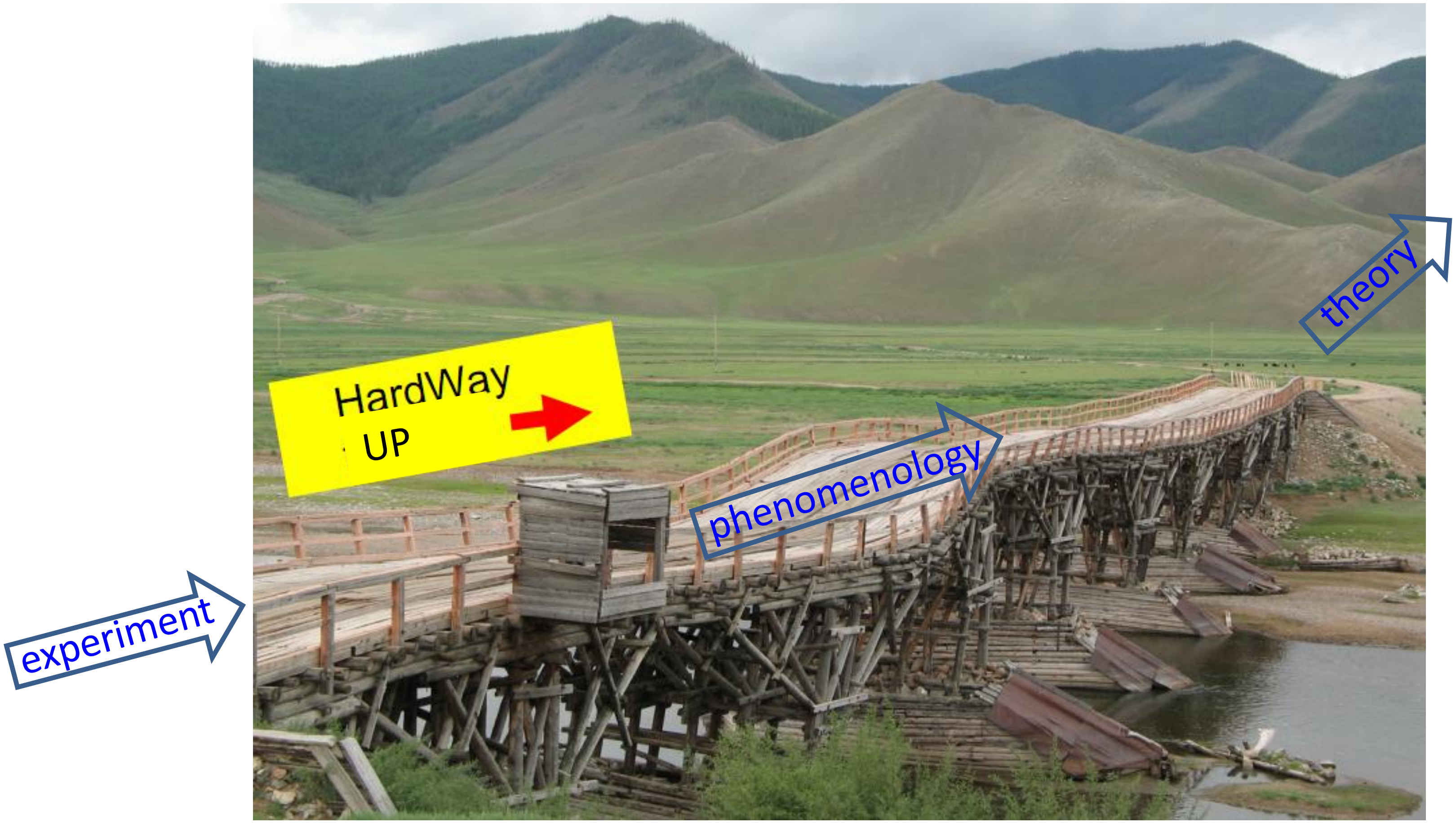
Deuteron as an Effective Neutron Target

Igor Strakovsky
The George Washington University

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

Phenomenology for non-strange Resonances



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

CNS
Center for Nuclear Studies
Data Analysis Center

Below 4 GeV

Partial-Wave Analyses at GW
[See Instructions]

31,402	Pion-Nucleon		
	Pion-Pion-Nucleon	241,214 evts	[W = 1320 to 1930 MeV]
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 π→2π, we use log-likelihood while for the rest – least-squares technologies

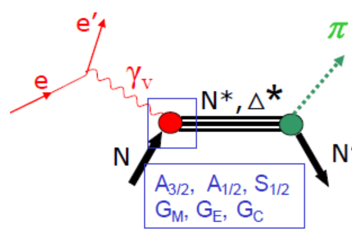
N^* and Δ^* States coupled to πN

[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

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)

Contact

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SAID for Pion Photoproduction

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

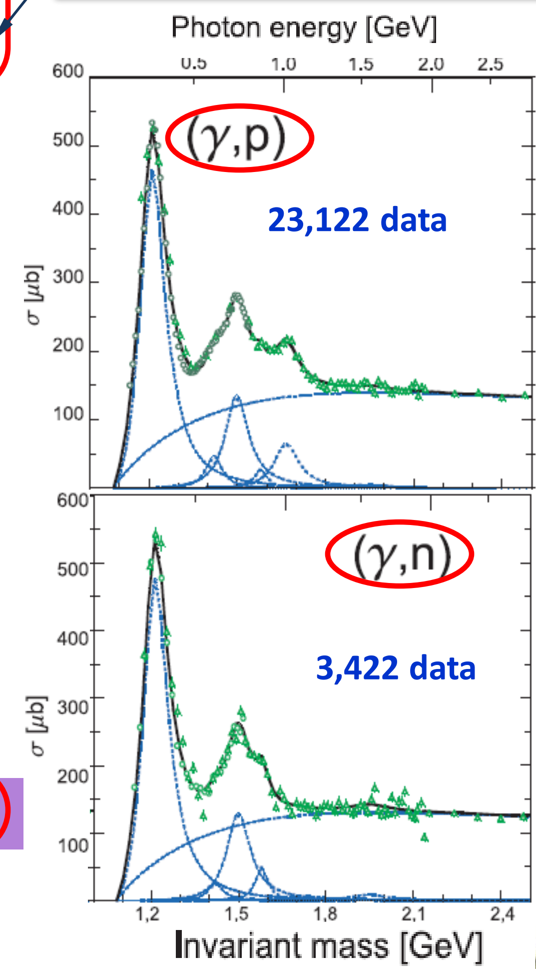
- Energy dependent GB12 and associated SES
- E = 145 – 2700 MeV [W = 1080 – 2460 MeV]
- PWs = 60 [E & M multipoles] [J < 6]
- Prms = 210
- Constraint: $M = (Born + A)(1+iT_{\pi N}) + BT_{\pi N} + (C+iD)(ImT_{\pi N}-|T_{\pi N}|^2)$

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

- 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 Photoproduction

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

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)]

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

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}
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].

Minimization and Normalization Factor for Pion Prod [χ^2/Data]

- In fitting the data, the stated exp syst errs have been used as an overall norm adjustment factor for the angular distribution

- Modified χ^2 function, to be minimized

[systematics plays important role]

$$\chi^2 = \sum_i \left(\frac{X\theta_i - \theta_i^{\exp}}{\epsilon_i} \right)^2 + \left(\frac{X-1}{\epsilon_X} \right)^2$$

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

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

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

- **Normalization freedom** provides a significant improvement for our best fit results, we cannot ignore experimental input

χ^2/Data	GB12		SM02		MAID07	
Reaction	Norm	UnNorm	Norm	UnNorm	Norm	UnNorm
$\gamma p \to \pi^0 p$	2.2	3.6	3.2	5.7	7.7	12.3
$\gamma p \to \pi^+ n$	1.9	3.4	2.1	3.9	8.1	11.7
$\gamma n \to \pi^- p$	2.1	6.5	1.8	2.5	2.9	3.8
$\gamma n \to \pi^0 n$	3.3	5.3	2.8	2.8	6.4	6.4

- MAID is valid below W = 2 GeV
- For MAID07, the normalization constants were searched to minimize χ^2 (no adjustment of the partial waves was possible)
- MAID07 does not include recent CLAS $\pi^0 p$, $\pi^+ n$, & $\pi^- p$ LEPS $\pi^0 p$ GRAAL $\pi^- p$ & $\pi^0 n$ data

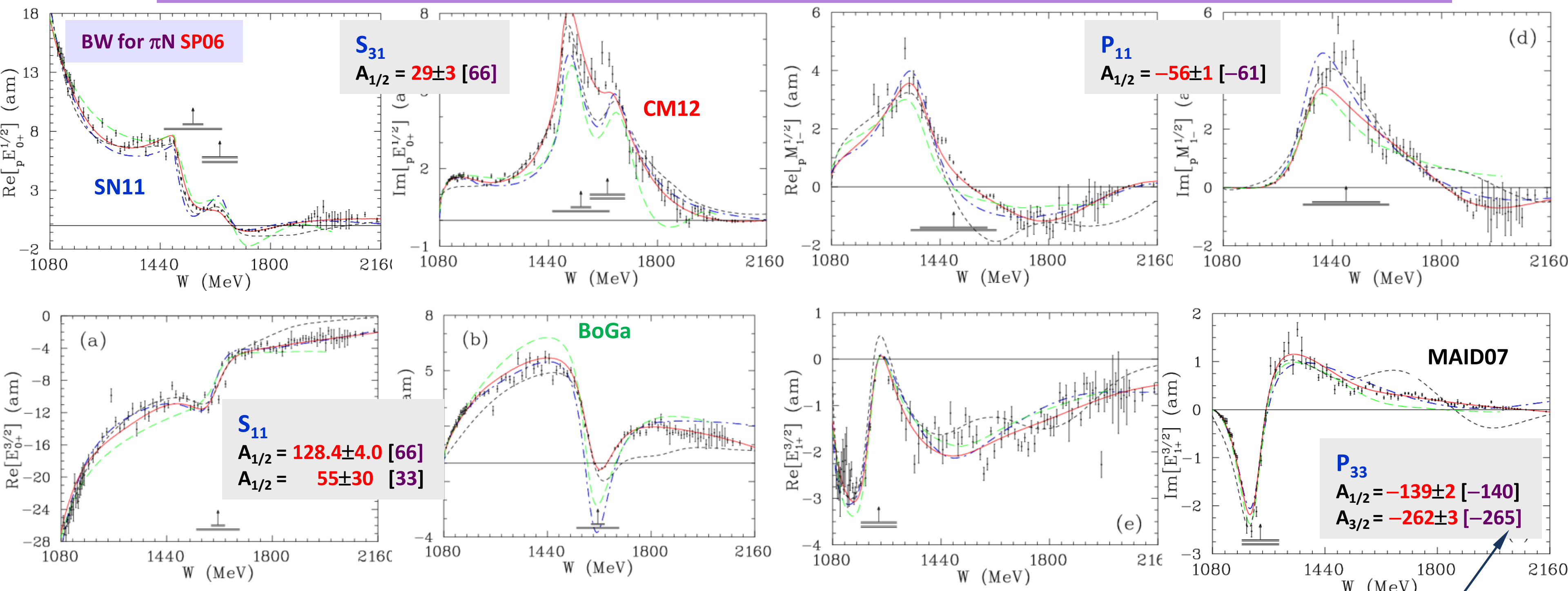
[D. Drechsel, *et al*, Eur Phys J A 34, 69 (2007)]

Proton Multipoles

Proton Multipoles for CM12

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

- **Overall: the difference between MAID07 or BoGa and SAID-CM12 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 & 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

MAID07: D. Drechsel, *et al,* Eur Phys J A 34, 69 (2007)
BoGa: A. Anisovich, *et al,* Eur Phys J A 44, 203 (2010)

Neutron-Target Experiments

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,

  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 (**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: $\pi^- p \to \gamma n$.
  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 ***CLAS*** cross section set has **quadrupled** the world database for $\gamma n \to \pi^- p$ above **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

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

PDG10: **$N(1675)5/2^- \to p\gamma$, helicity-1/2 ampl A1/2: +0.019±0.008**
$N(1675)5/2^- \to n\gamma$, helicity-1/2 ampl A1/2: −0.043±0.012

SAID **$N(1675)5/2^- \to p\gamma$, helicity-3/2 ampl A3/2: +0.016±0.001**
$N(1675)5/2^- \to n\gamma$, 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

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

	PDG10	SAID
$N(1720)3/2^+ \to p\gamma$, helicity-1/2 ampl A1/2:	+0.018±0.030	+0.095±0.002
$N(1720)3/2^+ \to p\gamma$, helicity-3/2 ampl A3/2:	−0.019±0.020	−0.048±0.002

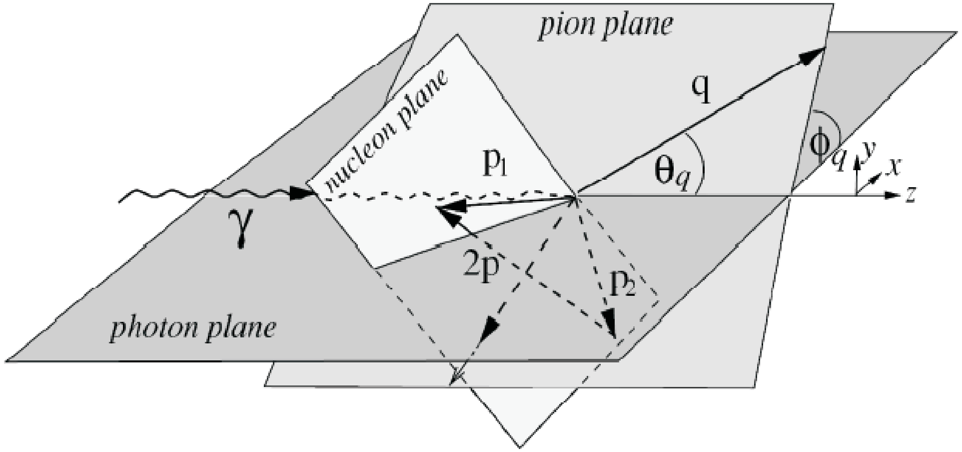
- Other unresolved issues relate to the second P_{11}, N(1710)1/2⁺, that are not seen in the recent πN PWA, contrary to other PWAs used by the **PDG10**

$N(1710)\ P_{11}$ $I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ 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.

Final-State Interaction



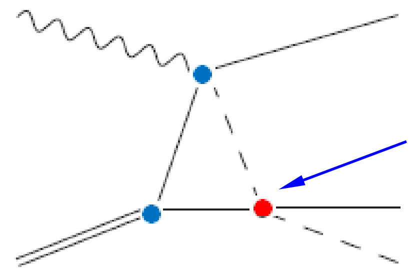
FSI and $\gamma d \to \pi^- p\, p \Longrightarrow \gamma n \to \pi^- p$

[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)

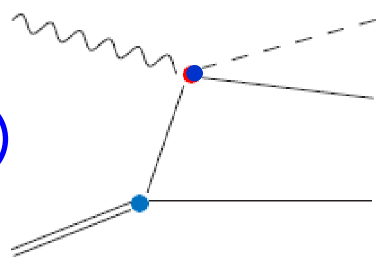
Input: **SAID** $\gamma N \to \pi N$, πN, NN amplitudes for 3 leading terms

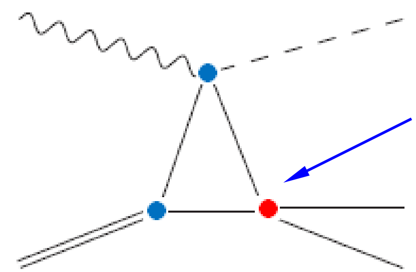
DWF: CD-Bonn



πN-**fsi** vertex

IA





NN-**fsi** vertex

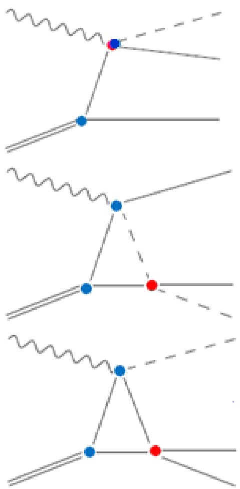
Fermi motion of nucleons included

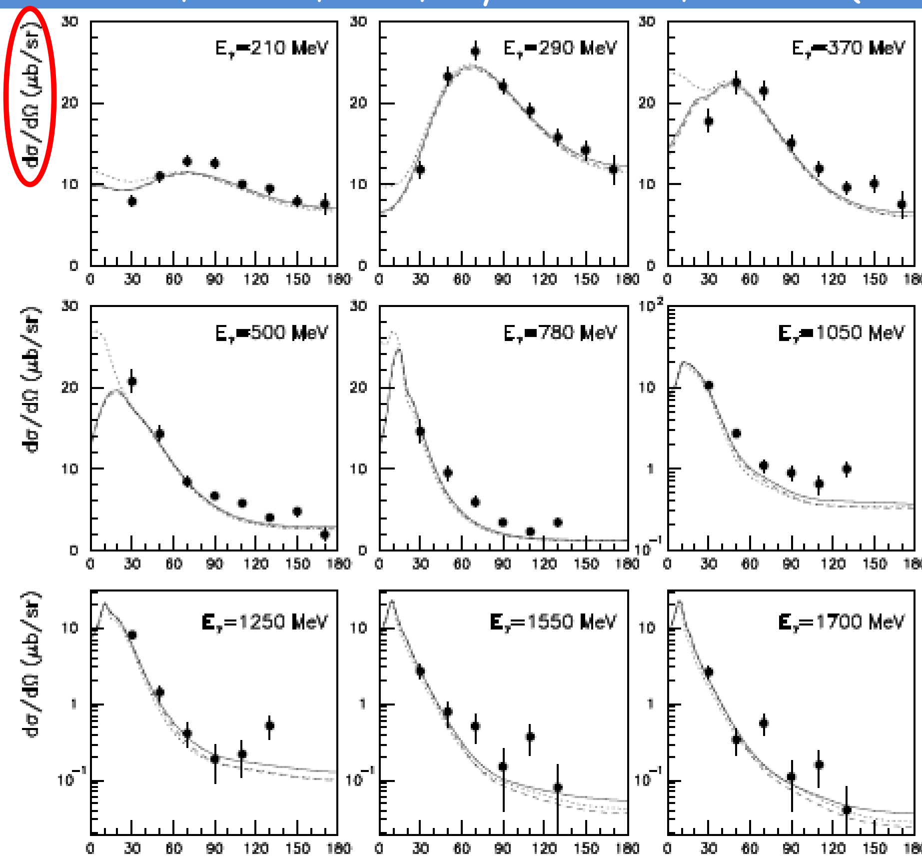
$$R_{FSI} = (d\sigma/d\Omega_{\pi p})/(d\sigma^{IA}/d\Omega_{\pi p})$$

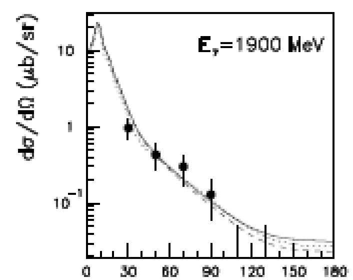
$\gamma d \to \pi^- pp$

[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 *ea* Nucl Phys **B65**, 158 (1973)

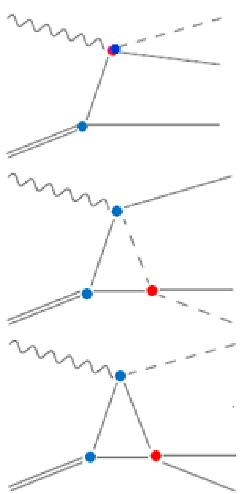
FSI for CLAS $\gamma n \to \pi^- p$

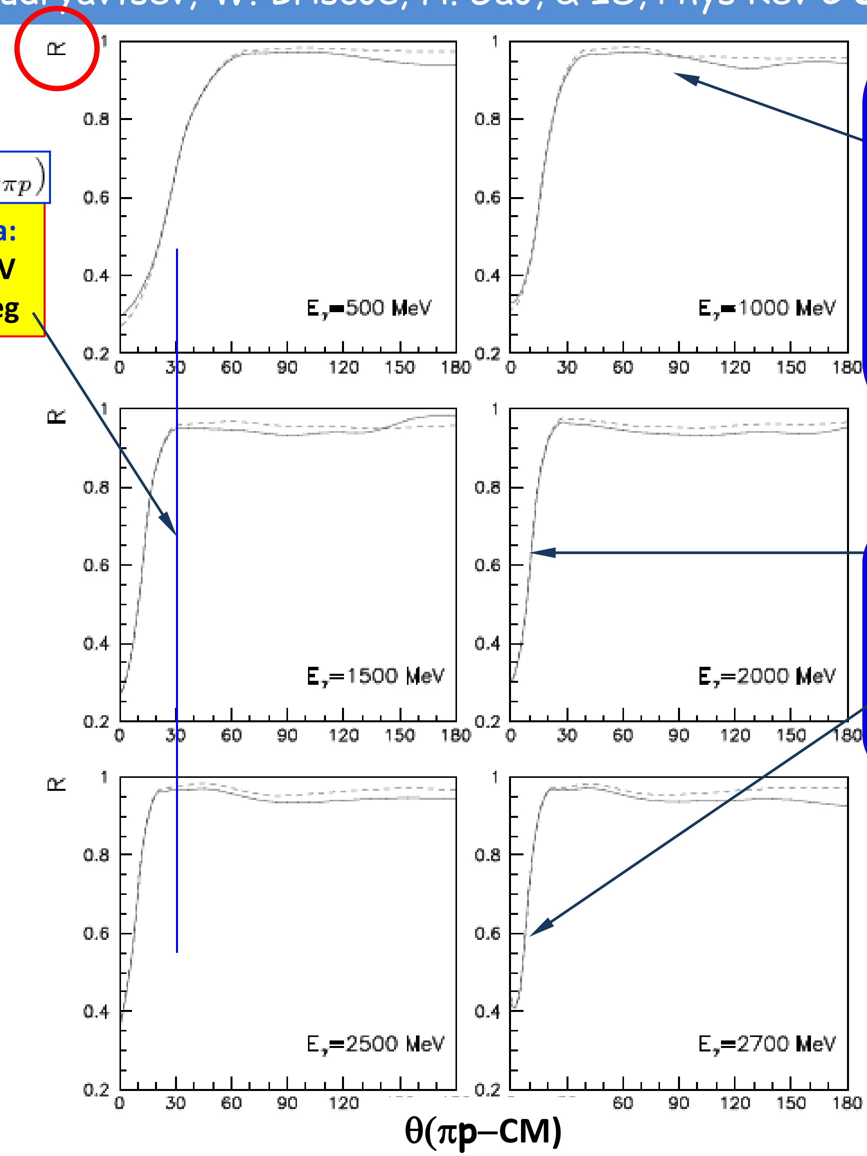
[V. Tarasov, A. Kudryavtsev, W. Briscoe, H. Gao, & IS, Phys Rev C **84**, 035203 (2011)]

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

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

CLAS data:
E > 1 GeV
θ > 32 deg





- For **CLAS** data
  - The **FSI** correction factor **R < 1**
  - The effect **(1 - R) < 10%**
  - The behavior is smooth vs. **θ**
- Our estimation of the **Glaber FSI** corrections gives the value of **5%.** Previous estimations gave the order of **15-30%.**

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

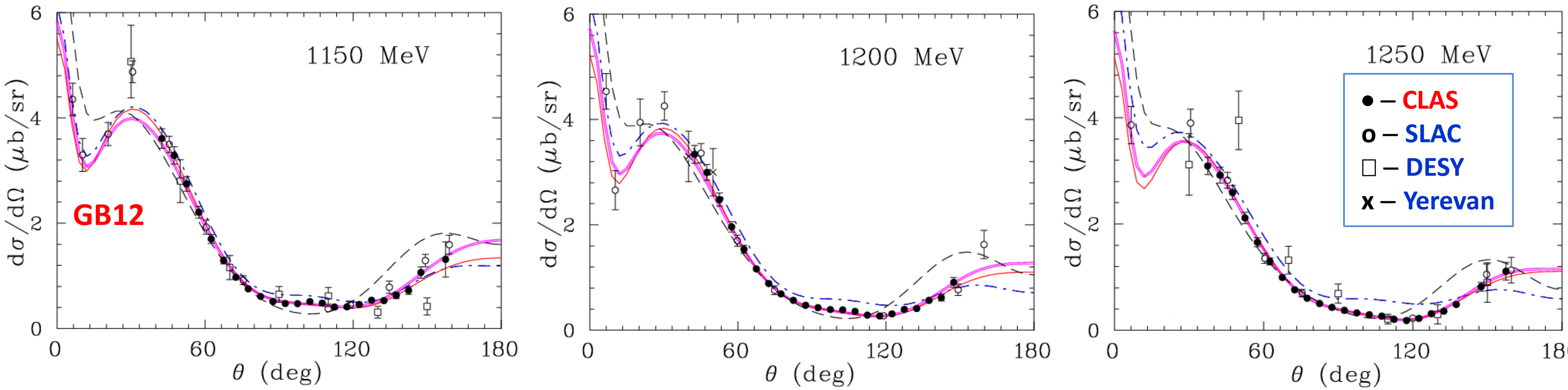
-- -- $[IA + NN_{fsi}] / IA$
____ $[IA + (NN+\pi N)_{fsi}] / IA$

FSI for CLAS Data

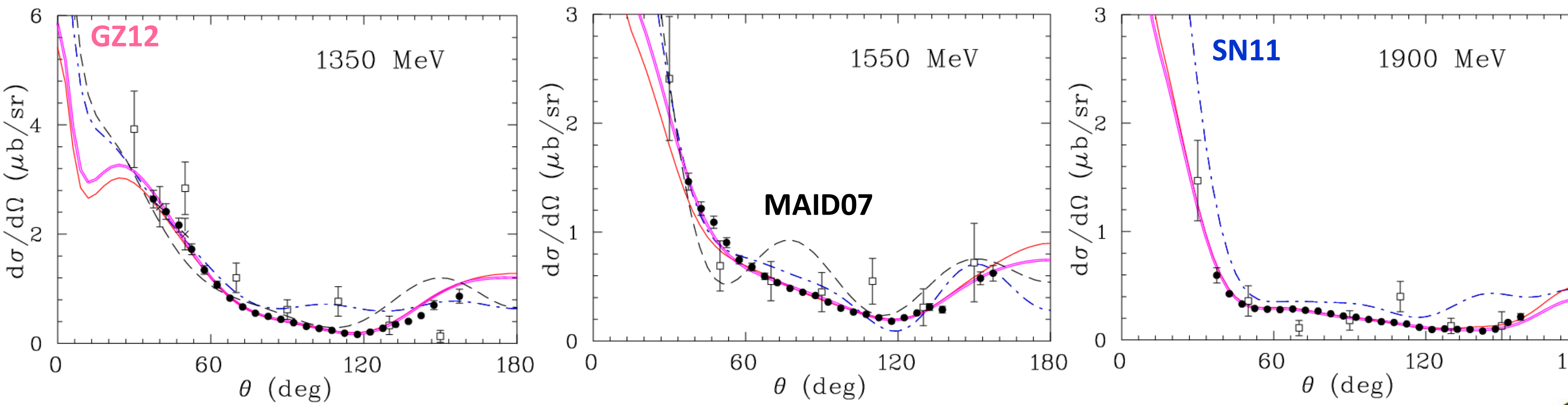
CLAS data vs. previous Brem Measurements

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

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

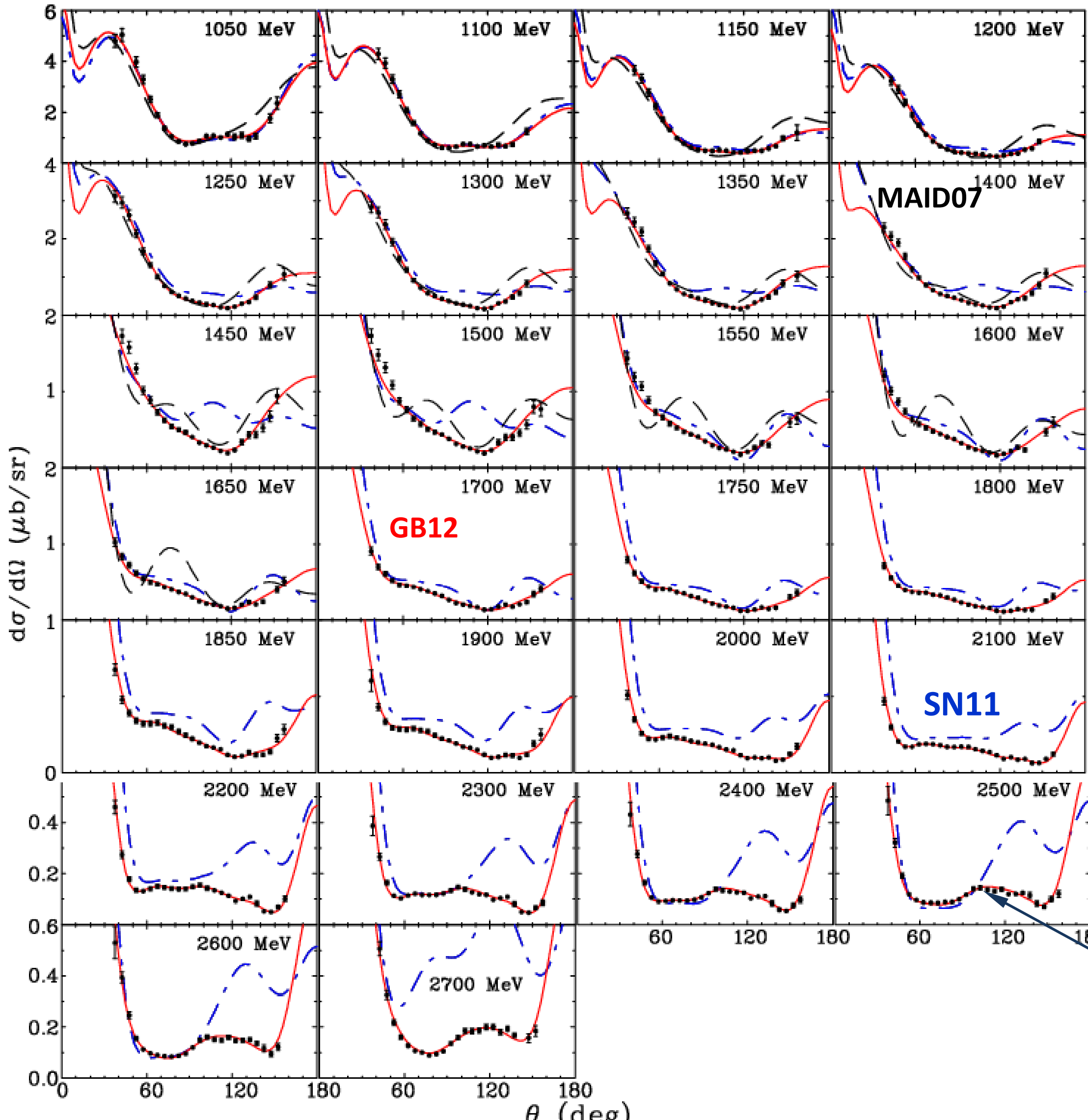


• Previous measurements used a modified **Glauber** approach and the procedure of unfolding the **Fermi** motion of the **neutron** target.



CLAS g10 for $\gamma n \rightarrow \pi^- p$

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



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

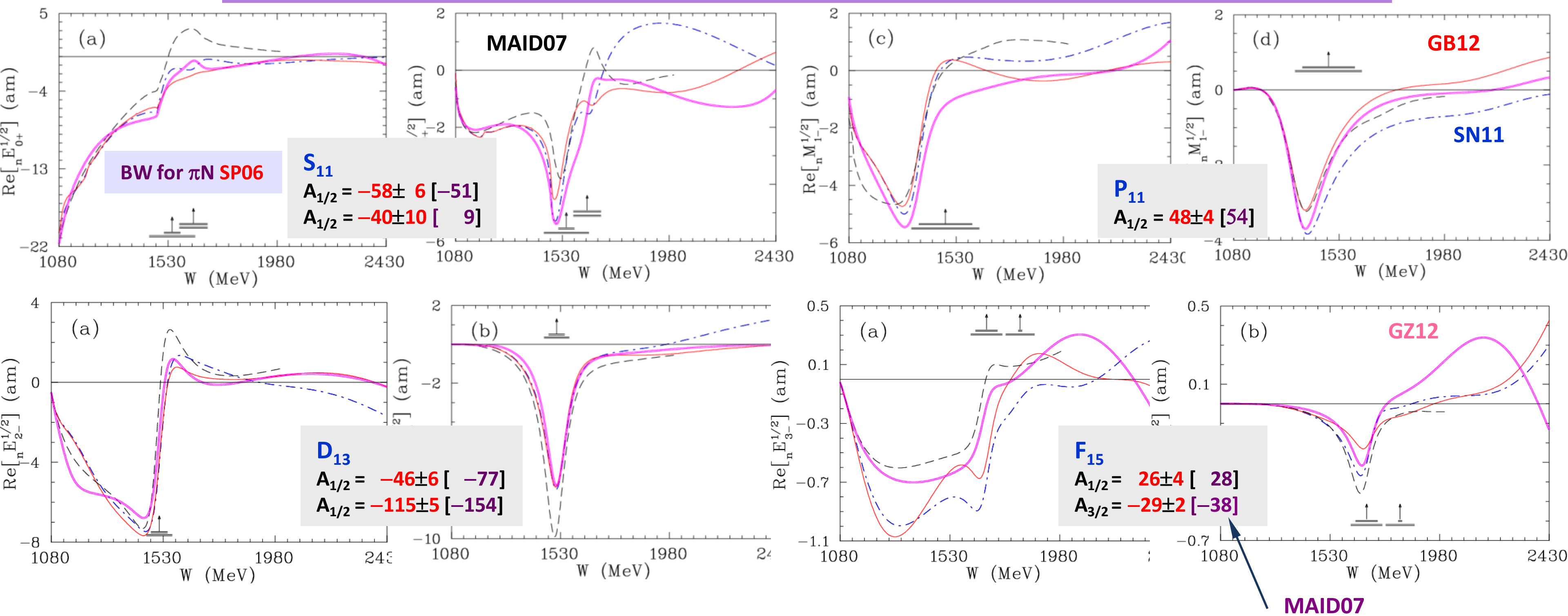
- CLAS data appear to have fewer angular structures than the earlier fits

Neutron Multipoles

Neutron Multipoles for 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**

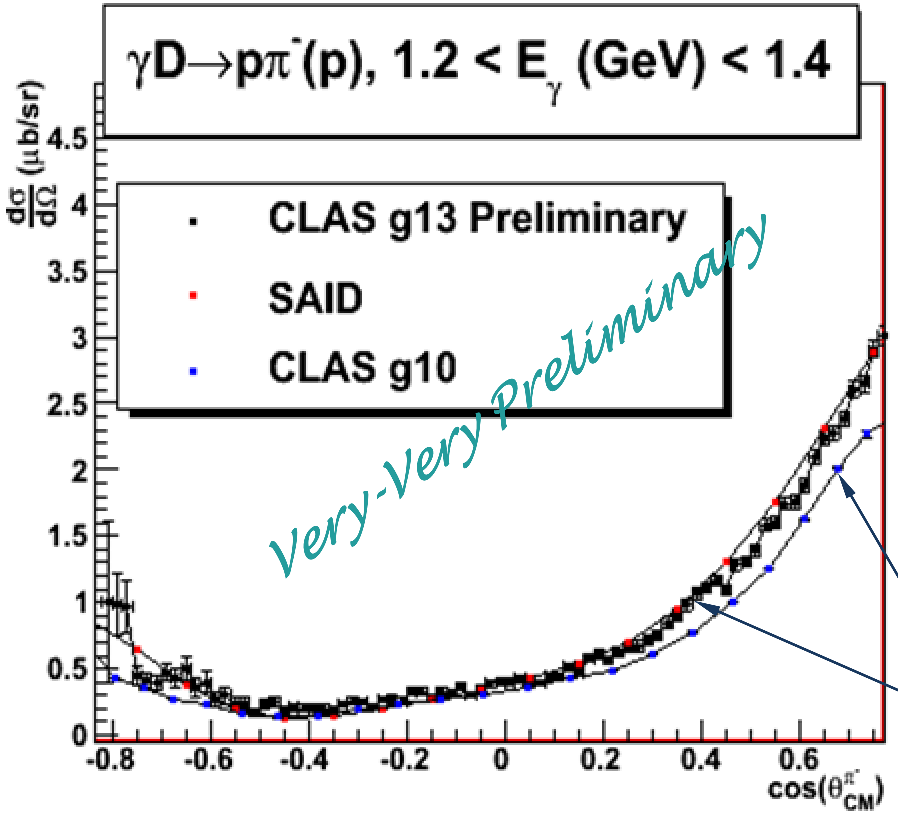
MAID07: D. Drechsel, *et al*, Eur Phys J A 34, 69 (2007)

CLAS g13 Data

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

[g13: P. Mattione, *et al*, in progress]

- Complementary measurements of π^- Photo Prod, required for an isospin decomposition of the multipoles



- G13 vs. g10:
  - broad angular coverage
  - smaller errs

- No FSI included in both CLAS g10 [50 – 100 MeV binning] g13 data [2% statistics in 200 MeV binning]

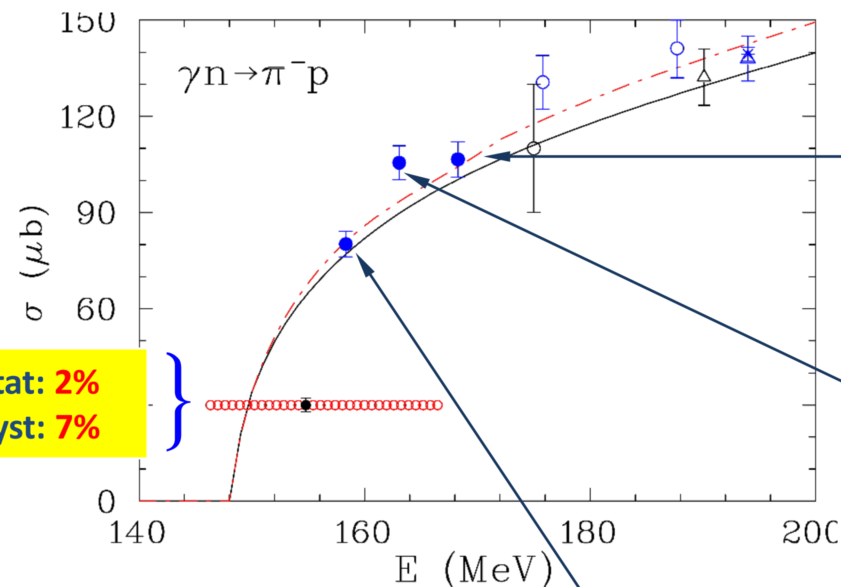
[Courtesy of Paul Mattione, CLAS Meeting 2010]

MAX-lab for the Threshold

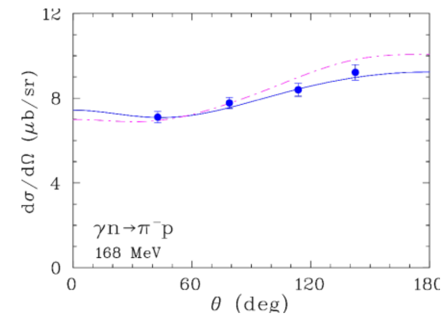
MAX-lab

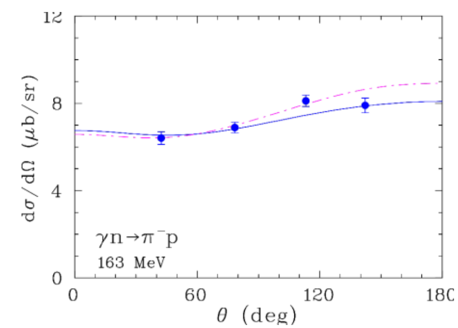
$\gamma n \rightarrow \pi^- p$ at Threshold

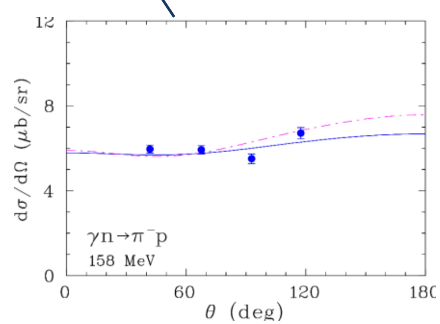
• New MAX-lab data will provide a constraint for PWA



Stat: 2%
Syst: 7%





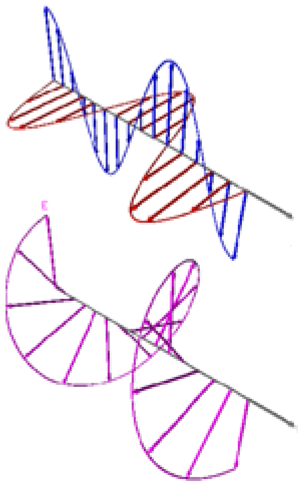


• TRIUMF95
___ SAID07
_._._ MAID07

• $E_{0+}(\pi^- p)$ determined on the base of these prlm TRIUMF data is off by more than 3 standard deviations while SAID has no problem with these data vs. world database.

Polarized Measurements

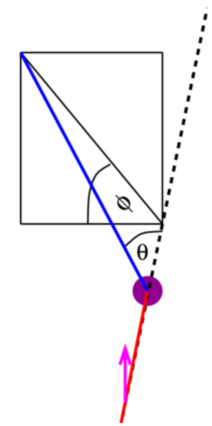
Complete Experiment in Pion Photo Production



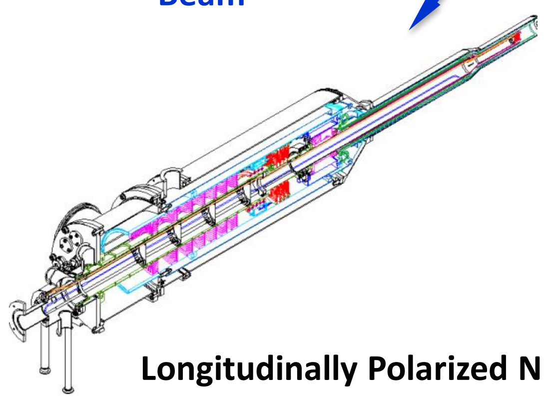
Linear Polarized Beam

Circular Polarized Beam

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



Nucleon Recoil Polarization



Longitudinally Polarized Nucleon Target
Transverse Polarized Nucleon Target

Direct Amplitude Reconstruction in Pion Photo Production

γ **N** → **N** π

spin: 1 $\frac{1}{2}$ → $\frac{1}{2}$ 0

helicities: 2 x 2 x 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

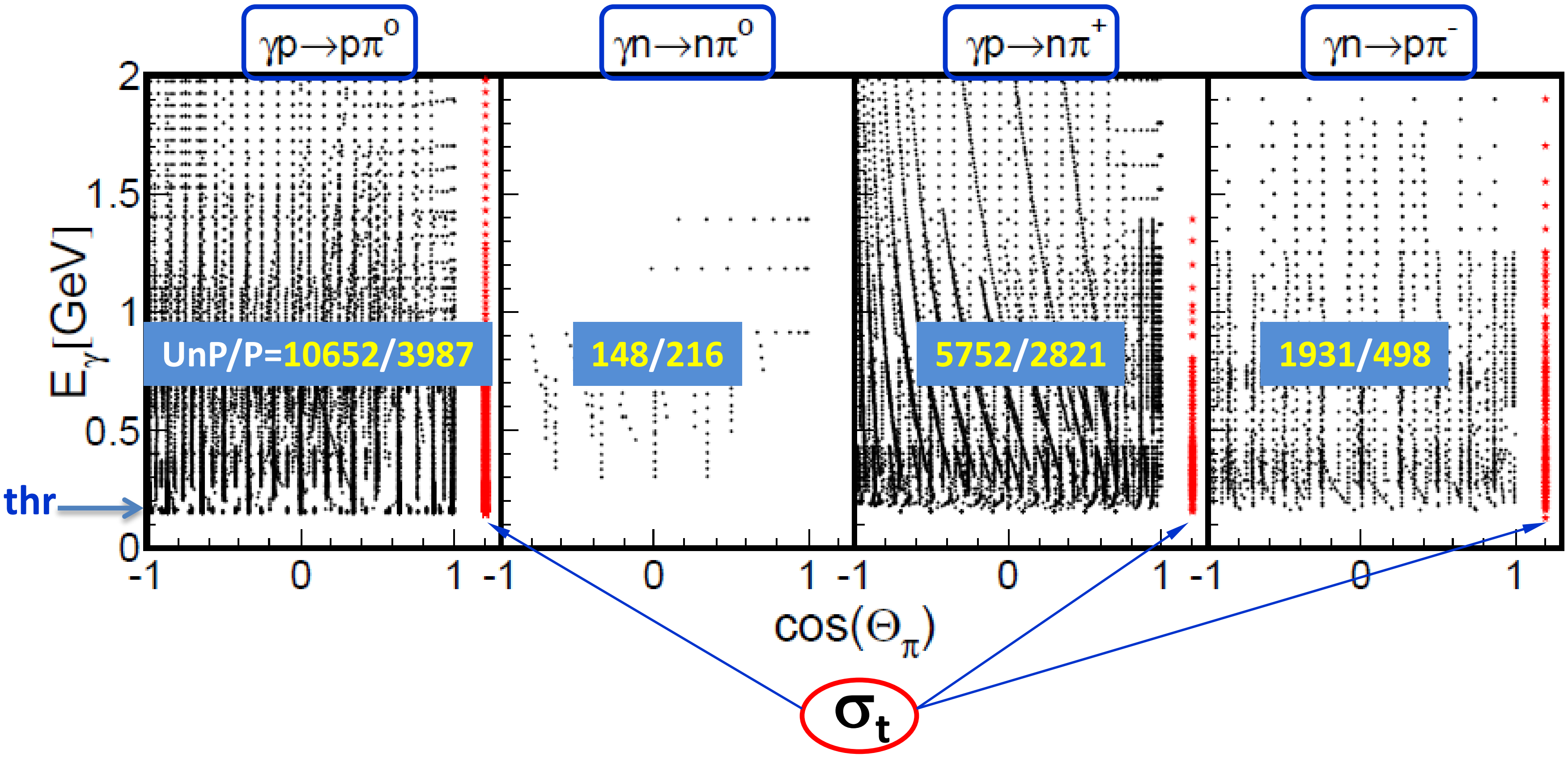
Department of Physics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

(Received 19 April 1996)

This extra observable is necessary to eliminate a sign ambiguity

World Neutral and Charged Pion Photo Prod Data

Neutron data / Proton data = 2793/23212 = **0.12**



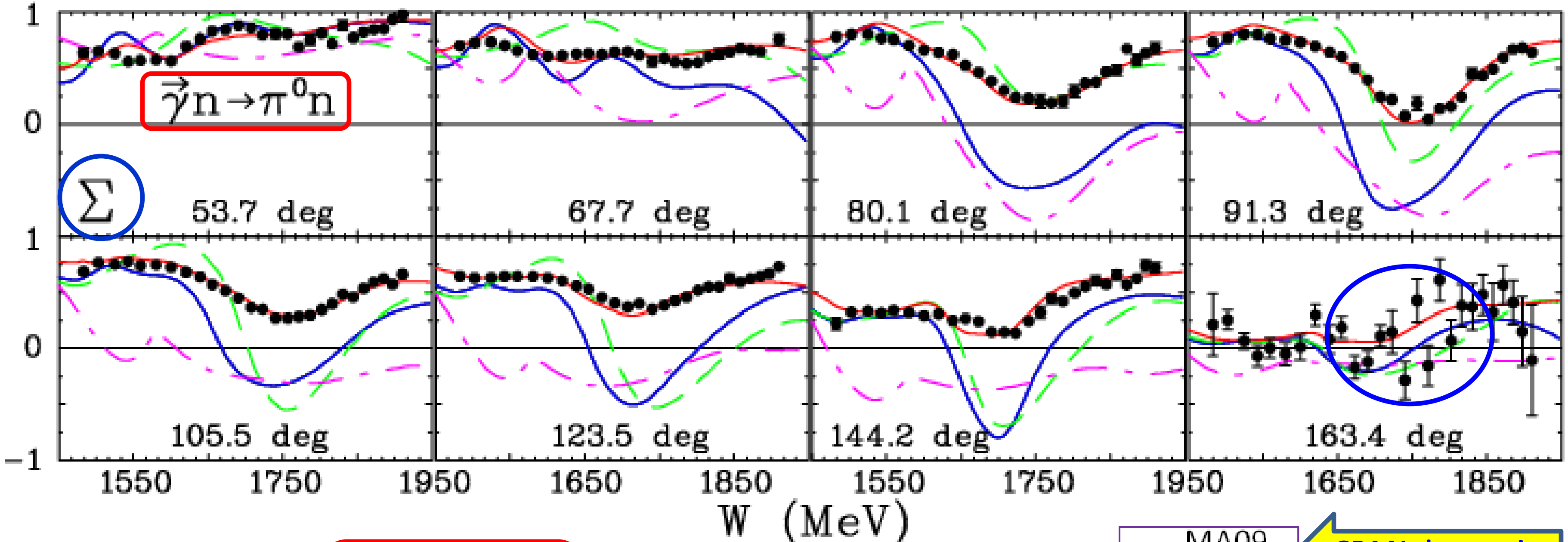
JLab has a good chance to file empty spots specifically for **n**-target

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

[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 Σs are **60**% of the World π^0**n** data



	χ^2/dp
MAID07	100
SP09	223
MA09	3.1

No FSI included

----- MA09
----- SP09
- - - MAID07
-.-.- DTM

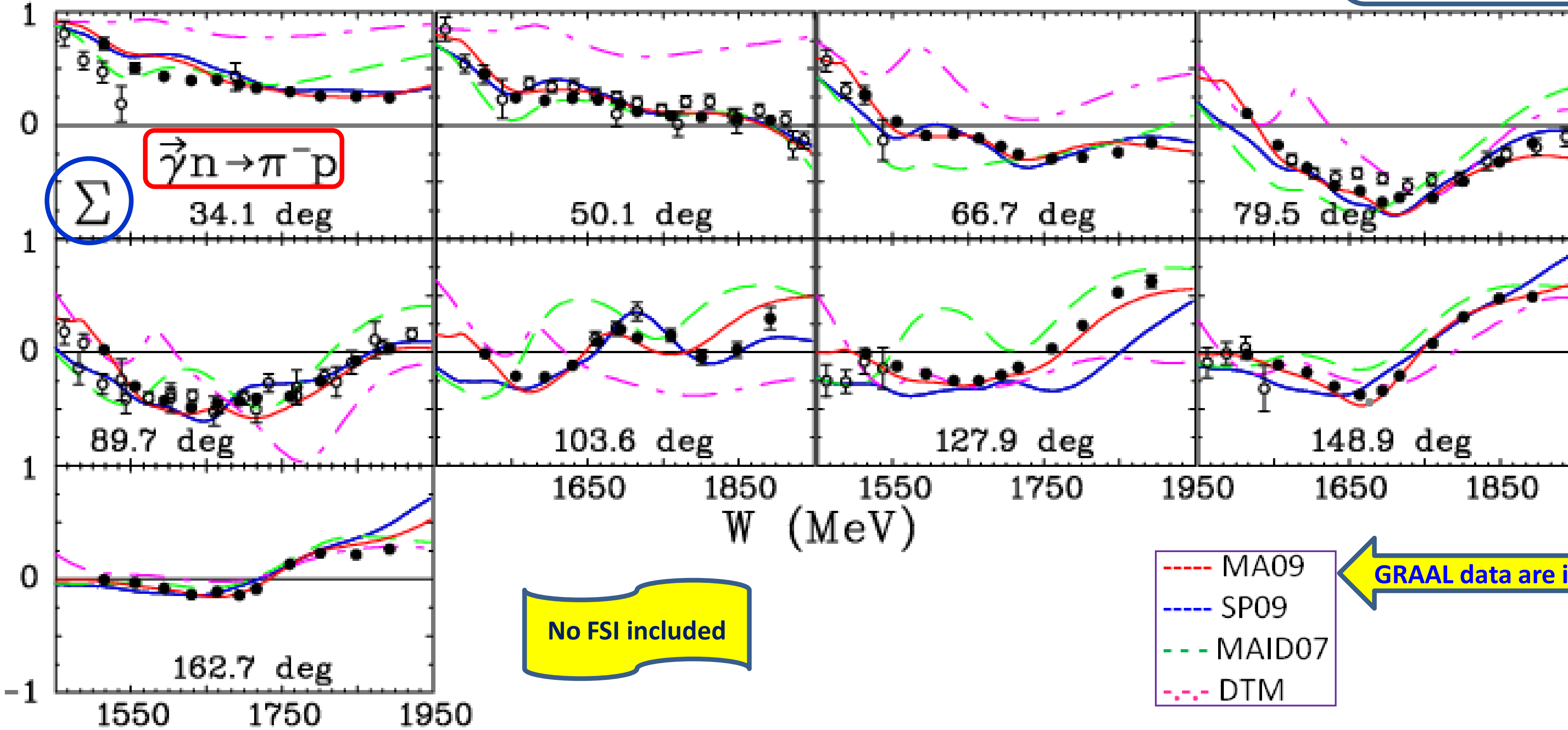
GRAAL data are in

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

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

	χ^2/dp
MAID07	27
SP09	89
MA09	4.9

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

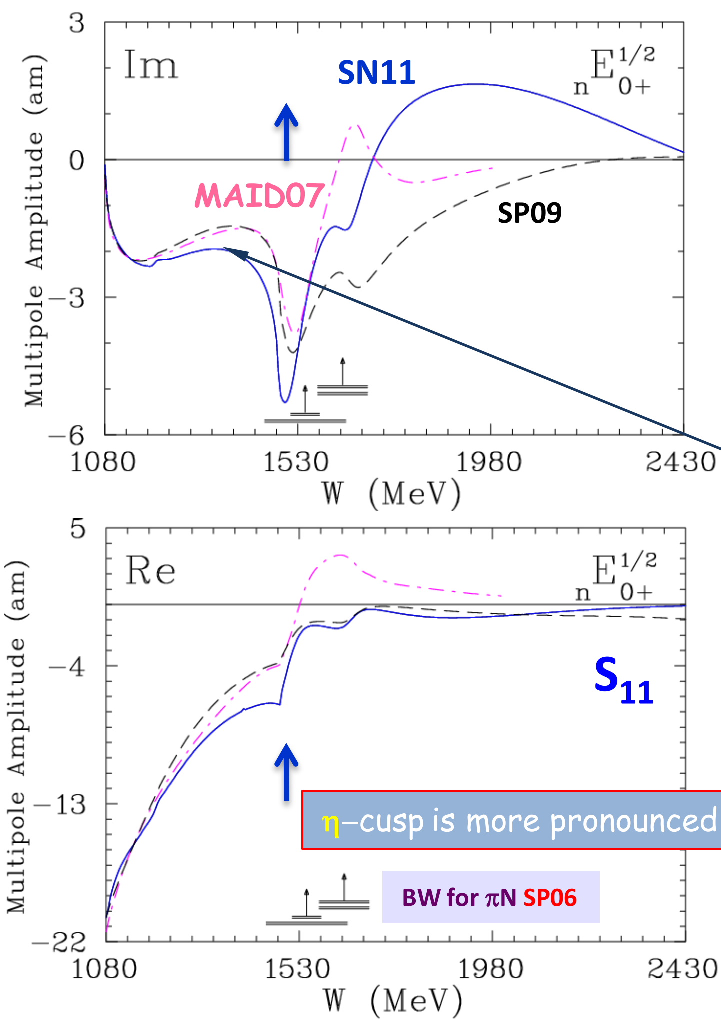


GRAAL data are in

No FSI included

E_{0+} Neutron Multipole

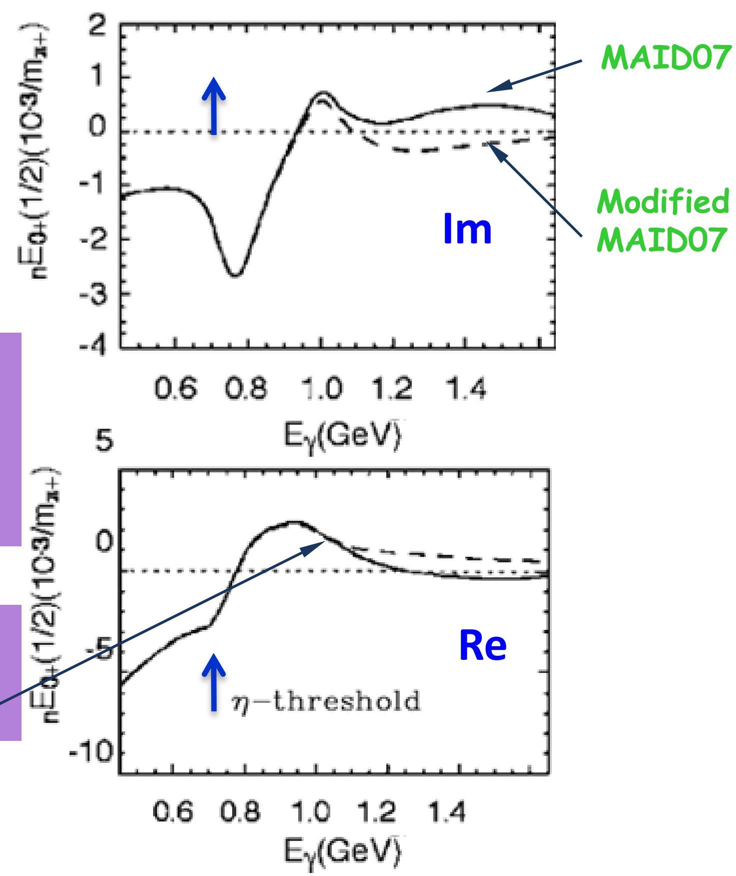
[R. Workman, *et al*, Phys Rev C **85**, 025201 (2012)]



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

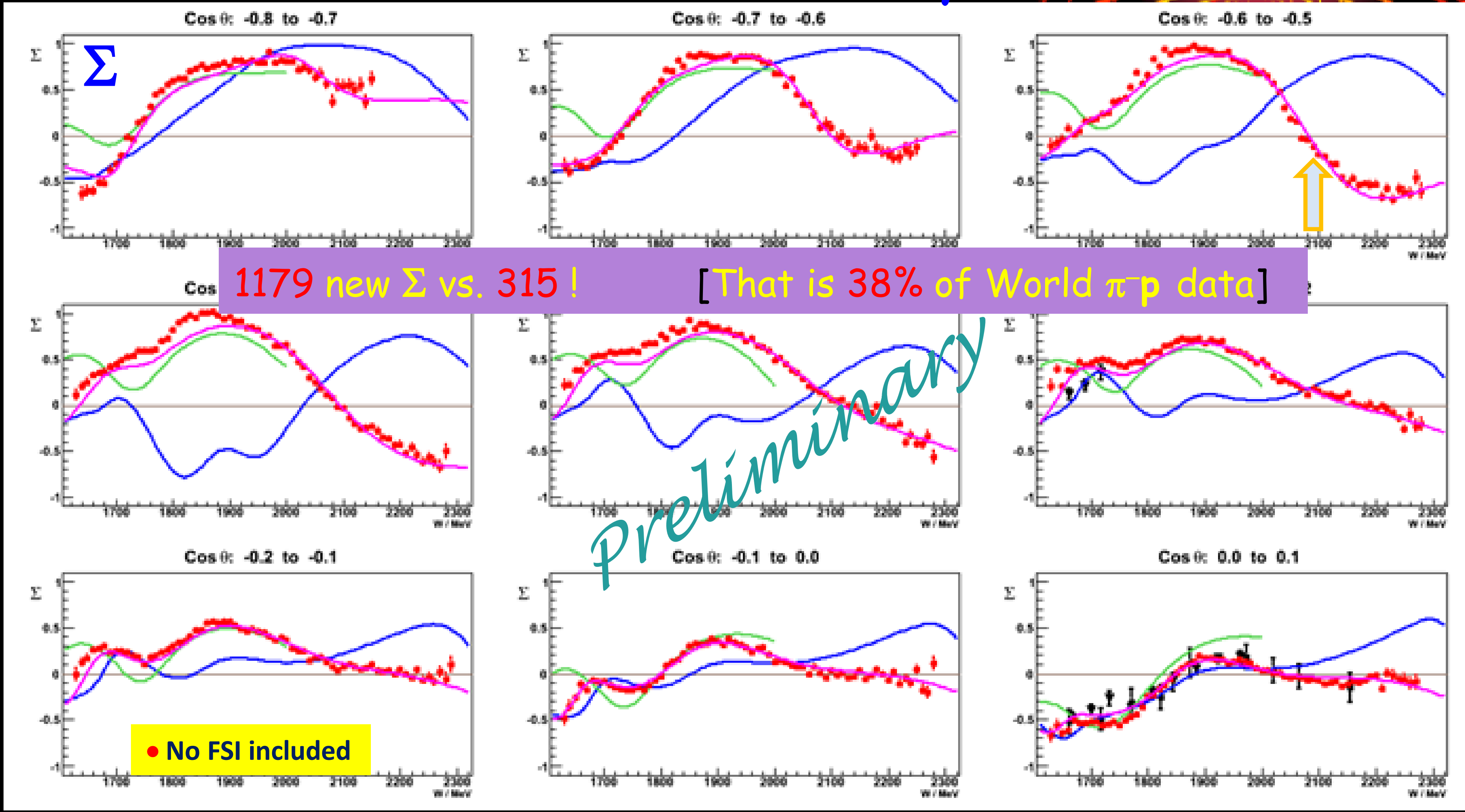
- Modified MAID07 is different above E = 1000 MeV

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



Preliminary Σ Measurement I

Backward $\vec{\gamma} n \to \pi^- p$

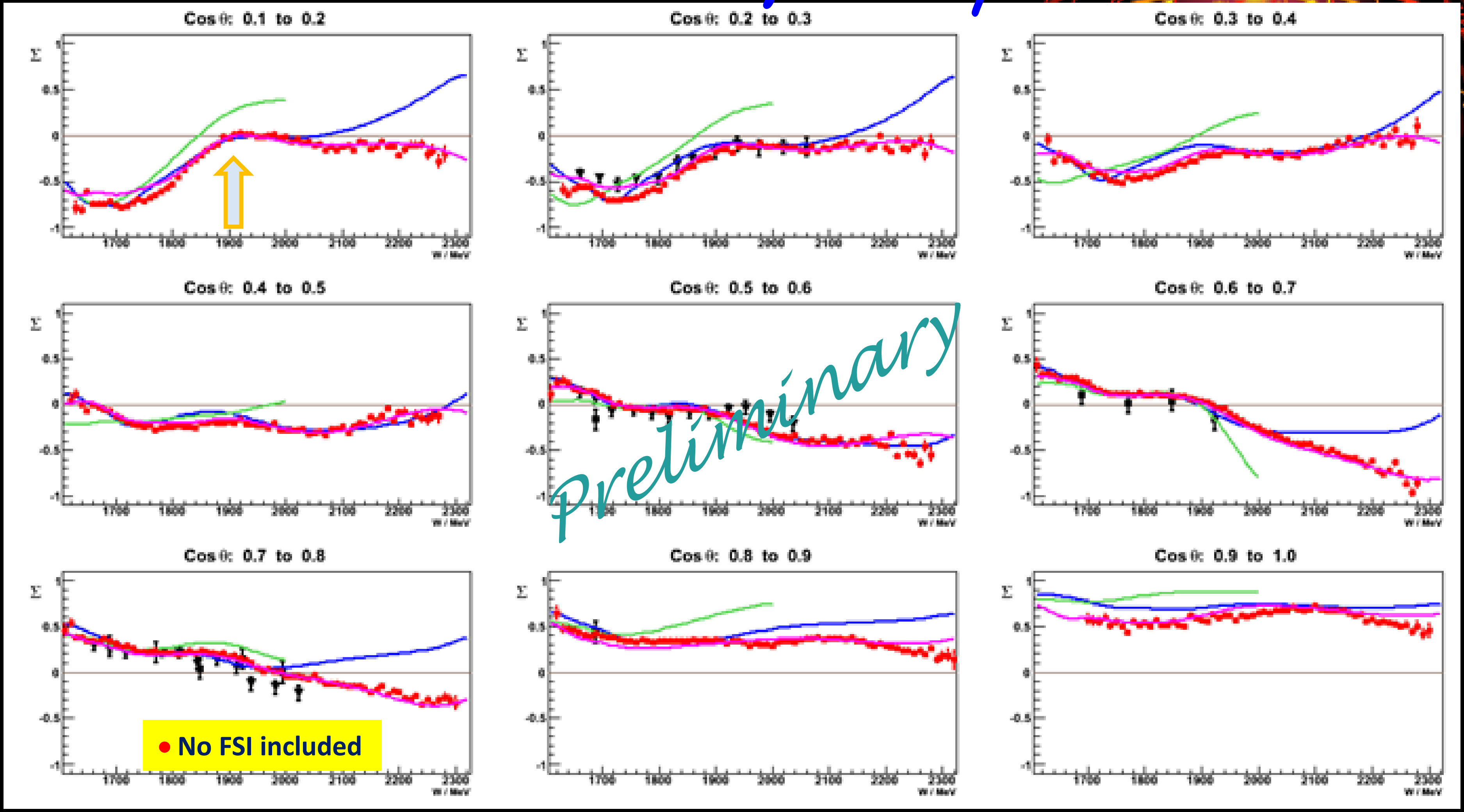


SAID 09 — MAID 07

χ^2 from new SAID PWA fit: 2.6

Preliminary Σ Measurement II

Forward $\vec{\gamma} n \to \pi^- p$



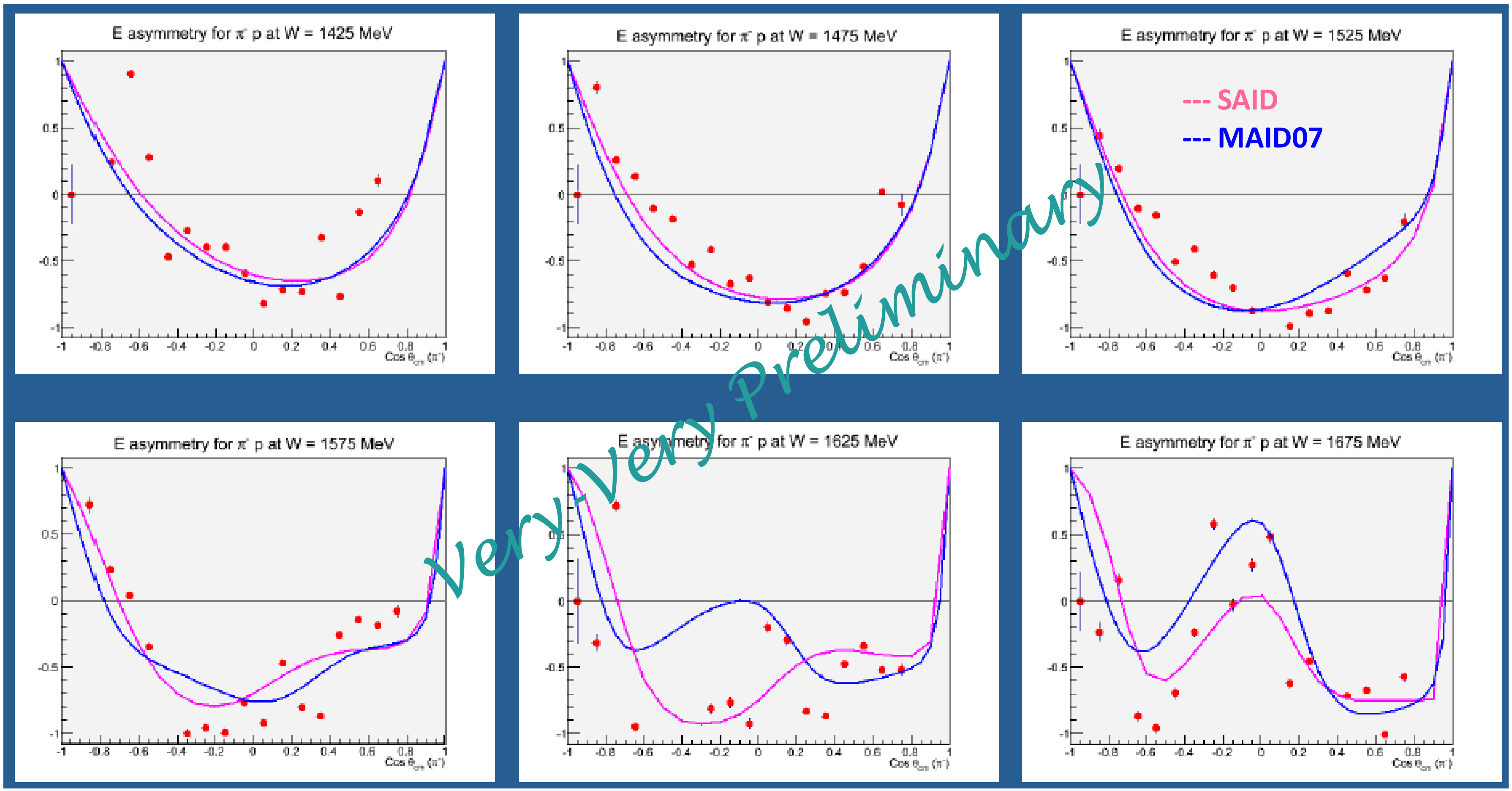
SAID 09 MAID 07 χ^2 from new SAID PWA fit: 2.6

HD-ICE for Polarized Measurements for $\vec{\gamma}\vec{n} \rightarrow \pi^- p$

E

$$E = \frac{D_{eff}}{P_T P_\gamma} \frac{N_{1/2} - N_{3/2}}{N_{1/2} + N_{3/2}}$$

$P_D \sim 27\%$
$P_\gamma \sim 85\%$



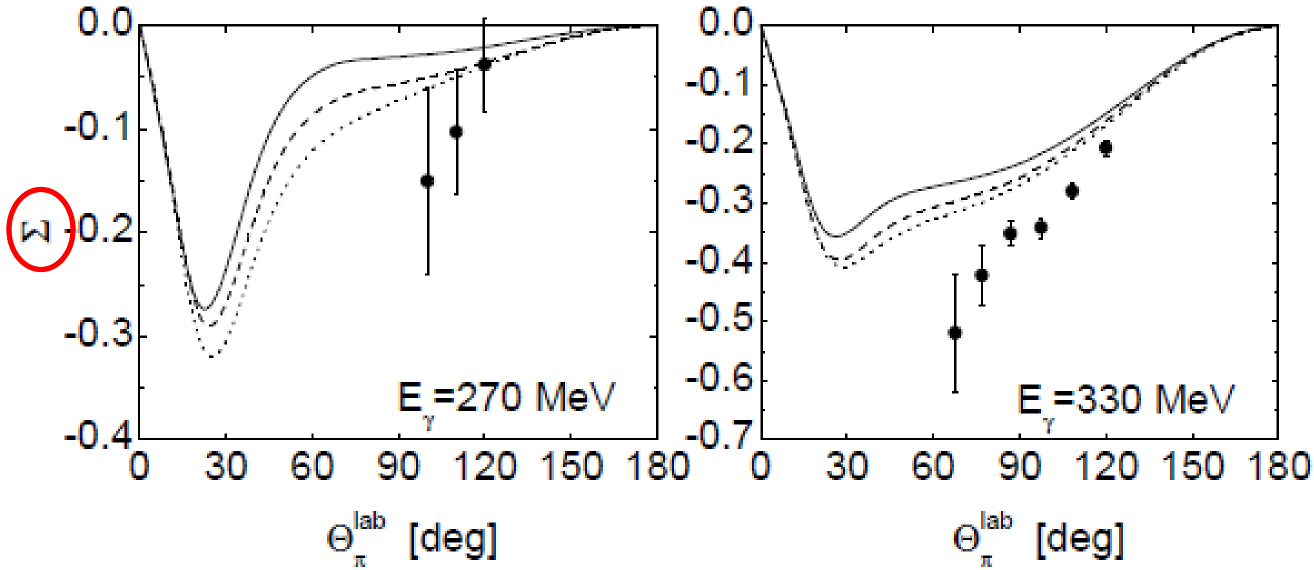
[Courtesy of Natalie Walford, CLAS Meeting , May2012]

- No FSI included

FSI for Polarized Measurements at Δ

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

- There were several attempts to estimate FSI for $\vec{\gamma}d \to \pi^- pp$



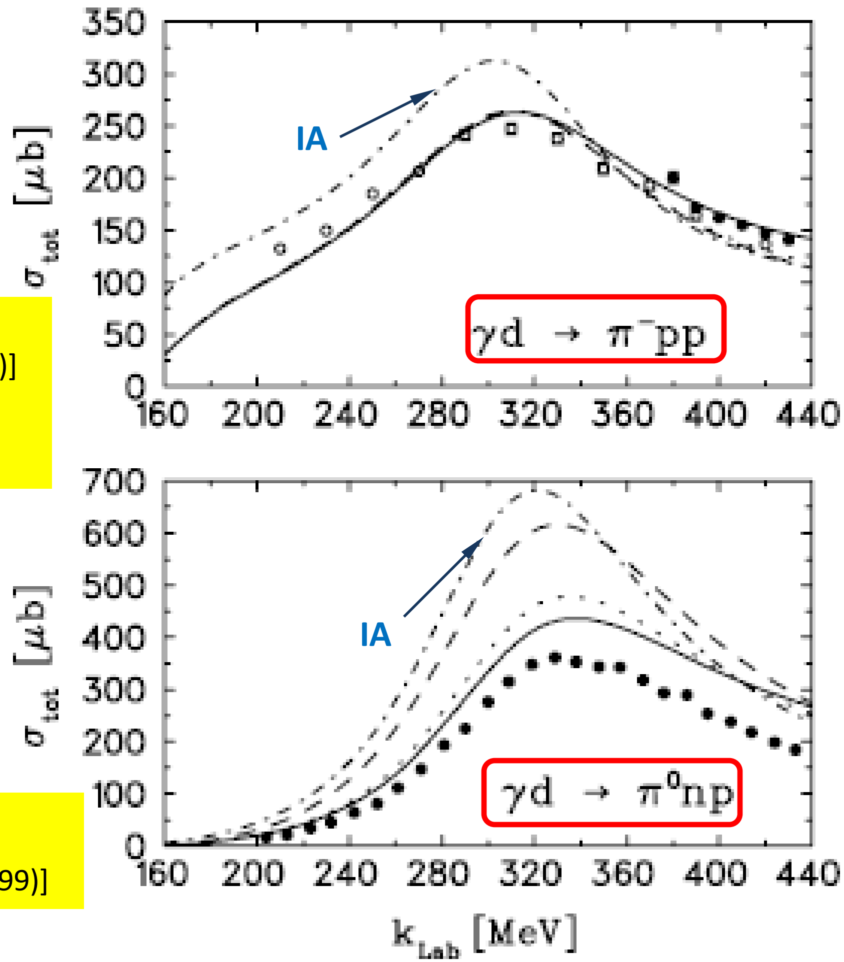
Data: prlm **LEGS**@BNL using **HD-ICE**

- There are no estimations below and above the Δ-region
- The effect from **FSI** is small and at the lowest energy has a noticeable impact on Σ

More Neutron-Target Data

Next Step is $\gamma n \to \pi^0 n$

[M. Schwamb, Phys Rep **485**, 109 (2010)]



- **INS, Tokyo**:
  [M. Asai *ea* Phys Rev C **42**, 837 (1990)]
- **DESY** [Bubble Chamber data]:
  [P. Benz *ea* Nucl Phys **B65**, 158 (1973)]

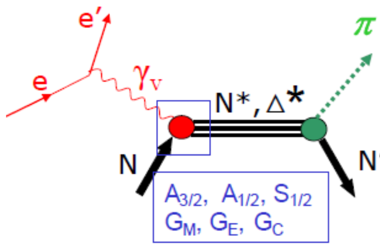
- **MAMI-B**:
  [B. Krusche *ea* Eur Phys J A **6**, 309 (1999)]

- **IA** contribution for $\gamma d \to \pi^0 np$ is much larger than for $\gamma d \to \pi^- pp$

Pion Electroproduction on the Neutron

GW DAC for Pion Electro Prod

- 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]



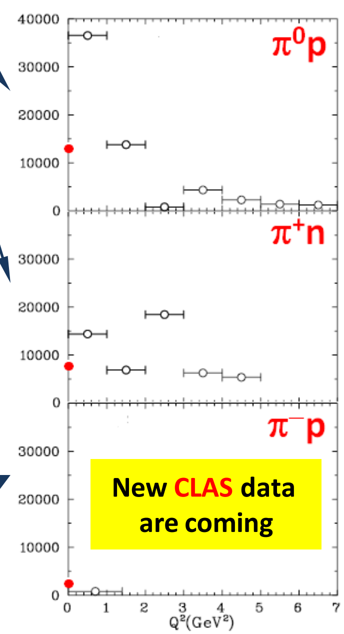
- 0.85 World Electro Prod = JLab CLAS

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

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

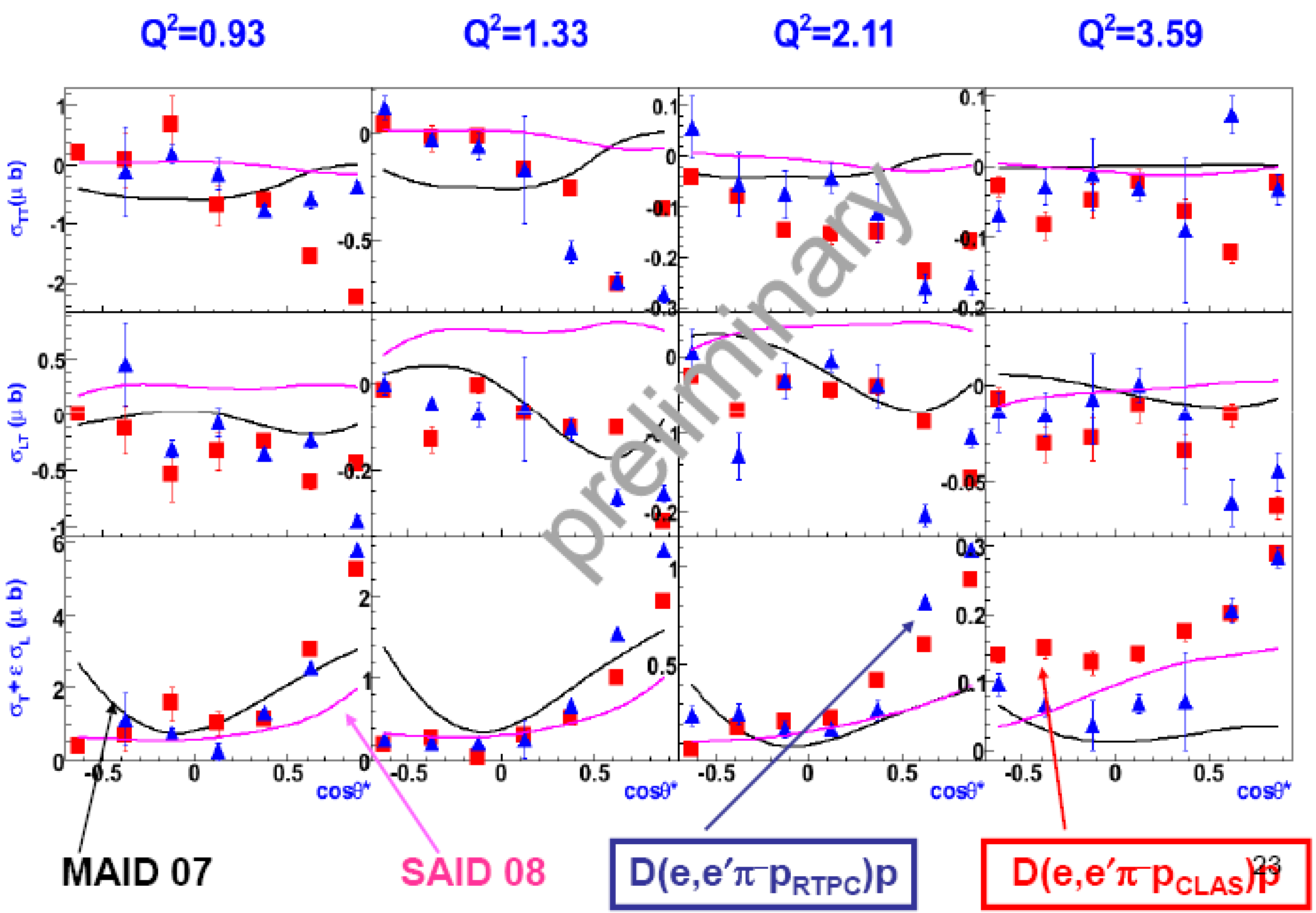
Reaction	Data	χ^2
$\gamma^* p \to \pi^0 p$	55,766	81,284
$\gamma^* p \to \pi^+ n$	51,312	80,004
Redundant	14,772	17,375
Total	121,850	178,663
$\gamma N \to \pi N$	25,358	53,458
All Photo*	148,404	235,229
$\pi N \to \pi N$	31,479	57,157
All πN	179,883	292,386
$\gamma^* n \to \pi^- p$	801	
$\gamma^* n \to \pi^0 n$	No Data	

Q^2-Data



CLAS for $\gamma^* n \rightarrow \pi^0 n$

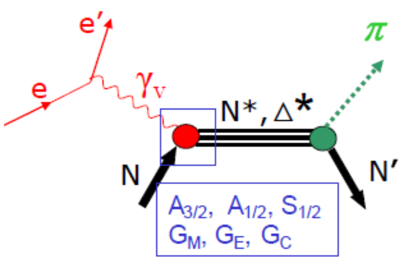
BoNuS Vs Models, 5 GeV, W = 1.525



[Courtesy of Jixie Zhang, MENU2010]

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 FROST & 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



T H A N K S

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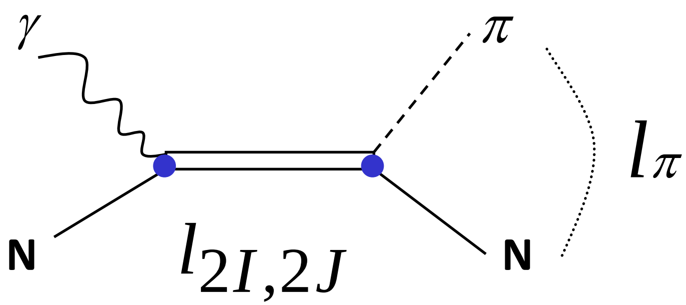
Pion Photoproduction with Polarized Beam and Polarized Target

$$L = l_{\gamma N} + 1$$



EL, ML

Multipole components of the electromagnetic radiation

$$E_{l\pm}, M_{l\pm}$$

Angular momentum and parity conservation

$$J^P(\gamma N) = J^P(R) = J^P(\pi N)$$

Angular momentum

$$L \pm \frac{1}{2} = J = l_\pi \pm \frac{1}{2}$$

Parity

EL : $(-1)^L = (-1)^{l_\pi + 1} \Rightarrow |L - l_\pi| = 1$

ML : $(-1)^{L+1} = (-1)^{l_\pi + 1} \Rightarrow L = l_\pi$

Multipole amplitudes:

$$E_{l+}, E_{l-}, M_{l+}, M_{l-}$$

$J = l + \frac{1}{2}$ (for $l+$)

$J = l - \frac{1}{2}$ (for $l-$)