Partial Wave Analysis of Single Pion Production Reactions

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Based on work in collaboration with
Dick Arndt
Bill Briscoe
Ron Workman

- GW DAC N^* Program
- Crucial role of the πN analysis
- Recent CLAS $\gamma N \rightarrow \pi N$ data and Multipole fits
- JLab effort in $\gamma^* N \rightarrow \pi N$
- N^* Puzzles
- Summary and Prospects

Center for Nuclear Studies

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EmNN, Oct 2008

GW SAID (Scattering Analysis Interactive Dial-in) Facility

[http://gwdac.phys.gwu.edu/]

[ssh -C -X said@gwdac.phys.gwu.edu [no passwd]

CNS Center for Nuclear Studies
Data Analysis Center

- CNS DAC Home
- CNS DAC [SAID]
- CNS Home

Partial-Wave Analyses at GW
[See Instructions]

- Pion-Nucleon
- Kaon-Nucleon
- Nucleon-Nucleon
- Pion Photoproduction
- Pion Electroproduction
- Kaon Photoproduction
- Eta Photoproduction
- Pion-Deuteron (elastic)
- Pion-Deuteron to Proton+Proton

Analyses From Other Sites

- Mainz (MAID – Analyses)
- Nijmegen (Nucleon-Nucleon Online)
- Hamburg (Inversion Online)

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CNS DAC Services [SAID Program]

- The Virginia Tech Partial-Wave Analysis Facility (SAID) has moved to GW!
- New features are being added and will first appear at this site. Suggestions for improvements are always welcomed.
- Once fully operational, this web page will become the main entry for the full range of services presently available through SAID.

Instructions for Using the Partial-Wave Analyses

The programs accessible with the left-hand side navigation bar allow the user to access a number of features available through the SAID program. Contact a member of our group if you are unfamiliar with the SSH version. If you enter choices which are unphysical, you may still get an answer (accordance with the `garbage in, garbage out' rule). Please report unexpected garbage-out to the management.

Note: These programs use HTML forms to run the SAID code. If unfamiliar with the options, run the default setup first. The output is an (edited echo of an interactive session which would have resulted had you used the SSH version. If the default example fails to clarify the specific task you have in mind, we can help (just send an e-mail message).

All programs expect energies in **MeV** units. All of the solutions and potentials have limited ranges of validity. Some are unstable beyond their uppe energy limits. Extrapolated results may not make much sense.
Increments: The programs will not allow an arbitrary number of points to be generated. As a rule, stay below **100**.

ACKNOWLEDGMENTS

The **CNS Data Analysis Center** is partially funded by the U.S. Department of Energy, the Thomas Jefferson Lab, and the Research Enhancement Funds of The George Washington University, with strong support from the GW Northern Virginia Camp

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N^* and Δ^* States Coupled to πN

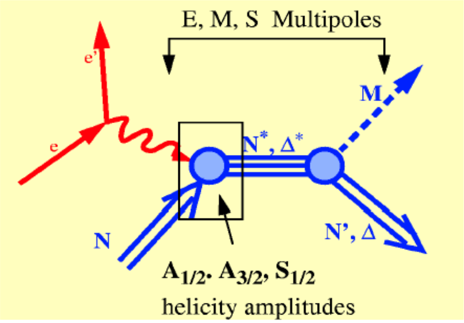
- One of the most convincing ways to study Spectroscopy of N^* & Δ^* is πN PWA
- Main objects in the PDG Listings [http://pdg.lbl.gov/] come from: Karlsruhe-Helsinki, Carnegie-Mellon-Berkeley, and GW/VPI

- GW DAC SAID program: $\pi N \rightarrow \pi N \Rightarrow \gamma N \rightarrow \pi N \Rightarrow \gamma^* N \rightarrow \pi N$

- πN elastic amplitudes from fits to the observables:
  σ^{tot}, $d\sigma/d\Omega$, and P plus a few R and A measurements [0.4 %]

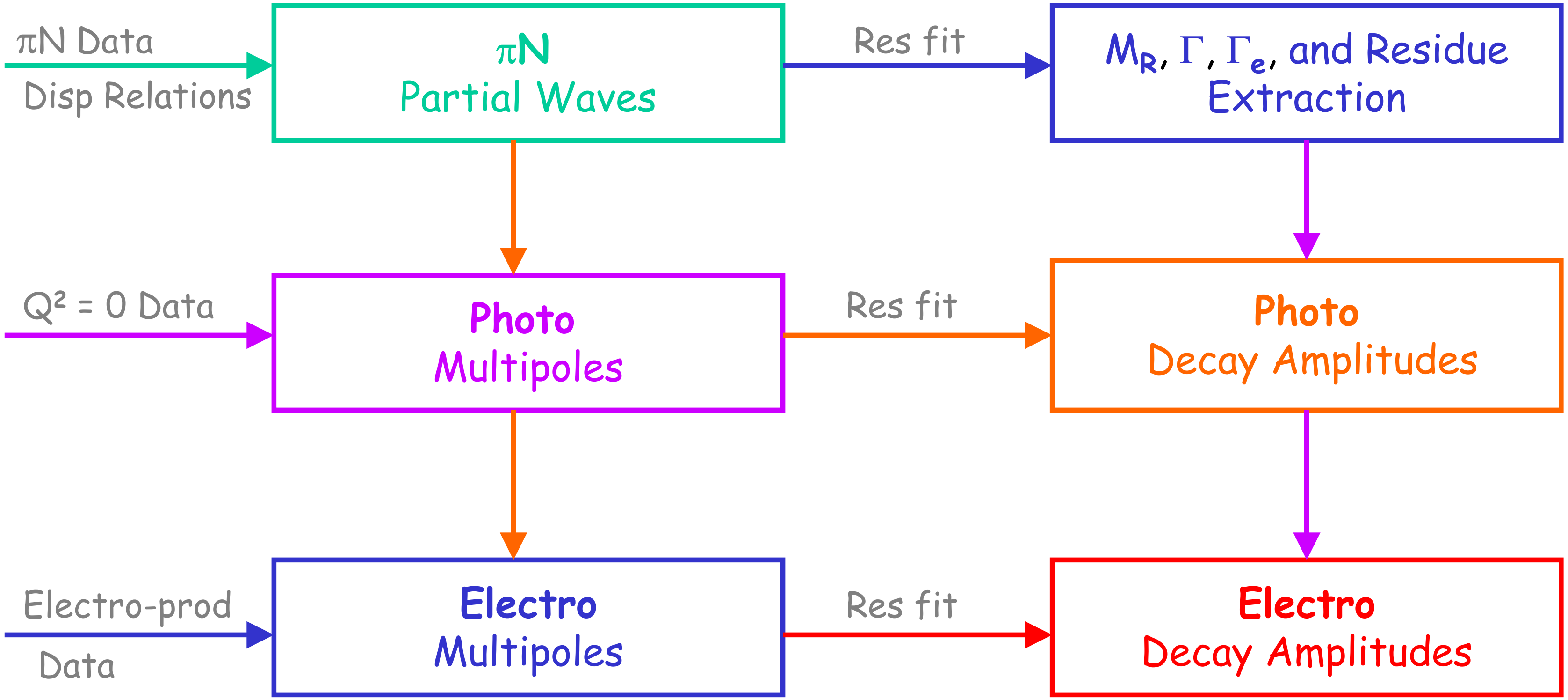
- Assuming dominance of 2 hadronic channels, can parametrize
  $\gamma^* N \rightarrow \pi N$ in terms of $\pi N \rightarrow \pi N$ amplitudes alone

- Resulting multipoles can be
  - re-fitted in terms of Res/Bckgr contributions or
  - used as input to multi-channel fits with more elaborate constraints



Road Map for GW SAID Analysis of Scattering Data

- πN PWA provides the base for Spectroscopy studies for *non-strange* baryons in all other processes



Coupled Channel Fit of πN and ηN data [SP06]

[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **74**, 045205 (2006)]

- Energy dependent SP06 and associated SES
- T_π = 0 – 2600 MeV [W = 1080 – 2460 MeV]
- PWs = 15 [I=1/2] + 15 [I=3/2] + 5 [ηN] [l < 9]
- Prms = 94 [I=1/2] + 80 [I=3/2]
- 4-channel Chew-Mandelstam **K**-matrix parameterization [πN, $\pi\Delta$, ρN, ηN]
- 3 mapping variables: $g^2/4\pi$, $a[\pi^- p]$, Eth

- Recent Contribution:
  - HE, CHAOS → $\pi^+ p \to \pi^+ p$
  - HE, CHAOS, ITEP-PNPI → $\pi^- p \to \pi^- p$
  - HE, CB, PSI, RMC → $\pi^- p \to \pi^0 n$
  - CB → $\pi^- p \to \eta n$

Reaction	Data	χ^2
$\pi^+ p \to \pi^+ p$	13,344	27,242
$\pi^- p \to \pi^- p$	11,967	22,705
$\pi^- p \to \pi^0 n$	2,933	6,091
$\pi^- p \to \eta n$	257	628
DRs	3,375	671
Total	31,876	57,241

[0 – 2600 MeV] (for $\pi^+ p \to \pi^+ p$, $\pi^- p \to \pi^- p$, $\pi^- p \to \pi^0 n$)

[550 – 800 MeV] (for $\pi^- p \to \eta n$)

- 106 data above 800 MeV and
- Very little Pol measurements

- In future, J-PARC and GSI can contribute a lot of hadronic data

Minimization and Normalization Factor [χ^2/Data]

[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **74**, 045205 (2006)]

- Modified χ^2 function, to be minimized

[systematics plays important role]

$$\chi^2 = \sum_i [(X\theta_i - \theta_i^{exp}) / \varepsilon_i]^2 + [(X - 1) / \varepsilon_X]^2$$

Modified χ^2 [Norm]
Standard χ^2 [UnNorm]

θ_i^{exp} measured, ε_i stat error, θ_i calculated, X norm const, ε_X its error

- If the systematic uncertainty varies with angle, this procedure may be considered as a first approximation

Renormalization freedom provides a significant improvement for our best fit results

χ^2/Data	SP06		FA02		KA84	
Reaction	Norm	UnNorm	Norm	UnNorm	Norm	UnNorm
$\pi^+p \rightarrow \pi^+p$	2.0	6.7	2.1	9.3	3.6	10.0
$\pi^-p \rightarrow \pi^-p$	1.9	6.2	2.0	7.1	5.2	13.0
$\pi^-p \rightarrow \pi^0n$	2.1	4.5	2.4	9.5	3.2	7.8
$\pi^-p \rightarrow \eta n$	2.4	10.1	2.5	4.6		

- Only the normalization constants were searched to minimize χ^2 for KA84 (no adjustment of the partial waves was possible)

- Over last 30 years, πN database increased by a factor of 3 – 4

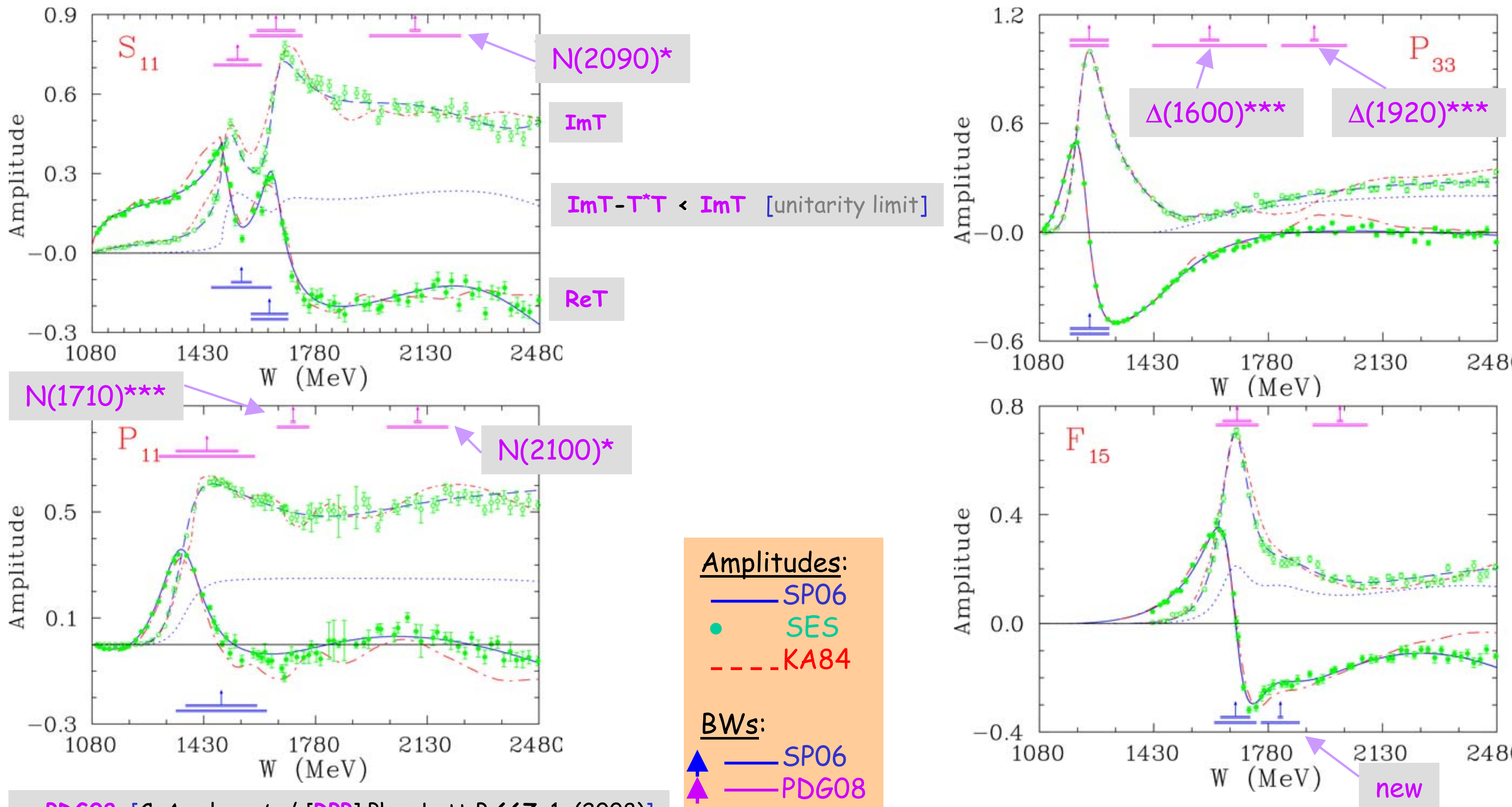
- GW solutions look more stable vs previous

- FA02 [R. Arndt, W. Briscoe, IS, R. Workman, and M. Pavan, Phys Rev C **69**, 035213 (2004)]
- KA84 [R. Koch, Z Phys C **29**, 597 (1985)]

Partial Waves [L^{P}_{2I2J}] for SP06

[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **74**, 045205 (2006)]

- Overall: the difference between KH and GW is rather small but…
  Resonances may be essentially different



- **PDG08** [C. Amsler *et al.* [RPP] Phys Lett B **667**, 1 (2008)]
- **KA84** [R. Koch, Z Phys C **29**, 597 (1985)]

Summary of N* and Δ* Finding from πN PWA

[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **74**, 045205 (2006)]

<u>Standard PWA</u>

- Allows to determine the N^*s, Δ^*s, and their quantum numbers using
  - The complex energy plain and
  - Breit-Wigner technique
- Tends (by construction) to miss narrow Resonances with $\Gamma < 30$ MeV
- Reveals only wide Resonances, but not too wide ($\Gamma < 500$ MeV) and possessing not too small BR (BR > 4%)

- <u>Our study</u> does not support several N*s and Δ*s reported by PDG08:

  *** $\Delta(1600)P_{33}$, $N(1700)D_{13}$, $N(1710)P_{11}$, $\Delta(1920)P_{33}$

  ** $N(1900)P_{13}$, $\Delta(1900)S_{31}$, $N(1990)F_{17}$, $\Delta(2000)F_{35}$, $N(2080)D_{13}$, $N(2200)D_{15}$, $\Delta(2300)H_{39}$, $\Delta(2750)I_{313}$

  * $\Delta(1750)P_{31}$, $\Delta(1940)D_{33}$, $N(2090)S_{11}$, $N(2100)P_{11}$, $\Delta(2150)S_{31}$, $\Delta(2200)G_{37}$, $\Delta(2350)D_{35}$, $\Delta(2390)F_{37}$

PDG08 states

The latest GWU analysis (ARNDT 06) finds no evidence for this resonance.

- <u>Our study</u> does suggest several 'new' N*s and Δ*s:

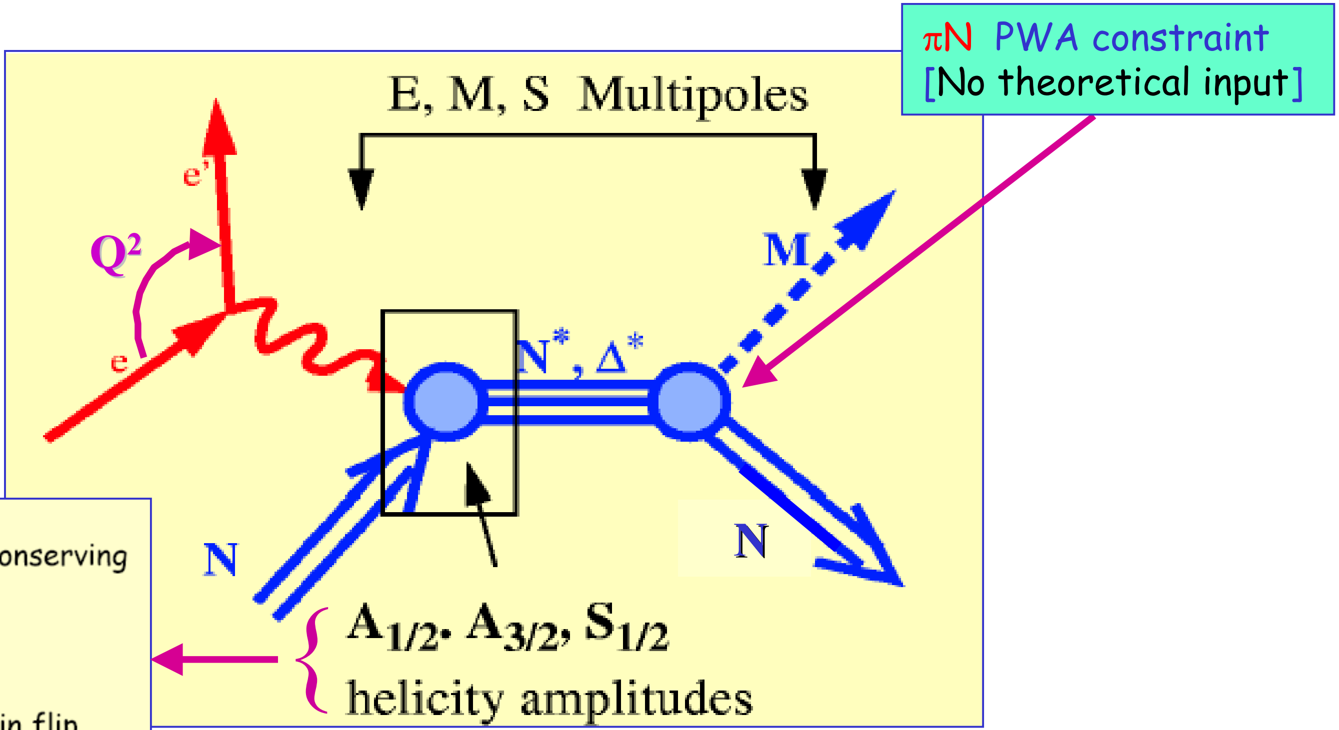
  **** $\Delta(2420)H_{311}$

  *** $\Delta(1930)D_{35}$, $N(2600)I_{111}$ [BW, no Pole]

  ** $N(2000)F_{15}$, $\Delta(2400)G_{39}$

  new $N(2245)H_{111}$ [CLAS ?]

Electromagnetic Probe for Resonance Physics



$A^{\Delta}_{1/2} = -\frac{1}{2}(3E2 + M1)$ Helicity conserving

$S^{\Delta}_{1/2} = -C2$ Spin flip

$A^{\Delta}_{3/2} = -\frac{\sqrt{3}}{2}(E2 - M1)$ Double spin flip

- For $Q^2 = 0$: $M = (\text{Born} + \alpha_B)(1 + iT_{\pi N}) + \alpha_R T_{\pi N} + \text{higher terms}$
- For $Q^2 \neq 0$: $f(Q^2) = \frac{k}{k(Q^2=0)}\left(\frac{1}{1+Q^2/0.7}\right)^2 e^{-\Lambda Q^2}\left(1 + Q^2\left(a + b\left[\frac{W}{W_R} - 1\right] + cQ^2\right)\right)$

Pion Photoproduction Analysis [FA06]

[M. Dugger *et al* Phys Rev C **76**, 025211 (2007)]
[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **66**, 055213 (2002)]

- Energy dependent FA06 and associated SES
- E_γ = 145 – 2700 MeV [W = 1080 – 2460 MeV]
- PWs = 48 [multipoles] [J < 6]
- Prms = 161
- Constraint: πN PWA (no theoretical input) $M = (\text{Born} + \alpha_B)(1 + iT_{\pi N}) + \alpha_R T_{\pi N} + \text{higher terms}$

- Recent Contribution:
  - MAMI-B, GRAAL, CB-ELSA, Hall A, CLAS → $\gamma p \to \pi^0 p$
  - MAMI-B, GRAAL, Hall A → $\gamma p \to \pi^+ n$
  - CB, Hall A → $\gamma n \to \pi^- p$

Reaction	Data (Dpol)	χ^2
$\gamma p \to \pi^0 p$	13,326 (7 %)	30,989
$\gamma p \to \pi^+ n$	7,976 (9 %)	15,877
$\gamma n \to \pi^- p$	2,333 (4 %)	4,259
$\gamma n \to \pi^0 n$	148 (0 %)	364
Total	25,524	55,640

Coming soon:
- CLAS, MAMI-C → $\gamma p \to \pi^0 p$
- CLAS, MAX-lab → $\gamma p \to \pi^+ n$
- CLAS, LEGS, MAX-lab → $\gamma n \to \pi^- p$
- MAMI-C → $\gamma n \to \pi^0 n$

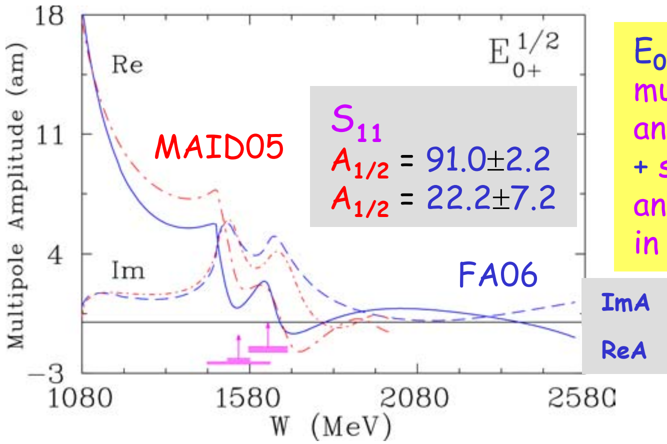
FROST, 2007, 2010

HD-ICE, 2010

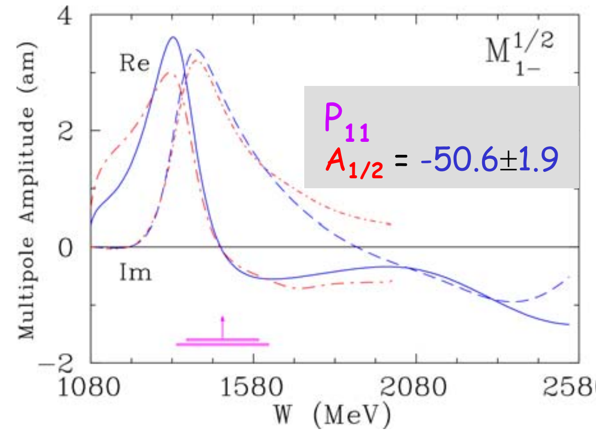
Proton Multipoles for FA06 (CLAS $\pi^0 p$ data included)

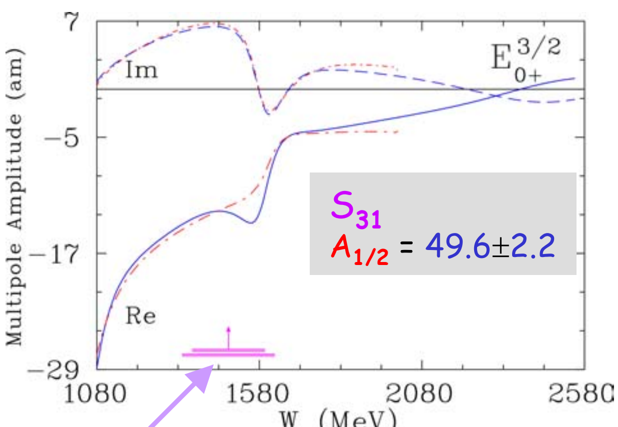
[M. Dugger *et al* Phys Rev C **76**, 025211 (2007)]

- Overall: the difference between MAID and GW is rather small but… Resonances may be essentially different

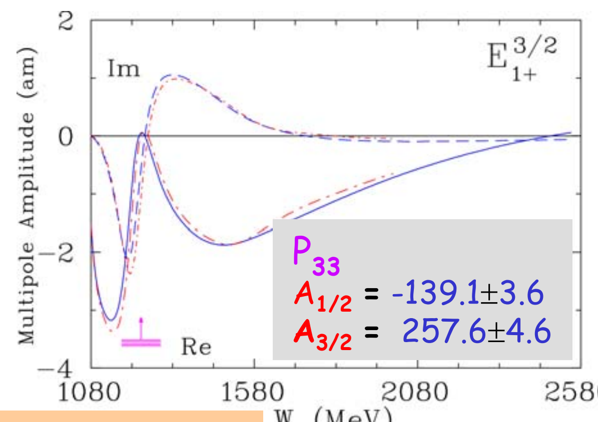


E_{0+} is pion production multipole, where 0 is angular momentum and + shows that spin and angular momentum in parallel ($J = l + \frac{1}{2}$)





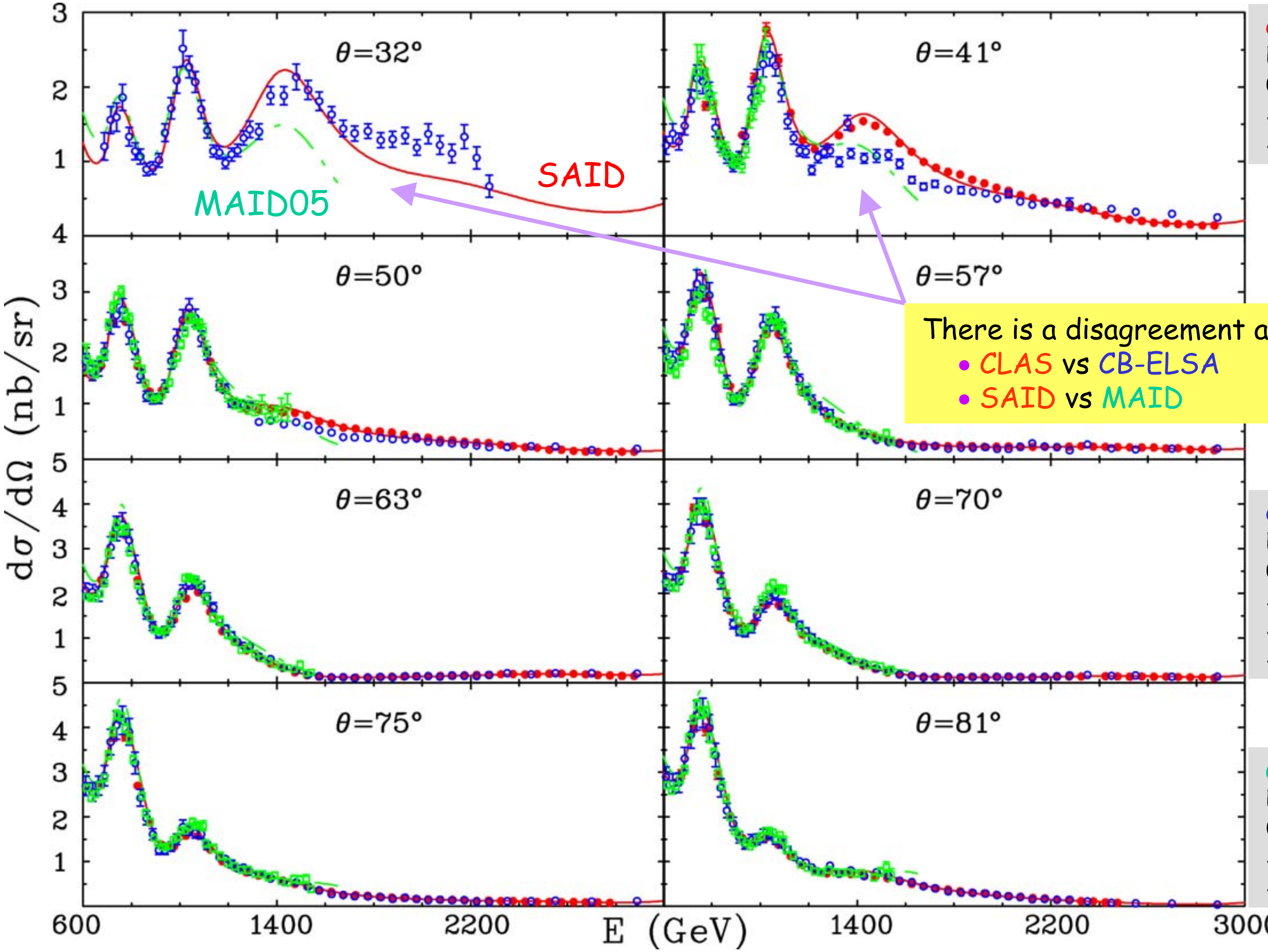
BW for πN SP06



R_{EM} [Δ(1232)] = -1.79±0.18 %

CLAS $\gamma p \to \pi^0 p$ and CB-ELSA with GRAAL

[M. Dugger *et al* Phys Rev C **76**, 025211 (2007)]



There is a disagreement at forward angles
- CLAS vs CB-ELSA
- SAID vs MAID

CLAS: 620 $d\sigma/d\Omega$
E_γ =675-2875 MeV
θ = 40- 150 deg
Stat = 3 %
Syst = 5 %

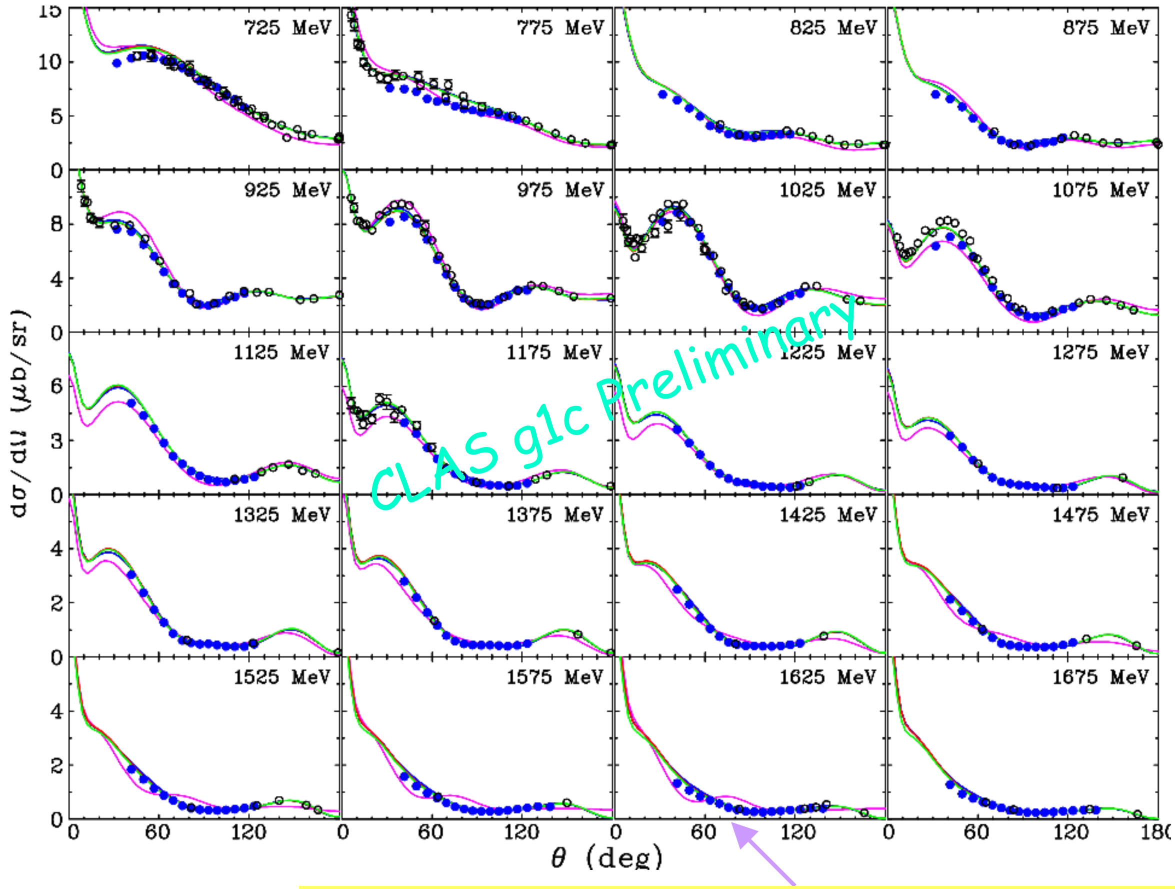
CB-ELSA: 1106 $d\sigma/d\Omega$
E_γ =320-2890 MeV
θ = 30- 140 deg
Stat = 5 %
Syst = 5 % (> 1.3 GeV)
Syst = 15 % (< 1.3 GeV)

GRAAL: 861 $d\sigma/d\Omega$
E_γ = 550-1540 MeV
θ = 49- 162 deg
Stat = 5 %
Syst = 2 %

CLAS $\gamma p \rightarrow \pi^+ n$

[M. Dugger *et al* to be submitted]

- No prior comprehensive tagged π^+n measurements



CLAS: 618 dσ/dΩ
E_γ =725–2875 MeV
θ = 32– 148 deg
Stat = 3 %
Syst = 6 %

PWA/Model:
FA08 [CLAS is in]
FA07 [No CLAS]
MAID07

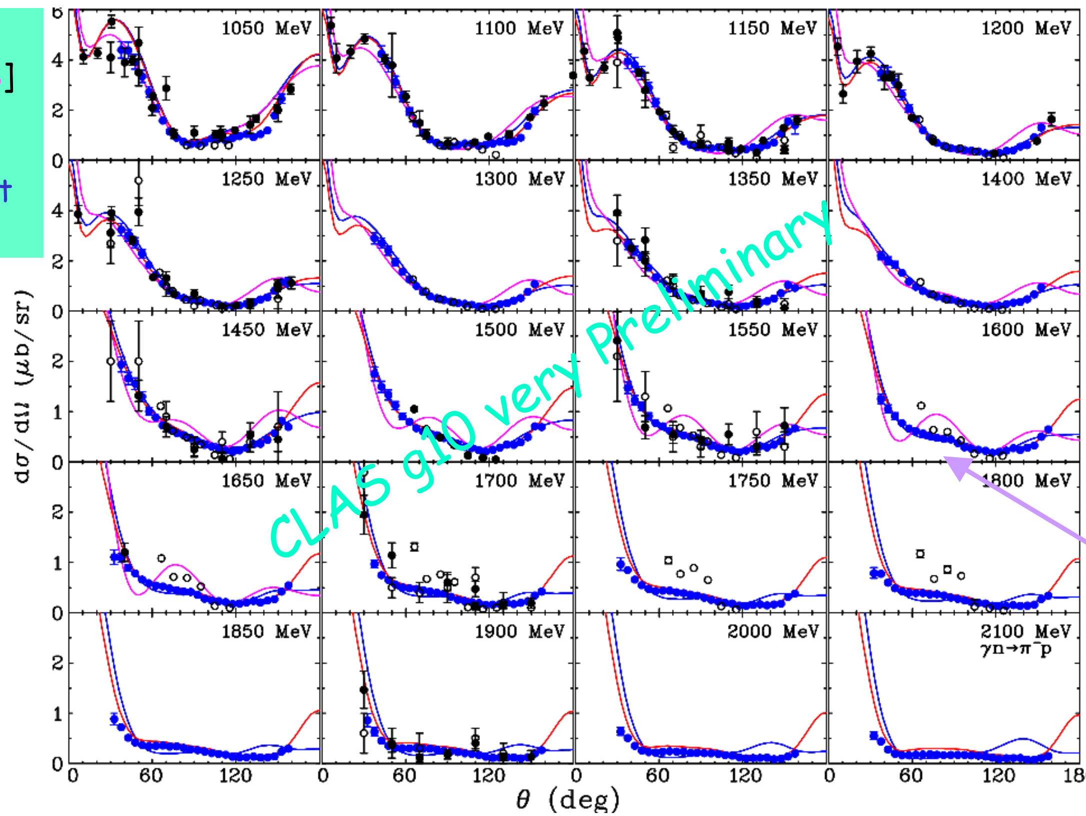
- Near its upper energy limit, MAID07 exhibits structures not seen in the data

CLAS $\gamma n \rightarrow \pi^- p$

[W. Chen *et al* in progress]

- Complementary measurements of $\pi^\pm$ photoproduction, required for an isospin decomposition of the multipoles

FSI
[prlm: 15 – 40 %]
plays a critical role in the state-of-the-art analysis



CLAS: 850 dσ/dΩ
E_γ = 1050–3500 MeV
θ = 37– 152 deg
Stat = 3 %
Syst = 7 %

PWA/Model:
FA08 [CLAS is in]
FA07 [No CLAS]
MAID07

- Near its upper energy limit, **MAID07** exhibits structures not seen in the data

- No prior comprehensive tagged measurements
  Principal π^- experiments (using pion beams) were done at Meson Factories

- The difference between previous and CLAS measurements may result in significant changes in the neutron couplings

CLAS FROST, HD-ICE and so on

- The data generated by this work will fill a number of gaps in the existing database of single and double meson photoproduction
- Transversely Pol target is more favorable for PWA

- FROST project for meson Photo Prod measurements will utilize
  - polarized photon beam,
  - polarized hydrogen target, and
  - CLAS

- FROST (proton):
  - E-06-013: V. Crede, M. Bellis, S. Strauch, $\gamma p \to \pi^+\pi^- p$
  - E-05-012: M. Dugger, E. Pasyuk, $\gamma p \to \eta p$, $\eta' p$
  - { E-04-102: D.I. Sober, M. Khandaker, D.G. Crabb, GDH: $\gamma p \to \pi^+ n$, $\pi^0 p$
  - { E-03-105: N. Benmouna, W.J. Briscoe, IS,S. Strauch, G.V.O'Rially, $\gamma p \to \pi^+ n$, $\pi^0 p$
  - E-02-112: F.J. Klein, L. Todor, P. Euginio, $\gamma p \to KY$

- HD-ICE (neutron):
  - E-06-101: F.J. Klein, A. Sandorfi, $\gamma n \to \pi^- p$, KY

- CAA:
  - HS05-01: D. Dutta, H. Gao, P. Rossi, $\gamma n \to \pi^- p$ (g10)
  - HS06-03: P. Collins, M. Dugger, $\gamma p \to \pi^+ n$, $\pi^0 p$, ηp, $\eta' p$ (g8b)
  - HS07-01: F. Klein, $\gamma n \to \pi^- p$ (g13)

Pion Electroproduction Analysis [SM08]

[R. Arndt, W. Briscoe, IS, R. Workman, in progress]

- Energy dependent SM08 and associated SQS
- W = 1080 – 2000 MeV Q^2 = 0 – 7 GeV^2
- PWs = 72 [multipoles]   [J < 6]
- Prms = 110
- Constraint: πN + pion Photo Prod PWAs (no theor input)

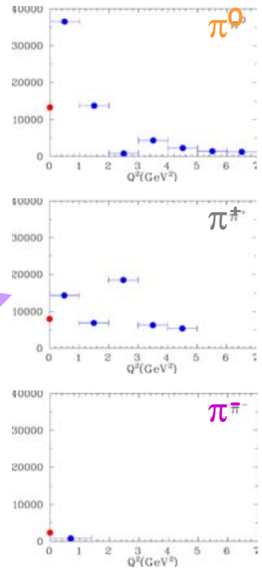
$$f(Q^2) = \frac{k}{k(Q^2=0)}\left(\frac{1}{1+Q^2/0.7}\right)^2 e^{-\Lambda Q^2}\left(1+Q^2(a+b\left[\frac{W}{W_R}-1\right]+cQ^2)\right)$$

- PWA Problems:
  - Additional [S] Multipoles
  - Q^2 dependence

- Database Problems:
  - Most of data are unPolarized measurements
  - There are no $\pi^0 n$ data and very little $\pi^- p$ (no Pol measurements)
    That does not allow to determine n-couplings at $Q^2 > 0$

Reaction	Data	χ^2
$\gamma^* p \to \pi^0 p$	69,323	96,689
$\gamma^* p \to \pi^+ n$	51,312	84,455
Total	120,636	181,144
$\gamma^* n \to \pi^- p$	801	
$\gamma^* n \to \pi^0 n$	No Data	

Data



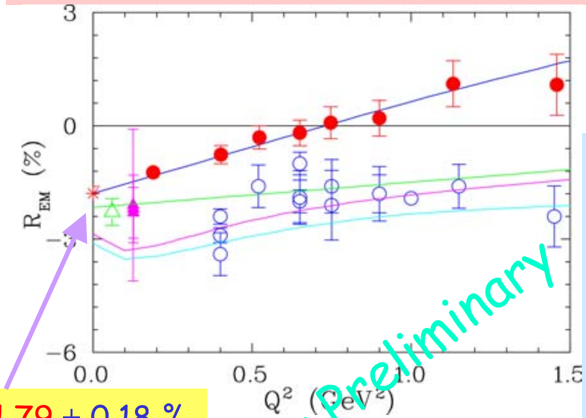
- World = ¾ JLab [CLAS] + ¼ Others

- More JLab data are coming and coming soon

Preliminary R_{EM} and R_{SM} Ratios for P_{33} vs Q^2

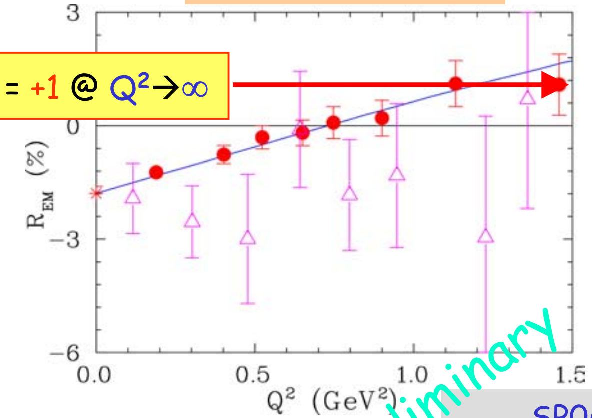
[R. Arndt, W. Briscoe, IS, and R. Workman, SOH, Greece, April, 2006; nucl-th/0607017]

- No recent CLAS π^+ and DoblP π^0 in this GW fit



- GW: -1.79 ± 0.18 %

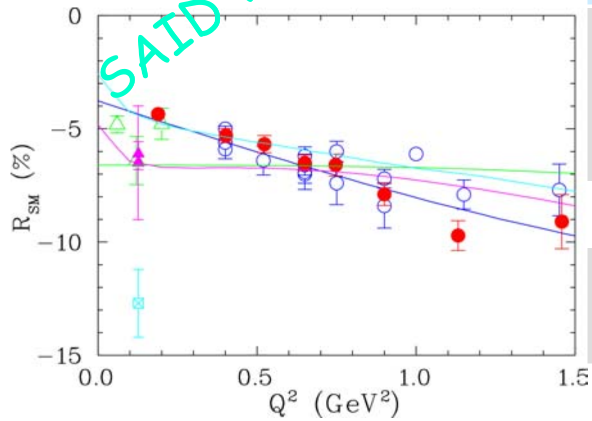
- Lattice05 (Δ)



PQCD: R_{EM} = +1 @ $Q^2 \to \infty$

- The large M-multipole is not significantly different in these analyses
- Differences for the E-multipole are much larger

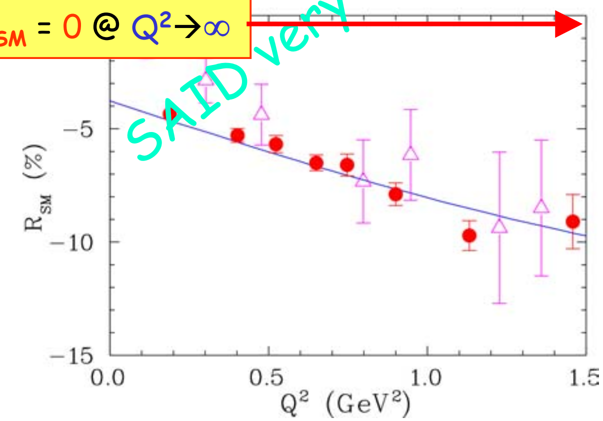
___ SP06
• SQS



o JLab
Δ Mainz
Δ Bates
Δ ELSA

____ MAID05
____ DMT
____ S-L

PQCD: R_{SM} = 0 @ $Q^2 \to \infty$

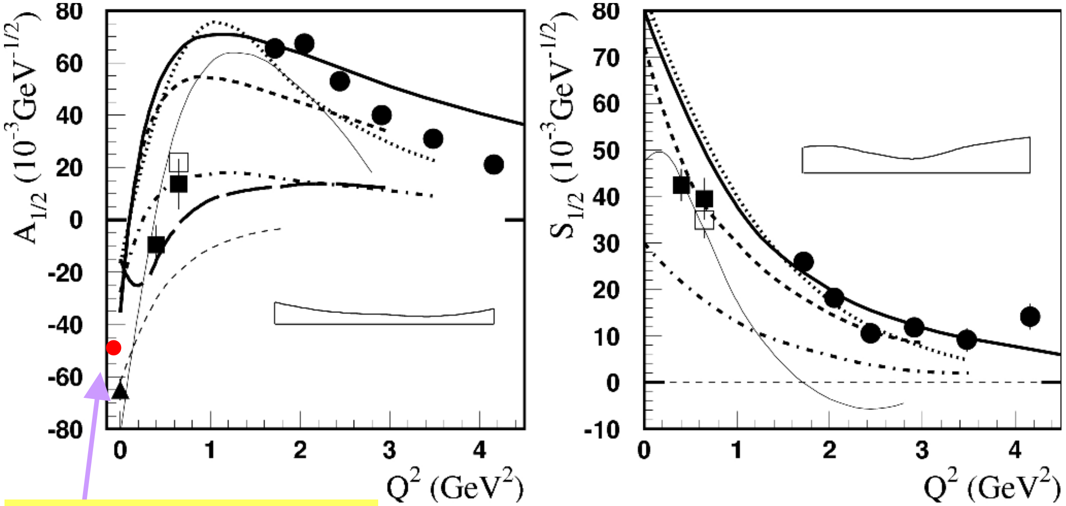


SAID very Preliminary

SAID very Preliminary

- The question is – can Electro Prod experiment reach asymptotic regime as PQCD predicted ?

N(1440)P_{11}'s Puzzle



- GW: $A_{1/2}$ = -50.6±1.9

- The analysis of the recent CLAS π^+ electroproduction data [W = 1.15 - 1.69 GeV & Q^2 = 1.7 - 4.5 GeV^2] allows to extract helicities for $\gamma^* p \rightarrow N(1440)P_{11}$ transition [I.G. Aznauryan *et al*, arXiv:0804.0447 [nucl-ex]

- Model predictions allow to conclude that N(1440) is a first radial excitation of 3q ground state

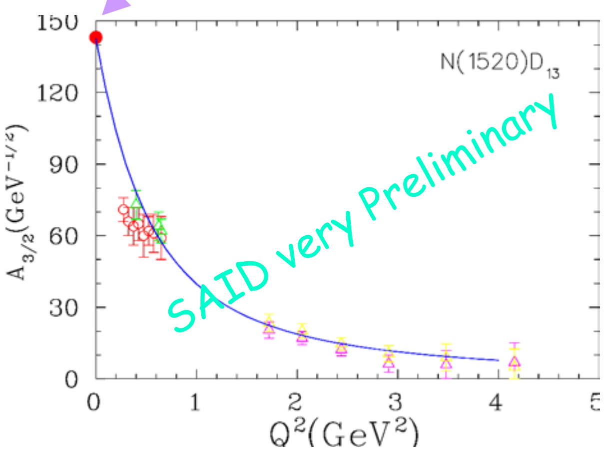
- Most of analyses of N(1440) are based on its BW parameterization, which assumes that the Res is related to an isolated Pole
- However, the latest GW PWAs for the elastic πN scattering gives evidence that N(1440) corresponds to a more complicated case of several nearby singularities in the amplitude
- Then, the BW description is only an efficient one for N(1440), which could be different in different processes
- Some inelastic data indirectly support this point: they give the N(1440) BW mass and width essentially different from the PDG BW values

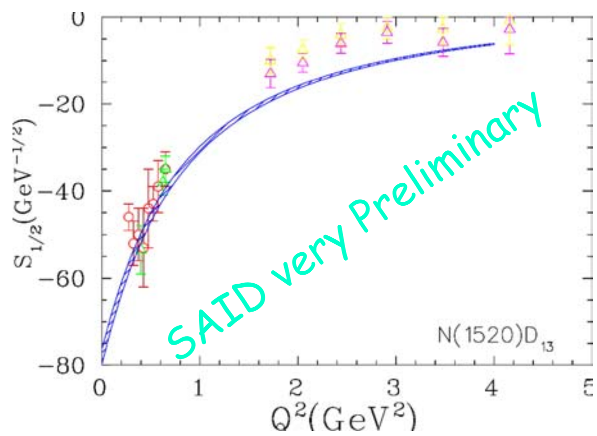
- Since Q^2-dependences for contributions of different singularities may be different, the set of several singularities might provide the N(1440) BW mass and width depending on the Q^2

- This problem can be studied in future measurements with CLAS12

N(1520)D_{13}'s Puzzle

• GW: $A_{3/2}$ = 143.1±2.0





χ^2/dp

W < 1650 MeV Q^2 = 0.40±0.05 GeV²

	SM08	CLAS40	MAID07	Data
π^0	1.6	1.6	1.5	5820
π^+	1.5	1.2	2.2	3352

W < 1650 MeV Q^2 = 0.65±0.05 GeV²

	SM08	CLAS65	MAID07	Data
π^0	1.3	1.3	1.1	8271
π^+	1.1	1.3	1.8	2515

___	SM08	
•	FA06	[Q^2 = 0]
o	CLAS	[2π]
Δ	CLAS	[1π]
Δ	DR	[1π]
Δ	Isobar	[1π]

Viktor Mokeev, PC 2008

Resonance fit done over a narrow range in W but for all Q^2
a and b are free prmts
(no W dependence for the polynomial piece of the structure function)

• The good agreement for $A_{3/2}$ and $S_{1/2}$ determination between various resonance extractions gives a more reliable estimate of systematics

• CLAS12 is favorable for Q^2 evaluation

Summary and Prospects

Where we are now

- πN analysis is crucial for the N* program
- Extended πN elastic and Pion Prod analyses are done up to $W = 2.5$ GeV

What we have to do

- FROST, MAMI-C, CB-ELSA, MAX-lab data could yield surprises
- Proton Electroproduction PWA is included 120k data up to $W = 2$ GeV and $Q^2 = 7$ GeV^2

What to Expect when we are Expecting

- Q^2 evaluation of Res couplings up to very large Q^2
- Can we reach an asymptotic regime as PQCD predicted ?
- Neutron Electroproduction measurements are necessary to determine neutron couplings at $Q^2 > 0$