Partial-Wave Analysis of Pion Scattering Reactions

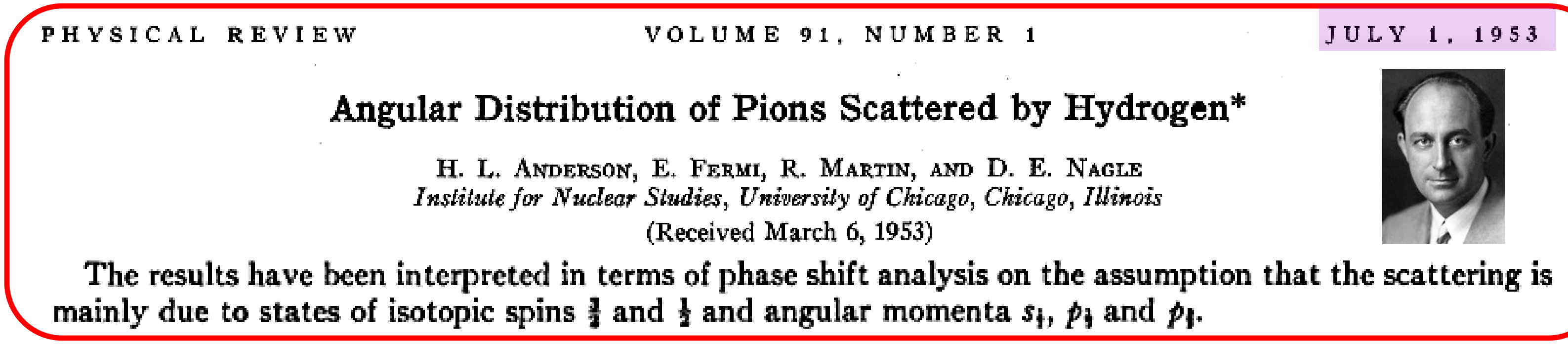
Igor Strakovsky

The George Washington University

- **S**pectroscopy of Baryons.
- **SAID** for Baryon Spectroscopy.
- πN Elastic Scattering.
  - **N**(1440)$1/2^+$.
- πN inElastic Scattering.
  - $\pi^-p\to\eta p$.
  - $\pi^-p\to KY$.
  - $\pi\to 2\pi$.
- **P**ion Photoproduction.
- **P**ion Electroproduction.

Spectroscopy of Baryons

A bit of History…



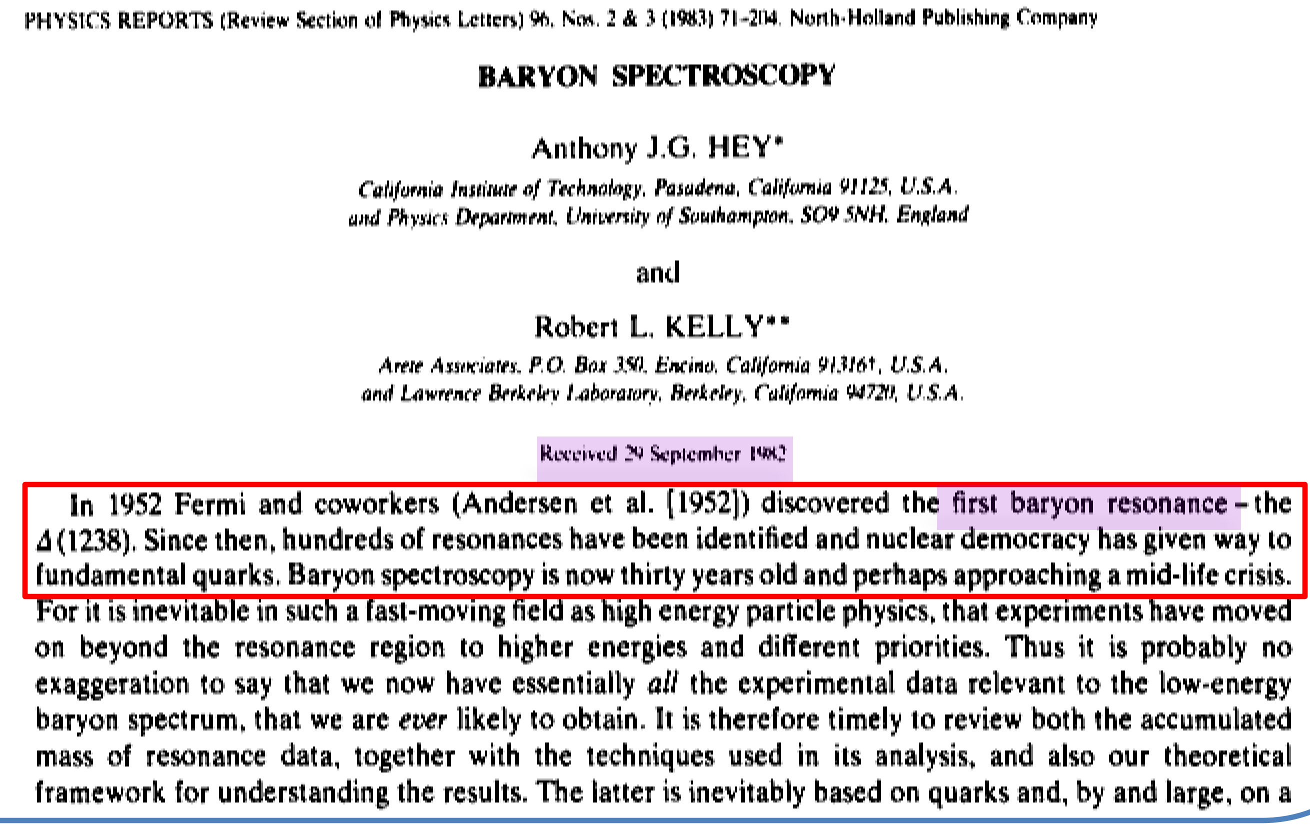
PHYSICAL REVIEW VOLUME 91, NUMBER 1 JULY 1, 1953

Angular Distribution of Pions Scattered by Hydrogen*

H. L. ANDERSON, E. FERMI, R. MARTIN, AND D. E. NAGLE
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received March 6, 1953)

The results have been interpreted in terms of phase shift analysis on the assumption that the scattering is mainly due to states of isotopic spins $\frac{3}{2}$ and $\frac{1}{2}$ and angular momenta $s_{\frac{1}{2}}$, $p_{\frac{3}{2}}$ and $p_{\frac{1}{2}}$.



PHYSICS REPORTS (Review Section of Physics Letters) 96, Nos. 2 & 3 (1983) 71-204. North-Holland Publishing Company

BARYON SPECTROSCOPY

Anthony J.G. HEY*
California Institute of Technology, Pasadena, California 91125, U.S.A.
and Physics Department, University of Southampton, SO9 5NH, England

and

Robert L. KELLY**
Arete Associates, P.O. Box 350, Encino, California 913161, U.S.A.
and Lawrence Berkeley Laboratory, Berkeley, California 94720, U.S.A.

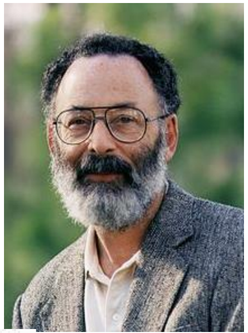
Received 29 September 1982

In 1952 Fermi and coworkers (Andersen et al. [1952]) discovered the first baryon resonance – the Δ(1238). Since then, hundreds of resonances have been identified and nuclear democracy has given way to fundamental quarks. Baryon spectroscopy is now thirty years old and perhaps approaching a mid-life crisis. For it is inevitable in such a fast-moving field as high energy particle physics, that experiments have moved on beyond the resonance region to higher energies and different priorities. Thus it is probably no exaggeration to say that we now have essentially *all* the experimental data relevant to the low-energy baryon spectrum, that we are *ever* likely to obtain. It is therefore timely to review both the accumulated mass of resonance data, together with the techniques used in its analysis, and also our theoretical framework for understanding the results. The latter is inevitably based on quarks and, by and large, on a

Spectroscopy of Baryons

``It is clear that we still need much more information about the existence and parameters of many baryon states, especially in the N=2 mass region, before this question of non-minimal SU(6) x O(3) super-multiplet can be settled.” **Dick Dalitz**, **1976**.

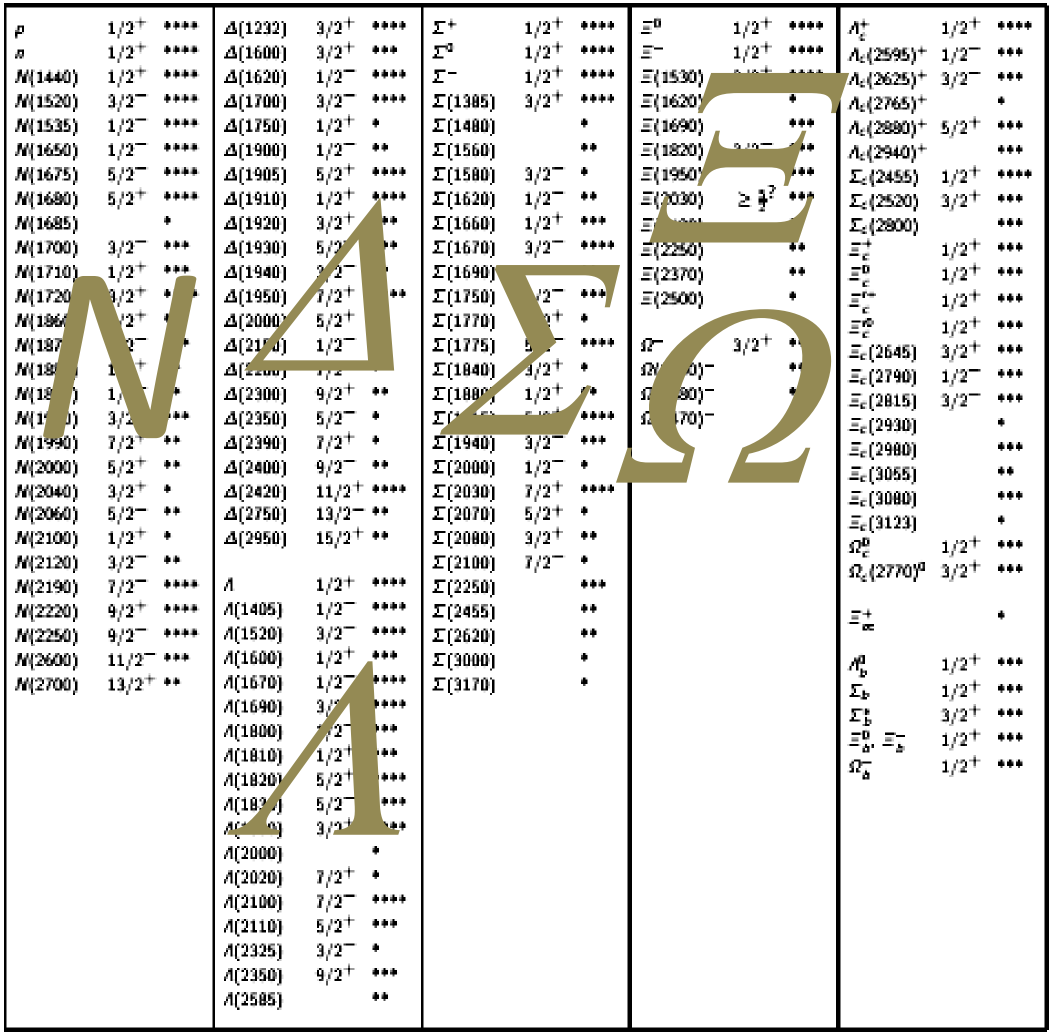
``The first problem is the notion of a resonance is not well defined. The ideal case is a narrow resonance far away from the thresholds, superimposed on slowly varying background. It can be described by a Breit-Wigner formula and is characterized by a pole in the analytic continuation of the partial wave amplitude into the low half of energy plane.’’ **Gerhard Hoehler, 1987**.



``Why N*s are important – The *first* is that nucleons are the stuff of which our world is made. My *second* reason is that they are simplest system in which the quintessentially non-Abelian character of QCD is manifest. The *third* reason is that history has taught us that, while relatively simple, Baryons are sufficiently complex to reveal physics hidden from us in the mesons.” **Nathan Isgur**, **2000**.

Baryon Sector at PDG

[J. Beringer *et al* [PDG] Phys Rev D **86**, 010001 (2012)]



p	$1/2^+$	****
n	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1685)$		*
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	***
$N(1720)$	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
$N(1990)$	$7/2^+$	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	**
$N(2100)$	$1/2^+$	*
$N(2120)$	$3/2^-$	**
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**
$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	***
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	**
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	****
$\Delta(1920)$	$3/2^+$	[illegible]
$\Delta(1930)$	[illegible]	[illegible]
$\Delta(1940)$	[illegible]	[illegible]
$\Delta(1950)$	$7/2^+$	[illegible]
$\Delta(2000)$	$5/2^+$	[illegible]
$\Delta(2150)$	$1/2^-$	[illegible]
[illegible]	[illegible]	[illegible]
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**
Λ	$1/2^+$	****
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	***
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	[illegible]	****
$\Lambda(1800)$	[illegible]	[illegible]
$\Lambda(1810)$	$1/2^+$	[illegible]
$\Lambda(1820)$	$5/2^+$	[illegible]
[illegible]	$5/2^-$	[illegible]
[illegible]	[illegible]	[illegible]
$\Lambda(2000)$		*
$\Lambda(2020)$	$7/2^+$	*
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		**
Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	**
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1690)$	[illegible]	[illegible]
$\Sigma(1750)$	[illegible]	***
$\Sigma(1770)$	[illegible]	*
$\Sigma(1775)$	[illegible]	****
$\Sigma(1840)$	$3/2^+$	*
$\Sigma(1880)$	$1/2^+$	[illegible]
[illegible]	[illegible]	****
$\Sigma(1940)$	$3/2^-$	***
$\Sigma(2000)$	$1/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	**
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*
Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(1530)$	[illegible]	[illegible]
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	[illegible]	[illegible]
$\Xi(1950)$		[illegible]
$\Xi(2030)$	$\geq \frac{5}{2}?$	***
[illegible]		[illegible]
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	$3/2^+$	[illegible]
[illegible]		[illegible]
[illegible]		[illegible]
[illegible]		[illegible]
Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$		***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	***
$\Xi_c'^+$	$1/2^+$	***
$\Xi_c'^0$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		*
$\Xi_c(2980)$		***
$\Xi_c(3055)$		**
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	$1/2^+$	***
$\Omega_c(2770)^0$	$3/2^+$	***
Ξ_{cc}^+		*
Λ_b^0	$1/2^+$	***
Σ_b	$1/2^+$	***
Σ_b^*	$3/2^+$	***
Ξ_b^0, Ξ_b^-	$1/2^+$	***
Ω_b^-	$1/2^+$	***

- **PDG12** has **112** Baryon Resonances (**58 4*** & **3*** of them).

- For example for **SU(6) x O(3)**, it would be **434** resonances, if all revealed **three 70**– and **four 56**– multiplets were filled in.

- There are many **more states** in the **QCD** inspired models than currently observed.

- A quick check of the **PDG Listings** reveals that resonance parameters of many established states are not well determined.

*There are Many Ways to Study N**

Prolific source of **N*** & **Δ*** baryons

Measure many channels with different combinations of quantum numbers.

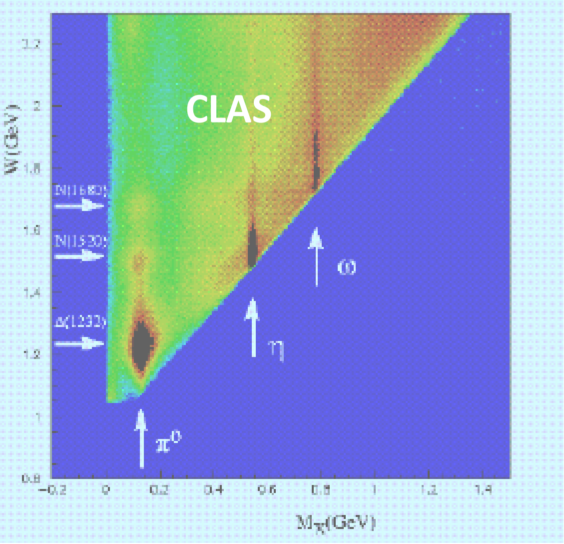
$\pi N \to \pi N,\ \pi\pi N,\ \ldots$

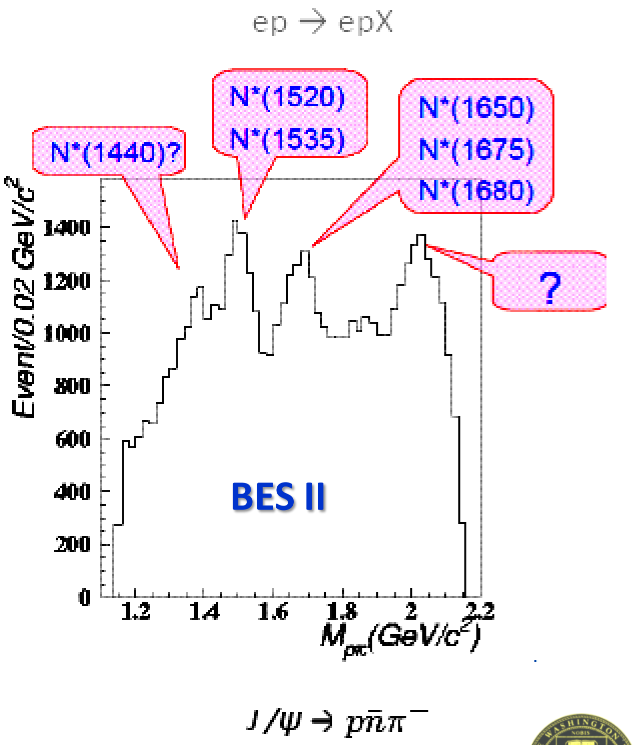
$\gamma N \to \pi N,\ \pi\pi N,\ \ldots$

$\gamma^* N \to \pi N,\ \pi\pi N,\ \ldots$

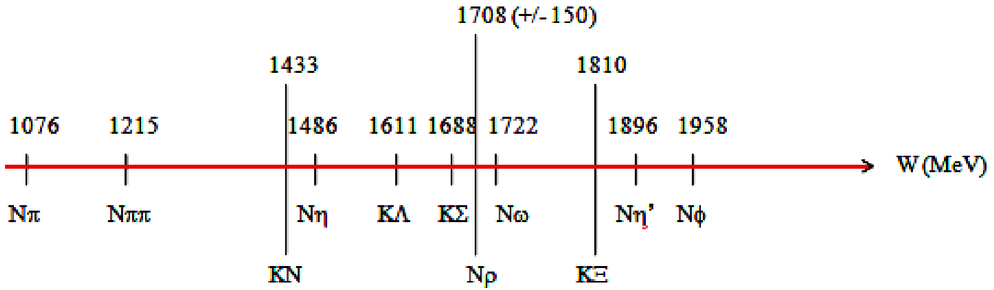
$pp \to pp\pi^0,\ pp\pi\pi,\ \ldots$

$J/\psi \to p\bar{p}\pi^0,\ p\bar{n}\pi^-,\ \ldots$





- Most of **PDG** info comes from these sources and **PWA** is main of them.
- **πN elastic** scattering is highly constrained.
- Resonance structure is correlated.
- Two-body final state, fewer amplitudes.

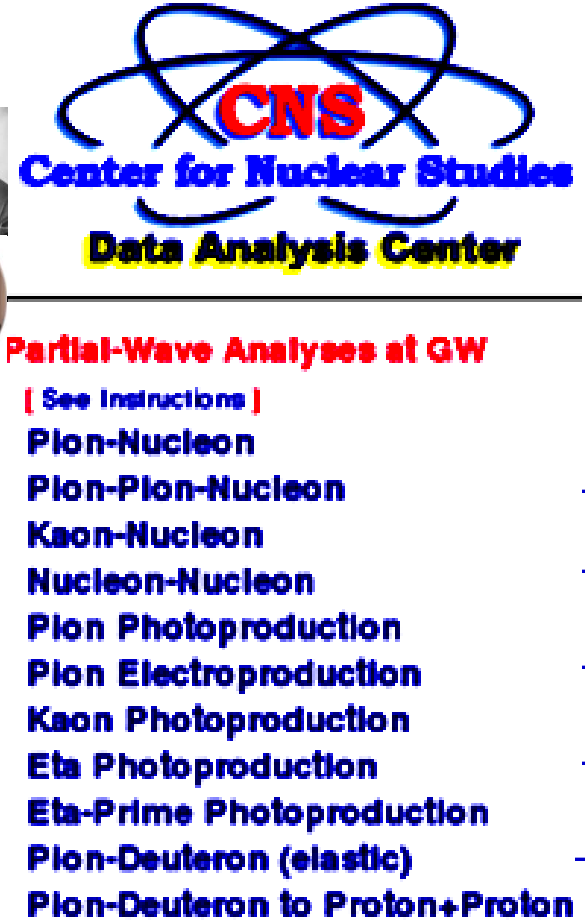


PWA for non-Strange Baryons & SAID Database

Originally: PWA arose as the technology to determine amplitude of the reaction via fitting scattering data which is a non-trivial mathematical problem
[*Solution of ill-posed problem*
– Hadamard, Tikhonov, *et al*]

Resonances appeared as a by-product
[Bound states objects with definite quantum numbers, mass, lifetime, *etc*]

That is the strategy of the GW/VPI πN PWA since 1987



CNS

Center for Nuclear Studies

Data Analysis Center

Below 4 GeV

Partial-Wave Analyses at GW

[See Instructions]

[W = 1320 to 1930 MeV]

31,479	Pion-Nucleon	
	Pion-Pion-Nucleon	241,214 evts
5,267	Kaon-Nucleon	
	Nucleon-Nucleon	38,162
27,265	Pion Photoproduction	
	Pion Electroproduction	113,900
9,086	Kaon Photoproduction	
	Eta Photoproduction	6,235
1,030	Eta-Prime Photoproduction	
	Pion-Deuteron (elastic)	1,914
6,083	Pion-Deuteron to Proton+Proton	

For $\pi \rightarrow 2\pi$, we use log-likelihood while for the rest – least-squares technologies.

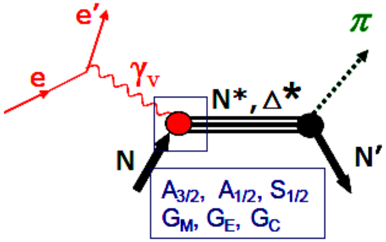
SAID for Baryon Spectroscopy

N^* and Δ^* States coupled to πN

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

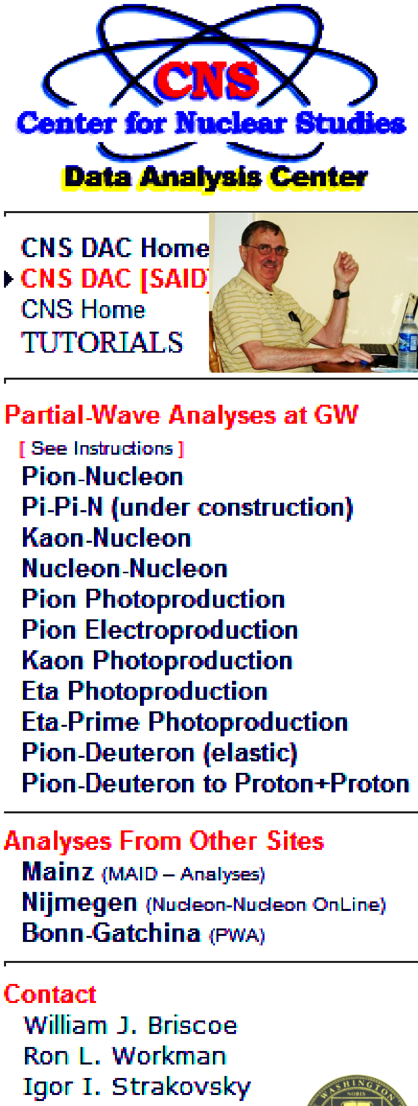
- GW SAID N* program consists of $\pi N \to \pi N \Longrightarrow \gamma N \to \pi N \Longrightarrow \gamma^* N \to \pi N$
  As was established by Dick Arndt on 1997.

Assuming dominance of 2-hadronic channels [πN elastic & $\pi^- p \to \eta n$], we parameterize $\gamma^* N \to \pi N$ in terms of $\pi N \to \pi N$ amplitudes.



- One of the most convincing ways to study a non-strange baryon Spectroscopy [a key to our understanding of QCD] is πN PWA.

- Non-strange objects in the PDG Listings come mainly from:
  Karlsruhe-Helsinki, Carnegie-Mellon-Berkeley, GW, & BnGa now.
- The main source of EM couplings is the GW & BnGa analyses.



Partial-Wave Analyses at GW

[See Instructions]

Pion-Nucleon
Pi-Pi-N (under construction)
Kaon-Nucleon
Nucleon-Nucleon
Pion Photoproduction
Pion Electroproduction
Kaon Photoproduction
Eta Photoproduction
Eta-Prime Photoproduction
Pion-Deuteron (elastic)
Pion-Deuteron to Proton+Proton

Analyses From Other Sites

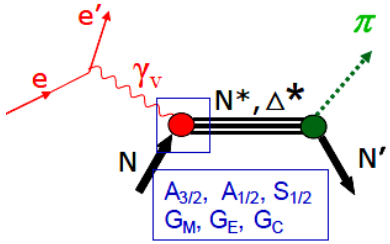
Mainz (MAID – Analyses)
Nijmegen (Nucleon-Nucleon OnLine)
Bonn-Gatchina (PWA)

Contact

William J. Briscoe
Ron L. Workman
Igor I. Strakovsky

GW N* Program

- Energy dependent **SM08** and associated SES & SQS
- W = 1080 – 2000 MeV $Q^2 = 0 - 6\ \mathrm{GeV}^2$
- PWs = 60 [multipoles] [J < 6]
- Prms = 171
- Constraint: πN + Pion Photo Prod PWAs [no theoretical input]



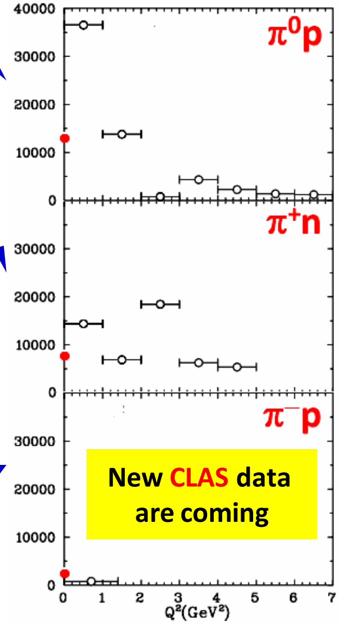
- 0.85 World Electro Prod from JLab CLAS

- **PWA Problems:**
  - Additional [18 S] Multipoles
  - Q^2 dependence

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

Reaction	Data	χ^2
$\gamma^* p \to \pi^0 p$	55,766	81,284
$\gamma^* p \to \pi^+ n$	51,312	80,004
Redundant	14,772	17,375
Total	121,850	178,663
$\gamma N \to \pi N$	25,358	53,458
All Photo*	147,208	232,121
$\pi N \to \pi N$	31,479	57,157
All πN	178,687	289,278
$\gamma^* n \to \pi^- p$	801	
$\gamma^* n \to \pi^0 n$	No Data	

Q^2-Data



New CLAS data are coming

πN Elastic Scattering

SAID for $\pi N \to \pi N$ & $\pi^- p \to \eta n$

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

- Energy dependent SP06/WI08 and associated SES
- $T = 0 - 2600$ MeV [$W = 1078 - 2460$ MeV]
- 4-channel Chew-Mandelstam K-matrix parameterization [πN, $\pi\Delta$, ρN, ηN]
- 3 mapping variables: $g^2/4\pi$, $a[\pi^- p]$, Eth
- PWs = 30 πN {15 [I=1/2] + 15 [I=3/2]} + 4 ηN [$l < 9$]
- Prms = 99 [I=1/2] + 89 [I=3/2]

- **1st generation** ('57–'79)
  Used by CMB79 and KH84 analyses.
  10k $\pi^\pm p$ each & 1.5k CXS.
  17% data is polarized.
- **2nd generation** ('80–'06)
  SAID fits:
  13k $\pi^\pm p$ each, 3k CXS & 0.3k $\pi^- p \to \eta n$
  25% data is polarized.
  Meson Factories [LAMPF, TRIUMF, & PSI] are the main source of new measurements.
  There is no discrimination against data
- **3rd generation** (07'+)
  New data may come from
  J-PARC, HADES, EPECUR, *etc*

Reaction	Data	χ^2
$\pi^+ p \to \pi^+ p$	13,354	27,136
$\pi^- p \to \pi^- p$	11,978	22,632
$\pi^- p \to \pi^0 n$	3,115	6,068
$\pi^- p \to \eta n$	257	650
DR constraint	2,775	671
Total	31,479	57,157

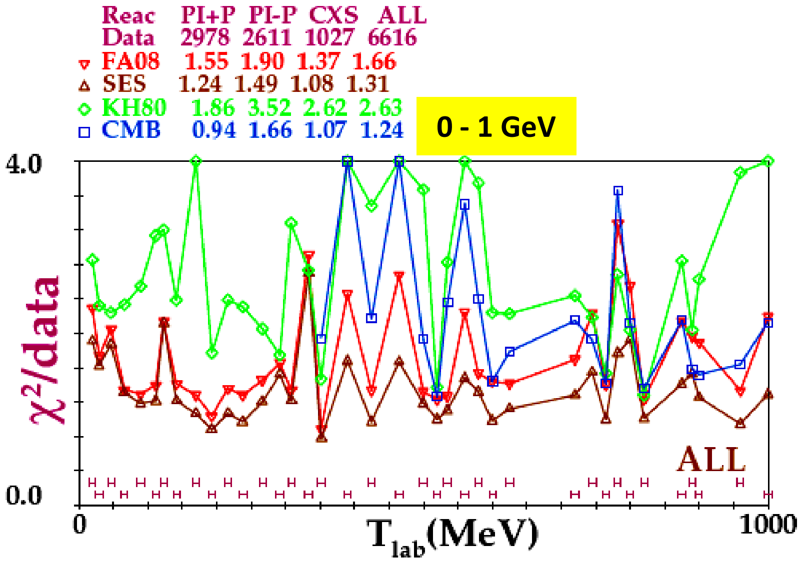
[0 – 2600 MeV] → 10 data/MeV

[550 – 800 MeV] → 1 data/MeV

27 σ^{tot} & 37 P data
above 800 MeV → 0.03 data/MeV

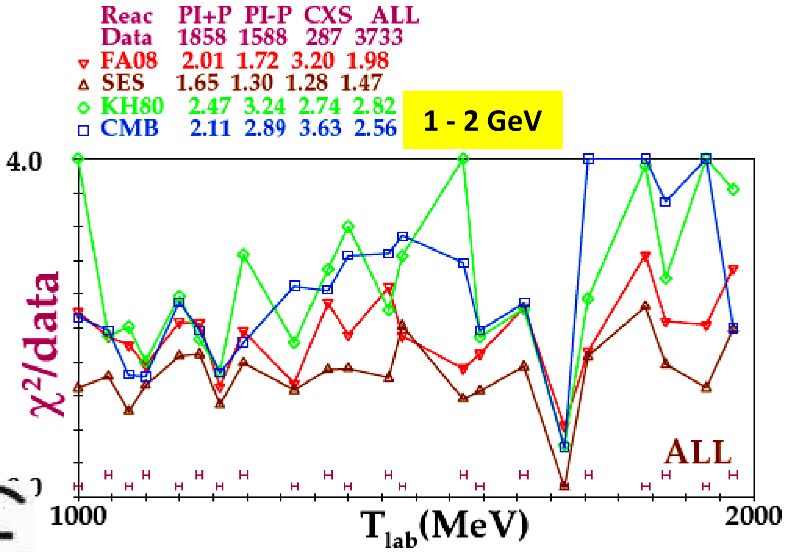
DRs have been derived from the *first principles.*

Fit to πN Elastic Scattering Data



Reac	PI+P	PI-P	CXS	ALL
Data	2978	2611	1027	6616
▽ FA08	1.55	1.90	1.37	1.66
△ SES	1.24	1.49	1.08	1.31
◇ KH80	1.86	3.52	2.62	2.63
□ CMB	0.94	1.66	1.07	1.24

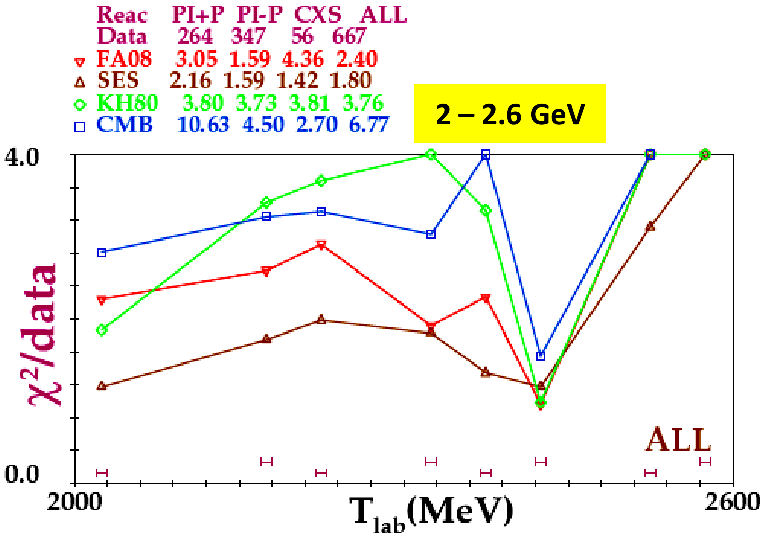
0 - 1 GeV



Reac	PI+P	PI-P	CXS	ALL
Data	1858	1588	287	3733
▽ FA08	2.01	1.72	3.20	1.98
△ SES	1.65	1.30	1.28	1.47
◇ KH80	2.47	3.24	2.74	2.82
□ CMB	2.11	2.89	3.63	2.56

1 - 2 GeV

- Some of structures in 35-year old solutions.
- [KH and CMB] are still considered as resonances.
- W > 1.5 GeV is less constrained by data.



Reac	PI+P	PI-P	CXS	ALL
Data	264	347	56	667
▽ FA08	3.05	1.59	4.36	2.40
△ SES	2.16	1.59	1.42	1.80
◇ KH80	3.80	3.73	3.81	3.76
□ CMB	10.63	4.50	2.70	6.77

2 – 2.6 GeV

New Observables

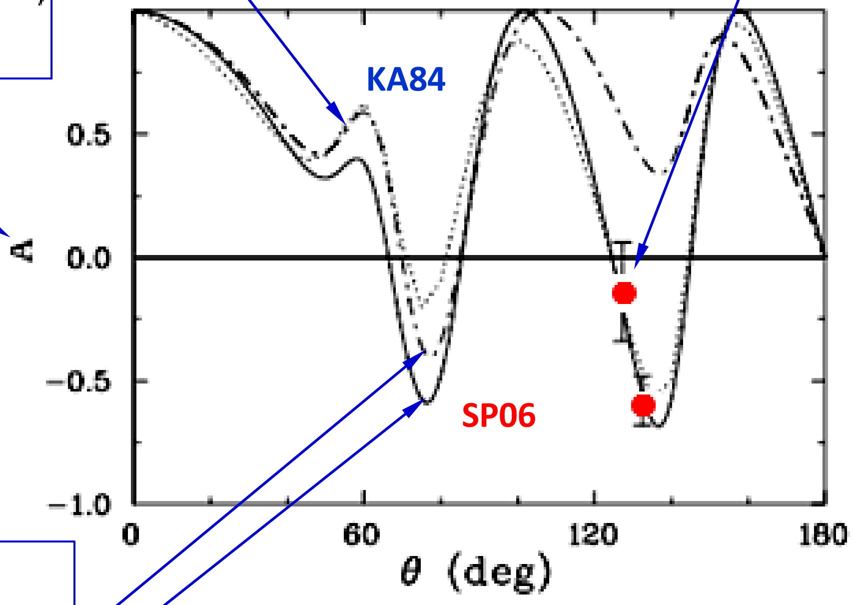
[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **74**, 045205 (2006)]

Some **Old** solutions may be not able to reproduce **New** measurements

πN scattering data:

$d\sigma/d\Omega$	(unpolarized)
P	(polarized target or recoil nucleon)
R and A	(polarized target and recoil measured)

Not Independent: $P^2 + R^2 + A^2 = 1$



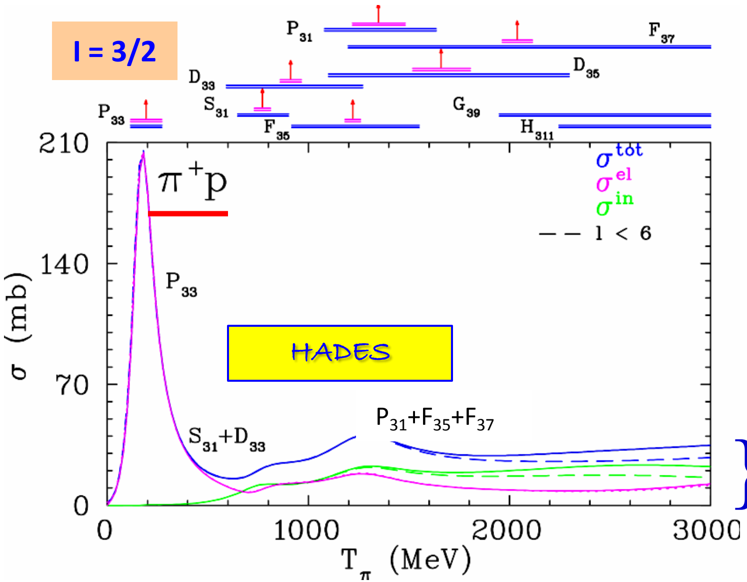
π^+p: 1300 MeV

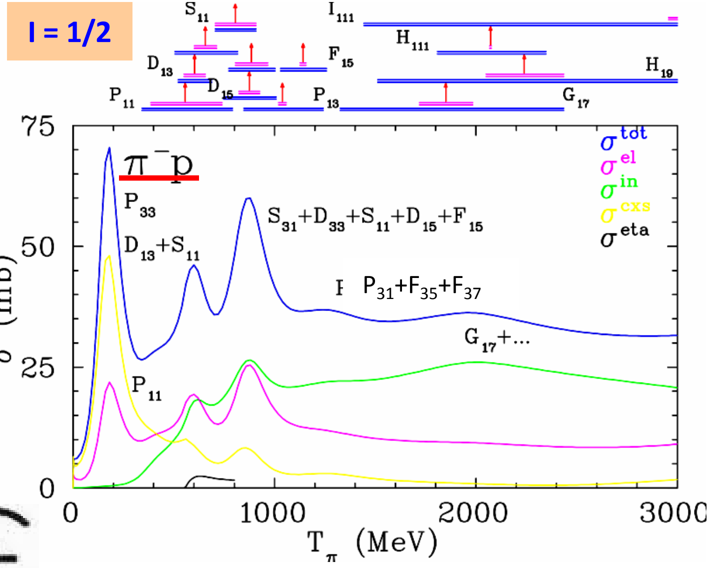
Data:
ITEP: $\pi^+p \rightarrow \pi^+p$ @ 1300 MeV
[I. Alekseev *et al* Phys Lett B 351, 585 (1995)]
PWA:
KA84: Karlsruhe-Helsinki fit, 1984
KB84: KH Barrelet corrected solution, 1997
SP06: GW fit, 2006

Polarized measurements is an important part of a hadron program

Where is a Resonance ?

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





↑ M

— Γ_{tot}

— $\Gamma_{\pi N}$

Here you are...

- **To determine Resonance parameters with SAID:**
  - Fit data to get $\mathbf{T}_{\pi\pi}$
  - Fit $\mathbf{T}_{\pi\pi}$ over narrow **W** range
    → **Pole** position
  - Then fit **DATA** over same W range
    → **BW** parameters

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

- **Assertions:**

Argand plot,	**Im(Re)**
Speed plot,	**Sp(W) = |dT/dW|**
Time-delay,	**τ = dδ/dW**
Crossover energy,	**ReA = 0**
etc	

- **Below W = 1900 MeV,**
  The highest wave contribution is small.

GW DAC Search for N^* and Δ^*

- We are considering a resonance as a Pole in the complex plane which is not far away from the physical axis.

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

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

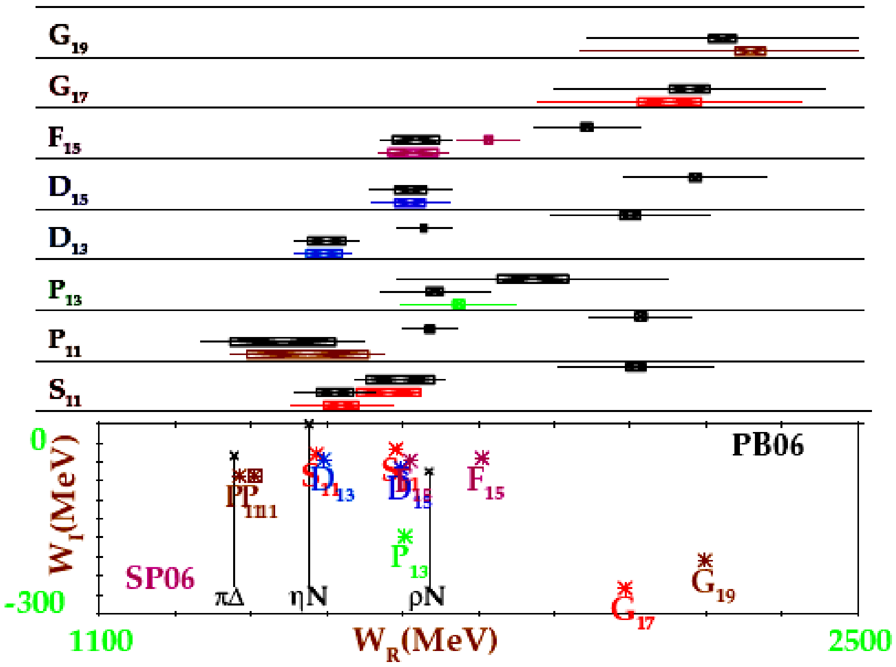
$$\Gamma = \Gamma_e + \Gamma_I \qquad \Gamma_e = \rho_e \Gamma R \qquad \Gamma_I = \rho_i \Gamma\,(1 - R)$$

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

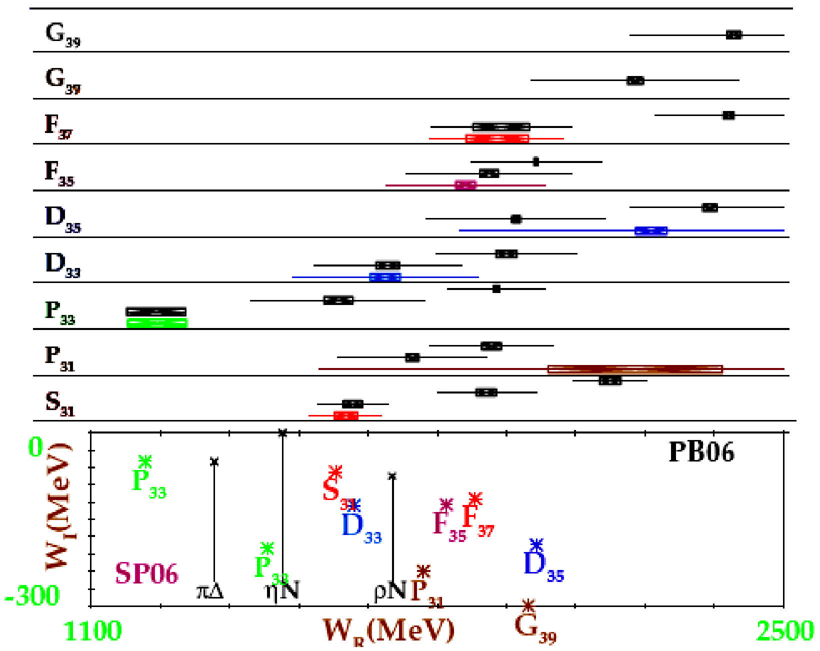
- **Map** $\chi^2[W_R,\Gamma]$ while searching all other PW parameters
  Look for significant improvement
- **Subjective variables are**
  - Energy binning
  - Strength of constraints
  - Which PW to be searched
- **Standard PWA**
  - Tends (by construction) to miss narrow Resonances with $\Gamma < 30$ MeV
  - Reveals only wide Resonances, but not too wide [$\Gamma < 500$ MeV]
    and possessing not too small BR [BR > 0.04]
- **Modified PWA**
  - Allows to put a resonance by hands with subsequent refitting the data
    Then the search will allow to see how reliable/tolerable it is

Complex Energy Plane vs BW fits

I = 1/2



I = 3/2



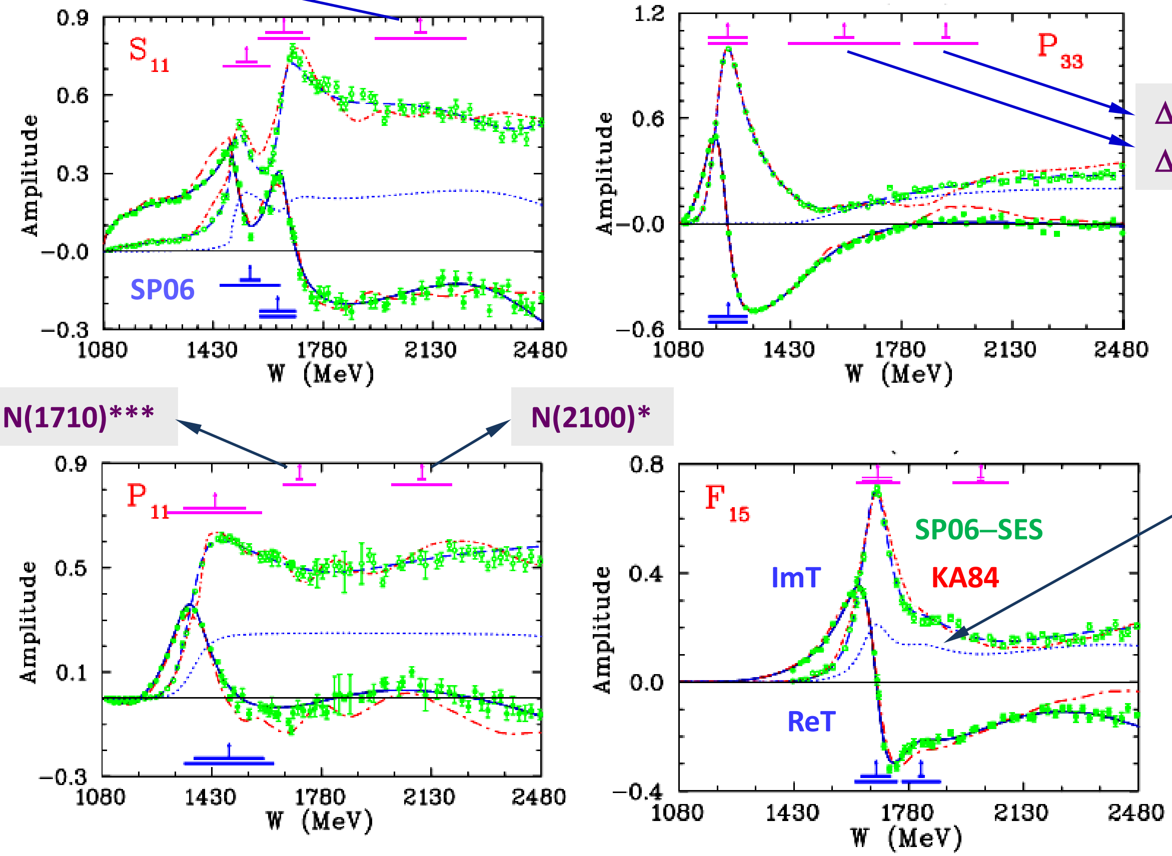
- There are shifts between **Pole** and **BW** prms.

M = ReW$_p$
Γ = 2*ImW$_p$

Partial Waves [$L_{(2I)(2J)}$]

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

Overall: the difference between KA'84 and GW'08 is rather small but… resonances may be essentially different



N(2090)*

Δ(1920)***

Δ(1600)***

N(1710)***

N(2100)*

1964: 1.2k data below 700 MeV
2012: 32k data below 2600 MeV

ImT-T*T ≥ 0 [unitarity boundary]

There are several SESs which one can possible to consider as samples of complete experiments.

Pion PhotoProduction complete experiments are under the consideration now.

PDG12 [J. Beringer *et al* [PDG] J Phys D 86, 010001 (2012)]
KA84 [R. Koch, Z Phys C 29, 597 (1985)]

$\mathcal{N}(1440)1/2^+$

Courtesy of Donna Arndt, 2010

N(1440)**** – What is Known

[J. Beringer *et al* [PDG] Phys Rev D **86**, 010001 (2012)]

Two-faced Janus
Roman God of Gates & Doors

- **Dick Arndt:** *``This is one of mysterious Resonances”*

PWA-Pole Ref	Re(MeV)	−2xIm(MeV)	
BnGa12	1370 ± 4	190 ± 7	
SAID-SP06	1359	164	1st Riemann sheet
	1388	166	2nd Riemann sheet
KH93	1385	164	
CMU80	1375 ± 30	180 ± 40	

PWA-BW Ref	Mass(MeV)	Width(MeV)	BR
BnGa12	1430 ± 8	365 ± 35	0.62 ± 0.03
SAID-SP06	1485 ± 1.2	284 ± 18	0.787 ± 0.016
KSU92	1462 ± 10	391 ± 34	0.69 ± 0.03
CMU80	1440 ± 30	340 ± 70	0.68 ± 0.04
KH79	1410 ± 12	135 ± 10	0.51 ± 0.05

$$f(E) = \frac{k}{\left(E^2 - M^2\right)^2 + M^2\Gamma^2}$$

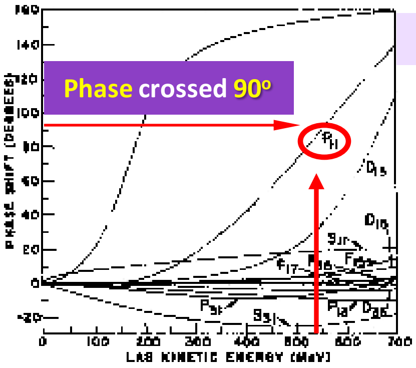
$M = \mathrm{Re}W_p$
$\Gamma = 2*\mathrm{Im}W_p$

Discovery and First Direct Measurements of N(1440)

- **Just after the N(1440) discovery via πN PWA.**
  [L.D. Roper, *Phys Rev Lett* **12**, 340 (1964)]
- **Several direct searches got a signal.**
  [R.B. Bell *et al* Phys Rev Lett **20**, 164 (1968)]

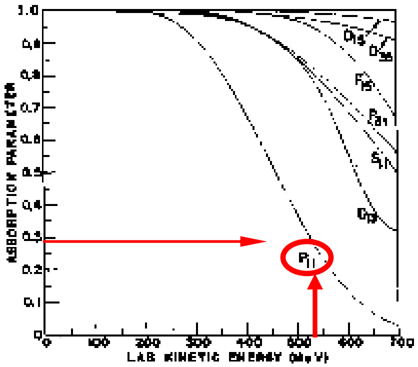
BROOKHAVEN NATIONAL LABORATORY

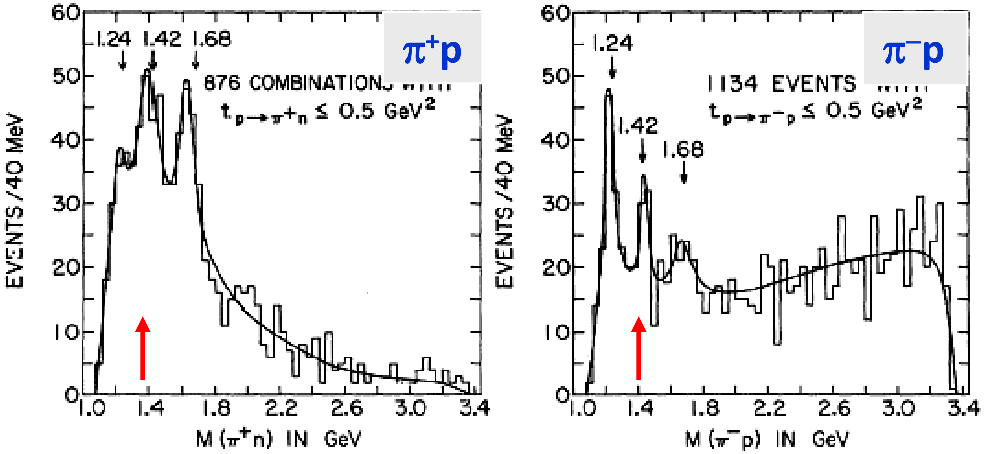
- **BNL-LHBC:** $\pi^{\pm}p$ at 6 GeV/c



Phase crossed 90°

M = 1485 MeV





M = 1405±30 MeV Γ = 100 MeV
Significance[$N_s/\sqrt{(N_b+N_s)}$] = 3.1 σ

M = 1436±20 MeV Γ = 50 MeV
Significance[$N_s/\sqrt{(N_b+N_s)}$] = 2.8 σ

Courtesy of Cole Smith, June 2005

- **Both BNL masses are less than M = 1485 MeV determined originally via πN PWA and by SP06 BW**

Complex Energy Plane for P_{11}

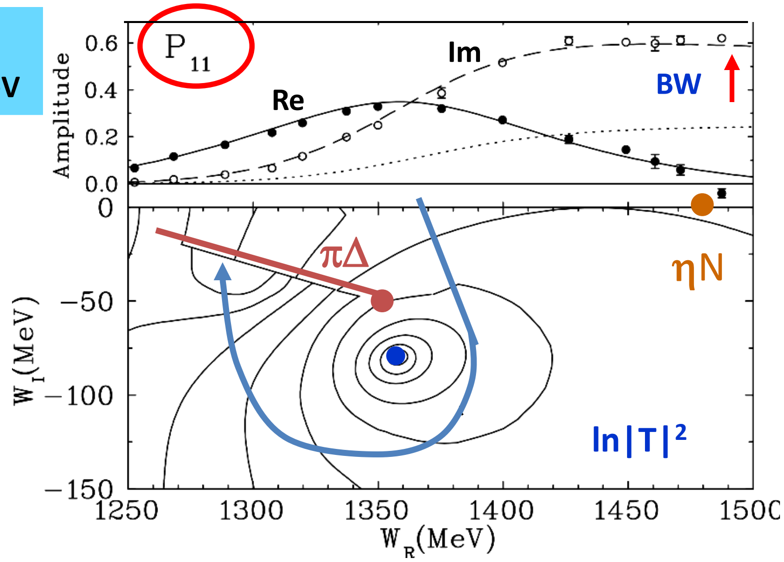
[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **74**, 045205 (2006)]

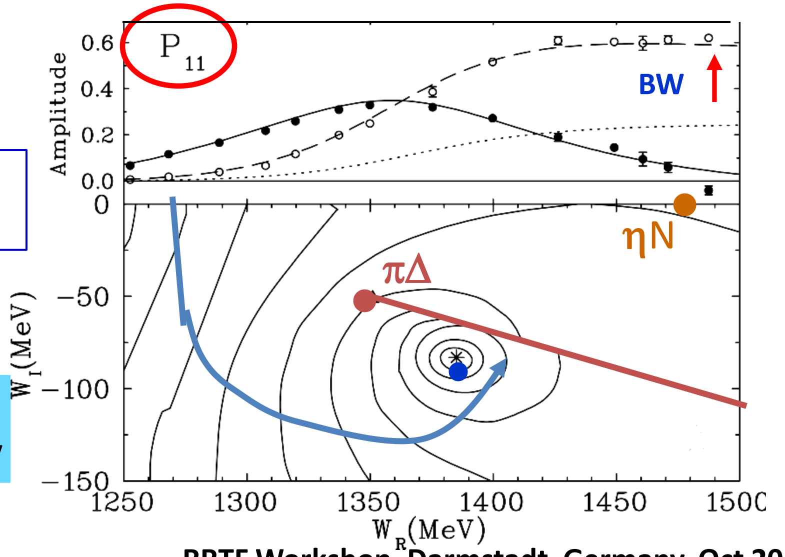
- 1st Riemann sheet
  Pole 1: W_p = 1359–i82 MeV

- There is a shift between Pole positions at two sheets, due to a non-zero jump on the πΔ-cut

M = ReW_p
Γ = 2*ImW_p

- 2nd Riemann sheet
  Pole 2: W_p = 1388–i83 MeV





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

Branch-points:
- πΔ thr [W = 1350 - i50 MeV]
- ηN thr [W = 1487 - i0 MeV]
- πΔ Branch Cut is two-body and has 2 Riemann sheets

- Sheet 1 is the sheet reached most directly the real axis
- Sheet 2 is behind the πΔ Branch Cut

- N(1440) is a Resonance which manifests itself via 2 Poles at 2 different Riemann sheets (with respect to the πΔ cut)

- Due to nearby πΔ Branch Point, both poles are not far from physical region

- Simple BW is not adequate to such a complex structure [2 Poles & 2 Branch-Points πΔ & ηN]

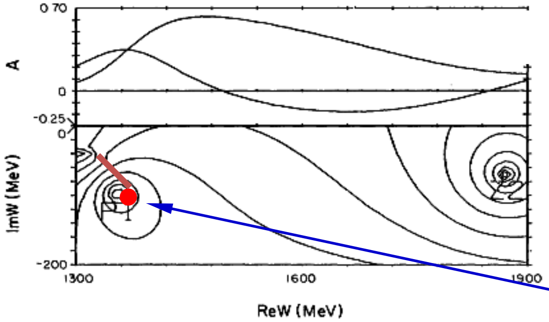
Two *Pole* Observation

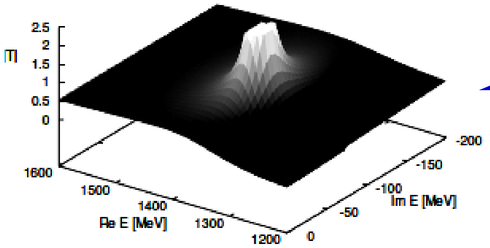
PHYSICAL REVIEW D VOLUME 32, NUMBER 5 1 SEPTEMBER 1985

Pion-nucleon partial-wave analysis to 1100 MeV

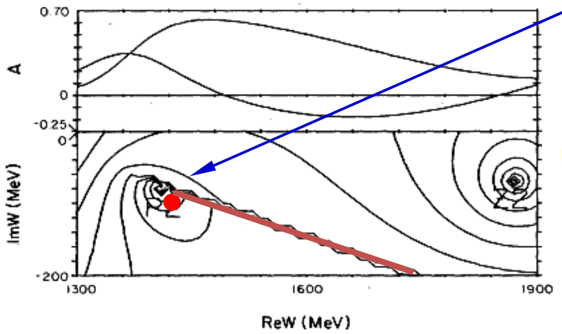
Richard A. Arndt, John M. Ford,* and L. David Roper
Department of Physics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia

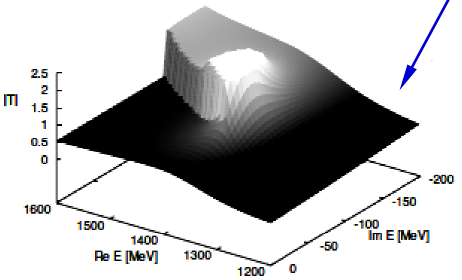
(Received 24 January 1985)





Pole 1: W = 1359–i100 MeV
Pole 2: W = 1410– i80 MeV





- [R.E. Cutkosky & S. Wang, Phys Rev D **42**, 235 (1990)]

Pole 1: W = 1370–i114 MeV
Pole 2: W = 1360–i120 MeV

- **SAID PWA:**
  [R. Arndt *et al*
  Chinese Phys C **33**, 1063 (2009)]

Pole 1: W_p = 1359–i82 MeV
Pole 2: W_p = 1388–i83 MeV

- **Juelich Model:**
  [M. Doering *et al* Nucl Phys **A829**, 170 (2009)]

Pole 1: W = 1387–i73 MeV
Pole 2: W = 1387–i71 MeV

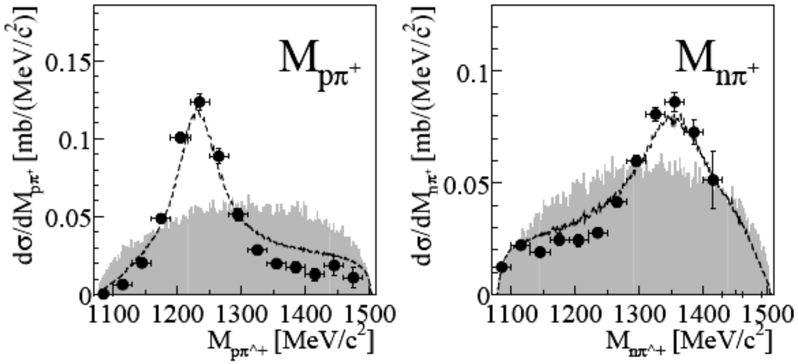
- **JLab ANL-Osaka (EBAC) Model:**
  [H. Kamano *et al* Phys Rev C **81**, 065207 (2010)]

Pole 1: W = 1357– i76 MeV
Pole 2: W = 1364–i105 MeV

Direct Measurements of N(1440): Hadronic Probes

- **CELSIUS-WASA: $pp \to n p \pi^+$**

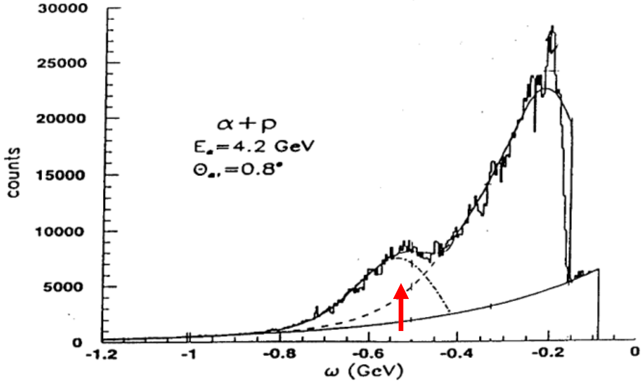
[T. Skorodko *et al* Eur Phys J A **61**, 168 (2009)]



M=1360 MeV **Γ = 150 MeV**	- **Looks similar to Pole at 1st sheet in GW πN**

- **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±20 MeV **Γ= 190±30 MeV**	- **Looks similar to Pole at 2nd sheet in GW πN**

[S. Hirenzaki *et al*. Phys. Rev. C **53**, 277 (1996)]

M=1430 MeV
Γ= 300 MeV

- **All Masses in Direct Measurements are smaller than BW and close to GW πN Pole positions.**

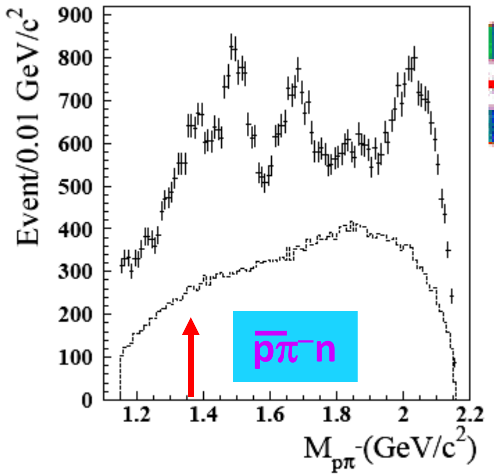
- **SATURNE II: $\alpha p \to \alpha' p \pi\pi$**

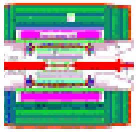
[G.D. Alkhasov *et al* Phys Rev C **78**, 025205 (2008)]

Difficulties in N(1440) description do not allow to make a conclusive treatment.

Direct Measurements of N(1440): EM Probes

- Relative contributions of various singularities may be different in different processes





- **BES II: $e^+e^- \to J/\psi \to \bar{p}\pi^-n + p\pi^+\bar{n}$**

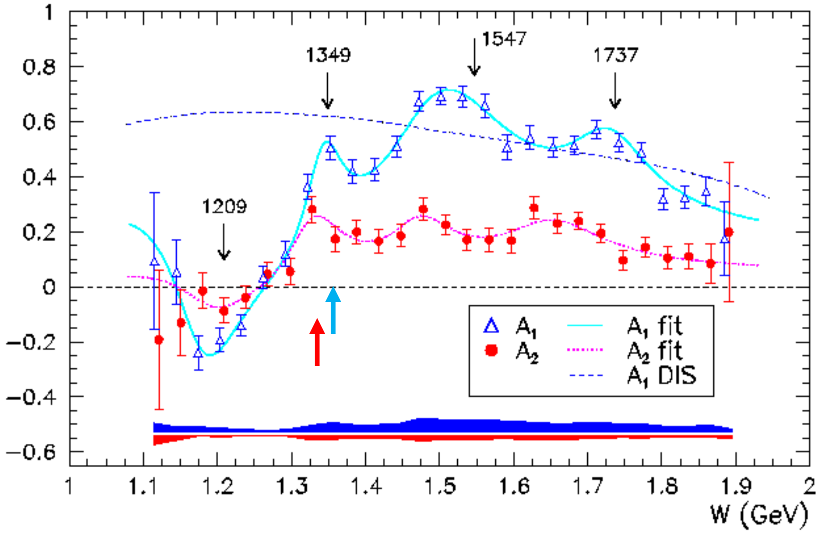
[M. Ablikim *et al* (BES Collaboration)
Phys Rev Lett **97,** 062001 (2006)]

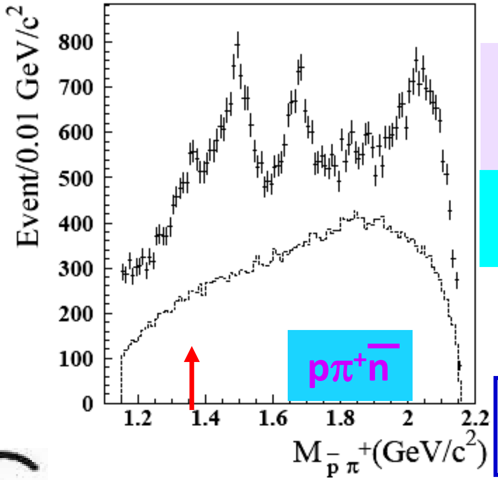
- **JLab-RSS: $ep \to e'X$**

[F.R. Wesselmann *et al*
Phys Rev Lett **98,** 132003 (2007)]

Virtual Photon Asymmetries:

$$A_1 = \frac{1}{(E-E')}\left((E-E'\cos\theta)A_\parallel - \frac{E'\sin\theta}{\cos\phi}A_\perp\right) \qquad A_2 = \frac{\sqrt{Q^2}}{2E}\left(A_\parallel - \frac{E-E'\cos\theta}{E'\sin\theta\cos\phi}A_\perp\right)$$





PWA: $J^P=1/2^+$

M=1358± 6±16 MeV
Γ= 179±26±50 MeV

- **Looks similar to Pole at 1st sheet in GW πN**

$M = \mathrm{Re}W_p$
$\Gamma = 2*\mathrm{Im}W_p$

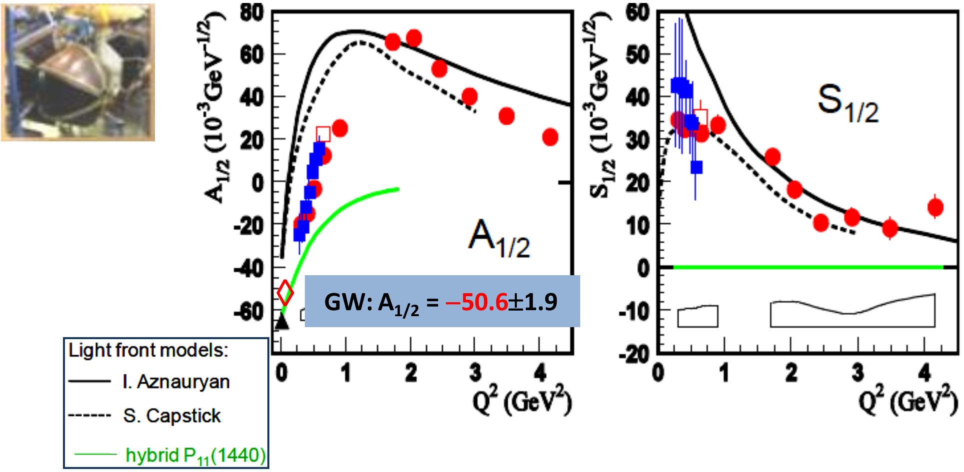
- **Evidence for two poles ?**

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

N(1440) Puzzle for Jlab CLAS12

- 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 PWA 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



GW: $A_{1/2} = -50.6\pm1.9$

- The analysis of the recent CLAS Single and Double π^+ Electro Prod 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
  [1π: I.G. Aznauryan *et al* Phys Rev C 80, 055203 (2009)
  2π: V. Mokeev, PC 2010]

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

- 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 JLab CLAS12**

Status of Non-strange Resonances

J. Beringer *et al* (PDG) Phys Rev D **86**, 010001 (2012)

- More than half of states have poor evidence.
- Most of states need more work to do.
- Most of QCD models predict more states than observed.
- Where are missing resonances?

GW SAID Contribution

I = 1/2

Particle J^P	Status overall	πN	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
N $1/2^+$	****									
$N(1440)$ $1/2^+$	****	****	****		***				*	***
$N(1520)$ $3/2^-$	****	****	****	***					***	***
$N(1535)$ $1/2^-$	****	****	****	****					**	*
$N(1650)$ $1/2^-$	****	****	***	***			***	**	**	***
$N(1675)$ $5/2^-$	****	****	***	*			*		*	***
$N(1680)$ $5/2^+$	****	****	****	*	**				***	***
$N(1685)$??	*									
$N(1700)$ $3/2^-$	***	***	**	*			*	*	*	***
$N(1710)$ $1/2^+$	***	***	***	***		**	***	**	*	**
$N(1720)$ $3/2^+$	****	****	***	***			**	**	**	*
$N(1860)$ $5/2^+$	**	**							*	*
$N(1875)$ $3/2^-$	***	*	***			**	***	**		***
$N(1880)$ $1/2^+$	**	*	*		**		*			
$N(1895)$ $1/2^-$	**	*	**	**			**	*		
$N(1900)$ $3/2^+$	***	**	***	**		**	***	**	*	**
$N(1990)$ $7/2^+$	**	**	**					*		
$N(2000)$ $5/2^+$	**	*	**	**			**	*	**	
$N(2040)$ $3/2^+$	*									
$N(2060)$ $5/2^-$	**	**	**	*				**		
$N(2100)$ $1/2^+$	*									
$N(2150)$ $3/2^-$	**	**	**				**			**
$N(2190)$ $7/2^-$	****	****	***				**		*	
$N(2220)$ $9/2^+$	****	****								
$N(2250)$ $9/2^-$	****	****								
$N(2600)$ $11/2^-$	***	***								
$N(2700)$ $13/2^+$	[illegible]	**								

26 N*
11 ****
5 ***
7 **
3 *

I = 3/2

Particle J^P	Status overall	πN	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
$\Delta(1232)$ $3/2^+$	****	****	****	F						
$\Delta(1600)$ $3/2^+$	***	***	***	o					*	***
$\Delta(1620)$ $1/2^-$	****	****	***		r				***	***
$\Delta(1700)$ $3/2^-$	****	****	****		b				**	***
$\Delta(1750)$ $1/2^+$	*	*			i					
$\Delta(1900)$ $1/2^-$	**	**	**			d		**	**	**
$\Delta(1905)$ $5/2^+$	****	****	****			d		***	**	**
$\Delta(1910)$ $1/2^+$	****	****	**			e		*	*	**
$\Delta(1920)$ $3/2^+$	***	***	**				n	***		**
$\Delta(1930)$ $5/2^-$	***	***								
$\Delta(1940)$ $3/2^-$	**	*	**	F				(seen	in	$\Delta\eta$)
$\Delta(1950)$ $7/2^+$	****	****	****	o				***	*	***
$\Delta(2000)$ $5/2^+$	**				r					**
$\Delta(2150)$ $1/2^-$	*	*			b					
$\Delta(2200)$ $7/2^-$	*	*			i					
$\Delta(2300)$ $9/2^+$	**	**				d				
$\Delta(2350)$ $5/2^-$	*	*				d				
$\Delta(2390)$ $7/2^+$	*	*				e				
$\Delta(2400)$ $9/2^-$	**	**					n			
$\Delta(2420)$ $11/2^+$	****	****								
$\Delta(2750)$ $13/2^-$	**	**								
$\Delta(2950)$ $15/2^+$	[illegible]	**								

22 Δ*
7 ****
3 ***
7 **
5 *

BnGa Additional States

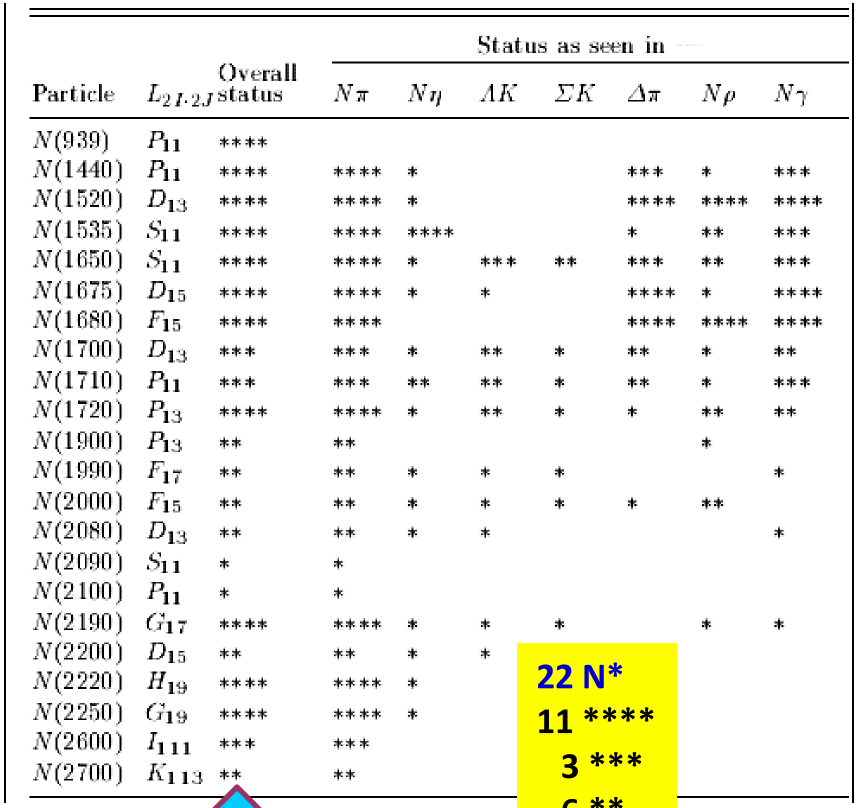
The latest GWU analysis (ARNDT 06) finds no evidence for this resonance.

Status of Non-strange Resonances

Twenty Years Ago – Rosenfeld Tables

L. Montanet *et al* (PDG) Phys Rev D **50**, 1173 (1994)

I = 1/2



			Status as seen in —						
Particle	$L_{2I\cdot 2J}$	Overall status	$N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
$N(939)$	P_{11}	****							
$N(1440)$	P_{11}	****	****	*			***	*	***
$N(1520)$	D_{13}	****	****	*			****	****	****
$N(1535)$	S_{11}	****	****	****			*	**	***
$N(1650)$	S_{11}	****	****	*	***	**	***	**	***
$N(1675)$	D_{15}	****	****	*	*		****	*	****
$N(1680)$	F_{15}	****	****				****	****	****
$N(1700)$	D_{13}	***	***	*	**	*	**	*	**
$N(1710)$	P_{11}	***	***	**	**	*	**	*	***
$N(1720)$	P_{13}	****	****	*	**	*	*	**	**
$N(1900)$	P_{13}	**	**					*	
$N(1990)$	F_{17}	**	**	*	*	*			*
$N(2000)$	F_{15}	**	**	*	*	*	*	**	
$N(2080)$	D_{13}	**	**	*	*				*
$N(2090)$	S_{11}	*	*						
$N(2100)$	P_{11}	*	*						
$N(2190)$	G_{17}	****	****	*	*	*		*	*
$N(2200)$	D_{15}	**	**	*	*				
$N(2220)$	H_{19}	****	****	*					
$N(2250)$	G_{19}	****	****	*					
$N(2600)$	$I_{1\,11}$	***	***						
$N(2700)$	$K_{1\,13}$	**	**						

22 N*

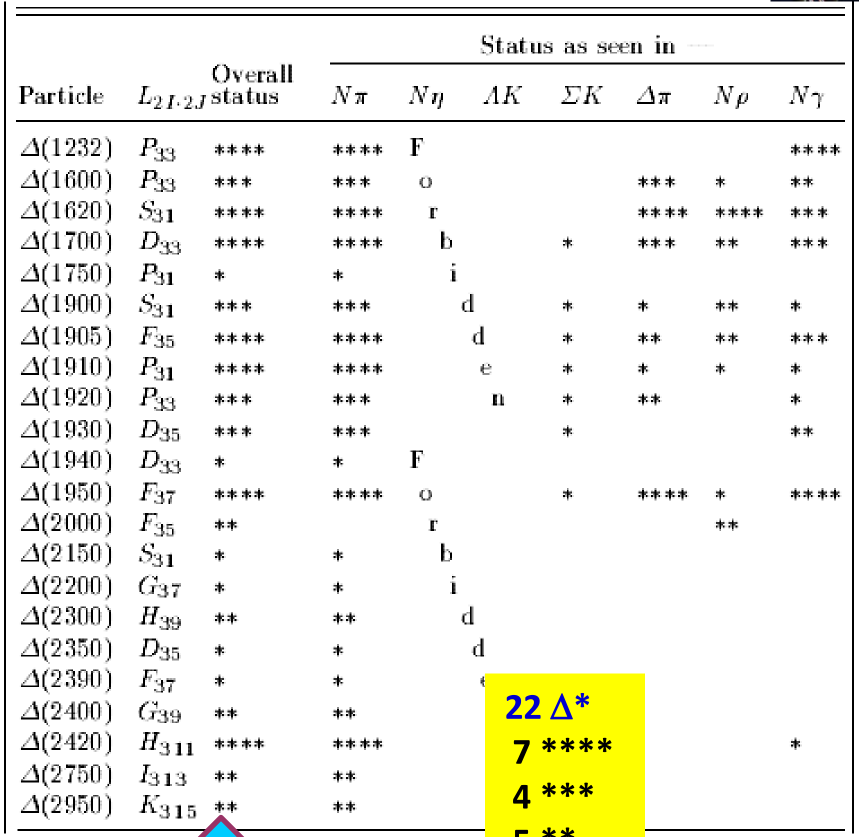
11 **
**

3 ***

6 **

2 *

I = 3/2



			Status as seen in —						
Particle	$L_{2I\cdot 2J}$	Overall status	$N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
$\Delta(1232)$	P_{33}	****	****	F					****
$\Delta(1600)$	P_{33}	***	***	o			***	*	**
$\Delta(1620)$	S_{31}	****	****	r			****	****	***
$\Delta(1700)$	D_{33}	****	****	b		*	***	**	***
$\Delta(1750)$	P_{31}	*	*	i					
$\Delta(1900)$	S_{31}	***	***	d		*	*	**	*
$\Delta(1905)$	F_{35}	****	****	d		*	**	**	***
$\Delta(1910)$	P_{31}	****	****	e		*	*	*	*
$\Delta(1920)$	P_{33}	***	***	n		*	**		*
$\Delta(1930)$	D_{35}	***	***			*			**
$\Delta(1940)$	D_{33}	*	*	F					
$\Delta(1950)$	F_{37}	****	****	o		*	****	*	****
$\Delta(2000)$	F_{35}	**		r				**	
$\Delta(2150)$	S_{31}	*	*	b					
$\Delta(2200)$	G_{37}	*	*	i					
$\Delta(2300)$	H_{39}	**	**	d					
$\Delta(2350)$	D_{35}	*	*	d					
$\Delta(2390)$	F_{37}	*	*						
$\Delta(2400)$	G_{39}	**	**						
$\Delta(2420)$	$H_{3\,11}$	****	****						*
$\Delta(2750)$	$I_{3\,13}$	**	**						
$\Delta(2950)$	$K_{3\,15}$	**	**						

22 Δ*

7 **
**

4 ***

5 **

6 *

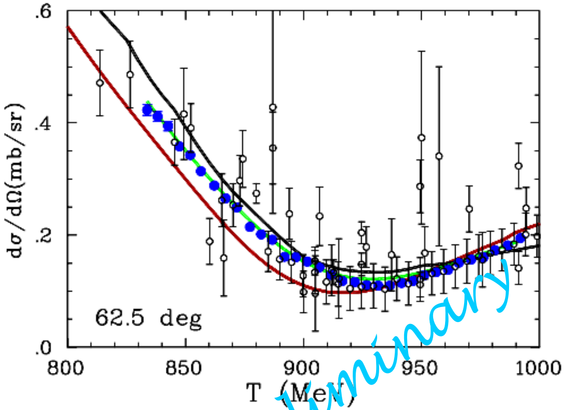
ITEP for $\pi^{\mp} p \rightarrow \pi^{\mp} p$ *&* $\pi^{-} p \rightarrow K^{0} \Lambda$

[I.G. Alekseev *ea* arXiv: 1204.6433]

- **Precise cross section measurements**:

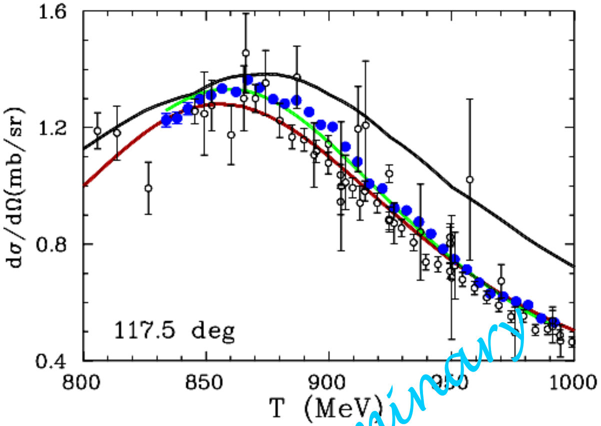
$\pi p \rightarrow \pi p$: $d\sigma/d\Omega$ – **0.5%** statistical precision and 1 MeV momentum step

$\pi^{-} p \rightarrow K^{0} \Lambda$: σ_{REAC} – **15 %** statistical precision and the same mom step



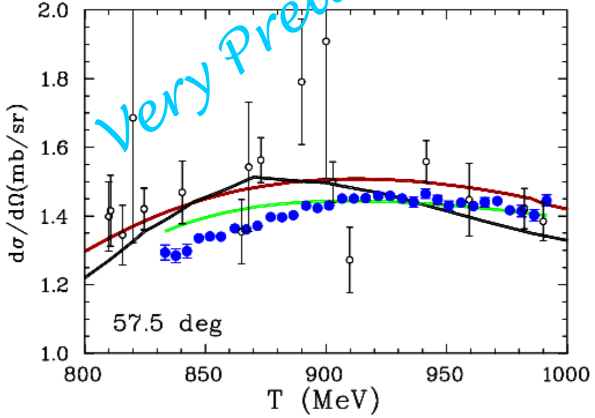
o EPECUR
Tπ= 834–992 MeV
θ= 48–117 deg

o Previous [available in Hoehler's time]:
± 2.5 deg or
± 2 MeV



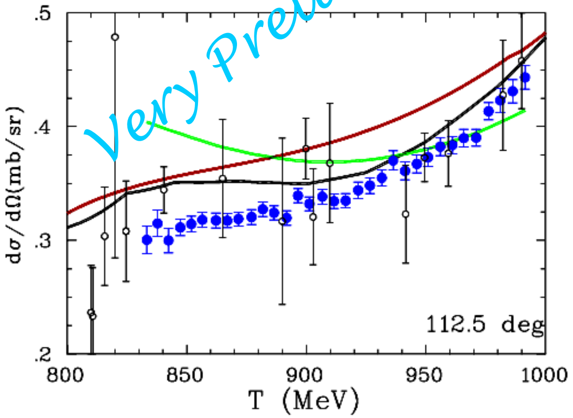
$\pi^{-} p \rightarrow \pi^{-} p$

	Wi08	KA84
χ^2/dp=	6090/495	36394/495



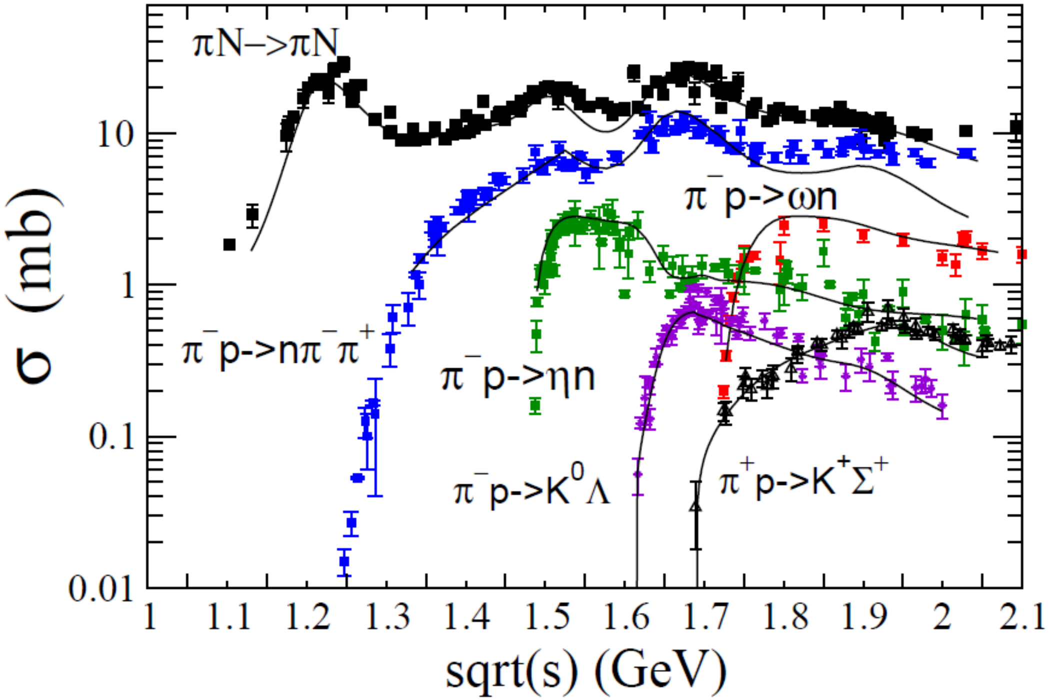
$\pi^{+} p \rightarrow \pi^{+} p$

	Wi08	KA84
χ^2/dp=	4748/528	2387/528 11980/528



GW-Wi08 }
KH-KA84 } EPECUR data are out of the fit
Gridnev12 EPECUR data are in the fit No norm

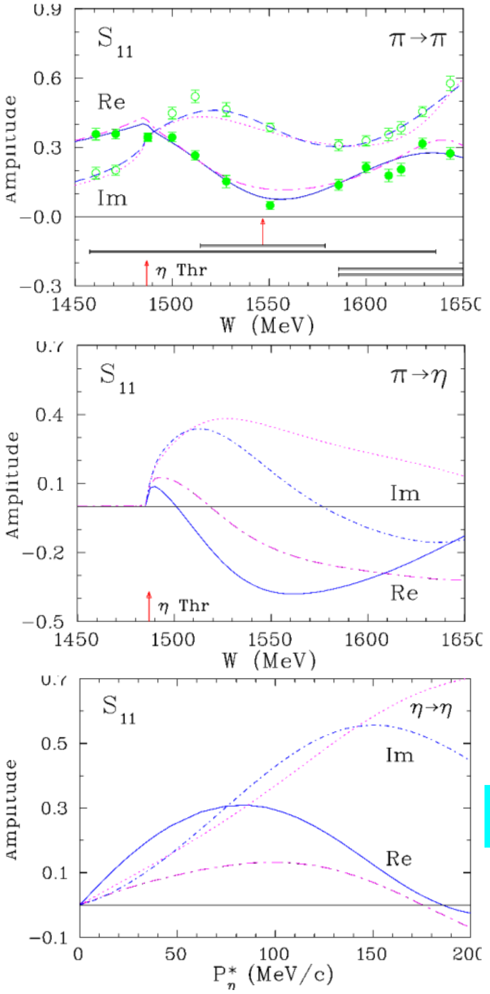
πN inElastic Scattering



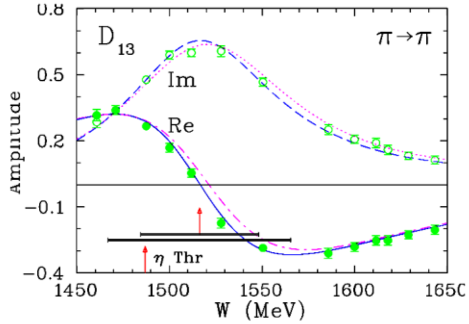
Courtesy of Vitaly Shklyar, Spring 2013

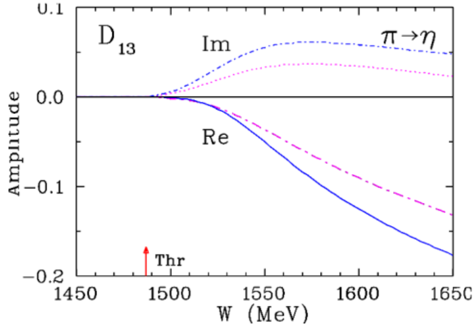
Coupled Channel Fit for S_{11} & D_{13}: ηn BRs

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



- Limited energy range limits possibilities to determine resonance parameters





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

N(1520)D_{13}: Γ_η/Γ = 0.0008 – 0.0016

D_{13} [Mainz (γ, η)]: Γ_η/Γ = 0.0008±0.0001

D_{13} [Giessen, multi-ch]: Γ_η/Γ = 0.0023±0.0004

[G. Penner and U. Mosel, Phys Rev C 66, 055211 (2002)
L. Tiator *et al* Phys Rev C 60, 035210 (1999)]

No E913/914 BNL thr data

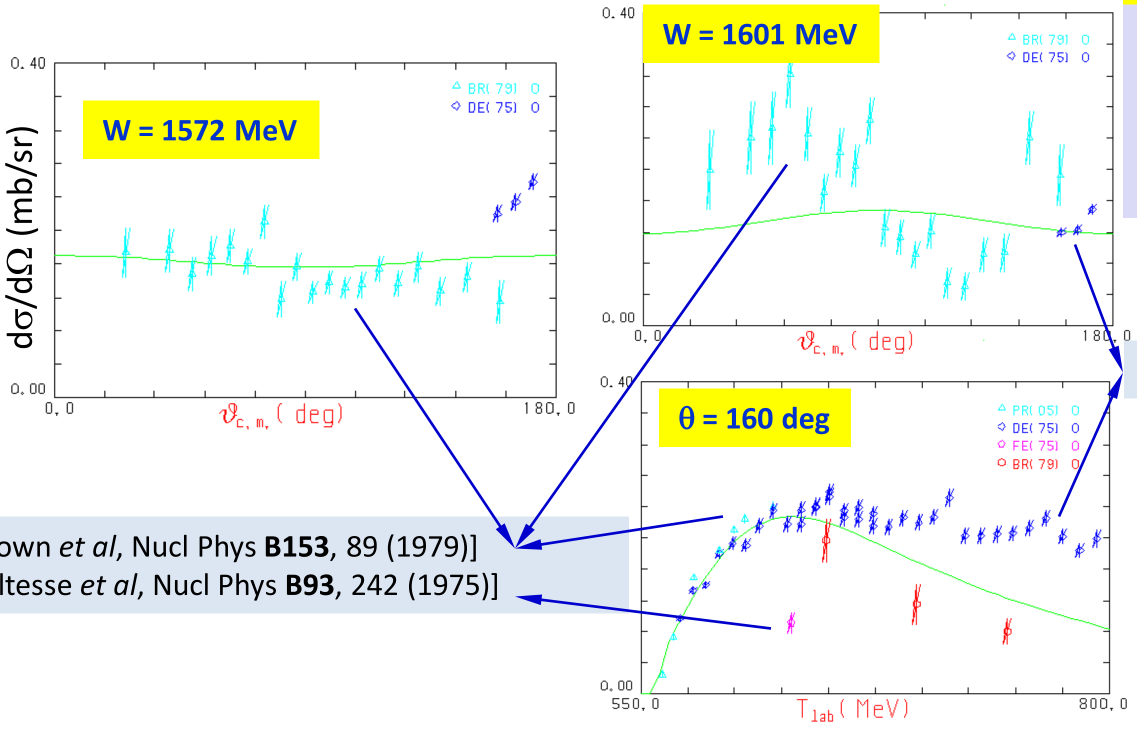
Added E913/914 BNL thr data

[S. Prakhov *et al* Phys Rev C 72, 015203 (2005)]

$\pi^- p \rightarrow \eta n$ Puzzle

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

- **Several groups evaluated $\pi^- p \rightarrow \eta n$ data**
  - Cutkosky *et al* Phys Rev D **20**, 2804 (1979)
  - Koch & Pietarinen, Nucl Phys **A336**, 331 (1980)
  - Wighman *et al* Phys Rev D **38**, 3365 (1988)
  - Clajus & Nefkens, πN News Lett **7**, 76 (1992)
  - Arndt *et al* Phys Rev C **74**, 045205 (2006)



[Debenham *et al*, Phys Rev D **12**, 2545 (1975)]

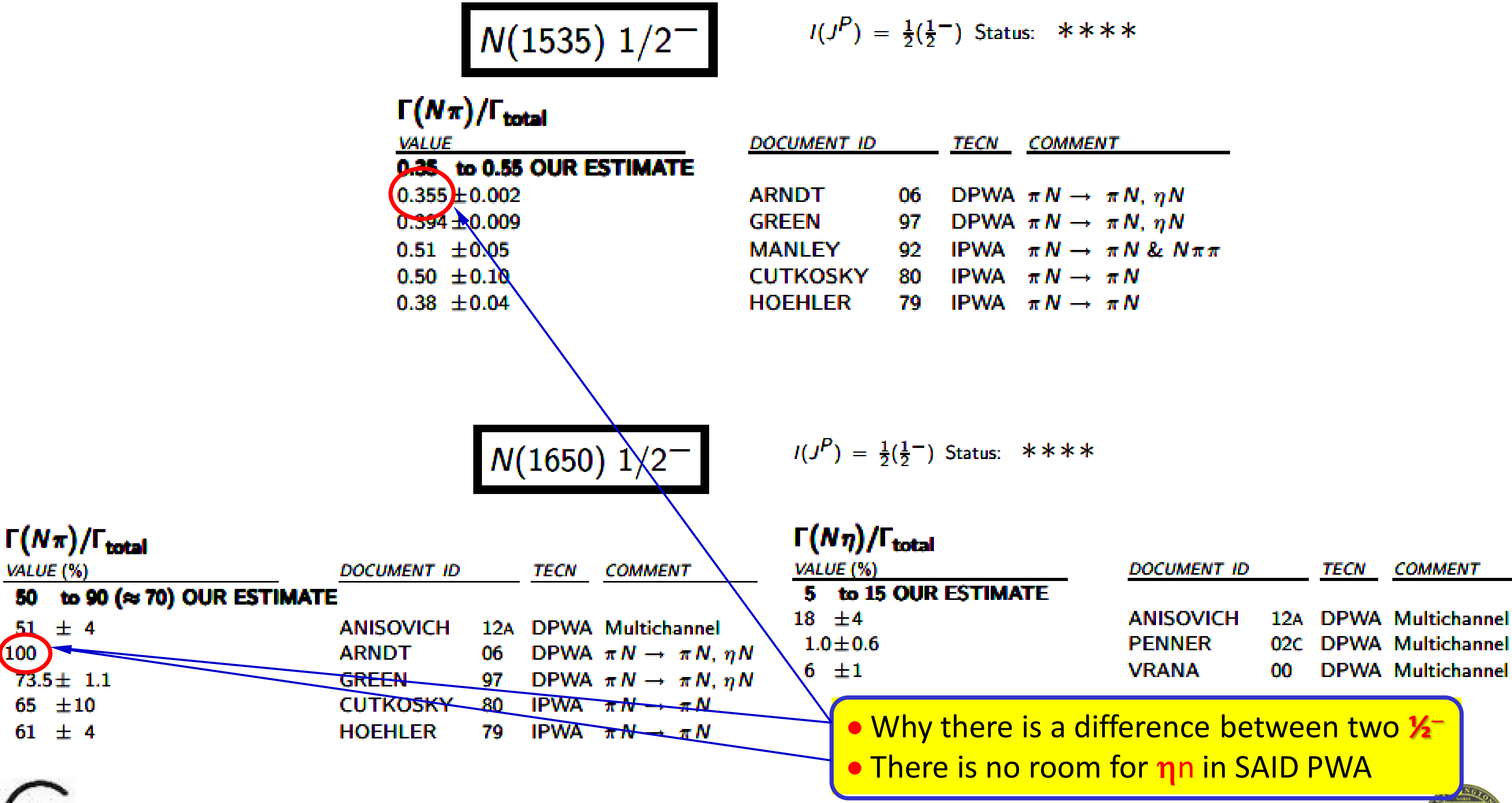
[Brown *et al*, Nucl Phys **B153**, 89 (1979)]
[Feltesse *et al*, Nucl Phys **B93**, 242 (1975)]

was the 7 GeV proton synchrotron operating in the Rutherford Appleton Laboratory in UK between **1964** and **1978**

- Most of **Nimrod** data do not satisfy requirements [systematics (10% or more), momentum err (up to 50 MeV/c), and so on]
- For that reason, **SAID** is not able to use them in $\pi^- p \rightarrow \pi^- p$, $\pi^0 n$, & ηn PWAs

$\pi^- p \rightarrow \eta n$ Puzzle

[R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **74**, 045205 (2006)]
[R. Arndt, W. Briscoe, IS, R. Workman, A. Gridnev, Phys Rev C **72**, 045202 (2005)]



$N(1535)\ 1/2^-$

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ Status: ∗∗∗∗

$\Gamma(N\pi)/\Gamma_{\text{total}}$

VALUE	DOCUMENT ID		TECN	COMMENT
0.35 to 0.55 OUR ESTIMATE				
0.355 ±0.002	ARNDT	06	DPWA	$\pi N \rightarrow \pi N, \eta N$
0.394 ±0.009	GREEN	97	DPWA	$\pi N \rightarrow \pi N, \eta N$
0.51 ±0.05	MANLEY	92	IPWA	$\pi N \rightarrow \pi N$ & $N\pi\pi$
0.50 ±0.10	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
0.38 ±0.04	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$

$N(1650)\ 1/2^-$

$I(J^P) = \frac{1}{2}(\frac{1}{2}^-)$ Status: ∗∗∗∗

$\Gamma(N\pi)/\Gamma_{\text{total}}$

VALUE (%)	DOCUMENT ID		TECN	COMMENT
50 to 90 (≈ 70) OUR ESTIMATE				
51 ± 4	ANISOVICH	12A	DPWA	Multichannel
100	ARNDT	06	DPWA	$\pi N \rightarrow \pi N, \eta N$
73.5± 1.1	GREEN	97	DPWA	$\pi N \rightarrow \pi N, \eta N$
65 ±10	CUTKOSKY	80	IPWA	$\pi N \rightarrow \pi N$
61 ± 4	HOEHLER	79	IPWA	$\pi N \rightarrow \pi N$

$\Gamma(N\eta)/\Gamma_{\text{total}}$

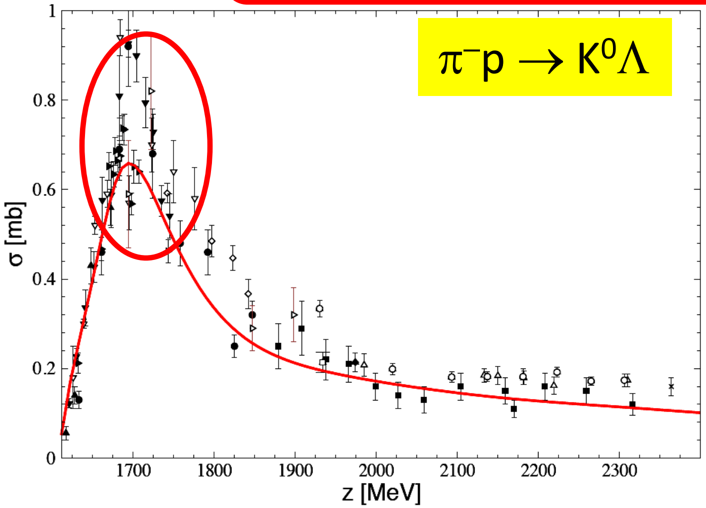
VALUE (%)	DOCUMENT ID		TECN	COMMENT
5 to 15 OUR ESTIMATE				
18 ±4	ANISOVICH	12A	DPWA	Multichannel
1.0±0.6	PENNER	02C	DPWA	Multichannel
6 ±1	VRANA	00	DPWA	Multichannel

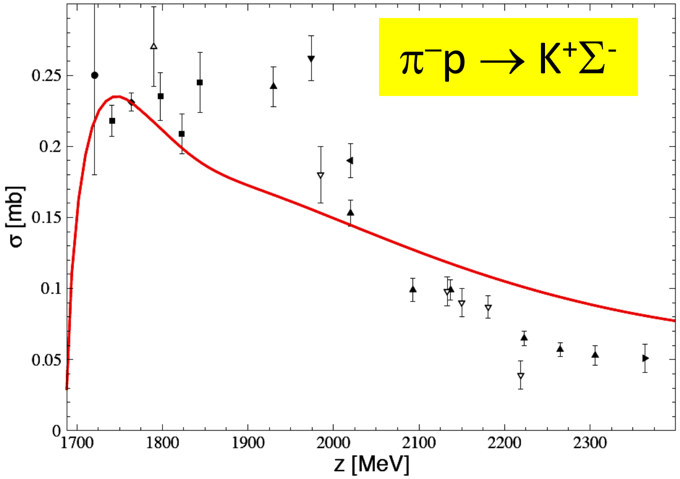
- Why there is a difference between two ½⁻
- There is no room for ηn in SAID PWA

$\pi N \rightarrow KY$ Puzzle

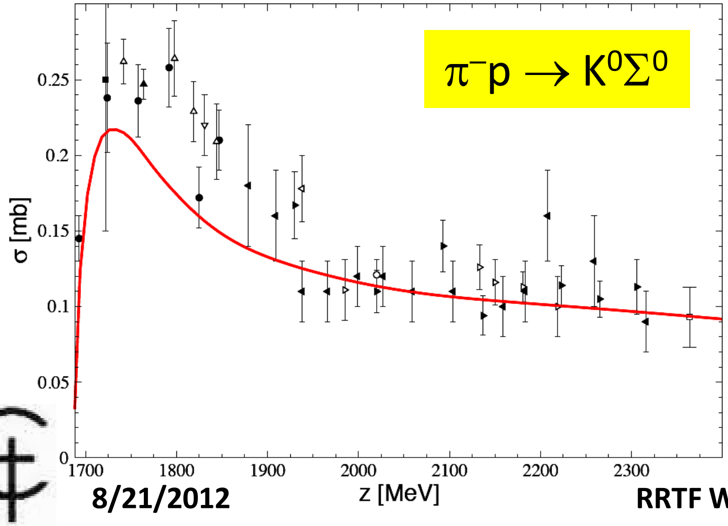
- The evaluation for reactions with **KY**, **η’N**, **ωN**, and **ϕN,** final states are **not possible** now because of small databases.

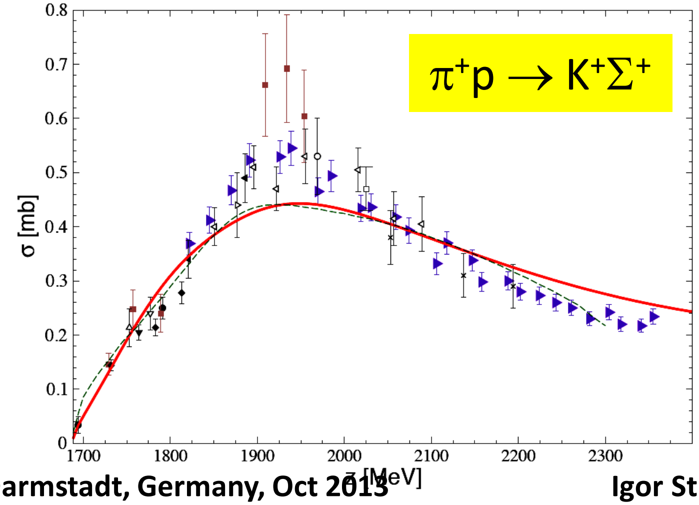
Curves:
Jülich DCC
model, 2012



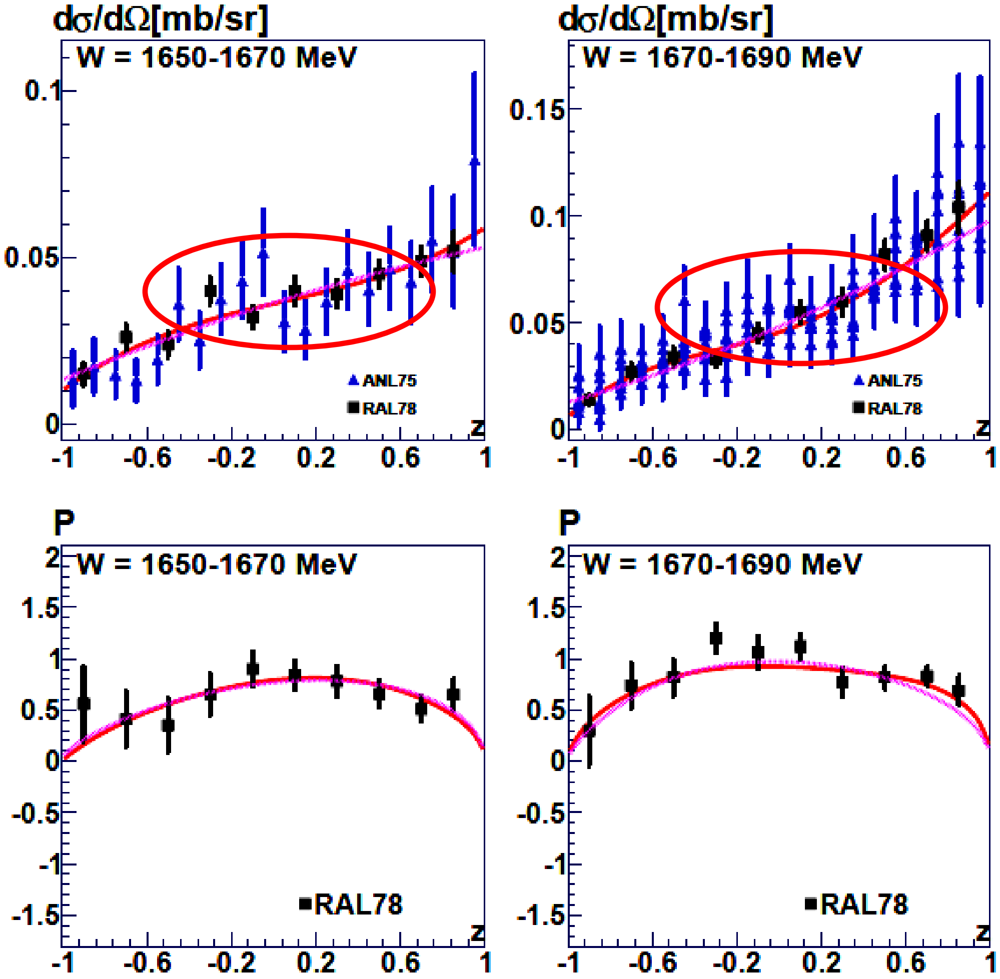


Courtesy of Kanzo Nakayama, GW EIC Workshop, April 2012



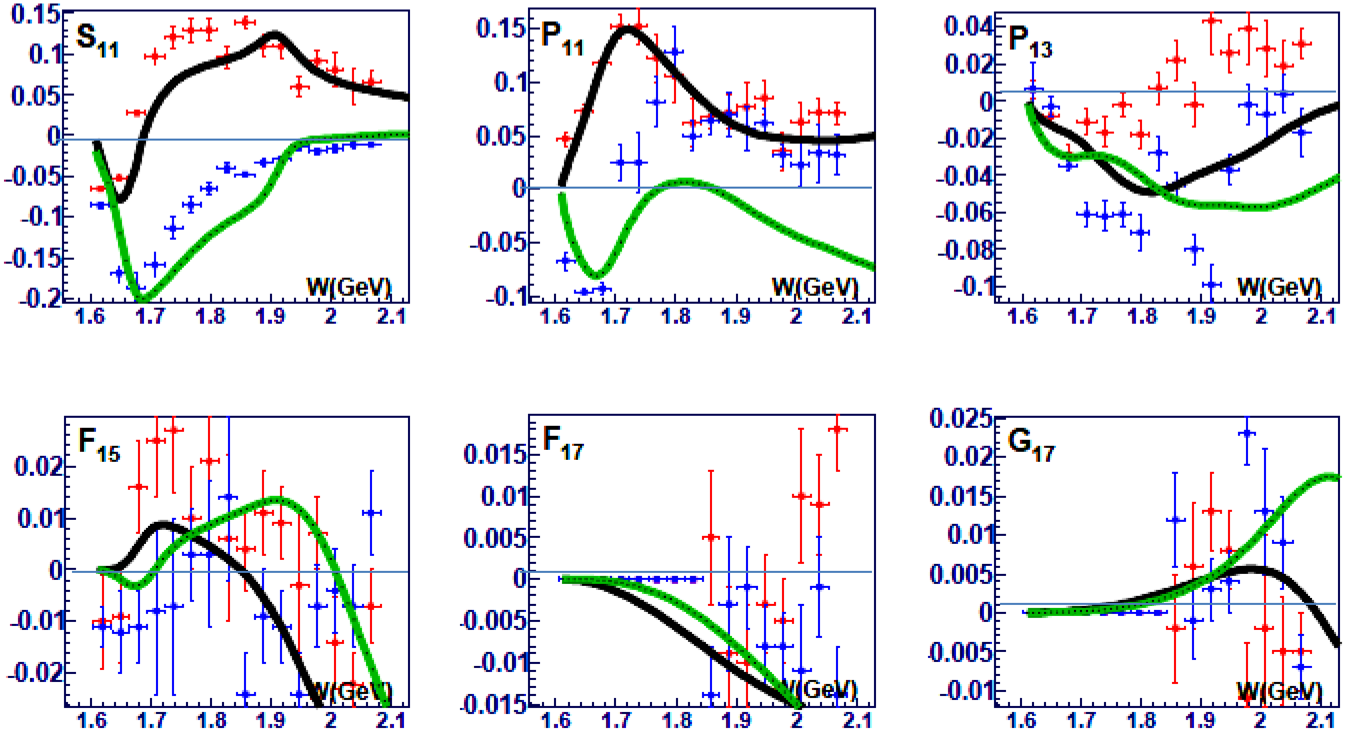


$\pi N \to K\Lambda$



Courtesy of Eberhard Klempt, PWA7 Workshop, Sept 2013

$\pi N \rightarrow K\Lambda$ *Amplitudes*



- Points with error bars: SES of Shresta and Manley. Curves: BnGa2011.
- Shresta and Manley start from a model-dependant fit and select the solution of the SES which is closest to the energy-dependent fit.
- They first freeze the S_{11} wave, then S_{11} and P_{11}, to the energy dependent solution.

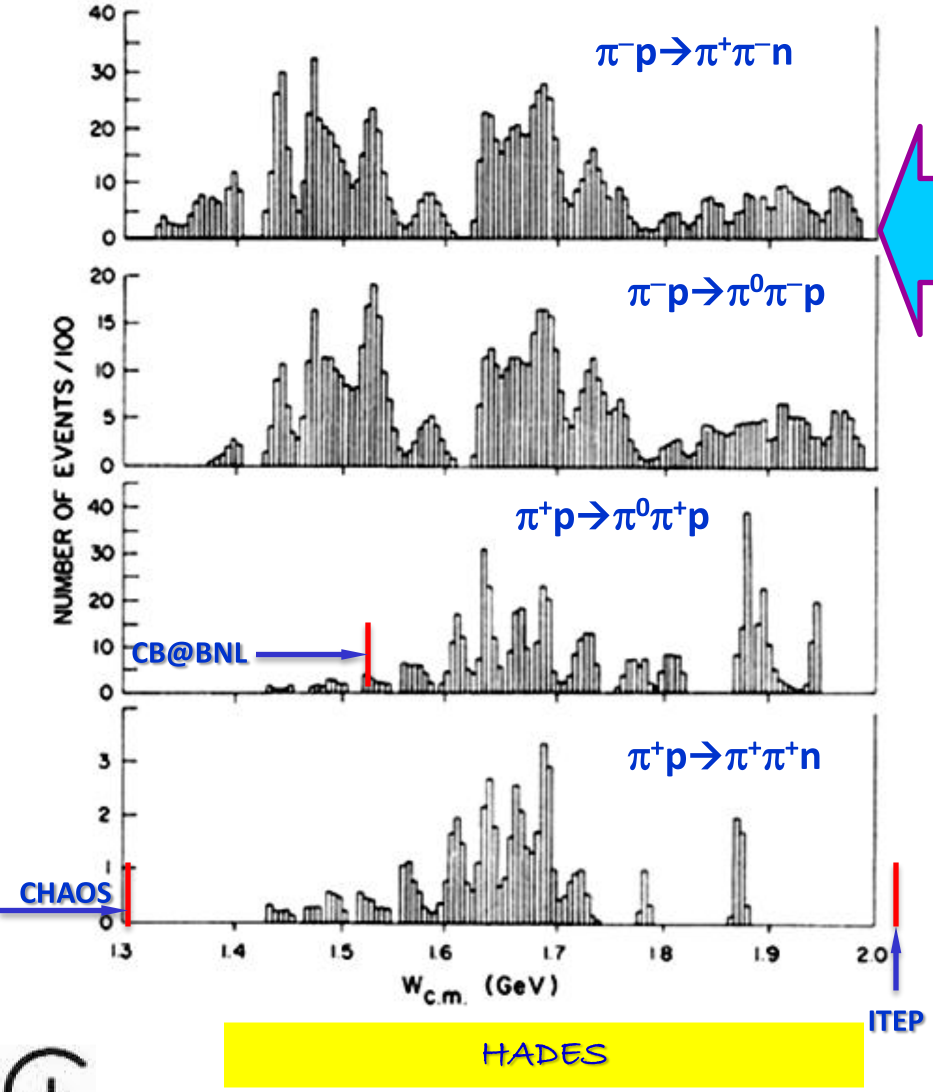
Courtesy of Eberhard Klempt, PWA7 Workshop, Sept 2013

$\pi \rightarrow 2\pi$

$$\left\{ \begin{array}{l} \pi^- p \rightarrow \pi^+\pi^- n \\ \pi^- p \rightarrow \pi^0\pi^0 n \\ \pi^- p \rightarrow \pi^-\pi^0 p \\ \pi^+ p \rightarrow \pi^+\pi^0 p \\ \pi^+ p \rightarrow \pi^+\pi^+ n \end{array} \right.$$

Our knowledge of **πΔ**, **ρN**, and other quasi-two-body **ππN** channels comes mainly from **Isobar-model** analyses of the **πN→ππN** data.

Previous $\pi N \to \pi \pi N$ Measurements

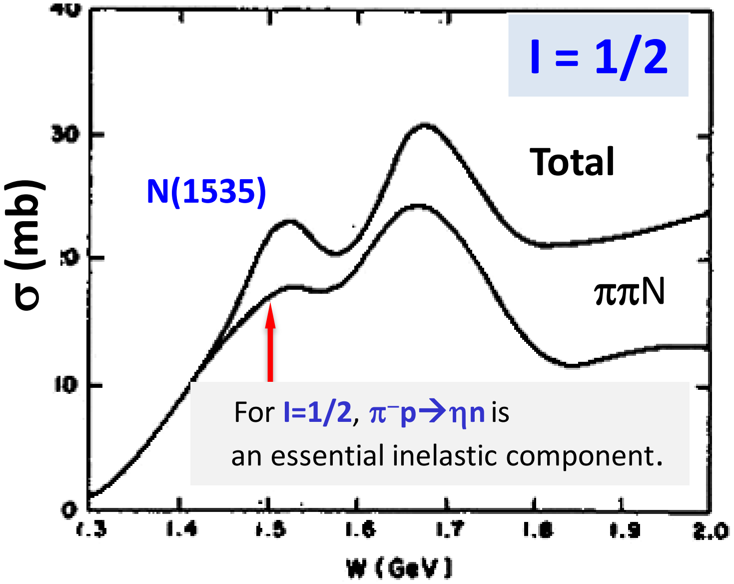


- **241,214** **Bubble Chamber** events for $\pi N \to \pi\pi N$ have been analyzed in **Isobar-model** **PWA** at W = **1320** to **1930** MeV.
  [D.M. Manley, **R. Arndt**, Y. Goradia, V. Teplitz, Phys Rev D **30**, 904 (1984)]

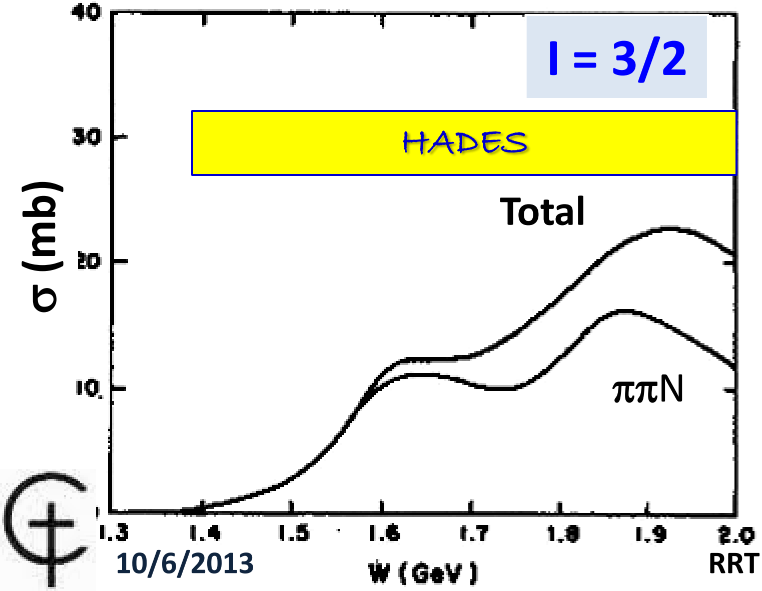
- Recent **post-Bubble Chamber** measurements:
  - **349,611** events for $\pi^- p \to \pi^0 \pi^0 n$ from **CB@BNL** at W = **1213** to **1527** MeV.
    [S. Prakhov *et al* Phys Rev C **69**, 045202 (2004)]
  - **20,000** events for $\pi^{+-} p \to \pi^{+-} \pi^{-+} n$ from **CHAOS@TRIUMF** at W = **1257** to **1302** MeV. [M. Kermani *et al* PRC **58**, 3431 (98)]
  - **40,000** events for $\pi^- \vec{p} \to \pi^- \pi^+ n$ from **ITEP** at W = **2060** MeV.
    [I. Alekseev *et al* Phys At Nucl **61**, 174 (1998)]

$\pi N \rightarrow \pi\pi N$ in Isobar Model

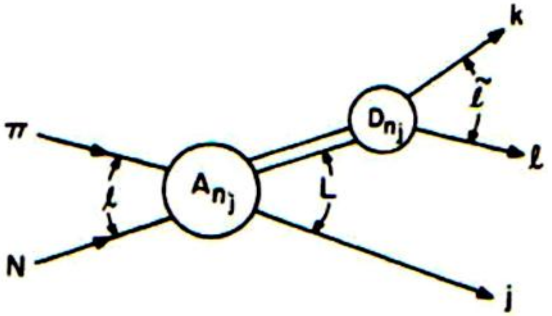
[D.M. Manley, R. Arndt, Y. Goradia, V. Teplitz, Phys Rev D **30**, 904 (1984)]



For **I=1/2**, $\pi^- p \rightarrow \eta n$ is an essential inelastic component.



- $\pi N \rightarrow \pi\pi N$ is the dominant inelastic reaction in πN scattering above **1300** MeV, $\sigma_{inel} \sim \sigma(\pi\pi N)$
- **Drawbacks** – analysis of 3-body final states is complicated (many partial waves are involved).



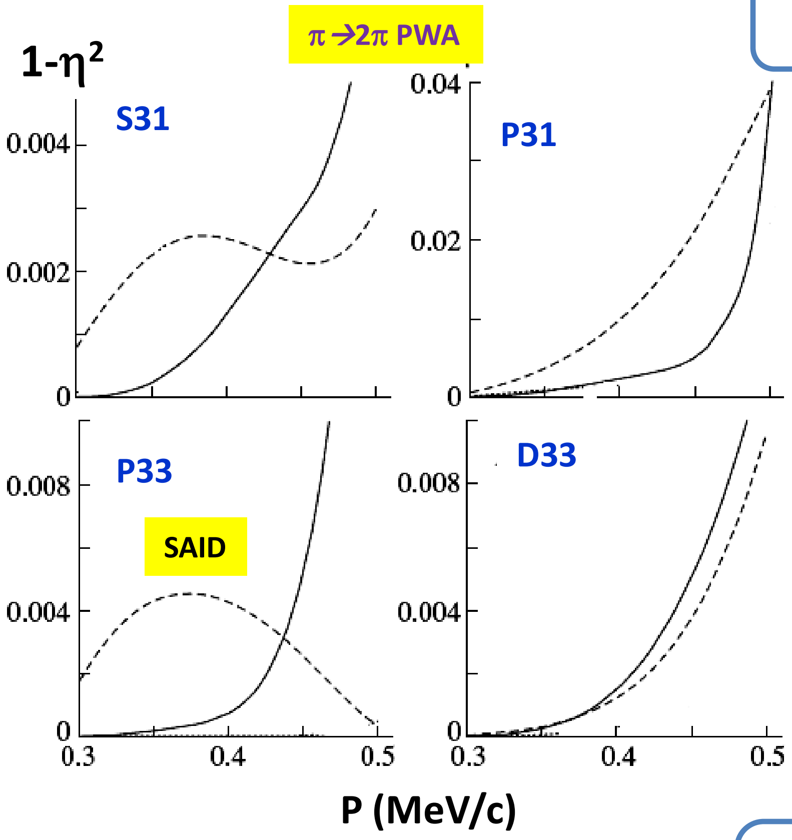
The **total amplitude** for a given charge channel can be written as a coherent sum over all **isobars** and **partial waves**.

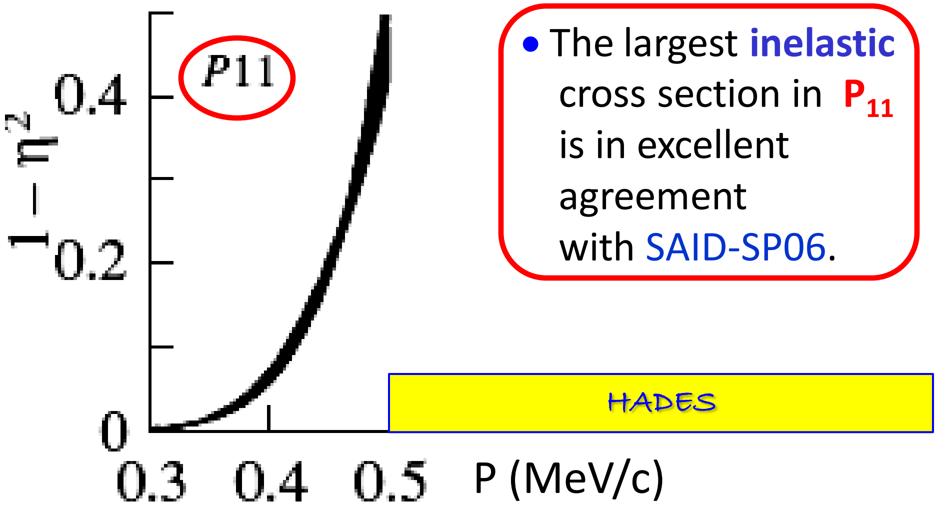
- Many of the **3**- and **4**-star resonances have large decay branching ratios to **ππN** channels.
- **There remains a strong need for detailed new measurements in all charge channels!**

πN→ππN in Isobar Model at low Energies

[V. Kozhevnikov & S. Sherman, Phys Atom Nucl **71**, 1860 (2008)]

- Unfortunately, it is hard to merge **πN→πN** and **πN→ππN** databases to make a joint **PWA**.



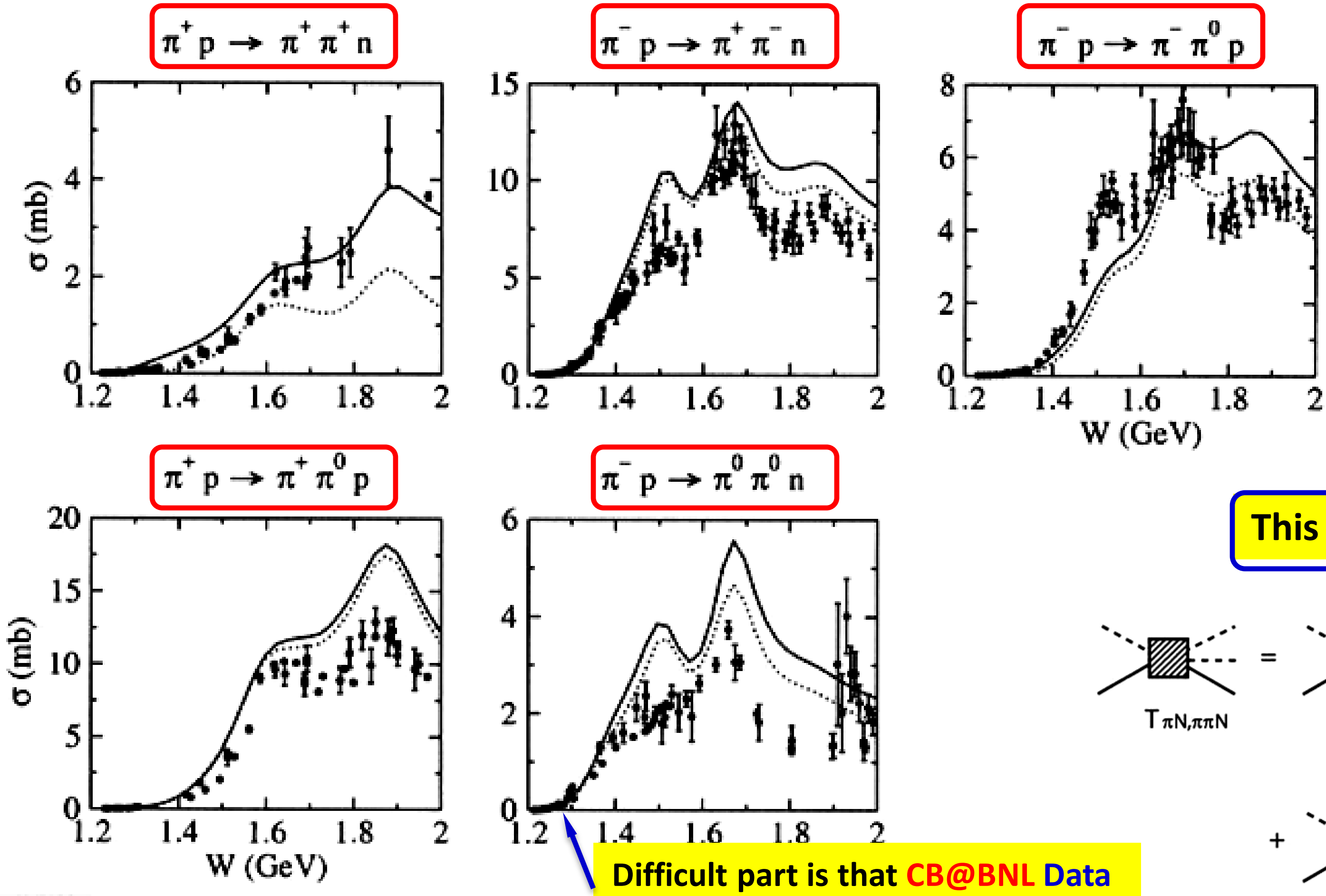


- The largest **inelastic** cross section in **P_{11}** is in excellent agreement with SAID-SP06.

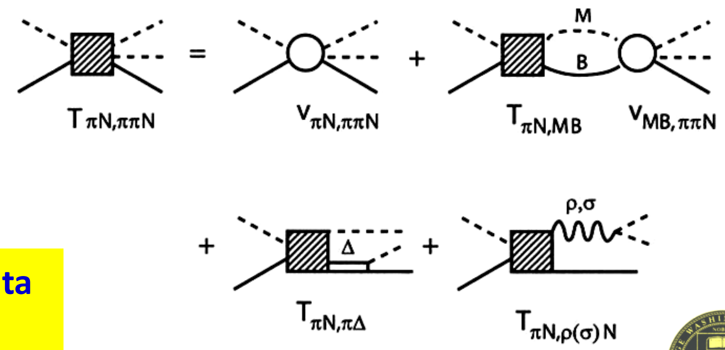
- A complete analysis of **γN→ππN** ideally would require fitting all data obtained with both **pion** and **photon** beams.

ANL-OSAKA (EBAC) Dynamical Coupled-Channels Study of $\pi N \rightarrow \pi\pi N$ Reactions

[H. Kamano, et al Phys Rev C 79, 025206 (**2009**)]



This approach may work



Difficult part is that CB@BNL Data require acceptance corrections

Resonance $\rightarrow N\rho$ Branching Ratios

	GiBUU12	UrQMD09	KSU12	KSU92	BnGa12	CLAS12	PDG12	
$N(1520)3/2^-$	21	15	20.9(7)	21(4)	10(3)	12.7(4.3)	20(5)	**D13**
$N(1720)3/2^+$	87	73	1.4(5)	87(5)	10(13)	47.5(21.5)	77.5(7.5)	**P13**
$\Delta(1620)1/2^-$	29	5	26(2)	25(6)	12(9)	37(12)	16(9)	**S31**
$\Delta(1905)5/2^+$	87	80	<6	86(3)	42(8)		>60	**F35**

Partial courtesy of Piotr Salabura, Sept 2013

CLAS12: V. Mokeev *et al*, Phys Rev C **86**, 035203 (2012); V. Mokeev, PC
BnGa12: A.V, Anisovich *et al*, Eur Phys J A **48**, 15 (2012)
GiBUU12: J. Weil *et al*, Eur Phys J A **48**, 111 (2012); J. Weil, PC
KSU92: D.M. Manley and E.M. Saleski, Phys Rev D **45**, 055203 (1992)
KSU12: M. Shrestha and D.M. Manley, Phys Rev D **86**, 055203 (2012)
PDG12: J. Beringer *et al* [RPP] Phys Rev D **86**, 010001 (2012)
UrQMD09: K. Schmidt *et al*, Phys Rev C **79**, 4002 (2009)

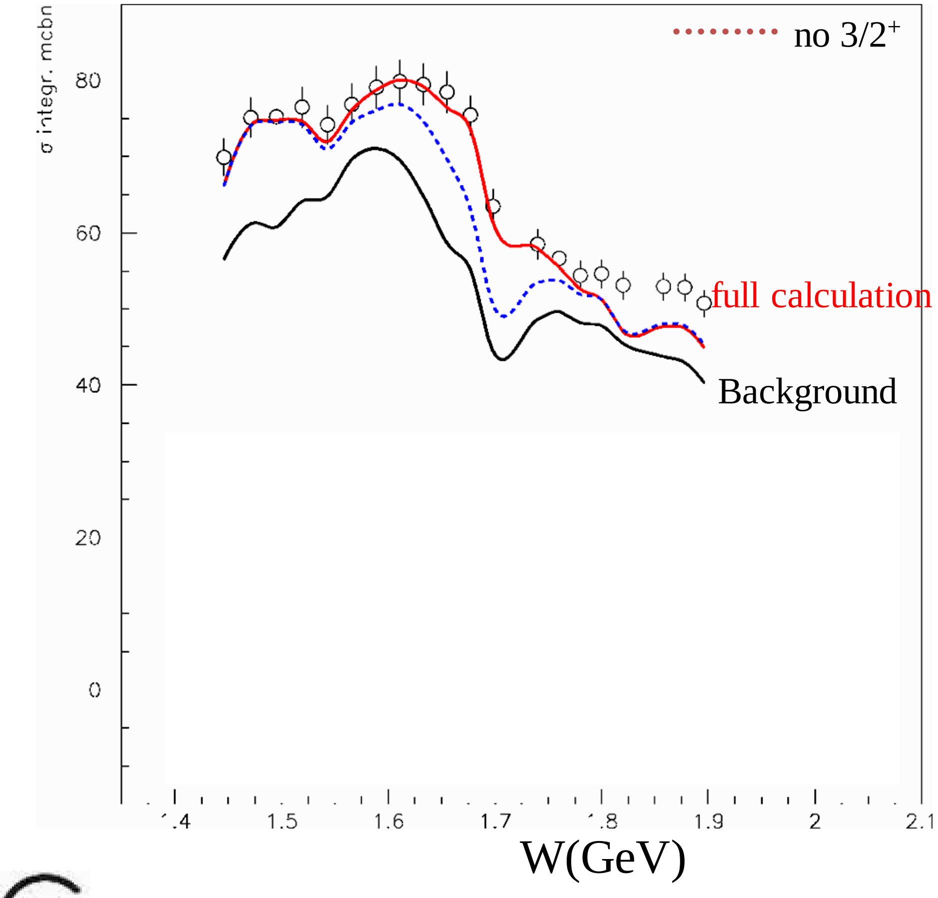
CLAS N^* candidate at 1720 MeV in $p\pi^+\pi^-$?

Courtesy of Victor Mokeev, Sept 2013

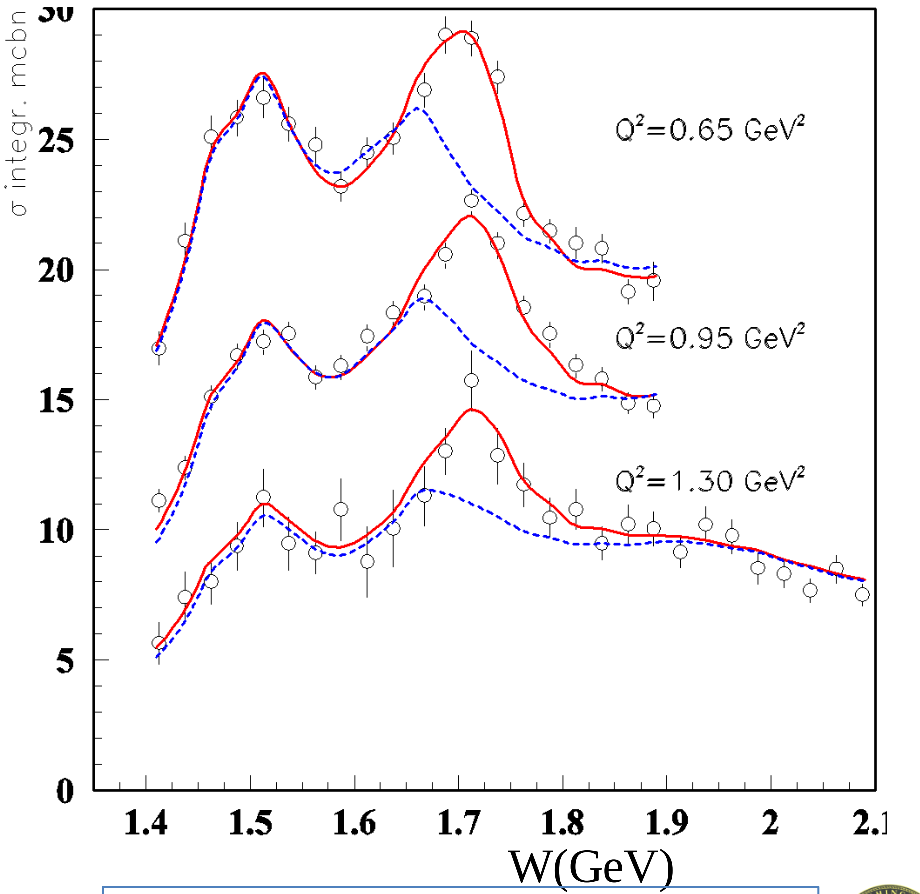
⋯⋯ no $3/2^+$ (1720)

— full

Pion Photoproduction



Pion Electroproduction



[M. Ripani *et al*, Phys.Rev.Lett. 91, 022002 (2003)]

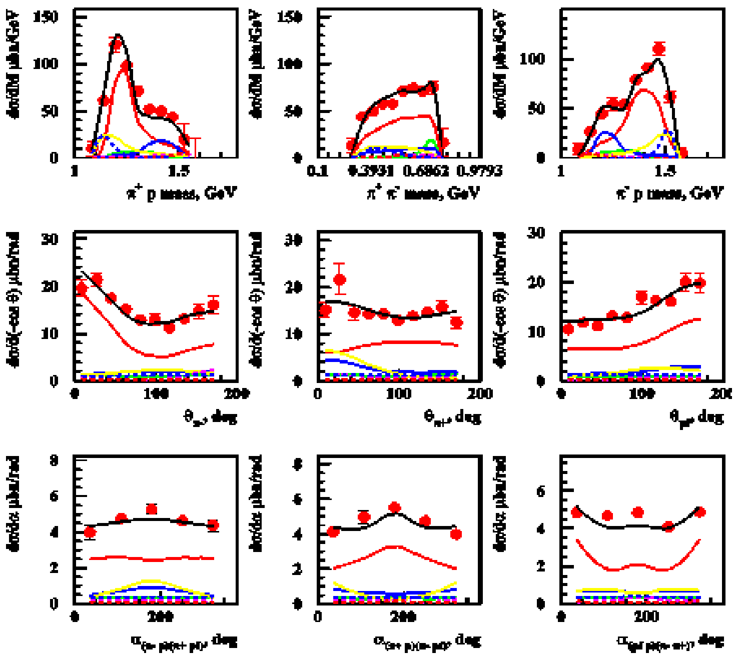
Origin of the structure at W~1.7 GeV for the first time observed in the CLAS Nππ data

- **P_{13}(1720) state with hadronic decays fit to the CLAS data $2.94<\chi^2/dp<3.15$**

	M (GeV)	Γ_{tot} (MeV)	BR($\pi\Delta$) (%)	BR(ρp) (%)
P_{13}(1720) CLAS	**1.728± 0.005**	**133±19**	**66±26**	**16±11**
P_{13}(1720) PDG	**1.70 -1.75**	**150-400**	**comp. with 0.**	**70-85**

Courtesy of Victor Mokeev, Sept 2013

W=1.71 GeV, Q^2=0.65 GeV^2



- **$3/2^+$(1725) candidate state, hadronic parameters of others N*'s are within PDG uncertainties $2.78<\chi^2/dp<2.9$**

	M (GeV)	Γ_{tot} (MeV)	BR($\pi\Delta$) (%)	BR(ρp) (%)
3/2+(1725)	**1.725± 0.004**	**80±6.0**	**48±10**	**7.7±2.2**
P_{13}(1720)	**1.747± 0.004**	**161±31**	**comp. with 0.**	**60-100**

Precise data on πΔ & ρp hadronic decays of P_{13}(1720) is critical in order to understand origin of the structure at W~1.7 GeV in Nππ electroproduction cross sections. This information can be obtained in the studies of πN→ππN reactions at **J-PARC** and **HADES**…

Pion Photoproduction

Single Pion Photoproduction

- An accurate evaluation of the **EM** couplings $N^*(\Delta^*)\rightarrow\gamma N$ from **meson photoproduction** data remains a paramount task in **hadron** physics.

- Only with good data on both the **proton** and **neutron** **targets**, one can hope to disentangle the **isoscalar** & **isovector** **EM** couplings of various N^* & Δ^* resonances,
  as well as the **isospin** properties of non-resonant **background** **amplitudes**.

K.M. Watson, Phys Rev **95**, 228 (1954); R.L. Walker, Phys Rev **182**, 1729 (1969)

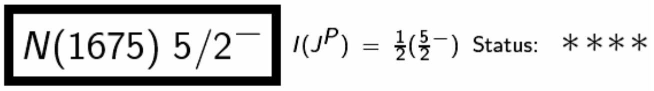
- The lack of the $\gamma n\rightarrow\pi^- p$ & $\gamma n\rightarrow\pi^0 n$ data does not allow us to be as confident about the determination of **neutron** couplings relative to those of the **proton**.

- The **radiative** **decay** width of **neutral** **baryons** may be extracted from π^- & π^0 photoproduction off the **neutron**, which involves a **bound** **neutron** **target** and needs the use of **model-dependent** **nuclear** (**FSI**) **corrections**.

A.B. Migdal, JETP **1**, 2 (1955); K.M. Watson, Phys Rev **95**, 228 (1954)

Where We Are Now

- Some of the N* baryons [**N(1675)D_{15}**, for instance] have ***stronger* EM** coupling to the **neutron** than to the **proton** but parameters are very uncertain.



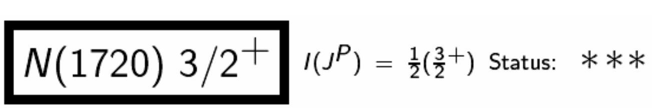
N(1675) 5/2⁻ $I(J^P) = \frac{1}{2}(\frac{5}{2}^-)$ Status: ∗∗∗∗

D_{15}

PDG12: **N(1675)5/2⁻→pγ , helicity-1/2 ampl, A1/2: +0.019±0.008**
N(1675)5/2⁻→nγ , helicity-1/2 ampl, A1/2: –0.043±0.012

SAID13 **N(1675)5/2⁻→pγ , helicity-3/2 ampl, A3/2: +0.016±0.001**
N(1675)5/2⁻→nγ , helicity-3/2 ampl, A3/2: –0.058±0.002

- **PDG** estimates for the **$A_{1/2}$** & **$A_{3/2}$** decay amplitudes of the **N(1720)P_{13}** state are consistent with ***zero***, while the recent **SAID** determination gives small but non-vanishing values.

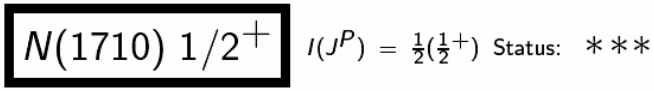


N(1720) 3/2⁺ $I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$ Status: ∗∗∗∗

P_{13}

	PDG12	**SAID13**
N(1720)3/2⁺→pγ , helicity-1/2 ampl, A1/2:	**–0.01 to 0.11**	**+0.095±0.002**
N(1720)3/2⁺→pγ , helicity-3/2 ampl, A3/2:	**–0.019±0.020**	**–0.048±0.002**

- Other unresolved issues relate to the second **P_{11}**, **N(1710)P_{11}**, that are not seen in the recent ***πN* PWA**, contrary to other PWAs used by the **PDG12**.



N(1710) 1/2⁺ $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗

P_{11}

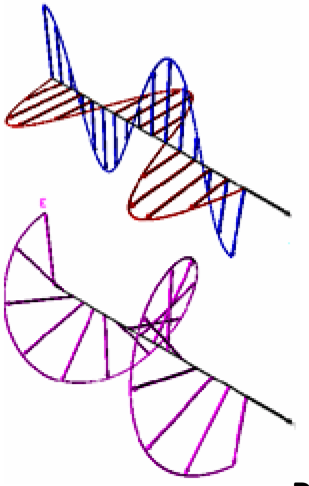
The latest GWU analysis (ARNDT 06) finds no evidence for this resonance.

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

N(1680) 1/2⁺

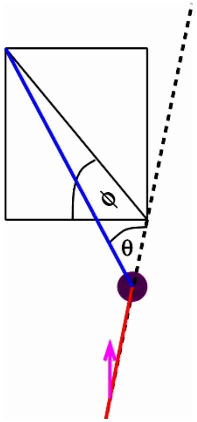
Complete Experiment in Pion Photo Production

$$\vec{\gamma}\ \vec{N} \rightarrow \vec{N}\ \pi$$

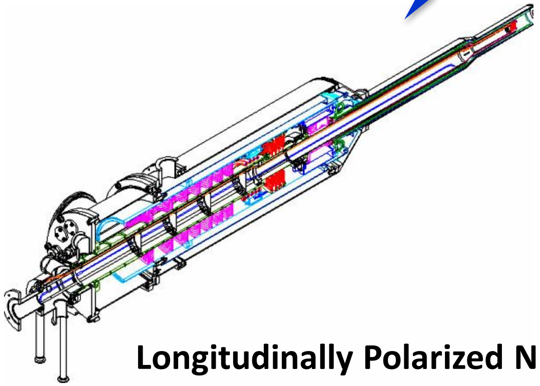


Linear Polarized Beam

Circular Polarized Beam



Nucleon Recoil Polarization



Longitudinally Polarized Nucleon Target
Transverse Polarized Nucleon Target

There are several πN SESs which one can possible to consider as samples of complete experiments.

Pion PhotoProduction complete experiments are under the consideration now.

Direct Amplitude Reconstruction in Pion Photo Production

$\gamma \; N \rightarrow N \; \pi$

spin: $1 \quad \frac{1}{2} \rightarrow \frac{1}{2} \quad 0$

helicities: $2 \times 2 \times 2 \,/\, 2 = 4$

parity conservation

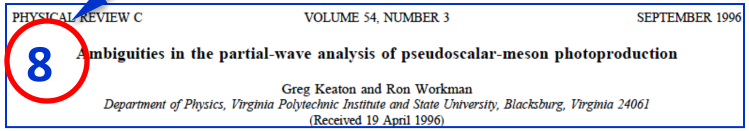
- In **particle physics**, **helicity** is the projection of the spin $\vec{S}$ onto the direction of momentum, $\hat{p}$:

$$h = \vec{J}\cdot\hat{p} = \vec{L}\cdot\hat{p} + \vec{S}\cdot\hat{p} = \vec{S}\cdot\hat{p}$$

$$\hat{p} = \frac{\vec{p}}{|\vec{p}|}$$

Therefore, there are 4 independent invariant amplitudes

- In order to determine the pion photo production amplitude, one has to carry out 7 **independent** measurements at **fixed** (**W**, **t**) or (**E**$_\gamma$, **θ**)



8

PHYSICAL REVIEW C VOLUME 54, NUMBER 3 SEPTEMBER 1996

Ambiguities in the partial-wave analysis of pseudoscalar-meson photoproduction

Greg Keaton and Ron Workman

Department of Physics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

(Received 19 April 1996)

This extra observable is necessary to eliminate a **sign ambiguity.**

SAID for Pion Photoproduction

[W. Chen *et al*, Phys Rev C **86**, 015206 (2012)]

- Energy dependent **GB12** and associated SES
- E = 145 – 2700 MeV [W = 1080 – 2460 MeV]
- PWs = 60 [E & M multipoles] [$J < 6$]
- Prms = 210
- Constraint: $M = (\mathrm{Born} + A)(1+iT_{\pi N}) + BT_{\pi N} + (C+iD)(\mathrm{Im}T_{\pi N} - |T_{\pi N}|^2)$

Born [no free parameters to fit]

πN-PWA [no theoretical input]

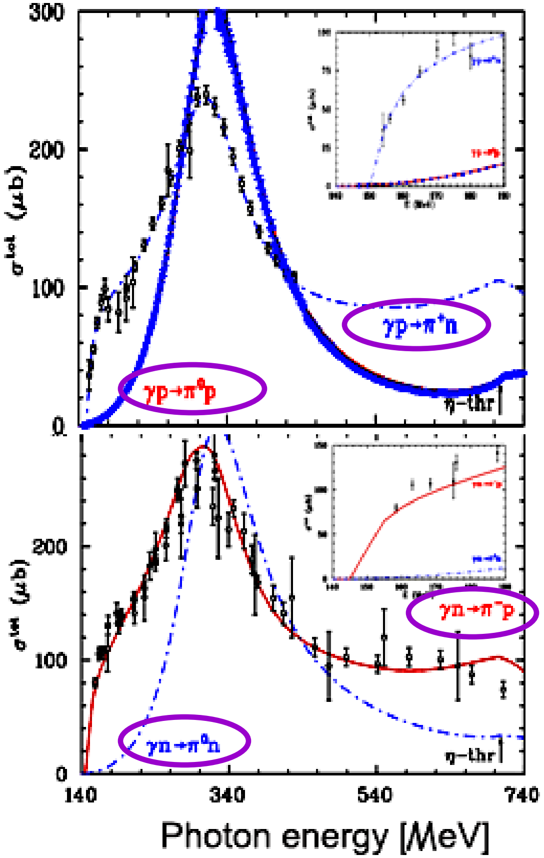
Reaction	Data (Dpol)	χ^2
$\gamma p \to \pi^0 p$	14,612 (3 %)	32,449
$\gamma p \to \pi^+ n$	8,510 (5 %)	16,520
$\gamma n \to \pi^- p$	3,058 (0 %)	6,396
$\gamma n \to \pi^0 n$	364 (0 %)	1,201
Total	26,554	56,566

23,122 data

3,422 data

- 1st generation – ('60–'90)
  10k data [85% bremsstrahlung data.]
  30% data is polarized.
  [limited coverage, broad energy binning.]
- 2nd generation – ('90–'10) → SAID fits.
  25k data [60% tagged data.]
  30% data is polarized.
  Dearth of neutron data.
- 3rd generation – ('10+)
  New data will come from JLab, CB@MAMI-C, SPring-8, CB-ELSA, MAX-lab, & LNS.

Much less known, 15%



Recent SAID Progress in PionPR

DU13: included recent *CLAS* $\pi^0 p$ & $\pi^+ n$ Σ [M. Dugger *et al*, arXiv:1308.4028[nucl-ex]]

GB12/**GZ12**: included recent *CLAS* $\pi^- p$ $d\sigma/d\Omega$ [W. Chen *et al*, Phys Rev C **86**, 015206 (2012)]

CM12: CM parameterization for $T_{\pi N}$ [R. Workman *et al*, Phys Rev C **86**, 015202 (2012)]

SN11/**SK11**: included recent *GRAAL* $\pi^- p$ & $\pi^0 n$ Σ

LEPS $\pi^0 p$ $d\sigma/d\Omega$ [R. Workman *et al*, Phys Rev C **85**, 025201 (2012)]

$$M = (\text{Born} + A)(1 + iT_{\pi N}) + BT_{\pi N} + (C + iD)(\text{Im}T_{\pi N} - |T_{\pi N}|^2)$$

SP09: included recent *CLAS* $\pi^+ n$ $d\sigma/d\Omega$ [M. Dugger *et al*, Phys Rev C **79**, 065206 (2009)]

$$M = (\text{Born} + \alpha_R)(1 + iT_{\pi N}) + \alpha_R T_{\pi N} + \text{higher terms}$$

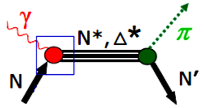
Solution	Energy Limit (MeV)	χ^2/N_{Data}	N_{Data}
DU13	2700	2.23	**27,265**
GB12	2700	2.09	26,179
CM12	2700	2.01	25,814
SN11	2700	2.08	25,553
SP09	2700	2.05	24,912
FA06	3000	2.18	25,524
SM02	2000	2.01	17,571
SM95	2000	2.37	**13,415**

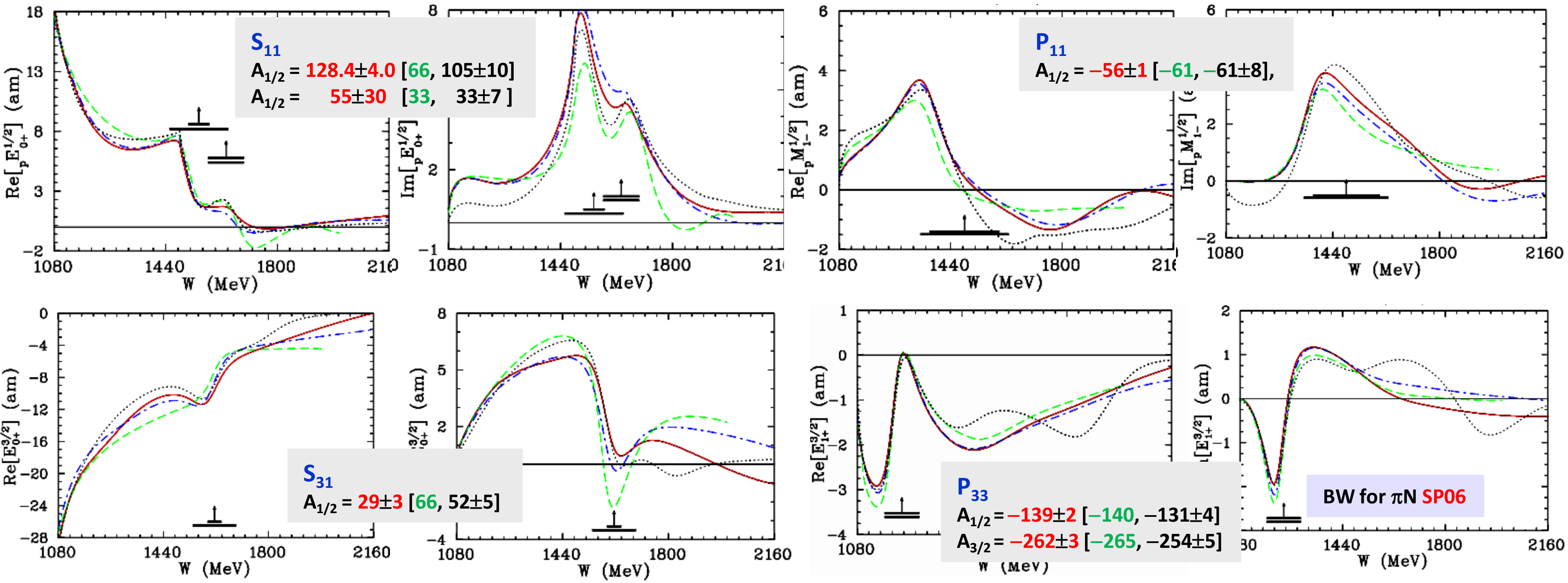
- The overall SAID χ^2 has remained stable against the growing database, which has increased by a factor of 2 since **1995.**
- Most of this increase coming from **photon-tagging** facilities.

Proton Multipoles from DU13 & CM12

[R. Workman *et al*, Phys Rev C **86**, 015202 (2012); M. Dugger *et al*, arXiv:1308.4028 [nucl-ex]]

- **Overall**: the difference between MAID07 or BnGa and SAID DU13 is rather small but… Resonances may be essentially different.





S_{11}
$A_{1/2}$ = 128.4±4.0 [66, 105±10]
$A_{1/2}$ = 55±30 [33, 33±7]

P_{11}
$A_{1/2}$ = −56±1 [−61, −61±8],

S_{31}
$A_{1/2}$ = 29±3 [66, 52±5]

P_{33}
$A_{1/2}$ = −139±2 [−140, −131±4]
$A_{3/2}$ = −262±3 [−265, −254±5]

BW for πN SP06

- Significant changes have occurred at high energies.
- Comparisons to earlier SAID fits and fit from the Mainz & BnGa groups show that the new DU13 & CM12 solutions is much more satisfactory at higher energies.

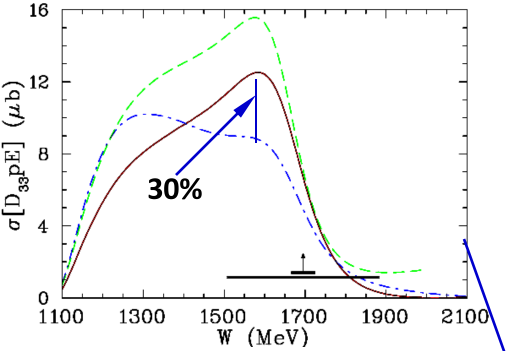
SAID DU13
SAID CM12
MAID07
BnGa13

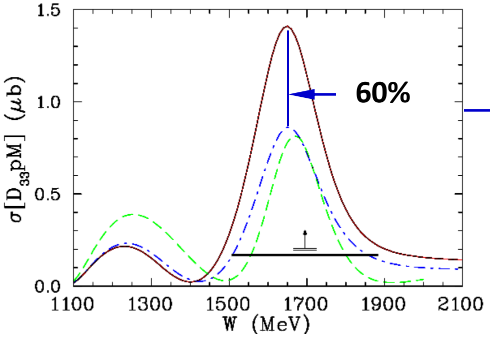
MAID07: D. Drechsel *et al*, Eur Phys J A 34, 69 (2007)
BnGa: A. Anisovich *et al*, Eur Phys J A 48, 15 (2012)

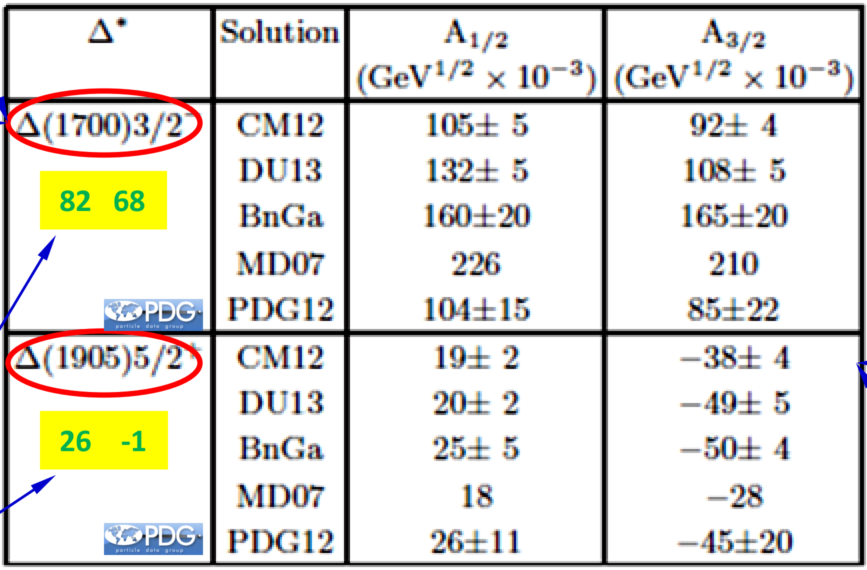
CLAS Σ Data Impact for Proton S = 0 & I = ½ Couplings

[M. Dugger *et al*, arXiv:1308.4028 [nucl-ex]]

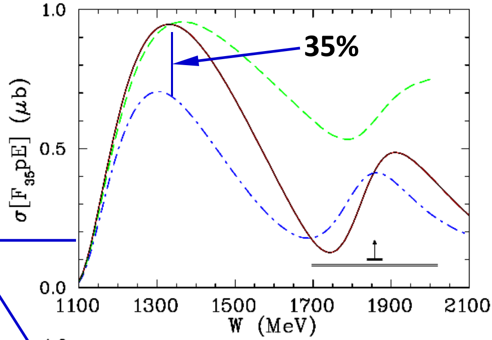
- The largest change is found for the **Δ(1700)3/2⁻** and **Δ(1905)5/2⁺** states, for which the various analyses disagree significantly in terms of photo-decay amplitudes.

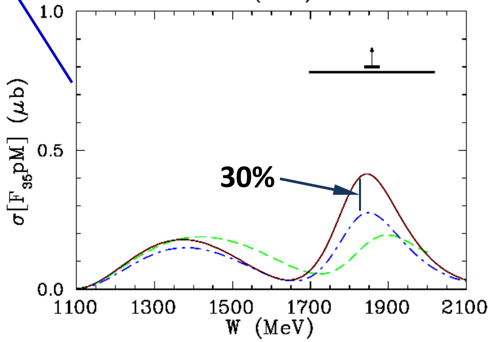






Δ*	Solution	$A_{1/2}$ $(GeV^{1/2} \times 10^{-3})$	$A_{3/2}$ $(GeV^{1/2} \times 10^{-3})$
Δ(1700)3/2⁻ 82 68	CM12	105± 5	92± 4
	DU13	132± 5	108± 5
	BnGa	160±20	165±20
	MD07	226	210
PDG	PDG12	104±15	85±22
Δ(1905)5/2⁺ 26 -1	CM12	19± 2	−38± 4
	DU13	20± 2	−49± 5
	BnGa	25± 5	−50± 4
	MD07	18	−28
PDG	PDG12	26±11	−45±20





SAID DU12
SAID CM12
MAID07

Relativized Quark Model:
S. Capstick, Phys Rev D **46**, 2864 (1992)

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

- The existing $\gamma n \rightarrow \pi^- p$ database contains mainly differential cross sections (**17%** of which are from **polarized** measurements.)

- Many of these are old **bremsstrahlung** measurements with limited **angular** (θ = **40** - **140**^{0}) coverage and large **energy** binning (E_γ = **100** – **200** MeV.) In several cases, the **systematic** uncertainties have not been given.

- At lower energies (E_γ < **700** MeV,) there are data sets for the inverse π^- photoproduction reaction: $\pi^- p \rightarrow \gamma n$. This process is free from complications associated with a **deuteron** **target**.

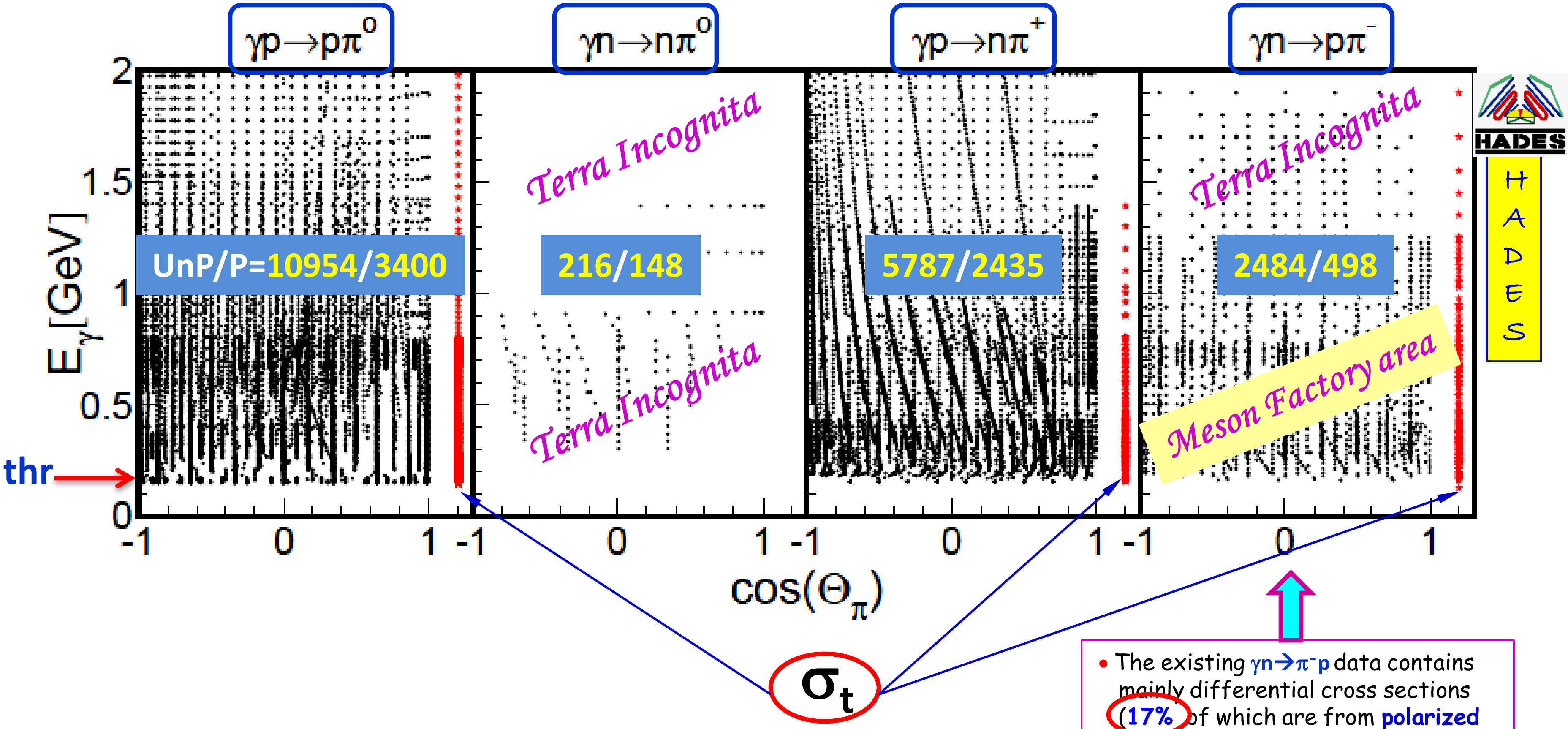
eg, **CB@BNL:** A. Shafi, *et al,* PRC**70**, 035204 (2004)

- However, the disadvantage of using $\pi^- p \rightarrow \gamma n$ is the **large background** because of the **5** to **500** times larger cross section for $\pi^- p \rightarrow \pi^0 n \rightarrow \gamma\gamma n$.

World Neutral and Charged PionPR Data

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

Future exp activity will fill empty spots specifically for **n**-target.

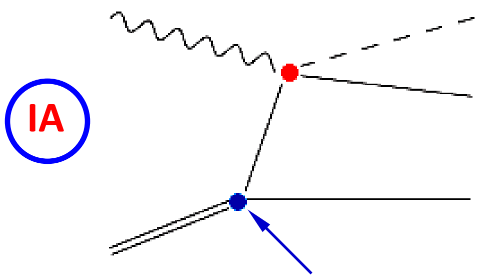


- The existing $\gamma n \to \pi^- p$ data contains mainly differential cross sections (**17%** of which are from **polarized** measurements.)

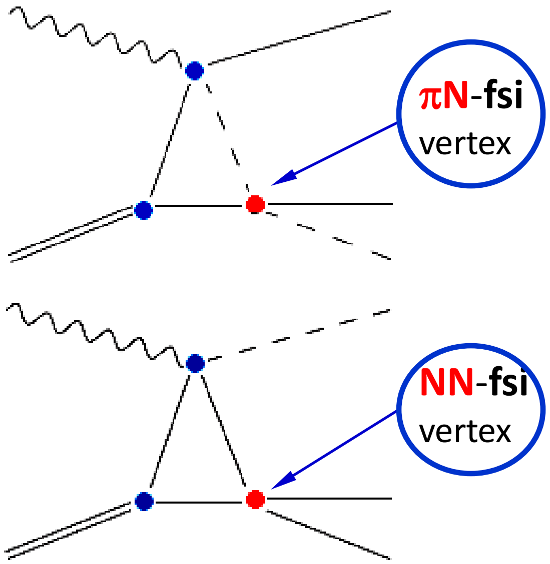
FSI and $\gamma d \to \pi^- p\, p \Longrightarrow \gamma n \to \pi^- p$

[V. Tarasov, A. Kudryavtsev, W. Briscoe, H. Gao, & IS, Phys Rev C **84**, 035203 (2011)]

- **FSI plays a critical role in the state-of-the-art analysis of γn→πN data.**
- **For $\gamma n \to \pi^- p$** the effect: **5% – 60%.** It depends on (**E**,**θ**).



Fermi motion of nucleons included.



Input: **SAID** γN→πN, πN →πN, NN →NN amplitudes for **3** leading terms.
DWF: Bonn Potential.

$$\boxed{R = (d\sigma/d\Omega_{\pi p})/(d\sigma^{IA}/d\Omega_{\pi p})}$$

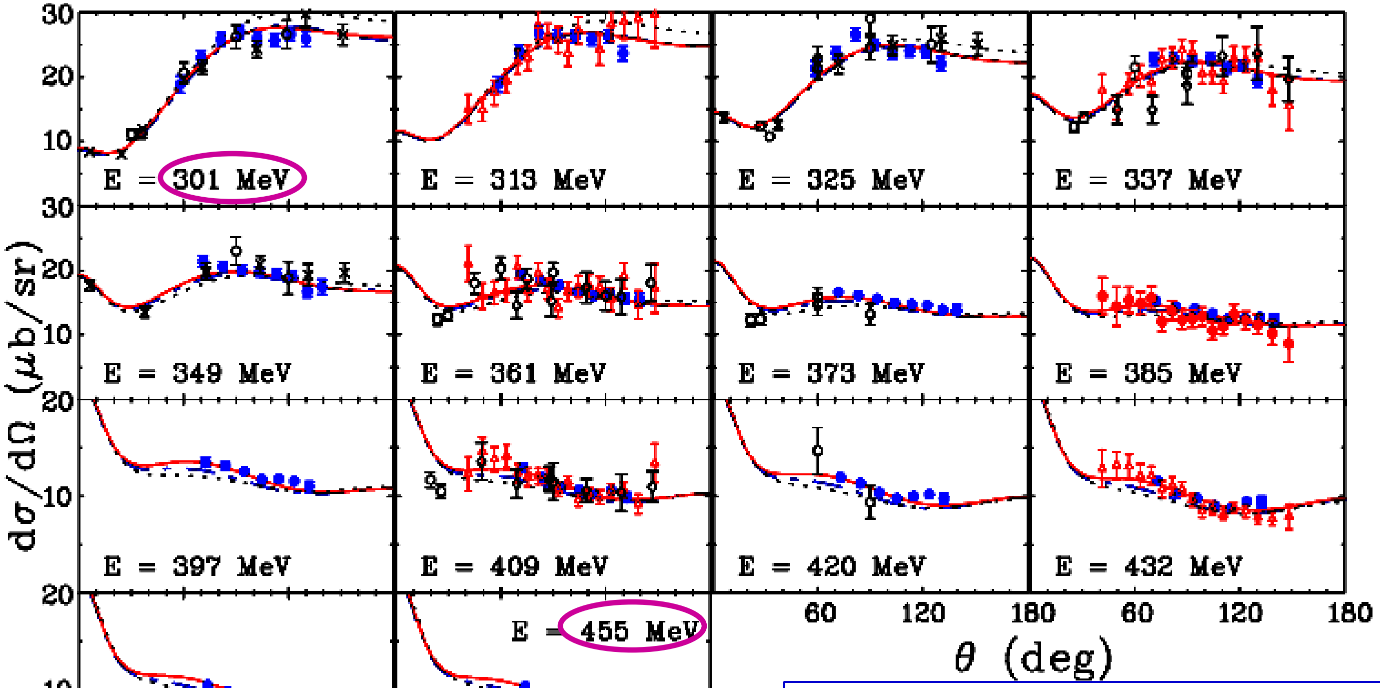
⇒

$$\boxed{\frac{d\sigma}{d\Omega}(\gamma n) = R^{-1}\frac{d\sigma}{d\Omega}(\gamma d)}$$

MAMI-B for $\gamma n \rightarrow \pi^- p$ around the Δ

[W.J. Briscoe *et al*, Phys Rev *C* **86**, 065207 (2012)]

- **MAMI-B** data for $\gamma n \rightarrow \pi^- p$ (including **FSI** corrections) and previous hadronic data for $\pi^- p \rightarrow n\gamma$ appear to **agree well**.



SAID-PE12
SAID-SN11
MAID07

Data:

● – **MAMI-B** for $\gamma n \rightarrow \pi^- p$

Δ – **CB@BNL** for $\pi^- p \rightarrow n\gamma$

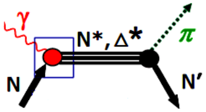
A. Shafi, *et al*, Phys Rev C **70**, 035204 (2004)

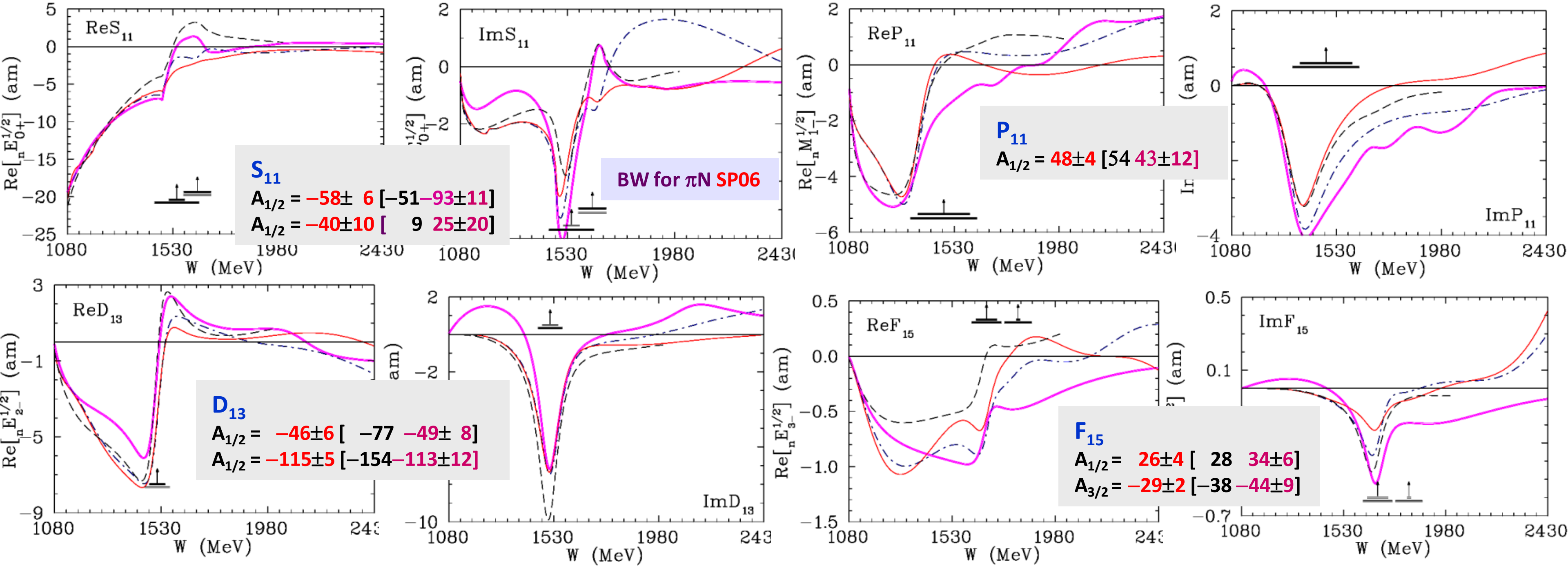
o – **TRIUMF**, **CERN**, **LBL**, **LAMPF** for $\pi^- p \rightarrow n\gamma$

Neutron Multipoles from SAID GB12 & SN11

[W. Chen *et al*, Phys Rev C **86**, 015206 (2012); R. Workman *et al*, Phys Rev C **85**, 025201 (2012)]

- **Overall: the difference between MAID07 with BnGa13 and SAID GB12 is rather small but… Resonances may be essentially different.**





S_{11}

$A_{1/2}$ = −58± 6 [−51−93±11]

$A_{1/2}$ = −40±10 [9 25±20]

BW for πN SP06

P_{11}

$A_{1/2}$ = 48±4 [54 43±12]

D_{13}

$A_{1/2}$ = −46±6 [−77 −49± 8]

$A_{1/2}$ = −115±5 [−154−113±12]

F_{15}

$A_{1/2}$ = 26±4 [28 34±6]

$A_{3/2}$ = −29±2 [−38 −44±9]

- **Significant changes have occurred at high energies.**
- **Comparisons to earlier SAID and fit from the Mainz and BnGa groups show that the new GB12 solution is much more satisfactory at higher energies.**

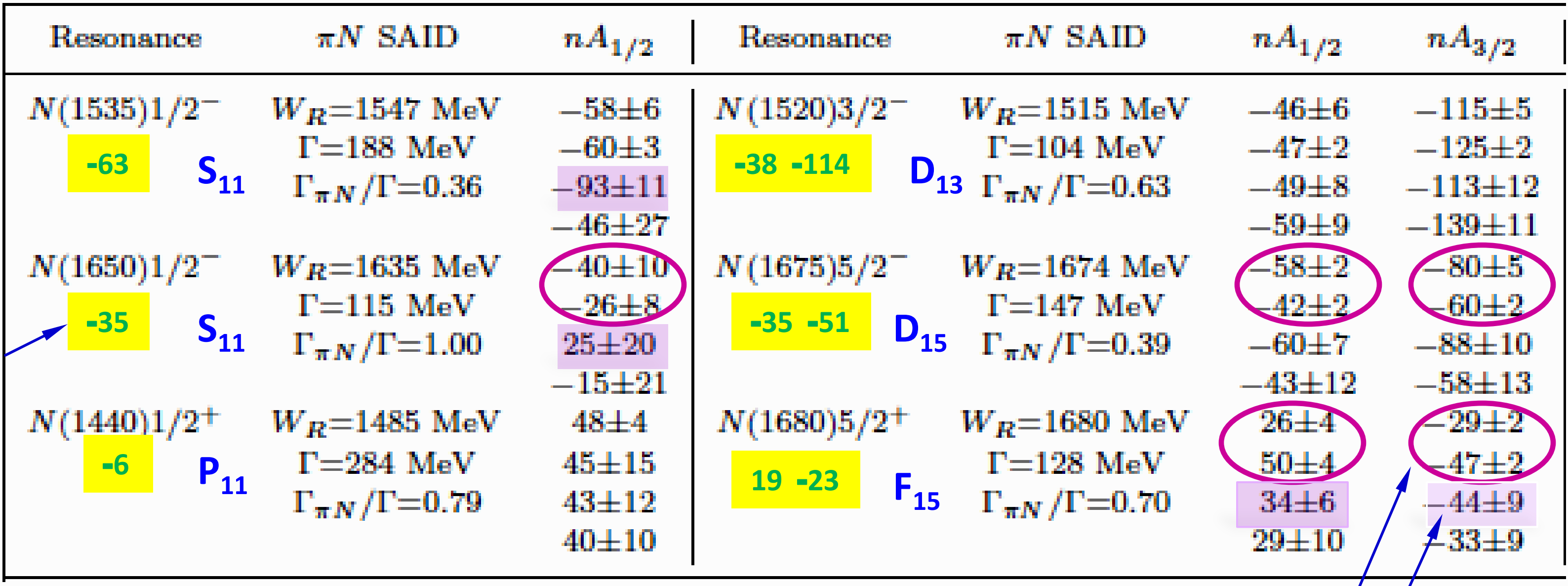
SAID GB12
SAID SN11
MAID07
BnGa13

MAID07: D. Drechsel, *et al*, Eur Phys J A 34, 69 (2007)
BnGa13: A. Anisovich *et al*, Eur Phys J A 49, 67 (2013)

CLAS Data Impact for Neutron S = 0 & I = ½ Couplings

[W. Chen *et al*, Phys Rev C **86**, 015206 (2012)]

- **BnGa13** and **SAID GB12** used the same (almost) data to fit them while **BnGa13** has several new **Ad Hoc** resonances.



Resonance	πN SAID	$nA_{1/2}$	Resonance	πN SAID	$nA_{1/2}$	$nA_{3/2}$
$N(1535)1/2^-$	W_R=1547 MeV	−58±6	$N(1520)3/2^-$	W_R=1515 MeV	−46±6	−115±5
-63 S_{11}	Γ=188 MeV	−60±3	-38 -114 D_{13}	Γ=104 MeV	−47±2	−125±2
	$\Gamma_{\pi N}/\Gamma$=0.36	−93±11		$\Gamma_{\pi N}/\Gamma$=0.63	−49±8	−113±12
		−46±27			−59±9	−139±11
$N(1650)1/2^-$	W_R=1635 MeV	−40±10	$N(1675)5/2^-$	W_R=1674 MeV	−58±2	−80±5
-35 S_{11}	Γ=115 MeV	−26±8	-35 -51 D_{15}	Γ=147 MeV	−42±2	−60±2
	$\Gamma_{\pi N}/\Gamma$=1.00	25±20		$\Gamma_{\pi N}/\Gamma$=0.39	−60±7	−88±10
		−15±21			−43±12	−58±13
$N(1440)1/2^+$	W_R=1485 MeV	48±4	$N(1680)5/2^+$	W_R=1680 MeV	26±4	−29±2
-6 P_{11}	Γ=284 MeV	45±15	19 -23 F_{15}	Γ=128 MeV	50±4	−47±2
	$\Gamma_{\pi N}/\Gamma$=0.79	43±12		$\Gamma_{\pi N}/\Gamma$=0.70	34±6	−44±9
		40±10			29±10	−33±9

GB12
SN11
BnGa13
PDG

S. Capstick, Phys Rev D **46**, 2864 (1992).

- New **GB12** $nA_{1/2}$ & $nA_{3/2}$ couplings shown sometimes a significant deviation from our previous SAID determination (**SN11**) and **PDG12** average values, e.g., for **N(1650)1/2⁻**, **N(1675)5/2⁻**, and **N(1680)5/2⁺**.

- Fresh **BnGa13** has some difference vs. **GB12**, **PDG12**, and the **relativized quark model**, e.g., for **N(1650)1/2⁻** , **N(1650)1/2⁻** , and **N(1680)5/2⁺**.

BnGa13: A. Anisovich *et al*, EPJA 49, **67 (2013)**

Status of Non-strange Resonances

J. Beringer *et al* (PDG) Phys Rev D **86**, 010001 (2012)

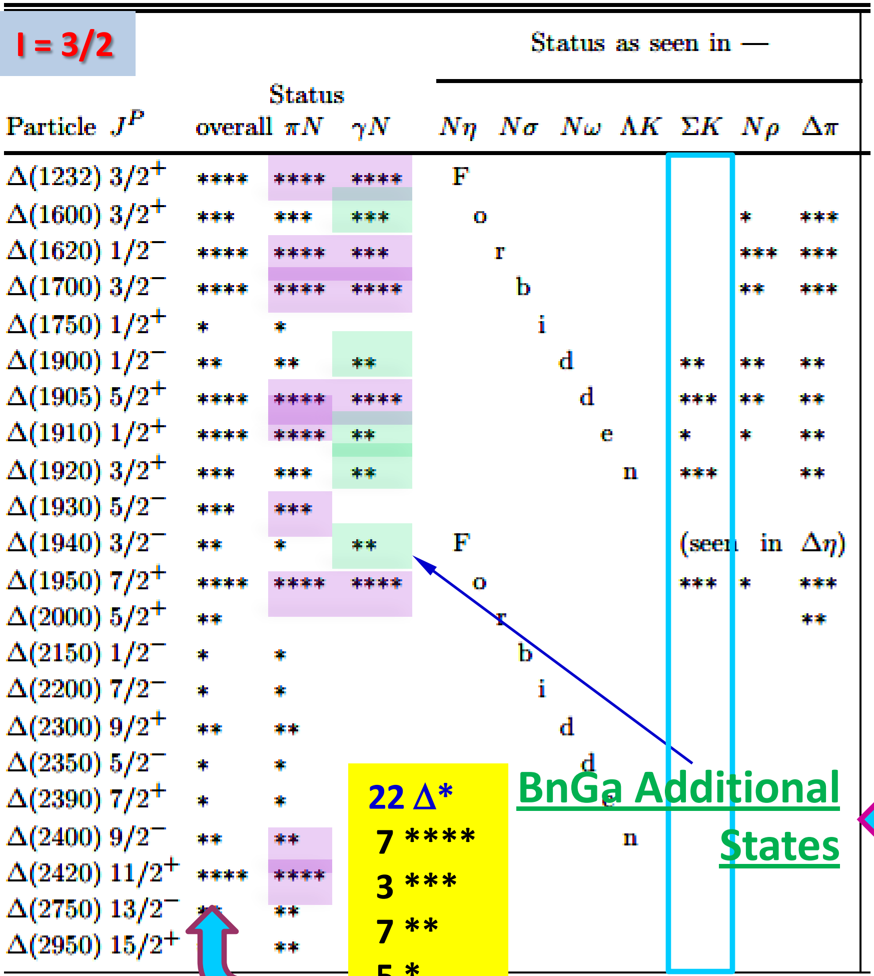
- More than half of states have poor evidence.
- Most of states need more work to do.
- Most of QCD models predict more states than observed.
- Where are missing resonances?

GW SAID Contribution

Status as seen **I = 1/2**

Particle	J^P	Status overall	πN	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
N	$1/2^+$	****									
$N(1440)$	$1/2^+$	****	****	****		***				*	***
$N(1520)$	$3/2^-$	****	****	****	***					***	***
$N(1535)$	$1/2^-$	****	****	****	****					**	*
$N(1650)$	$1/2^-$	****	****	***	***			***	**	**	***
$N(1675)$	$5/2^-$	****	****	***	*			*		*	***
$N(1680)$	$5/2^+$	****	****	****	*	**				***	***
$N(1685)$	??	*									
$N(1700)$	$3/2^-$	***	***	**	*			*	*	*	***
$N(1710)$	$1/2^+$	***	***	***	***		**	***	**	*	**
$N(1720)$	$3/2^+$	****	****	***	***			**	**	**	*
$N(1860)$	$5/2^+$	**	**							*	*
$N(1875)$	$3/2^-$	***	*	***			**	***	**		***
$N(1880)$	$1/2^+$	**	*	*		**		*			
$N(1895)$	$1/2^-$	**	*	**	**			**	*		
$N(1900)$	$3/2^+$	***	**	***	**		**	***	**	*	**
$N(1990)$	$7/2^+$	**	**	**					*		
$N(2000)$	$5/2^+$	**	*	**	**			**	*	**	
$N(2040)$	$3/2^+$	*									
$N(2060)$	$5/2^-$	**	**	**	*				**		
$N(2100)$	$1/2^+$	*									
$N(2150)$	$3/2^-$	**	**	**				**			**
$N(2190)$	$7/2^-$	****	****	***				**		*	
$N(2220)$	$9/2^+$	****	****								
$N(2250)$	$9/2^-$	****	****								
$N(2600)$	$11/2^-$	***	***								
$N(2700)$	$13/2^+$	**	**								

26 N*
11 ****
5 ***
7 **
3 *



I = 3/2

Status as seen in —

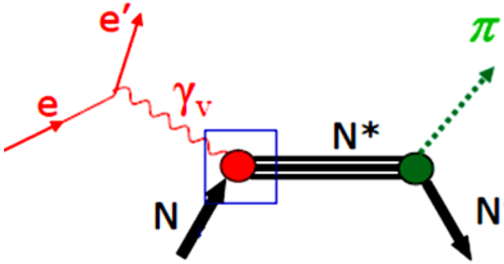
Particle	J^P	Status overall	πN	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
$\Delta(1232)$	$3/2^+$	****	****	****	F						
$\Delta(1600)$	$3/2^+$	***	***	***	o					*	***
$\Delta(1620)$	$1/2^-$	****	****	***	r					***	***
$\Delta(1700)$	$3/2^-$	****	****	****		b				**	***
$\Delta(1750)$	$1/2^+$	*	*			i					
$\Delta(1900)$	$1/2^-$	**	**	**			d		**	**	**
$\Delta(1905)$	$5/2^+$	****	****	****			d		***	**	**
$\Delta(1910)$	$1/2^+$	****	****	**			e		*	*	**
$\Delta(1920)$	$3/2^+$	***	***	**				n	***		**
$\Delta(1930)$	$5/2^-$	***	***								
$\Delta(1940)$	$3/2^-$	**	*	**	F				(seen	in	$\Delta\eta$)
$\Delta(1950)$	$7/2^+$	****	****	****	o				***	*	***
$\Delta(2000)$	$5/2^+$	**			r						**
$\Delta(2150)$	$1/2^-$	*	*			b					
$\Delta(2200)$	$7/2^-$	*	*			i					
$\Delta(2300)$	$9/2^+$	**	**				d				
$\Delta(2350)$	$5/2^-$	*	*				d				
$\Delta(2390)$	$7/2^+$	*	*				e				
$\Delta(2400)$	$9/2^-$	**	**					n			
$\Delta(2420)$	$11/2^+$	****	****								
$\Delta(2750)$	$13/2^-$	**	**								
$\Delta(2950)$	$15/2^+$	[illegible]	**								

22 Δ*
7 ****
3 ***
7 **
5 *

BnGa Additional States

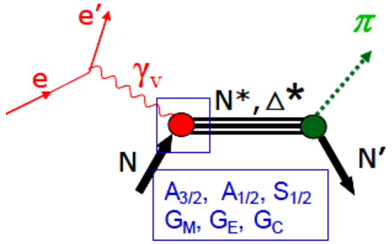
The latest GWU analysis (ARNDT 06) finds no evidence for this resonance.

Pion Electroproduction



GW N^* Program

- Energy dependent **SM08** and associated SES & SQS
- W = 1080 – 2000 MeV Q^2 = 0 – 6 GeV^2
- PWs = 60 [multipoles] [J < 6]
- Prms = 171
- Constraint: πN + Pion Photo Prod PWAs [no theoretical input]



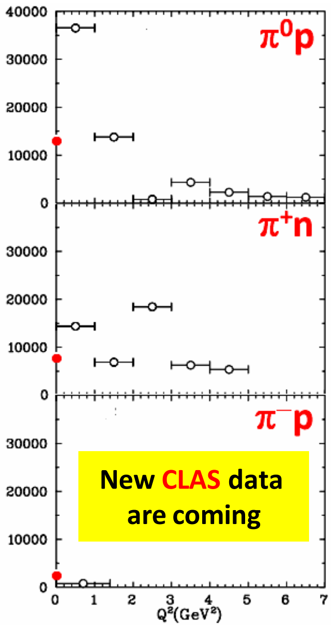
- 0.85 World Electro Prod from **JLab CLAS**

- **PWA Problems:**
  - Additional [18 S] Multipoles
  - Q^2 dependence

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

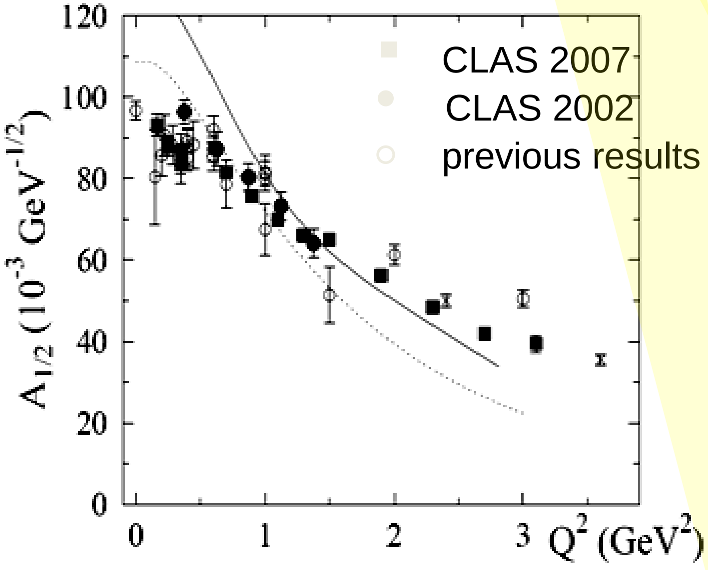
Reaction	Data	χ^2
$\gamma^* p \to \pi^0 p$	55,766	81,284
$\gamma^* p \to \pi^+ n$	51,312	80,004
Redundant	14,772	17,375
Total	121,850	178,663
$\gamma N \to \pi N$	25,358	53,458
All Photo*	147,208	232,121
$\pi N \to \pi N$	31,479	57,157
All πN	178,687	289,278
$\gamma^* n \to \pi^- p$	801	
$\gamma^* n \to \pi^0 n$	No Data	

Q^2-Data



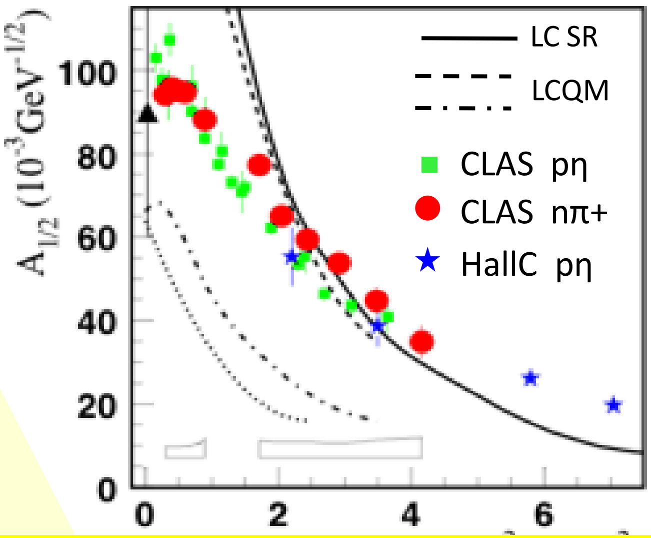
New CLAS data are coming

Helicity Amplitudes : $S_{11}(1535)$

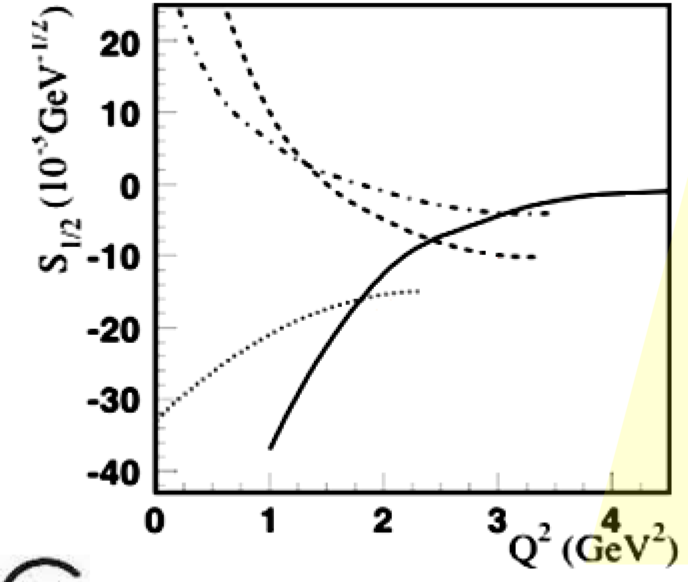


Analysis of pη assumes $S_{1/2}$=0

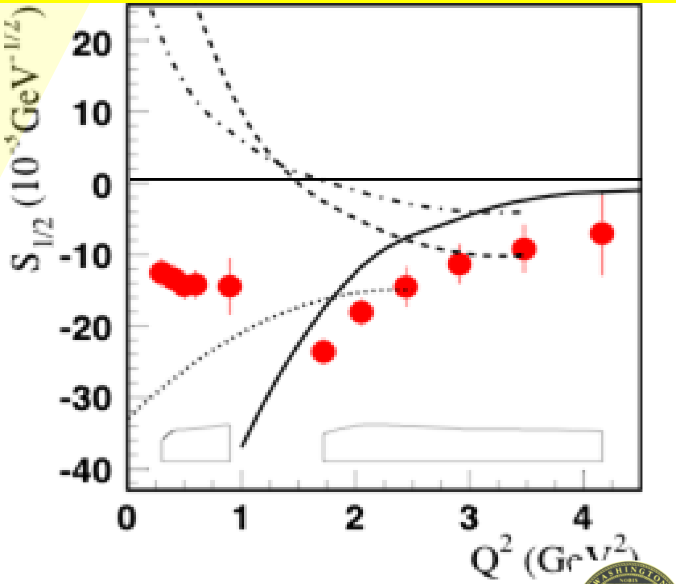
Branching ratios $\beta_{N\pi} = \beta_{N\eta} = 0.45$



Courtesy of Kijun Park, QCD2010 @ Montpillier France June -July, 2010



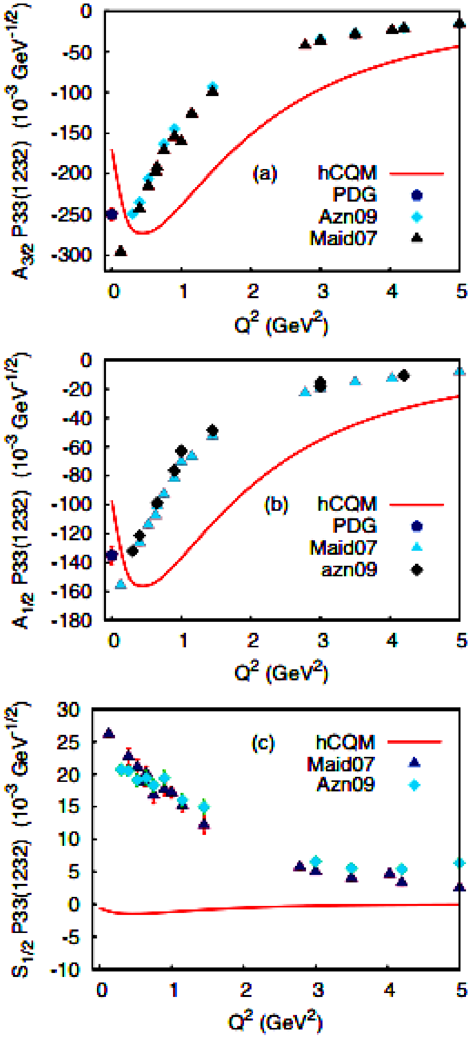
- $A_{1/2}$ (Q^2) from Nπ and pη are consistent
- First extraction of $S_{1/2}$(Q^2) amplitude.



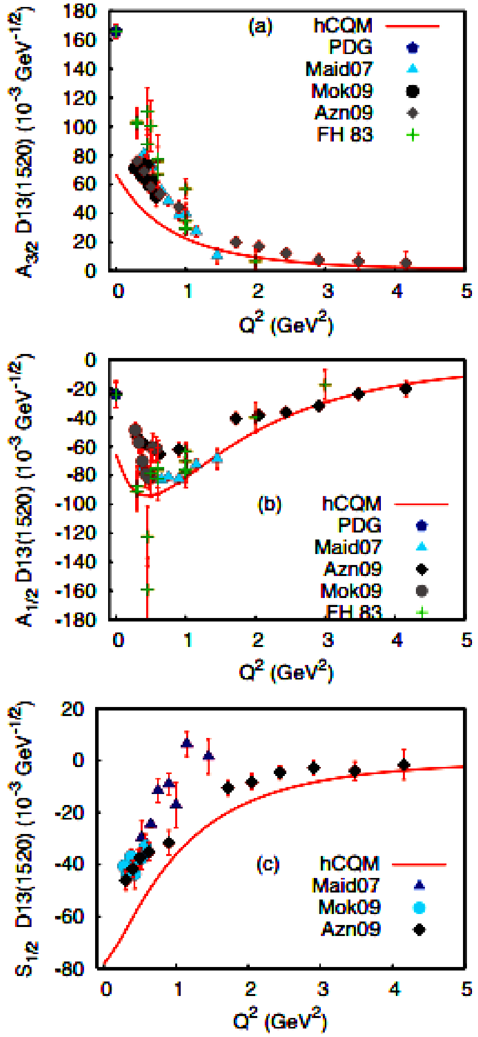
Constituent Quark Model Predictions

[E. Santopinto and M. Giannini, Phys Rev C **86**, 065202 (2012)]

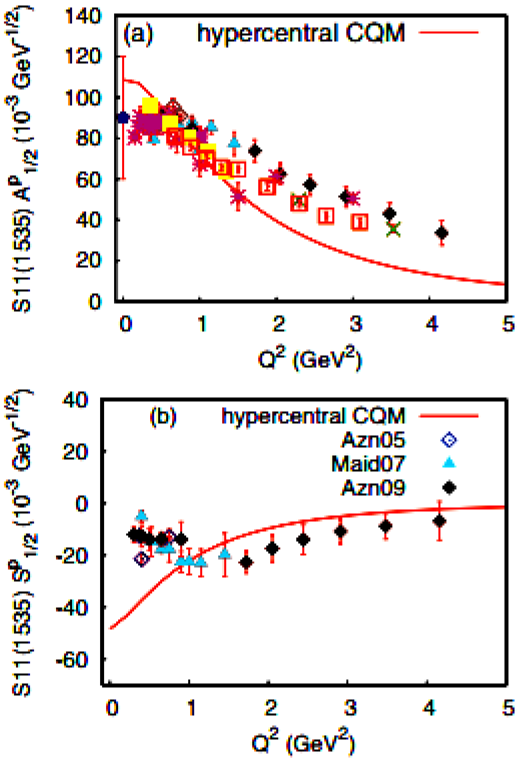
Δ(1232)3/2⁺



N(1520)3/2⁻



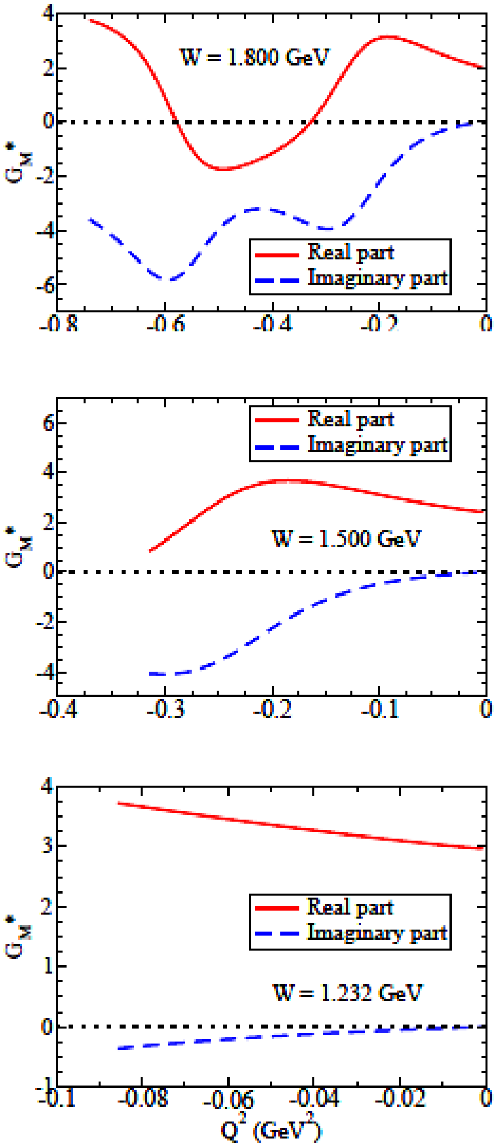
N(1535)1/2⁻

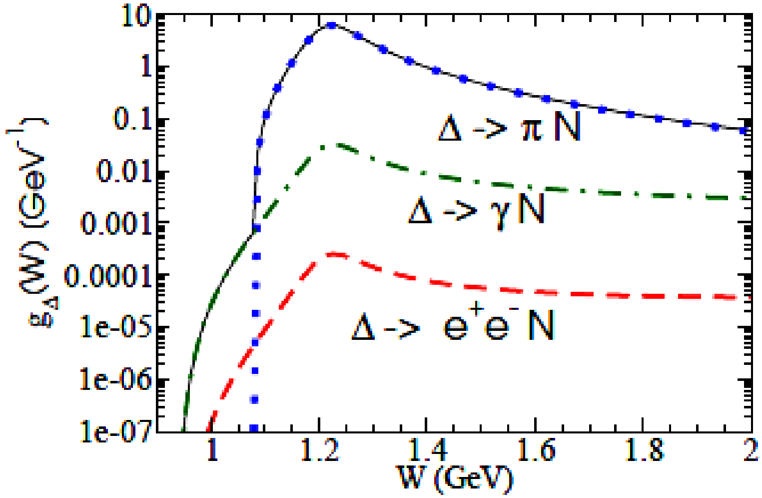


Timelike $\gamma^* N \rightarrow \Delta$ form factors and Δ Dalitz decay

[G. Ramalho and M.T. Pena, Phys Rev D **85**, 113014 (2012)]

Δ(1232)3/2⁺





$$g_\Delta(W) = A\frac{W^2\Gamma_{tot}(W)}{(W^2 - M_\Delta^2)^2 + W^2\left[\Gamma_{tot}(W)\right]^2}$$

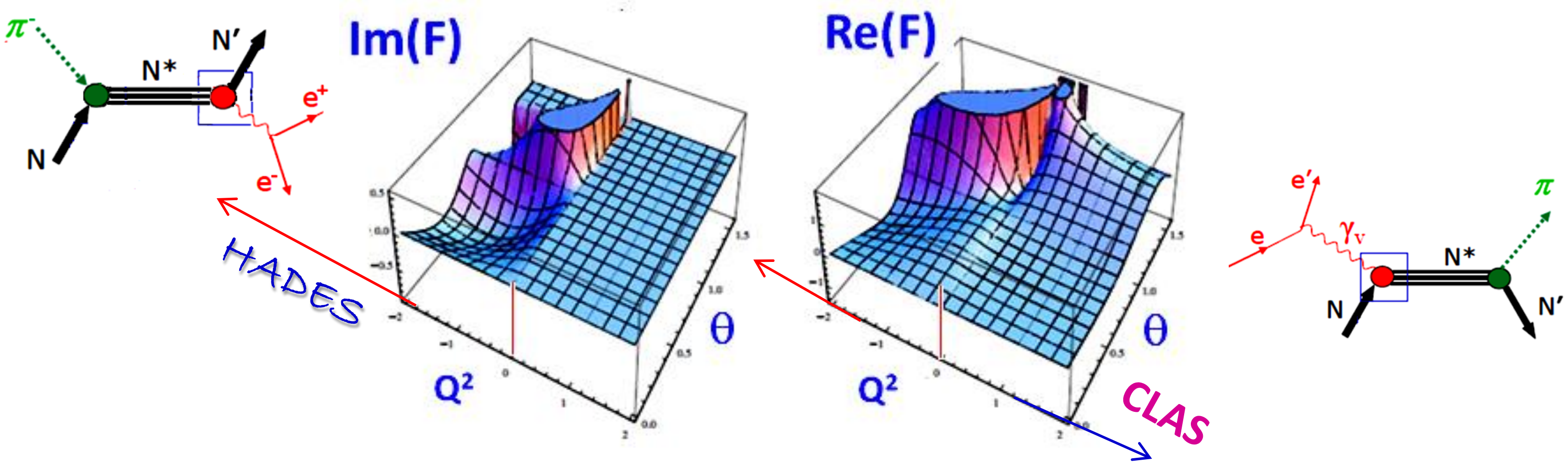
$$\Gamma_{tot}(W) = \Gamma_{\pi N}(W) + \Gamma_{\gamma N}(W) + \Gamma_{e^+e^-N}(W)$$

Inverse Pion Electroproduction (IPE)

- **IPE** is the only process which allows the determination of **EM nucleon** & pion **formfactors** in the intervals

$0 < k^2 < 4\,M^2 = 3.53\ \text{GeV}^2$ $\qquad$ $0 < k^2 < 4\,m_\pi = 0.08\ \text{GeV}^2$

which are kinematically unattainable from e^+e^- initial states.



- **IPE** $\pi^- p \to e^+ e^- n$ measurements will significantly complement the current **electroproduction** $\gamma^* N \to \pi N$ study for the evolution of baryon properties with increasing momentum transfer by investigation of the case for the ***time-like virtual photon***.

Phenomenology for Baryon Resonances

Do you have any questions to the speaker?