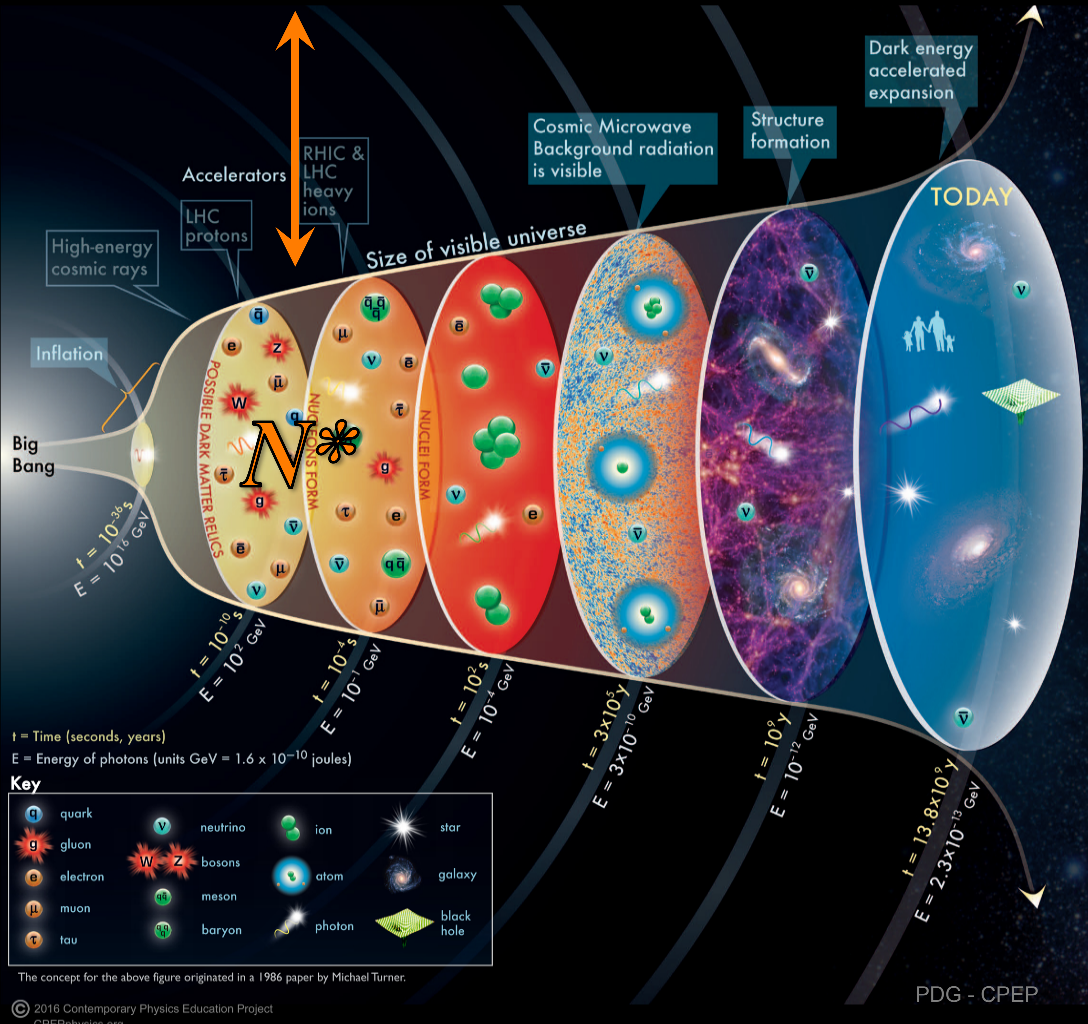
Excitations of the Nucleon – N spectroscopy with clas*

A.M. Sandorfi

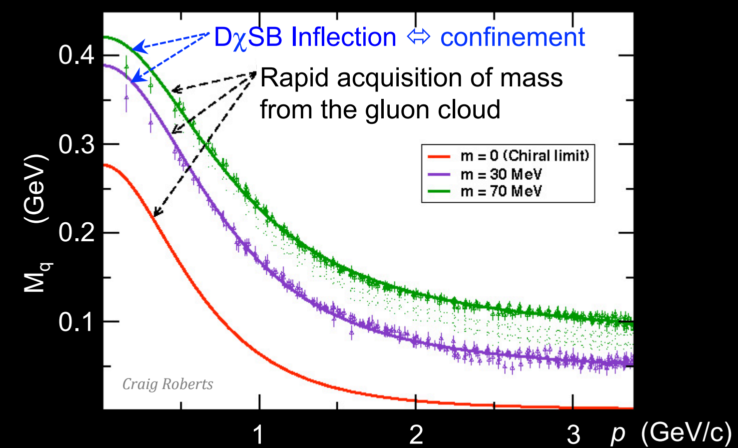
Thomas Jefferson National Accelerator Facility, Newport News VA

N resonances in the early universe*

Dramatic chiral crossover at about $t_0 + 1\ \mu s$ ⇔ $T_c = 154 \pm 9$ MeV



- *Chiral symmetry is broken*
- *quarks acquire mass*



- *color confinement emerges*
- *copious production of hadronic resonances*

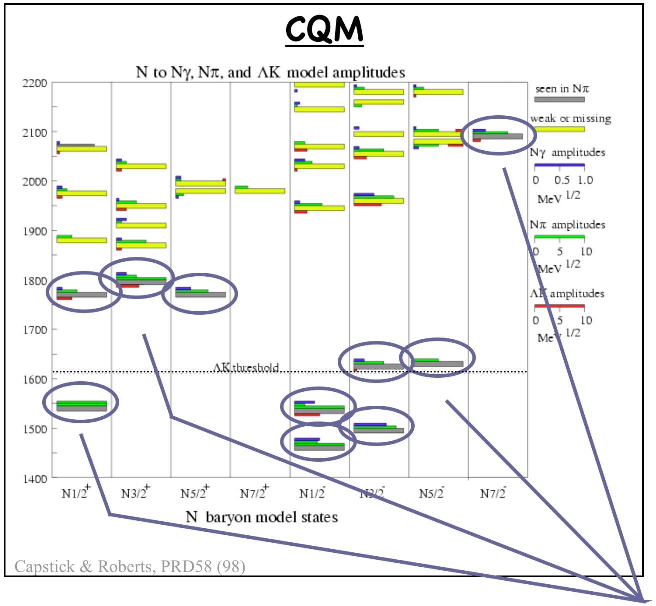
embracing QCD …

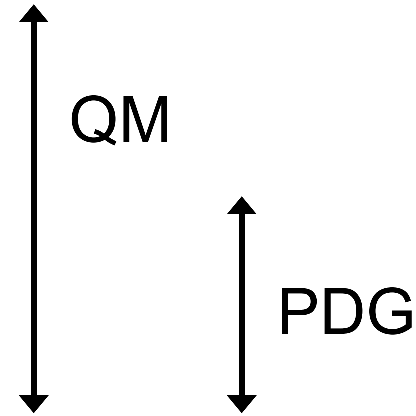
- *Paolo Neruda (paraphrased):*

" Make you choice in life, but then embrace the consequences. "

⇔ *leaves little room for desperation or depression* !

Where are these N resonances ?*





- *...up to a decade ago:*
  only the lowest few in each band correspond to 4 or 3* PDG states*

- *Vintage explanations:* { *eg. Anselmino et al., Rev. Mod. Phys.* ***65*** *(93) 1199* }
  - *2 quarks in a baryon quasibound in a color isotriplet* [*diQ+q* ⇔ *isosinglet*]
  - *internal "diQuark" excitations frozen out in spin =0, isospin =0 states*

  ⇔ *fewer degrees of freedom* ⇔ *fewer states*

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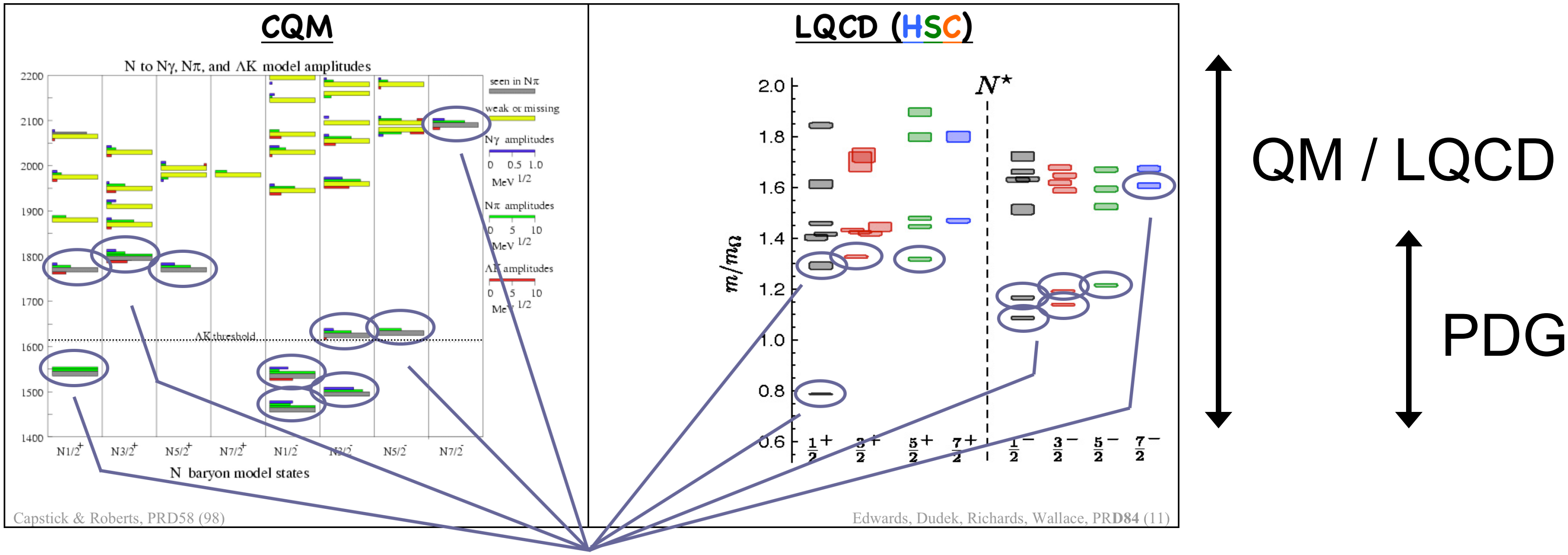

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N s that just can't go away …*

DSE & LQCD calculations of N* spectrum:

- *axial-vector color-triplet q-q correlations are attractive*
  - *diQuarks correlations must exist*
  - *BUT, they are not point-like, eg. r[ud]$_1$ ~ pion radius* {Few Body Sys **35** (04); PRL**97**(06)}

⇔ *internal diQuark excitations are NOT frozen out*

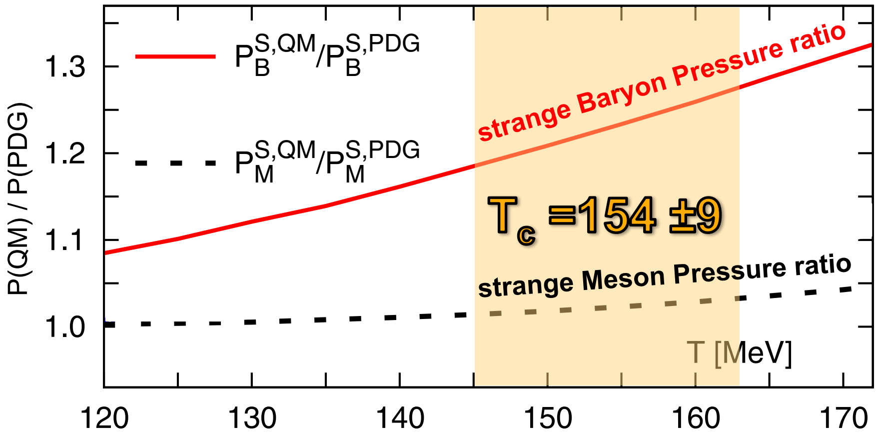
⇔ *diQuark correlations are already observed in the LQCD calculations*

LQCD calculations of the T_c phase transition in the ~1 μs universe:

- *PDG states alone are insufficient*
- *full suite of QM/LQCD states needed*

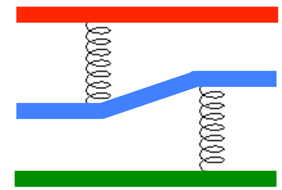
⇔ *~ 25% baryon pressure increase needed from as yet unobserved N*s*

{ *Bazavov et al., PRL **113** (2014) 072001* }



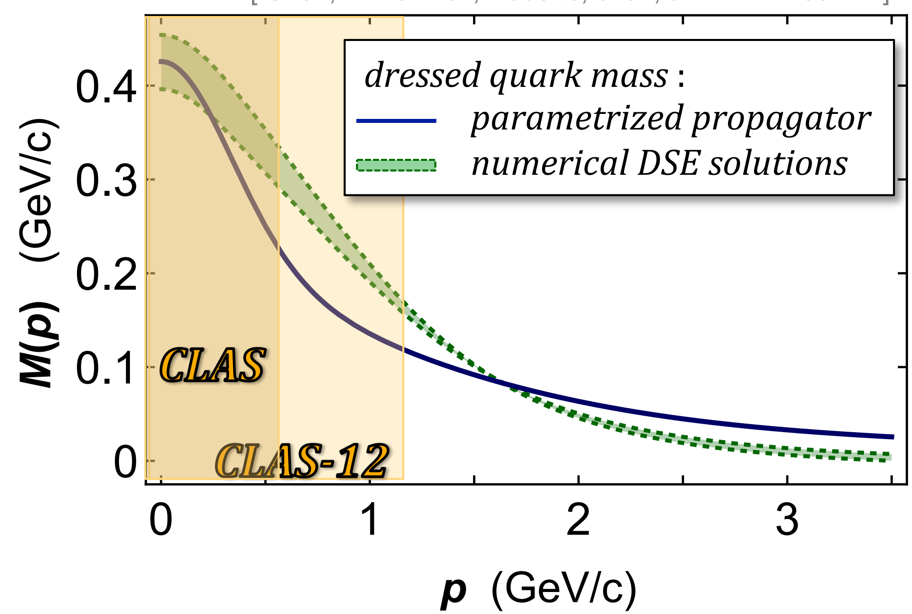
goals of the N program with CLAS at Jefferson Lab*

- *dressings of strongQCD (non-perturbative) generate a running quark-mass function*
  ⇔ *"constituent-like" correlations at low **p** that generate the N* spectrum*
  ⇔ *account for ~98% of the visible mass (Higgs mechanism is the other ~2%)*



*sQCD emerged at ~t_0 +1 μs when N*s filled the Universe*

[Chen, El-Bennich, Roberts, et al., arXiv:1711.03142]



"constituent" range ◄-------

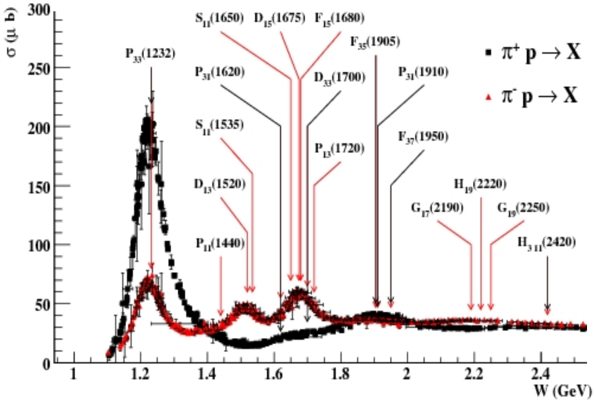
Higgs range -------►

- ***CLAS goals**:*
  - ***elucidate the structure of N* states that are observed, and find the ones that aren't !***
  - ***clarify the role of complex correlations:***
    - *meson cloud*
    - *dynamical meson-baryon "molecules"*

Challenge #1 – N resonances are broad and overlapping*

- ***πN ➔ πN ⬄ chief source of pre-2008 PDG states***
  - *2 complex spin-dependent amplitudes*
    ⬄ requires 3 observables to define the full amplitude, within a phase
  - *there are only 4 observables* (*σ, P,* ***R, A***)
  - *data base: ~40,000 pts on* ***σ****; ~8300 pts on* ***P***

$\sigma_{tot}(\pi + N)$



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  - *almost no data on **R** & **A** (~30 pts above the Δ)*

    ⬄ amplitude is under-determined

    ⬄ very difficult to isolate weaker states

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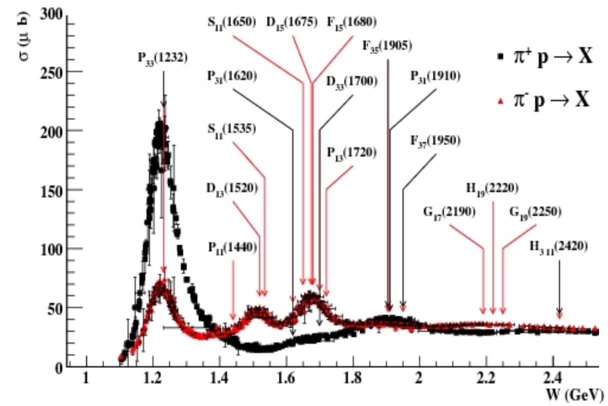

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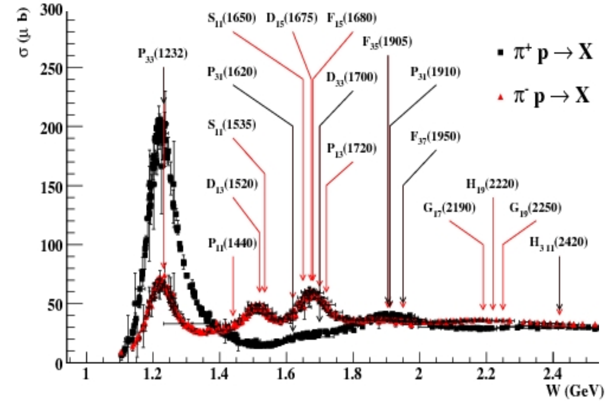
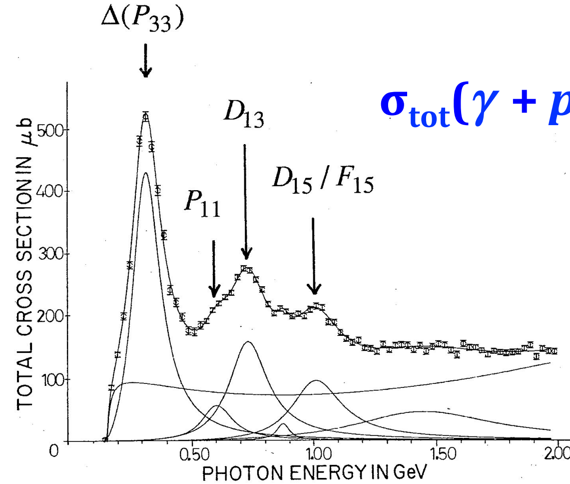


- ***γN ➔ πN, ηN, KY, …***
  - *4 complex amplitudes*
    ⬄ requires 7 (8) observables to define the full amplitude, within a phase
  - *<u>there are 16 observables:</u>*
    ($\sigma, \Sigma, T, P, E, G, F, H, O_{x'}, O_{z'}, C_{x'}, C_{z'}, L_{x'}, L_{z'}, T_{x'}, T_{z'}$)

    ⬄ possible to over-determine the amplitude

$\sigma_{tot}(\gamma + p)$

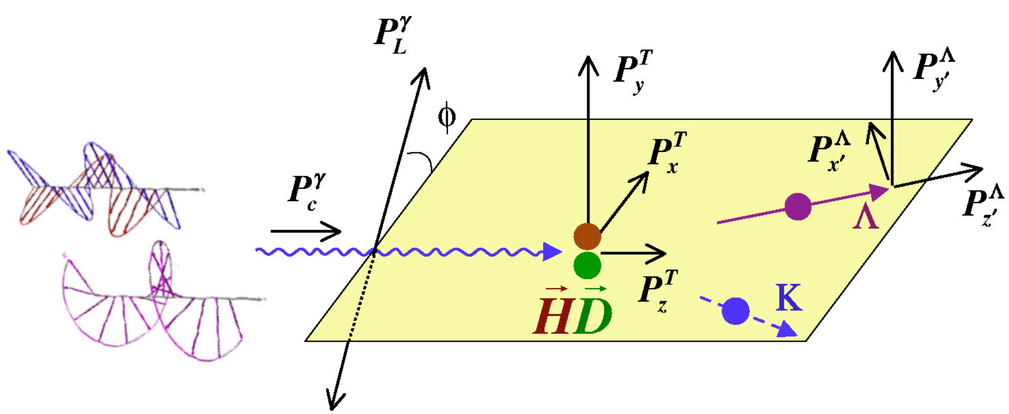


NP B41(1972) 445

Measurements of "everything" in $J=0^-$ meson photo-production

[SHKL, J Phys G**38** (11) 053001]

Photon beam		*Target*			*Recoil*			*Target - Recoil*								
					x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
		x	y	z				x	y	z	x	y	z	x	y	z
unpolarized	σ_0		T			P		$T_{x'}$		$L_{x'}$		Σ		$T_{z'}$		$L_{z'}$
$P_L^\gamma \sin(2\phi_\gamma)$		H		G	$O_{x'}$		$O_{z'}$		$C_{z'}$		E		F		$-C_{x'}$	
$P_L^\gamma \cos(2\phi_\gamma)$	$-\Sigma$		$-P$			$-T$		$-L_{z'}$		$T_{z'}$		$-\sigma_0$		$L_{x'}$		$-T_{x'}$
circular P_c^γ		F		$-E$	$C_{x'}$		$C_{z'}$		$-O_{z'}$		G		$-H$		$O_{x'}$	



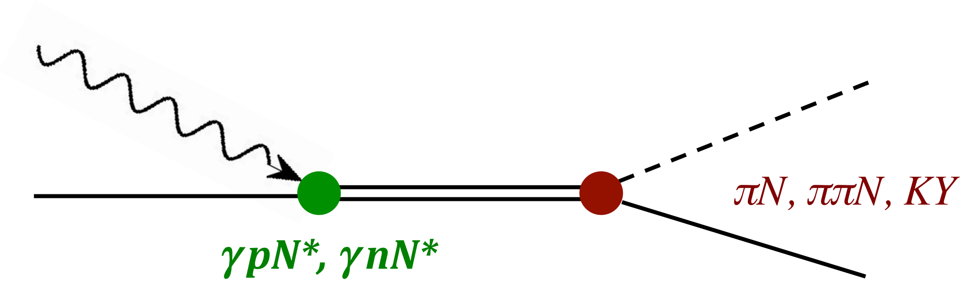
- ***16 different observables***
- ***combine asymmetries for different final states in a coupled-channel PWA***

⇔ ***identify N* resonances***

⇔ ***extract γNN* couplings***

Challenge #2: the dressings of sQCD

N resonance ⇔ s-channel pole*

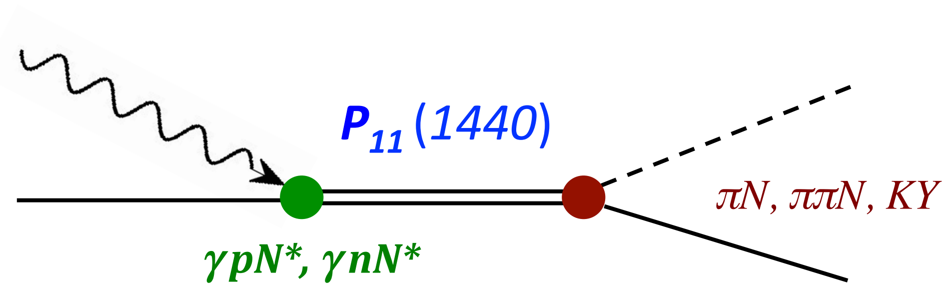


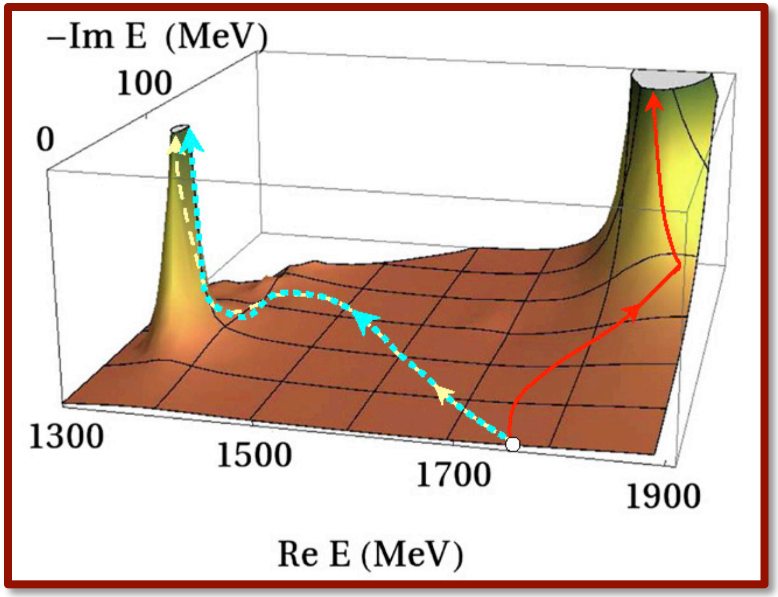
- *meson-loop "dressings" of the Electromagnetic vertex affect the dynamical properties (excitation mechanism) and determine Q^2 evolution, but not spectral properties*

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

Challenge #2: the dressings of sQCD – eg. the P_{11} Roper

N resonance ⇔ s-channel pole*





- *coupled-channel "dressings" of the strong vertex determine the N* spectral properties*
- *dynamic coupled-channel model of πN, γN ➔ πN, $\pi\Delta$, ηN, KY*

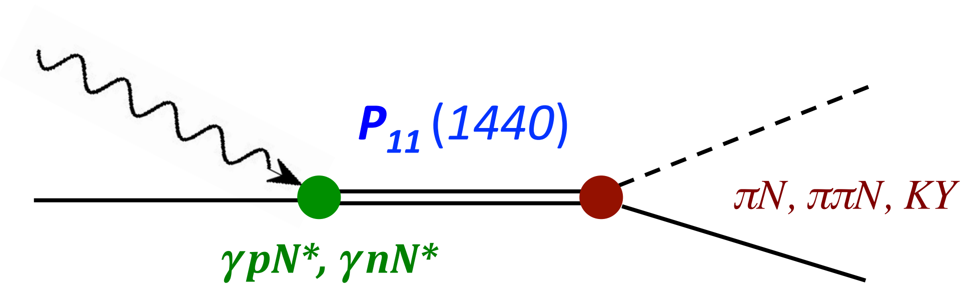
[EBAC/AO, PRL **104** (2010) 042302]

⇔ "bare" N excitation at 1763 evolves to doublet of poles at ~1360*

⇔ no PWA of a single channel can be sufficient with such couplings

Challenge #2: the dressings of sQCD – eg. the P_{11} Roper

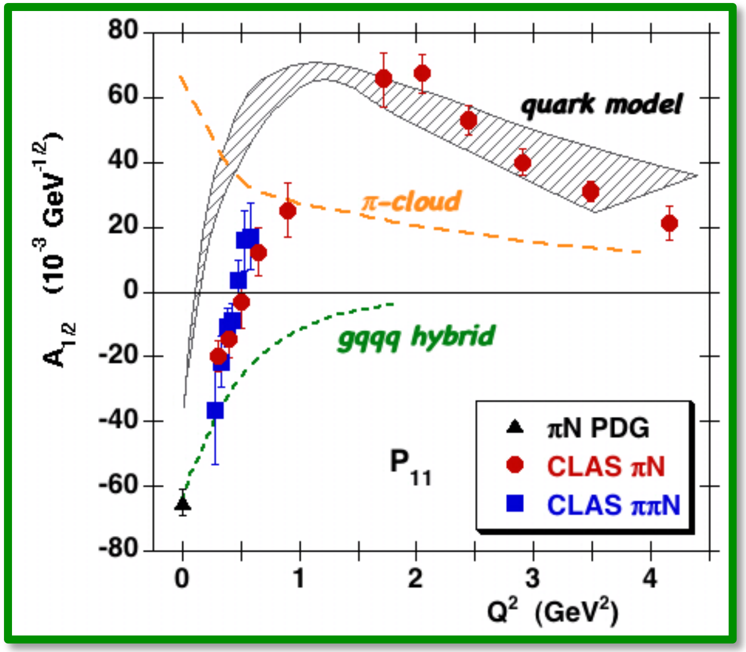
N resonance ⇔ s-channel pole*



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

- *Q^2 evolution demonstrates the basic character of the second $J^{\pi}=1/2^+$ state of the nucleon as a radial excitation of a dressed 3q core*

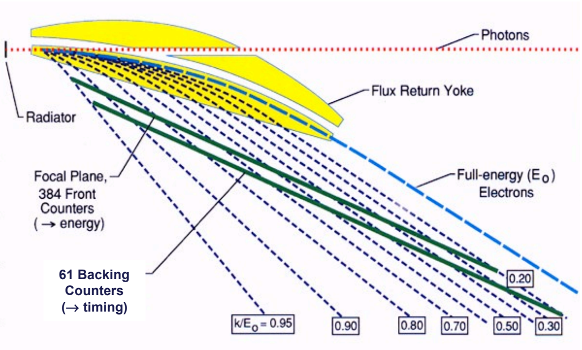
[Chen, El-Bennich, Roberts, et al., arXiv:1711.03142]

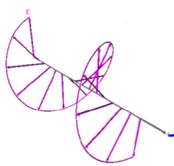


[AMS, J. Phys. Conf. **424** (2013) 012001, & ref therein]

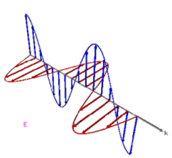
CEBAF Large Acceptance Spectrometer (CLAS): 1997 - 2012

- ***tagged photon beams***



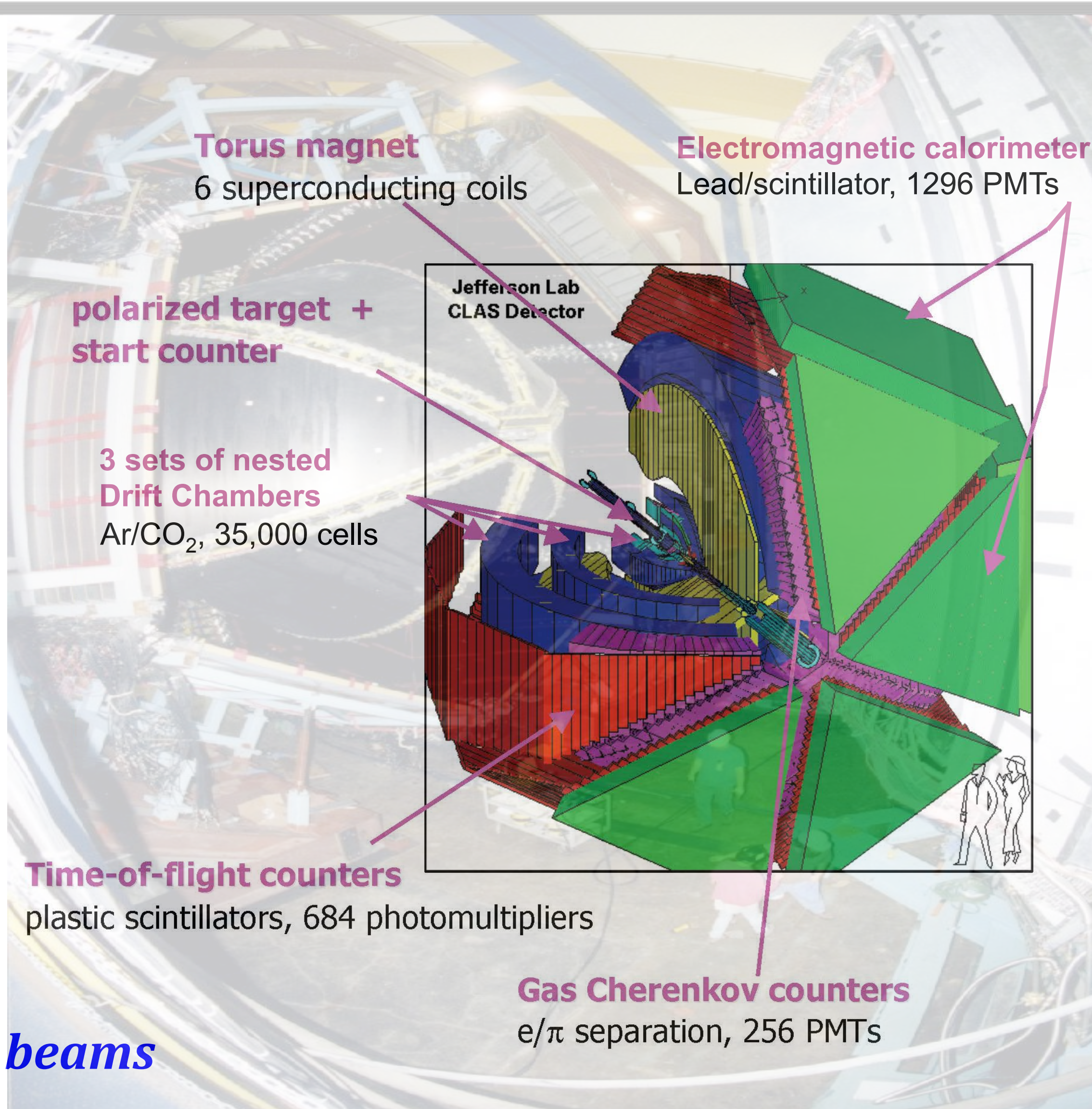


circular polarization from brem of polarized e⁻

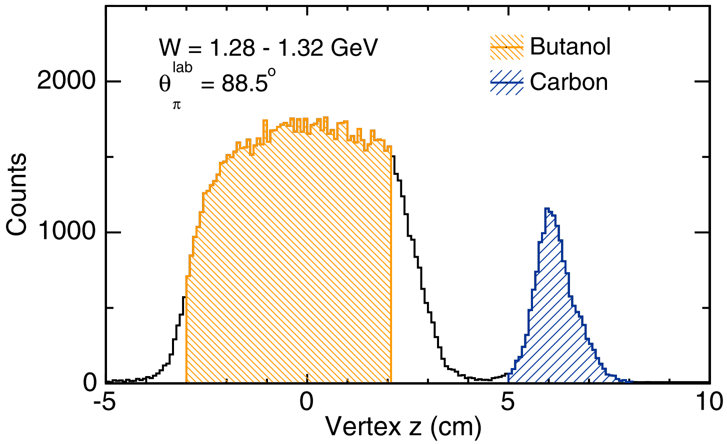


linear polarization from e⁻ brem in diamond

- ***longitudinally polarized e⁻ beams***

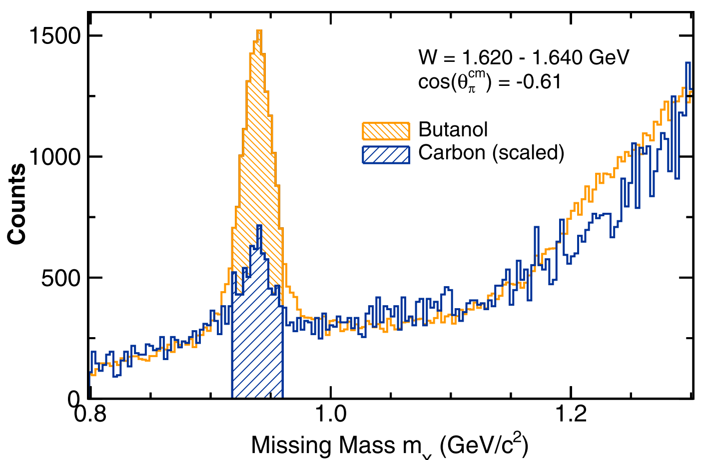


FROST – frozen-spin proton target

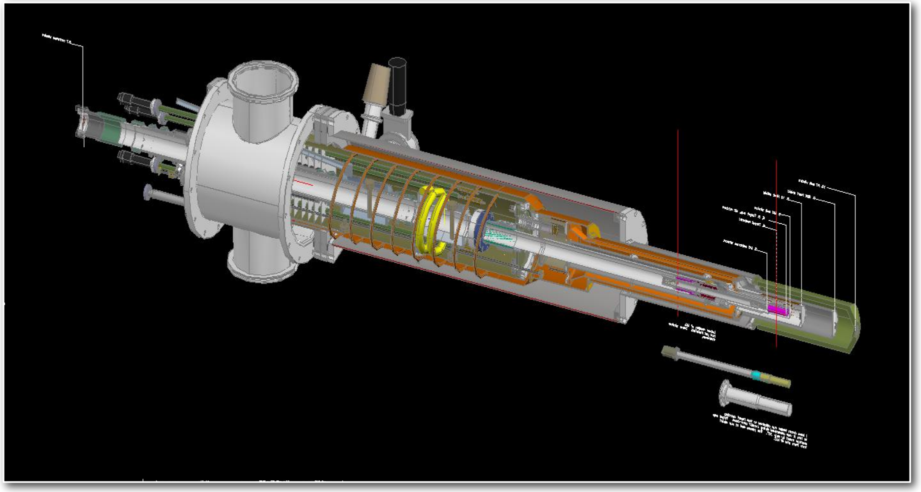


$$\gamma p \rightarrow \pi^+ (n)$$

g9a: Strauch et al., PL B**750** (2015) 53

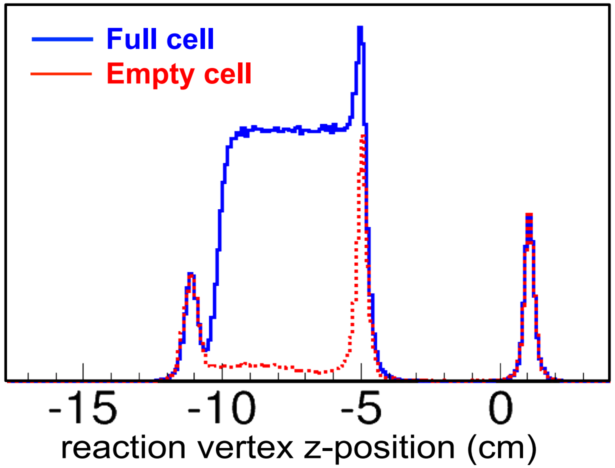


- target: 15mm Ø x 50mm
- material: C_4H_9OH (butanol)
- p-dilution: 10/74
- P(H) = 83%
- T_1 (1/e spin relaxation) = 115 d (+h)
= 65 d (-h)
- repolarize ~ weekly



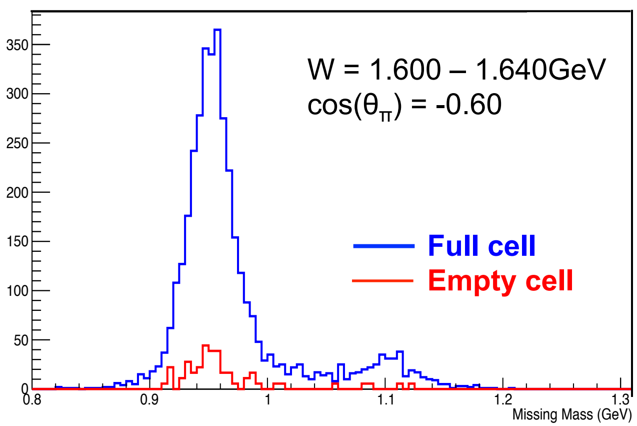
FROST: NIM A**684** (2012) 27

HDice – frozen-spin target for neutrons

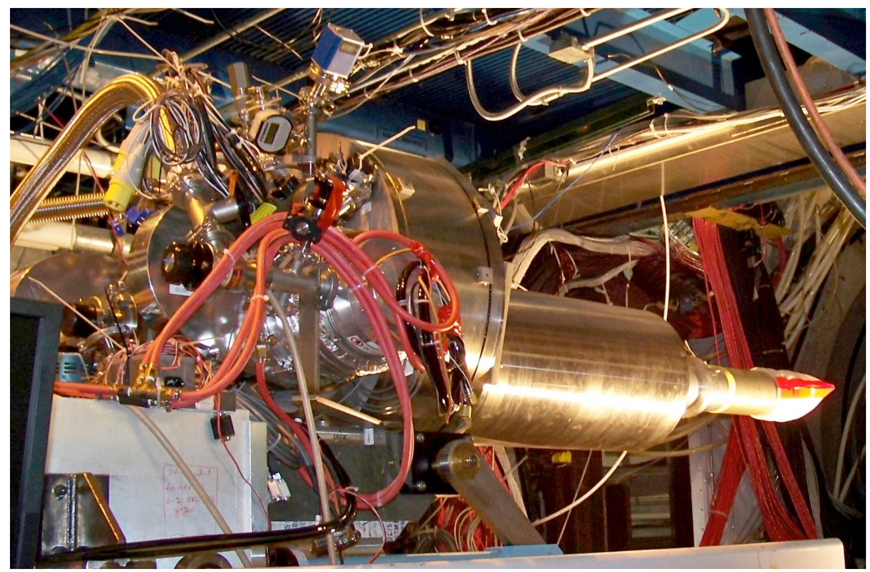


$$\gamma n \rightarrow \pi^- p$$

g14: Ho et al., PRL 118 (2017) 242002



- target: 15mm Ø x 50mm
- material: solid HD
- p-dilution: 1/2; n-dilution: 1/1
- P(H) = 60% or P(D) = 30%
- T_1 (1/e spin relaxation) ~ years

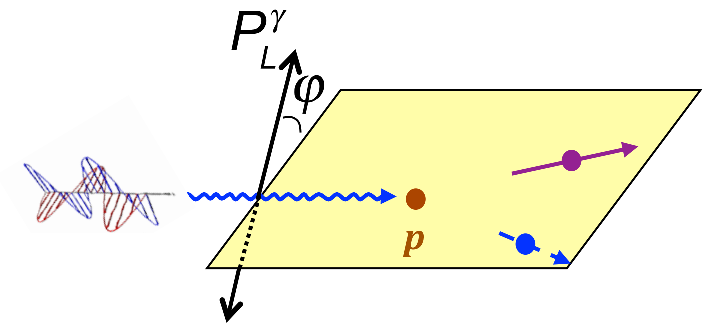


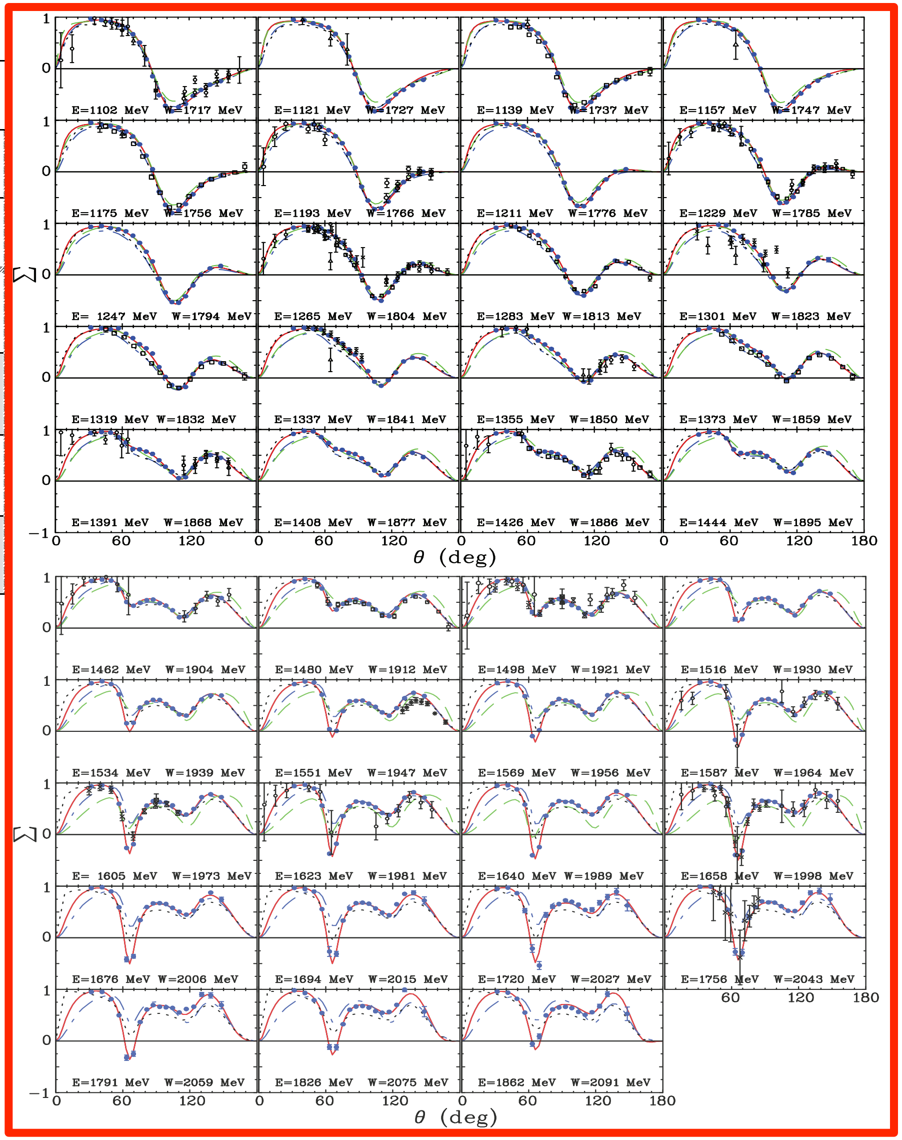
HDice-I: NIM A**737** (2014) 107 HDice-II: NIM A**815** (2016) 31

$\Sigma\ (\vec{\gamma}\, p \rightarrow \pi^0 n)$

CLAS-g8b: PRC**88** (2013) 065203

Photon beam		*Target*			*Recoil*		
					x′	*y′*	*z′*
		x	*y*	*z*			
unpolarized	σ_0		***T***			***P***	
$P_L^\gamma\ \sin(2\phi_\gamma)$		***H***		***G***	$O_{x'}$		$O_{z'}$
$P_L^\gamma\ \cos(2\phi_\gamma)$	$-\Sigma$		$-P$			$-T$	
circular P_c^γ		***F***		$-E$	$C_{x'}$		$C_{z'}$

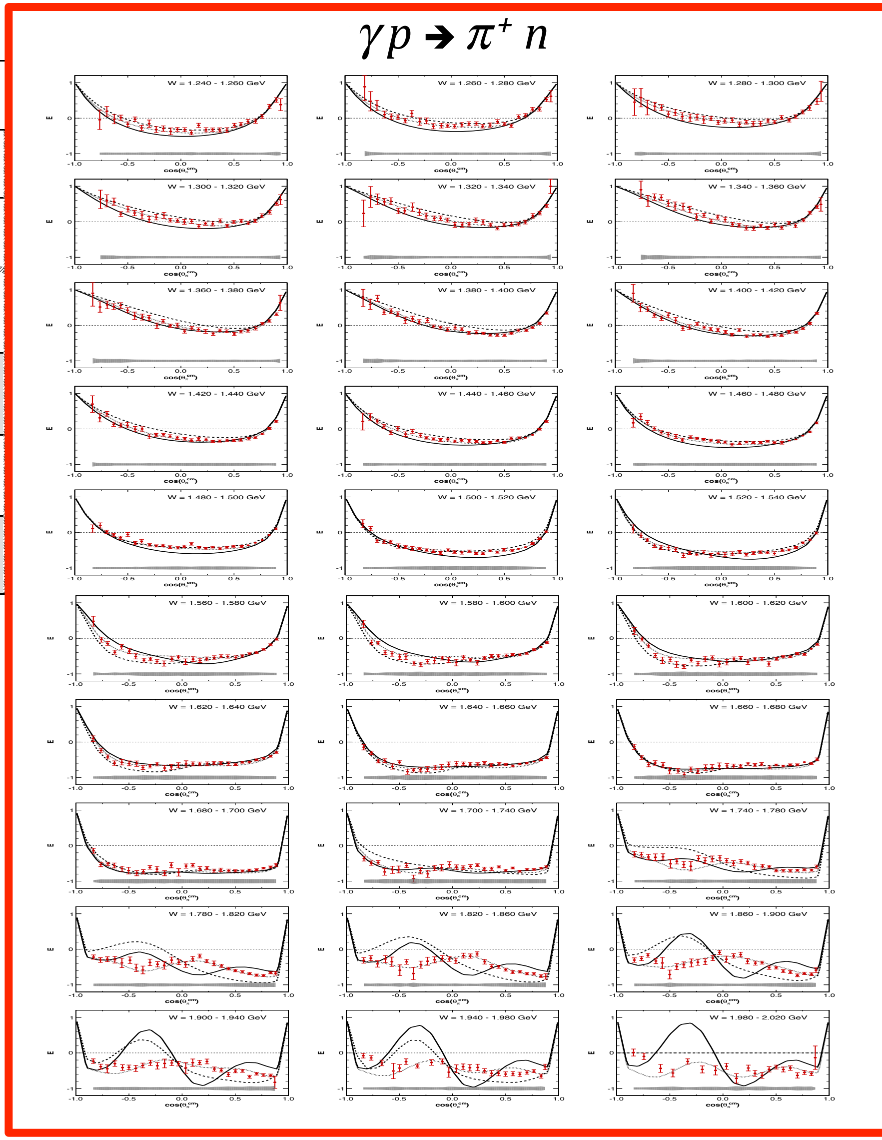


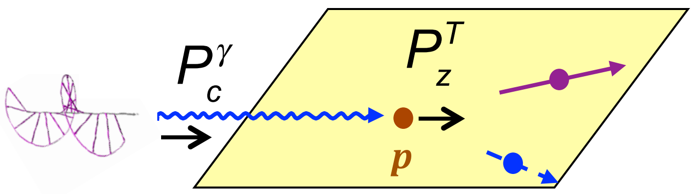


$E(\vec{\gamma}\vec{p} \rightarrow \pi^+ n)$

CLAS-g9a: *Phys Lett **B750** (2015) 53*

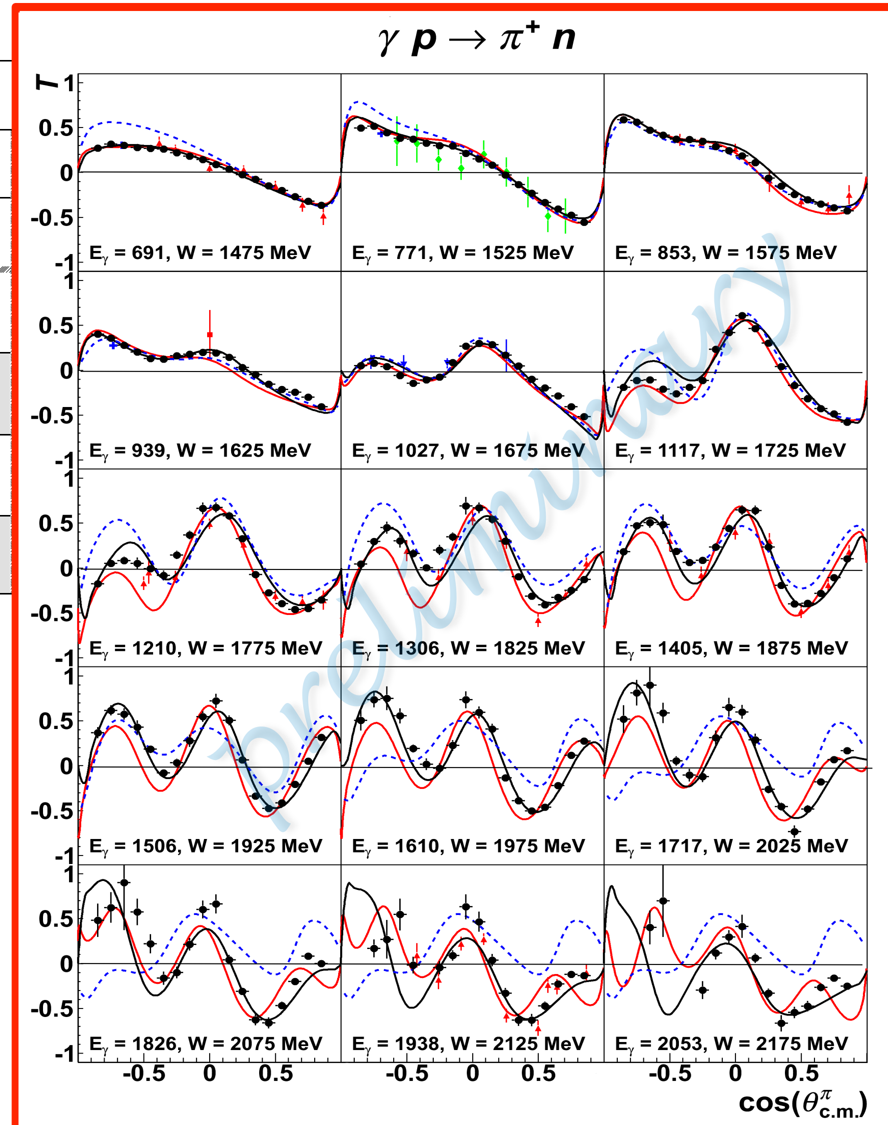
Photon beam		Target			Recoil		
					x'	y'	z'
		x	y	z			
unpolarized	σ_0		***T***			***P***	
$P_L^\gamma \sin(2\phi_\gamma)$		***H***		***G***	$O_{x'}$		$O_{z'}$
$P_L^\gamma \cos(2\phi_\gamma)$	$-\Sigma$		***−P***			***−T***	
circular P_c^γ		***F***		***−E***	$C_{x'}$		$C_{z'}$

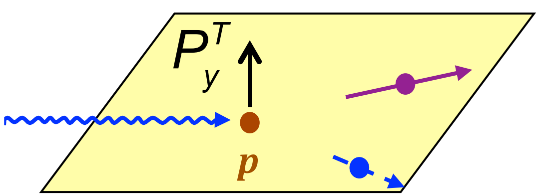




$T(\gamma\vec{p} \to \pi^+ n)$ CLAS-g9b (prelim): courtesy of M. Dugger

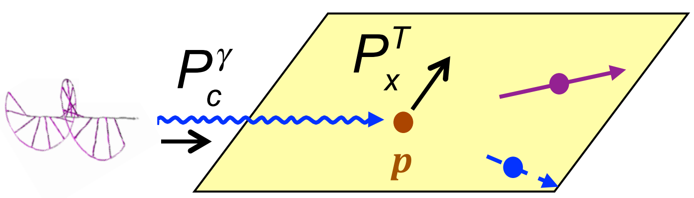
Photon beam		Target			Recoil		
					x'	y'	z'
		x	y	z			
unpolarized	σ_0		T			P	
$P_L^\gamma \sin(2\phi_\gamma)$		H		G	$O_{x'}$		$O_{z'}$
$P_L^\gamma \cos(2\phi_\gamma)$	$-\Sigma$		$-P$			$-T$	
circular P_c^γ		F		$-E$	$C_{x'}$		$C_{z'}$

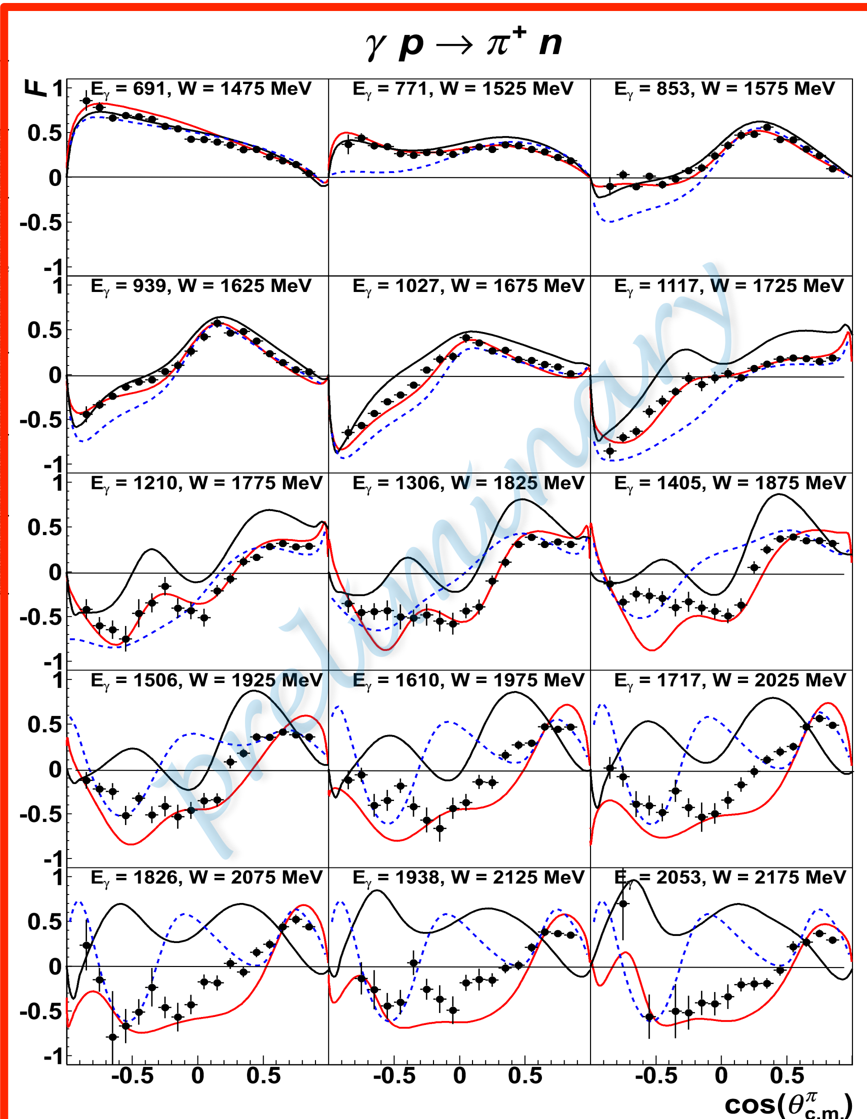




$F(\vec{\gamma}\vec{p} \rightarrow \pi^+ n)$ CLAS-g9b (prelim): courtesy of M. Dugger

Photon beam		Target			Recoil		
					x'	y'	z'
		x	y	z			
unpolarized	σ_0		T			P	
$P_L^\gamma \sin(2\phi_\gamma)$		H		G	$O_{x'}$		$O_{z'}$
$P_L^\gamma \cos(2\phi_\gamma)$	$-\Sigma$		$-P$			$-T$	
circular P_c^γ		F		$-E$	$C_{x'}$		$C_{z'}$

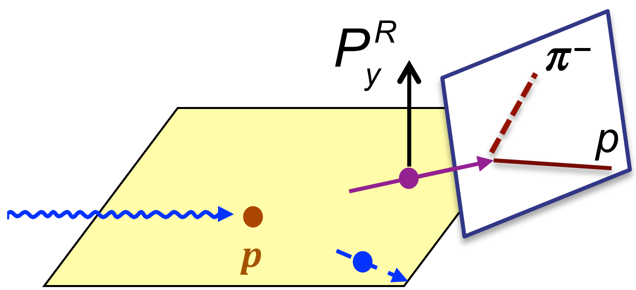


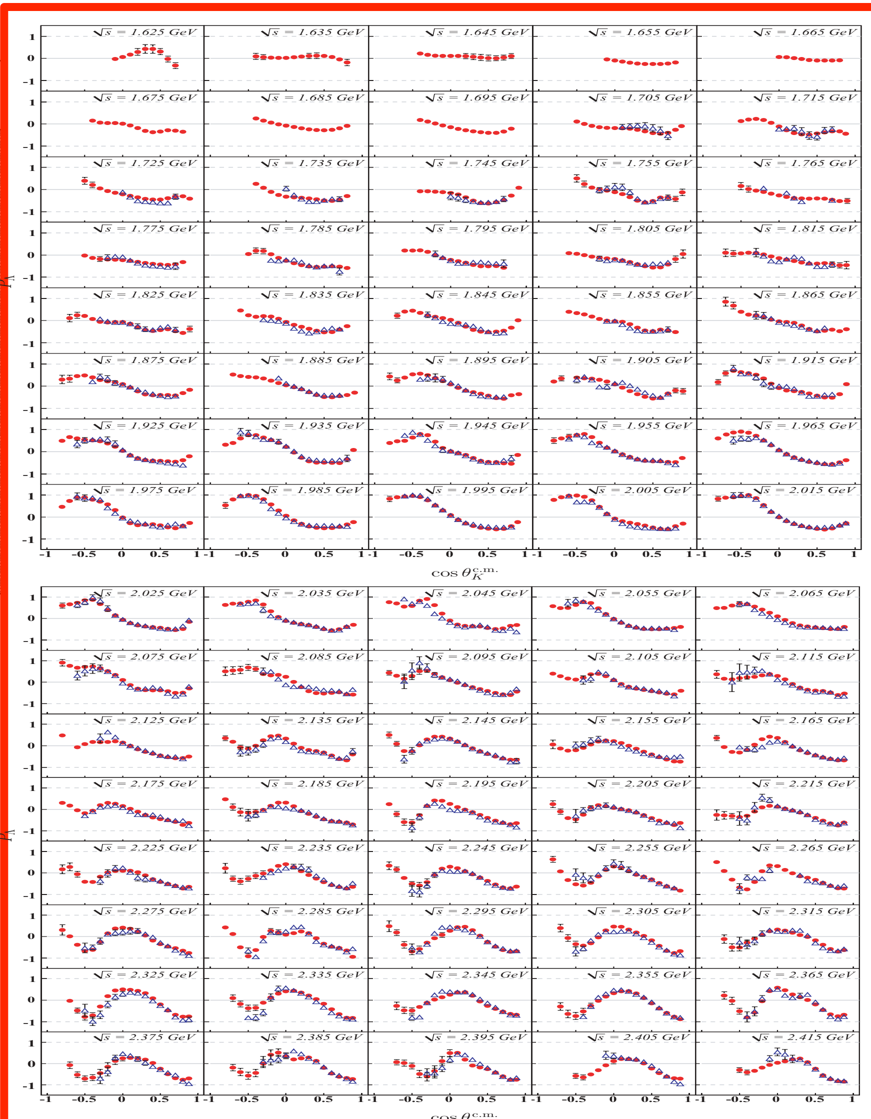


$P_\Lambda(\gamma p \to K^+\vec{\Lambda})$

CLAS-g11 : *Phys Rev C81 (2010) 025201*

Photon beam		Target			Recoil		
					x'	y'	z'
		x	y	z			
unpolarized	σ_0		T			P	
$P_L^\gamma \sin(2\phi_\gamma)$		H		G	$O_{x'}$		$O_{z'}$
$P_L^\gamma \cos(2\phi_\gamma)$	$-\Sigma$		$-P$			$-T$	
circular P_c^γ		F		$-E$	$C_{x'}$		$C_{z'}$

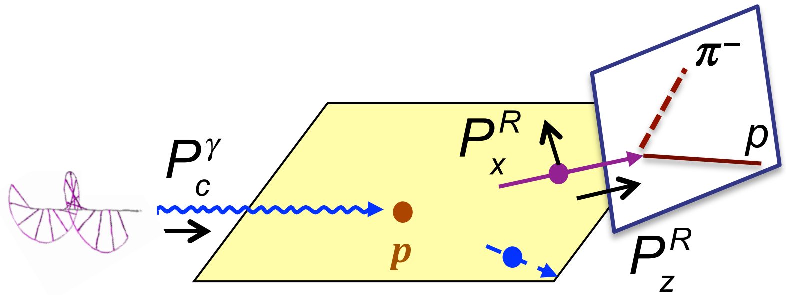


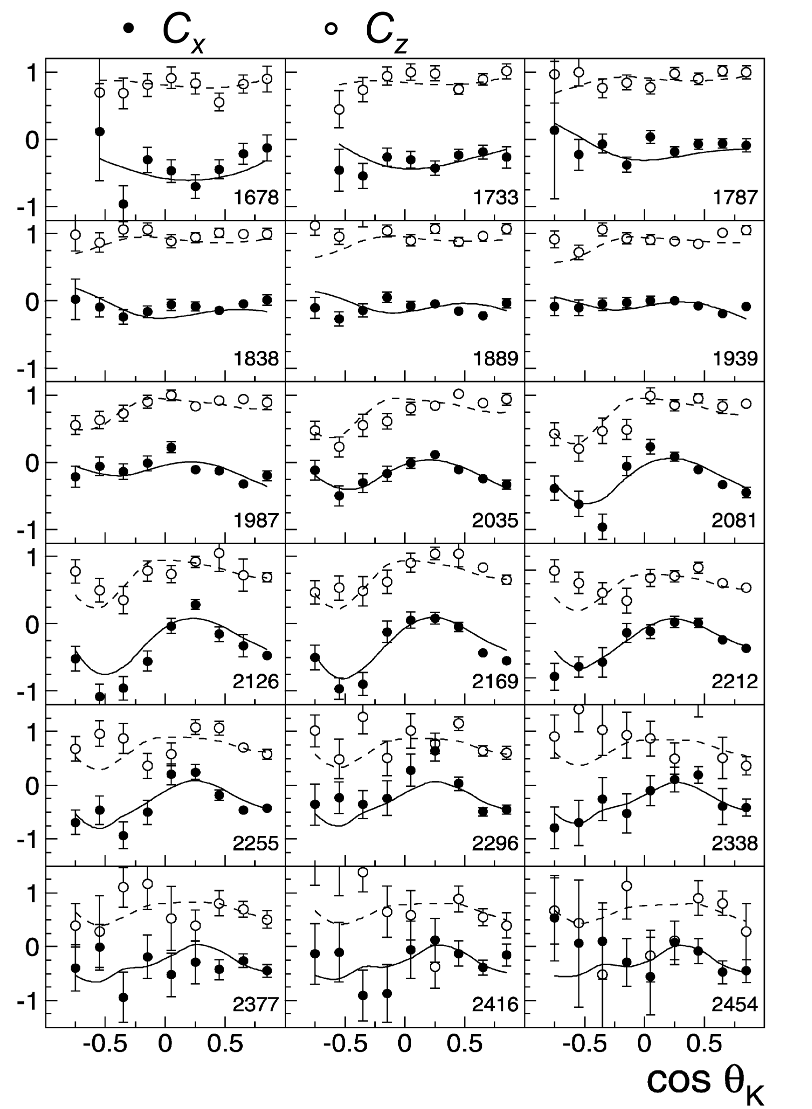


C_x , C_z ($\vec{\gamma} p \to K^+ \vec{\Lambda}$)

CLAS-g1c : *Phys Rev C75 (2007) 035205*

Photon beam		Target			Recoil		
					x'	y'	z'
		x	y	z			
unpolarized	σ_0		T			P	
$P_L^\gamma \sin(2\phi_\gamma)$		H		G	$O_{x'}$		$O_{z'}$
$P_L^\gamma \cos(2\phi_\gamma)$	$-\Sigma$		$-P$			$-T$	
circular P_c^γ		F		$-E$	$C_{x'}$		$C_{z'}$

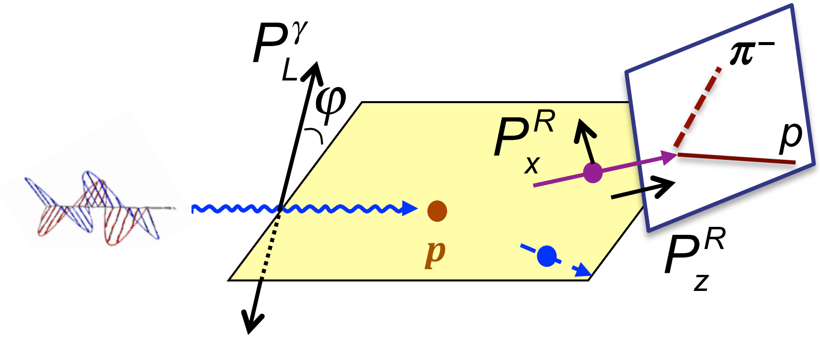




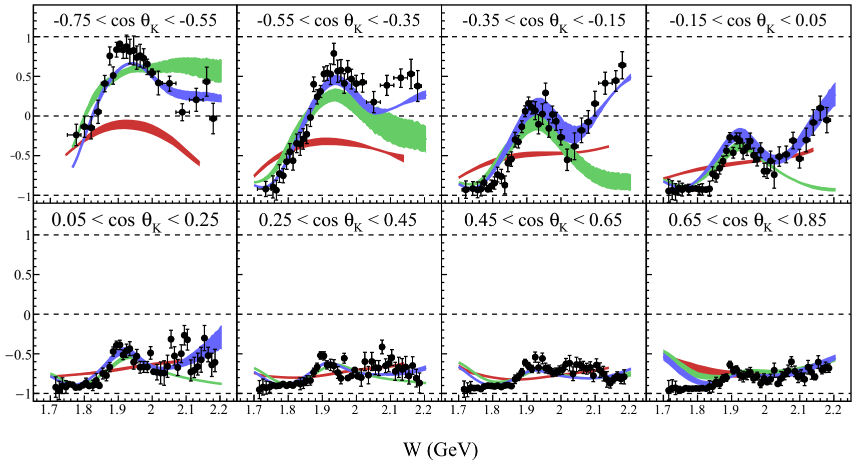
$O_x, O_z\ (\vec{\gamma} p \to K^+ \vec{\Lambda})$

CLAS-g8 : *Phys Rev C93 (2016) 065201*

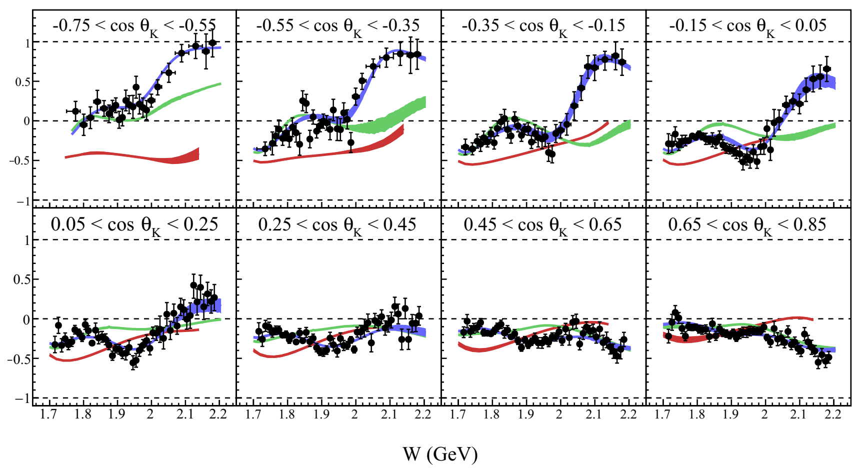
Photon beam		*Target*			*Recoil*		
					x'	y'	z'
		x	y	z			
unpolarized	σ_0		T			P	
$P_L^\gamma \sin(2\phi_\gamma)$		H		G	$O_{x'}$		$O_{z'}$
$P_L^\gamma \cos(2\phi_\gamma)$	$-\Sigma$		$-P$			$-T$	
circular P_c^γ		F		$-E$	$C_{x'}$		$C_{z'}$



- O_x



- O_z



Final states and observables measured in CLAS

	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
Proton target: $\gamma p \rightarrow X$																
$p\pi^0$	✔ (red)	✔ (red)	✔ (green)	✔ (green)	✔ (red)	✔ (green)	✔ (green)	✔ (green)								
$n\pi^+$	✔ (red)	✔ (red)	✔ (green)	✔ (green)	✔ (red)	✔ (green)	✔ (green)	✔ (green)								
$p\eta$	✔ (red)	✔ (red)	✔ (green)	✔ (green)	✔ (red)	✔ (green)	✔ (green)	✔ (green)								
$p\eta'$	✔ (red)	✔ (red)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)								
$p\pi^+\pi^-$	✔ (blue)	✔ (green)			✔ (green)		✔ (green)	✔✔✔✔ + 8 more ππ observables ✔✔✔✔ (green)								
$p\omega$	✔ (red)	✔ (red)	✔ (blue)	✔ (green)	✔ (blue)	✔ (green)	✔ (green)	✔ (green)	SDME							
$K^+\Lambda$	✔ (red)	✔ (red)	✔ (red)	✔ (red)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (red)	✔ (red)	✔ (red)	✔ (red)
$K^+\Sigma^0$	✔ (red)	✔ (red)	✔ (red)	✔ (red)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (red)	✔ (red)	✔ (red)	✔ (red)
$K^{0*}\Sigma^+$	✔ (red)															
$K^0\Sigma^+$	✔ (red)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)	✔ (green)								
"Neutron" target: $\gamma n \rightarrow X$																
$p\pi^-$	✔ (red)	✔ (blue)			✔ (red)		✔ (green)									
$n\pi^+\pi^-$	✔ (green)	✔ (green)			✔ (green)		✔ (green)	✔✔ + 4 more ππ observables ✔✔ (green)								
$K^+\Sigma^-$	✔ (red)	✔ (green)			✔ (blue)		✔ (green)									
$K^0\Lambda$	✔ (blue)	✔ (green)	✔ (green)	✔ (green)	✔ (blue)								✔ (green)	✔ (green)	✔ (green)	✔ (green)
$K^0\Sigma^0$	✔ (green)	✔ (green)	✔ (green)	✔ (green)									✔ (green)	✔ (green)	✔ (green)	✔ (green)

✔ (red) *Published*

✔ (blue) *analysis complete*

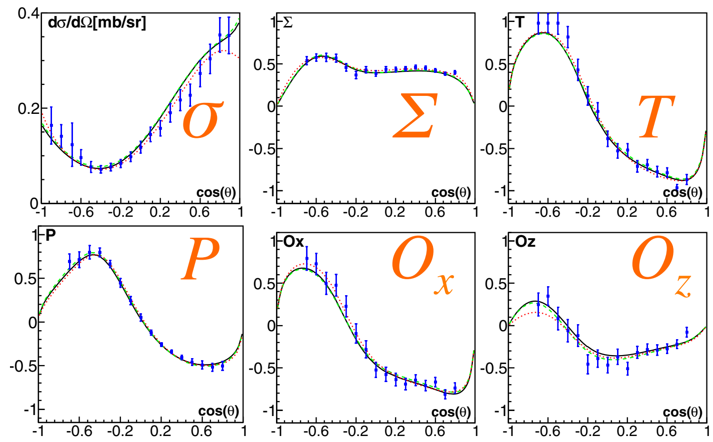
✔ (green) *acquired*

Confirmation of new states near W=1900

[*PRL* ***119*** *(2017) 062004*]

- ***Bonn-Gatchina + Zagreb PWA***:
  - *CLAS $\gamma p \rightarrow K^+\Lambda$ used to fix L=0,1 multipoles*
  - *used in a coupled-channel search for poles*

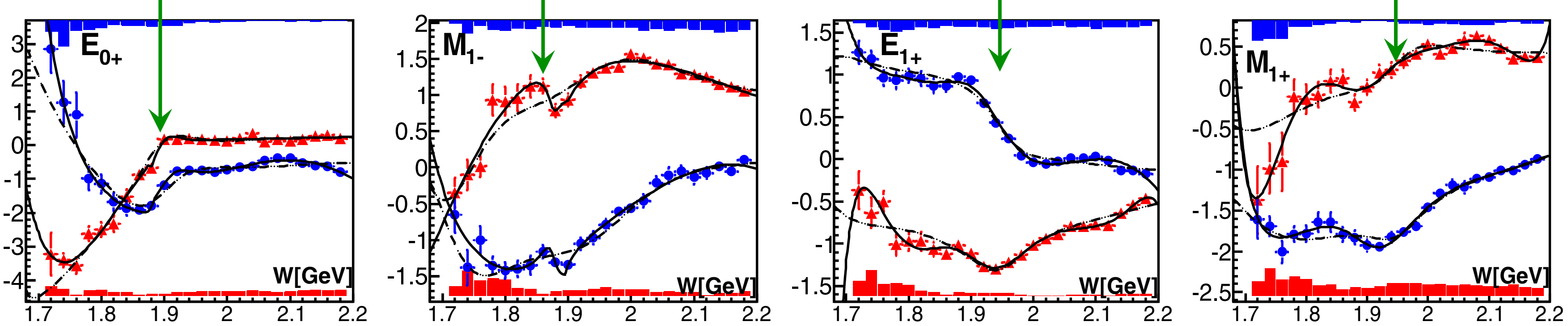
⬄ *reveals new N*s that couple strongly to $K\Lambda$ (but weakly to πN; not evident in $\pi N \rightarrow \pi N$)*



N(1895) **1/2⁻**

N(1860) **1/2⁺**

N(1945) **3/2⁺**



*Confirmation of 1-star **Δ(2200)7/2⁻** in coupled-channel PWA*

- *well established Δ(1950) 7/2⁺ [PDG ****] missing a parity-partner*

  *⇔ possible weak Δ(2200) 7/2⁻ [PDG *] ?*

- *Bonn-Gatchina coupled-channel PWA of CLAS and CBELSA/TAPS data from many channels*

  *[Phys Lett B**766** (2017) 357]*

  *⇔ requires **Δ(2176) 7/2⁻***
  - *small πN branch ⇔ very weak in πN scattering*
  - *but reflected in the γN→πN "E" asymmetries*

- *no evidence of mass-degenerate partners near 1950 (arguing against Chiral restoration)*

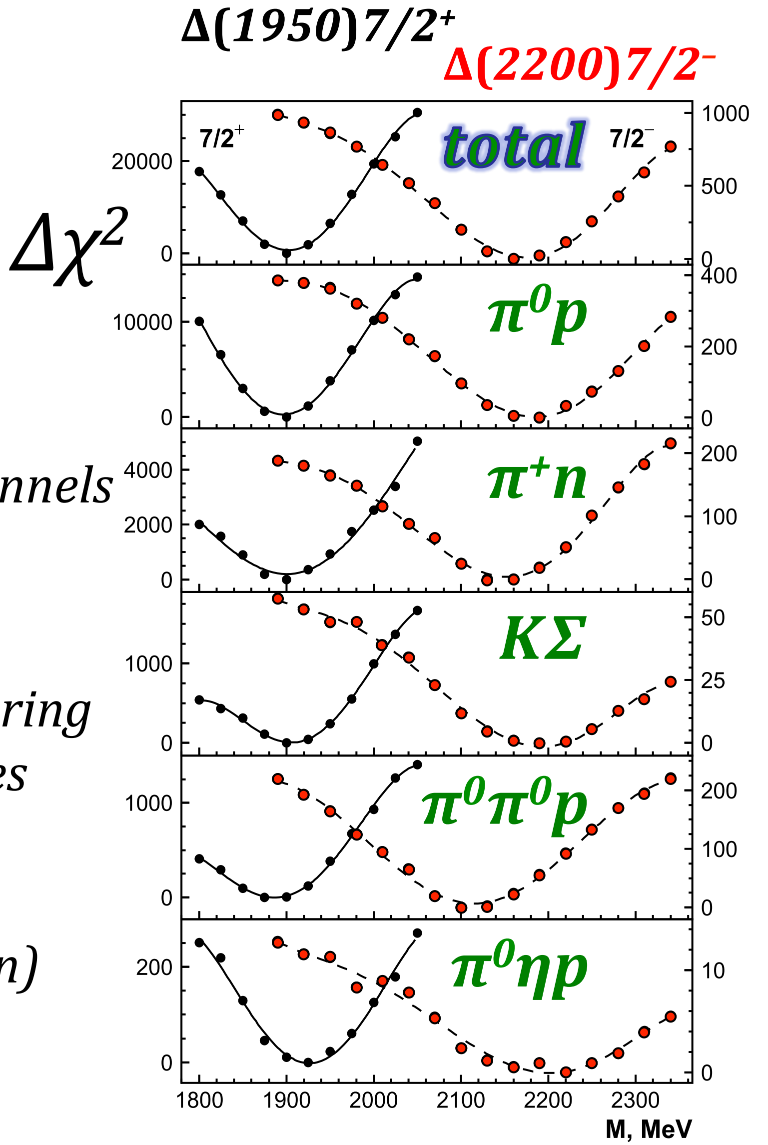


Photo-production from neutrons

- 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***

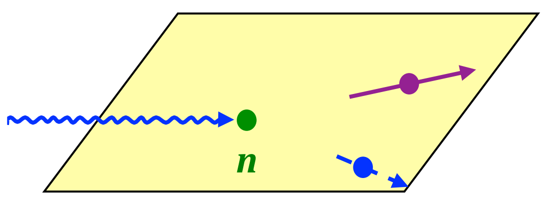
⇔ CLAS run periods g10 $(\gamma + D)$,

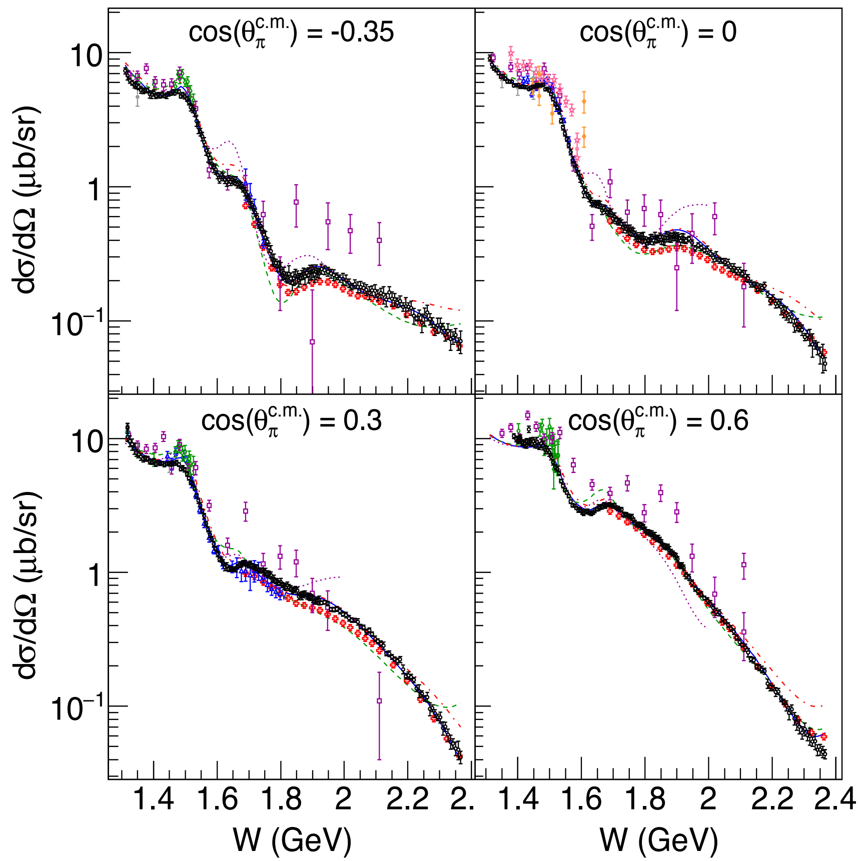
g13 $(\vec{\gamma} + D)$,

g14 $(\vec{\gamma} + \vec{D})$

$\sigma\ (\gamma n \rightarrow \pi^- p)$ — *CLAS-g13: 8424 kin pts* [Phys Rev C (in press)]

Photon beam		*Target*			*Recoil*		
					x'	*y'*	*z'*
		x	*y*	*z*			
unpolarized	σ_0		***T***			***P***	
$P_L^\gamma\ \sin(2\phi_\gamma)$		***H***		***G***	$O_{x'}$		$O_{z'}$
$P_L^\gamma\ \cos(2\phi_\gamma)$	$-\Sigma$		***–P***			***–T***	
circular P_c^γ		***F***		***–E***	$C_{x'}$		$C_{z'}$





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

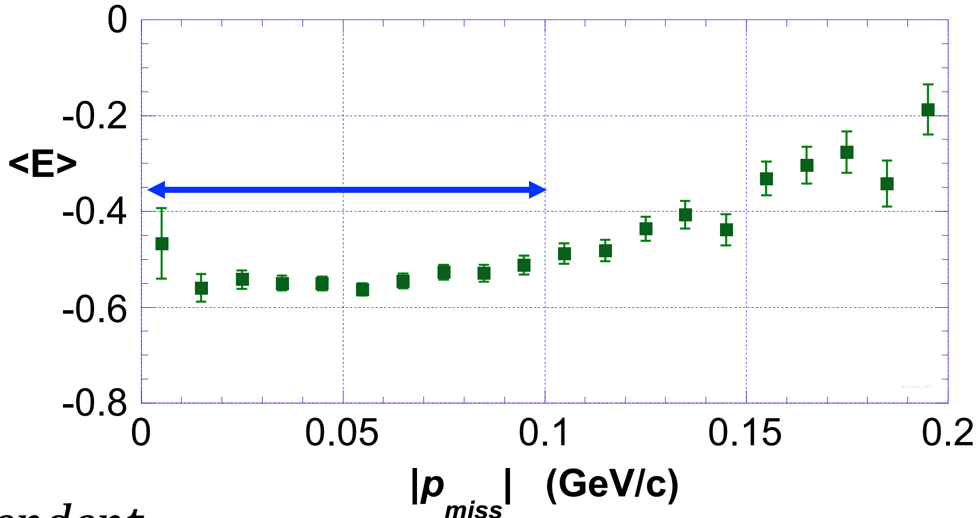
Deuteron reactions restricted to create an effective neutron target

- *select events for which the proton in Deuterium is a passive "spectator"*
  ⬄ *key variable is its momentum,*
  eg. equivalently, the momentum of the undetected proton in $\gamma + n(p) \rightarrow \pi^- p(p)$

  ⬄ *use the data itself to determine the kinematic region in which a measured observable is stable*

- *eg. the beam-target helicity asymmetry "E" :* [*PRL* ***118*** *(2017) 242002*]

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



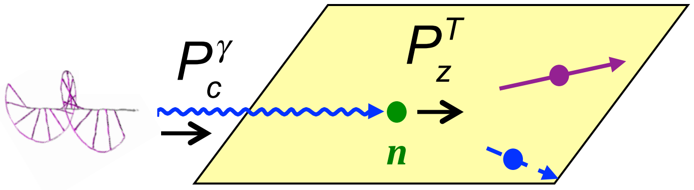
- *with these tight requirements, the D-state gives no contribution*

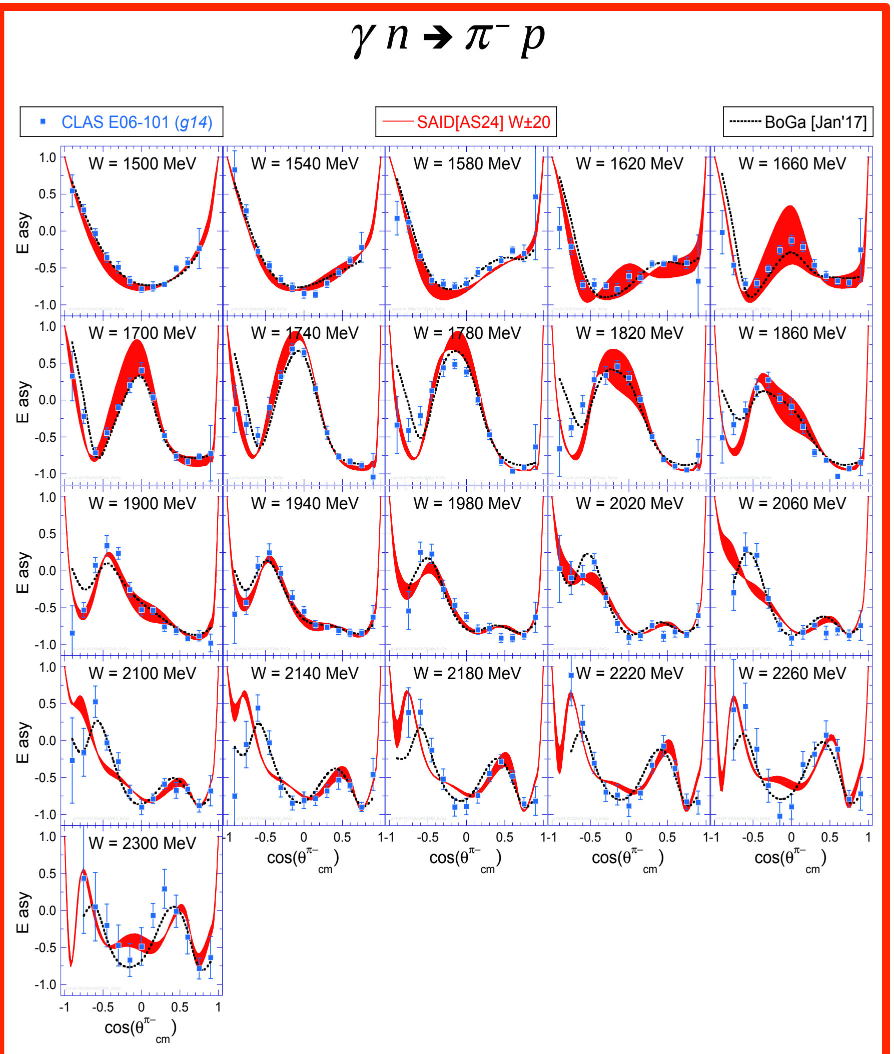
- *NB: stable region is observable dependent*

$E(\vec{\gamma}\vec{n} \to \pi^- p)$

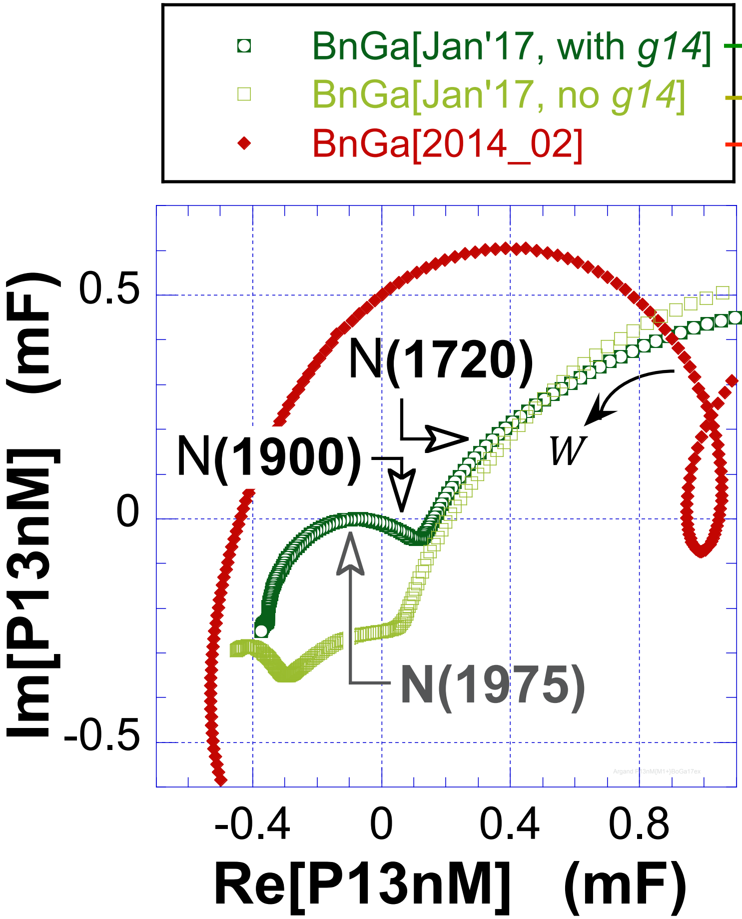
CLAS-g14: *Phys Rev Lett* **118** *(2017) 242002*

Photon beam		Target *x*	Target *y*	Target *z*	Recoil *x'*	Recoil *y'*	Recoil *z'*
unpolarized	σ_0		*T*			*P*	
$P_L^\gamma \sin(2\phi_\gamma)$		*H*		*G*	$O_{x'}$		$O_{z'}$
$P_L^\gamma \cos(2\phi_\gamma)$	$-\Sigma$		$-P$			$-T$	
circular P_c^γ		*F*		$-E$	$C_{x'}$		$C_{z'}$





Evidence for an N(1975)3/2+ from E ($\vec{\gamma}\vec{n} \rightarrow \pi^- p$)



PWA w world data AND new CLAS E results

PWA w world data as of Jan/17, excluding g14

last published BnGa PWA

N(1720)3/2$^+$ ⇔ PDG ****

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

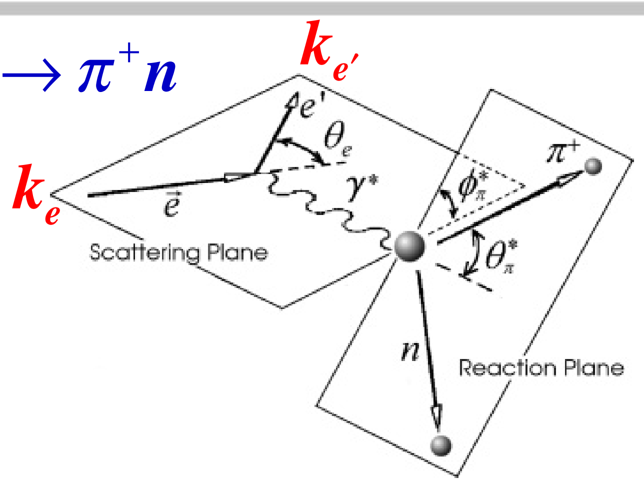
- **new BnGa PWA** [PRC (*in press*)]:
  - ➔ **highest 3/2$^+$ at W=1975 MeV**
  - ⇔ **possible N(1975)3/2$^+$**
  - $A_n^{1/2}$ = **-26** ±13 , $A_n^{3/2}$ = -77 ±15

A decade of advances in mapping the N spectrum*

N(W) J^π	PDG'08	PDG'17	*+ recent*	γ N	πN	KY
N(1710)1/2$^+$	★★★	★★★★		✓✓✓✓	✓✓✓✓	✓✓✓✓
N(1860)1/2$^+$			+ ✓	✓	✓	✓
N(1860)5/2$^+$		★★			✓✓	
N(1875)3/2$^-$		★★★		✓✓✓	✓	✓✓✓
N(1880)1/2$^+$		★★		✓	✓	✓
N(1895)1/2$^-$		★★	+ ✓	✓✓	✓	✓✓
N(1900)3/2$^+$	★★	★★★	+ ✓	✓✓✓	✓✓	✓✓✓
N(1975)3/2$^+$			+ ✓	✓	✓	
N(2040)3/2$^+$		★			✓	
N(2060)5/2$^-$		★★		✓✓	✓✓	✓✓
N(2100)1/2$^+$	★	★	+ ✓	✓	✓	
N(2120)3/2$^-$		★★		✓✓	✓✓	✓
N(2300)1/2$^+$		★★			✓✓	
N(2570)5/2$^-$		★★			✓✓	
Δ(1940)3/2$^-$	★	★★		✓✓	✓	
Δ(2200)7/2$^-$	★	★	+ ✓	✓	✓	

Probing the dynamics of N excitation with Q^2 in (e,e')*

$\vec{\gamma}^{\,*} p \rightarrow \pi^+ n$



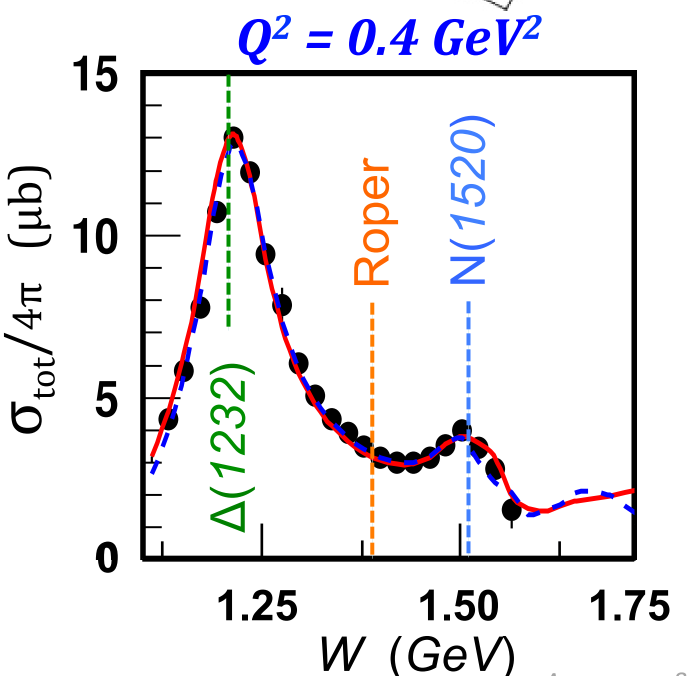
- *N* excitation depend on $Q^2 = -(k_e - k_{e'})^2$*

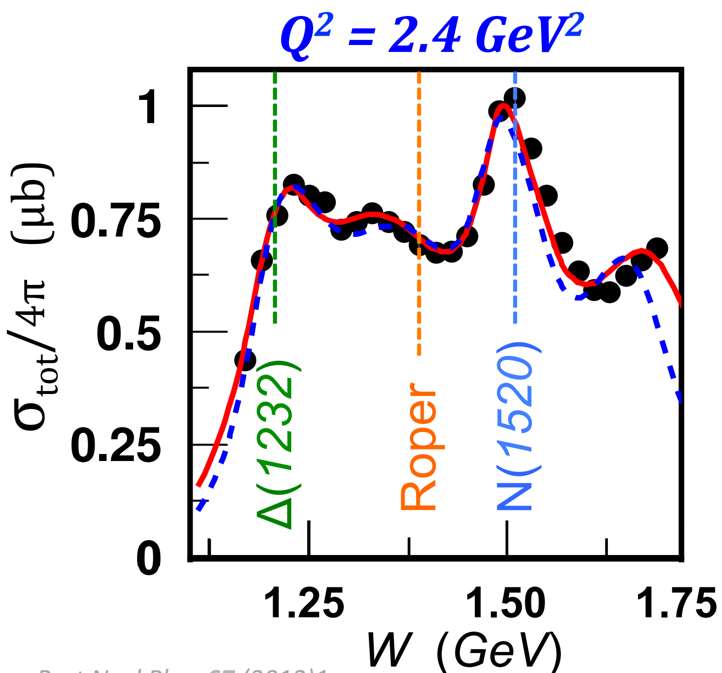
  ⇔ ***different responses to changes in Q^2***

- *mapped out in large CLAS data sets*

  *eg. PRC **77** (2008)015208 ~ 35,000 data pts*

  *PRC **91** (2015) 045203 ~ 37,000 data pts*





*Aznauryan & Burkert, Prog Part Nucl Phys **67** (2012)1*

Published CLAS data on exclusive meson electroproduction from protons

Hadronic final state	Covered W range (GeV)	Covered Q^2 range (GeV^2/c^2)	Measured observables
$\pi^+ n$	1.1-1.38 1.1-1.55 1.1-1.7 1.6-2.0	0.16-0.36 0.3-0.6 1.7-4.5 1.8-4.5	$d\sigma/\Omega$ $d\sigma/\Omega$ $d\sigma/\Omega$, A_b $d\sigma/\Omega$
$\pi^0 p$	1.1-1.38 1.1-1.68 1.1-1.39	0.16-0.36 0.4-1.8 3.0-6.0	$d\sigma/\Omega$ $d\sigma/\Omega$, A_b,A_t,A_{bt} $d\sigma/\Omega$
ηp	1.5-2.3	0.2-3.1	$d\sigma/\Omega$
$K^+\Lambda$	thresh-2.6	1.40-3.90 0.70-5.40	$d\sigma/\Omega$ P^0, P'
$K^+\Sigma^0$	thresh-2.6	1.40-3.90 0.70-5.40	$d\sigma/\Omega$ P'
$\pi^+\pi^- p$	1.3-1.6 1.4-2.1 1.4-2.0	0.2-0.6 0.5-1.5 2.0-5.0	Nine 1-fold differential cross sections

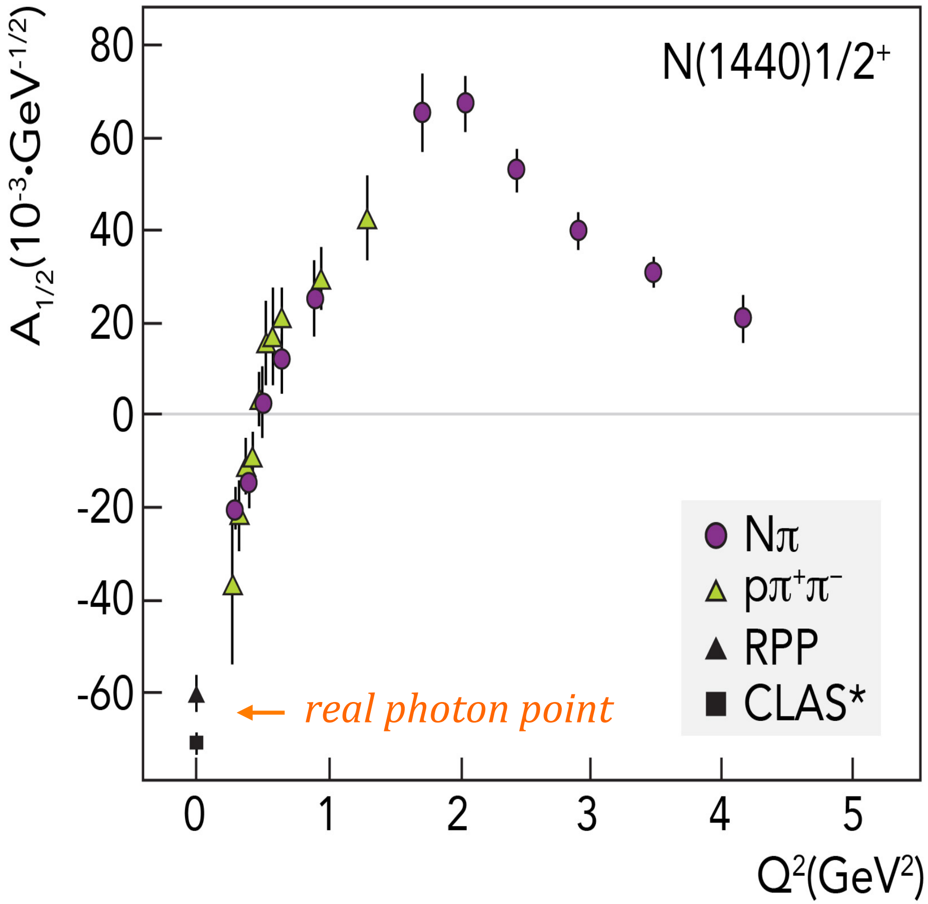
Observables

- *cross section angular distributions*
- *Longitudinal Beam,Target, and Beam-Target asy*
- *recoil and transfer polarization asy*

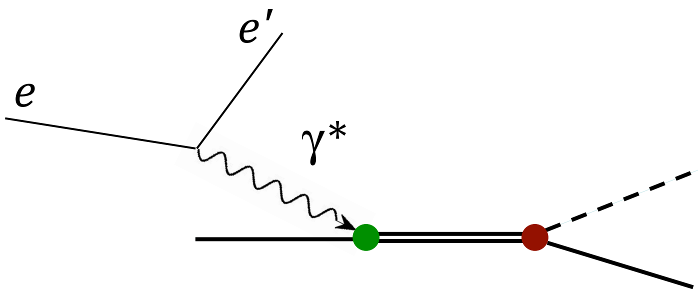
⇔ nearly full phase space coverage for final hadron channel

From V. Mokeev, NSTAR'2017

Q^2 evolution of photo ➔ electro-couplings probe the N^* excitation mechanisms



V. Burkert & C. Roberts, arXiv:1710.02549

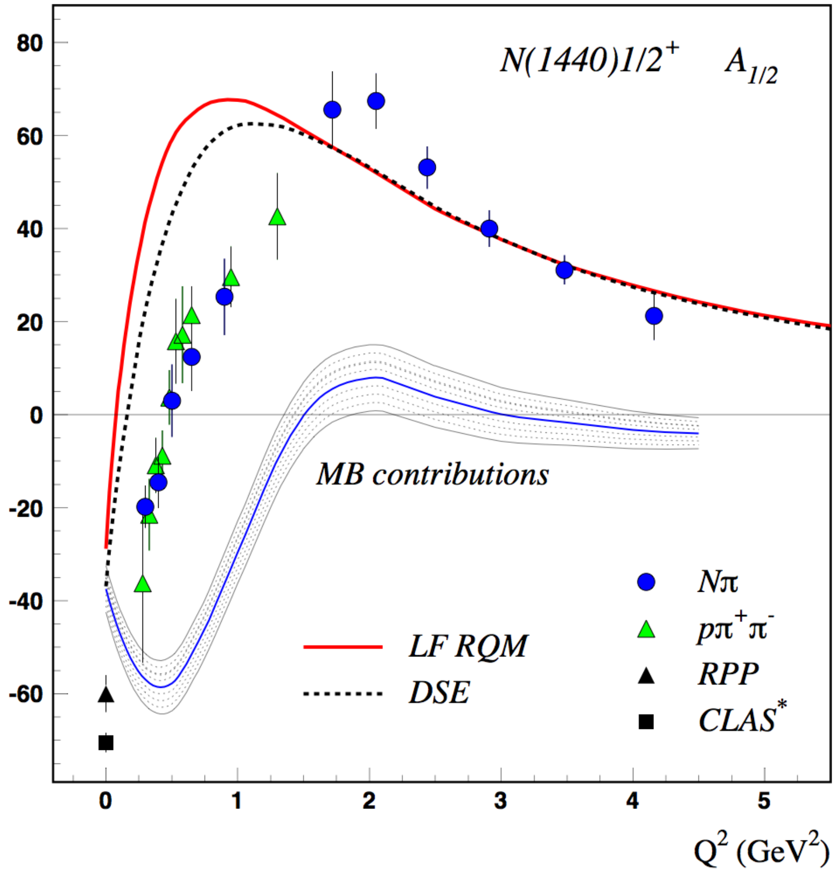


$$T_{\alpha\gamma^*} = \sum \frac{A^h g_\alpha(s)}{\left[M^2 - s - i\sum c_j g_j^2(s)\right]}$$

- ***different electro-production channels***
- ***different analysis approaches***

➔ ***consistent $\gamma^*NN^\star$ couplings***

eg. N(1440)1/2⁺, the "Roper" resonance



***LF RQM**: I. Aznauryan, V.B. arXiv:1603.06692*
***DSE:** J. Segovia, C.D. Roberts et al., PRC94 (2016) 042201*

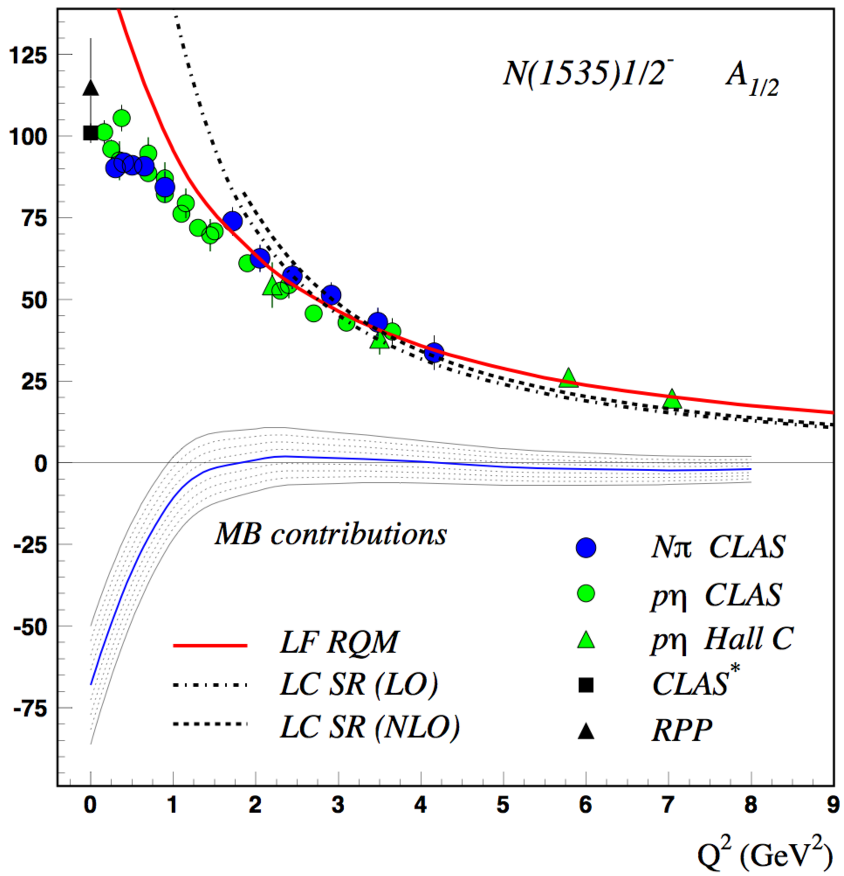
➔ Non-quark contributions are significant at $Q^2 < 2.0$ GeV^2.

➔ The 1st radial excitation of the q^3 core emerges as the probe penetrates the MB cloud

"Nature" of the Roper – its core is the 1st radial excitation of the nucleon.

V. Burkert, NSTAR'2017

eg. N(1535)1/2⁻ , the parity partner of the nucleon



- *consistent couplings extracted from different decay channels (again)*
- *non-quark contributions are significant for $Q^2 < 1$ GeV^2*
- *LF RQM describes data for $Q^2 > 1.5$ GeV^2*

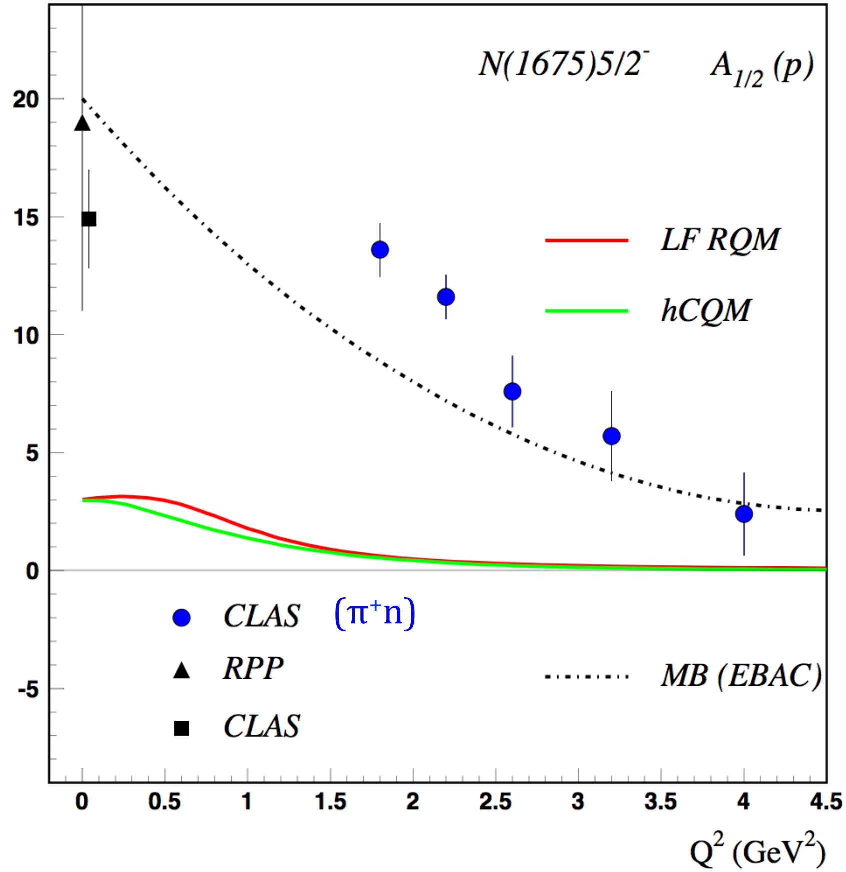
  [I. Aznauryan & V. Burkert, arXiv:1603.06692]

➔ *N(1535)1/2⁺ is consistent with the 1st orbital excitation of the nucleon*

V. Burkert, NSTAR'2017

eg. N(1675)5/2⁻ , a cloud-dominated resonance

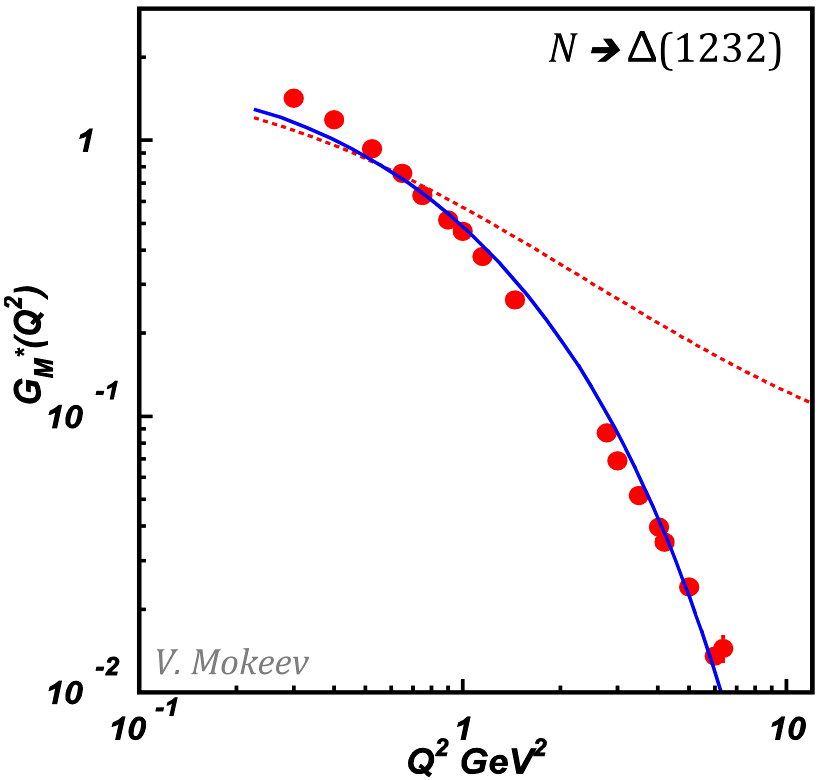
*K. Park et al, PRC **91** (2015) 045203*



- *γpN* (Q^2 =0) >> RQM*
  - ⇔ *RQM is suppressed by selection rules, if only a single quark is excited*
    - [*Moorhouse, Phys Rev Lett* ***16*** (1966) 772]
    - [*Burkert et al, Phys Rev C****67*** (2003) 035204]
  - (*NOT a meson-Baryon molecule*)
- *BUT, non-quark (meson-baryon cloud) contributions are significant for all Q^2*

V. Burkert, NSTAR'2017

*γ*N → N* reveals a running quark-mass*



- *CLAS $G_M(N \to \Delta)$ (normalized to dipole)*

------ *"frozen" momentum-independent M_q*

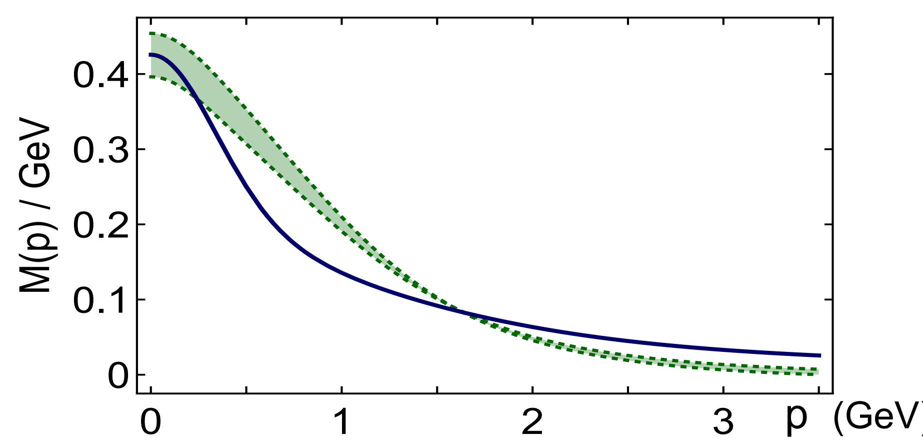
[*Wilson et al., Phys Rev C* ***85*** *(2012)025205*]

⇔ *M_q~ 300 MeV, dynamically generated by contact interactions btw current quarks*

—— *dressed quark mass-function $M_q(p_q)$*

[*Roberts, J. Phys. Conf.* ***706*** *(2016) 022003*]

[*Segovia et al., Few Body Phys* ***55*** *(2014) 1185*]



*γ*N → N* transitions are sensitive to long-range QCD and probe the running quark mass function*

Summary

- *LQCD has confirmed Quark Model predictions for large numbers of N* states*

  ⇔ *no reduction in the effective degrees of freedom within the Nucleon*

  ⇔ *full LQCD/QM range of states required to provide the baryon pressure at T_c*

- *polarization in photo-production reactions can over-determine the amplitude*

  ⇔ *extensive data on large numbers of polarization observables and final states have been collected and are in various stages of analysis*

  ⇔ *coupled-channel PWA have been essential in disentangling the N* spectrum*

  ⇔ *large numbers of new candidate states have been identified*

- *Q^2 dependence of electro-production couplings provide insights to the role of the meson cloud and of the N* excitation mechanism*

  ⇔ *large data sets have been collected and analysis is ongoing …*

  ⇔ *meson cloud effects are generally very strong below ~ 1 – 2 GeV^2*

  ⇔ *transitions to N*s confirm a running quark mass-function*