

New Neutron Electromagnetic Couplings for Non-Strange Baryons

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- SAID for Baryon Spectroscopy.
- Pion photoproduction off the neutron.
- FSI for $\gamma n \rightarrow \pi^- p$.
- Recent GW-ITEP FSI for $\gamma n \rightarrow \pi^- p$.
- New neutron EM couplings.
- Polarized Measurements.



SQSD for Baryon Spectroscopy



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 π N PWA since 1987



Below 4 GeV

Partial-Wave Analyses at GW

[See Instructions]

31,402

Pion-Nucleon

[W = 1320 to 1930 MeV]

5,267

Pion-Pion-Nucleon

241,214 evts

27,265

Kaon-Nucleon

38,162

Nucleon-Nucleon

9,086

Pion Photoproduction

113,900

Pion Electroproduction

1,030

Kaon Photoproduction

6,235

Eta Photoproduction

6,083

Eta-Prime Photoproduction

1,914

Pion-Deuteron (elastic)

Pion-Deuteron to Proton+Proton

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

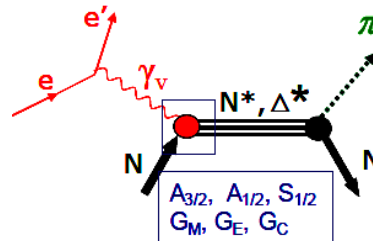


N^* and Δ^* States coupled to πN

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

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

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



CNS DAC Home
▶ CNS DAC [SAID]
CNS Home
TUTORIALS



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

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GW SAID Contribution

- 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?**

I = 1/2

| Particle | J^P | Status overall | Status | | Status as seen in — | | | | | | | | | |
|----------|----------|----------------|---------|------------|---------------------|-----------|-----------|-------------|------------|---------|-------------|-----|-----|--|
| | | | 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) | $13/2^+$ | ** | ** | | | | | | | | | | | |

I = 3/2

| Particle | J^P | Status overall | Status | | Status as seen in — | | | | | | | | | |
|----------------|----------|----------------|---------|------------|---------------------|-----------|-----------|-------------|------------|-------------------------|-------------|-----|-----|--|
| | | | 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 | | | | | | | | | |
| $\Delta(2200)$ | $7/2^-$ | | | | | | | | | | | | | |
| $\Delta(2300)$ | $9/2^+$ | | | | | | | | | | | | | |
| $\Delta(2350)$ | $5/2^-$ | | | | | | | | | | | | | |
| $\Delta(2390)$ | $7/2^+$ | | | | | | | | | | | | | |
| $\Delta(2400)$ | $9/2^-$ | | | | | | | | | | | | | |
| $\Delta(2420)$ | $11/2^+$ | **** | **** | * | | | | | | | | | | |
| $\Delta(2750)$ | $13/2^-$ | ** | ** | | | | | | | | | | | |
| $\Delta(2950)$ | $15/2^+$ | ** | ** | | | | | | | | | | | |

SAID:

- Tends (by construction) to miss narrow N*s with $\Gamma < 30$ MeV
- Reveals only wide N*s, but not too wide [$\Gamma < 500$ MeV] and possessing not too small BR [BR > 0.04]



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.

$$N(1675) 5/2^- \quad I(J^P) = \frac{1}{2}(\frac{5}{2}^-) \quad \text{Status: } **** \quad D_{15}$$

| | |
|--------|--|
| PDG12: | $N(1675)5/2^- \rightarrow p\gamma$, helicity-1/2 ampl, $A_{1/2}$: $+0.019 \pm 0.008$ |
| | $N(1675)5/2^- \rightarrow n\gamma$, helicity-1/2 ampl, $A_{1/2}$: -0.043 ± 0.012 |
| SAID12 | $N(1675)5/2^- \rightarrow p\gamma$, helicity-3/2 ampl, $A_{3/2}$: $+0.016 \pm 0.001$ |
| | $N(1675)5/2^- \rightarrow n\gamma$, helicity-3/2 ampl, $A_{3/2}$: -0.058 ± 0.002 |

- PDG estimate 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.

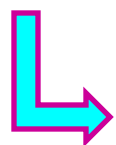
$$N(1720) 3/2^+ \quad I(J^P) = \frac{1}{2}(\frac{3}{2}^+) \quad \text{Status: } **** \quad P_{13}$$

| | PDG12 | SAID12 |
|---|--------------------|--------------------|
| $N(1720)3/2^+ \rightarrow p\gamma$, helicity-1/2 ampl, $A_{1/2}$: | -0.01 to 0.11 | $+0.095 \pm 0.002$ |
| $N(1720)3/2^+ \rightarrow p\gamma$, helicity-3/2 ampl, $A_{3/2}$: | -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.

$$N(1710) 1/2^+ \quad I(J^P) = \frac{1}{2}(\frac{1}{2}^+) \quad \text{Status: } *** \quad P_{11}$$

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)

$$N(1680) 1/2^+$$



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

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

- Energy dependent **SPO6/WI08** and associated **SES**
- $T = 0 - 2600$ MeV [$W = 1078 - 2460$ MeV]
- 4-channel Chew-Mandelstam **K-matrix** parameterization [$\pi N, \pi\Delta, \rho N, \eta N$]
- 3 mapping variables: $g^2/4\pi, a[\pi p], E_{th}$
- PWs = 30 πN {15 [I=1/2] + 15 [I=3/2]} + 4 ηN [$l < 9$]
- Prms = 99 [I=1/2] + 89 [I=3/2]



[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*.

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

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



*Pion Photoproduction:
Phenomenological Point of View Shot*



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**.
- 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**.

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

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



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

Born [no free parameters to fit]

πN -PWA [no theoretical input]

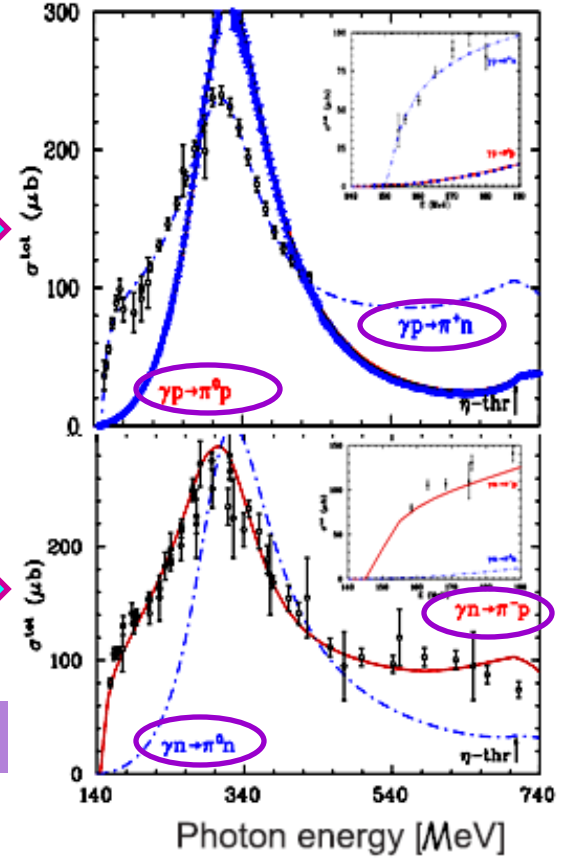
| Reaction | Data (Dpol) | χ^2 |
|--------------------------------|---------------|---------------|
| $\gamma p \rightarrow \pi^0 p$ | 14,612 (3 %) | 32,449 |
| $\gamma p \rightarrow \pi^+ n$ | 8,510 (5 %) | 16,520 |
| $\gamma n \rightarrow \pi^- p$ | 3,058 (0 %) | 6,396 |
| $\gamma n \rightarrow \pi^0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

23,122 data

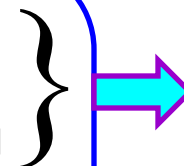
3,422 data

Much less known, 15%

- **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**.



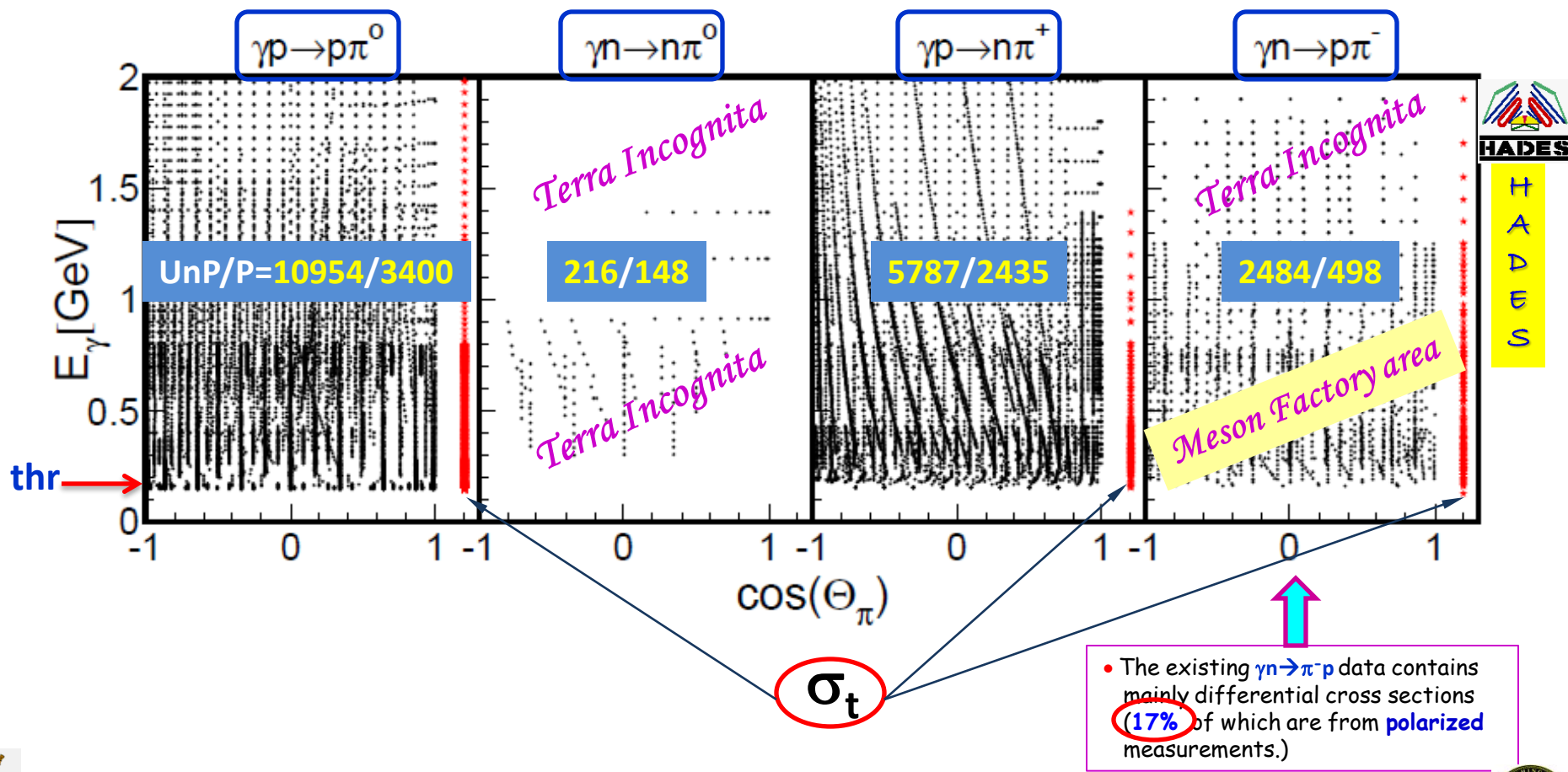
- DU13:** included recent **CLAS** $\pi^0 p$ & $\pi^+ n$ Σ [M. Dugger *et al*, arXiv:1308.4028 [nucl-ex]
- GB12/GZ12:** included recent **CLAS** $\pi^- p$ $d\sigma/d\Omega$ [W. Chen *et al*, Phys Rev C **86**, 015206 (2012)]
- CM12:** **CM** parameterization for $T_{\pi N}$ [R. Workman *et al*, Phys 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.

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



$\gamma n \rightarrow \pi^- p$ 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** ($\theta = 40 - 140^\circ$) coverage and large **energy** binning ($E_\gamma = 100 - 200$ MeV.) In several cases, the **systematic** uncertainties have not been given.
- At lower energies ($E_\gamma < 700$ 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*, PRC70, 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 $\pi^- p \rightarrow \pi^0 n \rightarrow \gamma \gamma n$.



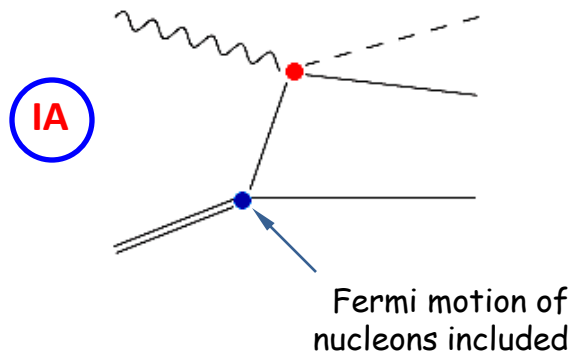
FSS for $\gamma N \rightarrow \pi N$



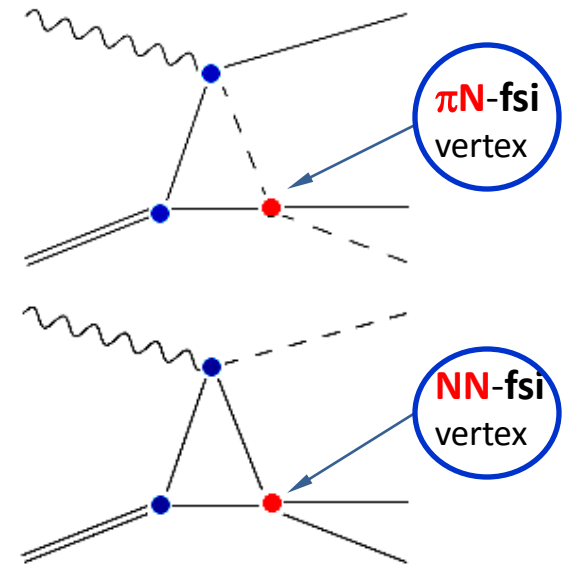
FSI and $\gamma d \rightarrow \pi^- p p \Rightarrow \gamma n \rightarrow \pi^- p$

[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 $\gamma n \rightarrow \pi N$ data.
- For $\gamma n \rightarrow \pi^- p$ the effect: **5% - 60%**. It depends on (E, θ) .



Input: SAID $\gamma N \rightarrow \pi N$, $\pi N \rightarrow \pi N$, $NN \rightarrow NN$ amplitudes for 3 leading terms.
DWF: Bonn Potential.



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



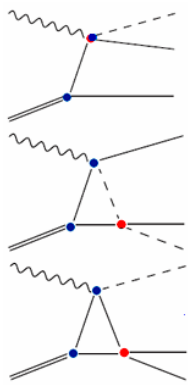
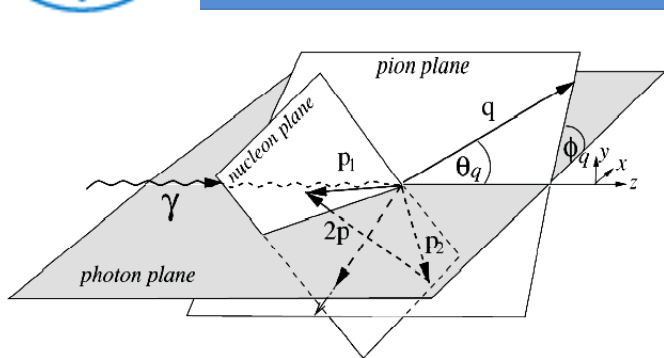
$$\frac{d\sigma}{d\Omega}(\gamma n) = R^{-1} \frac{d\sigma}{d\Omega}(\gamma d)$$





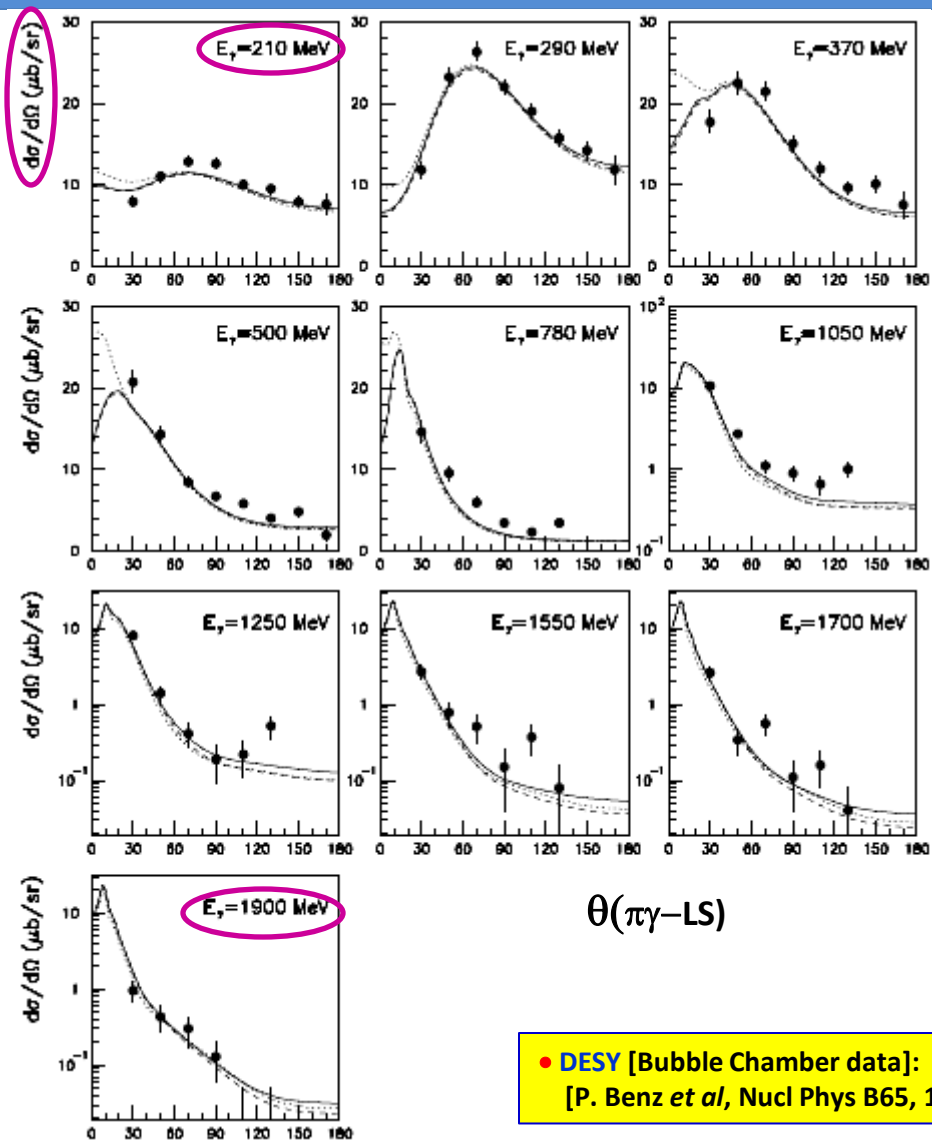
$\gamma d \rightarrow \pi^- pp$ from DESY Bubble Chamber

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



No fit to the data

..... IA
 - - - IA + NN_{fsi}
 — IA + (NN+πN)_{fsi}



• DESY [Bubble Chamber]:
 [P. Benz *et al*, Nucl Phys B65, 158 (1973)]



FSI for $\gamma n \rightarrow \pi^- p$

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

$$R_{FSI} = (d\sigma/d\Omega_{\pi p}) / (d\sigma^{IA}/d\Omega_{\pi p})$$

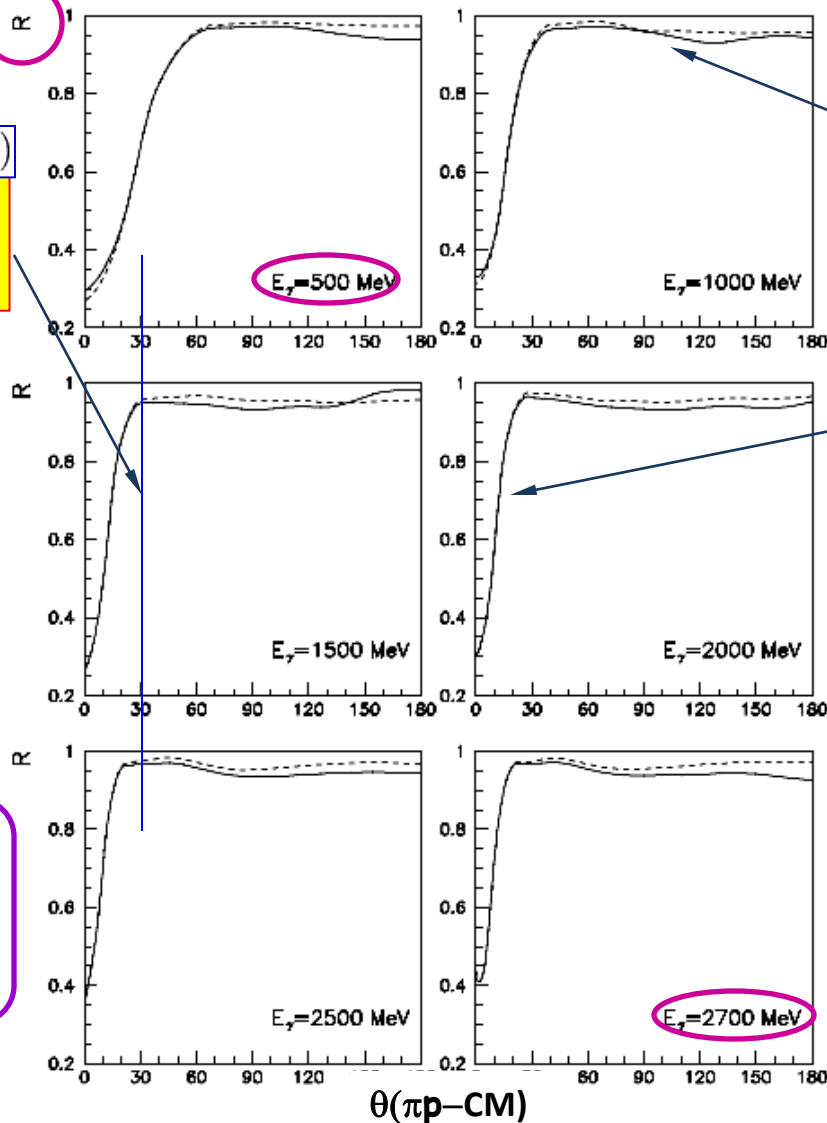
Cuts:

$p_s > 200 \text{ MeV}/c$
 $p_f > 200 \text{ MeV}/c$

CLAS data:

$E > 1 \text{ GeV}$
 $\theta > 32 \text{ deg}$

- There is no large sensitivity to cuts.



- For **CLAS** data
 - The **FSI** correction factor $R < 1$.
 - The behavior is smooth vs. θ .
 - The effect $\Delta\sigma/\sigma \leq 10\%$.

- There is a **sizeable FSI** effect from **S-wave** part of **pp-FSI** at small angles.
- This region **narrows** as the E_γ increases.

- Our estimation of the **Glauber FSI** corrections gives the value of **5%**.
- **Previous** estimations gave the order of **15-30%**.

-- [IA + NN_{fsi}] / IA
 — [IA + (NN+ π N)_{fsi}] / IA

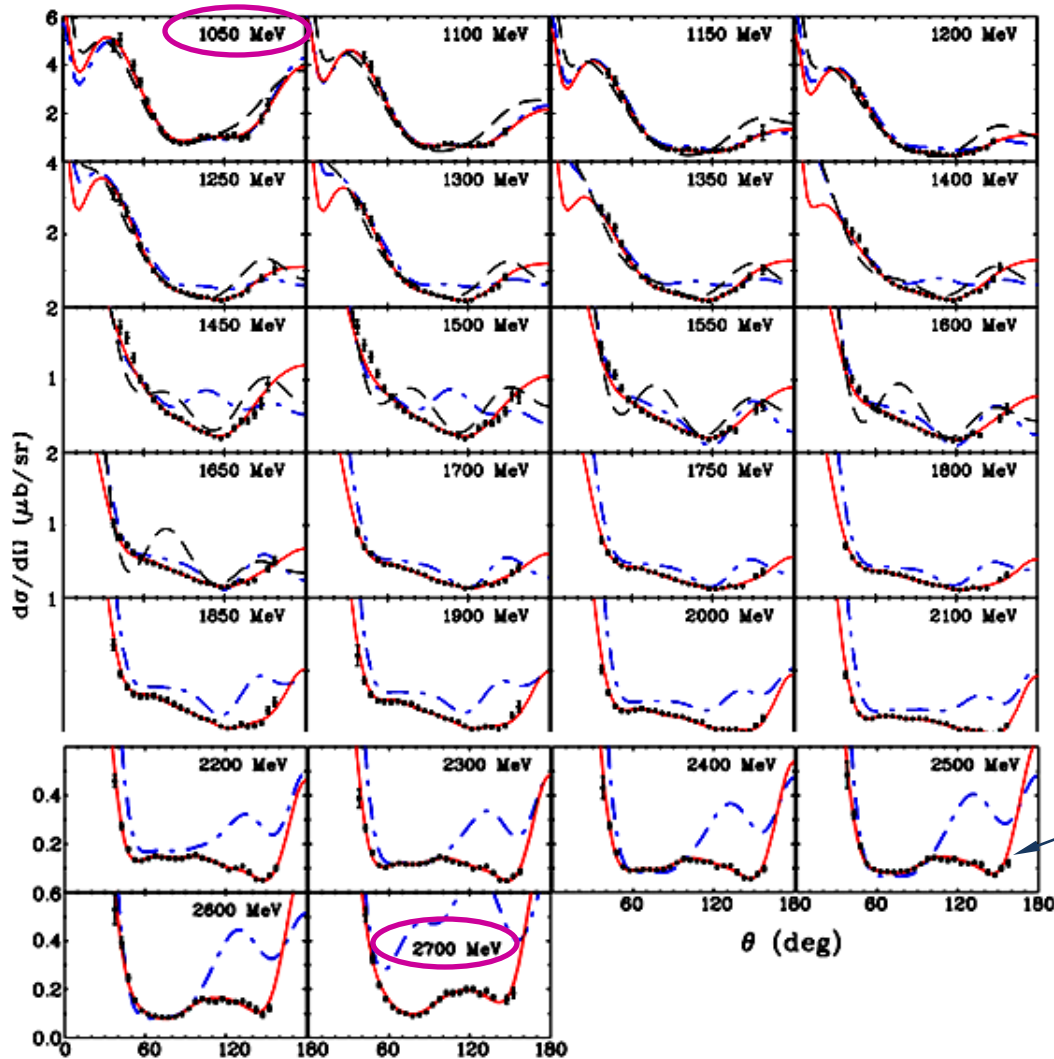


$$\gamma n \rightarrow \pi^- p$$

from CLAS and MAMI-B



[W. Chen *et al*, Phys Rev C 86, 015206 (2012) ; Phys Rev Lett 103, 012301 (2009)]



• The new **CLAS** cross sections have **quadrupled** the world database for $\gamma n \rightarrow \pi^- p$ above $E_\gamma = 1 \text{ GeV}$.

Systematics:

Exp: 6-9%

FSI: 2-3%

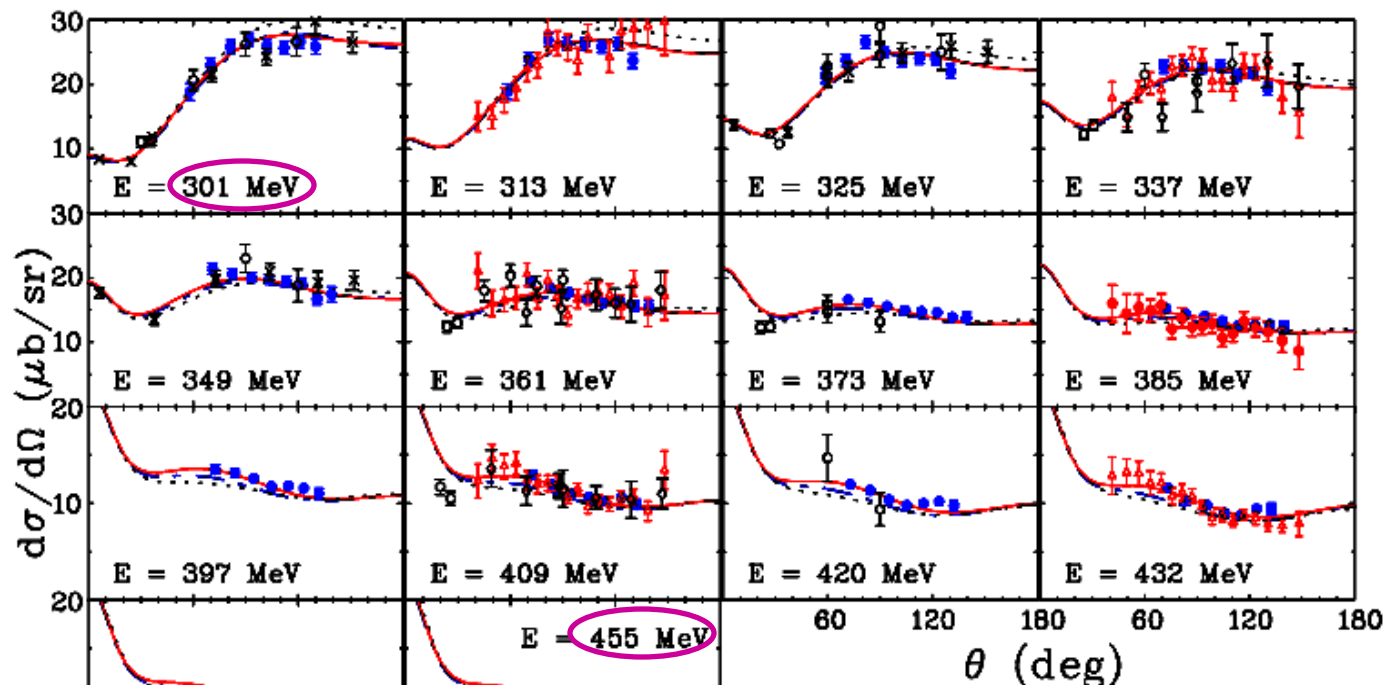
$\chi^2/dp = 45636/626 = 72.9$ [SN11 – no fit]
 $\chi^2/dp = 1580/626 = 2.5$ [GB12 – fit]

• CLAS data appear to have fewer angular structures than the earlier fits.

SAID-GB12
 SAID-SN11
 MAID07



- 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 $\gamma n \rightarrow \pi^- p$
- △ – CB@BNL for $\pi^- p \rightarrow n \gamma$
- o – TRIUMF, CERN, LBL, LAMPF for $\pi^- p \rightarrow n \gamma$

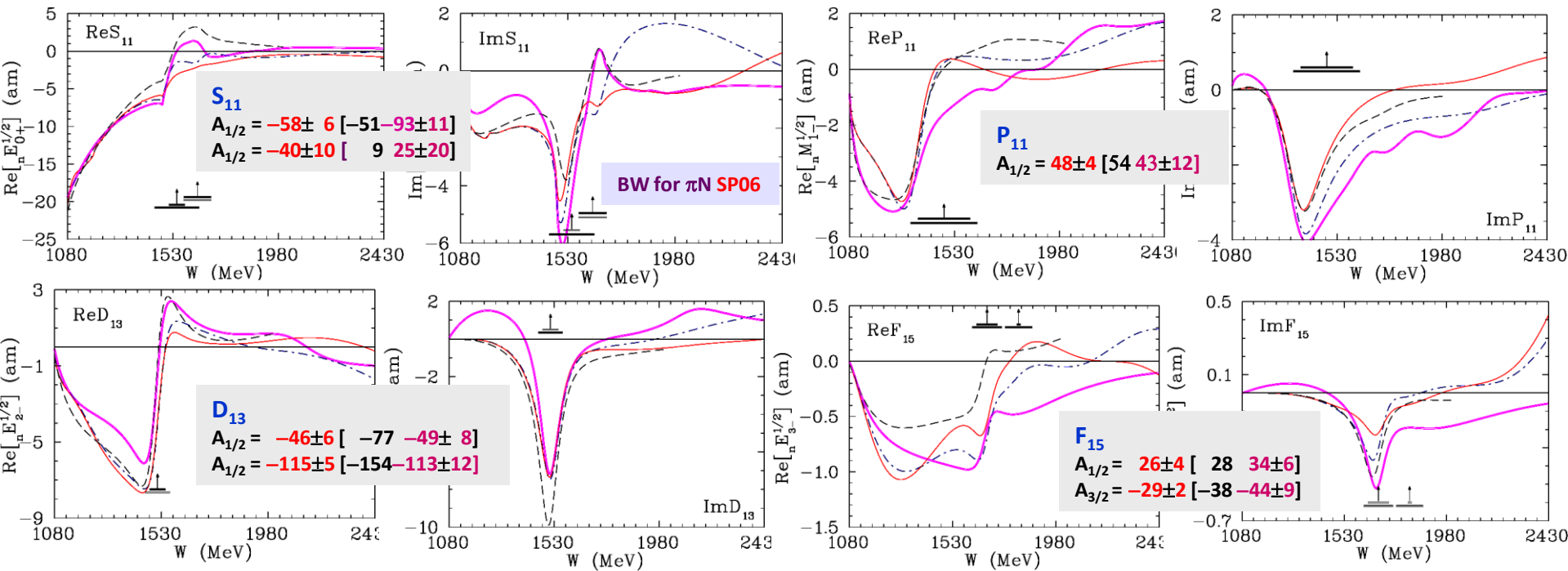
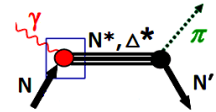
A. Shafi, *et al*, Phys Rev C **70**, 035204 (2004)



Neutron Multipoles from SAID GB12

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

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



- Significant changes have occurred at high energies.
- Comparisons to earlier SAID and fit from the Mainz and BnGa13 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 $S = 0$ & $I = 1/2$ 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 | $nA_{1/2}$ | $nA_{3/2}$ |
|--------------------------------|--|------------------------------------|-------------------------------------|--|-----------------------------------|--|
| $N(1535)1/2^-$ -63 S_{11} | $W_R=1547$ MeV $\Gamma=188$ MeV $\Gamma_{\pi N}/\Gamma=0.36$ | -58±6 -60±3 -93±11 -46±27 | $N(1520)3/2^-$ -38 -114 D_{13} | $W_R=1515$ MeV $\Gamma=104$ MeV $\Gamma_{\pi N}/\Gamma=0.63$ | -46±6 -47±2 -49±8 -59±9 | -115±5 -125±2 -113±12 -139±11 |
| $N(1650)1/2^-$ -35 S_{11} | $W_R=1635$ MeV $\Gamma=115$ MeV $\Gamma_{\pi N}/\Gamma=1.00$ | -40±10 -26±8 25±20 -15±21 | $N(1675)5/2^-$ -35 -51 D_{15} | $W_R=1674$ MeV $\Gamma=147$ MeV $\Gamma_{\pi N}/\Gamma=0.39$ | -58±2 -42±2 -60±7 -43±12 | -80±5 -60±2 -88±10 -58±13 |
| $N(1440)1/2^+$ -6 P_{11} | $W_R=1485$ MeV $\Gamma=284$ MeV $\Gamma_{\pi N}/\Gamma=0.79$ | 48±4 45±15 43±12 40±10 | $N(1680)5/2^+$ 19 -23 F_{15} | $W_R=1680$ MeV $\Gamma=128$ MeV $\Gamma_{\pi N}/\Gamma=0.70$ | 26±4 50±4 34±6 29±10 | -29±2 -47±2 -44±9 -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)



GW SAID Contribution

$I = 1/2$

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

- 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?**

$I = 3/2$

| Particle | J^P | Status as seen in — | | | | | | | | | |
|----------------|----------|---------------------|---------|------------|---------|-----------|-----------|-------------|-------------------------|---------|-------------|
| | | 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 | | | | | | |
| $\Delta(2390)$ | $7/2^+$ | * | * | | n | | | | | | |
| $\Delta(2400)$ | $9/2^-$ | ** | ** | | | | | | | | |
| $\Delta(2420)$ | $11/2^+$ | **** | **** | * | | | | | | | |
| $\Delta(2750)$ | $13/2^-$ | ** | ** | | | | | | | | |
| $\Delta(2950)$ | $15/2^+$ | ** | ** | | | | | | | | |

BnGa Additional States

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



Summary for *Neutron* Couplings

- The differential cross section for the processes $\gamma n \rightarrow \pi^- p$ was extracted from new **CLAS** and **MAMI-B** measurements accounting for **Fermi** motion effects in the **IA** as well as **NN**- and πN -**FSI** effects beyond the **IA**.

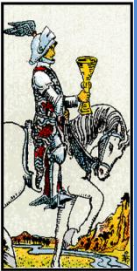
Consequential calculations of the **FSI** corrections, as developed by the **GW-ITeP** Collaboration, was applied.

- New cross sections departed significantly from our predictions, at the higher energies, and greatly modified the fit result.
 - New $\gamma n \rightarrow \pi^- p$ and $\gamma n \rightarrow \pi^0 n$ data will provide a critical constraint on the determination of the multipoles and couplings of low-lying baryon resonances using the **PWA** and **coupled channel** techniques.
- **Polarized measurements** [JLab, CB@MAMI, Spring-8, CB-ELSA...] will help to bring more physics in. **FSI** corrections need to apply.



Polarized Measurements off Neutron



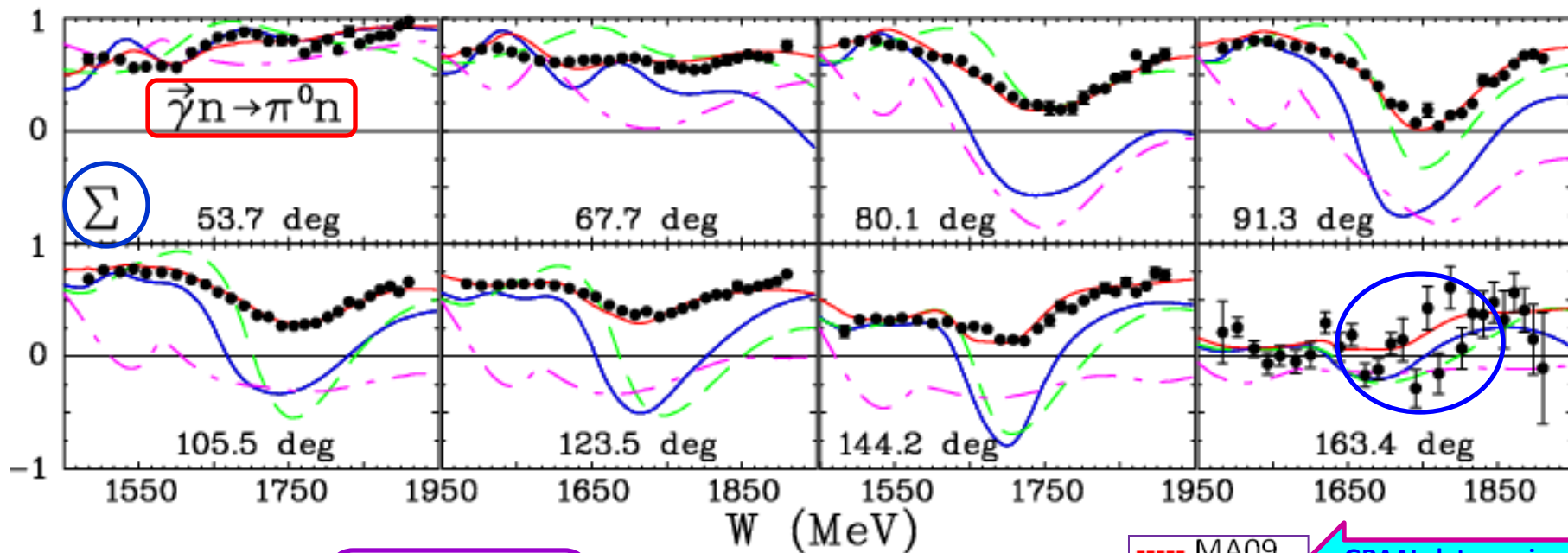


Recent GRAAL Σ for $\vec{\gamma}n \rightarrow \pi^0 n$

[R. Di Salvo *et al*, Eur Phys J A 42, 151 (2009)]

• The difference between previous Pion Prod and new **GRAAL** measurements may result in significant changes in the **neutron** couplings.

• 216 GRAAL Σ s are 60% of the World $\pi^0 n$ data



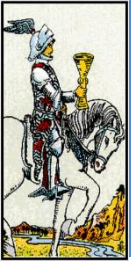
| | χ^2/dp |
|--------|-------------|
| MAID07 | 100 |
| SP09 | 223 |
| MA09 | 3.1 |

No FSI included

- MA09
- SP09
- MAID07
- DTM

← GRAAL data are in

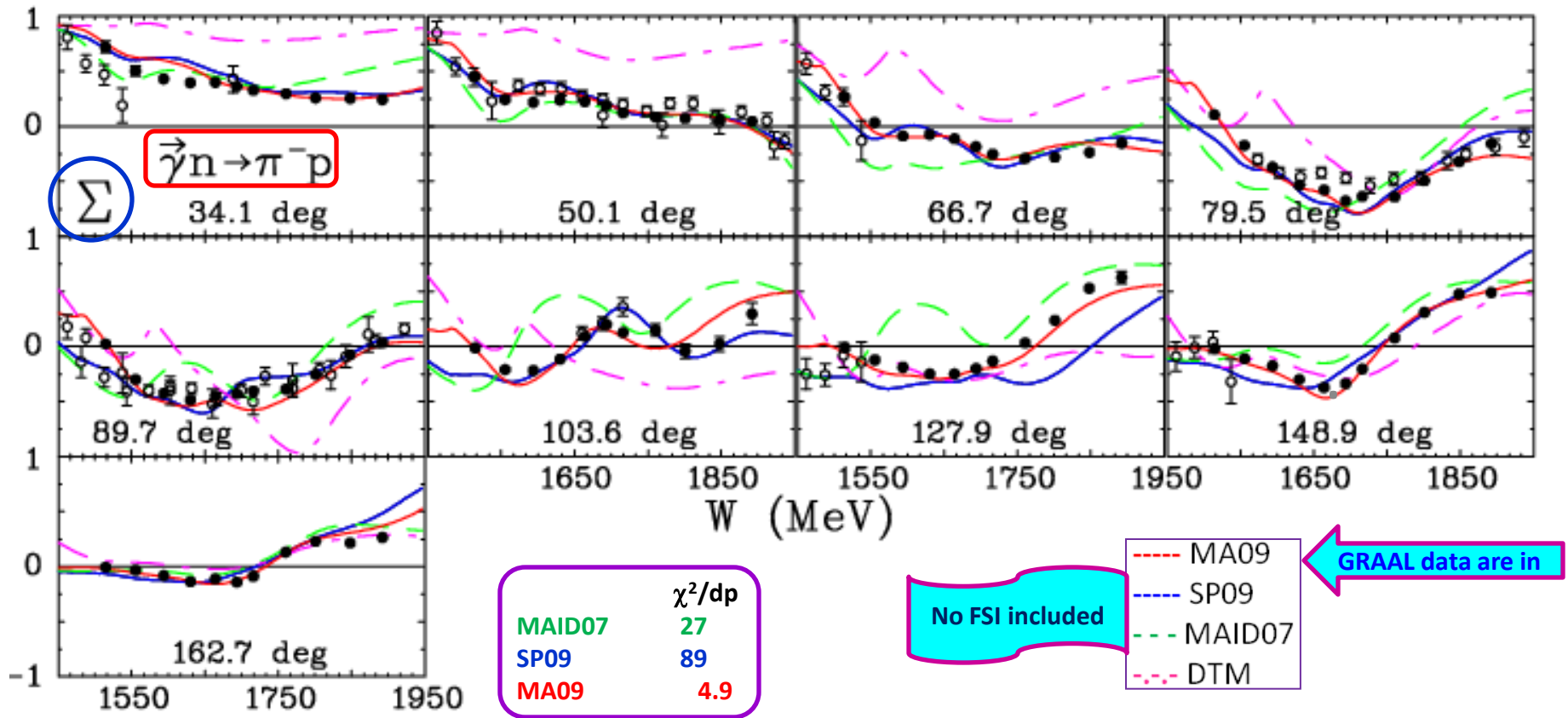




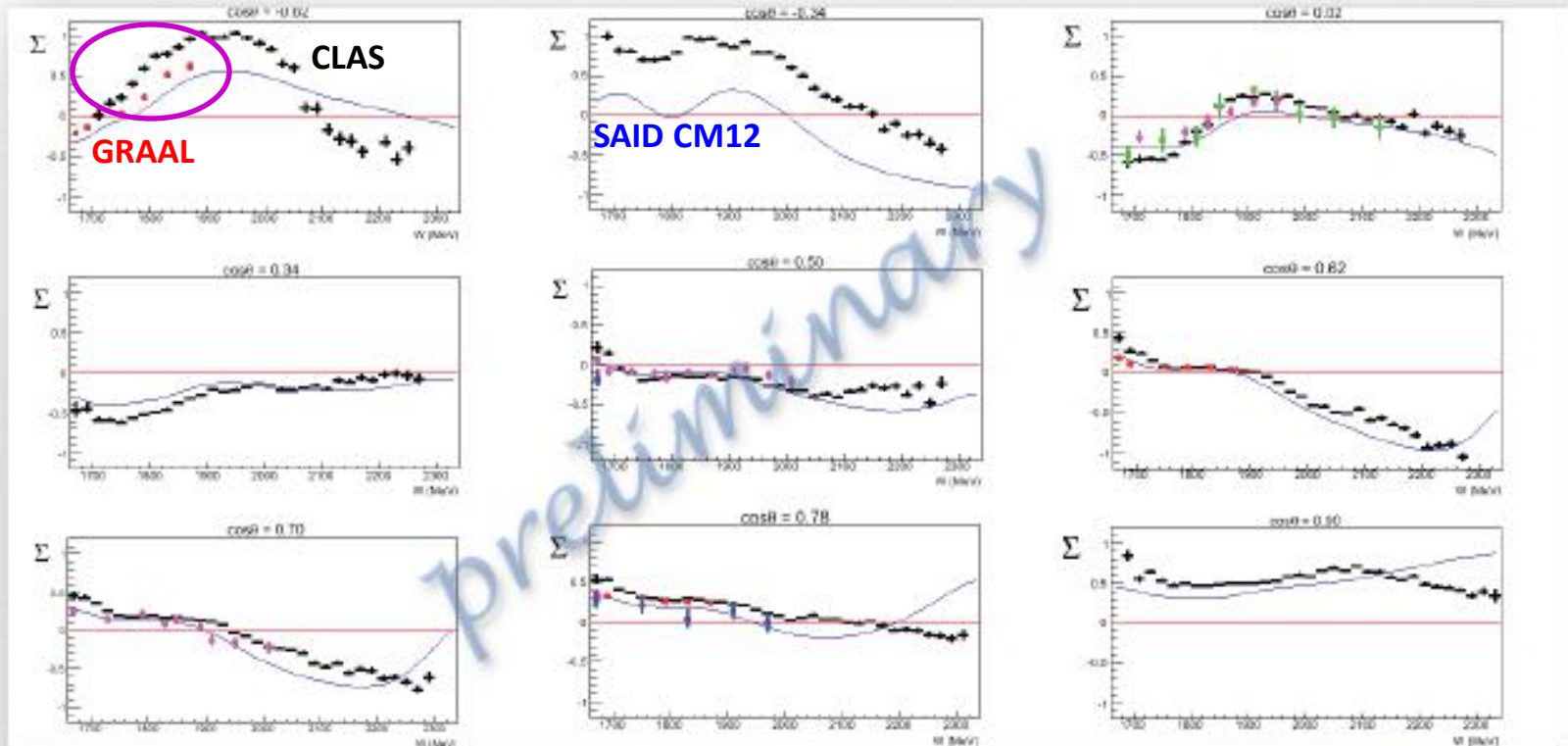
Recent GRAAL Σ for $\vec{\gamma}n \rightarrow \pi^- p$

[G. Mandaglio *et al*, Phys Rev C 82, 045209 (2010)]

- Previous $\gamma n \rightarrow \pi^- p$ measurements provided a better constraint vs. $\gamma n \rightarrow \pi^0 n$ case.



Σ for $\vec{\gamma} n \rightarrow p \pi^-$



Curve - SAID
 Red GRAAL
 Magenta and Blue - Erevan

No FSI included

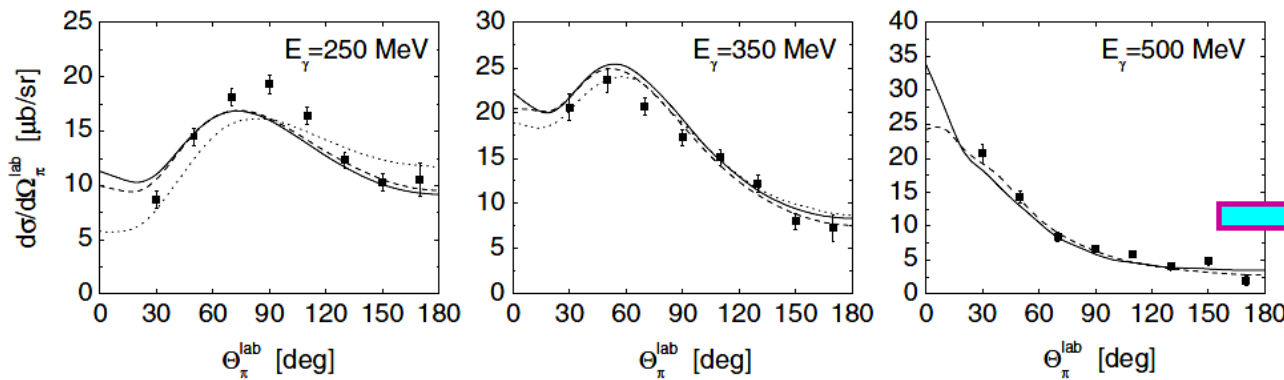
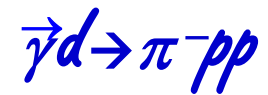
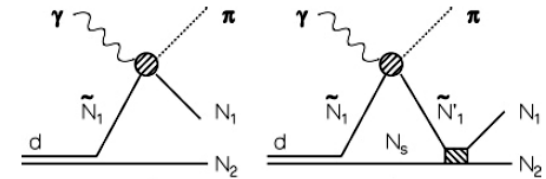
D. Sokhan

9 out of 40 angular bins are shown
 Bins 0.04 in cos and 20 MeV in W

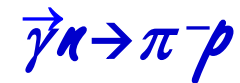
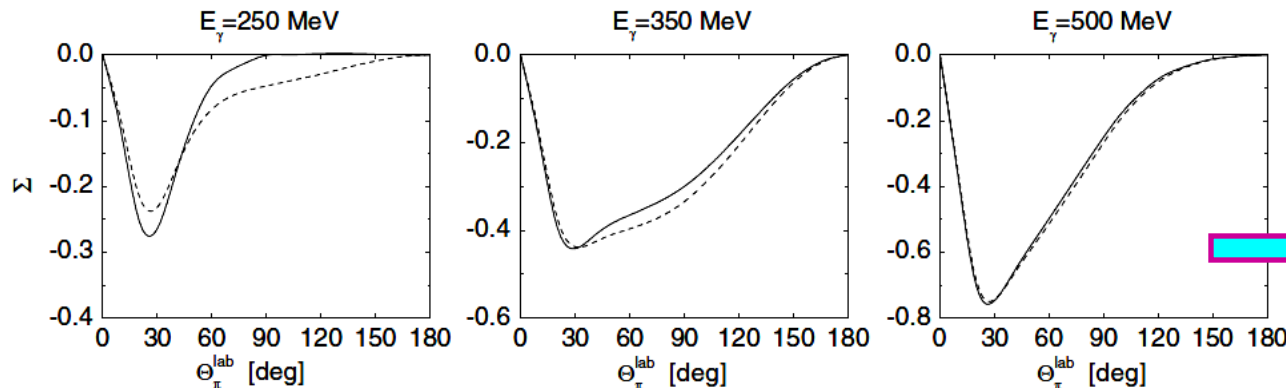


Σ -beam Asymmetry & FSI

[M.I. Levchuk *et al*, Phys Rev C 74, 014004 (2006)]



- FSI correction factor looks similar as for us, GW/ITEP.

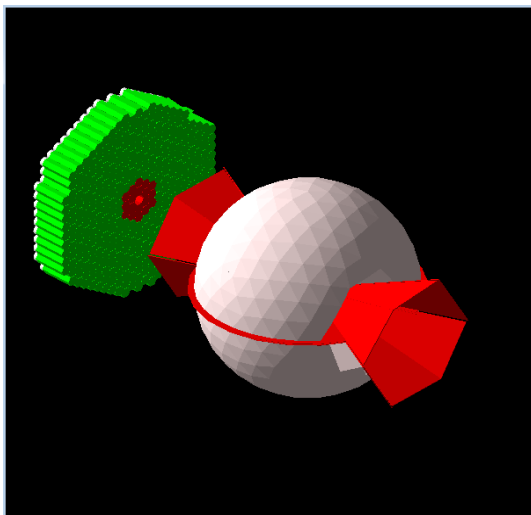


- FSI correction factor drops down vs. E_γ



For Tomorrow

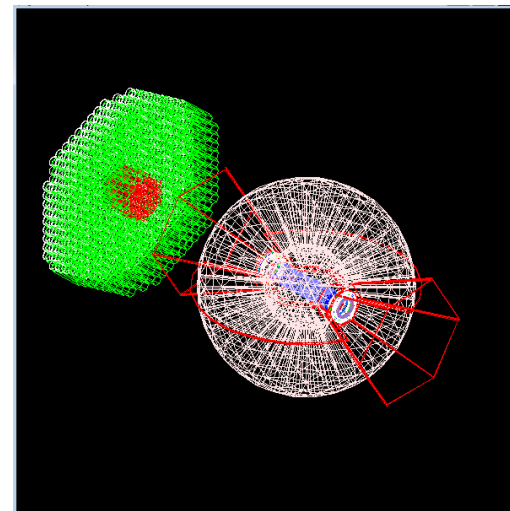


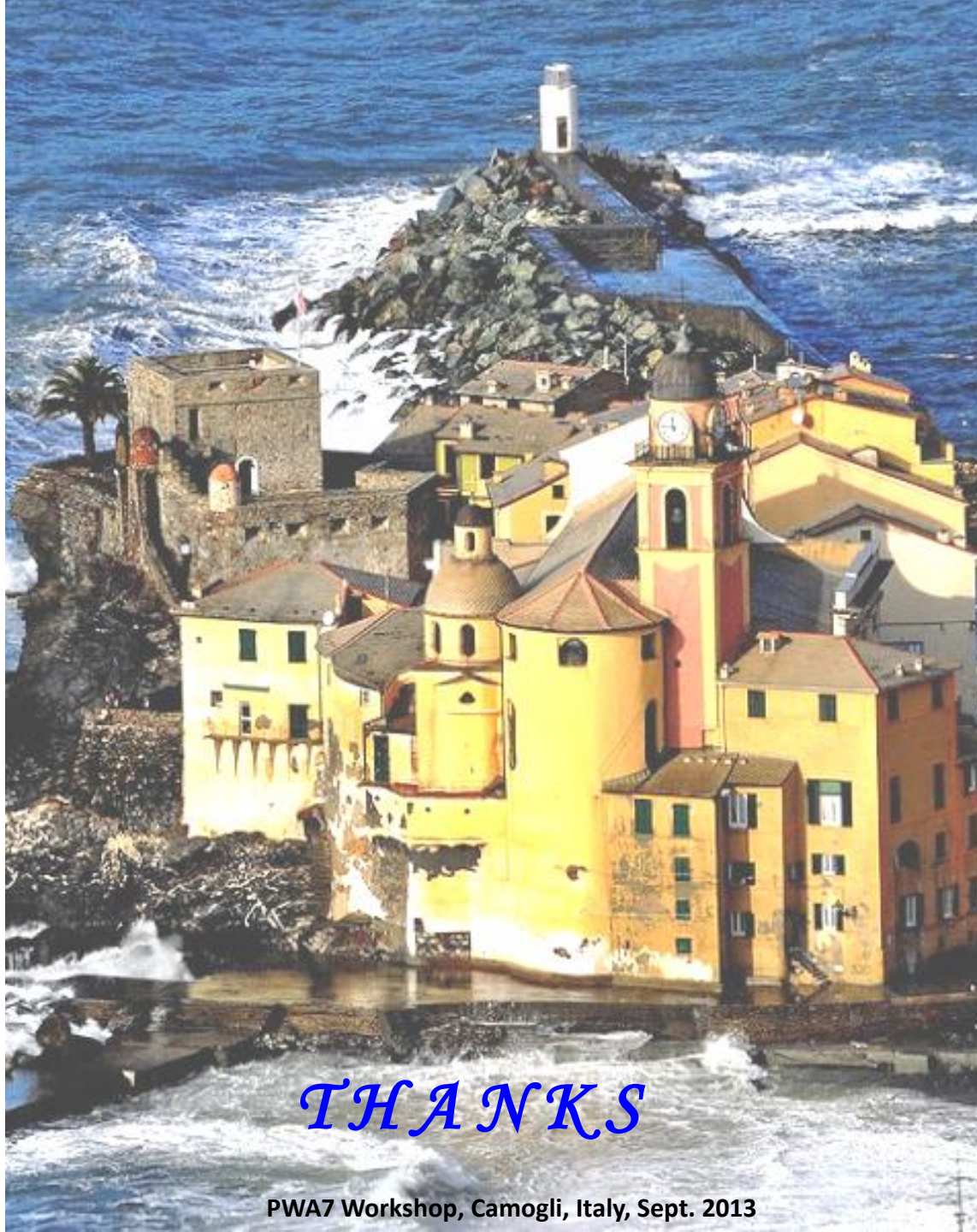


- We propose to perform a precision measurement of $d\sigma/d\Omega$ in the reactions $\gamma d \rightarrow \pi^- p$ and $\gamma d \rightarrow \pi^0 n$ in the tagged-photon energy region from **threshold** to **800 MeV**.
- The $d\sigma/d\Omega$ for the processes $\gamma n \rightarrow \pi^- p$ and $\gamma n \rightarrow \pi^0 n$ will be extracted from these **CB@MAMI-C** measurements accounting for Fermi motion effects in **IA** as well as NN- and π N-**FSI** effects beyond the IA.

- **Data** were taken in **March 2013** and **analysis** in progress.
- Consequential calculations of the **FSI** corrections, as developed by the **GW-ITEP** Collab, will be applied. We have $\pi^- p$ **FSI** already while $\pi^0 n$ **FSI** in progress.

- New **CB@MAMI** data will provide a critical constraint on the determination of the multipoles and couplings of low-lying baryon resonances using the PWA techniques developed by the **SAID** group.





THANKS

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9/22/2013

PWA7 Workshop, Camogli, Italy, Sept. 2013

Igor Strakovsky 32





Watson's Theorem



Watson's Theorem as Sample of FSI in πN Rescattering

- Connection between **scattering** and **decay processes** provides a solid theoretical ground for describing some hadronic effects – “**Watson's theorem**.”



PHYSICAL REVIEW

VOLUME 95, NUMBER 1

JULY 1, 1954

Some General Relations between the Photoproduction and Scattering of π Mesons

KENNETH M. WATSON

Department of Physics, University of Wisconsin, Madison, Wisconsin

(Received February 19, 1954)

M. Gell-Mann & K.M. Watson, Ann Rev Nucl Sci **4**, 219 (1954)

- For **pion photoproduction**, **isospin amplitudes** have to satisfy **Watson's theorem** below the **2π -threshold** allowing for a smooth departure from constraint at high energies.




$$\text{atan}\left(\frac{\text{Im}A_l}{\text{Re}A_l}\right) = \delta_l(\pi N)$$

- Above **2π -threshold**, the rule may still be true, if **inelasticity** of the corresponding **πN -elastic** amplitude is small (as, eg, for **P_{33}** .)



Evaluation of *PionPR* Amplitudes below 2π -Threshold

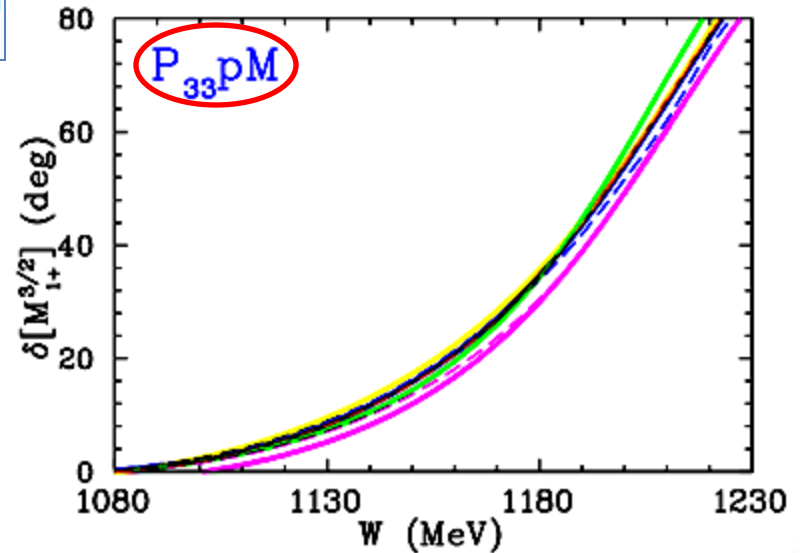
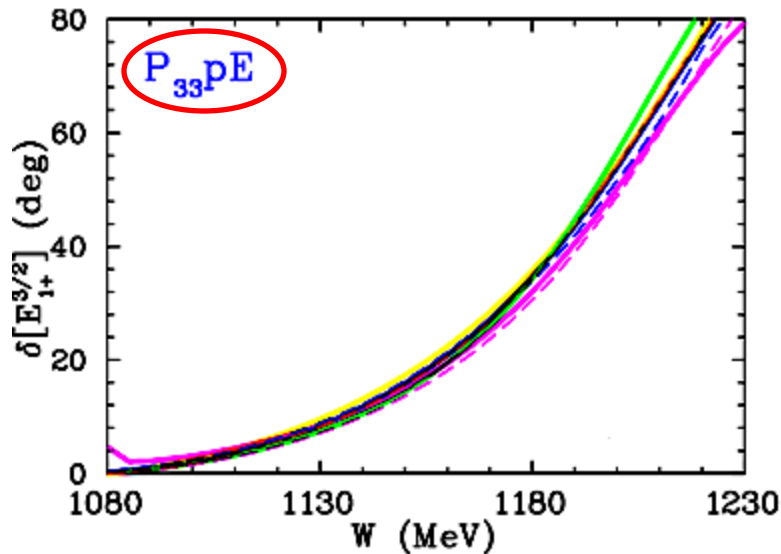
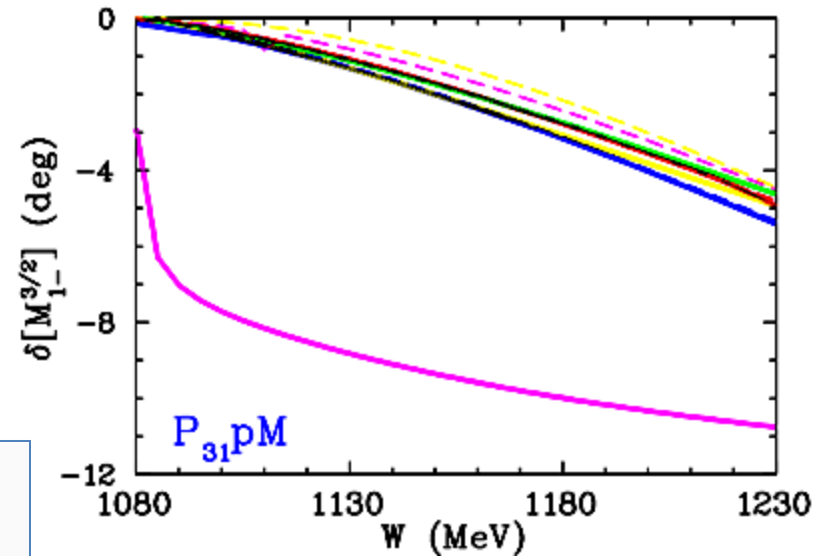
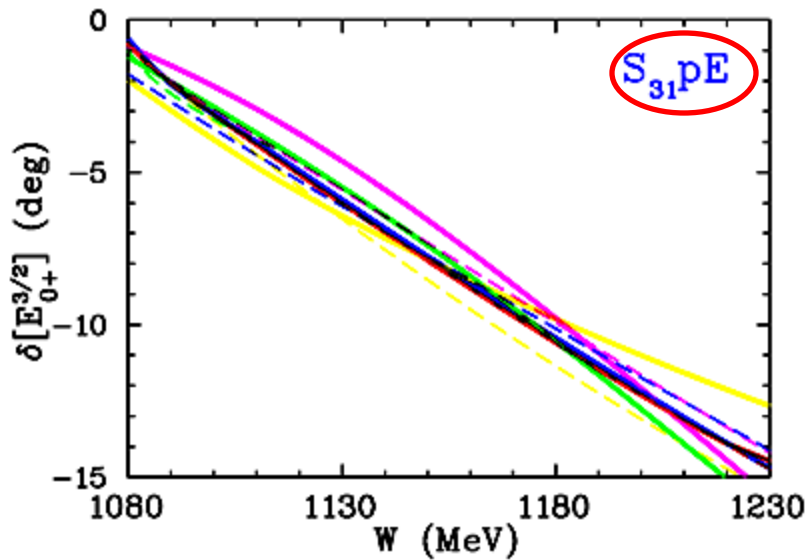
- **SAID** uses πN PWA results as a constraint for analysis of **PionPR data**  [see pg 9]
- Most of **PionPR** analyses are doing the same and uses **SAID** πN outcome or its modification as input.
- Let us evaluate several **PionPR** analyses such as **SAID**, **MAID**, **EBAC**, **Giessen**, & **BnGa** and compare πN phases coming from πN and **PionPR amplitudes** on proton target.
- **SAID database** has **all** these amplitudes which came from authors or we used WebSites.

| | πN - - - - - | PionPR ——— |
|----------------|---|---|
| SAID | R. Arndt, <i>et al</i> , PRC 74 , 045205(2006). | R. Workman, <i>et al</i> , PC 2012. |
| MAID | L. Tiator, <i>et al</i> , PC 2008. | D. Drechsel, <i>et al</i> , EPJA 34 , 69(2007). |
| EBAC | B. Julia-Diaz, <i>et al</i> , PRC 76 , 065201(2007). | T. Sato, <i>et al</i> , PRC 54 , 2660(1996). |
| Giessen | V. Shklyar, <i>et al</i> , PRC 71 , 055206 (2005). | V. Shklyar, <i>et al</i> , PRC 71 , 055206 (2005). |
| BnGa | A. Sarantsev, <i>et al</i> , PC 2009. | A. Anisovich, <i>et al</i> , EPJA 48 , 15(2012). |

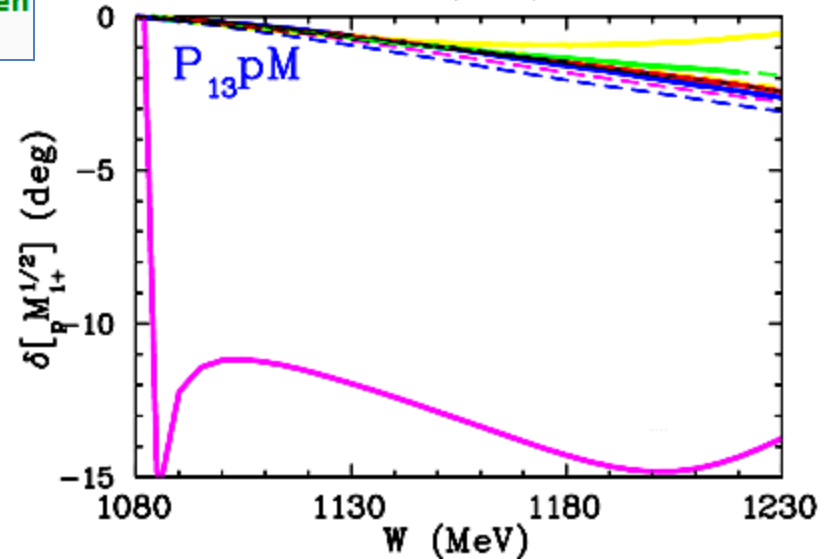
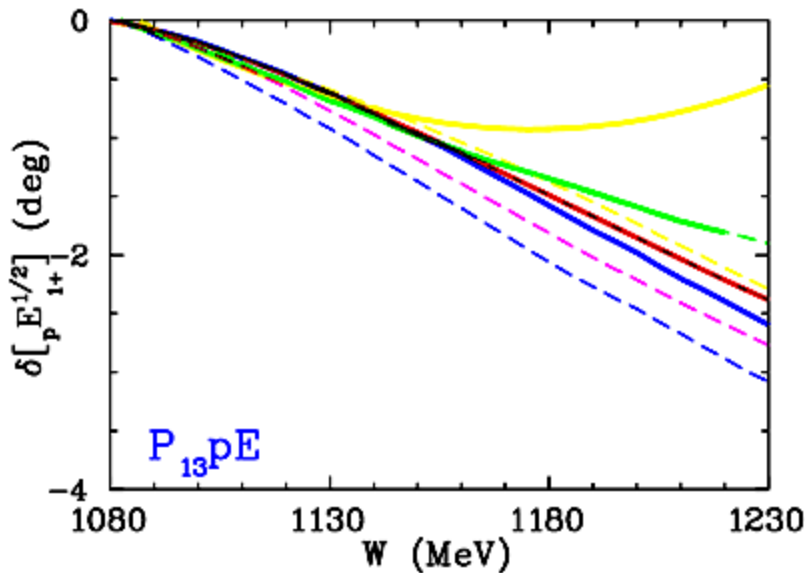
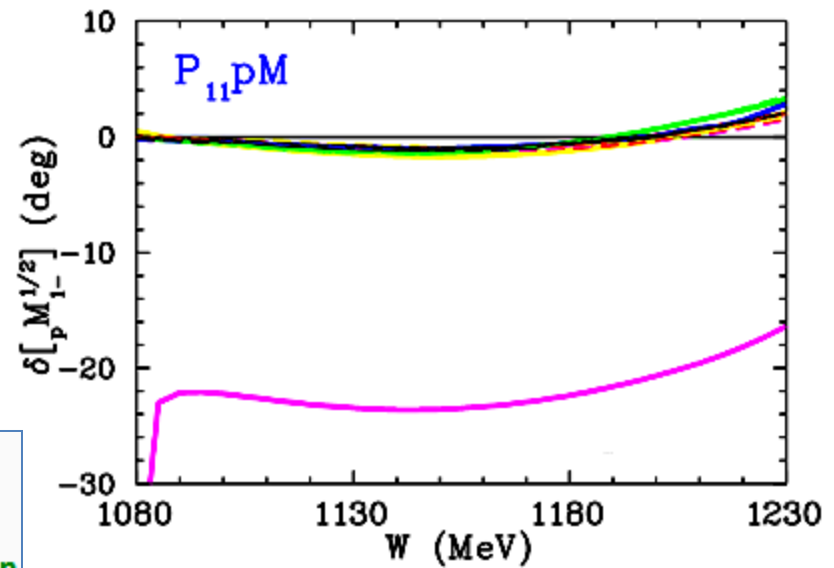
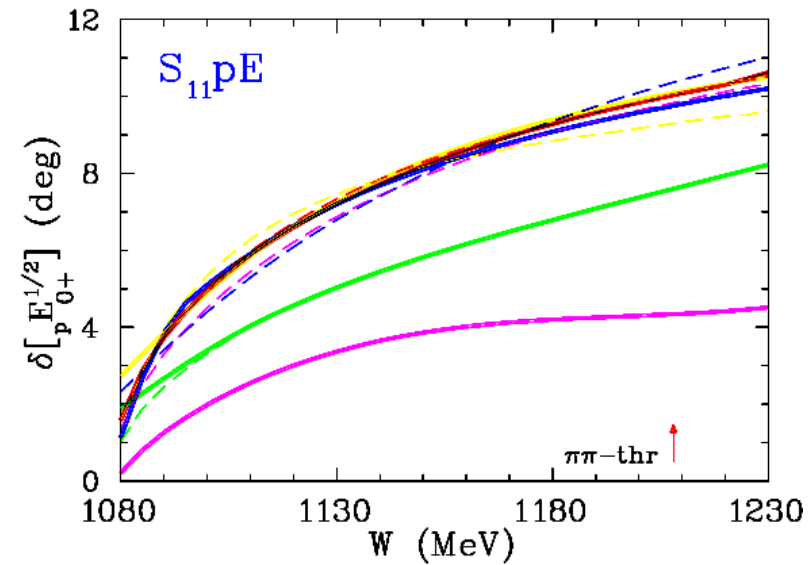
| Thresholds | | |
|--------------------------------|--------|--------------------|
| React | W(GeV) | E_{γ} (MeV) |
| $\gamma p \rightarrow \pi^0 p$ | 1.073 | 144.7 |
| $\gamma p \rightarrow \pi^+ n$ | 1.079 | 151.4 |



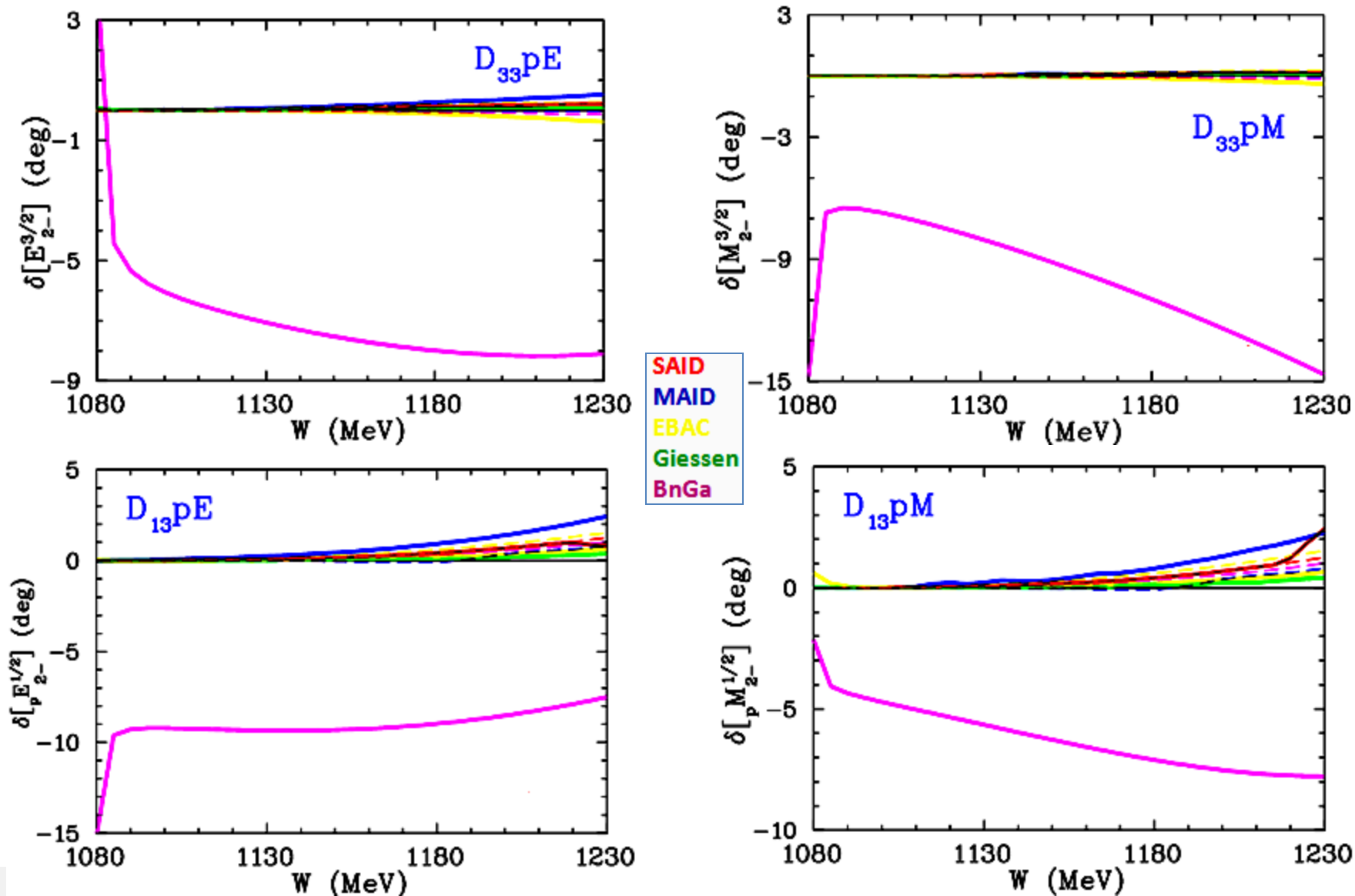
3/2 Isospin Amplitudes for E & M



1/2 Isospin Amplitudes for E & M



3/2 & 1/2 Isospin Amplitudes for E & M



Summary for *Watson's Theorem* for *Proton Amplitudes*

- **Phases** coming from πN **amplitudes** of different analyses are *consistent*.
- Some **phases** coming from different **PionPR** analyses are *consistent* to each other and phases coming from πN **amplitudes**:
3/2 Isospin Amplitudes: $E0+$, $E1+$, & $M1+$.
- Some **phases** coming from different **PionPR** analyses are *inconsistent* to each other and phases coming from πN **amplitudes**:
3/2 Isospin Amplitudes: $M1-$, $E2-$, $M2-$, $E2+$, & $M2+$.
1/2 Isospin Amplitudes: $E0+$, $M1-$, $E1+$, $M1+$, $E2-$, $M2-$, $E2+$, & $M2+$.
- Some **phases** coming from **E & M multipoles** are *inconsistent* to each other and phases coming from πN **amplitudes**.

