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

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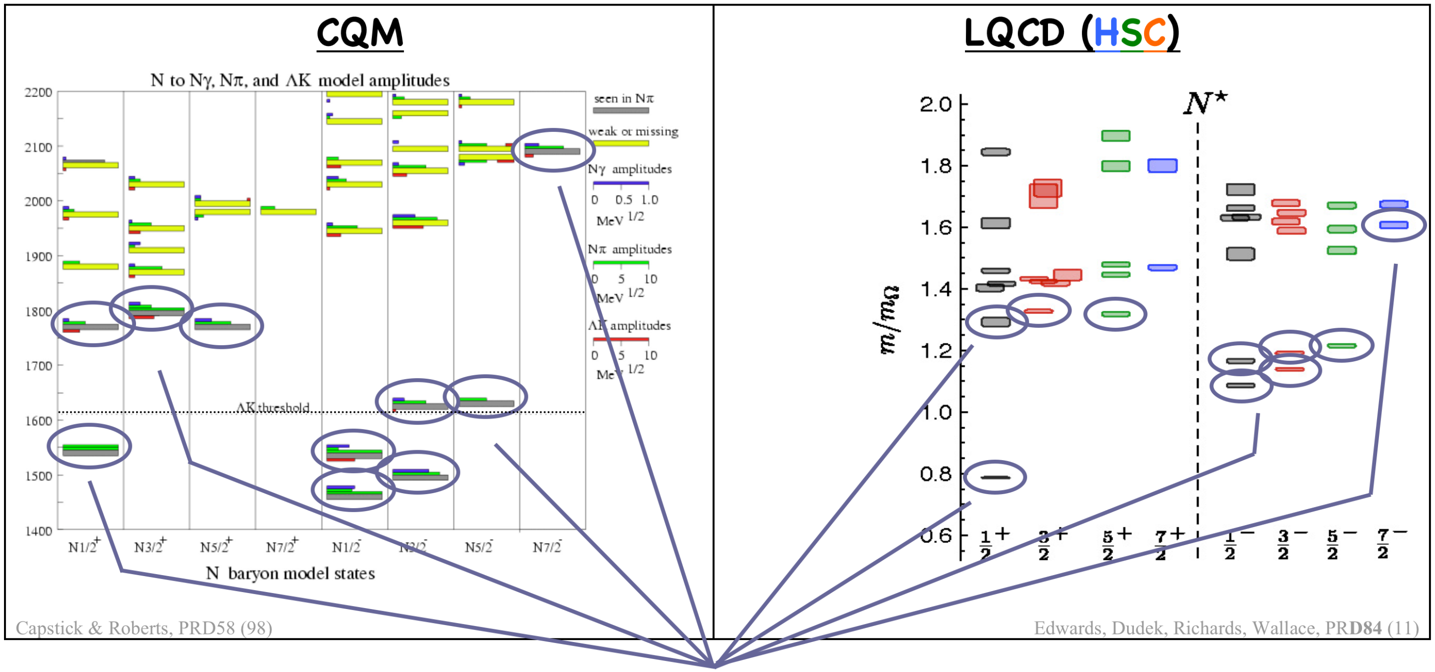
(*for the CLAS-g14 Collaboration*)

(Peking University, Beijing – October 21, 2014)

![HDice logo]

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)

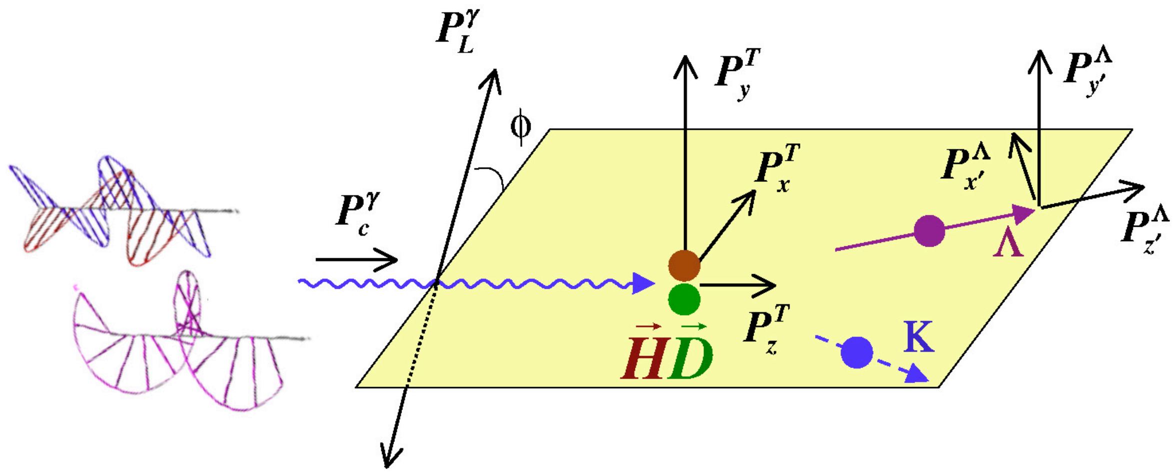
⇨ 4 complex amplitudes describe photo-production
⇨ 8 quantities to be determined
⇨ the 16 possible observables (matrix elements) are not independent

- 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		$T_{z'}$		$L_{z'}$
$P_L^\gamma \sin(2\phi_\gamma)$		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		$-H$		$O_{x'}$	

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

- the electromagnetic interactions do not conserve isospin
  ⇨ **requires data from both proton and neutron targets**

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

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Tues Parallel-IV: S6

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HD exps

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⇔ **N* (I=1/2) states**

the E06-101 (g14) experiment & crew

the components

- CLAS detector
- polarized *HDice* target
- calibrations
and ongoing analyses

the crew

- Jlab Hall-B staff, CLAS collaboration
- **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
- 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

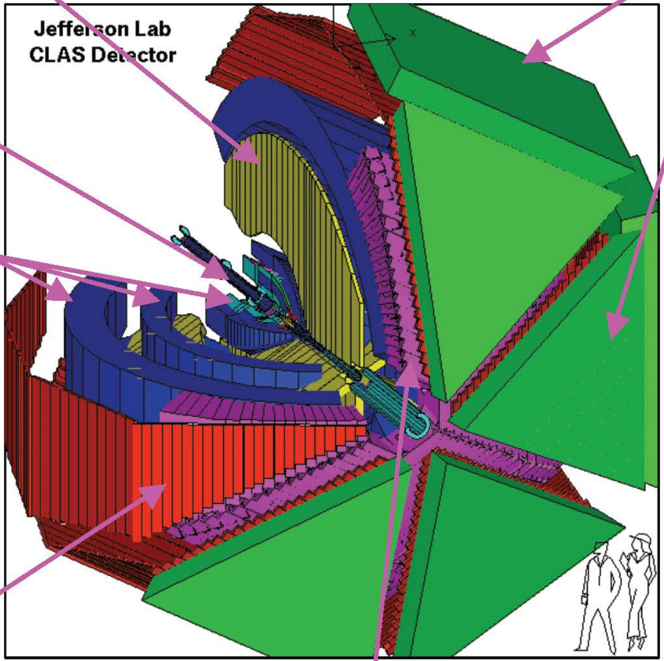
Jlab Hall-B – the CLAS(6) detector

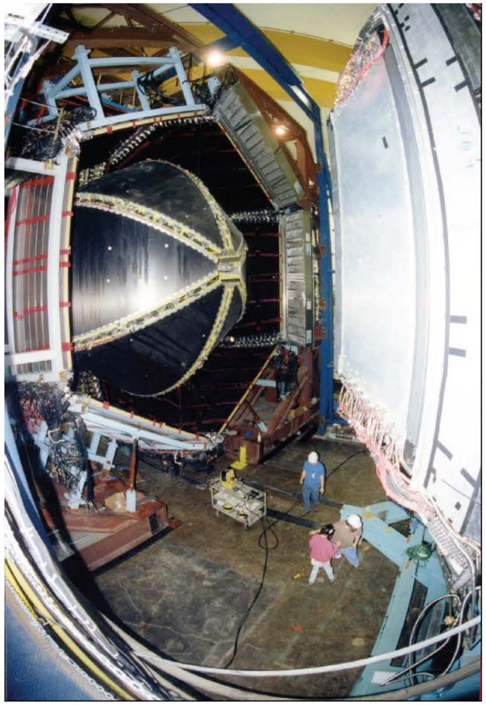
Torus magnet
6 superconducting coils

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 frozen-spin target

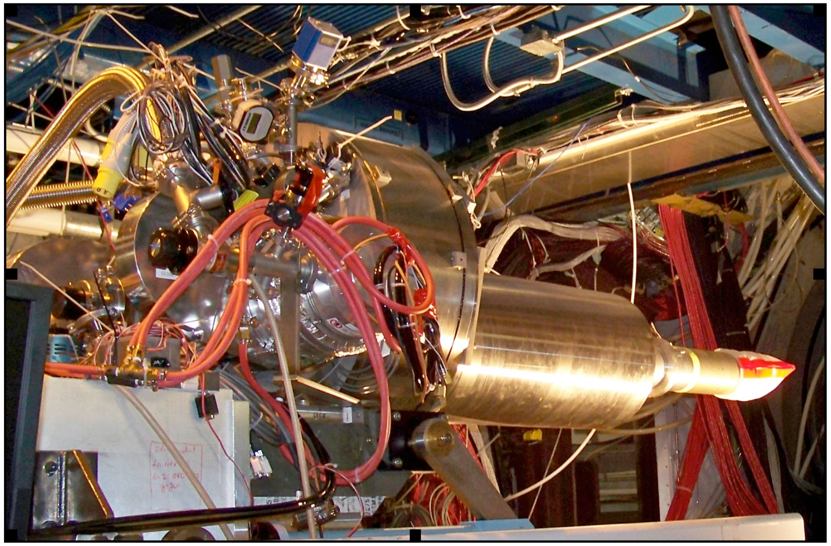
⇨ talk by X. Wei
Friday, Parallel-VII: S10

- 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

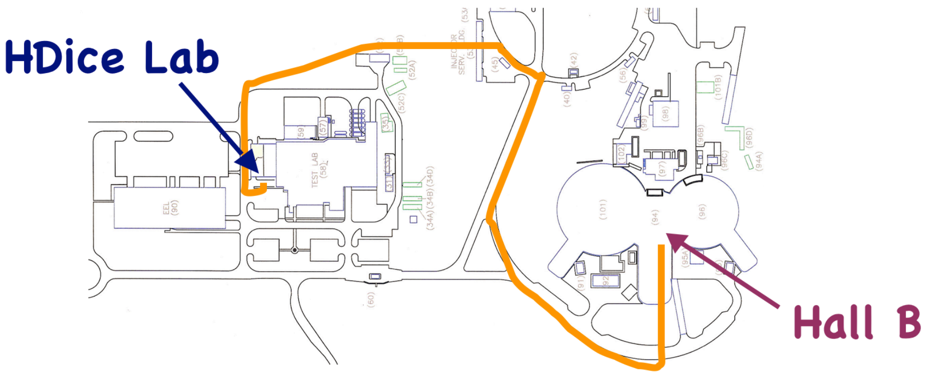
⇒

transfers are the trickest part

- NIM A737 (14) 107

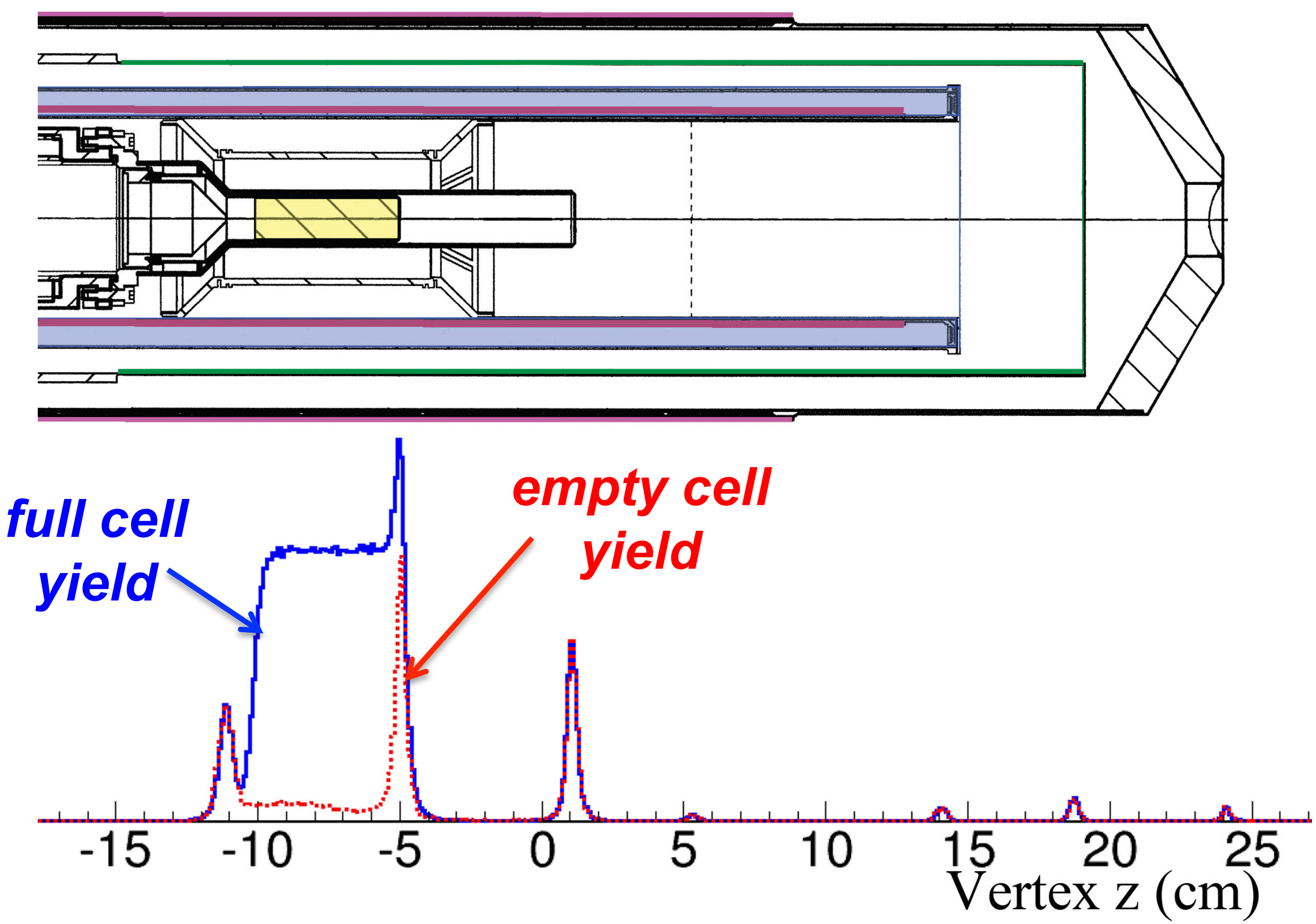
Hall-B

- 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

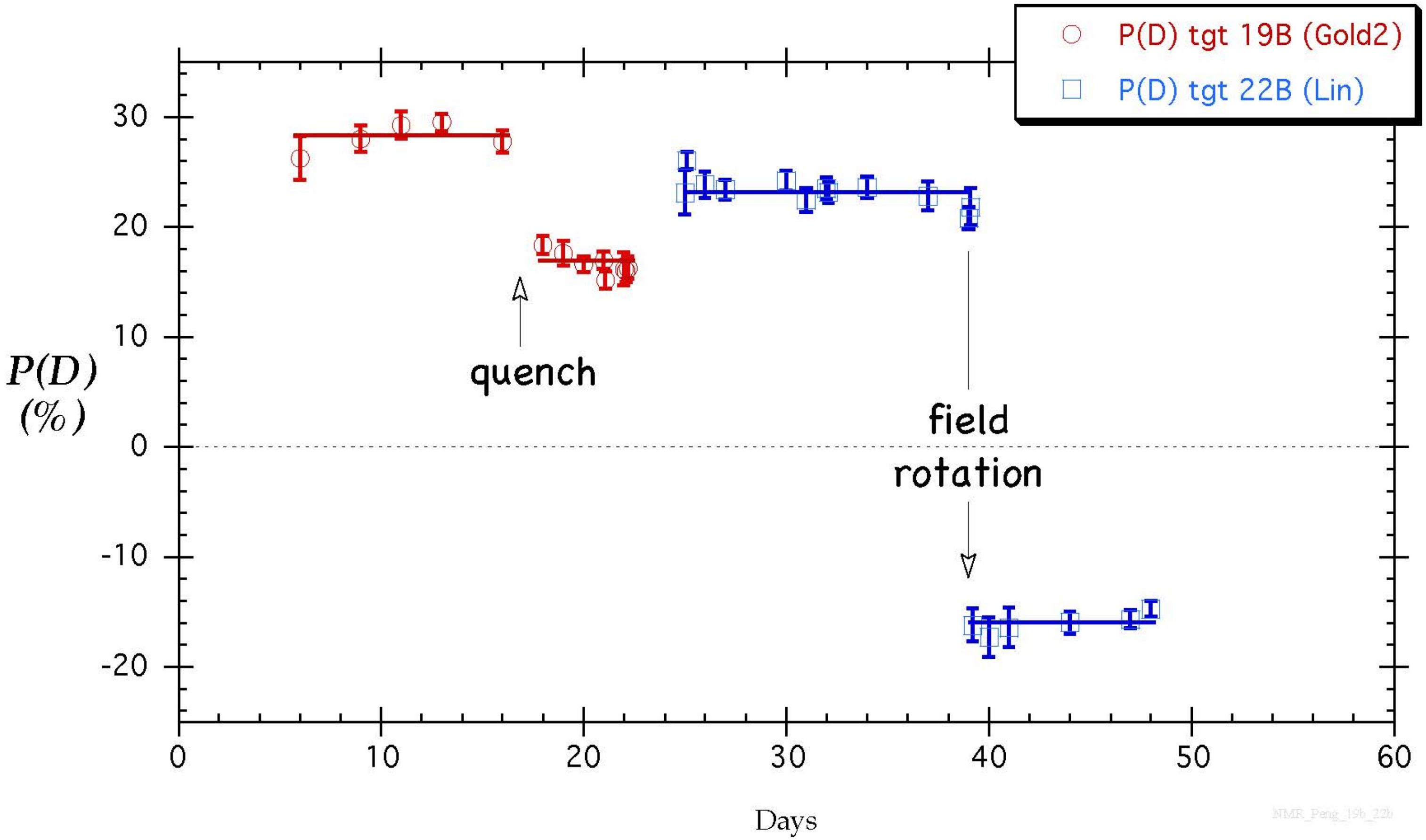


non-HD target-cell backgrounds

- 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)

On-going Analyses:

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

⇨ some examples with ~ ⅓ to ⅔ data processed

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): $\gamma_c\, n(p) \rightarrow \pi^- p(p)$
- H. Lu (CMU, U. Iowa): $\gamma_L\, n(p) \rightarrow \pi^- p(p)$

Kinematic fitting

- P. Peng (U. Virginia): $\gamma_c\, p \rightarrow \pi^+\pi^- p$; $\gamma_c\, n(p) \rightarrow \pi^+\pi^- n(p)$
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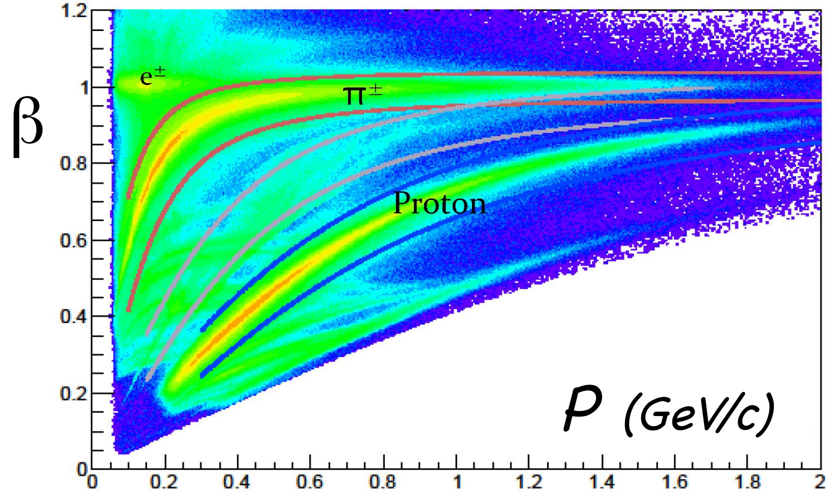
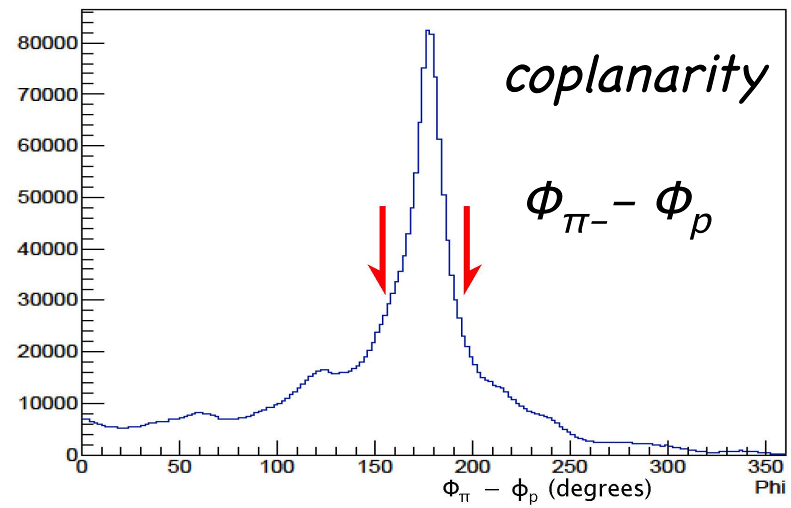
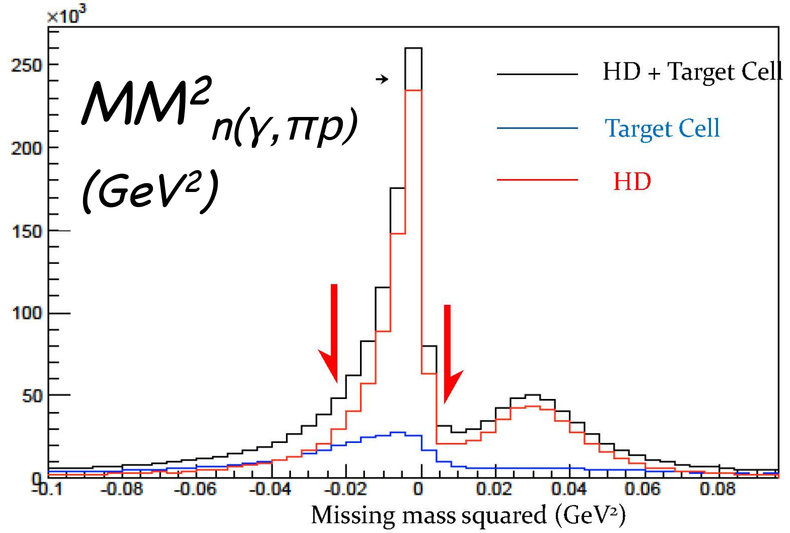
Boosted Decision Trees

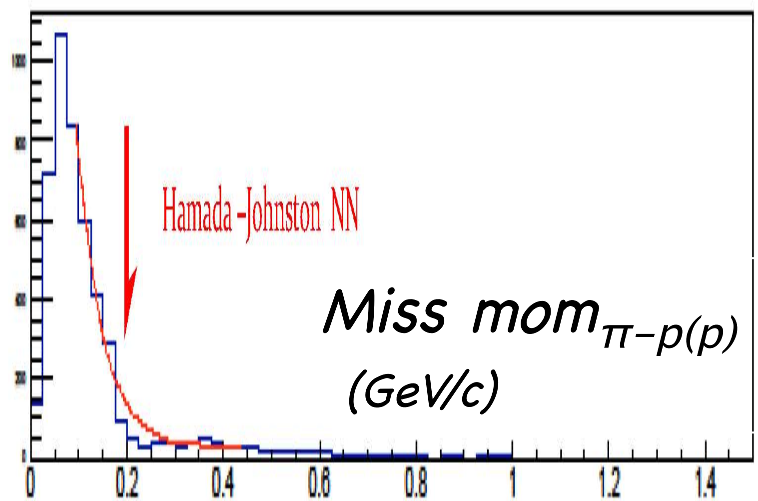
⇨ some examples with ~ ⅓ to ⅔ data processed

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

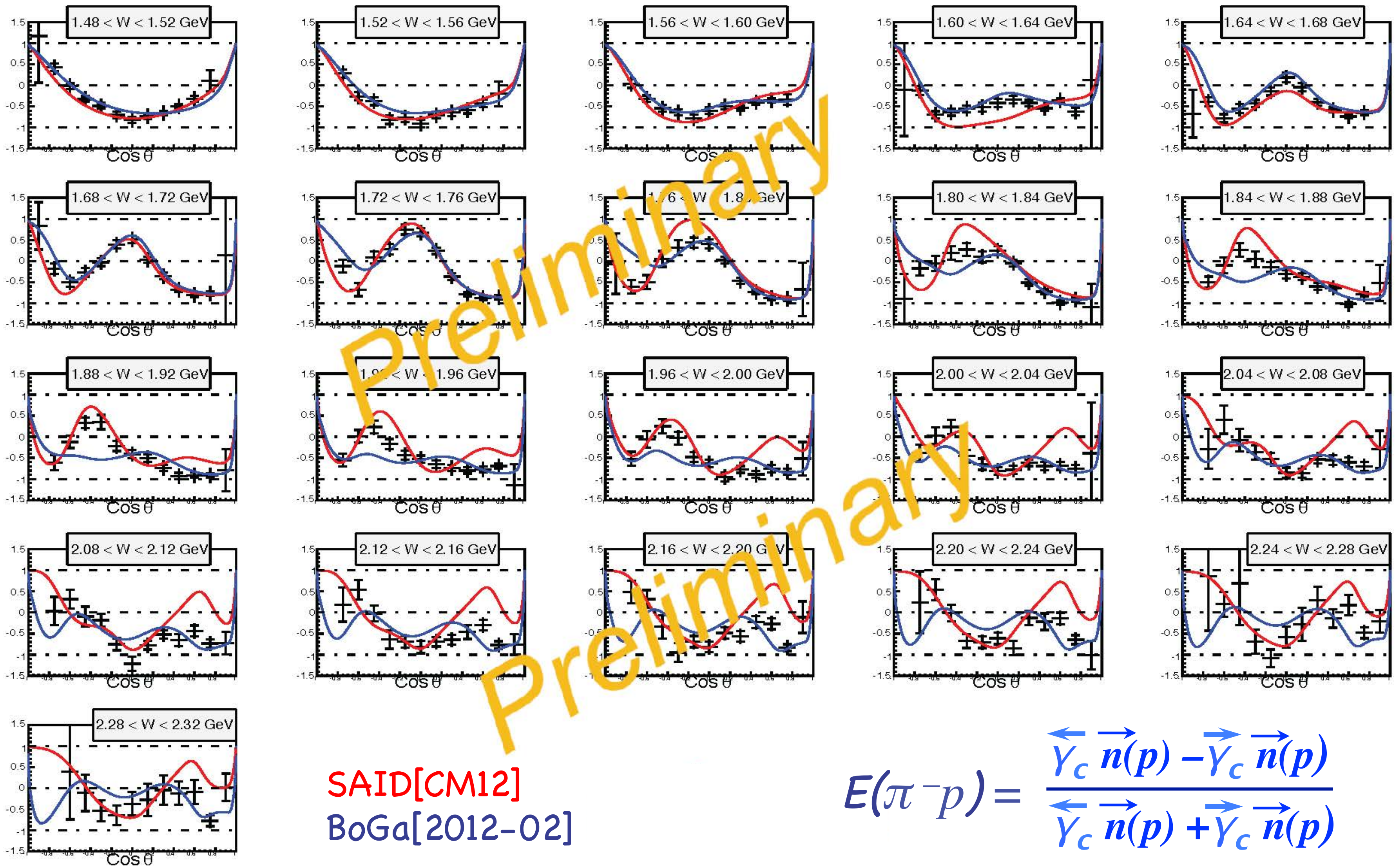






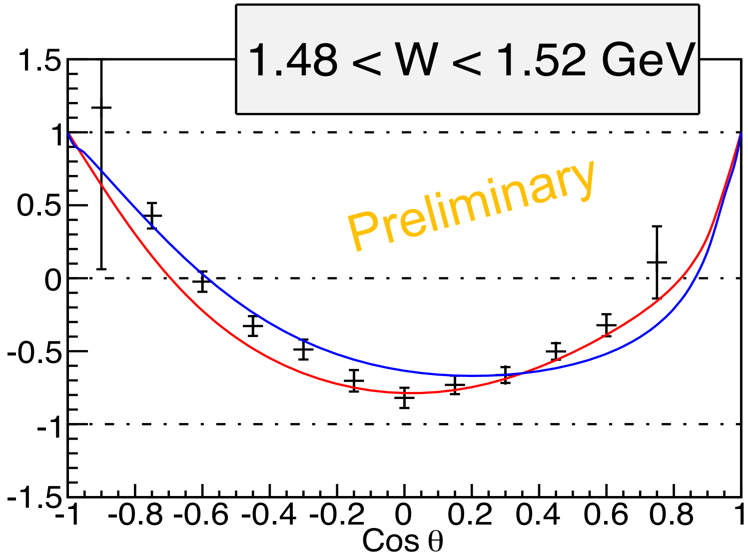


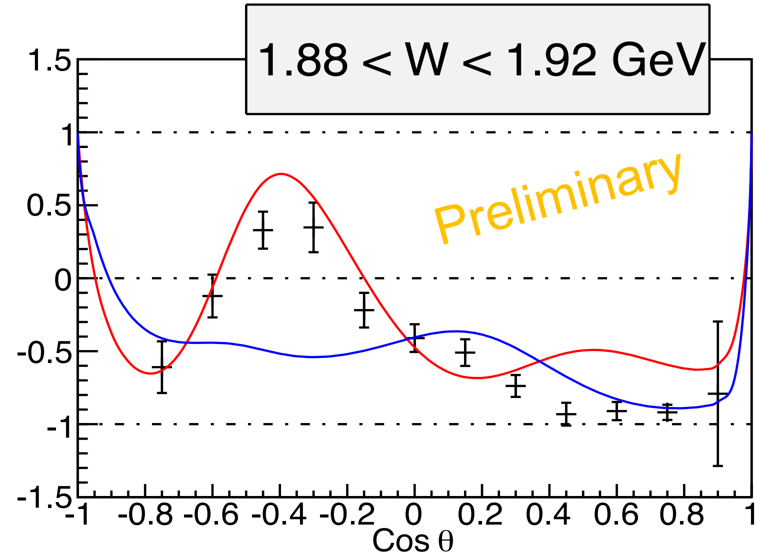
Beam-Target Helicity asymmetry $E(\pi^- p)$ – T. Kageya (Jlab)

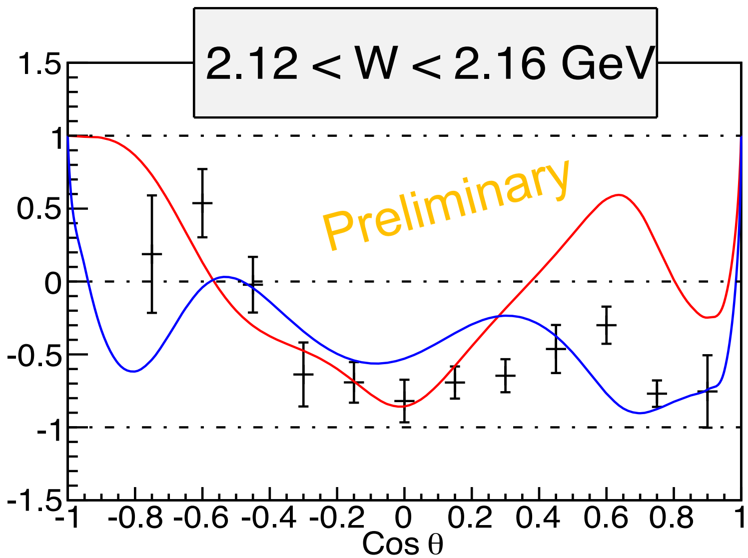


$$E(\pi^- p) = \frac{\overleftarrow{\gamma_c}\,\overrightarrow{n(p)} - \overrightarrow{\gamma_c}\,\overrightarrow{n(p)}}{\overleftarrow{\gamma_c}\,\overrightarrow{n(p)} + \overrightarrow{\gamma_c}\,\overrightarrow{n(p)}}$$

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







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

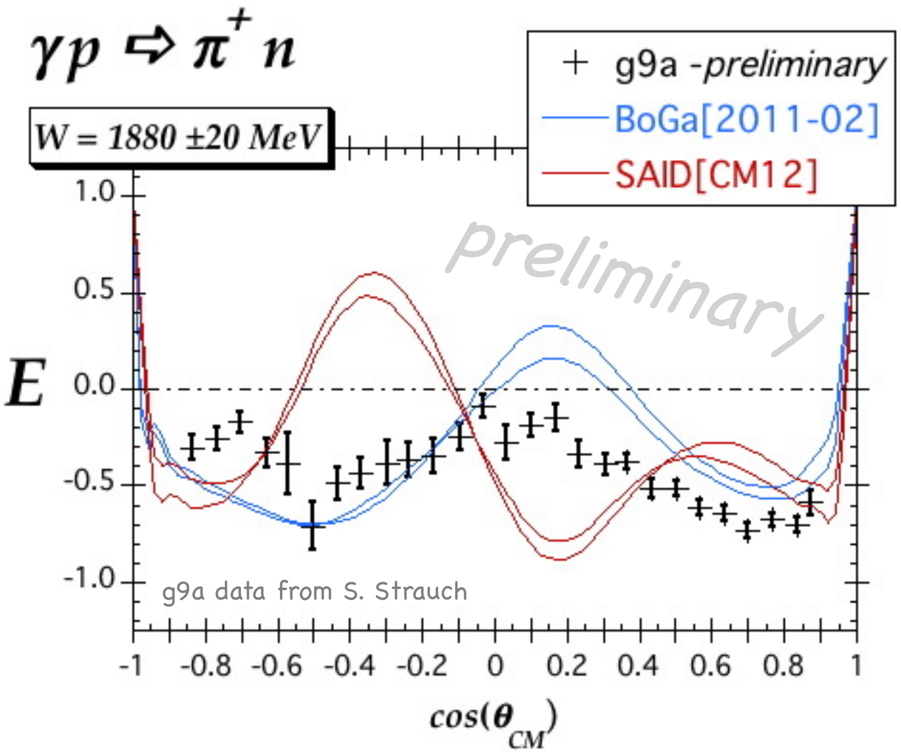
PWA: SAID[CM12]
BoGa[2012-02]

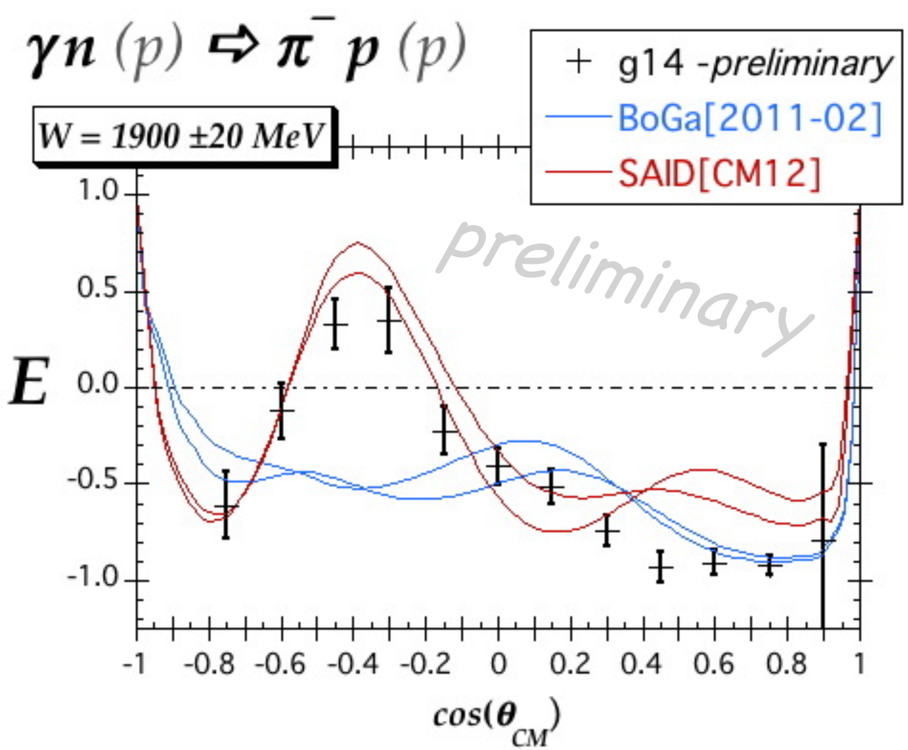
Comparing proton and neutron targets in the N* hunt

$P_{13}(1900)$ –driven by BoGa

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

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

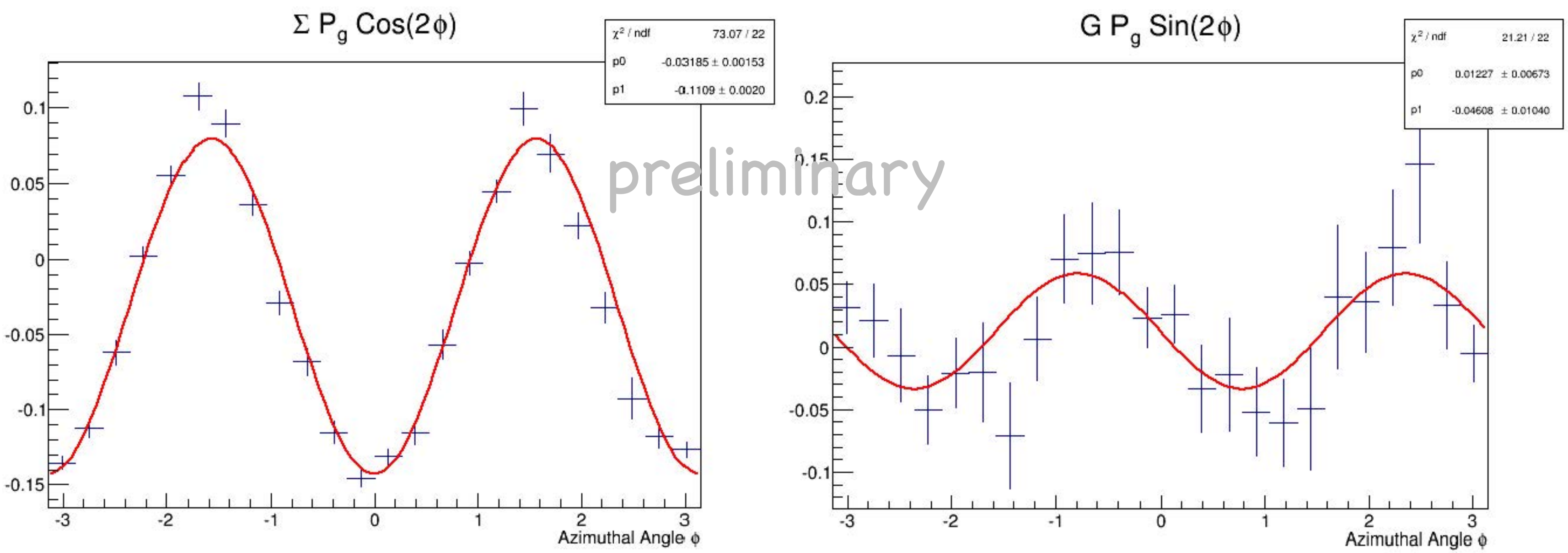




HDice

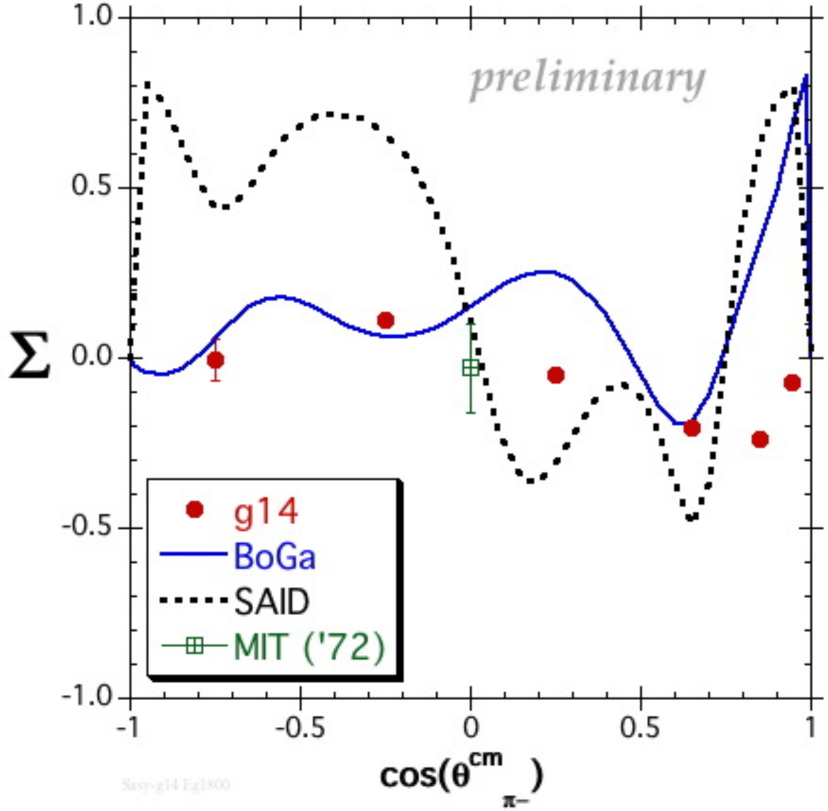
$\vec{\gamma}_L + \vec{n}(p) \rightarrow \pi^- p\ (p)$ - *Haiyun Lu (CMU, U Iowa)*

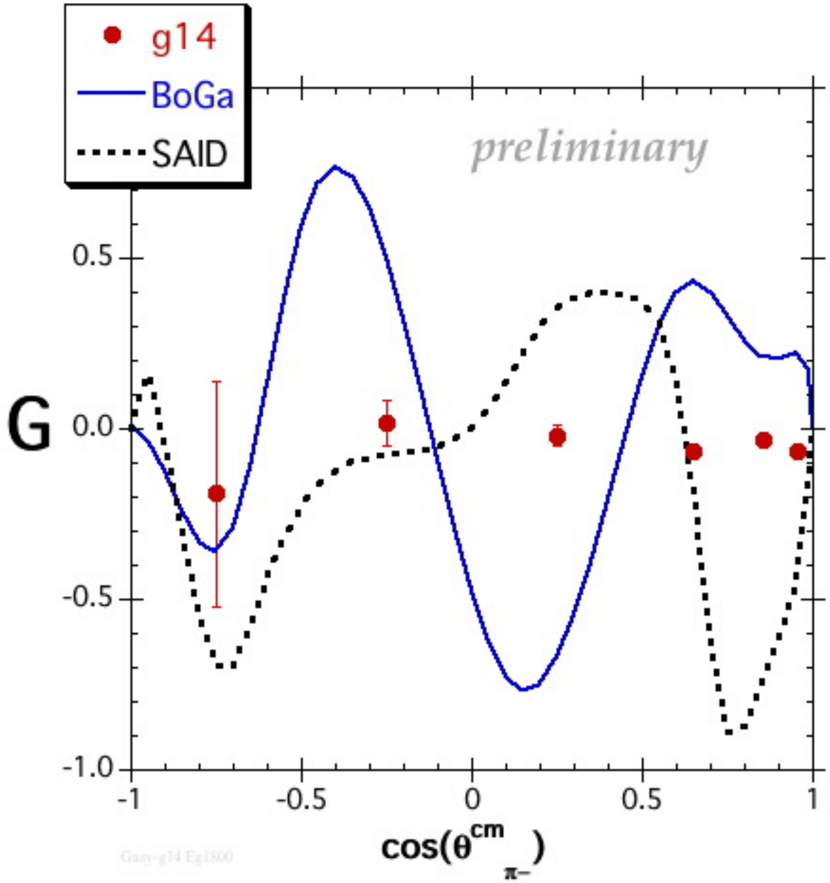
- linearly polarized beam from bremsstrahlung in diamond
- $d\sigma_{(B,T)} = \frac{1}{2} d\sigma_0 \left\{ 1 - \Sigma(\theta) \cdot P_L^{\gamma} cos(2\varphi_\gamma) + G(\theta) \cdot P_L^{\gamma} \cdot P_z^T \cdot sin(2\varphi_\gamma) \right\}$
- combine diff beam and target orientations to separate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



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

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

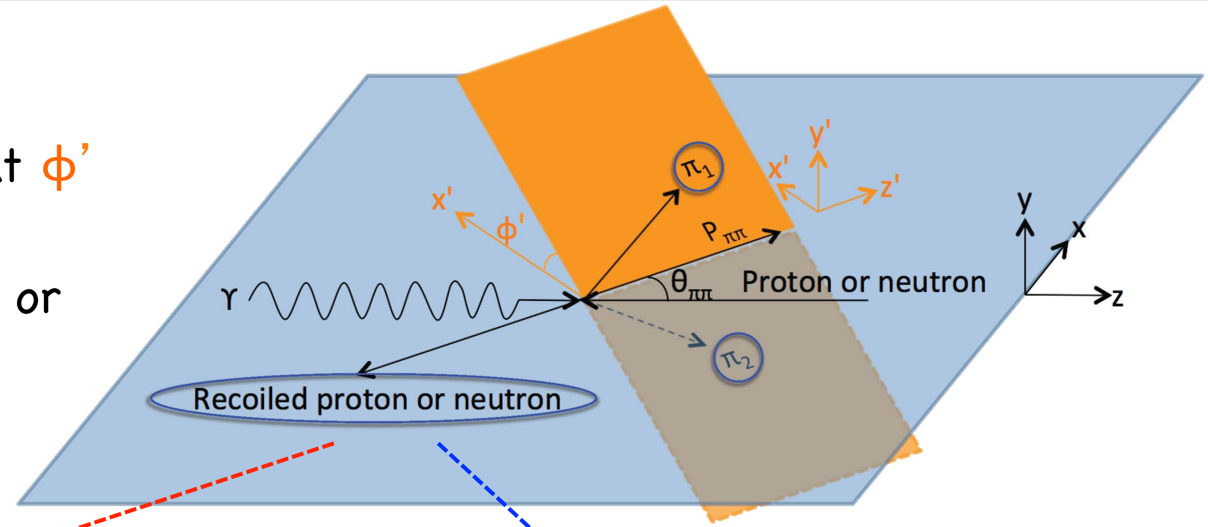




$\gamma\, pn \rightarrow \pi^+\pi^- p(n),\ \pi^+\pi^- n(p)$

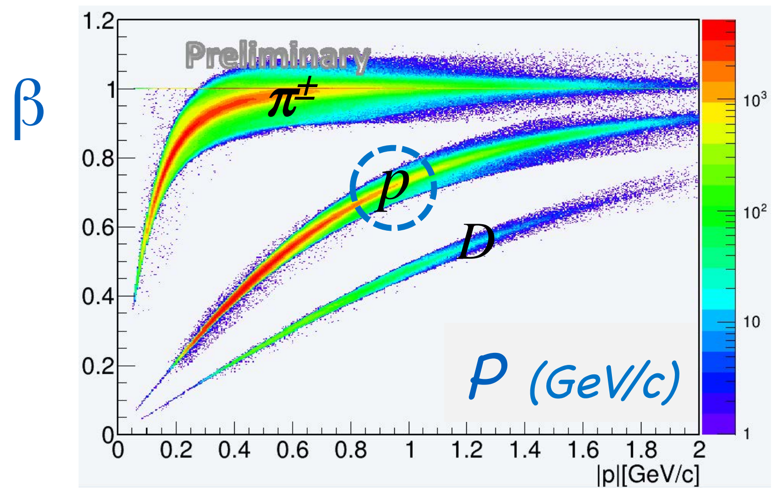
- P. Peng (UVa)

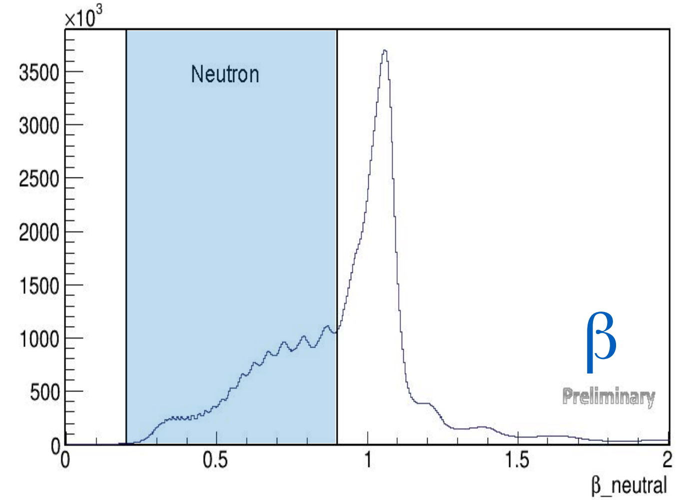
- elementary $d^5\sigma$
- $\pi^+\ \pi^-$ define a plane at ϕ' *wrt reaction plane*
- observables are even or odd *wrt* ϕ'
- $P_{\pi\pi}(\theta_{\pi\pi}) = P_{\pi+} + P_{\pi-}$



protons in drift chambers

neutrons in forward calorimeter

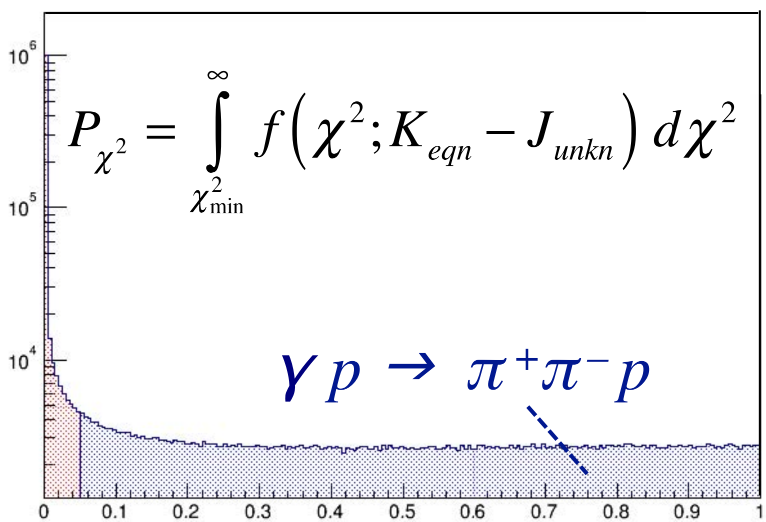




Kinematic fitting $\gamma\, pn \rightarrow \pi^+\pi^- pn$ - P. Peng (UVa)

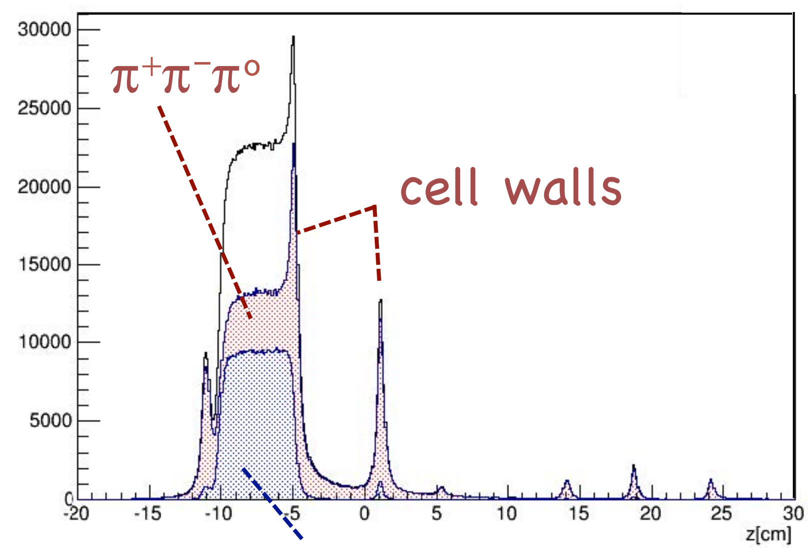
- kinematic fitting uses (p, E) constraints to improve measured quantities and estimate unmeasured ones
- bound nucleons in target cell (C, Al, F) do not strictly follow elementary kinematics ⇨ separate cell without subtraction
- requires accurate knowledge of the detector's covariance matrix

Confidence Level



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

Vertex reconstruction



$\gamma\, p \rightarrow \pi^+\pi^- p$

$\pi^+\pi^-$ 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'

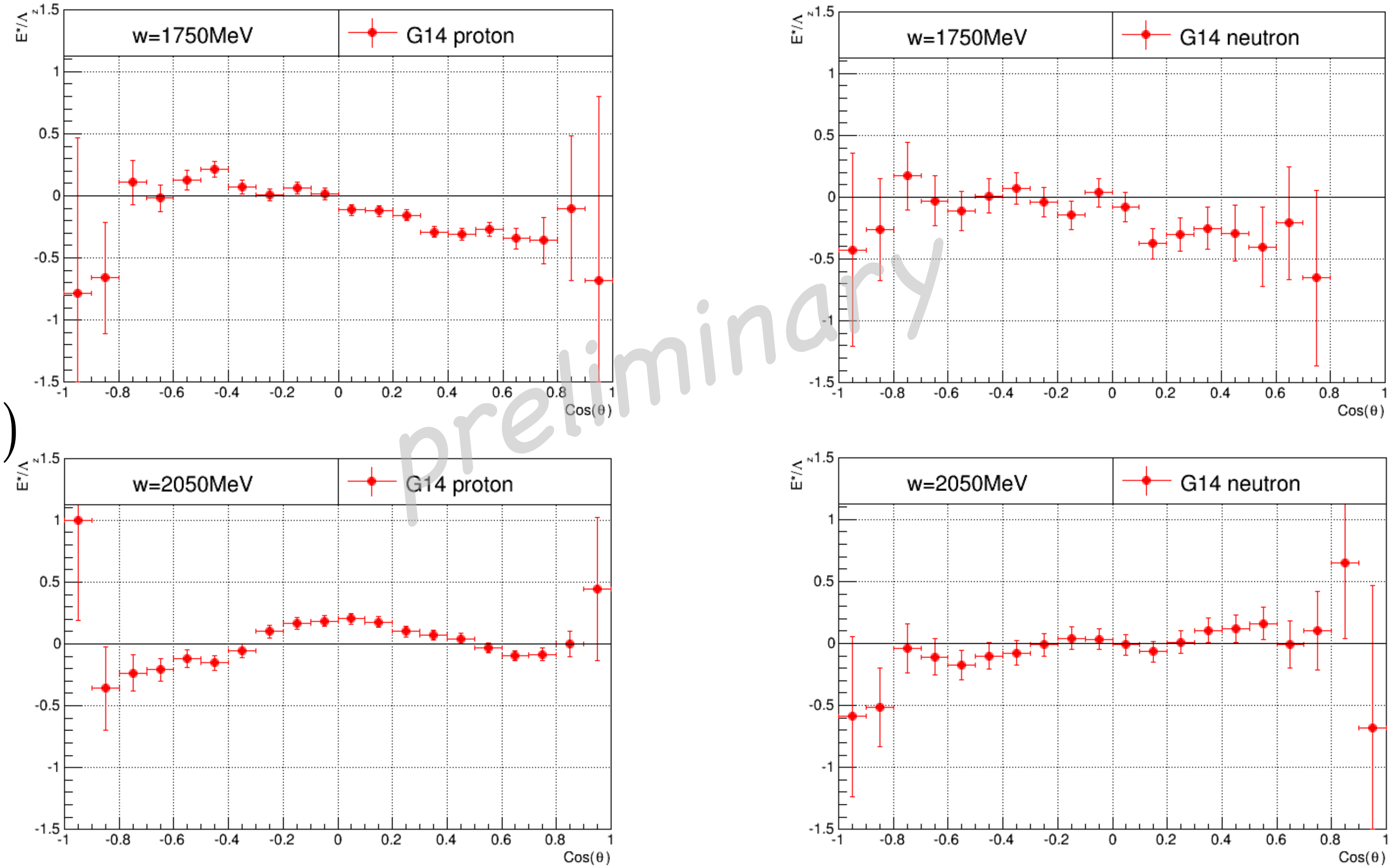
$$\frac{1}{\Lambda_z}\int E^*(\theta_{\pi\pi},\phi'_{\pi\pi})\cdot d\phi'_{\pi\pi} \cong P_z^{\odot}(\theta_{\pi\pi})$$

- P. Peng (UVa)

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

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

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



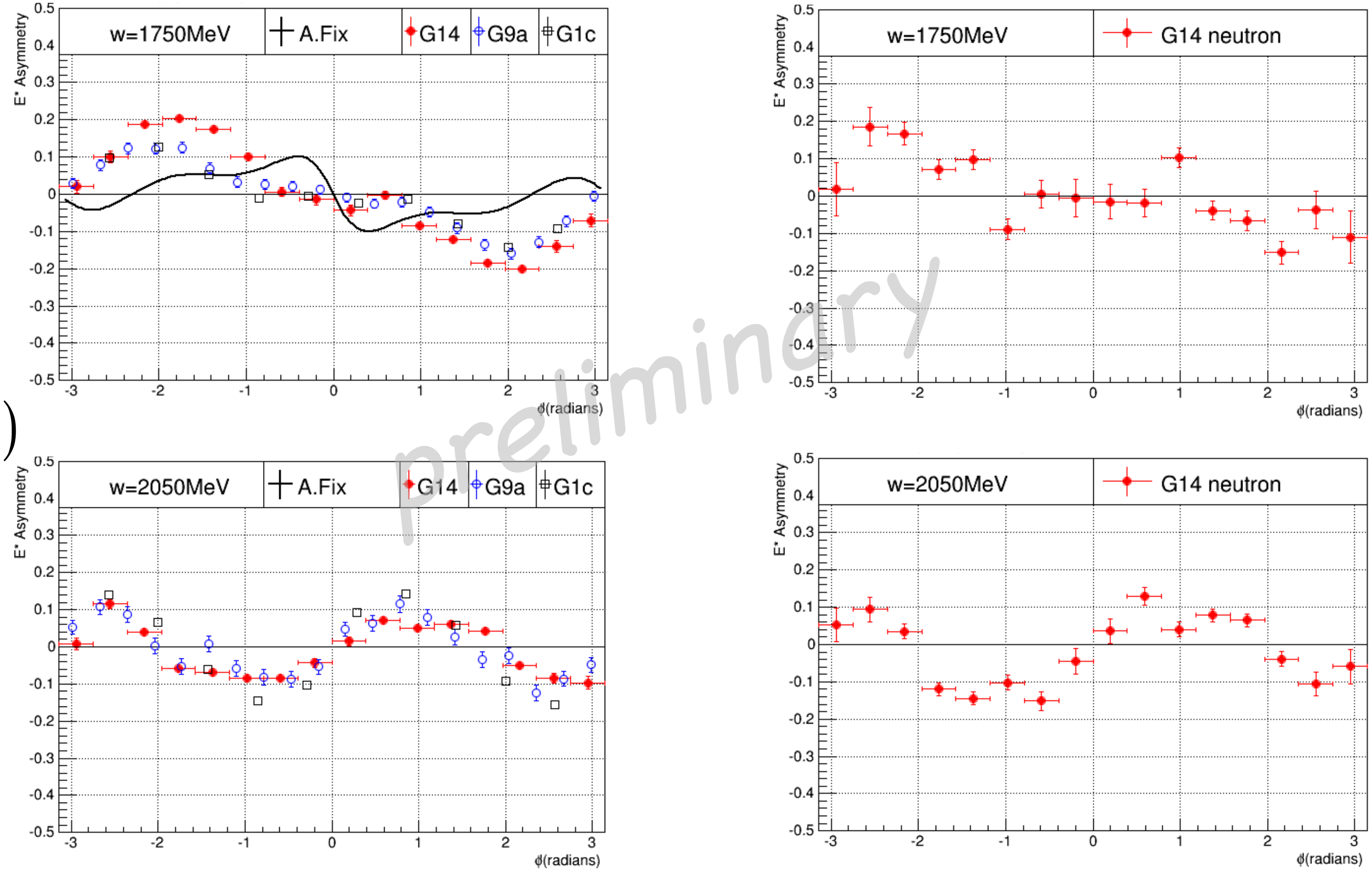
$\cos(\theta_{\pi\pi})$ $\cos(\theta_{\pi\pi})$

HDice

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

- *P. Peng (UVa)*

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

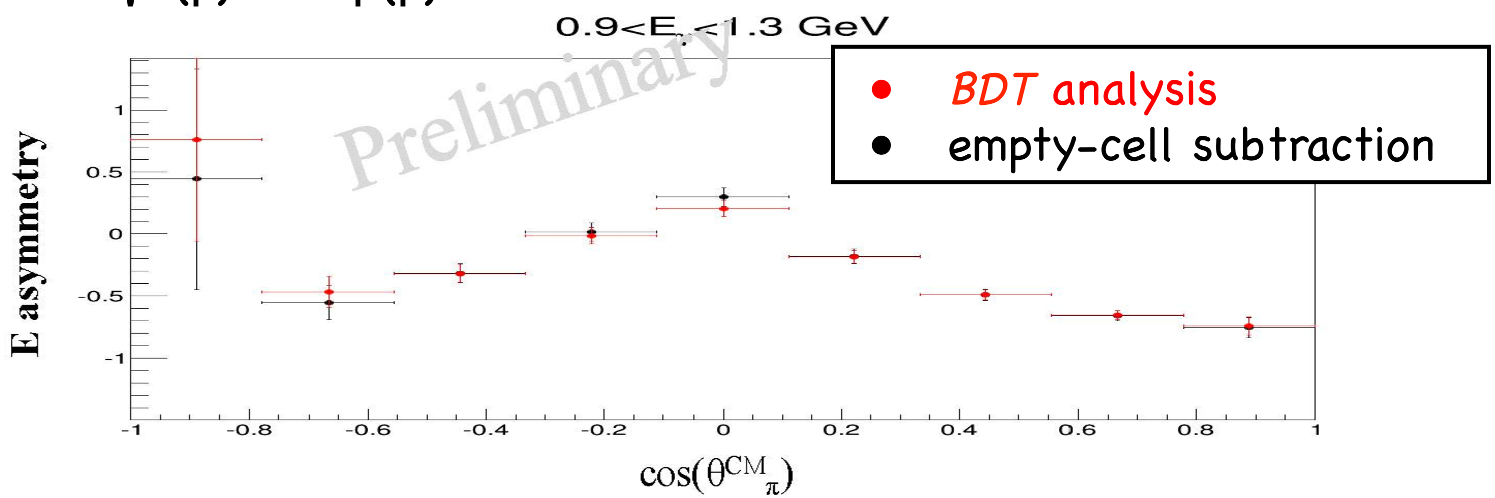


$I^{\odot}(\phi'_{\pi\pi})$

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

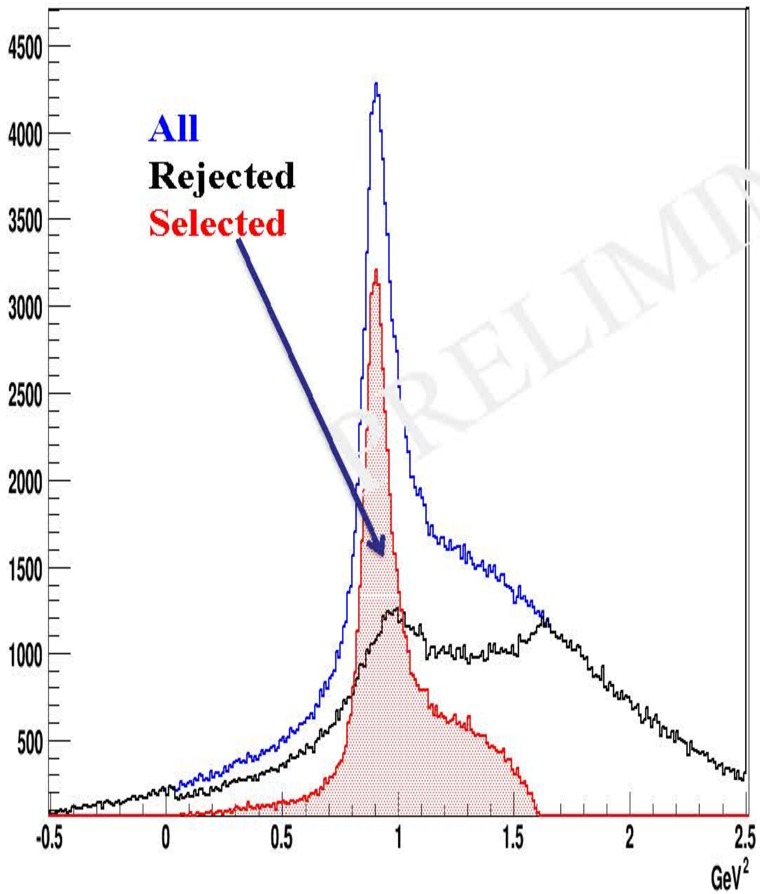
HDice $\gamma\ n(p) \to K^0 \Lambda \to \pi^+\pi^-\ \pi^- p\ (p)$ - D. Ho (Carnegie-Mellon U)

- 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 $\gamma n(p) \to \pi^- p(p)$:

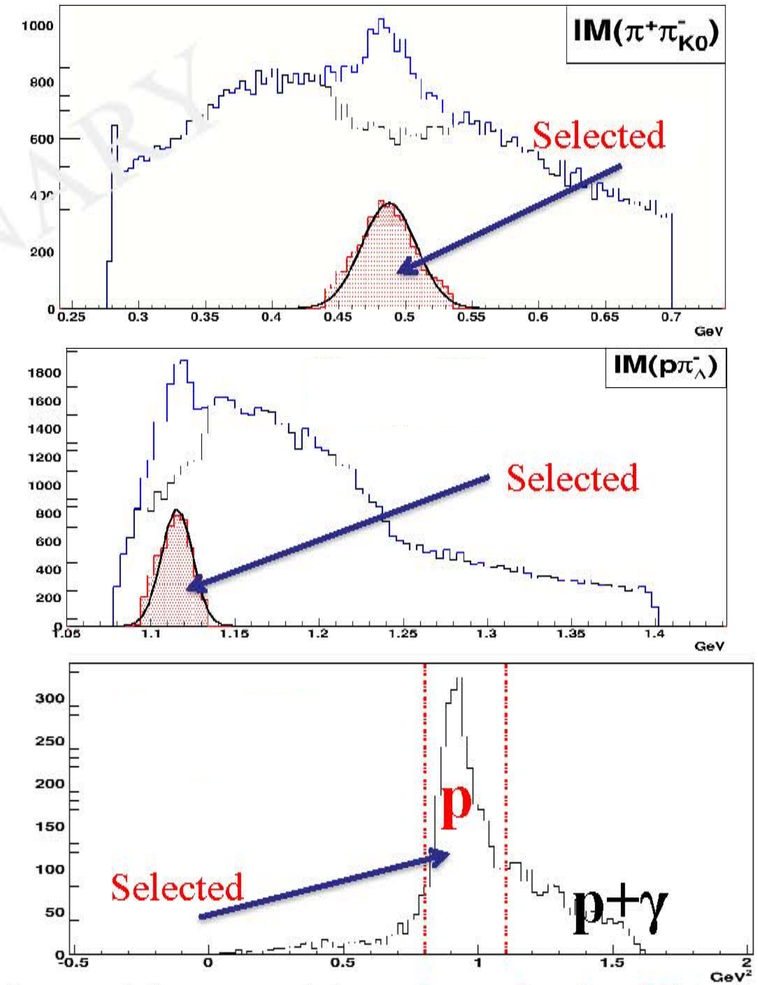


$\gamma\ n(p) \rightarrow K^0\,\Lambda(p) \rightarrow \pi^+\pi^-\ \pi^-p\ (p)$ - D. Ho (Carnegie-Mellon U)

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

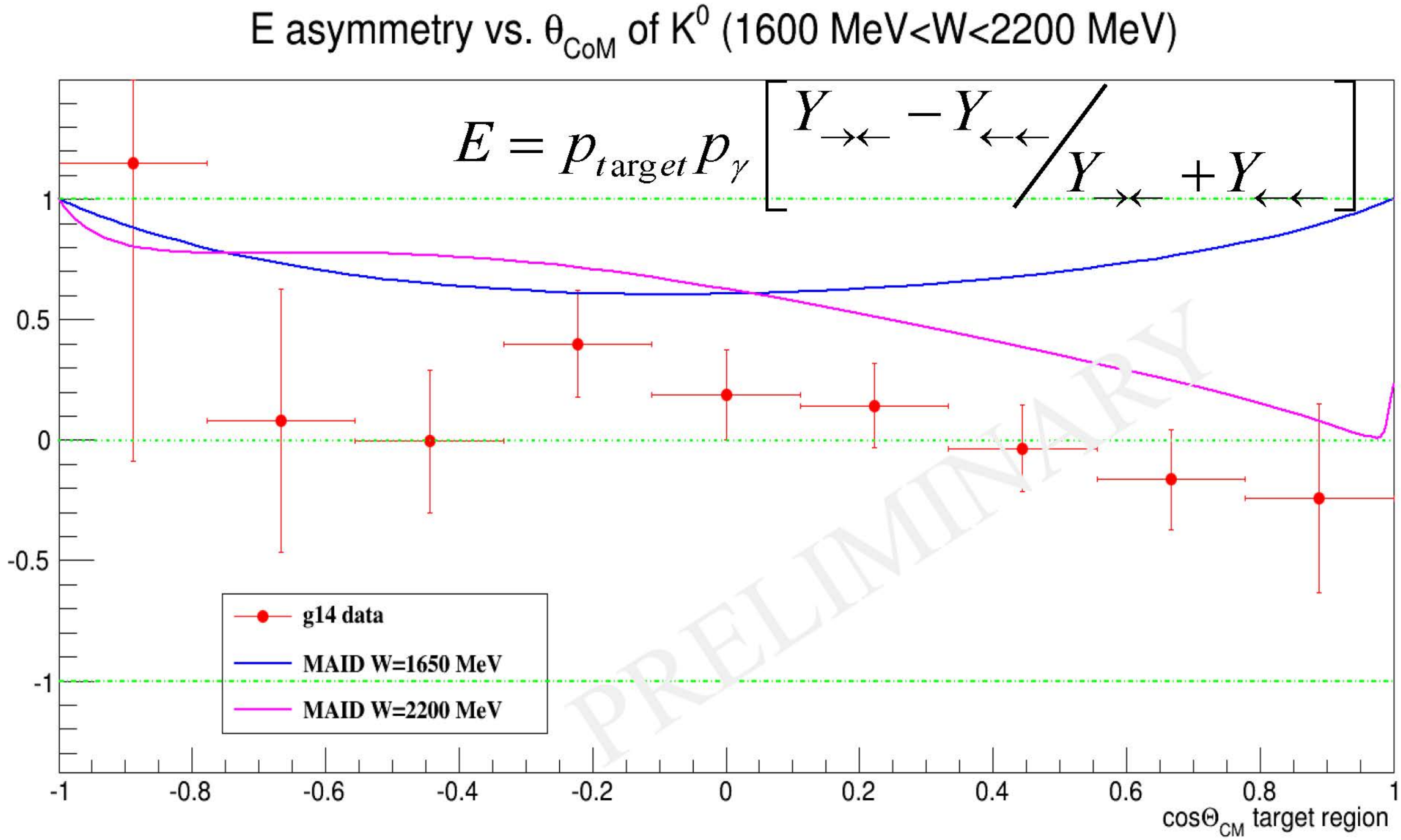


Squared Spectator Mass



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)

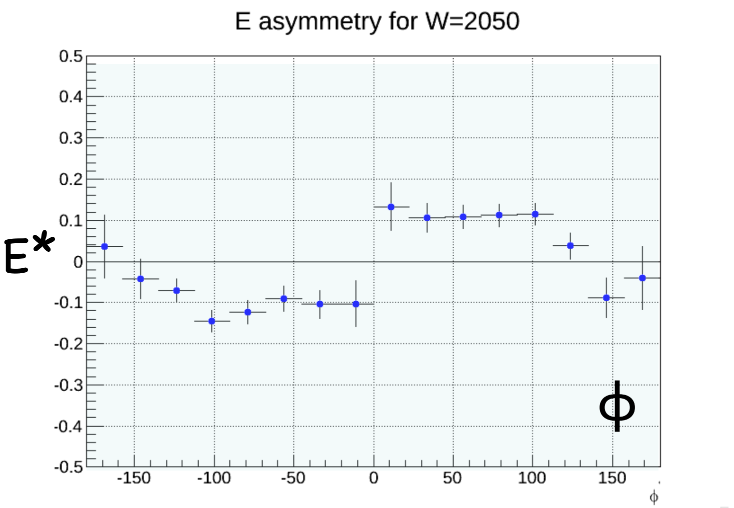


After selecting $K^0\Lambda$ (rejecting possible $K^0\Sigma^0$) events

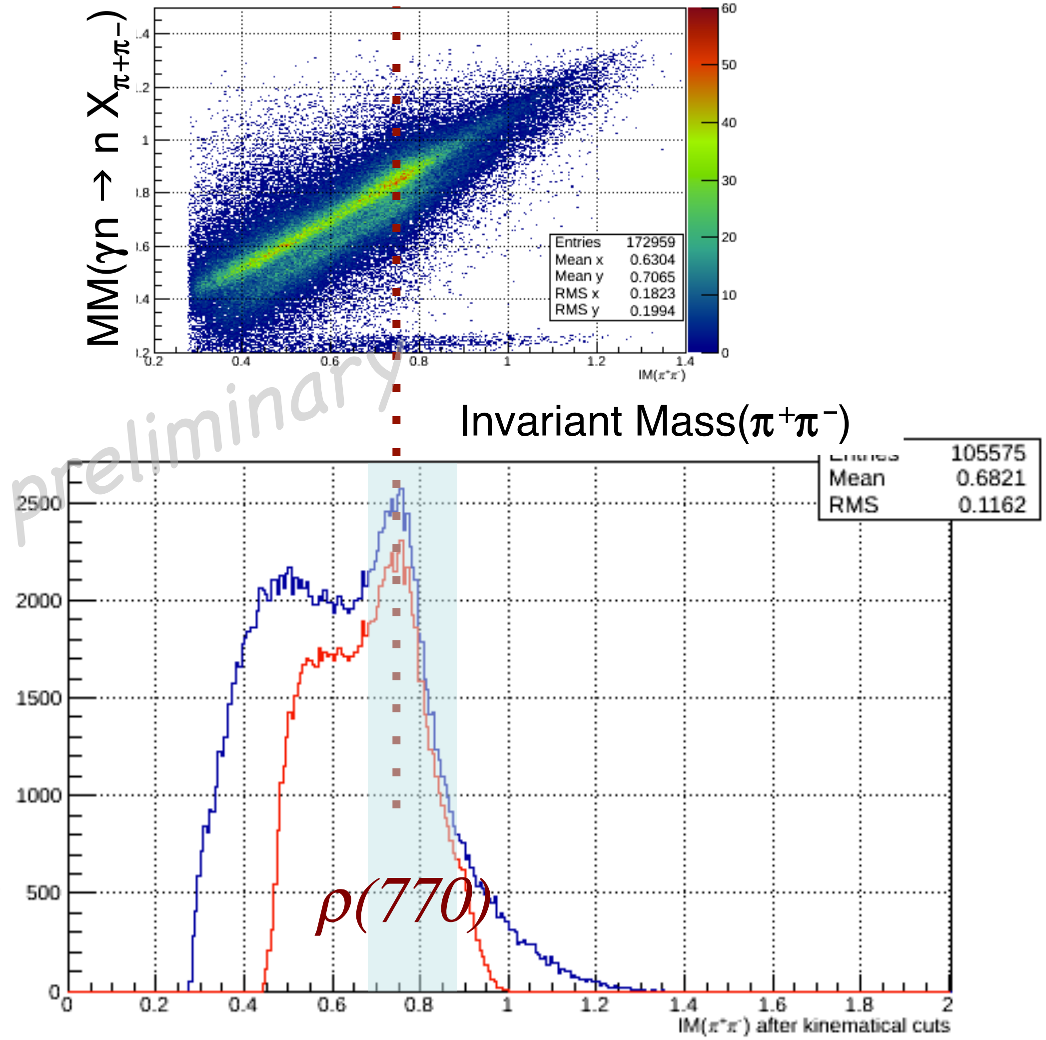
$\vec{\gamma}\,\vec{n}(p) \rightarrow \rho^0 n(p) \Rightarrow \pi^+\pi^- n(p)$ - *I. Zonta (U Roma-II)*

- ρ^0 photo-production from polarized neutrons in D; $\rho^0 \Rightarrow \pi^+\pi^-$, ~100% branch

- test of ρ^0 separation: $E^*(\phi) = 0$ for 2-body decay



- 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