Progress on Neutron -Target Multipoles above 1 GeV

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- Single Pion PhotoProd
- Proton Multipoles
- FSI for $\gamma n \to \pi^- p$
- CLAS $\gamma n \to \pi^- p$ data for PWA
- Neutron Multipoles
- Summary & Prospects

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 quantum numbers and mass, lifetime, *etc]*

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

Center for Nuclear Studies

Data Analysis Center

Partial-Wave Analyses at GW

[See Instructions]

Below 4 GeV

Data	Reaction	Data
31,402	Pion-Nucleon	
	Pion-Pion-Nucleon	[W = 1320 to 1930 MeV] 241,214 evts
5,267	Kaon-Nucleon	
	Nucleon-Nucleon	38,162
26,554	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	

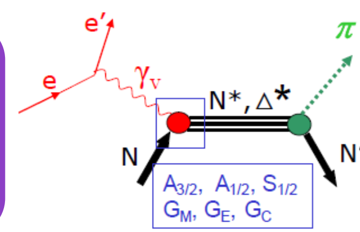
For $\pi \rightarrow 2\pi$, we use log-likelihood while for the rest – least-squares technologies

N^* and Δ^* States coupled to πN

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

- **GW SAID N* program consists of $\pi N \rightarrow \pi N$ → $\gamma N \rightarrow \pi N$ → $\gamma^* N \rightarrow \pi N$**
  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 **Spectroscopy** of **N*** & **Δ*** is **πN PWA**

- Non-strange objects in the PDG Listings come mainly from: Karlsruhe-Helsinki, Carnegie-Mellon-Berkeley, & GW/VPI
- The main source of EM couplings is the GW/VPI analysis

PDG particle data group

CNS Center for Nuclear Studies
Data Analysis Center

Partial-Wave Analyses at GW
[See Instructions]
- Pion-Nucleon
- Pion-Pion-Nucleon
- 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)

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SAID for Pion Photoproduction

[W. Chen, *et al*, arXiv:1203.4412 [hep-ph]]

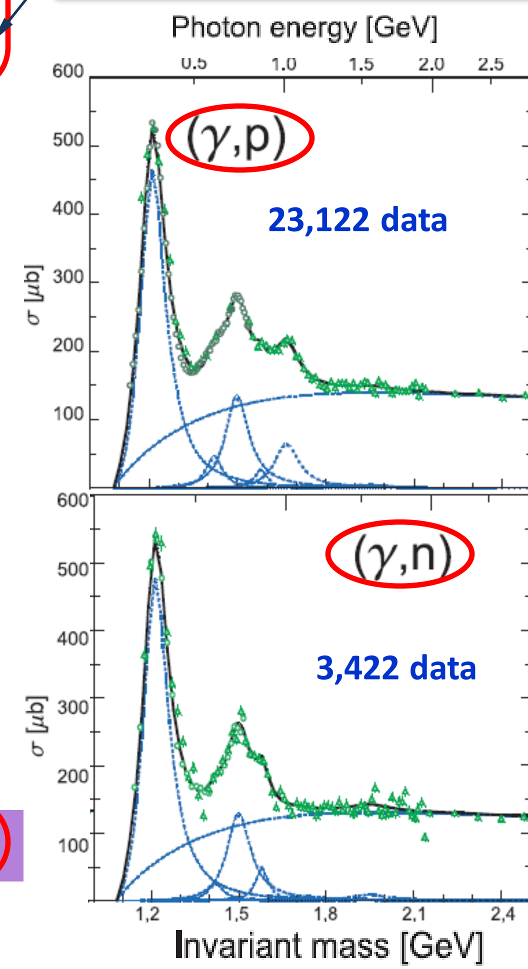
- Energy dependent GB12 and associated SES
- E = 145 – 2700 MeV [W = 1080 – 2460 MeV]
- PWs = 60 [E & M multipoles] [J < 6]
- Prms = 210
- Constraint: $M = (\mathrm{Born} + A)(1+iT_{\pi N}) + BT_{\pi N} + (C+iD)(\mathrm{Im}T_{\pi N} - |T_{\pi N}|^2)$

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

- 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, MAMI-C, SPring-8, CB-ELSA, MAX-lab, & LNS



Much less known, 15%

Recent SAID results for Pion Photo Prod

GB12: included recent ***CLAS*** $\pi^- p$ $d\sigma/d\Omega$ [W. Chen, *et al*, arXiv:1203:4412 [hep-ph]]

CM12: CM parameterization for $T_{\pi N}$ [R. Workman, *et al*, arXiv:1202.0845 [hep-ph]]

SN11: 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)]

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

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

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

Solution	Energy Limit (MeV)	χ^2/N_{Data}	N_{Data}
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**

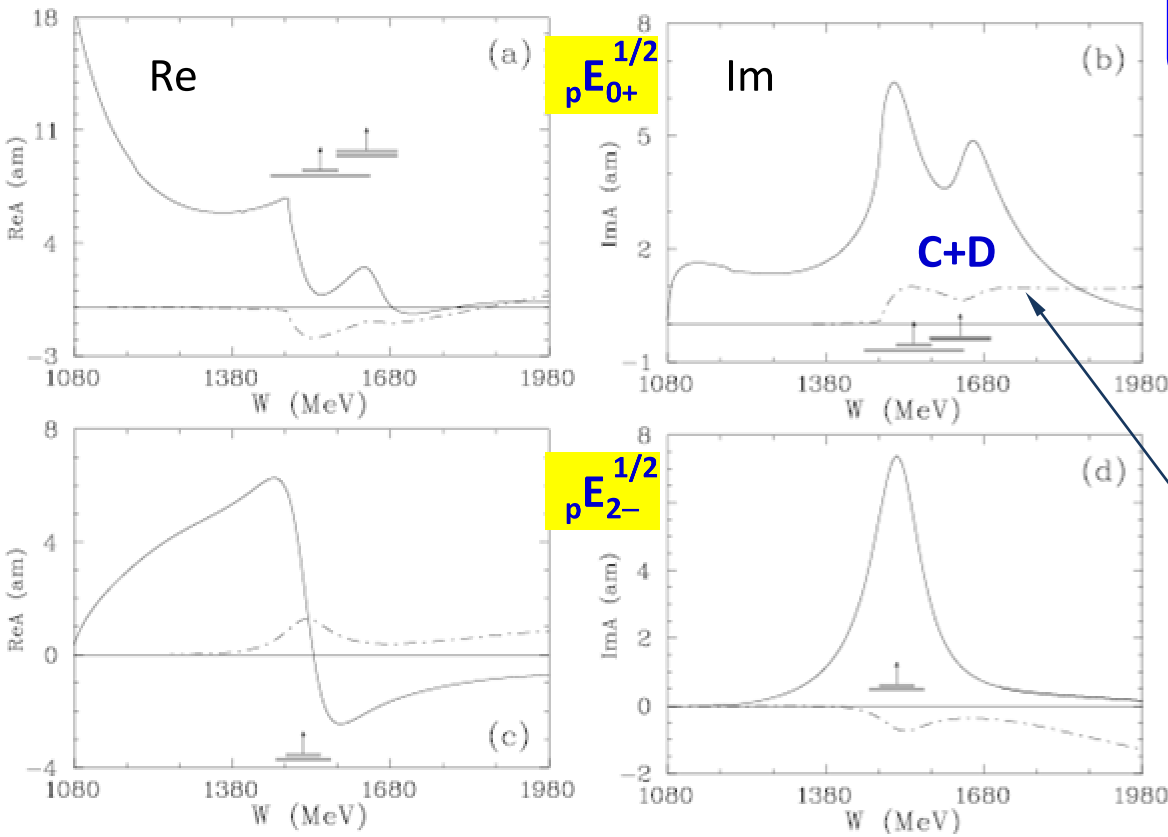
[most of this increase coming from data from **photon-tagging** facilities].

More details about **proton-target** measurements are in **Eugene Pasyuk's talk**

Recent SAID parameterization for Pion Photoproduction

[R. Workman, *et al*, Phys Rev C 85, 025201 (2012)]

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



- Terms **A – D** were parametrized in terms of **polynomials** with the correct threshold behavior.

- The **Born** and Phenomenological **A** & **B** contributions are generally found to cancel – effectively reducing the **Born** at high energies.

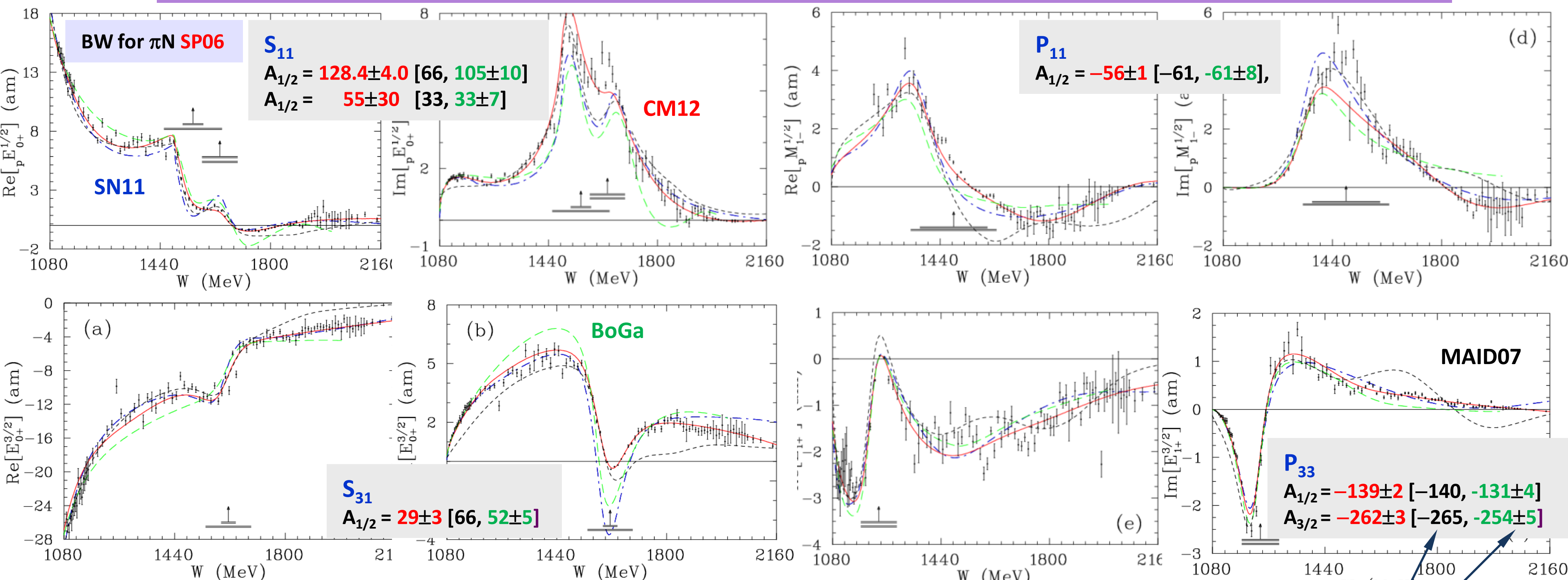
- **C** and **D** terms contributions grows with πN reaction **Xsection**.

- **Amplitude** satisfy **Watson's** [K.M. Watson, Phys Rev **95**, 228 (1954)] theorem below the 2π threshold allowing for a smooth departure from constraint at high energies.

Proton Multipoles from CM12

[R. Workman, W. Briscoe, M. Paris, IS, arXiv:1202.0845 – to be published in Phys Rev C **85** (2012)]

• **Overall: the difference between MAID07 or BoGa and SAID-CM12 is rather small but…**
Resonances may be essentially different



MAID07
BoGa

• **Significant changes have occurred at high energies**

• **Comparisons to earlier SAID fits and fit from the Mainz & BoGa groups show that the new CM12 solution is much more satisfactory at higher energies**

• **Subjective variables for SES are**
- **Energy binning**
- **Strength of constraints**
- **Which PW to be searched**

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

Single Pion Photoproduction

- Only with good data on both **proton** and **neutron** targets, one can hope to disentangle the **isoscalar** & **isovector EM** couplings of the various **N^*** & **Δ^*** resonances, [K.M. Watson, Phys Rev **95**, 228 (1954);
R.L. Walker Phys Rev **182**, 1729 (1969)]
as well as the **isospin** properties of the non-resonant **background amplitudes**.

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

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

$\gamma n \to \pi^- p$ *Experiment*

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

- Many of these are old **bremsstrahlung** measurements with limited angular coverages and large energy binnings (E_γ = **100 - 200** MeV).
  In several cases, the **systematic** uncertainties have not been given.

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

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

- The new **CLAS** cross section set has **quadrupled** the world database for $\gamma n \to \pi^- p$ above E_γ = **1** GeV.

Where we Are now

- Some of the N* baryons [N(1675)5/2⁻, for instance] have stronger **EM** couplings to the **neutron** than to the **proton** but parameters are very uncertain

$\boxed{N(1675)\ D_{15}}$ $I(J^P) = \frac{1}{2}(\frac{5}{2}^-)$ Status: ∗∗∗∗

PDG10: **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

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

$\boxed{N(1720)\ P_{13}}$ $I(J^P) = \frac{1}{2}(\frac{3}{2}^+)$ Status: ∗∗∗∗

	PDG10	SAID
N(1720)3/2⁺→pγ , helicity-1/2 ampl A1/2:	+0.018±0.030	+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 $\mathbf{P_{11}}$, N(1710)1/2⁺, that are not seen in the recent ***πN* PWA**, contrary to other PWAs used by the **PDG10**

$\boxed{N(1710)\ P_{11}}$ $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗

Most of the results published before 1975 were last included in our 1982 edition, Physics Letters **111B** 1 (1982). Some further obsolete results published before 1984 were last included in our 2006 edition, Journal of Physics, G **33** 1 (2006).

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

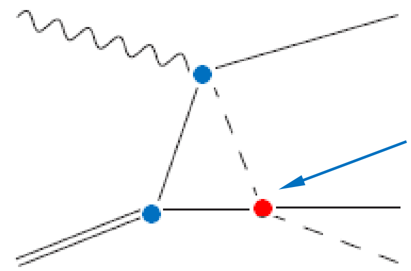
FSI and $\gamma d \to \pi^- p\, p \Longrightarrow \gamma n \to \pi^- p$

[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
- Effect: **5**% – **60**% It depends on (E,θ)

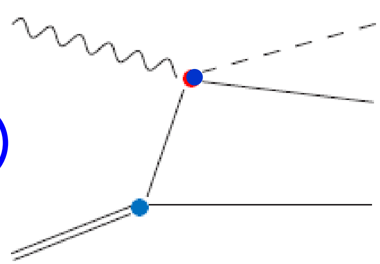
Input: **SAID** γN→πN, πN, NN amplitudes for **3** leading terms

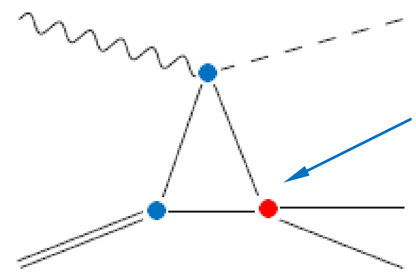
DWF: CD-Bonn



πN-**fsi** vertex

IA





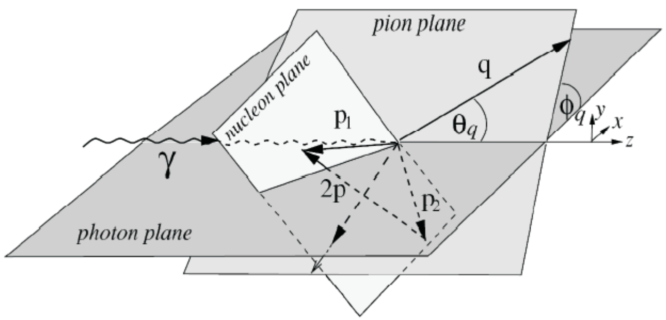
NN-**fsi** vertex

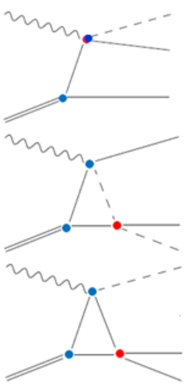
Fermi motion of nucleons included

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

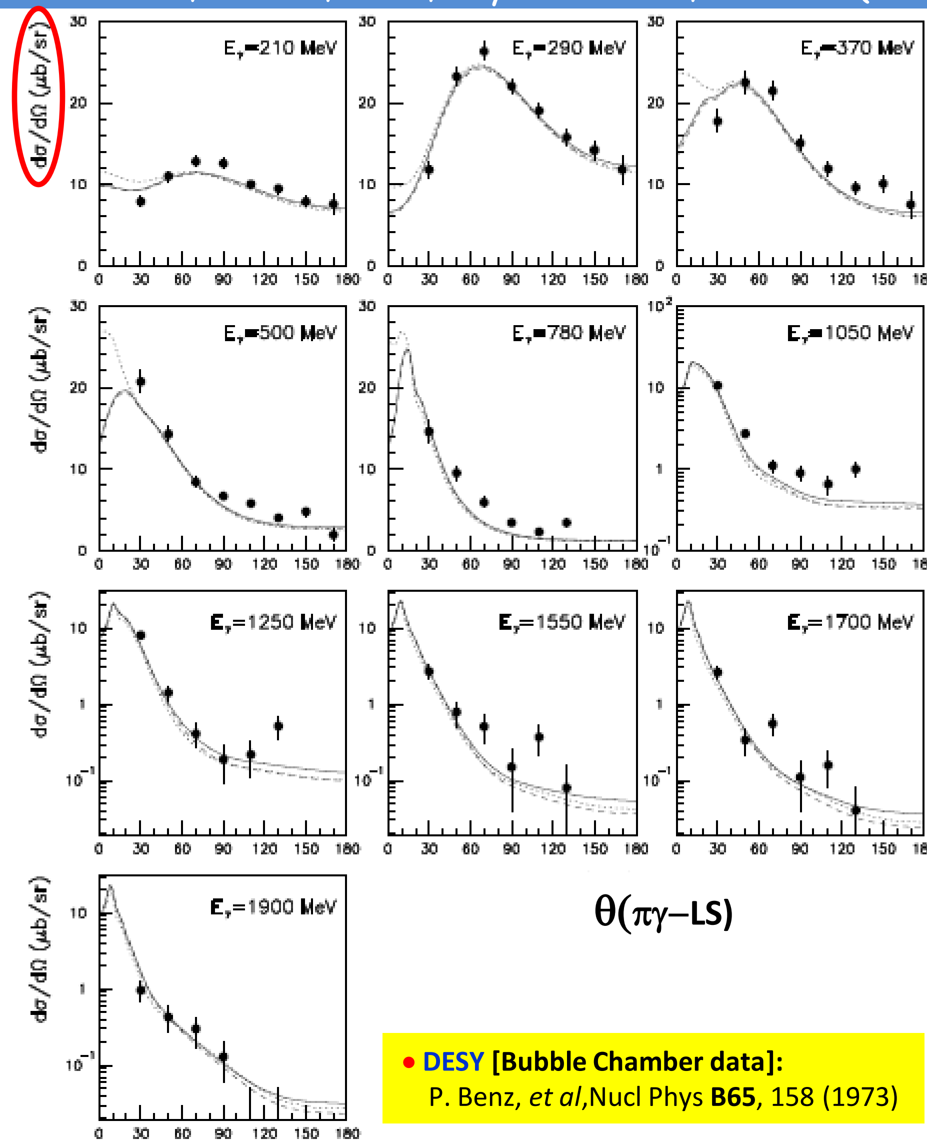
$\gamma d \rightarrow \pi^- pp$

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





No fit to the data



$\theta(\pi\gamma\text{–LS})$

..... IA
- - - IA + NN_{fsi}
___ IA + $(NN+\pi N)_{fsi}$

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

FSI for CLAS $\gamma n \to \pi^- p$

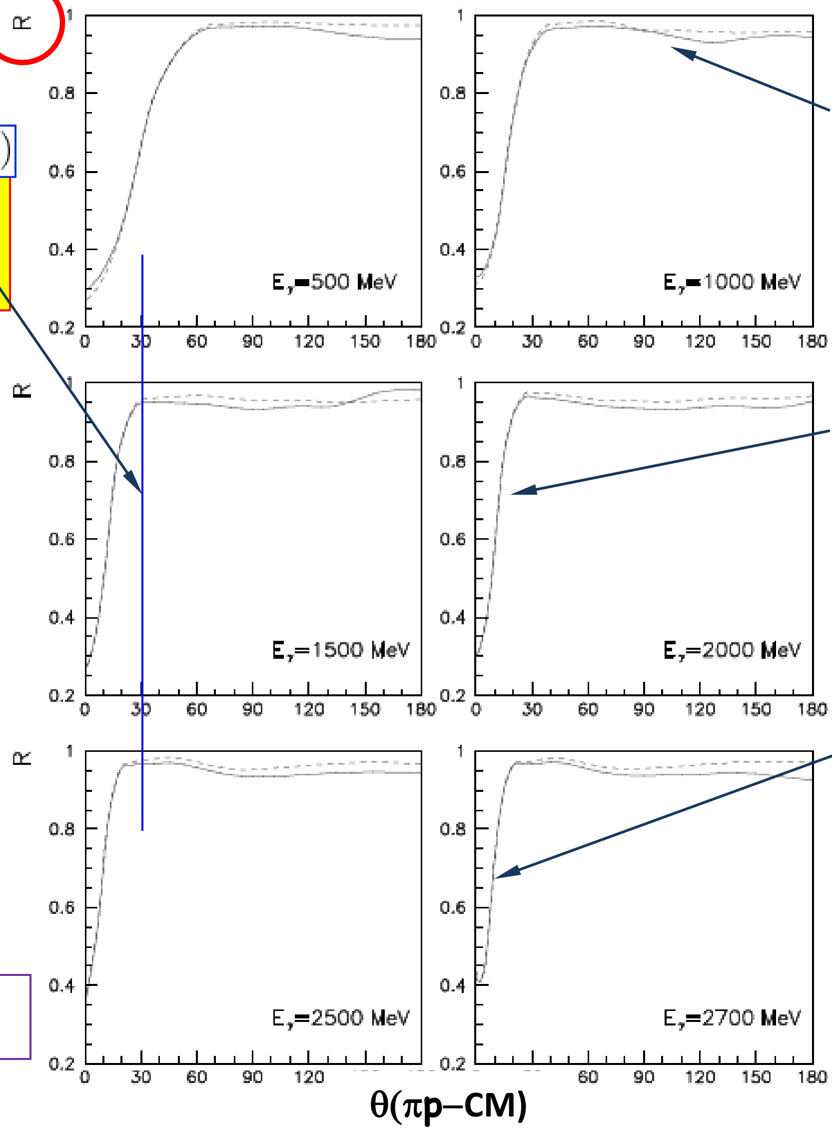
[V. Tarasov, A. Kudryavtsev, W. Briscoe, H. Gao, & IS, Phys Rev C **84**, 035203 (2011)]

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

Cuts:
p_s > 200 MeV/c
p_f > 200 MeV/c

CLAS data:
E > 1 GeV
θ > 32 deg

- There is no large sensitivity to cuts



--- [IA + NN_{fsi}] / IA
___ [IA + $(NN+\pi N)_{fsi}$] / IA

- For **CLAS** data
  - The **FSI** correction factor **R < 1**
  - The behavior is smooth vs. **θ**
  - The effect **(1 - R) < 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.

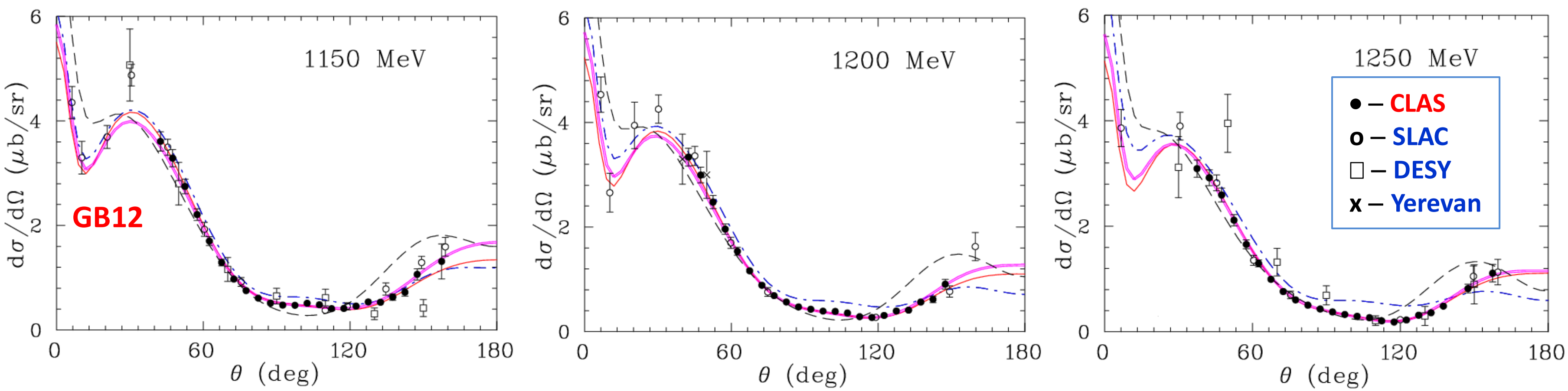
- Our estimation of the **Glaber FSI** corrections gives the value of **5**%.

  Previous estimations gave the order of **15-30**%.

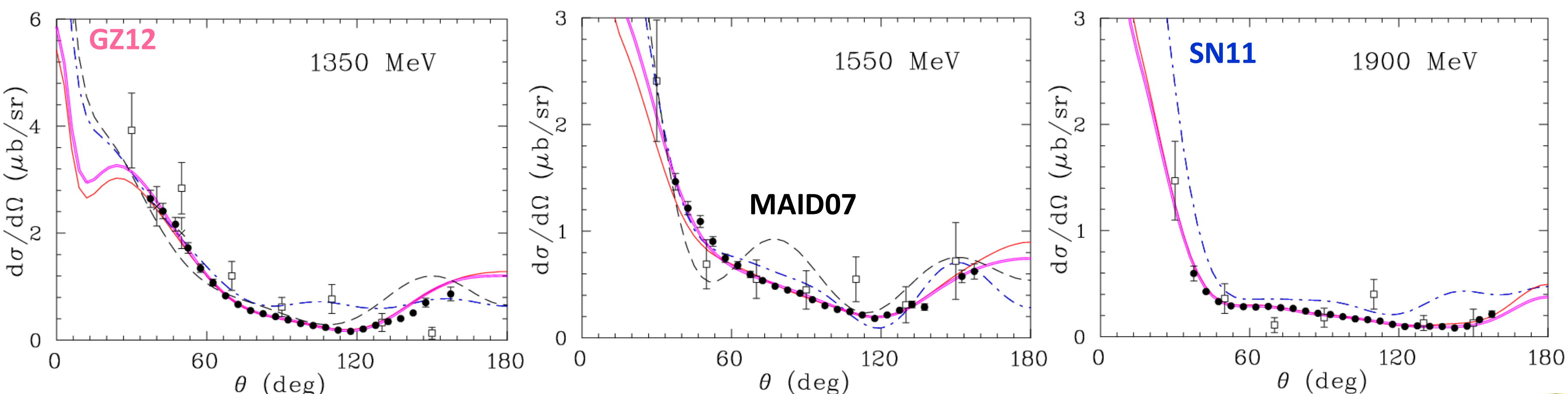
CLAS data vs previous Brem Measurements

[W. Chen, *et al*, arXiv:1203.4412 [hep-ph]]

• Principal π^- experiments below 1 GeV were done at Meson Factories: LAMPF, TRIUMF, & PSI

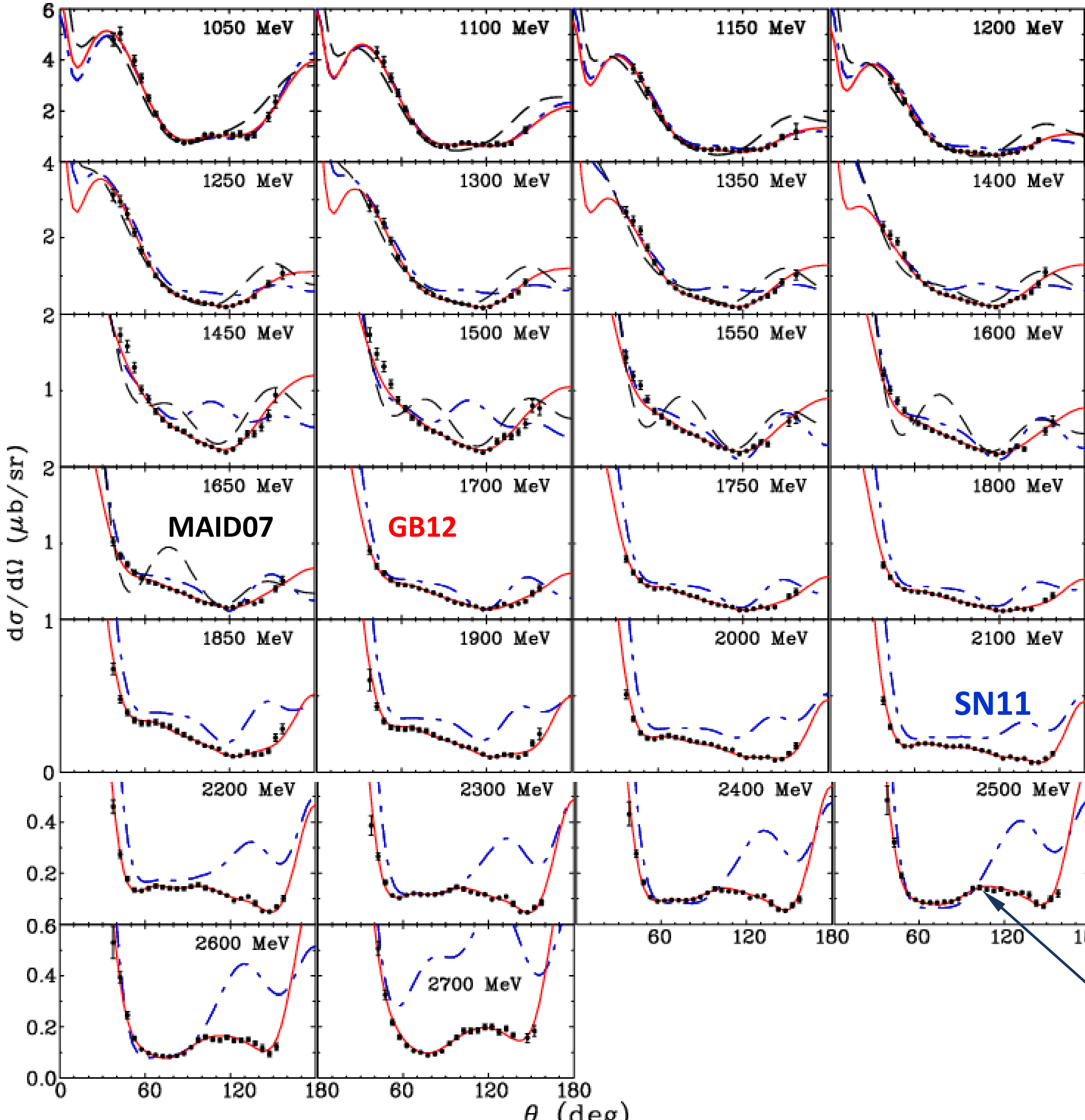


• **Previous measurements** used a modified **Glauber** approach and the procedure of unfolding the **Fermi** motion of the `**neutron**' target.



CLAS for $\gamma n \to \pi^- p$

[W. Chen, *et al*, arXiv:1203.4412 [hep-ph]]



Systematics:
Exp: 6-9%
FSI: 2-3%

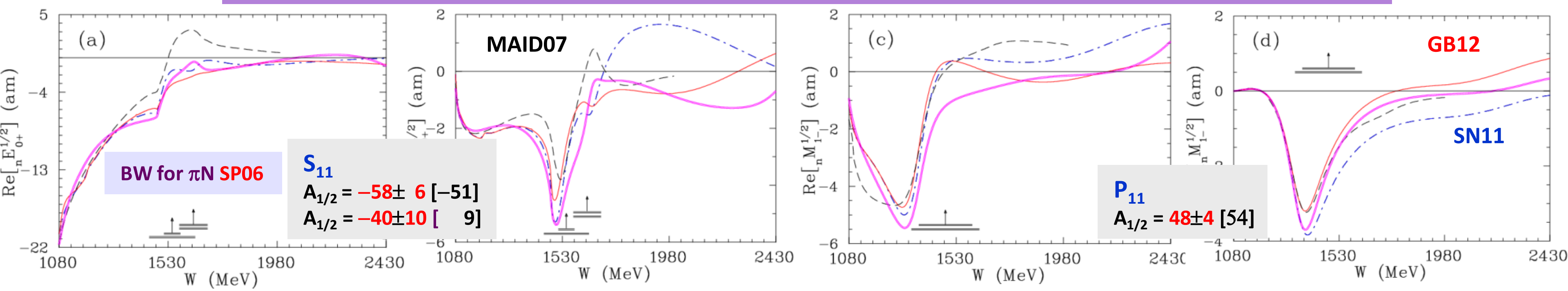
χ^2/dp = 45636/626 = 72.9 [SN11 – no fit]
χ^2/dp = 1580/626 = 2.5 [GB12 - fit]

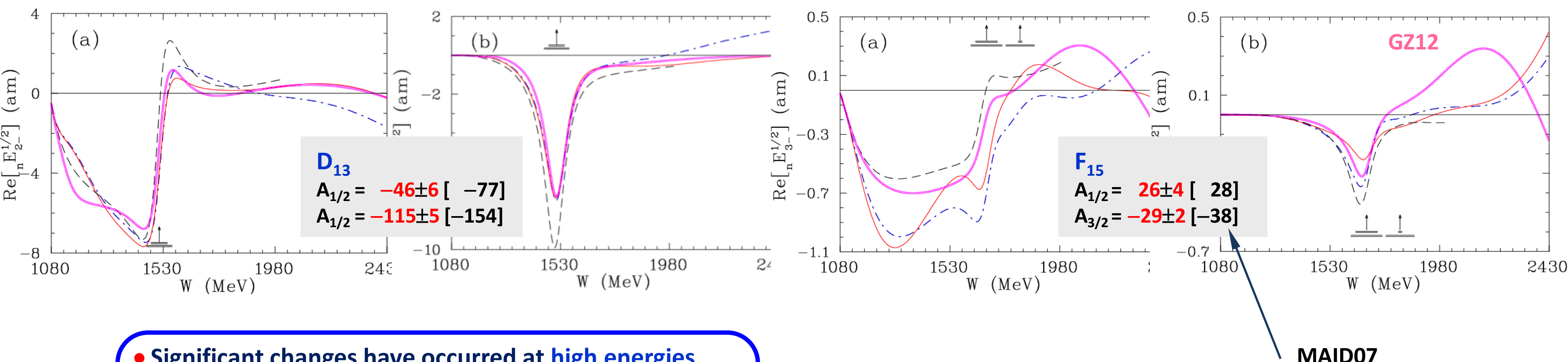
- **CLAS data appear to have fewer angular structures than the earlier fits.**

Neutron Multipoles from GB12

[W. Chen, *et al*, arXiv:1203.4412 [hep-ph]]

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





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

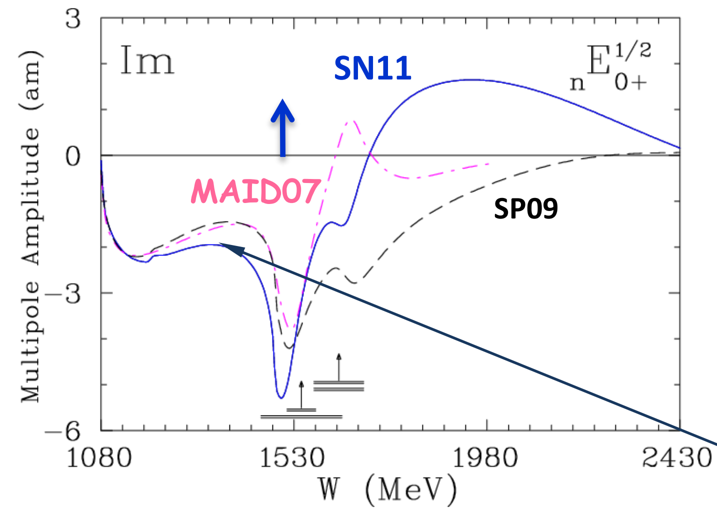
MAID07: D. Drechsel, *et al,* Eur Phys J A 34, 69 (2007)

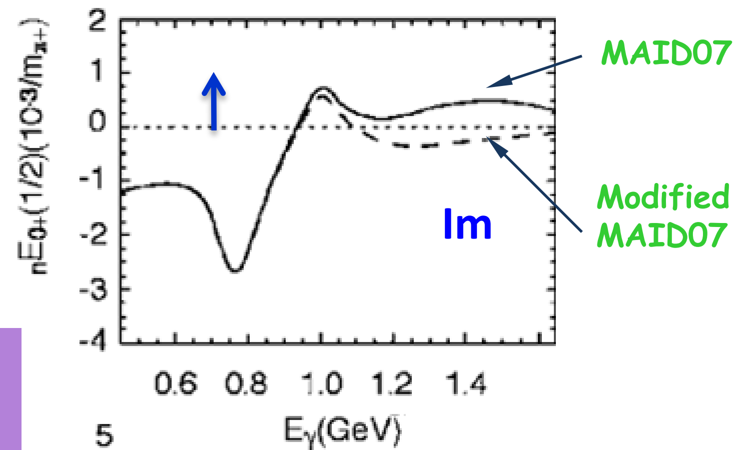
$E_{0}+$ Neutron Multipole

[R. Workman, *et al* , Phys Rev *C* **85**, 025201 (2012)]

No new CLAS $\pi^{-}p$ $d\sigma/d\Omega$

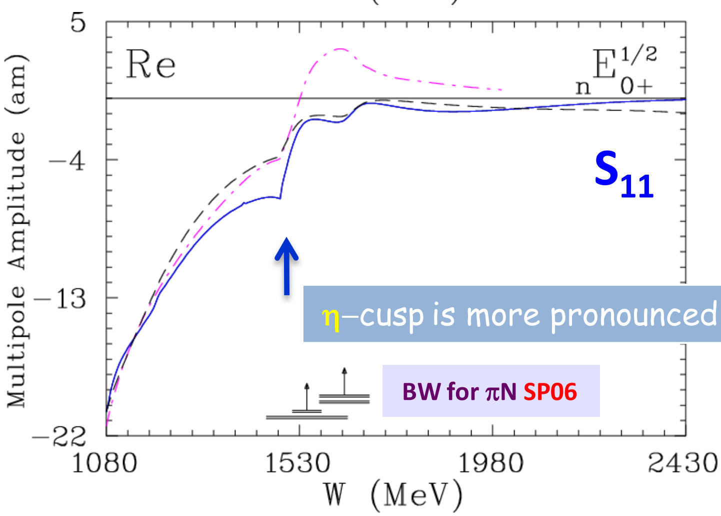
[R. Di Salvo, *et al* ,Eur Phys J *A* **42**, 151 (2009)]

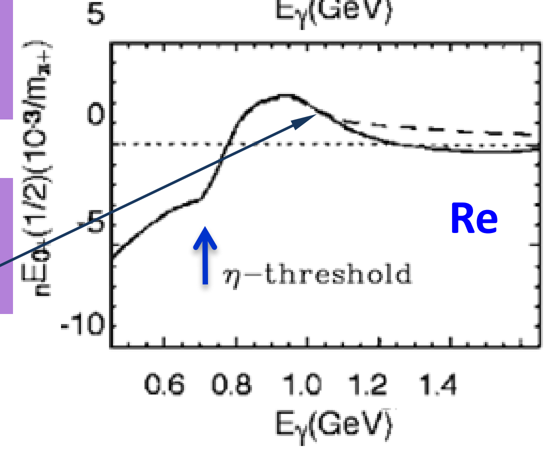




- The difference between **SN11** & **SP09** is visible above E = 400 MeV

- Modified MAID07 is different above E = 1000 MeV





η−cusp is more pronounced for SN11

Summary and Prospects

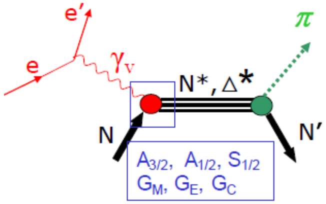
- Pion Photo Prod measurements on the '**neutron**' target are necessary to determine neutron couplings at $Q^2 = 0$ GeV^2

- Future experiments on the reactions $\gamma d \to \pi NN$ are welcome, especially at small angles $\theta < 30^0$, where data are absent

- JLab HD-ICE, CB@MAMI-C, LEPS II, CB-ELSA, & MAX-lab data could yield surprises

- Complete experiment would make possible a direct reconstruction of helicity amplitudes for Pseudo-Scalar Meson Photo Prod

- Pion Electro Prod measurements on the '**neutron**' target are necessary to determine neutron couplings at $Q^2 > 0$ GeV^2



- Any meson Photo Prod treatment on the 'neutron' target requires a FSI study

T H A N K S

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