Partial-Wave Analysis and Baryon Spectroscopy in Pion-Nucleon Scattering

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Based on work in collaboration with
R. Arndt, W. Briscoe, R. Workman

- GW DAC N^* Program
- SAID πN Analysis
- PW Amplitudes
- Resonances for S = 0 with I = 1/2 and 3/2
  Poles and BWs
- Summary

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N^* and Δ^* States Coupled to πN

- One of the most convincing ways to study Spectroscopy of N^* 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 %)
- Contain resonances contributing to $\gamma N \rightarrow \pi N$
- 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
- A comparison of various resonance-extraction methods gives a more reliable estimate of systematic (model) errors

Objective

- Our PWAs have been as model-independent as possible, so as to avoid bias when used in resonance extraction or coupled-channel analysis

- An example is provided by our elastic πN analysis
  - Resonances are found through a search for poles in the complex plane and are not put in by hand as BW terms
  - This distinction is important for more complicated structures, such as the $N(1440)P_{11}$ and $N(1535)S_{11}$
  - Also, it is an issue in search for `missed' or `hidden' resonances

GW SAID (Scattering Analysis Interactive Dial-in) Facility

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

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

CNS
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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 upp 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

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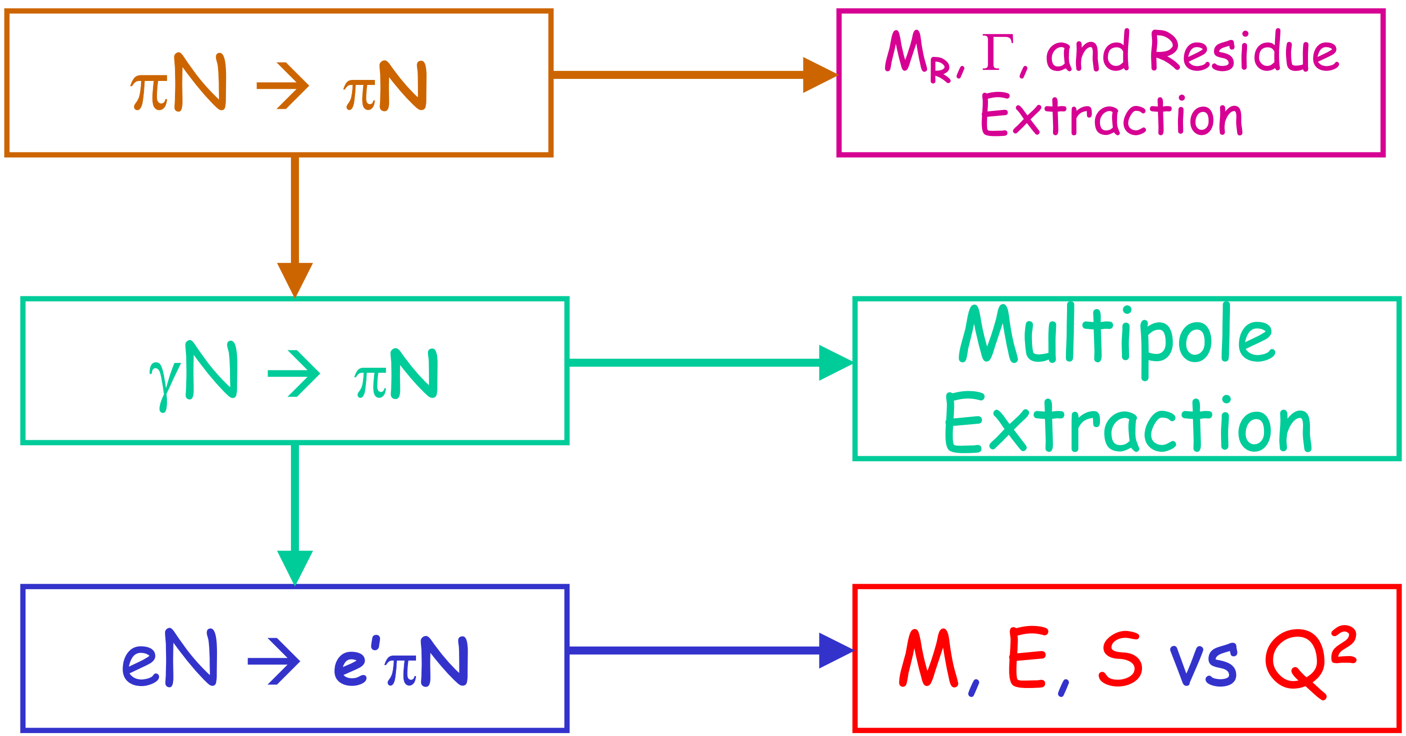
Road Map for Multipoles from GW SAID Analyses of Scattering Data

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



Summary of Coupled Channel GW SAID Fit of πN and ηN data

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

- T_{π} = 0 - 2600 MeV [W = 1080 - 2460 MeV]
- PW = 15 [I=1/2] + 15 [I=3/2] + 5 [ηN]
- Prms = 94 [I=1/2] + 80 [I=3/2]
- 4-channel Chew-Mandelstam K-matrix parameterization [πN, $\pi\Delta$, ρN, ηN]

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

Reaction	Data	χ^2
$\pi^+ p \to \pi^+ p$	13344	27242
$\pi^- p \to \pi^- p$	11967	22705
$\pi^- p \to \pi^0 n$	2933	6091
$\pi^- p \to \eta n$	257	628
DRs	3375	671
Total	31,876	57,241

$\pi^+ p \to \pi^+ p$, $\pi^- p \to \pi^- p$, $\pi^- p \to \pi^0 n$: [0 - 2600 MeV]

$\pi^- p \to \eta n$: [550 - 800 MeV]

- 106 data above 800 MeV
- Very little Pol measurements

- In the future, **MIPP-FNAL** and J-PARC 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

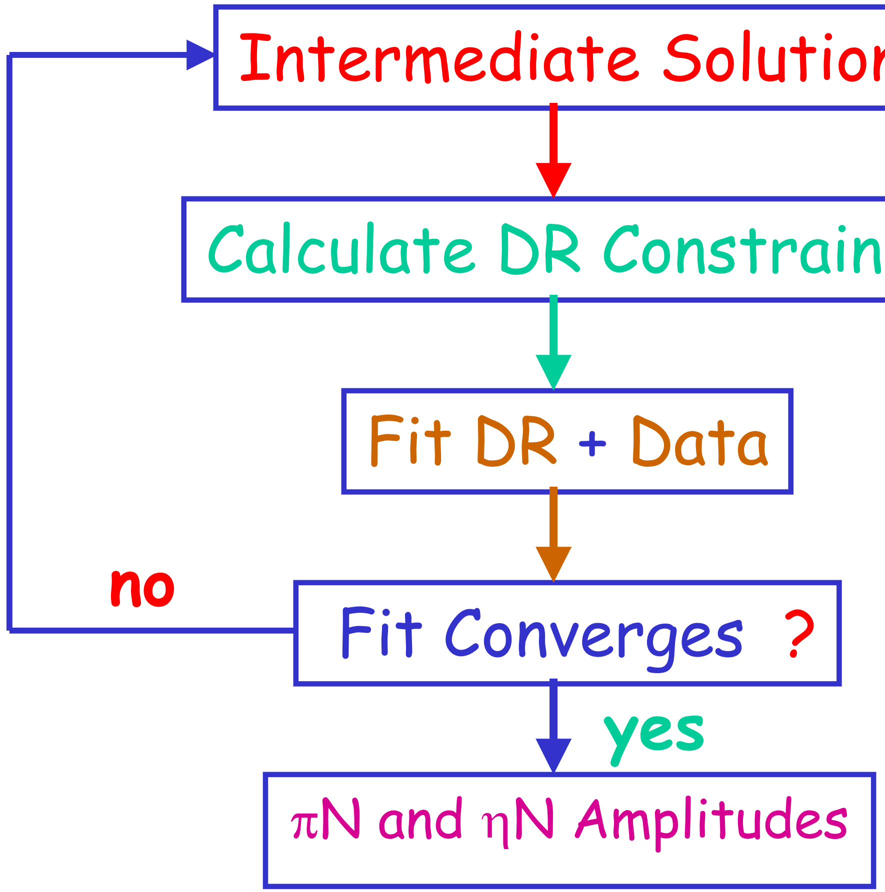
$$\chi^2 = \Sigma_i\, [(X\theta_i - \theta_i^{exp}) / \varepsilon_i]^2 + [(X - 1) / \varepsilon_X]^2$$

Θ_i^{exp} measured, ε_i stat err; Θ_i calculated; X norm const, ε_X its err

Reac	SP06		FA02		KA84	
	Norm	UnNorm	Norm	UnNorm	Norm	UnNorm
π^+p	2.0	6.7	2.1	9.3	3.6	10.0
π^-p	1.9	6.2	2.0	7.1	5.2	13.0
cxs	2.1	4.5	2.4	9.5	3.2	7.8
ηn	2.4	10.1	2.5	4.6		

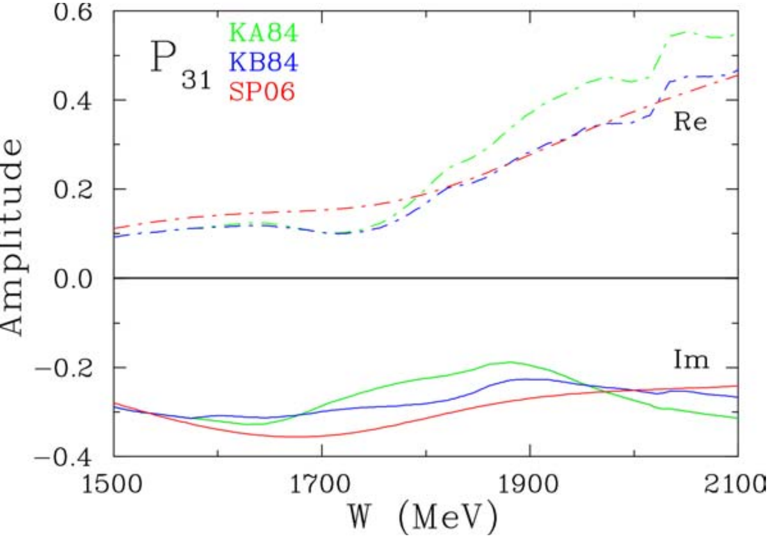
Number of datapoints for KA84 corresponds to the modern SAID database

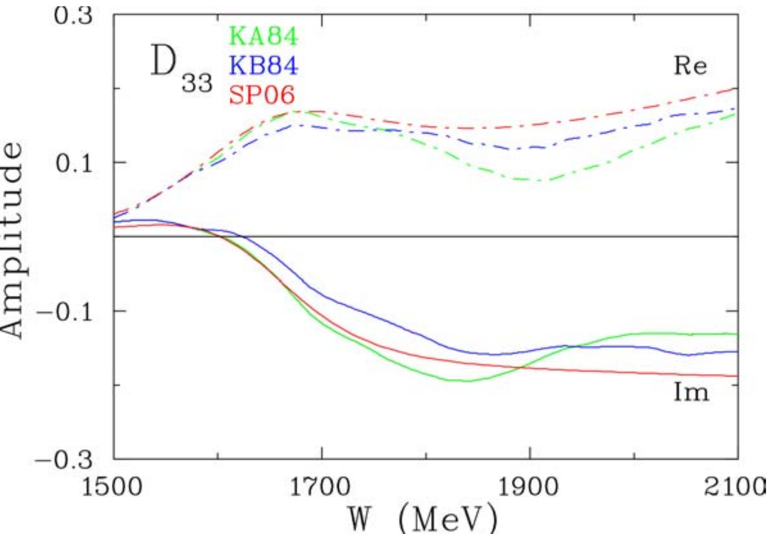
πN Analysis Flow Chart

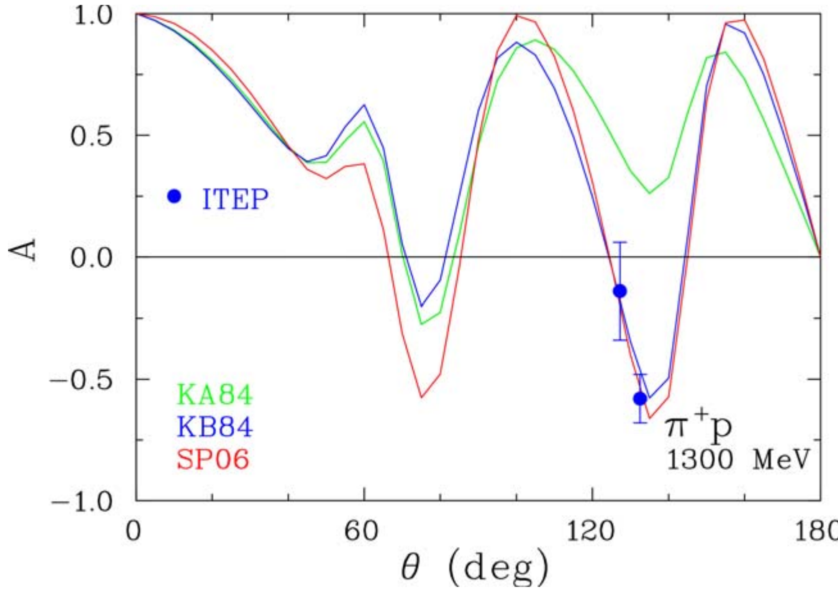


Cook until DONE !

Influence of Spin-rotation Measurements on PWA of Elastic πN
[I. Alekseev *et al* (ITEP-SAID) Phys Rev C **55**, 2049 (1997)]







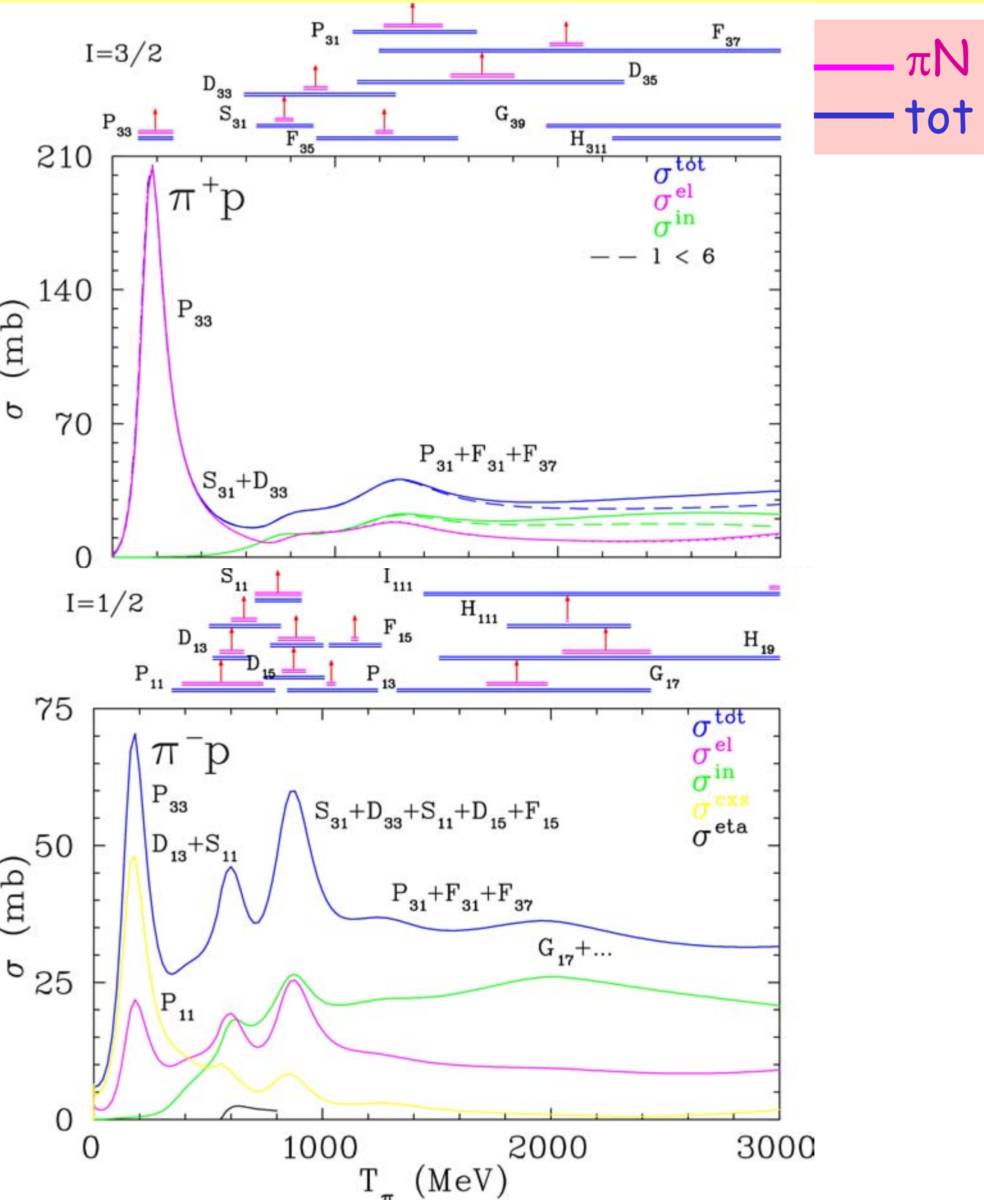
KA84: Karlsruhe-Helsinki (KH)

KB84: KH Barrelet corrected

SP06: GW DAC fit

Where is Resonance ?

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



Here you Are...

- Main techniques:
  - Pole on complex energy plane
  - Breit-Wigner fit (data, SES, or global)

- Additional:
  - Speed plot, Sp(W)
  - Argand plot, Im(Re)
  - Crossover energy, ReA = 0
  - Time-delay
  - *etc*

Search for N* and Δ*

- 'Extra' structures ?

- Applied directly to the data via BW + bckgr
- Assume: $S \rightarrow S_R S_B$ $\quad S_R = 1 + 2iT_R$

$$T_R = (\Gamma_e/2) / [W_R - W - i(\Gamma_e/2 + \Gamma_I/2)]$$

$$\Gamma = \Gamma_e + \Gamma_I \qquad \Gamma_e = \rho_e \Gamma \mathbf{R} \qquad \Gamma_I = \rho_i \Gamma (1 - R)$$

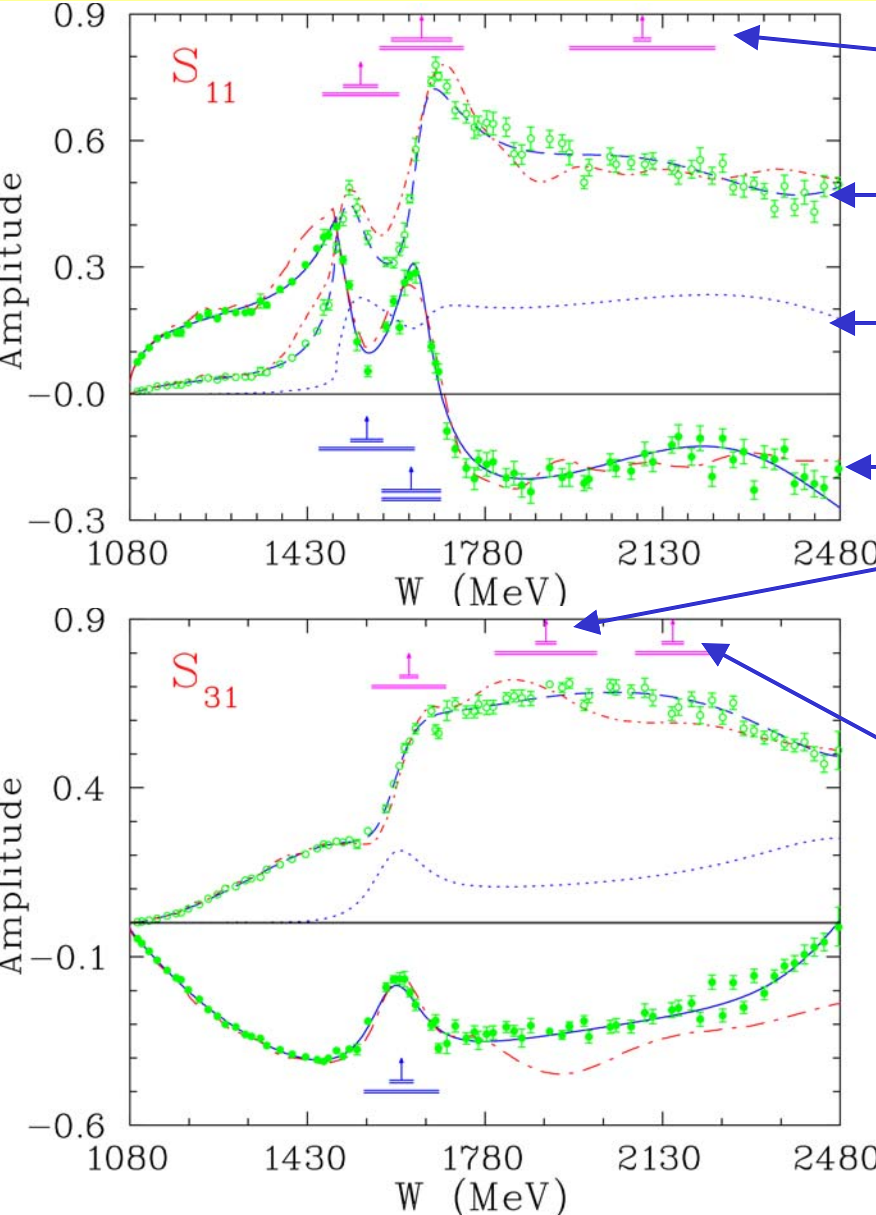
$$T_B = K_B(1 - iK_B)^{-1} \qquad K_B = a + b(W - W_R) + c$$

- Map $\chi^2[W_R, \Gamma]$ while searching all other PW prms

  Look for significant improvement

S-waves

$L_{(2I)(2J)}$



N(2090)*

ImT

ImT-T*T < ImT [unitarity limit]

ReT

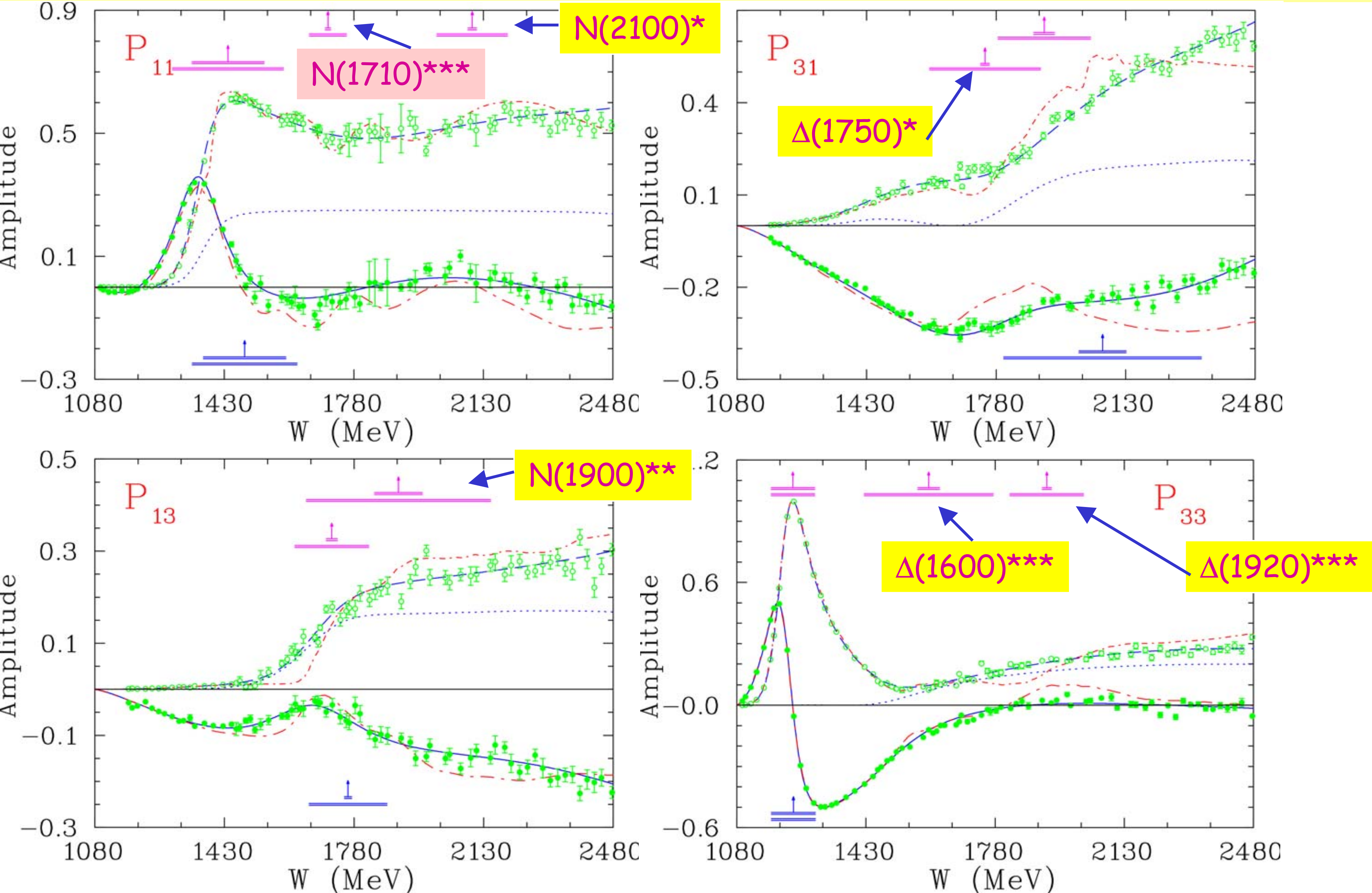
Δ(1900)**

Δ(2150)*

- SP06 vs SES in Ampl
- SP06 vs KA84 in Ampl
- SP06 vs PDG06 in BW [BW(M_R, Γ, Γ_{el})]

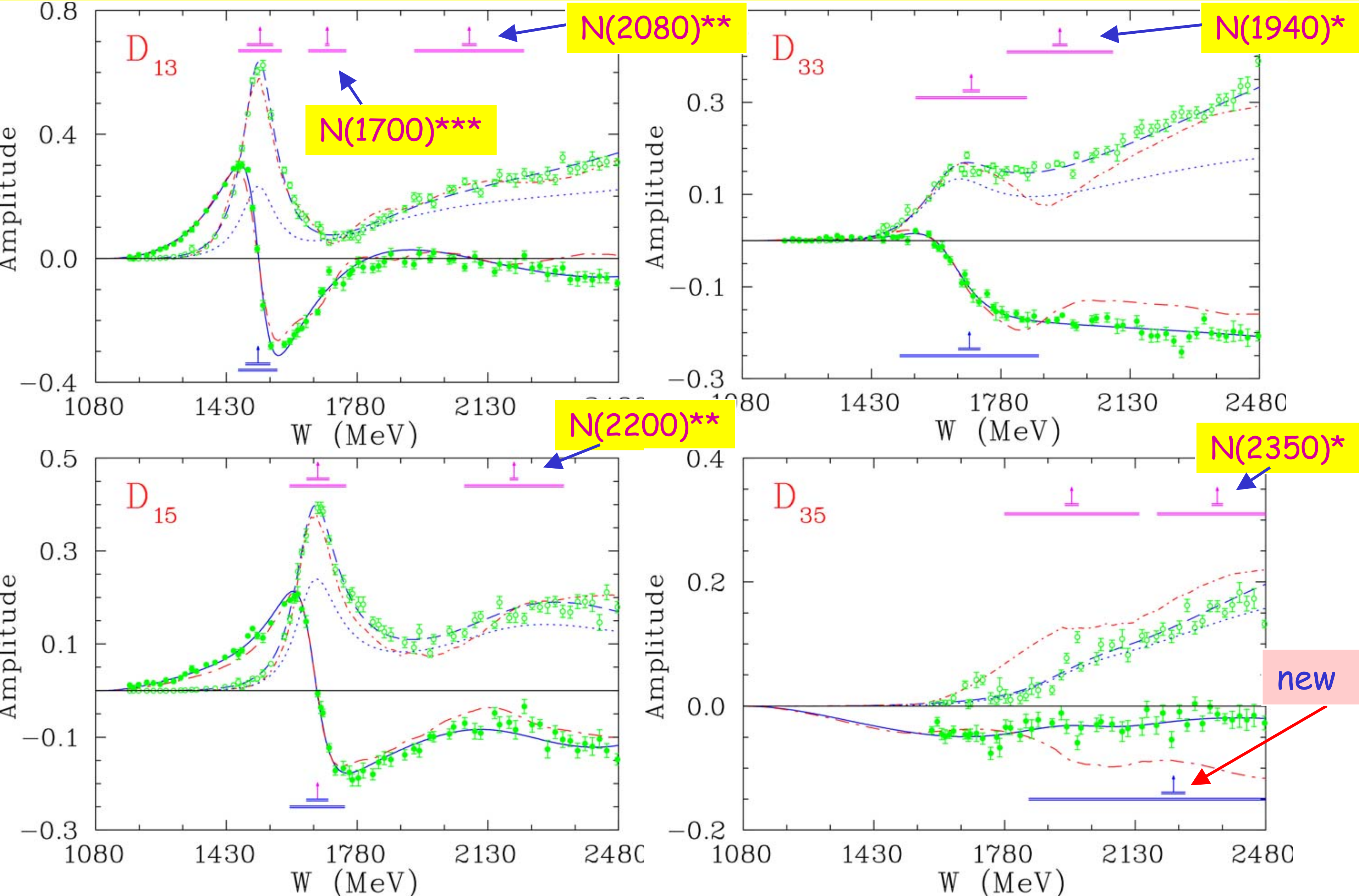
- PDG06 [W.-M. Yao *et al.* [RPP] J Phys G **33**, 1 (2006)]
- KA84 [R. Koch, Z Phys C **29**, 597 (1985)]

P-waves

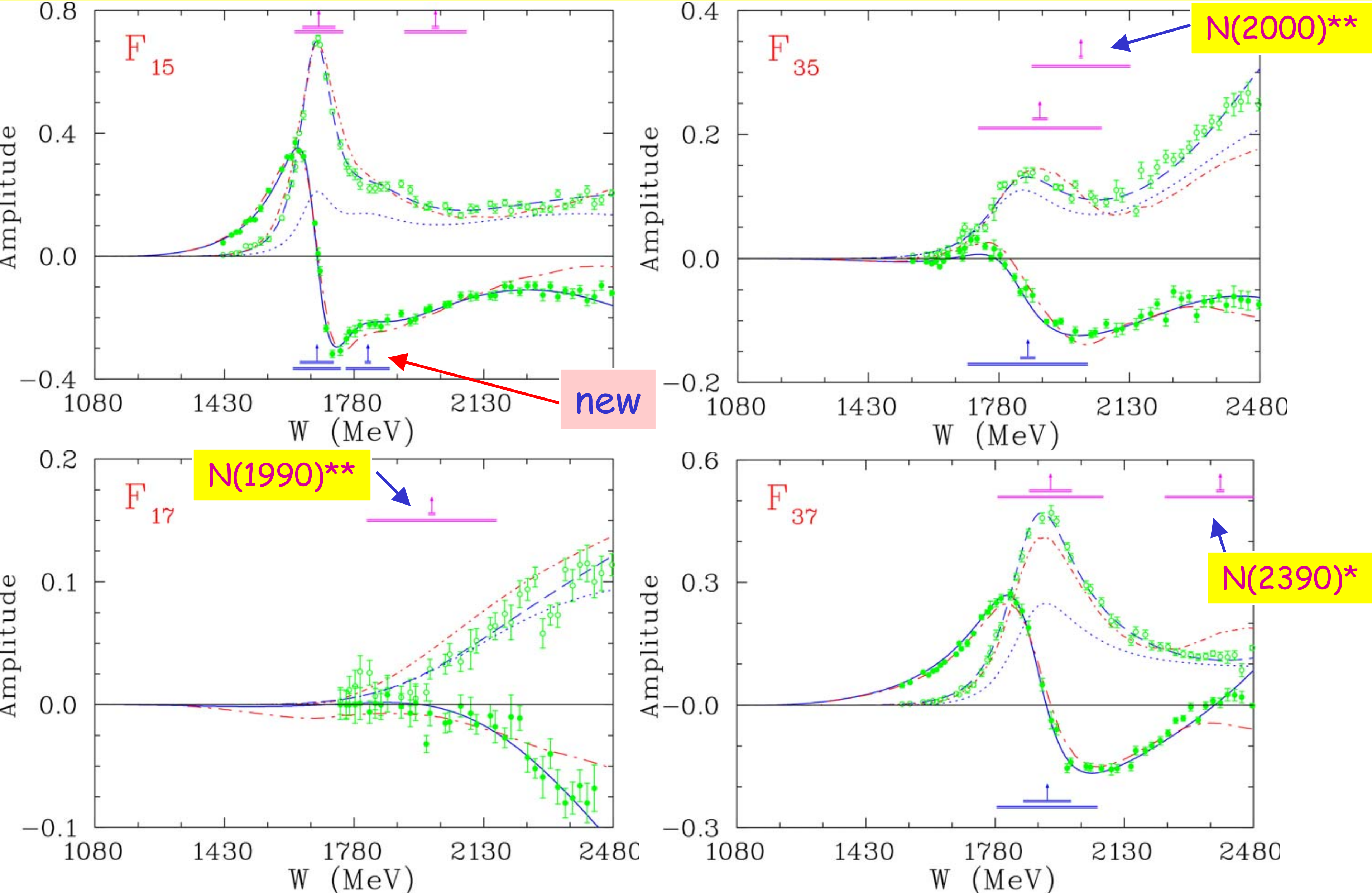


P11
N(1710)***
N(2100)*
P31
Δ(1750)*
P13
N(1900)**
P33
Δ(1600)***
Δ(1920)***
Amplitude
W (MeV)
1080
1430
1780
2130
2480
0.9
0.5
0.1
−0.3
0.4
0.1
−0.2
−0.5
0.3
−0.1
0.6
−0.0
−0.6

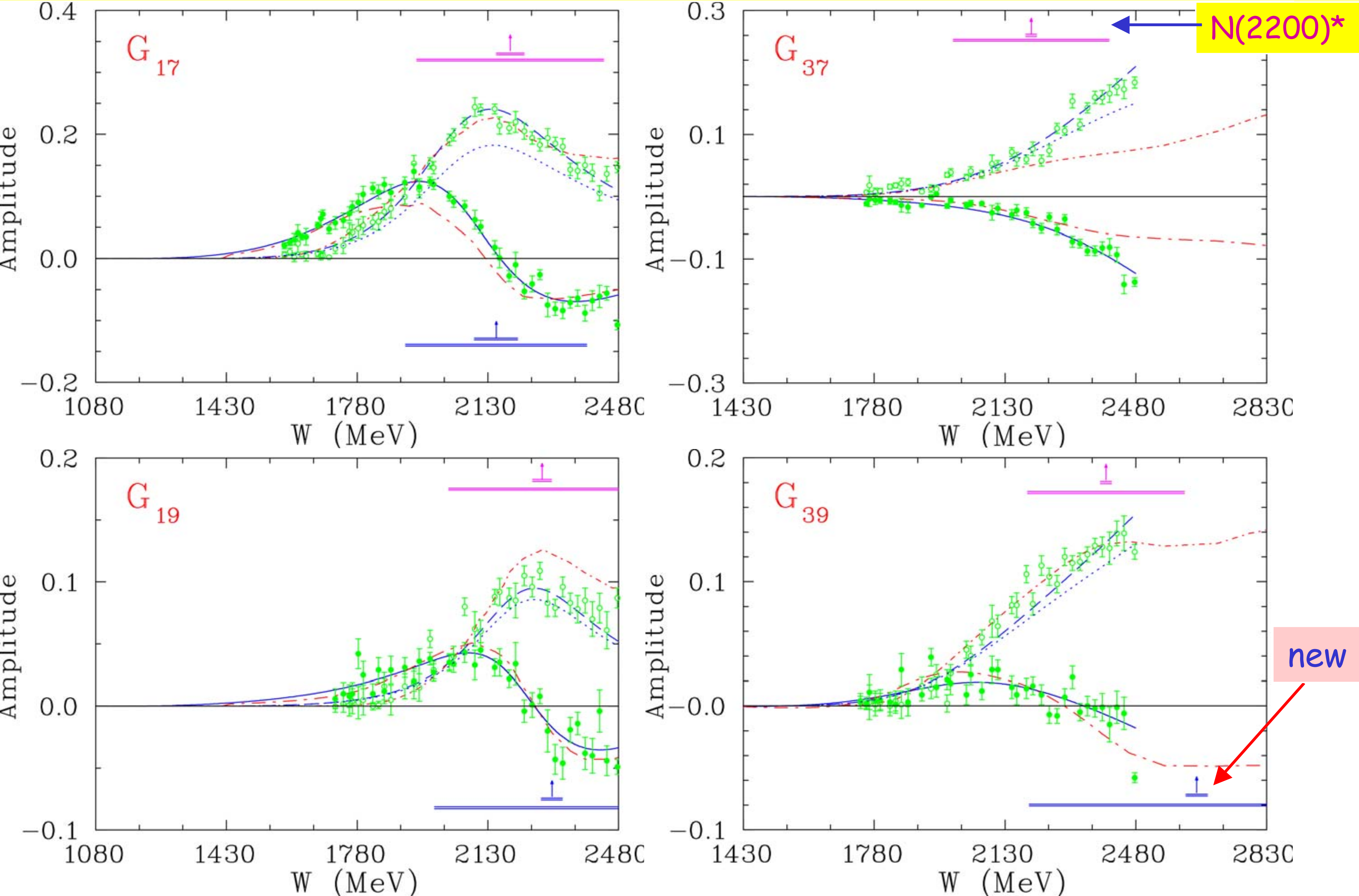
D-waves


D13
D33
D15
D35
N(2080)**
N(1700)***
N(1940)*
N(2200)**
N(2350)*
new
Amplitude
W (MeV)
1080
1430
1780
2130
2480
0.8
0.4
0.0
−0.4
0.3
0.1
−0.1
−0.3
0.5
0.4
0.2
−0.2

F-waves

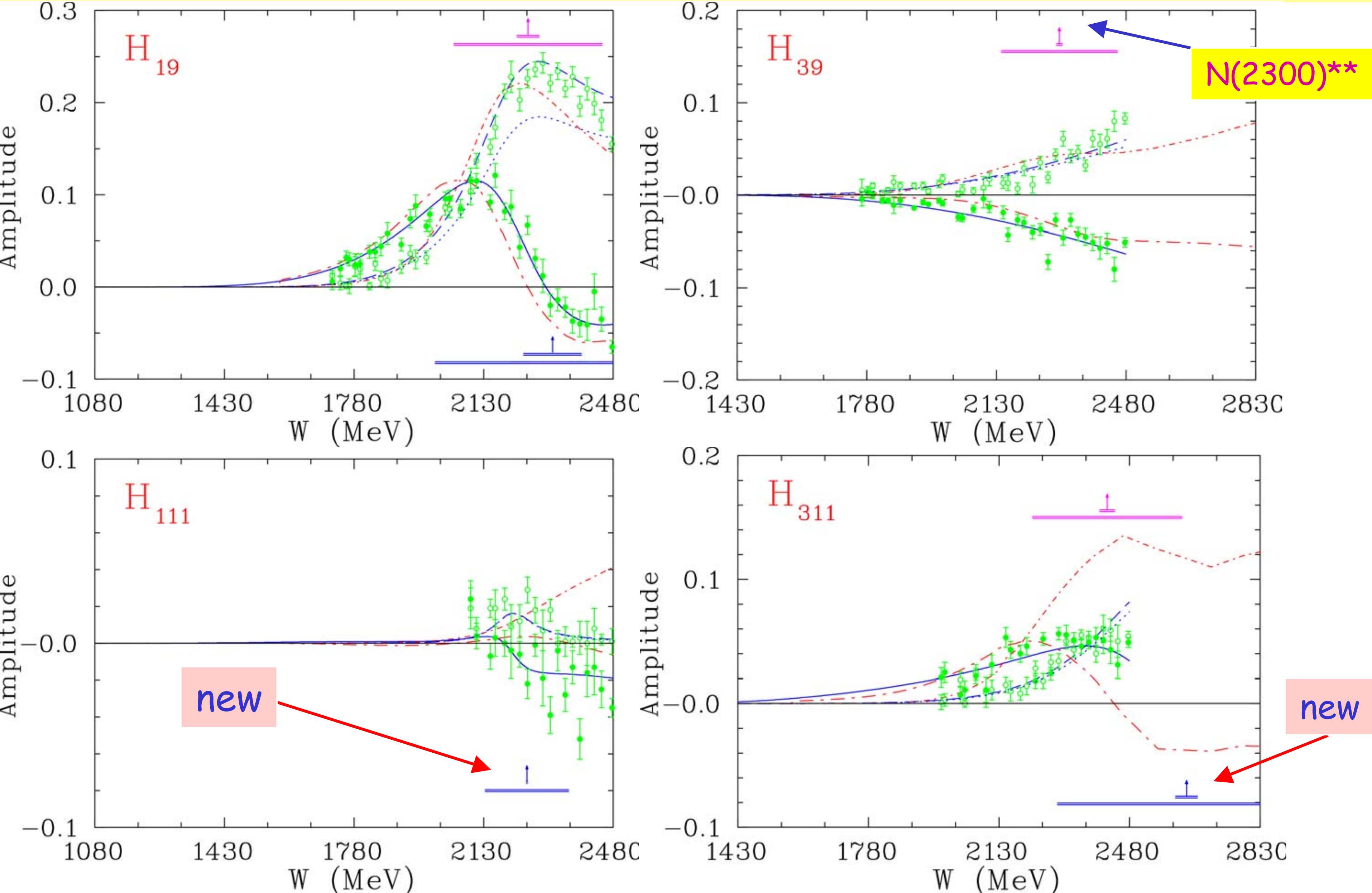

F15
F35
F17
F37
Amplitude
W (MeV)
1080
1430
1780
2130
2480
0.8
0.4
0.0
−0.4
0.2
−0.2
0.1
−0.1
0.6
0.3
−0.0
−0.3
N(2000)**
new
N(1990)**
N(2390)*

G-waves



G17
G37
G19
G39
N(2200)*
new
Amplitude
W (MeV)
0.4
0.2
0.0
−0.2
0.3
0.1
−0.1
−0.3
0.1
−0.1
−0.0
1080
1430
1780
2130
2480
2830

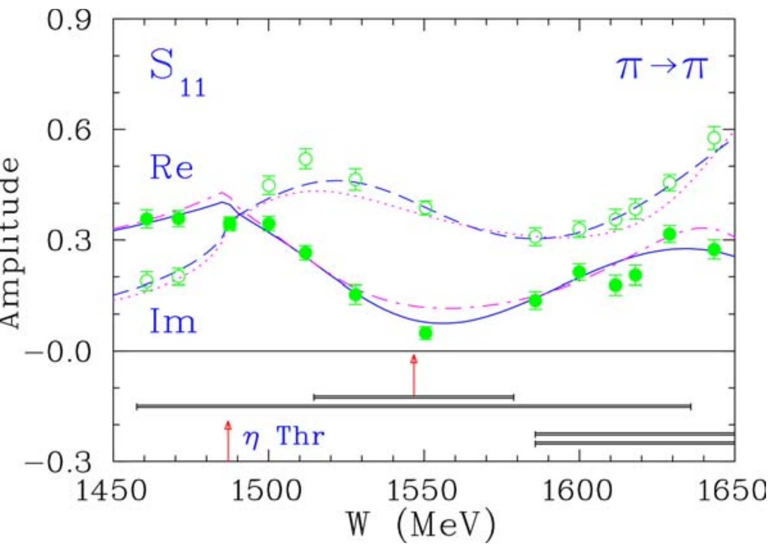
H-waves

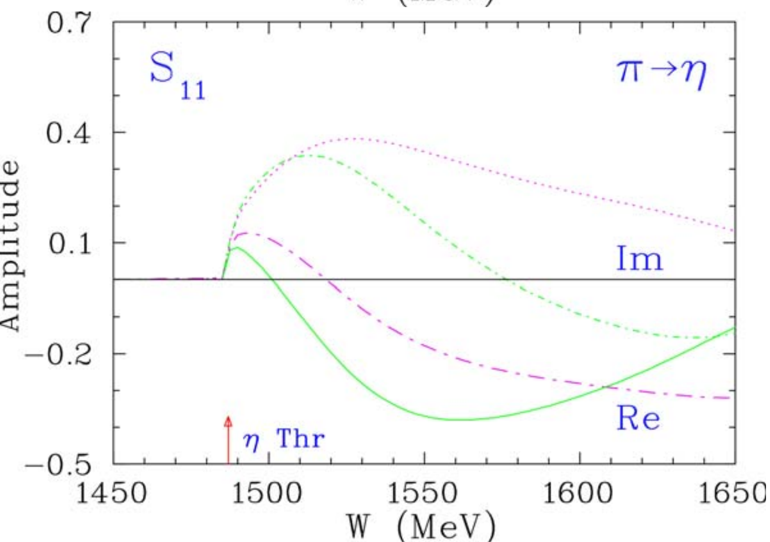


H19
Amplitude
W (MeV)
0.3
0.2
0.1
0.0
−0.1
1080
1430
1780
2130
2480
H39
N(2300)**
−0.2
2830
H111
new
H311
new

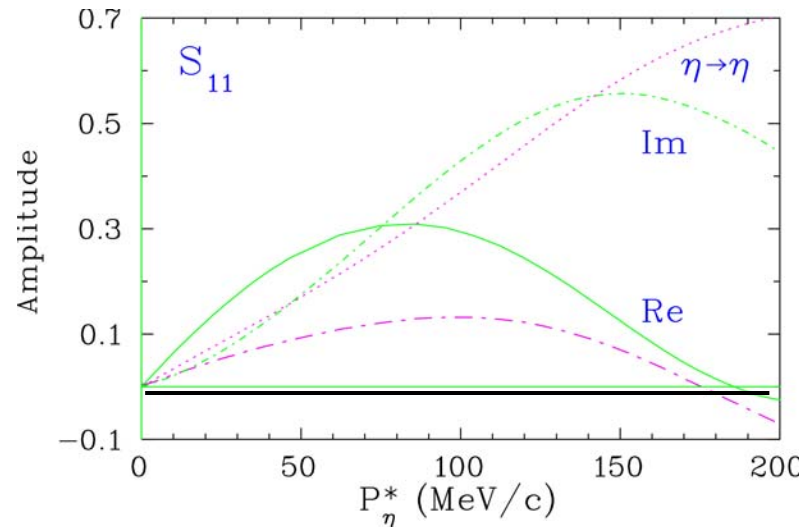
S_{11} within Coupled Channel Fit

[R. Arndt, W. Briscoe, IS, R. Workman, A. Gridnev, Phys Rev C **72**, 045202 (2005)]





- N(1535)S_{11}: $\Gamma\eta$ > $\Gamma\pi$



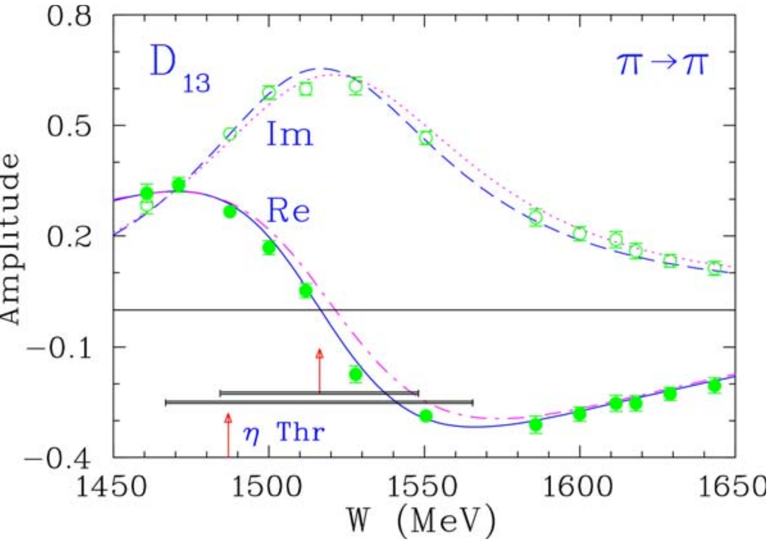
N(1535)S_{11}

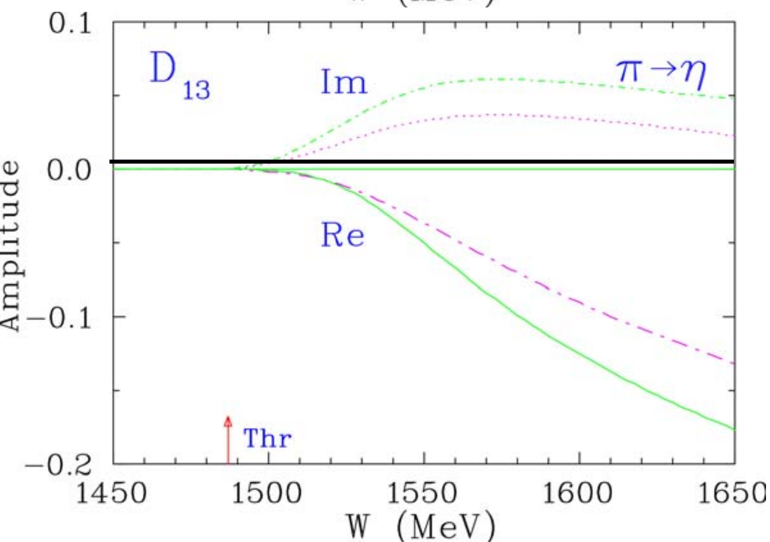
Soln	$\Gamma\pi$ (MeV)	Γ_η (MeV)	$\Gamma_{\pi\Delta}$ (MeV)	$\Gamma_{\rho N}$ (MeV)	$\Gamma\eta/\Gamma$
Fit A	30±2	45± 3	15±1		0.50
Fit B	32±3	45± 4	16±1		0.48
Fit C	39±3	67± 4	9±2		0.58
Fit D	42±6	70±10	11±2		0.57

Fit A, C (with Xball)
Fit B, D (no Xball)

D_{13} within Coupled Channel Fit

[R. Arndt, W. Briscoe, IS, R. Workman, A. Gridnev, Phys Rev C **72**, 045202 (2005)]





- N(1520)D_{13}: $\Gamma\eta/\Gamma t$ = **0.0008 – 0.0016**

N(1520)D_{13}

Soln	Γ_π (MeV)	Γ_η (MeV)	$\Gamma_{\pi\Delta}$ (MeV)	$\Gamma_{\rho N}$ (MeV)	Γ_η/Γ
Fit A	68±1	.12±.03	19±5	19±5	.0012
Fit B	68±1	.17±.12	19±6	19±6	.0016
Fit C	67±1	.08±.03	14±4	24±4	.0008
Fit D	67±1	.09±.07	14±5	24±5	.0009

Fit A, C (with Xball)
Fit B, D (no Xball)

- D_{13} [Mainz (γ, η)]: Γ_η/Γ = 0.0008±0.0001
  D_{13} [Giessen, multi-ch]: Γ_η/Γ = 0.0023±0.0004

What is Known about $N^* \to \eta N$

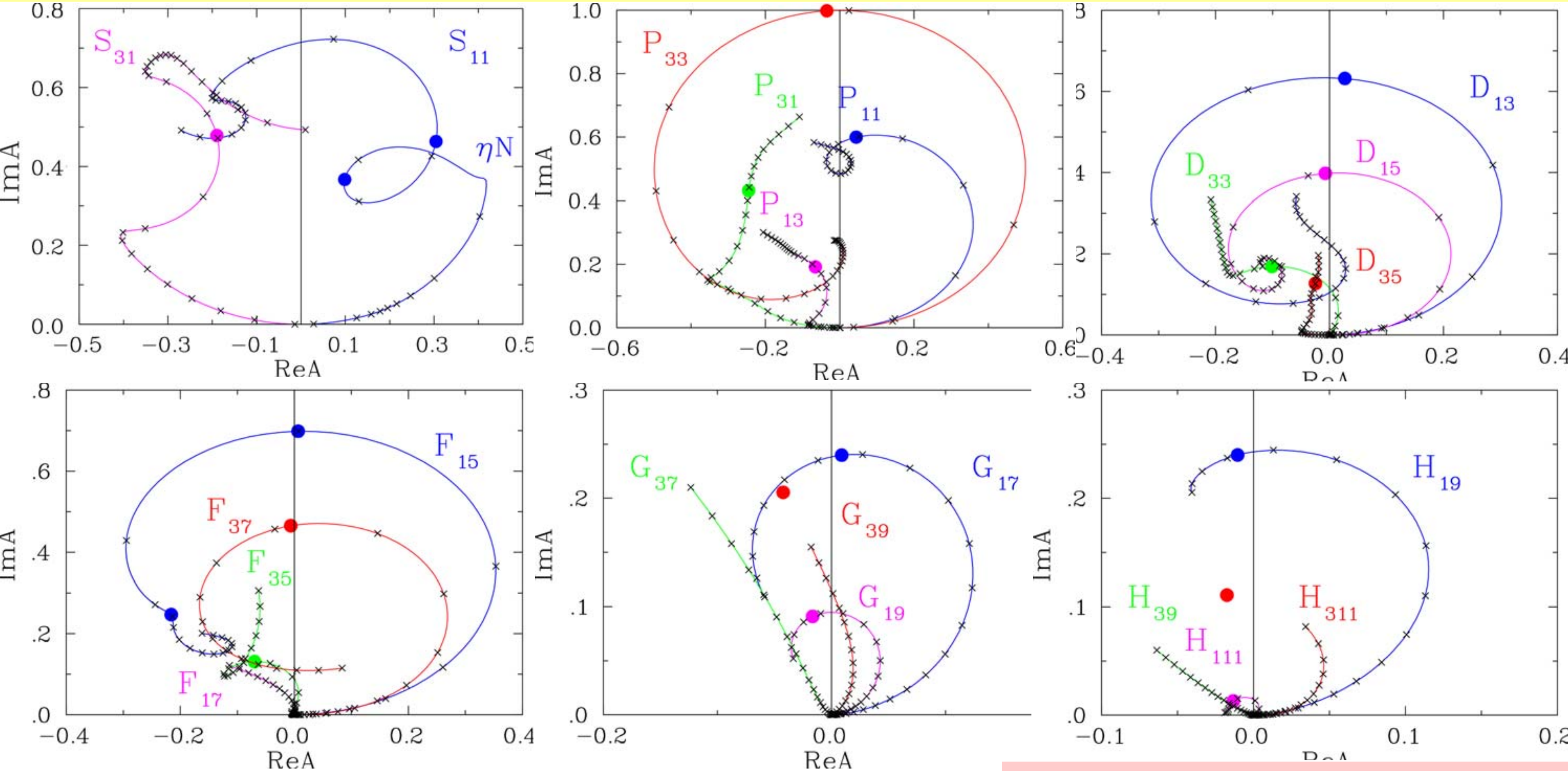
[W.-M. Yao *et al.* [RPP] J Phys G **33**, 1 (2006)]

PDG	N*	BR→ηN	SAID
****	$N(1520)D_{13}$	0.0023 ± 0.0004	0.0010 ± 0.0002
****	$N(1535)S_{11}$	0.52 ± 0.08	0.54 ± 0.04
****	$N(1650)S_{11}$	0.06 ± 0.03	?
****	$N(1675)D_{15}$	0.000 ± 0.010	?
****	$N(1680)F_{15}$	0.000 ± 0.010	?
***	$N(1700)D_{13}$	0.000 ± 0.010	No
***	$N(1710)P_{11}$	0.062 ± 0.010	No
****	$N(1720)P_{13}$	0.040 ± 0.010	?
**	$N(1900)P_{13}$	0.14 ± 0.05	No
**	$N(1990)F_{17}$	?	No
**	$N(2000)F_{15}$	?	?
**	$N(2080)D_{13}$	0.035 ± 0.035	No
*	$N(2090)S_{11}$	?	No
*	$N(2100)P_{11}$	0.61 ± 0.60	No
****	$N(2190)G_{17}$	0.000 ± 0.010	?
**	$N(2200)D_{15}$	?	No
****	$N(2220)H_{19}$	?	?
****	$N(2250)G_{19}$	?	?
***	$N(2600)I_{1\,11}$	?	?
**	$N(2700)K_{1\,13}$	?	No

- The attractive fact is that $\pi^- p \to \eta n$ is an `isospin filter' to the nucleon response, as ηN final states can originate only from the isospin $I = 1/2$ system

Argand Plots up to 2.5 GeV

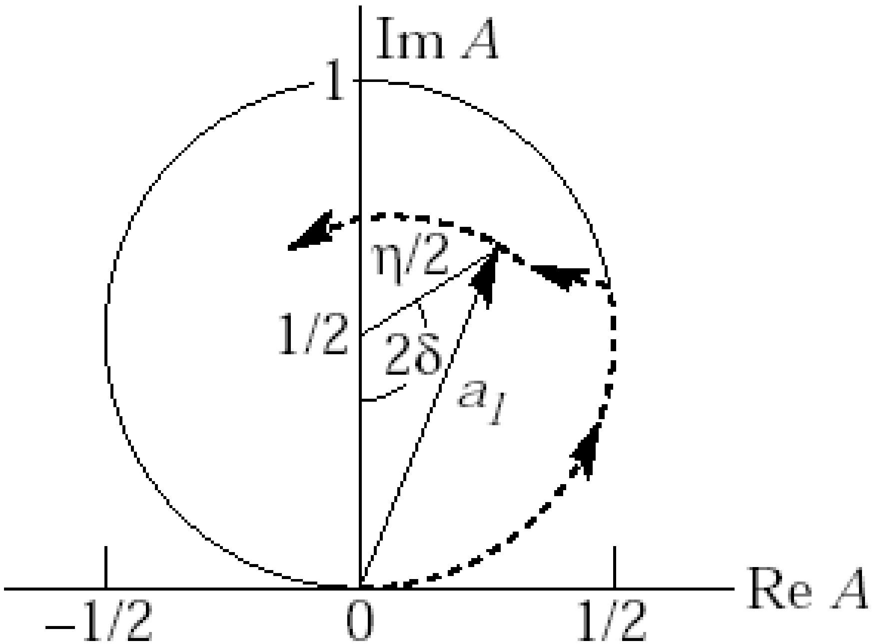
[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **74**, 045205 (2006)]

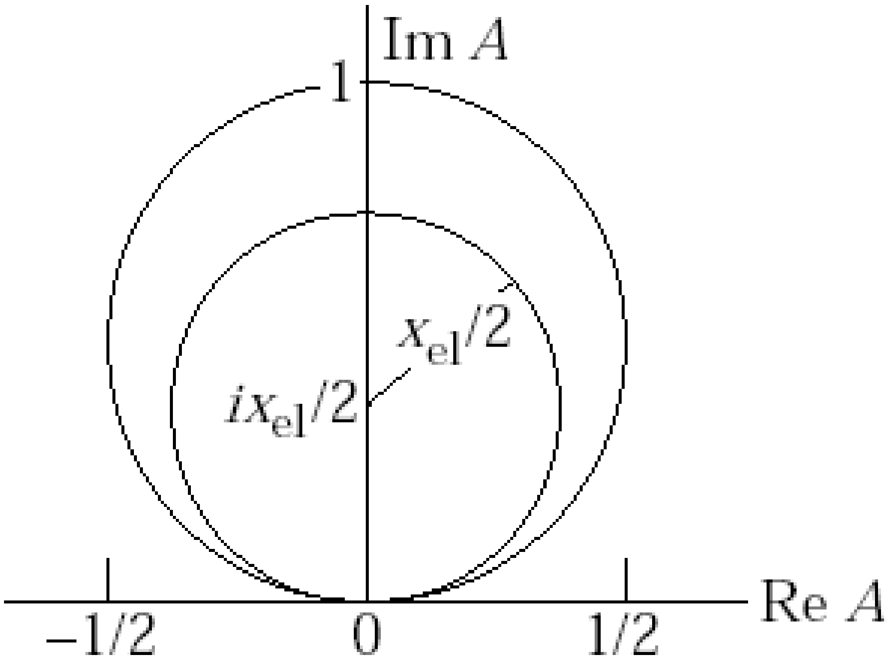


- Crosses indicate every 50 MeV step in W
- Dots correspond to BW, $W_R = M_R$

- Every PW has a single BW except S_{11} and F_{15} which have two BWs, while F_{17} has no pole

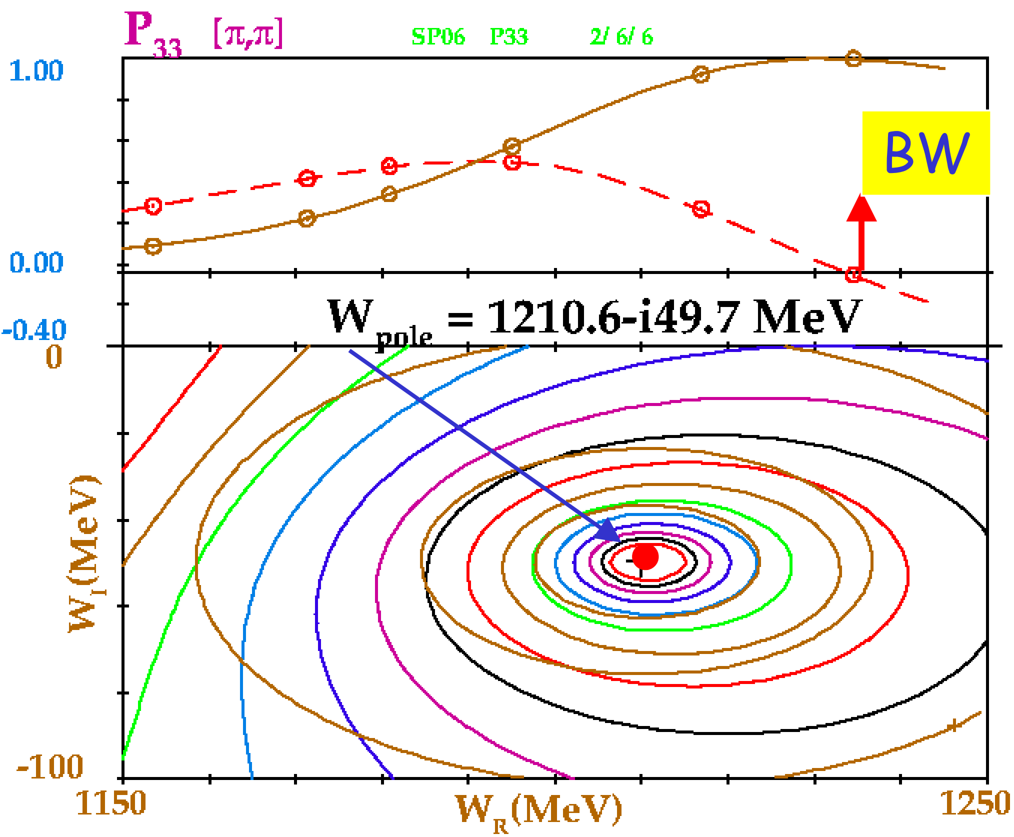
Some History: `new' or well forgotten





- [J.-R. Argand, *Essai sur une maniere de representer les quantites imaginaires dans les constructions geometriques* (Sans nom d'auteur) (Paris, 1806) **I** vol. petit in-8°, 78 pages]
- [J. Ashkin and S. H. Vosko, *Graphical method for obtaining phase shifts from the experimental data on meson-nucleon scattering,* Phys Rev **91**, 1248 (1953)]

Where is $\Delta(1232)P_{33}$?



- ReA = 0 at 'crossover' energy
- But crossover energy is NOT mass

Ampl	crossover	ImA	σ_{reac}
H^+	1231.32	1.000	0.00
π^+p	1231.17	1.000	0.00
H^-	1231.38	0.994	1.12
π^-N	1231.38	0.994	1.12

- BW-fit [+ bgrd] yields:

  M_Δ = 1232.86 ± 0.74 MeV

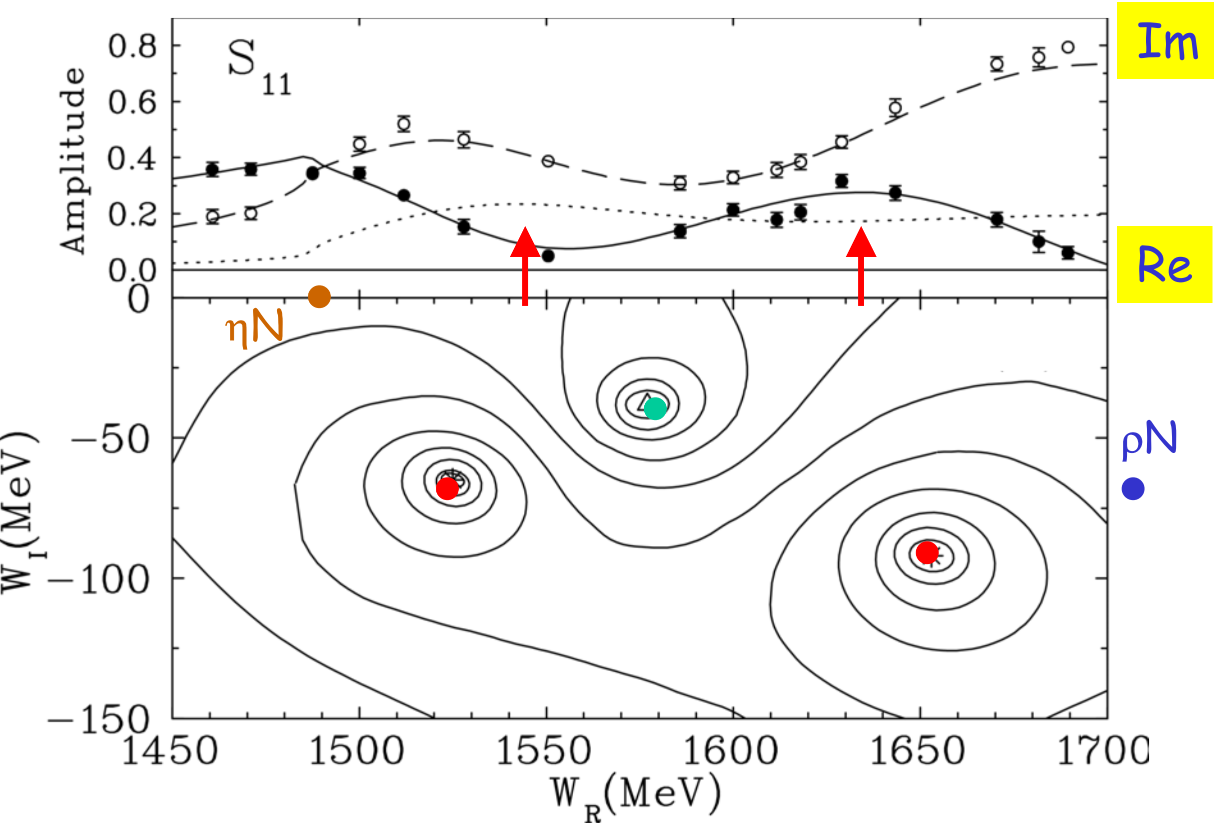
  Γ_Δ = 118.06 ± 1.20 MeV

- Pole:

  W = 1210.6 - i49.7 MeV

Complex Energy Plane for S_{11} [FA02]

[R. Arndt, W. Briscoe, IS, R. Workman, M. Pavan, Phys Rev C **69**, 035213 (2004)]

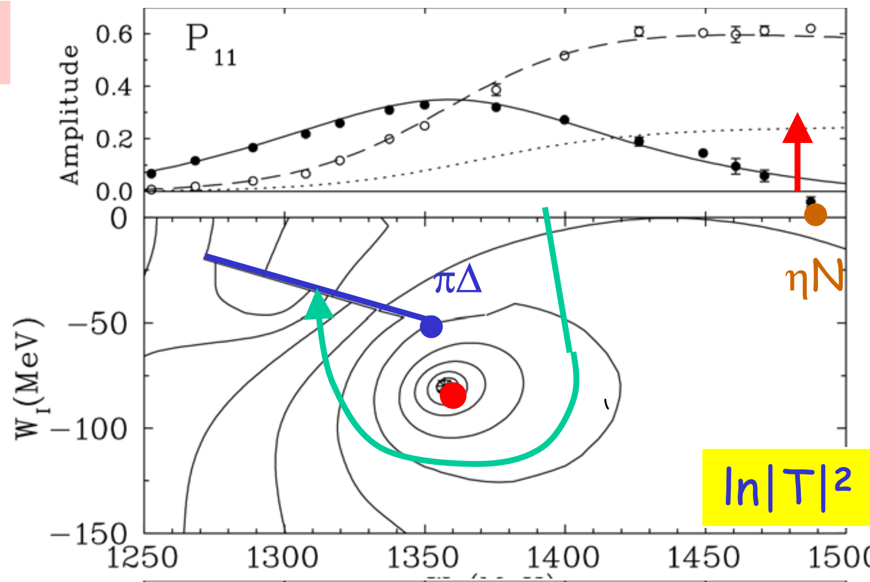


- BWs:
  - W_R = 1546.7± 2.2 MeV
  - Γ = 178.0± 12.0 MeV
  - W_R = 1651.2± 4.7 MeV
  - Γ = 130.6± 7.0 MeV
- Poles:
  - 1526 - i65 MeV
  - 1653 - i91 MeV
- Branch-points:
  - ηN thr: 1487 - i0 MeV
  - ρN thr: 1715 - i73 MeV
- Zero:
  - 1578 - i38 MeV

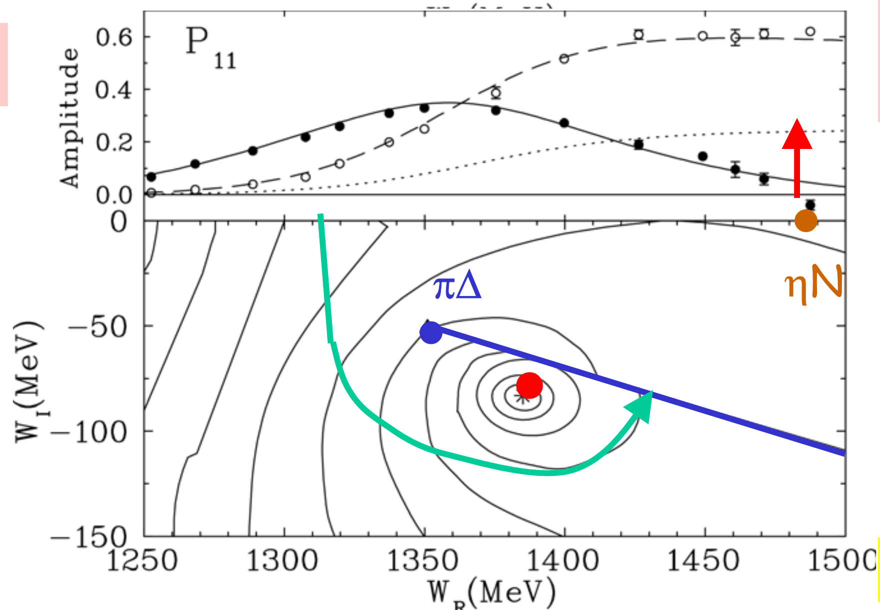
Complex Energy Plane for P_{11} [SP06]

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

1st sheet



2nd sheet



- BW: W_R = 1485.0±1.2 MeV
  Γ = 248 ±18 MeV

- Pole 1: 1359-i82 MeV

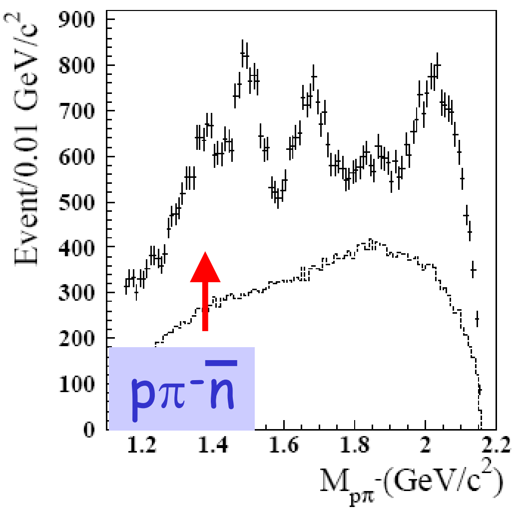
- Poles of the P_{11} amplitude
- Branch-point [πΔ thr] [1350 - i50 MeV]
- Branch-point [ηN thr] [1487 - i0 MeV]
- πΔ branch cut

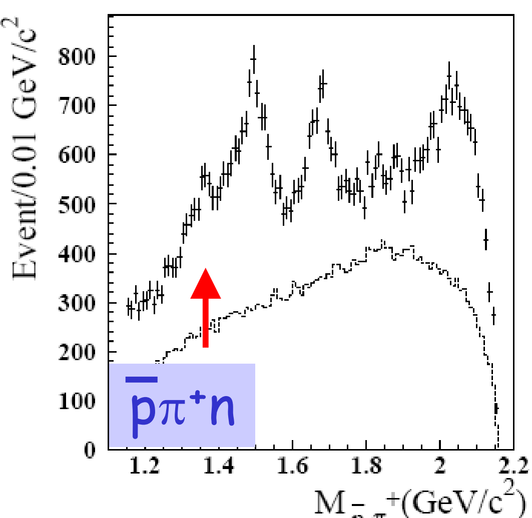
- Two poles at 2 different Riemann sheets, both are very near to the branch-point [πΔ-thr], and the additional branch-point [ηN-thr]
- A simple BW does not account for such complexity

- Pole 2: 1388 - i83 MeV

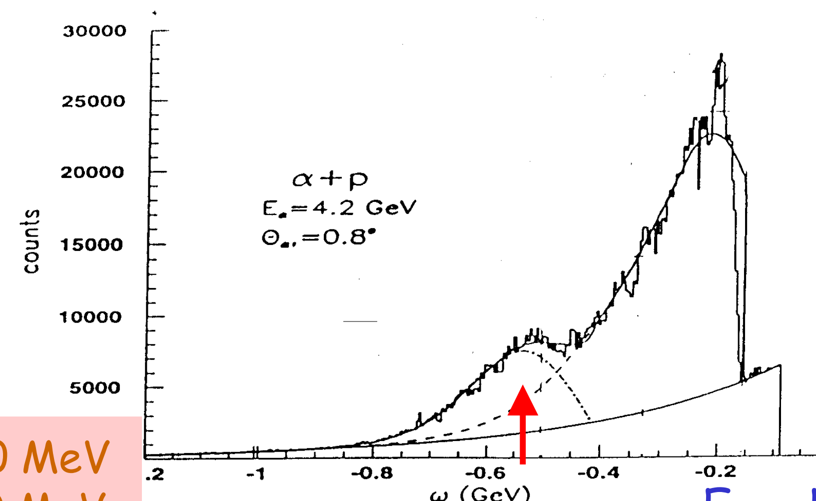
Direct Measurements of N(1440)P_{11}

- **BEPC**: $e^+e^- \to J/\psi \to p\pi^-\bar{n} + \bar{p}\pi^+n$
  [M. Ablikim *et al.* (BES Collaboration)
  Phys Rev Lett **97** 062001 (2006)]





- **SATURNE II**: $\alpha p \to \alpha' X$
  [H.P. Morsch and P. Zupranski,
  Phys Rev C **61**, 024002 (2000)]



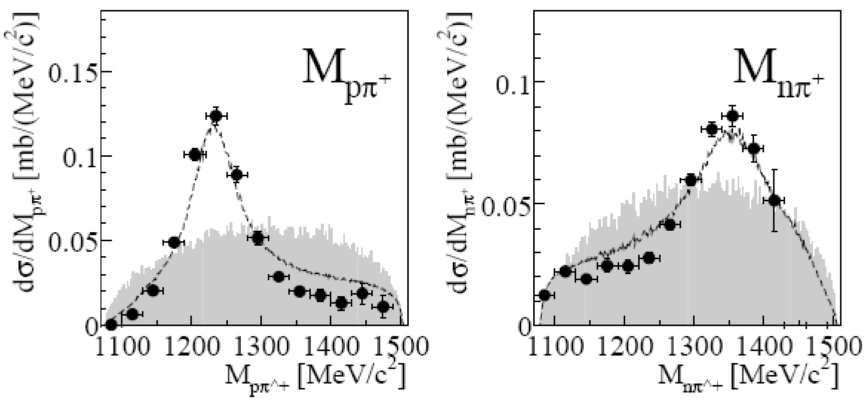
$\omega = E_{\alpha'} - E_\alpha$

- $M = 1390 \pm 20$ MeV
  $\Gamma = 190 \pm 30$ MeV
- Looks similar as pole at 2nd sheet in GW πN

- PWA: $J^P = 1/2^+$
  $M = 1358 \pm 6 \pm 16$ MeV
  $\Gamma = 179 \pm 26 \pm 50$ MeV
- Looks similar as pole at 1st sheet in GW πN

More Direct Measurements of N(1440)P_{11}

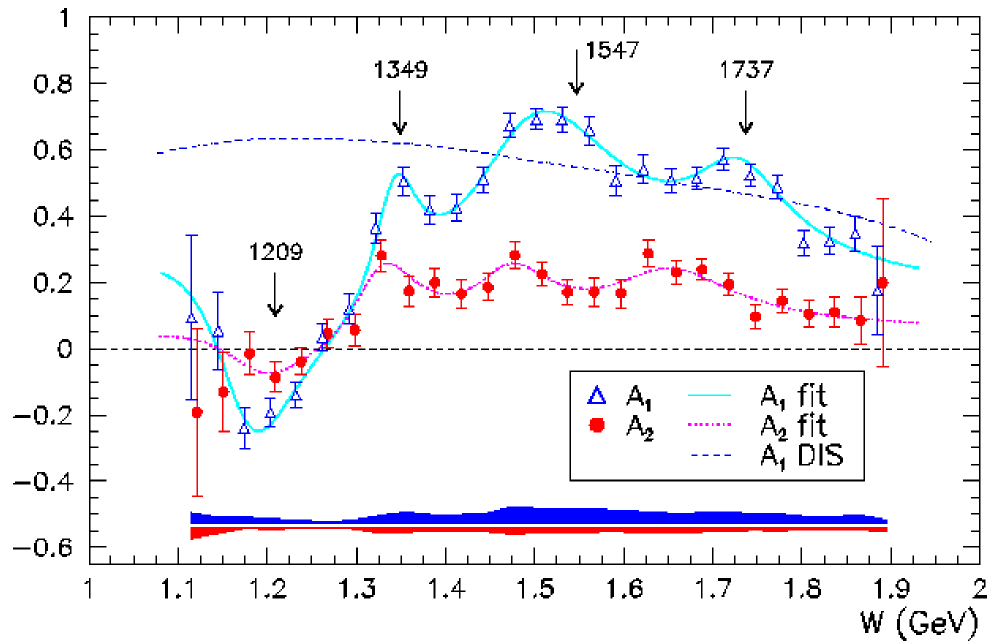
- **CELSIUS-WASA**: $pp \to np\pi^+$
  [H. Clement *et al* nucl-ex/0612015]



- M=1360 MeV
  Γ= 140 MeV

- Looks similar as pole at 1st sheet in GW πN

- **JLab-RSS**: ep→e'X
  [F.R. Wesselmann *et al* nucl-ex/0608003]

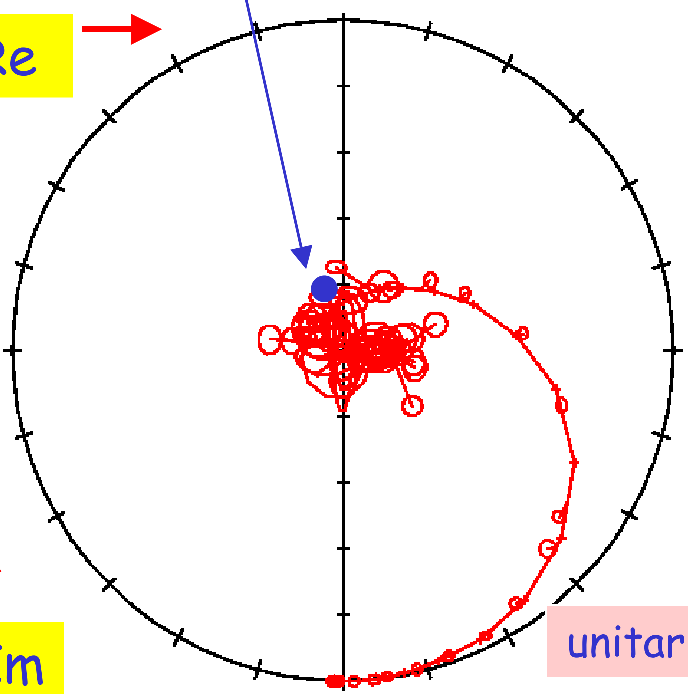


- M=1338±10 MeV
  Γ= 65±26 MeV
- M=1346± 5 MeV
  Γ= 71±35 MeV

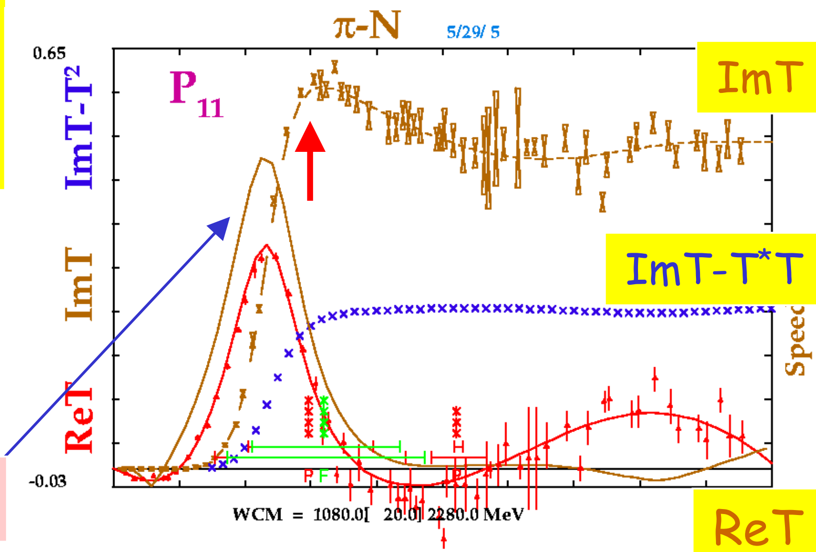
- Looks similar as poles at 1st and 2nd sheets in GW πN
- evidence of two poles ?

P_{11} via Argand and Speed plots

- Is standard BW an appropriate form to extract N(1440) from the set of several nearby singularities [2 poles and $\pi\Delta$, ηN branch-points with a very prominent cut] ?!!



W = 1080 [20] 2280 MeV



- Sp(W) = |dT/dW|

  → peak at W=M (pole)

  at NonRes→0

  [G. Hoehler, πN Newslett. (1993)]

- Above 1400 MeV, Sp(W) is flat

N(1710)P_{11} – What was Known

[W.-M. Yao *et al.* [RPP] J Phys G **33**, 1 (2006)]

PDG06 = PDG04

χSA	DPP97	1710 [inp]	~40 [est]
PWA-BW	Ref	Mass(MeV)	Width(MeV)
	KH79	1723± 9	120± 15
	CMU80	1700±50	90± 30
	KSU92	1717±28	480±230
	GW06	not seen	
PWA-Pole		Re(MeV)	-2xIm(MeV)
	CMU80	1690±20	80± 20
	CMU90	1698	88
	KH93	1690	200
	GW06	not seen	

No BW, No pole, No Sp

[Sp(W)]

- The spread of Γ, Γ_π/Γ, and Γ_η/Γ, selected by PDG, is very large
- Γ is too large, $\geq$ 100 MeV
- If this state is related to the Θ^+ then it would be more natural for the same unitary multiplet (with Θ^+ and N*) to have comparable widths

Direct Anti-Evidences for N(1710)P_{11}

- CLAS single- and double-charged-pion electroproduction off protons data in an isobar approach at W = 1100 to 1780 MeV and Q^2 = 0.65 GeV^2
  [I. Aznauryan *et al*, Phys Rev C **72**, 045201 (2005)]:
  '*At $Q^2 = 0$, the coupling of the resonance N(1710)P_{11} to γN is small. Our analysis showed that this resonance make minor contribution to the resonant electroproduction cross section*'

- 2500 $\gamma p \to K^+\Lambda$ data below W = 2500 MeV in a multipole approach
  [T. Mart and A. Sulaksono, Phys Rev C **74**, 055203 (2006)]:
  '*The 3* resonance N(1710)P_{11} that has been used in almost all isobar models within both single-channel and multi-channel approaches is found to be insignificant to the $K^+\Lambda$ photoproduction by both SAPHIR and CLAS data*'

- Combined analysis of CLAS 2π electroproduction data at photon virtualities from 0.5 to 1.5 GeV^2 and for W from 1400 to 1900 MeV
  [V. Mokeev, PC 2006]:
  `*Electroproduction strength $\sqrt{(A_{1/2}^2 + S_{1/2}^2)}$ for N(1710)P_{11} should be below 0.02 $GeV^{-1/2}$*'

Narrow Resonances in PWA

[R. Arndt, Ya. Azimov, M. Polyakov, IS, R. Workman, Phys Rev C **69**, 035208 (2004)]

- Because PWA (by construction) tends to miss narrow Res with $\Gamma < 30$ MeV
- We assume the existence of a Res and refit over the whole database
- Insertion of a narrow Res in PWA for

  elastic case: $e^{2i\delta} \Rightarrow e^{2i\delta_R} e^{2i\delta_B}$

  $e^{2i\delta_R} = (M_R - W + i\,\Gamma_R/2)/(M_R - W - i\,\Gamma_R/2)$

  inelastic case: $\eta\, e^{2i\delta} \Rightarrow \langle a|S|a\rangle = r_a\, A(W)\, e^{2i\delta_R} + (1 - r_a)\, B(W)$

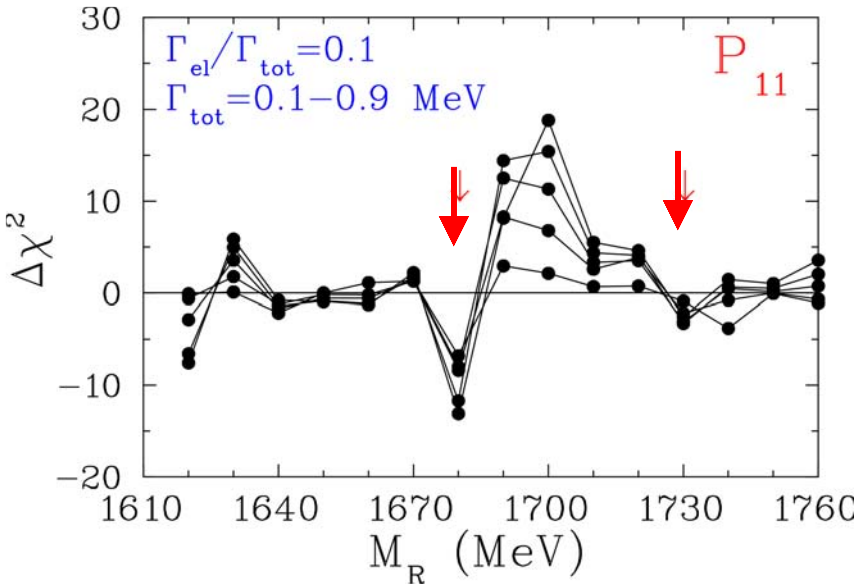
  $r_a = BR(R \to a)$ $\quad |A(M_R)| = 1 \quad \Sigma r_a = 1$

  $\eta \leq 1 \Rightarrow \quad r_a\, |A(W)| + (1 - r_a)\, |B(W)| \leq 1$

- How does this insertion change χ^2? (Will it decrease ?)

Modified πN PWA

- $\Delta\chi^2$ due to insertion of a Res into P_{11} ($J^P = 1/2^+$)



- At $|M_R - W| \gg \Gamma_R$, Res contributes $\sim \Gamma_{el}/(M_R - W)$

- Two candidates: M_R = 1680 MeV 1730 MeV
  $\Gamma_{\pi N}$ < 0.5 MeV < 0.3 MeV

- The procedure is less sensitive to Γ_{tot}

Features

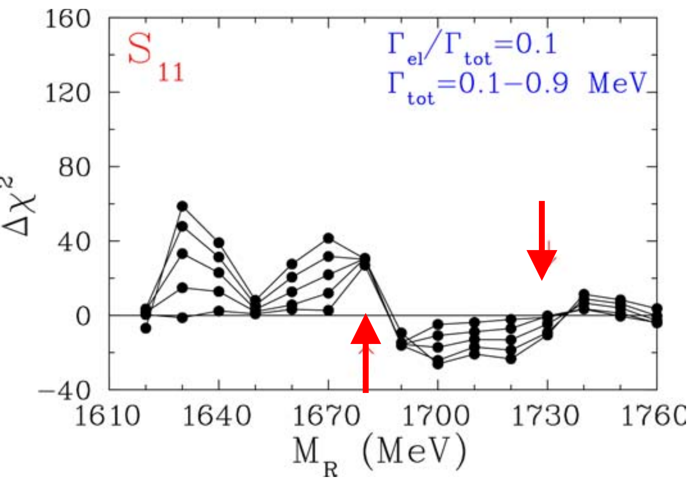
- Refitting
  - Worse description
    - ⇒ a Res with corresponding M and Γ is not supported
  - Better description
    - ⇒ a Res may exist
    - ⇒ effect can be due to various corrections (*eg,* thresholds)
    - ⇒ both possibilities can contribute

  Some additional checks are necessary

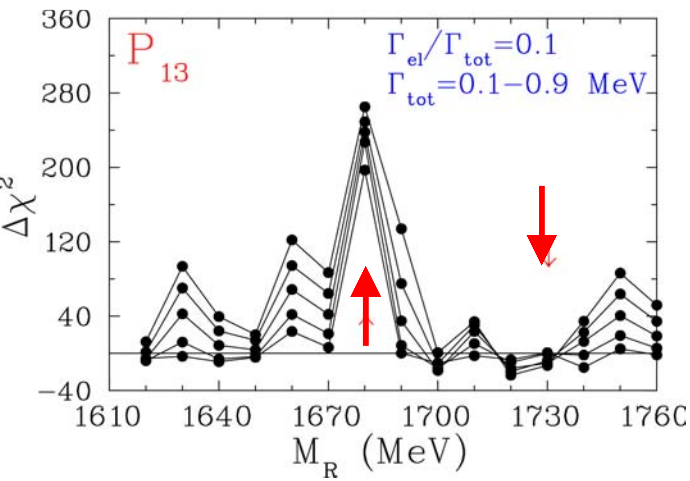
- A true Res should provide the effect only in a particular PW

- While NonRes source may show similar effects in various PWs

Check other Partial Waves



- $\Delta\chi^2$ due to insertion of a Res into S_{11} ($J^P = 1/2^-$)



- $\Delta\chi^2$ due to insertion of a Res into P_{13} ($J^P = 3/2^+$)

- No effects at M = 1680 MeV and possible (small) effects at M = 1730 MeV

Conclusion from Modified πN PWA for S- and P-waves

(dedicated for the search for narrow states, $\Gamma < 30$ MeV)

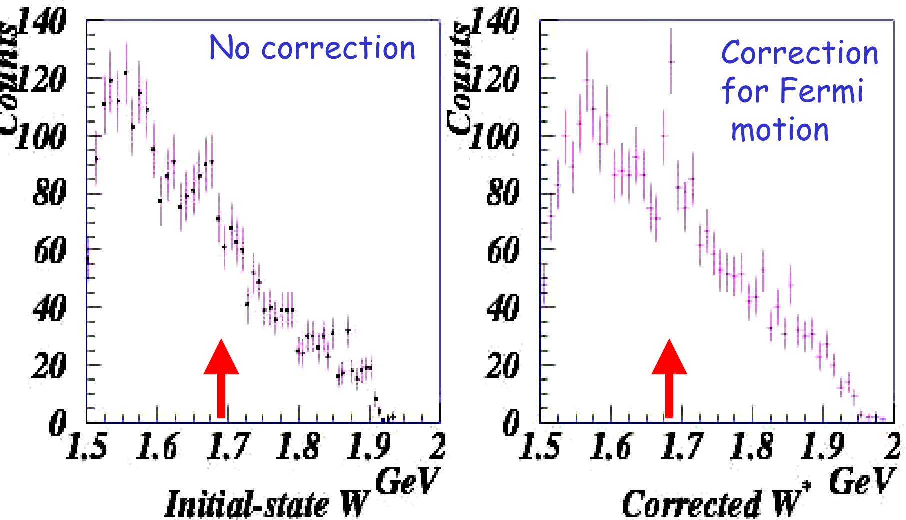
[R. Arndt, Ya. Azimov, M. Polyakov, IS, R. Workman, Phys Rev C **69**, 035208 (2004)]

- 1680 MeV – only one partial wave (P_{11}) reveals the effect: support to the resonance, $\Gamma_{\pi N} < 0.5$ MeV
- 1730 MeV – P_{11} may also reveal a resonance with $\Gamma_{\pi N} < 0.3$ MeV but differently: Res is still possible, if accompanied by different corrections

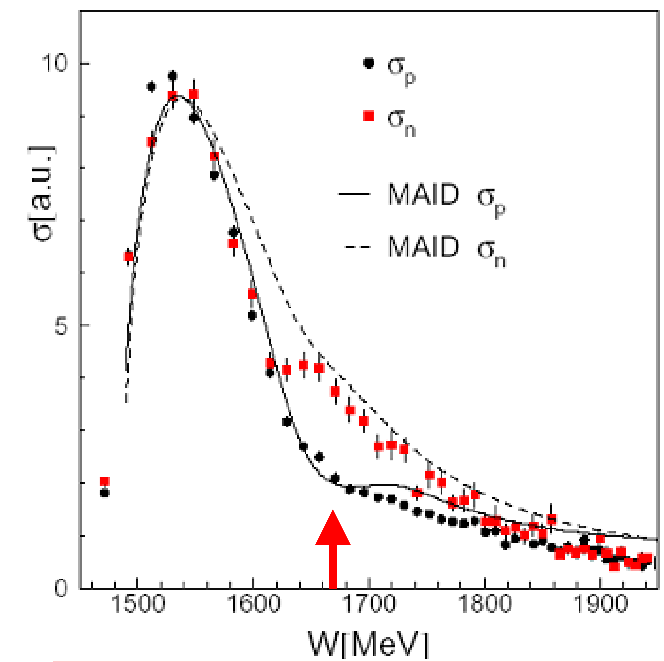
- The Res at 1730 MeV may appear in P_{13} or S_{11} (less probable), if accompanied by different corrections [*eg*, thresholds: $N\omega$(1720), $N\rho$(1715) ?, $K\Sigma$(1685)]
- The rest of partial waves (D_{15}, *etc*) do not support narrow states

Direct Evidences for N(1680)P_{11} in $\gamma n \to \eta n$

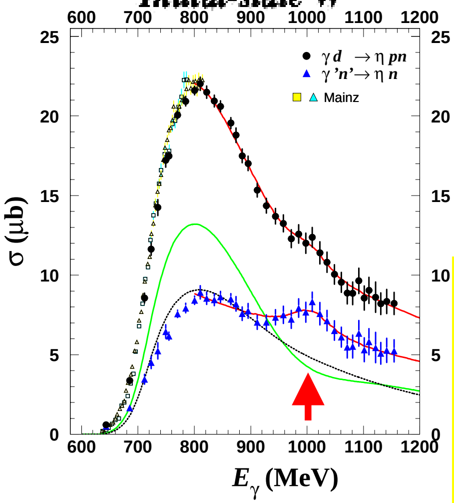
- **GRAAL**: backward $\gamma n \to \eta n$
  [V. Kuznetsov, Phys Lett B **647**, 23 (2007)]



- **CB-ELSA**: Very preliminary $\sigma(\gamma n \to \eta n)$
  [I. Jaegle, NSTAR 2005 Proc, Oct 2005]



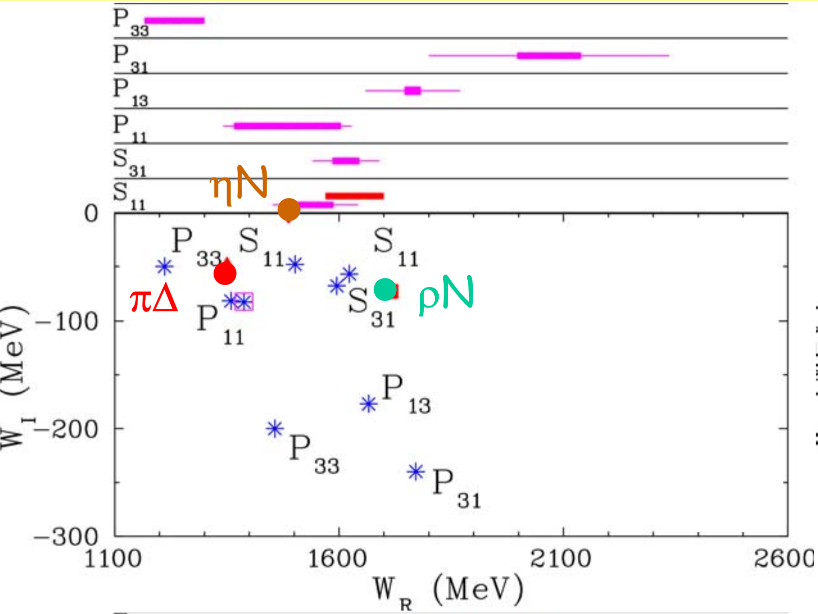
- **LNS**: Very preliminary $\gamma n \to \eta n$
  [J. Kasagi, YKIS 2006, Nov 2006]

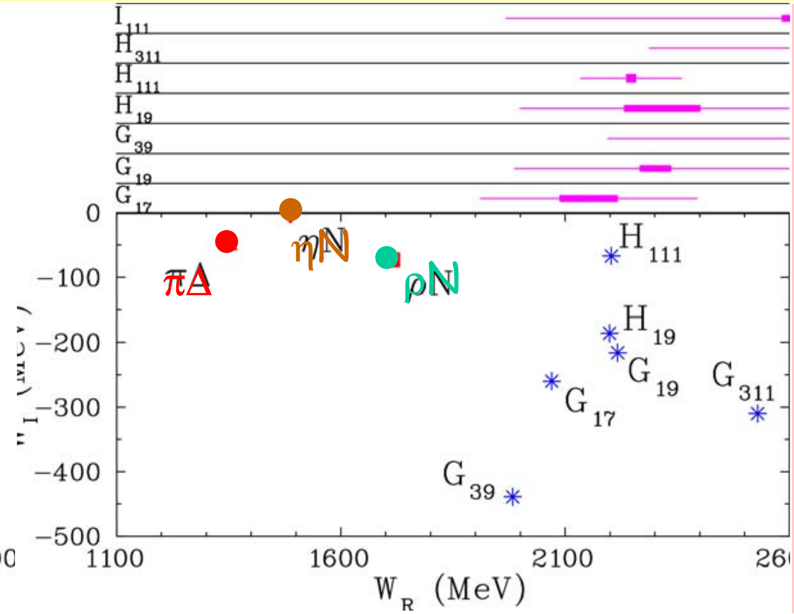


- Independent CB-ELSA & LNS measurements confirm the GRAAL observation
- EtaMAID does not reproduce both p and n data well

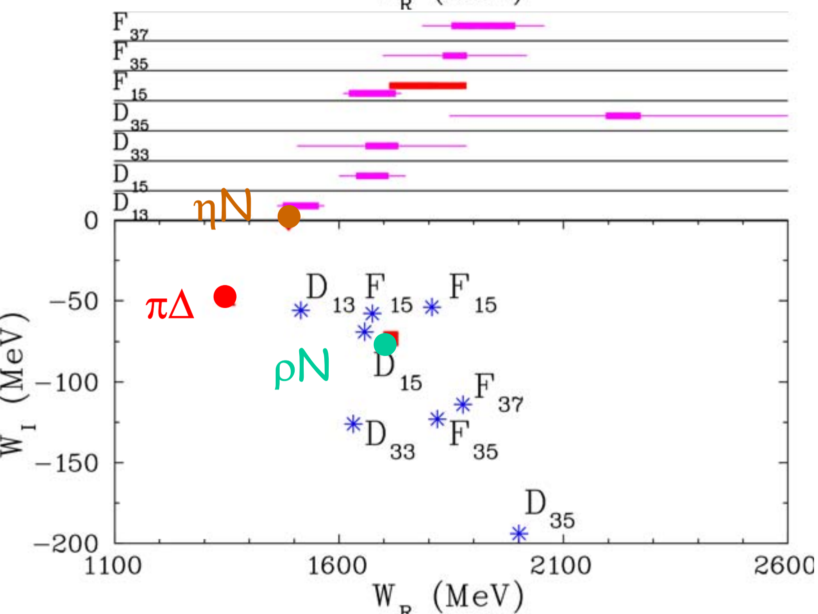
- There is a good candidate for missed N*
- Its width is much less than any S=0 N*
- Agreed with γn vs γp within ChSA [M. Polyakov and A. Rathke, Eur Phys J A **18**, 691 (2003)]

Complex Plane vs BW fits





- P_{11} has 1 BW and 2 poles
- P_{31}, D_{35}, and G_{39}, possessed large W_I, do not allow well determ on-shell Res prms



BW fit:

- —— Γ
- ▬▬ $\Gamma_{\pi N}$

* Poles of amplitudes

● Branch points: [πΔ thr] [1350-i50 MeV]

● [ηN thr] [1487- i0 MeV]

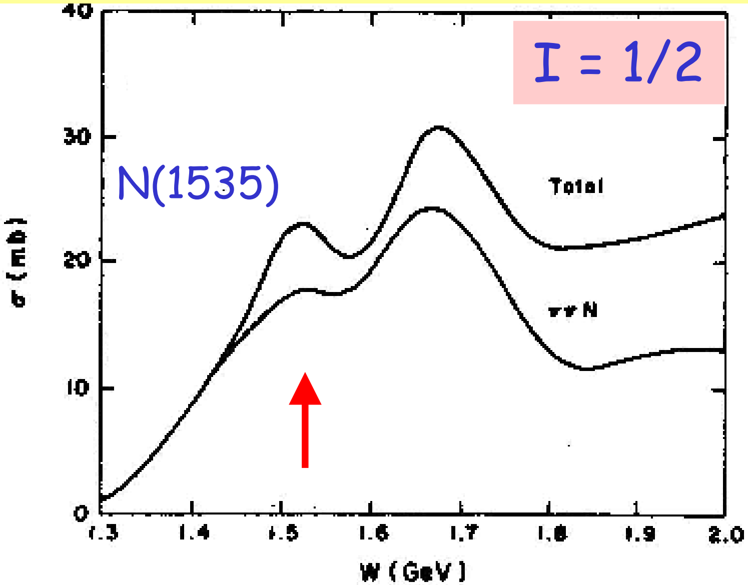
● [ρN thr] [1715-i73 MeV]

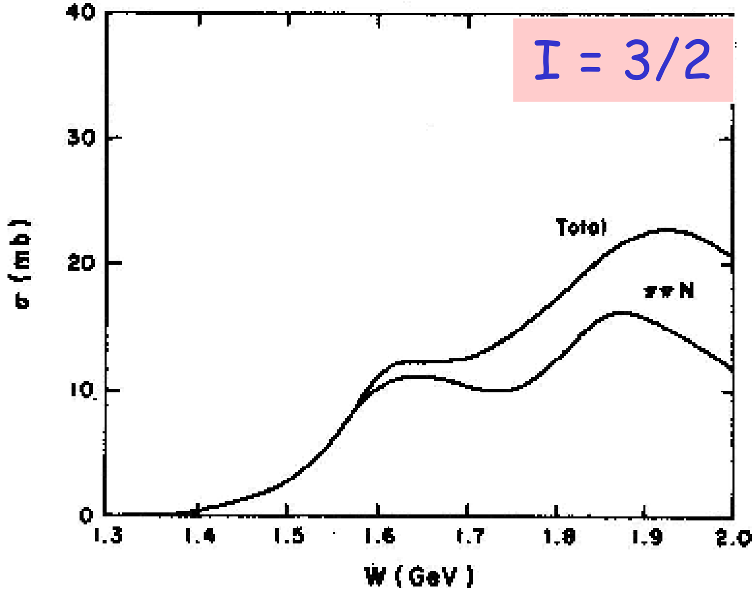
Summary of N* and Δ* finding

- Standard PWA reveals only wide Resonances, but not too wide (Γ < 500 MeV) and possessing not too small BR (BR > 4%)
- PWA (by construction) tends to miss narrow Resonances with Γ < 30 MeV
- Our study does not support several N* and Δ* reported by PDG2006:
  *** $\Delta(1600)P_{33}$, $N(1700)D_{13}$, $N(1710)P_{11}$, $\Delta(1920)P_{33}$
  ** $N(1900)P_{13}$, $\Delta(1900)S_{31}$, $N(1990)F_{17}$, $\Delta(2000)F_{35}$, $N(2080)D_{13}$, $N(2200)D_{15}$, $\Delta(2300)H_{39}$, $\Delta(2750)I_{313}$
  * $\Delta(1750)P_{31}$, $\Delta(1940)D_{33}$, $N(2090)S_{11}$, $N(2100)P_{11}$, $\Delta(2150)S_{31}$, $\Delta(2200)G_{37}$, $\Delta(2350)D_{35}$, $\Delta(2390)F_{37}$
- Our study does suggest several 'new' N* and Δ*:
  **** $\Delta(2420)H_{311}$
  *** $\Delta(1930)D_{35}$, $N(2600)I_{111}$ [no pole]
  ** $N(2000)F_{15}$, $\Delta(2400)G_{39}$
  new $N(2245)H_{111}$ [CLAS ?]

$\pi N \to \pi\pi N$ in Isobar Model

[D.M. Manley, R. Arndt, Y. Goradia, V. Teplitz, Phys Rev D **30**, 904 (1984)].





- 241,214 events for $\pi N \to \pi\pi N$ have been analyzed in Isobar-model PWA at W = 1320 to 1930 MeV
- $\pi N \to \pi\pi N$ is essential above 1300 MeV, $\sigma_{2\pi N} \sim \sigma_{inel}$
- That is the main source of πN inelastic amplitudes and ρN with $\pi\Delta$ contribution
- This 1984 analysis is rather old and there are no new comprehensive analyses
- Looks promising PWA, W = 1274 to 1370 MeV [A.A. Bolokhov, V.A.Kozhevnikov and D.N.Tatarkin, and S.G.Sherman, Phys Rev C **61**, 055203, 1 (2000)]

Recent $\pi N \to \pi\pi N$ Measurements

- New data came late (most of them are total Xsections):

W = 1078 to 1127 MeV:
- $\pi^- p \to \pi^0 \pi^0 n$ [BNL: J. Lowe *et al* Phys Rev C **44**, 956 (1991)]

W = 1221 to 1356 MeV:
- $\pi^+ p \to \pi^+ \pi^+ n$ [PNPI: A. Kravtsov *et al* Nucl Phys B **134**, 413 (1978)]
- $\pi^+ p \to \pi^+ \pi^+ n$ [TRIUMF: M. Sevior *et al* Phys Rev Lett **66**, 2569 (1991)]
- $\pi^+ p \to \pi^+ \pi^0 p$ [LAMPF: D. Pocanic *et al* Phys Rev Lett **72**, 1156 (1994)]
- $\pi^{+-} p \to \pi^{+-} \pi^{-+} n$ [TRIUMF: M. Kermani *et al* Phys Rev C **58**, 3419 (1998)]
- $\pi^- p \to \pi^- \pi^+ n$ [CERN: G. Kernel *et al* Z Phys C **48**, 201 (1990)]
- $\pi^{-+} p \to \pi^{-+} \pi^+ n$ [TRIUMF: J. Lange *et al* Phys ReV Lett **80**, 1597 (1998)]

W = 1213 to 1527 MeV:
- $\pi^- p \to \pi^0 \pi^0 n$ [BNL: S. Prakhov *et al* Phys Rev C **69**, 045202 (2004)]

W = 1257 to 1302 MeV:
- $\pi^{+-} p \to \pi^{+-} \pi^{-+} n$ [20,000 events] [TRIUMF: M. Kermani *et al* Phys Rev C **58**, 3431 (1998]

W = 1300 MeV:
- $\pi^- p \to \pi^+ \pi^- n$ [PSI: R. Mueller *et al* Phys Rev C **48**, 981 (1993)]

W = 2060 MeV:
- $\pi^- p \to \pi^- \pi^+ n$ [40,000 events] [ITEP: I. Alekseev *et al* Phys At Nucl **61**, 174 (1998)]

Backup

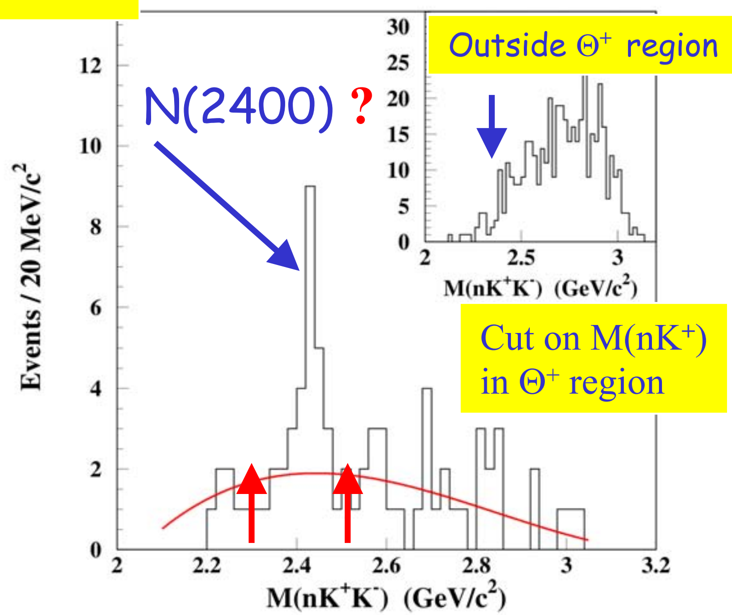
•

Possible Mechanism of Θ^+ Production, N(2400)

[Ya. Azimov, IS, Phys Rev C **70**, 035210 (2004)]

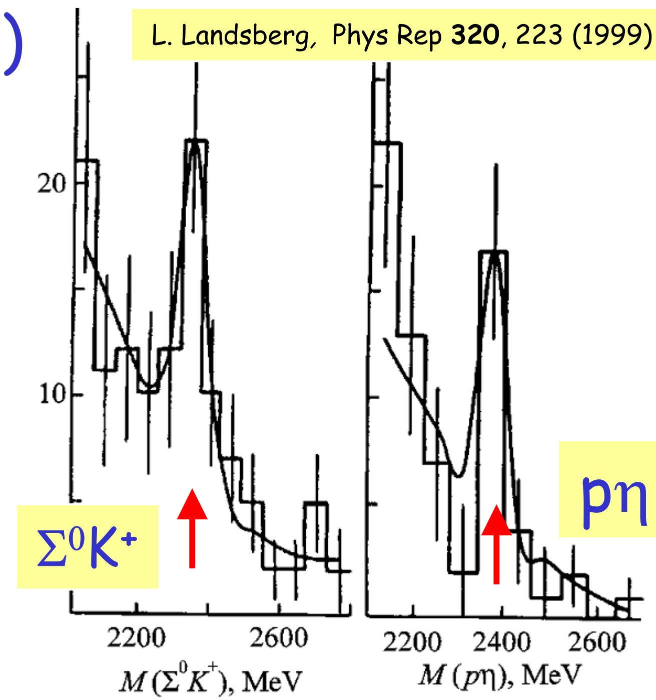
- CLAS at JLab:
  $\gamma p \to \pi^+ n(2400) \to \pi^+ K^- \Theta^+$

nK⁺K⁻



V. Kubarovsky *et al*, PRL **92**, 032001 (2004)

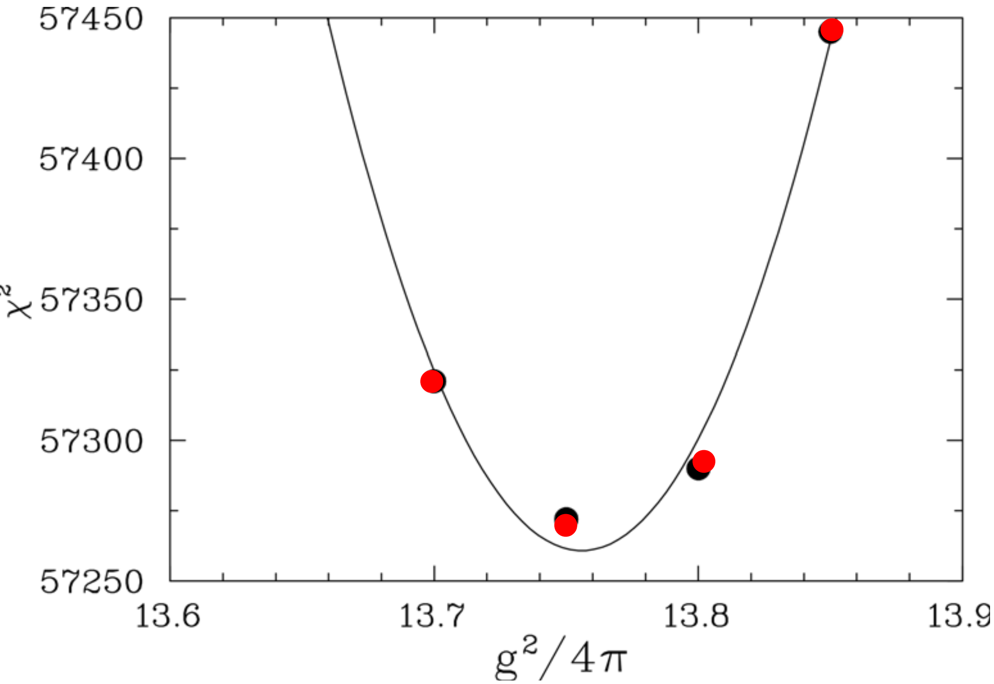
- SPHINX at IHEP:
  $pN \to Nn(2400) \to \Sigma^0 K^+,\ p\eta$



- N(2400)
  8, 10, or 27
  $I = \frac{1}{2}$ $J^P = ??$
  $\sigma(n) \gg \sigma(p)$

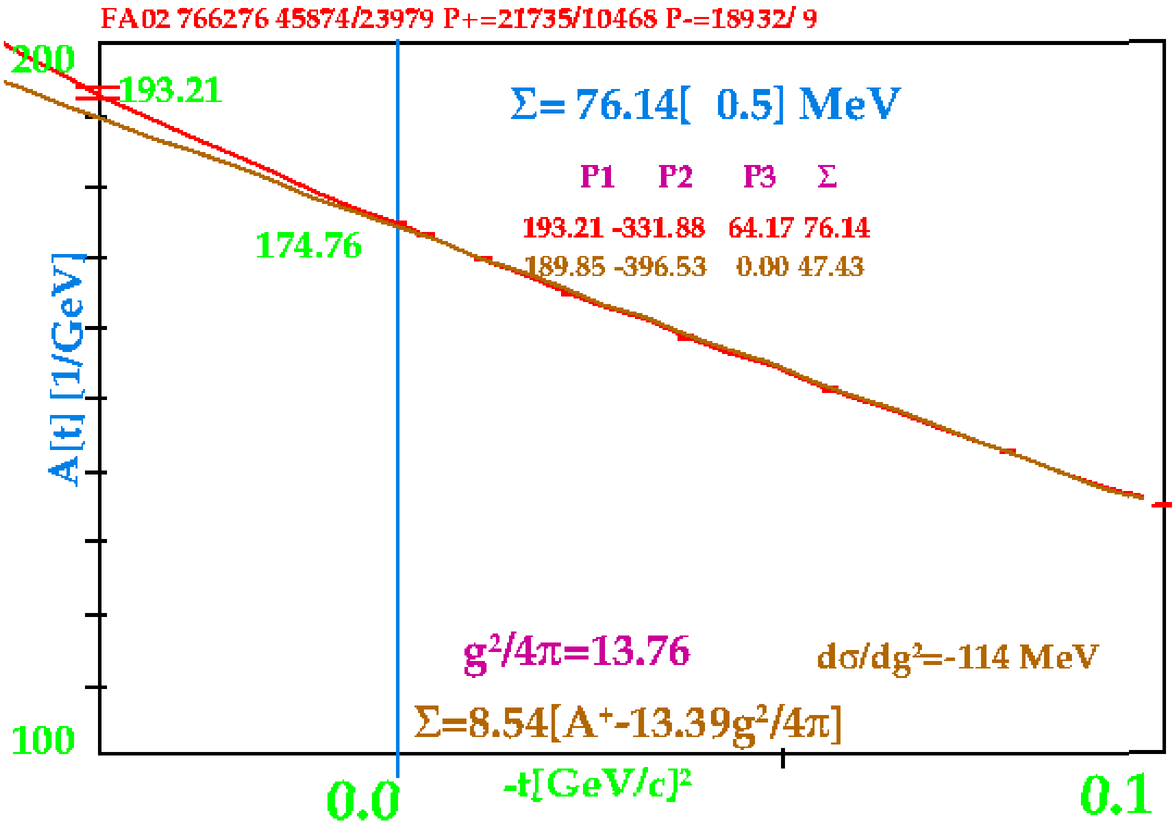
- No πN PWA has seen an N(2400) at $\pi^- p \to \pi N$ with $\Gamma_{tot} \geq 100$ MeV and $BR(R \to a) \geq 5\%$ [G. Hoehler, Springer, 1983]

LE Quantities – $g^2_{\pi NN}/4\pi$



- min = 13.756±0.007
- $\Delta(g^2/4\pi)$ corresponds to $\Delta\chi^2=1$ ['canonical' error]

LE Quantities - Σ-term



- Σ=76.1±0.5 MeV
- Σ=81±6 MeV [G.E. Hite *et al* Phys Rev C **71**, 065201 (2005)]