Non-Strange & Strange Baryon Spectroscopy @ GW

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The George Washington University

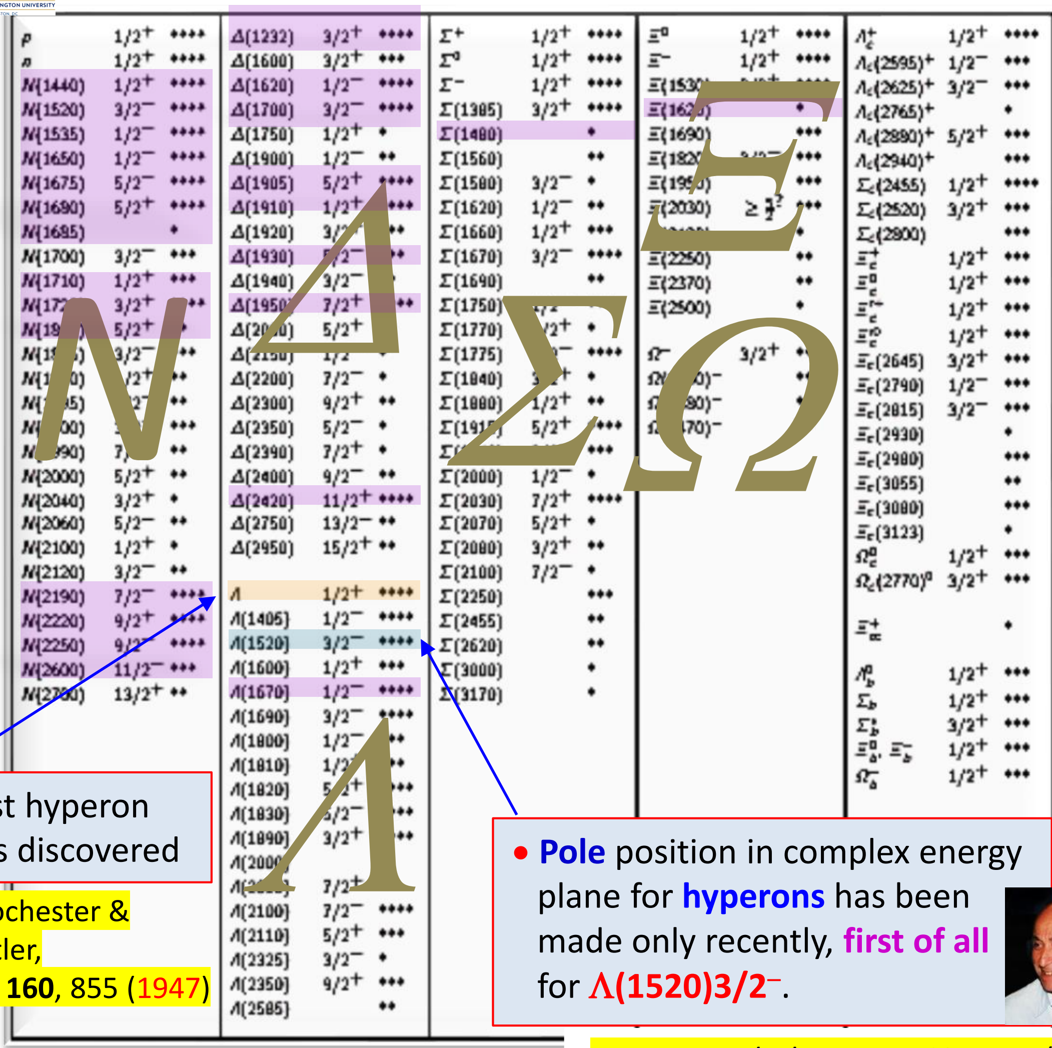
- **πN elastic** for Baryon Spectroscopy.
- **Pion PhotoProd** for Baryon Spectroscopy.
- **Pion ElectroProd** for Baryon Spectroscopy.
- **First pole** for hyperons from Hall A.
- **Very Strange** study with CLAS12.
- **KLF** study with GlueX.
- Summary.

Supported by DE-SC0016583

Baryon Sector @ PDG particle data group

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

GW Contribution for M. Tanabashi *et al,* Phys Rev D **98**, 030001 (2018)



p	$1/2^+$	****
n	$1/2^+$	****
$N(1440)$	$1/2^+$	****
$N(1520)$	$3/2^-$	****
$N(1535)$	$1/2^-$	****
$N(1650)$	$1/2^-$	****
$N(1675)$	$5/2^-$	****
$N(1680)$	$5/2^+$	****
$N(1685)$		*
$N(1700)$	$3/2^-$	***
$N(1710)$	$1/2^+$	***
$N(172$[illegible]$)$	$3/2^+$	[illegible]
$N(18$[illegible]$)$	$5/2^+$	[illegible]
$N(1$[illegible]$)$	$3/2^-$	[illegible]
$N(1$[illegible]$)$	[illegible]	[illegible]
$N($[illegible]$5)$	[illegible]	**
$N($[illegible]$00)$	[illegible]	***
$N($[illegible]$90)$	[illegible]	**
$N(2000)$	$5/2^+$	**
$N(2040)$	$3/2^+$	*
$N(2060)$	$5/2^-$	**
$N(2100)$	$1/2^+$	*
$N(2120)$	$3/2^-$	**
$N(2190)$	$7/2^-$	****
$N(2220)$	$9/2^+$	****
$N(2250)$	$9/2^-$	****
$N(2600)$	$11/2^-$	***
$N(27$[illegible]$)$	$13/2^+$	**

$\Delta(1232)$	$3/2^+$	****
$\Delta(1600)$	$3/2^+$	***
$\Delta(1620)$	$1/2^-$	****
$\Delta(1700)$	$3/2^-$	****
$\Delta(1750)$	$1/2^+$	*
$\Delta(1900)$	$1/2^-$	**
$\Delta(1905)$	$5/2^+$	****
$\Delta(1910)$	$1/2^+$	[illegible]
$\Delta(1920)$	[illegible]	[illegible]
$\Delta(1930)$	[illegible]	[illegible]
$\Delta(1940)$	$3/2^-$	[illegible]
$\Delta(195$[illegible]$)$	$7/2^+$	[illegible]
$\Delta(2$[illegible]$)$	$5/2^+$	[illegible]
$\Delta($[illegible]$)$	[illegible]	[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]
$\Lambda(1810)$	[illegible]	[illegible]
$\Lambda(1820)$	[illegible]	[illegible]
$\Lambda(1830)$	[illegible]	[illegible]
$\Lambda(1890)$	$3/2^+$	[illegible]
$\Lambda(200$[illegible]$)$	[illegible]	[illegible]
$\Lambda($[illegible]$)$	$7/2^+$	[illegible]
$\Lambda(2100)$	$7/2^-$	****
$\Lambda(2110)$	$5/2^+$	***
$\Lambda(2325)$	$3/2^-$	*
$\Lambda(2350)$	$9/2^+$	***
$\Lambda(2585)$		**

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]	*
$\Sigma(1775)$	[illegible]	****
$\Sigma(1840)$	[illegible]	*
$\Sigma(1880)$	$1/2^+$	**
$\Sigma(191$[illegible]$)$	$5/2^+$	[illegible]
$\Sigma($[illegible]$)$	[illegible]	***
$\Sigma(2000)$	$1/2^-$	*
$\Sigma(2030)$	$7/2^+$	****
$\Sigma(2070)$	$5/2^+$	*
$\Sigma(2080)$	$3/2^+$	**
$\Sigma(2100)$	$7/2^-$	*
$\Sigma(2250)$		***
$\Sigma(2455)$		**
$\Sigma(2620)$		**
$\Sigma(3000)$		*
$\Sigma(3170)$		*

Ξ^0	$1/2^+$	****
Ξ^-	$1/2^+$	****
$\Xi(153$[illegible]$)$	[illegible]	[illegible]
$\Xi(162$[illegible]$)$		*
$\Xi(1690)$		***
$\Xi(182$[illegible]$)$	[illegible]	***
$\Xi(195$[illegible]$)$		***
$\Xi(2030)$	$\geq \frac{5}{2}^?$	***
[illegible]		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-	$3/2^+$	[illegible]
$\Omega($[illegible]$)^-$		[illegible]
$\Omega($[illegible]$80)^-$		[illegible]
$\Omega($[illegible]$70)^-$		

Λ_c^+	$1/2^+$	****
$\Lambda_c(2595)^+$	$1/2^-$	***
$\Lambda_c(2625)^+$	$3/2^-$	***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2880)^+$	$5/2^+$	***
$\Lambda_c(2940)^+$		***
$\Sigma_c(2455)$	$1/2^+$	****
$\Sigma_c(2520)$	$3/2^+$	***
$\Sigma_c(2800)$		***
Ξ_c^+	$1/2^+$	***
Ξ_c^0	$1/2^+$	***
$\Xi_c^{\prime +}$	$1/2^+$	***
$\Xi_c^{\prime 0}$	$1/2^+$	***
$\Xi_c(2645)$	$3/2^+$	***
$\Xi_c(2790)$	$1/2^-$	***
$\Xi_c(2815)$	$3/2^-$	***
$\Xi_c(2930)$		*
$\Xi_c(2980)$		***
$\Xi_c(3055)$		**
$\Xi_c(3080)$		***
$\Xi_c(3123)$		*
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

G.D. Rochester & C.C Butler, Nature **160**, 855 (1947)

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

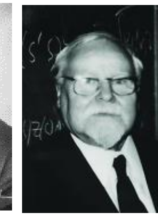
Y. Qung *et al,* Phys Lett B **694**, 123 (2010)

- **PDG18** has **109 Baryon Resonances** (**64** 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**).

Jefferson Lab — Thomas Jefferson National Accelerator Facility

Phenomenology 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**.

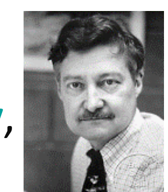
- **Resonances** appeared as **by-product**
  [bound states objects with definite quantum numbers, mass, lifetime, & so on].

- **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.

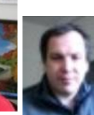
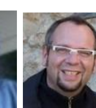
PDG particle data group

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 & **KentState**.





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

for $\pi N \rightarrow \pi N$ & $\pi^- p \rightarrow \eta n$

R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **74**, 045205 (2006)

- Energy dependent SP06/WI08 and associated SES
- T = 0 – 2600 MeV
- 4-channel Chew-Mandelstam K-matrix parameterization
- DR constraint
- 3 mapping variables: $g^2/4\pi$, $a[\pi^- p]$, η–th
- PWs = 30 πN {15 [I=1/2] + 15 [I=3/2]} + 4 ηN
- Prms = 99 [I=1/2] + 89 [I=3/2]

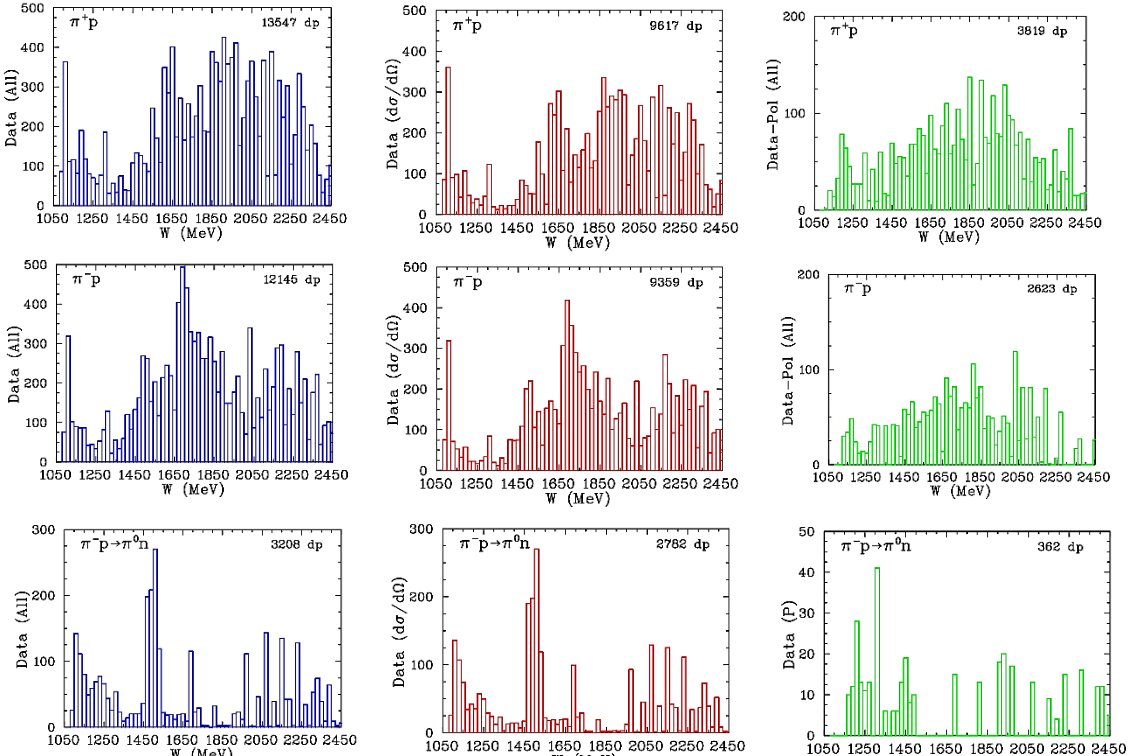
[W = 1078 – 2460 MeV]
[πN, $\pi\Delta$, ρN, ηN]

[l < 9]

$\pi^+ p \rightarrow \pi^+ p$

$\pi^- p \rightarrow \pi^- p$

$\pi^- p \rightarrow \pi^0 n$



10 data/MeV

Pol=28%

Pol=22%

Pol=11%

Recent for $\pi^{\mp}p \to \pi^{\mp}p$

I. Alekseev *et al*, Phys Rev C **91**, 025205 (2015)

- New precise cross section measurements: $\Delta\sigma$ = **0.5%** stat, Δp = **1 MeV**, $\Delta\vartheta = \pm 1^{o}$

PHYSICAL REVIEW C 91, 025205 (2015)

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

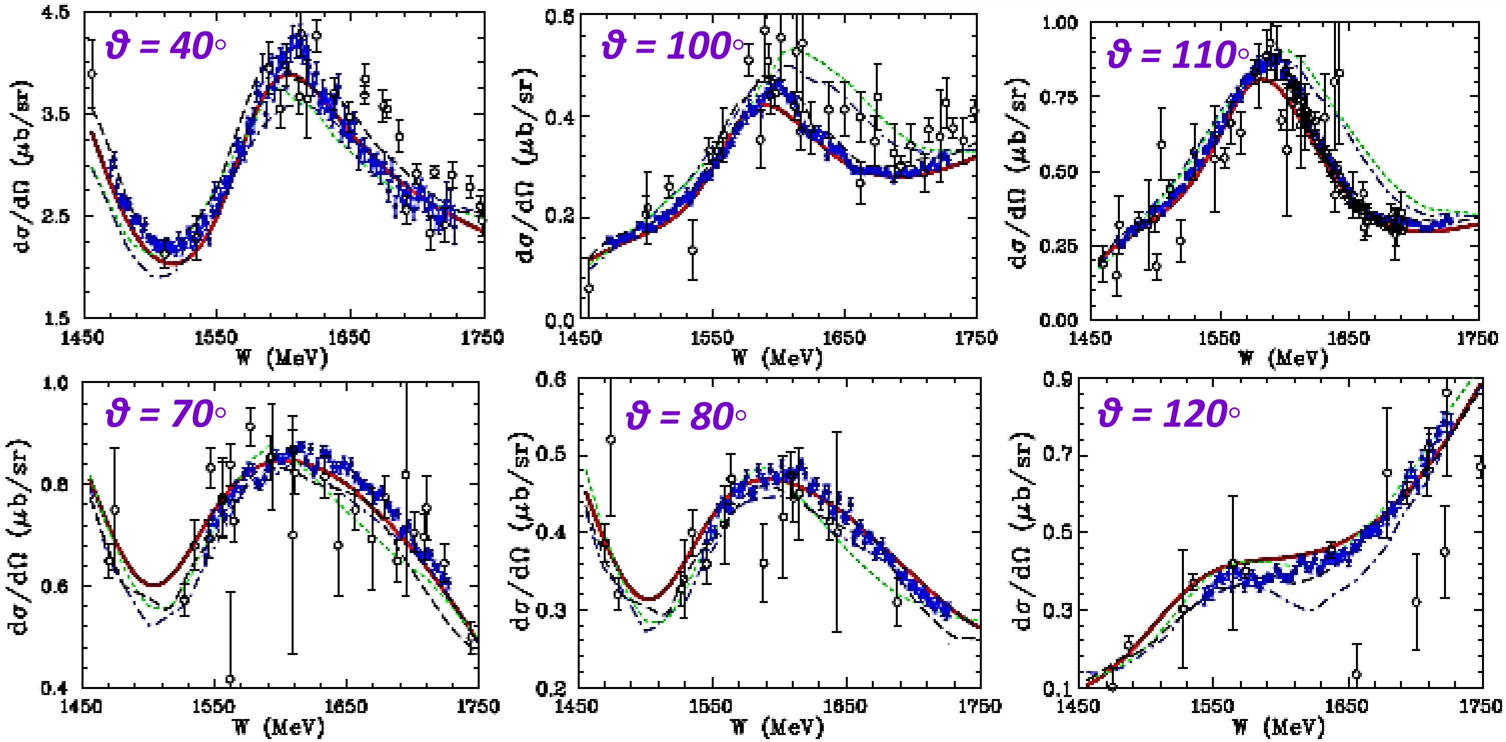
I. G. Alekseev,[1] V. A. Andreev,[3] I. G. Bordyuzhin,[1,5] W. J. Briscoe,[2] Ye. A. Filimonov,[3] V. V. Golubev,[3] A. B. Gridnev,[3] D. V. Kalinkin,[1] L. I. Koroleva,[1] N. G. Kozlenko,[3] V. S. Kozlov,[3] A. G. Krivshich,[3] B. V. Morozov,[1] V. M. Nesterov,[1] D. V. Novinsky,[3] V. V. Ryltsov,[1] 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 Analysis Center)

$\pi^- p \to \pi^- p$

4277 $d\sigma/d\Omega$:
800 – 1243 MeV/c
40 – 122 deg

$\pi^+ p \to \pi^+ p$

2638 $d\sigma/d\Omega$:
918 – 1240 MeV/c
40 – 122 deg



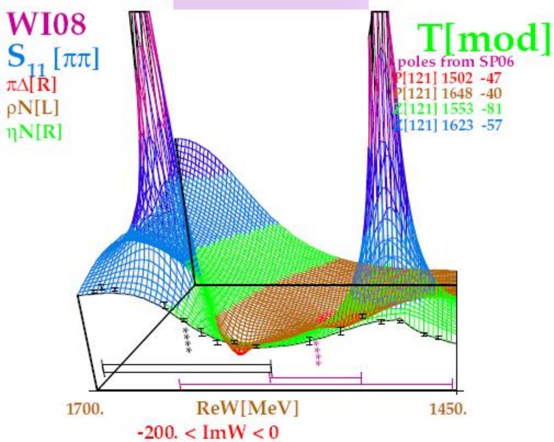
- **CMB** analysis significantly more **predictive** when compared to versions of **KH** analyses.

Predictions: WI08, KH80, KA84, CMB

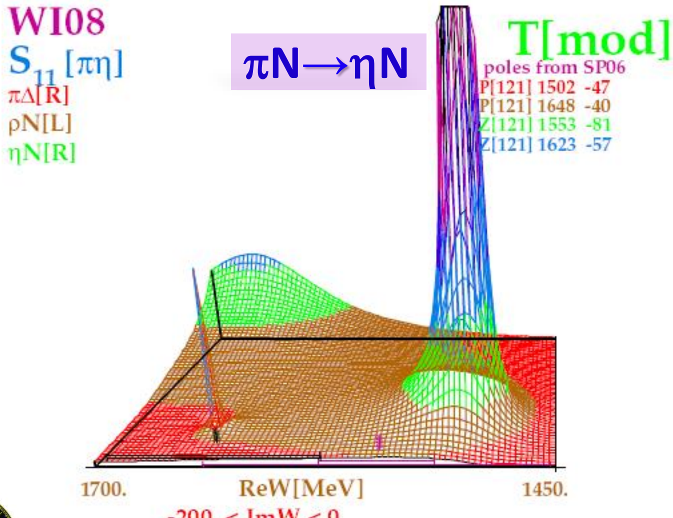
Determination Pole Positions & Residues for πN scattering amplitudes

R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **74**, 045205 (2006)

πN→πN



πN→ηN



- **Interpretation** of **PW amplitudes** may appear not simple.
- **Resonances** found through search for **Poles** in **complex plane** are not put in by hand, contrary to **BW** parameterization.
- There is **shift** between **Pole** & **BW mass** (**0** – **10**%) & **width**.

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]

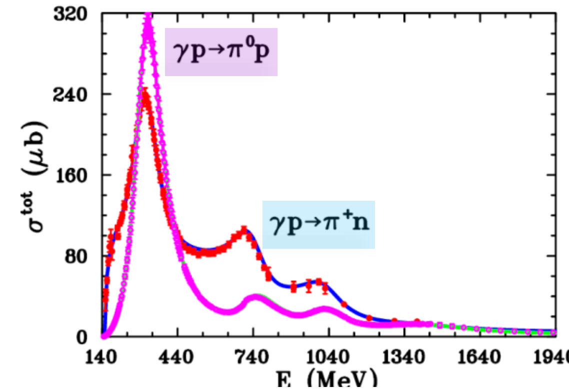
GW **SAID** PWA facility allows

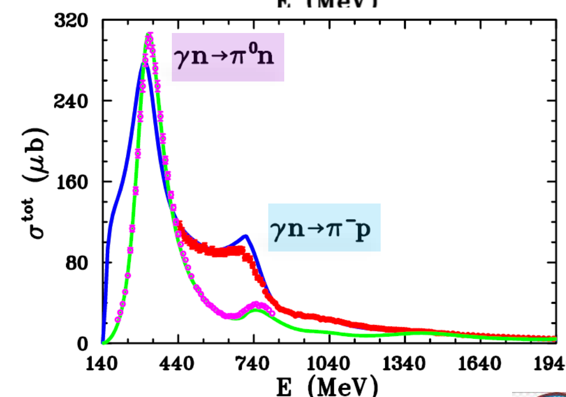
- To **fit** new data vs World Database.
- To validate **acceptance** & **flux** of new measurements.
- To validate **systematics**.
- To provide realistic event **generator** for MC simulations.

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





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

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

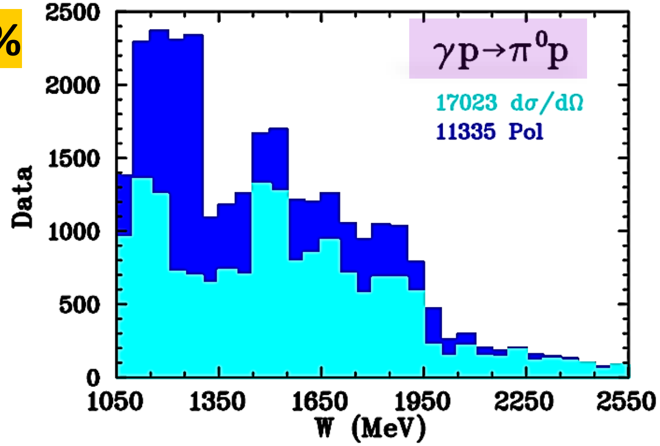
World Progress in Pion PhotoProduction

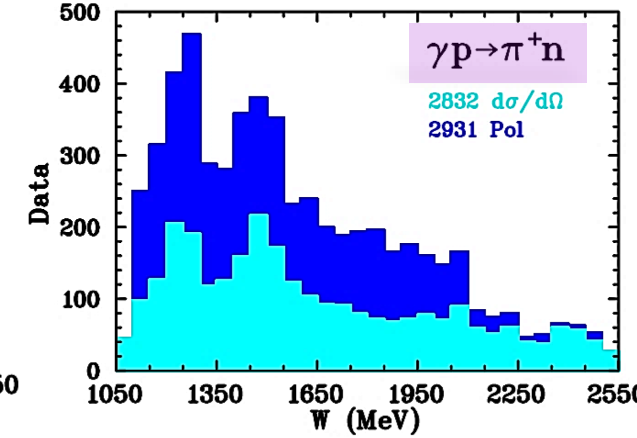
1996–2018

Pol = 40%

Pol = 51%

π^+n/π^0p = 20%

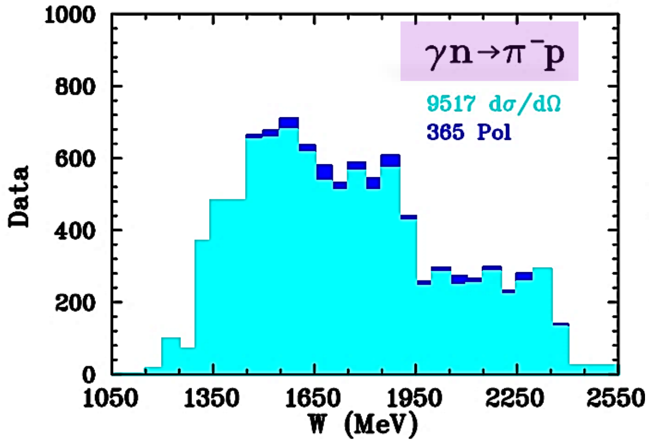


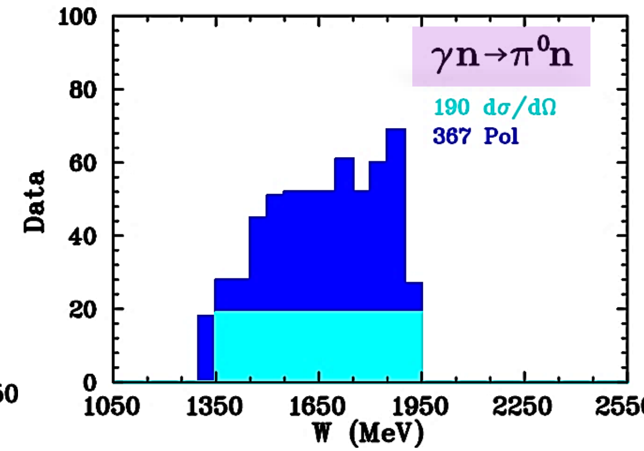


Pol = 4%

Pol = 66%

π^-p/π^0n = 6%

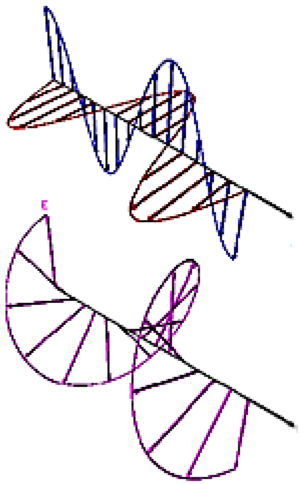




- There is disbalance between π^0p & π^+n data, π^+n / π^0p=20%.
- Pion photoproduction on **neutron** much less known, **n /p**=31%.

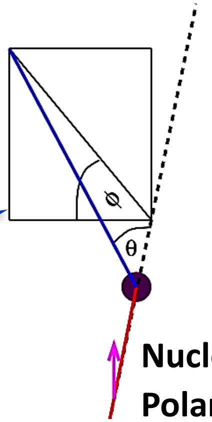
Complete Experiment for Pion PhotoProduction

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



Linear Polarized *Beam*

Circular Polarized *Beam*



Nucleon *Recoil* Polarization

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

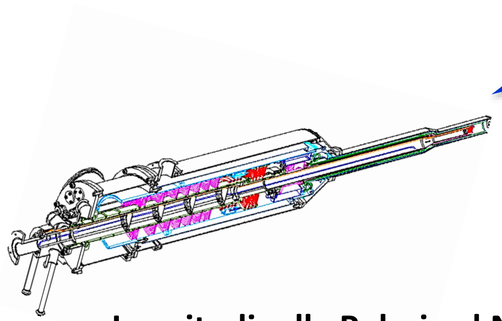
1 un-pol measurement: **$d\sigma/d\Omega$**

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



Longitudinally Polarized Nucleon *Target*

Transverse Polarized Nucleon *Target*

A. Sandorfi *et al*, AIP Conf. Proc. **1432**, 219 (2012)
K. Nakayama, arXiv:1903.05015, 2019

Single Pion PhotoProduction on "Neutron" Target

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

- Only with good data on both **proton** & **neutron** **targets**, one can hope to disentangle **isoscalar** & **isovector** **EM** couplings of various **N^***& **Δ^*** resonances,
as well as **isospin** properties of non-resonant **background amplitudes**.

K.M. Watson, Phys Rev **95**, 228 (1954); R.L. Walker, Phys Rev **182**, 1729 (1969)

- The lack of **$\gamma n\to\pi^- p$** & **$\gamma n\to\pi^0 n$** data does not allow us to be as confident about determination of **neutron** couplings relative to those of **proton**.

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



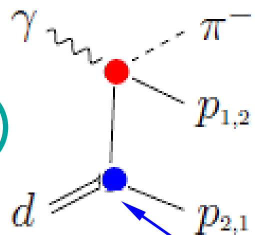
A.B. Migdal, JETP **1**, 2 (1955); K.M. Watson, Phys Rev **95**, 228 (1954)

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

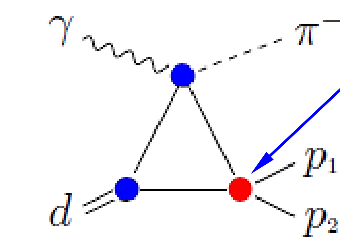
V. Tarasov, A. Kudryavtsev, W. Briscoe, H. Gao, IS, Phys Rev C **84,** 035203 (2011)
V. Tarasov, A. Kudryavtsev, W. Briscoe, B. Krusche, IS, M. Ostrick, Phys At Nucl **79**, 216 (2016)

- **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**).

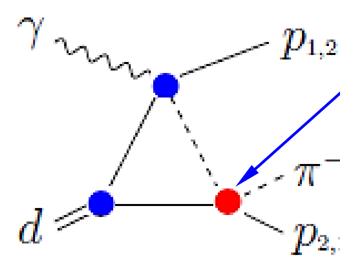
IA



Fermi Smearing

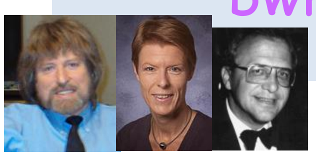


NN-fsi vertex



πN-fsi vertex

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



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

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

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

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

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

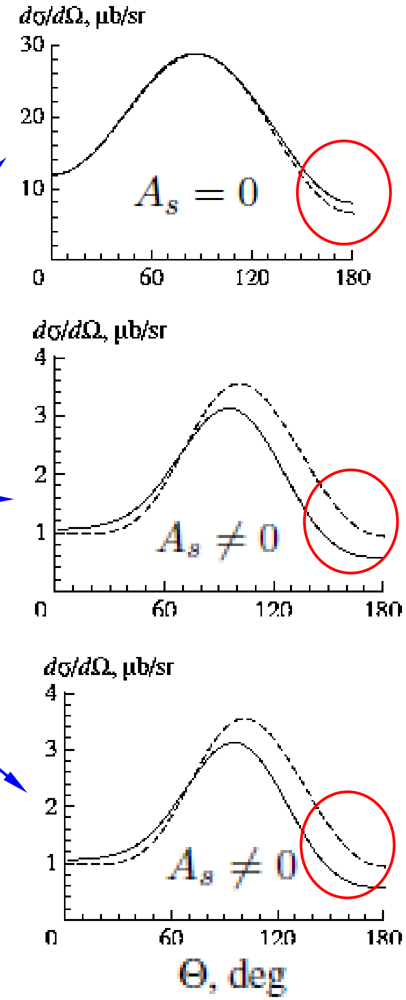
$$A(\gamma p \to \pi^0 p) = A_v + A_s$$
$$A(\gamma n \to \pi^0 n) = A_v - A_s$$

- 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 $A_v = 0$

$R_n = R_p$



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

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

Δ(1232)3/2+

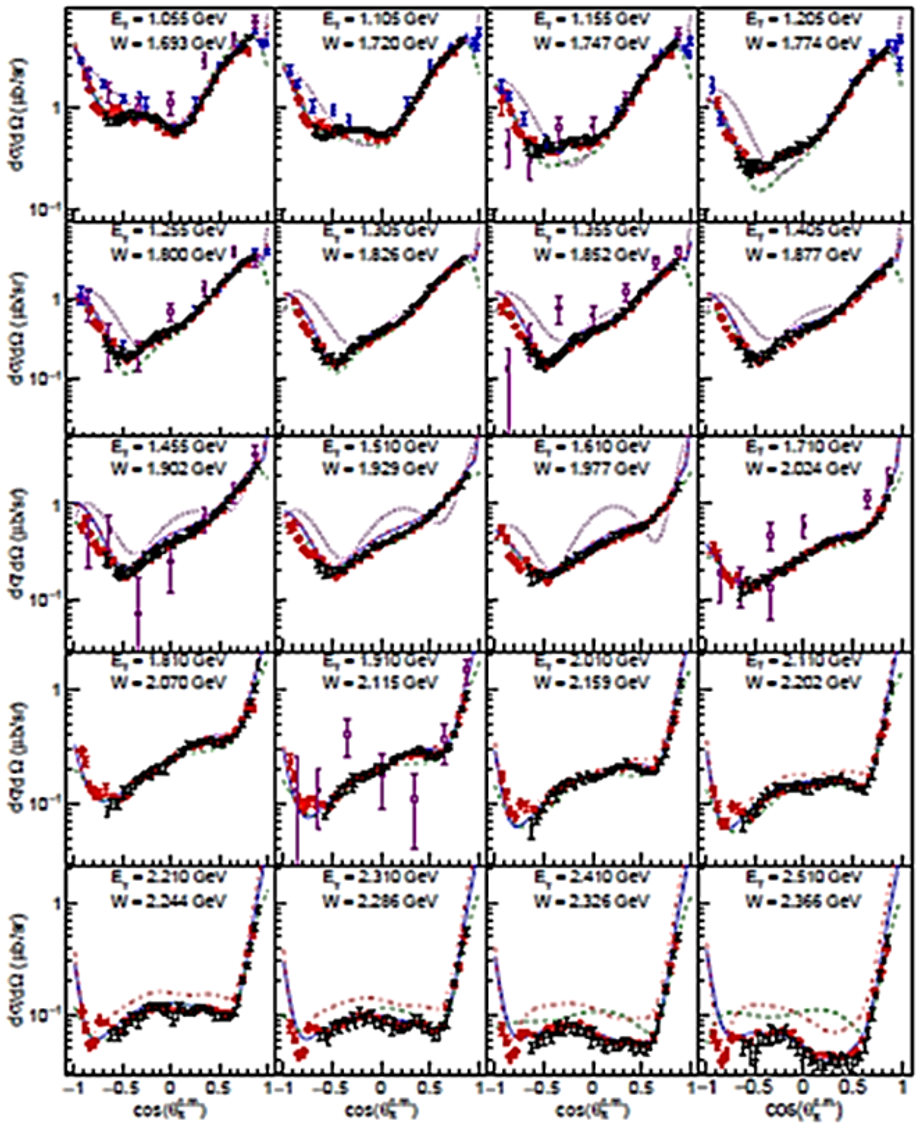
N(1440)1/2+

N(1535)1/2–

- In general case, $R_n \neq R_p$

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

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



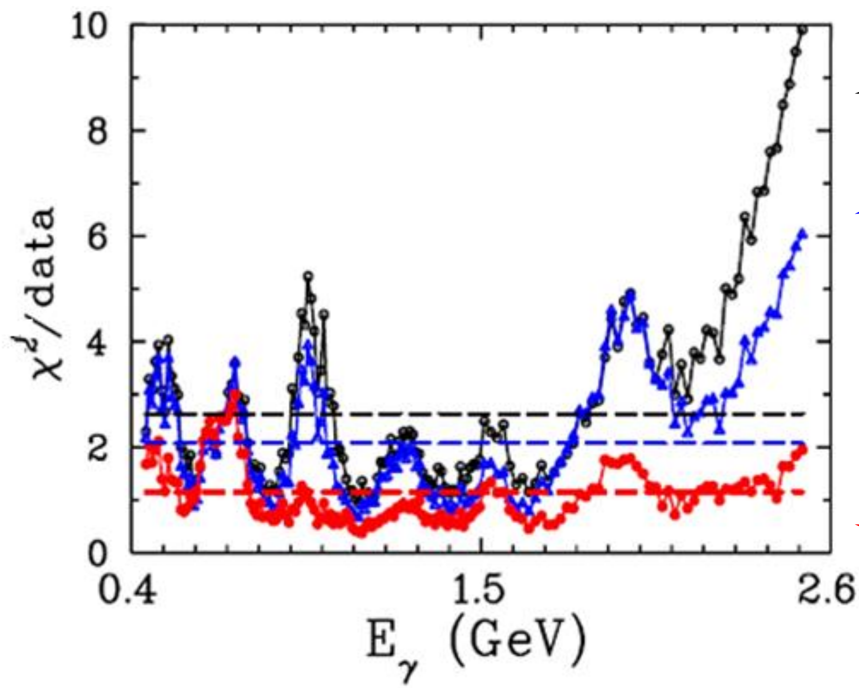
E = 445–2510 MeV
π^-p: 8428 dσ/dΩ

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

FSI included

Comparison of Previous & New Fits for g13

MA27: P. Mattione *et al*, Phys. Rev. C **96**, 035204 (2017)
PR15: P. Adlarson *et al*, Phys Rev C **92**, 024617 (2015)



- Recent SAID **PR15** applied to **g13** data **without** & **with FSI** corrections.

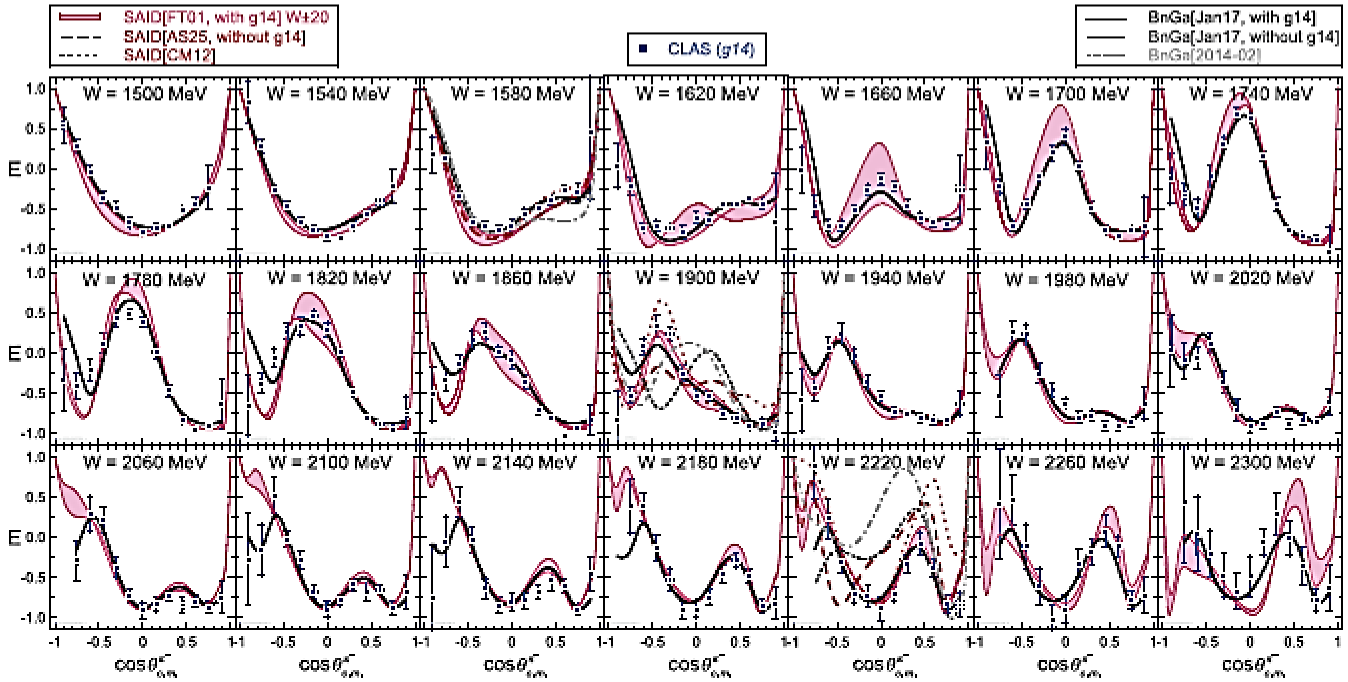
- New SAID **MA27** fit obtained after adding new **g13** data **with FSI** corrections.

Karl Pearson

- Obviously, **FSI** plays important role in $\gamma n \to \pi^- p$ $d\sigma/d\Omega$ determination.
- Same for $\gamma n \to \pi^0 n$ $d\sigma/d\Omega$.

g14 Data Impact for Neutron
S = 0 & I = ½ Couplings

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

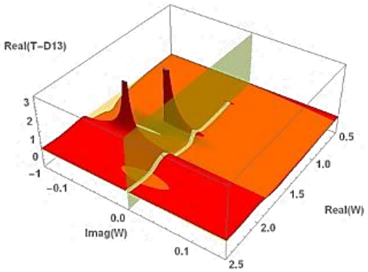


E = **730–2345** MeV
π⁻p: **266 E**

Assumption is FSI is small

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

MA27: 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 particle data group
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

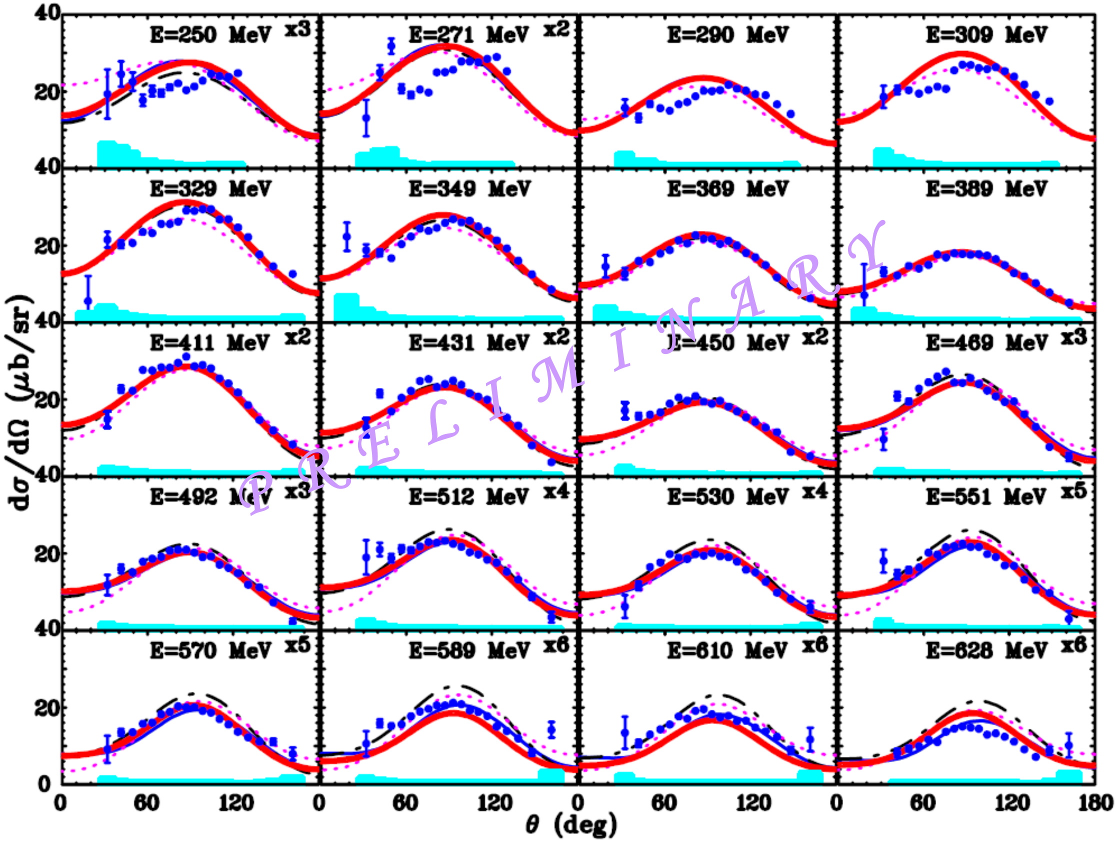
MAID

A2 Meson Production off Deuteron with CB @ MAMI

M. Martemianov *et al*, in progress

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

E = 200 – 800 MeV
$\pi^0 n$: 523 $d\sigma/d\Omega$



FSI included

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

PDG particle data group

N(1680)5/2$^+$→Nγ

pA$^{3/2}$=+133 ±12 **pA$^{1/2}$**=−15 ±6
nA$^{3/2}$=−33 ±9 **nA$^{1/2}$**=+29 ±10

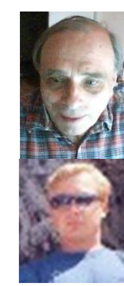
- It couples **weakly** to **neutron**.

N(1675)5/2$^-$→Nγ

pA$^{3/2}$=+20 ±5 **pA$^{1/2}$**=+19 ±8
nA$^{3/2}$=−85 ±10 **nA$^{1/2}$**=−60 ±5

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

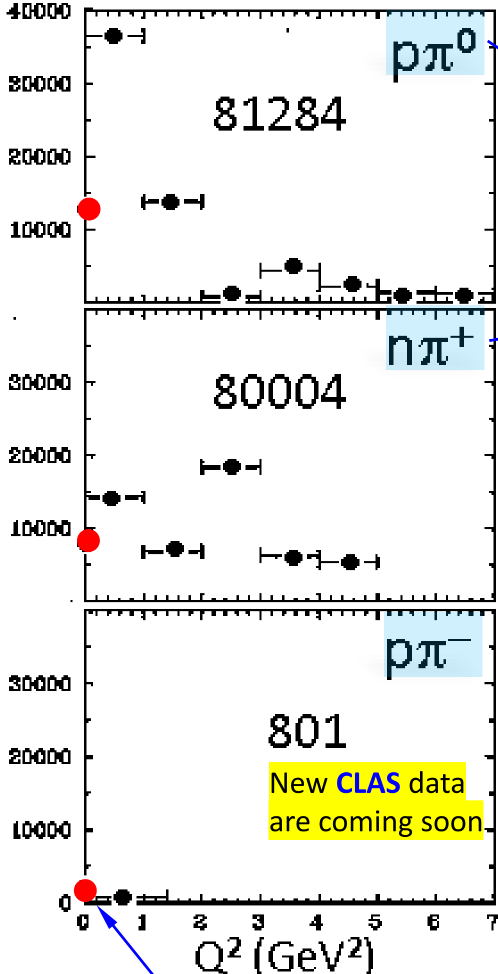
- New **dσ/dΩ**s by **A2** contribution is **200%** to previous world **$\pi^0 n$** data.



World Neutral & Charged PionEPR Data

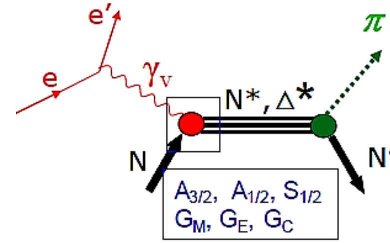
R. Arndt, W. Briscoe, M. Paris, IS, R. Workman, Chin Phys C **33**, 1063 (2009)

W < 2 GeV @ 2009



Pion PhotoProduction

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



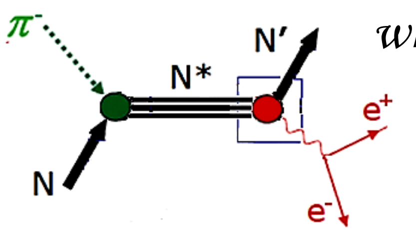
reaction	data	χ^2
$\gamma^* p \to \pi^0 p$	55,766	81,284
$\gamma^* p \to \pi^+ n$	51,312	80,004
redundant	14,772	17,375
total	124,453	178,663
$\gamma p \to \pi N$	24,888	50,684
all photo	159,341	229,317
$\pi N \to \pi N$	31,876	57,255
all πN	191,217	286,572

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

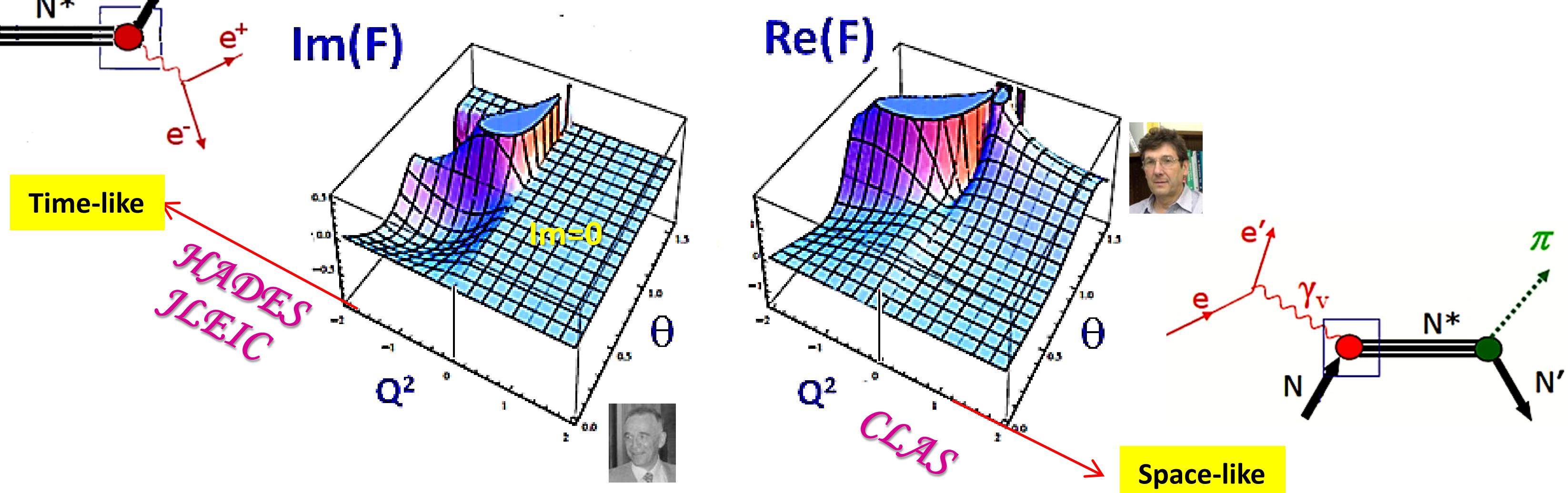
Form-Factor Measurements

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

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



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

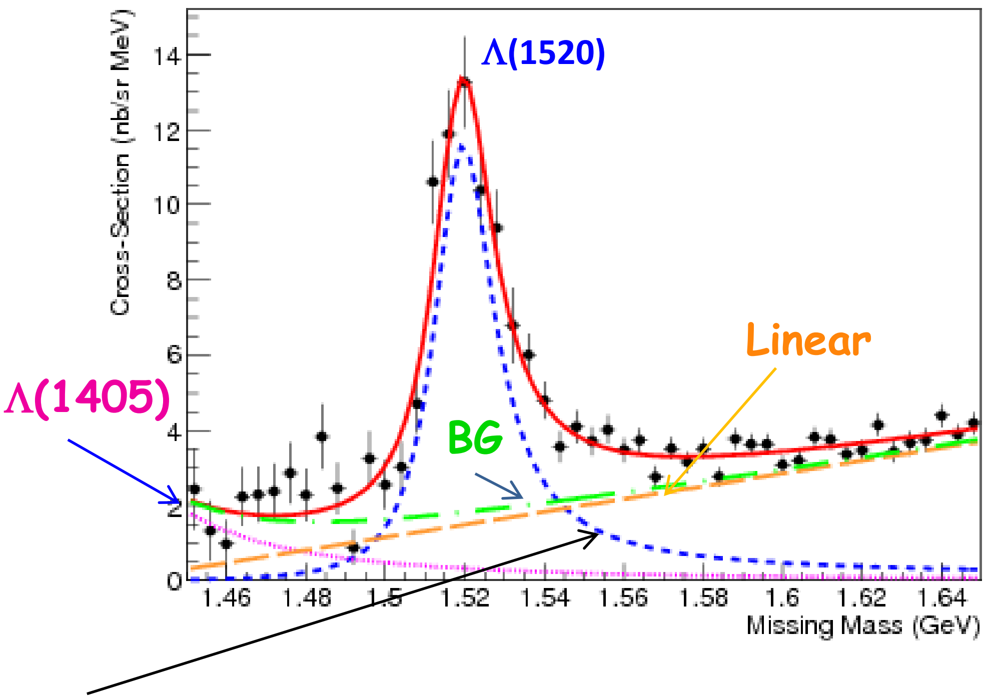


- $\pi^- p \to e^+ e^- n$ measurements will significantly complement current **electroproduction**.
- $\gamma^* N \to \pi N$ study for evolution of **baryon** properties with increasing momentum transfer by investigation of case for ***time-like virtual photon***.

Hall A Results for $\Lambda(1520)$

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

- $e + p \to e' + K^+(\pi^+,K^-) + MM$ [**Hall A**: **E** = **5.09** GeV **Q^2** ~ **0.1** $(GeV/c)^2$ **Statistics** = **13k**]
- In fitting, we applied MM resolution, σ = **1.5** MeV
- We did not take into account any **Res** with M > **1670** MeV



BW [Asymmetry form due to $\Gamma(W)$]

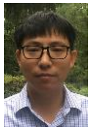
- **BW** with **Least-Squares** & **Log-Likelihood**

M = 1520.4 ± 0.6 ± **1.0** MeV
Γ= 18.6 ± 1.9 ± **1.0** MeV

- **Pole** position

M = 1518.3 MeV
Γ= 17.2 MeV

- Having **BW** mass & width, we also give **first** estimate of **pole** parameters for **$\Lambda(1520)$**.
- **Pole** values for both mass & width tend to be lower than **BW** values.



Cross Section Estimations for Jefferson Lab *(RGA)*

Thomas Jefferson National Accelerator Facility

E12-11-005a

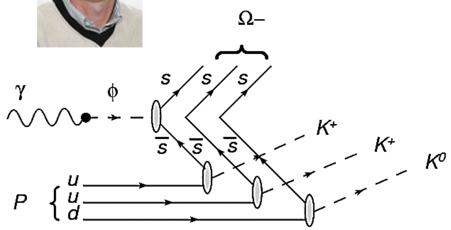
- **Andrey Afanasev:**

  Translation hadronic into EM Xsec:
  - SLAC $K^-p \to \Xi^-X$ Xsec,
  - ϕ-VMD,
  - CLAS $\gamma p \to \Xi^-KK$ Xsec

  ➡ **σ ~ 0.4 nb**

  - SLAC $K^-p \to \Xi^-X$,
  - $K^-p \to \Omega^-X$ Xsec,
  - CLAS $\gamma p \to \Xi^-KK$ Xsec

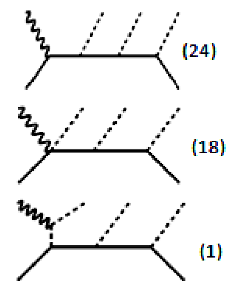
  ➡ **σ ~ 0.5 nb**



- **Winston Roberts:**

  Phenomenological Lagrangian:
  - Not all couplings known
  - Born terms are in

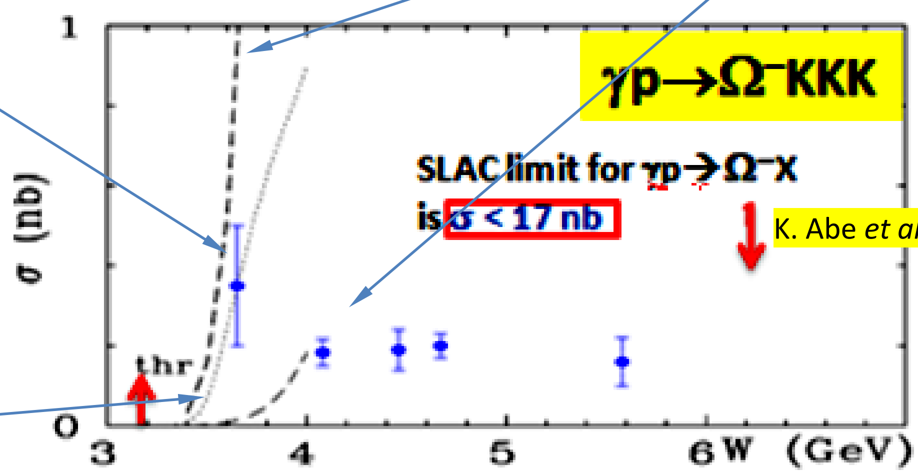
  ➡ **σ ~ 0.2–1 nb**



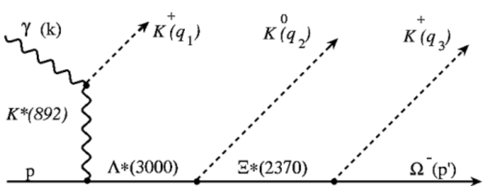
- **Vitaly Shklyar:**

  Effective Lagrangian:
  There are three additional diagrams obtained by permutations of final Kaon momenta

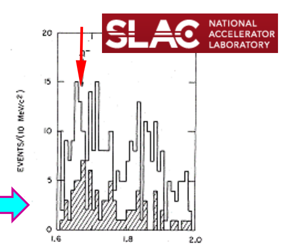
➡ **σ ~ 2 nb**



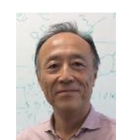
K. Abe *et al* Phys Rev D **32**, 2869 (1985)

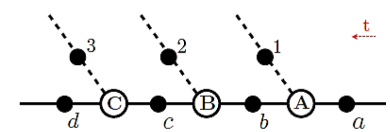


No Ω-signal is seen ➡



- Alternative Xsec estimation came recently, it resulted in **~1 pb**.





H. Y. Ryu *et al*, PoS Hadron **2013**, 140 (2013)

Why We Have to Measure Double-Strange Cascades in Jefferson Lab

- **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:

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

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

PDG particle data group

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

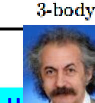
Courtesy of Dan-Olof Riska, 2017

- Jefferson Lab can do **double cascade** spectrum. As LHCb is doing **double charm cascade** spectrum.

$$\Xi_c(2790)1/2^-\text{–}\Xi_c(2815)3/2^-$$

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

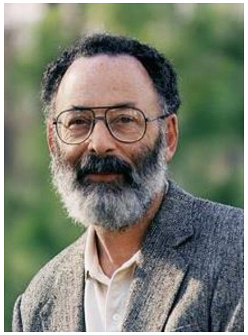
See Moskov Amaryan's talk



Spectroscopy of Baryons

It is clear that we still need much more information about the existence and parameters of many baryon states, especially in the N=2 mass region, before this question of non-minimal SU(6) x O(3) super-multiplet can be settled. **Richard Dalitz**, **1976**.

The first problem is the notion of a resonance is not well defined. The ideal case is a narrow resonance far away from the thresholds, superimposed on slowly varying background. It can be described by a Breit-Wigner formula and is characterized by a pole in the analytic continuation of the partial wave amplitude into the low half of energy plane. **Gerhard Höhler, 1987**.



*Why N*s are important – The first is that nucleons are the stuff of which our world is made. My second reason is that they are simplest system in which the quintessentially non-Abelian character of QCD is manifest. The third reason is that history has taught us that, while relatively simple, Baryons are sufficiently complex to reveal physics hidden from us in the mesons*. **Nathan Isgur**, **2000**.

Thank you for invitation & your attention

First Baryon Resonance Discovery

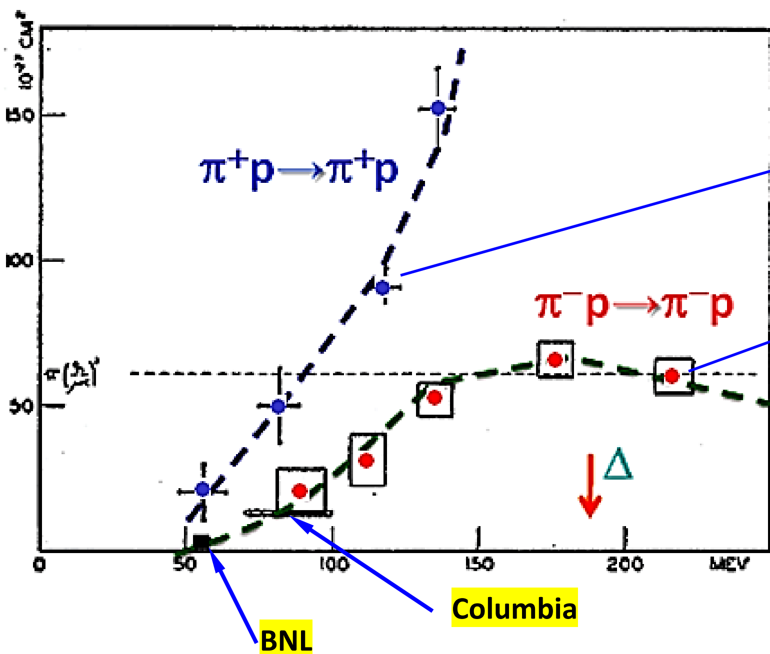
936 LETTERS TO THE EDITOR

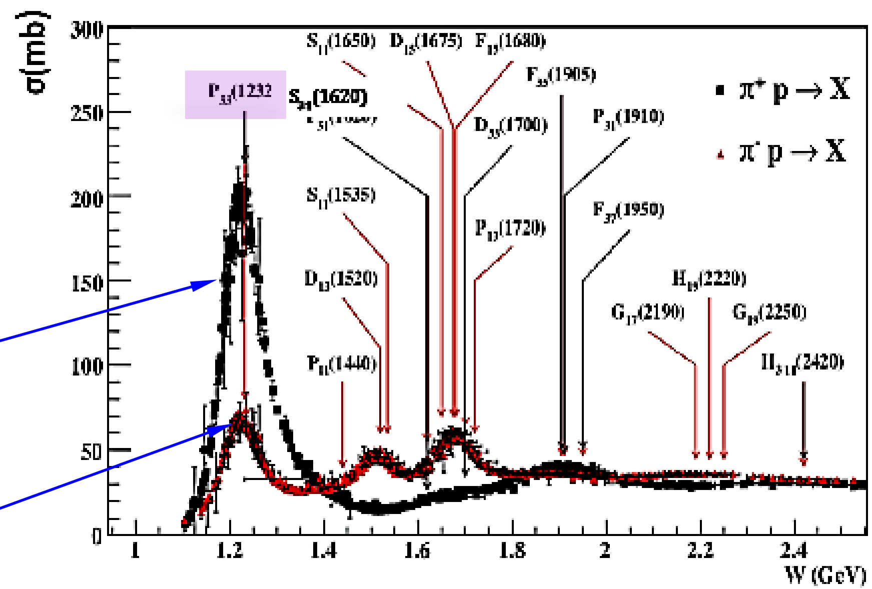
Total Cross Sections of Positive Pions in Hydrogen*

H. L. ANDERSON, E. FERMI, E. A. LONG,† AND D. E. NAGLE
Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received January 21, 1952)

Δ(1232)3/2+





• Then, since **1952** many **states** were **discovered**.

• Charged **Pions** were discovered in **1947**.

*There are Many Ways to Study N**

Prolific source of N* & Δ* baryons

Measure many channels with different combinations of quantum numbers.

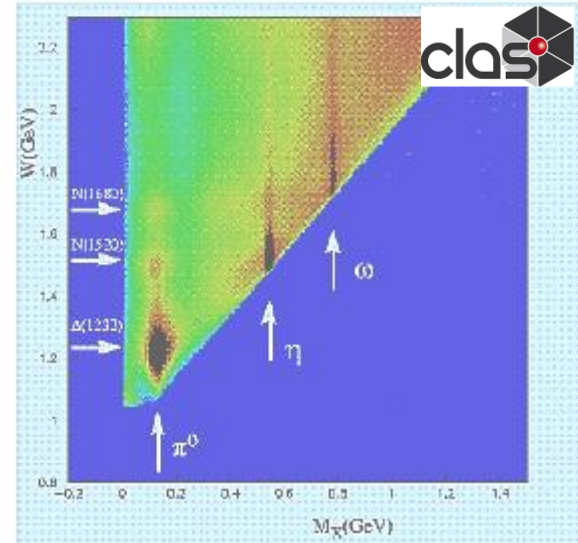
$\pi N \to \pi N, \pi\pi N, \ldots$

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

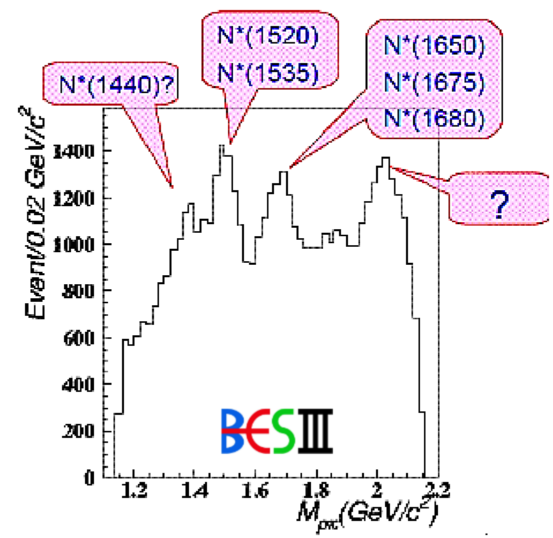
$\gamma^* N \to \pi N, \pi\pi N, \ldots$

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

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

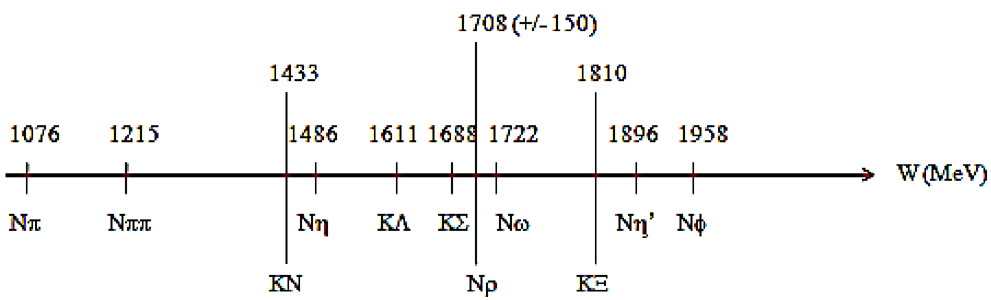


ep → epX



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

- Most of **PDG** info comes from these sources & **PWA** is main of them.
- **πN elastic** scattering is highly constrained.
- Resonance structure is correlated.
- Two-body final state, fewer amplitudes.



Double Polarized Measurements

SP06: R. Arndt, W. Briscoe, IS, R. Workman, Phys Rev C **74**, 045205 (2006)

- πN scattering data:

dσ/dΩ	(unpolarized)
P	(polarized target or recoil nucleon)
R and A	(polarized target and recoil measured)

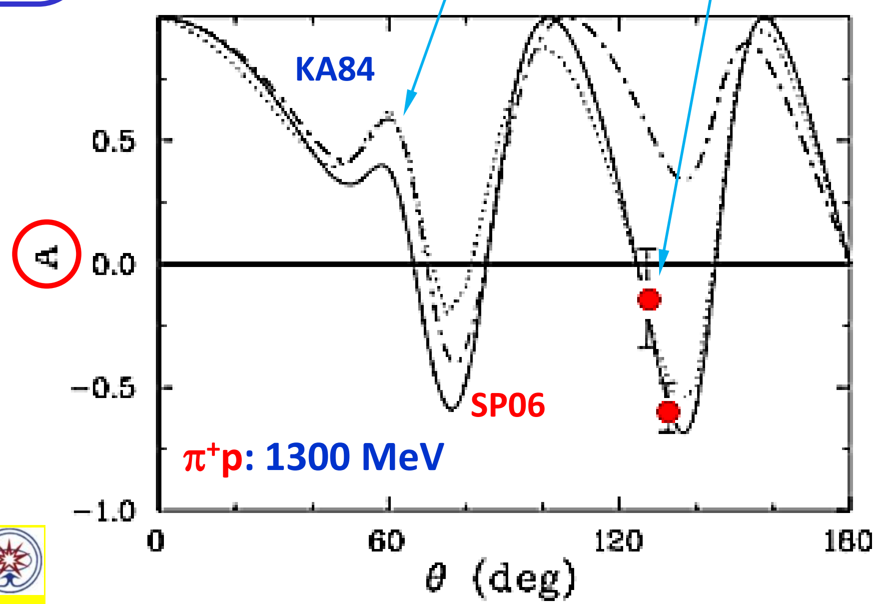
Not Independent: $P^2 + R^2 + A^2 = 1$

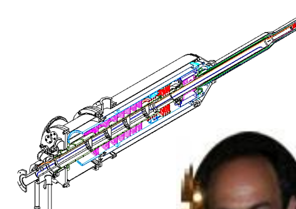
$$P\left(\frac{d\sigma}{d\Omega}\right) = 2\,\mathrm{Im}(fg^*)$$

$$R\left(\frac{d\sigma}{d\Omega}\right) = (|f|^2 - |g|^2)\cos\theta - 2\,\mathrm{Re}(fg^*)\sin\theta$$

$$A\left(\frac{d\sigma}{d\Omega}\right) = (|f|^2 - |g|^2)\sin\theta + 2\,\mathrm{Re}(fg^*)\cos\theta$$

- **Old PWA** solutions may be not able to reproduce **New** measurements.





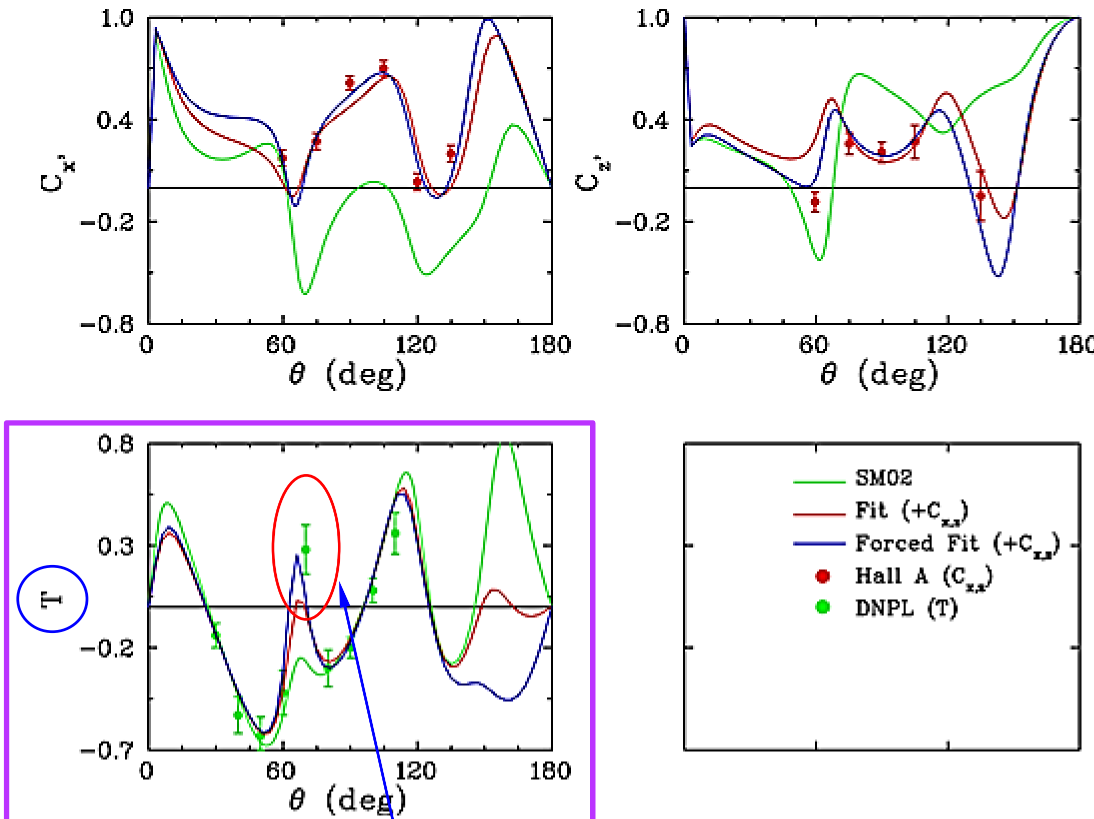
Data:
ITEP: $\pi^+p \rightarrow \pi^+p$ **@ 1300 MeV**
I. Alekseev *et al*, Phys Lett B 351, 585 (1995)
PWA:
KA84: Karlsruhe-Helsinki fit, 1984
KB84: KH Barrelet corrected solution, 1997
SP06: GW fit, 2006

- **Polarized measurements** would also be important part of **hadron program**.

Forced Fit for Double-Polarization 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 solution.

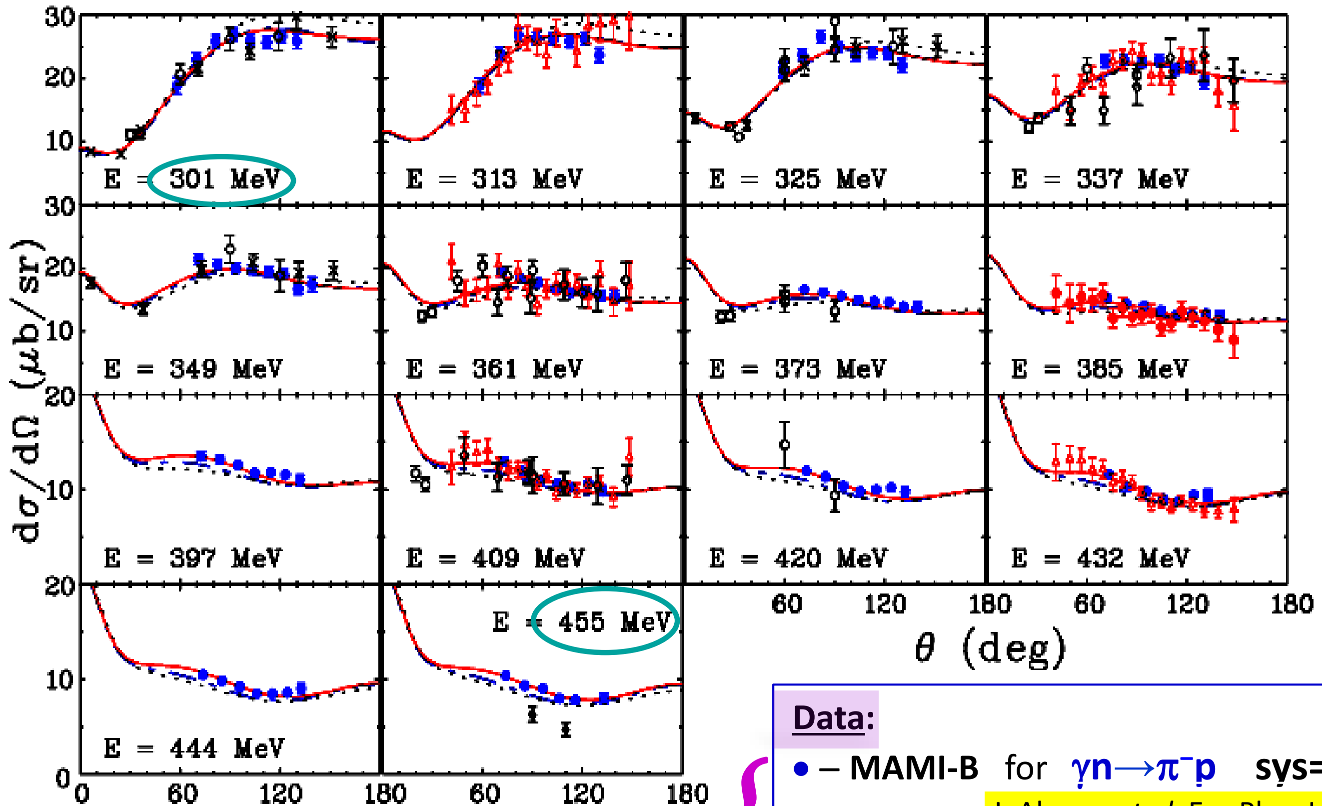
- **DNPL**: **T** measurements
  P.J. Bussey *et al*, Nucl Phys B **159**, 383 (1979)
- **JLab Hall A**:
  There are **22** $C_{x'}$ & **21** $C_{z'}$ below 2 GeV
  K. Wijesooriya *et al*, Phys Rev C **66**, 034614 (2002)

- That is not **artifact** as was possible to think a while ago **!**
- **Hall A** data do allow to reproduce previous **T** measurements well.

MAMI-B for $\gamma n \rightarrow \pi^- p$ 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 $\gamma n \rightarrow \pi^- p$ (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}

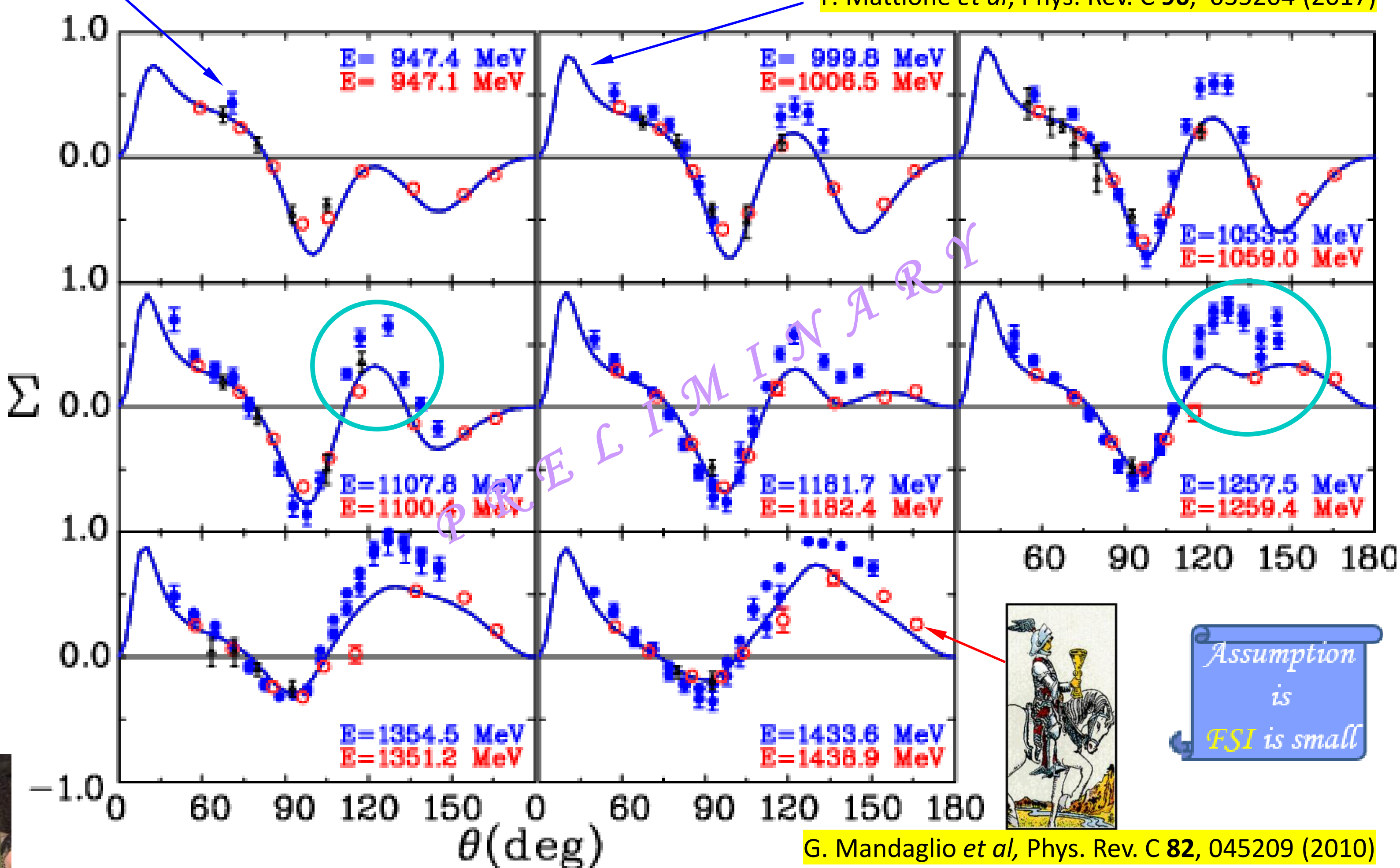
Data:

- ● – **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)
- o – **TRIUMF, CERN, LBL, LAMPF** for $\pi^- p \rightarrow n\gamma$

$g13$ Σ for $\vec{\gamma} n \rightarrow \pi^- p$

D. Sokhan *et al*, in progress

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



Assumption is FSI is small

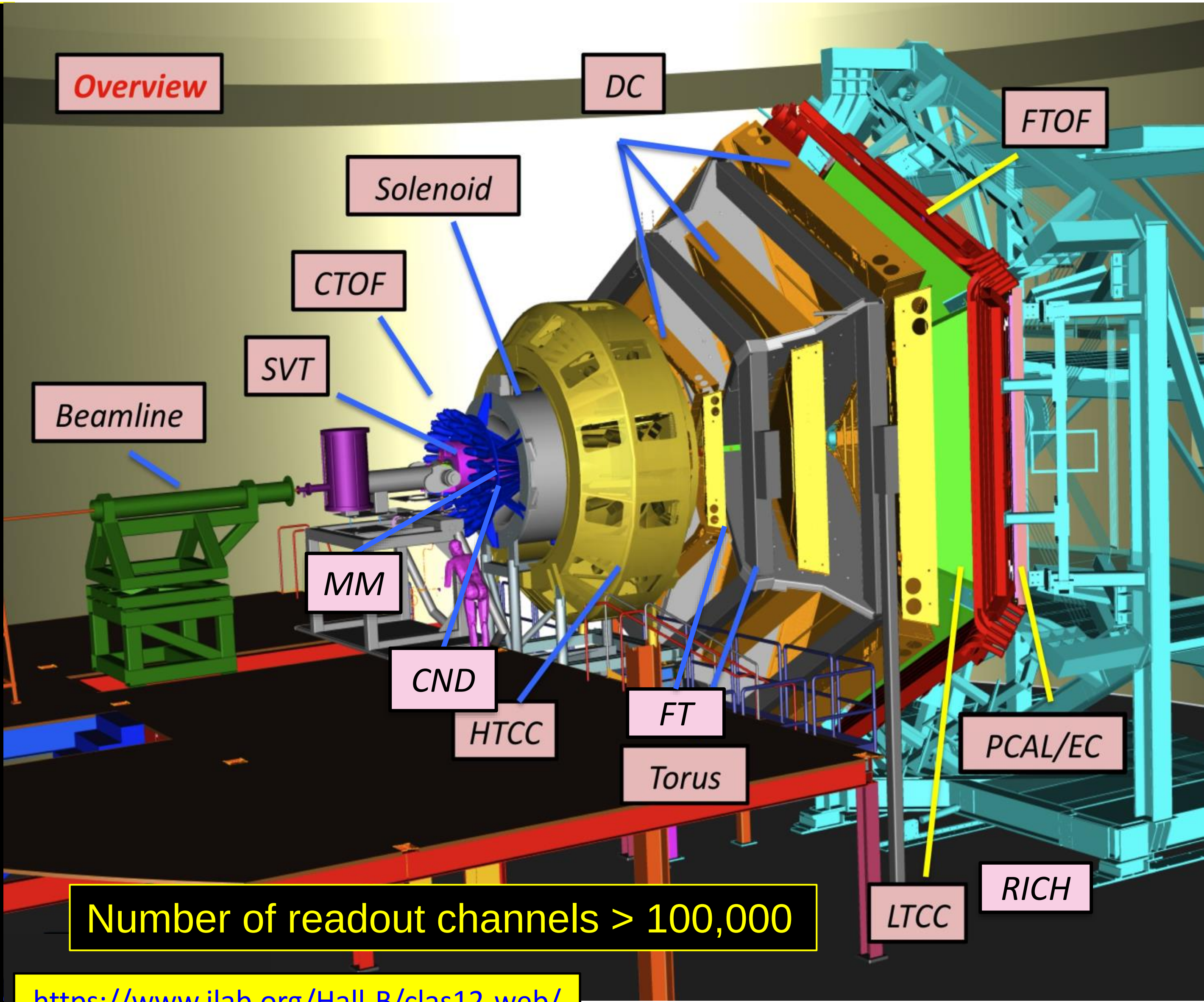
G. Mandaglio *et al*, Phys. Rev. C **82**, 045209 (2010)

CLAS12 Detector Systems

Forward Detector (FD)
- TORUS magnet
- HT Cherenkov Counter
- Drift chamber system
- LT Cherenkov Counter
- Forward ToF System
- Pre-shower calorimeter
- E.M. calorimeter
- Forward Tagger
- RICH detector

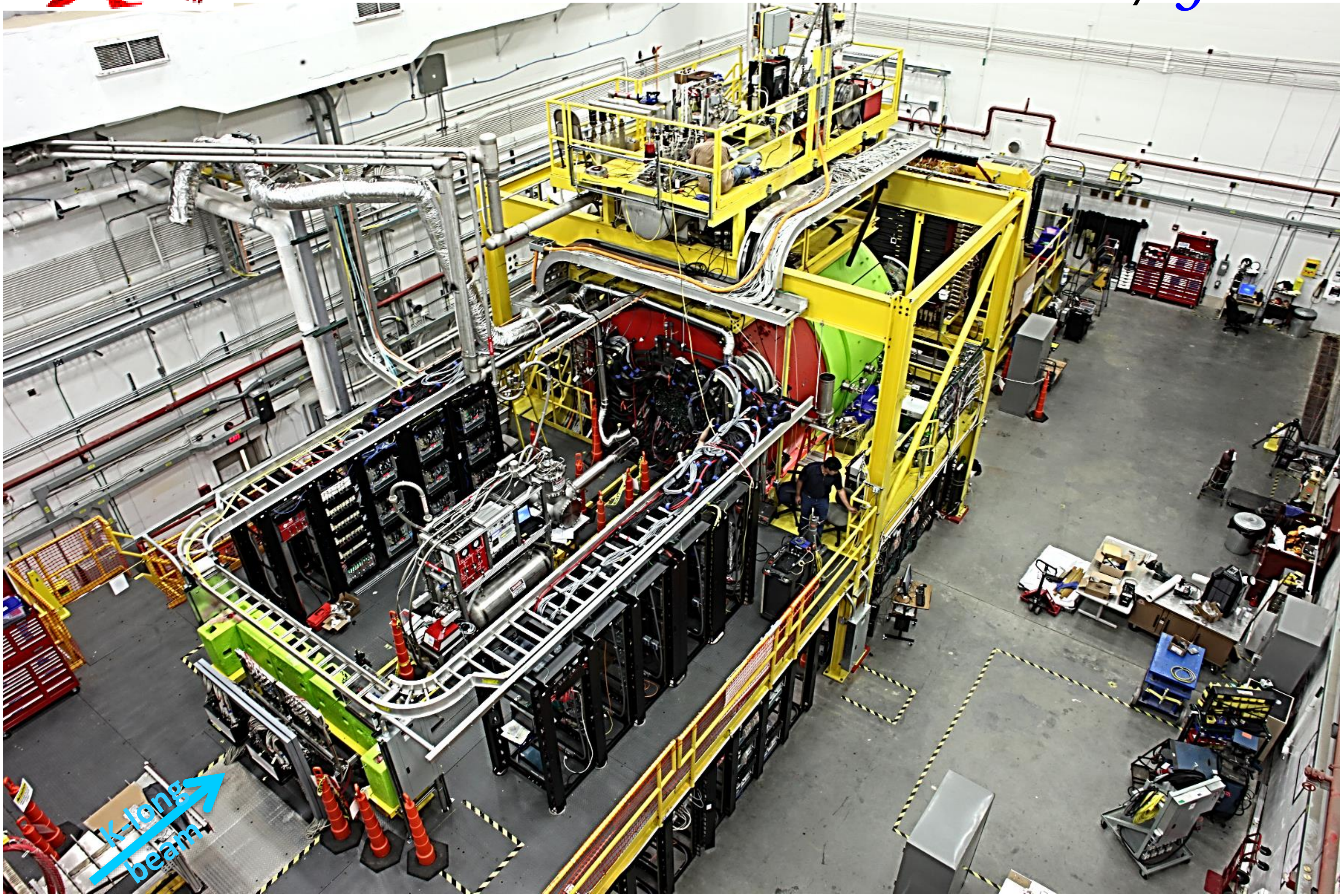
Central Detector (CD)
- Solenoid magnet
- Silicon Vertex Tracker
- Central Time-of-Flight
- Central Neutron Detector
- MicroMegas

Beamline
- Diagnostics
- Shielding
- Targets
- Polarimeter
- Faraday Cup



Number of readout channels > 100,000

https://www.jlab.org/Hall-B/clas12-web/


K-long beam