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Progress in Neutron EM Couplings

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The George Washington University

- Pion photoproduction.
- FSI for unpol $\gamma n \to \pi^- p$ and $\gamma n \to \pi^0 n$.
- CLAS and A2 for unpol $\gamma n \to \pi^- p$.
- Amplitudes and couplings.
- ~~$\gamma n \to \pi^- p$ coming from CLAS and MAX-lab with $\gamma n \to \pi^0 n$ coming from A2 and ELPH.~~
- ~~GRAAL for polarized $\gamma n \to \pi^- p$ and $\gamma n \to \pi^0 n$.~~
- ~~Coming polarized data.~~
- Summary.

Thank you:
Bill Briscoe
Sasha Kudryavtsev
Slava Kulikov
Maxim Martemianov
Vladimir Tarasov
Ron Workman

Pion Photoproduction Database

Only with good data on both the proton and neutron targets, one can hope to disentangle the isoscalar & isovector EM couplings of various N^* and Δ^* resonances.

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

- Many of $\gamma n \rightarrow \pi^- p$ data 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.

- The existing $\gamma n \rightarrow \pi^- p$ database contains mainly differential cross sections (15% of which are from **polarized** measurements.)

- 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 $\pi^- p \rightarrow \pi^0 n \rightarrow \gamma\gamma n$ and there were **no** ``**tagging**" high flux **pion** beams ($\Delta p/p$=6%).

- $\gamma n \rightarrow \pi^0 n$ measurement is a small fraction of $\gamma n \rightarrow \pi N$ database.

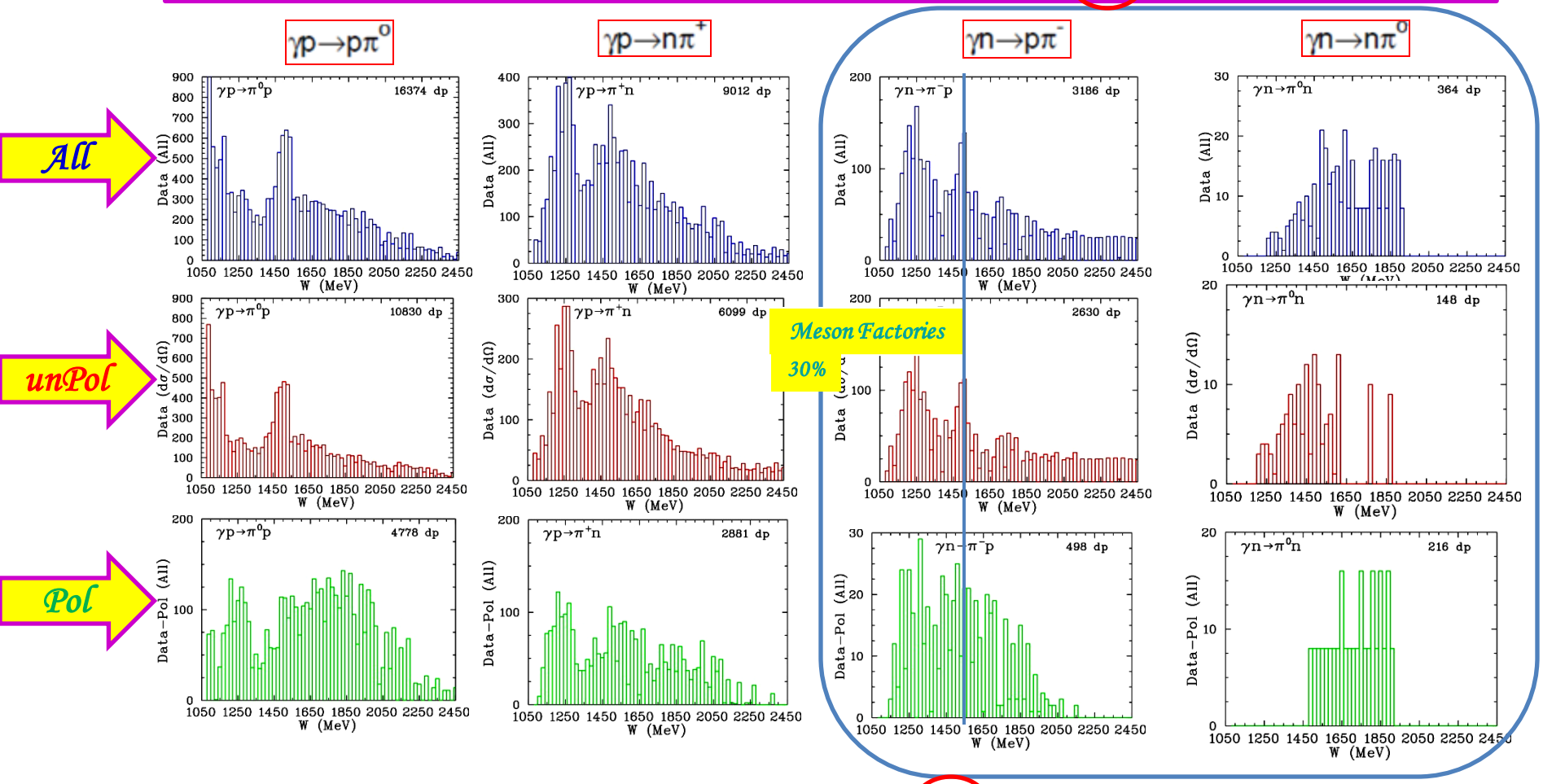
World Neutral and Charged PionPR Data

GW INS — Data Analysis Center — Institute for Nuclear Studies, THE GEORGE WASHINGTON UNIVERSITY, WASHINGTON, DC

W < 2.5 GeV

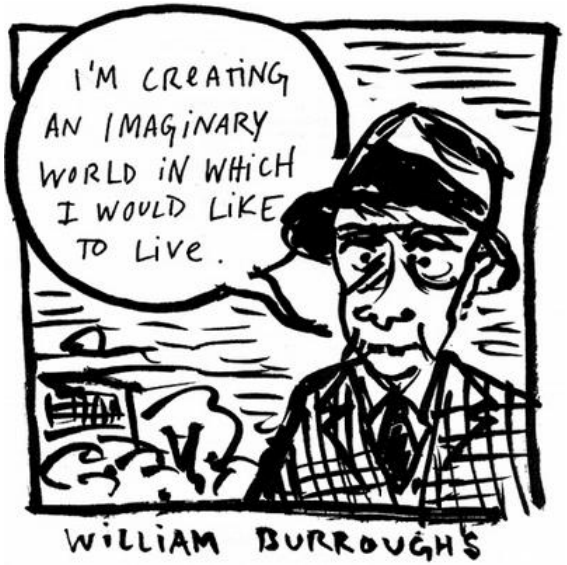
[**SAID**: http://gwdac.phys.gwu.edu/]

Future experiments will fill empty spots specifically for **n-target** which is **15%** of **p-target** measurements



- The existing $\gamma n \to \pi^- p$ data contains mainly differential cross sections, **15%** of which are from polarized measurements.

Pion Photoproduction:
Phenomenological Point of View



Direct Amplitude Reconstruction in Pion PhotoProduction

$$\gamma \quad N \rightarrow N \quad \pi$$

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 photoproduction amplitude [**4 modules** and **3 relative phases**], one has to carry out **7 independent** measurements at **fixed** **(W, t)** or **(E_γ, θ).**

8

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

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)

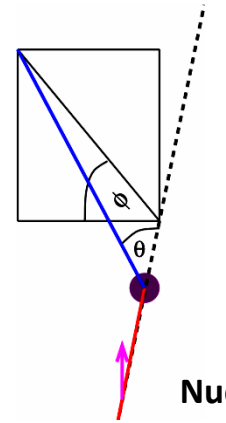
Complete Experiment in Pion PhotoProduction

- There are **16** non-redundant observables.
- They are **not completely independent** from each other.

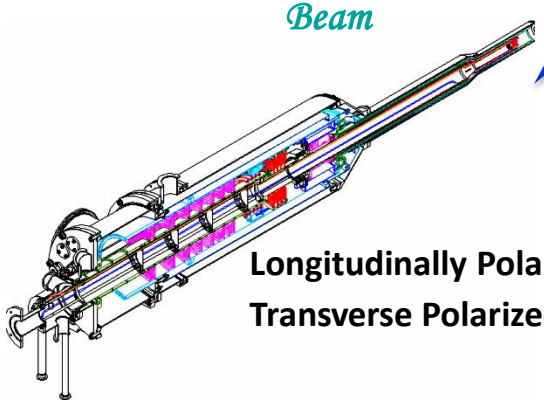
Linear Polarized *Beam*

Circular Polarized *Beam*

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



Nucleon *Recoil* **Polarization**



Longitudinally Polarized Nucleon *Target*

Transverse Polarized Nucleon *Target*

1 un-pol measurement: **dσ/dΩ**
3 single pol measurements: **Σ**, **T**, **P**
12 double pol measurements: **E**, **F**, **G**, **H**, **Cx**, **Cz**, **Ox**, **Oz**, **Lx**, **Lz**, **Tx**, **Tz**
18 triple polarization asymmetries
[**9** for linear pol beam]
[**9** for circular pol beam]
13 of them are non-vanishing

Q: *Can we avoid?* **A**: *NO!*

A. Sandorfi *et al*. AIP Conf. Proc. **1432**, 219 (2012).
K. Nakayama, private communication, 2014.

Single Pion PhotoProduction on Neutron Target

- An accurate evaluation of the **EM** couplings **$N^* \to \gamma N$** and **$\Delta^* \to \gamma N$** 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^*** and **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 **$\gamma n \to \pi^- p$** & **$\gamma n \to \pi^0 n$** data does not allow us to be as confident about the determination of **neutron** couplings relative to those of the **proton**.

- 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)

The Importance of the Neutron

- EM interaction do not conserve **isospin**, so multipole amplitudes contain **isoscalar** and **isovector** contributions of EM current.

Proton

$$A_{\gamma p\to\pi^0 p} = -\left[\frac{1}{3}A^{(0)} - \frac{1}{3}A^{(1)}\right]^{I-1/2} + \frac{2}{3}A^{(I-2/3)}$$

$$A_{\gamma p\to\pi^+ n} = \frac{1}{\sqrt{2}}\left[\frac{1}{3}A^{(0)} - \frac{1}{3}A^{(1)}\right]^{I-1/2} + \frac{\sqrt{2}}{3}A^{(I-2/3)}$$

Neutron

$$A_{\gamma n\to\pi^0 n} = \left[\frac{1}{3}A^{(0)} + \frac{1}{3}A^{(1)}\right]^{I-1/2} + \frac{2}{3}A^{(I-2/3)}$$

$$A_{\gamma n\to\pi^- n} = \frac{1}{\sqrt{2}}\left[\frac{1}{3}A^{(0)} + \frac{1}{3}A^{(1)}\right]^{I-1/2} + \frac{\sqrt{2}}{3}A^{(I-2/3)}$$

- **Proton** data alone does not allow separation of **isoscalar** $\mathbf{A^{(0)}}$, and **isovector**, $\mathbf{A^{(1)}}$, components.

Q: *Can we avoid?* **A**: *NO!*

- Need **data** on both **proton** and **neutron !**

Uncertainties for $A_{1/2}$ & $A_{3/2}$ Decay Amplitudes

- **Neutron** coupling quality are generally as **bad** or **worse** than **proton** one.

$N^* \rightarrow N\gamma$	$\delta A_{1/2}(p)$	$\delta A_{1/2}(n)$	$\delta A_{3/2}(p)$	$\delta A_{3/2}(n)$
$N(1440)1/2^+$	0.07	0.25		
$N(1520)3/2^-$	0.38	0.15	0.10	0.08
$N(1535)1/2^-$	0.33	0.59		
$N(1650)1/2^-$	0.30	1.40		
$N(1675)5/2^-$	0.42	0.28	0.60	0.22
$N(1680)5/2^+$	0.40	0.35	0.09	0.27
$N(1720)3/2^+$	1.20	3.75	1.05	3.00

- One of reasons of that is simple – the **neutron** database is much less than **proton**.

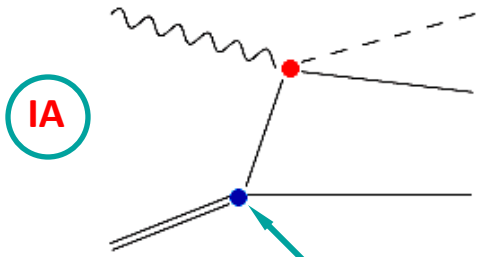
Final State Interaction

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

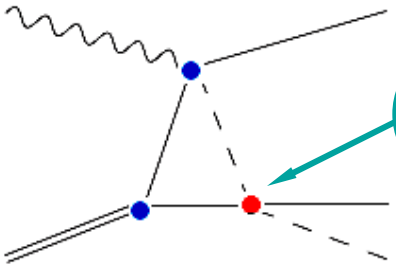
FSI and $\gamma d \to \pi p N \Rightarrow \gamma n \to \pi N$

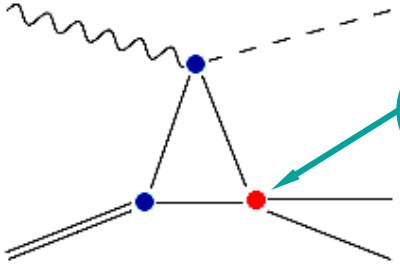
[V. Tarasov, A. Kudryavtsev, W. Briscoe, H. Gao, IS, Phys Rev C **84**, 035203 (2011)]
[V. Tarasov, A. Kudryavtsev, W. Briscoe, B. Krusche, IS, M. Ostrick, arXiv:**1503**.06671]

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

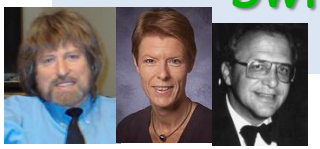


Fermi motion of nucleons included





<u>Input</u>: **SAID**: $\gamma N \to \pi N$, $\pi N \to \pi N$, $NN \to NN$ amplitudes for **3** leading terms.
DWF: full Bonn **NN** Potential (there is no sensitivity to DWF).



$$R = (d\sigma/d\Omega_{\pi p})/(d\sigma^{IA}/d\Omega_{\pi p}) \Rightarrow \frac{d\sigma}{d\Omega}(\gamma n) = R^{-1}\frac{d\sigma}{d\Omega}(\gamma d)$$

FSI for $\gamma d \to \pi^- pp \Rightarrow \gamma n \to \pi^- p$

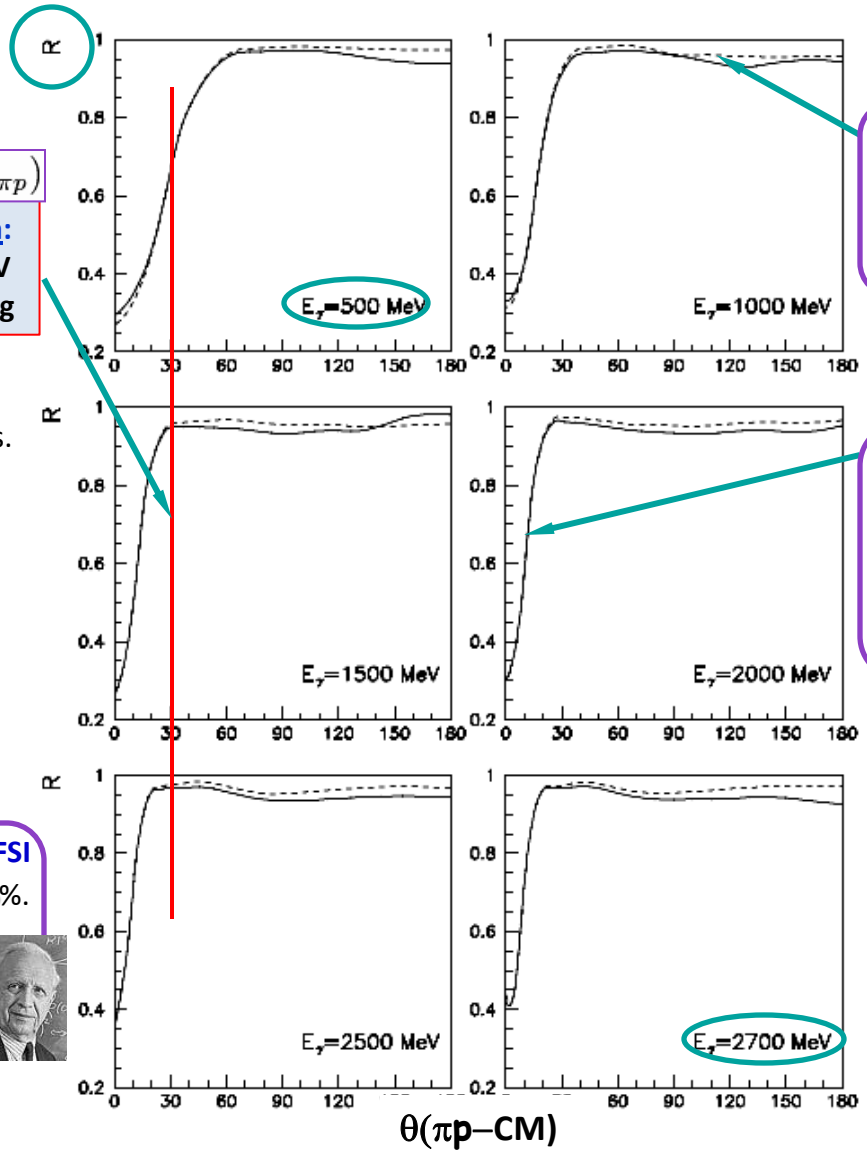
[V. Tarasov, A. Kudryavtsev, W. Briscoe, H. Gao, IS, Phys Rev C **84**, 035203 (2011)]

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

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

CLAS data:
E > 1 GeV
θ > 32 deg

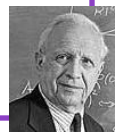
- There is no large sensitivity to cuts.



- For **CLAS** data
  - The **FSI** correction factor **R < 1**.
  - The behavior is smooth vs. **θ**.
  - The effect **Δσ/σ ≤ 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 + $(NN+\pi N)_{fsi}$] / IA

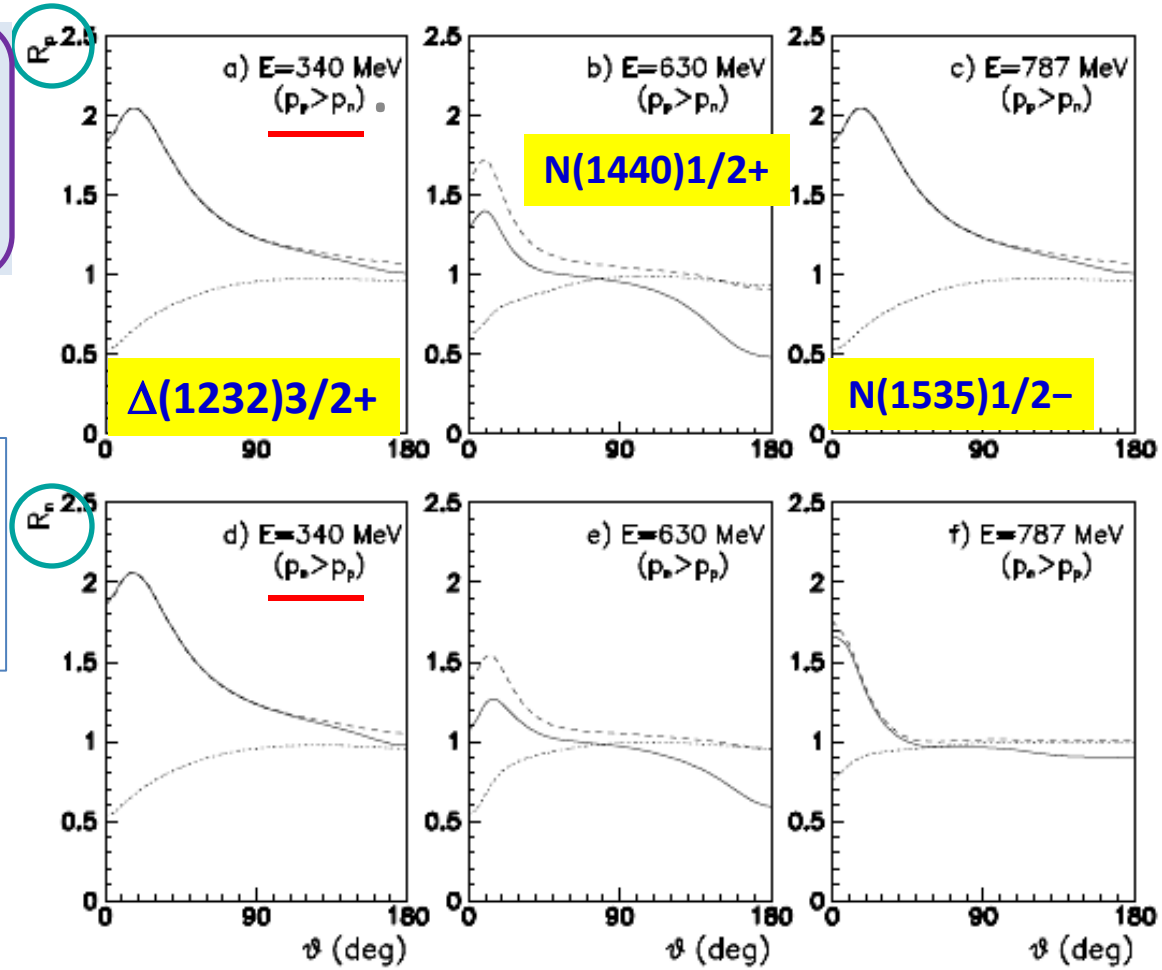
FSI for $\gamma d \to \pi^0 np \Rightarrow \gamma n \to \pi^0 n$

[V. Tarasov, A. Kudryavtsev, W. Briscoe, B. Krusche, IS, M. Ostrick, arXiv:**1503**.06671]

- $\gamma n \to \pi^0 n$ case is much more complicate vs. $\gamma n \to \pi^- p$ because π^0 can come from both γn and γp initial interactions

- The corrections for both target nucleons are **practically identical** for π^0 production in the energy range of the $\Delta(1232)3/2^+$ $R_n = R_p$

- In general , $R_n \neq R_p$

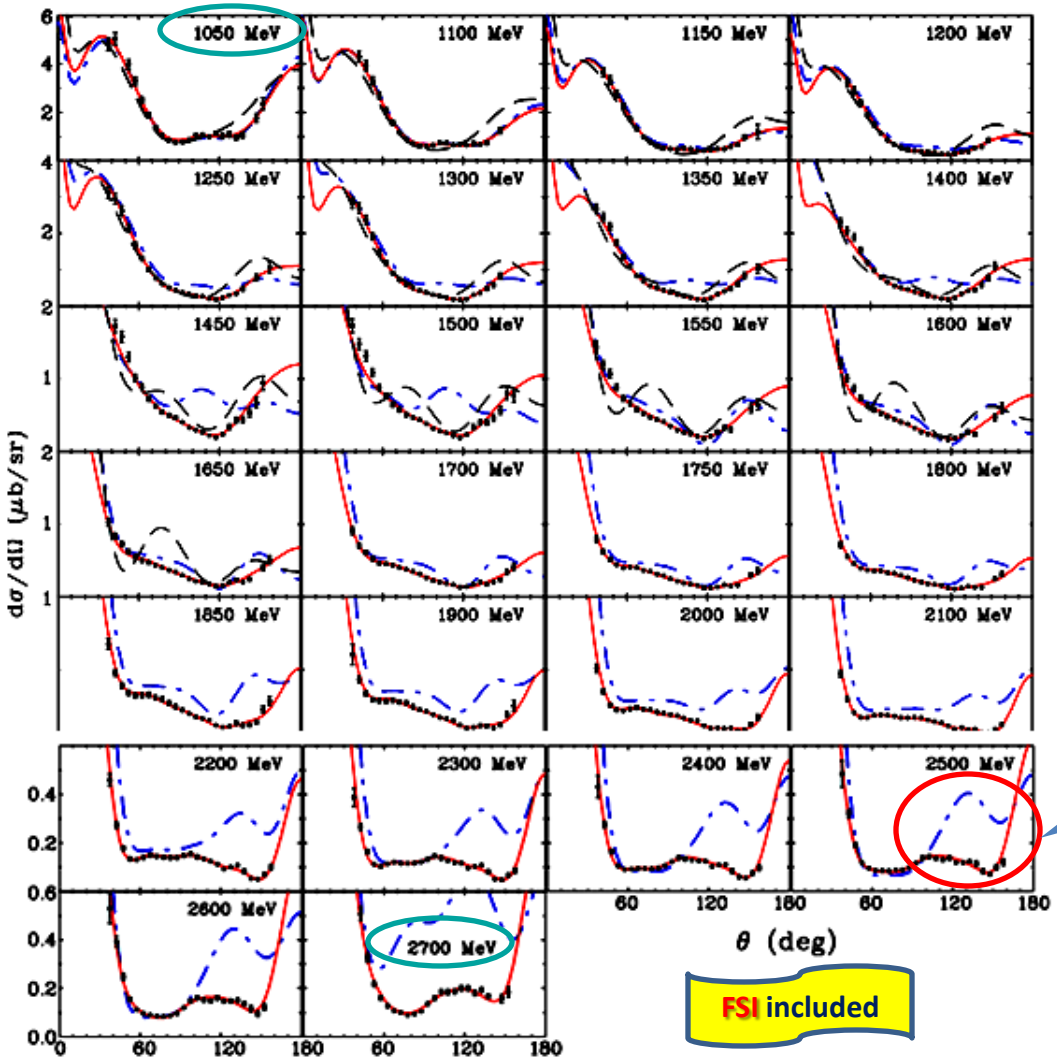


CLAS & MAMI–B

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

CLAS for $\gamma n \rightarrow \pi^- p$ above 1 GeV

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



- The **CLAS g10** cross sections have **quadrupled** the world database for $\gamma n \rightarrow \pi^- p$ above E_γ = **1 GeV**.

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]

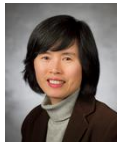
- **CLAS** data appear to have fewer angular structures than the earlier fits.

FSI included

SAID-GB12

SAID-SN11

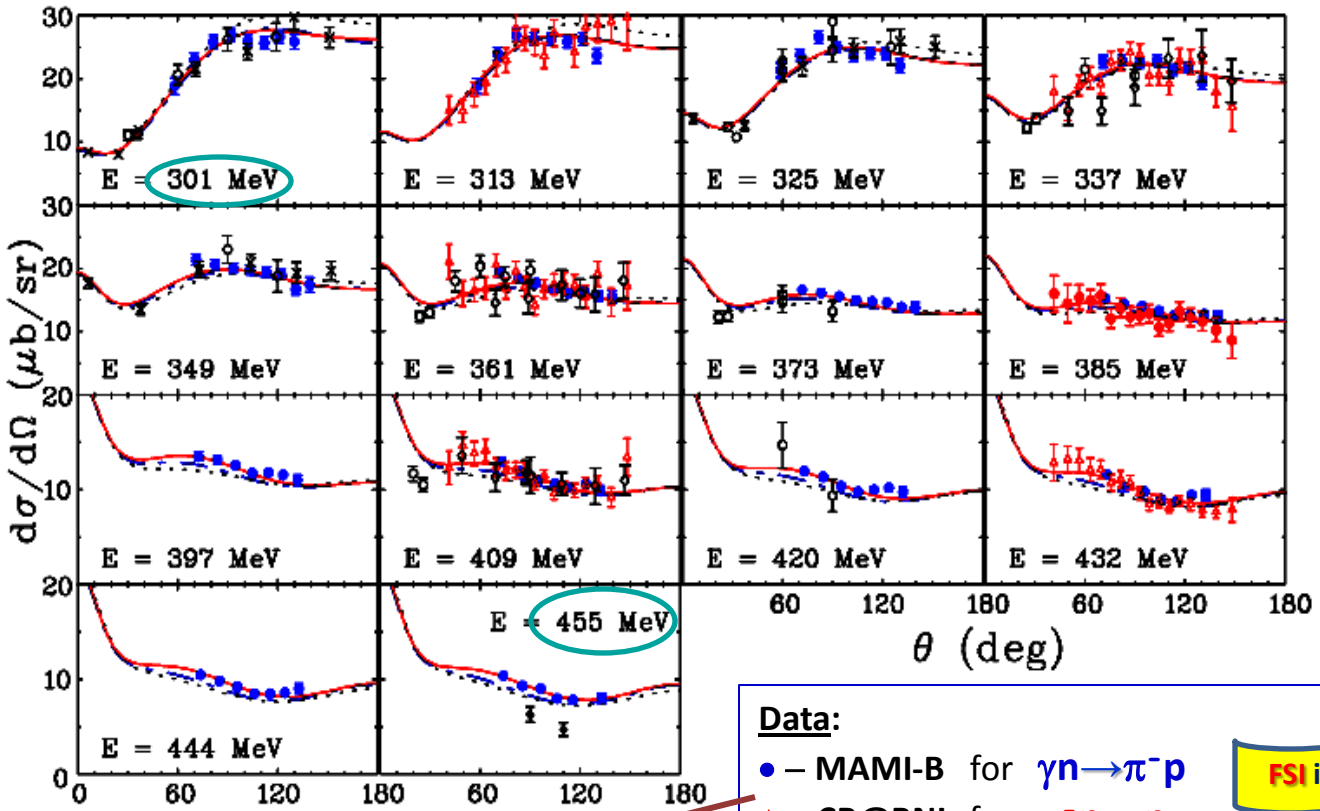
MAID07



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

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

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



SAID-PE12
SAID-SN11
MAID07

Data:

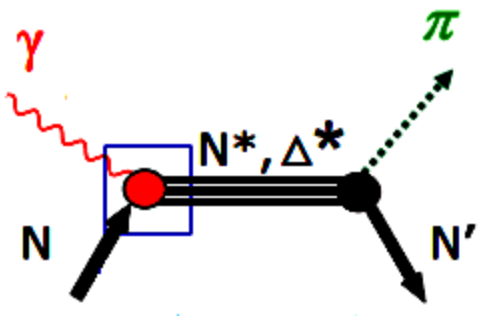
- – **MAMI-B** for $\gamma n \to \pi^- p$
- Δ – **CB@BNL** for $\pi^- p \to n\gamma$
- o – **TRIUMF, CERN, LBL, LAMPF** for $\pi^- p \to n\gamma$

FSI included

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

- **T-invariance is good as 2 x 10^{-3}**

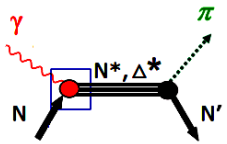
Amplitudes & Couplings

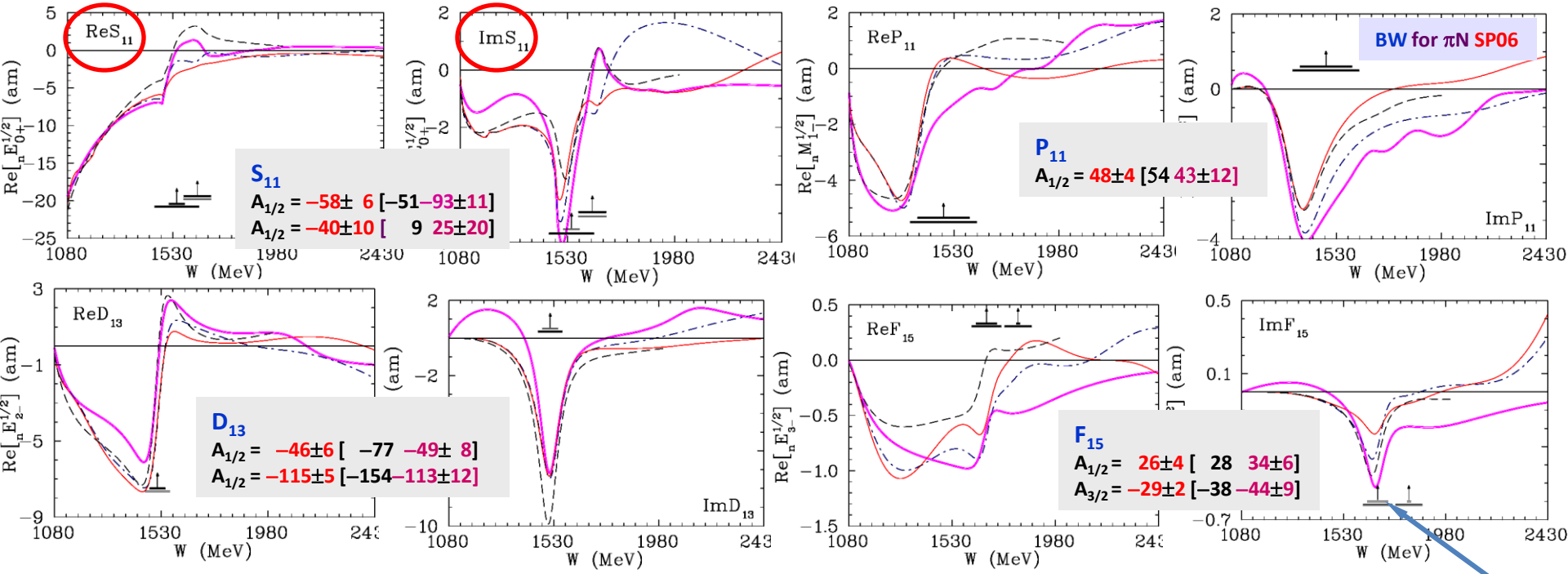


Neutron Multipoles from SAID GB12 & SN11

[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.**





- **Significant changes have occurred at high energies.**
- **Comparisons to earlier SAID and fits 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

BW: R. Arndt *et al*, Phys Rev C **74**, 045205 (2006)

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 Impact for Neutral $S = 0$ & $I = ½$ 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.

[$(\mathrm{GeV})^{-1/2} \times 10^{-3}$]

Resonance	$nA_{1/2}$	Resonance	$nA_{1/2}$	$nA_{3/2}$	Ref.
$N(1535)1/2^-$	-58 ± 6	$N(1520)3/2^-$	-46 ± 6	-115 ± 5	SAID GB12 [17]
	-60 ± 3		-47 ± 2	-125 ± 2	SAID SN11 [25]
S_{11}	-93 ± 11	D_{13}	-49 ± 8	-113 ± 12	BnGa13 [26]
-63	-49 ± 3	-38 -114	-38 ± 3	-101 ± 4	Kent12 [11]
	-46 ± 27		-59 ± 9	-139 ± 11	PDG [1]
$N(1650)1/2^-$	-40 ± 10	$N(1675)5/2^-$	-58 ± 2	-80 ± 5	SAID GB12 [17]
	-26 ± 8		-42 ± 2	-60 ± 2	SAID SN11 [25]
S_{11}	25 ± 20	D_{15}	-60 ± 7	-88 ± 10	BnGa13 [26]
-35	11 ± 2	-35 -51	-40 ± 4	-68 ± 4	Kent12 [11]
	-15 ± 21		-43 ± 12	-58 ± 13	PDG [1]
$N(1440)1/2^+$	48 ± 4	$N(1680)5/2^+$	26 ± 4	-29 ± 2	SAID GB12 [17]
	45 ± 15		50 ± 4	-47 ± 2	SAID SN11 [25]
P_{11}	43 ± 12	F_{15}	34 ± 6	-44 ± 9	BnGa13 [26]
-6	40 ± 5	19 -23	29 ± 2	-59 ± 2	Kent12 [11]
	40 ± 10		29 ± 10	-33 ± 9	PDG [1]

GB12
SN11
BnGa13
Kent12
PDG

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

- Recent **GB12** $nA_{1/2}$ & $nA_{3/2}$ couplings shown sometimes a significant deviation from our previous SAID determination (**SN11**) and **PDG14** average values, e.g., for **N(1650)1/2⁻**, **N(1675)5/2⁻**, and **N(1680)5/2⁺**.

- Recent **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⁺**.

Summary for Neutron Study

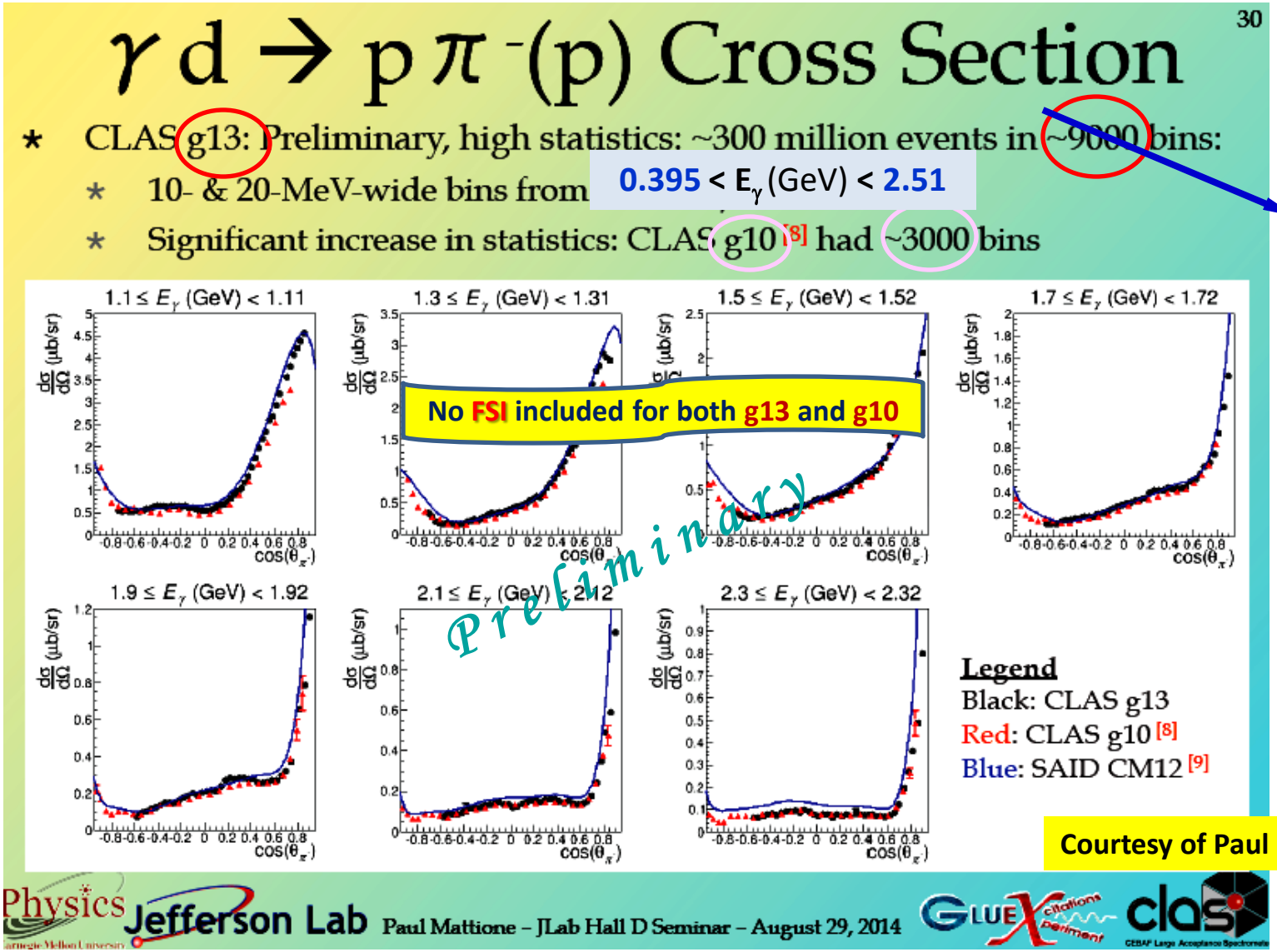
- The differential cross section for the processes **$\gamma n \to \pi^- p$** was extracted from recent **CLAS** and **MAMI-B** measurements accounting for **Fermi** motion effects in the **IA** as well as **NN**- and **πN-FSI** effects beyond the **IA**.
- Consequential calculations of the **FSI** corrections, 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 **$\gamma n \to \pi^- p$** and **$\gamma n \to \pi^0 n$** 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** from **JLab/JLab12**, **A2**, **LEPS/LEPS2**, **ELSA**, and **ELPH** will help to bring more physics in.
- **FSI** corrections need to apply.


Thank you for the invitation
and your attention
Courtesy of Eugene Pasyuk
igor@gwu.edu

Work in Progress

More CLAS for $\gamma n \rightarrow \pi^- p$ above 0.4 GeV

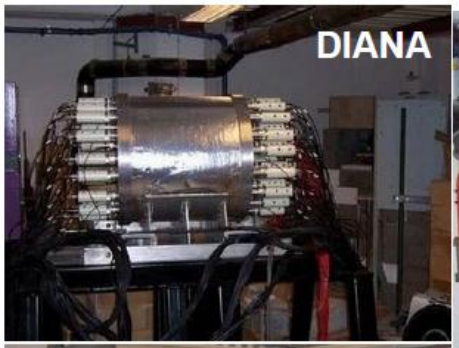


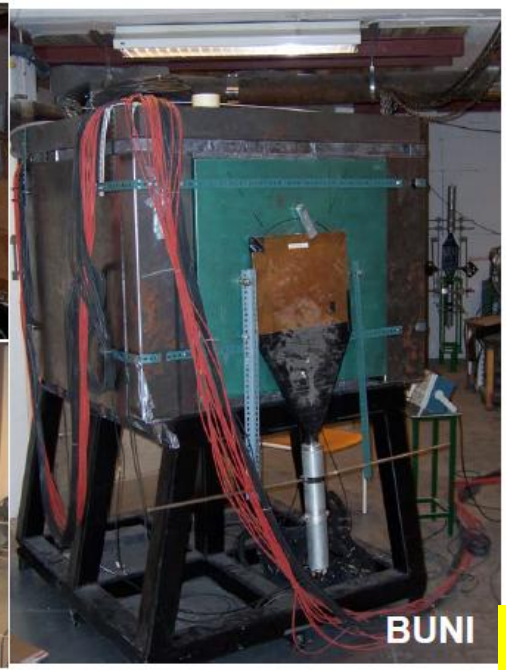
Courtesy of Paul Mattione

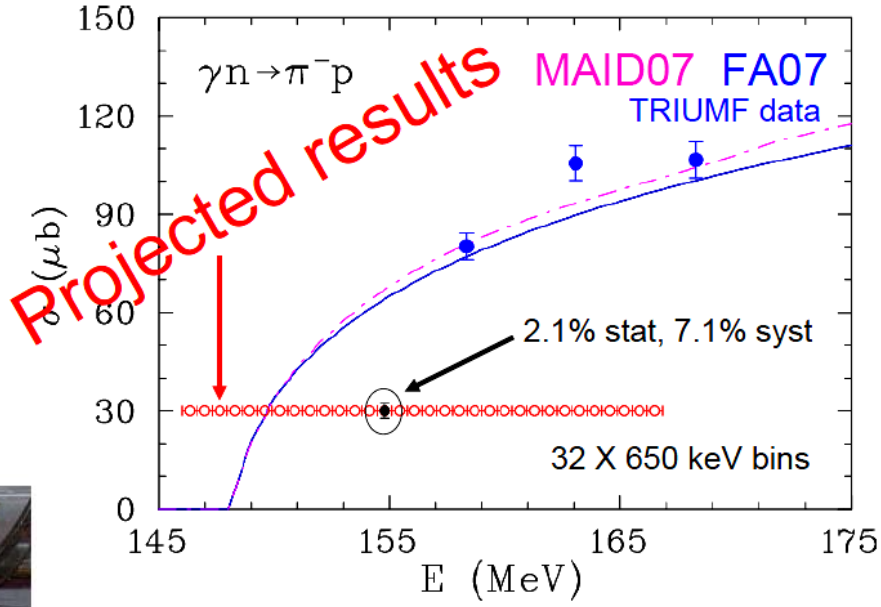
MAX-lab for $\gamma n \rightarrow \pi^- p$ at Threshold

Photon detectors

- Onsite: 3 of the largest (single-crystal) NaI(Tl) detectors ever built
  - BUNI (Boston University, USA)
  - CATS (University of Mainz, Germany)
  - DIANA (University of Kentucky, USA)
- at $E_\gamma \sim 130$ MeV (endpoint is 131.4 MeV)
  - $\Delta E_\gamma / E_\gamma \sim 2\%$
  - $\varepsilon_\gamma \sim 98\%$
- $\Delta\Omega \sim 40$ msr at nominal distances







- It is a difficult task to measure $\pi^- p$ final state close to the **threshold**.
- We measured π^0 decay in to 2γ from $\gamma n \rightarrow \pi^- p \rightarrow \pi^0 n$.

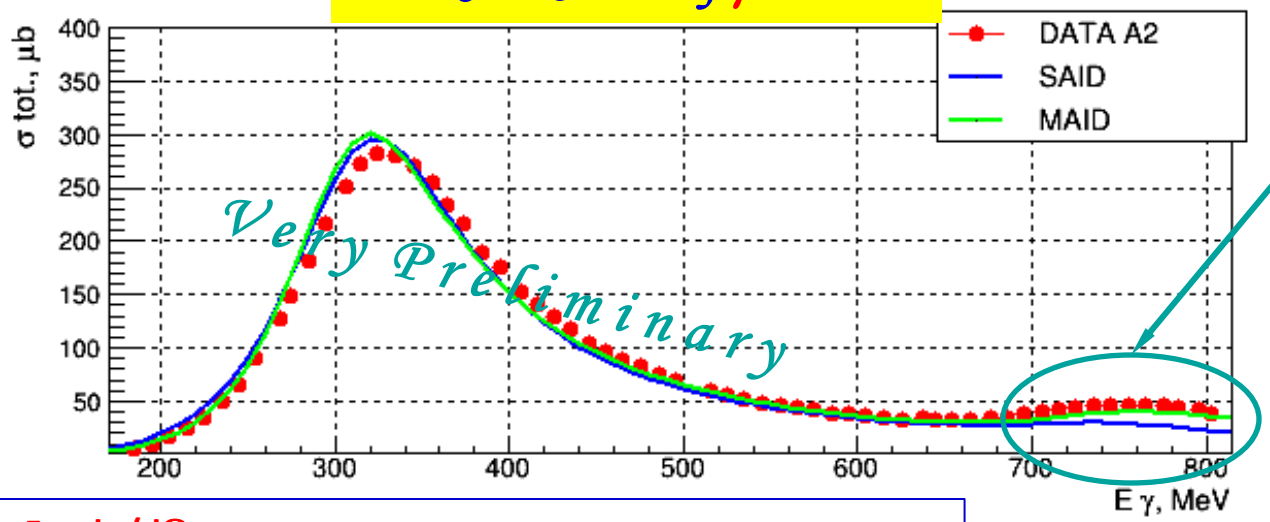
Courtesy of Kevin Fissum

Meson Production off the Deuteron at CB@MAMI

[**Spokespersons**: W. Briscoe, IS, **MAMI-A2-02/12**; W. Briscoe, V. Kulikov, K. Livingstone, IS, **MAMI-A2-02/13**]

- New **A2** data will provide a critical constraint on the determination of multipoles and **EM** couplings of **low-laying baryon** resonances using the **PWA** techniques developed by the **SAID** group.

Total Cross Section of $\gamma n \rightarrow \pi^0 n$



- Comparison of our **A2** exp data with **MAID07** predictions gives more reasonable agreement vs. **SAID CM12**, especially at higher energies.

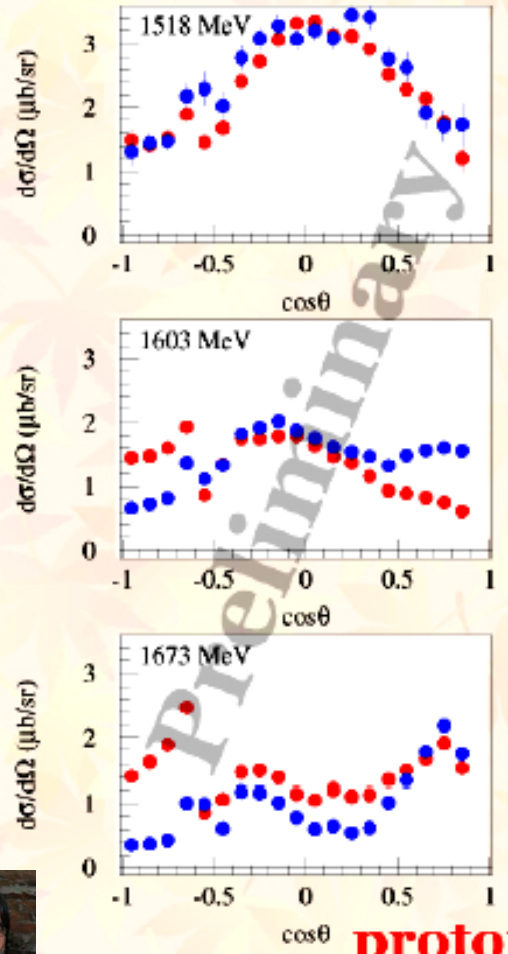
- **For dσ/dΩ:**
  W = 1105 – 1545 MeV, ΔW ~ 10 MeV, n_W = 31
  E_γ = 180 – 800 MeV, ΔE_γ ~ 20 MeV
  $-0.9 \leq \cos(\theta) \leq +1$, $\Delta\cos(\theta)$ = 0.01, $n_{\cos\theta}$ = 19
  Relative error of our measurement has a level of **1.5 – 3** %.

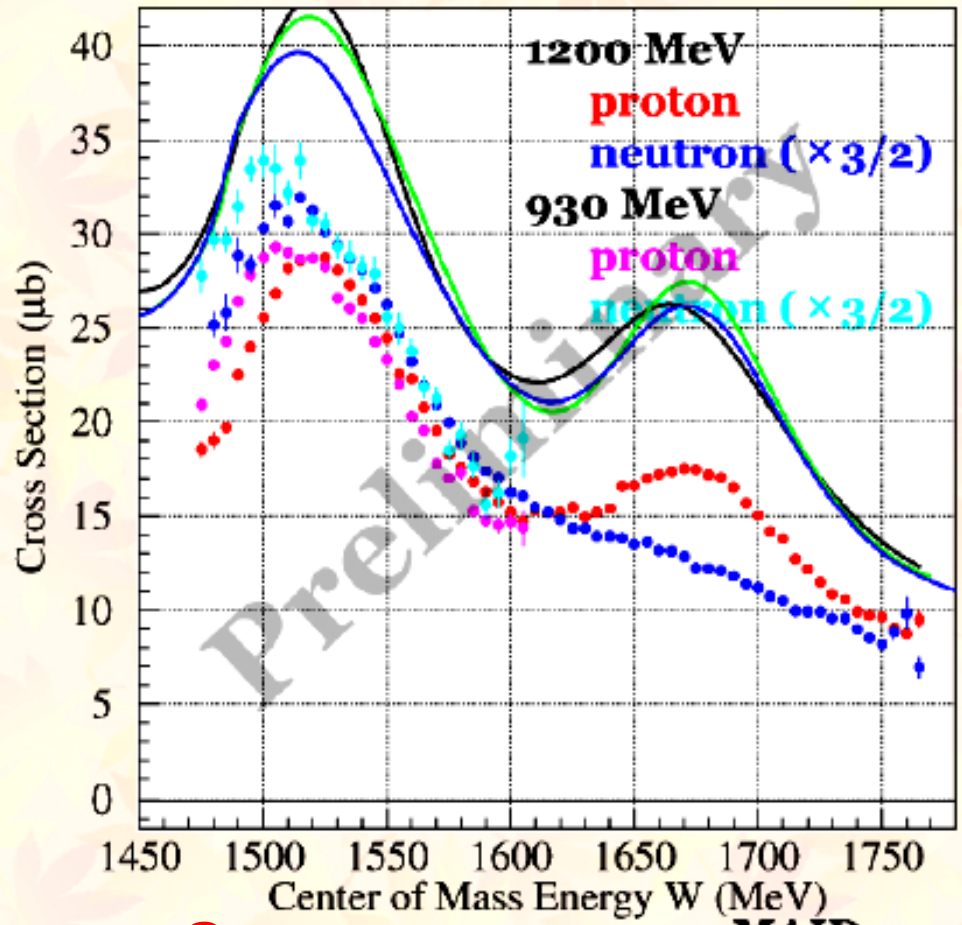
No FSI included yet

- New **589** **dσ/dΩ**s by the **A2** contribution is **160%** to the previous world **π^0n** database.

Exclusive Analysis for $\gamma N' \to \eta N$, $\gamma N' \to \pi^0 N$

Differential and total cross sections for $\gamma N' \to \pi^0 N$





proton
neutron (×3/2) ?

No FSI included

MAID2007
SAID 2012
BoGa 2011-2

T. Ishikawa, 05 Nov. 2013

HADRON2013

Polarized Measurements

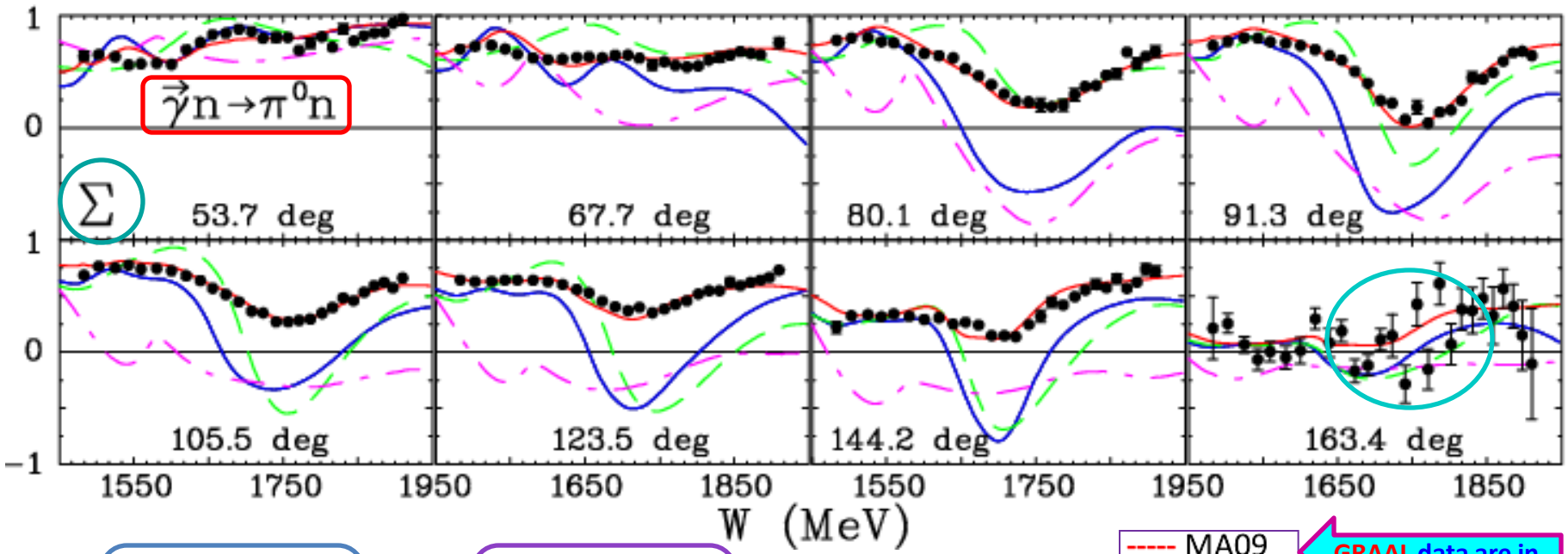
for $\gamma n \rightarrow \pi^0 p$ & for $\gamma n \rightarrow \pi^- p$

Situation is more complicate.
We have no FSI tool yet.

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 result in significant changes in the **neutron** couplings.



- 216 GRAAL Σs are 60% of the World π^0n data

	χ^2/dp
MAID07	100
SP09	223
MA09	3.1

No FSI included

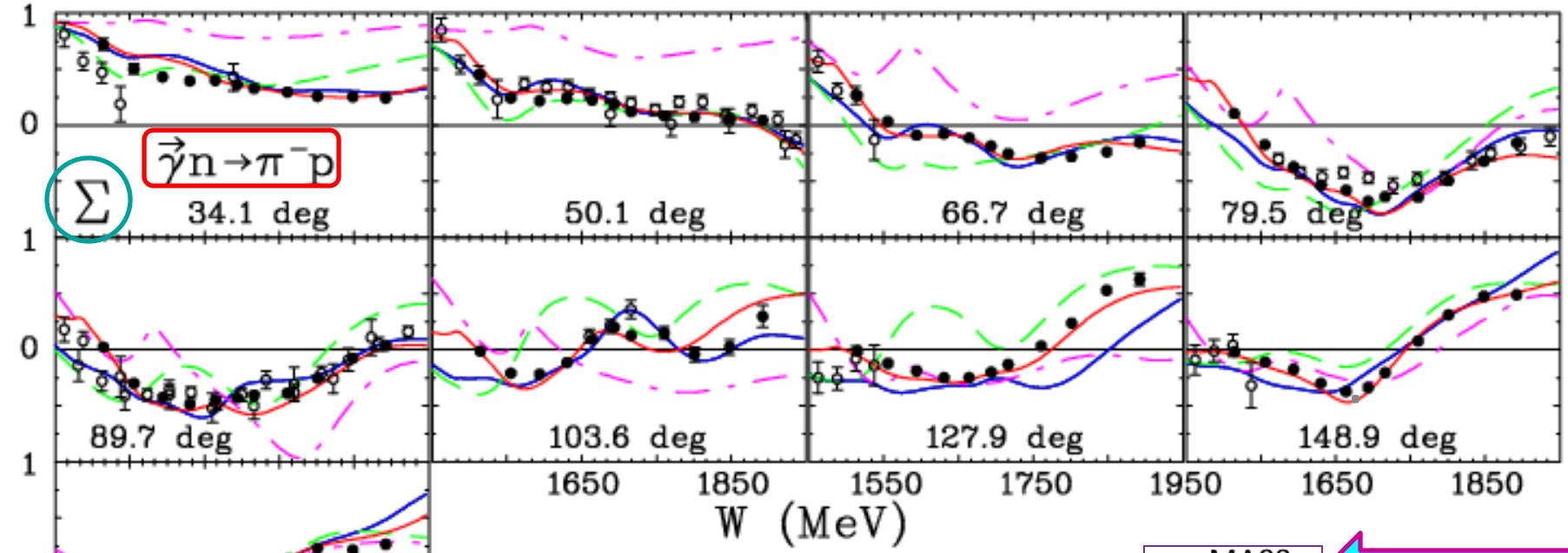
----- MA09
----- SP09
- - - MAID07
-.-.- DTM

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.



	χ^2/dp
MAID07	27
SP09	89
MA09	4.9

No FSI included

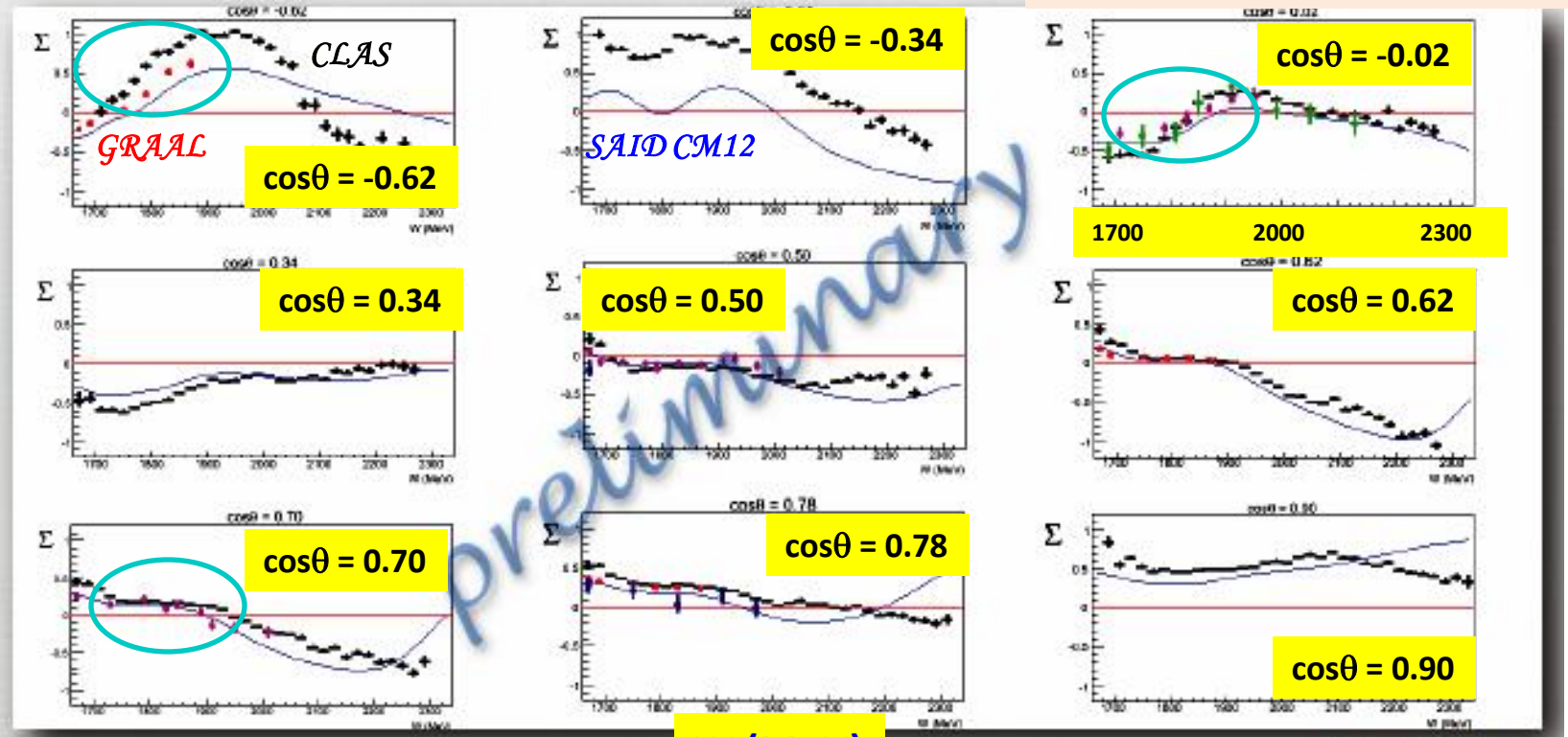
----- MA09
----- SP09
- - - MAID07
-.-.- DTM

GRAAL data are in

Work in Progress

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

- **SAID** can fit **CLAS** Σs with χ^2/dp = **2.6**



D. Sokhan

Curve - SAID
Red GRAAL
Magenta and Blue - Erevan

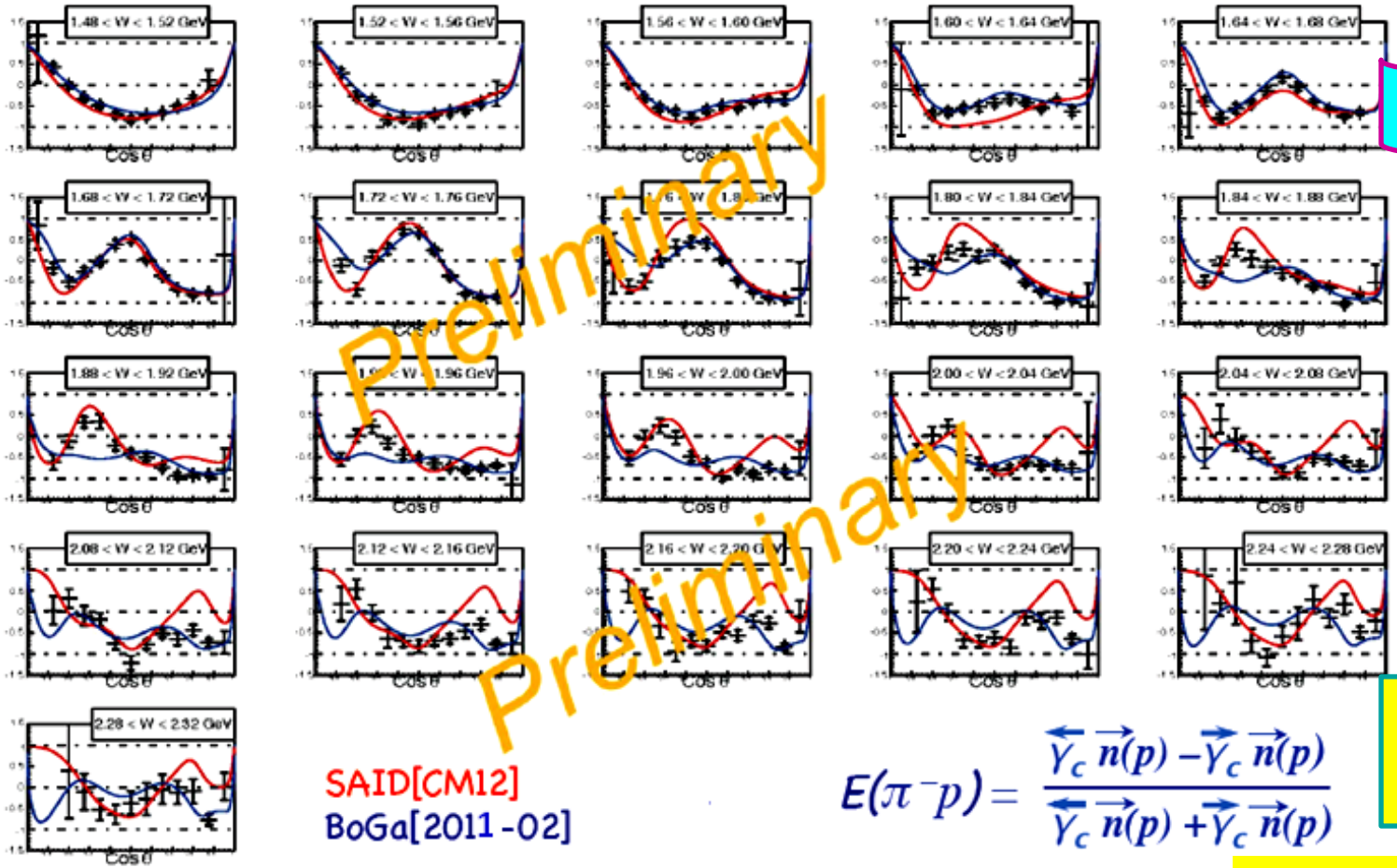
No FSI included

9 out of 40 angula

Bins 0.04 in cos and 20 MeV in W

Courtesy of Daria Sokhan

Beam-Target Helicity asymmetry $E(\pi^- p)$ - T. Kageya (Jlab)



No FSI included

SAID[CM12]
BoGa[2011-02]

$$E(\pi^- p) = \frac{\overleftarrow{\gamma}_c \vec{n}(p) - \vec{\gamma}_c \vec{n}(p)}{\overleftarrow{\gamma}_c \vec{n}(p) + \vec{\gamma}_c \vec{n}(p)}$$

Σ & G data are coming

Courtesy of Andy Sandorfi