

GW Partial Wave Analyses: from Photo- to Electroproduction

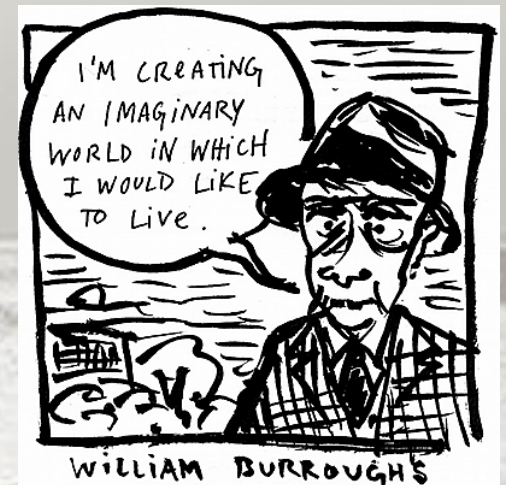
Igor Strakovsky & William Briscoe
The George Washington University



- Pion PhotoProduction for **Baryon Spectroscopy.**
- **Phenomenology** for Pion PhotoProduction.
- **SAID** for Pion PhotoProduction.
- **SAID: Features & Benefits.**
- **FSI** for $\gamma n \rightarrow \pi N$.
- **SAID** for Neutral Baryons.
- **SAID** for Pion ElectroProduction.
- **Summary.**



Pion Photo Production for Baryon Spectroscopy

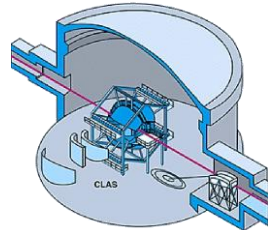


Road Map to Baryon Spectroscopy

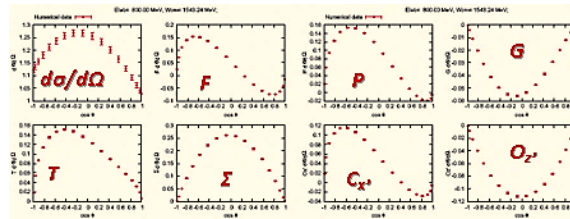
Facility



Experiment



Data



PWA



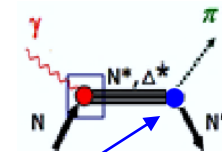
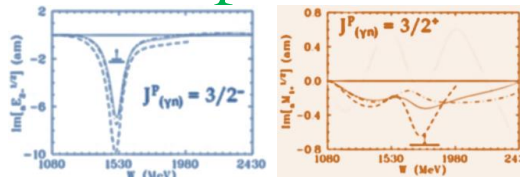
Citation: C. Pengfei et al. (Particle Data Group), Chin. Phys. C, 40, 080001 (2016) and 2017 update

$\Delta(1232) \ 3/2^+$ $I(J^P) = \frac{3}{2}(3/2^+)$ Status: ****
 Older and obsolete values are listed and referenced in the 2014 edition, Chinese Physics C38 070001 (2014).

$\Delta(1232)$ POLE POSITIONS

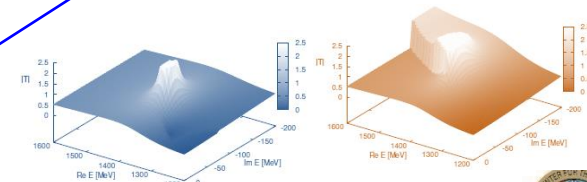
REALE PART, MIXED CHARGES	DOCUMENT ID	TECH	COMMENT
1232 ± 1 ± 1	14 LIP	n → n	
1218.5 ± 1.0	ANISOVICH 12A	DPWA	Multichannel
1213	ARNOT 66	DPWA	n → n, p → p
1200	HÖCHLER 93	ARGO	n → n
1218 ± 1	CUTKOSKY 88	IPWA	n → n

Amplitudes

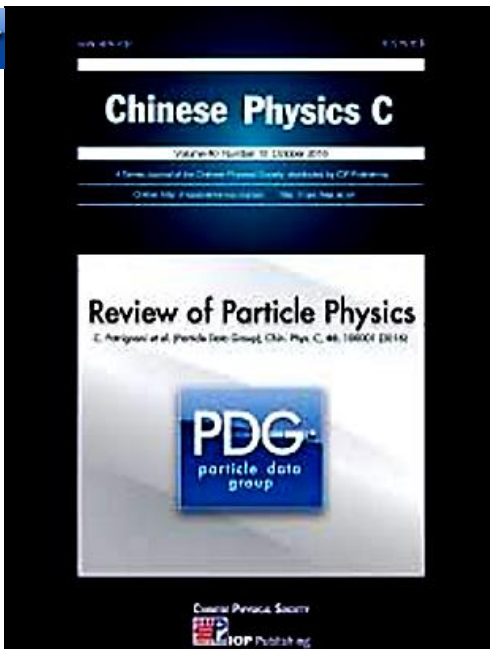


Resonances

πN PWA input



Baryon Sector at PDG16



GW Contribution C. Patrignani et al, Chin Phys C 40, 090001 (2016)

p	$1/2^+$ ****	$\Delta(1232)$	$3/2^+$ ****	Σ^+	$1/2^+$ ****	Ξ^0	$1/2^+$ ****	Λ_c^+	$1/2^+$ ****
n	$1/2^+$ ****	$\Delta(1600)$	$3/2^+$ ***	Σ^0	$1/2^+$ ****	Ξ^-	$1/2^+$ ****	$\Lambda_c(2595)^+$	$1/2^-$ ***
$N(1440)$	$1/2^+$ ****	$\Delta(1620)$	$1/2^-$ ****	Σ^-	$1/2^+$ ****	$\Xi(1530)^0$	$3/2^+$ ****	$\Lambda_c(2625)^+$	$3/2^-$ ***
$N(1520)$	$3/2^-$ ****	$\Delta(1700)$	$3/2^-$ ****	$\Sigma(1305)$	$3/2^+$ ****	$\Xi(1620)^0$	*	$\Lambda_c(2765)^+$	*
$N(1535)$	$1/2^-$ ****	$\Delta(1750)$	$1/2^+$ *	$\Sigma(1400)$	*	$\Xi(1690)^0$	***	$\Lambda_c(2890)^+$	$5/2^+$ ***
$N(1650)$	$1/2^-$ ****	$\Delta(1900)$	$1/2^-$ **	$\Sigma(1560)$	**	$\Xi(1820)^0$	***	$\Lambda_c(2940)^+$	*
$N(1675)$	$5/2^-$ ****	$\Delta(1905)$	$5/2^+$ ****	$\Sigma(1580)$	$3/2^-$ *	$\Xi(1950)^0$	***	$\Sigma_c(2455)$	$1/2^+$ ****
$N(1690)$	$5/2^+$ ****	$\Delta(1910)$	$1/2^+$ ****	$\Sigma(1620)$	$1/2^-$ **	$\Xi(2030)^0$	$\geq 3/2^+$ ***	$\Sigma_c(2520)$	$3/2^+$ ****
$N(1695)$	*	$\Delta(1920)$	$3/2^-$ **	$\Sigma(1660)$	$1/2^+$ ***	$\Xi(2250)^0$	**	$\Sigma_c(2800)$	***
$N(1700)$	$3/2^-$ ***	$\Delta(1930)$	$5/2^-$ **	$\Sigma(1670)$	$3/2^-$ ****	$\Xi(2250)^+$	**	Ξ_c^+	$1/2^+$ ***
$N(1710)$	$1/2^+$ ***	$\Delta(1940)$	$3/2^-$ **	$\Sigma(1690)$	**	$\Xi(2370)^0$	**	Ξ_c^0	$1/2^+$ ***
$N(1720)$	$3/2^+$ ***	$\Delta(1950)$	$7/2^+$ **	$\Sigma(1750)$	$1/2^-$ **	$\Xi(2500)^0$	**	Ξ_c^-	$1/2^+$ ***
$N(1830)$	$5/2^+$ **	$\Delta(2000)$	$5/2^+$ **	$\Sigma(1770)$	$1/2^+$ **	$\Xi(2500)^+$	**	Ξ_c^0	$1/2^+$ ***
$N(1850)$	$3/2^-$ **	$\Delta(2100)$	$1/2^-$ **	$\Sigma(1775)$	$1/2^-$ ****	Ω_c^0	$3/2^+$ *	$\Xi_c(2645)$	$3/2^+$ ***
$N(1875)$	$1/2^+$ **	$\Delta(2200)$	$7/2^-$ **	$\Sigma(1840)$	$3/2^+$ *	$\Omega_c(2700)^-$	*	$\Xi_c(2790)$	$1/2^-$ ***
$N(1915)$	$1/2^+$ **	$\Delta(2300)$	$9/2^+$ **	$\Sigma(1880)$	$1/2^+$ **	$\Omega_c(2800)^-$	*	$\Xi_c(2815)$	$3/2^-$ ***
$N(1950)$	$5/2^+$ **	$\Delta(2350)$	$5/2^-$ *	$\Sigma(1915)$	$5/2^+$ ****	$\Omega_c(2700)^-$	*	$\Xi_c(2930)$	*
$N(1990)$	$7/2^-$ **	$\Delta(2390)$	$7/2^+$ *	$\Sigma(1940)$	$1/2^-$ **	$\Omega_c(2770)^0$	***	$\Xi_c(2980)$	***
$N(2000)$	$5/2^+$ **	$\Delta(2400)$	$9/2^-$ **	$\Sigma(2000)$	$1/2^-$ *			$\Xi_c(3055)$	**
$N(2040)$	$3/2^+$ **	$\Delta(2420)$	$11/2^+$ ****	$\Sigma(2030)$	$7/2^+$ ****			$\Xi_c(3080)$	***
$N(2060)$	$5/2^-$ **	$\Delta(2750)$	$13/2^-$ **	$\Sigma(2070)$	$5/2^+$ **			$\Xi_c(3123)$	*
$N(2100)$	$1/2^+$ *	$\Delta(2950)$	$15/2^+$ **	$\Sigma(2080)$	$3/2^+$ **			$\Xi_c(3123)$	*
$N(2120)$	$3/2^-$ **			$\Sigma(2100)$	$7/2^-$ *			Ω_c^0	$1/2^+$ ***
$N(2190)$	$7/2^-$ ****	Λ	$1/2^+$ ****	$\Sigma(2250)$	***			$\Omega_c(2770)^0$	$3/2^+$ ***
$N(2220)$	$9/2^+$ ****	$\Lambda(1405)$	$1/2^-$ ****	$\Sigma(2455)$	**			Ξ_c^+	*
$N(2250)$	$9/2^-$ ****	$\Lambda(1520)$	$3/2^-$ ****	$\Sigma(2620)$	**			Ξ_c^0	*
$N(2600)$	$11/2^-$ ***	$\Lambda(1600)$	$1/2^+$ ***	$\Sigma(3000)$	*			Λ_b^0	$1/2^+$ ***
$N(2780)$	$13/2^+$ **	$\Lambda(1670)$	$1/2^-$ ****	$\Sigma(3170)$	*			Σ_b^+	$1/2^+$ ***
		$\Lambda(1690)$	$3/2^-$ ****					Σ_b^0	$1/2^+$ ***
		$\Lambda(1800)$	$1/2^-$ **					Σ_b^-	$3/2^+$ ***
		$\Lambda(1810)$	$1/2^-$ **					Ξ_b^0	$1/2^+$ ***
		$\Lambda(1820)$	$5/2^+$ **					Ξ_b^-	$1/2^+$ ***
		$\Lambda(1830)$	$3/2^-$ **					Ω_b^-	$1/2^+$ ***
		$\Lambda(1890)$	$3/2^+$ **						
		$\Lambda(2000)$	*						
		$\Lambda(2010)$	$7/2^+$ **						
		$\Lambda(2100)$	$7/2^-$ ****						
		$\Lambda(2110)$	$5/2^+$ ***						
		$\Lambda(2325)$	$3/2^-$ *						
		$\Lambda(2350)$	$9/2^+$ **						
		$\Lambda(2585)$	**						

• First hyperon was discovered in **1947**.

• Pole position in complex energy plane for hyperons has been made only recently, first of all for $\Lambda(1520)3/2^-$.



- PDG16 has **109 Baryon Resonances** (58 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** and **four 56**).



GLUEX Collaboration
6/30/2018

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

NHMQGC, Pohang, Korea, July 2018

William Briscoe 4



Phenomenology for Pion Photo Production



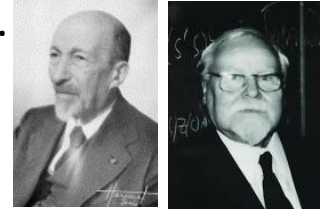
Phenomenology of Spirit charts development of consciousness as it rises from lowly common sense to heights of what **Hegel** calls “*absolute knowing*”
– unconditioned form of thinking proper to philosophy itself.



PWA for 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 ($\Gamma < 500$ MeV) & possessing not too **small** BR (BR > 4%).
- ⇒ Tends (by construction) to **miss** narrow Res with $\Gamma < 20$ MeV.



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



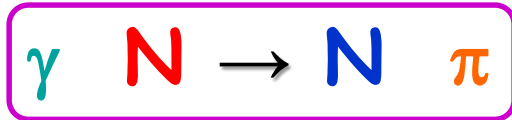
Karlsruhe–Helsinki,
Carnegie–Mellon–Berkeley,
& **GW.**



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



Direct Amplitude Reconstruction in Pion PhotoProduction



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

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

parity conservation \rightarrow

• 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

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SEPTEMBER 1996

Ambiguities in the partial-wave analysis of pseudoscalar-meson photoproduction

Greg Keaton and Ron Workman

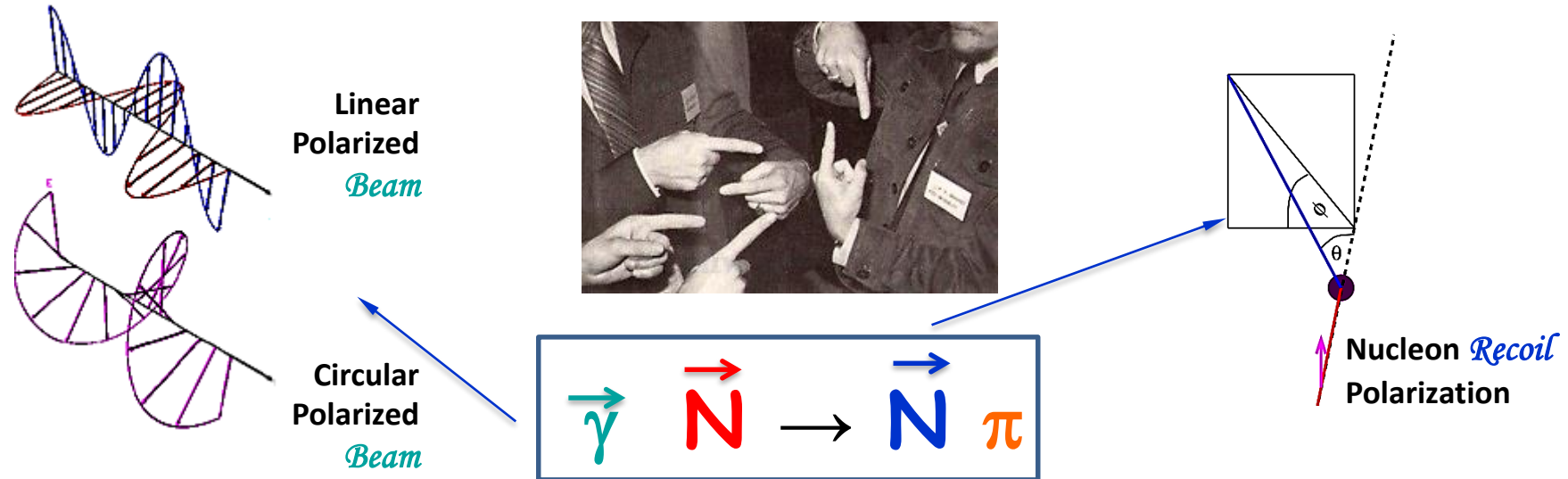
Department of Physics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

(Received 19 April 1996)



Complete Experiment for Pion PhotoProduction

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



- 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

$$\begin{aligned}
 A_{\pi^0 p} &= A^0 + \frac{1}{3} A^{1/2} + \frac{2}{3} A^{3/2} & A_{\pi^0 n} &= -A^0 + \frac{1}{3} A^{1/2} + \frac{2}{3} A^{3/2} \\
 A_{\pi^+ n} &= \sqrt{2} \left(A^0 + \frac{1}{3} A^{1/2} - \frac{1}{3} A^{3/2} \right) & A_{\pi^- p} &= \sqrt{2} \left(A^0 - \frac{1}{3} A^{1/2} + \frac{1}{3} A^{3/2} \right)
 \end{aligned}$$

- **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)



Single Pion PhotoProduction on “Neutron” Target

- Accurate evaluation of **EM** couplings $N^* \rightarrow \gamma N$ & $\Delta^* \rightarrow \gamma N$ 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 $\gamma n \rightarrow \pi^- p$ & $\gamma n \rightarrow \pi^0 n$ 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**.

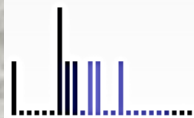


A.B. Migdal, JETP **1**, 2 (1955); K.M. Watson, Phys Rev **95**, 228 (1954)

SAID

for Pion Photo Production

Today per Hour »



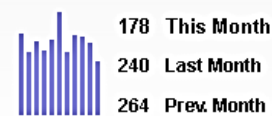
Visitors per Day »



Visitors per Week »



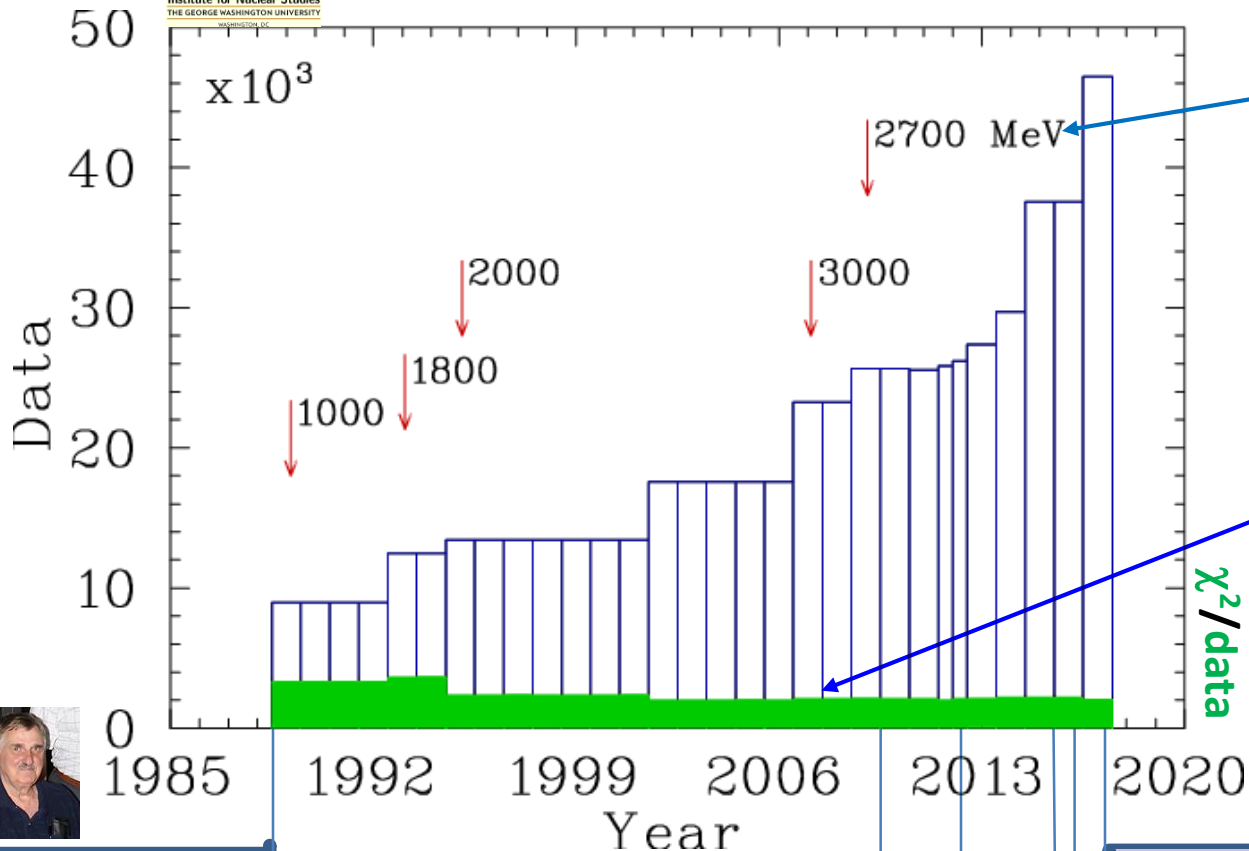
Visitors per Month »



Screenshot of SAID Website usage
<http://gwdac.phys.gwu.edu/>



World Progress in Pion PhotoProduction



Energy limit for SAID PWA

Overall, SAID χ^2 has remained stable ($\chi^2/\text{data} \sim 2$) against growing database, which has increased by factor of 5 since 1989.



1st SAID results

CLAS π^+ $d\sigma/d\Omega$

CLAS π^+/π^0 Σ

CLAS π^- $d\sigma/d\Omega$

A2 π^0 $d\sigma/d\Omega$

1st FROST π^+ E



SAID for Pion PhotoProduction

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

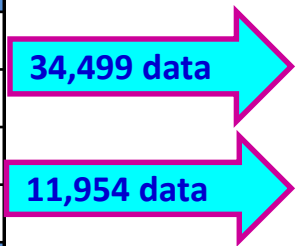
- Data driven (model independent) analysis [No Adhoc resonances in]
- Energy dependent **MA27**
- E = 145 - 2700 MeV [W = 1080 - 2460 MeV]
- PWs = 60 [EM multipoles] [J < 6]
- Prms = 210
- Constraint: **Born** [no free parameters to fit] **π N-PWA** [no theoretical input]



GW SAID PWA facility allows

- To **fit** new data vs World Database.
- To validate **acceptance** & **flux** of new measurements.
- To validate **systematics**.
- To provide realistic event **generator** for MC simulations.

Reaction	Data (Pol)	χ^2
$\gamma p \rightarrow \pi^0 p$	25,540 (23 %)	55,529
$\gamma p \rightarrow \pi^+ n$	8,959 (38 %)	20,736
$\gamma n \rightarrow \pi^- p$	11,590 (4 %)	16,453
$\gamma n \rightarrow \pi^0 n$	364 (59 %)	1,540
Total	46,453	94,258



• There is disbalance between π^0 & π^+ data, **35%**.

• Pion photoproduction on the **neutron** much less known, **35%**.



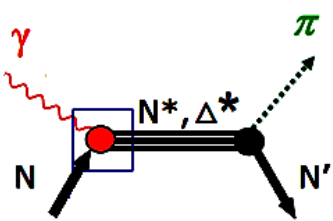


Photo-Decay Amplitudes in BW & Pole Forms

- Pole is main signature of resonance.

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

Evaluated at Res Energy

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

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



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

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



SASD Legacy



- *Minimization & Normalization Factor.*
- *Single-Energy Solutions.*
- *Forced Fit.*
- *Narrow Resonances in PWA.*
- *Quasi-Data Effect.*



Minimization & Normalization Factor for PionProd

$[\chi^2/\text{Data}]$

- **Modified χ^2** function, to be minimized

[systematics plays important role]

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

θ_i^{exp} measured, ϵ_i stat error, θ_i calculated,
 N norm const, ϵ_N its error.



Karl Pearson

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

- If systematic uncertainty varies with angle
 \Rightarrow This procedure may be considered as first approximation.

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

SAID < 2.5 GeV
 MAID < 2.0 GeV

χ^2/Data	SP09		SM02		MAID07	
Reaction	Norm	UnNorm	Norm	UnNorm	Norm	UnNorm
$\gamma p \rightarrow \pi^0 p$	2.2	3.6	3.2	5.7	7.7	12.3
$\gamma p \rightarrow \pi^+ n$	1.9	3.3	2.1	3.9	8.1	11.7
$\gamma n \rightarrow \pi^- p$	1.8	2.6	1.8	2.5	2.9	3.8
$\gamma n \rightarrow \pi^0 n$	2.1	2.1	2.8	2.8	6.4	6.4

- For MAID07, normalization constants were searched to minimize χ^2 (no adjustment of partial waves was possible).

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

• CLAS π^+ & π^0 & LEPS π^0 data included.

• SAID solutions look more stable vs. MAID.

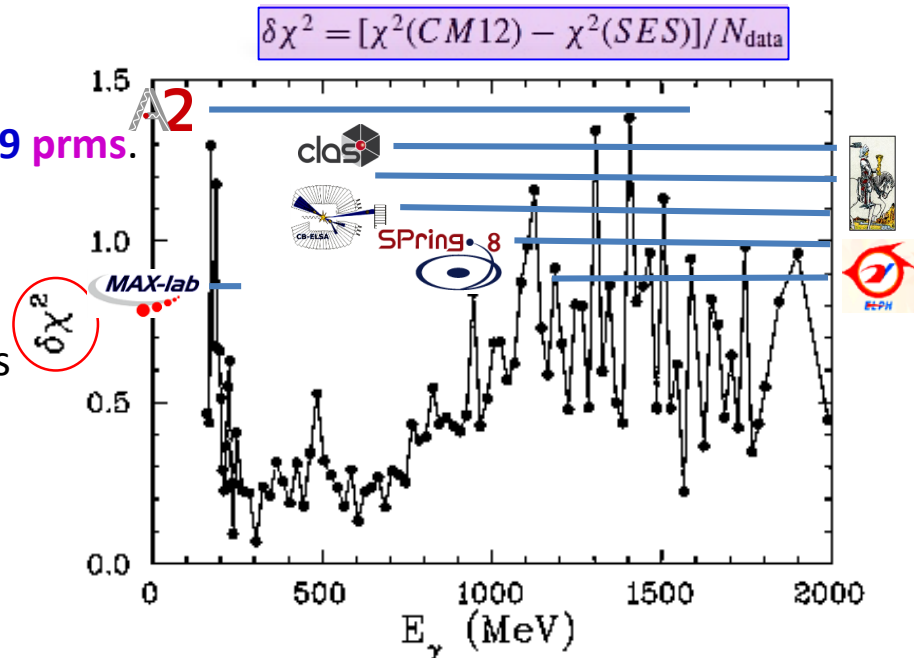


Single-Energy Solutions (SES)

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.

- **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.**

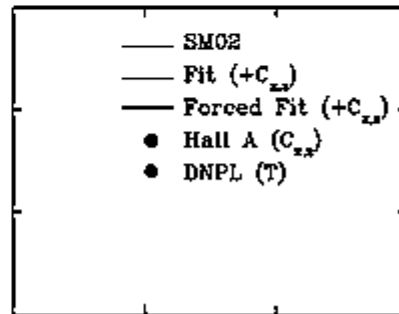
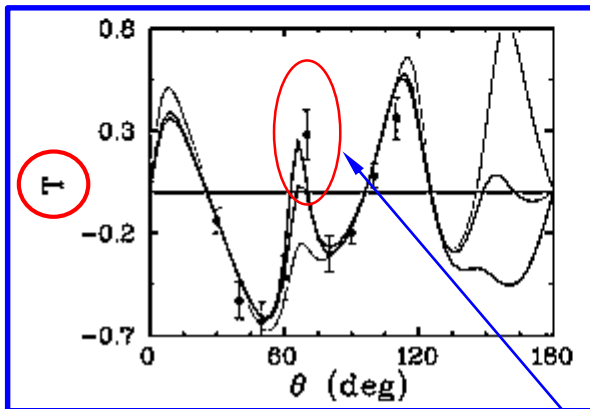
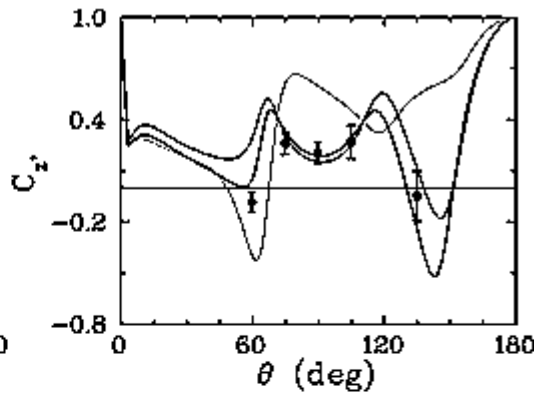
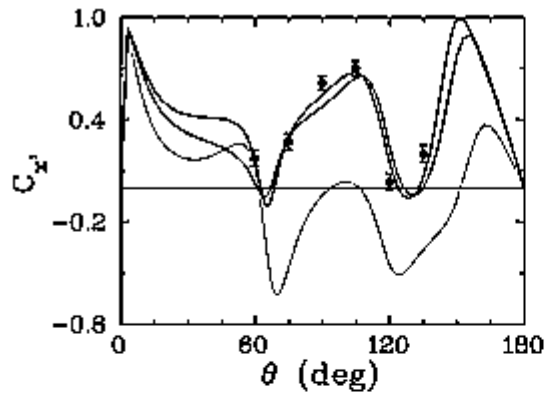


- **Diagonal Error Matrix** generated in **SES** fits.
It can be used to estimate the overall uncertainties for **Global** solution.

Forced Fit for Measurements

R. Arndt, IS, R. Workman, Phys Rev C **67**, 048201 (2003)

• $\vec{\gamma}p \rightarrow \pi^0 p$ at 1900 MeV



- **SAID Forced Fit** has weighted data by factor of **4 – 5**.
- By **weighting** data, we magnify changes in multipole amplitudes, & more clearly see where data conflicts occur.
- **Forced Fit** results indicate that what more measurements require for constraint **PWA** solution.

• **DNPL: T** measurements

P.J. Bussey *et al*, Nucl Phys B **159**, 383 (1979)

• **JLab Hall A:**

There are **22 C_x** & **21 C_z** below 2 GeV

K. Wijesooriya *et al*, Phys Rev C **66**, 034614 (2002)



• That is **not artifact** as was possible to think a while ago !

• **Hall A** data do allow to reproduce previous **T** measurements well.



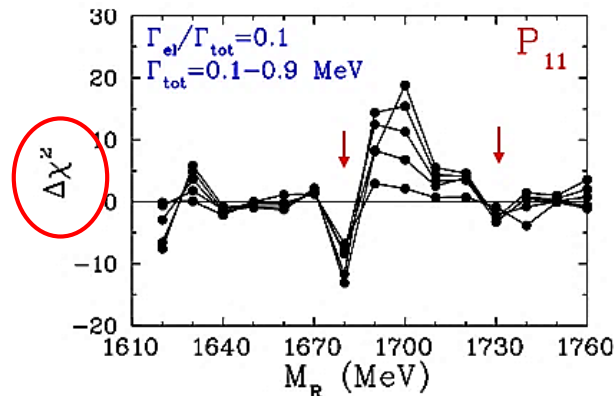
Narrow Resonances in [Modified] PWA

R. Arndt, Ya. Azimov, M. Polyakov, IS, R. Workman, Phys Rev C **69**, 035208 (2004)

- Conventional PWA (by construction) tends to miss narrow Res with $\Gamma < 20$ MeV.
- We assume existence of narrower Resonance, add it to amplitude, then re-fit over whole database.

Refitting

- If worse description:
 - ⇒ Resonance with corresponding M & Γ is not supported.
- If better description:
 - ⇒ Resonance may exist.
 - ⇒ Effect can be due to various corrections (eg, thresholds).
 - ⇒ Both possibilities can contribute.
- Some additional checks are necessary.



- True Resonance should provide the effect only in **single** particular PW.
- While non-Resonance source may show similar effects in various PWs.



Quasi-Data: *What to Expect When you're Expecting*



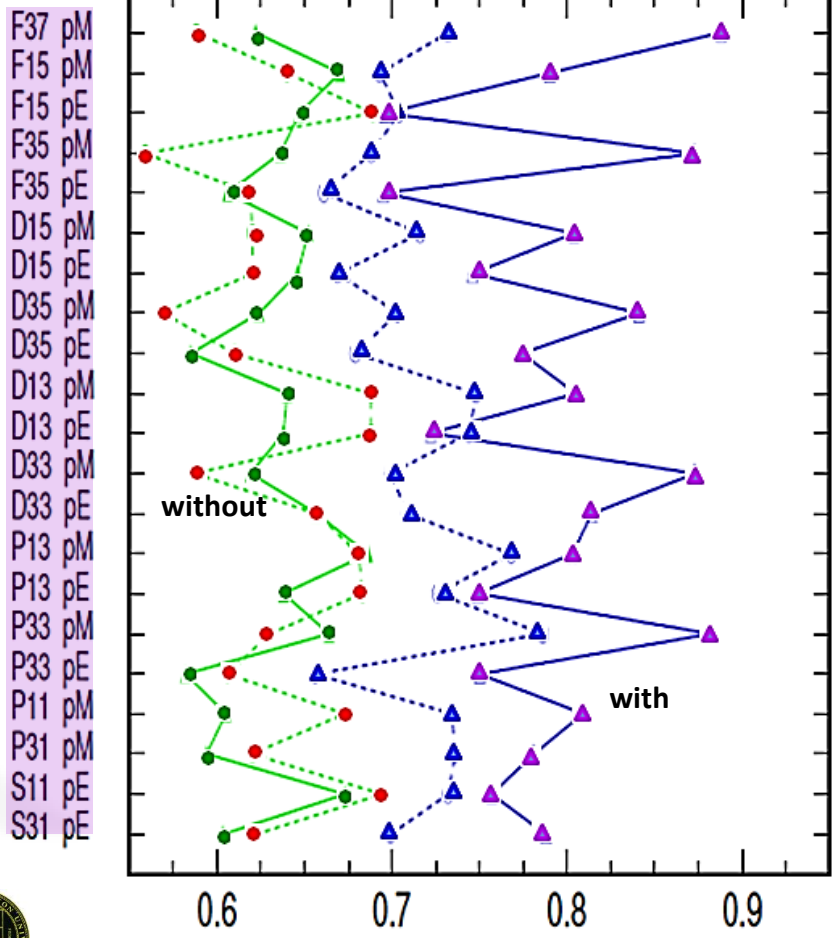
- Prove motivation of **JLab** Proposal **E-03-105**
Pion PhotoProduction from Polarized Target for **FROST** Project.



Transverse Polarization [H, P, T, F] Longitudinal Polarization [G, E]

$$R = u(A_{MC}) / u(A_{world})$$

Average ratio of uncertainties of amplitudes w/o expected FROST data.



- The data generated by this work will fill # of **gaps** in existing database of single & double meson photoproduction.

- Greatest effect naturally requires measurement of all possible quantities as accomplished by **FROST**.

π^+n E: S. Strauch *et al*, Phys Lett B **750**, 53 (2015)
 ηp E: I. Senderovich *et al*, Phys Lett B **755**, 64 (2016)
 ωp E: Z. Akbar *et al*, Phys Rev C **96**, 065209 (2017)
 More results are coming...



Final State Interaction (FSI)



Previous *neutron* measurements used modified *Glauber* approach & procedure of unfolding *Fermi* motion of “*neutron*” target.

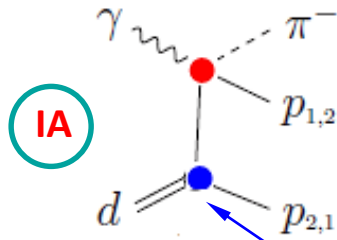




FSI for $\gamma d \rightarrow \pi p N \Rightarrow \gamma n \rightarrow \pi N$

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 $\gamma n \rightarrow \pi N$ data.
- For $\gamma n \rightarrow \pi N$, effect is **5% – 60%**. It depends on (E, θ) .



Fermi Smearing



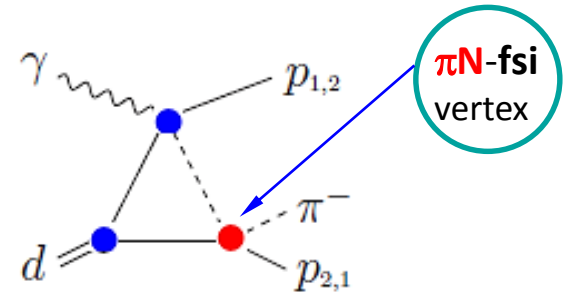
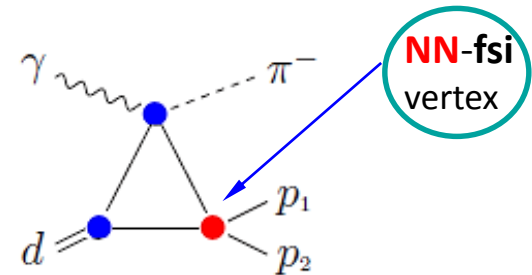
Input: SAID: $\gamma N \rightarrow \pi N$, $\pi N \rightarrow \pi N$, $NN \rightarrow NN$ amplitudes for 3 leading terms
 DWF: full Bonn NN Potential (there is no sensitivity to DWF).



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



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



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

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:

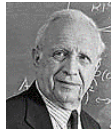
$p_s < 200$ MeV/c
 $p_f < 200$ MeV/c

CLAS g10 & g13:

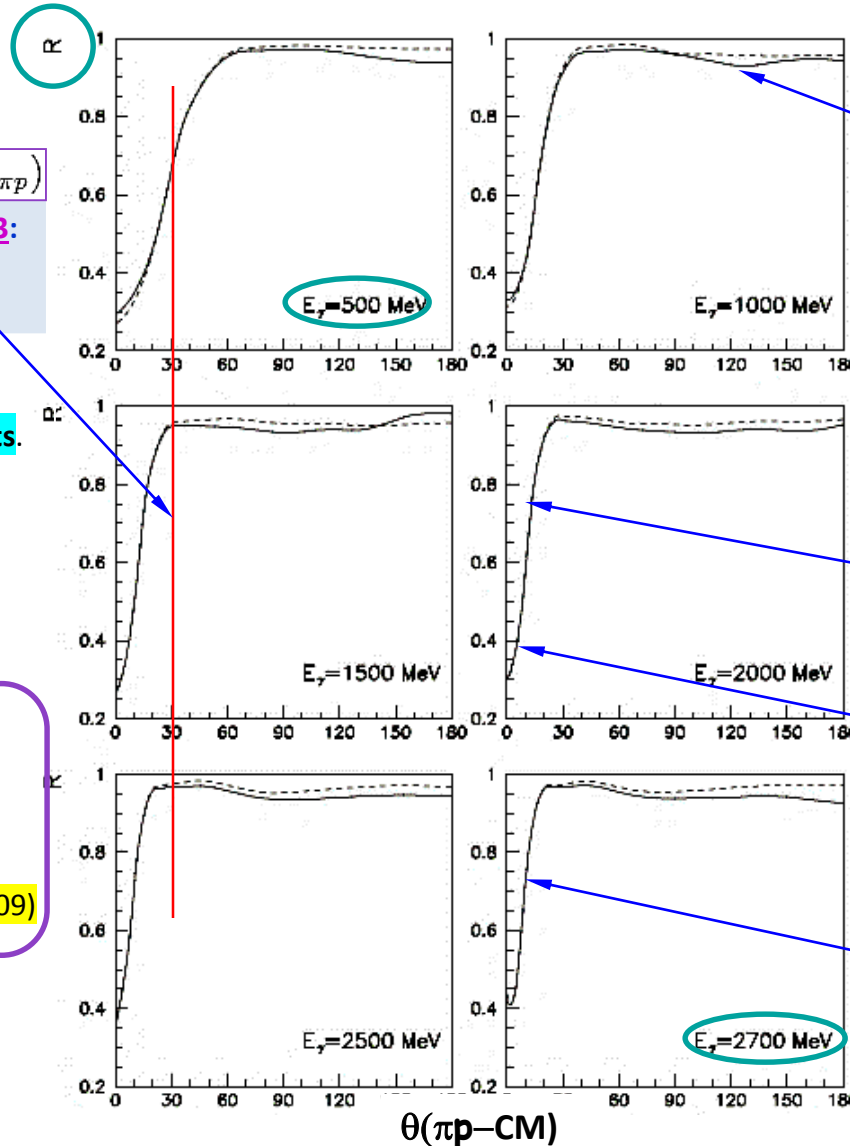
$E > 0.5$ GeV
 $\theta > 30$ deg

• There is no large sensitivity to cuts.

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



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



- For CLAS data:
 - FSI correction factor $R < 1$.
 - Behavior is smooth vs. θ .
 - Effect: $\Delta\sigma/\sigma \leq 10\%$.

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

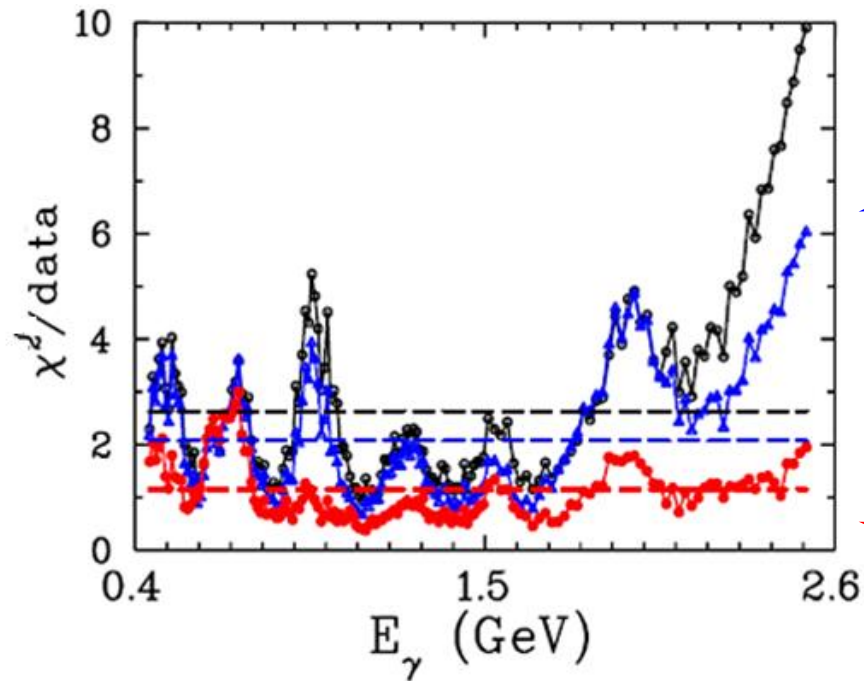
- There is sizeable FSI effect from S-wave part of pp-FSI at small angles.
- Region narrows as E increases.

Forward direction is Terra incognita



Comparison of Previous & New SAID Fits for g_{13}

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 $\gamma n \rightarrow \pi^- p$ $d\sigma/d\Omega$ determination.

FSI for $\gamma d \rightarrow \pi^0 np \Rightarrow \gamma n \rightarrow \pi^0 n$ & $\gamma p \rightarrow \pi^0 p$

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

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

$$A(\gamma p \rightarrow \pi^0 p) = A_v + A_s$$

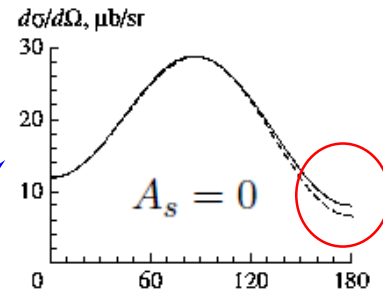
$$A(\gamma n \rightarrow \pi^0 n) = A_v - A_s$$

- The corrections for both target nucleons are **practically identical** for π^0 production in energy range of $\Delta(1232)3/2^+$ due to **isospin structure** of $\gamma N \rightarrow \pi N$ amplitude:

isoscalar *isovector*

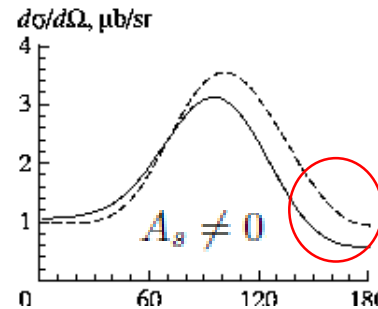
$$A_s = 0 \text{ or } A_v = 0$$

$$R_n = R_p$$

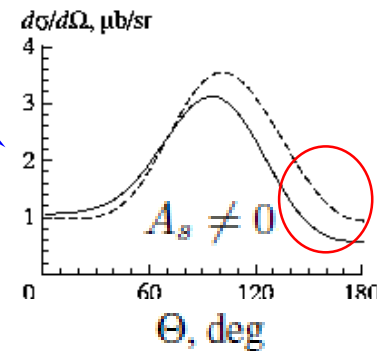


$\gamma p \rightarrow \pi^0 p$ (solid curves)
 $\gamma n \rightarrow \pi^0 n$ (dashed curves)

$\Delta(1232)3/2^+$



$N(1440)1/2^+$



$N(1535)1/2^-$

In general case, $R_n \neq R_p$

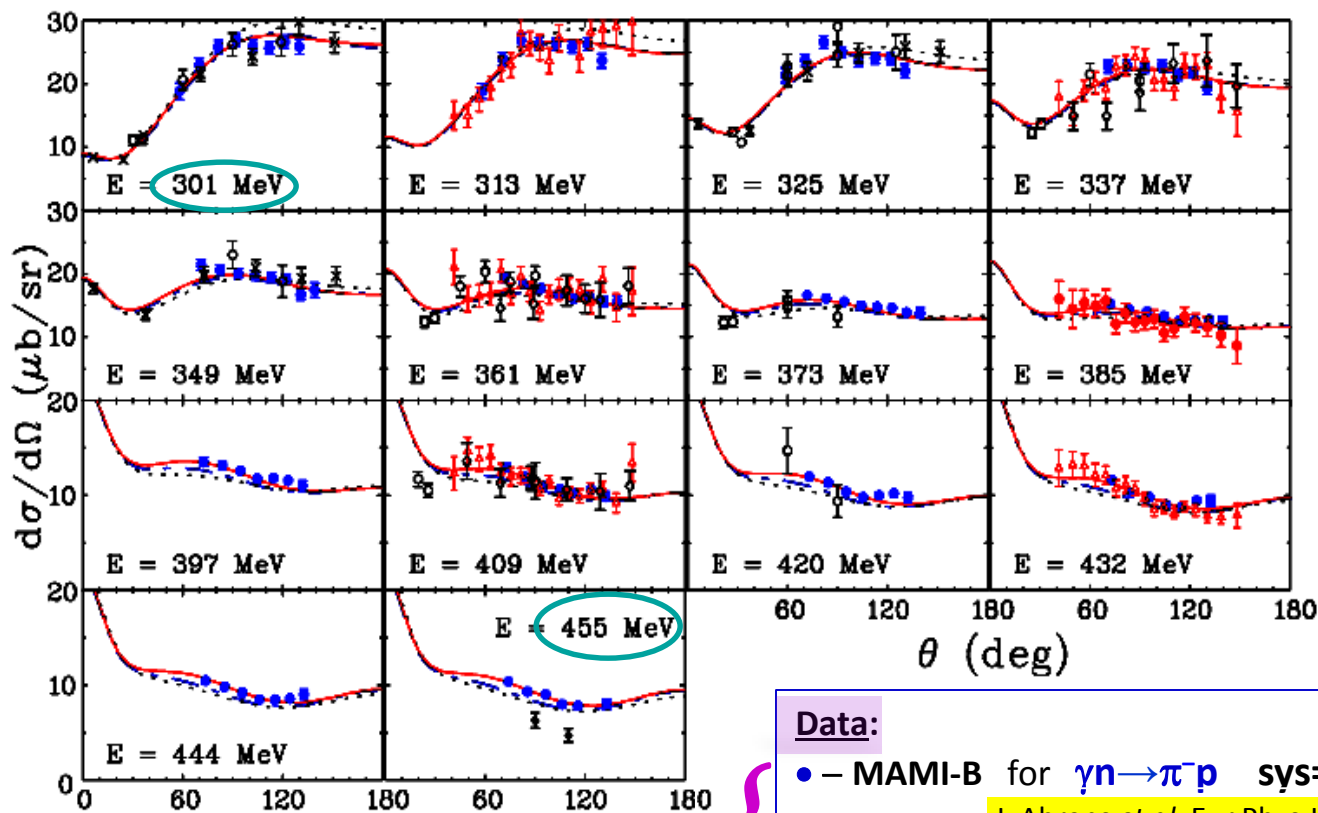


SASD for Neutral Baryon Spectroscopy: Differential Cross Section

FSI is essential



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



SAID-PE12
SAID-SN11
MAID07

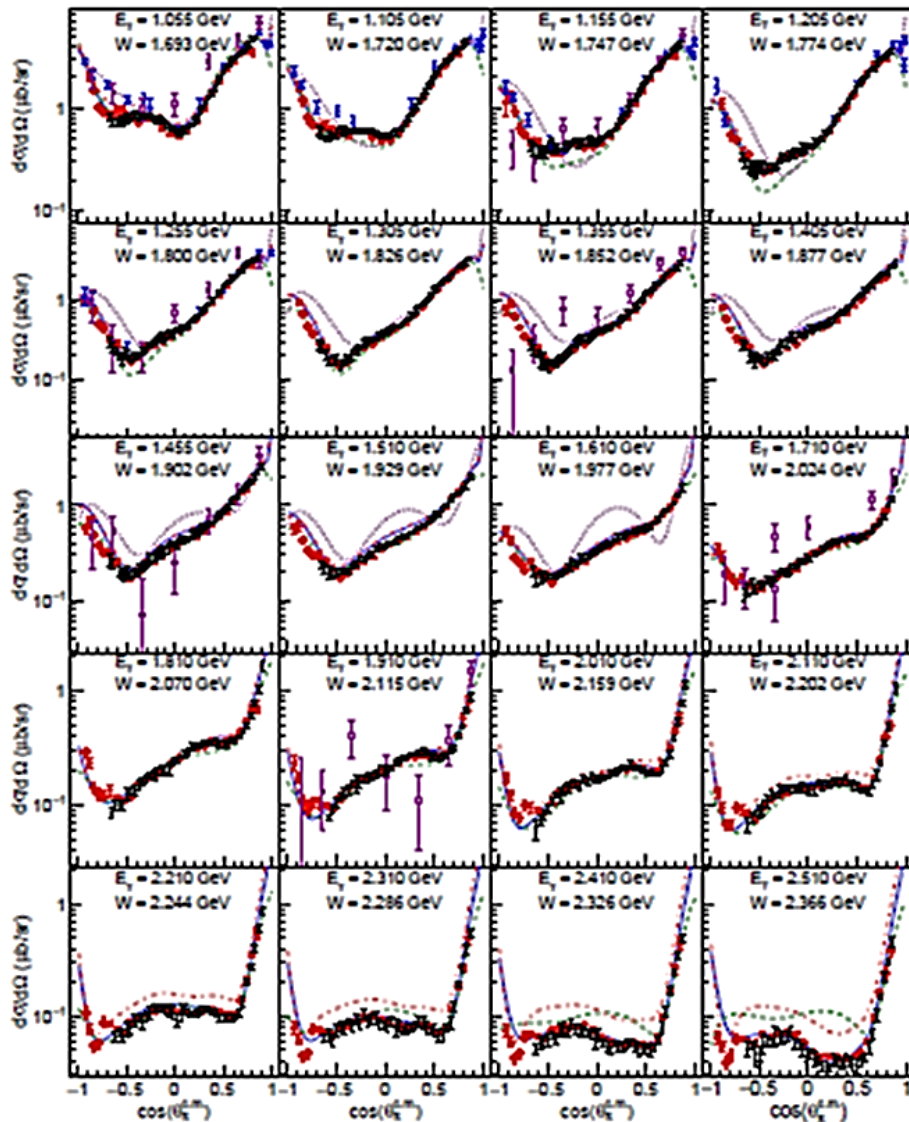
FSI included

• T -invariance is good as 2×10^{-3}

Data:

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





$E = 445-2510$ MeV
 $\pi^- p: 8428$ $d\sigma/d\Omega$

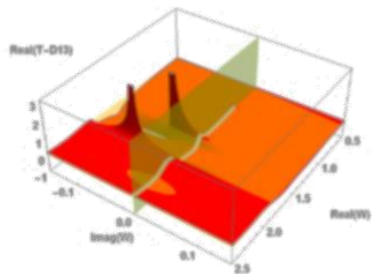
• These data a factor of nearly three increase in world statistics for this channel in this kinematic range.

FSI included



CLAS g13 Impact for Neutron S = 0 & I = 1/2 Couplings

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

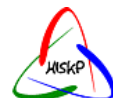
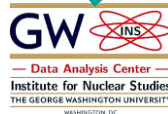


- Selected **photon decay amplitudes** $N^* \rightarrow \gamma n$ at resonance **poles** are determined for **the first time**.

Moduli & phases

BW neutron photo-decay amplitudes

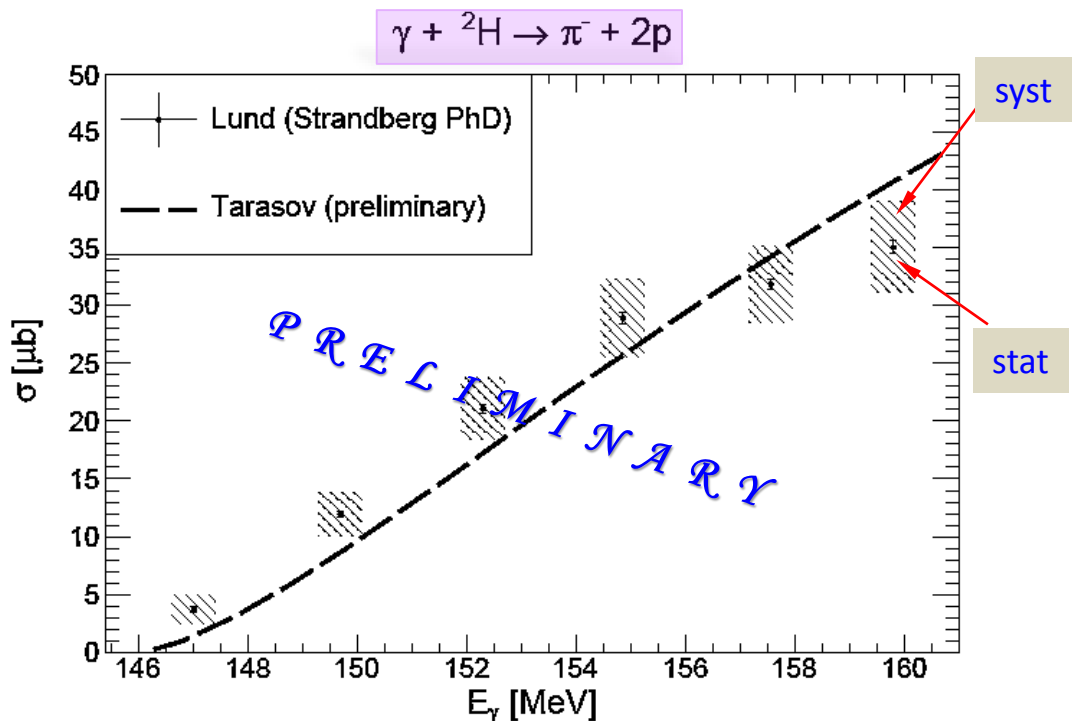
Resonance	Coupling	MA27 modulus, phase	GB12 [g10]	BG2013 [g10]	MAID2007	Capstick	PDG 2016
N(1440)1/2 ⁺	A _{1/2} (n)	0.065±0.005, 5°±3°	0.048± 0.004	0.043±0.012	0.054	-0.006	0.040±0.010
N(1535)1/2 ⁻	A _{1/2} (n)	-0.055±0.005, 5°±2°	-0.058± 0.006	-0.093±0.011	-0.051	-0.063	-0.075±0.020
N(1650)1/2 ⁻	A _{1/2} (n)	0.014±0.002, -30°±10°	-0.040± 0.010	0.025±0.020	0.009	-0.035	-0.050±0.020
N(1720)3/2 ⁺	A _{1/2} (n)	-0.016±0.006, 10°±5°		-0.080±0.050	-0.003	0.004	-0.080±0.050
N(1720)3/2 ⁺	A _{3/2} (n)	0.017±0.005, 90°±10°		-0.140±0.065	-0.031	0.011	-0.140±0.065



MAID



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



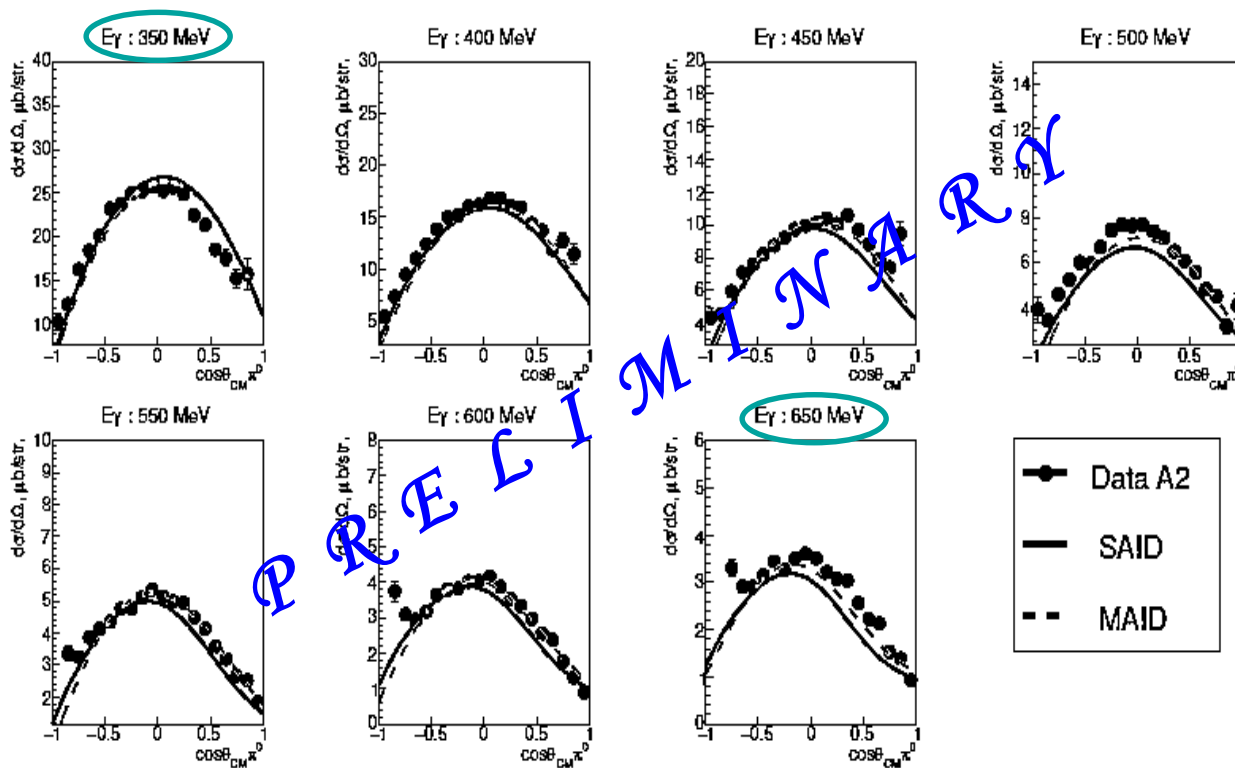
• Charged pion PhotoProd at **threshold** is well described by **Kroll-Ruderman** term which is non-vanishing in chiral limit.

N.M. Kroll & M.A. Ruderman, Phys Rev **93**, 233 (1954)



Courtesy of Bruno Strandberg, 2017

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



E = 180 – 800 MeV
 $\pi^0 n$: 589 $d\sigma/d\Omega$

- New $d\sigma/d\Omega$ s by A2 contribution is **160%** to previous world $\pi^0 n$ data.

FSI included



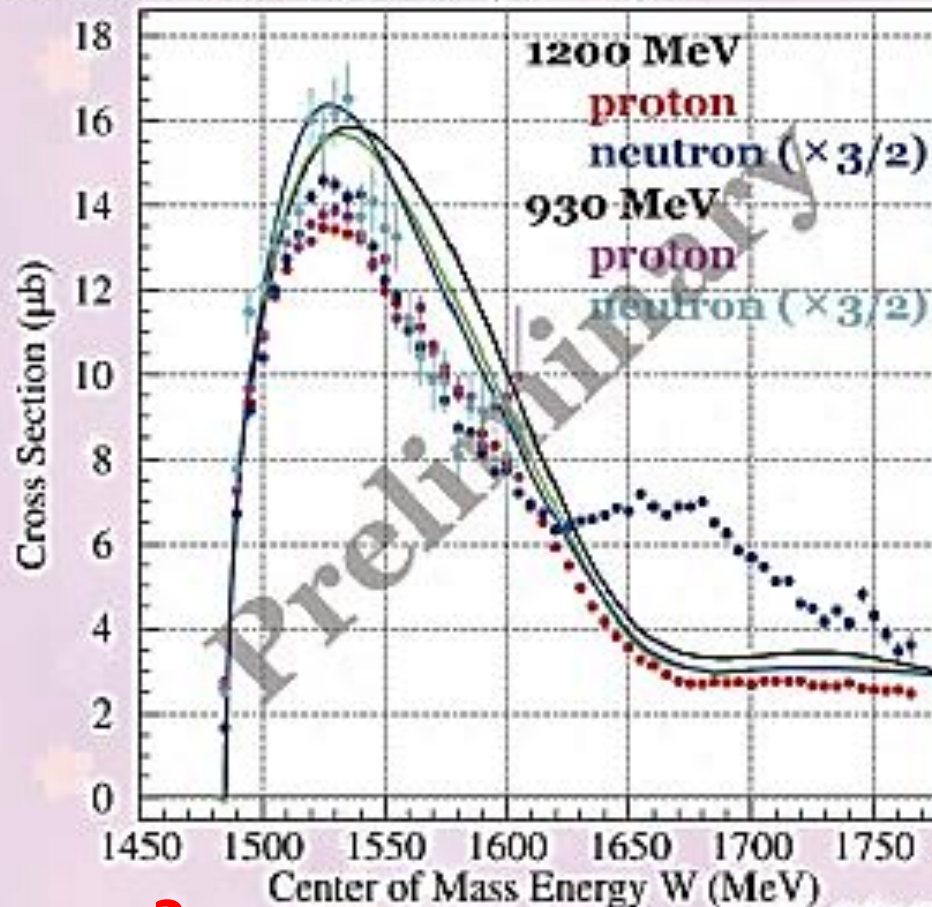
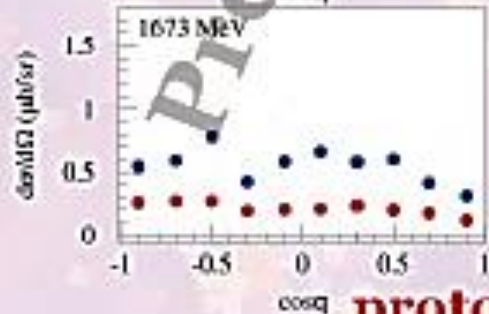
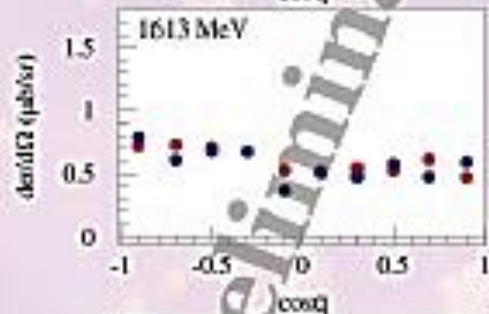
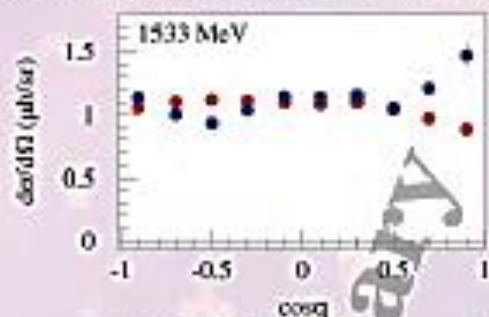
• Data up to **E = 1500 MeV** are coming.

Courtesy of Slava Kulikov, 2017



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

Differential and total cross sections for $\gamma N' \rightarrow \eta N$



proton
neutron ($\times 3/2$)

No FSI included

ETA-MAID2003
SAID GW2009
BoGa 2011-2



Courtesy of Takatsugu Ishikawa, 2017

T. Ishikawa, 2017.04.20, η photoproduction on the deuteron at $E_\gamma < 1.2$ GeV

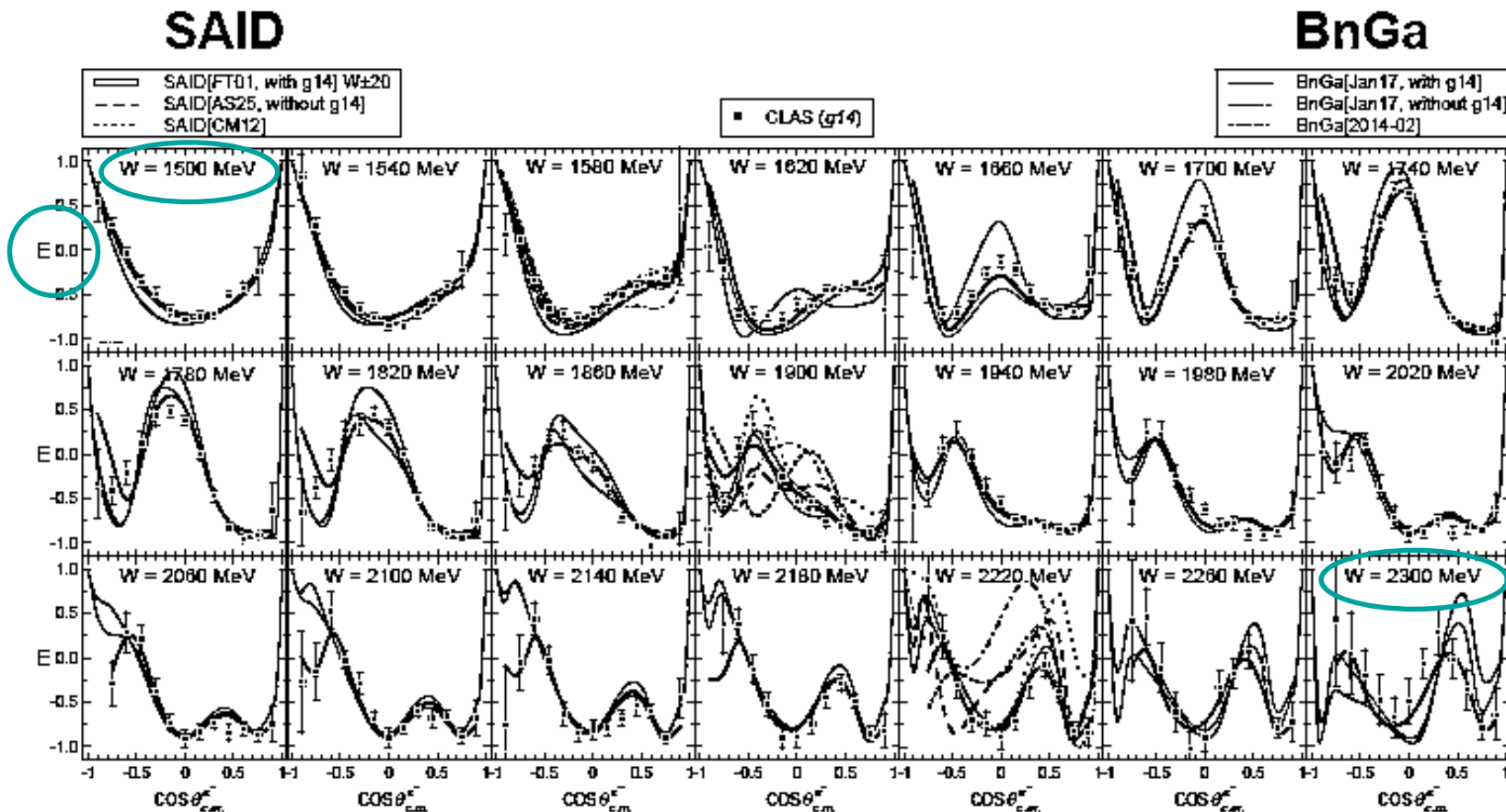
20



SASD for Neutral Baryon Spectroscopy: Polarized Measurements

*Assumption is
FSI is small*





$E = 730 - 2345$ MeV
 $\pi^- p$: 266 E

No FSI included



CLAS g14 Impact for Neutron

$S = 0$ & $I = 1/2$ Couplings

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

BW	$A_n^{1/2}$ ($10^{-3} \text{ GeV}^{-1/2}$)	$A_n^{3/2}$ ($10^{-3} \text{ GeV}^{-1/2}$)	$A_n^{3/2}$ ($10^{-3} \text{ GeV}^{-1/2}$)	$A_n^{3/2}$ ($10^{-3} \text{ GeV}^{-1/2}$)
	g14 PRL	previous	g14 PRL	previous
<u>SAID</u>				
N(1720)3/2 ⁺	-9 ± 2	-21 ± 4	+19 ± 2	-38 ± 7
N(2190)7/2 ⁻	-6 ± 9	---	-28 ± 10	---
<u>BnGa</u>				
N(1720)3/2 ⁺	tbd	-80 ± 50	tbd	-140 ± 65
N(2190)7/2 ⁻	+30 ± 7	-15 ± 12	-23 ± 8	-33 ± 20

- $I = 3/2$ waves ~ unchanged \longleftrightarrow determined by proton data.

- Inclusion of these **g14** data in new **PWA** calculations has resulted in revised γN^* couplings &, in case of **N(2190)7/2⁻**, convergence among different **PWA** groups.

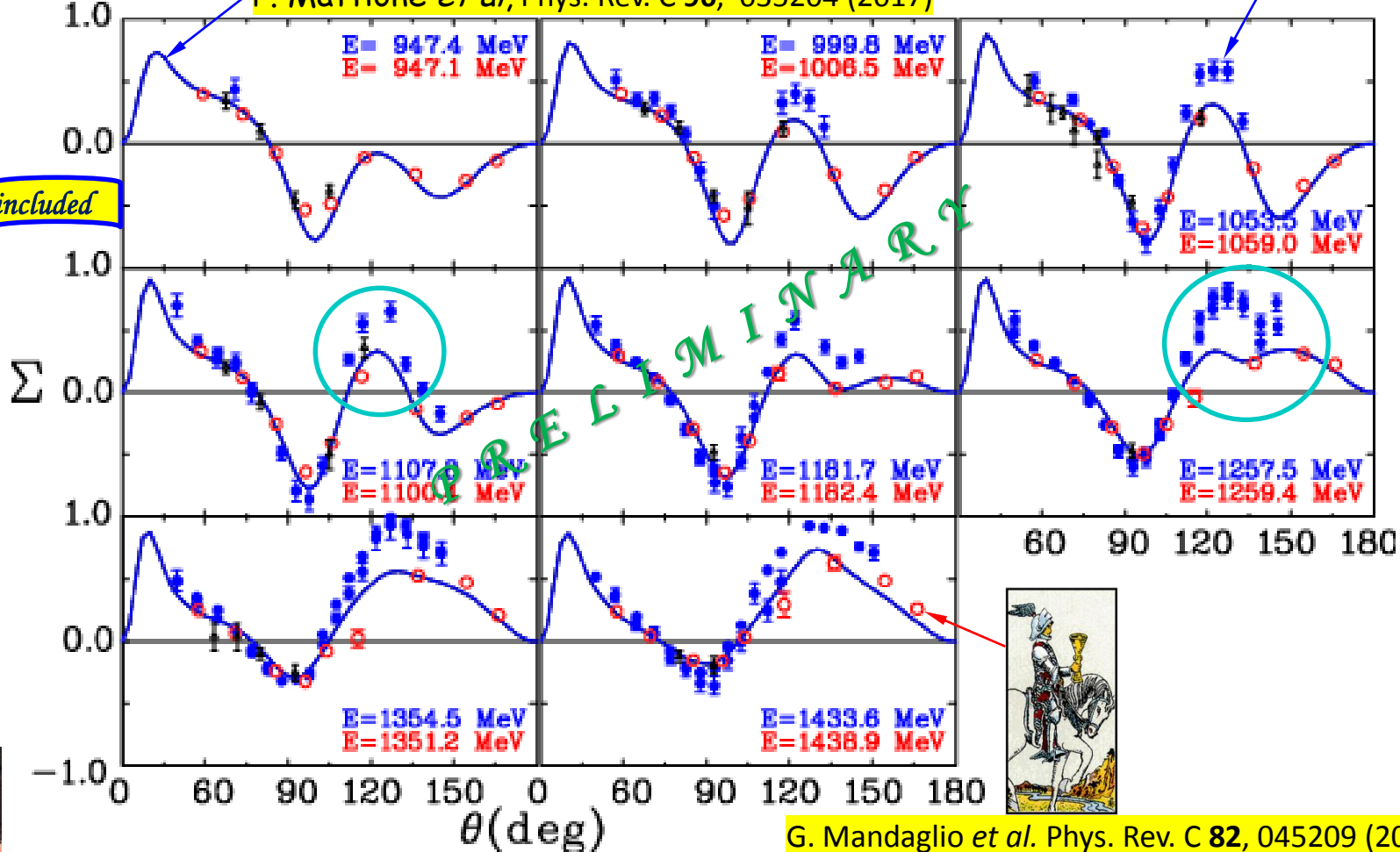
- Such couplings are sensitive to **dynamical** process of **N^{*}** excitation & provide important guides to nucleon structure models.

Courtesy of Andy Sandorfi, 2017

D. Sokhan *et al*, in progress

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

No FSI included



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

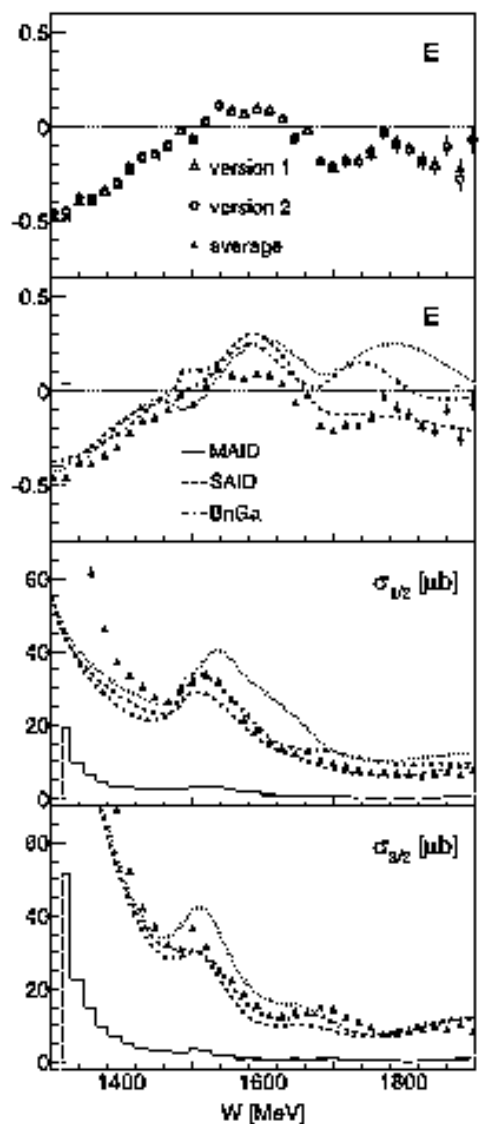
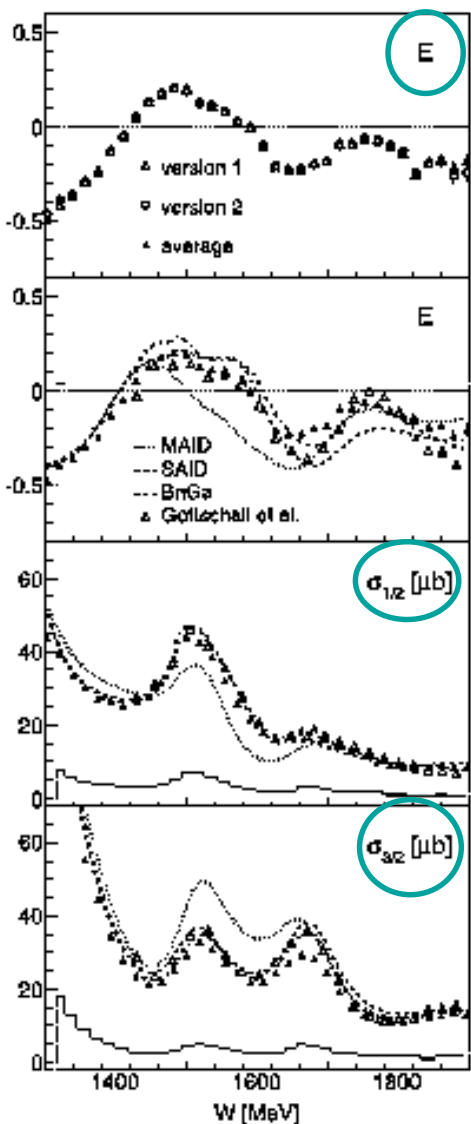


Courtesy of Daria Sokhan, 2018



"Proton"

"Neutron"



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

N(1680)5/2⁺ → Nγ

$pA^{3/2} = +133 \pm 12$ $pA^{1/2} = -15 \pm 6$
 $nA^{3/2} = -33 \pm 9$ $nA^{1/2} = +29 \pm 10$

• It couples **weakly** to **neutron**.

N(1675)5/2⁻ → Nγ

$pA^{3/2} = +20 \pm 5$ $pA^{1/2} = +19 \pm 8$
 $nA^{3/2} = -85 \pm 10$ $nA^{1/2} = -60 \pm 5$

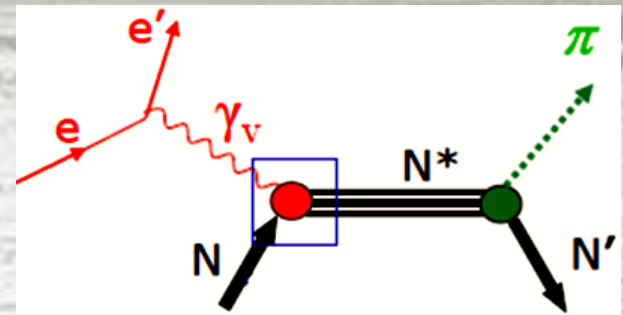
• It couples **strongly** to **neutron**.



No FSI included



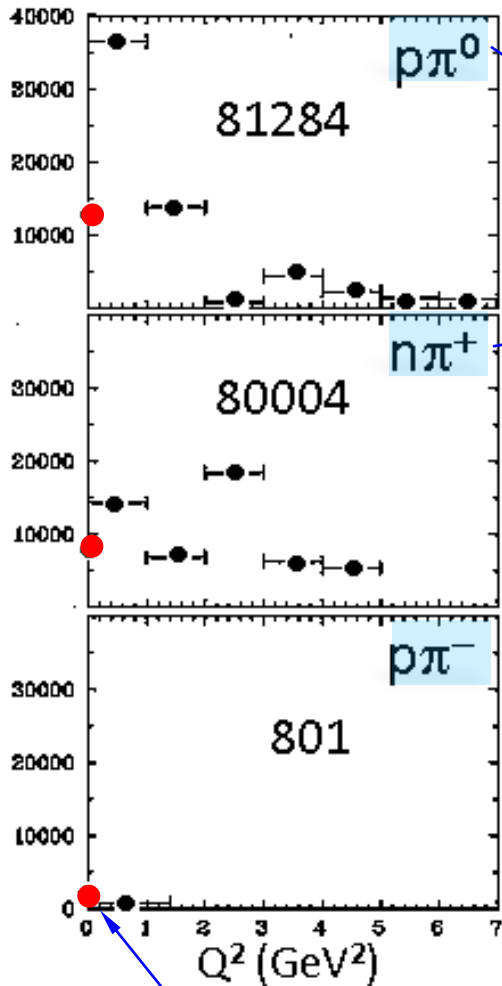
SASD for Neutral Baryon Spectroscopy: Pion ElectroProduction




World Neutral & Charged Pion EPR Data

R. Arndt, W. Briscoe, M. Paris, IS, R. Workman, Chin Phys C **33**, 1063 (2009)

W < 2 GeV @ 2009



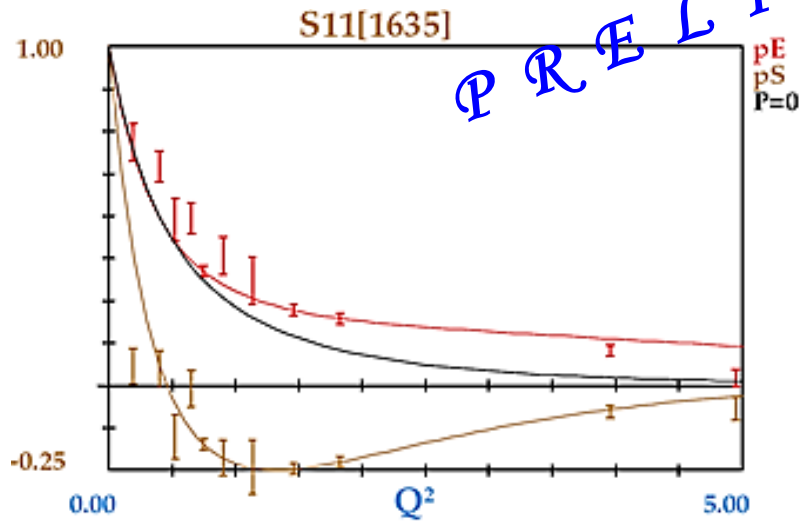
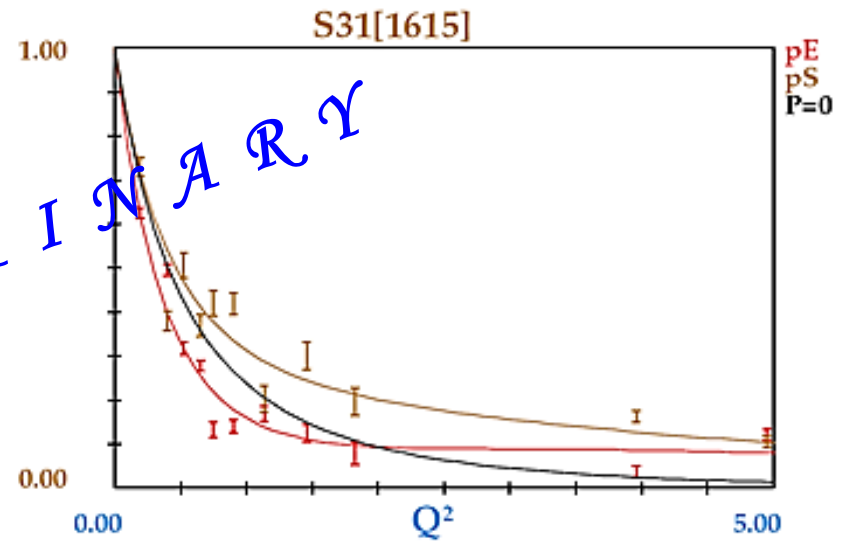
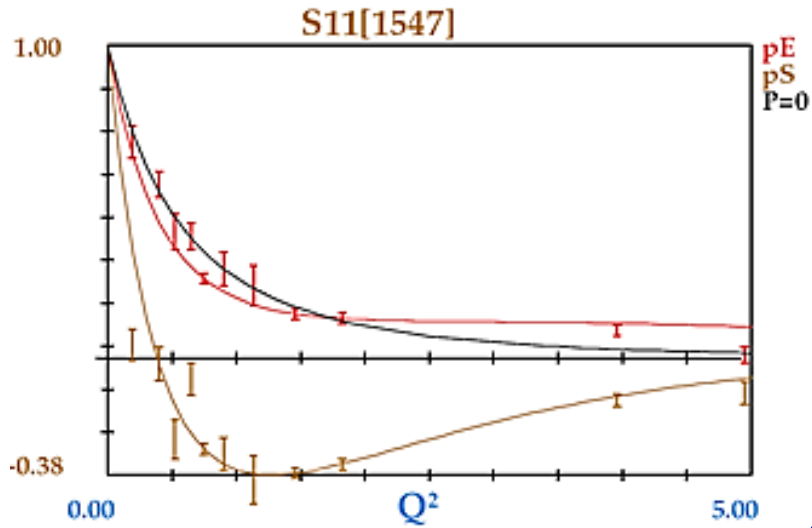
Pion PhotoProduction

• 85% of them are  data

reaction	data	χ^2
$\gamma^* p \rightarrow \pi^0 p$	55,766	81,284
$\gamma^* p \rightarrow \pi^+ n$	51,312	80,004
redundant	14,772	17,375
total	124,453	178,663
$\gamma p \rightarrow \pi N$	24,888	50,684
all photo	159,341	229,317
$\pi N \rightarrow \pi N$	31,876	57,255
all πN	191,217	286,572

- **Problem 1:** 18 new Multipoles
 [Parameterization as E, M]
- **Problem 2:** Q^2 dependence ??

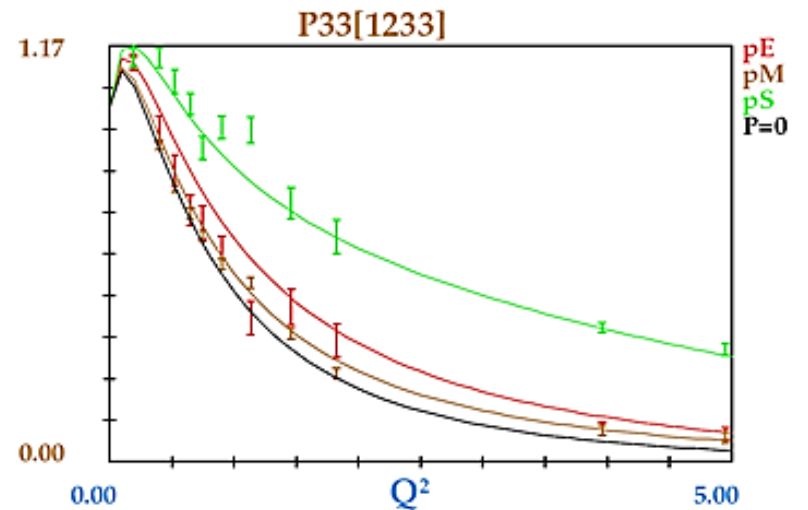
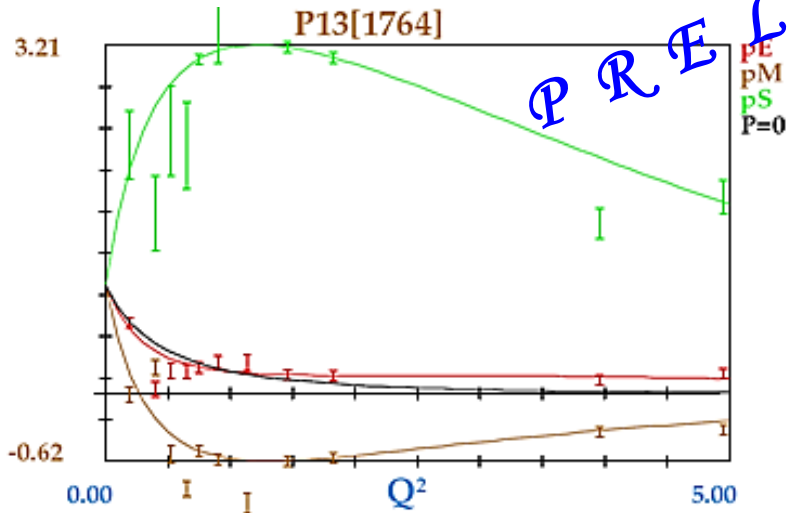
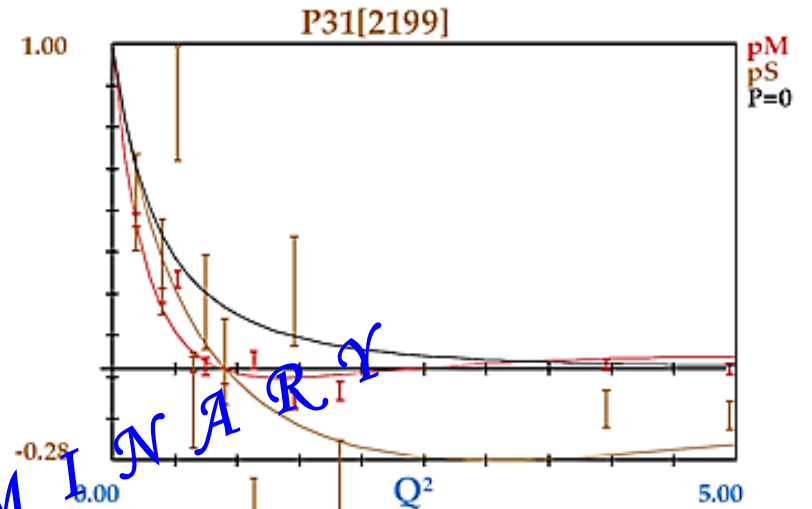
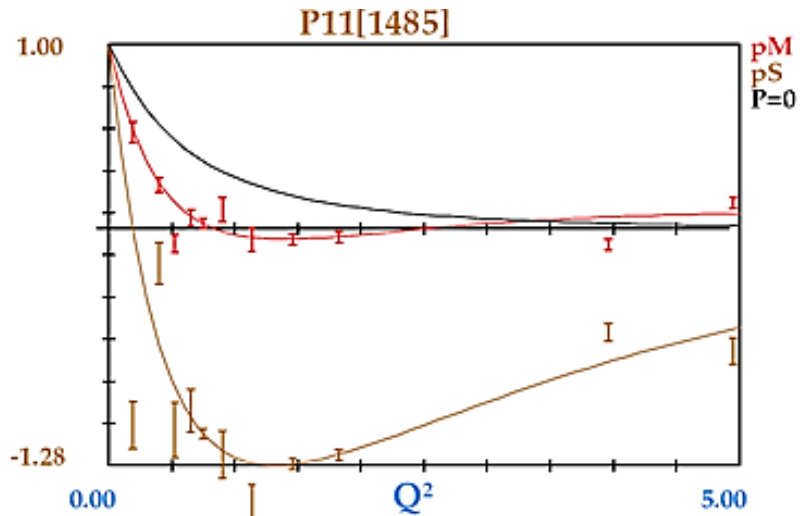
S_{11} & $\mathcal{I}S_{31}[Q^2]$



PRELIMINARY



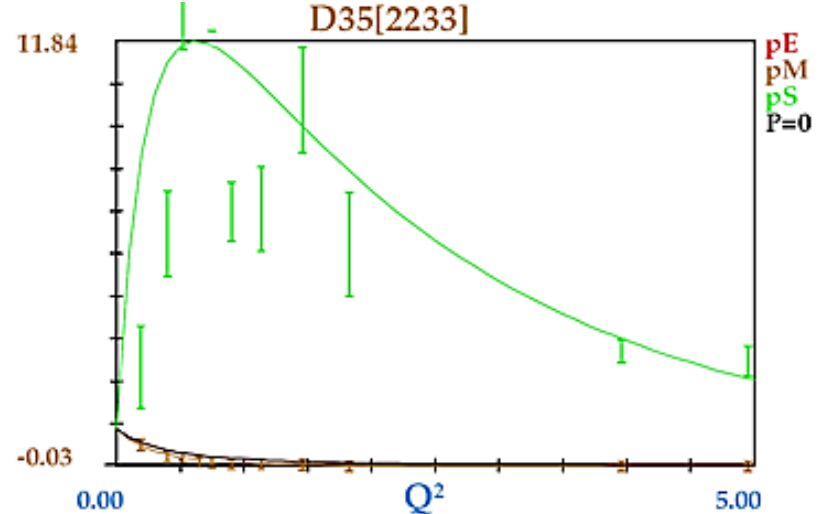
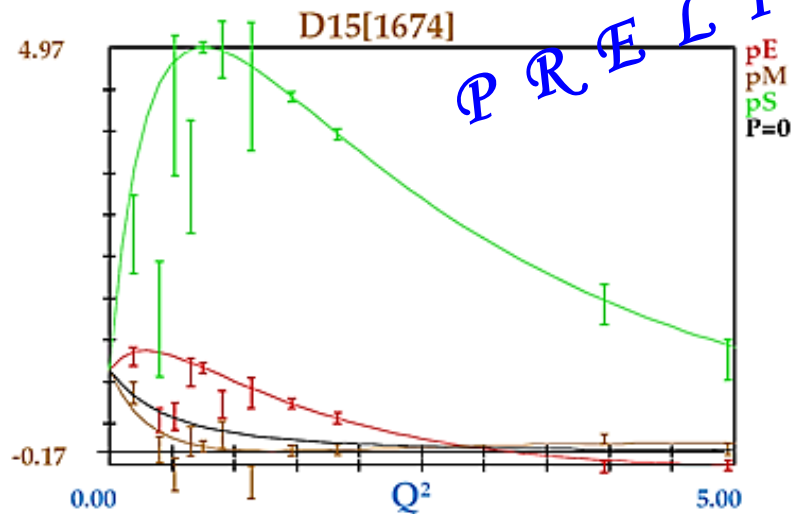
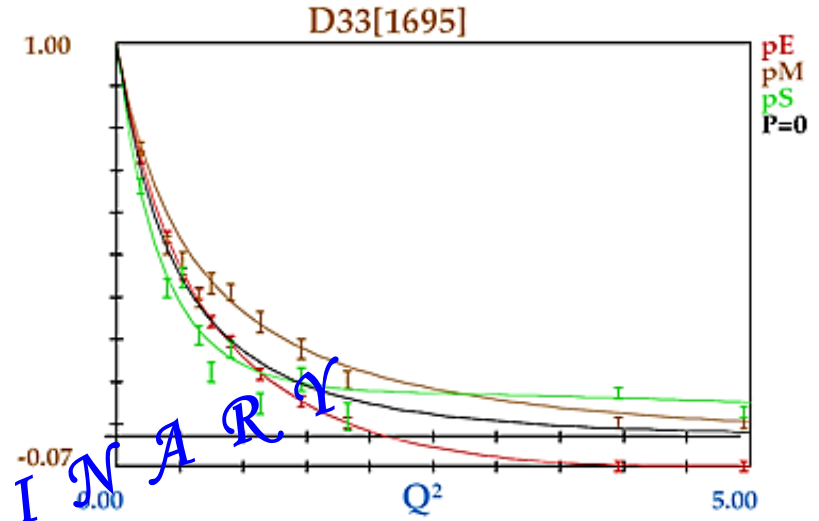
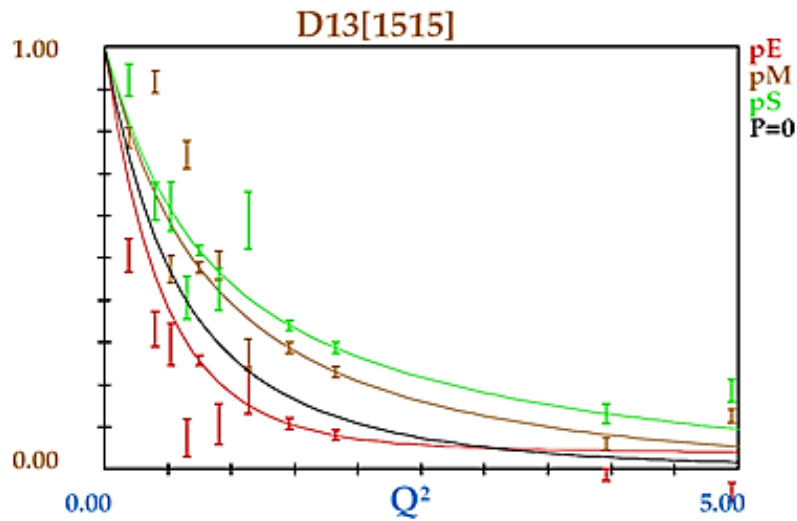
$P_{11} \mathcal{I} P_{13} \mathcal{I} P_{11} \mathcal{I} P_{33} [Q^2]$



PRELIMINARY



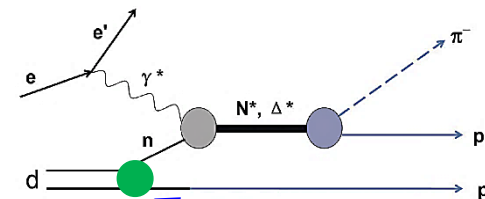
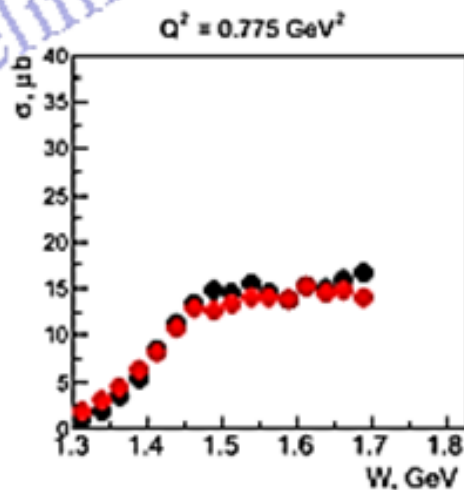
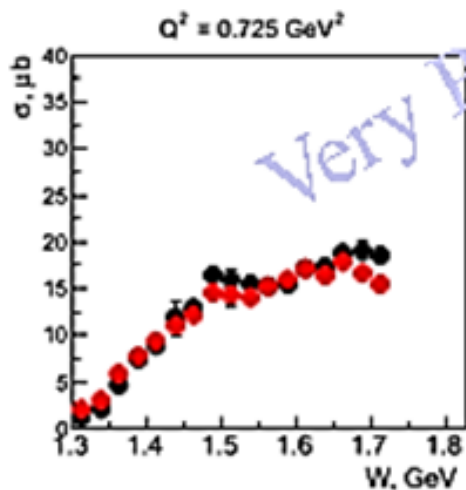
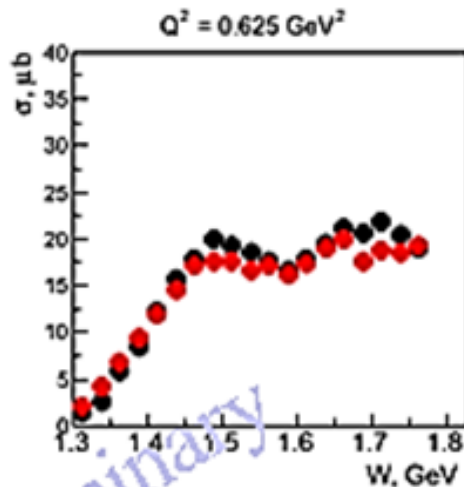
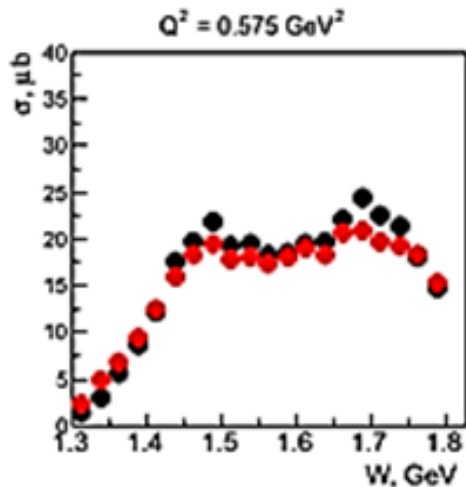
$D_{13} \mathcal{I} D_{15} \mathcal{I} D_{33} \mathcal{I} D_{35} [Q^2]$



PRELIMINARY



Unfolding Fermi Smearing via Event Generator



IA

Fermi Smearing

Black bullets – integrated cross section with Fermi correction

Red bullets – integrated cross section without Fermi correction

π missing topology

Very Preliminary



Courtesy of Ralf Gothe, 2017

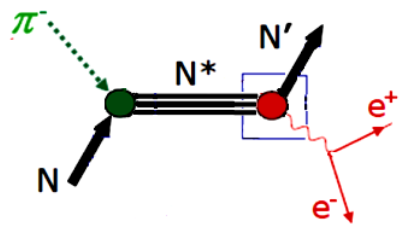


- *Inverse Pion Electroproduction* is only process which allows determination of **EM nucleon** & **pion form factors** in intervals:

$$0 < k^2 < 4 M^2$$

$$0 < k^2 < 4 m_\pi^2$$

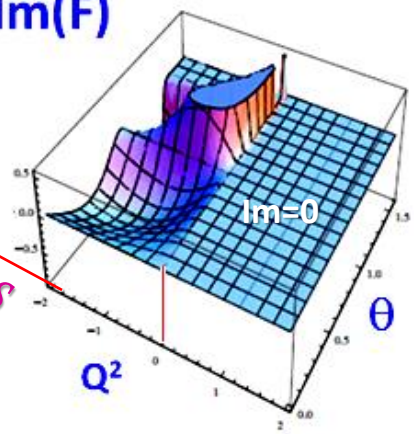
which are kinematically **unattainable** from e^+e^- initial states.



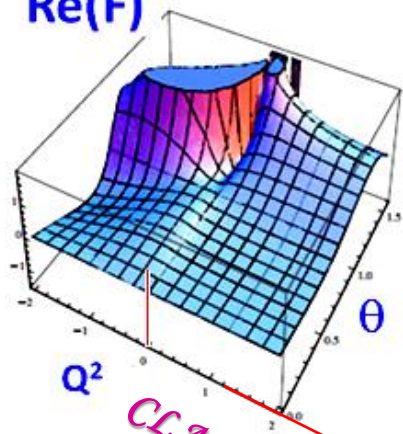
Time-like

HADES
MEIC

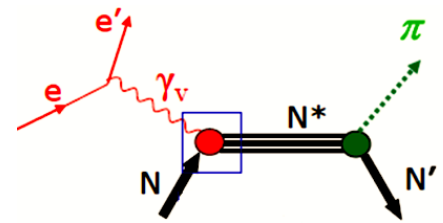
Im(F)



Re(F)



CLAS



Space-like

- $\pi p \rightarrow e^+e^- n$ measurements will significantly complement current **electroproduction**.
- $\gamma^* N \rightarrow \pi N$ study for evolution of **baryon** properties with increasing momentum transfer by investigation of case for **time-like virtual photon**.

Summary for Pion PhotoProduction off Bound Neutrons Study

- Since **1989** pion photoproduction **database** below $W = 2.5$ GeV was increased by factor of **5** (most of new data came for $\gamma p \rightarrow \pi^0 p$) & is compatible with $\pi N \rightarrow \pi N$ database now.
- Pion photoproduction on "**neutron**" much less known than on **proton** (**35%**) & **neutron database** grows.
- **FSI** correction factor for both $\pi^- p$ & $\pi^0 n$ final states is less than **15%** above 30° in CM. It is compatible with **Radiation** correction for **pion** ElectroProduction (**~30%**).
- We may assume that **FSI** corrections for **pion polarized** measurements are **small**.
- Now we are able to extract **pole** positions on complex energy plane for both $N^* \rightarrow \gamma p$ & $N^* \rightarrow \gamma n$ photo-decay amplitudes.
- Evaluation of Q^2 dependency of $\gamma^* N$ couplings is **new task – stay tuned**.





*Thank you for the invitation
and your attention*

6/30/2018

NHMQGC, Pohang, Korea, July 2018

Igor Strakovsky 46



World Neutral & Charged Pion PR Data

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

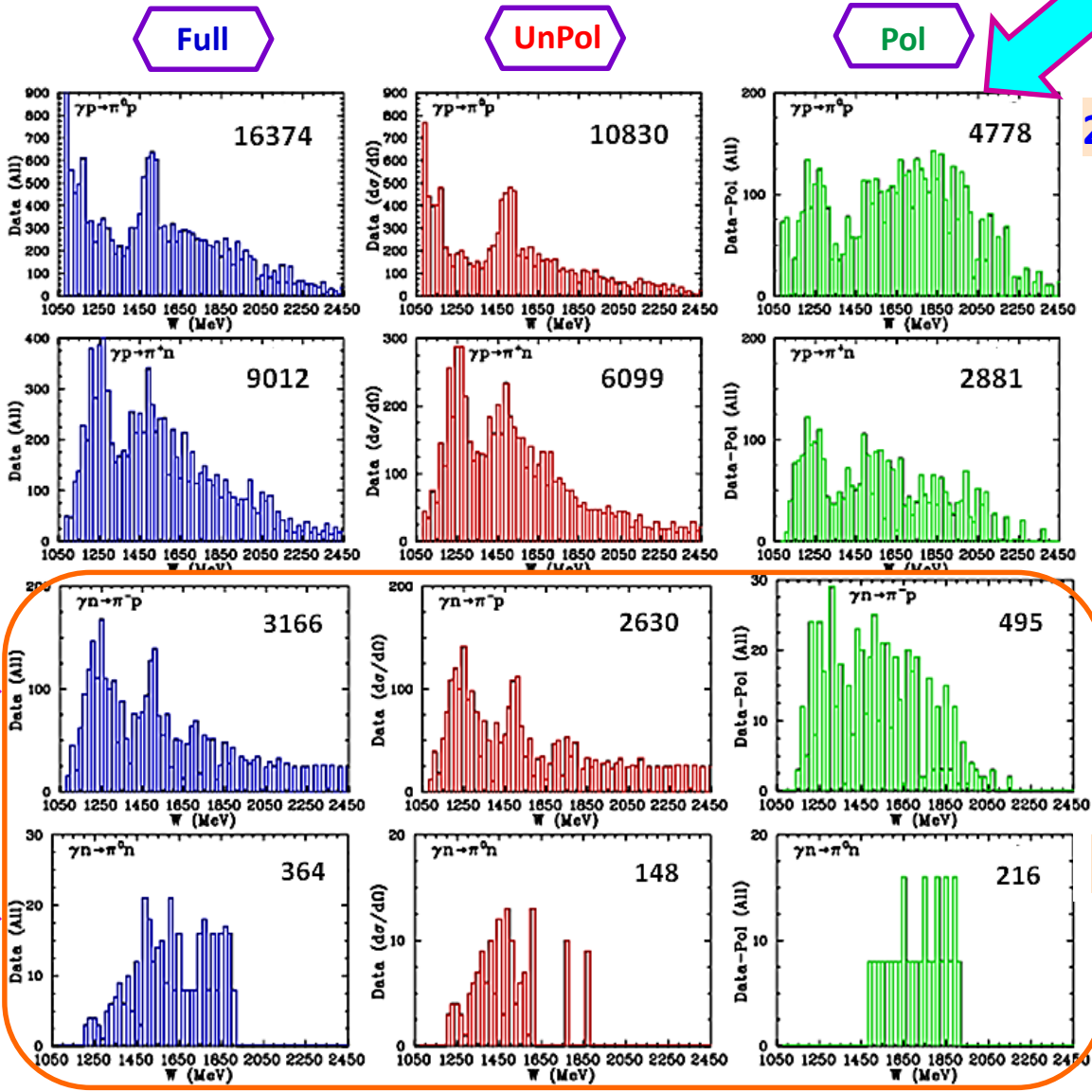
W < 2.5 GeV

$\gamma p \rightarrow \pi^0 p$

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

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

$\gamma n \rightarrow \pi^0 n$



2017

25858 — 19768 — 6090

9859 — 6078 — 3781

11856 — 11092 — 764

364 — 148 — 216

