SAID for Baryon Spectroscopy

William Briscoe
The George Washington University

- PWA for Baryon Spectroscopy
- Pion Photoproduction.
- Pion Photoproduction on Neutron.
- Pion-Proton Elastic.
- Nucleon-Nucleon Elastic.
- Strange Hadron Spectroscopy.
- Summary.

Supported by DE-SC0016583

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**
  $\Rightarrow$ Reveals only **wide** Resonances, but not too wide (Γ < 500 MeV)
  & possessing not too **small** BR (BR > 4%).
  $\Rightarrow$ 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,

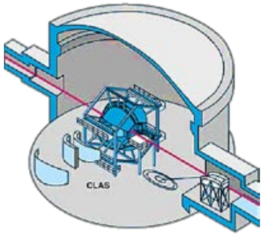
& **GW.**

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

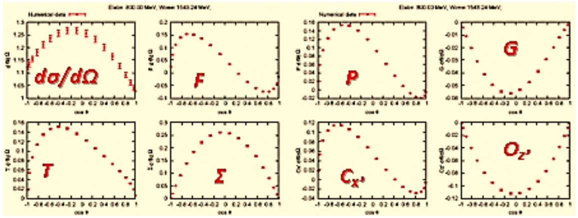
Road Map to Baryon Spectroscopy

Facility

Experiment

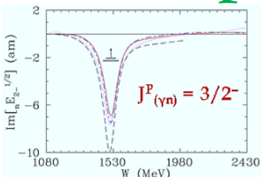


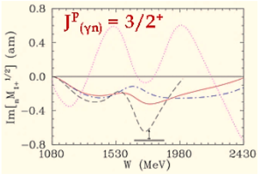
Data

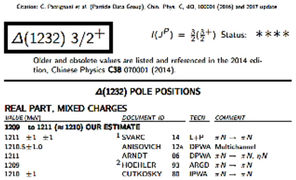


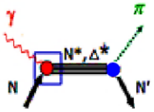
PWA

Amplitudes

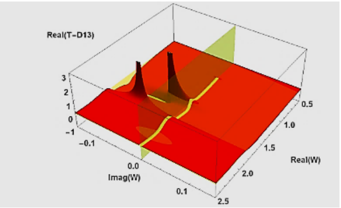








Resonances



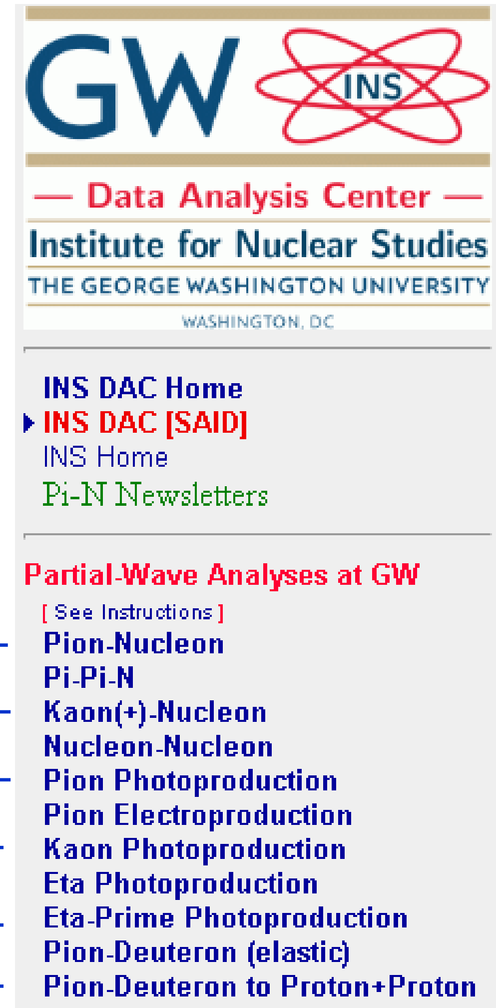
SAID Database below 4 GeV

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

- We update **SAID** databases, develop & study PWAs, & keep current versions of phenomenological & theoretical models, both those of CNS/DAC & other research groups, on continual basis for relevant two- & three-body reactions of interest.

- In the **full database**, one will occasionally find experiments which give conflicting results.
- **Some data** with very large χ^2 contributions have been excluded from our fits.
- **Redundant data** are also excluded [these include σ_{tot} based on $d\sigma/d\Omega$ already contained in database]
- Measurements of **pol observables** (**P**, for instance) with uncertainties more than 0.2 are not included as they have little influence in our fits.

- However, all available data have been **retained** in database (excluded data labeled as "*flagged*") so that comparisons can be made through our on-line facility



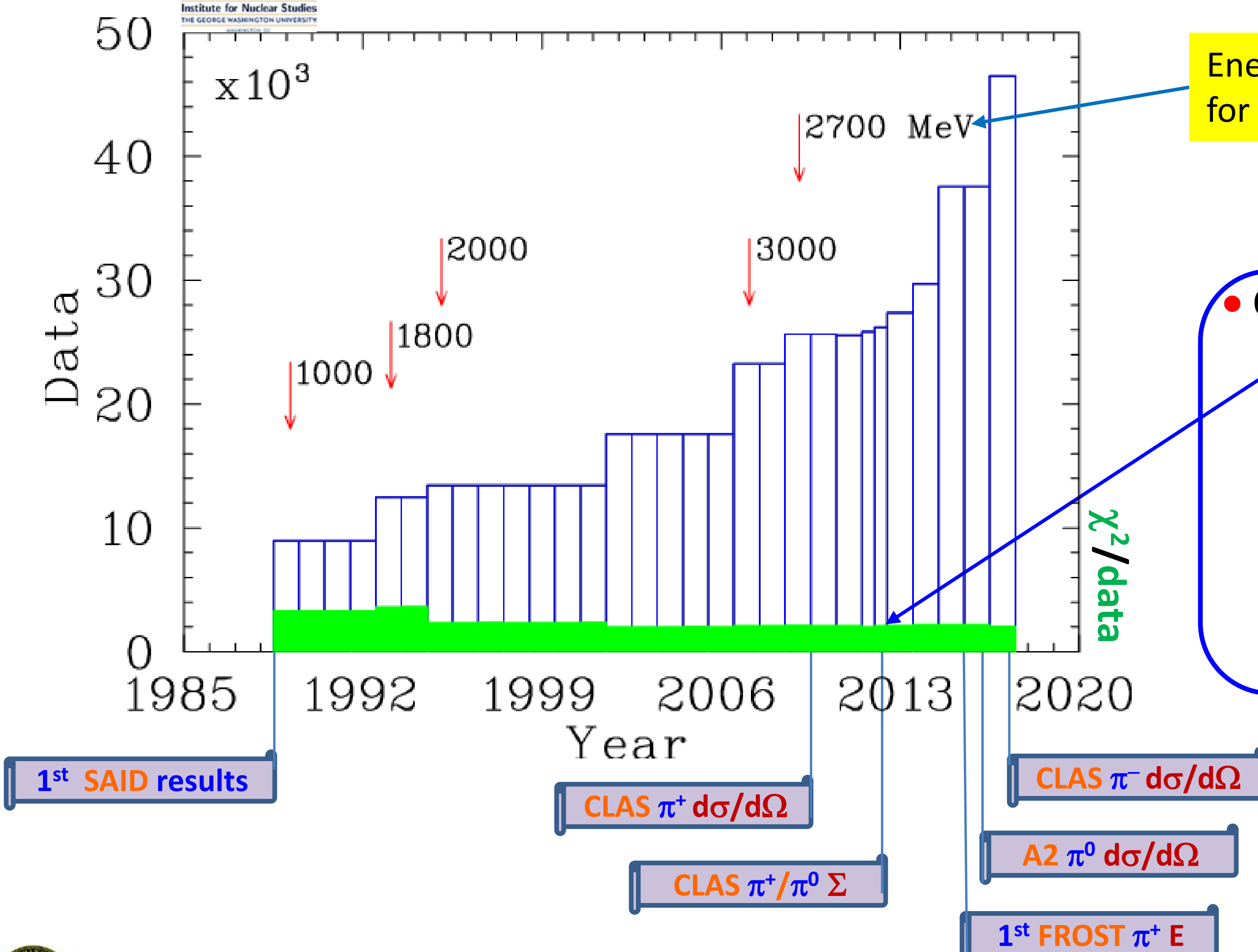
Reaction	Data
Pion-Nucleon	50,650
Pi-Pi-N	241,214 evts+
Kaon(+)-Nucleon	5,576
Nucleon-Nucleon	38,414
Pion Photoproduction	47,353
Pion Electroproduction	107.915
Kaon Photoproduction	12,864
Eta Photoproduction	6,502
Eta-Prime Photoproduction	852
Pion-Deuteron (elastic)	2,736
Pion-Deuteron to Proton+Proton	4,398

[W = 1320 to 1930 MeV]

For $\pi \rightarrow 2\pi$, we use log-likelihood while for rest – least-squares technologies.

Pion PhotoProduction

World Progress in Pion PhotoProduction



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

Direct Amplitude Reconstruction in Pion PhotoProduction

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

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

helicities: 2 x 2 x 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**.

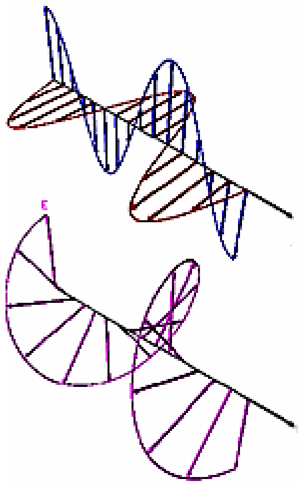
PHYSICAL REVIEW C VOLUME 54, NUMBER 3 SEPTEMBER 1996

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

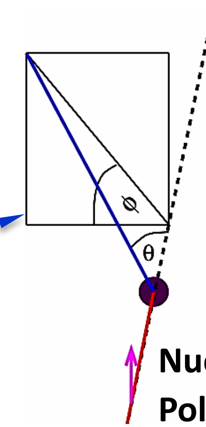
- There are **16** non-redundant observables.
- They are **not completely independent** from each other.



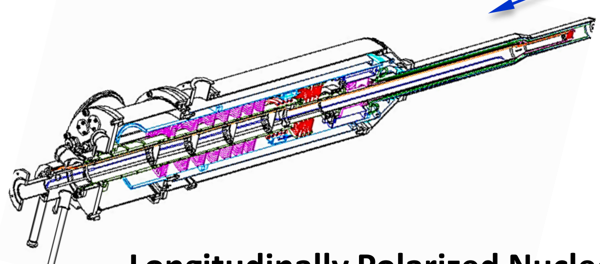
Linear Polarized *Beam*

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)

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

SAID for Pion PhotoProduction

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

- Data driven (model independent) analysis
- 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]

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%.

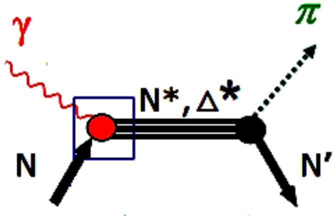


Photo-Decay Amplitudes in BW & Pole Forms

- **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

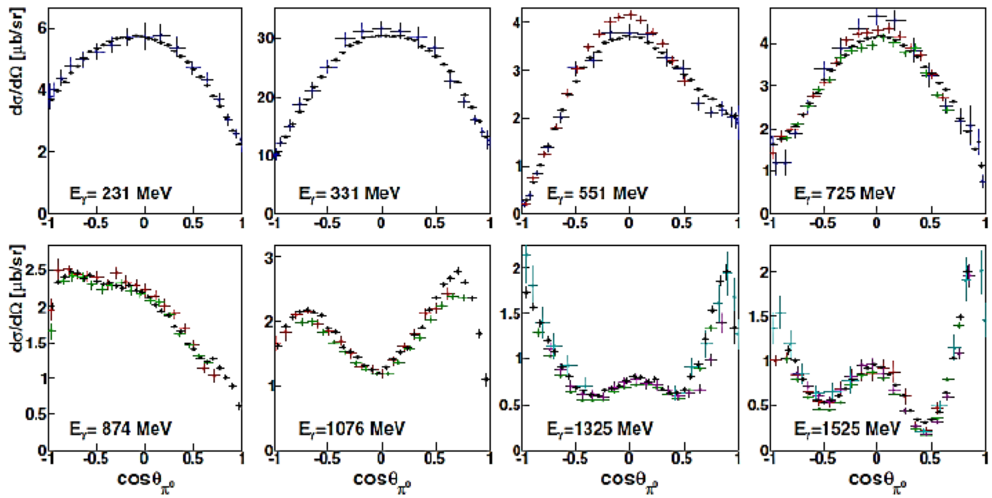
Evaluated at Pole

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	$+153 \pm 3$	(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)



PHYSICAL REVIEW C 92, 024617 (2015)

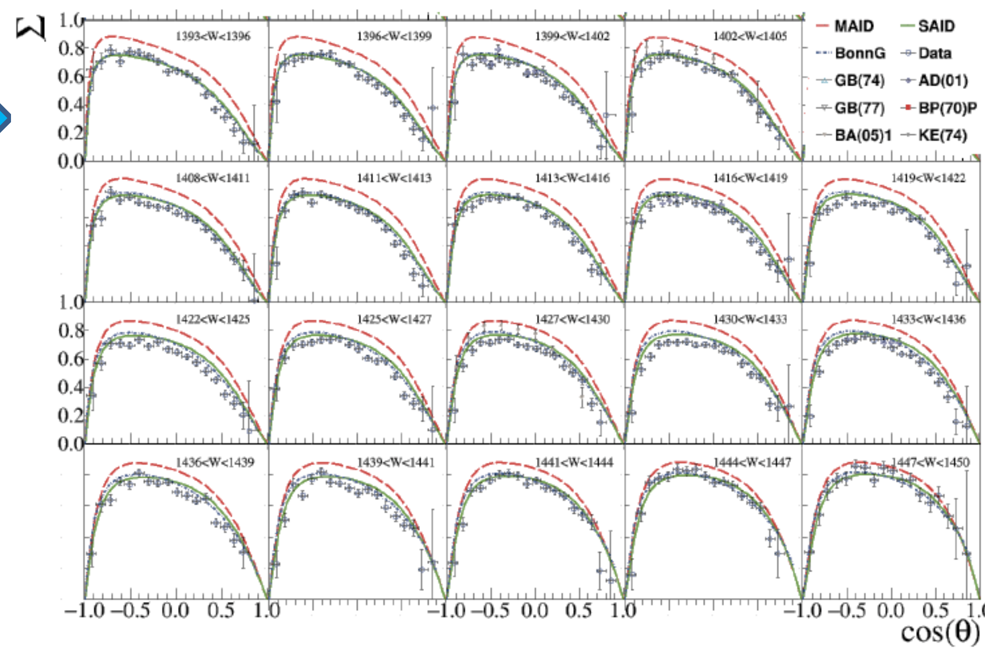
Measurement of π^0 photoproduction on the proton at MAMI C

P. Adlarson,[1] F. Afzal,[2] C. S. Akondi,[3] J. R. M. Annand,[4] H. J. Arends,[1] Ya. I. Azimov,[5] R. Beck,[2] N. Borisov,[6] A. Braghieri,[7] W. J. Briscoe,[8] S. Cherepnya,[9] F. Cividini,[1] C. Collicott,[10,11] S. Costanza,[7,12] A. Denig,[1] E. J. Downie,[1,8] M. Dieterle,[13] M. I. Ferretti Bondy,[1] L. V. Fil'kov,[9] A. Fix,[14] S. Gardner,[4] S. Garni,[13] D. I. Glazier,[4] ... W. Gradl,[1] G. Gurevich,[16] D. J. Hamilton,[4] D. Hornidge,[17] G. M. Huber,[18] A. Käser,[13] V. L. Kash... Keshelashvili,[13] R. Kondratiev,[16] M. Korolija,[19] B. Krusche,[13] V. V. Kulikov,[20] A. Laz... ...ston,[4] I. J. D. MacGregor,[4] D. M. Manley,[3] P. P. Martel,[1,21] M. Marte... D. G. Middleton,[1,17] R. Miskimen,[21] A. Mushkarenkov,[7,21] A. Neg... P. Ott,[1] P. B. Otte,[1] B. Oussena,[1,8] D. Paudyal,[18] P. Pedroni,[7] A. Polonski,[16] ... A. Rajabi,[21] G. Reicherz,[22] G. Ron,[24] T. Rostomyan,[13] A. Sarty,[11] D. M. Schott,[8] S. Sch... V. Sokhoyan,[1,8] K. Spieker,[2] O. Steffen,[1] I. I. Strakovsky,[8,†] Th. Strub,[13] I. Supek,[19] M. F. Taragin,[8] ... Thiel,[2] M. Thiel,[1] L. Tiator,[1] A. Thomas,[1] M. Unverzagt,[1] Yu. A. Usov,[6] S. Wagner,[1] D. P. Watts,[15] D. Werthmüller,[4,13] J. Wettig,[1] L. Witthauer,[13] M. Wolfes,[1] R. L. Workman,[8] and L. A. Zana[15]
(A2 Collaboration at MAMI)

dσ/dΩ for $\gamma p \to \pi^0 p$

W = 1135–1957 MeV
θ = 15–165^0
π^0p: 7978 dσ/dΩ

W = 1216–1448 MeV
θ = 31–158^0
π^0p: 1403 Σ



Eur. Phys. J. A (2016) 52: 333
DOI 10.1140/epja/i2016-16333-5

THE EUROPEAN PHYSICAL JOURNAL A

Regular Article – Experimental Physics

Photon asymmetry measurements of $\vec{\gamma}p \to \pi^0 p$ for E_γ = 320–650 MeV

The A2 Collaboration at MAMI

S. Gardner[1,a], D. Howdle[1], M.H. Sikora[6], Y. Wunderlich[4], S. Abt[10], P. Achenbach[2], F. Afzal[4], P. Aguar-Bartolome[2], Z. Ahmed[14], J.R.M. Annand[1], H.J. Arends[2], K. Bantawa[3], M. Bashkanov[6], R. Beck[4], M. Biroth[2], N.S. Borisov[15], A. Braghieri[5], W.J. Briscoe[7], S. Cherepnya[9], F. Cividini[2], S. Costanza[5], C. Collicott[7], B.T. Demissie[7], A. Denig[2], M. Dieterle[10], E.J. Downie[7], P. Drexler[2], M.I. Ferretti-Bondy[2], L.V. ... ov[9], D.I. Glazier[1], S. Garni[10], W. Gradl[2], M. Günther[10], G.M. Gurevich[12], P. Hall Barrientos[6], D. H... ...Ieid[2], D. Hornidge[11], G.M. Huber[14], O. Jahn[2], T.C. Jude[6], A. Käser[10], S. Kay[6], V.L. K... ...hvili[10], R. Kondratiev[12], M. Korolija[13], B. Krusche[10], J.M. Linturi[2], V. Lisin[12], ... J.D. MacGregor[1], R. Macrae[1], J. Mancell[1], D.M. Manley[3], P.P. Martel[2], J.C... D.G. Middleton[2,11], R. Miskimen[17], C. Mullen[1], ...enkov[5], A.B. Negano... ...kolaev[4], M. Oberle[10], M. Ostrick[2], R.O. Owens[1], P.B. Otte[2], ...[2], D. Paudyal[14], P. P... ...olonski[12], S. Prakhov[8], A. Rajabi[17], G. Rosner[1], ...an[10], A. Sarty[16], S. S...mann[2], V. Sokhoyan[2], K. Spieker[4], O. Steffen[2], C. Sfienti[2], I.I. Strakovsky[7], ...erg[1], Th. Strub[10], I. Supek[13], C.M. Tarbert[6], A. Thiel[4], M. Thiel[2], A. Thomas[2], M. Unverzagt[2], ...[15], D.P. Watts[6], D. Werthmüller[1,10], J. Wettig[2], M. Wolfes[2], L. Witthauer[10], and L. Zana[6]

Σ for $\vec{\gamma}p \to \pi^0 p$

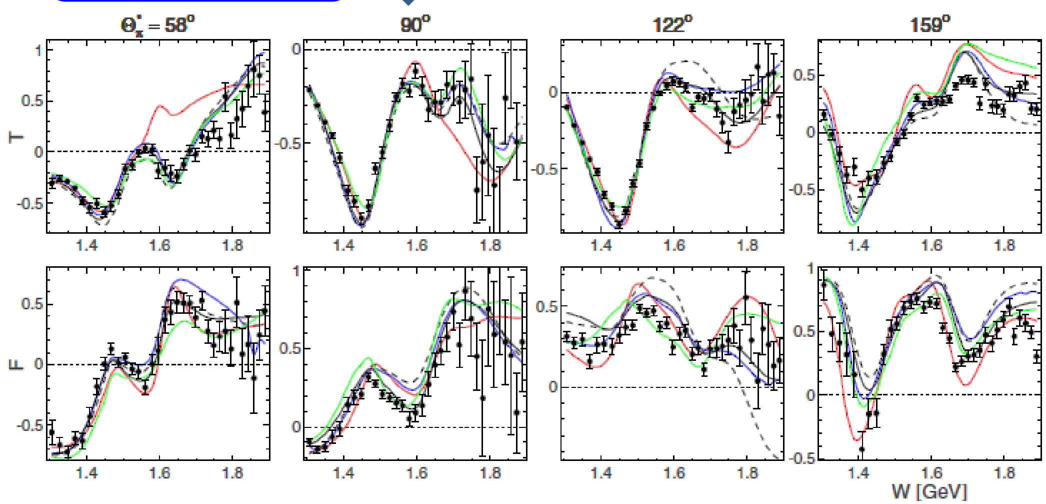
PHYSICAL REVIEW C 93, 055209 (2016)

T and F asymmetries in π^0 photoproduction on the proton

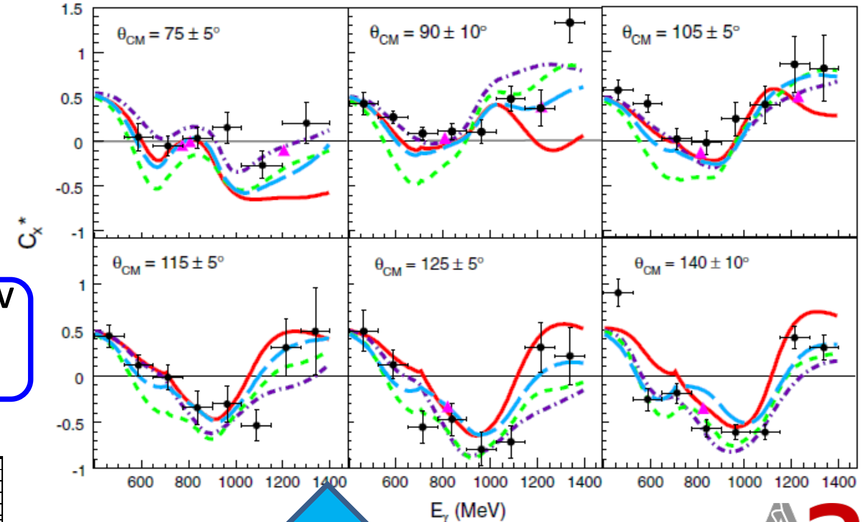
J. R. M. Annand,[1] H. J. Arends,[2] R. Beck,[3] N. Borisov,[4] A. Braghieri,[5] W. ... Cherepnya,[7] C. Collicott,[8] S. Costanza,[5] E. J. Downie,[2,6] M. Dieterle,[9] A. Fix,[10] L. V. Fil'kov ... W. Gradl,[2] G. Gurevich,[12] P. Hall Barrientos,[11] D. Hamilton,[1] D. Hornidge,[13] D. ... arov,[2,7] I. Keshelashvili,[9] R. Kondratiev,[12] M. Korolija,[15] B. Krusche ... D. MacGregor,[1] J. Mancel,[1] D. M. Manley,[16] P. P. Martel,[2,17] E. ... R. Miskimen,[17] A. Mushkarenkov,[5,17] A. Neganov,[4] A. Nikolaev,[3] M. Oberle, ... P. B. Otte,[2] B. Oussena,[2,6] P. Pedroni,[5] A. Polonski,[12] V. V. Polyanski,[7] S. Prakhov,[19] G. ... yan,[9] A. Sarty,[8] S. Schumann,[2] O. Steffen,[2] I. I. Strakovsky,[6] Th. Strub,[9] I. Supek,[15] L. Tiator, ... as,[2] M. Unverzagt,[2] Yu. A. Usov,[4] D. P. Watts,[11] D. Werthmüller,[1,9] L. Witthauer,[9] and M. Wolfes[2]
(A2 Collaboration at MAMI)

T & F for $\vec{\gamma}\vec{p} \to \pi^0 p$

W = 1305–1888 MeV
θ = 30–152⁰
π^0p: 397 T & 397 F



W = 1322–1841 MeV
θ = 75–140⁰
π^0p: 45 Cx'



PRL 112, 022501 (2014) PHYSICAL REVIEW LETTERS 17 JANUARY 2014

Measurement of the $^1H(\vec{\gamma},\vec{p})\pi^0$ Reaction Using a Novel Nucleon Spin Polarimeter

M. H. Sikora,[1,*] D. P. Watts,[1] D. I. Glazier,[1] P. Aguar-Bartolomé,[2] L. K. Akasoy,[2] J. R. M. Annand,[3] H. J. Arends,[2] K. Bantawa,[4] R. Beck,[5] V. S. Bekrenev,[6] H. Berghäuser,[7] A. Braghieri,[8] D. Branford ... J. Briscoe,[9] J. Brudvik,[10] S. Cherepnya,[11] R. F. B. Codling,[3] B. T. Demissie,[9] E. J. Downie,[2,3,9] P. ... B. Freehart,[9] R. Gregor,[7] D. Hamilton,[3] E. Heid,[2,9] D. Hornidge,[12] D. A. Ho... V. L. Kashevarov,[11] I. Keshelashvili,[13] R. Kondratiev,[14] M. K... B. Krusche,[13] V. Lisin,[14] K. Livingston,[3] I. J. D. MacGregor ... M. Martinez,[2] J. C. McGeorge,[3] B. McKinnon,[3] E. F. McNicoll,[3] D. ... S. Micanovic,[15] D. G. Middleton,[12] A. Mushkarenkov,[8] B. M. K. Nefkens,[10] A. Nikolaev, ... M. Ostrick,[2] P. B. Otte,[2] B. Oussena,[2,9] P. Pedroni,[8] F. Pheron,[13] A. Polonski,[14] S. Prakhov,[10] J. Robinson,[3] G. Rosner,[3] T. Rostomyan,[8,†] S. Schumann,[2] D. I. Sober,[16] A. Starostin,[10] I. I. Strakovsky,[9] I. M. Suarez,[10] I. Supek,[15] M. Thiel,[7] A. Thomas,[2] M. Unverzagt,[2] D. Werthmüller,[13] R. L. Workman,[9] I. Zamboni,[15] and F. Zehr[13]
(A2 Collaboration at MAMI)

C_x for $\vec{\gamma}\vec{p} \to \pi^0 p$

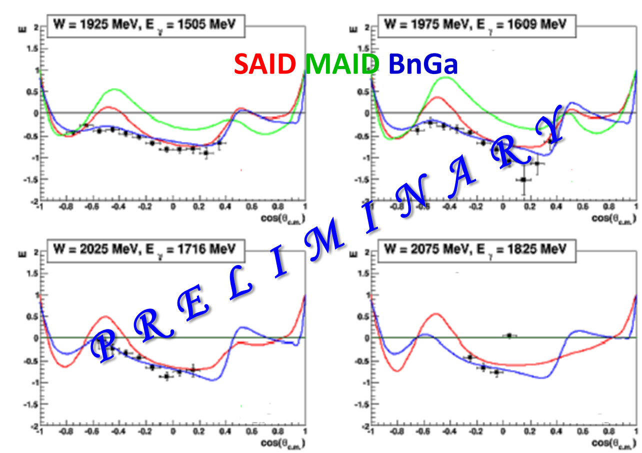
AIP Conference Proceedings

Helicity Asymmetry ... for π^0 Photoproduction on the CLAS Frozen Spin Target

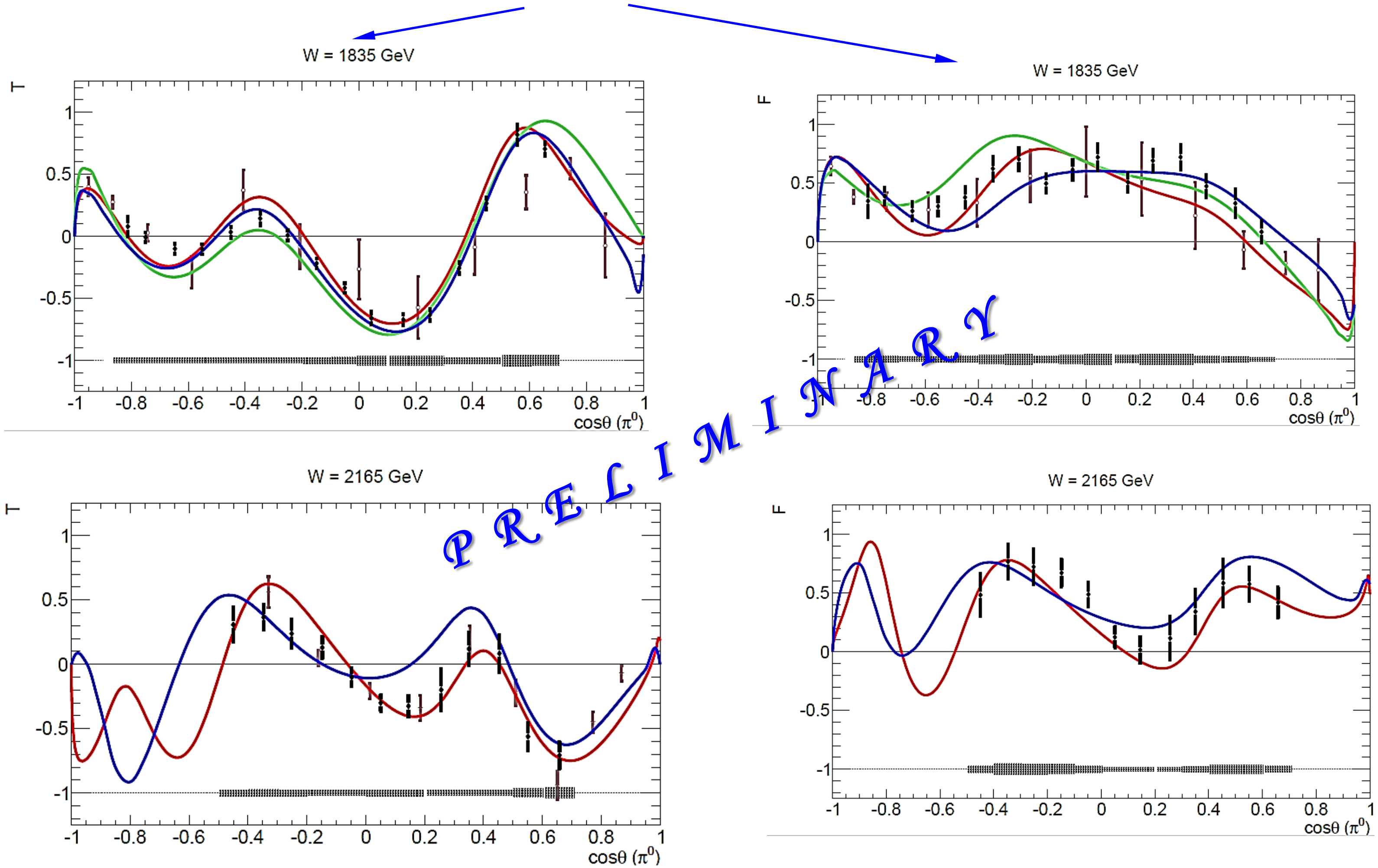
E for $\vec{\gamma}\vec{p} \to \pi^0 p$

AIP Conf. Proc. **1432**, 275 (2012)

Diane Schott[1], William Briscoe[1] and Igor Strakovsky[1,a)]
for CLAS Collaboration



T & F for $\vec{\gamma}\vec{p} \to \pi^0 p$



SAID-2017 BnGa2014 MAID2007

Courtesy of Steffen Strauch, 2018

PHYSICAL REVIEW C 88, 065203 (2013)

Beam asymmetry Σ for π^+ and π^0 photoproduction on the proton for ph[otons] from 1.102 to 1.862 GeV

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(CLAS Collaboration)

Σ for $\vec{\gamma} p \to \pi^+ n$ & $\vec{\gamma} p \to \pi^0 p$

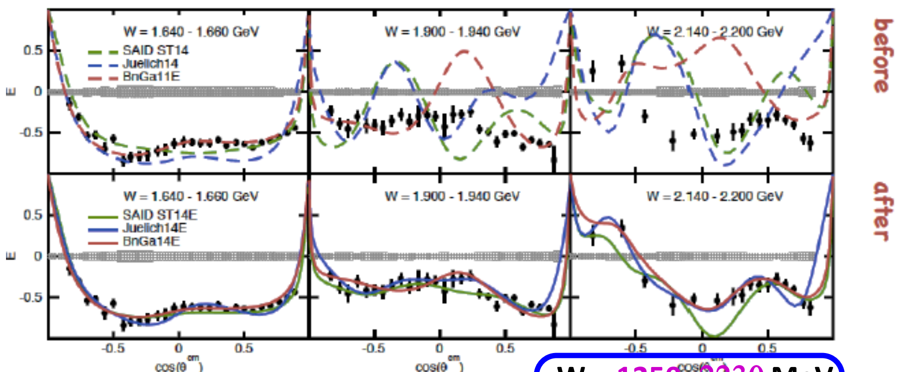
W = 1717–2091 MeV
θ = 32–148^0
$\pi^0 p$: 700 Σ & $\pi^+ n$: 386 Σ

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_0 (1 - P_z P_\odot E)$$

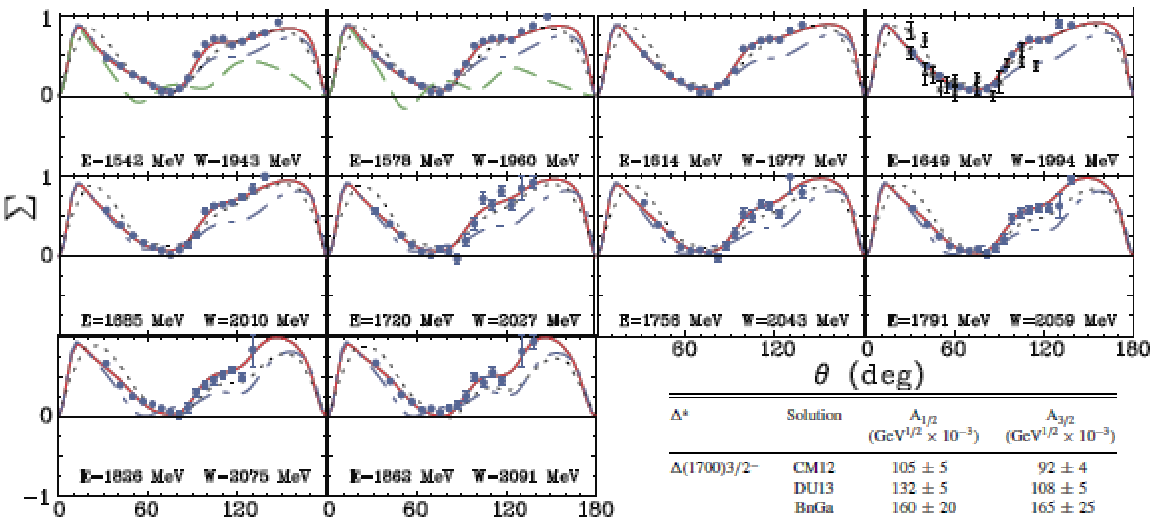
W = 1240 – 2260 MeV
$-0.9 \le \cos(\theta_\pi^{cm}) \le +0.9$

$\vec{\gamma}\vec{p} \to \pi^+ n$

W = 1.650 GeV   W = 1.920 GeV   W = 2.170 GeV



W = 1250–2230 MeV
θ = 20–148^0
$\pi^+ n$: 900 E



Δ*	Solution	$A_{1/2}$ ($\mathrm{GeV}^{1/2} \times 10^{-3}$)	$A_{3/2}$ ($\mathrm{GeV}^{1/2} \times 10^{-3}$)
Δ(1700)3/2−	CM12	105 ± 5	92 ± 4
	DU13	132 ± 5	108 ± 5
	BnGa	160 ± 20	165 ± 25
	MD07	226	210
	PDG12	104 ± 15	85 ± 22
Δ(1905)5/2+	CM12	19 ± 2	−38 ± 4
	DU13	20 ± 2	−49 ± 5
	BnGa	25 ± 5	−49 ± 4
	MD07	18	−28
	PDG12	26 ± 11	−45 ± 20

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First measurement of the polarization observable *E* in the $\vec{p}(\vec{\gamma}, \pi^+)n$ reaction up to 2.25 GeV

CLAS Collaboration

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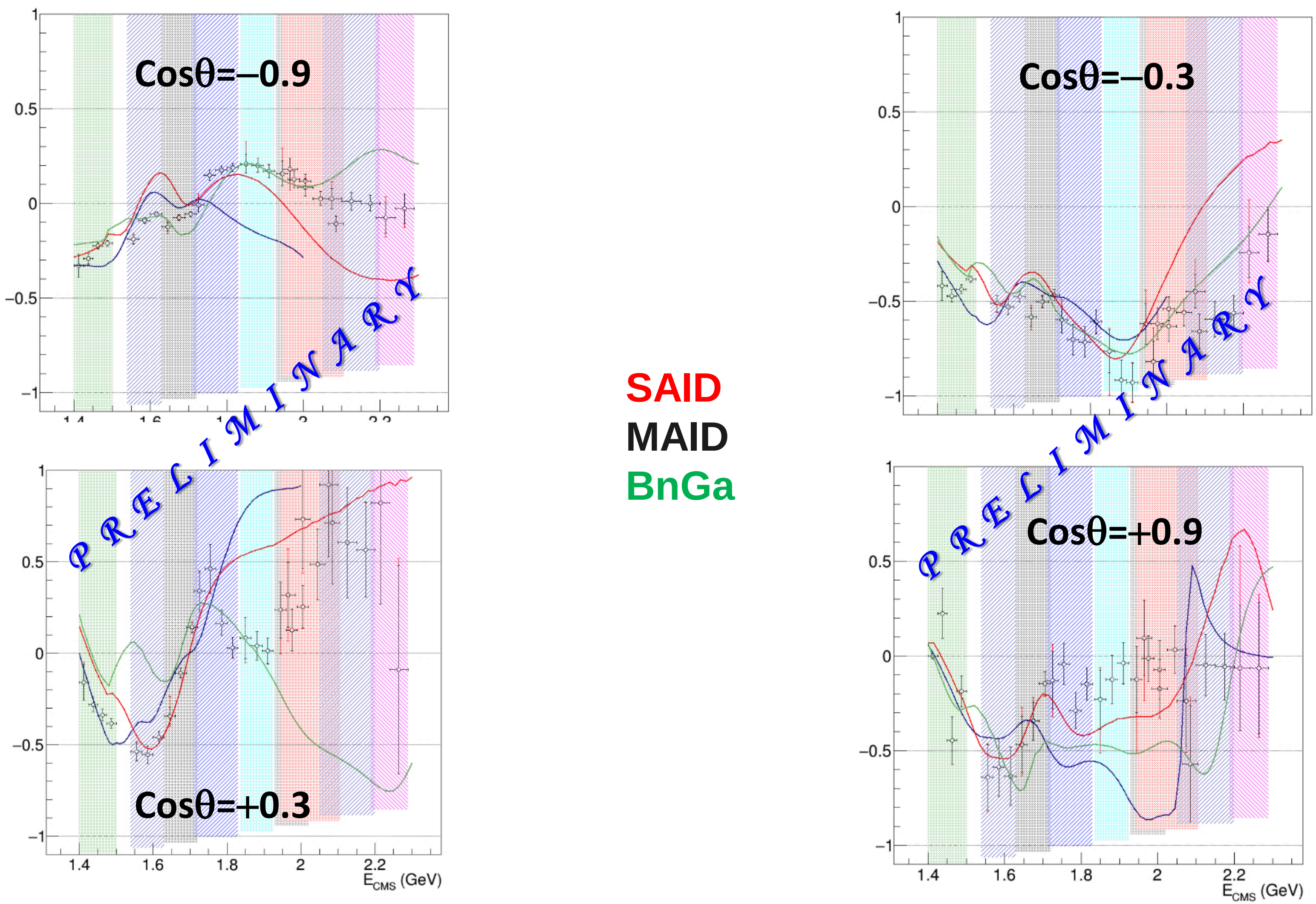
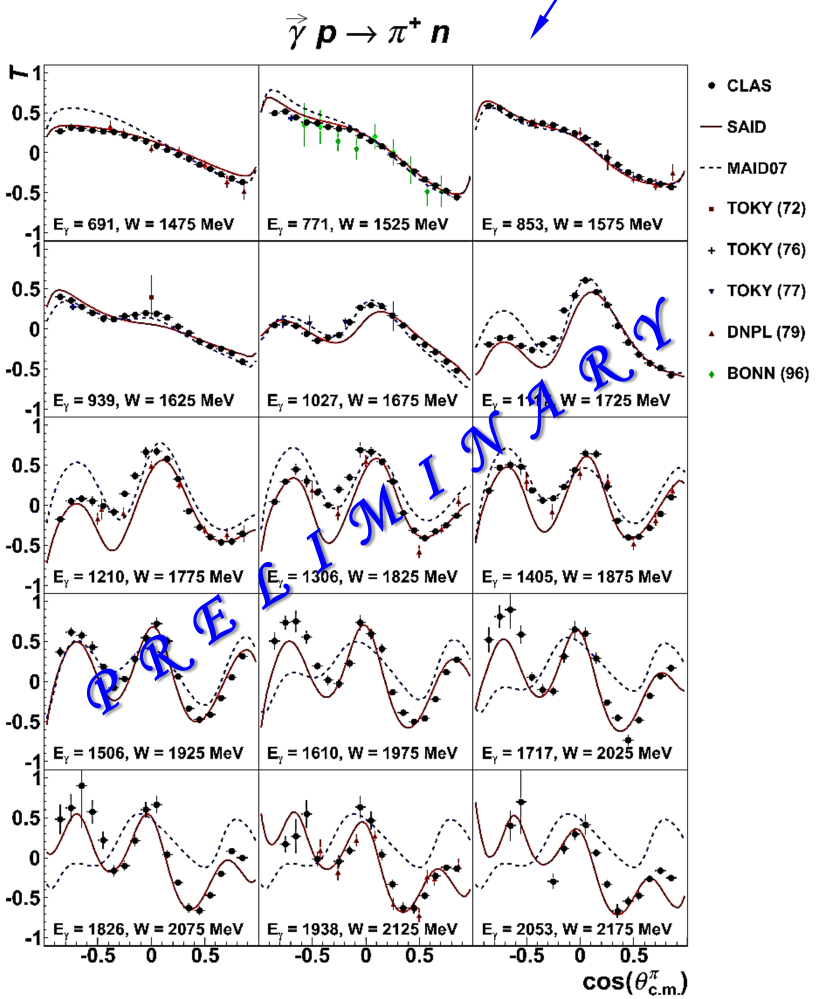
E for $\vec{\gamma}\vec{p} \to \pi^+ n$

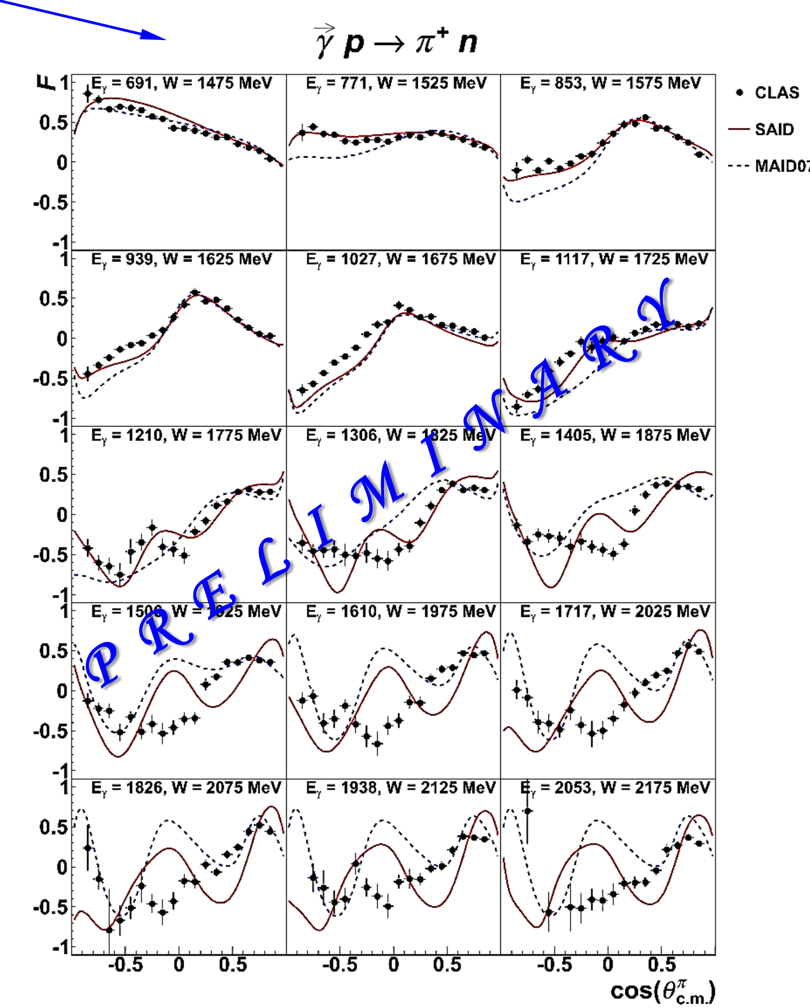
G for $\vec{\gamma}\vec{p} \rightarrow \pi^{+} n$



Courtesy of Lorenzo Zana 2018

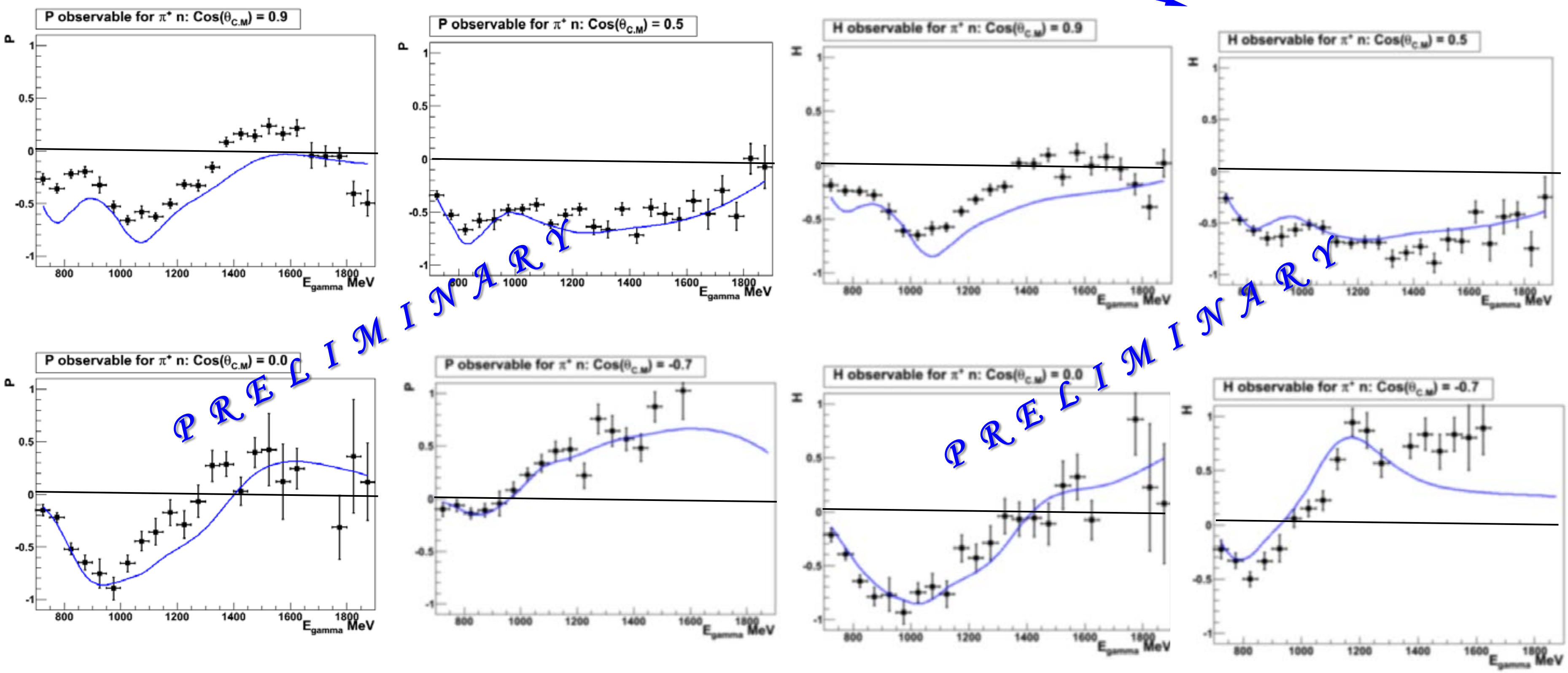
T & F for $\vec{\gamma}\vec{p} \rightarrow \pi^+ n$





Courtesy of Mike Dugger, 2018

P & H for $\vec{\gamma}\vec{p} \rightarrow \pi^+ n$



Courtesy of Mike Dugger, 2018

Pion PhotoProduction on Neutron Target

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,
  K.M. Watson, Phys Rev **95**, 228 (1954); R.L. Walker, Phys Rev **182**, 1729 (1969)
  as well as **isospin** properties of non-resonant **background amplitudes**.

- 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**.

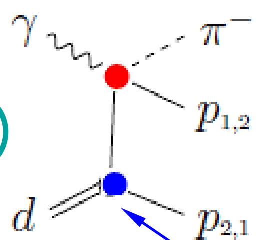
- **Radiative decay** width of **neutral baryons** may be extracted from π^- & π^0 photoproduction off **neutron**, which involves **bound neutron target** & needs use of **model-dependent nuclear** (**FSI**) **corrections**.
  A.B. Migdal, JETP **1**, 2 (1955); K.M. Watson, Phys Rev **95**, 228 (1954)

$\mathcal{FSI}$ *for* $\gamma d \longrightarrow \pi p N \Longrightarrow \gamma n \longrightarrow \pi N$

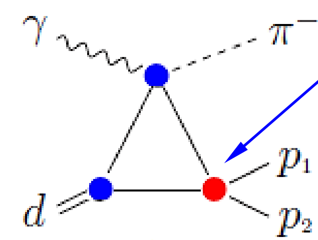
V. Tarasov, A. Kudryavtsev, W. Briscoe, H. Gao, IS, Phys Rev C **84,** 035203 (2011)
V. Tarasov, A. Kudryavtsev, W. Briscoe, B. Krusche, IS, M. Ostrick, Phys At Nucl **79**, 216 (2016)

- **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**).

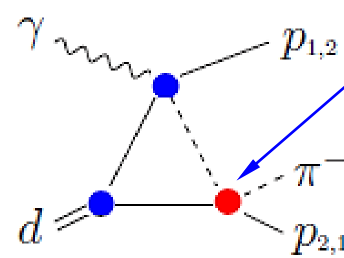
IA



Fermi motion of nucleons included



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**).

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

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

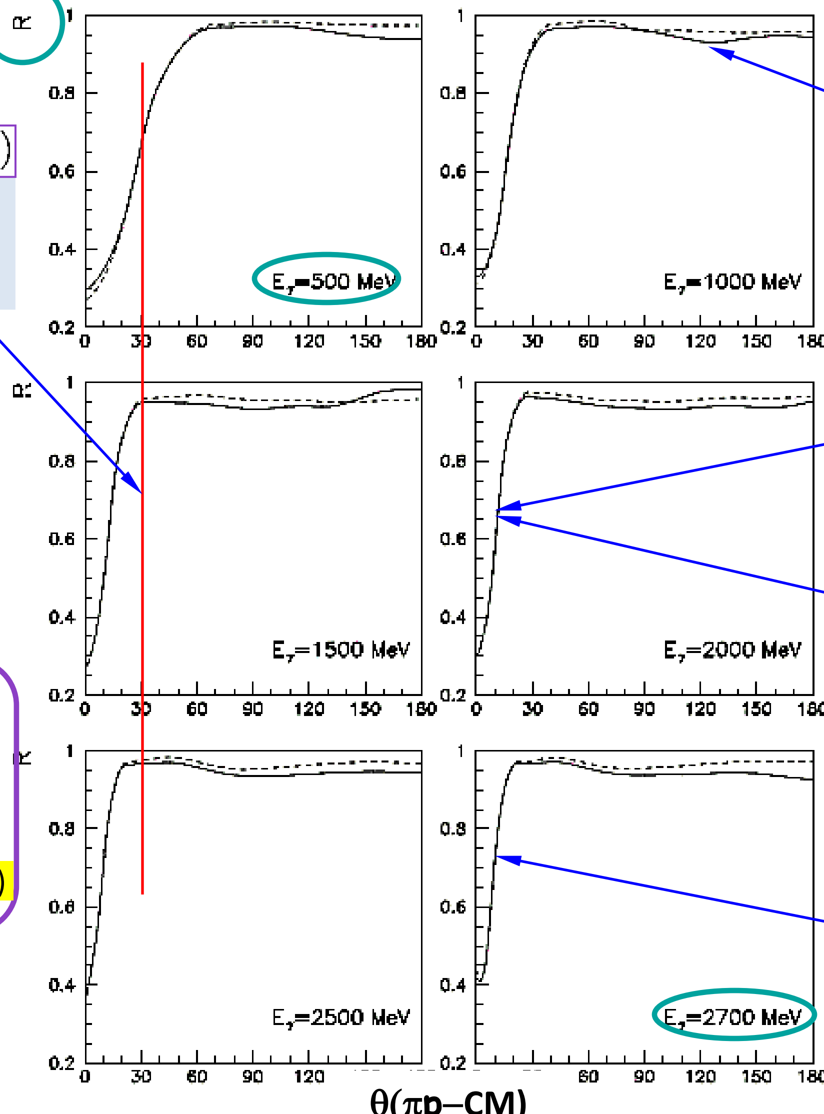
V. Tarasov, A. Kudryavtsev, W. Briscoe, H. Gao, IS, Phys Rev C **84**, 035203 (2011)

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

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

CLAS g10 & g13:
$E > 0.5$ GeV
$\theta > 30$ 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%.**

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

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

- **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

PRL 118, 242002 (2017) PHYSICAL REVIEW LETTERS 16 JUNE 2017

Beam-Target Helicity Asymmetry for $\vec{\gamma}\vec{n} \to \pi^- p$ in the N^* Resonance Region

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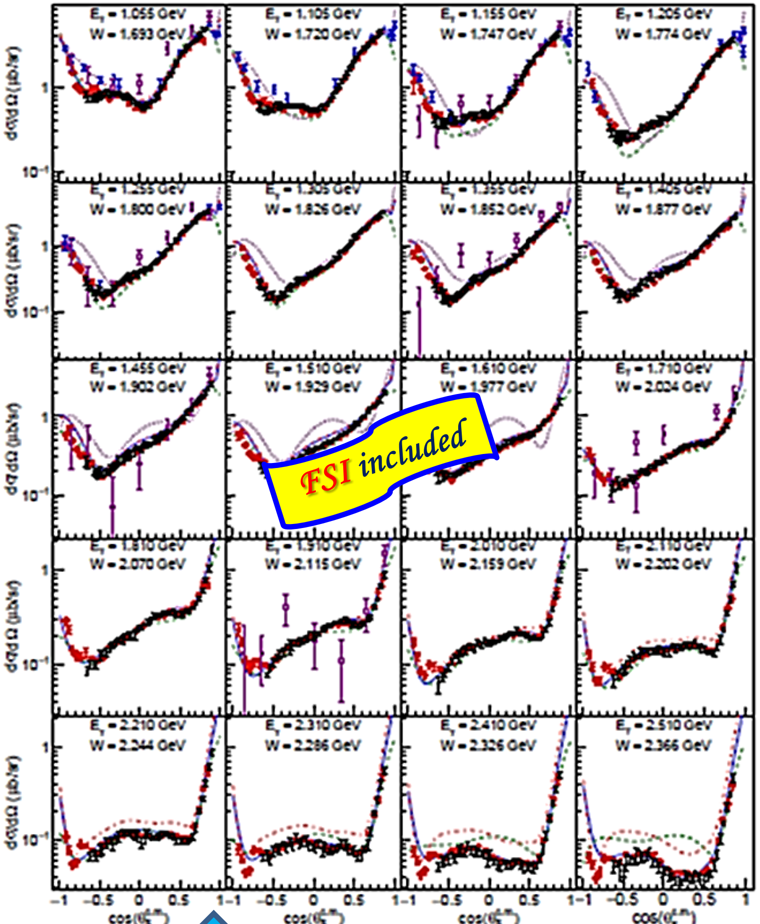
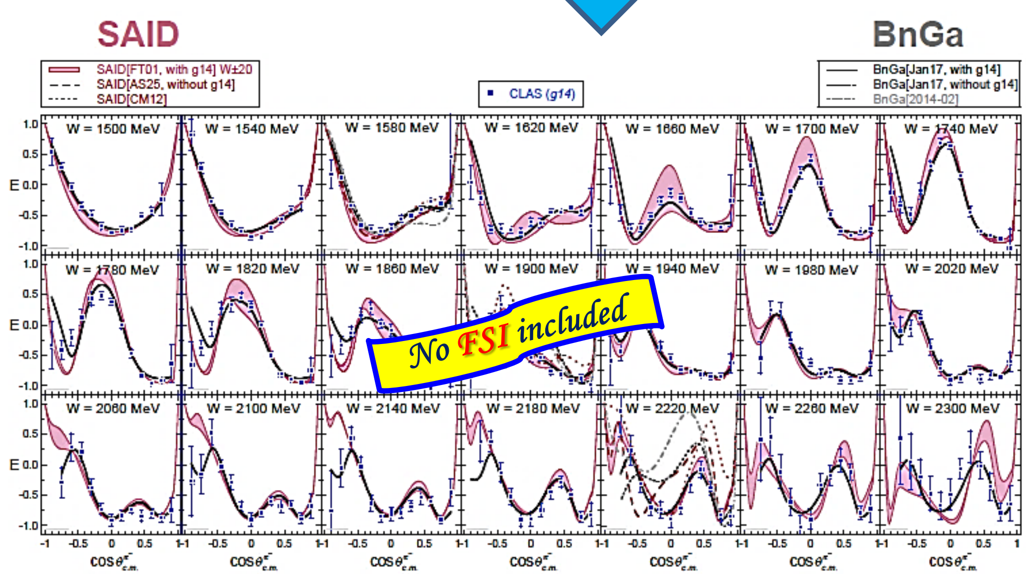
(CLAS Collaboration)

E for $\gamma n \to \pi^- p$

W = 1311–2355 MeV
θ = 25–135^0
$\pi^- p$: 8428 dσ/dΩ



W = 1500–2300 MeV
θ = 25–154^0
$\pi^- p$: 266 E



PHYSICAL REVIEW C 96, 035204 (2017)

Differential cross section measurements for $\gamma n \to \pi^- p$ above the first nucleon resonance region

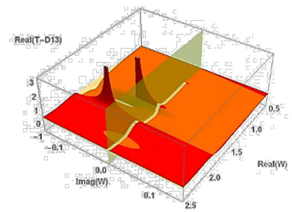
P. T. Mattione,[1] D. S. Carman,[1] I. I. Strakovsky,[20] R. L. Workman,[20] A. E. Kudryavtsev,[30] A. Svarc,[29] V. E. Tarasov,[30] K. P. Adhikari,[33] S. Adhikari,[16] D. Adikaram,[1,37] Z. Akbar,[17] S. Anefalos Pereira,[24] J. Ball,[8] N. A. Baltzell,[1,41] M. Bashkanov,[13] M. Battaglieri,[25] V. Batourine,[1,32] I. Bedlinskiy,[30] A. S. Biselli,[15] S. Boiarinov,[1] W. J. Briscoe,[20] V. D. Burkert,[1] T. Cao,[21,41] A. Celentano,[25] G. Charles,[37] T. Chetry,[36] G. Ciullo,[14,23] L. Clark,[19] P. L. Cole,[22] M. Contalbrigo,[23] O. Cortes,[22] V. Crede,[17] A. D'Angelo,[26,39] N. Dashyan,[47] R. De Vita,[25] E. De Sanctis,[24] ... M. Dugger,[3] R. Dupre,[28] H. Egiyan,[1] A. El Alaoui,[43] L. El Fassi,[33] P. Eugenio, ... R. Fersch,[9] A. Filippi,[27] J. A. Fleming,[13] A. Fradi,[11,28] Y. Ghandilyan,[47] G. P. Gilfoyle,[38] K. L. Gi... Gleason,[41] E. Golovatch,[40] R. W. Gothe,[41] K. A. Griffioen,[46] M. Guidal,[28] K. Hafidi,[2] ... Harrison,[1] M. Hattawy,[2] D. Heddle,[9,1] K. Hicks,[36] G. Hollis,[41] M. Holtrop,[34] ... G. Ireland,[19] B. S. Ishkhanov,[40] E. L. Isupov,[40] D. Jenkins,[44] H. Jiang,[41] H. S. Jo, ... G. Khachatryan,[47] M. Khachatryan,[37] M. Khandaker,[22,35] A. Kim,[10] W. Kim,[32] ... Kubarovsky,[1] S. V. Kuleshov,[30,43] L. Lanza,[26] P. Lenisa,[23] K. Livingston,[19] I. J. D. Ma... C. A. Meyer,[6] Z. E. Meziani,[42] T. Mineeva,[43] V. Mokeev,[1,40] R. A. Montg... Munoz Camacho,[28] G. Murdoch,[19] P. Nadel-Turonski,[1,20] L. A. Net,[41] S. Niccolai,[28] G. Niculescu, ... Osipenko,[25] A. I. Ostrovidov,[17] M. Paolone,[42] R. Paremuzyan,[34] K. Park,[1] ... W. Phelps, ... O. Pogorelko,[30] J. W. Price,[4] S. Procureur,[8] Y. Prok,[37,45] D. Protopopescu,[19] ... M. Ripani, ... G. Ritchie,[3] A. Rizzo,[26,39] G. Rosner,[19] F. Sabatié,[8] C. Salgado,[35] R. A. Schumacher,[6] ... Sharabian,[1] A. Simonyan,[47] Iu. Skorodumina,[40,41] G. D. Smith,[13] D. Sokhan,[19] N. Sparveris,[42] I. Stankovic,[13] ... S. Strauch,[41] M. Taiuti,[18,25] M. Ungaro,[1,10] H. Voskanyan,[47] E. Voutier,[28] N. K. Walford,[7] D. Watts,[13] X. Wei,[1] M. H. Wood,[5,41] N. Zachariou,[13] J. Zhang,[1] and Z. W. Zhao[12,37]

(CLAS Collaboration)

dσ/dΩ for $\gamma n \to \pi^- p$

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*→γn** 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

MAID

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.

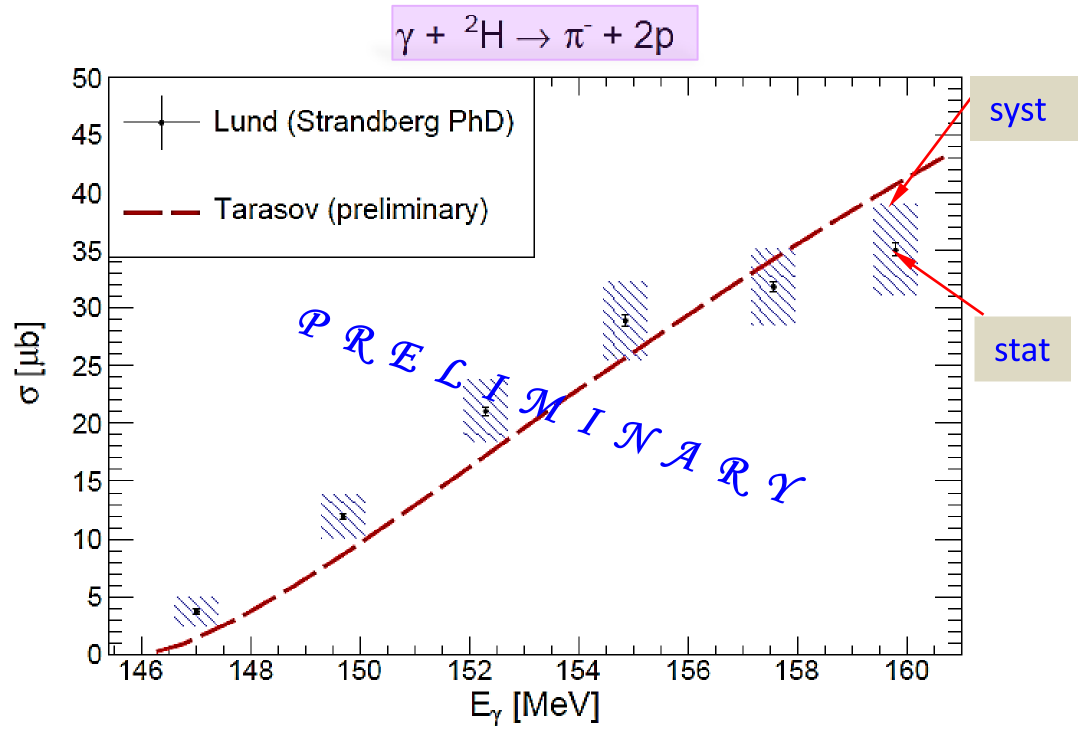
- Inclusion of these **g14** data in new **PWA** calculations has resulted in revised **γN*** couplings &, in case of **N(2190)7/2$^-$**, convergence among different **PWA** groups.

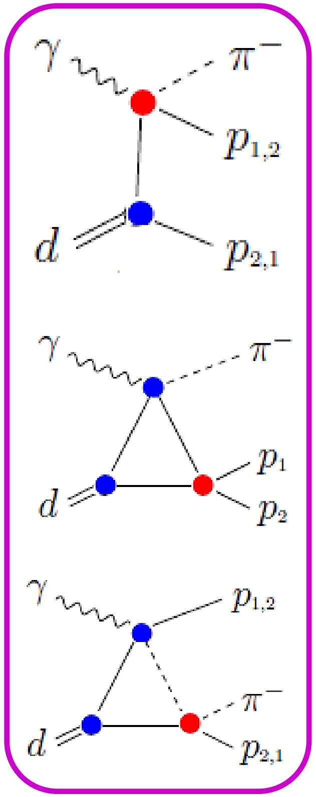
- Such couplings are sensitive to **dynamical** process of **N*** excitation & provide important guides to nucleon structure models.

MAX-lab for $\gamma n \rightarrow \pi^- p$ 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 $\gamma n \rightarrow \pi^- p \rightarrow \pi^0 n$.

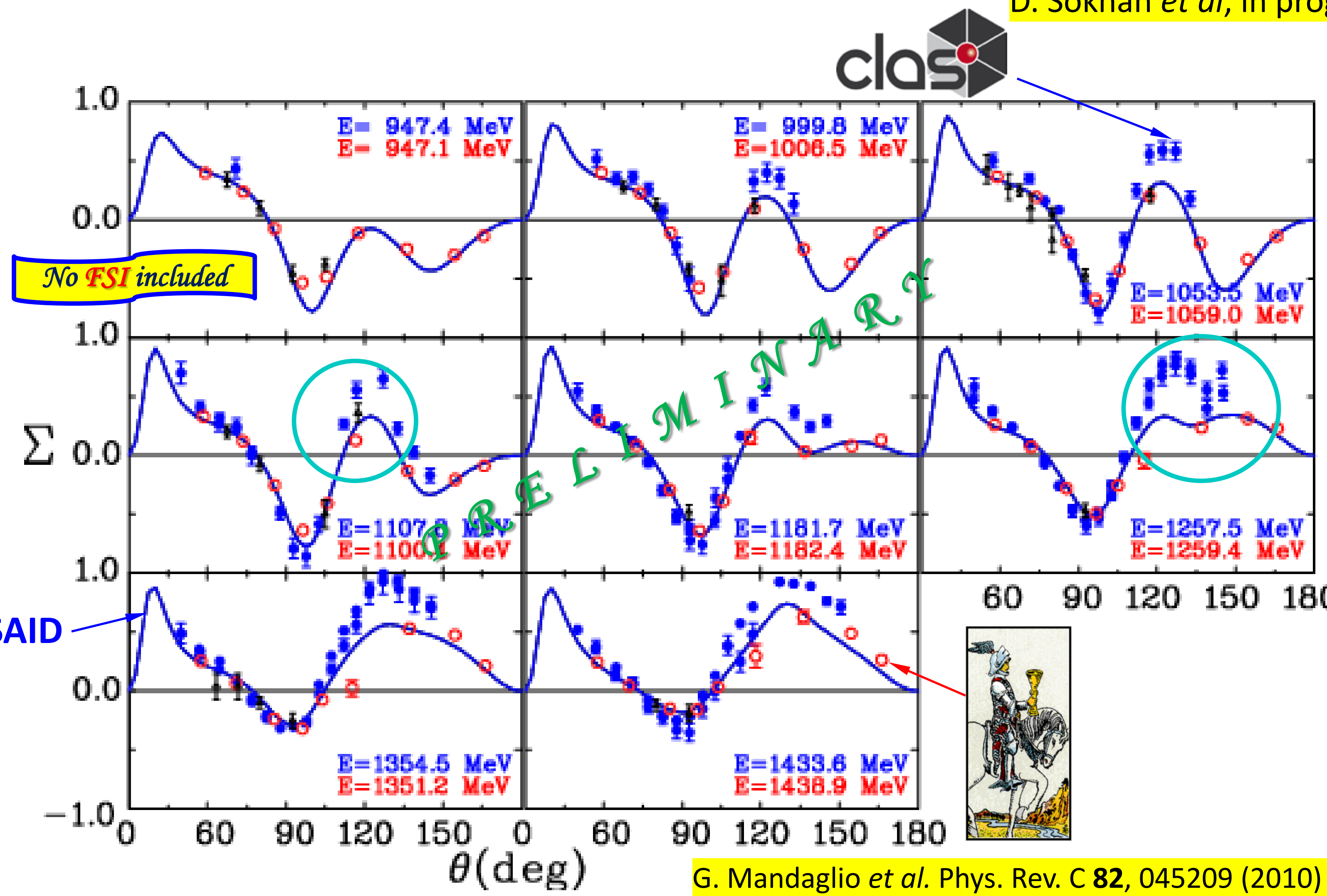




Courtesy of Bruno Strandberg, 2018

Σ for $\vec{\gamma} n \to \pi^- p$

D. Sokhan *et al*, in progress



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

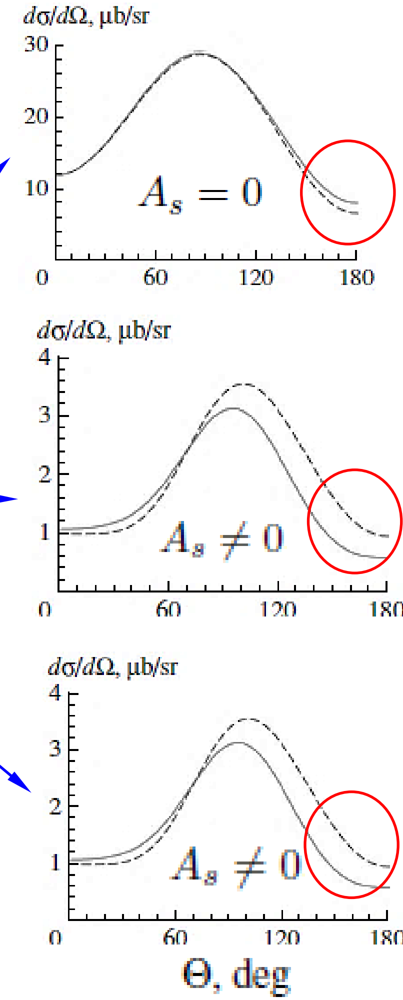
Courtesy of Daria Sokhan, 2018

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

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 **$\pi^0$** can come from both **$\gamma n$** & **$\gamma p$** **initial** interactions.

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



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

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

Δ(1232)3/2+

N(1440)1/2+

N(1535)1/2–

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

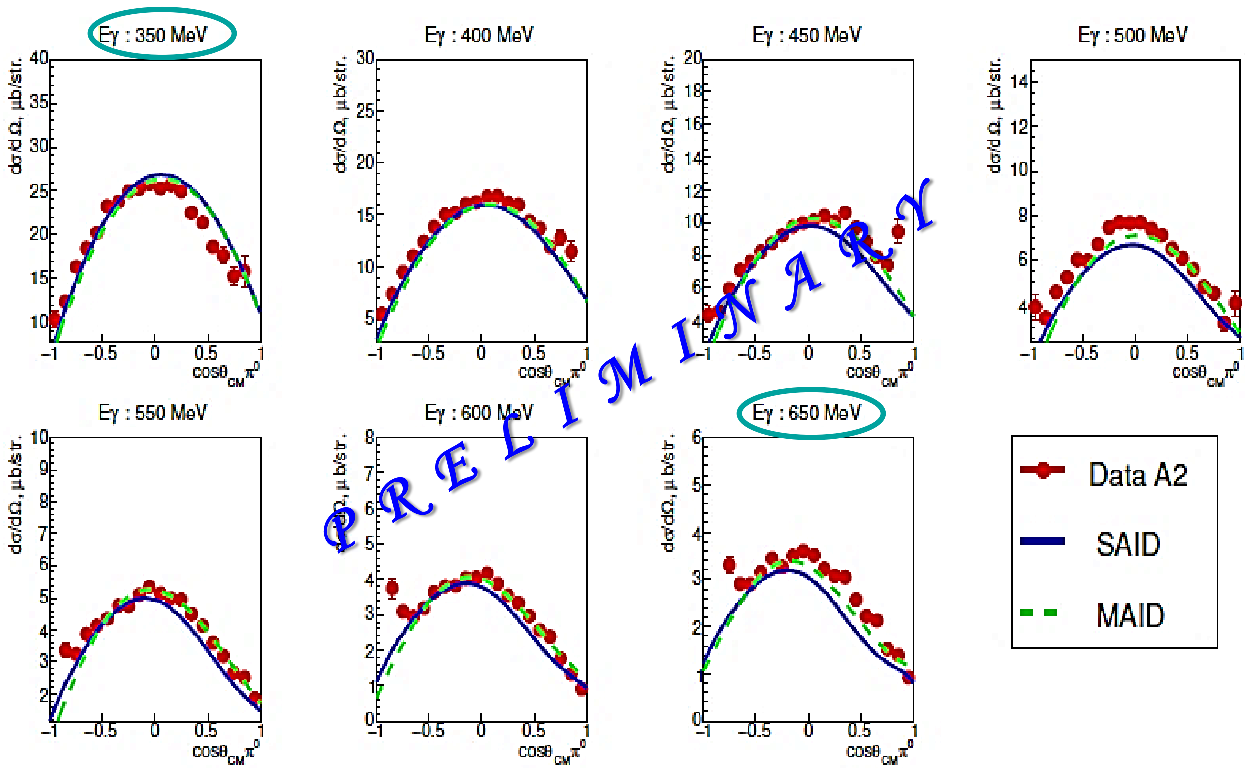
$$R_n = R_p$$

- In general case, $R_n \neq R_p$

Meson Production off Deuteron at CB@MAMI

V. Kulikov *et al*, in progress

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



E = 180 – 800 MeV
$\pi^0 n$: 589 dσ/dΩ

- New **dσ/dΩ**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, 2018

Pion-Proton Elastic Scattering

PHYSICAL REVIEW C 91, 025205 (2015)

High-precision measurements of πp elastic differential cross sections in the second resonance region

I. G. Alekseev,[1] V. A. Andreev,[3] I. G. Bordyuzhin,[1,5] W. J. Briscoe,[2] Ye. A. Filimonov,[3] V. V. Golubev,[3] A. B. Gridnev,[3] D. V. Kalinkin,[1] L. I. Koroleva,[1] N. G. Kozlenko,[3] V. S. Kozlov,[3] A. G. Krivshich,[3] B. V. Morozov,[1] V. M. Nesterov,[1] D. V. Novinsky,[3] V. V. Ryltsov,[1] M. Sadler,[4] B. M. Shurygin,[1] I. I. Strakovsky,[2] A. D. Sulimov,[1] V. V. Sumachev,[3] D. N. Svirida,[1] V. I. Tarakanov,[3] V. Yu. Trautman,[3] and R. L. Workman[2]
(EPECUR Collaboration and GW INS Data Anal[illegible] [illegible]ter)
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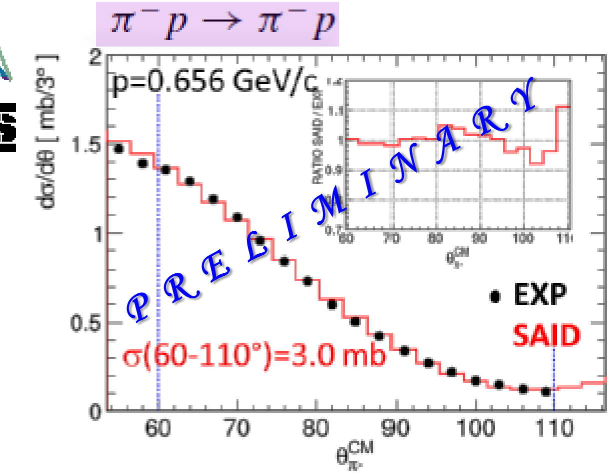
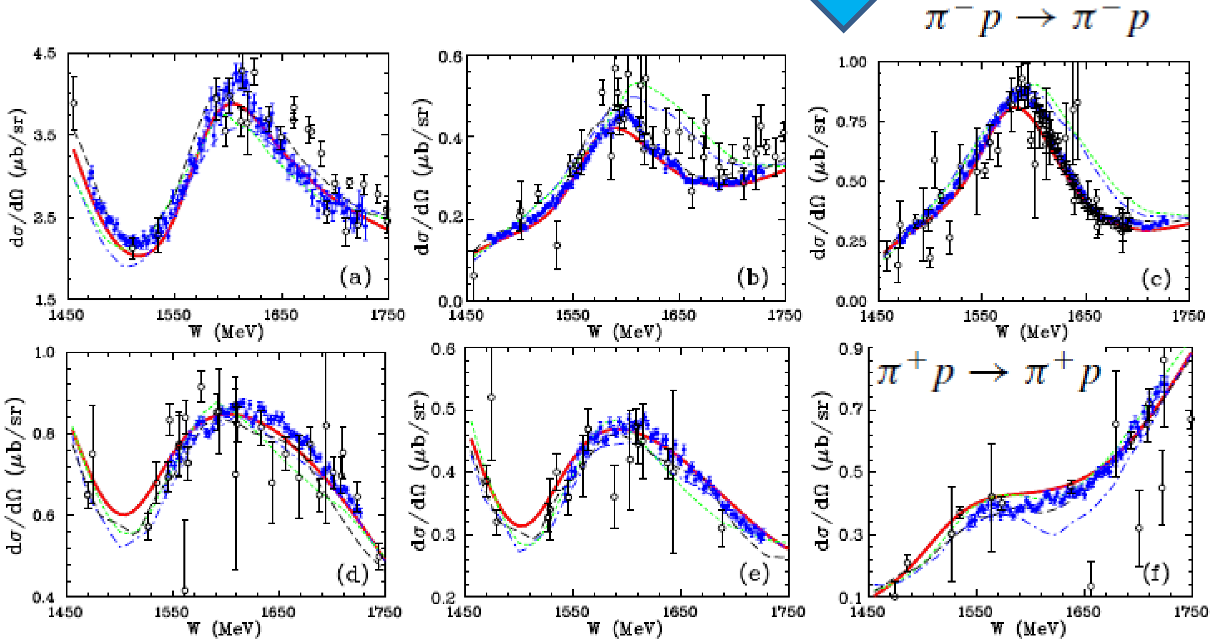
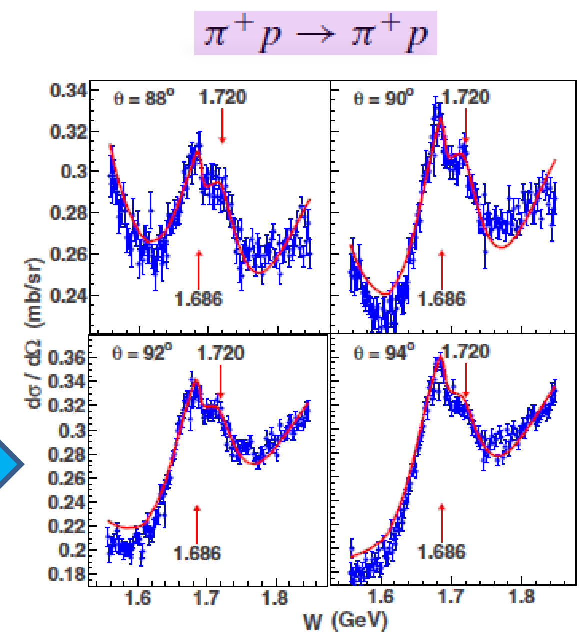
[5]National Univ[illegible] [illegible]ience and Technology "MISiS", Moscow, 119049, Russia
(Received 27 October 2014; published 24 February 2015)

$d\sigma/d\Omega$ for $\pi^{\pm} p \to \pi^{\pm} p$



Courtesy of Beatrice Ramstein, 2018





PHYSICAL REVIEW C 93, 062201(R) (2016)

Search for narrow resonances in πp elastic scattering from the EPECUR experiment

A. Gridnev,[1,*] I. G. Alekseev,[2,5] V. A. Andreev,[1] I. G. Bordyuzhin,[2] W. J. Briscoe,[3] Ye. A. Filimonov,[1] V. V. Golubev,[2] D. V. Kalinkin,[2] L. I. Koroleva,[2] N. G. Kozlenko,[1] V. S. Kozlov,[1] A. G. Krivshich,[1] V. A. Kuznetsov,[1] B. V. Morozov,[2] V. M. Nesterov,[2] D. V. Novinsky,[1] V. V. Ryltsov,[2] M. Sadler,[4] I. I. Strakovsky,[3] A. D. Sulimov,[2] V. V. Sumachev,[1] D. N. Svirida,[2] V. I. Tarakanov,[2] V. Yu. Trautman,[2] and R. L. Workman[3]

Nucleon-Nucleon Elastic Scattering

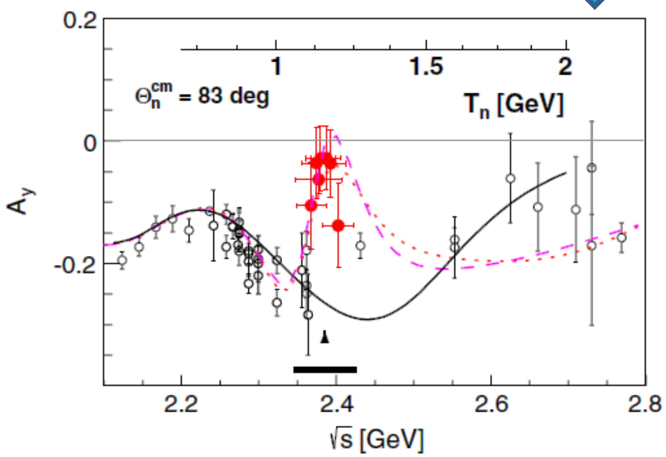
PRL 112, 202301 (2014) PHYSICAL REVIEW LETTERS 23 MAY 2014

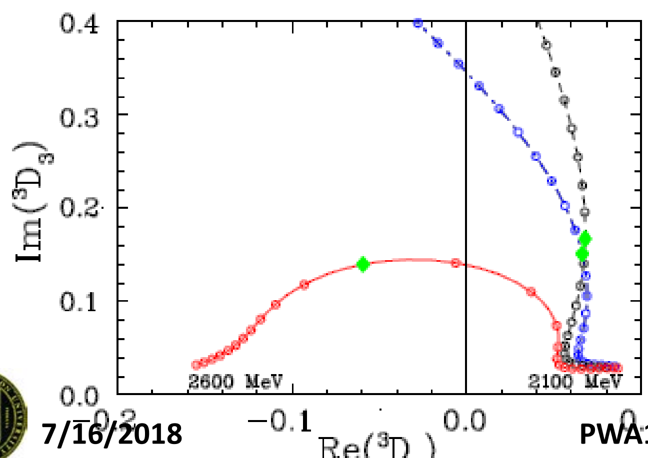
Evidence for a New Resonance from Polarized Neutron-Proton Scattering

P. Adlarson,[1] W. Augustyniak,[2] W. Bardan,[3] M. Bashkanov,[4,5] F. S. Bergmann,[6] M. Berłowski,[7] H. Bhatt,[8] M. Büscher,[9,10] H. Calén,[1] I. Ciepał,[3] H. Clement,[4,5] D. Coderre,[11,12,13,*] E. Czerwiński,[3] K. Demmich,[6] E. Doroshkevich,[4,5] R. Engels,[11,12] A. Erven,[14,12] W. Erven,[14,12] W. Eyrich,[15] P. Fedorets,[11,12,16] K. Föhl,[17] K. Fransson,[1] F. Goldenbaum,[11,12] P. Goslawski,[6] A. Goswami,[11,12,18] K. Grigoryev,[12,19,20] C.-O. Gullström,[1] F. Hauenstein,[15] L. Heijk... jöld,[1] V. Hejny,[11,12] M. Hodana,[3] B. Höistad,[1] N. Hüsken,[6] A. Jany,[3] B. R. Jany,[3] L. Jarczyk,[3] T. Johansson,[1] B. K... Kemmerling,[14,12] F. A. Khan,[11,12] A. Khoukaz,[6] D. A. Kirillov,[21] S. Kistryn,[3] H. Kleines,[14,12] B. Kłos,[22] ... ień,[3] P. Kulessa,[23] A. Kupść,[1,7] K. Lalwani,[8,†] D. Lersch,[11,12] B. Lorentz,[11,12] A. Magi... Marciniewski,[1] B. Mariański,[2] M. Mikirtychiants,[11,12,13,20] H.-P. Morsch,[2] P. Moskal ... anska,[3] E. Perez del Rio,[4,5] N. M. Piskunov,[21] ... suhn,[11,12] A. Pricking,[4,5] ... ysz,[23] A. Pyszniak,[1,3] C. F. Redmer,[1,‡] J. Ritman,[11,12,13] ... S. Sawant,[8,11,12] ... Sefzick,[11,12] V. Serdyuk,[11,12] V. Serdyuk,[11,12,24] R. Siudak,[23] ... kurzok,[3] J. Smyrs... ov,[16] R. Stassen,[11,12] J. Stepaniak,[7] E. Stephan,[22] G. Sterzenbach,[11,12] ... Ströher,[11,12] A. Sz...urek,[23] A. Täschner,[6] A. Trzciński,[2] R. Varma,[8] G. J. Wagner,[4,5] M. Wolke,[1] ... stner,[14,12] P. Wurm,[11,12] A. Yamamoto,[25] L. Yurev,[24,§] J. Zabierowski,[26] M. J. Zieliński,[3] A. Zink,[15] J. Złomańczuk,[1] P. Żupranski,[2] and M. Żurek[11,12]
(WASA-at-COSY Collaboration)

R. L. Workman,[27] W. J. Briscoe,[27] and I. I. Strakovsky[27]
(SAID Data Analysis Center)

Ay for $\bar{n}p \to np$





Physics Letters B 755 (2016) 92–96
Contents lists available at ScienceDirect
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Measurement of the absolute differential cross section of proton–proton elastic scattering at small angles

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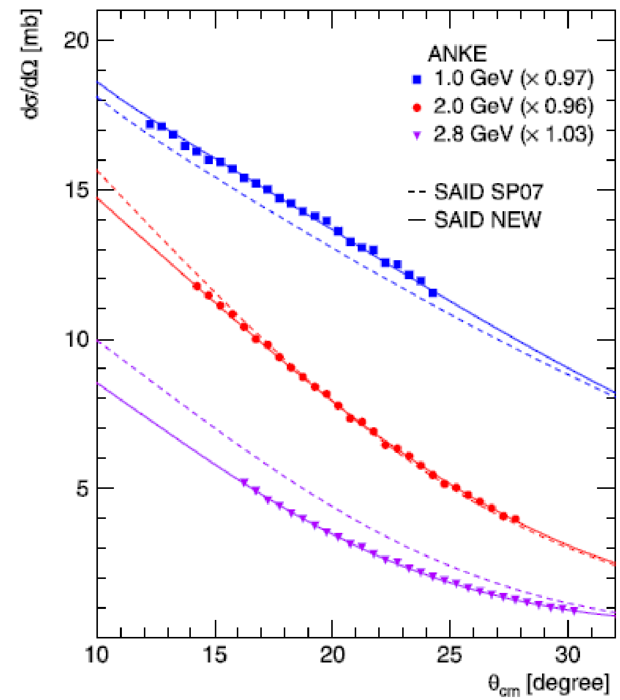
$d\sigma/d\Omega$ for $pp \to pp$



PHYSICAL REVIEW C 93, 045201 (2016)

Sensitivity of the COSY dibaryon candidate to *np* elastic scattering measurements

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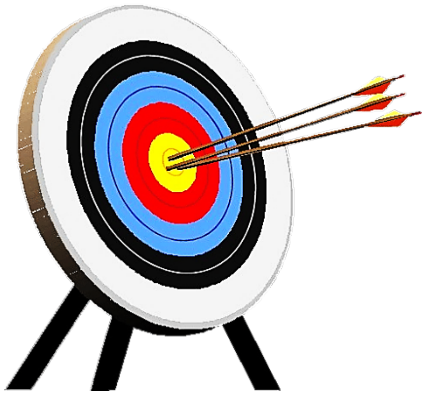
(Received 24 January 2016; published 1 April 2016)

Strange Hadron Spectroscopy with Secondary KL Beam at GlueX

Aims of Jlab KLF Project



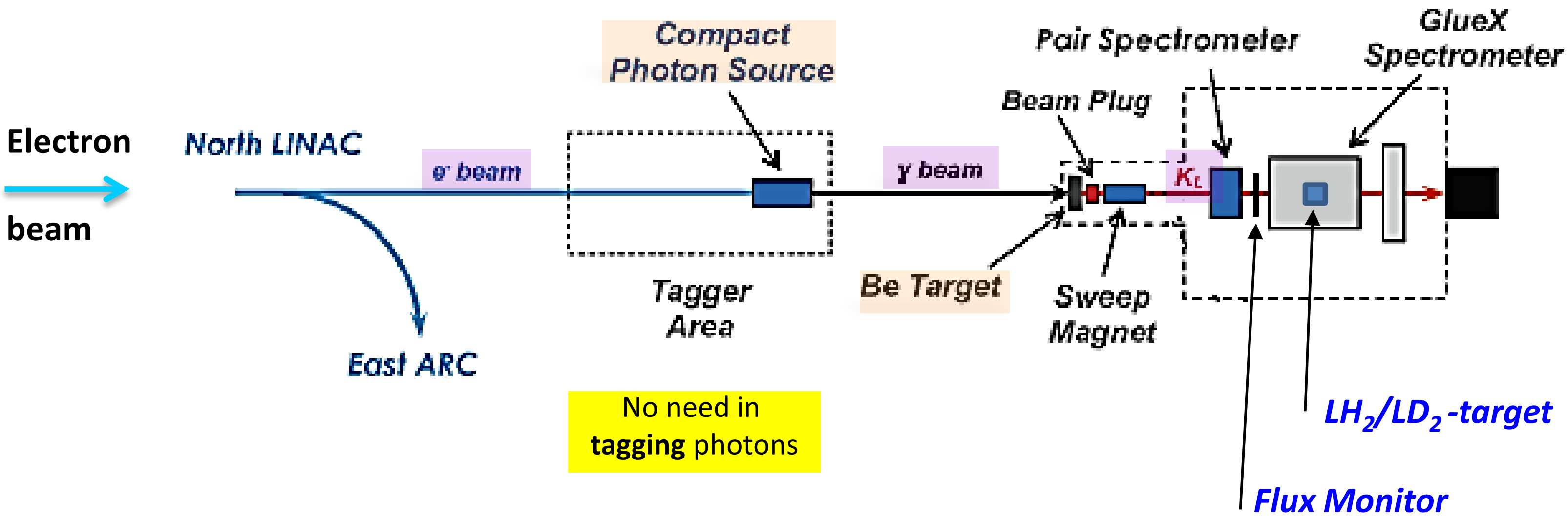
- **KLF** project has to **establish** secondary **K_L** beam line at Jefferson Lab Thomas Jefferson National Accelerator Facility with **flux** of ***three order of magnitude*** higher than SLAC NATIONAL ACCELERATOR LABORATORY had

- for scattering experiments on both **proton** & **neutron** (first time **!**) targets in order to determine **differential cross sections** & **self-polarization** of strange **hyperons** with GlueX detector to enable precise **PWA** in order to determine all **resonances** up to **3** GeV in spectra of **Λ***, **Σ***, **Ξ***, & **Ω***.

- In addition, we intend to do **strange meson spectroscopy** by studies of **π-K** interaction to locate **pole** positions in **I** = **1/2** & **3/2** channels.

- **KLF** has link to **ion-ion high energy** facilities as CERN & BROOKHAVEN NATIONAL LABORATORY & will allow understand formation of our world in **several microseconds** after **Big Bang**.

Hall D Beam Line Set up for K-longs



No need in **tagging** photons

I_e = **5** μA
W-radiator = **0.1** R.L.
Be-target = **1.7** R.L.

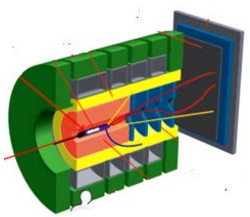
- **Electrons** are hitting **W**-radiator at **CPS**.
- **Photons** are hitting **Be**-target at **cave**.
- **K_Ls** are hitting the **LH_2/LD_2** target within **GLueX** setting.

Expected Cross Sections vs Bubble Chamber Data

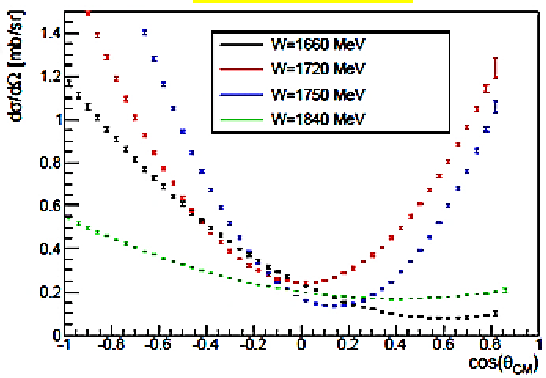
- **GlueX** measurements will span **cosθ** from **–0.95** to **0.95** in CM above **W** = **1490** MeV.

- K_L rate is 10^4 K_L/s = **2500 x** SLAC NATIONAL ACCELERATOR LABORATORY
- Uncertainties (statistics only) correspond to **100** days of running time for:

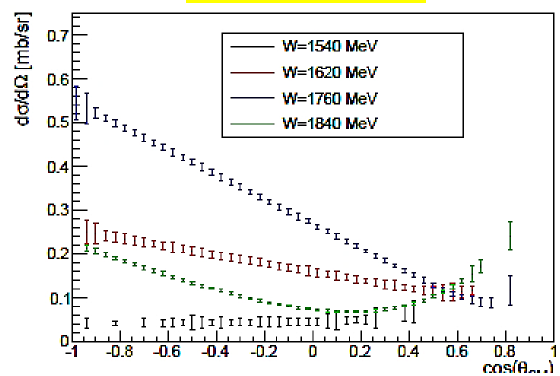
GEANT4 A SIMULATION TOOLKIT



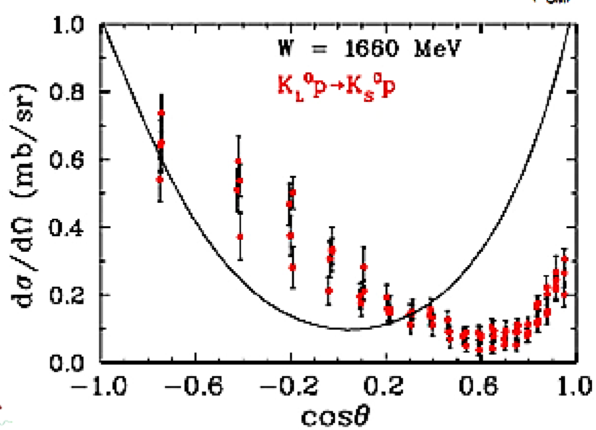
$K_Lp \to K_Sp$

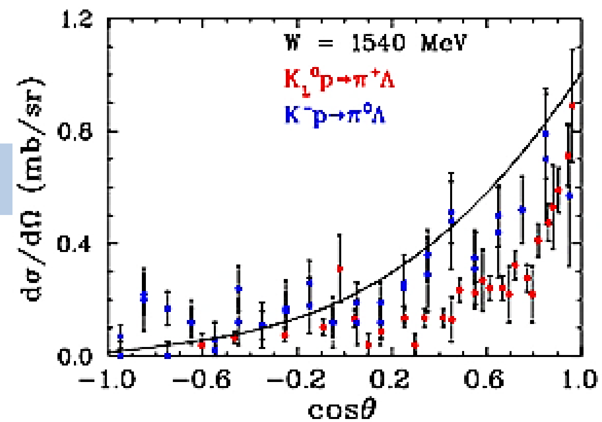


$K_Lp \to \pi^+\Lambda$



Expected GlueX Data





BC Data

Why We Have to Measure Double-Strange Cascades in JLab

- **Heavy quark symmetry** (**Isgur–Wise symmetry**) suggests that multiplet splittings in **strange**, **charm**, & **bottom hyperons** should scale as approximately inverses of corresponding **quark masses**: $\mathbf{1/m_s : 1/m_c : 1/m_b}$

N. Isgur & M.B. Wise, Phys Rev Lett **66** 1130 (1991)

- If they don't, that scaling failure implies that structures of corresponding states are **anomalous**, & very **different** from one another.

- So far only **hyperon** resonance multiplet, where this scaling can be ``tested" & seen is lowest **negative parity** multiplet:

$$\Lambda(1405)1/2^-–\Lambda(1520)3/2^-,\ \ \Lambda_c(2595)1/2^-–\Lambda_c(2625)3/2^-,\ \ \Lambda_b(5912)1/2^-–\Lambda_b(5920)3/2^-$$

- It works **approximately** (**30**%) well for those Λ-splittings. It would work **even better** for Ξ, Ξ_c, Ξ_b splittings, & should be **very good** for Ω, Ω_c, Ω_b splittings.

Particle	J^P	Overall status	Status as seen in — $\Xi\pi$	ΛK	ΣK	$\Xi(1530)\pi$	Other channels
$\Xi(1318)$	1/2+	****					Decays weakly
$\Xi(1530)$	3/2+	****	****				
$\Xi(1620)$		*	*				
$\Xi(1690)$		***		***	**		
$\Xi(1820)$	3/2−	***	**	***	**	**	
$\Xi(1950)$		***	**	**		*	
$\Xi(2030)$		***		**	***		
$\Xi(2120)$		*		*			
$\Xi(2250)$		**					3-body decays
$\Xi(2370)$		**					3-body decays
$\Xi(2500)$		*		*	*		3-body decays

- Jefferson Lab (Thomas Jefferson National Accelerator Facility) can do **double cascade** spectrum. As LHCb is doing **double charm cascade** spectrum.

$$\Xi_c(2790)1/2^-–\Xi_c(2815)3/2^-$$

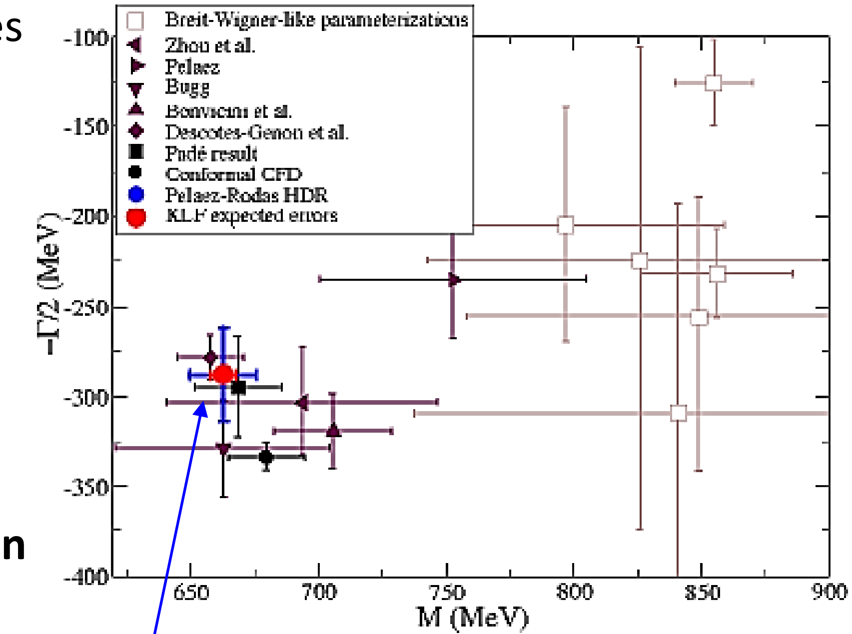
R. Aaij *et al*, Phys Rev Lett **119**, 112001 (2017)

Why We Have to Focus on $K\pi$ Scattering with Regards to κ Meson in JLab

- **KLF** proposal will have very significant impact in our knowledge of **Kπ** scattering amplitudes in scalar **I = ½** channel.

- It will reduce by more than factor of **two** uncertainty in **mass** determination & by a factor of **five** uncertainty on its **width** (and therefore on its coupling) of controversial or **k(800).**

- Neutral kaon beam scattering on both **proton** & **neutron** targets at low t-Mandelstam will allow to produce & identify **all four isospin partners of κ(800)**.



Expected **KLF** result

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Strange Hadron Spectroscopy with Secondary K_L Beam at GlueX

GlueX

A. Ali[18], M. B. Ali[47], M. J. Amaryan[45,*,†], E. G. Anassontzis[2], A. V. Anisovich[4,48],
A. Austregesilo[30], M. Baalouch[45], F. Barbosa[30], J. Barlow[13], A. Barnes[7], E. Barriga[13],
M. Bashkanov[10,†], A. Bazavov[39], T. D. Beattie[39], R. Bellwied[20], V. V. Berdnikov[8], V. Bernard[46],
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M. Hadžimehmedović[57], H. Hakobyan[53], A. Hamdi[18], S. Han[60], J. Hardin[36], A. Hayrapetyan[16],
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N. Jarvis[7], R. T. Jones[9], V. Kakoyan[61], G. Kalicy[8], M. Kamel[12], C. D. Keith[30], C. W. Kim[14],
F. J. Klein[14], B. Z. Kopeliovich[53], C. Kourkoumeli[2], G. Krafft[30], S. Kuleshov[53], I. Kuznetsov[54,55],
A. B. Laptev[33], I. Larin[35], D. Lawrence[30], D. I. Lersch[13], H. Leutwyler[3], M. Levillain[41], H. Li[7],
W. Li[59], K. Livingston[17], B. Liu[22], G. J. Lolos[50], V. E. Lyubovitskij[56,54,55,53], D. Mack[30],
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Hyperon & Strange Meson Spectroscopy

• Full **Proposal** was submitted for **JLab PAC46** .