

Precision Measurement of the Neutron Asymmetry A_1^n at Large Bjorken x at 12 GeV JLab

Mingyu Chen
University of Virginia
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Outline:

1. A_1^n at High x_{Bj} Region
2. Experimental Setup and Status
3. Polarized ^3He Target Performance
4. Asymmetry Results
5. Summary

- On Behalf of the E12-06-110 Collaboration



Longitudinal Virtual Photon Asymmetry A_1

- $Q^2 = 4\text{-momentum of virtual photon squared}$
- $v = \text{Energy transfer}$
- $\theta = \text{Scattering angle}$
- $x = \frac{Q^2}{2Mv} = \text{Fraction of nucleon momentum carried by the struck quark}$

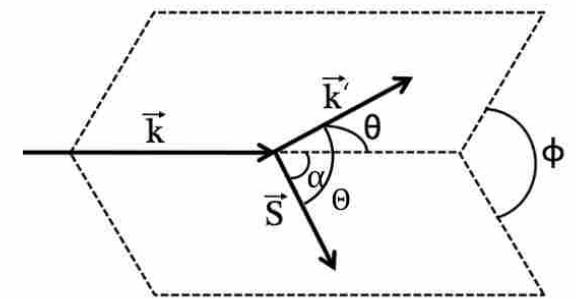
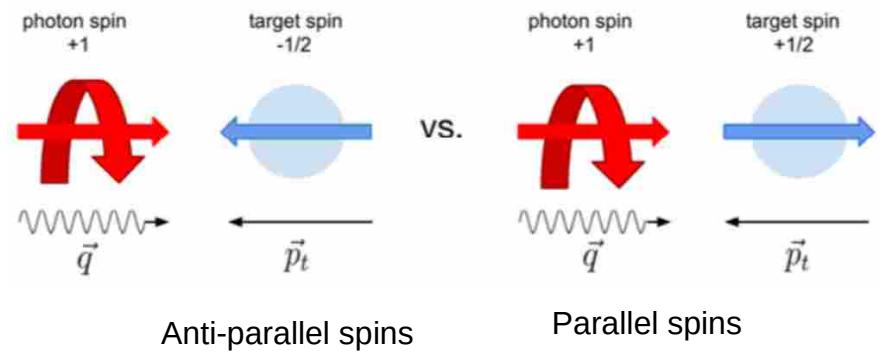
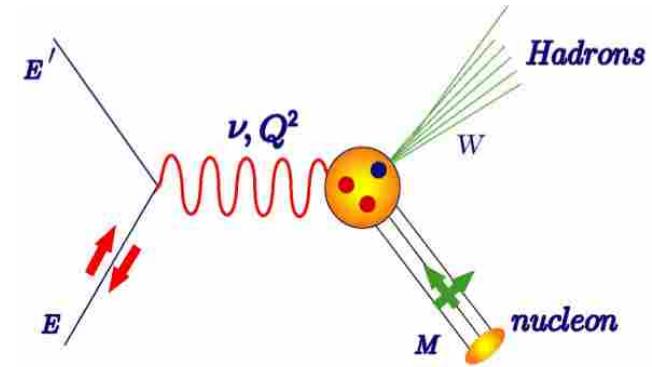
$$A_1 = \frac{g_1 - \frac{(2Mx)^2}{Q^2} g_2}{F_1} = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

$$A_1 = \frac{1}{(E+E')D'} [(E-E' \cos \theta) A_{||} - \frac{E' \sin \theta}{\cos \phi} A_{\perp}]$$

$$A_{||} = \frac{\sigma_{\downarrow\uparrow} - \sigma_{\uparrow\uparrow}}{\sigma_{\downarrow\uparrow} + \sigma_{\uparrow\uparrow}}$$

$$A_{\perp} = \frac{\sigma_{\downarrow\rightarrow} - \sigma_{\uparrow\rightarrow}}{\sigma_{\downarrow\rightarrow} + \sigma_{\uparrow\rightarrow}}$$

$$D' = \frac{(1-\epsilon)(2-y)}{y[1+\epsilon R]}$$



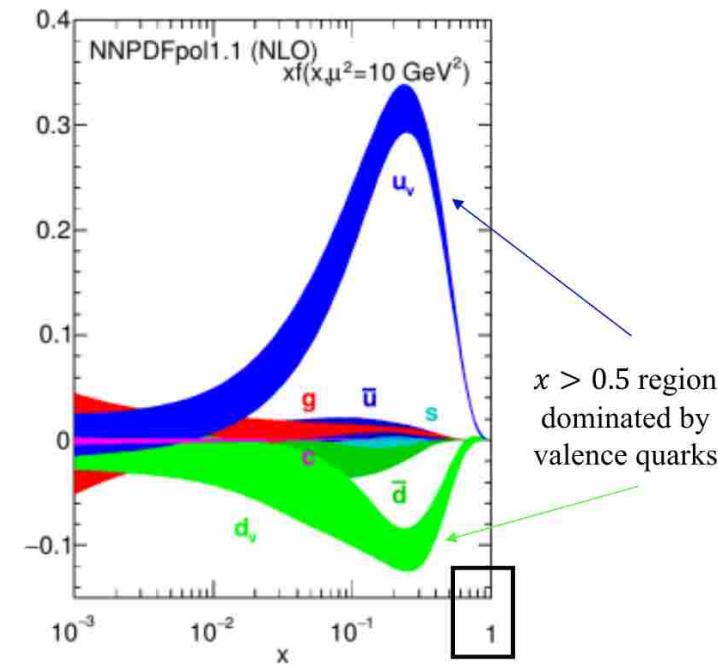
- Angular kinematics for polarized electron scattering

Goals for A_1^n Experiment

- Precisely measure the neutron spin asymmetry A_1^n in the far valence domain ($0.61 < x < 0.77$).
- Explore the Q^2 dependence of A_1^n with large x value.
- After combining with proton data (CLAS12), extract polarized to unpolarized parton distribution function (PDF) ratios $\Delta u/u$ ($\Delta d/d$) for large x region.
- Give more insights on understanding the spin structure of nucleon.

| | $\frac{F_2^n}{F_2^p}$ | $\frac{d}{u}$ | $\frac{\Delta d}{\Delta u}$ | $\frac{\Delta u}{u}$ | $\frac{\Delta d}{d}$ | A_1^n | A_1^p |
|--------------|-----------------------|---------------|-----------------------------|----------------------|----------------------|---------|---------------|
| DSE-1 | 0.49 | 0.28 | -0.11 | 0.65 | -0.26 | 0.17 | 0.59 |
| DSE-2 | 0.41 | 0.18 | -0.07 | 0.88 | -0.33 | 0.34 | 0.88 |
| $0^+_{[ud]}$ | $\frac{1}{4}$ | 0 | 0 | 1 | 0 | 1 | 1 |
| NJL | 0.43 | 0.20 | -0.06 | 0.80 | -0.25 | 0.35 | 0.77 |
| SU(6) | $\frac{2}{3}$ | $\frac{1}{2}$ | $-\frac{1}{4}$ | $\frac{2}{3}$ | $-\frac{1}{3}$ | 0 | $\frac{5}{9}$ |
| CQM | $\frac{1}{4}$ | 0 | 0 | 1 | $-\frac{1}{3}$ | 1 | 1 |
| pQCD | $\frac{3}{7}$ | $\frac{1}{5}$ | $\frac{1}{5}$ | 1 | 1 | 1 | 1 |

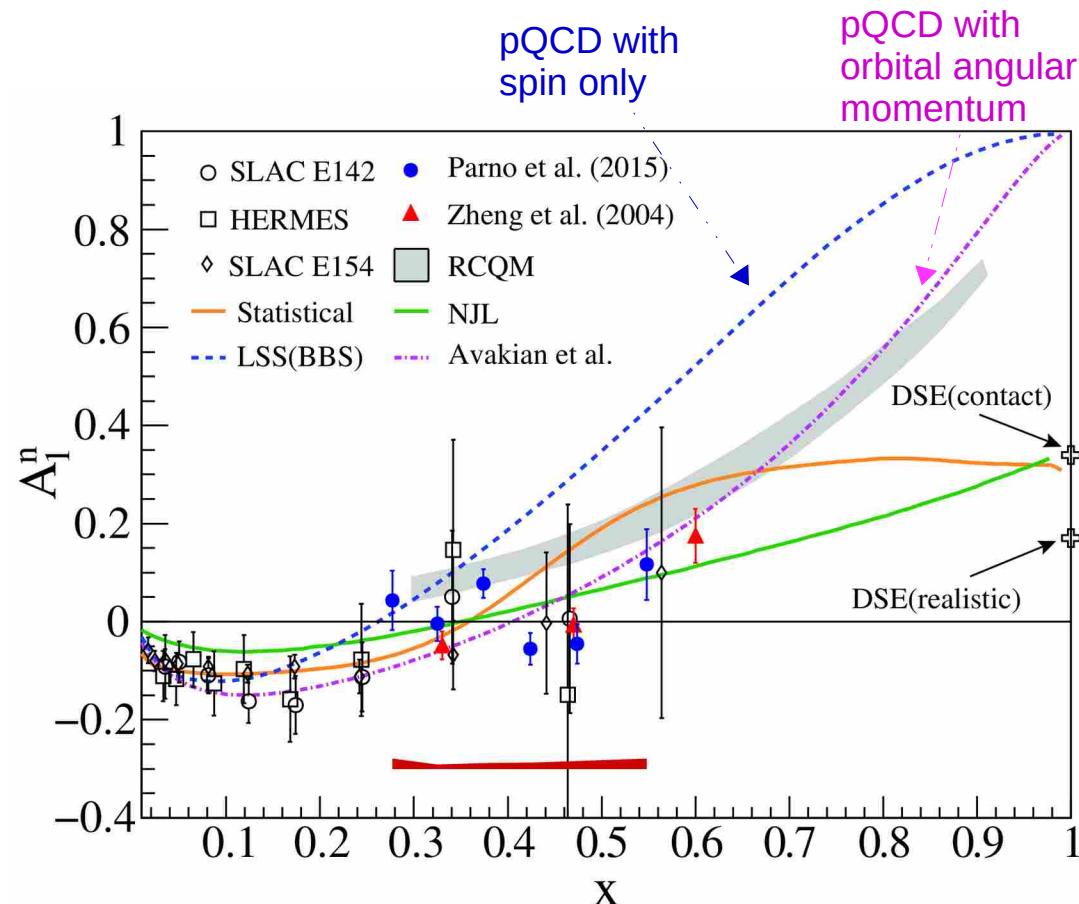
Table 1: Predictions for the $x = 1$ value of various models. From Craig D. Roberts et al 10.1016/j.physletb.2013.09.038



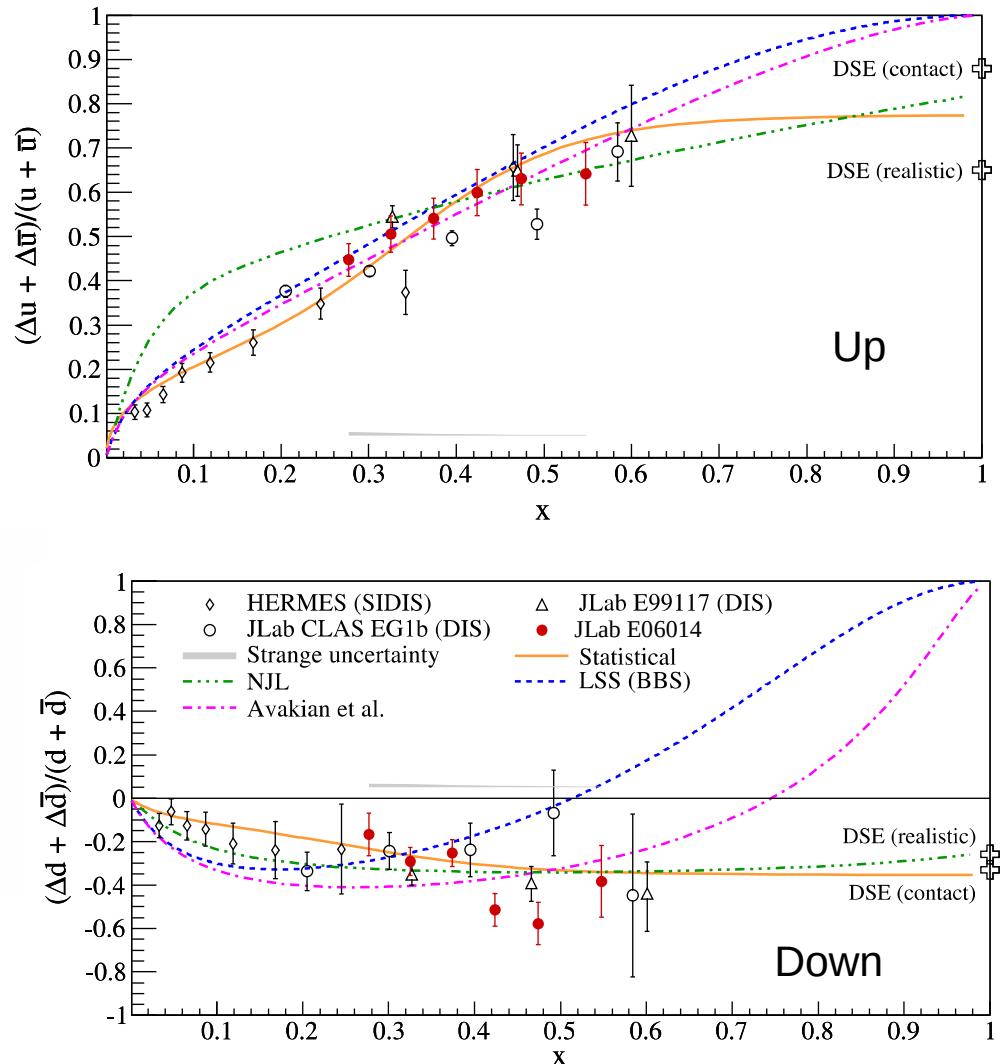
Polarized and sea quark PDFs for $Q^2 = 10 \text{ GeV}^2$ from the NNPDFpol1.1 parameterization

See Nocera ER, et al. Nucl. Phys. B887:276 (2014).

Previous Results for A_1^n and PDF



Parno et al., *Phy Let B* DOI: 10.1016/j.physletb.2015.03.067
 X. Zheng et al., *PRL* 92, 012004 (2004); *PRC* 70, 065207 (2004)



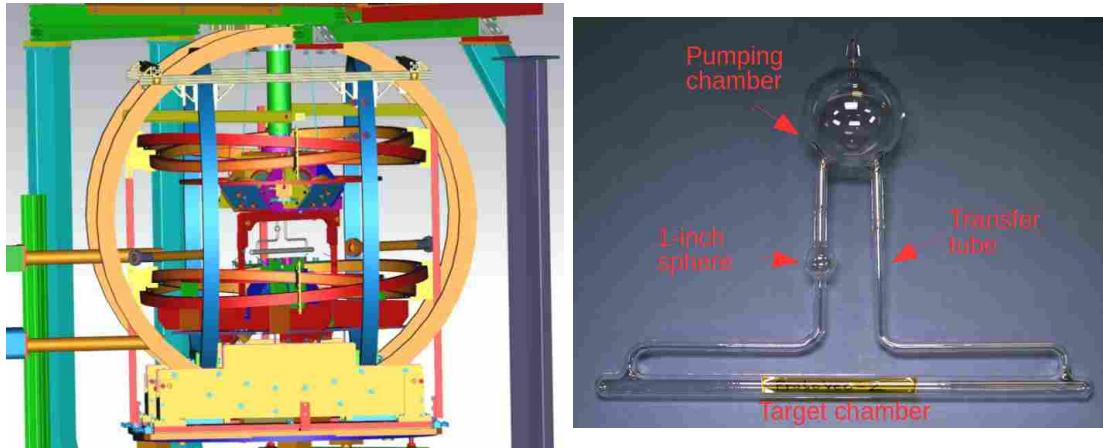
Experimental Setup

Electron Beam:

- $E_{beam}=2.17 \text{ GeV}$ (1-pass commission)
- $E_{beam}=10.38 \text{ GeV}$ (5-pass DIS production)
- Beam polarization: 85% ($<3\%$ uncertainty by Moller Polarimeter)
- Circular beam raster with 2.0-2.5mm radius
- $< 50 \text{ ppm}$ charge asymmetry (average over $\sim 1-2 \text{ hr}$ run)

| Kine | Spec | E_b GeV | E_p GeV | θ ($^{\circ}$) | beam time (hours) |
|----------------|------|--------------|--------------|----------------------------|----------------------|
| $\Delta(1232)$ | SHMS | 2.17 | -1.79736 | 8.5 | 4.0 |
| Elastic | SHMS | 2.17 | -2.12860 | 8.5 | 8.0 |

| Kine | Spec | E_b GeV | E_p GeV | θ ($^{\circ}$) | e^- production (hours) | e^+ prod. (hours) | Tot. Time (hours) |
|------|------|--------------|--------------|----------------------------|-----------------------------|------------------------|----------------------|
| DIS | | | | | | | |
| 3 | HMS | 10.38 | 2.90 | 30.0 | 88.0 | 0.0 | 88.0 |
| 4 | HMS | 10.38 | 3.50 | 30.0 | 511.0 | 0.0 | 511.0 |
| B | SHMS | 10.38 | 3.40 | 30.0 | 511.0 | 4.0 | 515.0 |
| C | SHMS | 10.38 | 2.60 | 30.0 | 88.0 | 4.0 | 92.0 |



Polarized ${}^3\text{He}$ target:

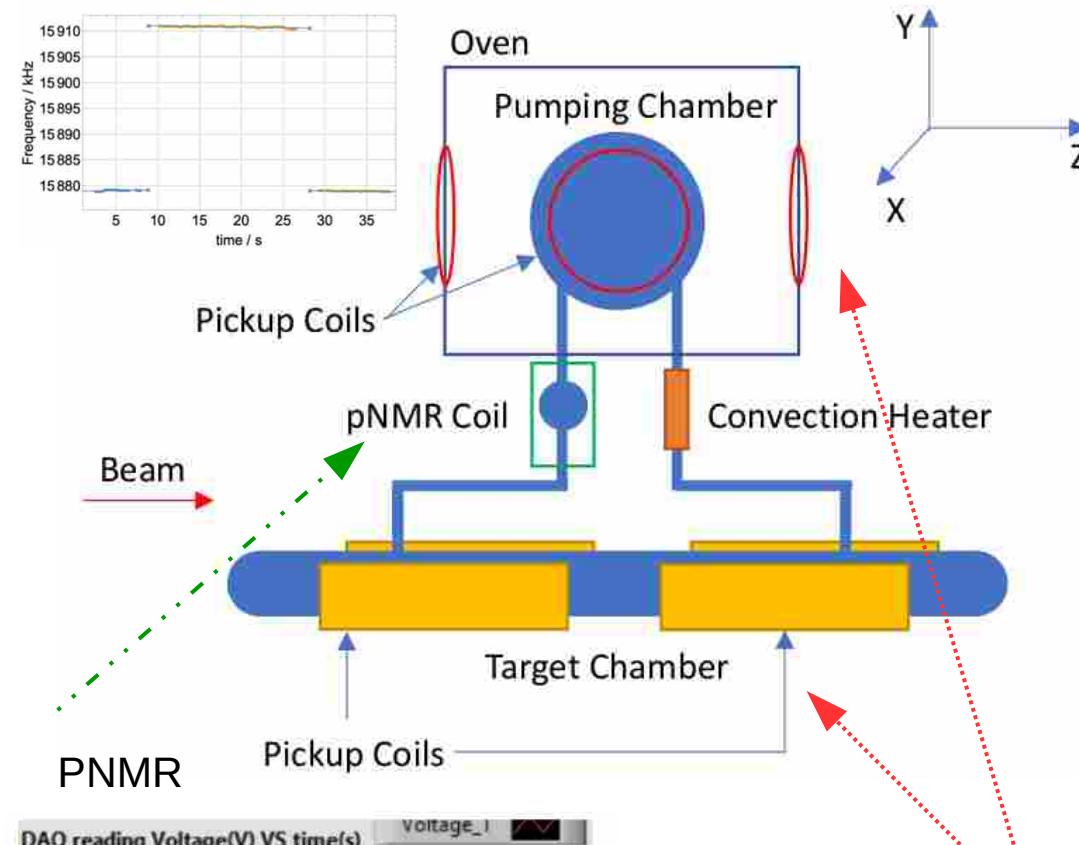
- ${}^3\text{He}$ production cell (40cm)
- 55–60% polarization without beam
- Reached over 50% polarization with 30 uA beam current
(doubles performance compare to 6 GeV era)
- About 3% uncertainty for polarimetry

- A_1^n production run begins on Jan 12th, 2020 and ended on March 13th, 2020.

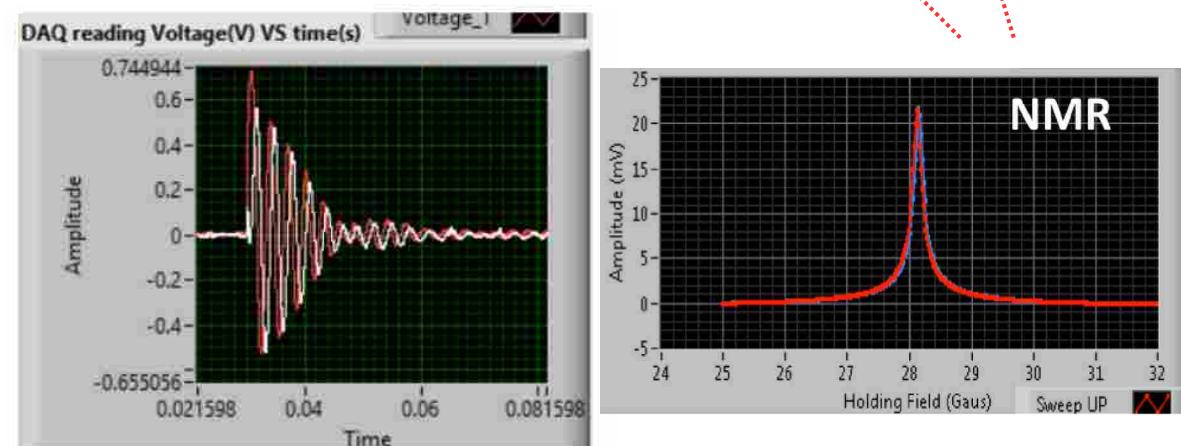


Polarimetry for ${}^3\text{He}$ in Target Cell

EPR



PNMR



1. Adiabatic Fast Passage Nuclear Magnetic Resonance (AFP-NMR)

- Magnetic Resonance of ${}^3\text{He}$ Nucleus
- Sweep the holding field under AFP condition to flip the Nucleon spin direction back and forth.
- Relative measurement, calibrate with water NMR or EPR.

2. Pulse NMR

- Use resonance RF pulse at ${}^3\text{He}$ Larmor frequency to tilts the Nucleon spin to a certain angle.
- Relative measurement, calibrate with AFP-NMR.
- Implemented for the first time on polarized ${}^3\text{He}$ target.

3. Electron Paramagnetic Resonance (EPR)

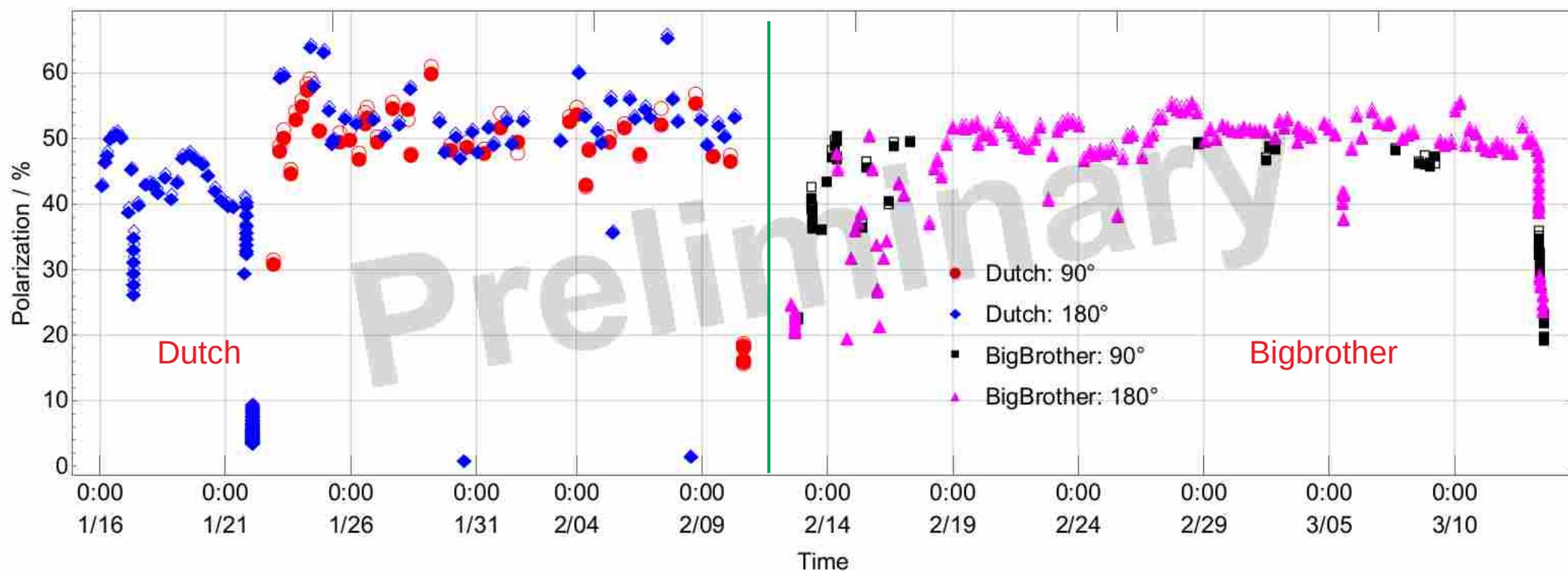
- Magnetic resonance of the alkali atoms
- Resonance shifted due to polarized ${}^3\text{He}$, get the resonance frequency difference by flipping the ${}^3\text{He}$ polarization direction.
- Get ${}^3\text{He}$ polarization from resonance frequency difference. Absolute measurement.

Production Cell Performance

(for targets used in A_1^n experiment)

A_1^n Experiment Target Performance

- Two production cells used
- Polarization: maximum reach 60+%, 55% in beam

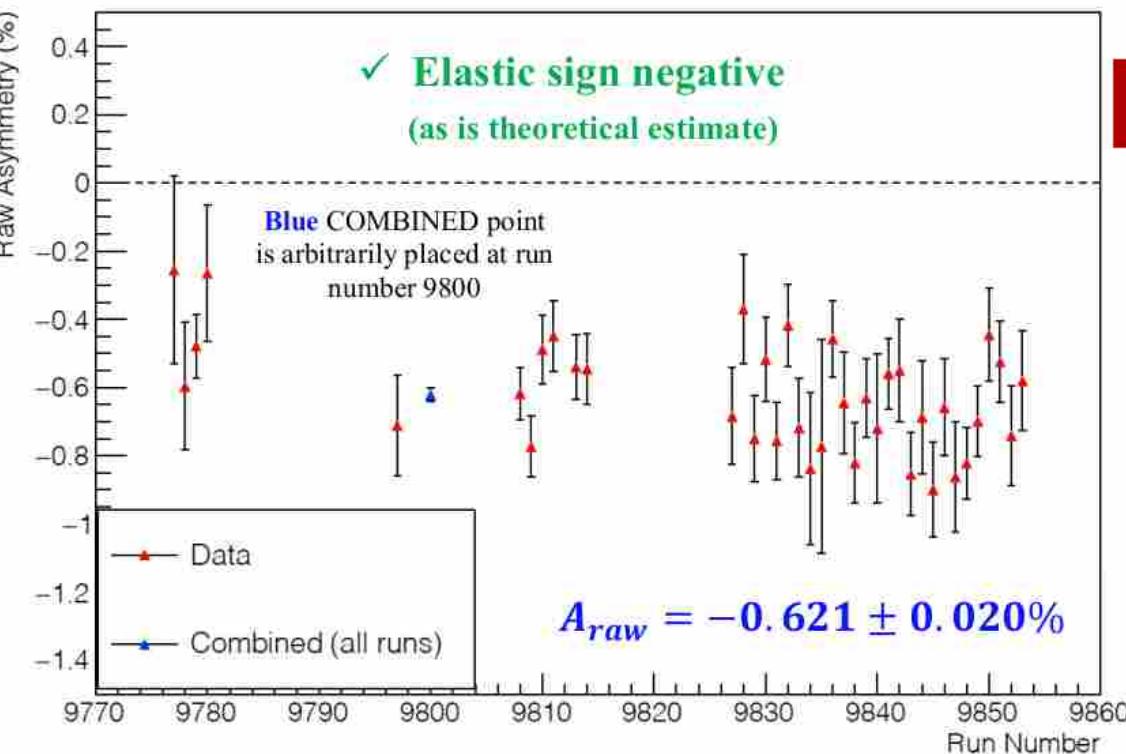


A_{para} : ^3He Elastic Asymmetries

By definition: N^+ should describe the # of incident e^- whose spin is **anti-||** to the ^3He target spin

$$A_{\parallel} = \frac{\sigma^{\downarrow\uparrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\downarrow\uparrow} + \sigma^{\uparrow\uparrow}}$$

SHMS Elastic Runs



| Period | IHWP = IN | IHWP = OUT | ^3He spin direction |
|--|--|--|------------------------------------|
| 1-pass (Dec. 2019) (elastic + delta) | UPSTREAM (\vec{e}^- anti- ^3He) (\vec{e}^- anti- beam direction) | DOWNSTREAM (\vec{e}^- ^3He) (\vec{e}^- beam direction) | 180°: DOWNSTREAM 90°: BEAM LEFT |
| 5-pass (DIS) (thru SHMS 10354, HMS 3162) | DOWNSTREAM (\vec{e}^- ^3He) (\vec{e}^- beam direction) | UPSTREAM (\vec{e}^- anti- ^3He) (\vec{e}^- anti- beam direction) | 180°:DOWNSTREAM 90°: BEAM LEFT |
| 5-pass (DIS) (SHMS 10355+, HMS 3163+) | UPSTREAM (\vec{e}^- anti- ^3He) (\vec{e}^- anti- beam direction) | DOWNSTREAM (\vec{e}^- ^3He) (\vec{e}^- beam direction) | 180°: DOWNSTREAM 90°: BEAM LEFT |

$$A_{\text{raw}} = \frac{N^+ - N^-}{N^+ + N^-}$$

SHMS Elastic Runs:

^3He @ 180°

$E_p = -2.1286 \text{ GeV}, 8.5^\circ$

- ^3He target spin direction fixed
- Incident e^- spin direction (relative to its momentum) changes with IHWP state, Wien-flip, and pass change → imperative to keep N^+, N^- consistent!

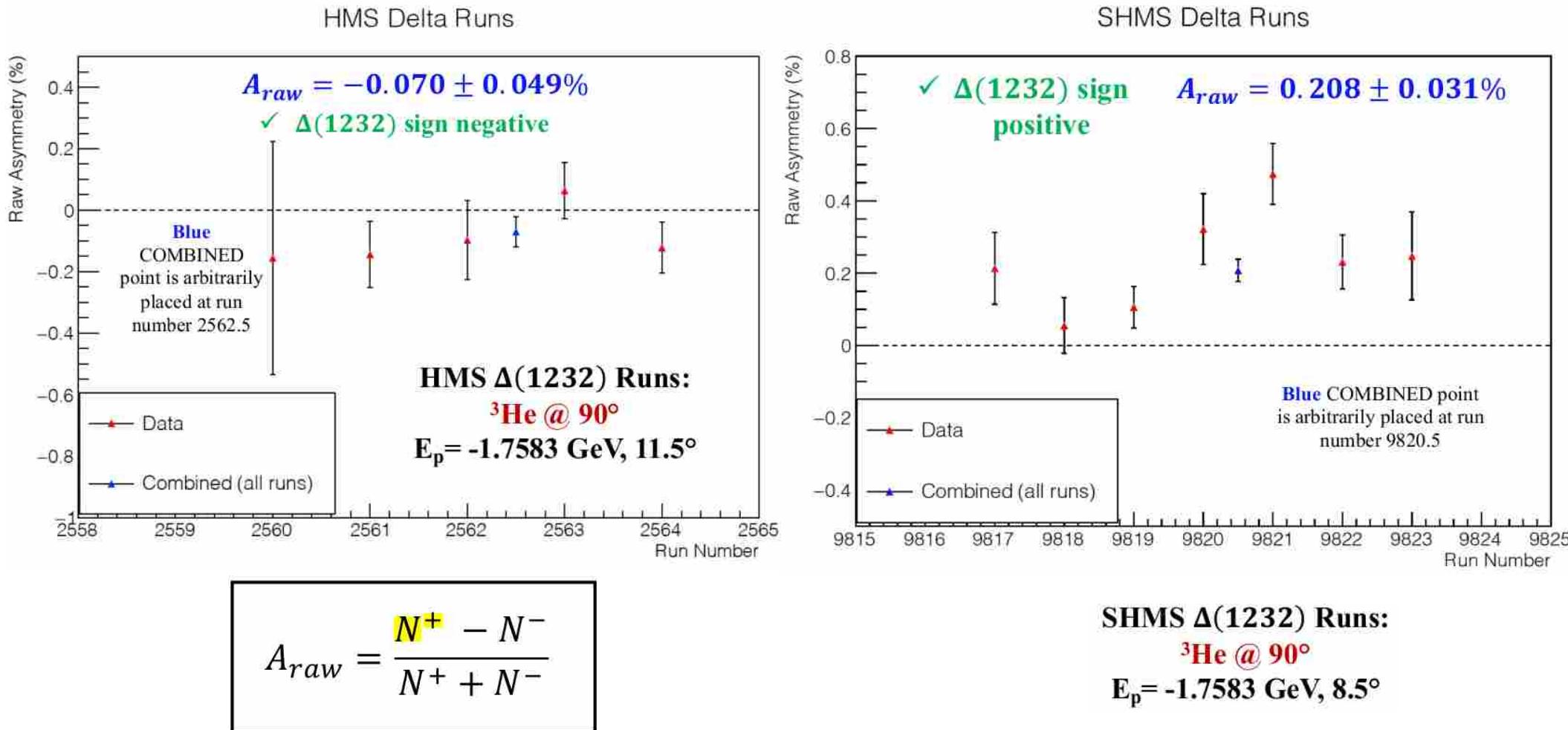
- Credit to Melanie Rehfuss (Tample)

A_{perp} : ^3He $\Delta(1232)$ Asymmetries

By definition: N^+ should describe the # of incident e^- whose spin is **anti-ll** to the **beam direction**, and the scattered e^- being detected on the **same side of the beam** as that to which the ^3He spins are **pointing**:

$$A_{\perp} = \frac{\sigma^{\downarrow\Rightarrow} - \sigma^{\uparrow\Rightarrow}}{\sigma^{\downarrow\Rightarrow} + \sigma^{\uparrow\Rightarrow}}$$

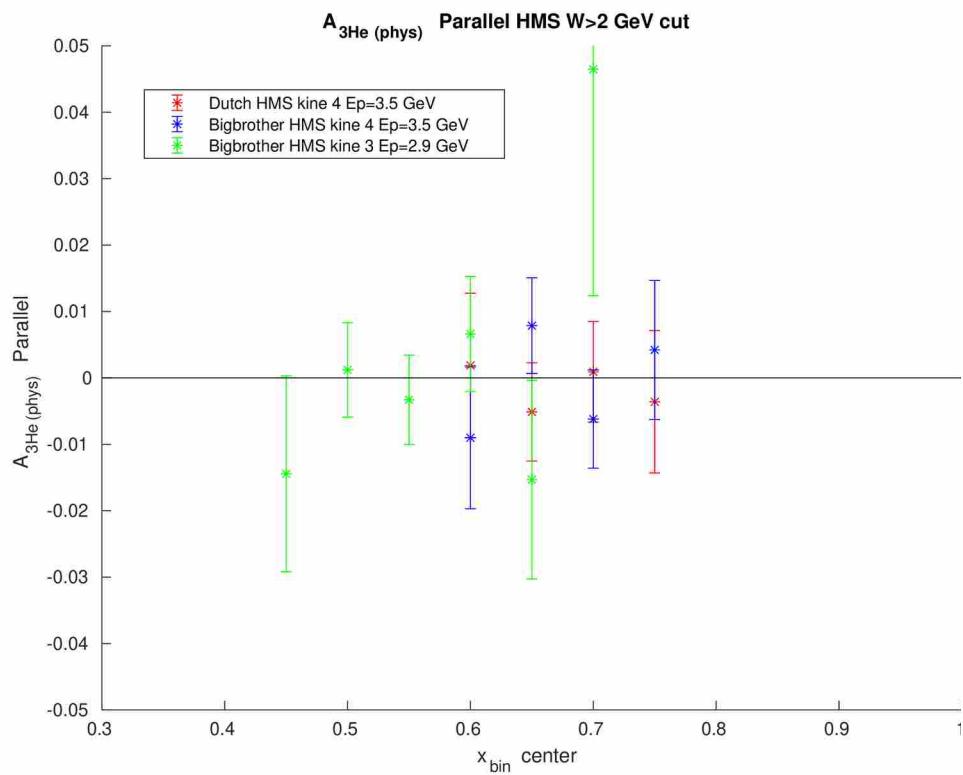
(beam left \rightarrow SHMS!)



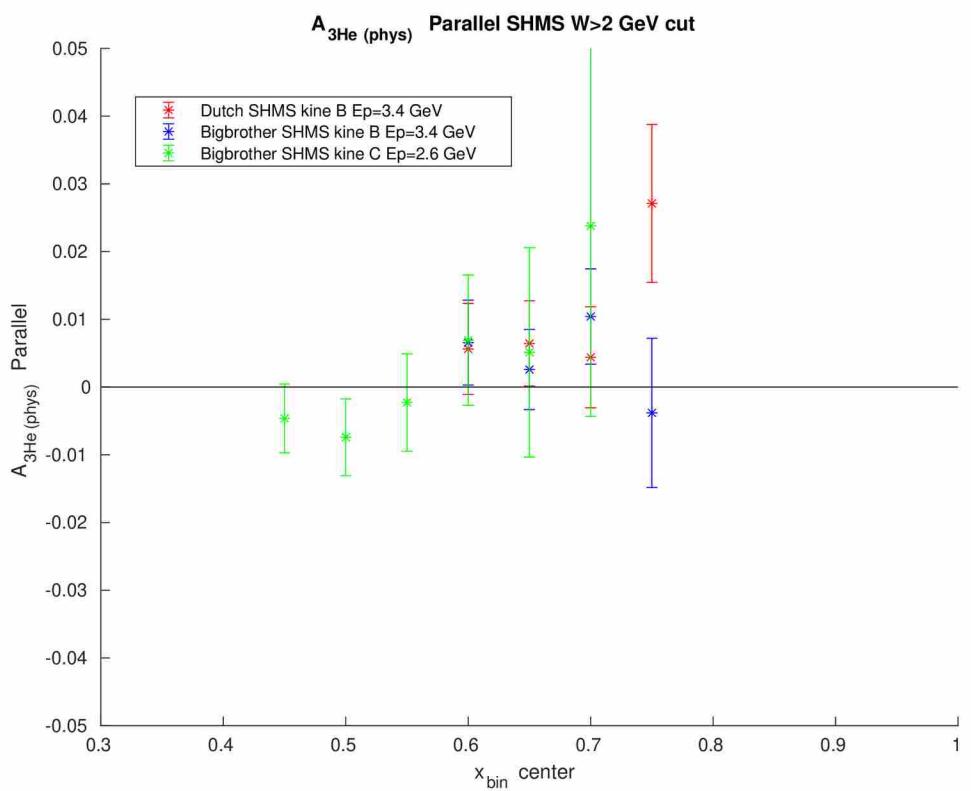
- Credit to Melanie Rehfuss (Tample)

$A_{\text{Phys}}^{\text{3He}}$ (with $W > 2 \text{ GeV}$ cut; for each Cell)

$$(A_{\text{phys}} * f_{N2})_i = \frac{A_{\text{corr}}}{P_b P_t}$$



$$A_{\text{raw,corr}} = \frac{\frac{N^+}{Q^+ \eta_{LT}^+} - \frac{N^-}{Q^- \eta_{LT}^-}}{\frac{N^+}{Q^+ \eta_{LT}^+} + \frac{N^-}{Q^- \eta_{LT}^-}}$$

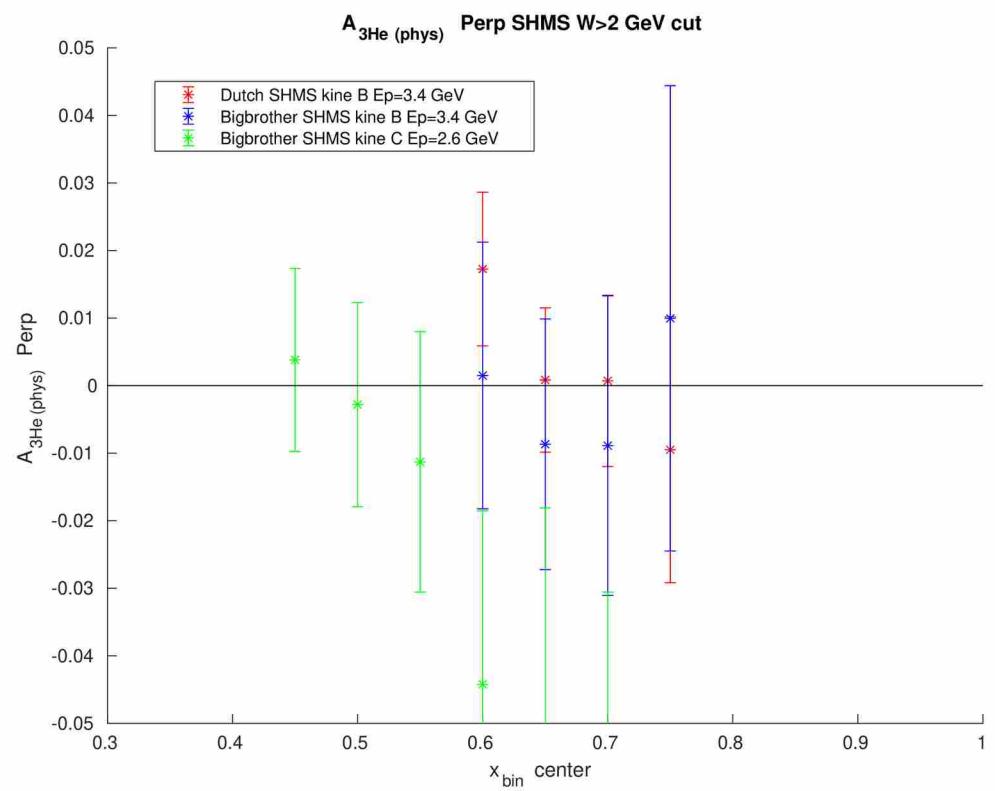
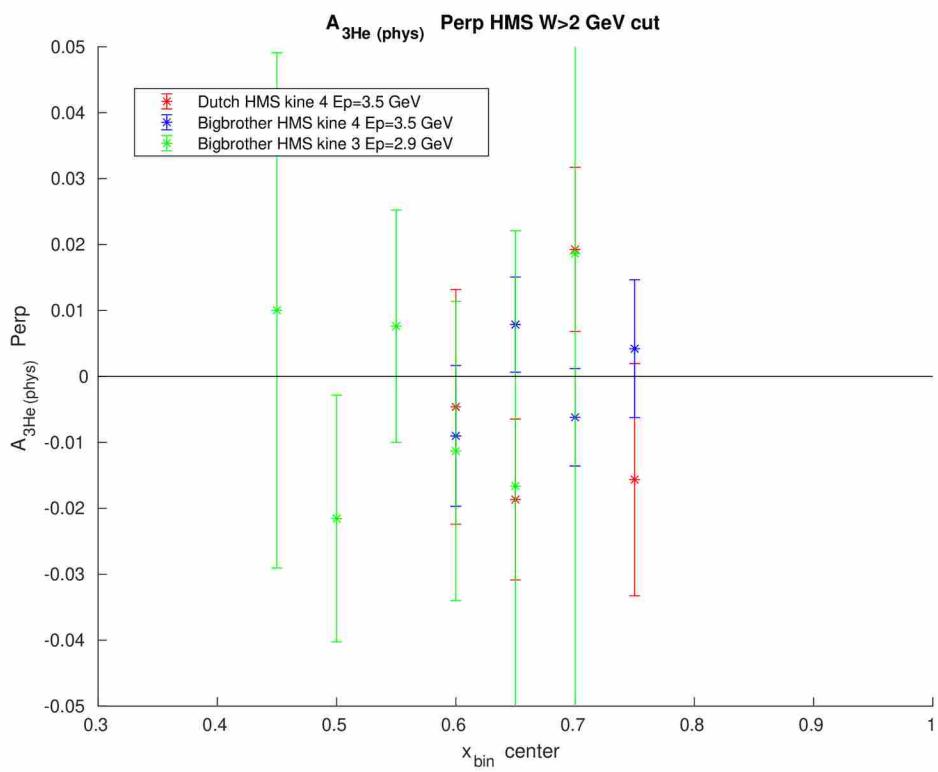


$$(A_{\text{phys}})_{\text{comb}} = (A_{\text{phys}} * f_{N2})_{\text{comb}} / (f_{N2})_{\text{comb}}$$

$A_{\text{Phys}}^{\text{3He}}$ (with $W > 2 \text{ GeV}$ cut; for each Cell)

$$(A_{\text{phys}} * f_{N2})_i = \frac{A_{\text{corr}}}{P_b P_t}$$

$$A_{\text{raw,corr}} = \frac{\frac{N^+}{Q^+ \eta_{LT}^+} - \frac{N^-}{Q^- \eta_{LT}^-}}{\frac{N^+}{Q^+ \eta_{LT}^+} + \frac{N^-}{Q^- \eta_{LT}^-}}$$

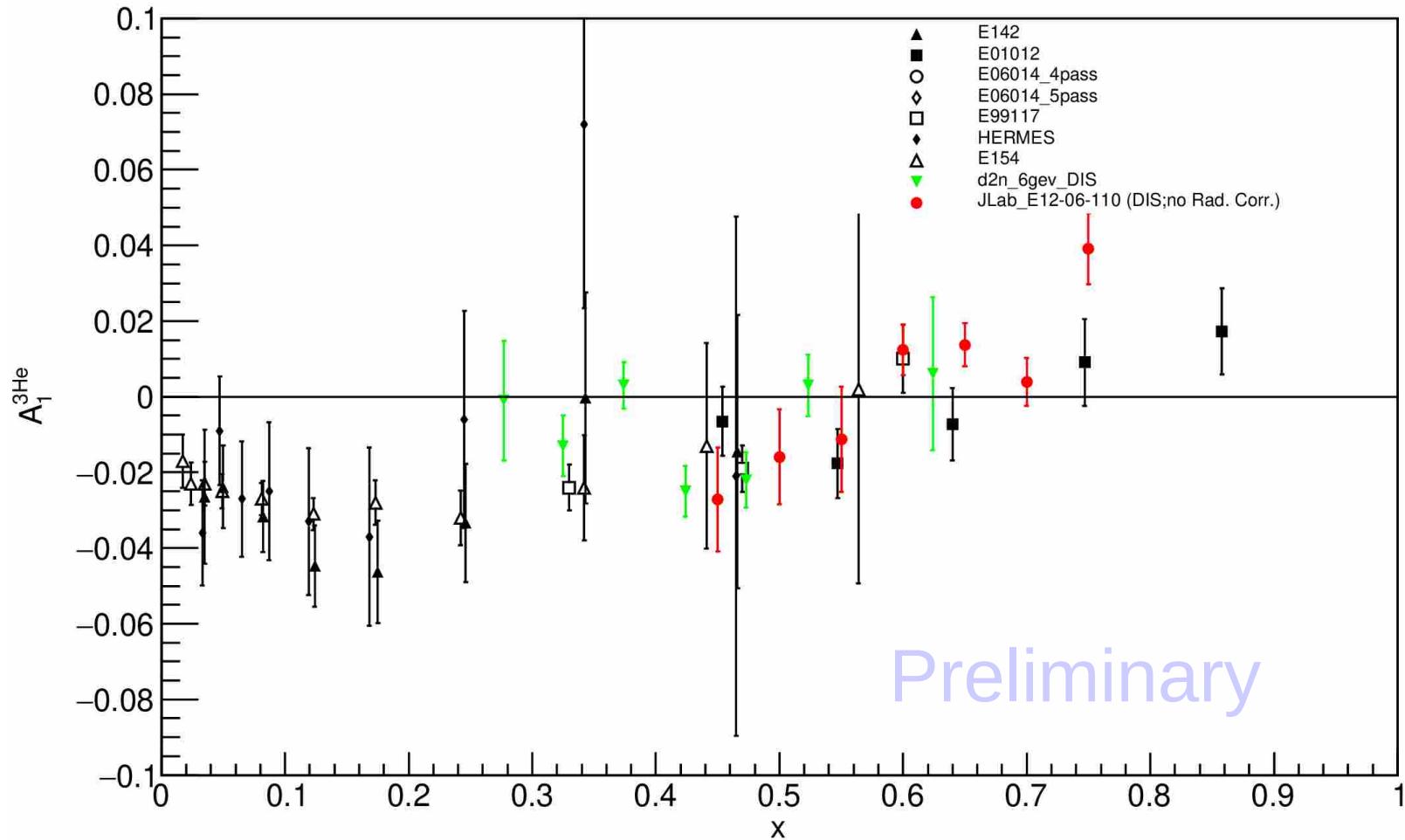


$$(A_{\text{phys}})_{\text{comb}} = (A_{\text{phys}} * f_{N2})_{\text{comb}} / (f_{N2})_{\text{comb}}$$

Asymmetry A_1 ^{3He}

(with W>2 GeV cut)

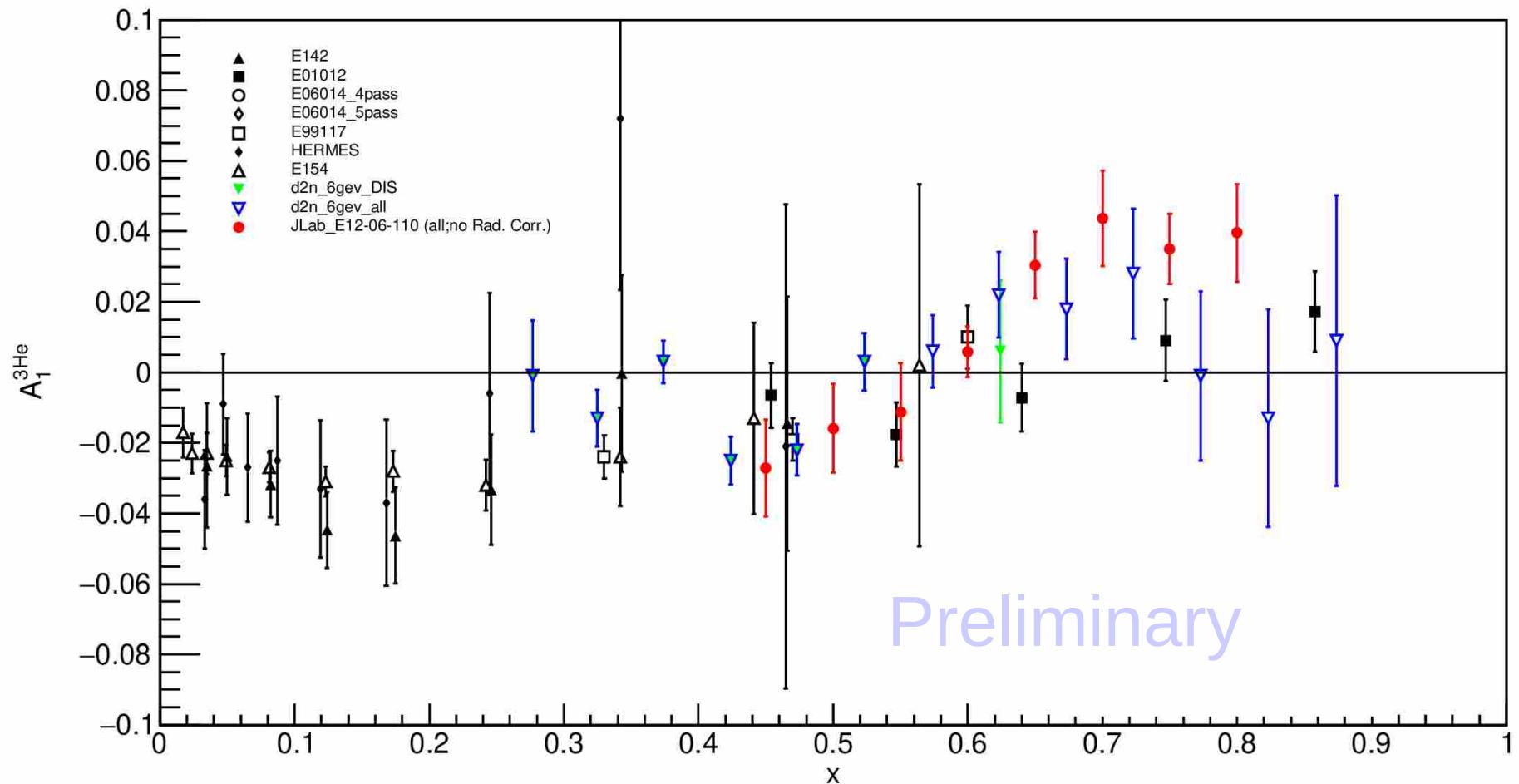
$$A_1 = \frac{A_{\parallel}}{D(1+\eta\xi)} - \frac{\eta A_{\perp}}{d(1+\eta\xi)}$$



Asymmetry A_1 ^{3He}

(no W cut)

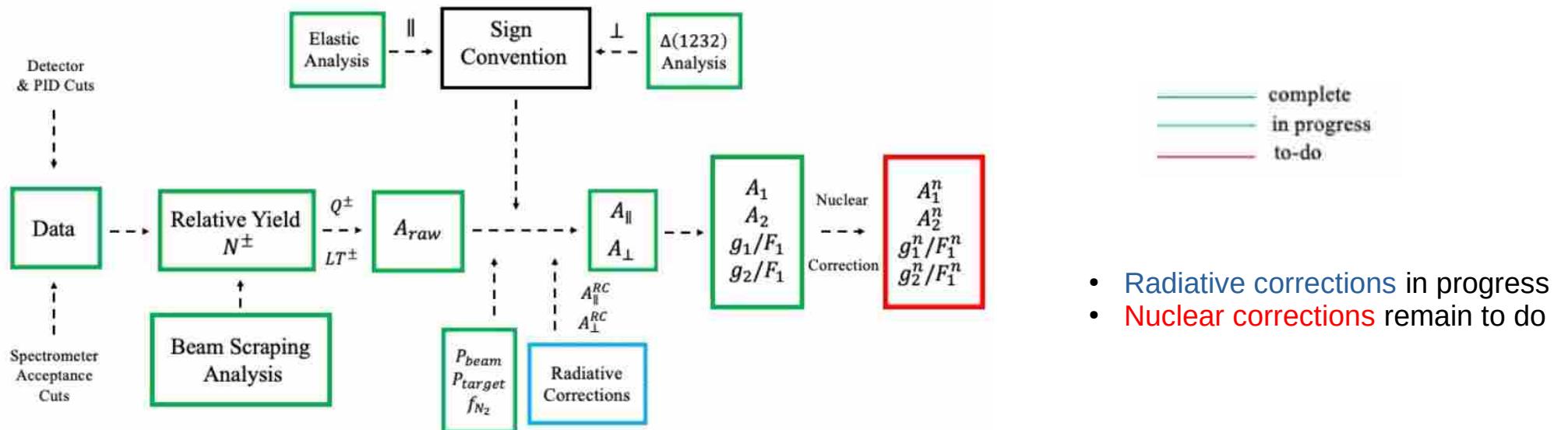
$$A_1 = \frac{A_{\parallel}}{D(1+\eta\xi)} - \frac{\eta A_{\perp}}{d(1+\eta\xi)}$$



Summary

- The A_1^n experiment (E12-06-110) is a flag-ship, high impact experiment which will give more insights on understanding the spin structure of nucleon.
- For the first time, install the upgraded polarized ^3He target for 12 GeV era in JLab Hall C. The target reached the expected performance with over 50% ^3He polarization in 30 uA electron beam.
- After combining with precision proton data (CLAS12), the high-precision neutron data will allow us to extract polarized to unpolarized parton distribution function (PDF) ratios $\Delta u/u$ ($\Delta d/d$) for large x region.

Analysis Flow Chart



Acknowledgments

People

D. Androic, W. Armstrong, [T. Averett](#), X. Bai, J. Bane, S. Barcus, J. Benesch, H. Bhatt, D. Bhetuwal, D. Biswas, A. Camsonne, [G. Cates](#), [J-P. Chen](#), [J. Chen](#), [M. Chen](#), C. Cotton, M-M. Dalton, A. Deur, B. Dhital, B. Duran, S.C. Dusa, I. Fernando, E. Fuchey, B. Gamage, H. Gao, D. Gaskell, T.N. Gautam, N. Gauthier, C.A. Gayoso, O. Hansen, F. Hauenstein, W. Henry, G. Huber, C. Jantzi, S. Jia, K. Jin, M. Jones, S. Joosten, A. Karki, B. Karki, S. Katugampola, S. Kay, C. Keppel, E. King, P. King, [W. Korsch](#), V. Kumar, R. Li, S. Li, W. Li, D. Mack, S. Malace, P. Markowitz, J. Matter, M. McCaughan, [Z-E. Meziani](#), R. Michaels, A. Mkrtchyan, H. Mkrtchyan, C. Morean, V. Nelyubin, G. Niculescu, M. Niculescu, M. Nyocz, C. Peng, S. Premathilake, A. Puckett, A. Rathnayake, [M. Rehfuss](#), P. Reimer, G. Riley, Y. Roblin, J. Roche, [M. Roy](#), M. Satnik, [B. Sawatzky](#), S. Seeds, S. Sirca, G. Smith, N. Sparveris, H. Szumila-Vance, A. Tadepalli, V. Tadevosyan, Y. Tian, A. Usman, H. Voskanyan, S. Wood, B. Yale, C. Yero, A. Yoon, J. Zhang, Z. Zhao, X. Zheng, J. Zhou

[PhD Candidates](#)



[Spokespeople](#)



Institutions

A.I. Alikhanian National Science Laboratory; Argonne National Laboratory; Artem Alikhanian National Laboratory (AANL); Christopher Newport University; Duke University; Florida International University; Hampton University ; James Madison University ; Jefferson Lab; Kent State University; Mississippi State University; Ohio University; Old Dominion University; Rutgers University; Syracuse University; Temple University; The College of William and Mary; Univ. of Ljubljana; University of Connecticut; University of Kentucky; University of Kentucky; University of New Hampshire; University of Regina; University of Tennessee; University of Virginia; University of Virginia; University of Zagreb



Backup Slides

Sign Correction

(based on Melanie's Notes)

In analysis: $A_{\parallel, \perp} = \frac{(N^+ - N^-)}{(N^+ + N^-)}$

\vec{e}^- : electron spin
 $\vec{^3He}$: target spin

e⁻ spin direction:

| Period | IHWP = IN | IHWP = OUT | 3He spin direction |
|---|---|---|------------------------------------|
| 1-pass (Dec. 2019) (elastic + delta) | UPSTREAM (\vec{e}^- anti- $\vec{^3He}$) (\vec{e}^- anti- beam direction) | DOWNSTREAM (\vec{e}^- $\vec{^3He}$) (\vec{e}^- beam direction) | 180°: DOWNSTREAM 90°: BEAM LEFT |
| 5-pass (DIS) (thru SHMS 10354, HMS 3162.) | DOWNSTREAM (\vec{e}^- $\vec{^3He}$) (\vec{e}^- beam direction) | UPSTREAM (\vec{e}^- anti- $\vec{^3He}$) (\vec{e}^- anti- beam direction) | 180°:DOWNSTREAM 90°: BEAM LEFT |
| 5-pass (DIS) (SHMS 10355+, HMS 3163+) | UPSTREAM (\vec{e}^- anti- $\vec{^3He}$) (\vec{e}^- anti- beam direction) | DOWNSTREAM (\vec{e}^- $\vec{^3He}$) (\vec{e}^- beam direction) | 180°: DOWNSTREAM 90°: BEAM LEFT |

A_1^n Running

If the above definition is used for the asymmetry, then for DIS w/ 3He @ 180 deg:

- before the Wien Flip on 2/17/20, IHWP = IN runs get a -1 correction
- after the Wien Flip on 2/17/20, IHWP = OUT runs get a -1 correction

If the above definition is used for the asymmetry, then for DIS w/ 3He @ 90 deg:

- before the Wien Flip on 2/17/20, IHWP = IN runs get a -1 correction on SHMS, IHWP = OUT get a -1 on HMS
- after the Wien Flip on 2/17/20, IHWP = OUT runs get a -1 correction on SHMS, IHWP = IN get a -1 on HMS

1.12 Electron Asymmetries

In an experiment it is usually difficult to align the virtual photon spin direction along the target spin direction, while keeping some flexibility in other kinematic variables. Alternatively the incident electron spin is aligned parallel (anti-parallel) or perpendicular (anti-perpendicular) to the target spin. The virtual photon asymmetries can be related to the measured lepton asymmetries through polarization and kinematic factors. For a target polarized parallel to the beam direction, the experimental longitudinal electron asymmetry is given by [12]

$$N^+ \rightarrow \vec{e}^- \text{ anti-|| } \vec{^3He} \quad A_{\parallel} \equiv \frac{\sigma_{\downarrow\parallel} - \sigma_{\uparrow\parallel}}{\sigma_{\downarrow\parallel} + \sigma_{\uparrow\parallel}} = \frac{1-\epsilon}{(1-\epsilon R)W_1} [M(E+E' \cos \theta)G_1 - Q^2 G_2], \quad (1.45)$$

where $\sigma_{\downarrow\parallel}(\sigma_{\uparrow\parallel})$ is the cross section for scattering off a longitudinally polarized target, with incident electron spin anti-parallel (parallel) to the target spin. Similarly the transverse electron asymmetry is defined for a target polarized perpendicular to the beam direction as [12]

$$N^+ \rightarrow \vec{e}^- \text{ anti-|| beam direction, } \vec{^3He} \text{ pointing toward SHMS} \quad A_{\perp} \equiv \frac{\sigma_{\downarrow\Rightarrow} - \sigma_{\uparrow\Rightarrow}}{\sigma_{\downarrow\Rightarrow} + \sigma_{\uparrow\Rightarrow}} = \frac{(1-\epsilon)E'}{(1-\epsilon R)W_1} [MG_1 + 2EG_2] \cos \theta, \quad (1.46)$$

where $\sigma_{\downarrow\Rightarrow}(\sigma_{\uparrow\Rightarrow})$ is the cross section for scattering off a transversely polarized target, with incident electron spin anti-parallel (parallel) to the beam direction, and the scattered electrons being detected on the same side of the beam as that to which the target spin is pointing. The electron asymmetries can be given in terms of A_1 and

Xiaochao Zheng Thesis, pg. 34

Sign Correction

(based on Melanie's Notes)

Target Field/Spin Direction

| Target Holding Field Direction | ${}^3\text{He}$ Spin Direction |
|--------------------------------|--------------------------------|
| +X Beam RIGHT (90°) | Beam LEFT |
| -X Beam LEFT (270°) | Beam RIGHT |
| +Z DOWNSTREAM (0°) | UPSTREAM |
| -Z UPSTREAM (180°) | DOWNSTREAM |

The target was always pumped in the low-energy state
(${}^3\text{He}$ spin is **opposite of the holding field**) during data-taking

Get Asymmetry

- For each run i:

$$A_{raw} = \frac{N^+ - N^-}{N^+ + N^-}$$

$$A_{raw,corr} = \frac{\frac{N^+}{Q^+ \eta_{LT}^+} - \frac{N^-}{Q^- \eta_{LT}^-}}{\frac{N^+}{Q^+ \eta_{LT}^+} + \frac{N^-}{Q^- \eta_{LT}^-}}$$

$$(A_{phys} * f_{N2})_i = \frac{A_{corr}}{P_b P_t}$$

$$\Delta A_{raw,corr} = 2 Q^+ Q^- \eta_{LT}^+ \eta_{LT}^- \sqrt{\frac{N^+ N^{-2} + N^- N^{+2}}{(N^+ Q^- \eta_{LT}^- + N^- Q^+ \eta_{LT}^+)^4}}$$

Where $A_{corr} = sign * (A_{raw,corr})$ is corrected asymmetry $\Delta A_{corr} = \Delta A_{raw,corr}$

$$\Delta (A_{phys} * f_{N2})_i = (A_{phys} * f_{N2})_i * \sqrt{\left(\frac{\Delta A_{corr}}{A_{corr}}\right)^2 + \left(\frac{\Delta P_b}{P_b}\right)^2 + \left(\frac{\Delta P_t}{P_t}\right)^2}$$

- For combined asymmetry:

$$(A_{phys} * f_{N2})_{comb} = \frac{\sum (A_{phys} * f_{N2})_i}{\sum \frac{1}{\Delta (A_{phys} * f_{N2})_i^2}}$$

$$\Delta (A_{phys} * f_{N2})_{comb} = \sqrt{\frac{1}{\sum \frac{1}{\Delta (A_{phys} * f_{N2})_i^2}}}$$

Get Asymmetry Notes

1) For online analysis, use

$$\frac{\Delta P_b}{P_b} = 0.03$$

$$\frac{\Delta P_t}{P_t} = 0.04$$

2) In order to avoid dividing by zero in the calculation:

- If $N^+ + N^- = 0$ or $\Delta A_{raw,corr} = 0$ set:

$$\frac{(A_{phys} * f_{N2})_i}{\Delta(A_{phys} * f_{N2})_i^2} = 0$$

$$\frac{1}{\Delta(A_{phys} * f_{N2})_i^2} = 0$$

- If $A_{corr} = 0$, then set $\Delta(A_{phys} * f_{N2})_i = 0$

- If $\sum \frac{1}{\Delta(A_{phys} * f_{N2})_i^2} = 0$, then log: $(A_{phys} * f_{N2})_{comb} = 0$

$$\Delta(A_{phys} * f_{N2})_{comb} = 0$$

(will not plot these values)

Cuts for Replayed Root Files

(for HMS and SHMS)

- HMS:

Acceptance Cuts:

- $-8 < H.gtr.dp < 8$
- $-0.06 < H.gtr.th < 0.06$
- $-0.1 < H.gtr.ph < 0.1$
- $-15 < H.react.z < 15$

PID cuts:

- $0.8 < H.cal.etracknorm < 2.0$
- $1. < H.cer.npeSum$

- SHMS:

Acceptance Cuts:

- $-10 < P.gtr.dp < 22$
- $-0.07 < P.gtr.th < 0.07$
- $-0.05 < P.gtr.ph < 0.05$
- $-15 < P.react.z < 15$

PID cuts:

- $0.8 < P.cal.etracknorm < 2$
- $2. < P.ngcer.npeSum$

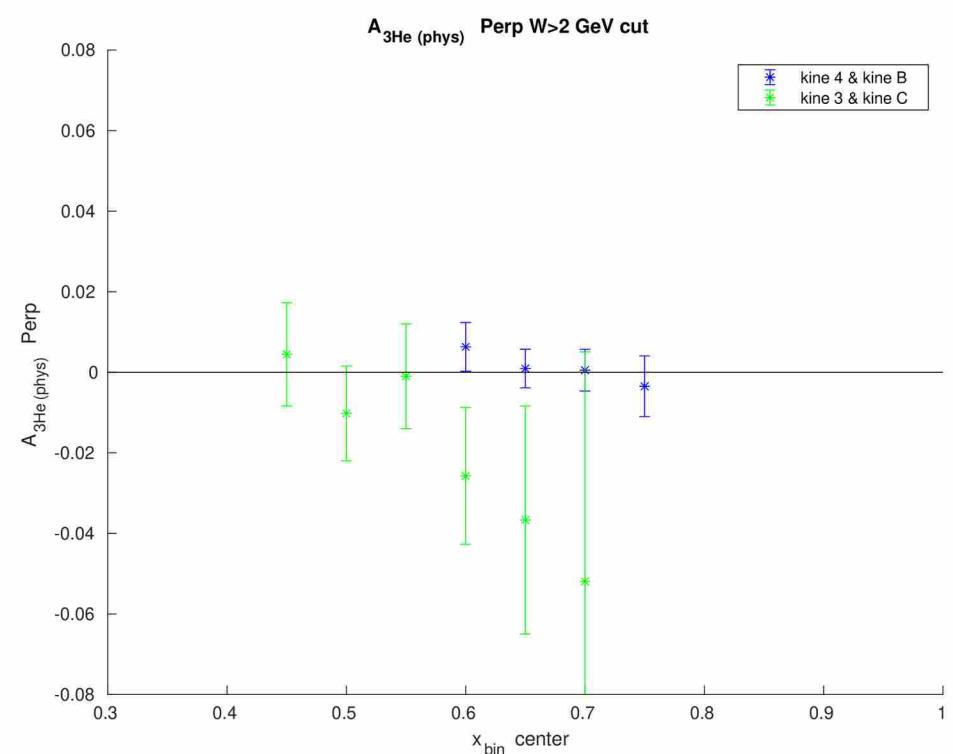
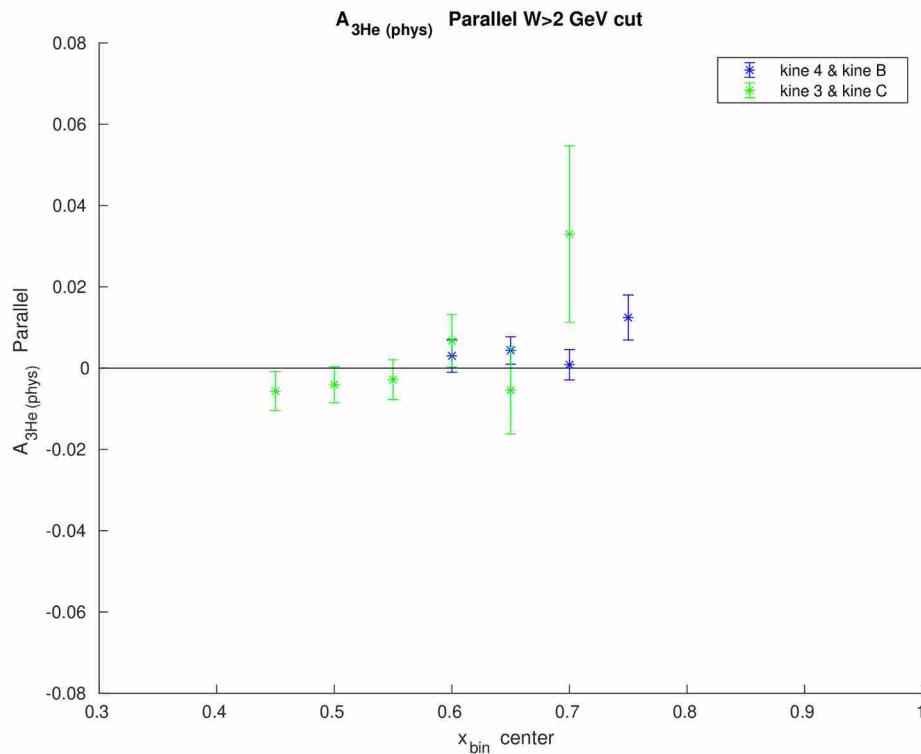
- Current cuts based on the stats. of T:ibcm1 :
 $ibcm1 > 3 \mu A$
- If the mean value of ibcm1 is less than $3.5 \mu A$, skip the run for average current too low.

$A_{\text{Phys}}^{3\text{He}}$

(with $W > 2 \text{ GeV}$ cut; combine two spec)

$$(A_{\text{phys}})_{\text{comb}} = (A_{\text{phys}} * f_{N2})_{\text{comb}} / (f_{N2})_{\text{comb}}$$

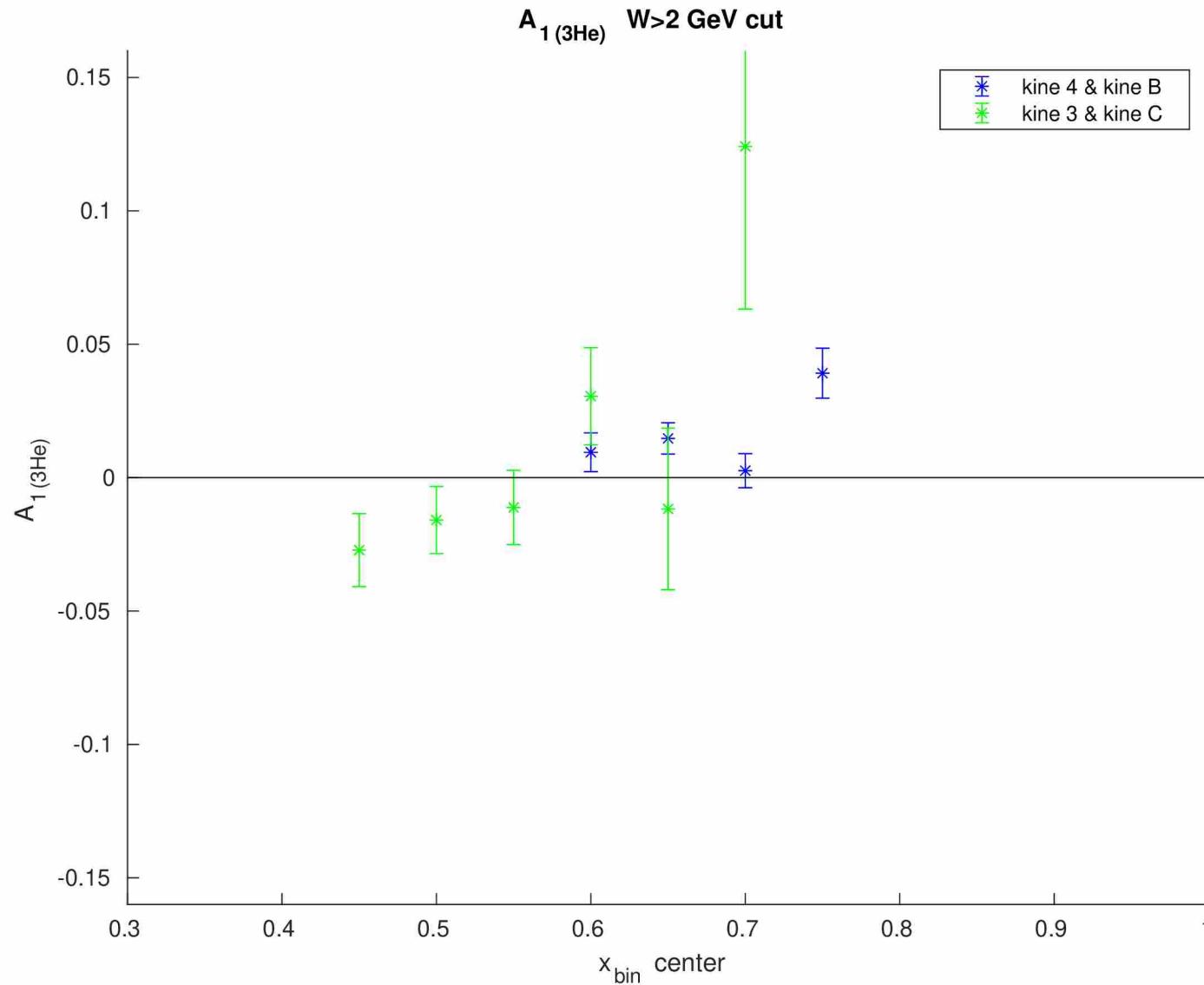
$$\Delta(A_{\text{phys}})_{\text{comb}} = (A_{\text{phys}})_{\text{comb}} * \sqrt{\left(\frac{\Delta(A_{\text{phys}} * f_{N2})_{\text{comb}}}{(A_{\text{phys}} * f_{N2})_{\text{comb}}}\right)^2 + \left(\frac{\Delta(f_{N2})_{\text{comb}}}{(f_{N2})_{\text{comb}}}\right)^2}$$



$A_1^{^3\text{He}}$

(with $W > 2$ GeV cut)

$$A_1 = \frac{A_{||}}{D(1+\eta\xi)} - \frac{\eta A_{\perp}}{d(1+\eta\xi)}$$



Extracting g_1/F_1 & A_1, A_2

Electron Beam Energy $E = 10.38 \text{ GeV}$ (fixed)

$$\frac{g_1^{^3He}}{F_1^{^3He}} = \left(\frac{1}{d'}\right) \left(A_{\parallel} + \tan\left(\frac{\theta}{2}\right) A_{\perp}\right)$$

$$\frac{g_2^{^3He}}{F_1^{^3He}} = \left(\frac{y}{2d'}\right) \left(-A_{\parallel} + \left(\frac{E - E' \cos(\theta)}{E' \sin(\theta)}\right) A_{\perp}\right)$$

$$A_1 = \frac{1}{D(1 + \eta\xi)} A_{\parallel} - \frac{\eta}{d(1 + \eta\xi)} A_{\perp}$$

$$A_2 = \frac{\xi}{D(1 + \eta\xi)} A_{\parallel} + \frac{1}{d(1 + \eta\xi)} A_{\perp}$$

A_{\parallel} & A_{\perp} are the electron **physics** double-spin asymmetries

$$D = \frac{E - \epsilon E'}{E(1 + \epsilon R)}$$

$$\epsilon = \frac{1}{1 + 2\left(1 + \frac{v^2}{Q^2}\right) \tan^2\left(\frac{\theta}{2}\right)}$$

$$\eta = \frac{\epsilon\sqrt{Q^2}}{E - E'\epsilon} \quad \xi = \eta(1 + \epsilon)/2\epsilon$$

$$v = E - E' \quad y = v/E$$

$$d = D \sqrt{\frac{2\epsilon}{1 + \epsilon}} \quad R(x, Q^2) = \frac{\sigma_L}{\sigma_T}(1998)$$

$$d' = \frac{(1 - \epsilon)(2 - y)}{y(1 + \epsilon R)}$$

Nuclear Corrections & Quark Flavor Decomposition

- A_1^n is ultimately extracted from $A_1^{^3He}$ as

$$A_1^n = \frac{F_2^{^3He} \left[A_1^{^3He} - 2 \left(\frac{F_2^p}{F_2^{^3He}} \right) P_p A_1^p \left(1 - \frac{0.014}{2P_p} \right) \right]}{P_n F_2^n \left(1 + \frac{0.056}{P_n} \right)}$$

where $P_n = 0.86_{-0.02}^{+0.036}$ and $P_p = -0.028_{-0.004}^{+0.009}$ are the effective nucleon polarizations of the neutron and proton inside ${}^3\text{He}$

- Combining neutron g_1/F_1 data with measurements on the proton allows a flavor decomposition to separate the polarized-to-unpolarized-PDF ratios for up and down quarks:

$$\frac{\Delta u + \Delta \bar{u}}{u + \bar{u}} = \frac{4}{15} \frac{g_1^p}{F_1^p} (4 + R^{du}) - \frac{1}{15} \frac{g_1^n}{F_1^n} (1 + 4R^{du})$$

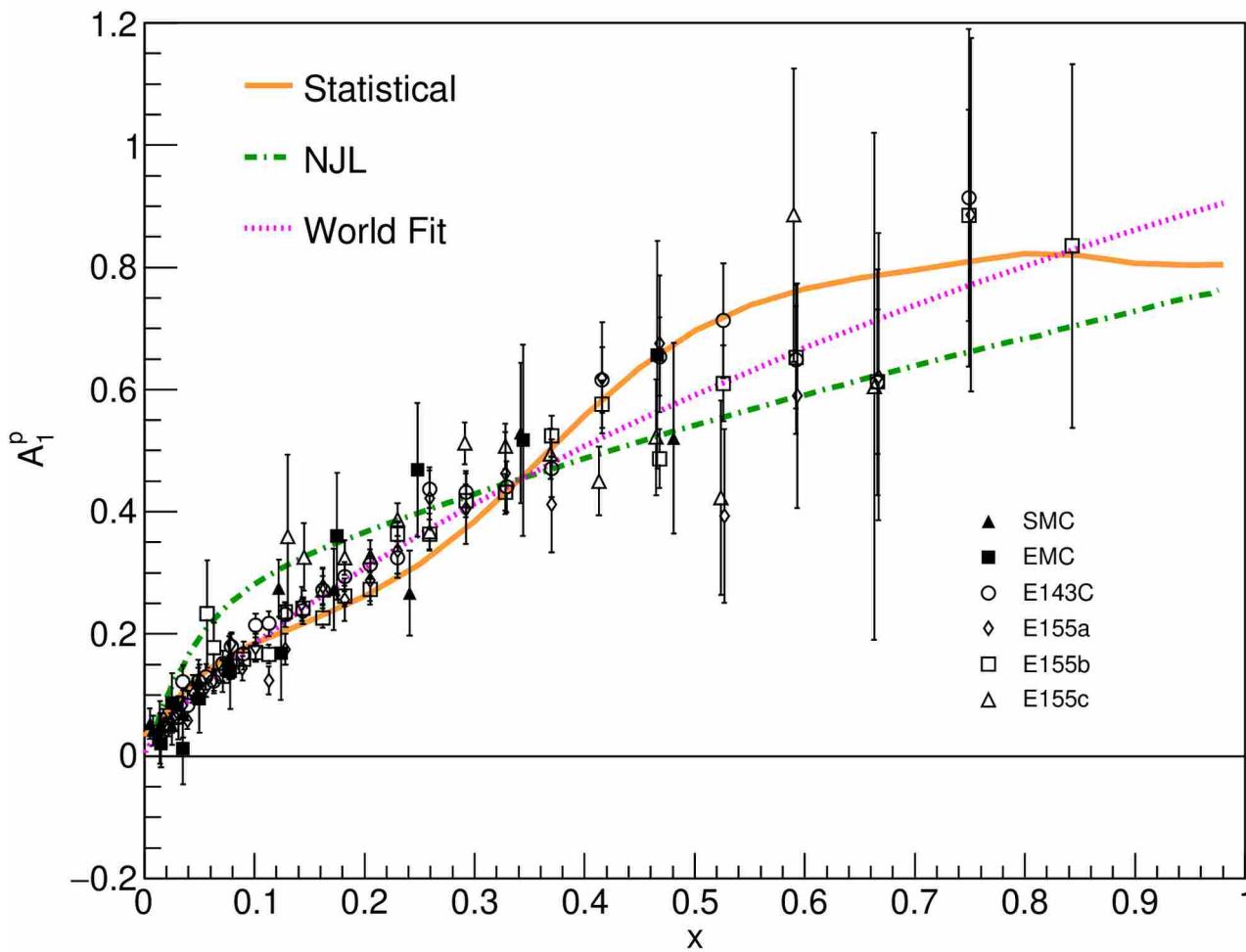
$$R^{du} = \frac{d + \bar{d}}{u + \bar{u}} \quad (\text{parameterization})$$

$$\frac{\Delta d + \Delta \bar{d}}{d + \bar{d}} = \frac{-1}{15} \frac{g_1^p}{F_1^p} \left(1 + \frac{4}{R^{du}} \right) + \frac{4}{15} \frac{g_1^n}{F_1^n} \left(4 + \frac{1}{R^{du}} \right)$$

$$\frac{g_1^p}{F_1^p} \quad (\text{modeled with world data})$$

$$g_1^p/F_1^p \equiv x^{0.813} (1.231 - 0.413x) \left(1 + \frac{0.030}{Q^2} \right)$$

A_1^p Fit from World Data



- Fit for E155, E143 at SLAC and EMC, SMC at CERN:

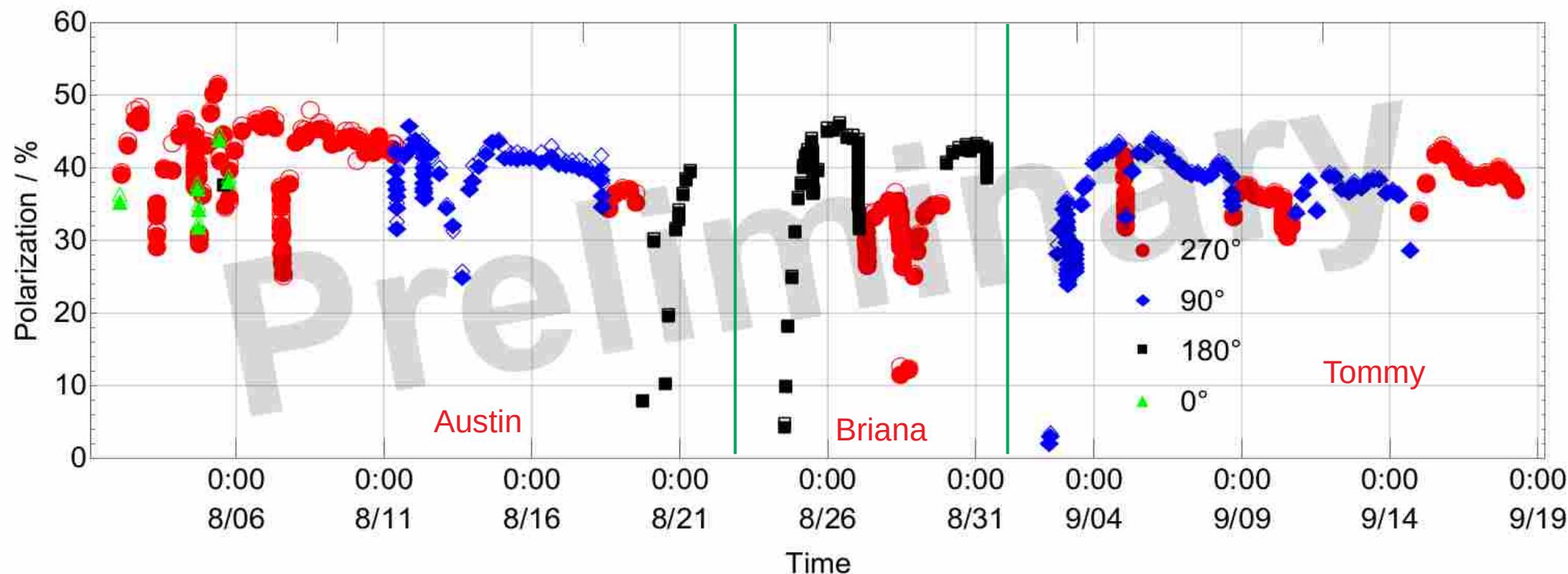
$$A_1^p = x^{0.771} (1.126 - 0.189x) \left(1 - \frac{0.09}{Q^2}\right)$$

Production Cell Performance

(for targets used in d_2^n experiment)

d_2^n Experiment Target Performance

- Three production cells used
- Polarization: ~45% in beam



$$n_{N_2}^{TC} = n_{N_2} (\text{filling density amg}) * f_{TC}$$

$$f_{TC} = V_{Tot} * \left(V_{TC} + V_{PC} \frac{T_{TC}}{T_{PC}} + V_{TT} \frac{T_{TC}}{T_{TT}} \right)^{-1}$$

| Date | Run start time | Run end time | Run num | Field Direction (deg) | Spec | Kine | Spec angle (deg) | E_p (GeV) | Trigger | Target Type | Replayed Event # | Beam Current (uA) | N2 Pressure TC (amg) | Comment |
|-------|----------------|--------------|---------|-----------------------|------|--------|------------------|-------------|---------|-------------|------------------|-------------------|----------------------|-----------------|
| 02/13 | 10:06 | 10:38 | 3085 | 90 | HMS | Kine-4 | 30 | -3.5 | 3/4 | Ref-N2 | All; -1 | 30 | 8.690 ± 0.006 | Cell Will |
| 03/02 | 15:08 | 16:09 | 3406 | 90 | HMS | Kine-4 | 30 | -3.5 | 3/4 | Pol-3He | All; -1 | 30 | 0.1460 ± 0.00147 | Cell Bigbrother |
| 01/20 | 14:10 | 16:00 | 2771 | 180 | HMS | Kine-4 | 30 | -3.5 | 3/4 | Pol-3He | All; -1 | 30 | 0.163 ± 0.00159 | Cell Dutch |
| 02/14 | 04:35 | 04:59 | 3105 | 90 | HMS | Kine-3 | 30 | -2.9 | 3/4 | Ref-N2 | All; -1 | 30 | 8.690 ± 0.006 | Cell Will |
| 02/16 | 22:49 | 00:07 | 3153 | 180 | HMS | Kine-3 | 30 | -2.9 | 3/4 | Pol-3He | All; -1 | 30 | 0.1460 ± 0.00147 | Cell Bigbrother |

Cell Info:

| | | | | | | Location | Average Temp (°C) | |
|------------|--|---------------------|---------------------|---------------------|--------------------|-----------------------------|-------------------|-------------|
| Cell Name | | V_{Tot} (mL) | V_{PC} (mL) | V_{TC} (mL) | V_{TT} (mL) | N_2 filling Density (amg) | | |
| Dutch | | 441.540 ± 0.001 | 297.151 ± 0.001 | 111.866 ± 0.001 | 32.523 ± 0.001 | 0.115 ± 0.001 | PC | 238 ± 2 |
| Bigbrother | | 427.182 ± 0.001 | 293.82 ± 0.001 | 100.759 ± 0.001 | 32.602 ± 0.001 | 0.110 ± 0.001 | TC | 35 ± 2 |
| | | | | | | | TT | 38 ± 2 |
| | | | | | | | Ref_N2 | 37 ± 2 |

N₂ Dilution Study

$$D_{N_2} = 1 - \frac{\Sigma_{N_2}(N_2)}{\Sigma_{tot}(^3He)} \frac{t_{ps}(N_2)}{t_{ps}(^3He)} \frac{Q(^3He)}{Q(N_2)} \frac{t_{LiveTime}(^3He)}{t_{LiveTime}(N_2)} \frac{n_{N_2}(^3He)}{n_{N_2}(N_2)}$$

$$= 1 - \frac{Yield_{N_2}(N_2)}{Yield_{tot}(^3He)} * \frac{n_{N_2}(^3He)}{n_{N_2}(N_2)}$$

$$t_{LiveTime} = \frac{\Sigma * t_{ps}}{s}$$

$$\sigma(t_{LiveTime}) = t_{LiveTime} * \sqrt{\frac{1}{\Sigma} + \frac{1}{s}}$$

- Σ : good event from T(spectrometer) tree with current cut, no pid or acceptance cut
- s : scaler from TSP(helicity scaler) tree with current cut

$$Yield = \frac{\Sigma * t_{ps}}{Q * t_{LiveTime}}$$

$$\sigma(Yield) = Yield * \sqrt{\frac{1}{\Sigma} + \frac{\sigma(t_{LiveTime})^2}{t_{LiveTime}^2}}$$

| Run Num | Cell Name | Target Type | spec | Prescale Factor (t _{ps}) | Yield | N ₂ Dilution Factor (D _{N2}) |
|----------|------------|-------------|--------|------------------------------------|--------------|---|
| Combined | Will | Ref-N2 | Kine-4 | 1.0 | 140201 ±1331 | 1-(0.097657 ±0.002661) |
| Combined | Bigbrother | Pol-3He | Kine-4 | 1.0 | 24120 ±32.93 | |
| Combined | Dutch | Pol-3He | Kine-4 | 1.0 | 25795 ±34.67 | 1-(0.10194 ±0.001866) |
| Combined | Will | Ref-N2 | Kine-3 | 1.0 | 436638 ±3616 | 1-(0.093793 ±0.001231) |
| Combined | Bigbrother | Pol-3He | Kine-3 | 1.0 | 78214 ±111.5 | |

- Combine yield for all good runs in same kinematics:
- For each run i get Yield_i and σ(Yield)_i

$$Yield_{comb} = \frac{\sum \frac{Yield_i}{\sigma(Yield)_i^2}}{\sum \frac{1}{\sigma(Yield)_i^2}}$$

$$\sigma(Yield_{comb}) = \sqrt{\frac{1}{\sum \frac{1}{\sigma(Yield)_i^2}}}$$

N₂ Dilution Study

$$D_{N_2} = 1 - \frac{\Sigma_{N_2}(N_2)}{\Sigma_{tot}(^3He)} \frac{t_{ps}(N_2)}{t_{ps}(^3He)} \frac{Q(^3He)}{Q(N_2)} \frac{t_{LiveTime}(^3He)}{t_{LiveTime}(N_2)} \frac{n_{N_2}(^3He)}{n_{N_2}(N_2)}$$

$$= 1 - \frac{Yield_{N_2}(N_2)}{Yield_{tot}(^3He)} * \frac{n_{N_2}(^3He)}{n_{N_2}(N_2)}$$

$$t_{LiveTime} = \frac{\Sigma * t_{ps}}{s}$$

$$\sigma(t_{LiveTime}) = t_{LiveTime} * \sqrt{\frac{1}{\Sigma} + \frac{1}{s}}$$

- Σ : good event from T(spectrometer) tree with current cut, no pid or acceptance cut
- s : scaler from TSP(helicity scaler) tree with current cut

$$Yield = \frac{\Sigma * t_{ps}}{Q * t_{LiveTime}}$$

$$\sigma(Yield) = Yield * \sqrt{\frac{1}{\Sigma} + \frac{\sigma(t_{LiveTime})^2}{t_{LiveTime}^2}}$$

| Run Num | Cell Name | Target Type | spec | Prescale Factor (t _{ps}) | Yield | N ₂ Dilution Factor (D _{N2}) |
|----------|------------|-------------|--------|---------------------------------------|---------------|--|
| Combined | Will | Ref-N2 | Kine-B | 1.0 | 179145 ±1526 | 1-(0.093689 ±0.001242) |
| Combined | Bigbrother | Pol-3He | Kine-B | 1.0 | 32125 ±39.15 | |
| Combined | Dutch | Pol-3He | Kine-B | 1.0 | 34474 ±40.26 | 1-(0.097471 ±0.001269) |
| Combined | Will | Ref-N2 | Kine-C | 1.0 | 759784 ±4692 | 1-(0.092457 ±0.001098) |
| Combined | Bigbrother | Pol-3He | Kine-C | 1.0 | 138064 ±149.7 | |

- Combine yield for all good runs in same kinematics:
- For each run i get Yield_i and σ(Yield)_i

$$Yield_{comb} = \frac{\sum \frac{Yield_i}{\sigma(Yield)_i^2}}{\sum \frac{1}{\sigma(Yield)_i^2}}$$

$$\sigma(Yield_{comb}) = \sqrt{\frac{1}{\sum \frac{1}{\sigma(Yield)_i^2}}}$$