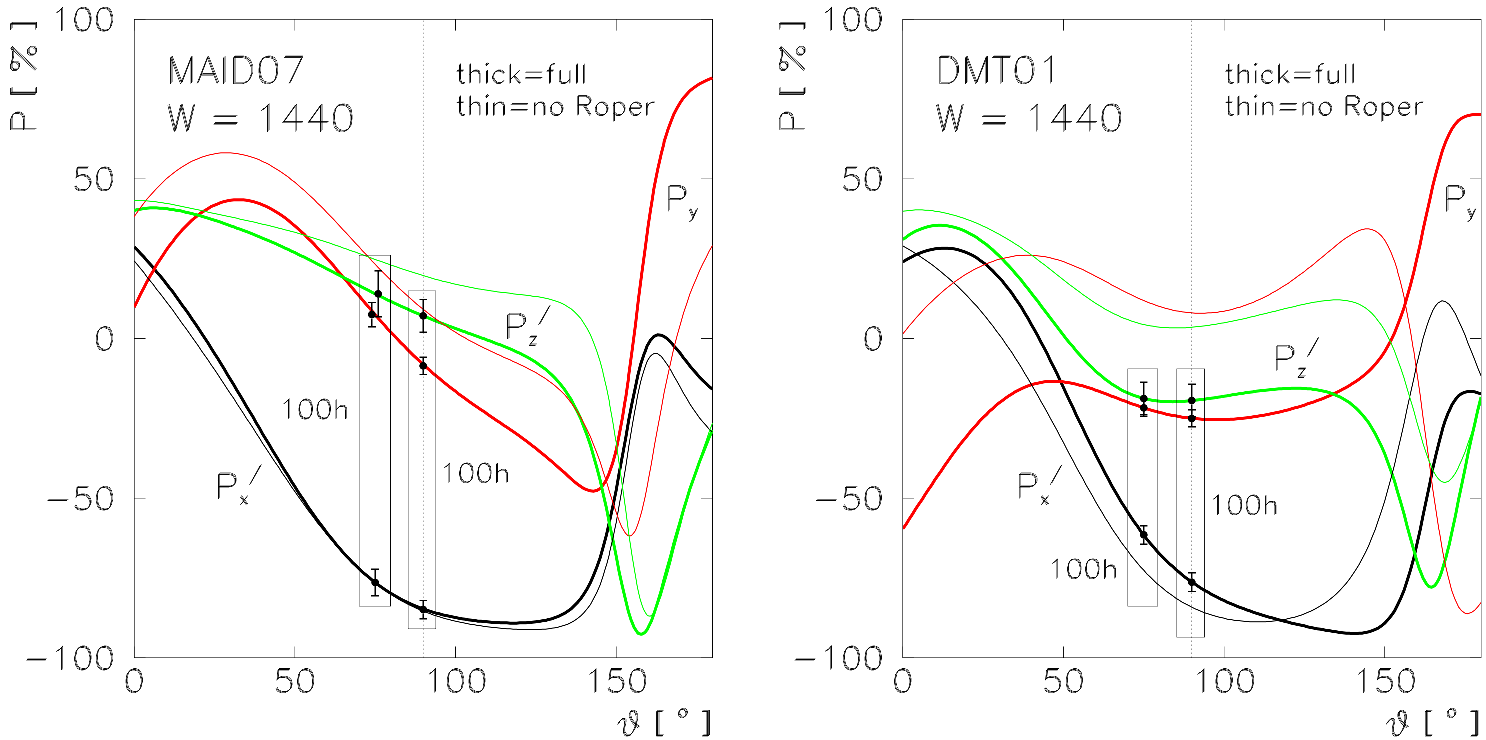
Amplify small resonant multipole by interference with large real background.

$\mathrm{Im}(S_{1-})$ $\mathrm{Re}(E_{0+})$

$P_{11}(1440)$

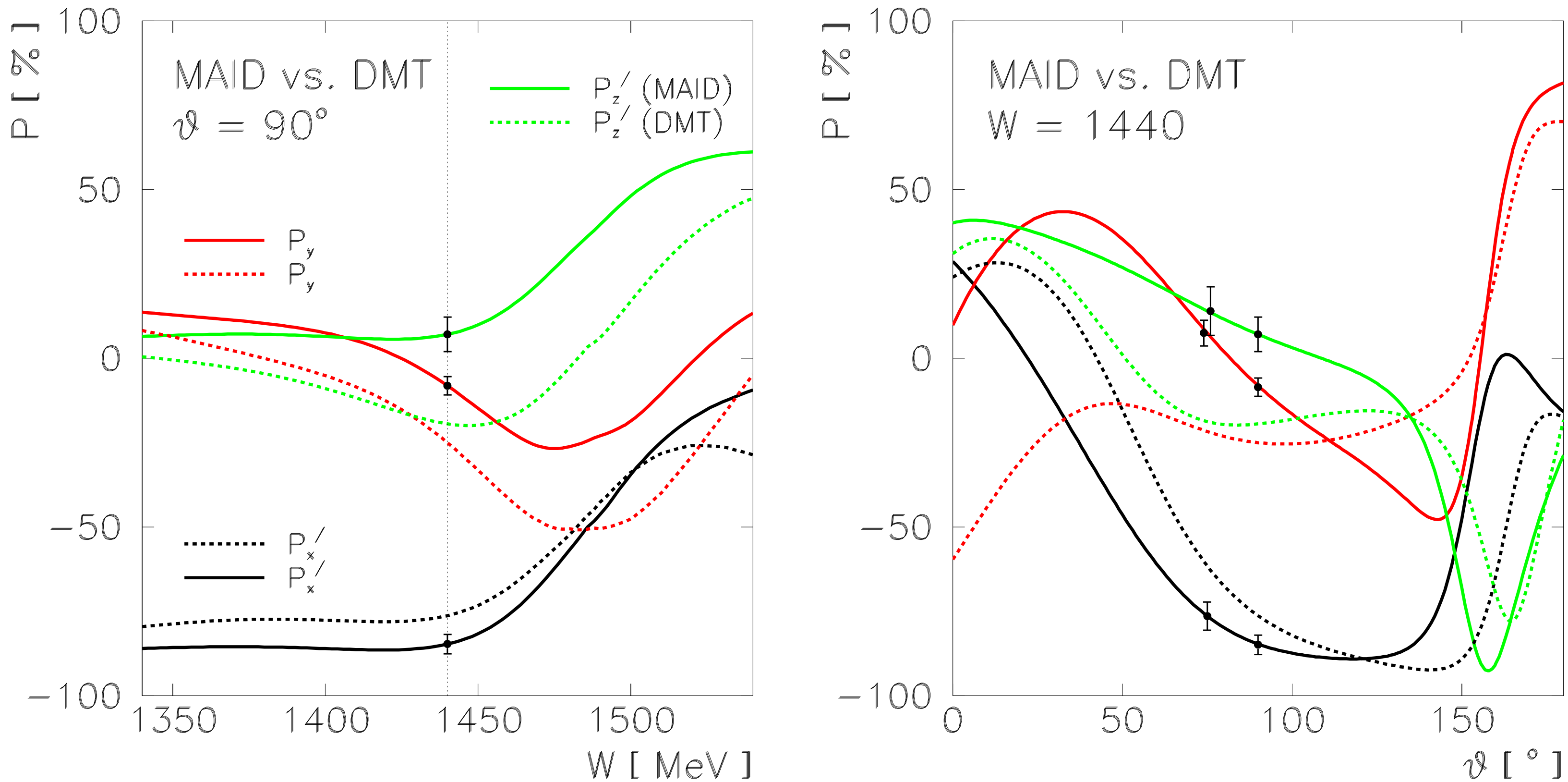


MAID07 vs. DMT01 (Roper “on”/“off”) $p(\vec{e}, e'\vec{p})\pi^0$



- Different treatment of resonances in isobar models (e.g. MAID) vs. dynamical models (e.g. DMT) ... “dressed” vs. “bare” vertices
- nice distinctions in all components of $\vec{P}$

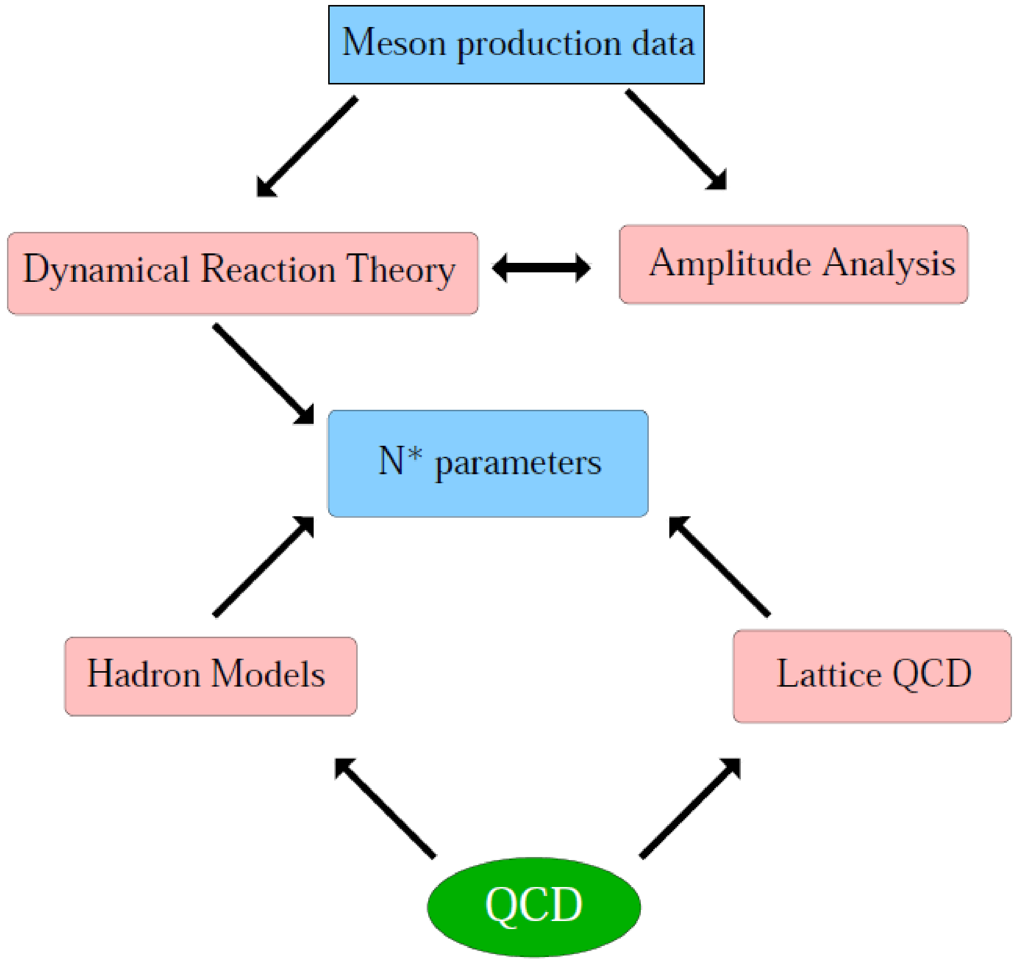
MAID07 vs. DMT01 (full calculations) $p(\vec{e}, e'\vec{p})\pi^0$



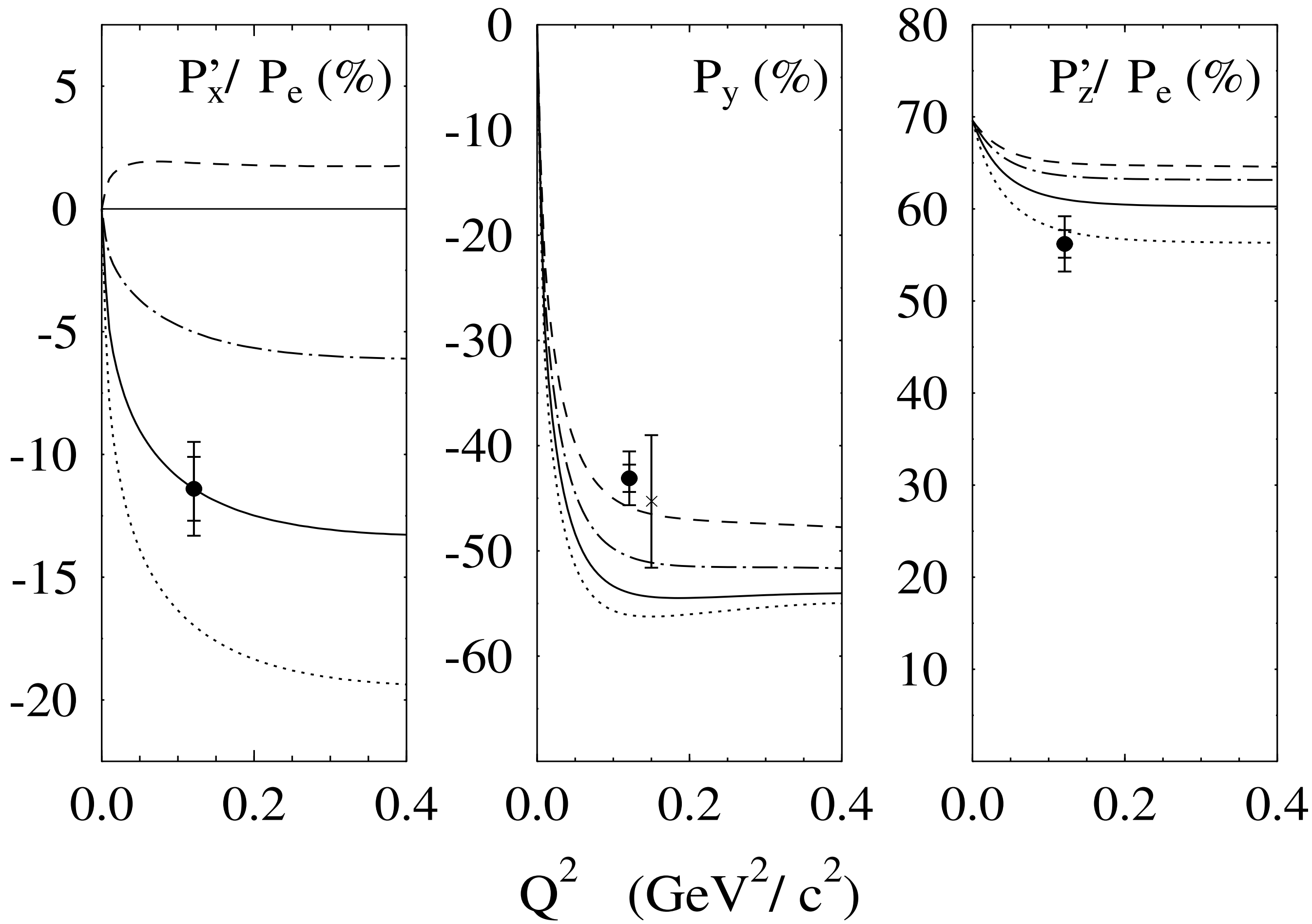
- Tremendous sensitivity to Roper
- CLAS results on P_{11}, S_{11}, D_{13} great, but lagging behind the $\Delta(1232)$ sophistication
- (Too) few measurements of double-polarization observables

Outlook: EBAC @ JLab

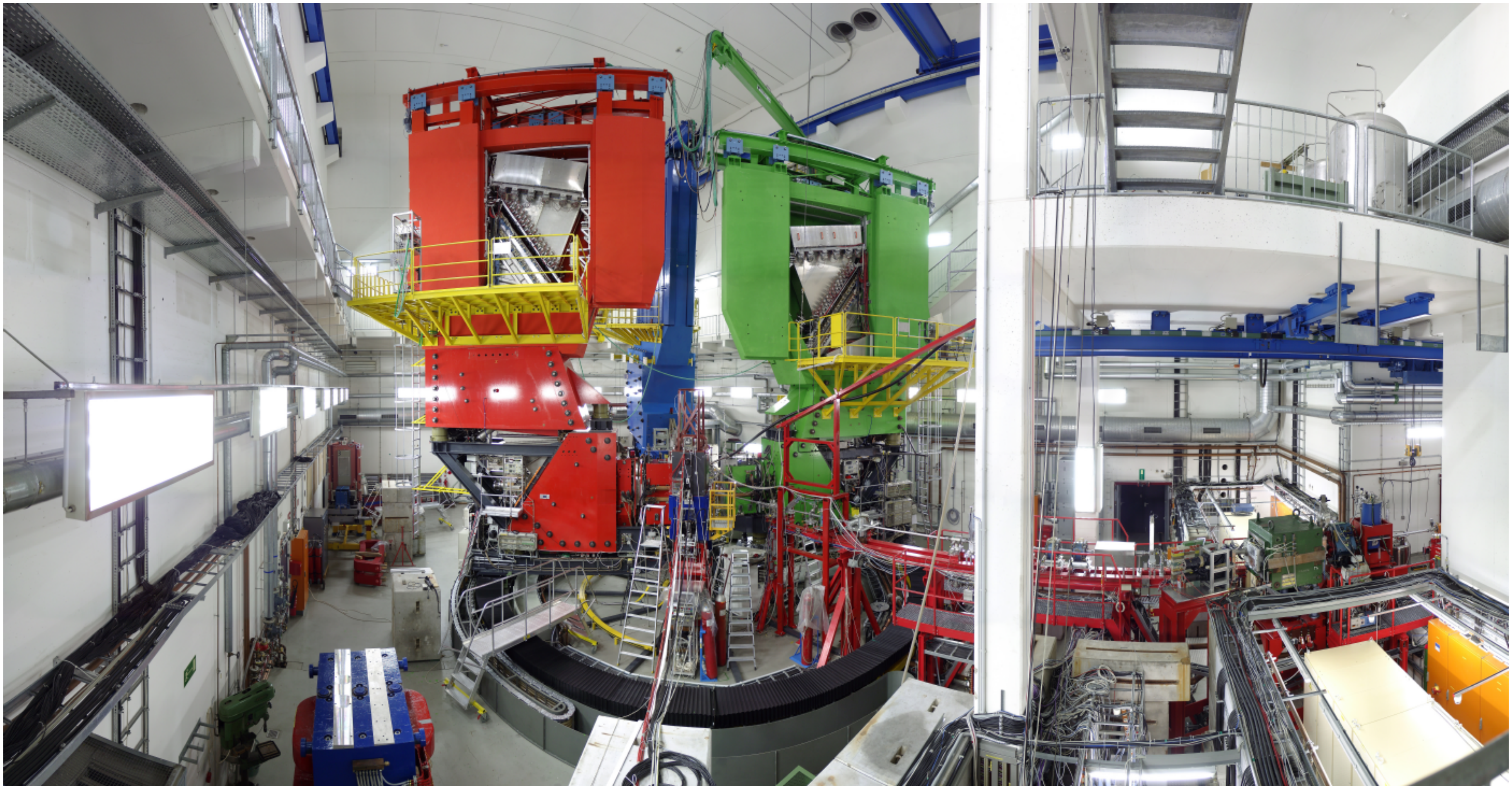
Goal (2009): "Complete the combined analysis of available single pion, eta and kaon photo-production data for nucleon resonances and incorporate analysis of two-pion final states into the coupled-channel analysis of resonances."



Wish list: this figure at $W = 1440$ instead of $W = 1232$ MeV



A1 @ MAMI



Hall A @ Jefferson Lab