Recent GW activity in pion photoproduction experiments and analysis within the SAID Framework

Presenter: William Briscoe

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GW Graduate Students: Phoebe Sharp, Sara Ratliff, Erin Seroka, Izzy Illari, Peter Solazzo, Chan Kim, Giovanni Angelini.

* Thanks for the help in preparing slides

QCD and the Hadron Spectrum

- QCD gives rise to the *hadron spectrum*.

Volume 8, number 3 PHYSICS LETTERS 1 February 1964

A SCHEMATIC MODEL OF BARYONS AND MESONS

M. GELL-MANN

If we assume that the strong interactions of baryons and mesons are correctly described in terms of the broken "eightfold way"

Baryons can now be constructed from quarks by using the combinations $(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$, etc., while mesons are made out of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$, etc.

CERN-TH-412 (Feb 21, 1964)

AN SU_3 MODEL FOR STRONG INTERACTION SYMMETRY AND ITS BREAKING

G. Zweig *)

CERN - Geneva

Both mesons and baryons are constructed from a set of three fundamental particles called aces. The aces break up into an isospin doublet and singlet. Each ace carries baryon number $\frac{1}{3}$ and is consequently fractionally charged. SU_3 (but not the Eightfold Way) is adopted as a higher symmetry for the strong interactions. The breaking of this symmetry is assumed to be universal, being due to mass differences among the aces. Extensive space-time and group theoretic structure is then predicted for both mesons and baryons, in agreement with existing experimental information. An experimental search for the aces is suggested.

- Many $\bar{q}q$ & qqq states have been *observed*.

  PDG 220 & 100.

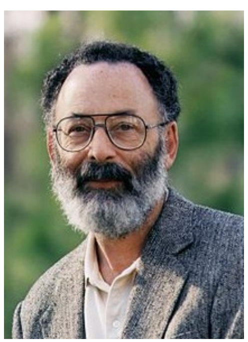
Hadron Spectroscopy

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

Dick Dalitz, 1976

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

Gerhard Höhler, 1987



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

Nathan Isgur, 2000

*There are Many Ways to Study N**

- **Prolific source** of **N*** & **Δ*** baryons is to measure many channels with different combinations of quantum numbers.

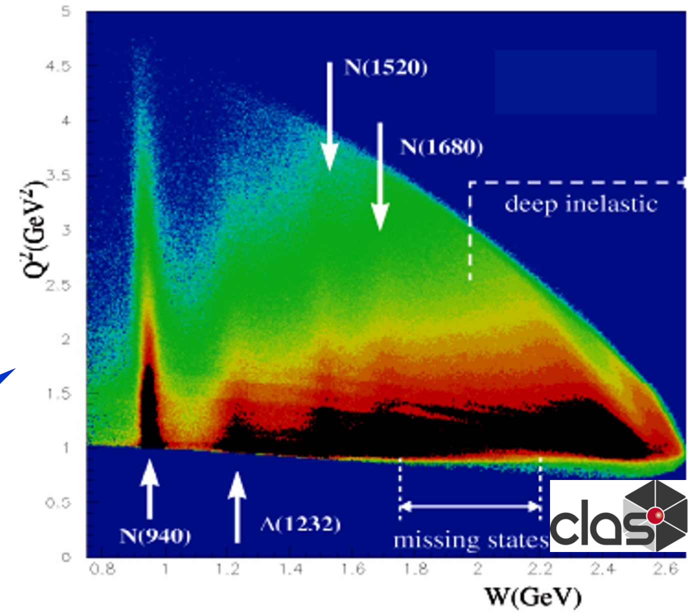
$\pi N \to \pi N, \pi\pi N, \ldots$

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

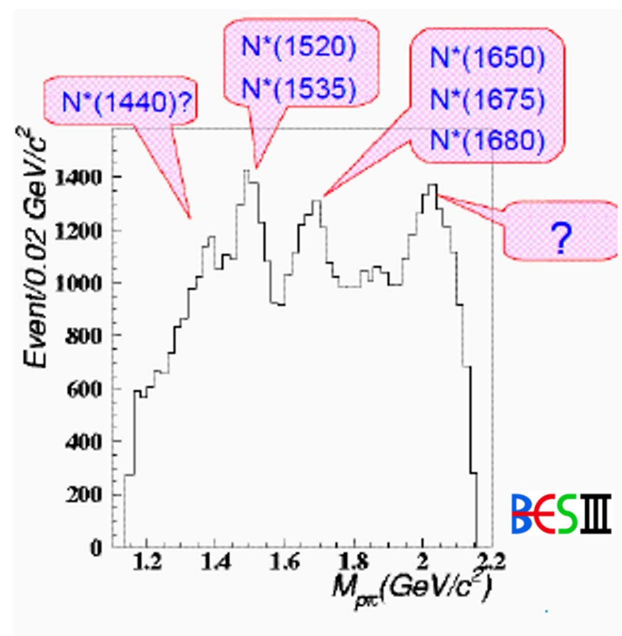
$\gamma^* N \to \pi N, \pi\pi N, \ldots$

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

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



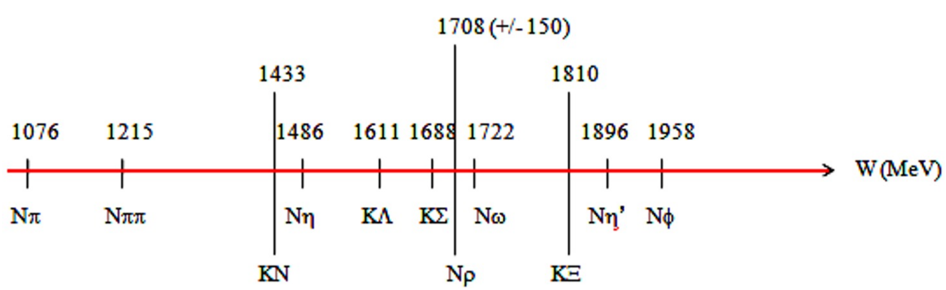
ep→epX



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

PDG Most of **PDG Listings** info comes from these sources.

- **πN** elastic scattering is highly constrained.
- **Resonance** structure is correlated.
- Two-body final state, **fewer amplitudes**.



Where Are We Now…

- Certain experiments provide unique info about resonance decay properties.
  - *helicity couplings **A1/2** & **A3/2** for **γp** and **γn** decays come only from **pion** photo- & electro-production measurements.*
- Helicity couplings normally extracted from full energy-dependent multipole amplitudes.
  - *Until recently, the only available multipole amplitudes were for single pion photoproduction.*
- Determination of **A1/2** & **A3/2** from meson photo- & electro-production requires knowledge of corresponding hadronic couplings.
  - *Photo- & electro-production alone determine only the product of couplings to the γN and hadronic channels.*

Every phenomenology group
[BnGa, EBAC, Gent, Giessen, JAW, Juelich, MAID, & SAID]
Uses the SAID πN results for constrain.

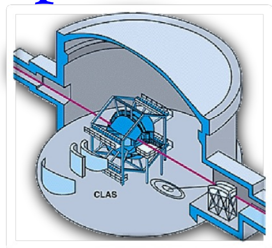
- Most modern **experimental efforts** focus on photo- or electro-production experiments
  - high-precision measurements with **hadron** beams (**pions** & **kaons**) are needed!
- PWAs are best way to determine **N*** properties
  - *Multichannel approaches can help resolve inconsistencies.*

Road Map to Baryon Spectroscopy

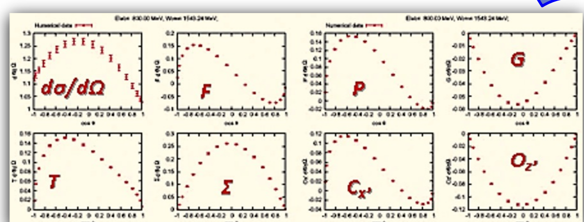
- *That is not hunting for bumps!*

Facility

Experiment

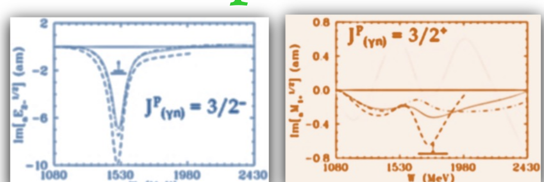


Data



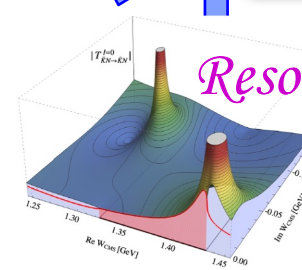
PWA

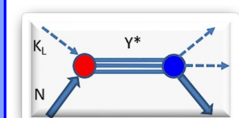
Amplitudes

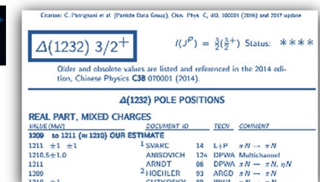


PWA

Resonances

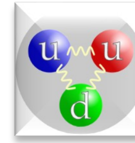


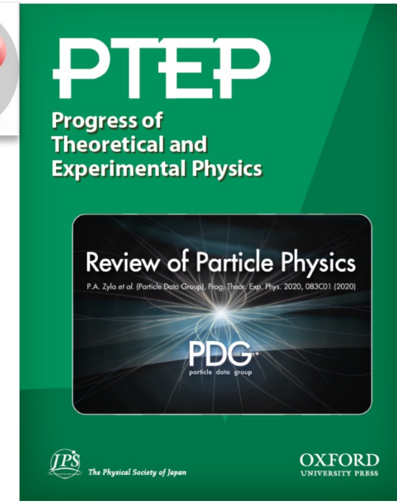




QCD   *LQCD*

Baryon Sector @ PDG2025





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

GW Contribution

S. Navas *et al,* Phys Rev D **110**, 030001 (**2024**)

p	1/2+	****
n	1/2+	****
N(1440)	1/2+	****
N(1520)	3/2−	****
N(1535)	1/2−	****
N(1650)	1/2−	****
N(1675)	5/2−	****
N(1680)	5/2+	****
N(1685)		*
N(1700)	3/2−	***
N(1710)	1/2+	***
N(172[illegible])	3/2+	[illegible]
N(18[illegible])	5/2+	[illegible]
N(18[illegible])	3/2−	[illegible]
N(1[illegible])	[illegible]/2+	[illegible]
N(1[illegible]5)	[illegible]	**
N([illegible]00)	[illegible]	***
N([illegible]90)	7/[illegible]	**
N(2000)	5/2+	**
N(2040)	3/2+	*
N(2060)	5/2−	**
N(2100)	1/2+	*
N(2120)	3/2−	**
N(2190)	7/2−	****
N(2220)	9/2+	****
N(2250)	9/2−	****
N(2600)	11/2−	***
N(2700)	13/2+	**

Δ(1232)	3/2+	****
Δ(1600)	3/2+	***
Δ(1620)	1/2−	****
Δ(1700)	3/2−	****
Δ(1750)	1/2+	*
Δ(1900)	1/2−	**
Δ(1905)	5/2+	****
Δ(1910)	1/2+	****
Δ(1920)	3/2[illegible]	[illegible]
Δ(1930)	5/2−	[illegible]
Δ(1940)	3/2−	[illegible]
Δ(1950)	7/2+	[illegible]
Δ(20[illegible])	5/2+	[illegible]
Δ([illegible])	[illegible]	[illegible]
Δ(2200)	7/2−	*
Δ(2300)	9/2+	**
Δ(2350)	5/2−	*
Δ(2390)	7/2+	*
Δ(2400)	9/2−	**
Δ(2420)	11/2+	****
Δ(2750)	13/2−	**
Δ(2950)	15/2+	**
Λ	1/2+	****
Λ(1405)	1/2−	****
Λ(1520)	3/2−	****
Λ(1600)	1/2+	***
Λ(1670)	1/2−	****
Λ(1690)	3/2−	****
Λ(1800)	1/2−	[illegible]
Λ(1810)	1/[illegible]	[illegible]
Λ(1820)	5/2+	[illegible]
Λ(1830)	5/2−	[illegible]
Λ(1890)	3/2+	[illegible]
Λ(200[illegible])	[illegible]	[illegible]
Λ([illegible])	7/2+	[illegible]
Λ(2100)	7/2−	****
Λ(2110)	5/2+	***
Λ(2325)	3/2−	*
Λ(2350)	9/2+	***
Λ(2585)		**

Σ+	1/2+	****
Σ0	1/2+	****
Σ−	1/2+	****
Σ(1385)	3/2+	****
Σ(1480)		*
Σ(1560)		**
Σ(1580)	3/2−	*
Σ(1620)	1/2−	**
Σ(1660)	1/2+	***
Σ(1670)	3/2−	****
Σ(1690)		**
Σ(1750)	[illegible]	[illegible]
Σ(1770)	[illegible]/2+	*
Σ(1775)	[illegible]	****
Σ(1840)	[illegible]	*
Σ(1880)	1/2+	**
Σ(191[illegible])	5/2+	[illegible]
Σ([illegible])	[illegible]	***
Σ(2000)	1/2−	*
Σ(2030)	7/2+	****
Σ(2070)	5/2+	*
Σ(2080)	3/2+	**
Σ(2100)	7/2−	*
Σ(2250)		***
Σ(2455)		**
Σ(2620)		**
Σ(3000)		*
Σ(3170)		*

Ξ0	1/2+	****
Ξ−	1/2+	****
Ξ(1530)	[illegible]	****
Ξ(162[illegible])		*
Ξ(1690)		***
Ξ(182[illegible])	3/2−	***
Ξ(195[illegible])		***
Ξ(2030)	≥ 5/2?	***
Ξ([illegible])		*
Ξ(2250)		**
Ξ(2370)		**
Ξ(2500)		*
Ω−	3/2+	****
Ω(2[illegible])−		***
Ω([illegible]0)−		**
Ω([illegible]70)−		*

Λ_c^+	1/2+	****
$\Lambda_c(2595)^+$	1/2−	***
$\Lambda_c(2625)^+$	3/2−	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2880)^+$	5/2+	***
$\Lambda_c(2940)^+$		***
$\Sigma_c(2455)$	1/2+	****
$\Sigma_c(2520)$	3/2+	***
$\Sigma_c(2800)$		***
Ξ_c^+	1/2+	***
Ξ_c^0	1/2+	***
$\Xi_c'^+$	1/2+	***
$\Xi_c'^0$	1/2+	***
$\Xi_c(2645)$	3/2+	***
$\Xi_c(2790)$	1/2−	***
$\Xi_c(2815)$	3/2−	***
$\Xi_c(2930)$		*
$\Xi_c(2980)$		***
$\Xi_c(3055)$		**
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
Ω_c^0	1/2+	***
$\Omega_c(2770)^0$	3/2+	***
Ξ_{cc}^+		*
Λ_b^0	1/2+	***
Σ_b	1/2+	***
Σ_b^*	3/2+	***
Ξ_b^0, Ξ_b^-	1/2+	***
Ω_b^-	1/2+	***

N Δ Σ Ξ Ω Λ

- PDG2024 has 133 Baryon Resonances (69 of them are 4* & 3*).
- In case of SU(6) x O(3), 434 states would be present if all revealed multiplets were fleshed out (*three* **70** & *four* **56**).

- LQCD results are similar.

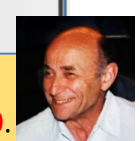
R. Koniuk & N. Isgur, Phys Rev Lett **44**, 845 (**1980**)

- First *hyperon* was discovered in **1950**.

THE UNIVERSITY OF MELBOURNE

V.D. Hopper & S. Biswas, Phys Rev **80**, 1099 (**1950**)

- Pole position in complex energy plane for *hyperons* has made *only* in **2010**.



Jefferson Lab

Y. Qung *et al,* Phys Lett B **694**, 123 (**2010**)

Complete Experiment for Pion PhotoProduction

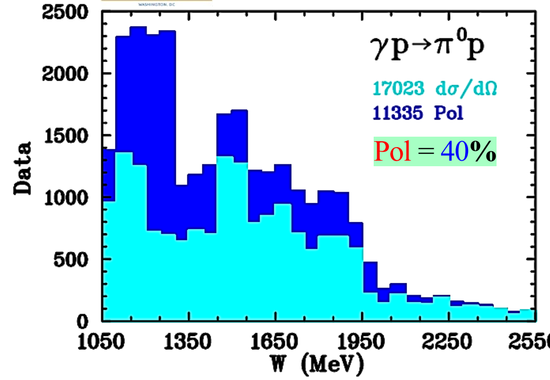
2002 → PDG particle data group → 2020

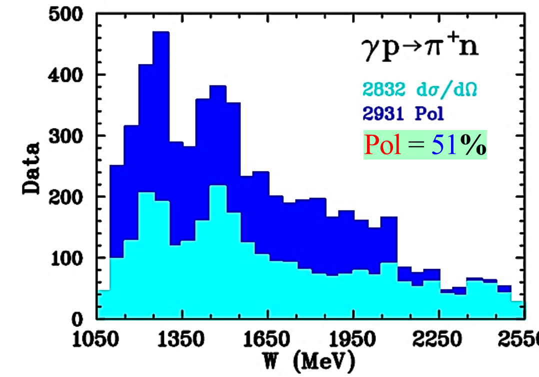
Particle	$L_{2I \cdot 2J}$	Overall status	$N\pi$	$N\eta$	ΛK	ΣK	$\Delta\pi$	$N\rho$	$N\gamma$
			Status as seen in —						
$N(939)$	P_{11}	****							
$N(1440)$	P_{11}	****	****	*			***	*	***
$N(1520)$	D_{13}	****	****	*			****	****	****
$N(1535)$	S_{11}	****	****	****			*	**	***
$N(1650)$	S_{11}	****	****	*	***	**	***	**	***
$N(1675)$	D_{15}	****	****	*	*		****	*	****
$N(1680)$	F_{15}	****	****				****	****	****
$N(1700)$	D_{13}	***	***	*	**	*	**	*	**
$N(1710)$	P_{11}	***	***	**	**	*	**	*	***
$N(1720)$	P_{13}	****	****	*	**	*	*	**	**
$N(1900)$	P_{13}	**	**					*	
$N(1990)$	F_{17}	**	**	*	*	*			*
$N(2000)$	F_{15}	**	**	*	*	*	*	**	
$\Delta(1232)$	P_{33}	****	****	F					****
$\Delta(1600)$	P_{33}	***	***	o			***	*	**
$\Delta(1620)$	S_{31}	****	****	r			****	****	***
$\Delta(1700)$	D_{33}	****	****	b		*	***	**	***
$\Delta(1750)$	P_{31}	*	*	i					
$\Delta(1900)$	S_{31}	**	**	d		*	*	**	*
$\Delta(1905)$	F_{35}	****	****	d		*	**	**	***
$\Delta(1910)$	P_{31}	****	****	e		*	*	*	*
$\Delta(1920)$	P_{33}	***	***	n		*	**		*
$\Delta(1930)$	D_{35}	***	***			*			**
$\Delta(1940)$	D_{33}	*	*	F					
$\Delta(1950)$	F_{37}	****	****	o		*	****	*	****
$\Delta(2000)$	F_{35}	**		r				**	

Particle	J^P	overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$
			Status as seen in									
N	$1/2^+$	****										
$N(1440)$	$1/2^+$	****	****	****	****	***						
$N(1520)$	$3/2^-$	****	****	****	****	**	****					
$N(1535)$	$1/2^-$	****	****	****	***	*	****					
$N(1650)$	$1/2^-$	****	****	****	***	*	****	*				
$N(1675)$	$5/2^-$	****	****	****	****	***	*	*	*			
$N(1680)$	$5/2^+$	****	****	****	****	***	*	*	*			
$N(1700)$	$3/2^-$	***	**	***	***	*	*			*		
$N(1710)$	$1/2^+$	****	****	****	*		***	**	*	*	*	
$N(1720)$	$3/2^+$	****	****	****	***	*	*	****	*	*	*	
$N(1860)$	$5/2^+$	**	*	**		*	*					
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****
$N(1900)$	$3/2^+$	****	****	**	**	*	*	**	**		*	**
$N(1990)$	$7/2^+$	**	**	**			*	*	*			
$N(2000)$	$5/2^+$	**	**	*	**	*	*				*	
$\Delta(1232)$	$3/2^+$	****	****	****								
$\Delta(1600)$	$3/2^+$	****	****	***	****		F					
$\Delta(1620)$	$1/2^-$	****	****	****	****		o					
$\Delta(1700)$	$3/2$	****	****	****	****				*	*		
$\Delta(1750)$	$1/2^+$	*	*	*			r		*			
$\Delta(1900)$	$1/2^-$	***	***	***	*		b		**	*		
$\Delta(1905)$	$5/2^+$	****	****	****	**		i		*	*		
$\Delta(1910)$	$1/2^+$	****	***	****	**		d		**			
$\Delta(1920)$	$3/2^+$	***	***	***	***				**			
$\Delta(1930)$	$5/2^-$	***	*	***	*		d		*			
$\Delta(1940)$	$3/2^-$	**	*	**	*		e					
$\Delta(1950)$	$7/2^+$	****	****	****	**		n		***			
$\Delta(2000)$	$5/2^+$	**	*	**	*					*		

GW — Data Analysis Center — Institute for Nuclear Studies, The George Washington University

1996-2018





π^+n/π^0p = **20%**

- Lack of $\gamma p \rightarrow \pi^+ n$ *vs* $\gamma p \rightarrow \pi^0 p$ data does not allow us to be as confident about determination of *neutron* couplings.

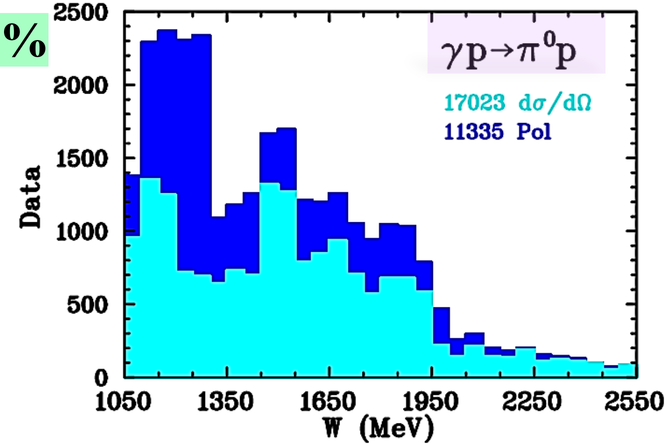
World Progress in Pion PhotoProduction

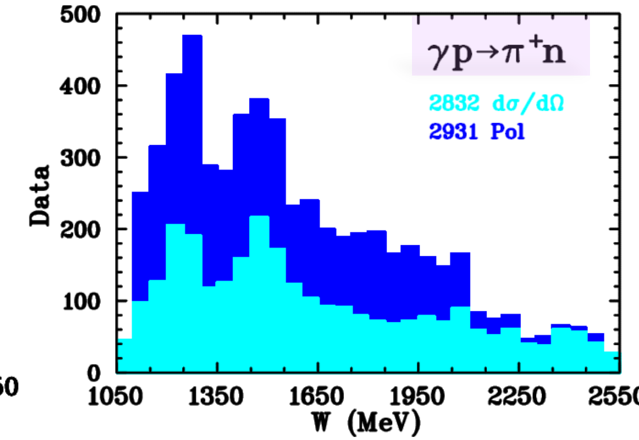
SAID: http://gwdac.phys.gwu.edu/

D. Ireland, E. Pasyuk, IIS, Prog Part Nucl Phys 111, 103752 (2020)

1996–2018

Pol = 40%

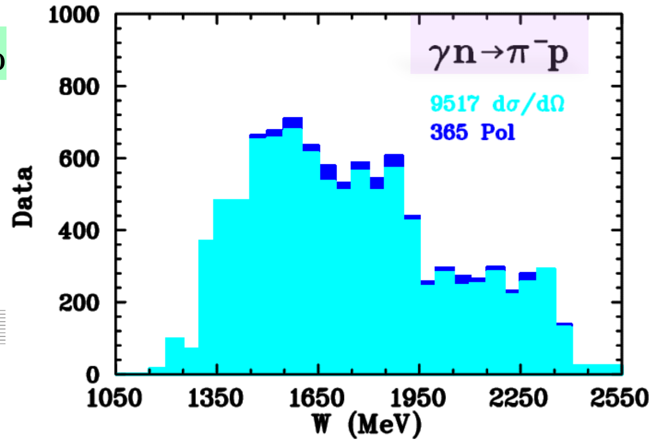


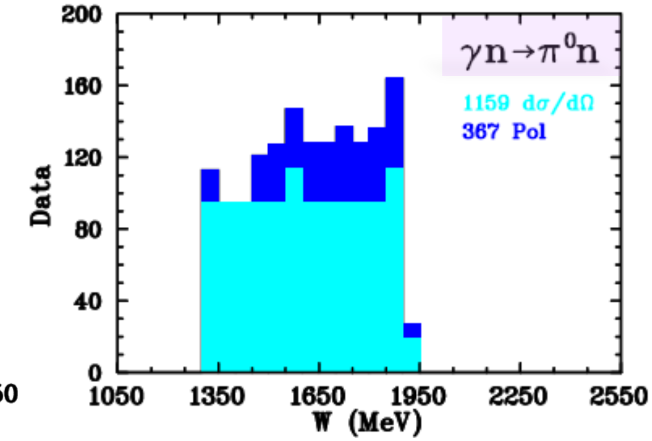


Pol = 51%

π^+n/π^0p = 20%

Pol = 4%





Pol = 24%

π^-p/π^0n = 15%

- There is disbalance between π^0p & π^+n data, 20%.
- Pion photoproduction on **neutron** much less known, 33%.

World Neutral & Charged PionPR Data

W.J. Briscoe, M. Doring, H. Haberzettl, M. Manley, M. Naruki, IS, E. Swanson, Eur Phys J A **51**, 129 (2015)

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

W < 2.5 GeV

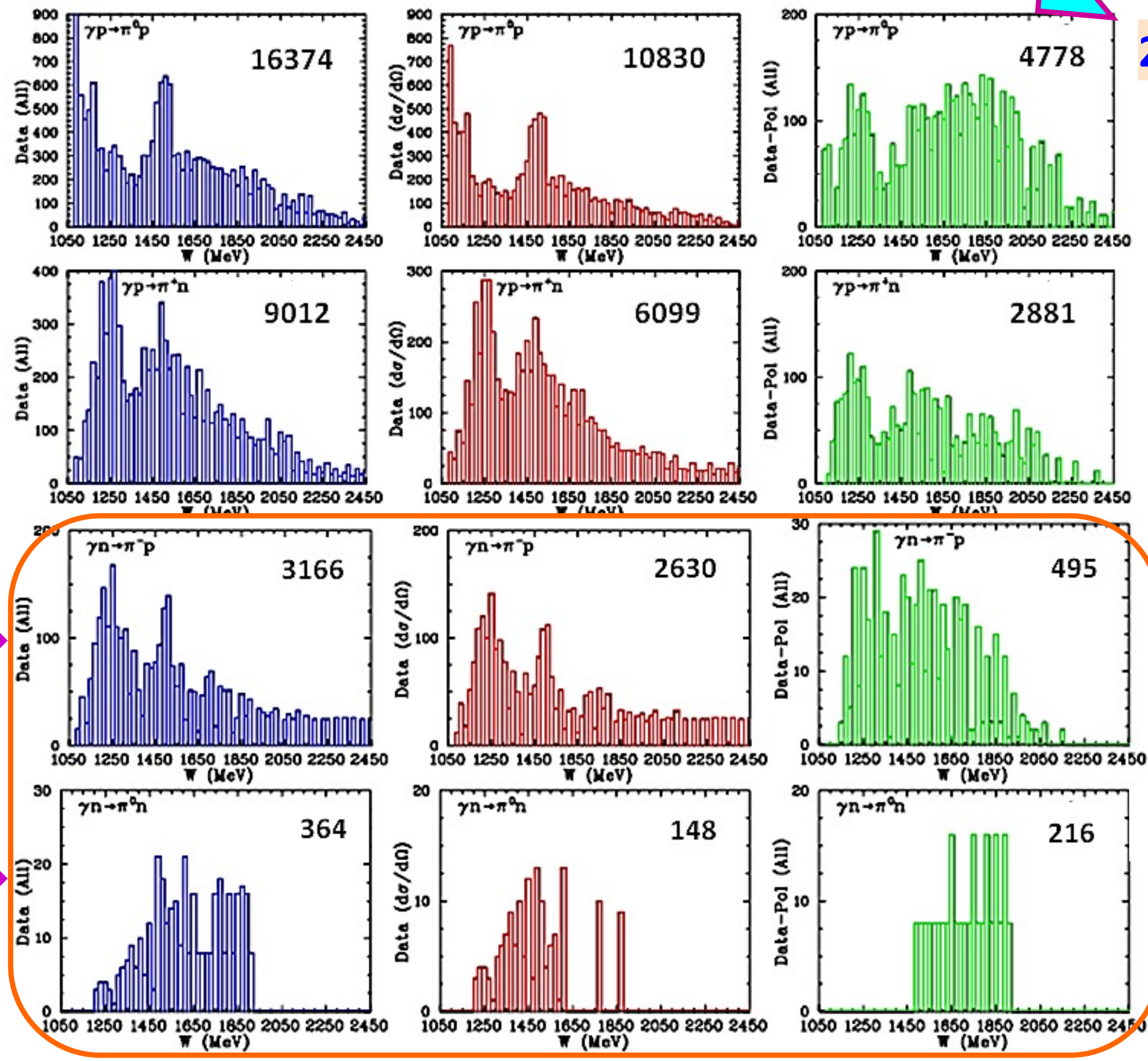
Full | **UnPol** | **Pol** | **2017**

$\gamma p \rightarrow \pi^0 p$ — 25858–19768–6090

$\gamma p \rightarrow \pi^+ n$ — 9859– 6078–3781

$\gamma n \rightarrow \pi^- p$ — 11856–11092– 764

$\gamma n \rightarrow \pi^0 n$ — 364– 148– 216



PWA for non-Strange Baryons

- Originally PWA arose as technology to determine amplitude of reaction via fitting scattering data.
  That is non-trivial mathematical problem – looking for solution of ill-posed problem following to Hadamard & Tikhonov.

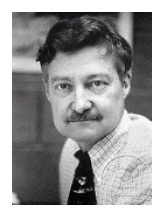
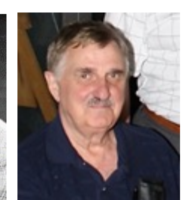

- Resonances appeared as by-product
  [bound states objects with definite quantum numbers, mass, lifetime, & so on].

- Standard PWA
  ⇒ Reveals only wide Resonances, but not too wide (Γ < 500 MeV)
  & possessing not too small BR (BR > 4%).
  ⇒ Tends (by construction) to miss narrow Res with Γ < 20 MeV.

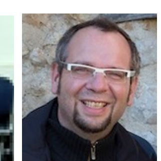
PDG particle data group

Most of our current knowledge about bound states of three light quarks has come mainly from $\pi N \to \pi N$ PWAs:

Karlsruhe-Helsinki,
Carnegie-Mellon-Berkeley,
& GW.

Main source of EM couplings is GW, BnGa, & JuBoWa analyses.

Direct Amplitude Reconstruction in Pion Photo-Production

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

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

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

parity conservation

- In **particle physics**, **helicity** is projection of the spin $\vec{S}$ onto 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** pion photoproduction amplitude [**4 modules** and **3 relative phases**], one has to carry out 7 **independent** measurements at **fixed** **(W, t)** or **(E, θ)**.

8
- This extra observable is necessary to eliminate **sign ambiguity**.

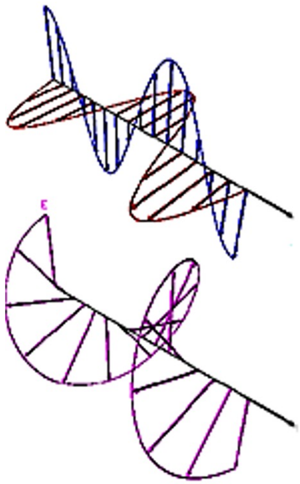
PHYSICAL REVIEW C VOLUME 54, NUMBER 3 SEPTEMBER 1996

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 for Pion PhotoProduction

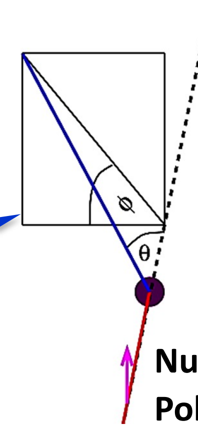
- There are **16** non-redundant observables.
- They are **not completely independent** from each other.



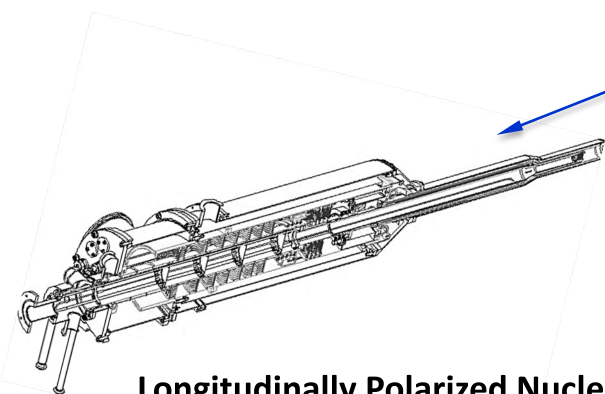
Linear Polarized *Beam*

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: **$d\sigma/d\Omega$**
3 single pol measurements: **Σ, T, P**
12 double pol measurements: **E, F, G, H,**
C_x, C_z, O_x, O_z, L_x, L_z, T_x, T_z
18 triple polarization asymmetries
[**9** for linear pol beam]
[**9** for circular pol beam]
13 of them are non-vanishing

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

Importance of Neutron Data

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

Proton	*Neutron*
$A_{\pi^0 p} = A^0 + \frac{1}{3} A^{1/2} + \frac{2}{3} A^{3/2}$	$A_{\pi^0 n} = -A^0 + \frac{1}{3} A^{1/2} + \frac{2}{3} A^{3/2}$
$A_{\pi^+ n} = \sqrt{2}\left(A^0 + \frac{1}{3} A^{1/2} - \frac{1}{3} A^{3/2}\right)$	$A_{\pi^- p} = \sqrt{2}\left(A^0 - \frac{1}{3} A^{1/2} + \frac{1}{3} A^{3/2}\right)$

- **Proton** data alone does not allow separation of **isoscalar** & **isovector** components.

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

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

D. Drechsel & L. Tiator, J. Phys. G **18**, 449 (1992)

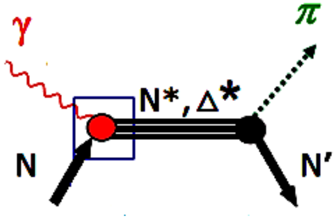


Photo-Decay Amplitudes in BW & Pole Forms

• **Pole** is **main signature** of **resonance**.

$$A_h^{BW} = C \sqrt{\frac{q_r}{k_r} \frac{\pi(2J+1)M_r\Gamma_r^2}{m_N \Gamma_{\pi,r}}}\, \tilde{A}_\alpha^h$$

$$A_h^{pole} = C \sqrt{\frac{q_p}{k_p} \frac{2\pi(2J+1)W_p}{m_N \mathrm{Res}_{\pi N}}}\, \mathrm{Res}\, A_\alpha^h$$

Evaluated at Res Energy

Evaluated at Pole

TABLE I. Breit-Wigner and pole values for selected nucleon resonances. Masses, widths, and residues are given in units of MeV, the helicity 1/2 and 3/2 photo-decay amplitudes in units of $10^{-3}(\mathrm{GeV})^{-1/2}$. Errors on the phases are generally 2–5 degrees. For isospin 1/2 resonances the values of the proton target are given.

Resonance	Breit-Wigner values				Pole values			
	(Mass, width)	$\Gamma_\pi/2$	$A_{1/2}$	$A_{3/2}$	(Re W_p, -2 Im W_p)	R_π	$A_{1/2}$	$A_{3/2}$
Δ(1232) $3/2^+$	(1233, 119)	60	-141 ± 3	-258 ± 5	(1211, 99)	52 [−47°]	-136 ± 5 [−18°]	-255 ± 5 [−6°]
N(1440) $1/2^+$	(1485, 284)	112	-60 ± 2		(1359, 162)	38 [−98°]	-66 ± 5 [−38°]	
N(1520) $3/2^-$	(1515, 104)	33	-19 ± 2	$+153 \pm 3$	(1515, 113)	38 [−5°]	-24 ± 3 [−7°]	$+157 \pm 6$ [+10°]
N(1535) $1/2^-$	(1547, 188)	34	$+92 \pm 5$		(1502, 95)	16 [−16°]	$+77 \pm 5$ [+4°]	
N(1650) $1/2^-$	(1635, 115)	58	$+35 \pm 5$		(1648, 80)	14 [−69°]	$+35 \pm 3$ [−16°]	

R.L. Workman *et al*, Phys Rev C **87**, 068201 (2013)

A. Svarc *et al*, Phys Rev C **89**, 065208 (2014)

Single-Energy Solutions (SES)

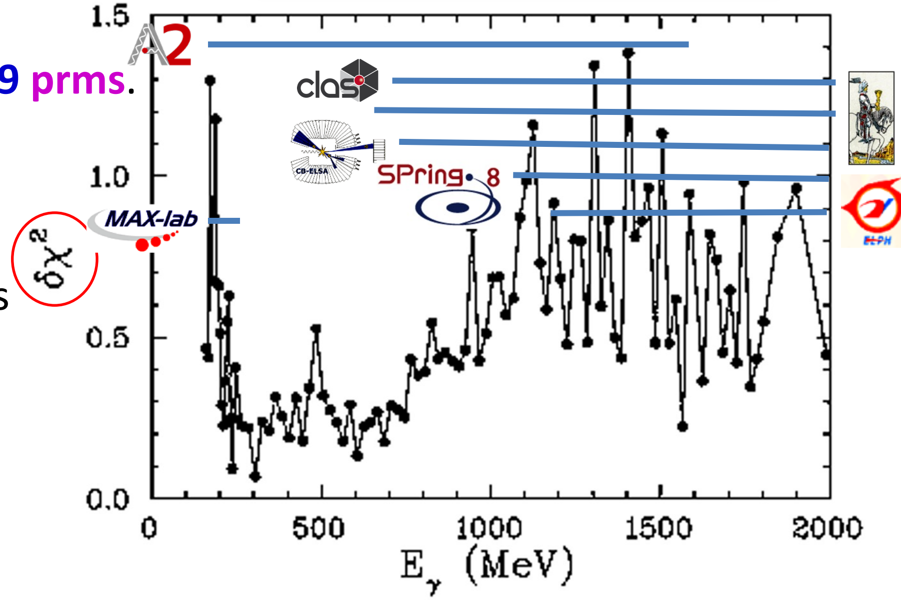
R.L. Workman, M.W. Paris, W.J. Briscoe, IS, Phys Rev C **86**, 015202 (2012)

- **SAID** has employed both single-energy (**SES**) & energy-dependent (**Global**) solutions using **least-squares** technology over variety of energy ranges in order to estimate uncertainties.

$$\delta\chi^2 = [\chi^2(CM12) - \chi^2(SES)]/N_{\text{data}}$$

- **SES**: based on bin of data spanning narrow **E** range [**5** – **75** MeV] searches **2** to **29** **prms**.
  110 SES have been generated with central **E** = **147** to **2650** MeV.
  \# of data in bin varies from **80** to **1100**.

- **Systematic deviation** between **SES** & **Global** fits is indication of
  ⇒ Missing structure in **global** fit.
  ⇒ Possible problems with particular **dataset**.



- **Diagonal Error Matrix** generated in **SES** fits.
  It can be used to estimate the overall uncertainties for **Global** solution.

Single Pion PhotoProduction on "Neutron" Target

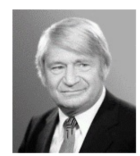
- Accurate evaluation of **EM** couplings **$N^* \to \gamma N$** & **$\Delta^* \to \gamma N$** from **meson photoproduction** data remains paramount task in **hadron** physics.

- Only with good data on both **proton** & **neutron** **targets**, one can hope to disentangle **isoscalar** & **isovector** **EM** couplings of various **N^***& **Δ^*** resonances, as well as **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 **$\gamma n \to \pi^- p$** & **$\gamma n \to \pi^0 n$** data does not allow us to be as confident about determination of **neutron** couplings relative to those of **proton**.

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



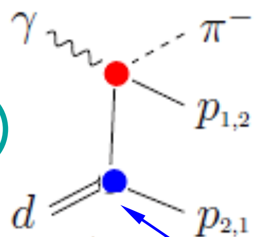
A.B. Migdal, JETP **1**, 2 (1955); K.M. Watson, Phys Rev **95**, 228 (1954)

FSI for $\gamma d \to \pi p N$ $\quad \gamma n \Rightarrow \pi N$

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, Phys At Nucl **79**, 216 (2016)

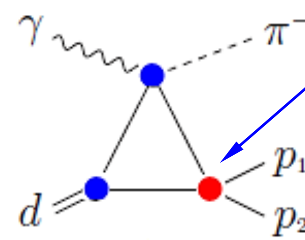
- **FSI plays critical role in state-of-the-art analysis of γn→πN data.**
- For **γn→πN**, effect is **5% – 60%**. It depends on (**E**,**θ**).

IA

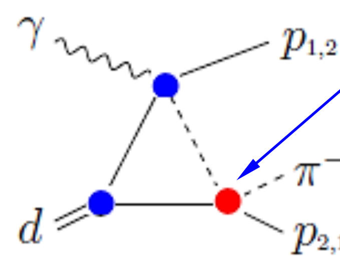


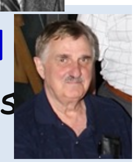
Fermi Smearing

NN-fsi vertex

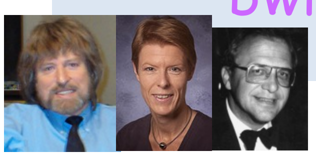


πN-fsi vertex





Input: SAID: γN→πN, πN→πN, NN→NN amplitudes for **3** leading terms
DWF: full Bonn NN Potential (there is no sensitivity to DWF).



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

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

FSI for $\gamma d \rightarrow \pi^- pp \Longrightarrow \gamma n \rightarrow \pi^- p$

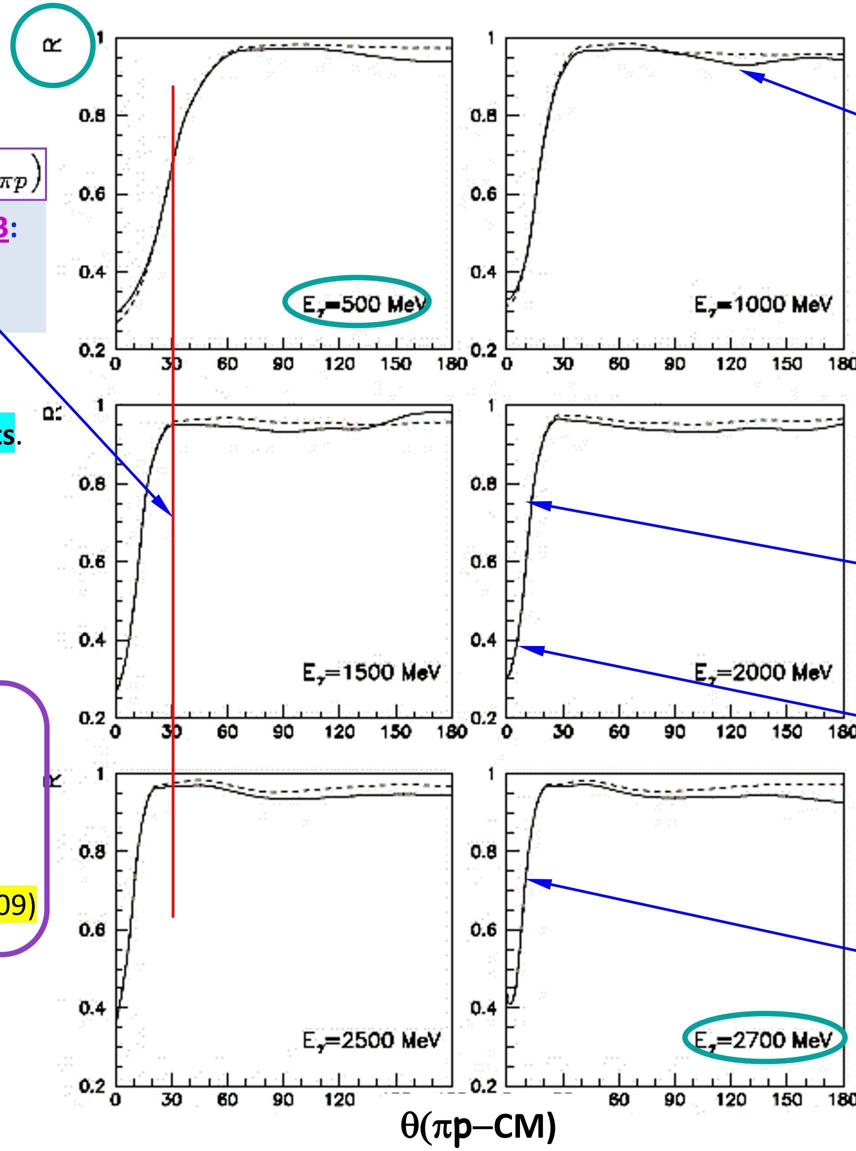
V. Tarasov, A. Kudryavtsev, W. Briscoe, H. Gao, IS, Phys Rev C **84**, 035203 (2011)

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

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

CLAS g10 & g13:
E > 0.5 GeV
θ > 30 deg

- There is no large sensitivity to **cuts**.

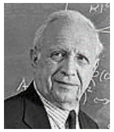


- For **CLAS** data:
  - **FSI** correction factor **R < 1.**
  - Behavior is **smooth** vs. **θ**.
  - **Effect: Δσ/σ ≤ 10%.**

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

- There is **sizeable FSI** effect from **S-wave** part of **pp-FSI** at small angles.
- Region **narrows** as **E** increases.

- **Previous** estimation of **Glauber FSI** gave order of **15–30**%.



W. Chen *et al*, Phys Rev Lett **103**, 012301 (2009)

Forward direction is Terra incognita

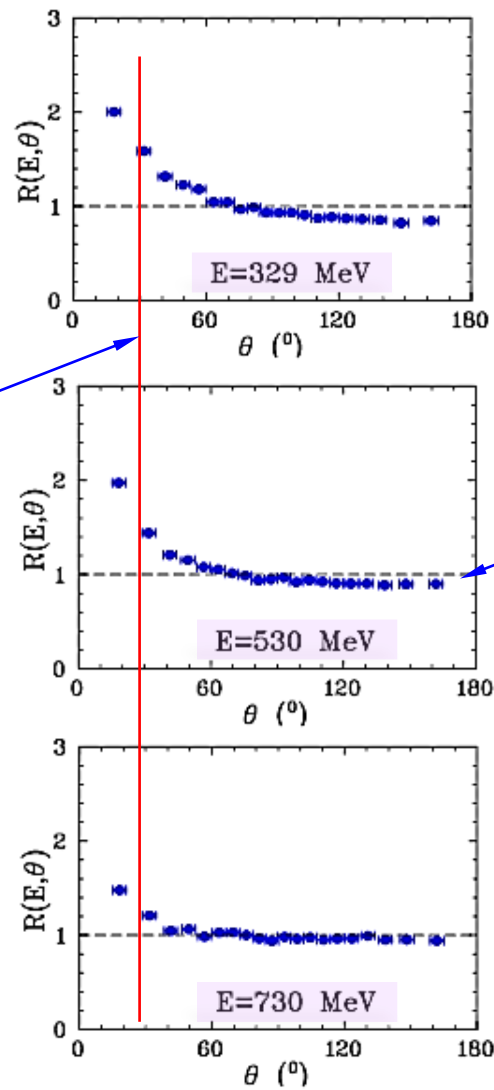
FSI for $\gamma d \to \pi^0 pn$ ➡ $\gamma n \to \pi^0 n$

V.E. Tarasov, A.E. Kudryavtsev, WJB, B. Krusche, IIS, M. Ostrick, Phys At Nucl **79**, 216 (2016)

$$R_{FSI} = (d\sigma/d\Omega_{\pi p})/(d\sigma^{1A}/d\Omega_{\pi p})$$

Cuts:
$p_s < 200$ MeV/c
$p_f < 200$ MeV/c

- There is no large sensitivity to cuts.



Forward direction is Terra incognita. There are no data for validation.

- For A2 data:
  - Behavior is smooth vs. θ.
  - Effect: $\Delta\sigma/\sigma \leq 15\%$.

- There is sizeable FSI effect from S-wave part of pp-FSI at small angles.

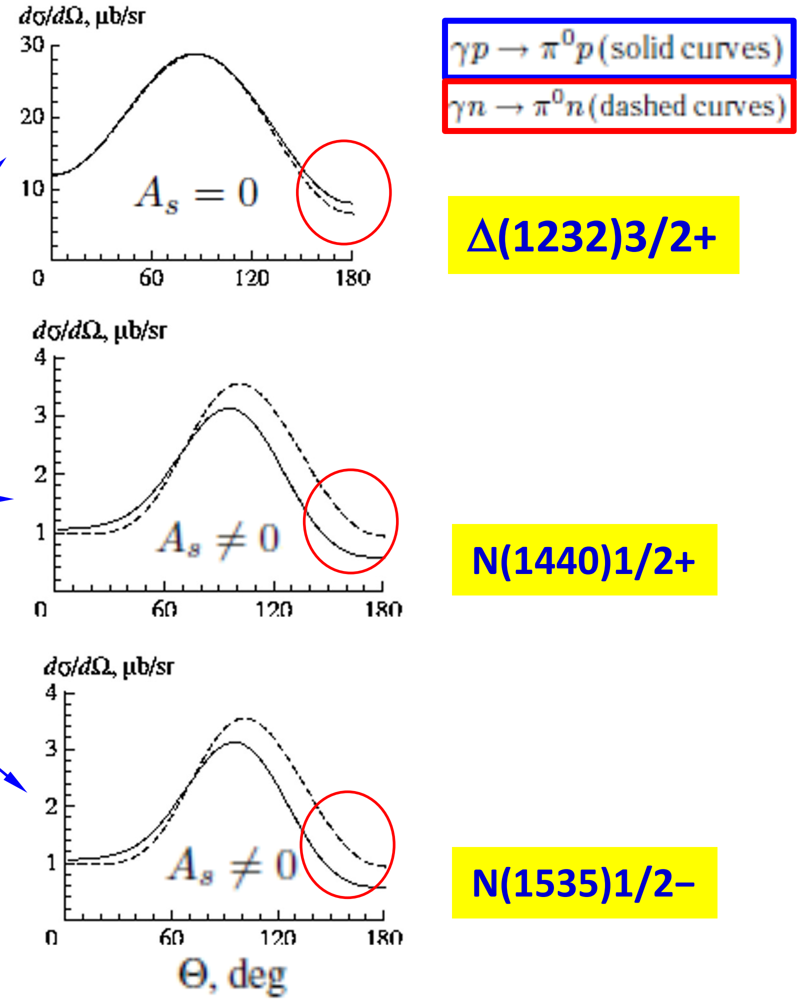
Assumption is FSI for polarized measurements is small.

FSI for $\gamma d \to \pi^0 np$ ➡ $\gamma n \to \pi^0 n$ & $\gamma p \to \pi^0 p$

V. Tarasov, A. Kudryavtsev, W. Briscoe, B. Krusche, IS, M. Ostrick, Phys At Nucl **79**, 216 (2016)

- **γn→π⁰n** case is much more complicated vs. **γn→π⁻p** because **π⁰** can come from both **γn** & **γp** **initial** interactions.

$$A(\gamma p \to \pi^0 p) = A_v + A_s$$
$$A(\gamma n \to \pi^0 n) = A_v - A_s$$



- The corrections for both target nucleons are **practically identical** for **π⁰** production in energy range of **Δ(1232)3/2⁺** due to **isospin structure** of **γN→πN** amplitude:

isoscalar *isovector*

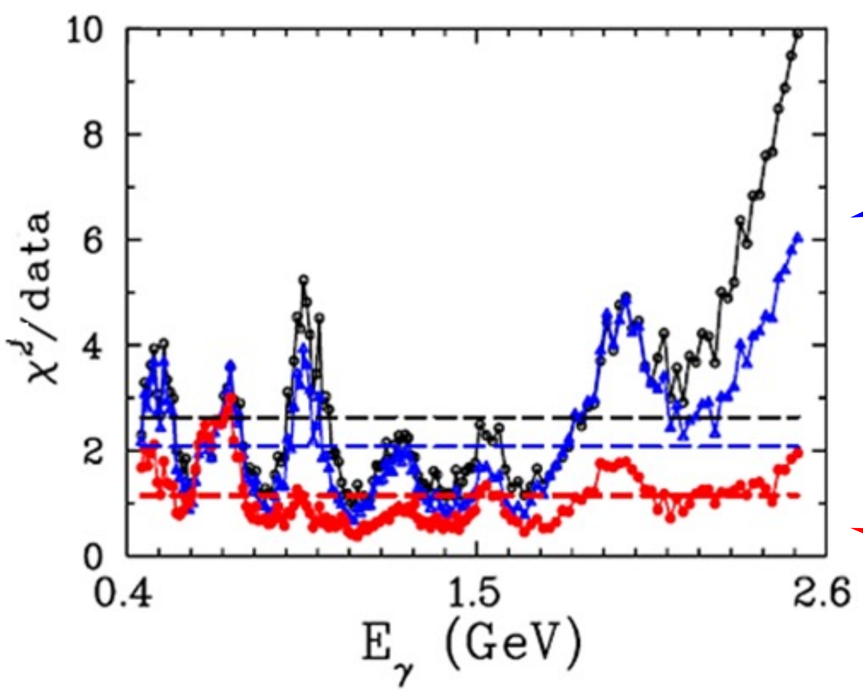
$A_s = 0$ or $A_v = 0$

$$R_n = R_p$$

- In general case, $R_n \neq R_p$

Comparison of Previous & New SAID Fits for g13

P. Mattione *et al*, Phys. Rev. C **96**, 035204 (2017)



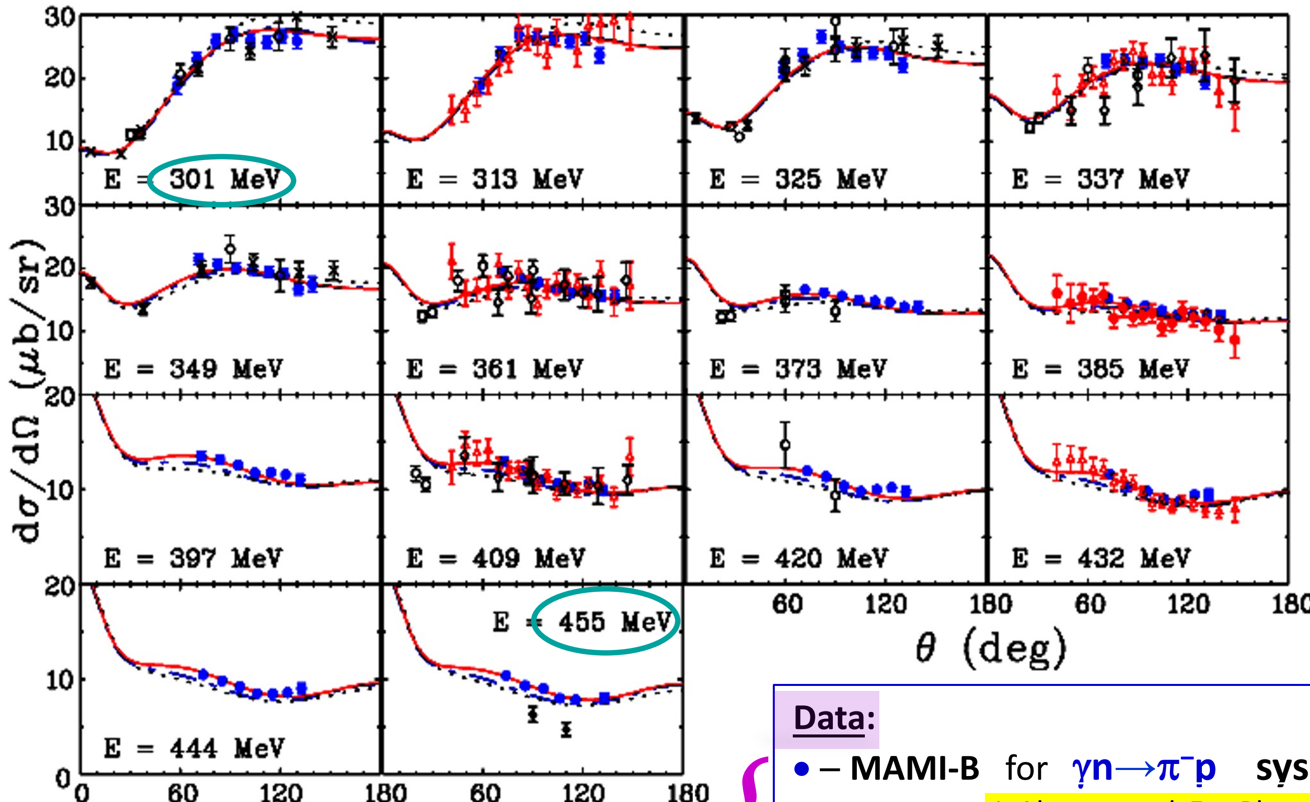
- Recent SAID **PR15** applied to **g13** data **without** & **with FSI** corrections.
- New SAID **MA27** fit obtained after adding new **g13** data **with FSI** corrections.

- Obviously, **FSI** plays important role in **$\gamma n \to \pi^- p$ $d\sigma/d\Omega$** determination.

MAMI-B for γn→π⁻p around Δ

W.J. Briscoe, A.E. Kudryavtsev, P. Pedroni, IS, V.E. Tarasov, R.L. Workman, Phys Rev C **86**, 065207 (2012)

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



SAID-PE12
SAID-SN11
MAID07

FSI included

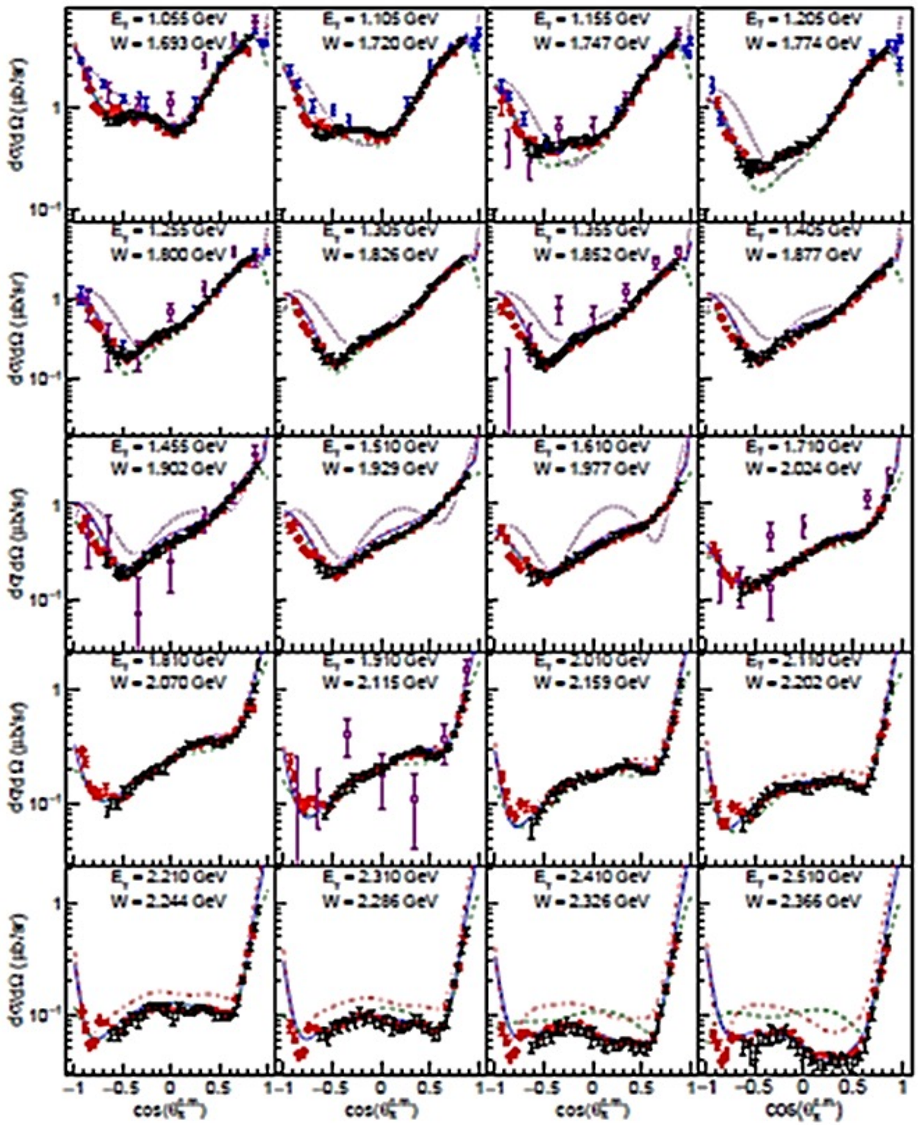
- *T-invariance is good as 2 x 10^{-3}*

Data:

- • – **MAMI-B** for **$\gamma n \to \pi^- p$** sys=**2%**
  J. Ahrens *et al*, Eur Phys J A **44**, 189 (2010)
- Δ – **CB@BNL** for **$\pi^- p \to n\gamma$** sys=**5%**
  A. Shafi *et al*, Phys Rev C **70**, 035204 (2004)
- o – **TRIUMF**, **CERN**, **LBL**, **LAMPF** for $\pi^- p \to n\gamma$

CLAS g13 for $\gamma n \to \pi^- p$ above 0.5 GeV

P. Mattione *et al*, Phys. Rev. C **96**, 035204 (2017)



E = 445–2510 MeV

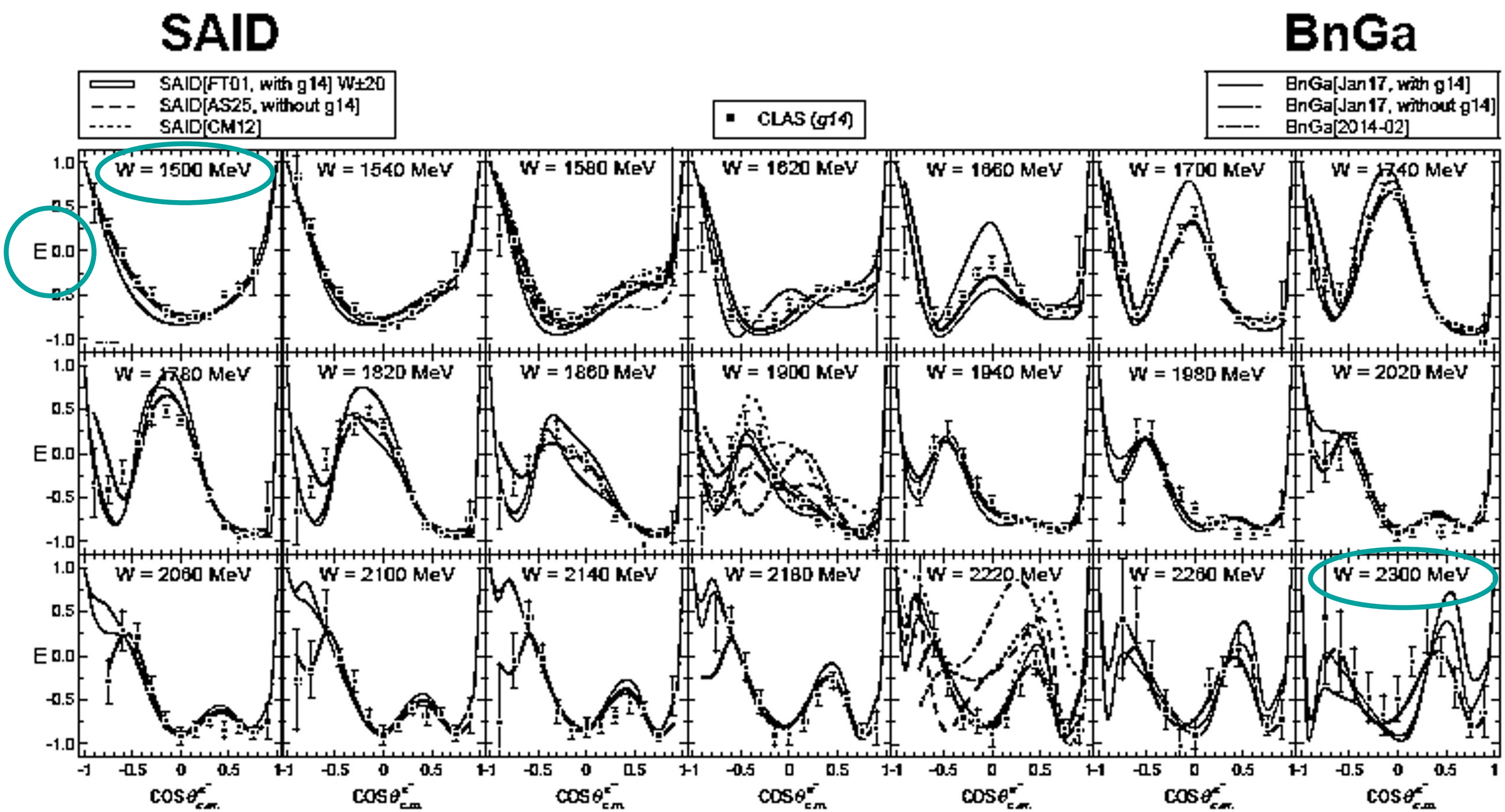
π^-p: 8428 **dσ/dΩ**

- These data a factor of nearly three increase in world statistics for this channel in this kinematic range.

FSI included

New CLAS g14 E for $\vec{\gamma}\vec{n} \to \pi^- p$

D. Ho *et al*, Phys Rev Lett **118**, 242002 (2017)



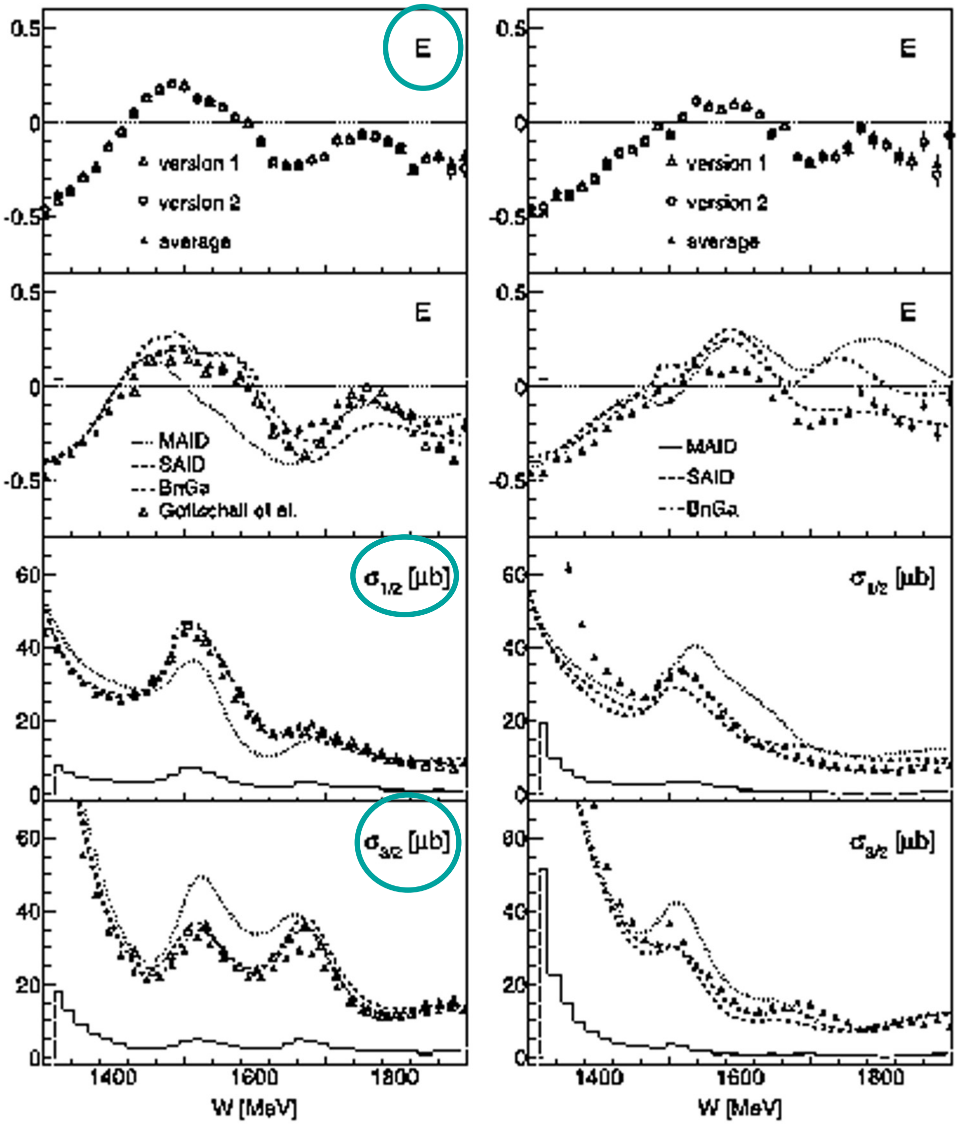
E = **730–2345** MeV
π⁻p: **266** **E**

No FSI included

Recent CB@MAMI *E* for $\vec{\gamma}\vec{n}\to\pi^0 n$

M.Dieterle *et al* Phys Let B **523,** 770 (2017)

"Proton" *"Neutron"*



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

$N(1680)5/2^+\to N\gamma$

$pA^{3/2}$=+133 ±12 $pA^{1/2}$=−15 ±6

$nA^{3/2}$=−33 ±9 $nA^{1/2}$=+29 ±10

- It couples **weakly** to **neutron**.

$N(1675)5/2^-\to N\gamma$

$pA^{3/2}$=+20 ±5 $pA^{1/2}$=+19 ±8

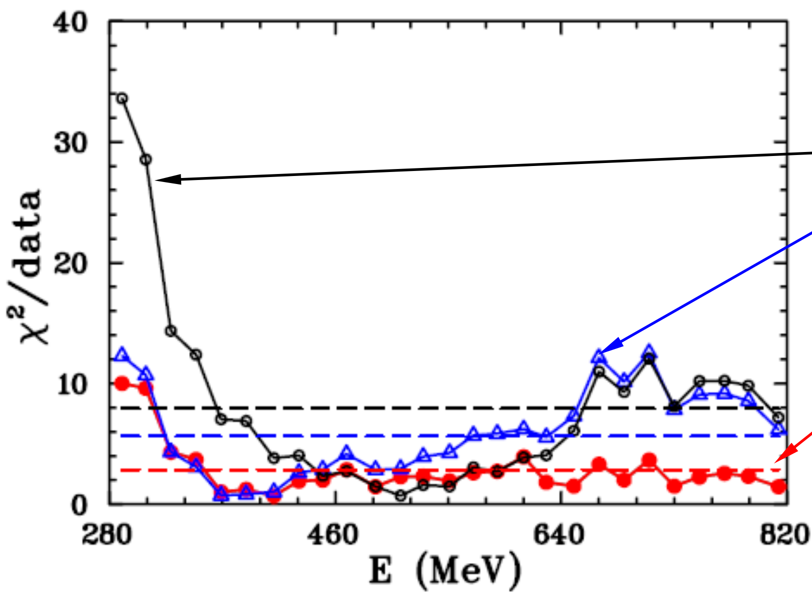
$nA^{3/2}$=−85 ±10 $nA^{1/2}$=−60 ±5

- It couples **strongly** to **neutron**.

No FSI included

Comparison of Previous & New SAID Fits for A2

WJB *et al*, Phys Rev C **100**, 065205 (2019)



- Recent SAID MA27 applied to A2 data without & with **FSI** corrections.
- New SAID MA19 fit obtained after adding new A2 data with FSI corrections.

Obviously, FSI plays important role in $\gamma n \rightarrow \pi^0 n$ $d\sigma/d\Omega$ determination.

Reaction	MAID2007	SAID MA27	SAID MA19
Present			
$\gamma n \rightarrow \pi^0 n$	1855/492=3.77	2765/492=5.62	1405/492=2.86
Previous			
$\gamma p \rightarrow \pi^0 p$	156700/13988=11.20	25856/13988=1.85	23954/13988=1.71
$\gamma p \rightarrow \pi^+ n$	121150/5225=23.19	10785/5225=2.06	10371/5225=1.99
$\gamma n \rightarrow \pi^- p$	49471/4142=11.94	7087/4142=1.71	6530/4142=1.58
$\gamma n \rightarrow \pi^0 n$	27060/515=52.54	2958/515=5.74	2320/515=4.51
Total	354373/23870=14.85	46686/23870=1.96	43174/23870=1.81

FSI included

WJB *et al*, Phys Rev C **100**, 065205 (2019)

- A2 data included in **SAID** fits.

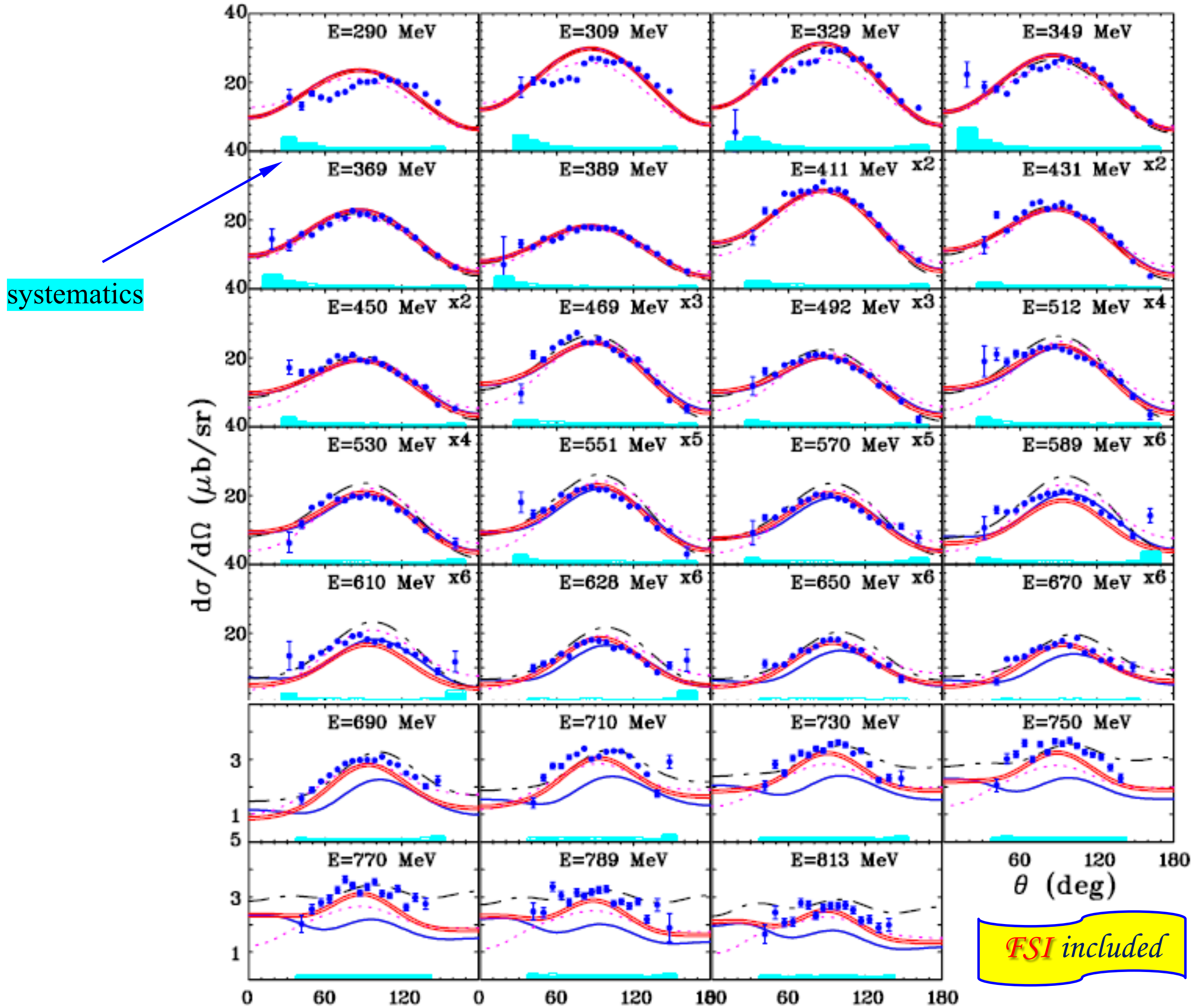
P. T. Mattione et al, Phys Rev C **96**, 035204 (2017) clas

D. Drechsel, S. S. Kamalov, & L. Tiator, Eur. Phys. J. A **34**, 69 (2007)

Meson Production off "Neutron" at CB@MAMI

WJB *et al*, Phys Rev C **100**, 065205 (2019)

- Differential cross sections for $\gamma n \rightarrow \pi^0 n$.



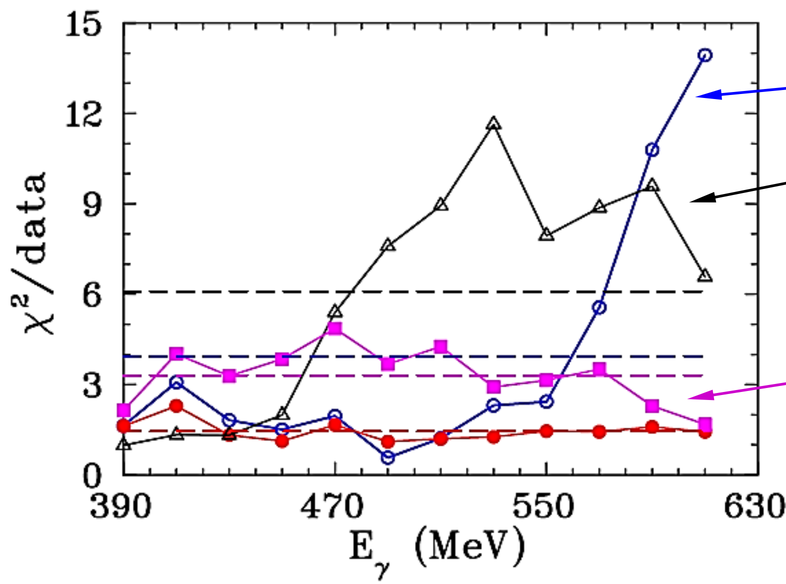
- New A2 data **cover** broader angular rangy & focus on low energies.

E = 290 – 813 MeV
W = 1195 – 1533 MeV
θ = 18 – 162^0
$\pi^0 n$: 492 dσ/dΩ

PWA:
SAID MA19
SAID MA27
MAID2007
BnGa2002

Comparison of Previous & New SAID Fits for A2

C. Mulen *et al*, arXiv:2103.08400 [nucl-ex]



- Recent SAID MA19

MAID2007 applied to A2 data

- New SAID MA19 fit obtained after adding new A2 data.

MUXX does not have any $\gamma n \to \pi^0 n$ data.

- New A2 Σ data.

Solution	$\chi^2/(\pi^0 n$ data)
MU22	275/189=1.46
MUXX	624/189=3.30
MA19	743/189=3.93
MAID2007	1151/189=6.09

- E_γ = 155 to 1000 MeV

Solution	$\chi^2/(\pi^0 p$ data)	$\chi^2/(\pi^+ n$ data)
MU22	13274/9534=1.39	7454/4039=1.85
MUXX	13171/9534=1.38	7259/4039=1.80
MA19	12565/9534=1.32	7461/4039=1.85
MAID2007	73638/9534=7.72	14599/4039=3.61
Solution	**$\chi^2/(\pi^0 n$ data)**	**$\chi^2/(\pi^- p$ data)**
MU22	2345/ 798=2.94	5879/3456=1.70
MUXX	7639/ 798=9.57	5384/3456=1.56
MA19	2649/ 798=3.32	5999/3456=1.74
MAID2007	4846/ 798=6.07	15365/3456=4.45

C. Mulen *et al*, arXiv:2103.08400 [nucl-ex]

WJB *et al*, Phys Rev C **100**, 065205 (2019)

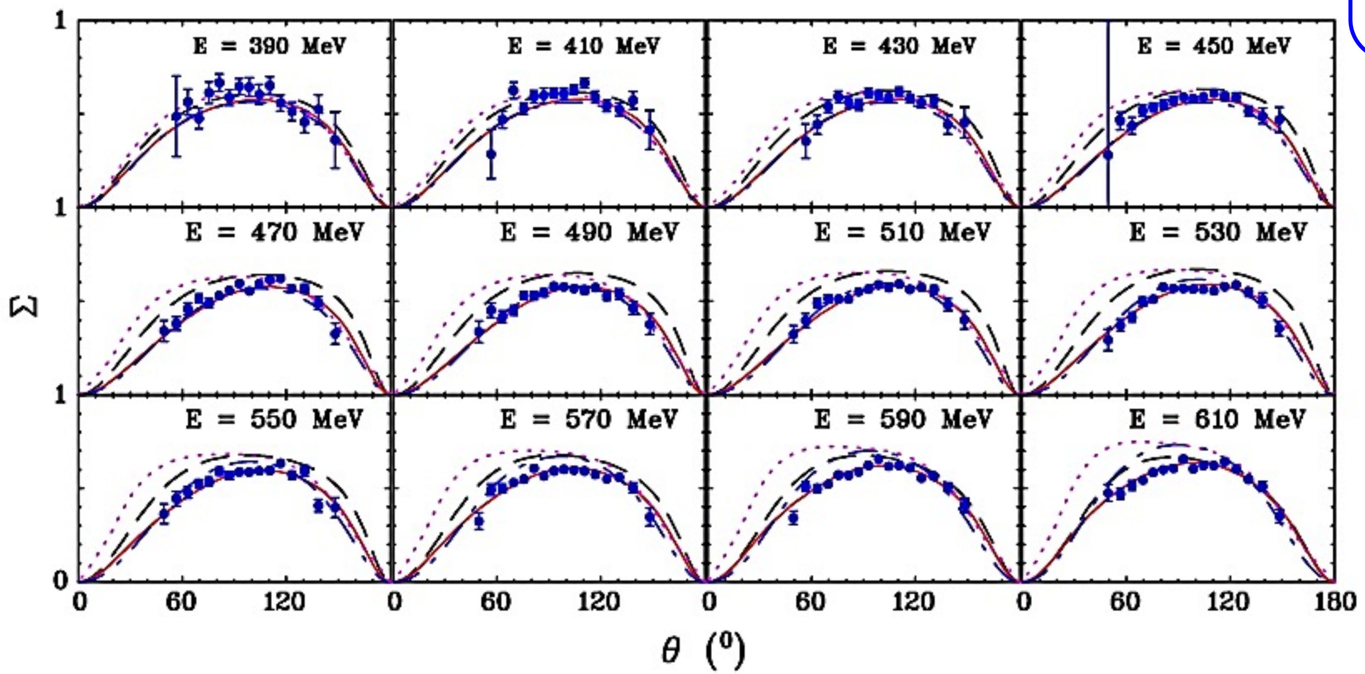
D. Drechsel, S. S. Kamalov, & L. Tiator, Eur. Phys. J. A **34**, 69 (2007)

Meson Production off "Neutron" at CB@MAMI

C. Mulen *et al*, arXiv:2103.08400 [nucl-ex]

- Σ beam asymmetry for $\gamma n \rightarrow \pi^0 n$.

E = 390 – 610 MeV
W = 1271 – 1424 MeV
θ = 49 – 148^0
$\pi^0 n$: 189 Σ



- Systematic uncertainties for each bin have been added in quadrature.

- New A2 data cover parts of **Δ** & **Roper** resonance regions.
- There are no significant changes in dominant multipoles below **1** GeV.

C. Mulen *et al*, arXiv:2103.08400 [nucl-ex]
WJB *et al*, Phys Rev C **100**, 065205 (2019)
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E. Gutz *et al*, Eur Phys J A **50**, 74 (2014)

PWA:
SAID MU22
SAID MA19
MAID2007
BnGa2002

Σ for $\vec{\gamma} n \to \pi^- p$

D. Sokhan, 8th International Conference on Quarks and Nuclear Physics 2018, Tsukuba, Japan

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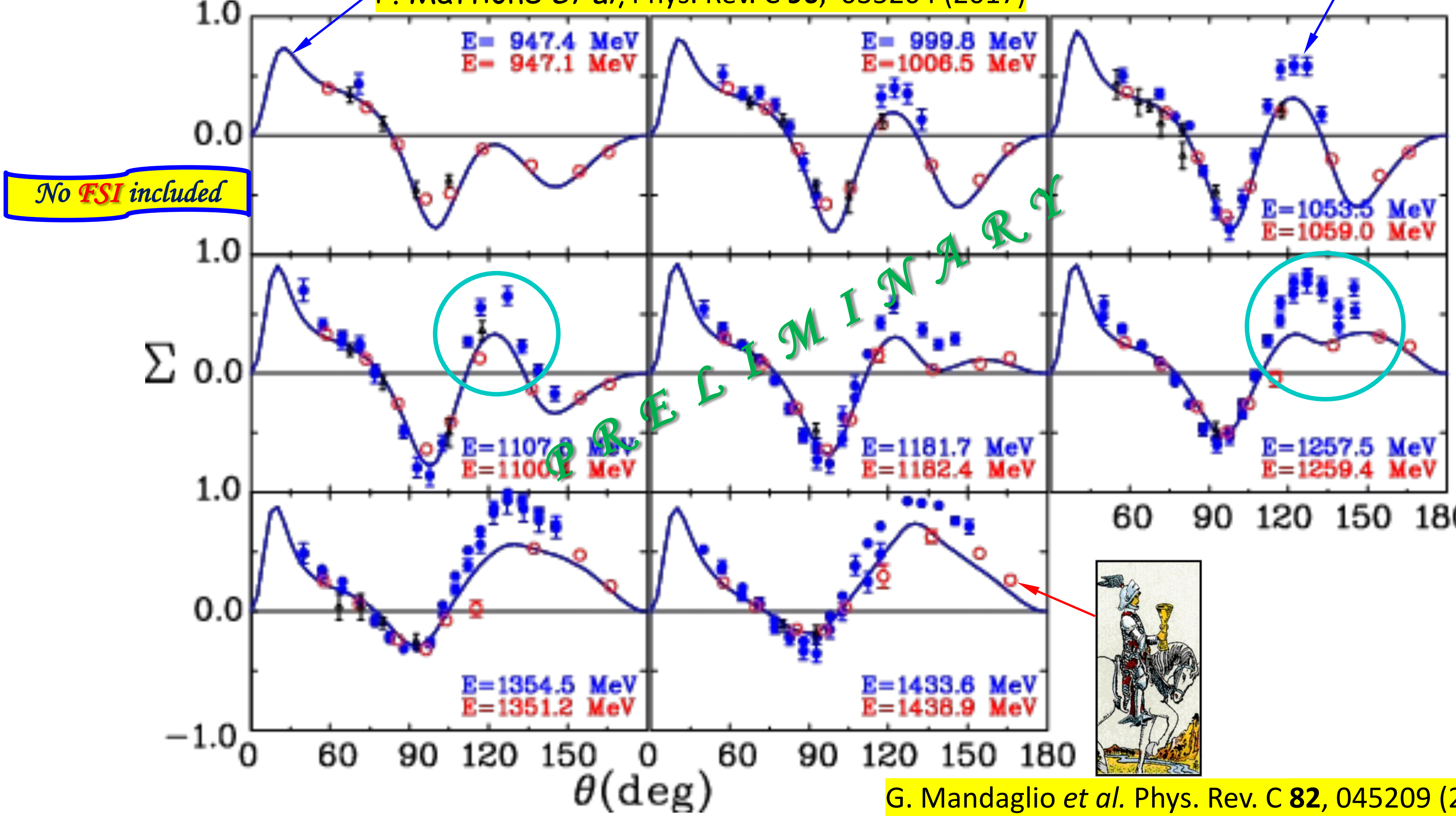

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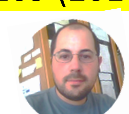

Conclusions
We are all in it together!