GW Partial Wave Analyses: from Photo- to Electroproduction

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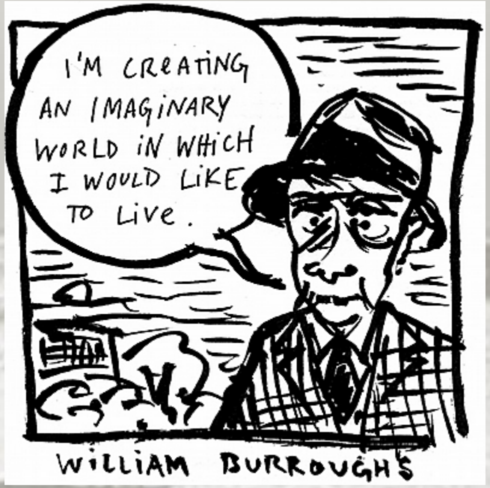
- Pion PhotoProduction for **Baryon Spectroscopy.**
- **Phenomenology** for Pion PhotoProduction.
- **SAID** for Pion PhotoProduction.
- **SAID:** Features & Benefits.
- **FSI** for $\gamma n \to \pi N$.
- **SAID** for Neutral Baryons.
- **SAID** for Pion ElectroProduction.
- **Summary**.

Supported by **DE-SC0016583**

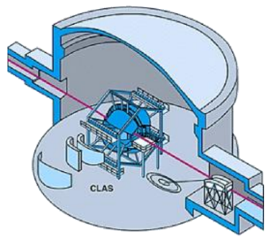
Pion PhotoProduction for Baryon Spectroscopy



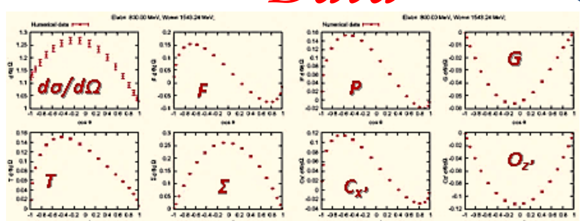
Road Map to Baryon Spectroscopy

Facility

Experiment

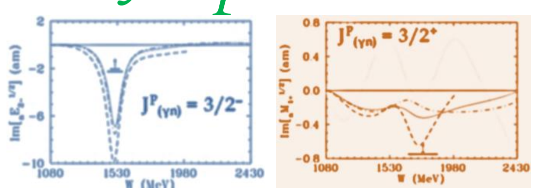


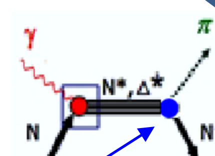
Data

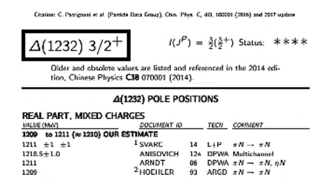


PWA

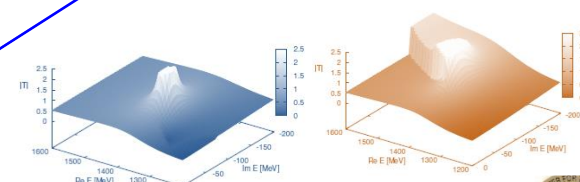
Amplitudes







Resonances



πN PWA input

Baryon Sector at PDG16

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

N Δ Σ Ξ Ω Λ

Particle	J^P	Status
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]**
$N(19$[illegible]$)$	$5/2^+$	[illegible]
$N(18$[illegible]$)$	$3/2^-$	[illegible]**
$N(1$[illegible]$)$	[illegible]$/2^+$	[illegible]**
$N($[illegible]$5)$	[illegible]	**
$N($[illegible]$00)$	[illegible]	***
$N($[illegible]$90)$	7[illegible]	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	**
$N(2100)$	$1/2^+$	*
$N(2120)$	$3/2^-$	**
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2600)$	$11/2^-$	***
$N(2700)$	$13/2^+$	**

Particle	J^P	Status
$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	***
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	**
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	[illegible]***
$\Delta(1920)$	$3/$[illegible]	[illegible]**
$\Delta(1930)$	[illegible]$/2^-$	[illegible]**
$\Delta(1940)$	$3/2^-$	[illegible]
$\Delta(1950)$	$7/2^+$	[illegible]**
$\Delta(20$[illegible]$0)$	$5/2^+$	
$\Delta(2150)$	$1/2^-$	[illegible]
$\Delta(2200)$	$7/2^-$	*
$\Delta(2300)$	$9/2^+$	**
$\Delta(2350)$	$5/2^-$	*
$\Delta(2390)$	$7/2^+$	*
$\Delta(2400)$	$9/2^-$	**
$\Delta(2420)$	$11/2^+$	****
$\Delta(2750)$	$13/2^-$	**
$\Delta(2950)$	$15/2^+$	**
Λ	$1/2^+$	****
$\Lambda(1405)$	$1/2^-$	****
$\Lambda(1520)$	$3/2^-$	****
$\Lambda(1600)$	$1/2^+$	***
$\Lambda(1670)$	$1/2^-$	****
$\Lambda(1690)$	$3/2^-$	****
$\Lambda(1800)$	$1/2^-$	[illegible]**
$\Lambda(1810)$	$1/2$[illegible]	[illegible]**
$\Lambda(1820)$	5[illegible]2^+	[illegible]***
$\Lambda(1830)$	[illegible]$/2^-$	[illegible]***
$\Lambda(1890)$	$3/2^+$	[illegible]**
$\Lambda(200$[illegible]$)$		[illegible]
$\Lambda($[illegible]$)$	$7/2^+$	[illegible]
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		**

Particle	J^P	Status
Σ^+	$1/2^+$	****
Σ^0	$1/2^+$	****
Σ^-	$1/2^+$	****
$\Sigma(1385)$	$3/2^+$	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	$3/2^-$	*
$\Sigma(1620)$	$1/2^-$	**
$\Sigma(1660)$	$1/2^+$	***
$\Sigma(1670)$	$3/2^-$	****
$\Sigma(1690)$		**
$\Sigma(1750)$	[illegible]	[illegible]
$\Sigma(1770)$	[illegible]2^+	*
$\Sigma(1775)$	[illegible]$^-$	****
$\Sigma(1840)$	3[illegible]$^+$	*
$\Sigma(1880)$	$1/2^+$	**
$\Sigma(191$[illegible]$)$	$5/2^+$	[illegible]***
$\Sigma($[illegible]$)$	[illegible]	***
$\Sigma(2000)$	$1/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	**
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

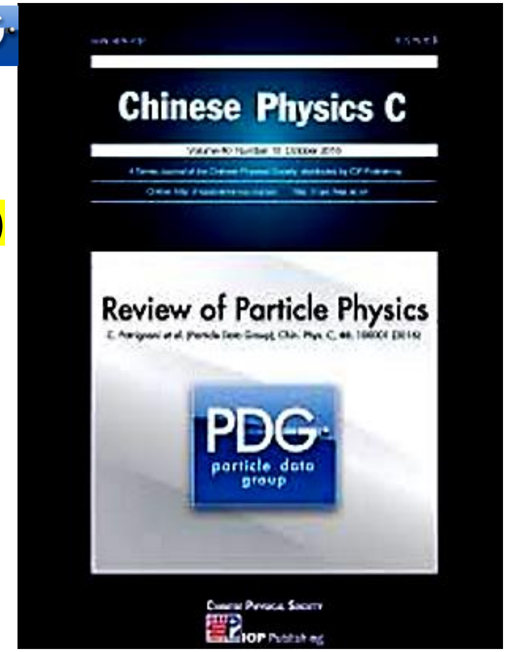
Particle	J^P	Status
Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(153$[illegible]$)$	[illegible]	[illegible]
$\Xi(162$[illegible]$)$		*
$\Xi(1690)$		***
$\Xi(182$[illegible]$)$	[illegible]	***
$\Xi(19$[illegible]$)$		***
$\Xi(2030)$	$\geq \frac{5}{2}?$	***
[illegible]		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	$3/2^+$	[illegible]
$\Omega($[illegible]$0)^-$		[illegible]
$\Omega($[illegible]$80)^-$		[illegible]
$\Omega($[illegible]$70)^-$		[illegible]

Particle	J^P	Status
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^-	$1/2^+$	***

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

- **Pole** position in complex energy plane for **hyperons** has been made only recently, **first of all** for **Λ(1520)3/2⁻**.

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



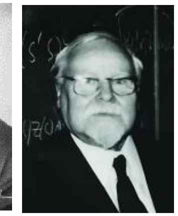
- **PDG16** has **109 Baryon Resonances** (**58** of them are **4*** & **3***).
- In case of **SU(6) X O(3)**, **434** states would be present if all revealed multiplets were fleshed out (**three 70** and **four 56**).

Phenomenology for Pion PhotoProduction

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 (Γ < 500 MeV) & possessing not too **small** BR (BR > 4%).
  ⇒ Tends (by construction) to **miss** narrow Res with Γ < 20 MeV.

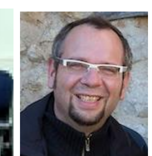
Most of our current knowledge about bound states of **three light quarks** has come mainly from **$\pi N \rightarrow \pi N$ PWAs**:

Karlsruhe–Helsinki,

Carnegie–Mellon–Berkeley,

& **GW**.


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

Direct Amplitude Reconstruction in Pion PhotoProduction

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

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**.

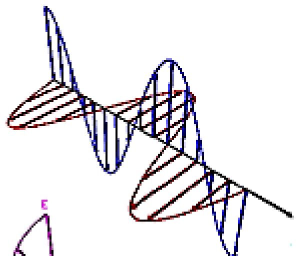
PHYSICAL REVIEW C VOLUME 54, NUMBER 3 SEPTEMBER 1996

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

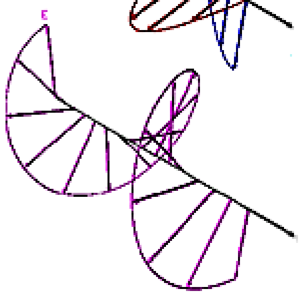
Greg Keaton and Ron Workman
Department of Physics, Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061
(Received 19 April 1996)

Complete Experiment for Pion PhotoProduction

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

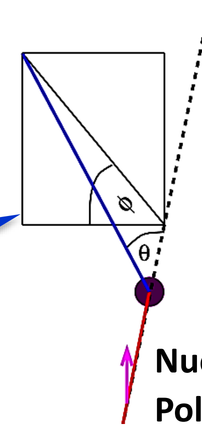


Linear Polarized *Beam*

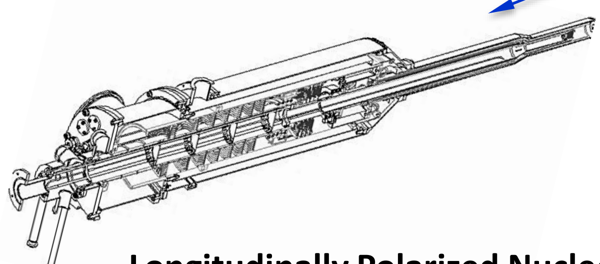


Circular Polarized *Beam*

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



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***

$$A_{\pi^0 p} = A^0 + \tfrac{1}{3} A^{1/2} + \tfrac{2}{3} A^{3/2} \qquad A_{\pi^0 n} = -A^0 + \tfrac{1}{3} A^{1/2} + \tfrac{2}{3} A^{3/2}$$

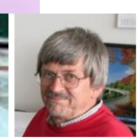
$$A_{\pi^+ n} = \sqrt{2}\left(A^0 + \tfrac{1}{3} A^{1/2} - \tfrac{1}{3} A^{3/2}\right) \qquad A_{\pi^- p} = \sqrt{2}\left(A^0 - \tfrac{1}{3} A^{1/2} + \tfrac{1}{3} A^{3/2}\right)$$

- **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)

Single Pion PhotoProduction on "Neutron" Target

- Accurate evaluation of **EM** couplings **N*→γN** & **Δ*→γN** 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**.

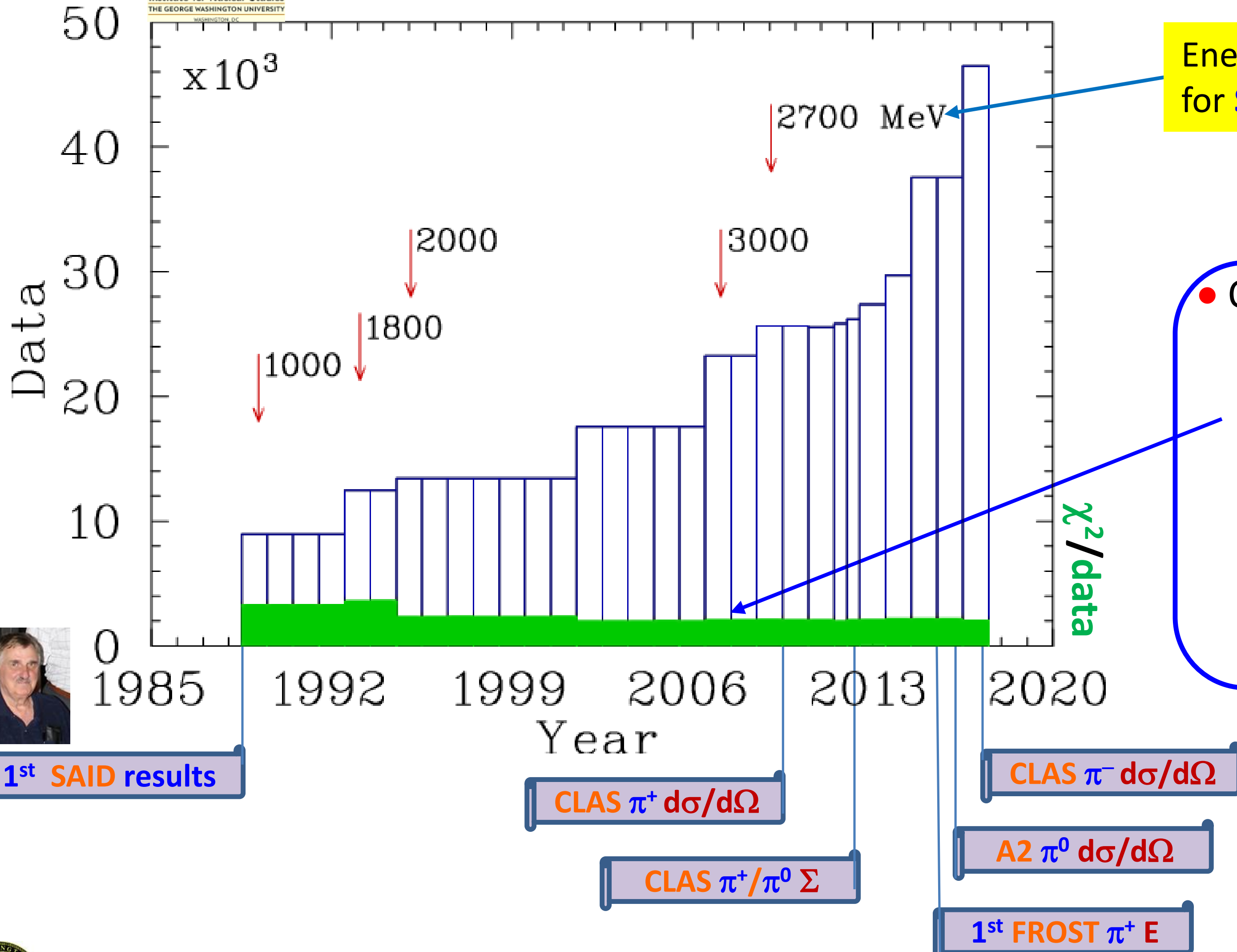
A.B. Migdal, JETP **1**, 2 (1955); K.M. Watson, Phys Rev **95**, 228 (1954)

SAID for Pion PhotoProduction

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

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

World Progress in Pion PhotoProduction



Energy limit for SAID PWA

- Overall, SAID χ^2 has remained stable (χ^2/data ~ 2) against growing database, which has increased by factor of 5 since 1989.

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] **πN-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
$\gamma p \to \pi^0 p$	25,540 (23 %)	55,529
$\gamma p \to \pi^+ n$	8,959 (38 %)	20,736
$\gamma n \to \pi^- p$	11,590 (4 %)	16,453
$\gamma n \to \pi^0 n$	364 (59 %)	1,540
Total	46,453	94,258

34,499 data

11,954 data

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

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

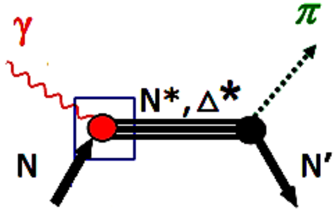


Photo-Decay Amplitudes in BW & Pole Forms

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

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

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

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	$A_{1/2}$	$A_{3/2}$
$\Delta(1232)\ 3/2^+$	(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	$+153\pm3$	(1515, 113)	38 [$-5°$]	-24 ± 3 [$-7°$]	$+157\pm6$ [$+10°$]
$N(1535)\ 1/2^-$	(1547, 188)	34	$+92\pm5$		(1502, 95)	16 [$-16°$]	$+77\pm5$ [$+4°$]	
$N(1650)\ 1/2^-$	(1635, 115)	58	$+35\pm5$		(1648, 80)	14 [$-69°$]	$+35\pm3$ [$-16°$]	

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

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

SAID Legacy

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

Minimization & Normalization Factor for PionProd

[χ^2/Data]

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

[systematics plays important role]

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

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

Karl Pearson

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

- If systematic uncertainty varies with angle
  ⇒ 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
$\gamma p \to \pi^0 p$	2.2	3.6	3.2	5.7	7.7	12.3
$\gamma p \to \pi^+ n$	1.9	3.3	2.1	3.9	8.1	11.7
$\gamma n \to \pi^- p$	1.8	2.6	1.8	2.5	2.9	3.8
$\gamma n \to \pi^0 n$	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)

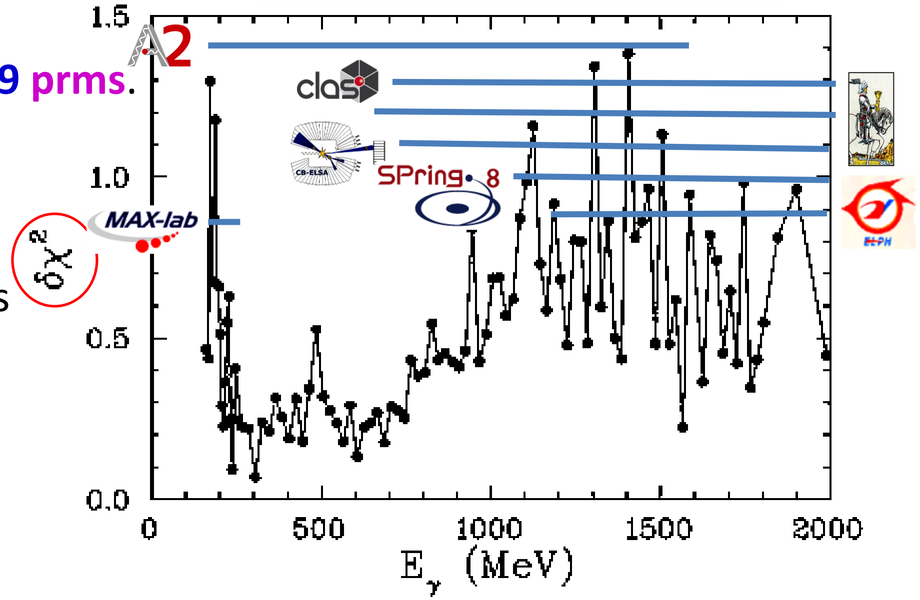
R.L. Workman, M.W. Paris, W.J. Briscoe, IS, Phys Rev C **86**, 015202 (2012)

- **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.

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

- **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**.

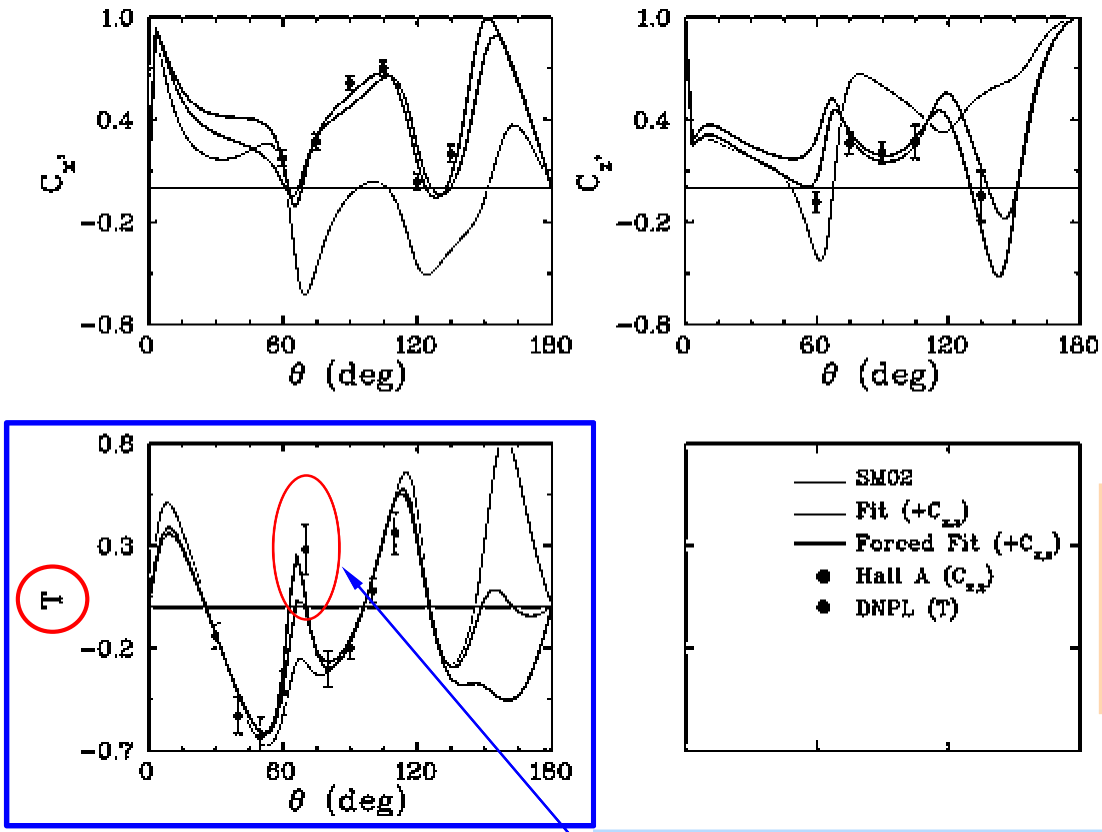


- **Diagonal Error Matrix** generated in **SES** fits.
  It can be used to estimate the overall uncertainties for **Global** solution.

Forced Fit for Measurements

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

- $\vec{\gamma} p \to \pi^0 \vec{p}$ 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.

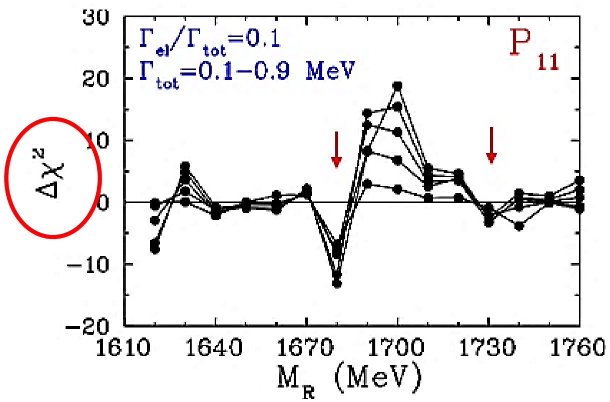
Narrow Resonances in [Modified] PWA

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.

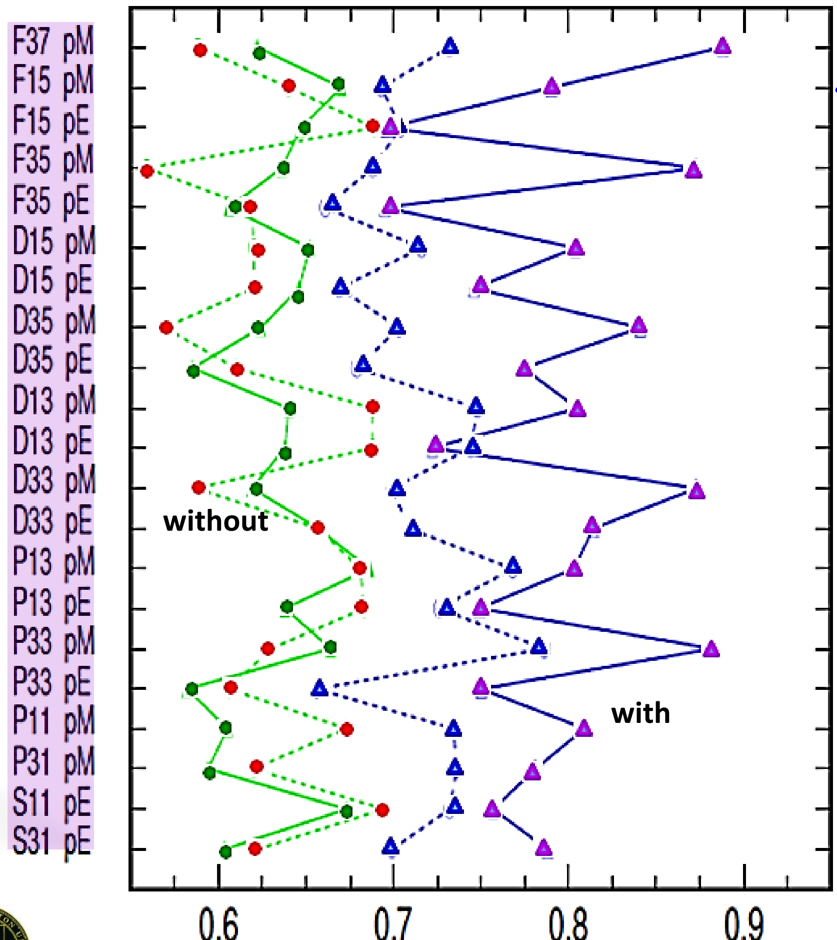
- While **non-Resonance** source may show similar effects in various PWs.

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**.



$\pi^+ n$ **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)

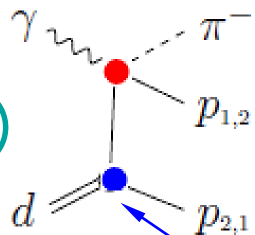
Previous *neutron* measurements used modified *Glauber* approach & procedure of unfolding *Fermi* motion of "*neutron*" target.

FSI for $\gamma d \to \pi p N$ ⟹ $\gamma n \to \pi N$

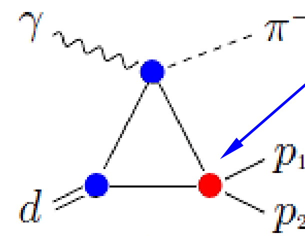
V. Tarasov, A. Kudryavtsev, W. Briscoe, H. Gao, IS, Phys Rev C **84,** 035203 (2011)
V. Tarasov, A. Kudryavtsev, W. Briscoe, B. Krusche, IS, M. Ostrick, Phys At Nucl **79**, 216 (2016)

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

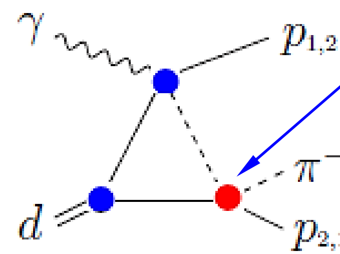

IA



Fermi Smearing



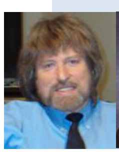
NN-fsi vertex



π**N**-fsi vertex

Input: **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).



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

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

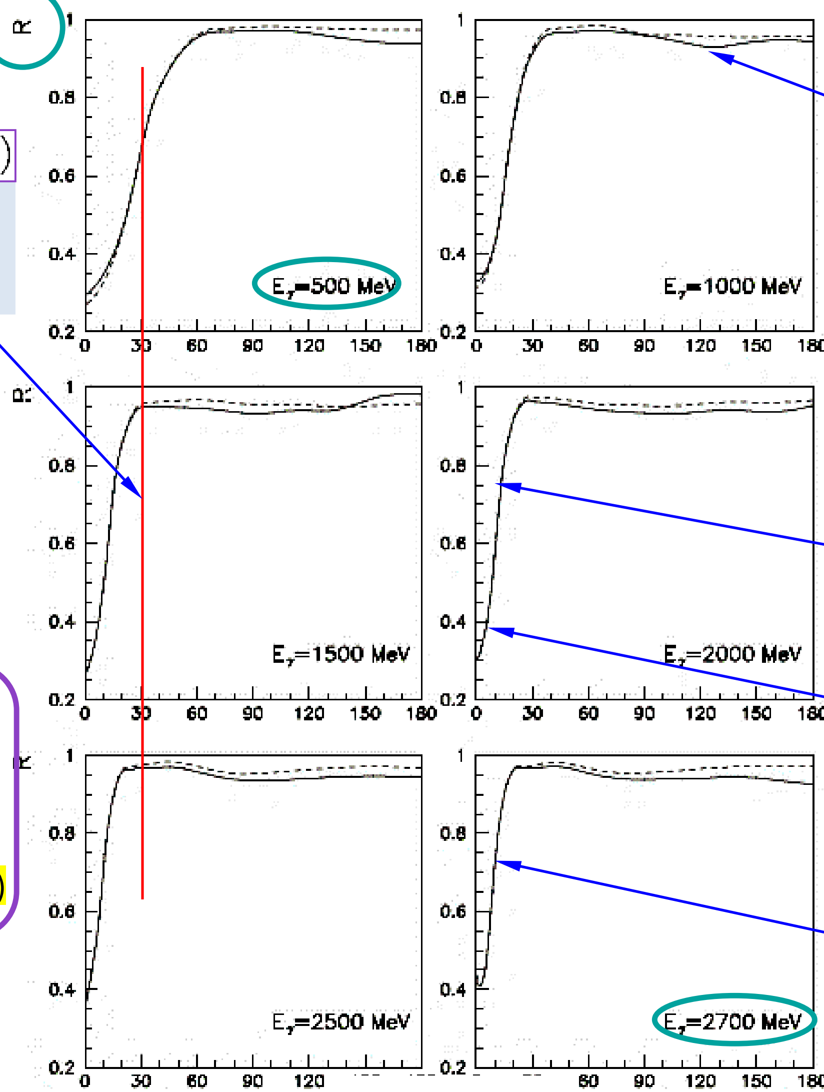
V. Tarasov, A. Kudryavtsev, W. Briscoe, H. Gao, IS, Phys Rev C **84**, 035203 (2011)

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

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

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

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

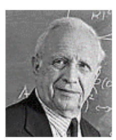


- For **CLAS** data:
  - **FSI** correction factor **R < 1**.
  - Behavior is **smooth** vs. **θ**.
  - **Effect**: **Δσ/σ ≤ 10%**.

- - [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**%.

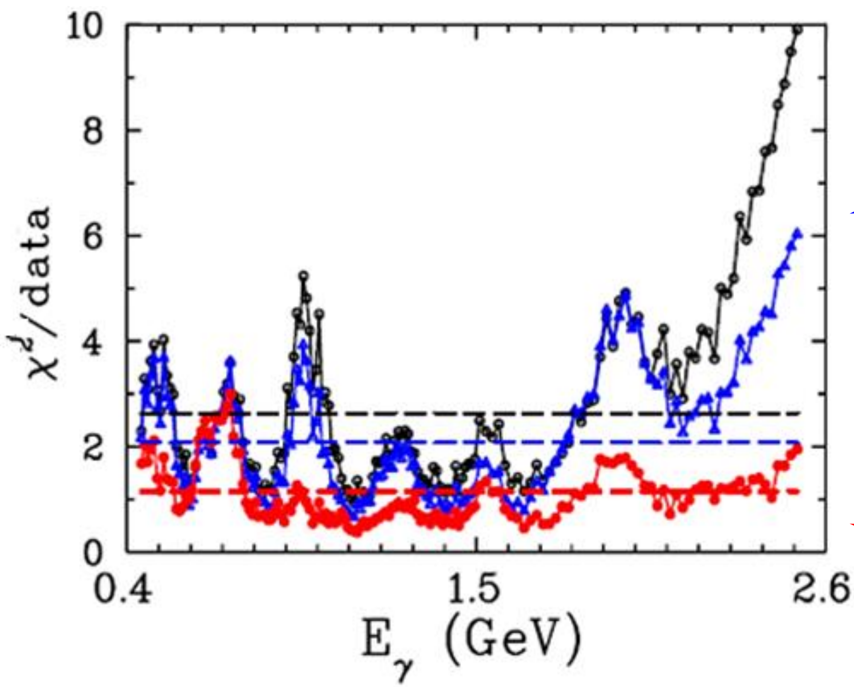


W. Chen *et al*, Phys Rev Lett **103**, 012301 (2009)

Forward direction is Terra incognita

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.

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

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

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

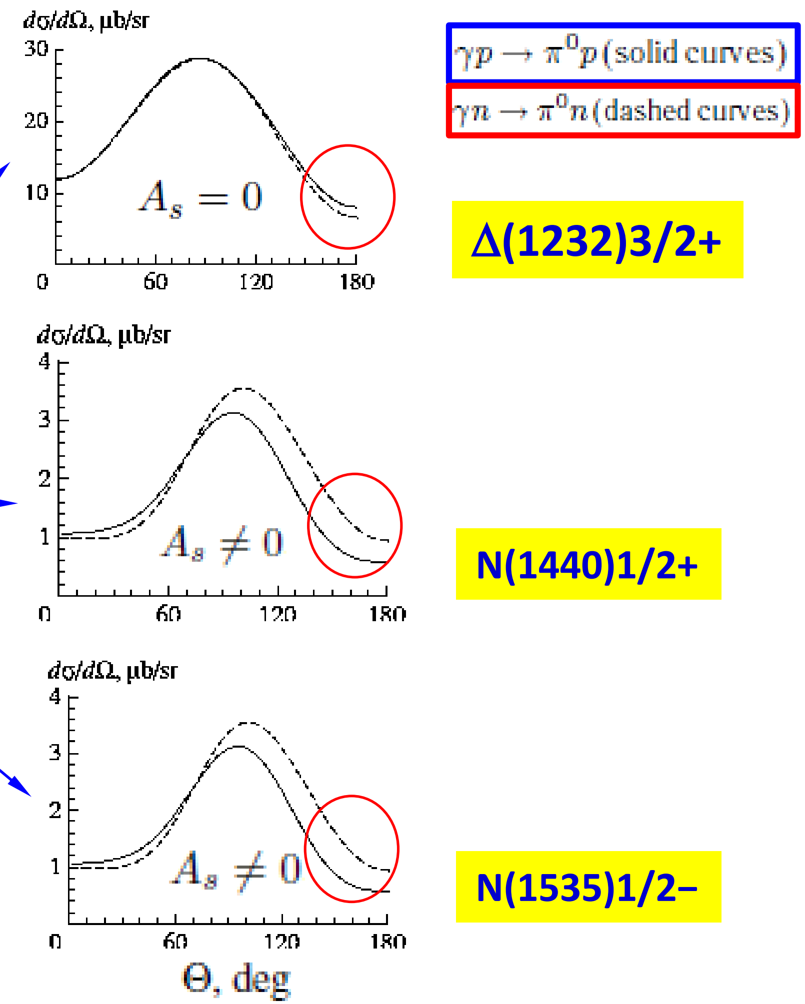
$$A(\gamma p \to \pi^0 p) = A_v + A_s$$
$$A(\gamma n \to \pi^0 n) = A_v - A_s$$

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

isoscalar *isovector*

$A_s = 0$ or $A_v = 0$

$R_n = R_p$



- In general case, $R_n \neq R_p$

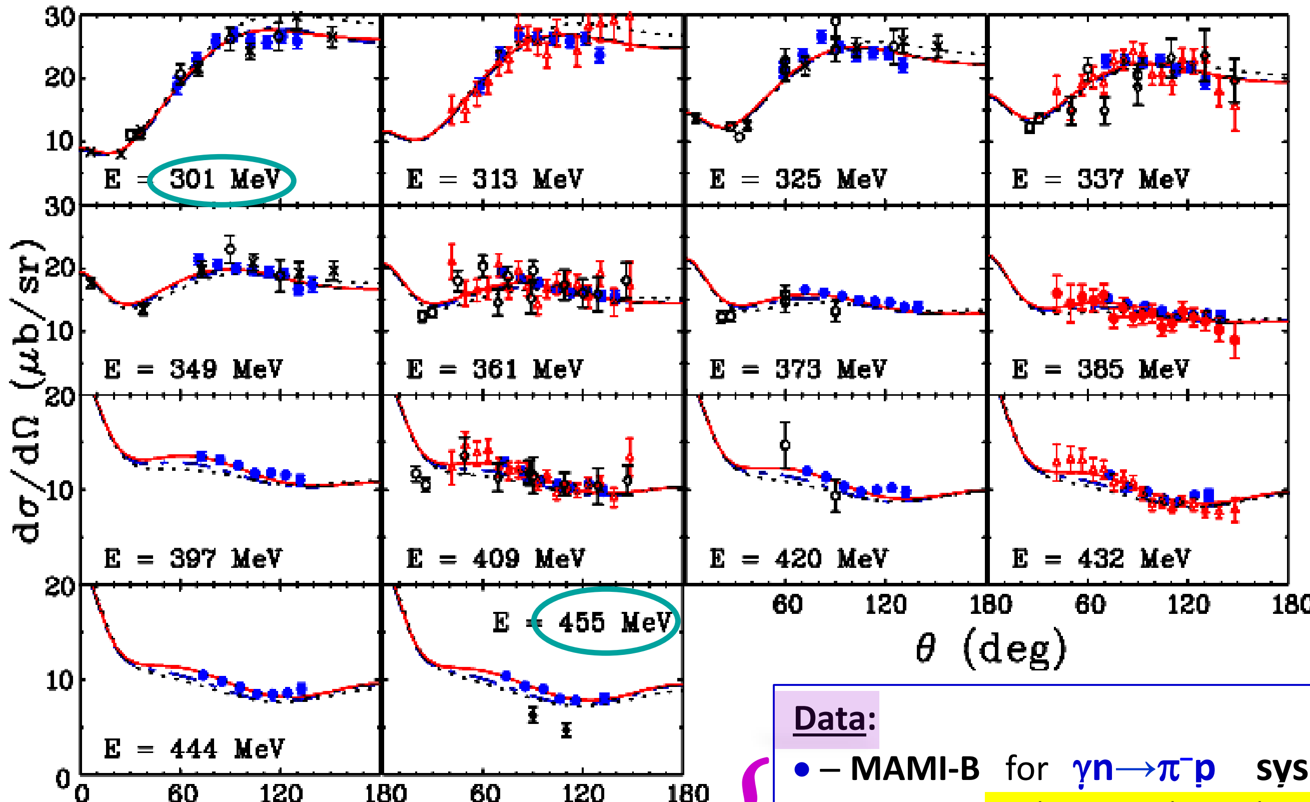
SAID for Neutral Baryon Spectroscopy: Differential Cross Section

FSI is essential

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

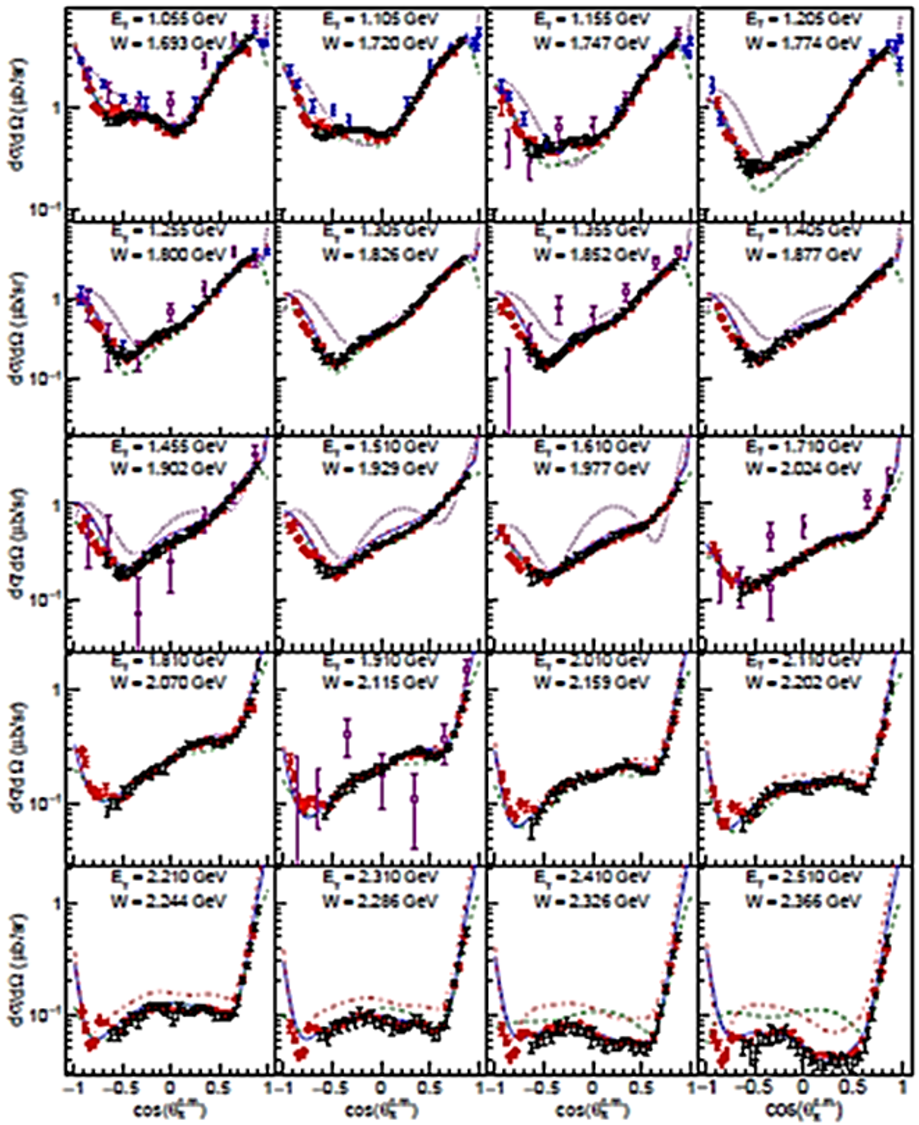
- *T-invariance is good as 2×10^{-3}*

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)



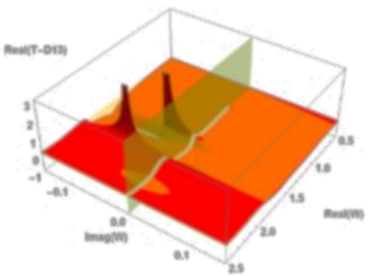
E = 445–2510 MeV
π^-p: 8428 **dσ/dΩ**

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

FSI included

CLAS g13 Impact for Neutron
$S = 0$ & $I = ½$ Couplings

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



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

[g13]

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

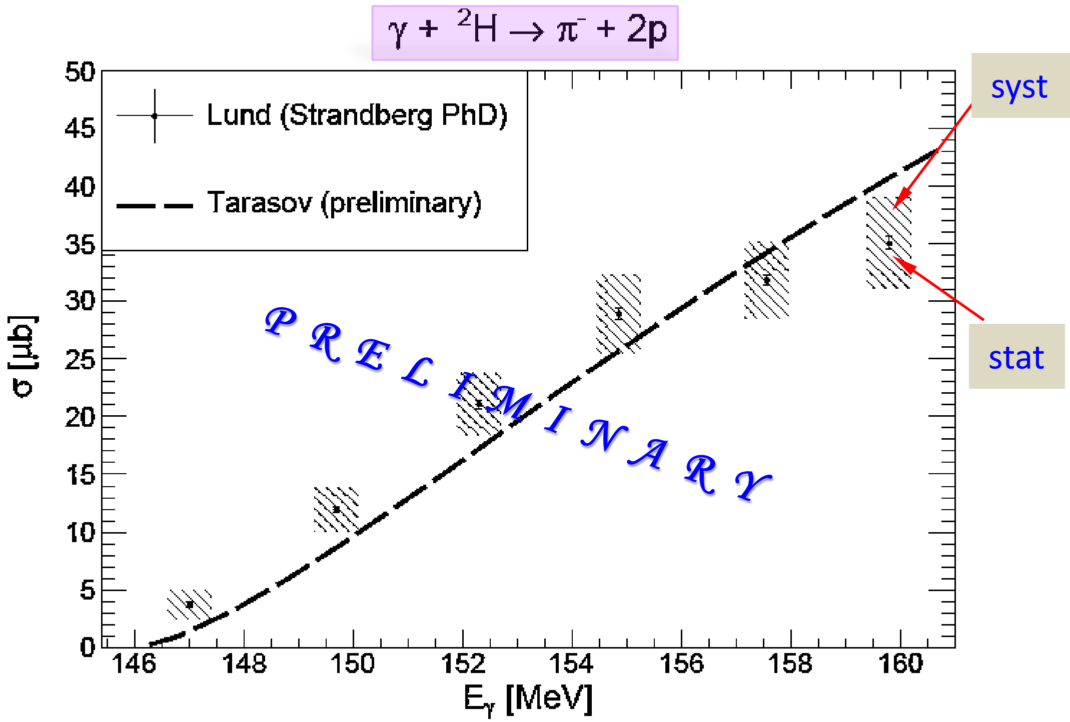
GW INS — Data Analysis Center — Institute for Nuclear Studies THE GEORGE WASHINGTON UNIVERSITY WASHINGTON, DC

HISKP MAID PDG particle data group

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

B. Strandberg *et al*, in progress

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



Courtesy of Bruno Strandberg, 2017

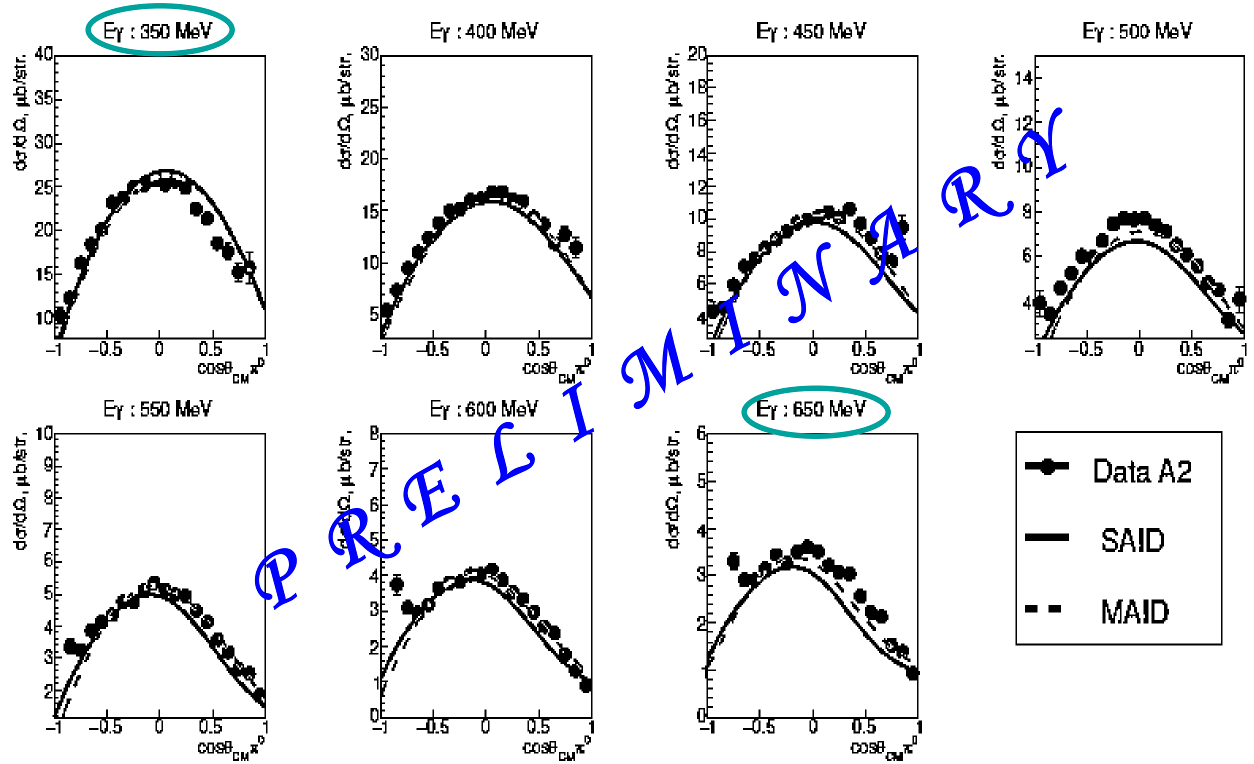
- Charged pion PhotoProd at **threshold** is well described by **Kroll-Ruderman** term which is non-vanishing in chiral limit.

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

A2 Meson Production off Deuteron at CB@MAMI

V. Kulikov *et al*, in progress

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



E = 180 – 800 MeV
π^0n: 589 dσ/dΩ

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

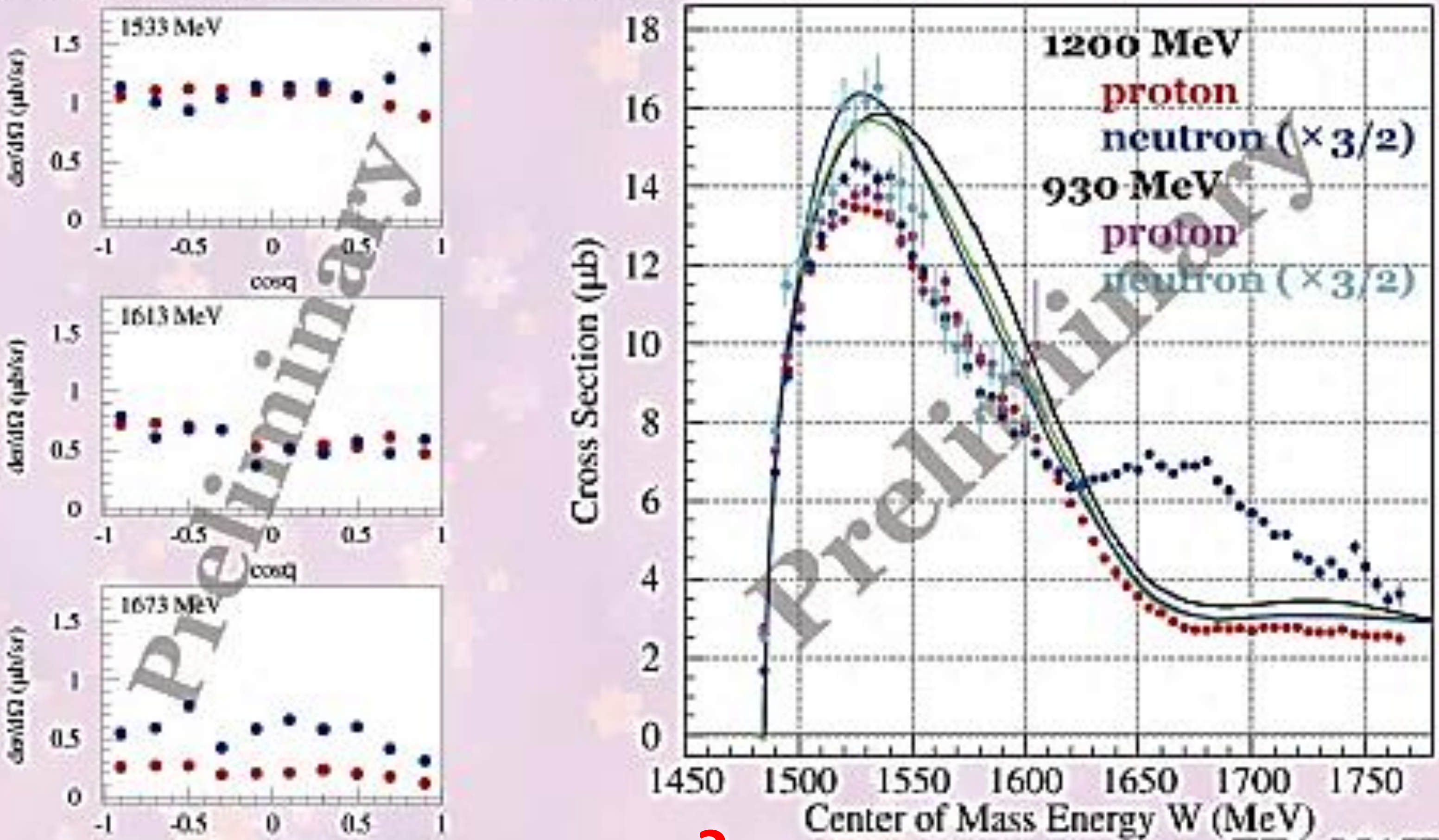
FSI included

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

Courtesy of Slava Kulikov, 2017

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

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



proton

neutron (×3/2) ?

No FSI included

ETA-MAID2003

SAID GW2009

BoGa 2011-2

Courtesy of Takatsugu Ishikawa, 2017

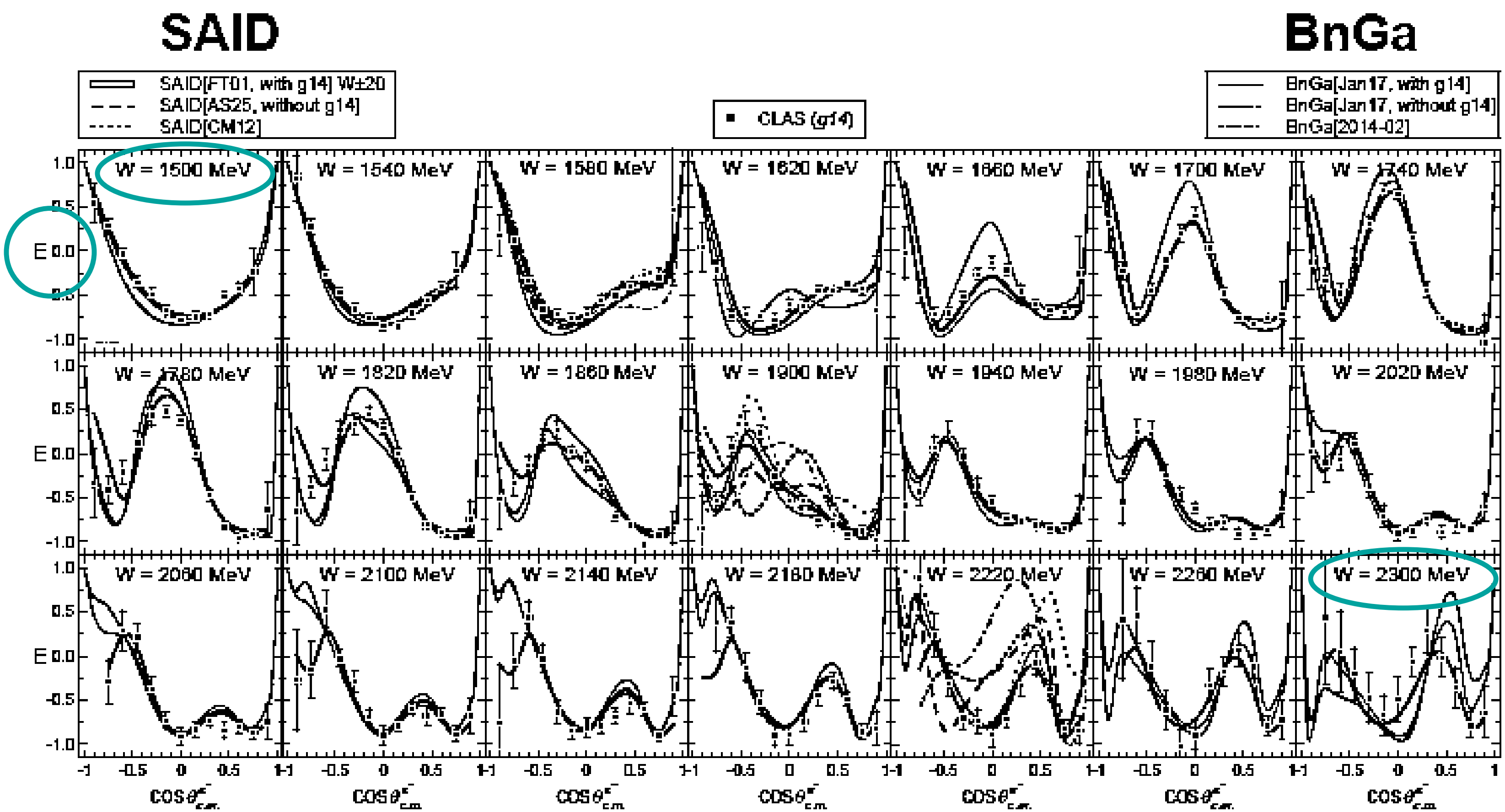
T. Ishikawa, 2017.04.20, η photoproduction on the deuteron at E_γ<1.2 GeV 20

SAID for Neutral Baryon Spectroscopy: Polarized Measurements

Assumption is FSI is small

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

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



E = 730–2345 MeV
π^-p: 266 E

No FSI included

CLAS g14 Impact for Neutron $S = 0$ & $I = ½$ Couplings

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

BW	$A_n^{1/2}$	(10^{-3} GeV$^{-1/2}$)	$A_n^{3/2}$	(10^{-3} GeV$^{-1/2}$)
	g14 PRL	previous	g14 PRL	previous
SAID				
N(1720)3/2⁺	**-9 ±2**	-21 ±4	**+19 ± 2**	-38 ±7
N(2190)7/2⁻	**-6 ±9**	---	**-28 ±10**	---
BnGa				
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 ⟺ 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.

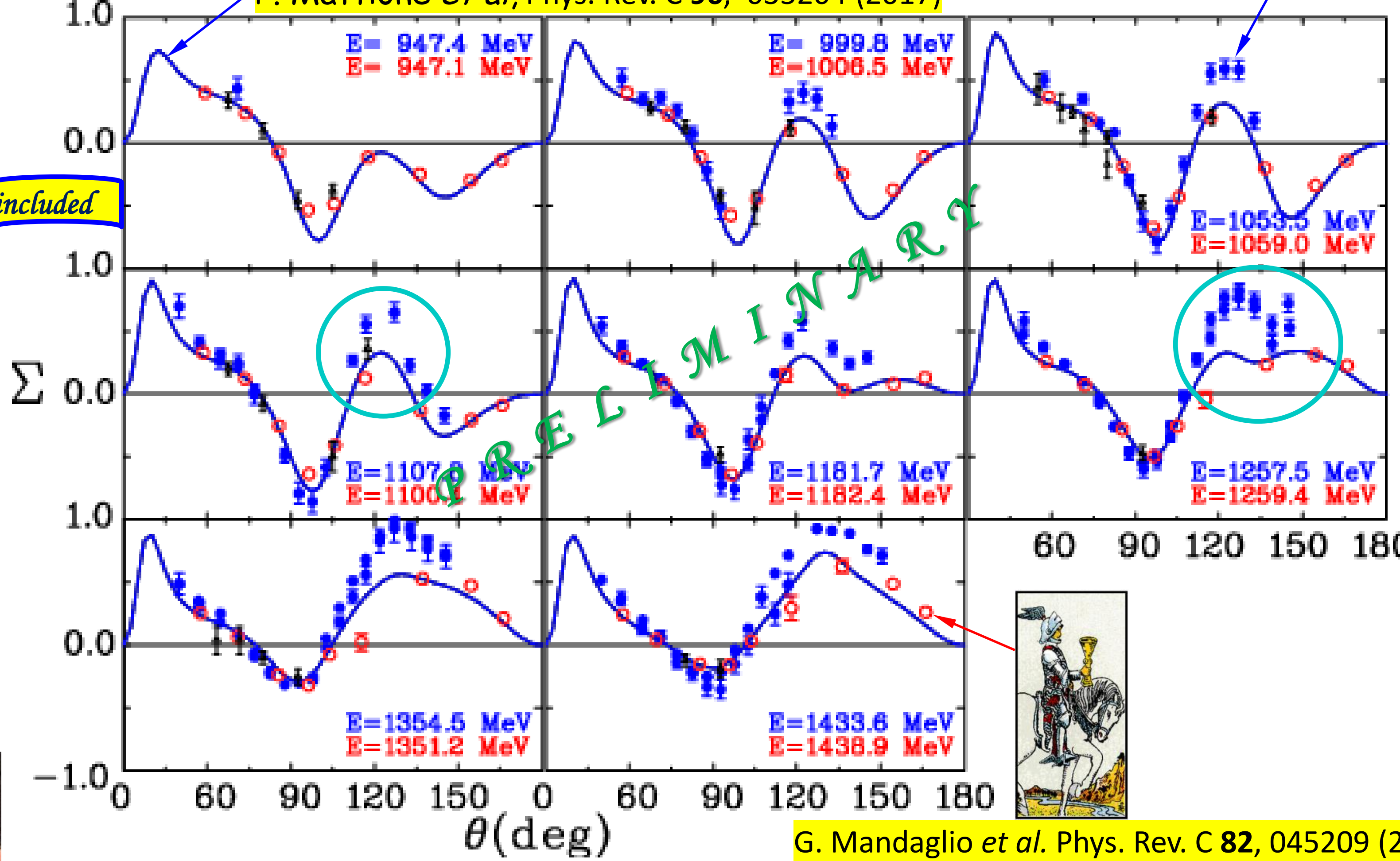
- Such couplings are sensitive to **dynamical** process of **N^*** excitation & provide important guides to nucleon structure models.

Courtesy of Andy Sandorfi, 2017

Σ for $\vec{\gamma} n \to \pi^- p$

D. Sokhan *et al*, in progress

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



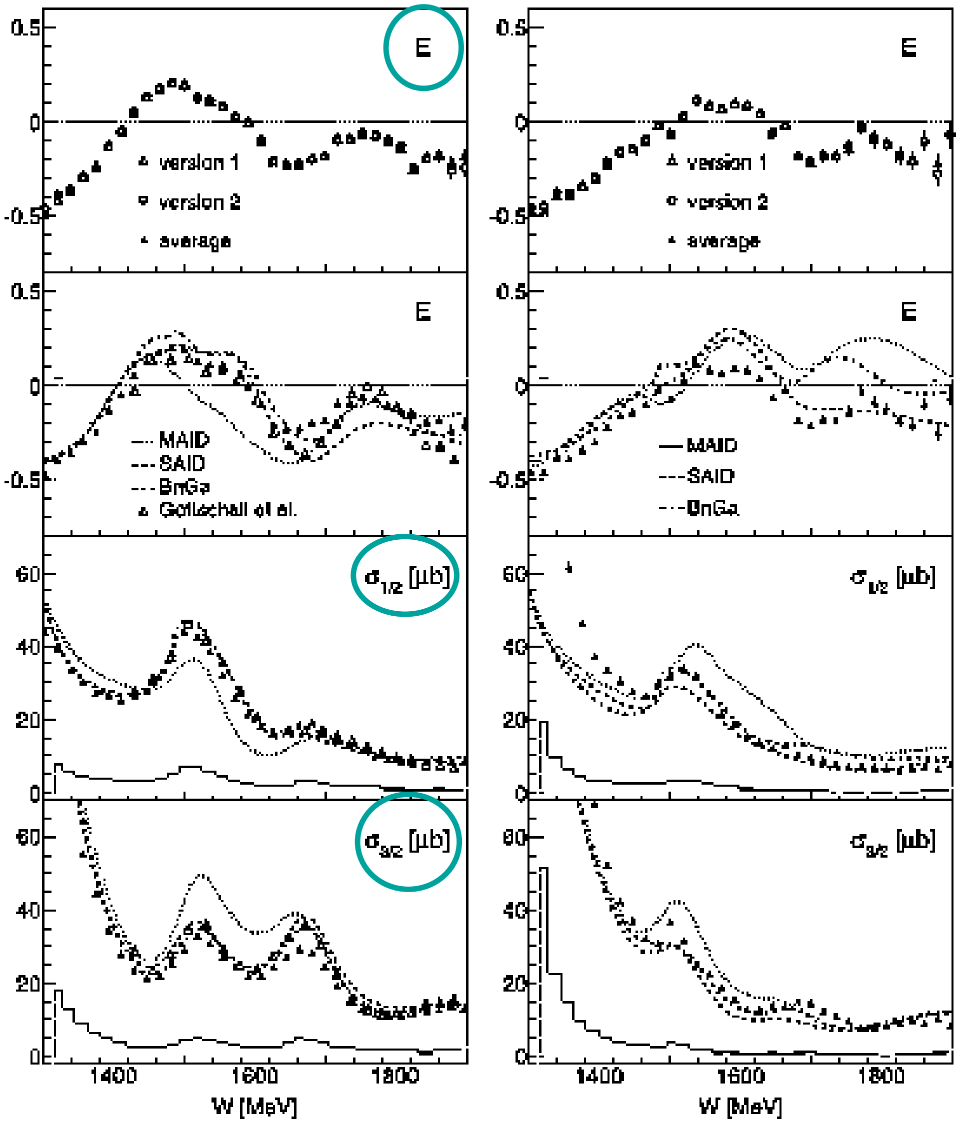
G. Mandaglio *et al.* Phys. Rev. C **82**, 045209 (2010)

Courtesy of Daria Sokhan, 2018

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

N(1680)5/2$^+$→Nγ

p$A^{3/2}$=+133 ±12 p$A^{1/2}$=−15 ±6

n$A^{3/2}$=−33 ±9 n$A^{1/2}$=+29 ±10

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

N(1675)5/2$^-$→Nγ

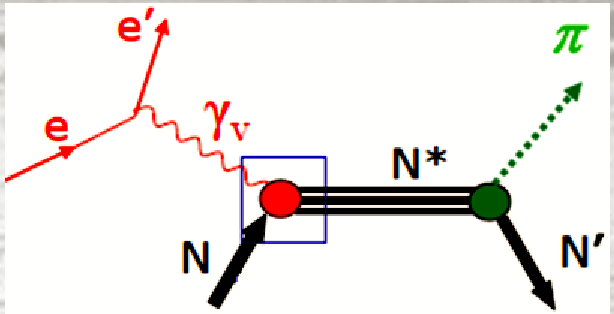
p$A^{3/2}$=+20 ±5 p$A^{1/2}$=+19 ±8

n$A^{3/2}$=−85 ±10 n$A^{1/2}$=−60 ±5

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

No FSI included

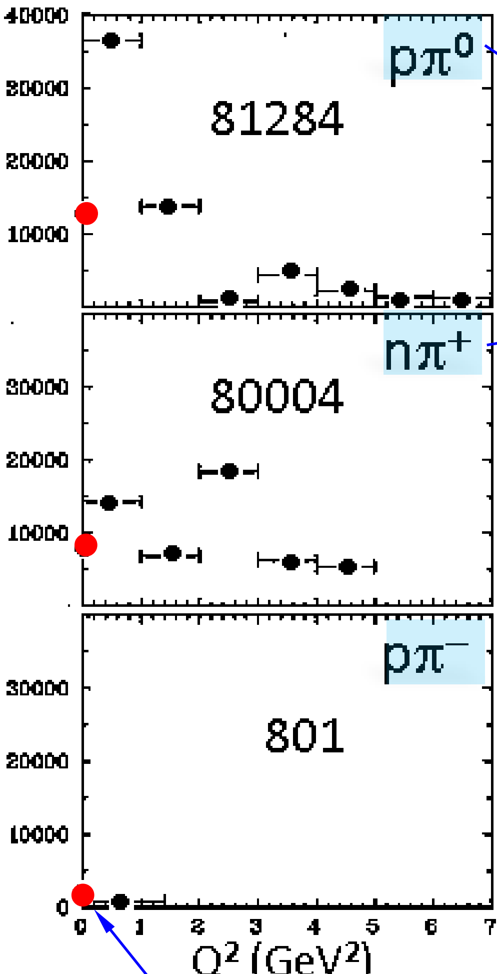
SAID for Neutral Baryon Spectroscopy: Pion ElectroProduction



World Neutral & Charged PionEPR Data

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

W < 2 GeV @ 2009

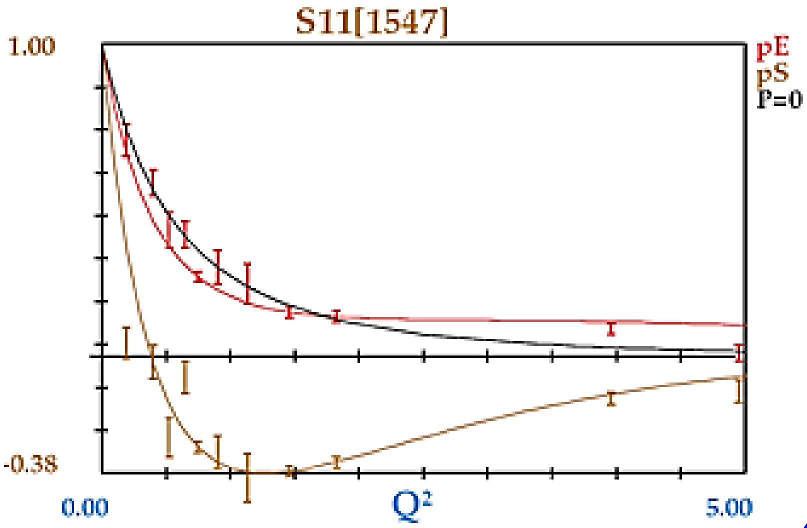


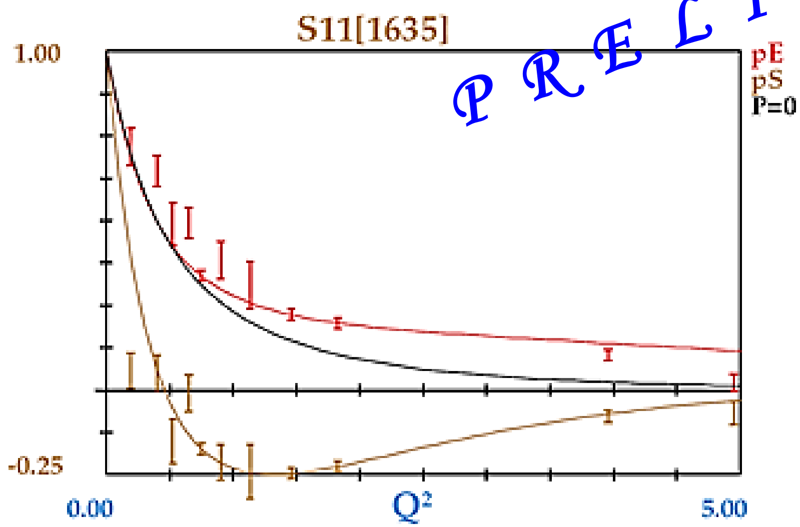
- **85**% of them are clas data

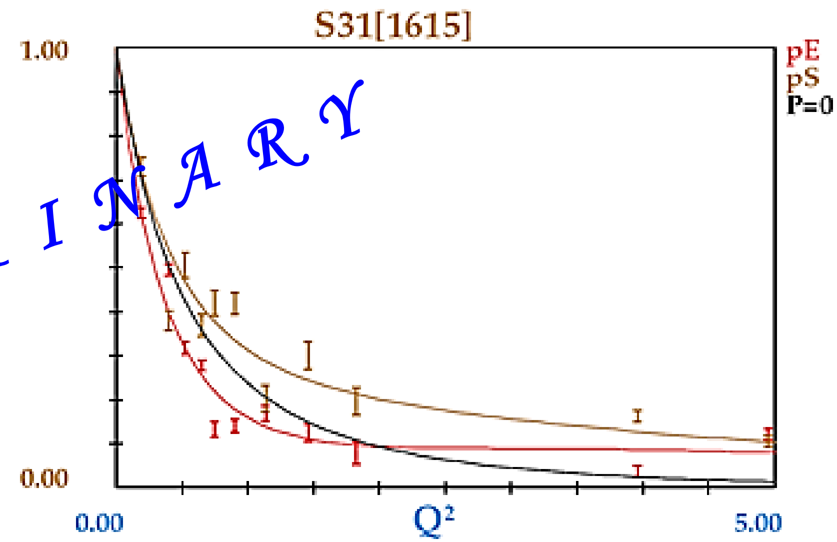
reaction	data	χ^2
$\gamma^* p \to \pi^0 p$	55,766	81,284
$\gamma^* p \to \pi^+ n$	51,312	80,004
redundant	14,772	17,375
total	124,453	178,663
$\gamma p \to \pi N$	24,888	50,684
all photo	159,341	229,317
$\pi N \to \pi N$	31,876	57,255
all πN	191,217	286,572

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

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

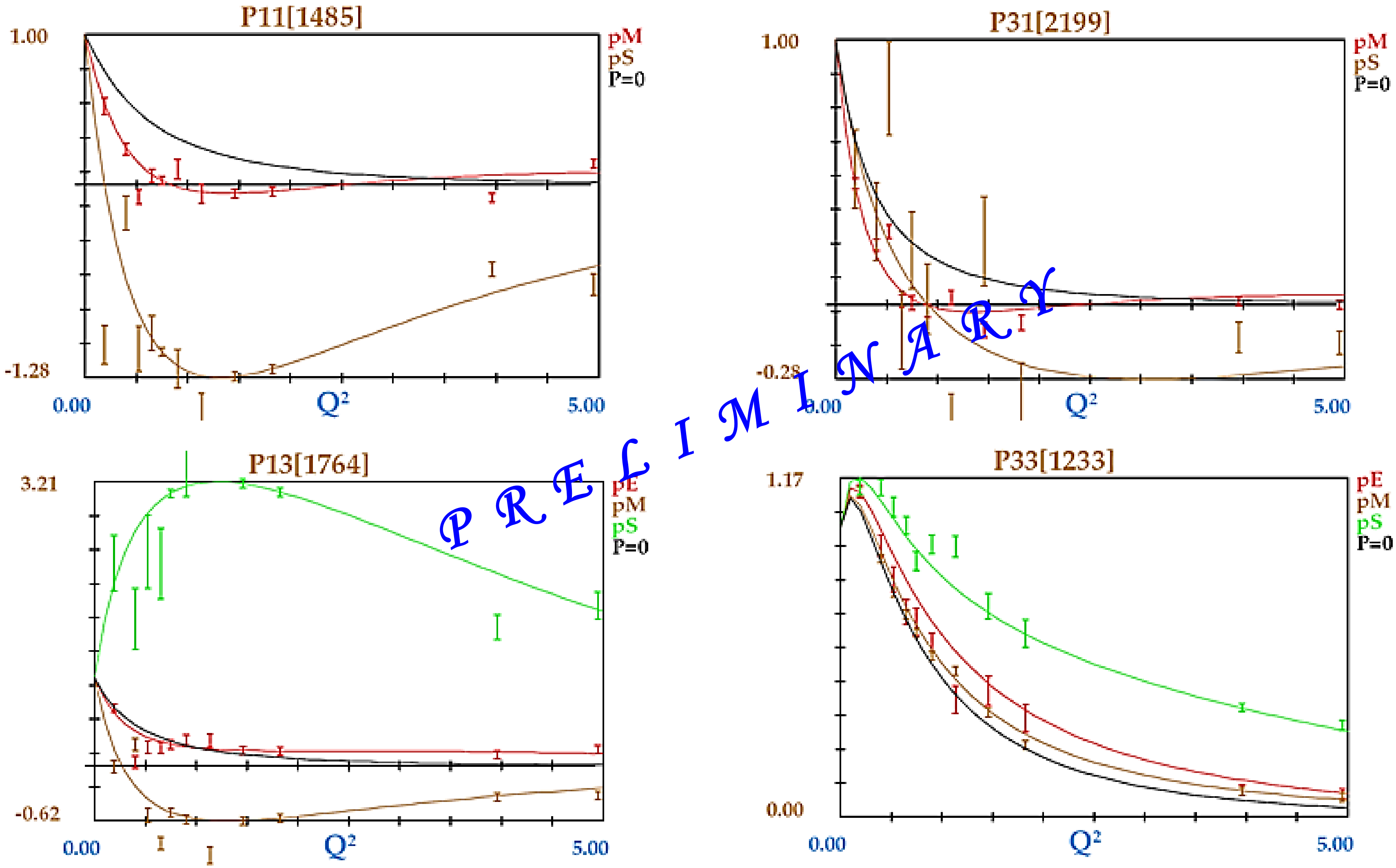




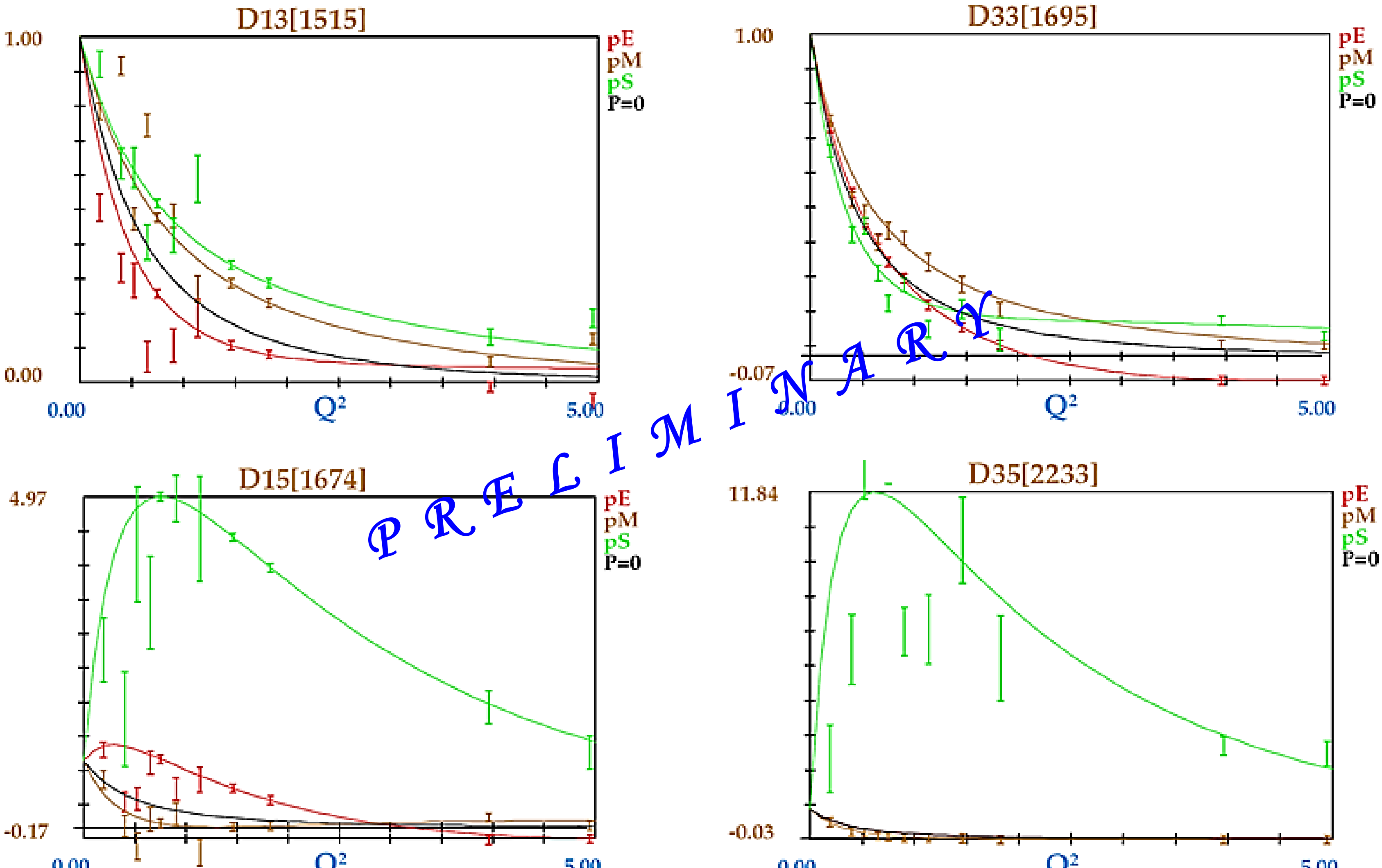


P R E L I M I N A R Y

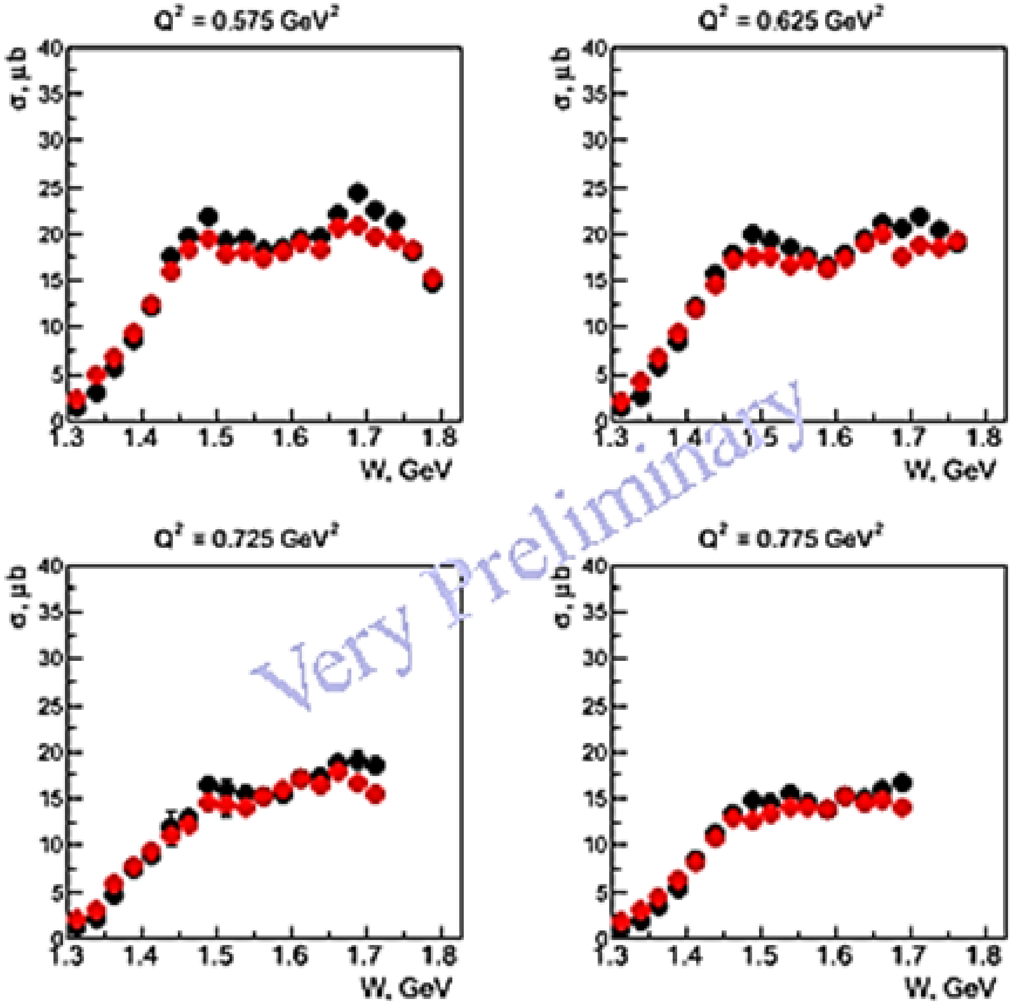
P_{11} & P_{13} & P_{11} & P_{33} [Q^2]

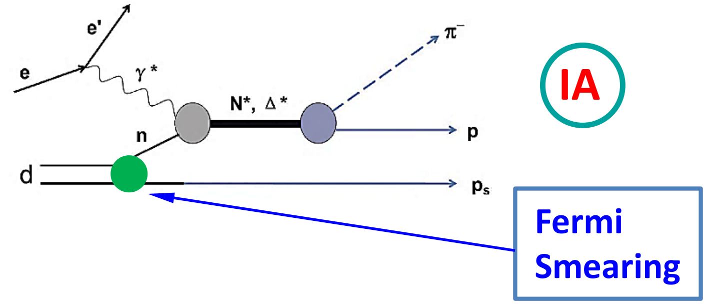


$\mathcal{D}_{13}$ & $\mathcal{D}_{15}$ & $\mathcal{D}_{33}$ & $\mathcal{D}_{35}$ [Q^2]



Unfolding Fermi Smearing via Event Generator





Black bullets – integrated cross section with Fermi correction

Red bullets – integrated cross Section without Fermi correction

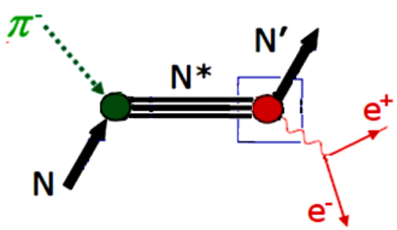
π missing topology

Courtesy of Ralf Gothe, 2017

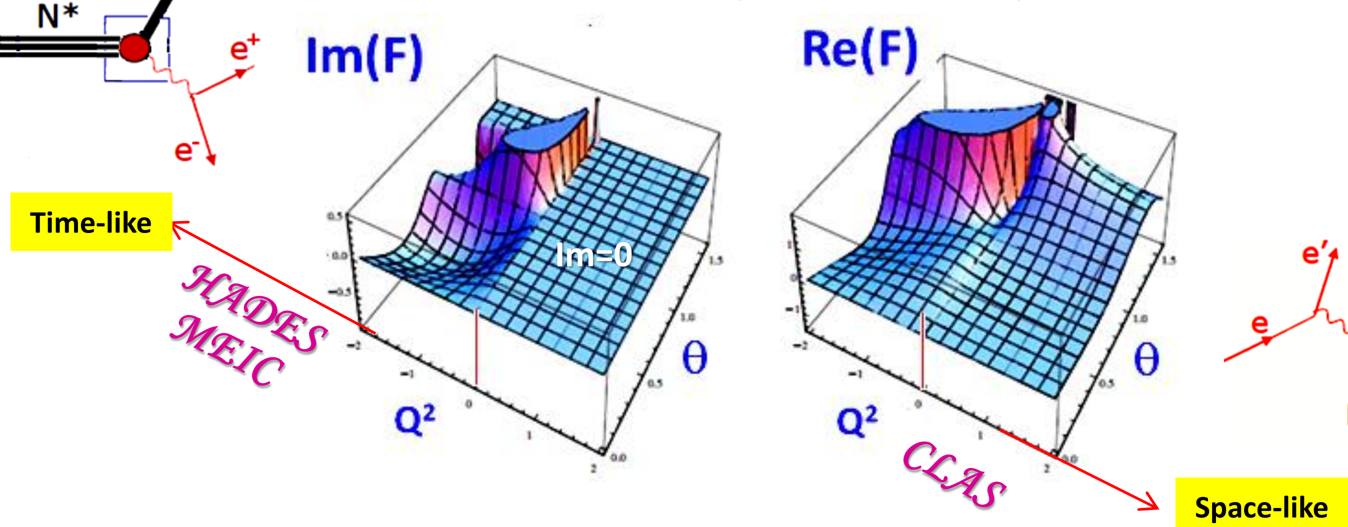
Form-Factor Measurements

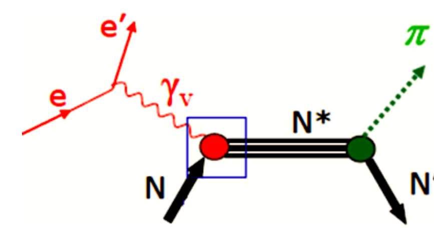
- ***Inverse Pion Electroproducion*** *is only process which allows determination of* ***EM nucleon*** *&* ***pion form factors*** *in intervals:*

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



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





- $\pi^- p \to e^+ e^- n$ measurements will significantly complement current **electroproduction.**
- $\gamma^* N \to \pi N$ 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 $\gamma p \to \pi^0 p$) & is compatible with $\pi N \to \pi N$ 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 **30^0** in CM. It is compatible with **Radiation** correction for **pion** ElectroProduction (**~30%**).

- We may assume that **FS**I corrections for **pion polarized** measurements are **small**.

- Now we are able to extract **pole** positions on complex energy plane for both $N^* \to \gamma p$ & $N^* \to \gamma n$ photo-decay amplitudes.

- Evaluation of Q^2 dependency of $\gamma^* N$ couplings is **new task** –**stay tuned**.

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Thank you for the invitation

and your attention

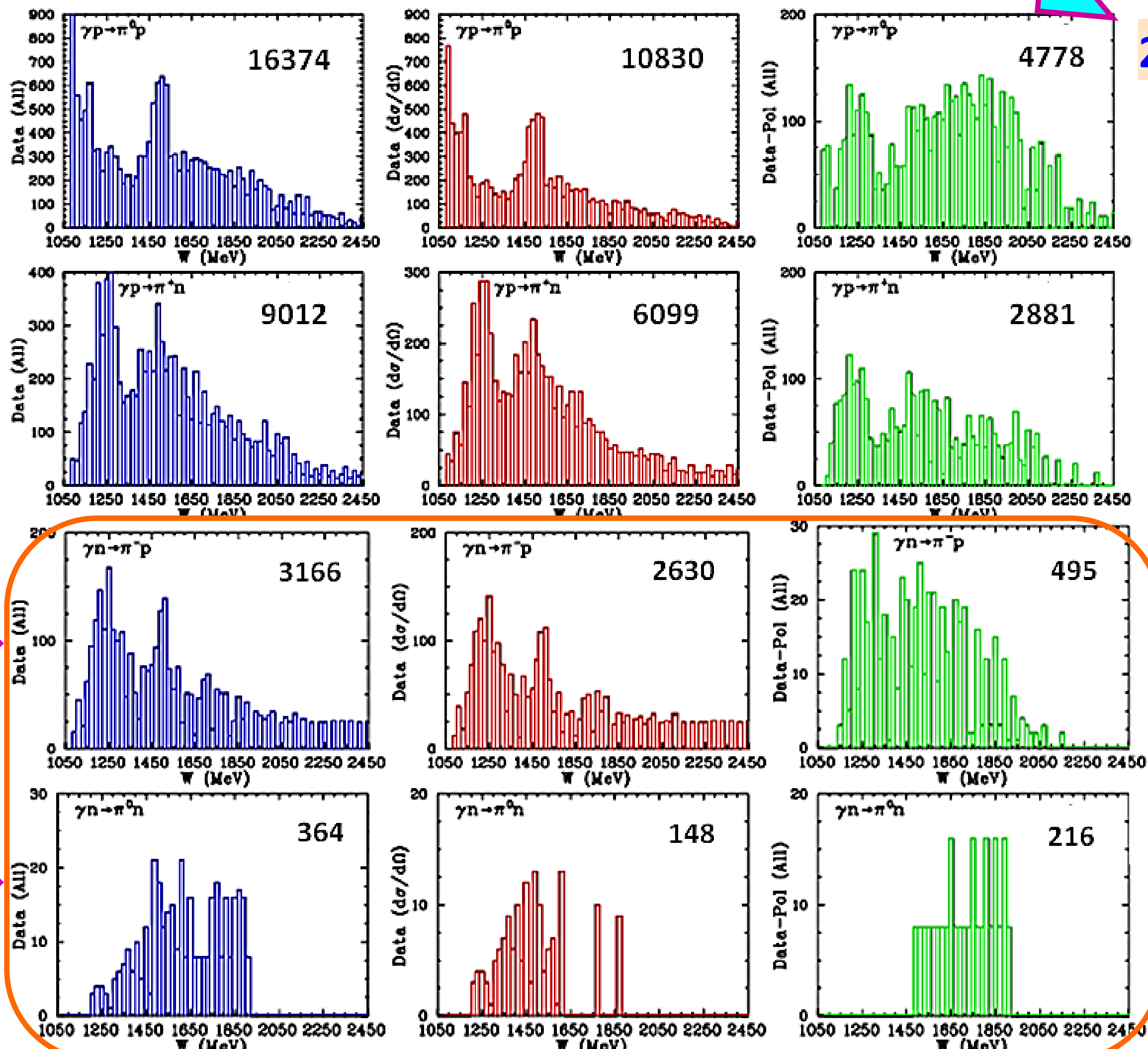
World Neutral & Charged PionPR Data

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

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

W < 2.5 GeV

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



Reaction	Full	UnPol	Pol
$\gamma p \to \pi^0 p$	25858	19768	6090
$\gamma p \to \pi^+ n$	9859	6078	3781
$\gamma n \to \pi^- p$	11856	11092	764
$\gamma n \to \pi^0 n$	364	148	216