Unraveling Excitations of the Nucleon:
Meson Photo-production from Polarized neutrons in $\vec{H}\vec{D}$ at CLAS

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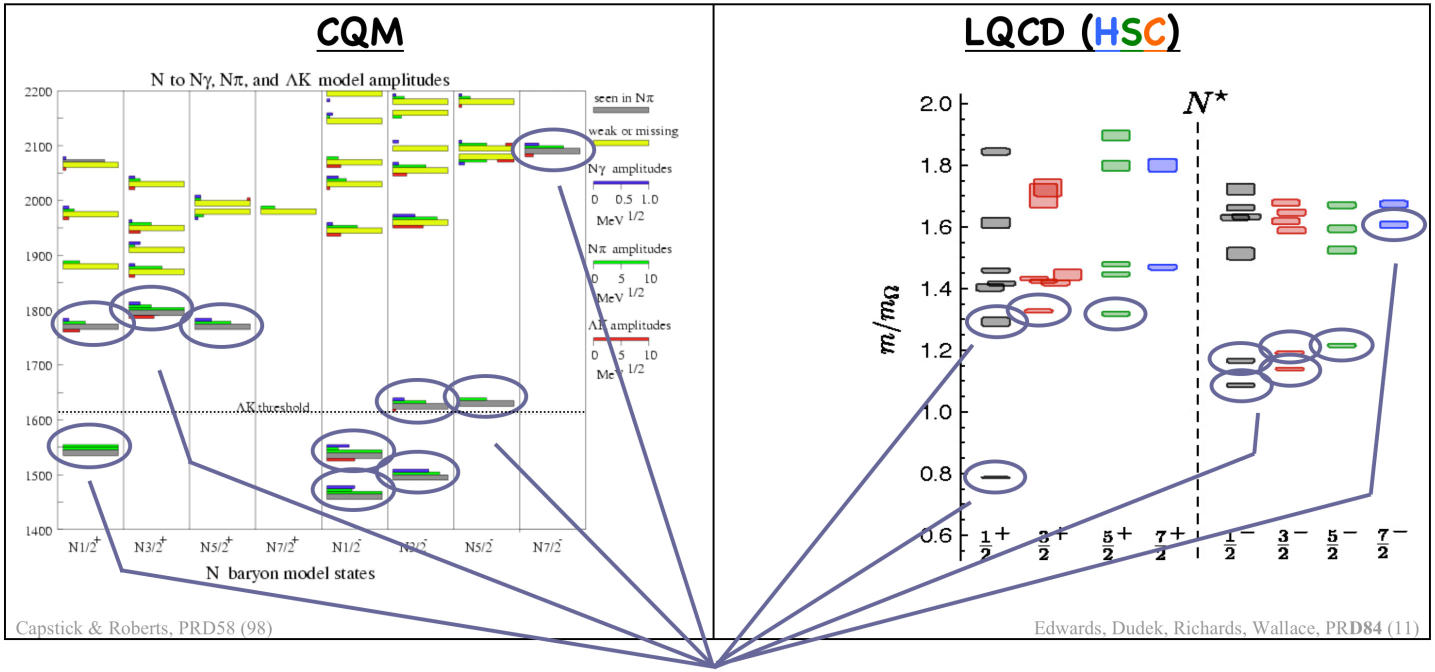
(for the CLAS-g14 Collaboration)

(Peking University, Beijing – October 21, 2014)

Unfolding and interpreting the N* spectrum

- low energy structure of QCD lies encoded in the excited-state spectrum of the nucleon, a complex overlap of resonances
- LQCD & CQM ⇨ majority of these levels have yet to be identified



- only lowest few in each band seen (in πN) with 4★ or 3★ status
- higher levels predicted to have larger couplings to ππN, KΛ, KΣ, …

N*s hiding in ambiguities ?

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

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

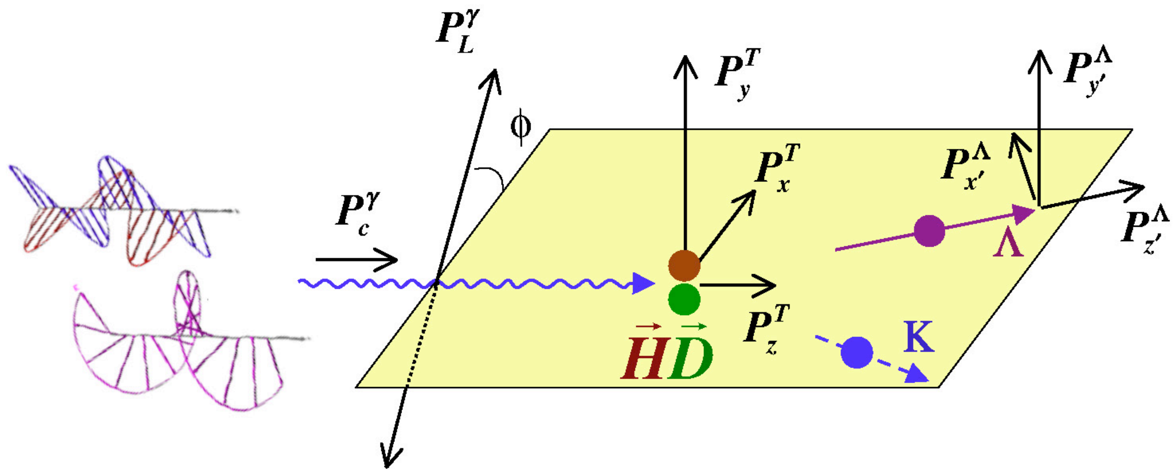
⇨ 4 complex amplitudes describe photo-production
⇨ 8 quantities to be determined
⇨ the 16 possible observables (matrix elements) are not independent

- uniqueness studies: Barker, Donnachie, Storrow, NP B95 (75) 347;
  Chiang, Tabakin, PR C55 (97) 2054;
  Sandorfi, Hoblit, Kamano, Lee, G Phys G38 (11) 053001 .

⇨ "mathematical solution" requires 8 *carefully chosen* observables
⇨ avoiding ambiguities require asymmetries with recoil polarization

⇨ **with realistic uncertainties, a nearly complete set (≥12) is needed**

Photo-production observables accessed through spin



SHKL, J Phys G38 (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^γ $\sin(2\phi_\gamma)$		H		G	$O_{x'}$		$O_{z'}$		$C_{z'}$		E		F		$-C_{x'}$	
P_L^γ $\cos(2\phi_\gamma)$	$-\Sigma$		$-P$			$-T$		$-L_{z'}$		$T_{z'}$		$-\sigma_0$		$L_{x'}$		$-T_{x'}$
circular P_c^γ		F		$-E$	$C_{x'}$		$C_{z'}$		$-O_{z'}$		G		$-H$		$O_{x'}$	

the new campaign to unravel the N* spectrum

The new goal: (Jlab, Bonn, Mainz)

- **measure large numbers of polarization observables,**

  up to all 16 ⇦ possible in at least a few channels (*eg. KY*)

  ⇨ greatly constrains the photo-production amplitudes

  ⇨ best hope to search for poles

Tues Parallel-IV: S6

- the electromagnetic interactions do not conserve isospin

  ⇨ **requires data from both proton and neutron targets**

HD exps

$$A^{\gamma N}\langle I=3/2\rangle \equiv A^{(3)}\langle I_\gamma=1, I_N=1/2;\ I=3/2\rangle \quad \Leftrightarrow \quad$$ **Δ* (I=3/2) states**

$$A^{\gamma N}\langle I=1/2\rangle \equiv A^{(o)}\langle I_\gamma=0, I_N=1/2;\ I=1/2\rangle \pm \tfrac{1}{\sqrt{3}} A^{(1)}\langle I_\gamma=1, I_N=1/2;\ I=1/2\rangle$$

⇔ **N* (I=1/2) states**

the E06-101 (g14) experiment & crew

the components	the crew
• CLAS detector	• Jlab Hall-B staff, CLAS collaboration
• polarized *HDice* target	• **C.D. Bass**, **P. Collins**, A. D'Angelo, A. Deur, G. Dezern, **C. Hanretty**, **D. Ho**, T. Kageya, M. Khandaker, **V. Laine**, M.M. Lowry, **C. Nepali**, **T. O'Connell**, **P. Peng**, A.M. Sandorfi, **D. Sokhan**, **N. Walford**, X. Wei, C.S. Whisnant
• calibrations and ongoing analyses	• A. D'Angelo, **P. Collins**, **J. Fleming**, **D. Ho**, T. Kageya, F. Klein, **H. Lu**, **P. Mattione**, E. Pasyuk, **P. Peng**, A.M. Sandorfi, R. Schumacher, **N. Walford**, D. Watts, **I. Zonta**

Legend: Students; PostDocs

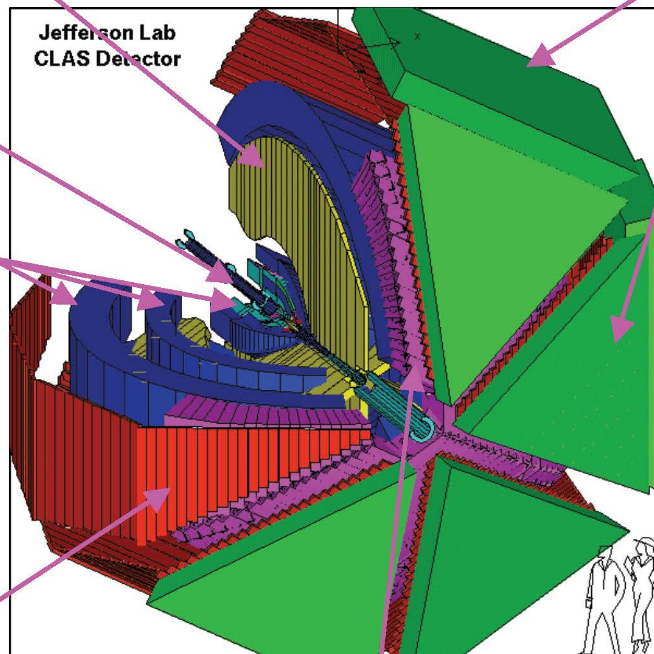
Jlab Hall-B – the CLAS(6) detector

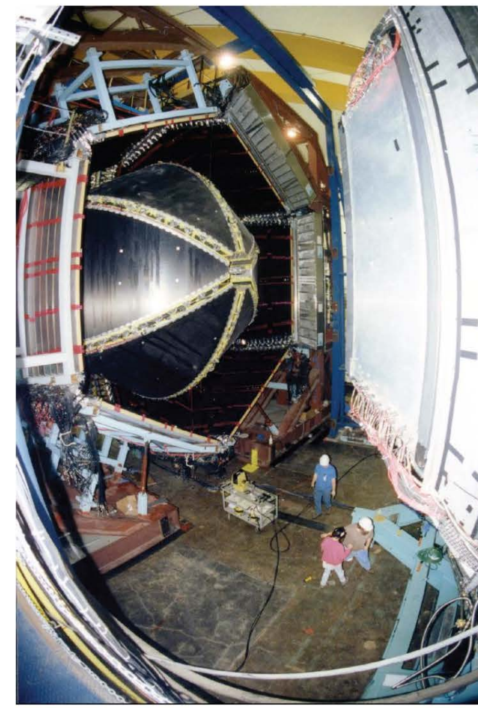
Torus magnet
6 superconducting coils

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

HDice frozen-spin target

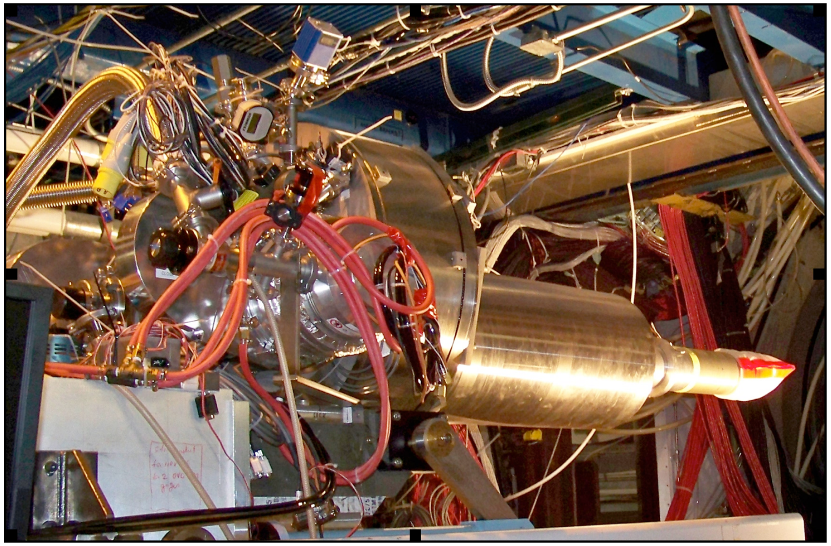
⇨ talk by X. Wei
Friday, Parallel-VII: S10

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

- P(H) = 60%, P(D) = 15%
  or = 30%, P(D) = 30%
- T_1 (1/e relaxation time) ~ years
- no repolarization needed

Polarization mechanism:

- polarize impurities (10^{-3}) of H_2 and D_2 at 0.010 K and 15 Tesla
- spin exchange w HD
  $\vec{H}_2 \Rightarrow \vec{H}\vec{D} \Leftarrow \vec{D}_2$
- wait for H_2 and D_2 to decay to inert ground st (~ 3 months)



HDice polarize/freeze-spins/run-exp sequence

HDice Target Lab

- condense HD gas → liquid → solid at 16°K
- calibrate pol-NMR at 2°K and 0.2 tesla
- transfer to dilution refrigerator & polarize at 15 Tesla and 10 mK
- hold at high-field and low-temp for >3 months
- transfer to 5 Tesla/1.6°K Storage Cryostat

⇒

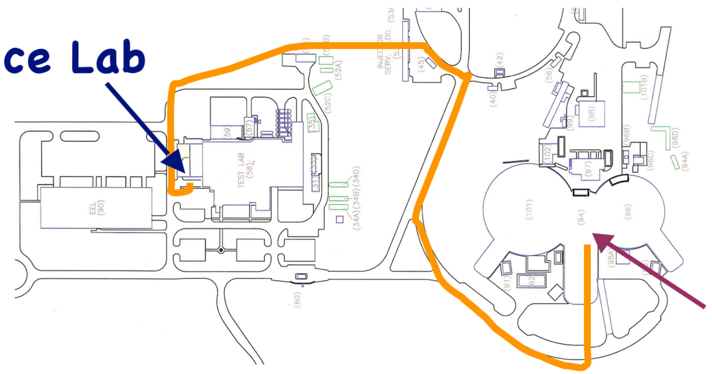
transfers are the trickest part

- NIM A737 (14) 107

Hall-B

- move to Hall B (~ 1 Km)
- transfer to In-Beam Cryostat (IBC)
- move spins $\vec{H} \Leftrightarrow \vec{D}$ w rf as needed
- roll IBC into CLAS
- run the exp

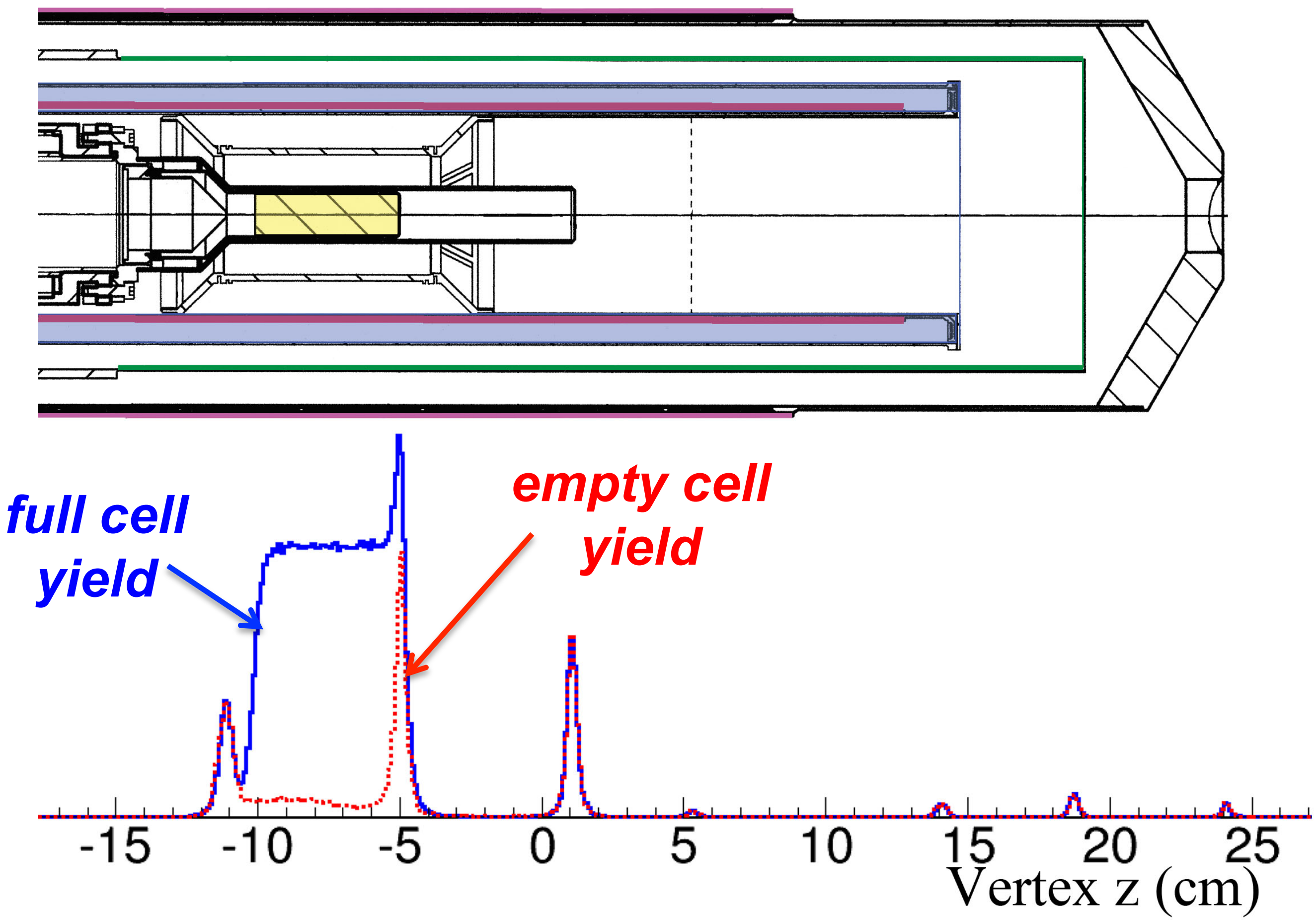
HDice Lab



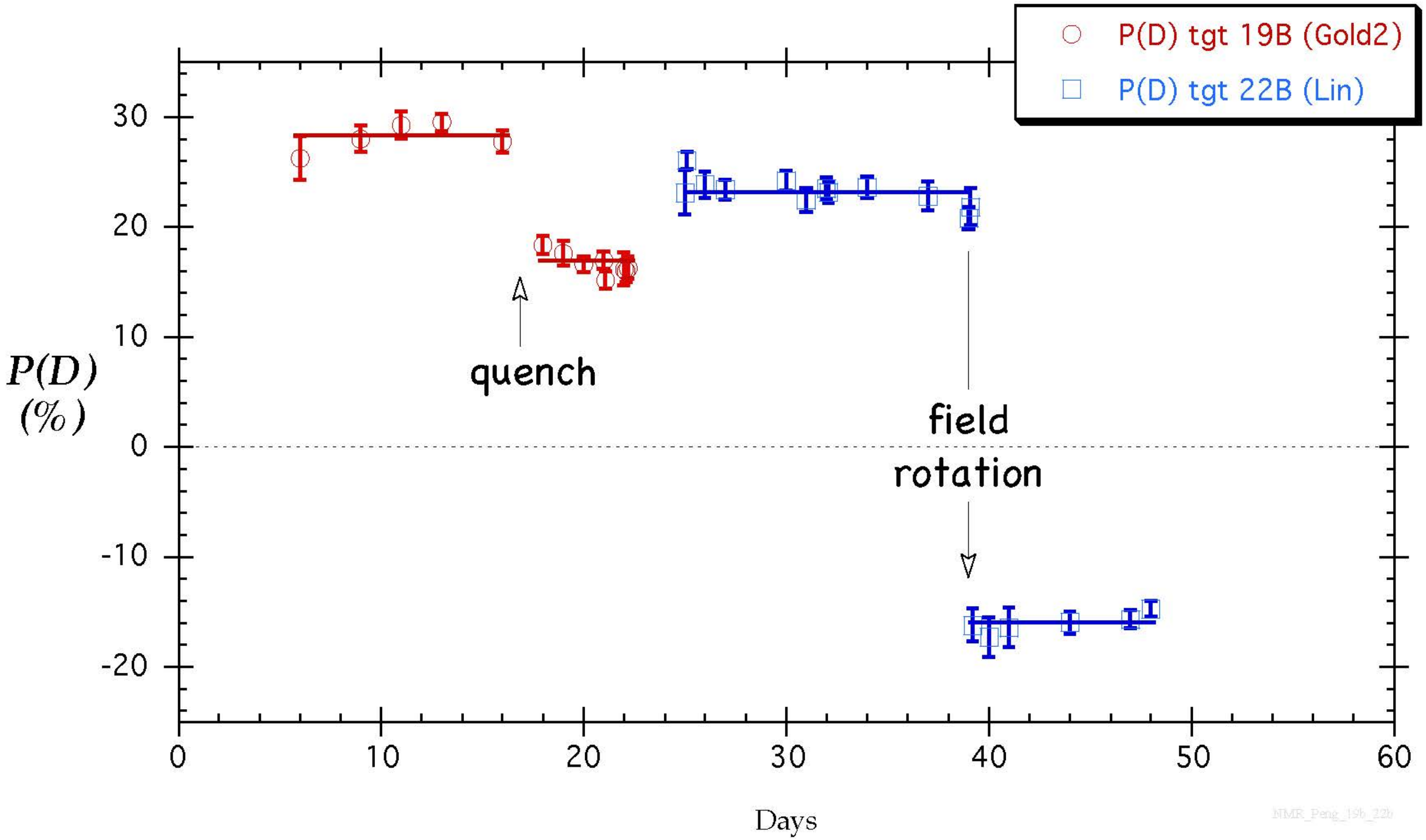
Hall B

non-HD target-cell backgrounds

- Evaporate and pump away the HD:
  - ⇨ residual non-HD backgrounds are small



D polarization with beam



- P(D) x HDice dilution ~ similar to FROST (DNP) polarization x dilution
- HD exp able to run with x 10 higher fluxes (due to lower Z)

Jlab E06-101 (g14) experiment

Run period: Dec'11 – May'12 (last CLAS6 experiment before Jlab upgrade)

eg of bkg removal methods

On-going Analyses:

empty subtraction

- T. Kageya (Jlab): γ_c n(p) → π^-p(p)
- H. Lu (CMU, U. Iowa): γ_L n(p) → π^-p(p)
- P. Peng (U. Virginia): γ_c p → $\pi^+\pi^-$p; γ_c n(p) → $\pi^+\pi^-$n(p)
- J. Fleming (U. Edinburgh): γ_L p → $\pi^+\pi^-$p; γ_L n(p) → $\pi^+\pi^-$n(p)
  γ_c n(p) → $K^+\Sigma^-$(p)
- I. Zonta (U. Roma-II): γ_c n(p) → ρn(p) → $\pi^+\pi^-$n(p)
- D. Ho (Carnegie-Mellon U.): γ_c n(p) → $K^0\Lambda$(p)

Kinematic fitting

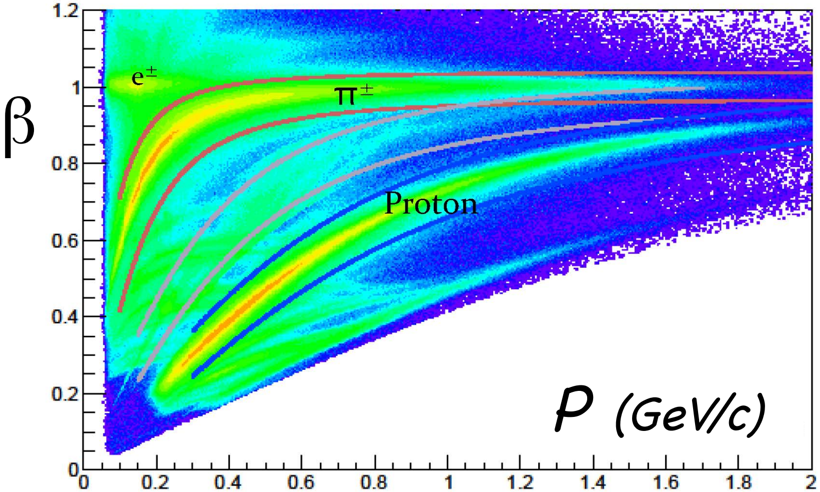
Boosted Decision Trees

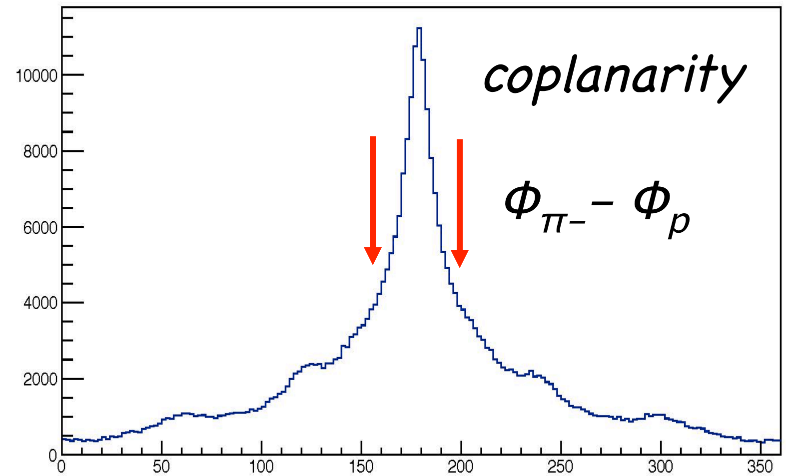
⇨ some examples with ~ ⅓ to ⅔ data processed

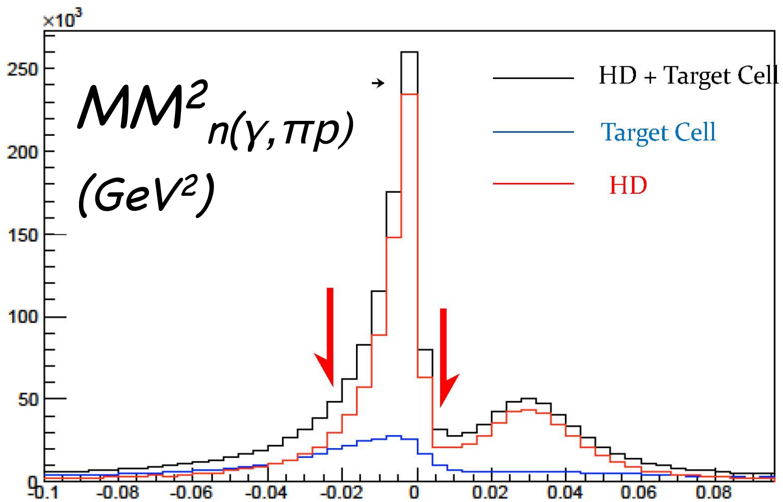
HDice

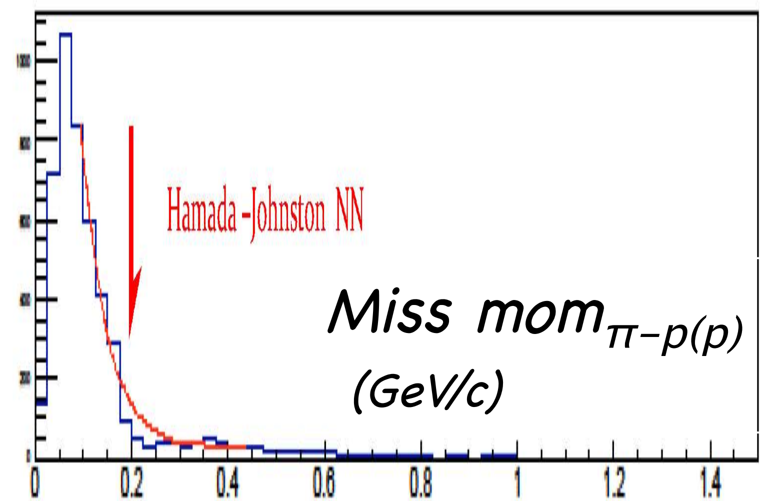
$\vec{\gamma}_c + \vec{n}(p) \rightarrow \pi^- p\ (p)$

- T. Kageya (Jlab)

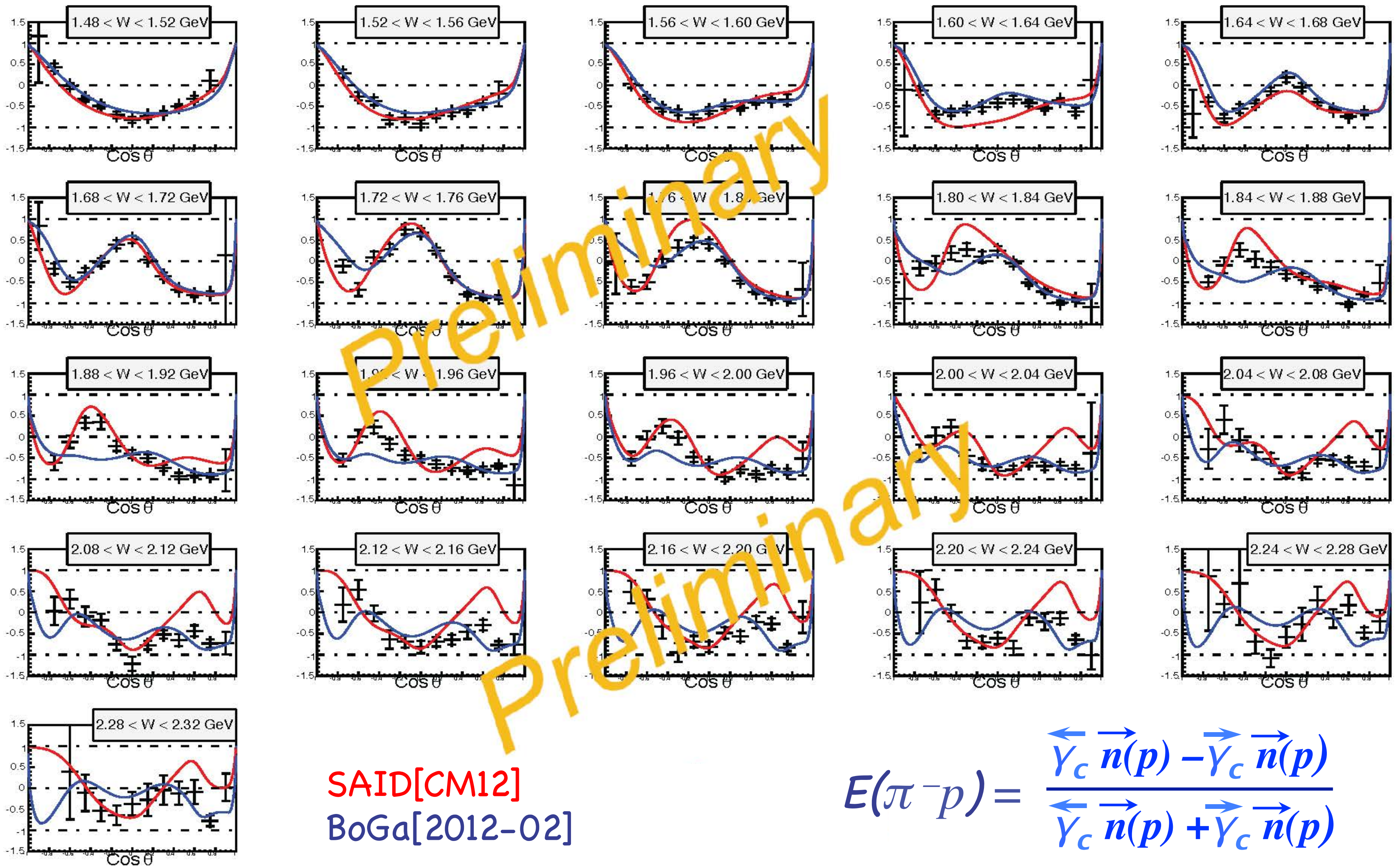






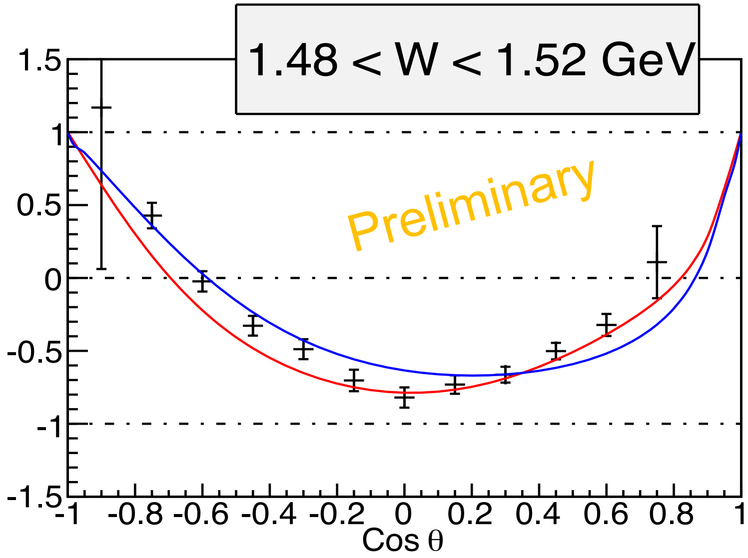


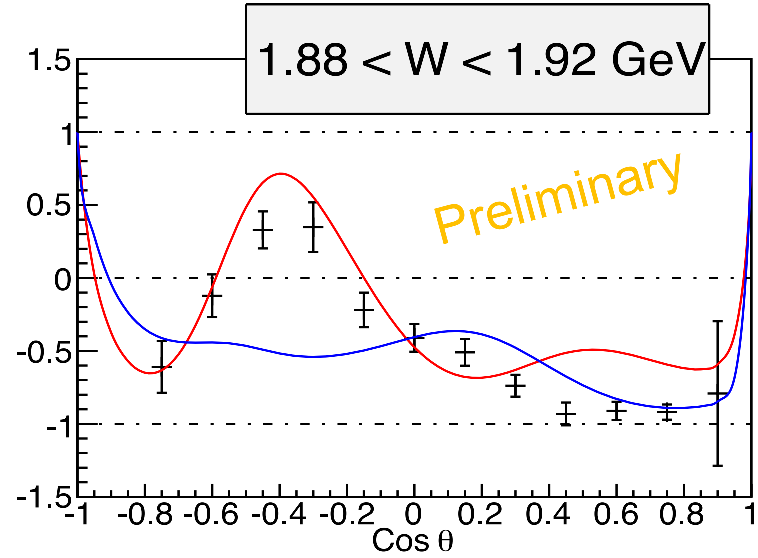
Beam-Target Helicity asymmetry *E*(π^-p) - T. Kageya (Jlab)

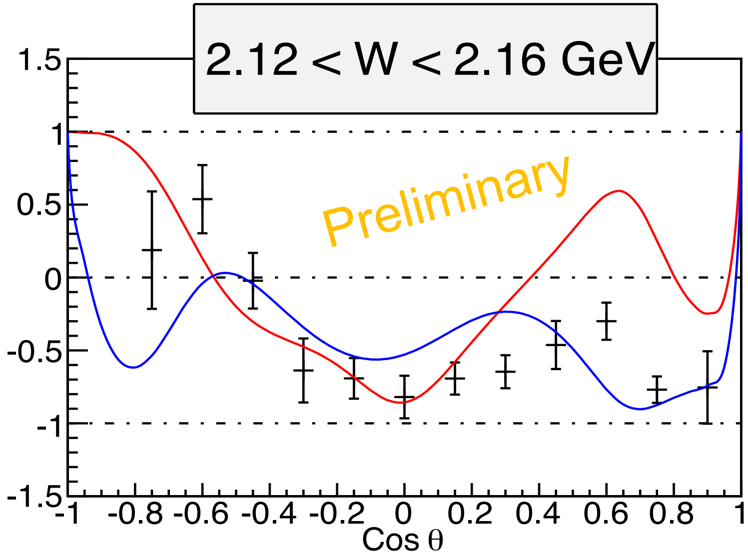


$$E(\pi^-p) = \frac{\overleftarrow{\gamma_c}\,\overrightarrow{n(p)} - \overrightarrow{\gamma_c}\,\overrightarrow{n(p)}}{\overleftarrow{\gamma_c}\,\overrightarrow{n(p)} + \overrightarrow{\gamma_c}\,\overrightarrow{n(p)}}$$

selected Helicity asymmetry $E(\pi^- p)$ – T. Kageya (Jlab)







$$E(\pi^- p) = \frac{\overleftarrow{\gamma_c}\,\overrightarrow{n(p)} - \overrightarrow{\gamma_c}\,\overrightarrow{n(p)}}{\overleftarrow{\gamma_c}\,\overrightarrow{n(p)} + \overrightarrow{\gamma_c}\,\overrightarrow{n(p)}}$$

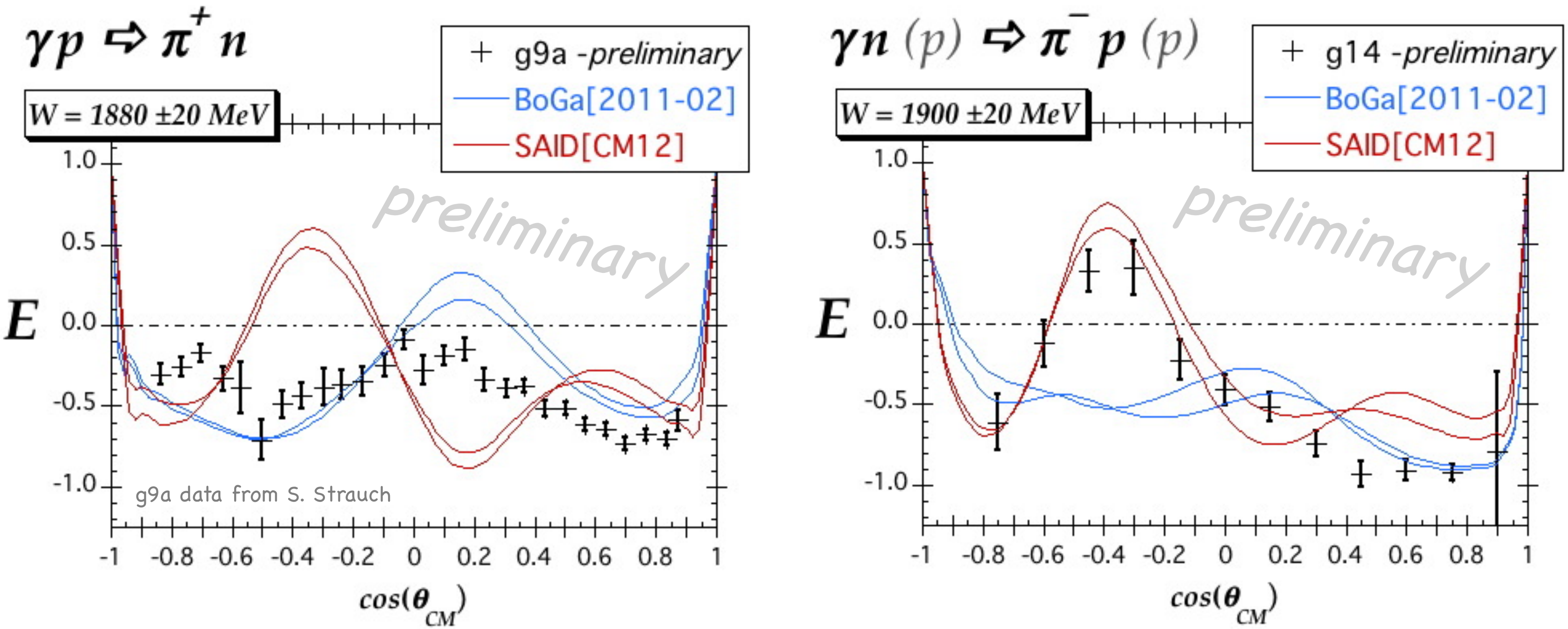
PWA: SAID[CM12]
BoGa[2012-02]

Comparing proton and neutron targets in the N* hunt

$P_{13}(1900)$ –driven by BoGa

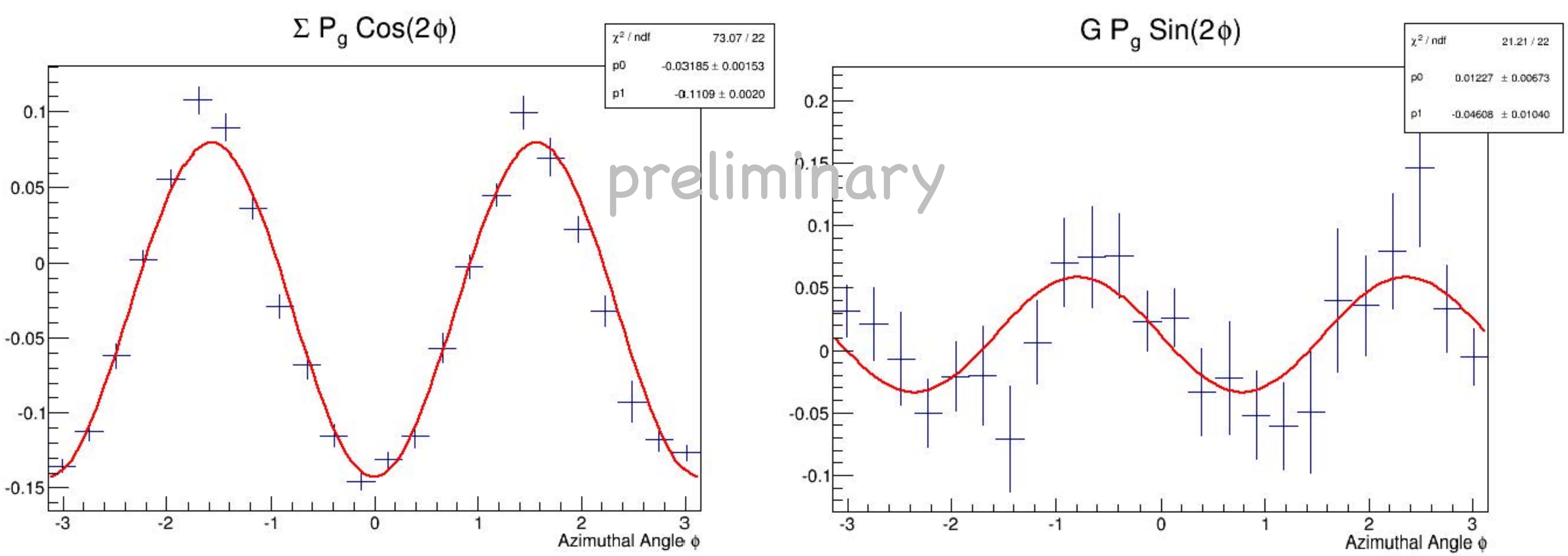
⇨ N(1900)$3/2^+$ *** PDG'12
Br(KΛ) ≈ Br(πN) ≈ 10%

- BoGa PWA *includes* $P_{13}(1900)$
- SAID PWA does not



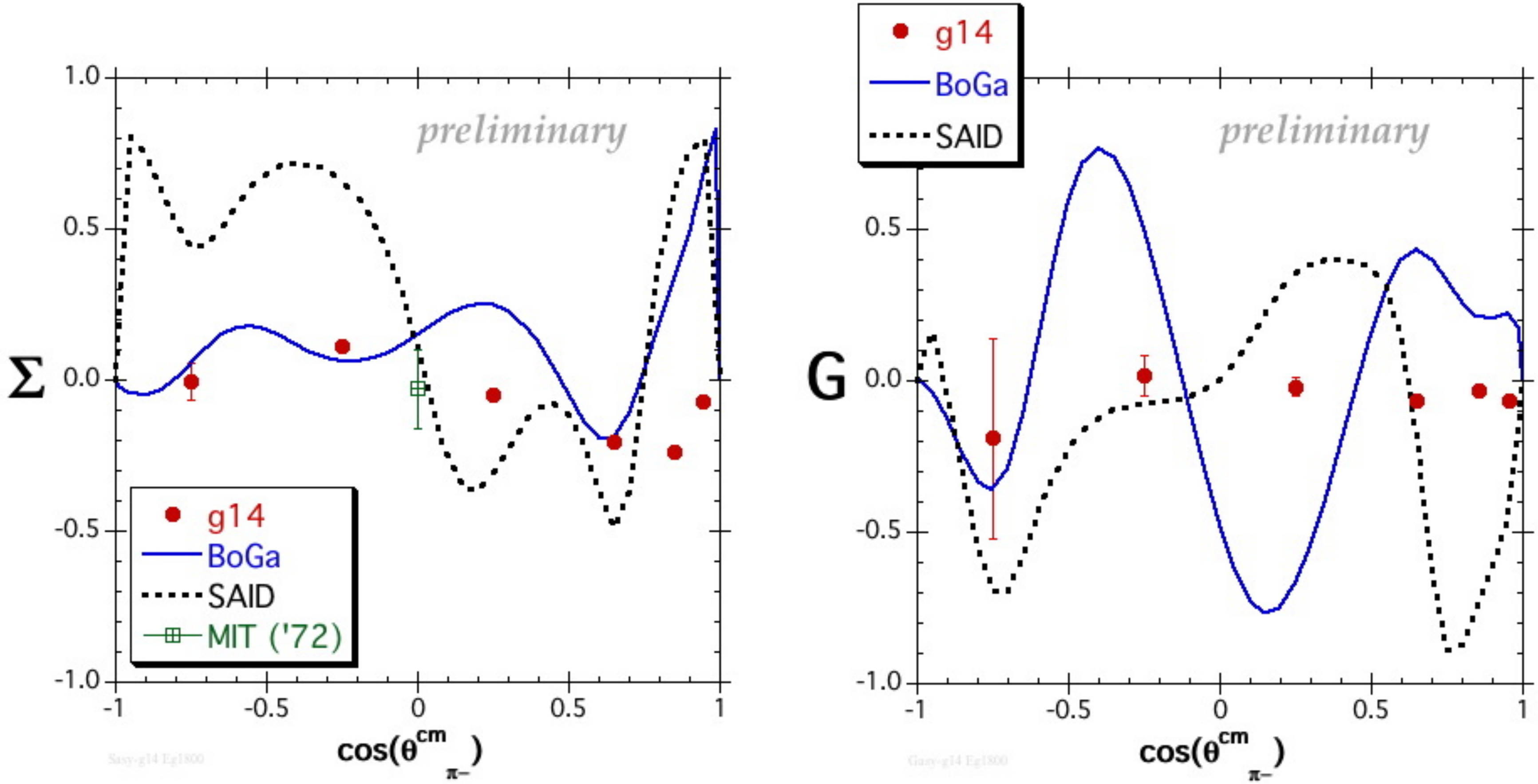
$\vec{\gamma}_L + \vec{n}(p) \rightarrow \pi^- p\ (p)$ - *Haiyun Lu (CMU, U Iowa)*

- linearly polarized beam from bremsstrahlung in diamond
- $d\sigma_{(B,T)} = \frac{1}{2} d\sigma_0 \left\{1 - \Sigma(\theta) \cdot P_L^\gamma cos(2\varphi_\gamma) + G(\theta) \cdot P_L^\gamma \cdot P_z^T \cdot sin(2\varphi_\gamma)\right\}$
- combine diff beam and target orientations to separate Σ and G



$\vec{\gamma}_L + \vec{n}(p) \rightarrow \pi^- p\ (p)$ - Haiyun Lu (CMU, U Iowa)

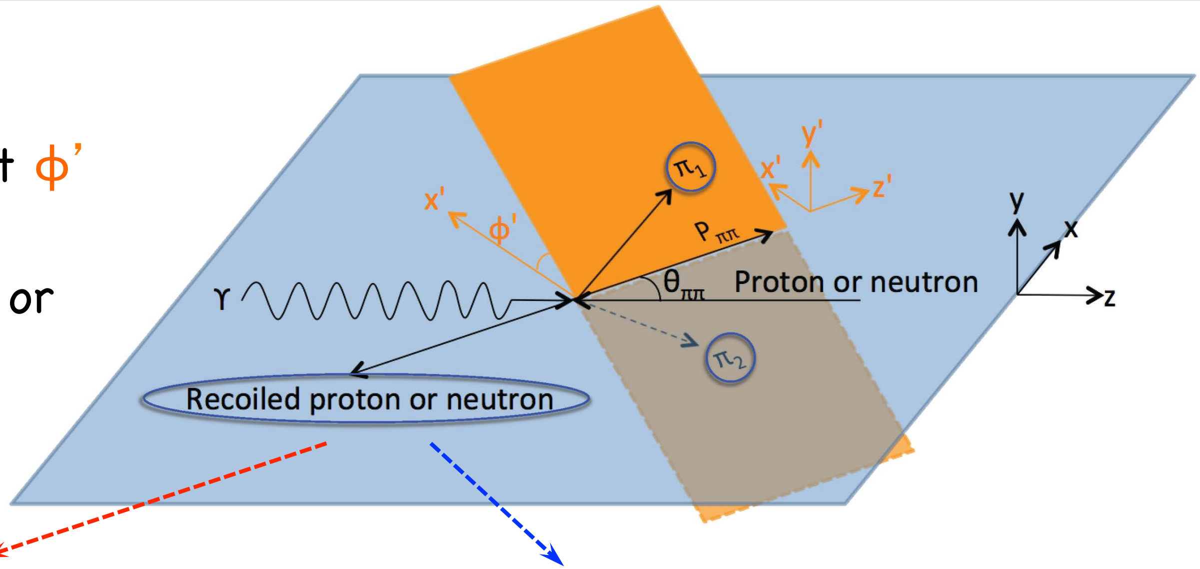
- $d\sigma_{(B,T)} = \frac{1}{2} d\sigma_0 \left\{1 - \Sigma(\theta) \cdot P_L^{\gamma} cos(2\varphi_{\gamma}) + G(\theta) \cdot P_L^{\gamma} \cdot P_z^T \cdot sin(2\varphi_{\gamma})\right\}$
- E_{γ} ~ 1800 MeV ⇔ W ~ 2060 MeV



$\gamma\, pn \rightarrow \pi^+\pi^-\, p(n),\ \pi^+\pi^-\, n(p)$

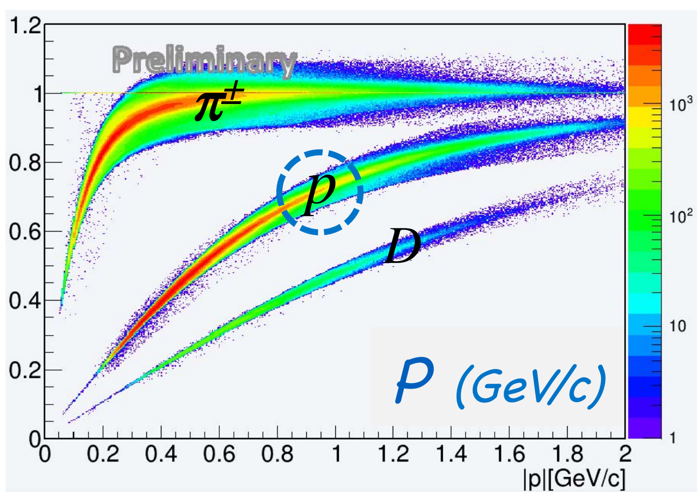
- P. Peng (UVa)

- elementary $d^5\sigma$
- $\pi^+\ \pi^-$ define a plane at ϕ' *wrt reaction plane*
- observables are even or odd *wrt* ϕ'
- $P_{\pi\pi}(\theta_{\pi\pi}) = P_{\pi+} + P_{\pi-}$

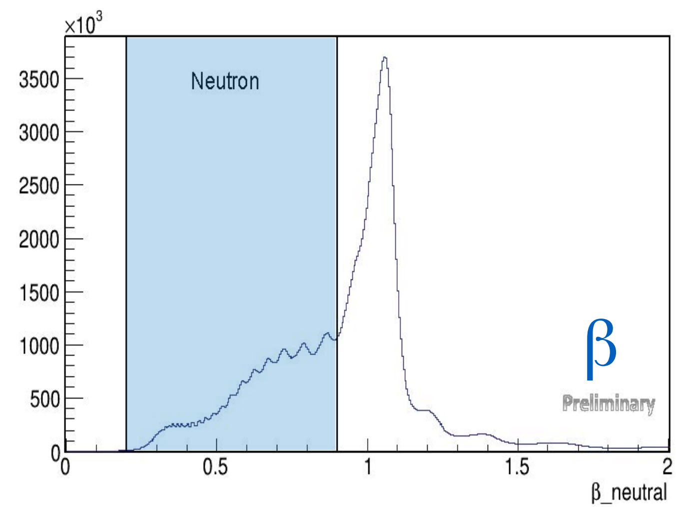


protons in drift chambers

β

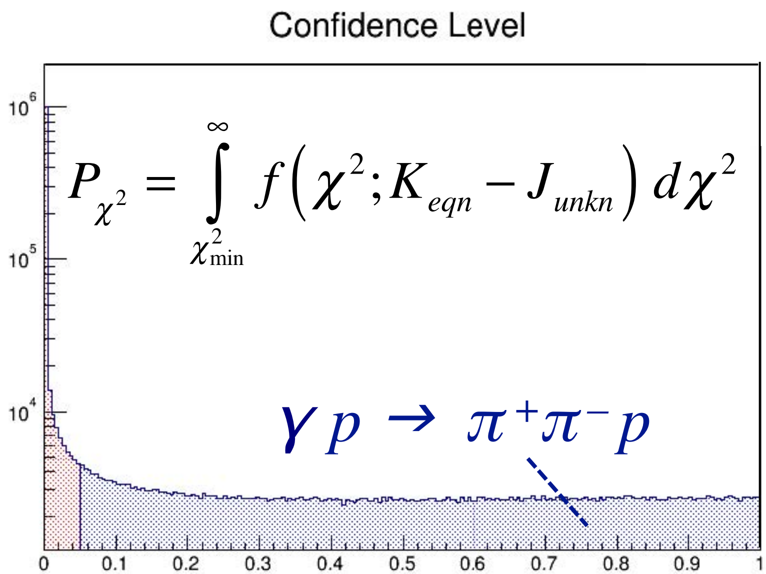


neutrons in forward calorimeter

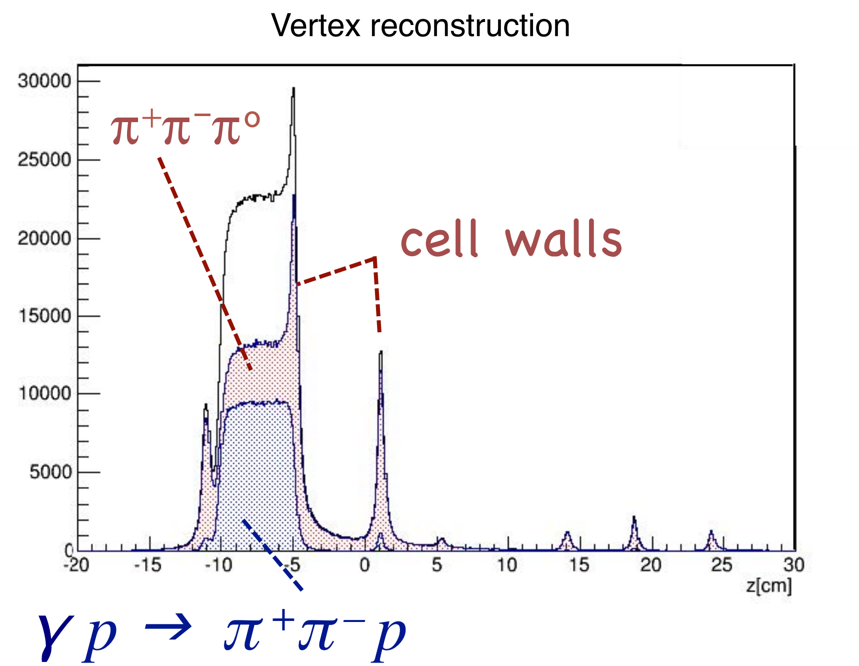


Kinematic fitting $\gamma\, pn \rightarrow \pi^+\pi^- pn$ - P. Peng (UVa)

- kinematic fitting uses (p, E) constraints to improve measured quantities and estimate unmeasured ones
- bound nucleons in target cell (C, Al, F) do not strictly follow elementary kinematics ⇨ separate cell without subtraction
- requires accurate knowledge of the detector's covariance matrix



$$P_{\chi^2} \in [0,1]$$



$\pi^+\pi^-$ observables - P. Peng (UVa)

- in the notation of Roberts and Oed, PR C71 (05) 055201
- 64 possible polarization observables; $\geq$ 15 needed to determine amplitude

$$\frac{d\sigma^{BT}}{d\Omega} = d\sigma_0 \left\{ \begin{array}{l} \left(1+\vec{\Lambda}\cdot\vec{P}\right)+\delta_\odot\left(I^\odot+\vec{\Lambda}\cdot\vec{P}^\odot\right) \\ +\delta_L\left[\sin(2\varphi_\gamma)\left(I^S+\vec{\Lambda}\cdot\vec{P}^S\right)+\cos(2\varphi_\gamma)\left(I^C+\vec{\Lambda}\cdot\vec{P}^C\right)\right] \end{array} \right\}$$

- $\delta_\odot, \delta_L$: beam polarization ;
- $\vec{\Lambda}$: target polarization

- eg. circularly polarized beam on a longitudinally polarized target

$$\frac{d\sigma}{d\Omega} = d\sigma_0 \left\{\left(1+\Lambda_z\cdot P_z\right)+\delta_\odot\left(I^\odot+\Lambda_z\cdot P_z^\odot\right)\right\}$$

$$E^* = \frac{1}{\delta_\odot}\frac{Y(\rightarrow\Rightarrow)-Y(\leftarrow\Rightarrow)}{Y(\rightarrow\Rightarrow)+Y(\leftarrow\Rightarrow)} = \frac{I^\odot+\Lambda_z P_z^\odot}{1+\Lambda_z P_z} \cong I^\odot+\Lambda_z P_z^\odot-\Lambda_z I^\odot P_z$$

odd functions of ϕ'

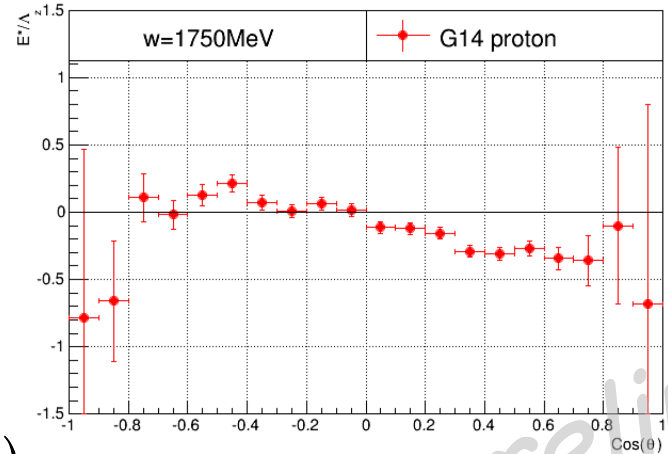
$$\frac{1}{\Lambda_z}\int E^*(\theta_{\pi\pi},\phi'_{\pi\pi})\cdot d\phi'_{\pi\pi} \cong P_z^{\odot}(\theta_{\pi\pi})$$

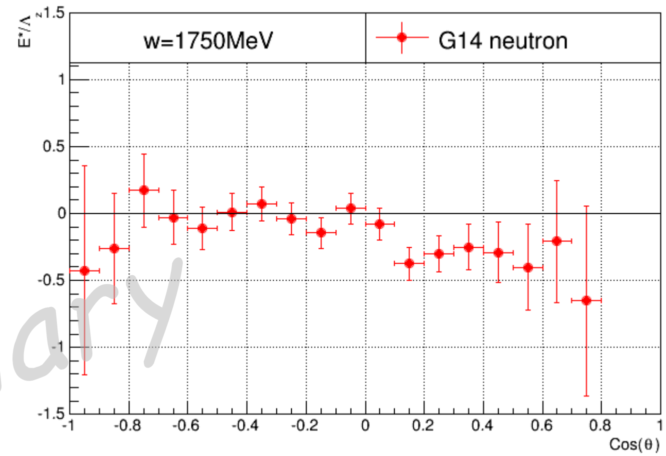
- P. Peng (UVa)

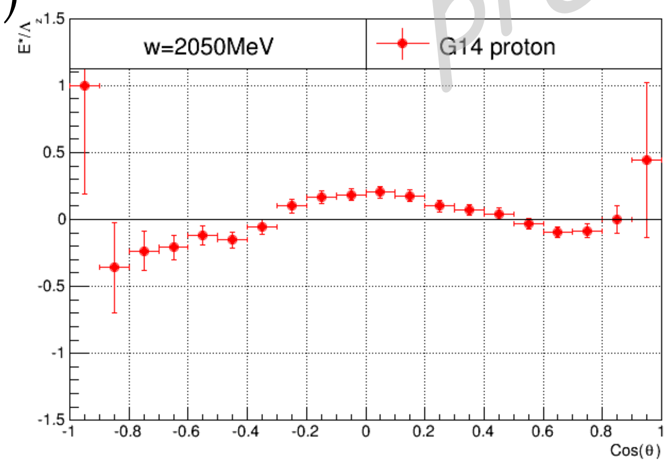
$\gamma + p, p(n) \Rightarrow \pi^+\pi^-$ *proton*

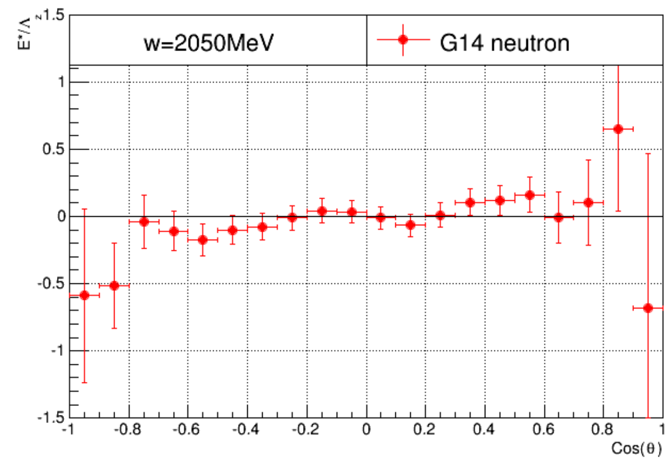
$\gamma + n(p) \Rightarrow \pi^+\pi^-$ *neutron*

$P_z^{\odot}(\theta_{\pi\pi})$









preliminary

$\cos(\theta_{\pi\pi})$ $\cos(\theta_{\pi\pi})$

Jefferson Lab

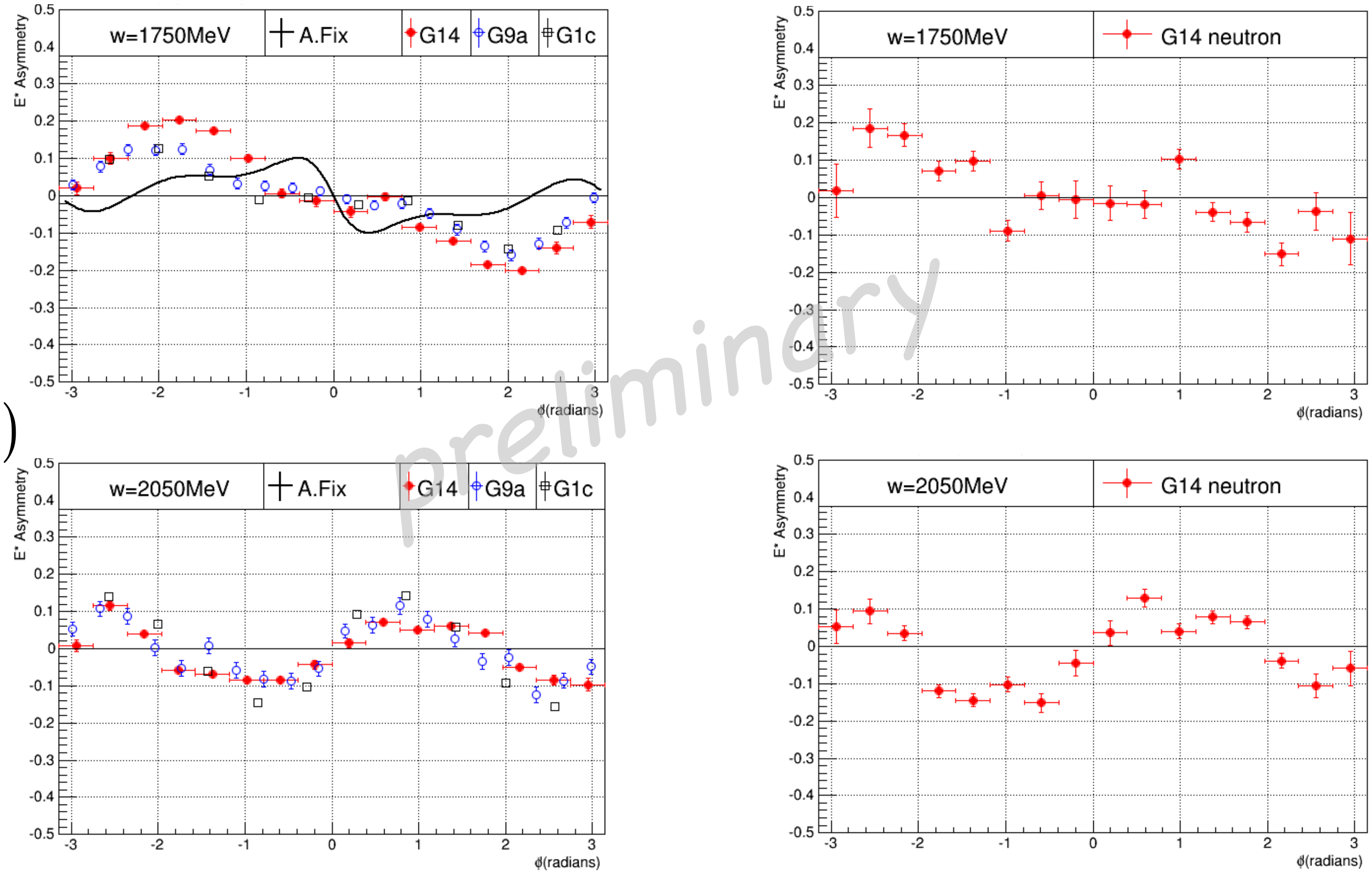
$$\int E^*(\theta_{\pi\pi}, \phi'_{\pi\pi}) \cdot d\cos(\theta_{\pi\pi}) \cong I^{\odot}(\phi'_{\pi\pi})$$

- *P. Peng (UVa)*

$\gamma + p, p(n) \Rightarrow \pi^+\pi^-$ *proton*

$\gamma + n(p) \Rightarrow \pi^+\pi^-$ *neutron*

$I^{\odot}(\phi'_{\pi\pi})$

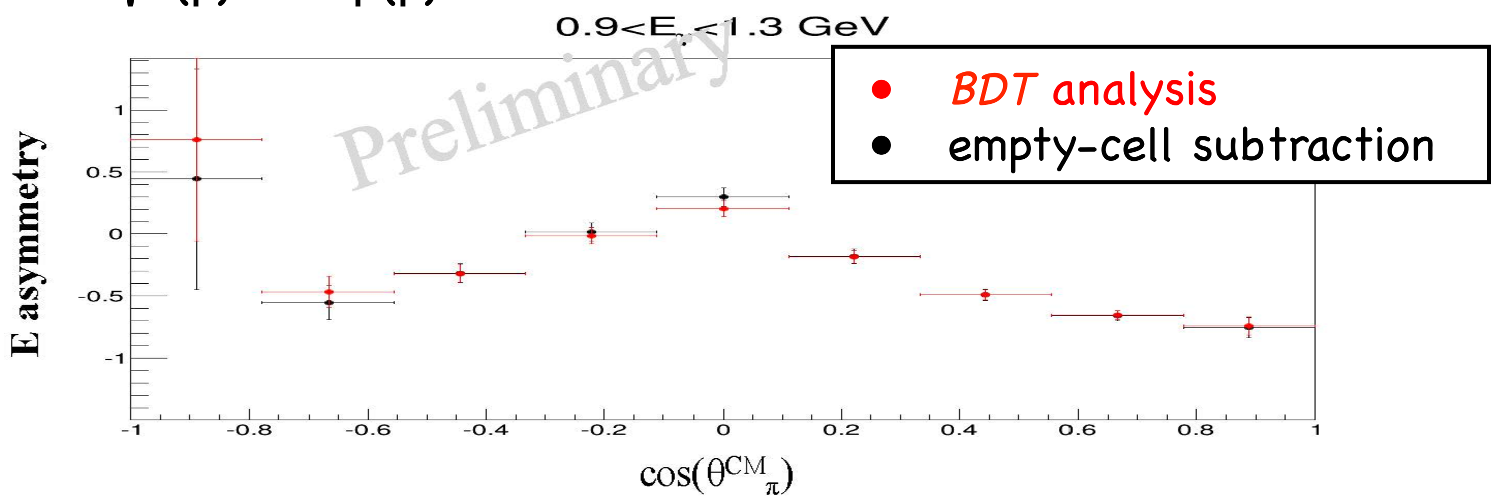


$\phi'_{\pi\pi}$ *(rad)*

$\phi'_{\pi\pi}$ *(rad)*

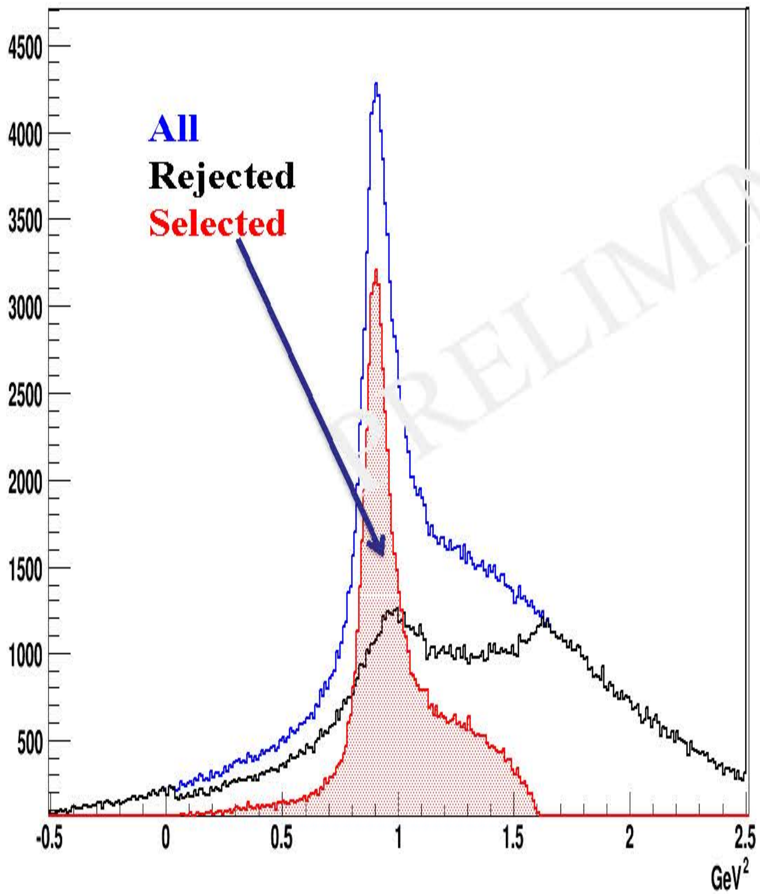
HDice $\gamma\, n(p) \rightarrow K^0 \Lambda \rightarrow \pi^+\pi^-\ \pi^- p\ (p)$ - D. Ho (Carnegie-Mellon U)

- no published data on $K^0 \Lambda$ photo-production
  ⇨ cross sections turned out to be smaller than anticipated (KaonMAID)
- maximize signal using a multivariate *Boosted-Decision-Tree* (*BDT*) (standard in HEP: arXiv.physics/0703039v5)
  ⇨ separate events into *signal* or *background* with simultaneous (rather than sequential) requirements/cuts on many variables
  ⇨ *BDT* is *trained* on *empty-target* data and on MC
- test on $\gamma n(p) \rightarrow \pi^- p(p)$:

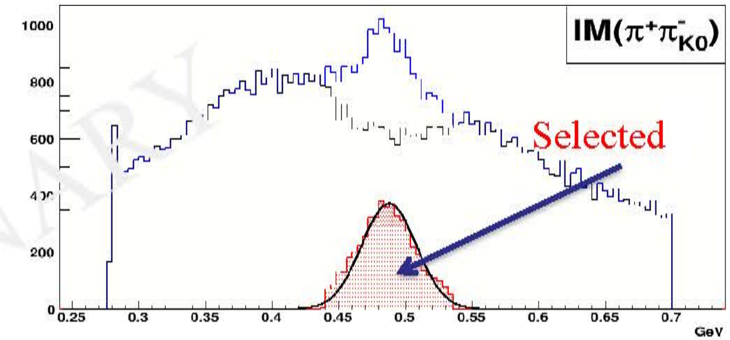


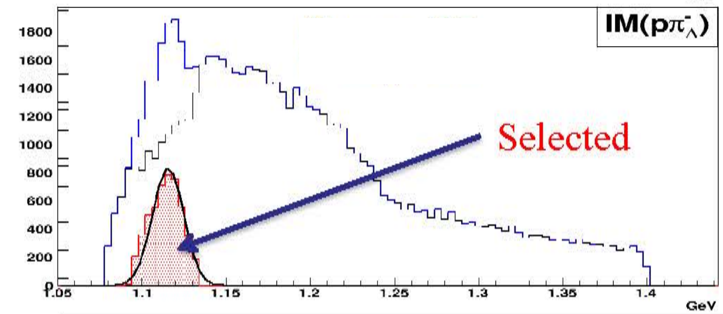
$\gamma\, n(p) \rightarrow K^0\, \Lambda(p) \rightarrow \pi^+\pi^-\ \pi^-\, p\ (p)$ - D. Ho (Carnegie-Mellon U)

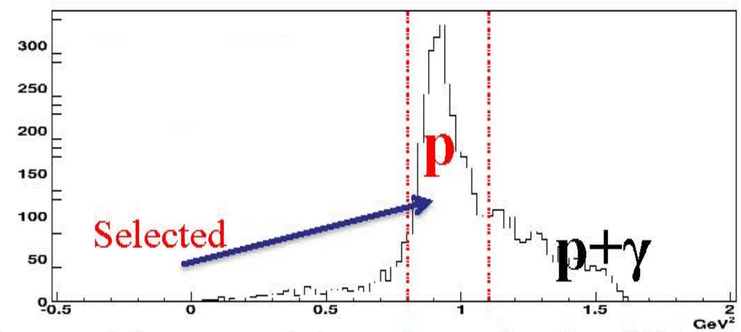
eg. stages in $K^0\, \Lambda$ (p_s) separation :



Squared Spectator Mass

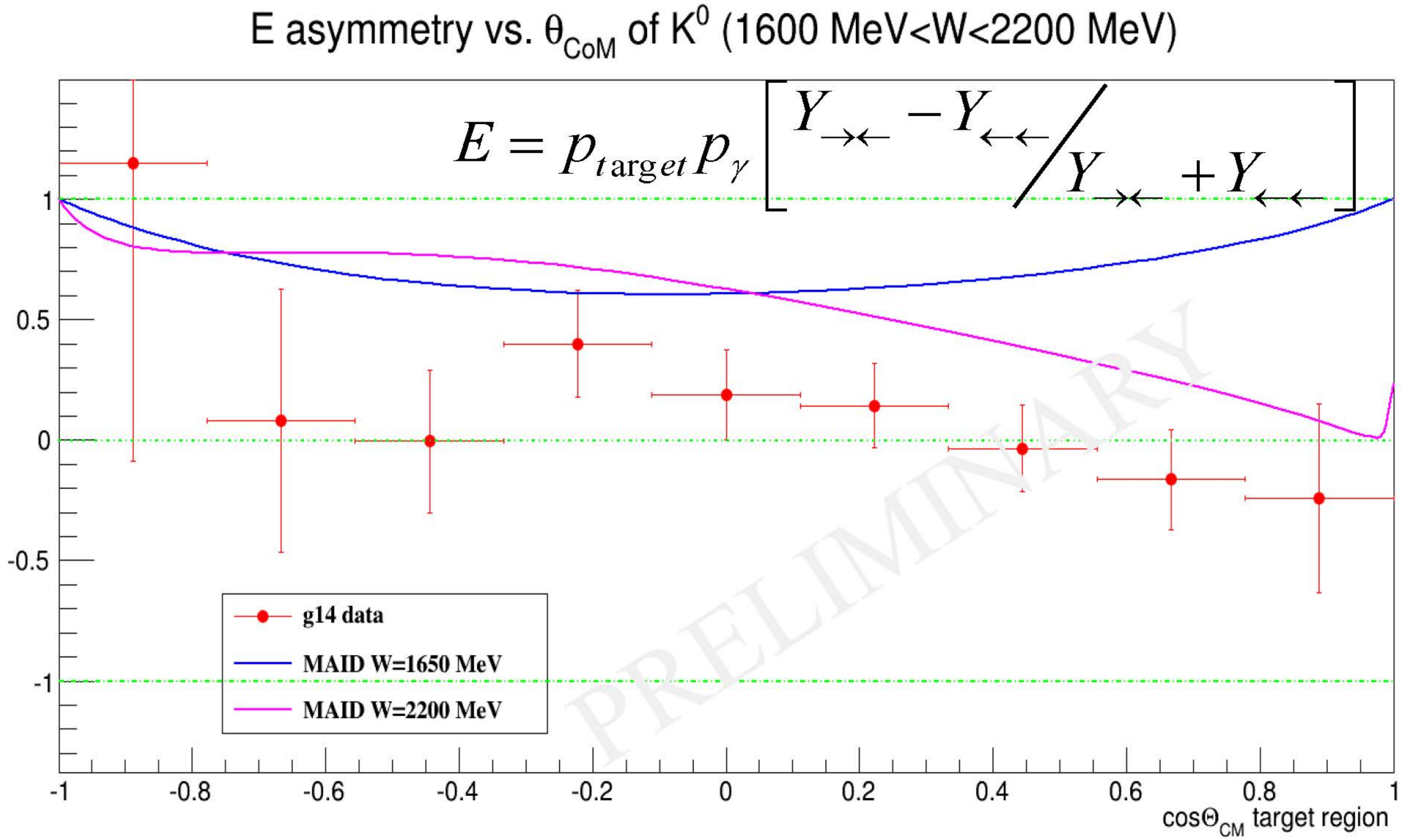






Squared Spectator Mass **after selecting $K^0\Lambda$**

$\gamma\ n(p) \rightarrow K^0\,\Lambda(p) \rightarrow \pi^+\pi^-\ \pi^- p\ (p)$ - D. Ho (Carnegie-Mellon U)

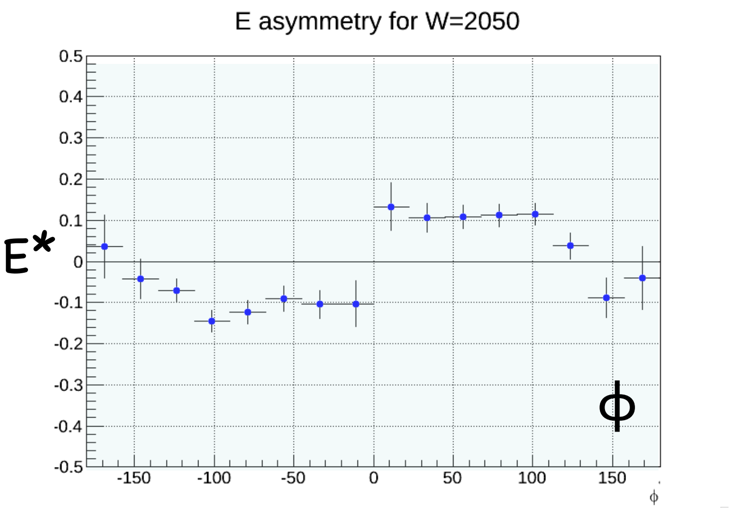


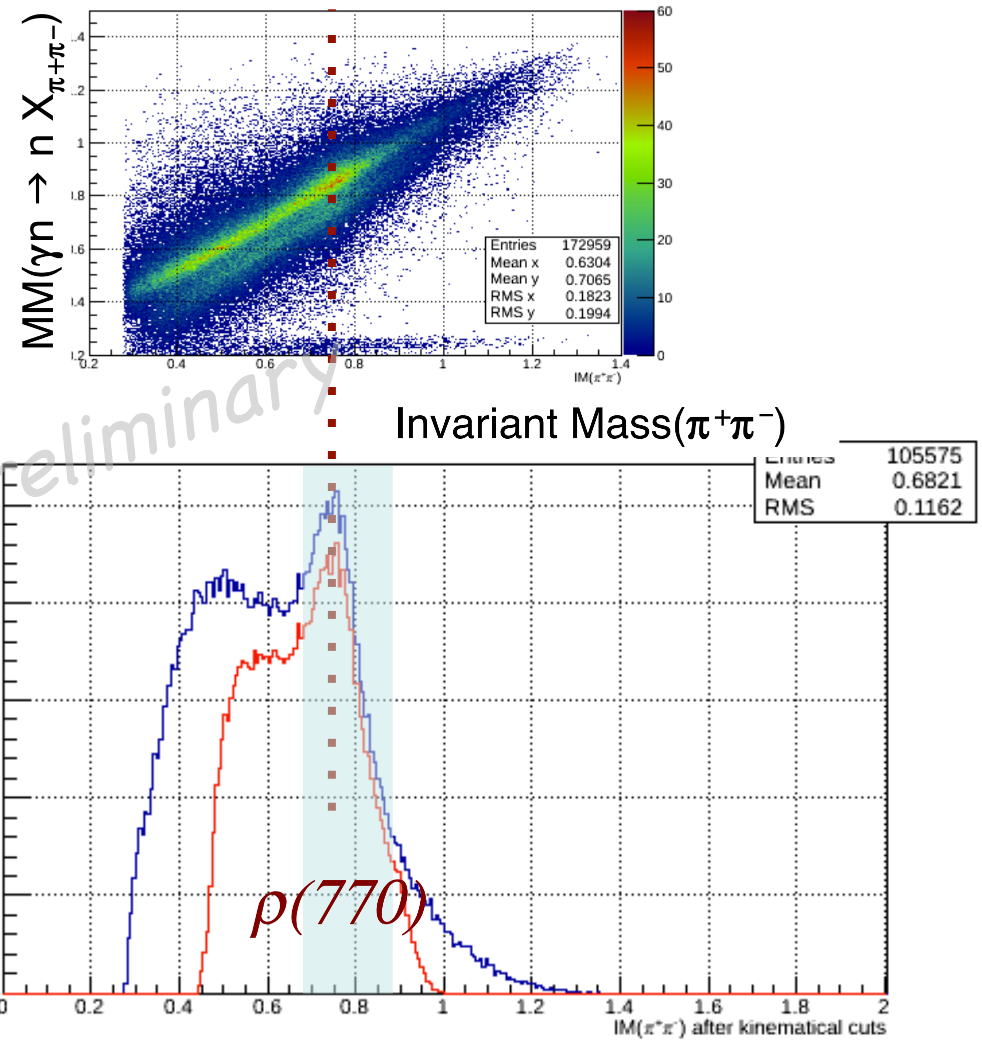
After selecting $K^0\Lambda$ (rejecting possible $K^0\Sigma^0$) events

$\vec{\gamma}\,\vec{n}(p) \rightarrow \rho^0 n(p) \Rightarrow \pi^+\pi^- n(p)$

- I. Zonta (U Roma-II)

- ρ^0 photo-production from polarized neutrons in D; $\rho^0 \Rightarrow \pi^+\pi^-$, ~100% branch
- test of ρ^0 separation: E*(ϕ) = const if 2-body





- Boosted-Decision-Tree (BDT) analysis under development to improve ρ separation

E06-101 (g14) – summary & outlook

- 1st look at "neutron" data from g14 suggests many *unexpected* differences from proton experiments,

  (although there was really no good reason to take any expectation too seriously result since all were badly under-constrained)

- collaboration goal for 1st data release:

  ➪ helicity asymmetry **E** for quasi-free $\pi^- p$ ↔ our bench-mark

- cross sections for hyperon production (KΛ, KΣ) smaller than expected

  ➪ *kinematic fitting* and *Boosted-Decision-Trees* are promising methods to maximize statistics and remove backgrounds

- a question we must eventually face:

  how close are "quasi-free" neutrons to a really *free neutron* !

  ➪ will require collaboration with theory efforts