Spin Asymmetries and Helicity Amplitudes from Pion Production from Polarized Neutrons at Jefferson Lab

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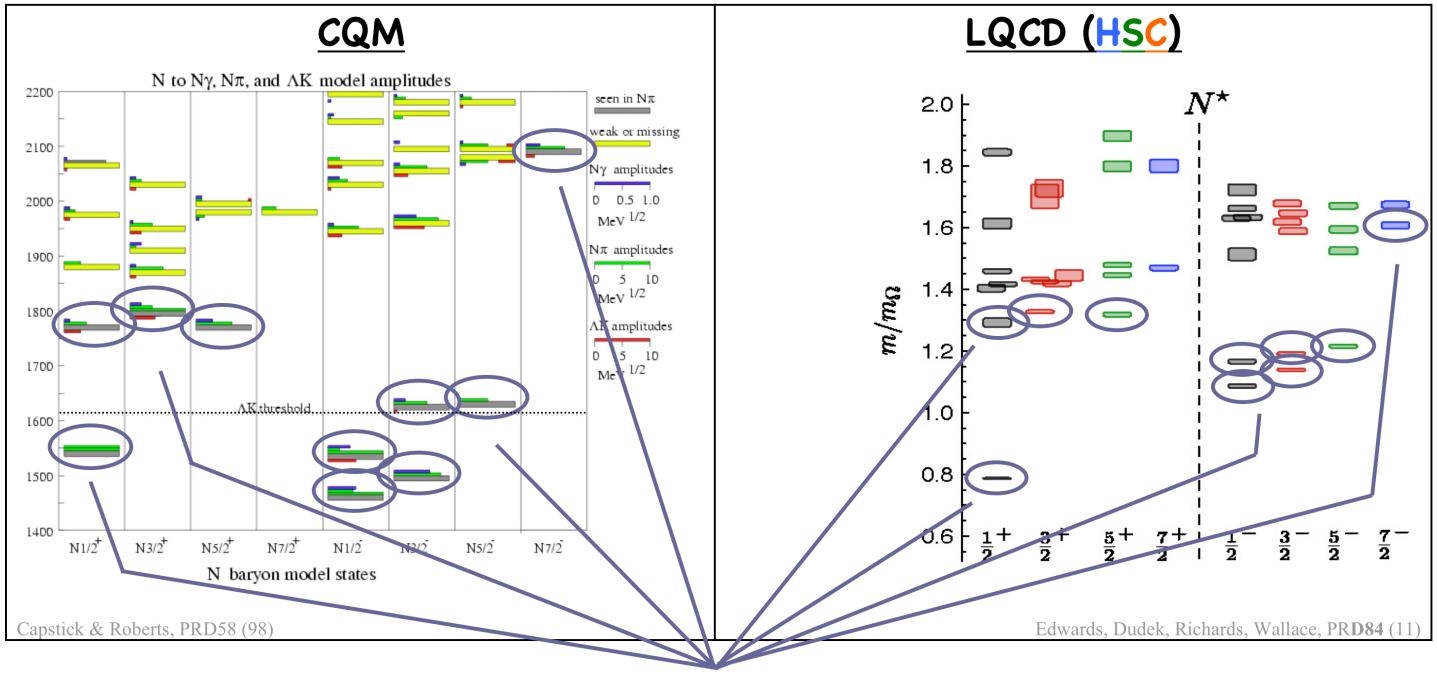
(for *the g14 analysis team and the CLAS Collaboration, together with the GWU-SAID and Bonn-Gatchina PWA groups*)

Unfolding and interpreting the N* spectrum

- low energy structure of QCD lies encoded in the excited N* spectrum, a complex overlap of resonances with "dressed" vertices

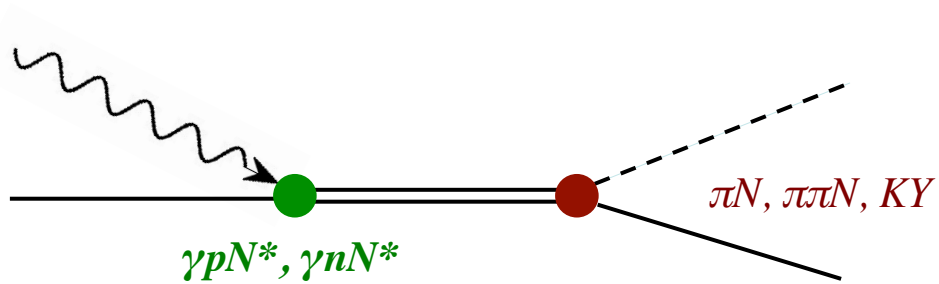


- only lowest few in each band "seen" with 4★ or 3★ PDG status

  ⇔ need to understand the structure of the states that are observed and find the ones that aren't !

the physics of "dressed" QCD

N resonance ⇔ s-channel pole*



- *meson-loop "dressings" of the Electromagnetic vertex affect the dynamical properties (excitation mechanism) and determine Q^2 evolution, but do not affect the N* spectral properties*

- *coupled-channel "dressings" of the strong vertex determine the N* spectral properties (mass/pole positions, widths)*

- *dressings are beyond the current sophistication of LQCD or DSE field theories*

⇔ we rely on models, constrained by the spectrum and its couplings

data needed to unravel the N* spectrum

- $\gamma + N \Rightarrow (J^{\pi}=0^{-}) + N/\Lambda/\Sigma$

spin states: 2 + 2 ⇨ **0 + 2** ⇨ 8 spin combinations
⇨ 4 unique (parity)

⇨ 4 complex amplitudes describe photo-production ⇔ 8 unknows

– Chiang & Tabakin, PR C**55**, (1997);
AMS, Hoblit, Kamano, Lee, J Phys G**38** (2011)

New goal: (Jlab, Bonn, Mainz)

- measure many polarization observables (of 16) ⇔ lots of proton data

- the electromagnetic interactions do not conserve isospin

$$\mathcal{A}_{\gamma p\to\pi^+ n} = \sqrt{2}\left\{\mathcal{A}_p^{I=1/2} - \tfrac{1}{3}\mathcal{A}^{I=3/2}\right\}$$
$$\mathcal{A}_{\gamma n\to\pi^- p} = \sqrt{2}\left\{\mathcal{A}_n^{I=1/2} + \tfrac{1}{3}\mathcal{A}^{I=3/2}\right\}$$

⇔ *proton data determine* $\mathcal{A}^{I=3/2}$

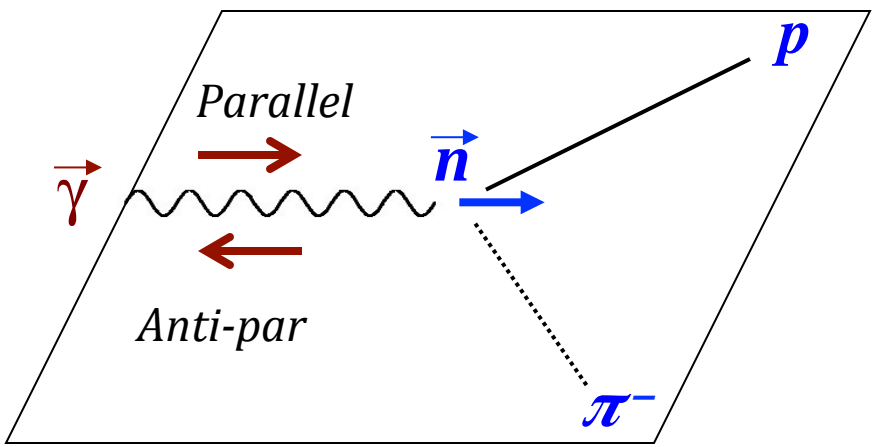
⇨ *both proton and neutron target data needed for the I= ½ amplitudes*

- *γ+n data base is very sparse*
  ⇔ ***γnN* couplings very poorly determined***

JLab E06-101 (g14 run in Hall-B)

- *Dec'2011 –to- May'2012*
- *tagged photons with circular and linear polarization on polarized HD, E_γ: 700 – 2400 MeV*

- *<u>PRL **118** (2017) 242002:</u>*
  the beam-target "E" asymmetry in $\gamma D \rightarrow \pi^- p(p)$
  with circularly polarized photons and longitudinally polarized Deuterons, W: 1500 – 2300 MeV



$$E = \frac{1}{P_\gamma P_T} \frac{\sigma_A - \sigma_P}{\sigma_A + \sigma_P}$$

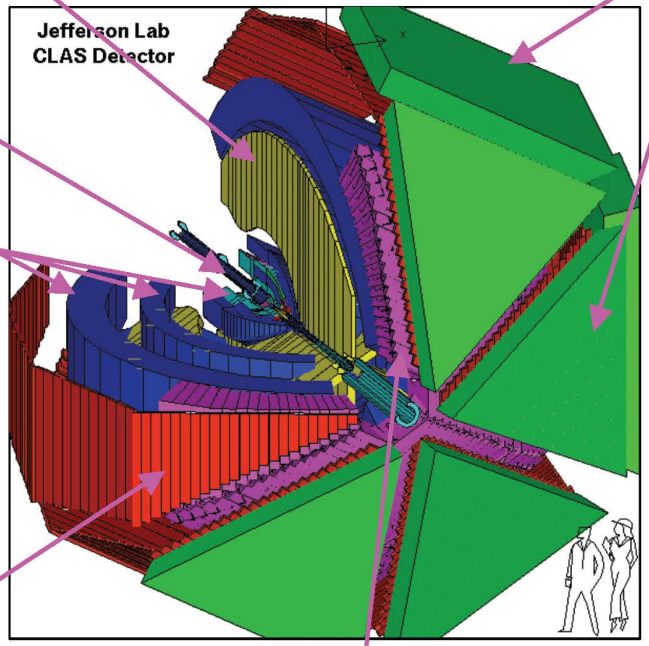
g14 … with the last breath of the CLAS(6) detector

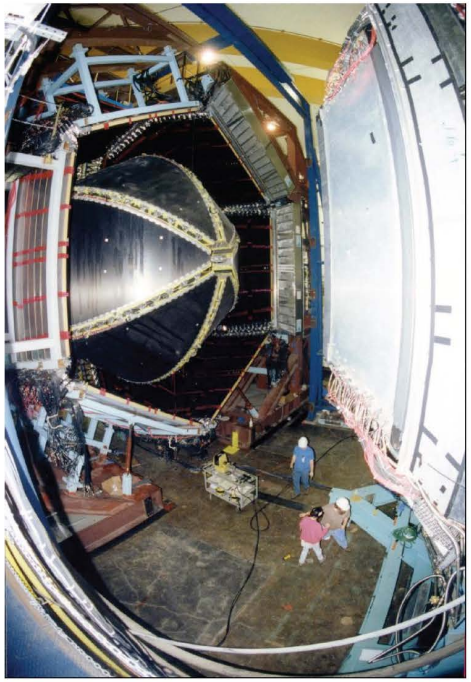
Torus magnet
6 superconducting coils

Electromagnetic calorimeters
Lead/scintillator, 1296 photomultipliers

polarized target + start counter

Drift chambers
argon/CO_2 gas, 35,000 cells





Time-of-flight counters
plastic scintillators, 684 photomultipliers

Gas Cherenkov counters
e/π separation, 256 PMTs

DAQ linit ~ 6kHz (~1.5TB/day)

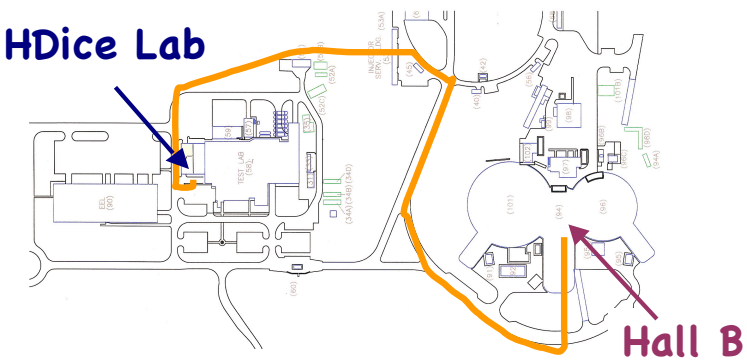
HDice frozen-spin target

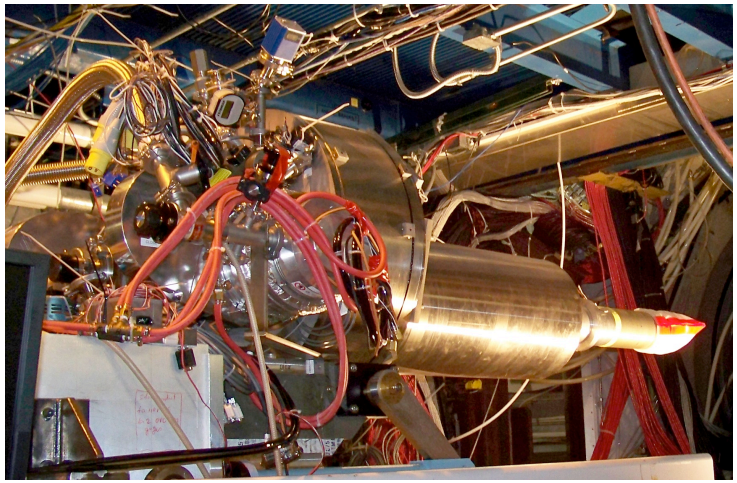
- target: ∅ 15 mm × 50 mm
- material: solid HD
- dilution factors: 1/1 for $\vec{n}$
  1/2 for $\vec{p}$

- < P(D) > = 25% (ave in g14)
- T_1 (1/e relaxation time) ~ years

- HDice-I: NIM A737 (2014) 107
- HDice-II: NIM A815 (2016) 31

- moved while polarized to Hall B





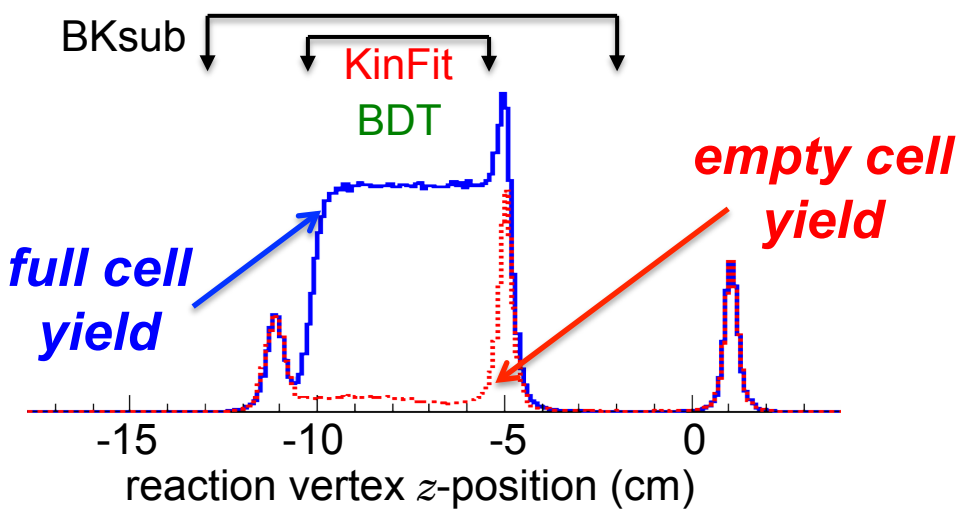
parallel analyses of $\gamma D \rightarrow \pi^- p\ (p)$

- *Bksub* – conventional application of sequential cuts, with **empty subtraction**

- *KinFit* – energy & momentum conservation used in ***Kinematic fitting*** to improve accuracy of measured quantities

- *BDT* – "**Boosted Decision Trees**" used to place *simultaneous* (rather than sequential) requirements

- Vertex preselection:



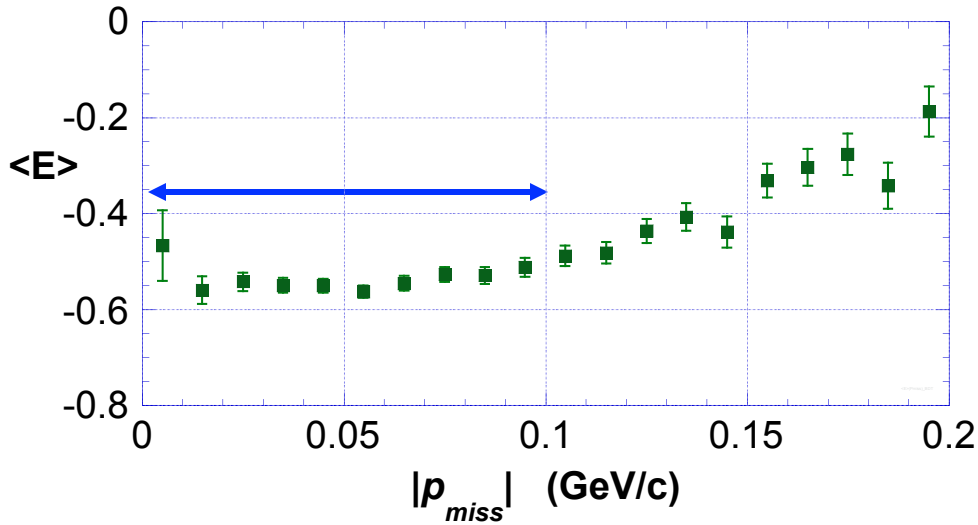
Restricting Deuteron reactions to create an effective neutron target

- *select events for which the proton in Deuterium is a passive "spectator"*
  ⇔ *key variable is the momentum of the undetected proton in γ+n(p) ➔ π^- p(p)*

  ⇔ *use the data itself to determine the kinematic region in which the result is stable*

  $|P_{miss}| < 0.1$ GeV/c

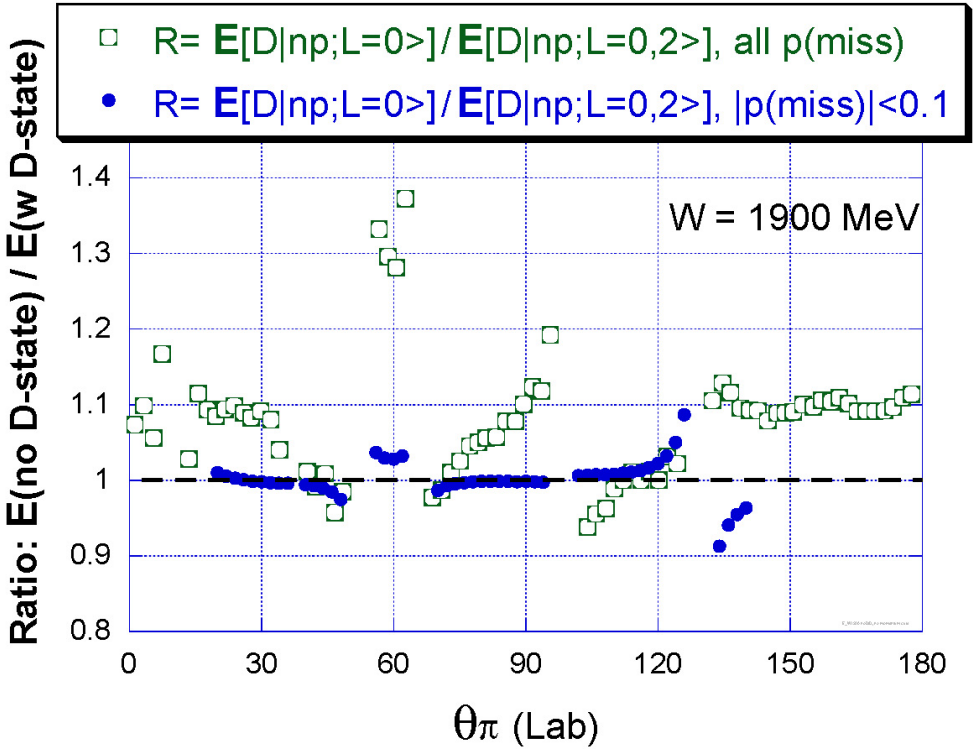
  ⇔ *applied in all three analyses*



- theory perspective:
  FSI have negligible effect on E asymmetry in π^- *p p final state*
  ⇔ *I* = 1 *pp* final state is orthogonal to the initial deuteron wavefunction
  (in contrast with π^o *n p final state, where FSI are essentially required)*

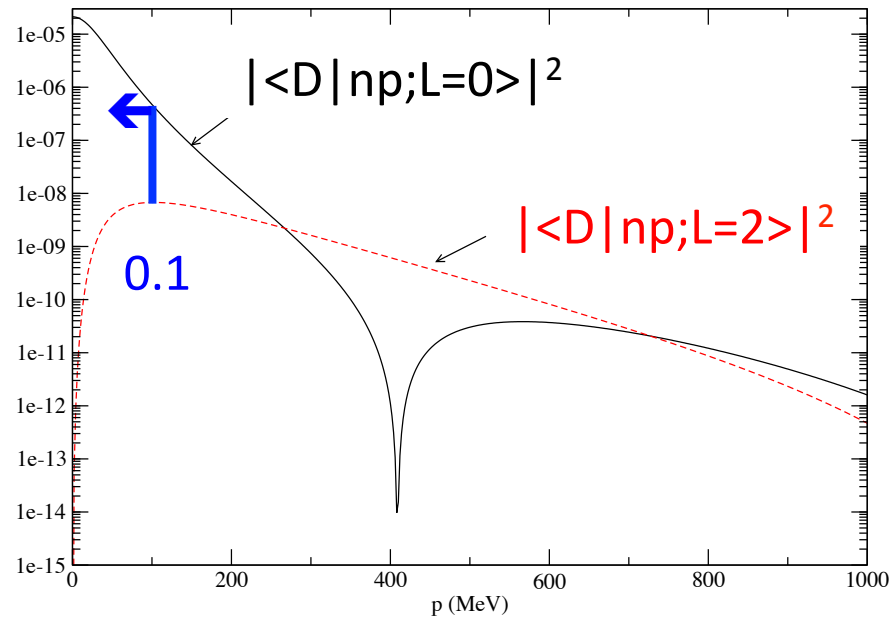
  ⇔ more details in talks by **Satoshi Nakamura** (B3) and **Igor Strakovsky** (B5)

Impact of the Deuteron's D-state on the effective neutron polarization



$\gamma(np) \rightarrow \pi^- p\ (p_{miss})$

Nucleon momenta within the deuteron



- T.-S. H. Lee: impulse calculation, extended to include all relativistic spin transformations of the moving neutron

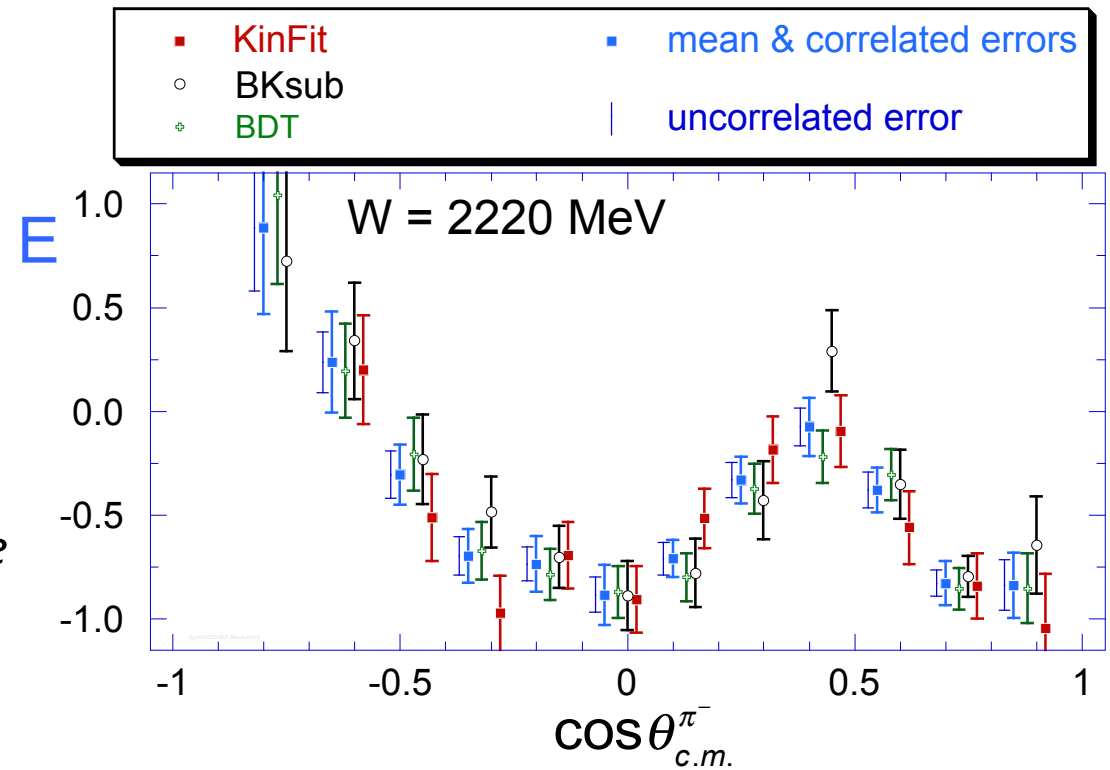
- effect of deuteron's D-state is negligible after $|P_{miss}| < 0.1$ requirement

Combining analyses into the final results

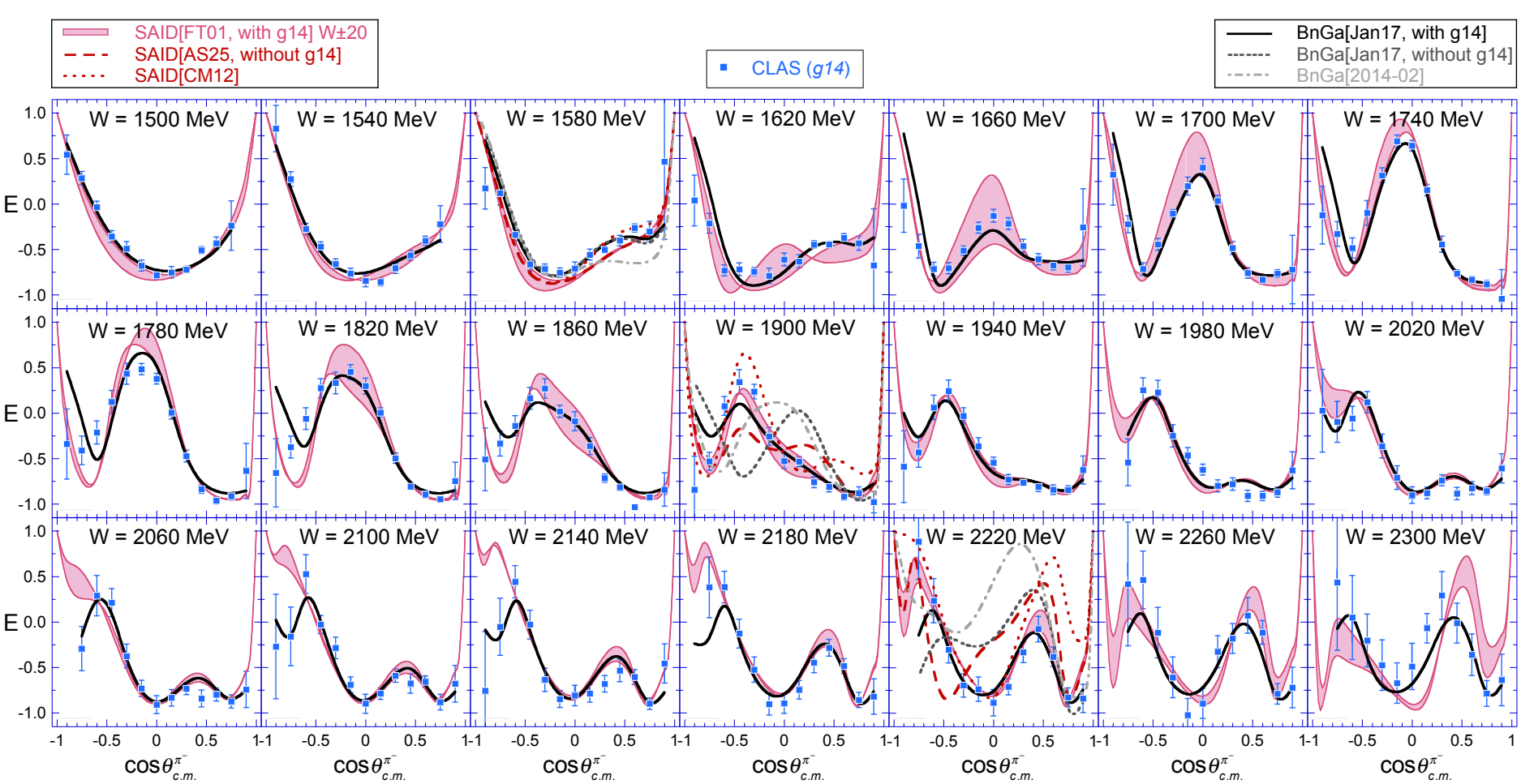
- *asymmetries from the three analyses are statistically consistent*
- *weighted mean is taken as the best estimate of the asymmetry*
- *correlated errors are fitted to the expected χ^2* { *Schmelling, Physica* ***51*** (*95*)676 }

<u>*Advantages*</u>

- *reduces hidden bias*
- *acceptance at extreme angles is different for the 3 methods; averaging improves reliability where PWA interference is large*



The g14 beam-target "E" asymmetries for $\gamma n \rightarrow \pi^- p$



*PRL **118** (2017) 242002*

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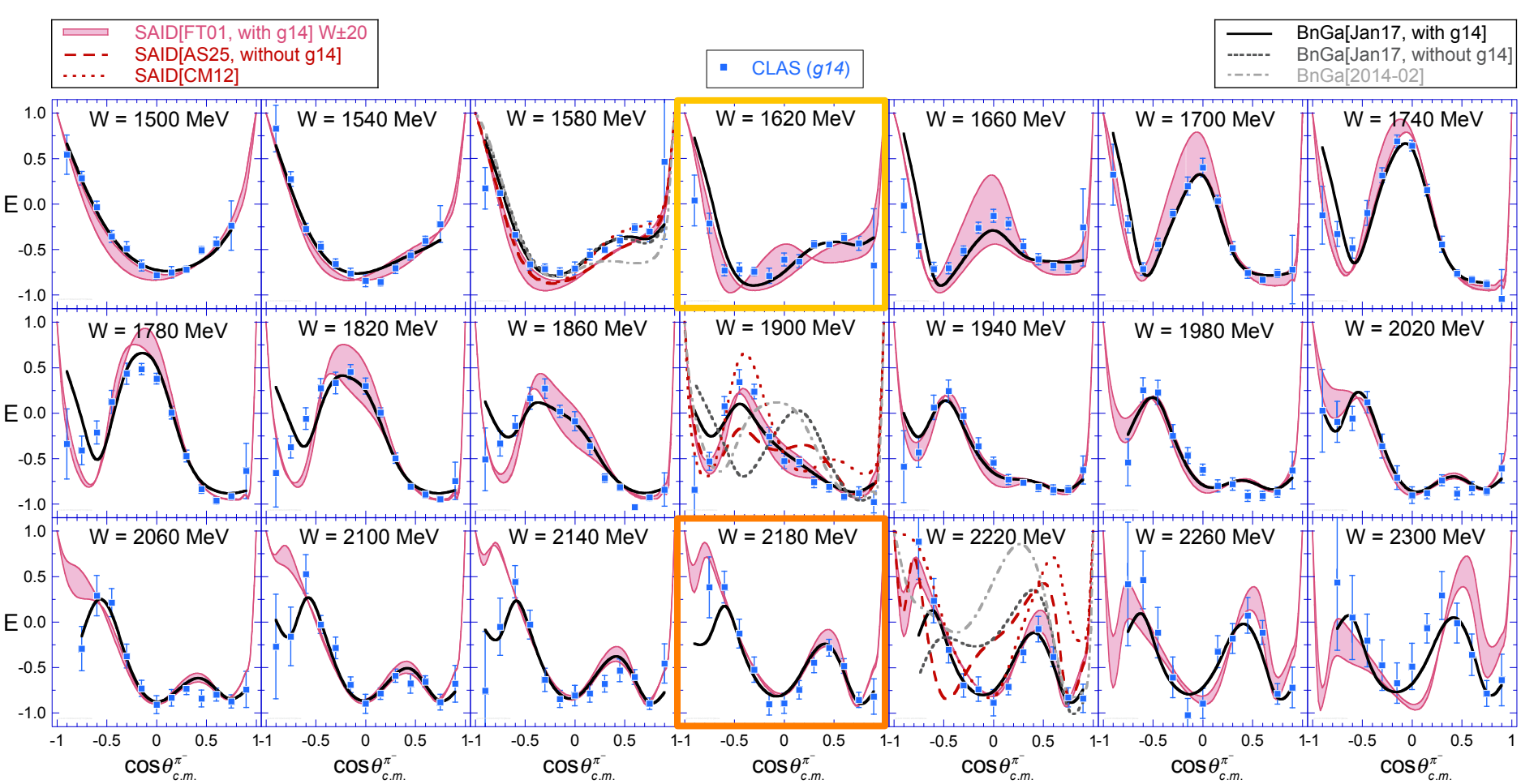

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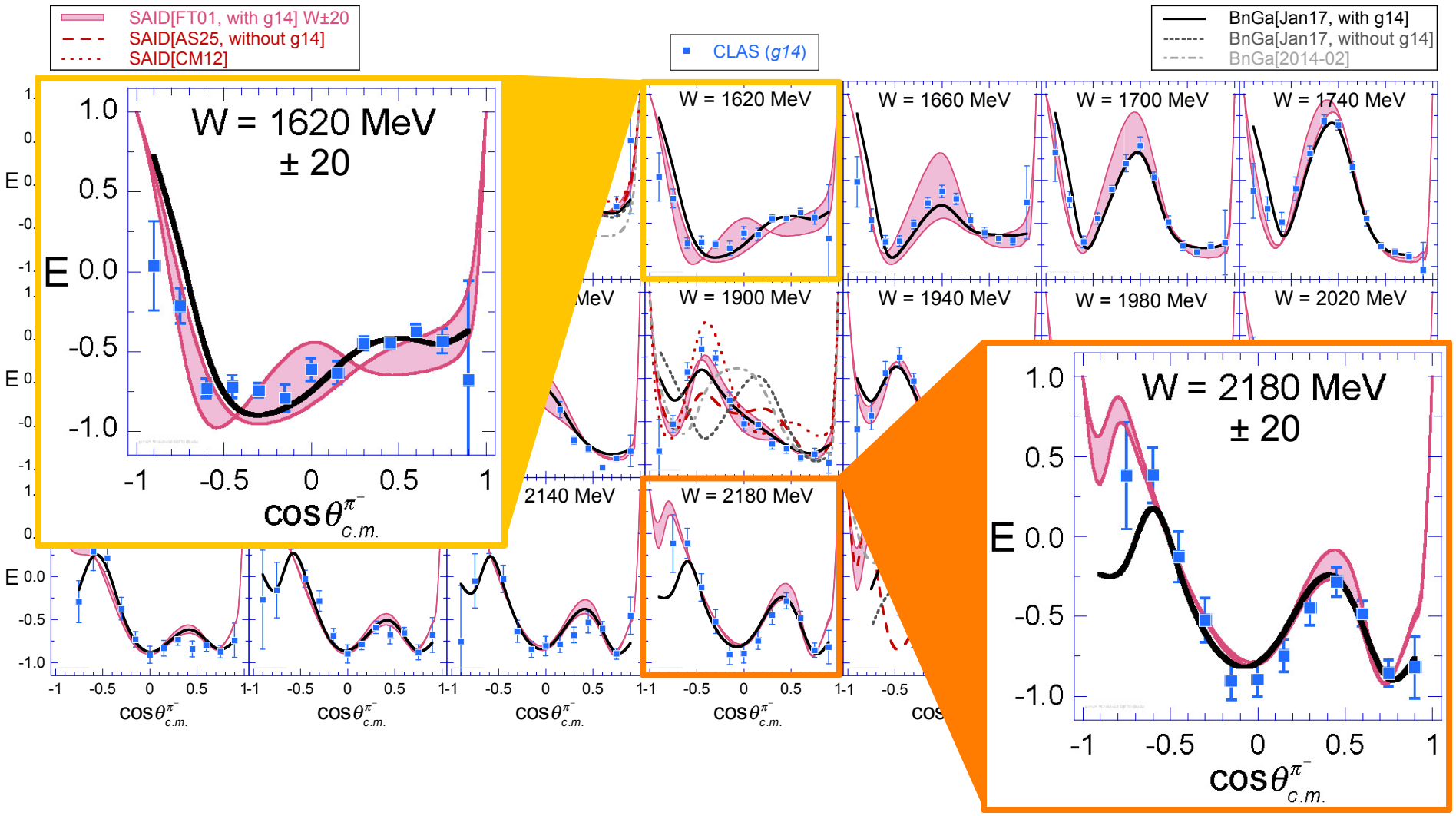

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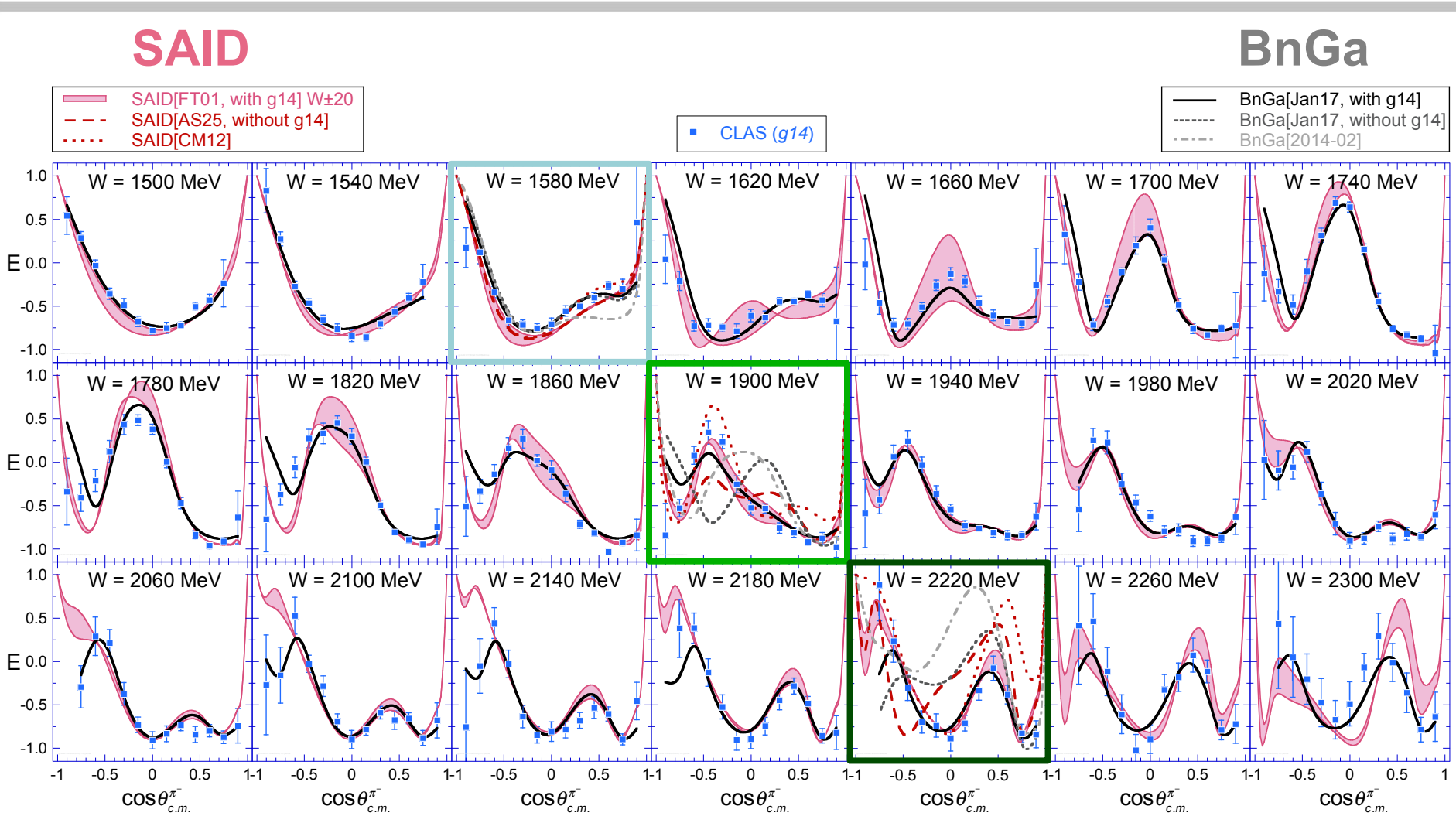

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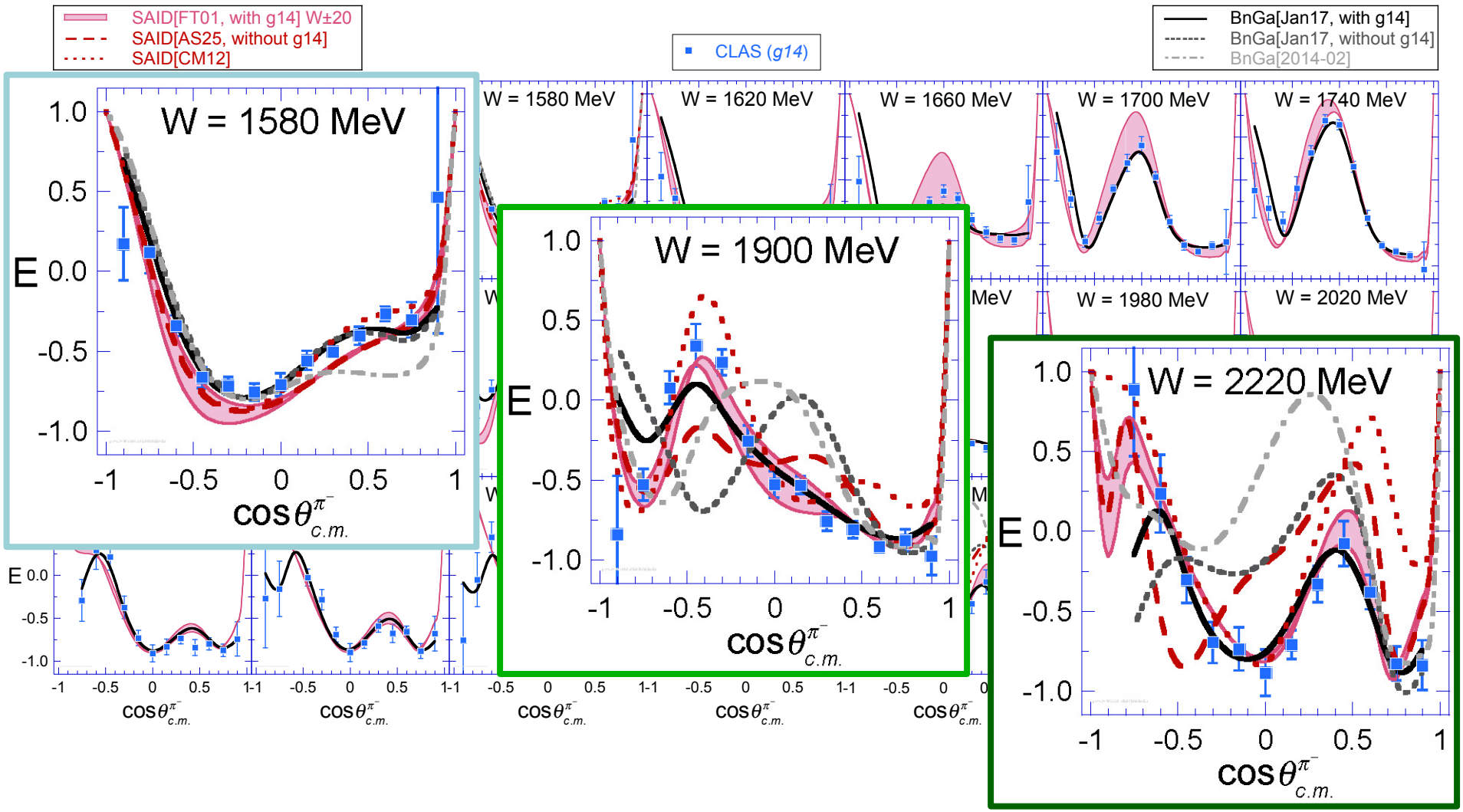


Partial Wave Analyses

$$T_{\alpha\gamma} = \sum_{\sigma} \frac{\bar{K}_{\sigma\gamma}}{\left[1 - c\bar{K}\right]_{\alpha\sigma}}$$

SAID (R. Workman, A. Švarc, I. Strakovsky, …)

- *sequential, unitary fit to all πN scattering and π−photoproduction data*

- fit $\left[1 - c\bar{K}\right]$ to πN ➔ πN and πN ➔ ηN

⇔ determines all poles

- vary K(W) as polynomials in W to fit photo-production

⇔ no *new* resonances

BnGa (E. Klempt, V. Nikonov, A. Sarantsev, …)

- *simultaneous, coupled-channel analysis of πN and γN ➔ πN, ππN, KY*

- fit to SAID amplitudes for πN ➔ πN
- include new resonances as needed to improve fits for γN channels

Status of γn → πN data base

⇨ 4 complex amplitudes describe photo-production ⇔ 8 unknows

⇨ 8 carefully chosen observables (out of 16) for a "mathematical soln"

- Chiang & Tabakin, PR C**55**, (1997)

⇨ in practice, *ie.* with realistically achievable uncertainties, even more

- AMS, Hoblit, Kamano, Lee, J Phys G**38** (2011)

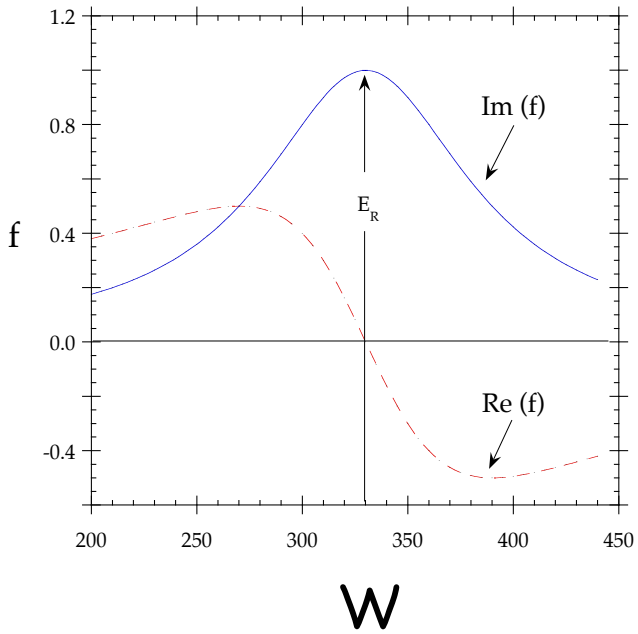
- $\gamma n \rightarrow \pi^- p$ Data Base:
  $d\sigma$ (2322 pts), Σ (315 pts), T (105 pts), P (75 pts), and now E (263 pts)
  (even less for $\pi^0 n$)

- insufficient to completely remove ambiguities:
  ⇔ deduced couplings can change with new data;
  ⇔ attach a higher significance when there is agreement btw very different PWA approaches

PWA: phase motion of a resonance

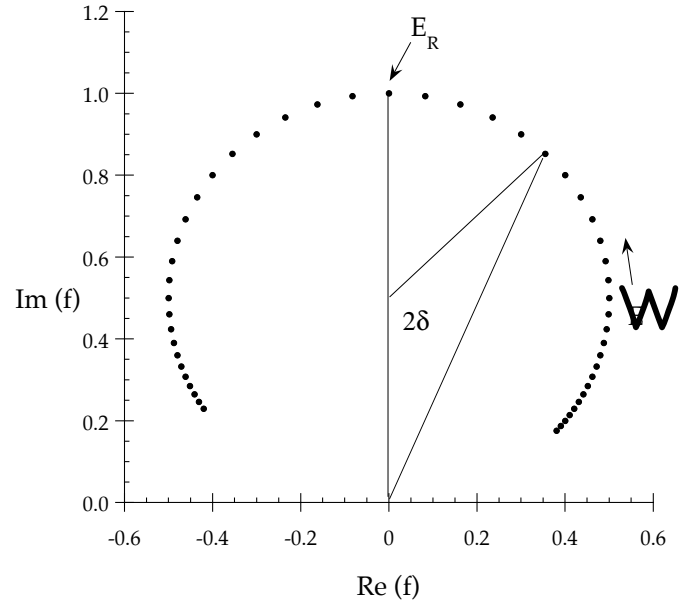
- expectation for an isolated resonance:

- **ideal single isolated resonance** (Breit-Wigner)



Argand plots:

- **counter-clockwise rotating amplitude**
  - characteristic resonance behavior

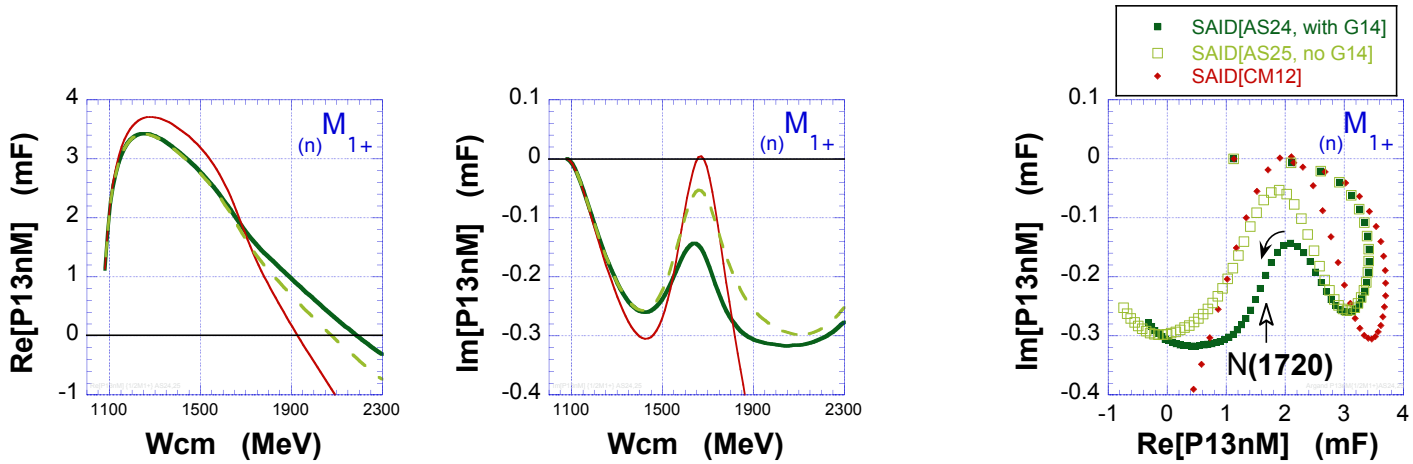


- caveat:
  every resonance produces a loop; but not every loop is a resonance

- amplitude decomposed into $(L^{\pi N})_{IJ}(n/p)E/M$ partial waves

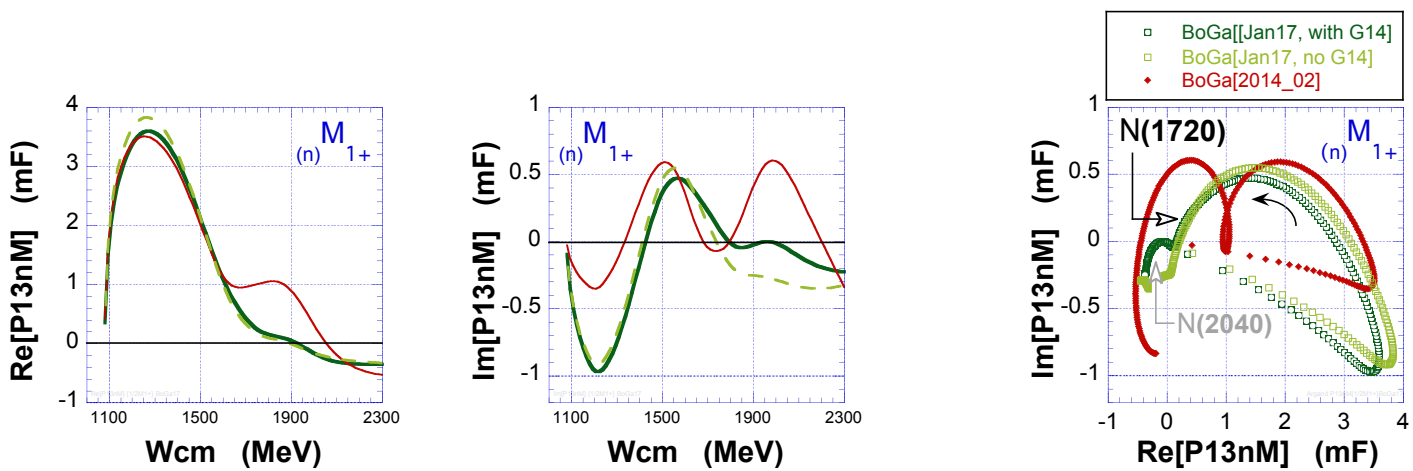
PWA: I = 1/2 (N^*) P-waves

eg. **SAID P13nM**



N(1720)3/2$^+$ (PDG ****)

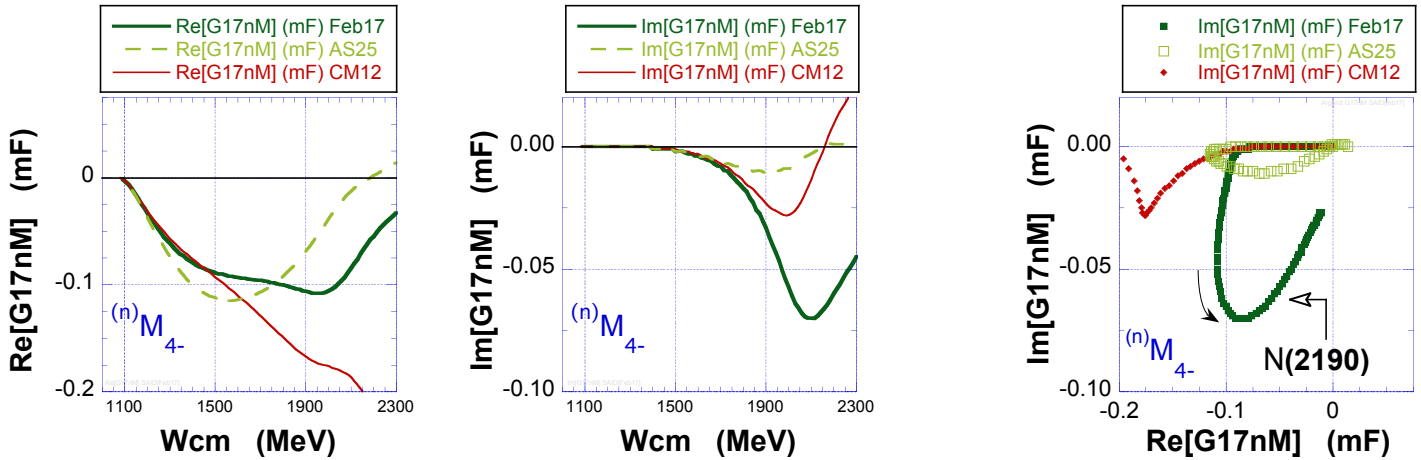
BnGa P13nM



PWA: I = 1/2 (N^*) G-waves

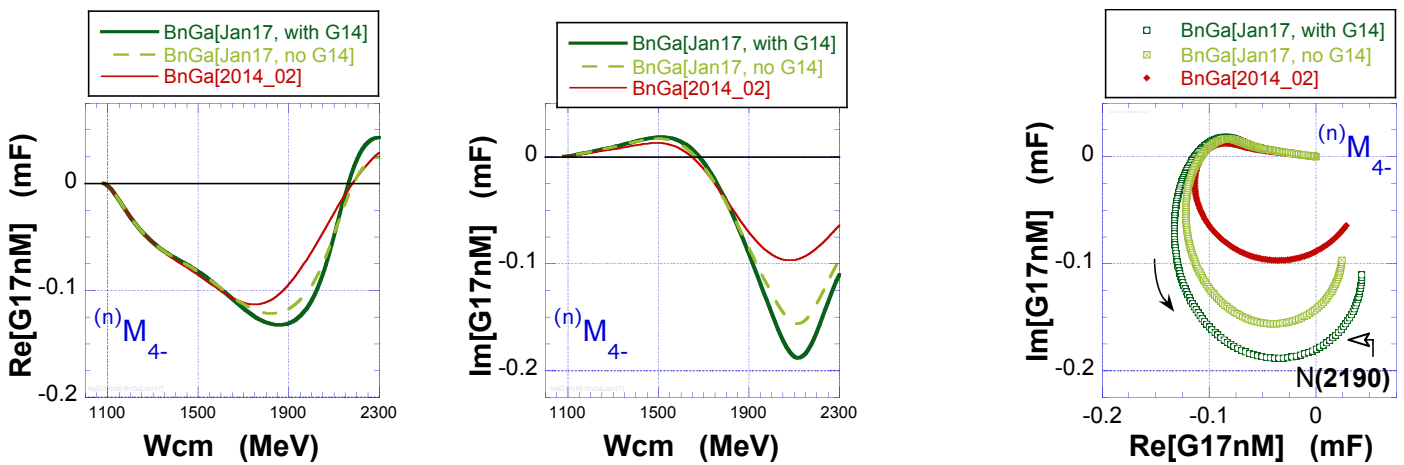
eg.

SAID G17nM



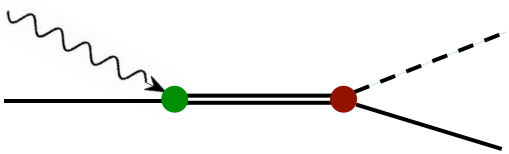
N(2190)7/2⁻
(PDG ****)

BnGa G17nM



γnN^* couplings ⇔ transverse helicity amplitudes

- $h_\gamma = 1$, $h_N = ½$ ⇔ $A^{1/2}$, $A^{3/2}$
- *residues from analytic continuation to a pole in the complex W plane*
- Breit-Wigner parameterization,



$$T_{\alpha\gamma} = \sum_\sigma \frac{\bar{K}_{\sigma\gamma}}{\left[1 - c\bar{K}\right]_{\alpha\sigma}} \quad \Rightarrow \quad \sum \frac{A^h g_\alpha(s)}{\left[M^2 - s - i\sum c_j g_j^2(s)\right]}$$

revisions to γnN couplings*

	$A_n^{1/2}$	(10^{-3} GeV$^{-1/2}$)	$A_n^{3/2}$	(10^{-3} GeV$^{-1/2}$)	
	g14 PRL **118** [1]	previous [2,3]	g14 PRL **118** [1]	previous [2,3]	
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$^+$	**-(28** +40/-15**)**	-80 ±50	**±(103** ±35**)**	-140 ±65	← ρN
N(2190)7/2$^-$	**+30** ±7	-15 ±12	**-23** ± 8	-33 ±20	

[1] CLAS/g14: *Phys. Rev. Lett.* ***118*** *(2017)*

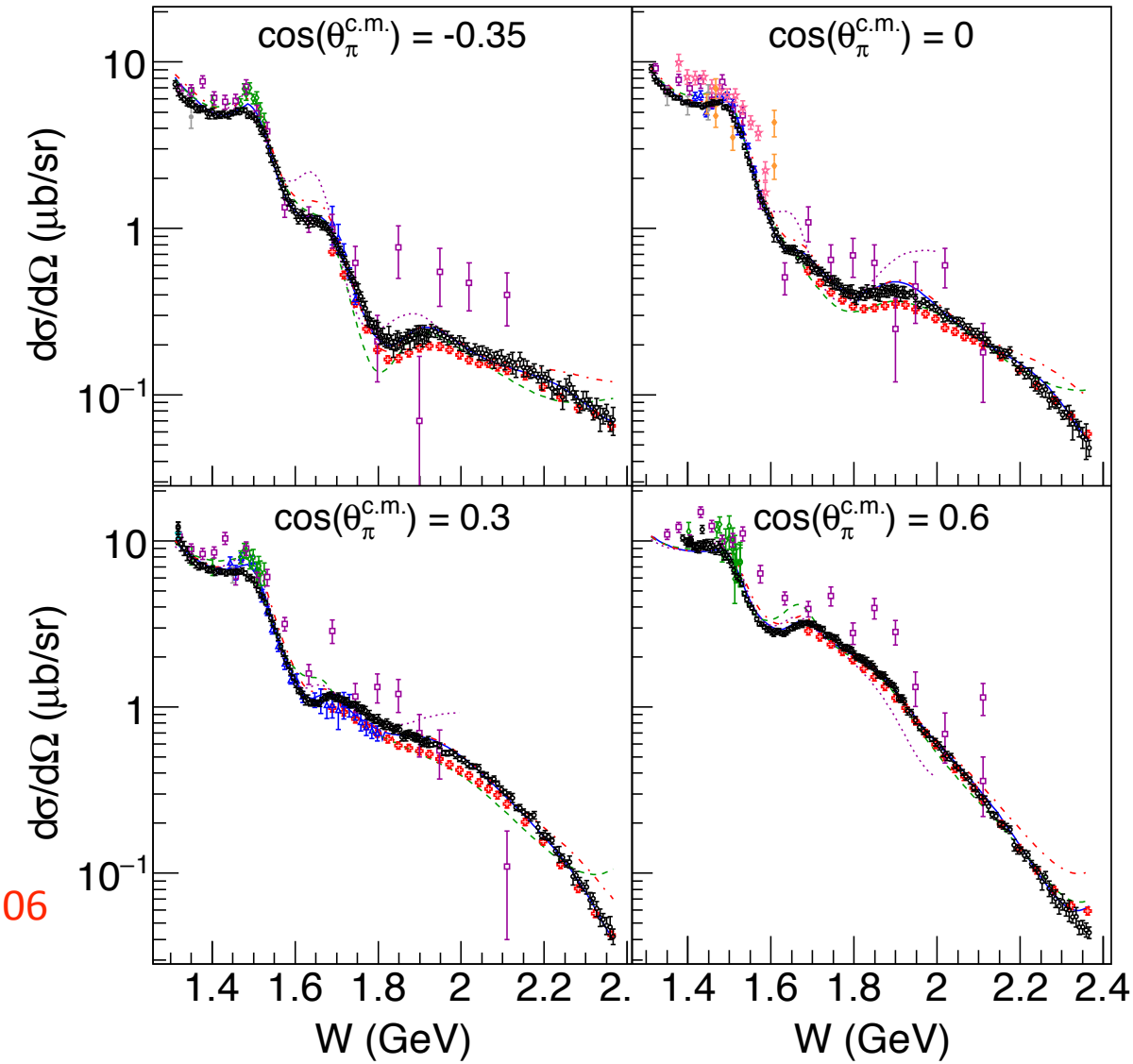
[2] *SAID: Phys. Rev. C**85** (2012) 025201*

[3] *BnGa: Eur. Phys. J. A **49** (2013) 67*

Sensitivities to new data

- new $\sigma(\pi^- p)$ data from CLAS/g13
  - $D(\gamma, \pi^- p)p$ with FSI correction
  - 8424 kinematic bins

⇔ **Paul Mattione's talk** (A2)



Legend

- ○ CLAS/g13 - arXiv1706.01963
- ✣ CLAS/g10 – PRC **86** (2012) 015206
- ◆ BNL – PRC **70** (2004) 035204
- Δ SLAC – NP B**75** (1974) 125

Convergence of γnN* couplings with new data

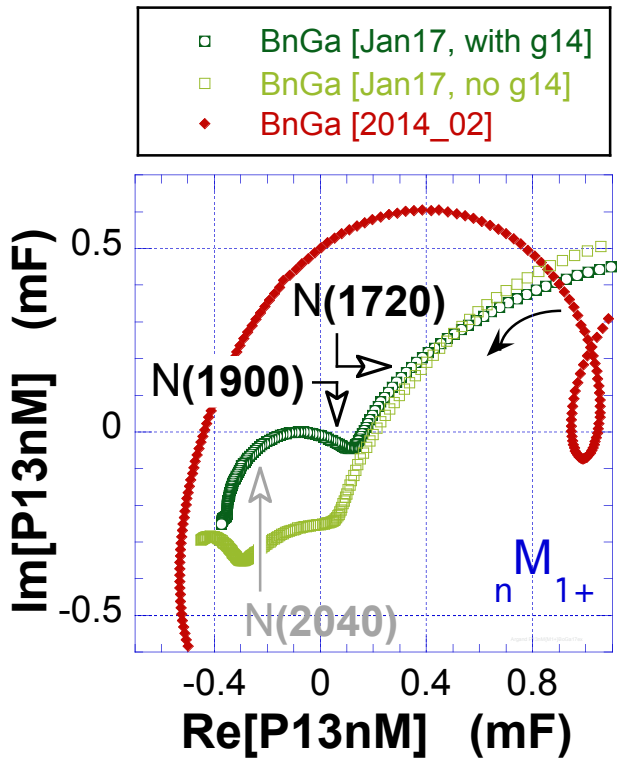
(10^{-3} GeV$^{-1/2}$)	Last published	+ CLAS/g14 (E)	+ CLAS/g13 (σ)	+ CLAS/g13 (σ) + CLAS/g14 (E)
	SAID[SN11] [1]	SAID[FT01] [2]	SAID[MA27] [3]	SAID[TS21] [4]
$A_n^{1/2}$				
N(1720)3/2$^+$	-21 ±4	**-9** ±2	**-16** ± 6	-15 ±5
N(2190)7/2$^-$	- -	**-6** ±9		-16 ±5
$A_n^{3/2}$				
N(1720)3/2$^+$	-38 ±7	**+19 ±2**	**+17** ±5	13 ±4
N(2190)7/2$^-$	- -	**-28 ±10**		-35 ±5

A. Švarc (P3)

[1] *SAID: Phys. Rev. C**85** (2012) 025201*
[2] CLAS/g14 (E): *Phys. Rev. Lett. **118** (2017)*
[3] CLAS/g13 (σ) - arXiv1706.01963
[4] R.L. Workman and A. Švarc (*priv. comm.)*

PWA: I = 1/2 (N^*) P-waves

BnGa:



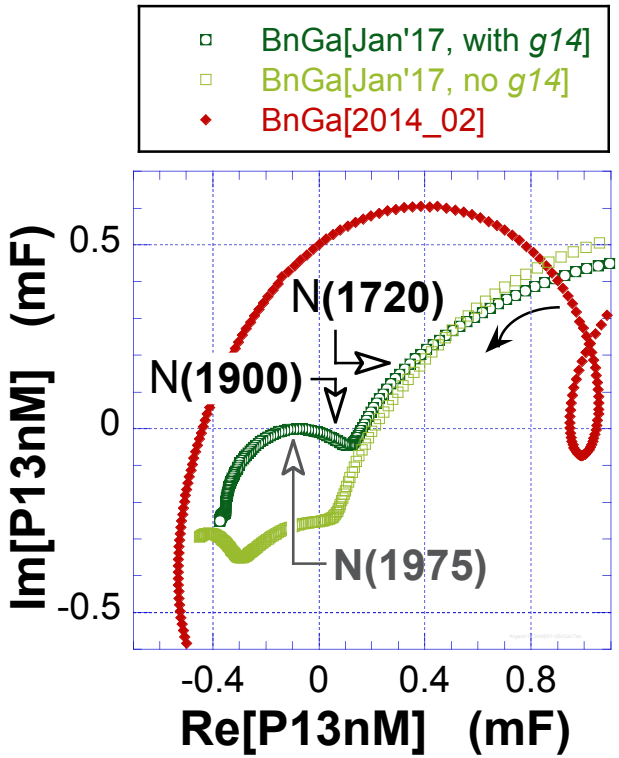
N(1720)3/2$^+$ ⇔ PDG ****

N(1900)3/2$^+$ ⇔ PDG ****
(but weakly coupled to πN)

N(2040)3/2$^+$ ⇔ PDG * ??? (PRL 118)

PWA: I = 1/2 (N^*) P-waves

BnGa:



N(1720)3/2$^+$ ⇔ PDG ****

N(1900)3/2$^+$ ⇔ PDG ****
(but weakly coupled to πN)

- **new BnGa PWA** (submitted to PRC):

  ➔ **highest 3/2$^+$ at W=1975 MeV**

  ⇔ **possible N(1975)3/2$^+$**

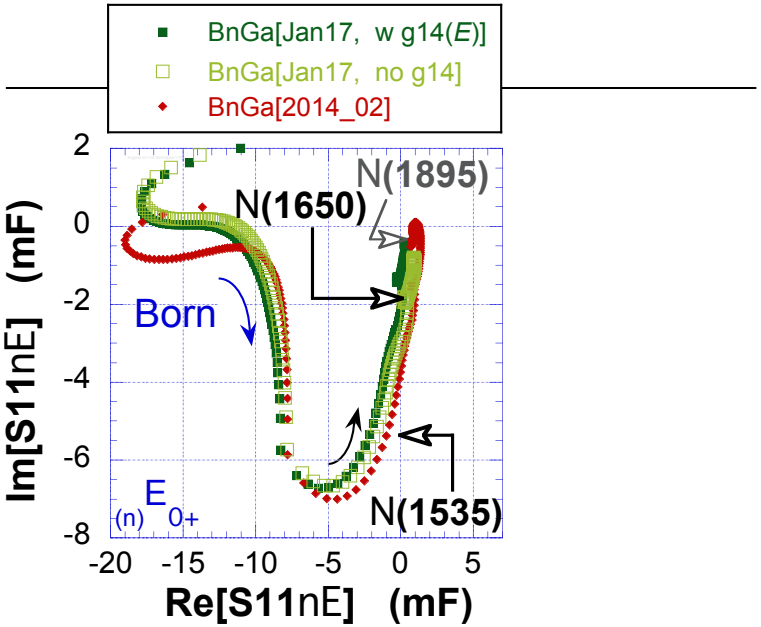
  $A_n^{1/2}$ = -26 ±13 , $A_n^{3/2}$ = -77 ±15

PWA: I = 1/2 (N^*) S-waves

N(1895)1/2$^-$
(PDG **)

N(1650)1/2$^-$
(PDG ****)

N(1535)1/2$^-$
(PDG ****)

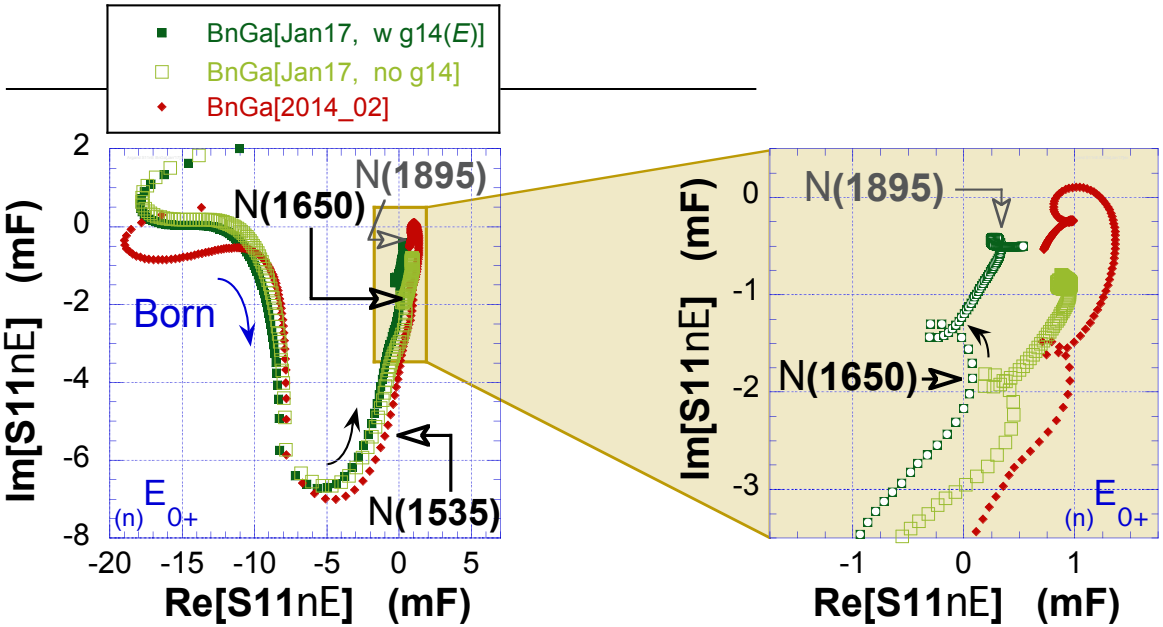


PWA: I = 1/2 (N^*) S-waves

N(1895)1/2$^-$
(PDG **)

N(1650)1/2$^-$
(PDG ****)

N(1535)1/2$^-$
(PDG ****)



- **new BnGa PWA** (submitted -PRC):

  ➔ **highest ½⁻ at W=1895 MeV**

  ⇔ **required N(1895)1/2⁻**

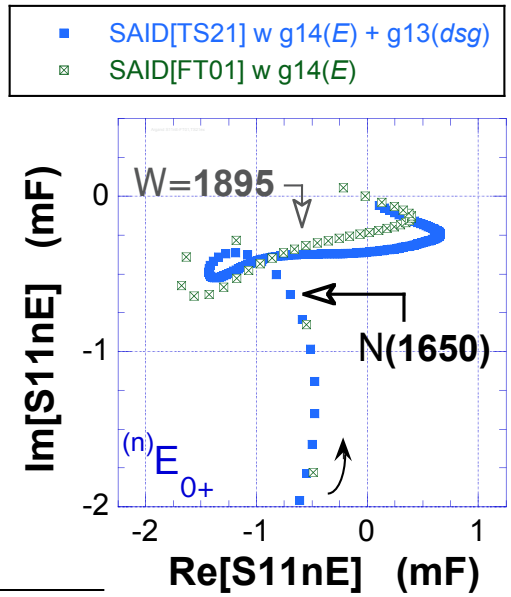
  $A_n^{1/2}$ **= -15 ±10**

PWA: I = 1/2 (N^*) S-waves

N(1895)1/2$^-$
(PDG **)

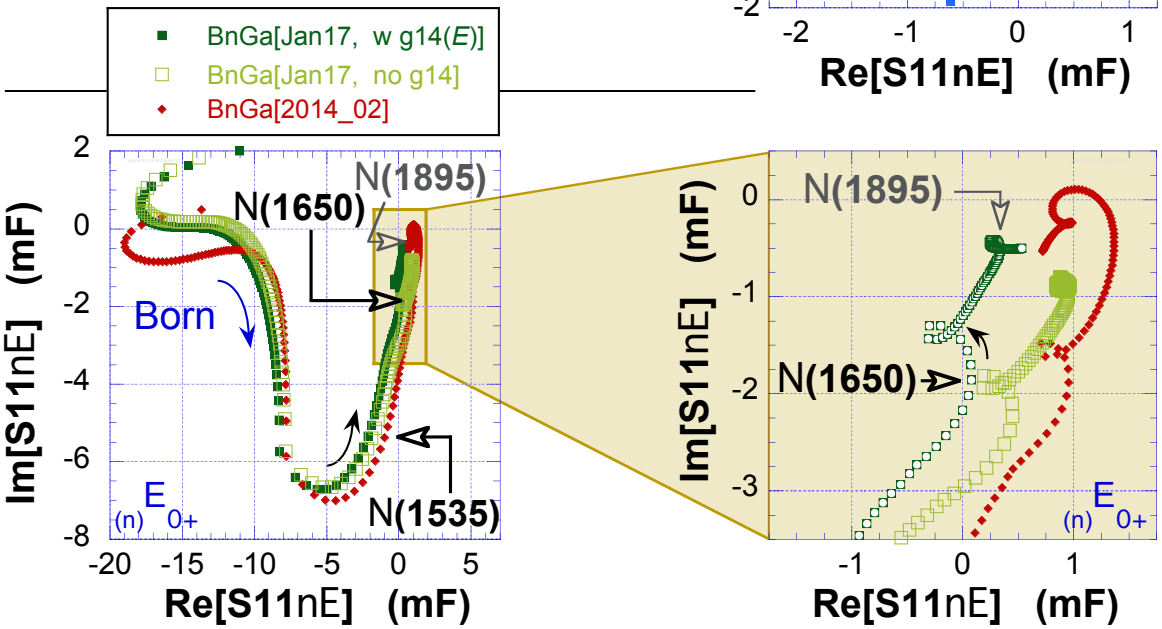
N(1650)1/2$^-$
(PDG ****)

N(1535)1/2$^-$
(PDG ****)



- similar phase motion in SAID fits to γN → πN, but not seen in πN → πN

⇔ not able to confirm



- new BnGa PWA (submitted -PRC):

→ highest ½$^-$ at W=1895 MeV

⇔ required N(1895)1/2$^-$

$A_n^{1/2}$ = -15 ±10

γnN^* vs γpN^* couplings

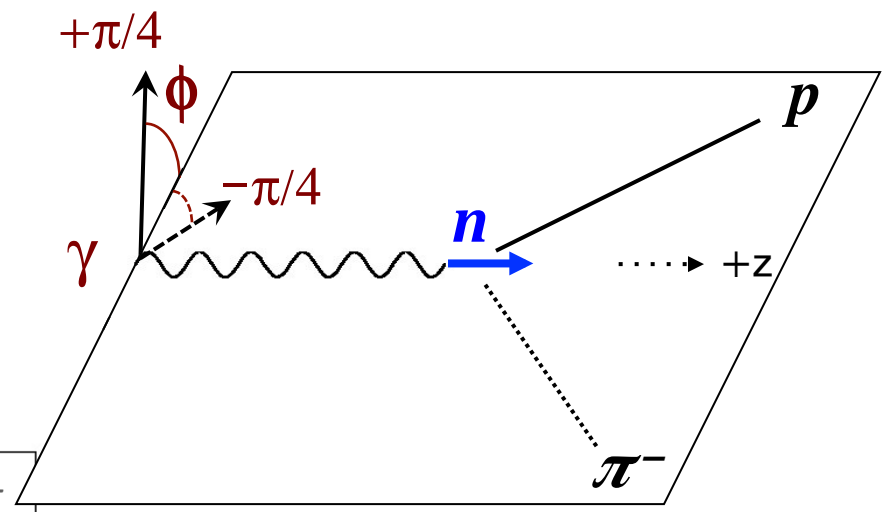
(10^{-3} GeV$^{-1/2}$)	$A_n^{1/2}$	$A_p^{1/2}$	$A_n^{3/2}$	$A_p^{3/2}$
SAID				
N(1720)3/2$^+$	-15 ±5 [4]	95 ±2 [6]	13 ± 4 [4]	-48 ±2 [6]
N(1895)1/2$^-$	----	----		
N(1975)3/2$^+$	----	----	----	----
N(2190)7/2$^-$	-16 ±5 [4]	- -	-35 ±5 [4]	- -
BnGa				
N(1720)3/2$^+$	-(28 +40/-15) [3]	110 ±45 [5]	±(103 ±35) [3]	150 ±30 [5]
N(1895)1/2$^-$	-15 ±10 [3]	-11 ±6 [5]		
N(1975)3/2$^+$	-26 ±13 [3]		-77 ±15 [3]	
N(2190)7/2$^-$	+30 ±7 [1]	-65 ±8 [5]	-23 ± 8 [1]	+35 ±17 [5]

[1] CLAS/g14: *Phys. Rev. Lett.* ***118*** *(2017)*
[2] *SAID: Phys. Rev. C**85** (2012) 025201*
[3] *BnGa: Phys. Rev. C (submitted)*
[4] R.L. Workman and A. Švarc (*priv. comm.)*
[6] *SAID: Phys. Rev. C**86** (2012) 015202*
[5] *BnGa: Eur. Phys. J. A**48** (2012) 15*

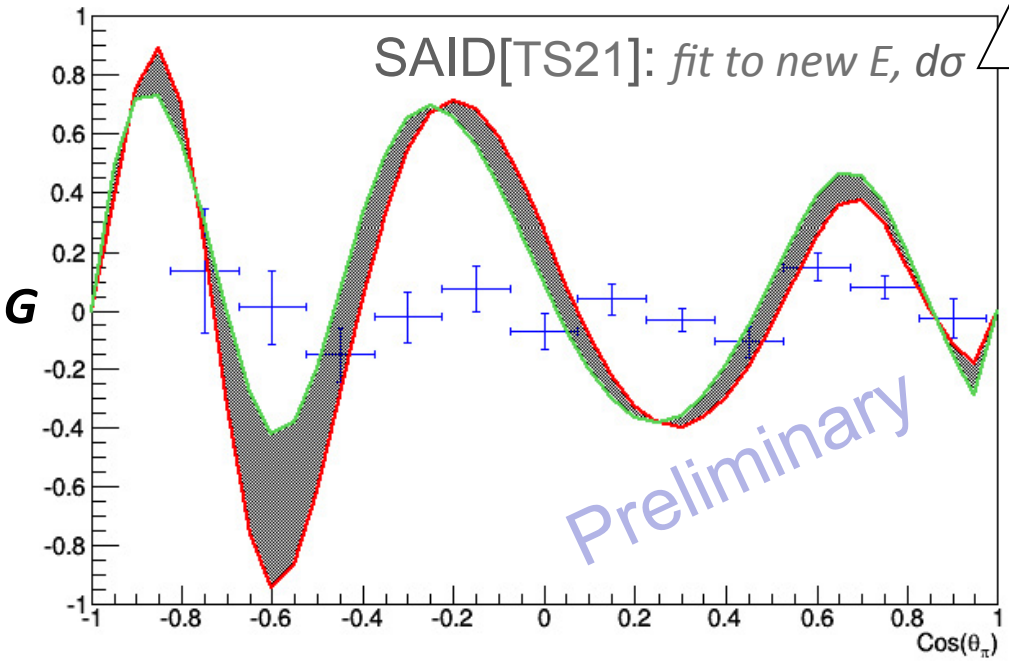
Couplings can only be as certain as the multipoles ⇔ could be impacted by data on new observable

E06-101 (g14 run with CLAS – 2012)

- *linearly-polarized photons on* $\vec{H}\vec{D}$
- E_γ: *1600 – 2200 MeV*
- $\gamma n\ (p) \rightarrow \pi^- p\ (p)$



W= 2020 ±40 MeV



$$G = \frac{1}{P_\gamma P_T} \frac{\sigma_{+\pi/4,+z} - \sigma_{-\pi/4,+z}}{\sigma_{+\pi/4,+z} + \sigma_{-\pi/4,+z}}$$

⇔ **Haiyun Lu's talk** (A2)

Summary

- *Beam-Target helicity asymmetries (E) for $\gamma n \rightarrow \pi^- p$ just out in PRL*
  - 1st data on this observable and spans the full N energy range*

- *significant addition to the sparse γn data base*
  ⇔ *inclusion in PWA have resulted in significant changes to I = ½ multipoles*
  ⇔ *improved determination of helicity amplitudes (γnN* couplings), with SAID and BnGa agreement for* $A_n^{1/2}$ [N(1720)3/2$^+$] and $A_n^{3/2}$ [N(2190)7/2$^-$]
  ⇔ *potential signals in BnGa PWA from PDG* and PDG** resonances*

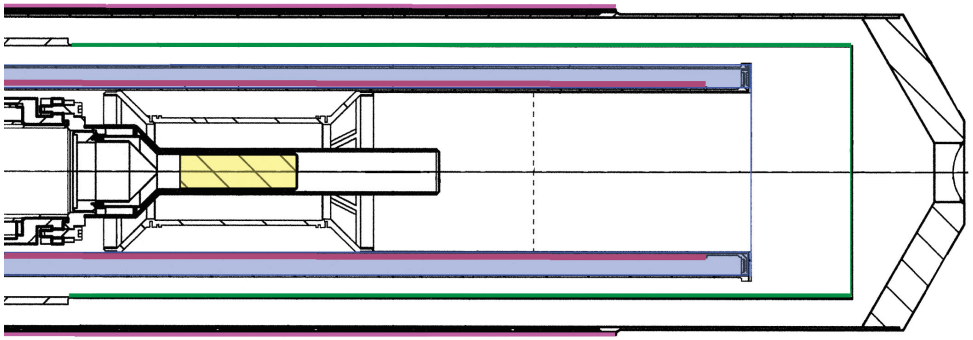
- *next observables in the g14 pipeline:*
  - beam asymmetry Σ *and beam-target asymmetry* ***G*** *for $\gamma n \rightarrow \pi^- p$*

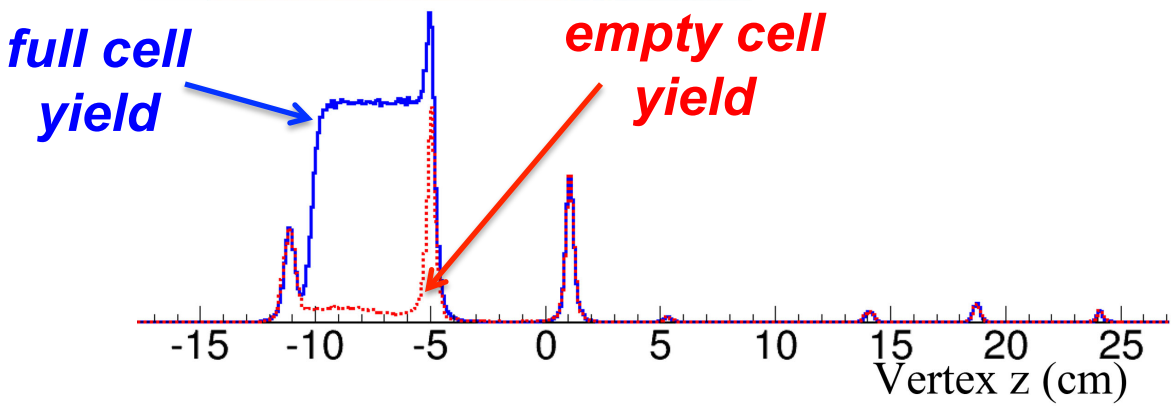
Extras

clean deuteron target

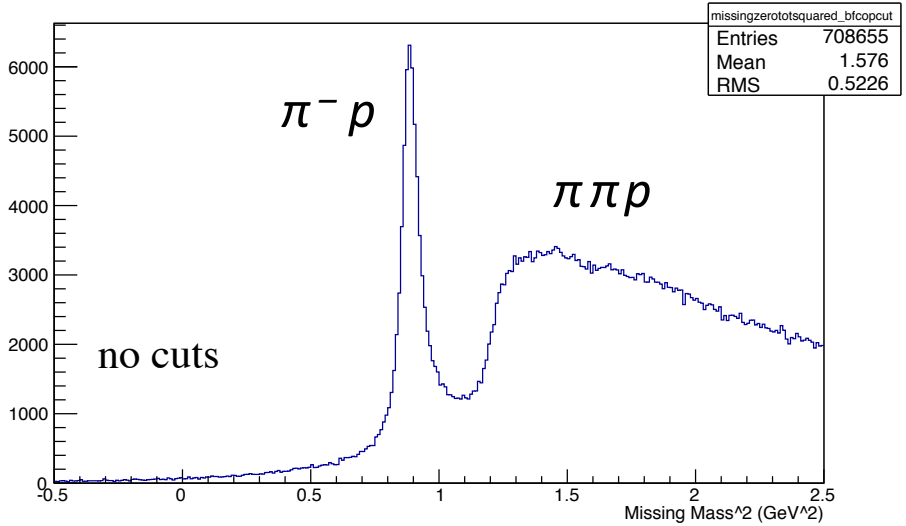
- sources of neutrons: D in HD and the target cell
- evaporate and pump away HD: residual backgrounds are small

⇨ after empty cell subtraction, all neutrons are polarizable

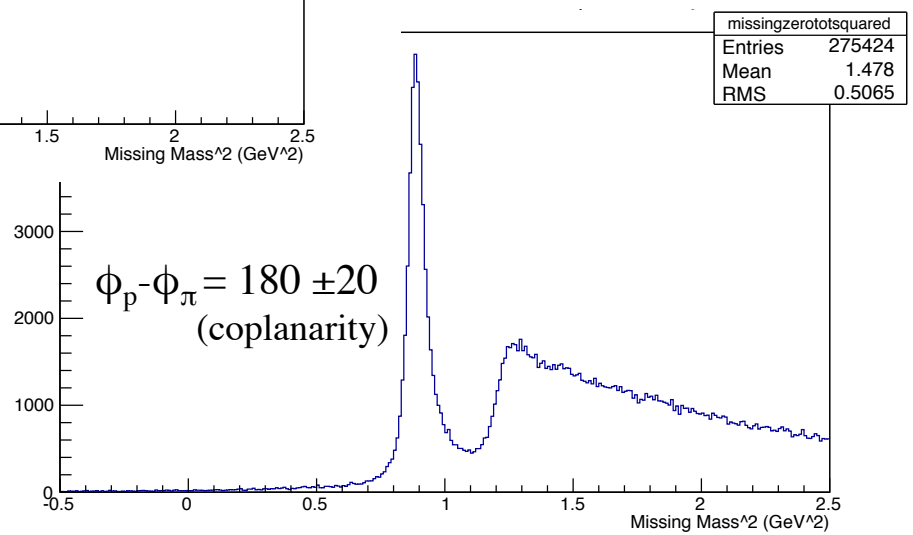




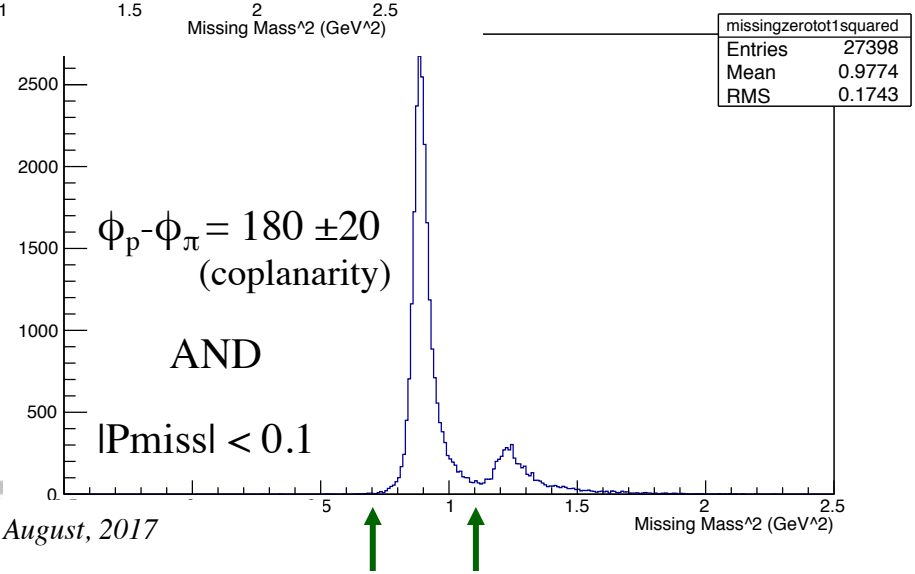
Bksub analysis



MM^2



$\gamma D \rightarrow \pi^- p$ (p) Missing Mass squared, with sequential 2-body requirements, followed by empty cell subtraction



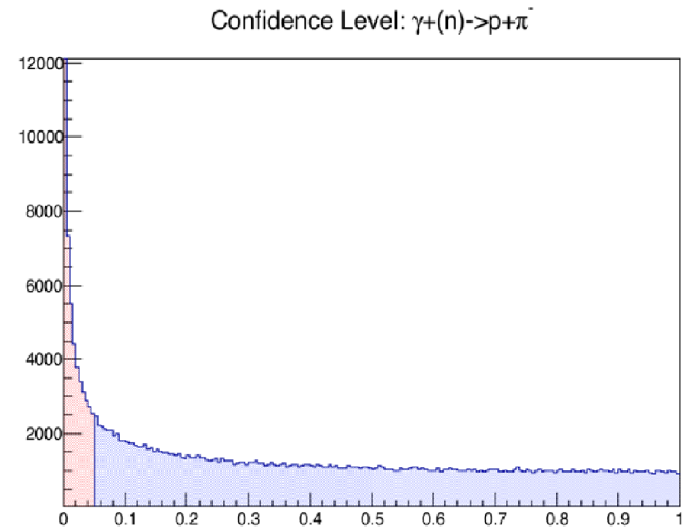
KinFit analysis

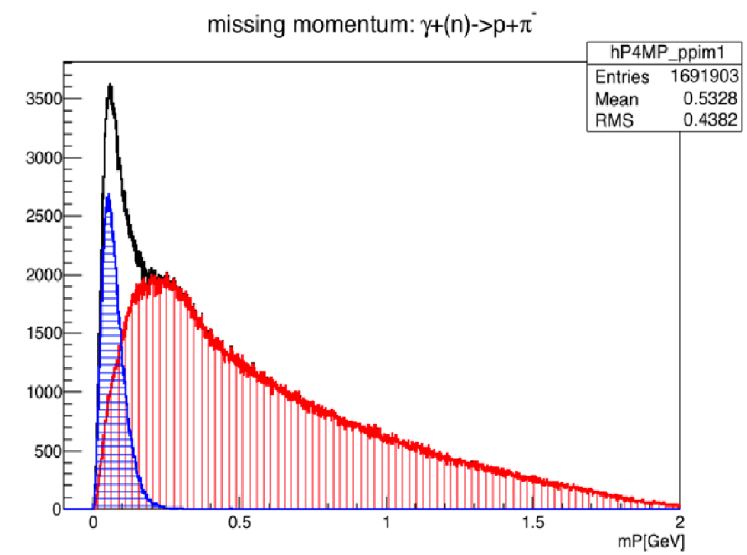
- *Kinematic Fitting carried out on candidates for γ+(n) ➔ π^- p*

  ⇔ *target assumed to have the neutron mass, but unknown momentum*

  ⇔ *amounts to a 1C fit*

- *2π & reactions on target cell nucleons fail with Confidence Level < 0.05*
- *accept events with Confidence Level > 0.05*
- apply $|P_{miss}| < 0.1$ GeV/c to accepted events





BDT analysis

- multivariate ***Boosted Decision Trees***

  ⇔ views the data in a higher dimension

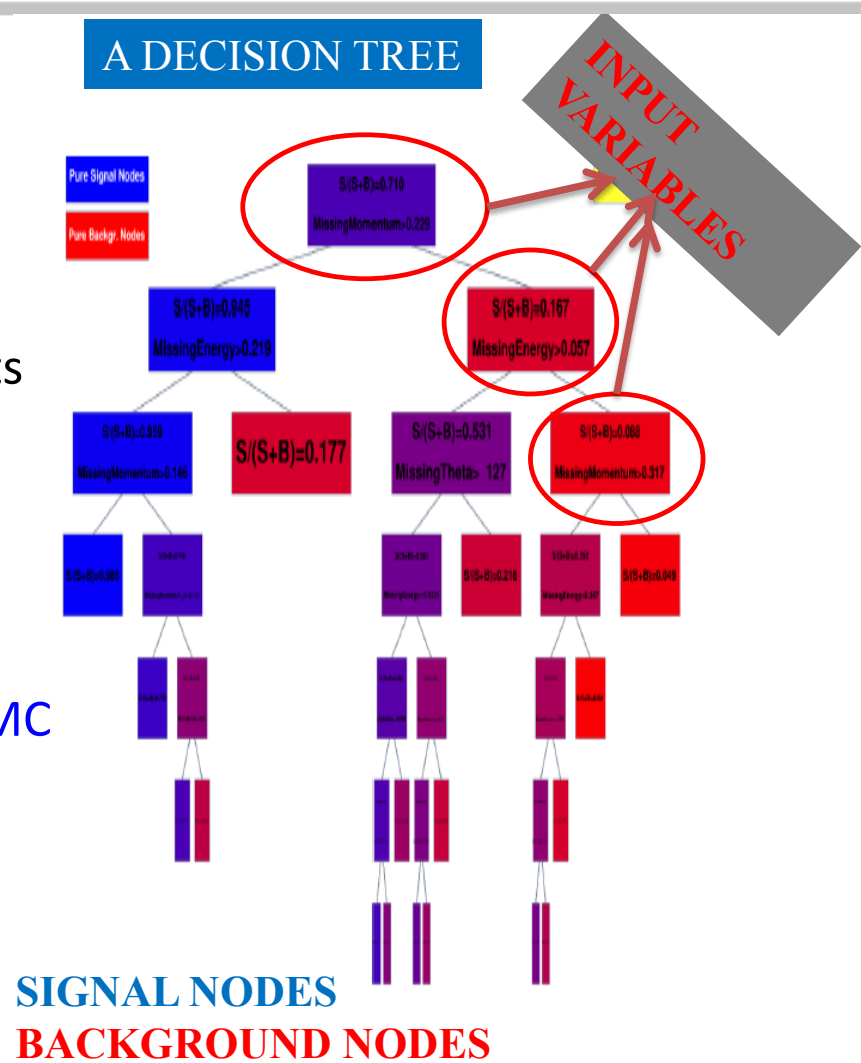
  ⇔ creates a forest of *if-then-else* logical tests on all kinematic variables <u>*simultaneously*</u>

- algorithm categorizes events as either ***signal*** or ***background***

  - *signal trained* on $\gamma D \rightarrow \pi^- p(p)$ from CLAS MC

  - *background trained* on empty-cell data

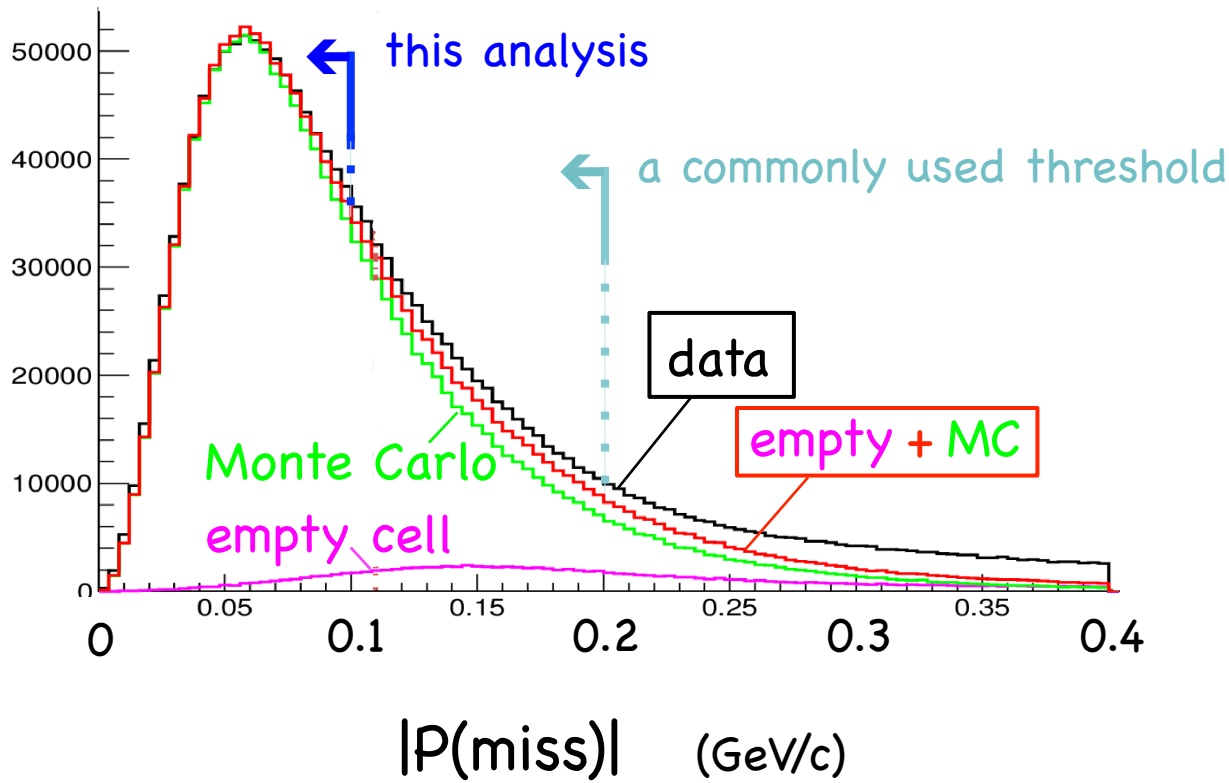
- apply $|P_{miss}| < 0.1$ GeV/c to *signal* events



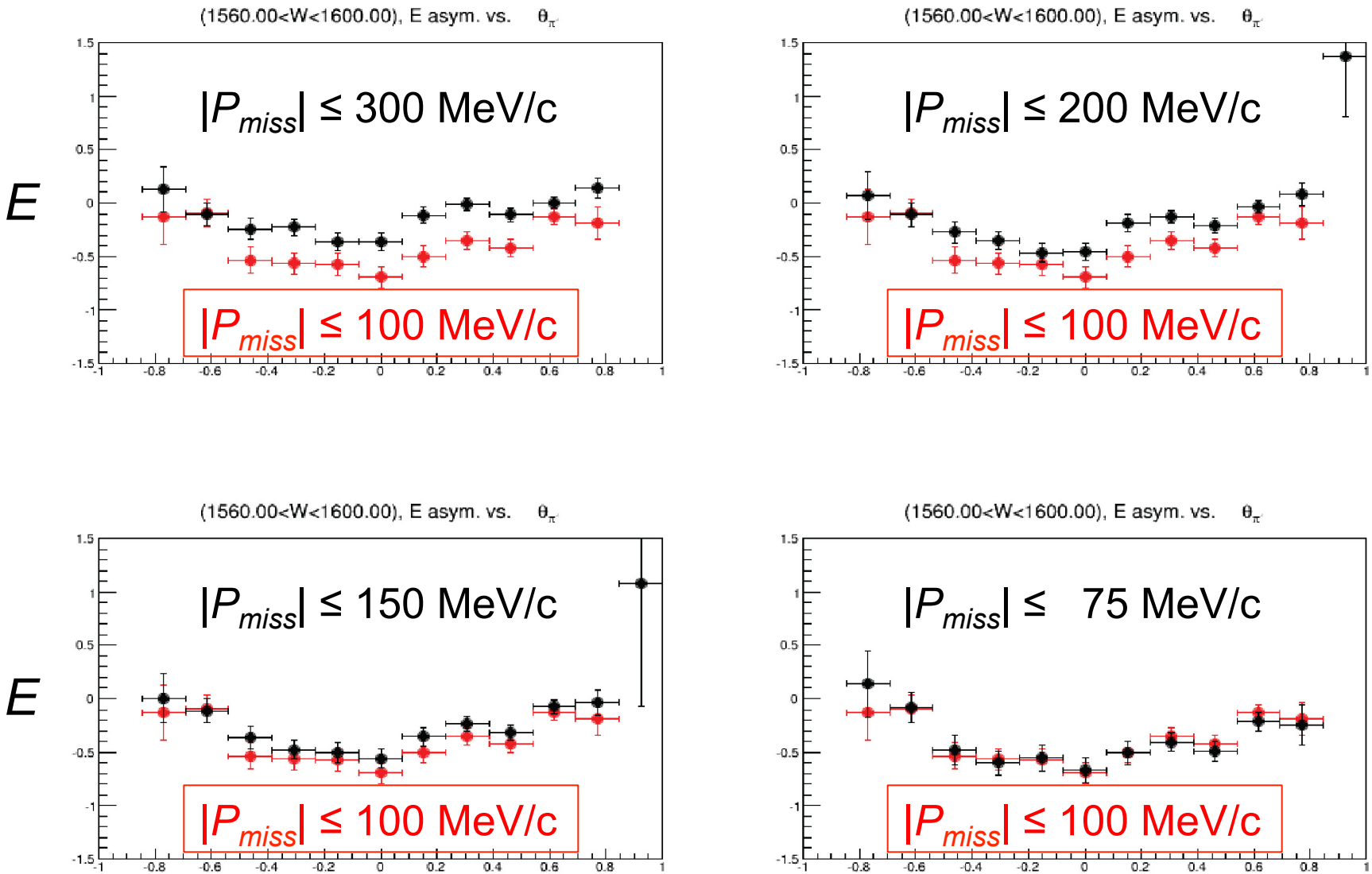
Dao Ho (2015)

Restricting Deuteron reactions to create an effective neutron target

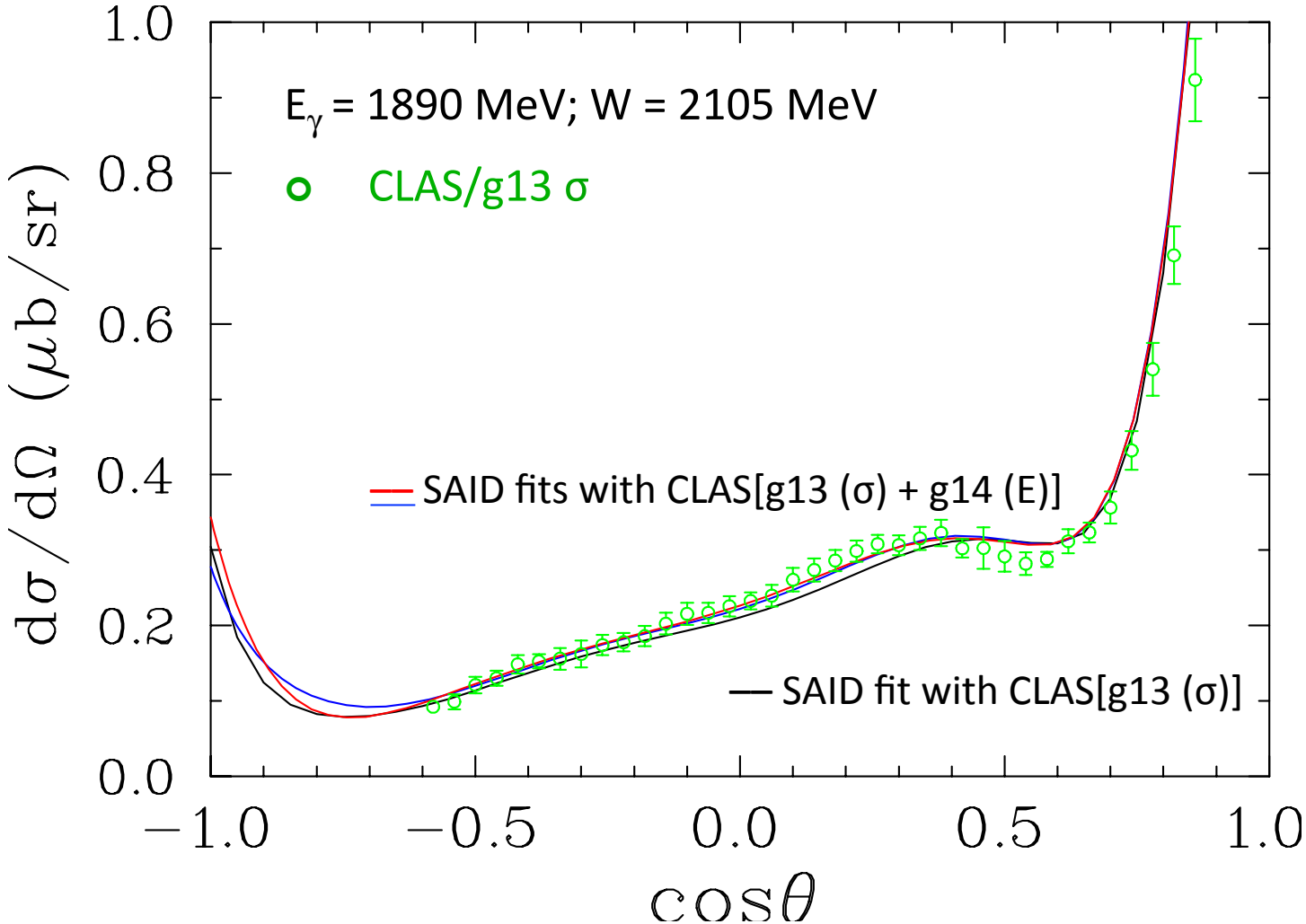
- *select events for which the proton in Deuterium is a passive "spectator"*
  ⇔ key variable is the momentum of the undetected proton in γ+n(p) ➔ π^- p(p)



$E(\pi^- p)$ vs $|P_{miss}|$



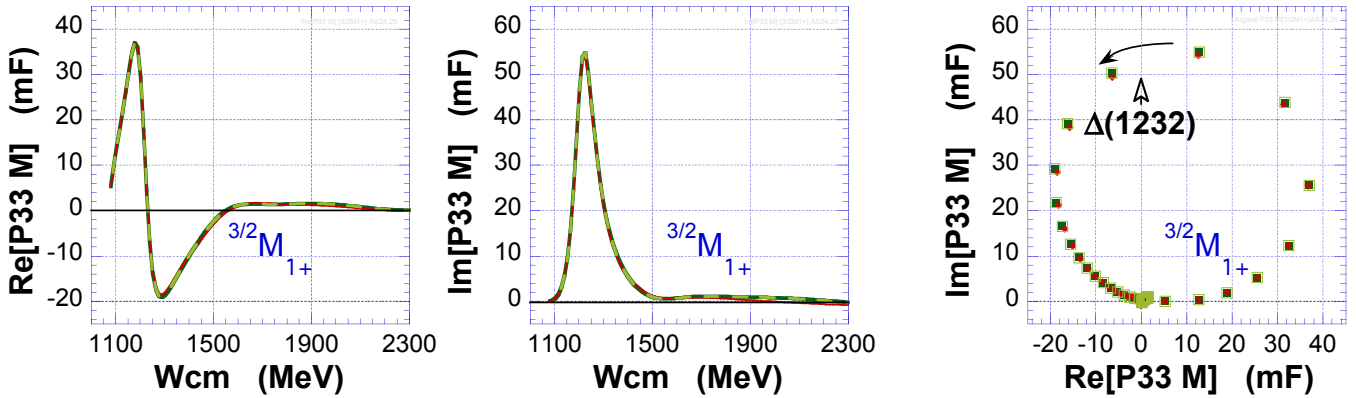
SAID: g13 (σ) + g14(E) PWA fits



PWA: I = 3/2 (Δ^*) partial waves

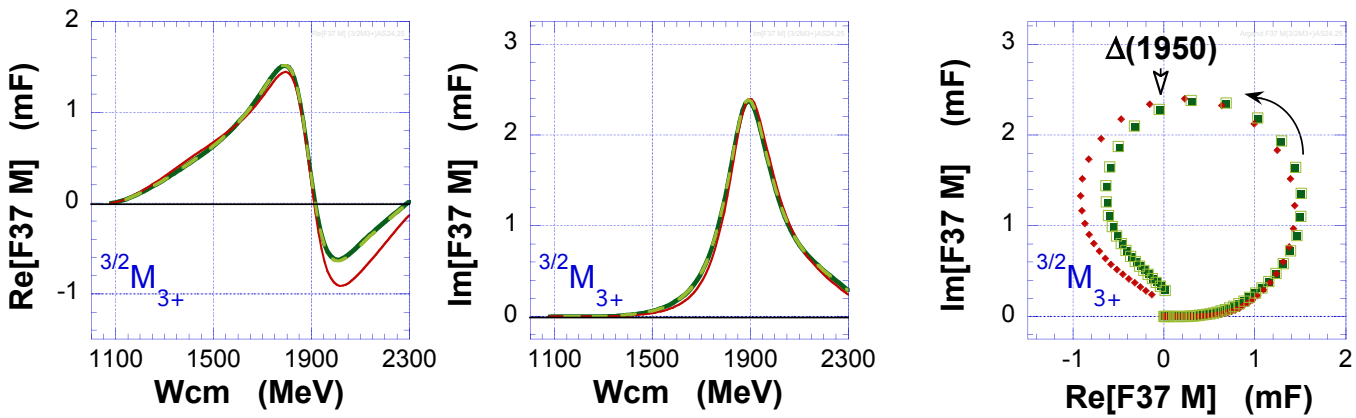
SAID [AS24; w g14]
SAID [AS25; w/o g14]
SAID [CM12]

eg. ***I=3/2, P wave***



Δ(1232)3/2$^+$
(PDG ****)

I=3/2, F wave



Δ(1950)7/2$^+$
(PDG ****)

I = 3/2 waves ~ unchanged ⇔ determined by proton data