Summary of 3 independent analyses of $\gamma n \rightarrow \pi^- p$ from g14 (HDice) data

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Motivation

- Study of $\gamma n \rightarrow \pi^- p$ is part of HDice program for observables: E (circ.p. beam on long.p. target), G (lin.p. beam on long.p. target)

- No published data for E svmmetrv on $\gamma n \rightarrow \pi^- p$

$$E = \frac{1}{P_\gamma P_t} \frac{N_{1/2} - N_{3/2}}{N_{1/2} + N_{3/2}}$$

- High-statistics reaction: was used (together with $\pi\pi N$) to check detector response, peculiarities of target and beam polarization, etc.

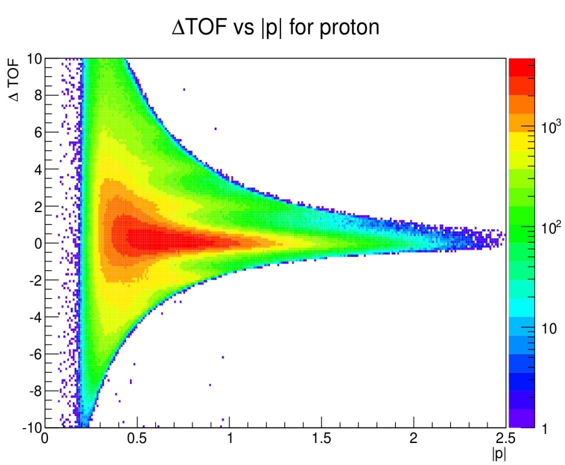
g14 run conditions

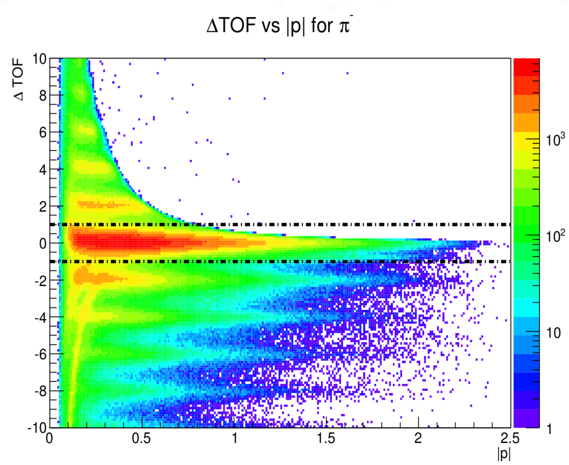
- Data taking Dec. 2011 – May 2012
(11.0 bill. events with circ. pol. beam; 3.8 bill. events with lin. pol. beam)
- Torus field +1920 A (2 bill. events); -1500 A (remaining 12.8 bill. events)
- Deuteron polarization rotated (12/16/11 and 5/9/12)
- Special beam helicity setting for Qweak (delayed reporting at 960 Hz flips)

Period	Beam Energy	Beam Pol.[1]	Date range	Events (Mill.)	Torus Current	Target Cell	Target Polarization[2] Deuteron (%)	Proton (%)
silver1	2280.96	81.7%	12/1–12/6	830	+1920 A	21a	+25.6± 0.7	+14.7± 0.2
silver2	2280.96	81.7%	12/6–12/11	1170	+1920 A	21a	+23.0± 0.6	-14.3± 1.2
silver3	2280.96	76.2%	12/12–12/16	250	-1500 A	21a	+20.9± 0.5	-0.3
silver4	2280.96	76.2%	12/16–1/4	820	-1500 A	21a	-17.2± 0.5 (?)	-0.3
silver5a	2257.75	76.2%	1/4–2/5	1750.8	-1500 A	21a	-15.5± 0.7 (?)	-0.8
silver5b	2257.75	88.8%	1/4–2/5	3081.7	-1500 A	21a	-15.5± 0.7 (?)	-0.8
gold2a	2541.31	88.2%	4/10–4/12	469.7	-1500 A	19b	+26.8± 0.9	+26.9± 0.4
gold2b	2541.31	83.7%	4/12–4/18	1625.6	-1500 A	19b	+26.8± 0.9	+26.9± 0.4

Event Selection

- Select events with one pos. & one neg. charged particle
- Energy loss, momentum corrections (using kinematic fit for $\gamma p \rightarrow \pi\pi p$)
- Fiducial cut
- Δt cut ($t_{meas} - t_{calc}$)$\leq$ 1ns or $\Delta\beta$ cut ($\beta_{meas} - \beta_{calc}$)$\leq$ 0.06 (p) or $\leq$0.03 (π)





Event Selection (II)

- Vertex cut $-10.5 \leq v_z \leq -5.0$ cm

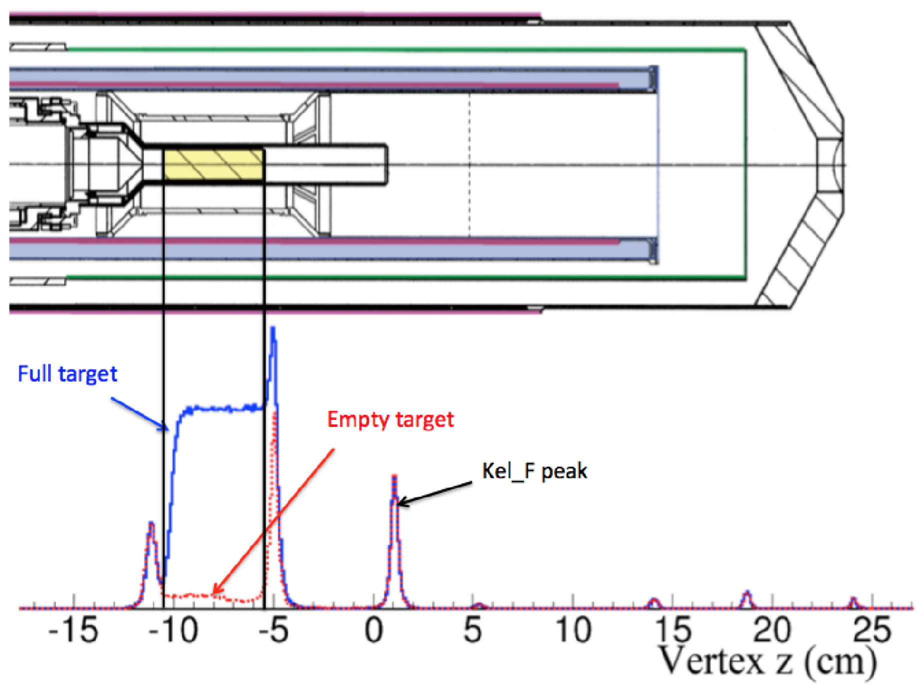
  (Notes: Kel_F peak will be used for relative normalization; empty target data 'subtracted')

- Missing mass, missing momentum, coplanarity cuts depending on analysis method:

(1) Sequence of 1-D cuts and background subtraction

(2) Kinematic fit of $\gamma(n) \rightarrow \pi^- p$

(3) BDT method



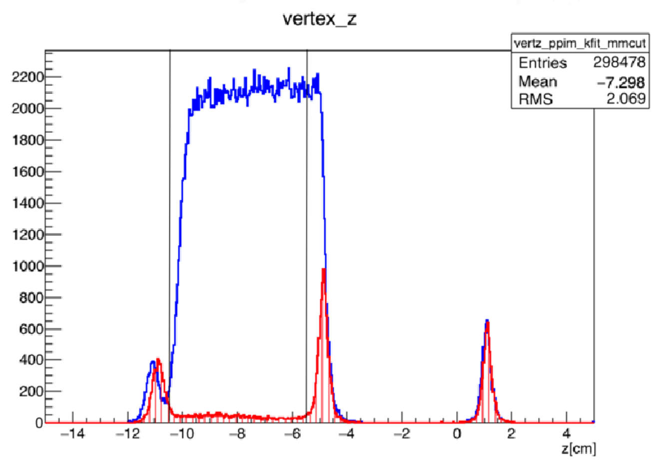
Coplanarity angle: $\Phi = \cos^{-1}\left((\hat{p}_p \times \hat{p}_\gamma) \cdot (\hat{p}_{\pi^-} \times \hat{p}_\gamma)\right)$

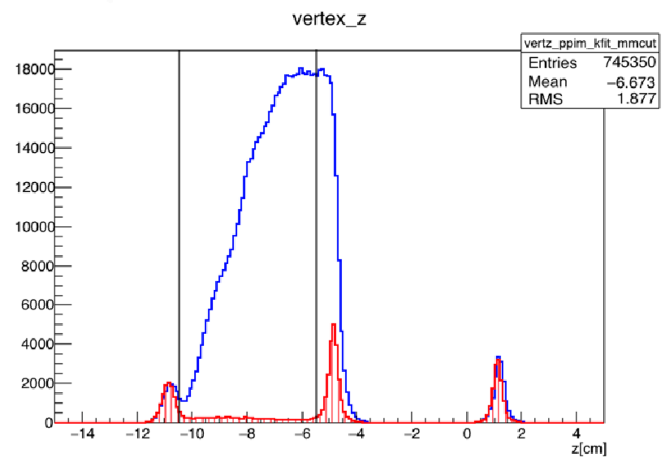
(1) Background subtraction

- Collinearity cut: $\Delta \phi = |\phi_p - \phi_\pi| \leq 20^o$
- Miss.Mass of spectator proton: $0.0 < MM(\gamma d \rightarrow \pi^- p\ X) < 1.1\ GeV^2$
- Miss.Momentum: $|P(\gamma n(p_s) \rightarrow \pi^- p\ (p_s))| \leq 0.1$ GeV
- Subtraction of scaled 'empty target' data (scaled to match foil at 1.1 cm) and correct for different amount of aluminum cooling wires
- Background in target region ($-5.0 < v_z < -10.5$ cm):

gold2:
2.4% bckgrd

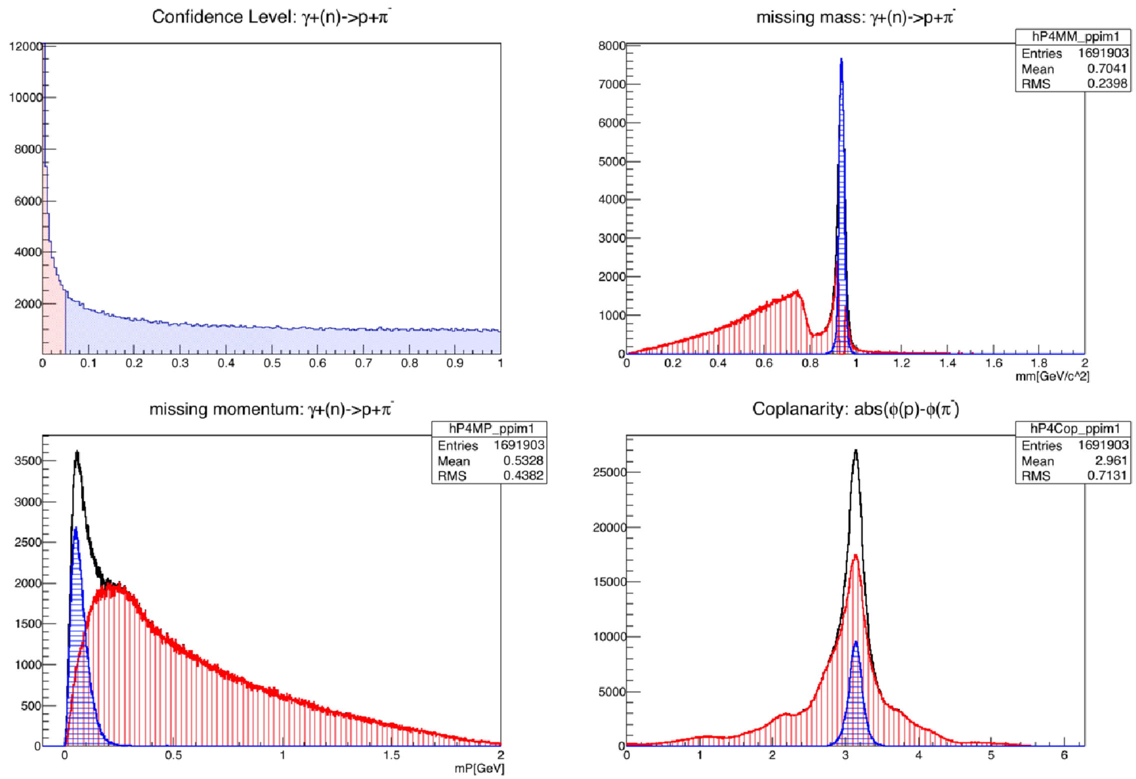
silver1:
3.6% bckgrd





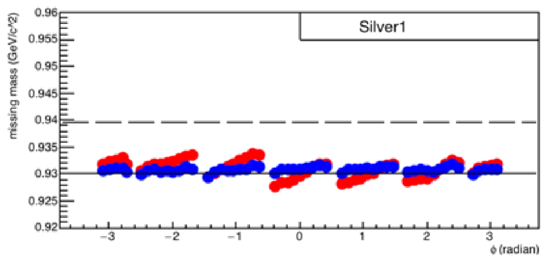
(2) Kinematic fitting

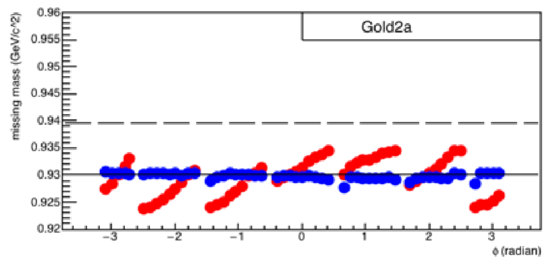
- 1-C fit of γ (n)→π^- p (neutron momentum unknown)

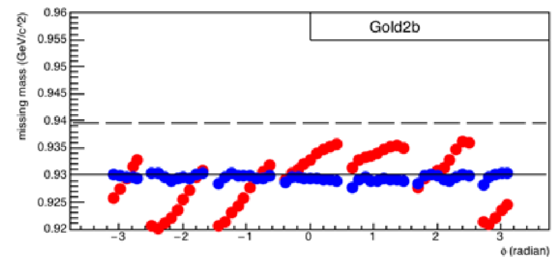


(2) Kinematic fitting (cont.)

- Effect of momentum corrections on Miss.Mass(γ (n)$\rightarrow\pi^-$ p) :



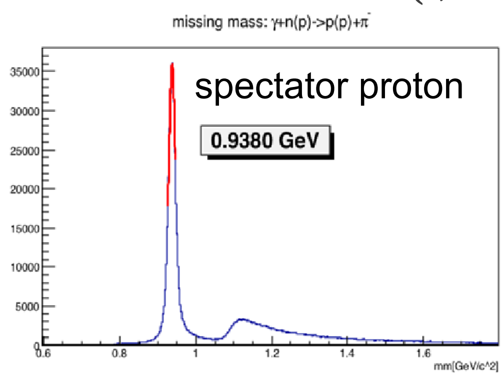


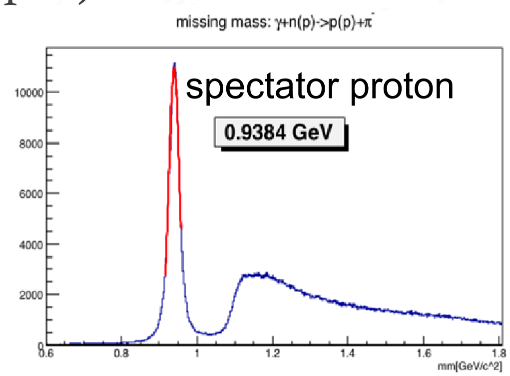


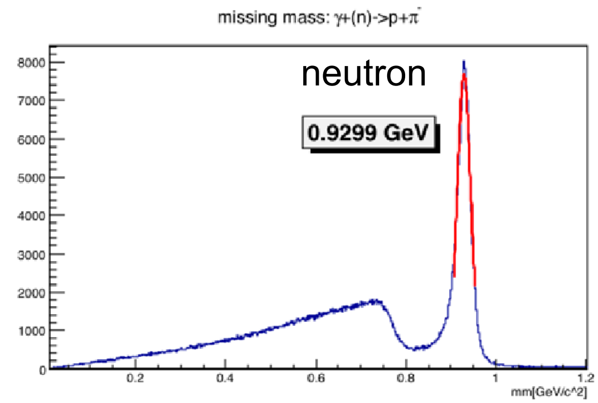
- Effective mass of quasi-free neutron: m*=930.3±0.3 MeV

- assuming spectator proton on mass shell:

Miss.Mass(γ d$\rightarrow\pi^-$p X)

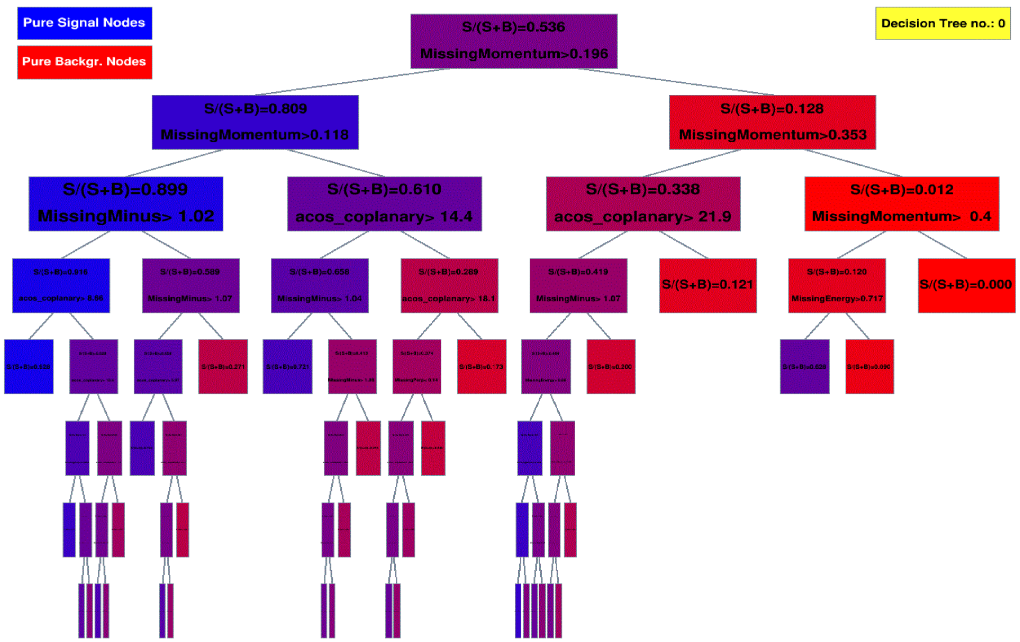






(3) Analysis using BDT

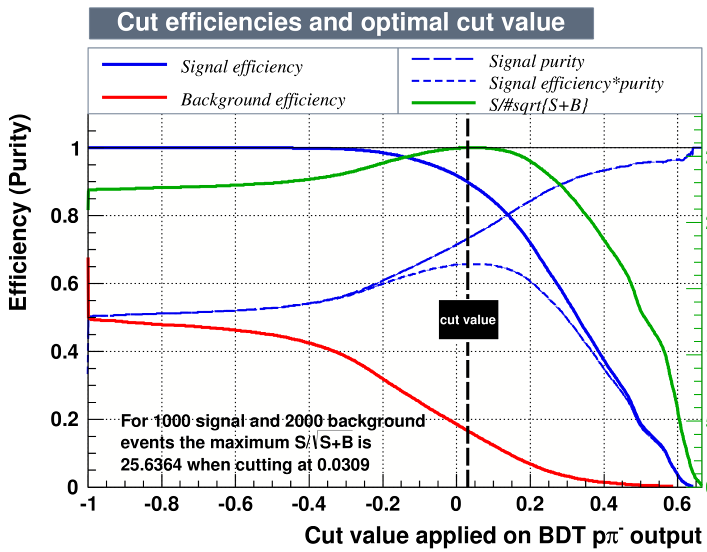
- Multivariate classification method using training data (signal data from quasi-free $\pi^- p$ MC; background data from empty target runs)

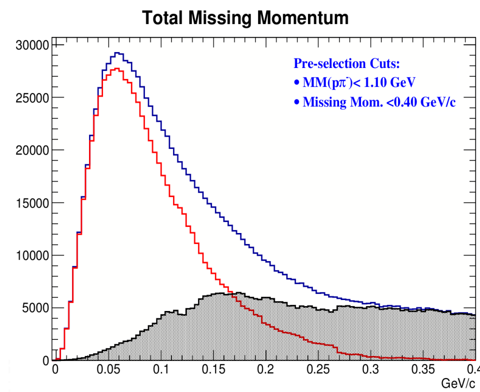


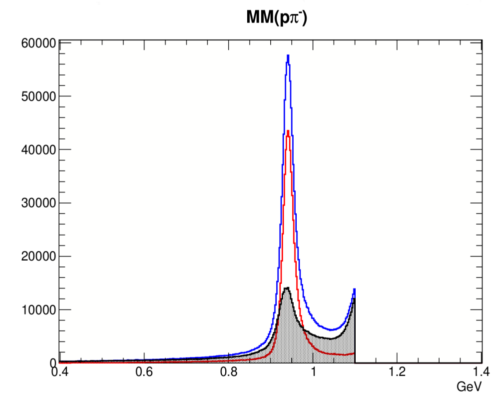
Variable Name	Description
$CoplanarityAngle$	$(\hat{p}_p \times \hat{p}_\gamma) \, . \, (\hat{p}_{\pi^-} \times \hat{p}_\gamma)$
$MissingMomentum$	Total missing momentum
$MissingEnergy$	Total missing energy
$MissingTheta$	Θ of missing momentum
$MissingPhi$	Φ of missing momentum
$MissingBeta$	β
$MissingGamma$	γ
$MissingPlus$	$E^{missing} - c\lvert p_z^{missing}\rvert$
$MissingMinus$	$E^{missing} + c\lvert p_z^{missing}\rvert$
$MissingPerp$	$\lvert p_{transverse}^{missing}\rvert$

(3) Analysis using BDT (cont.)

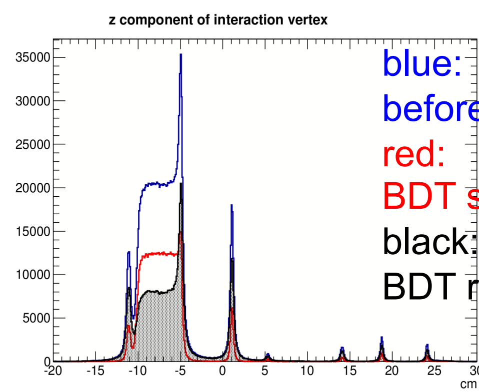
- Find optimal cut value (initial S/B ratio is 1:2 for miss.mom.<400 MeV)





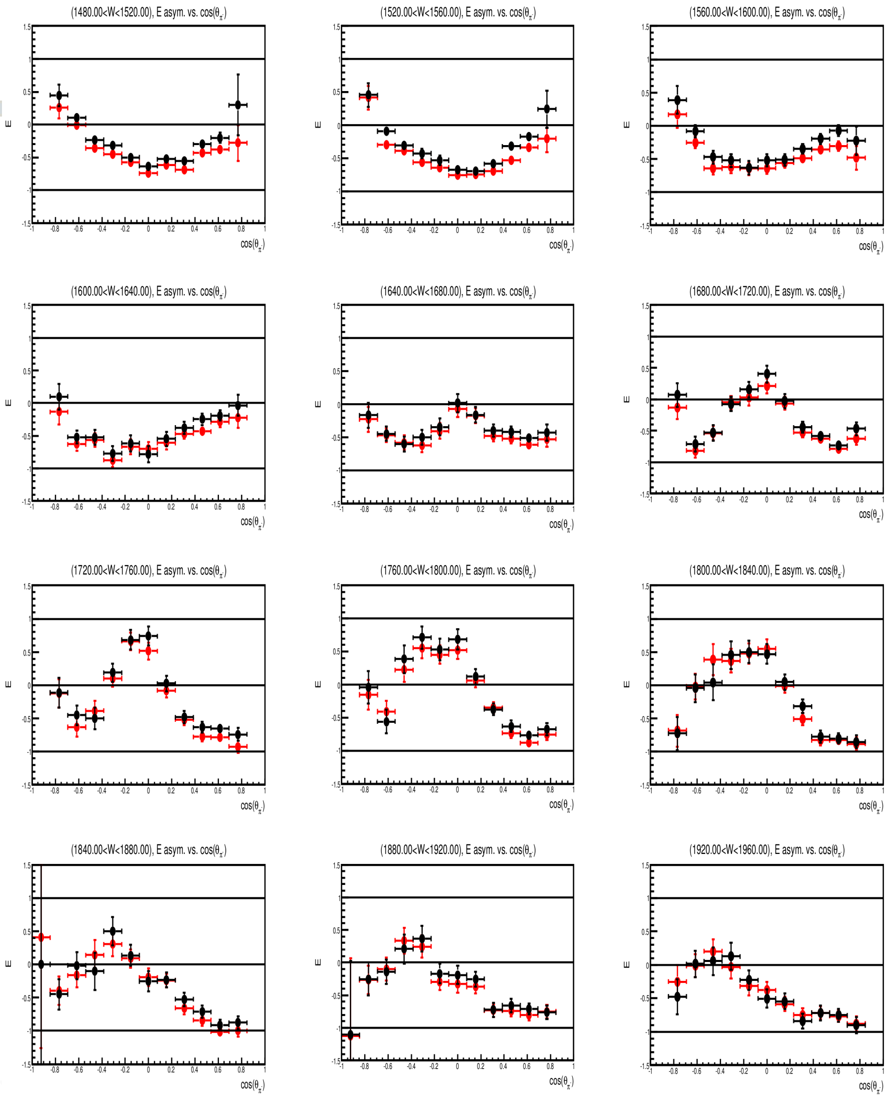


Variable Name	Relative Ranking
$MissingMomentum$	1.00
$coplanarityAngle$	0.37
$MissingMinus$	0.25
$MissingEnergy$	0.23
$MissingPerp$	0.07
$MissingTheta$	0.06
$MissingPlus$	0.05
$MissingGamma$	0.05
$MissingBeta$	0.04
$MissingPhi$	0.02

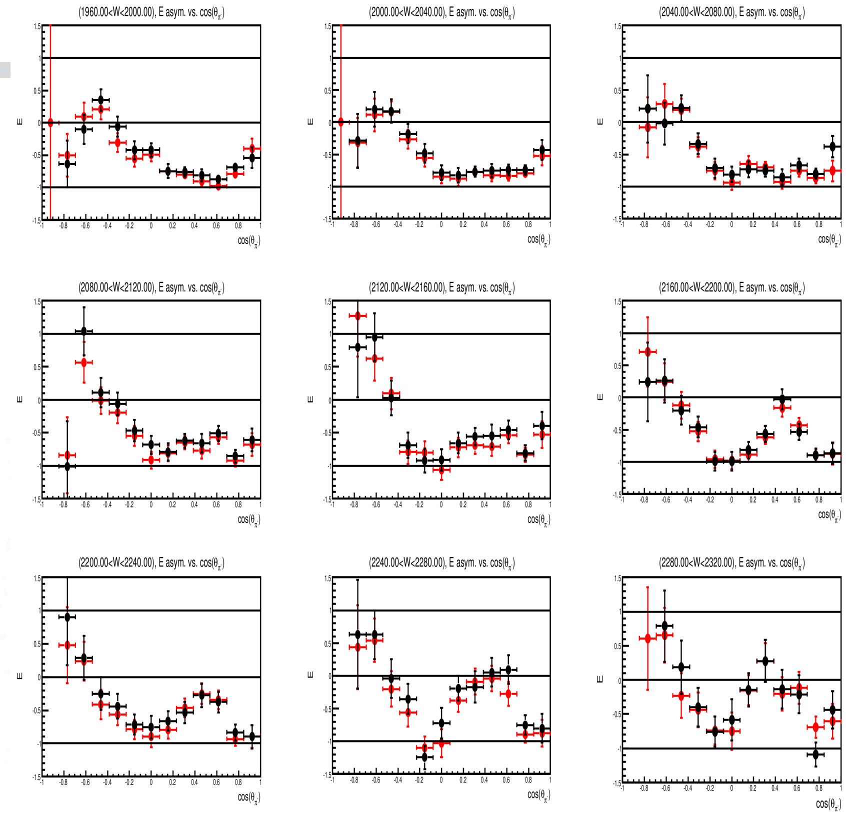


blue:
before BDT cut
red:
BDT selected events
black:
BDT rejected events

E asymm. using B.S. and BDT



Silver1&2 data



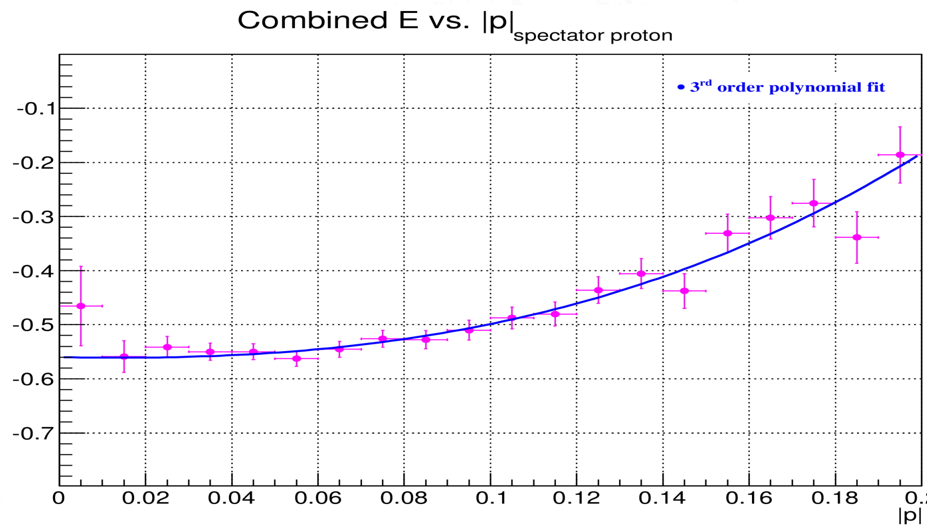
gold2 data

- both methods give consistent results,
- BDT method with higher statistics

Dependence of *E* on missing momentum

large miss.mom.: final-state interactions, deuteron D-state contributions

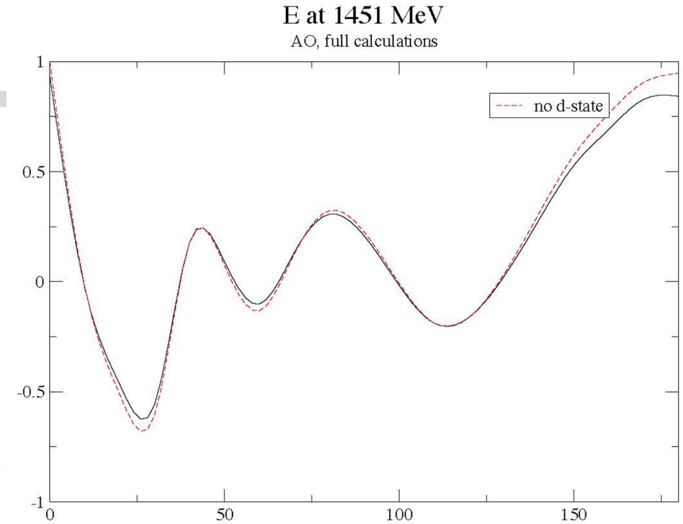
- consider average E as fcnt. of P_{miss}:
- BDT correction: 8.6%
- Backgrnd subtr.: 3.6%

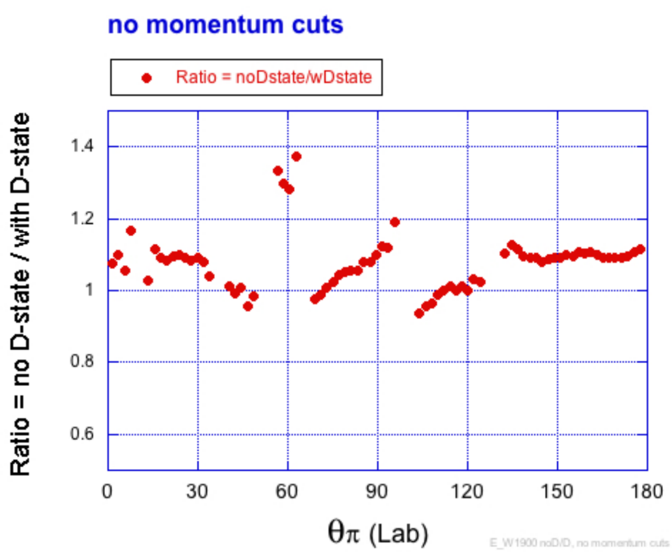


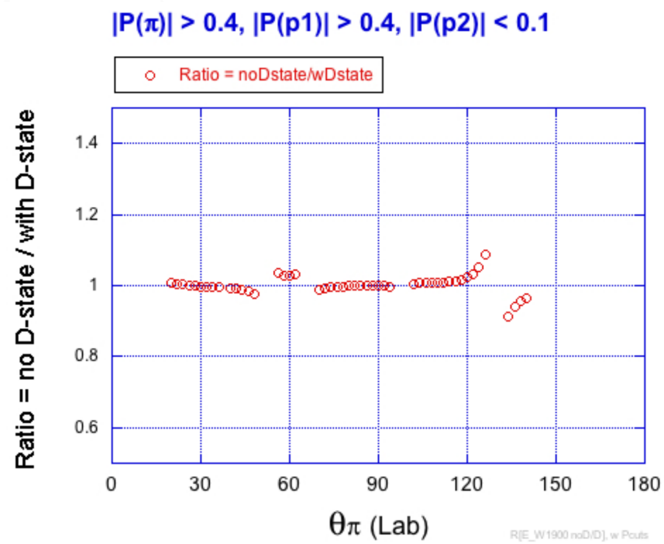
D-state contribution

- deuteron D-state only at large P_{miss}

- applied cuts practically remove all contributions from deuteron D-state







Averaging of correlated data

- 3 independent analyses of the same data up to some differences in the number of selected events
- Best estimator for mean: $\bar{x} = \frac{\sum_j w_j y_j}{\sum_j w_j}$ with $w_j = \frac{1}{\sigma_j^2}$ and $\sigma^2(\bar{x}) = \left(\sum_{i,j} w_{ij}\right)^{-1}$
- Expected test statistic (for n d.o.f.): $\langle\chi^2\rangle = \sum_{j=1}^{n} \left(\frac{y_j - \bar{x}}{\sigma_j}\right)^2 = n - 1$
- if $\langle\chi^2\rangle \gg n-1$ then probably errors underestimated => rescale $\sigma'_j = \sigma_j \sqrt{\frac{\langle\chi^2\rangle}{n-1}}$
- if $\langle\chi^2\rangle \ll n-1$ then either errors overestimated or data are positively correlated
- For correlated data define a correlation parameter f to construct a covariance matrix

$$\mathbf{C}_{eff} = \begin{pmatrix} c_{11} & c_{12} & \cdots \\ c_{21} & c_{22} & \cdots \\ \vdots & & \ddots \end{pmatrix} = \begin{pmatrix} \sigma_1^2 & f\sigma_1\sigma_2 & \cdots \\ f\sigma_1\sigma_2 & \sigma_2^2 & \cdots \\ \vdots & & \ddots \end{pmatrix}$$

and find an optimal f by solving

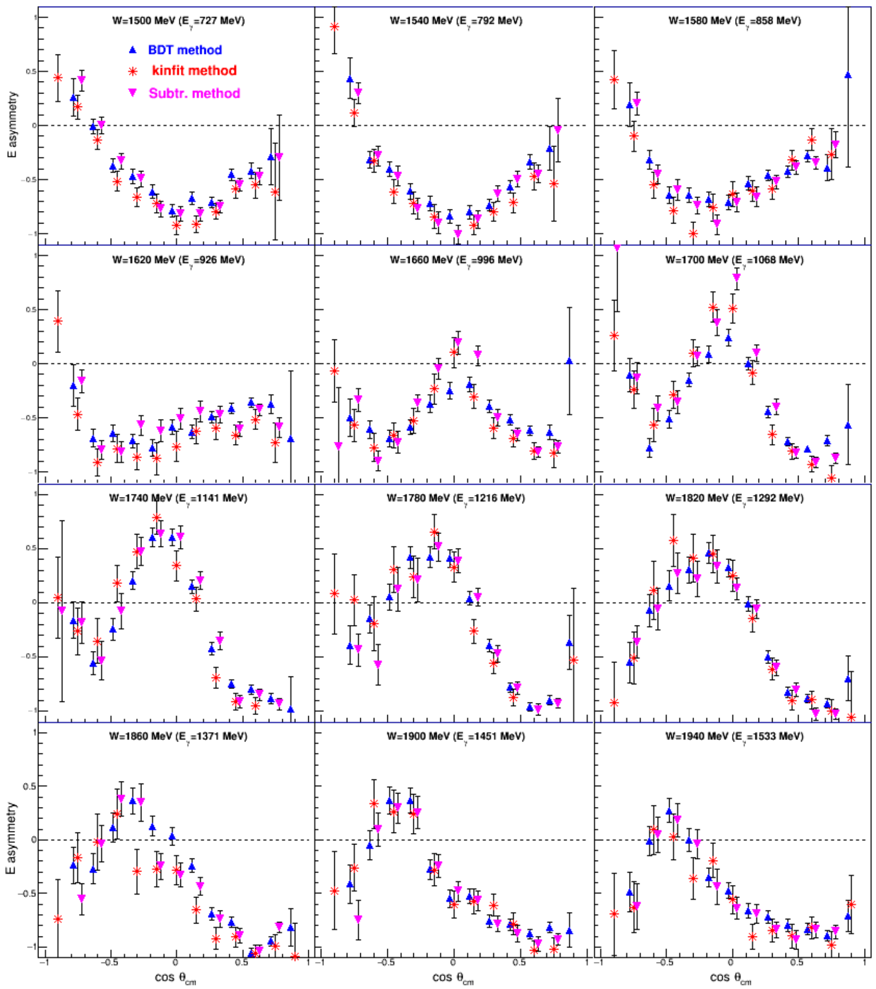
$$\chi^2(f) = \sum_{i,j} (y_i - \bar{x})(C^{-1})_{ij}(y_j - \bar{x}) = n - 1$$

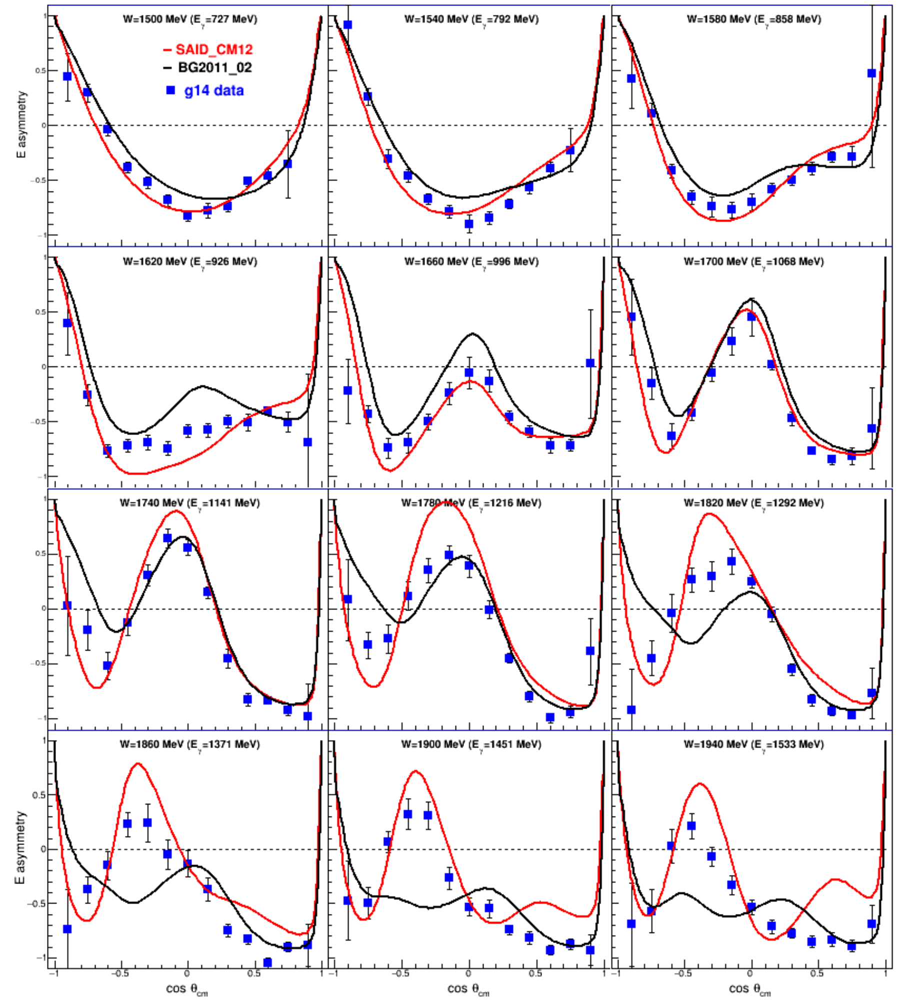
the corrected variance is then $\sigma^2(\bar{x}) = \sum_{i,j=1}^{n} \frac{c_{ij}}{\sigma_i \sigma_j}$

M. Schmelling 1994 (CERN-PPE 94-185)

E asymmetry for $\gamma n \to \pi^- p$

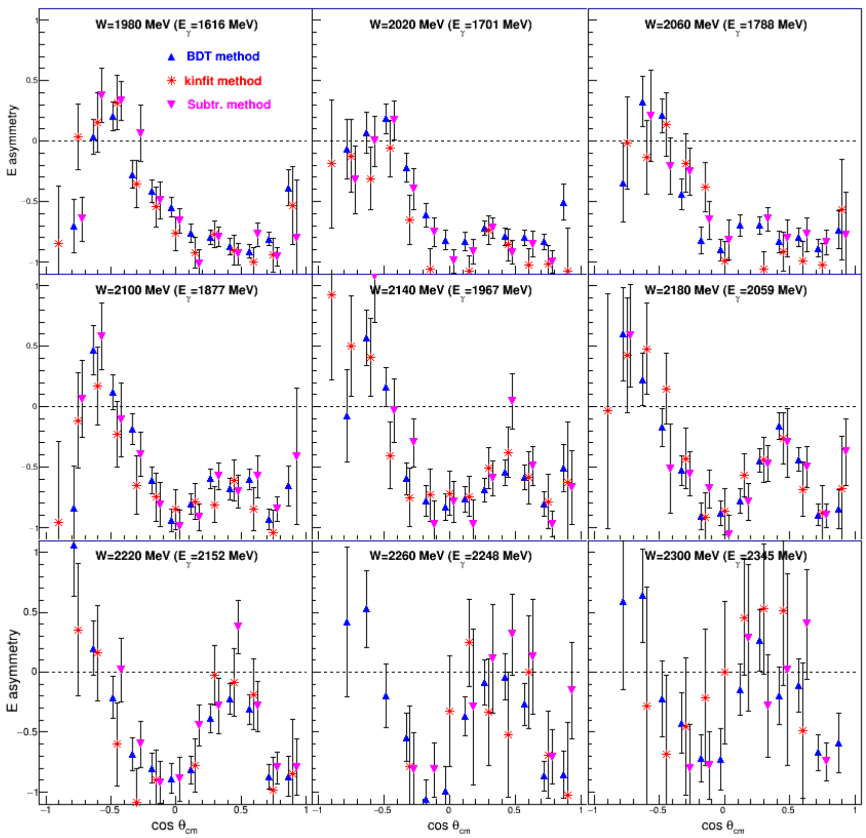
(W=1480-1960 MeV)

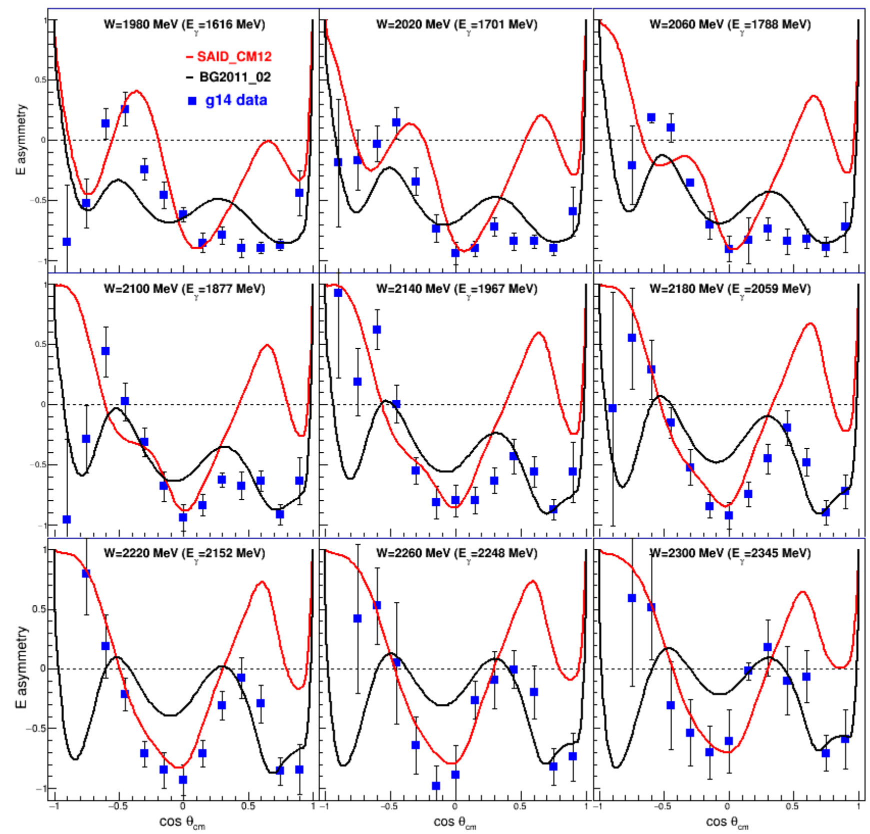




E asymmetry for $\gamma\, n \rightarrow \pi^- p$

(W=1960-2320 MeV)





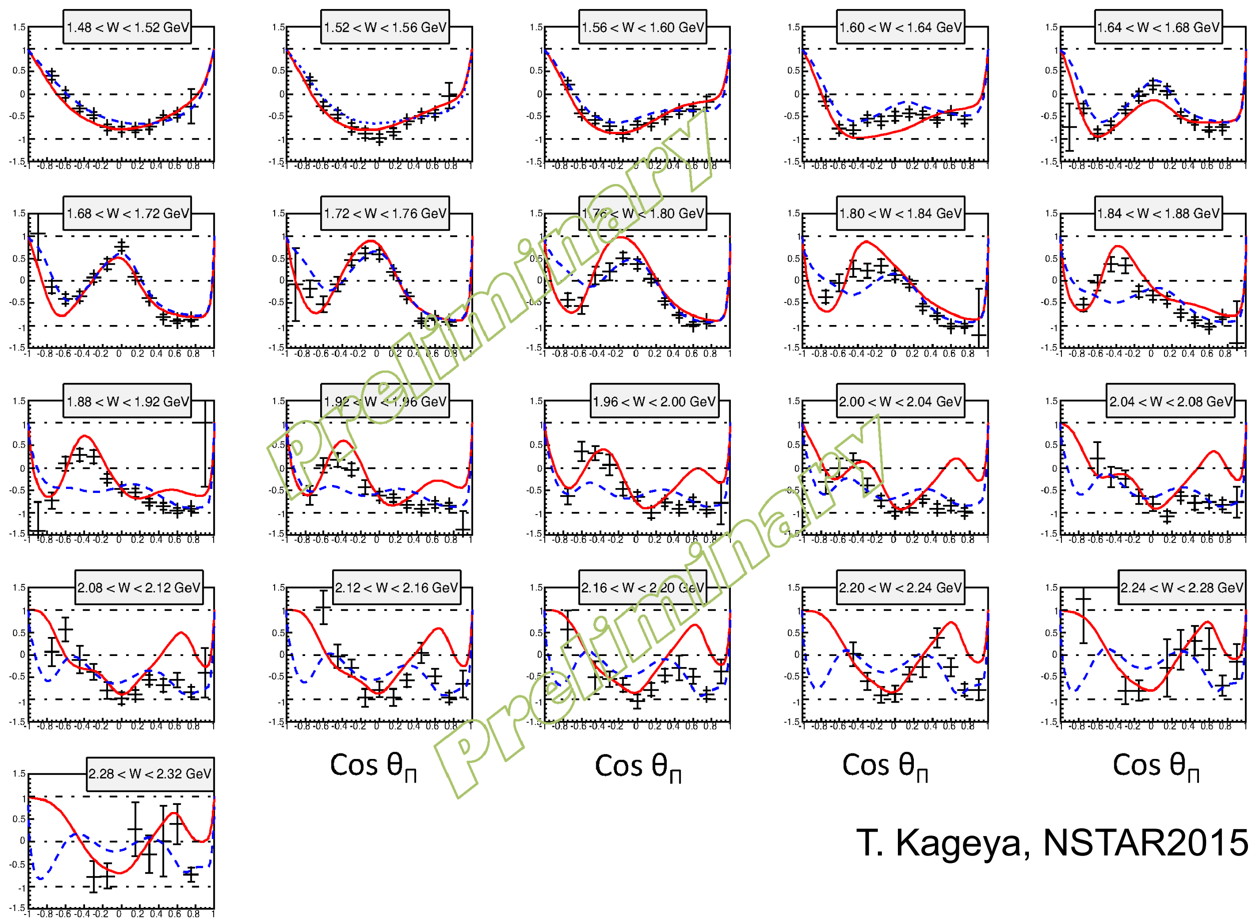
Note: large model discrepancies at higher W ➔ g14 data will have impact

Summary & Outlook

- First measurement of E for $\gamma\, n \rightarrow \pi^- p$ using 3 independent methods
- This reaction is being used for corrections & consistency checks
- Systematic studies largely completed (not shown here)
- **Analysis note almost ready for review**
- more to come from g14:
  G asym. for $\gamma\, n \rightarrow \pi^- p$, E asym. for $K^0 \Lambda$, observables for $\pi\pi N$

Thank you for your attention!

E asymmetry using 1-D cuts and background subtraction



T. Kageya, NSTAR2015

E asymmetry using kinematic fitting