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

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June 21, 2023

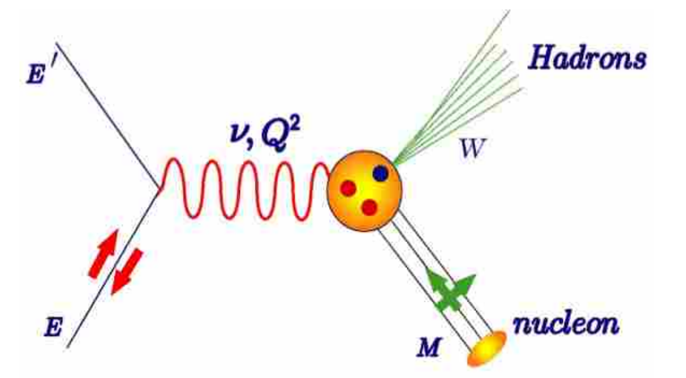
Outline:

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

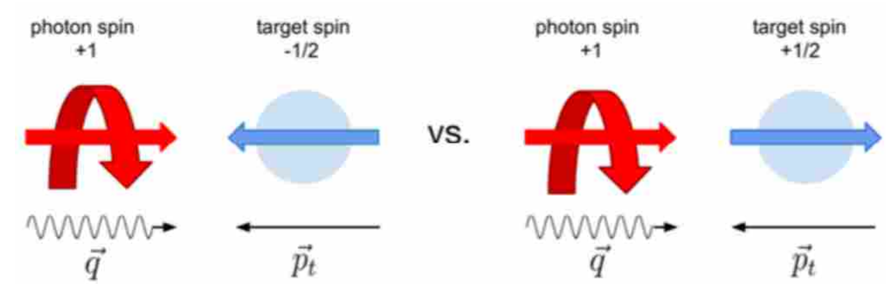
- On Behalf of the E12-06-110 Collaboration

Longitudinal Virtual Photon Asymmetry A_1

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



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



Anti-parallel spins

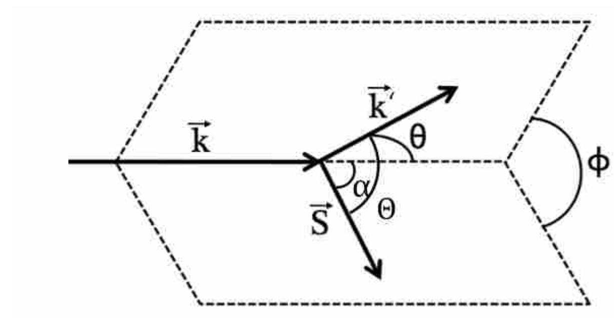
Parallel spins

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

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

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

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



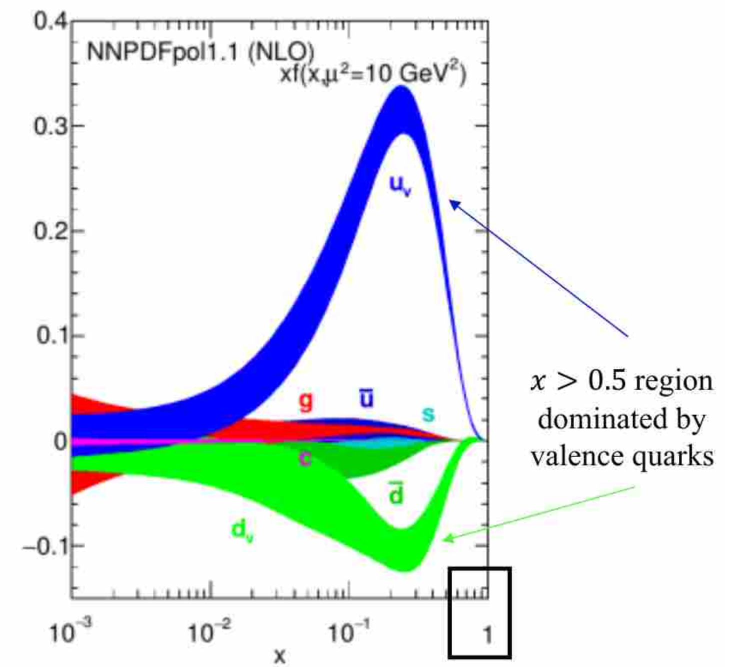
- Angular kinematics for polarized electron scattering

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 Δu/u (Δd/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

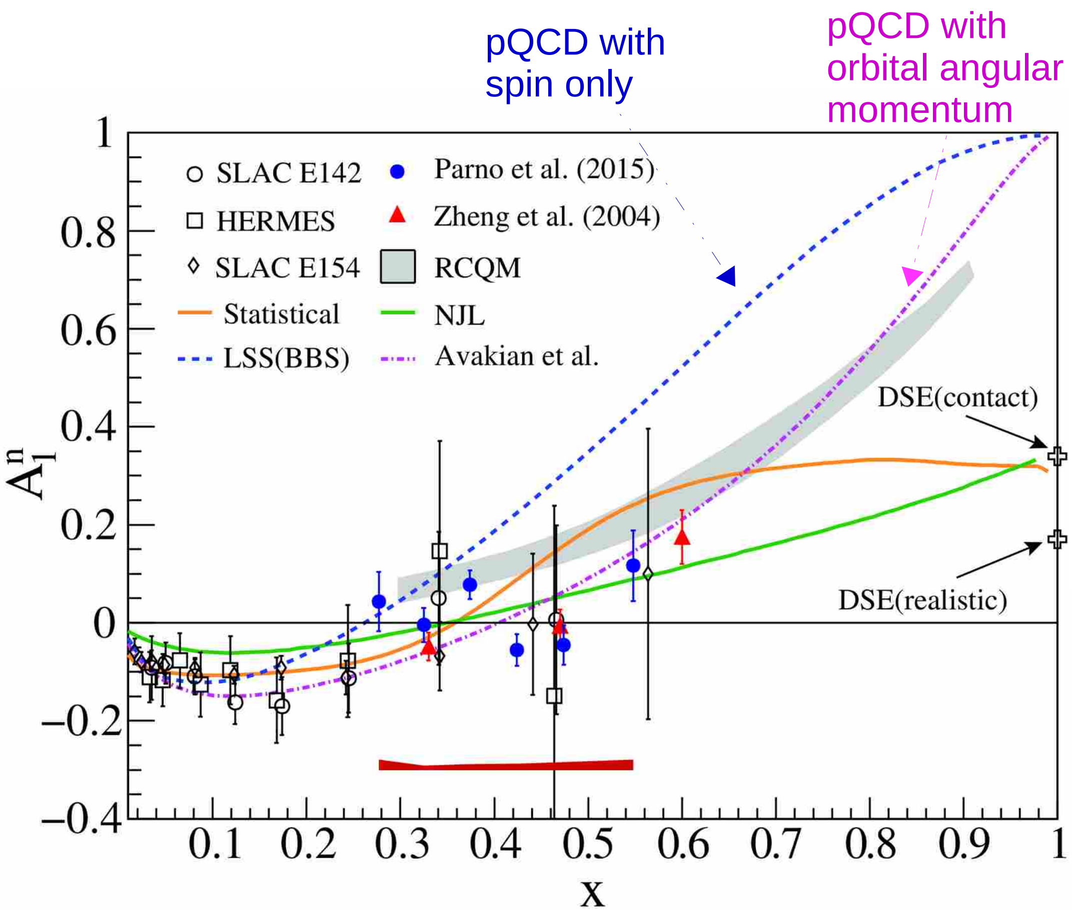
Table 1: Predictions for the x = 1 value of various models. From Craig D. Roberts et al 10.1016/j.physletb.2013.09.038



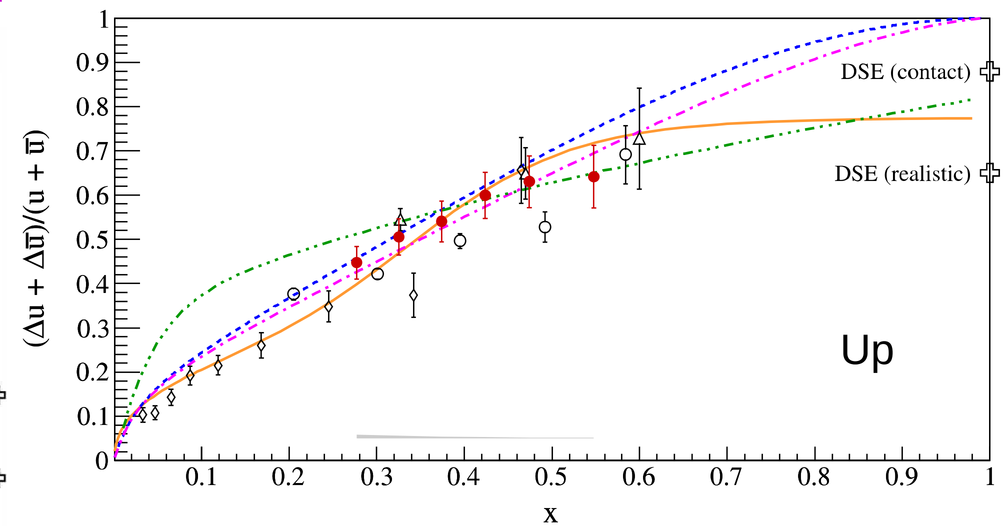
Polarized and sea quark PDFs for $Q^2 = 10$ GeV^2 from the NNPDFpol1.1 parameterization

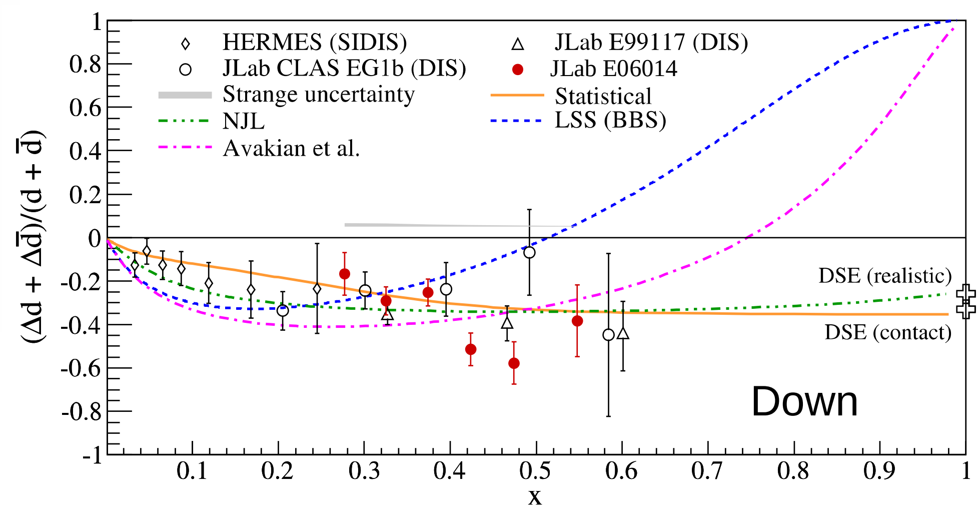
See *Nocera ER, et al. Nucl. Phys. B887:276 (2014).*

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

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

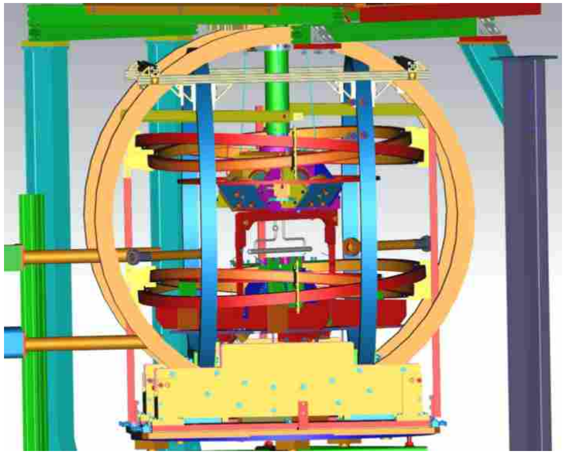
Electron Beam:

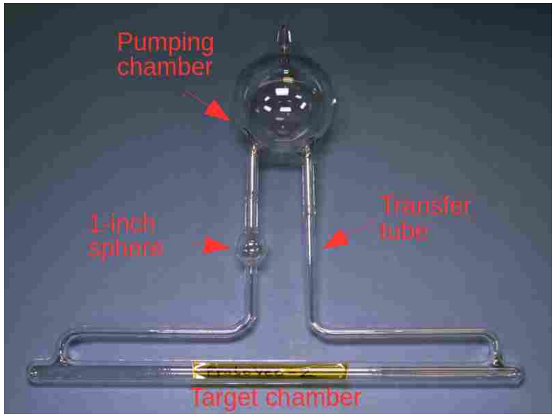
- E_{beam}=2.17 GeV (1-pass commission)
- E_{beam}=10.38 GeV (5-pass DIS production)
- Beam polarization: 85%

  (<3% uncertainty by Moller Polarimeter)
- Circular beam raster with 2.0-2.5mm radius
- < 50 ppm charge asymmetry

  (average over ~ 1–2 hr run)

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}He target:

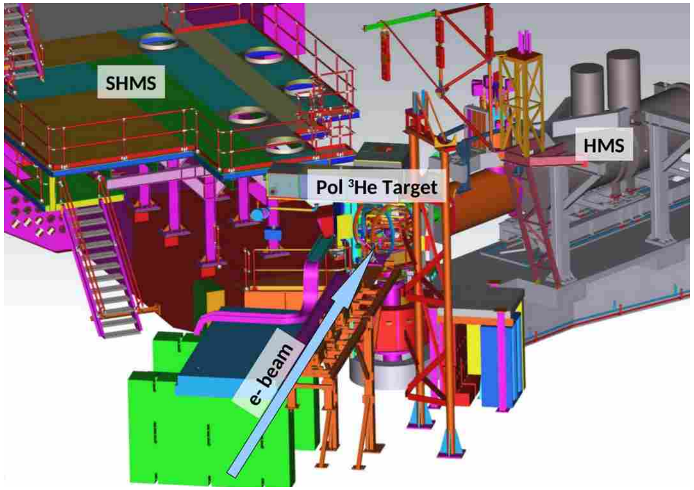
- ^{3}He production cell (40cm)
- 55–60% polarization without beam
- Reached over 50% polarization with 30 uA beam current

  (doubles performance compare to 6 GeV era)
- About 3% uncertainty for polarimetry

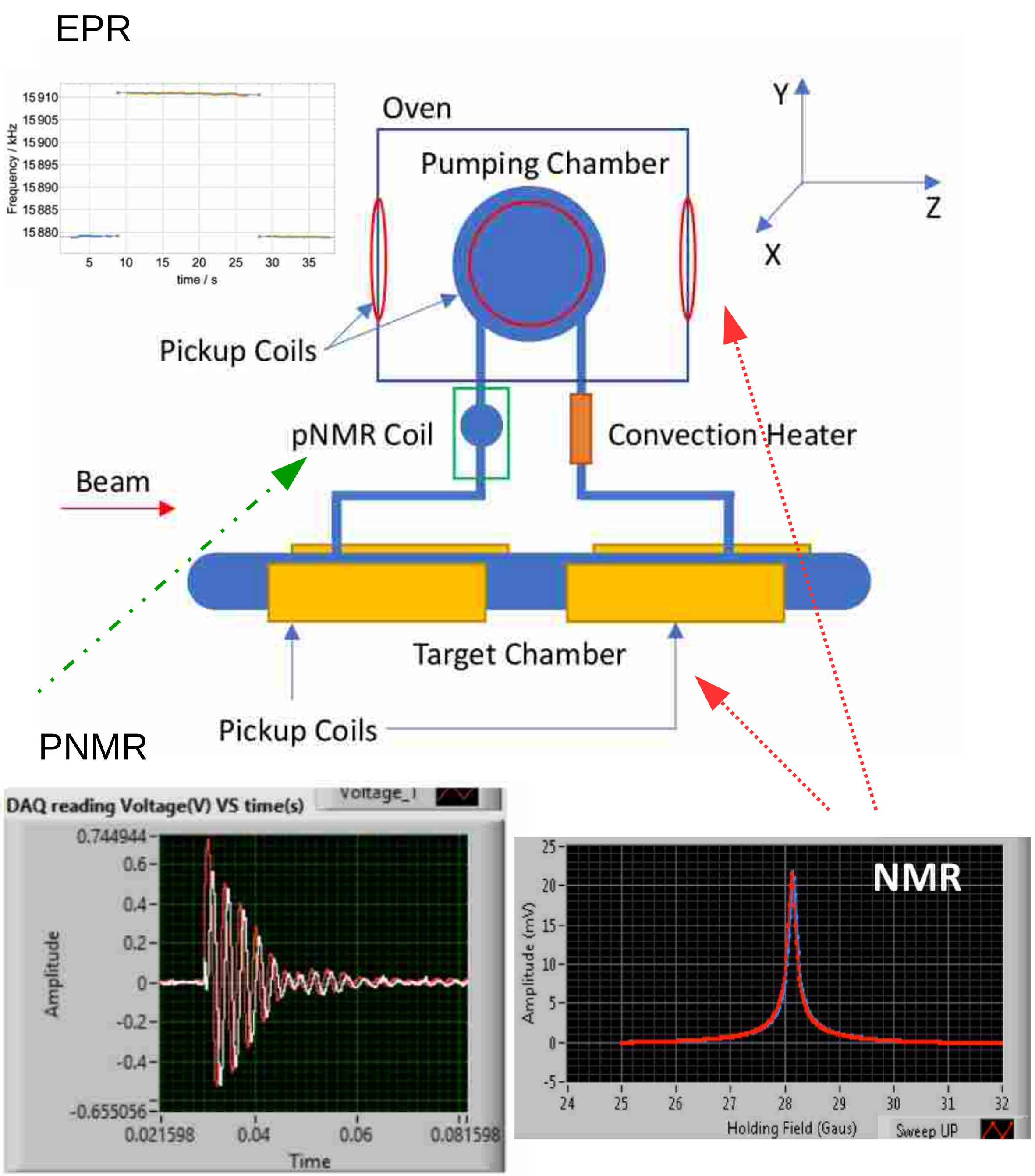
Spectrometers:

- High Momentum Spectrometer (HMS)
- Super HMS (SHMS)

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



Polarimetry for ³He in Target Cell



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

- Magnetic Resonance of ^{3}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}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}He target.

3. Electron Paramagnetic Resonance (EPR)

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

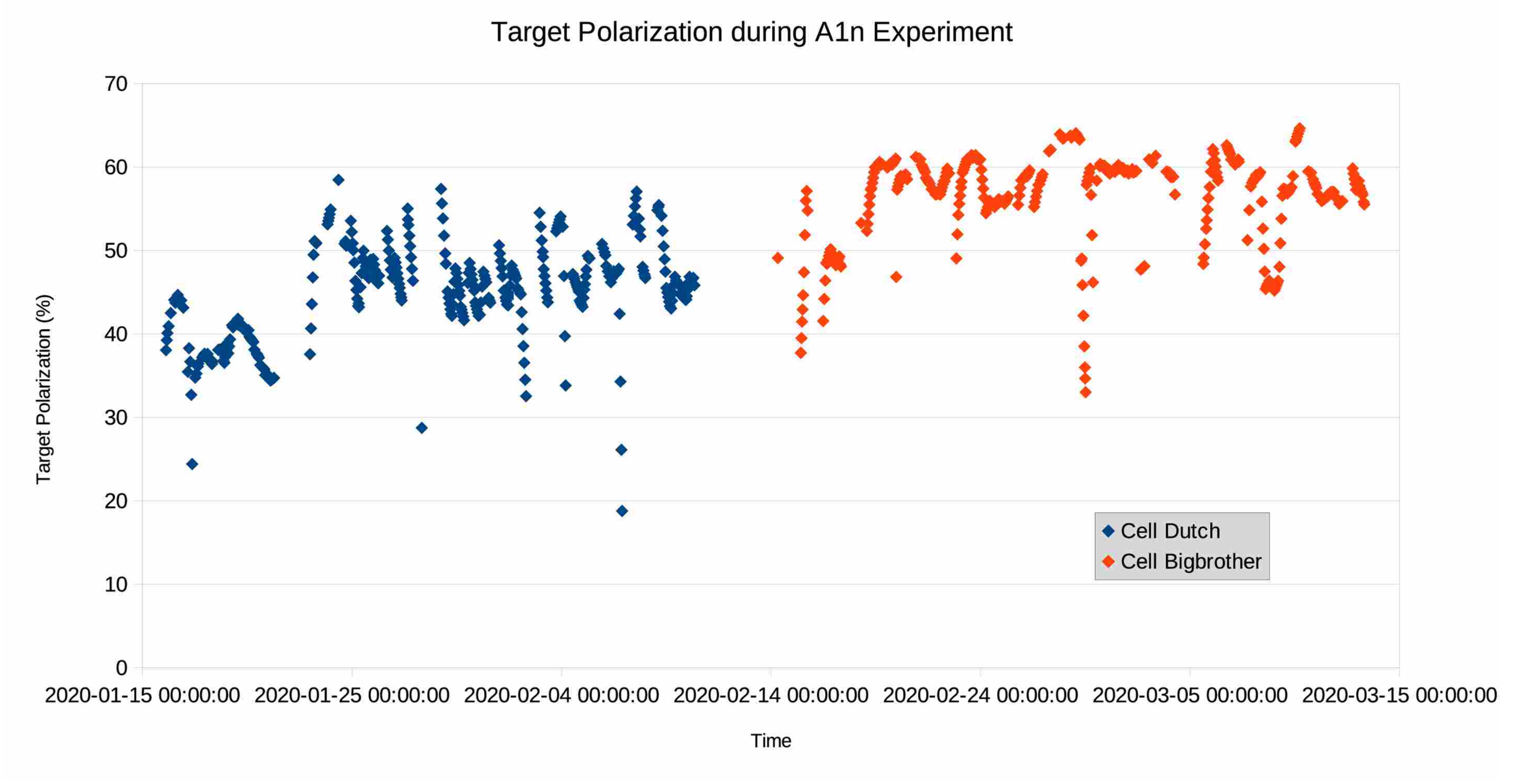
Production Cell Performance

(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
- Interpolate P_t to each production run with run time

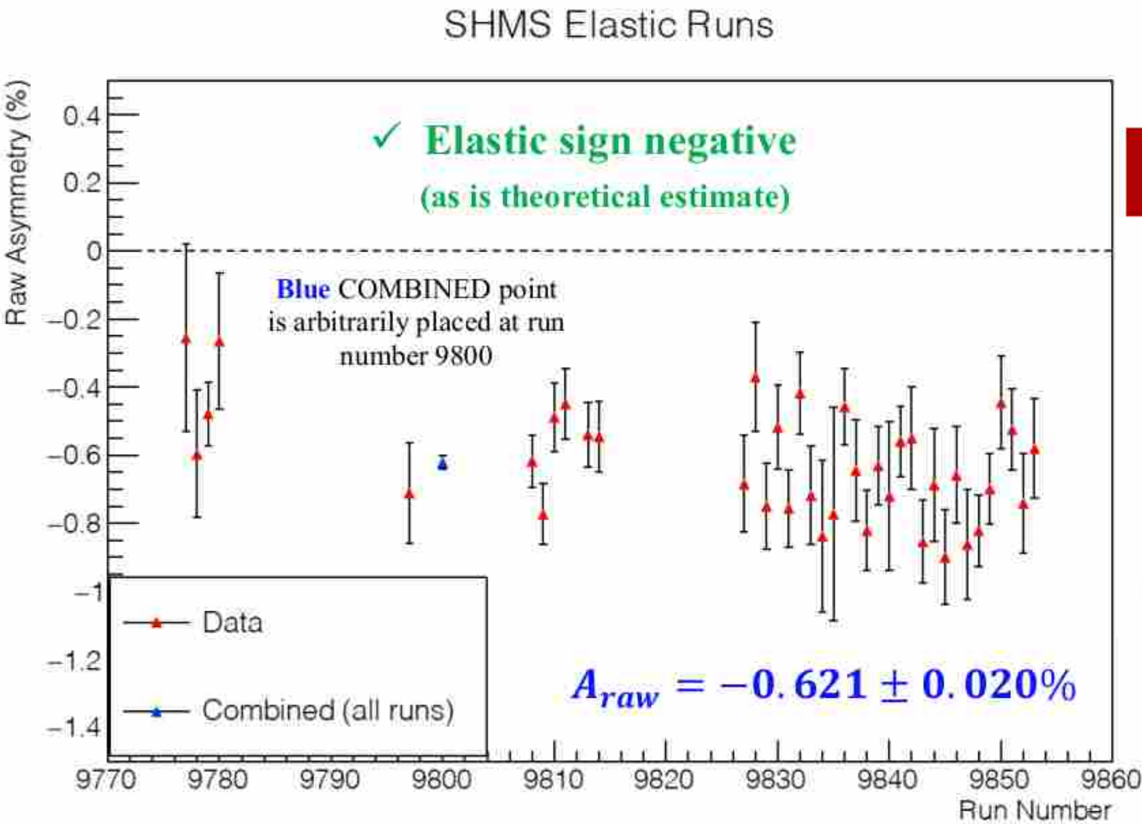
$$P_{TC}^{run_n} = P_{TC}^{init} + \left(P_{TC}^{end} - P_{TC}^{init}\right) \frac{T_{run_n}^{midpoint} - T_{nmr}^{init}}{T_{nmr}^{end} - T_{nmr}^{init}}$$



A_{para}: ^{3}He Elastic Asymmetries

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

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



e⁻ beam spin direction:

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

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

SHMS Elastic Runs:
^{3}He @ 180°
E_p= -2.1286 GeV, 8.5°

- **^{3}He 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!

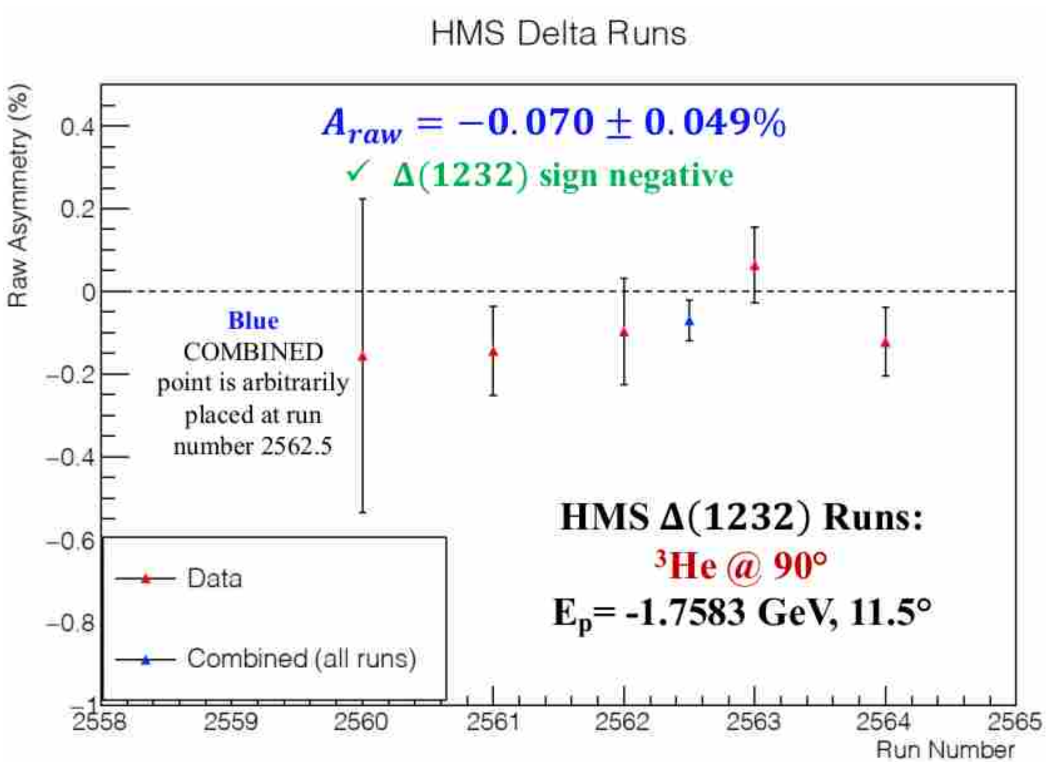
- Credit to Melanie Cardona (Temple)

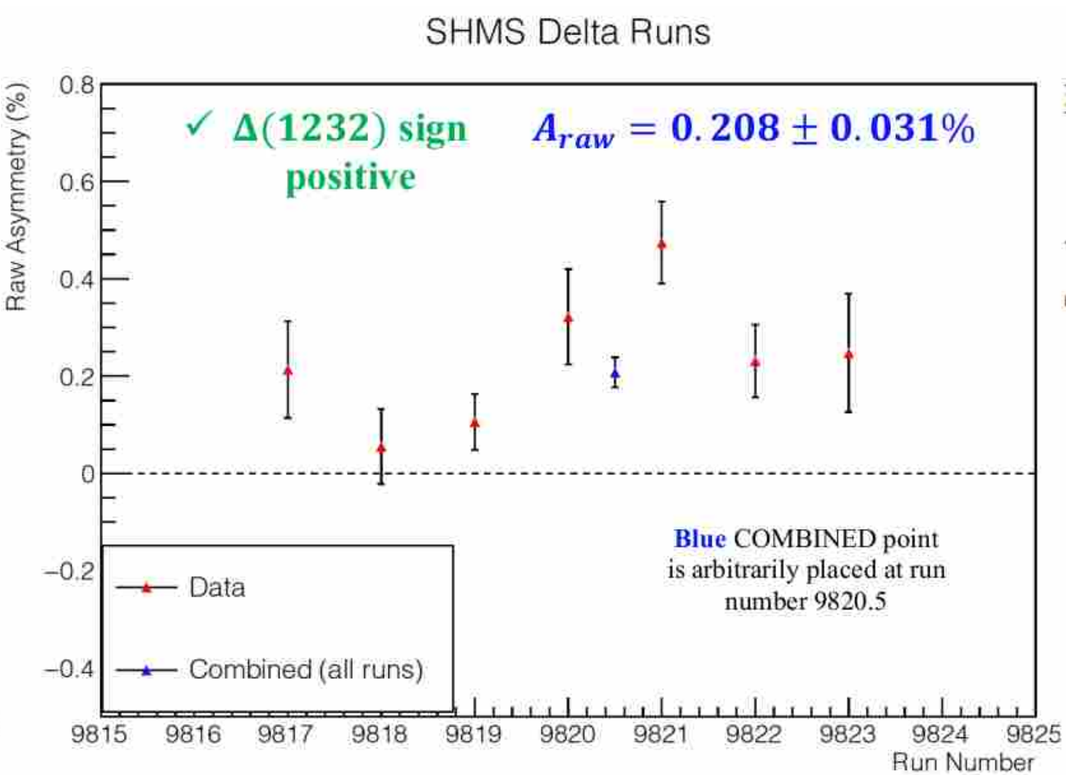
A_{perp}: ^{3}He Δ(1232) Asymmetries

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

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

(beam left → SHMS!)





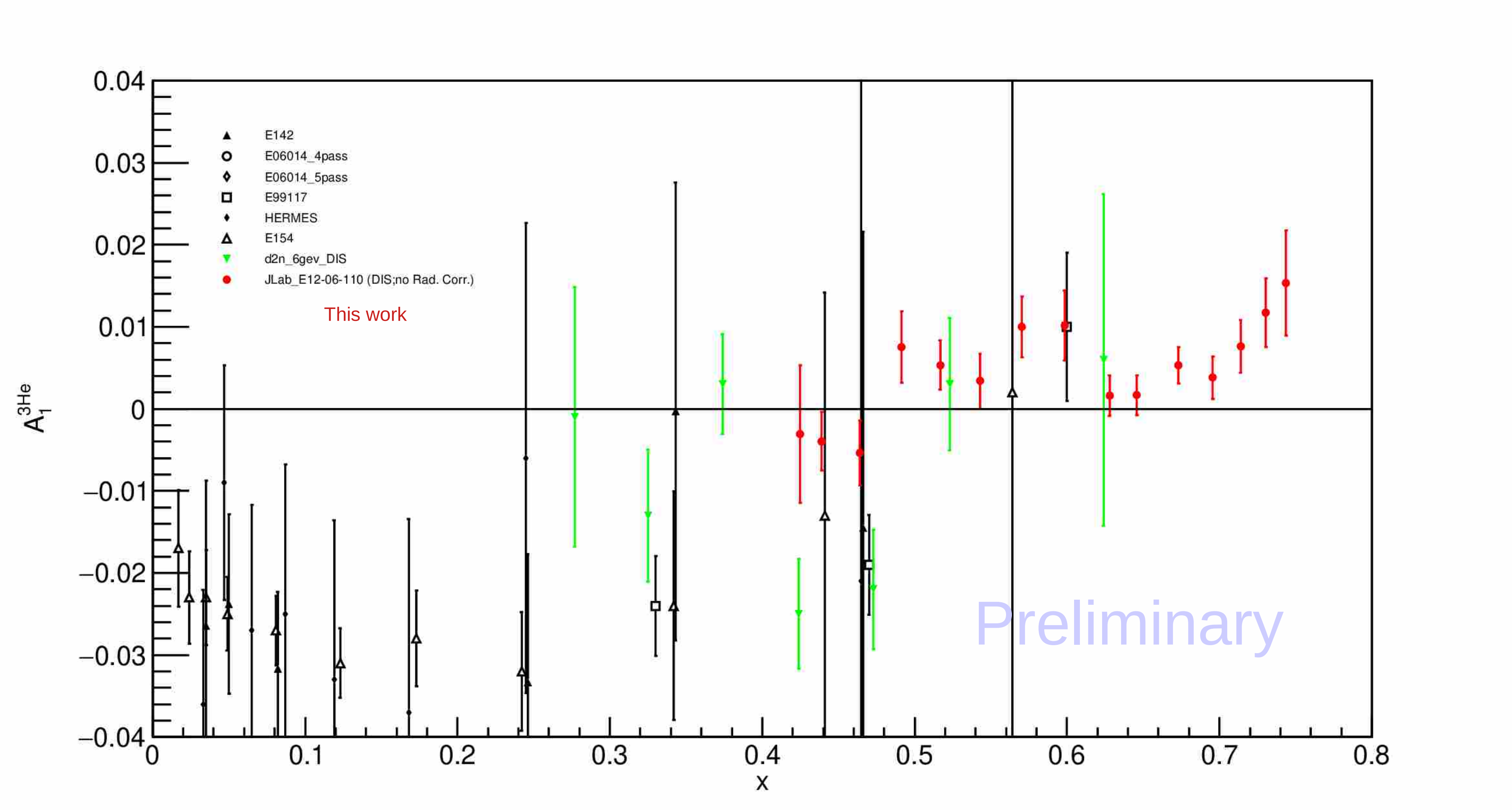
$$A_{raw} = \frac{N^+ - N^-}{N^+ + N^-}$$

SHMS Δ(1232) Runs:
^{3}He @ 90°
E_p= -1.7583 GeV, 8.5°

- Credit to Melanie Cardona (Temple)

Asymmetry A_1^{3He}

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

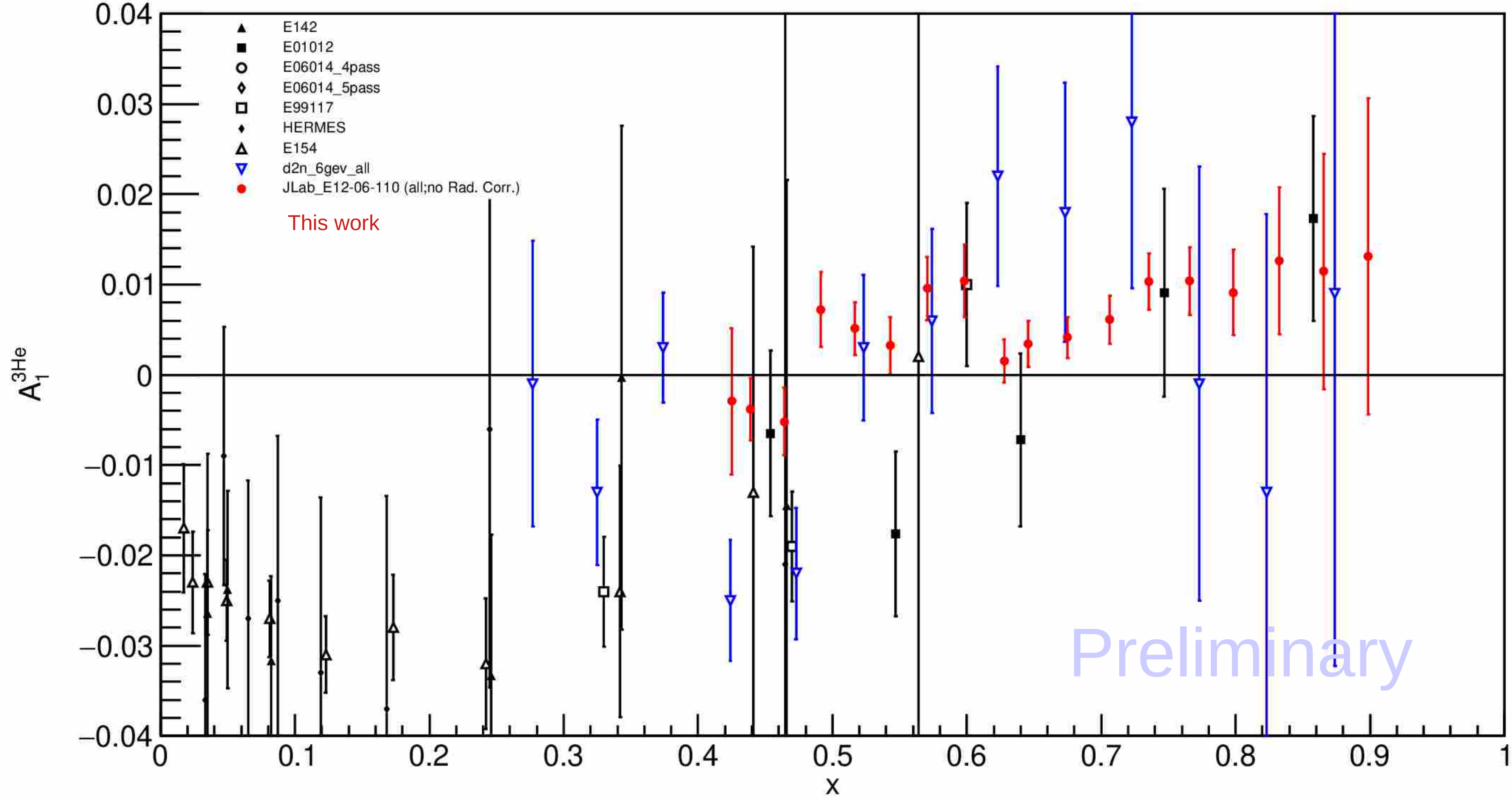


Note:

- Subscript “DIS” for W>2 GeV cut applied

Asymmetry A_1^{3He}

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



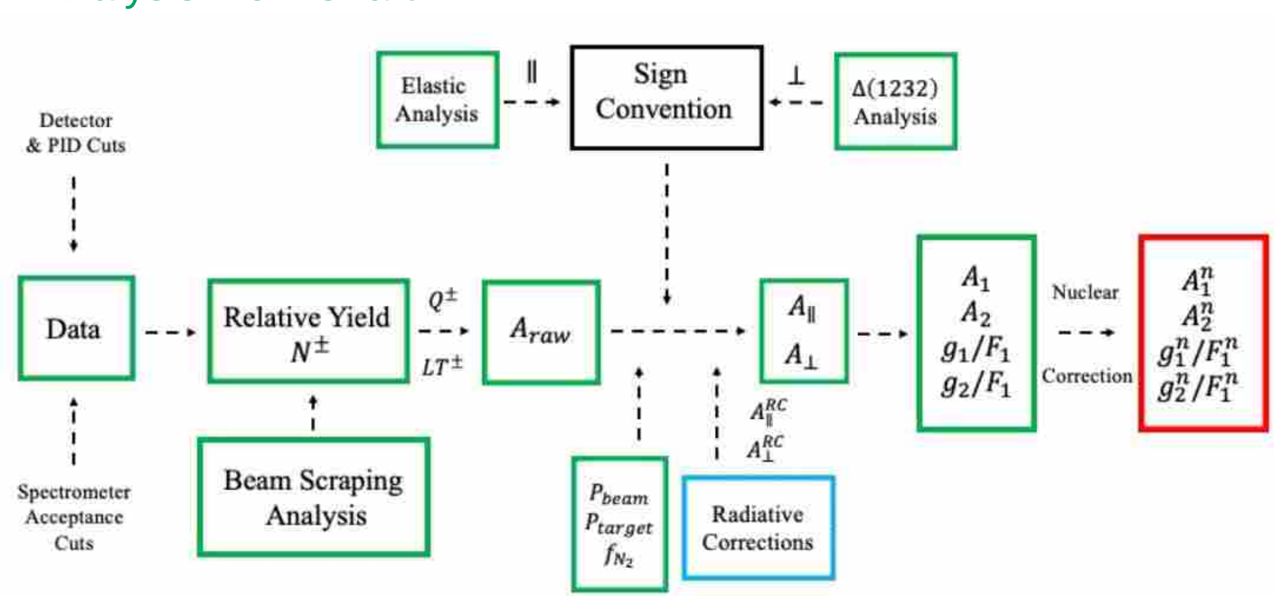
Note:

- Subscript "all" for no Wcuts

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 ^{3}He target for 12 GeV era in JLab Hall C. The target reached the expected performance with over 50% ^{3}He 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 Δu/u (Δd/d) for large x region.

Analysis Flow Chart



- Radiative corrections in progress
- Nuclear corrections remain to do

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. Nycz, 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

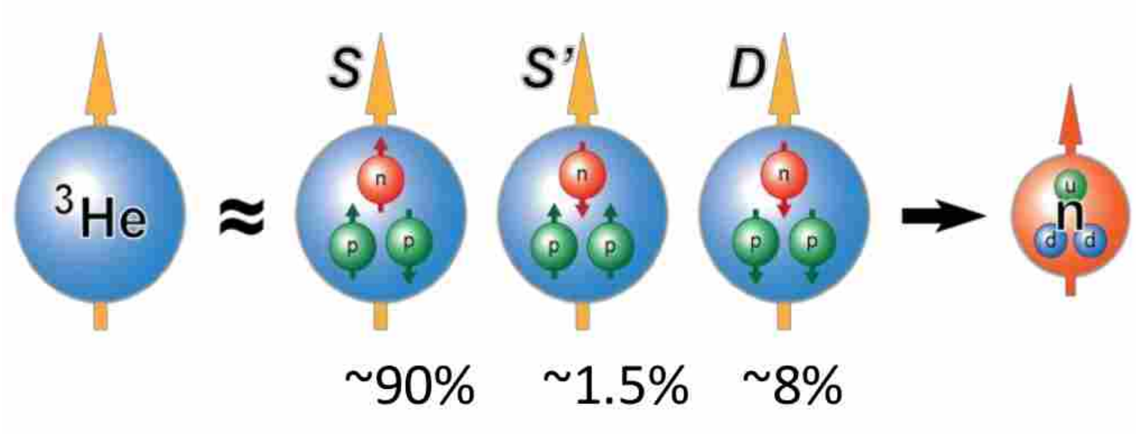
PhD Candidates | Spokespeople

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

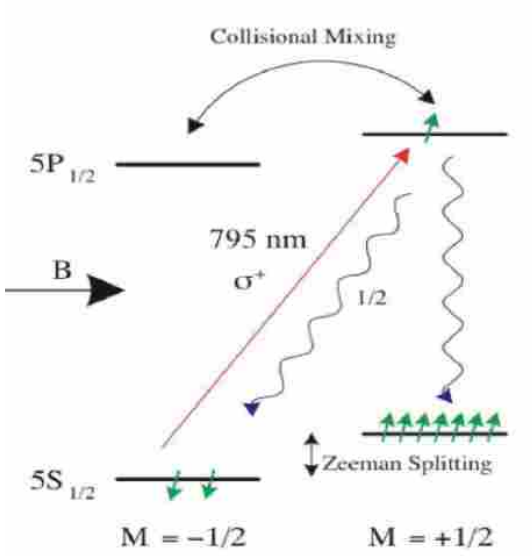
Backup Slides

Introduction to ^{3}He Polarization

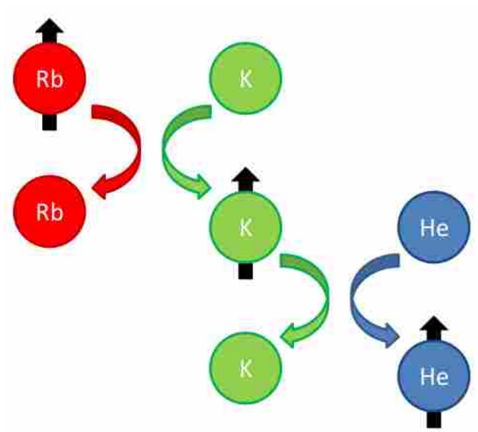


- Polarized target for study the spin structure of nucleon.
- Free neutron mean lifetime: 880.2 s.
- The unpaired neutron carries the majority of the ^{3}He nucleus polarization.
- Polarized ^{3}He is a good effective polarized neutron target.

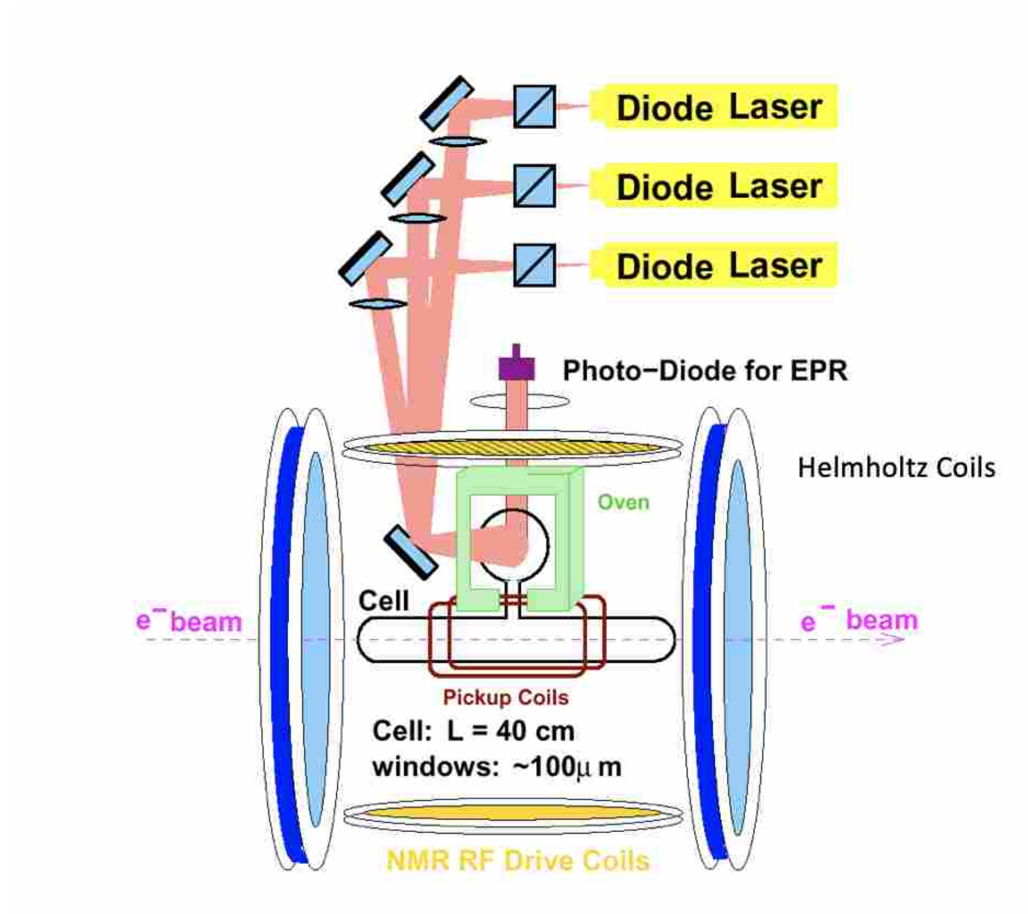
Spin Exchange Optical Pumping
(SEOP)



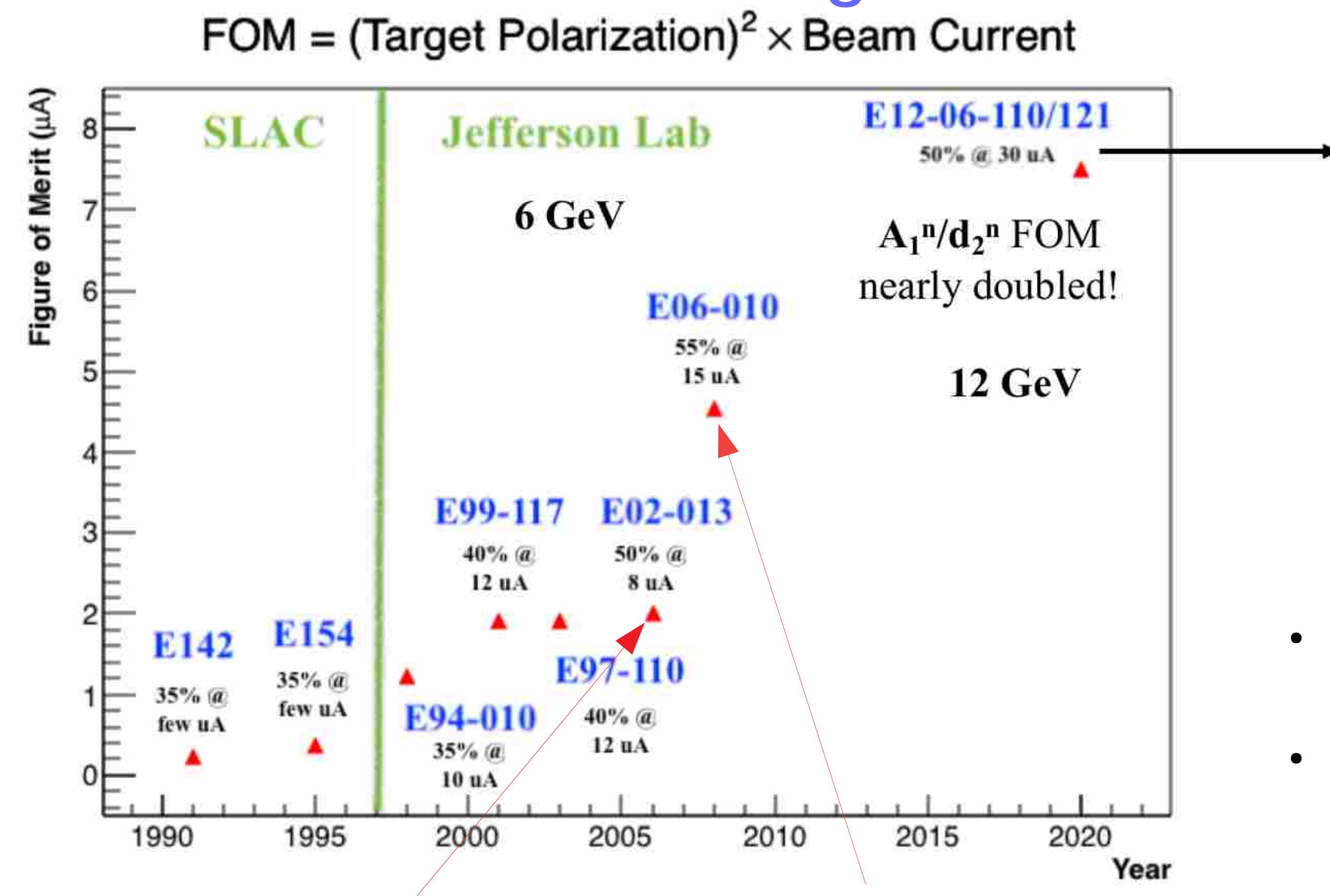
1. Optical Pumping

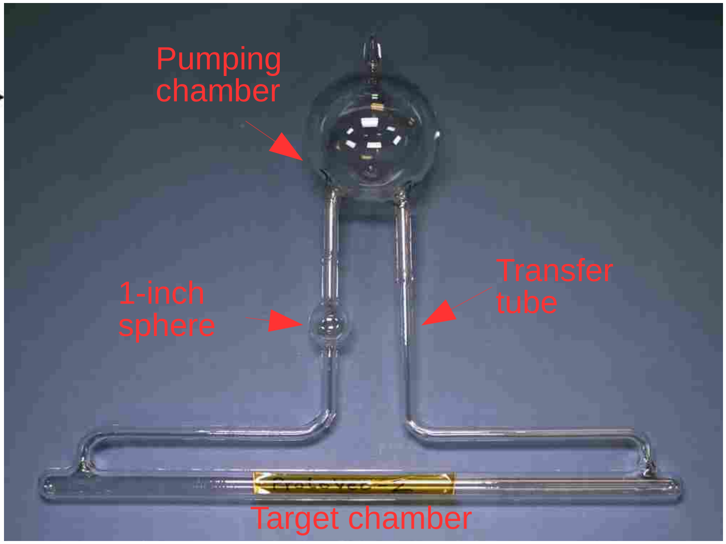


2. Spin Exchange



Polarized ^{3}He Targets Performance Evolution





- 12 GeV era Target Cell:

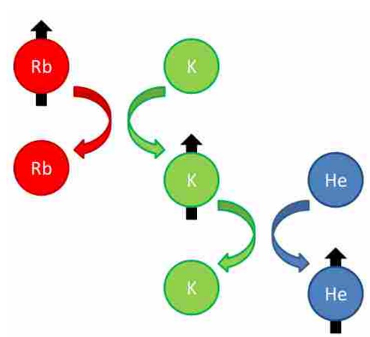
  Target chamber length: 40 cm
- Beam Current: 30uA

  Reached over 50% in beam polarization

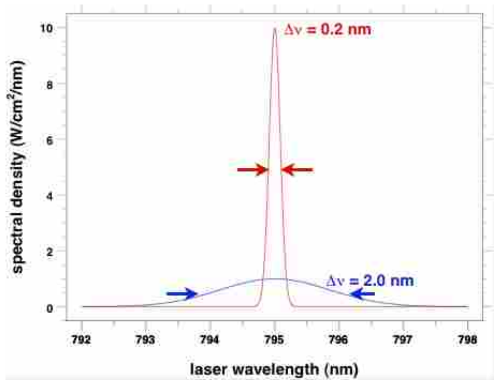
  Luminosity: ~ 2.2×10^{36} $cm^{-2}s^{-1}$
- Convection Cell (instead of diffusion cells used in the 6 GeV era)

  → convection allows for more uniform polarization between target and pumping chamber

G_E^n (E02-013):
Started to use Rb/K hybrid alkali cell.



Transversity (E06-010):
Started to use narrow band laser.



Sign Correction
(based on Melanie's Notes)

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

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

e⁻ spin direction:

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

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] $N^+ \rightarrow \vec{e}^-$ anti-‖ $^3\overrightarrow{He}$

$$A_{\parallel} \equiv \frac{\sigma_{\downarrow\Uparrow} - \sigma_{\uparrow\Uparrow}}{\sigma_{\downarrow\Uparrow} + \sigma_{\uparrow\Uparrow}} = \frac{1-\epsilon}{(1-\epsilon R)W_1}\left[M(E + E'\cos\theta)G_1 - Q^2 G_2\right], \quad (1.45)$$

where $\sigma_{\downarrow\Uparrow}(\sigma_{\uparrow\Uparrow})$ 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] $N^+ \rightarrow \vec{e}^-$ anti-‖ beam direction, $^3\overrightarrow{He}$ pointing toward SHMS

$$A_{\perp} \equiv \frac{\sigma_{\downarrow\Rightarrow} - \sigma_{\uparrow\Rightarrow}}{\sigma_{\downarrow\Rightarrow} + \sigma_{\uparrow\Rightarrow}} = \frac{(1-\epsilon)E'}{(1-\epsilon R)W_1}\left[MG_1 + 2EG_2\right]\cos\theta, \quad (1.46)$$

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

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

Sign Correction
(based on Melanie's Notes)

Target Field/Spin Direction

Target Holding Field Direction	^{3}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}He spin is **opposite of the holding field**) during data-taking

Cuts for Replayed Root Files

(for HMS and SHMS)

- HMS (thph cut0):

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 (thph cut2):

Acceptance Cuts:

- -10 < P.gtr.dp < 22
- -0.035 < P.gtr.th < 0.035
- -0.029 < P.gtr.ph < 0.034
- -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 uA
- If the mean value of ibcm1 is less than 3.5 uA, skip the run for average current too low.

Get Raw Asymmetry

$$A_{raw,corr}=\frac{\frac{\sum N_i^+/\eta_{LT_i}^+}{\sum Q_i^+}-\frac{\sum N_i^-/\eta_{LT_i}^-}{\sum Q_i^-}}{\frac{\sum N_i^+/\eta_{LT_i}^+}{\sum Q_i^+}+\frac{\sum N_i^-/\eta_{LT_i}^-}{\sum Q_i^-}}$$

- For each IHWP/target_spin setting:

$$A_{raw}=\frac{\sum N_i^+-\sum N_i^-}{\sum N_i^++\sum N_i^-}$$

$$\Delta A_{raw}=\frac{1}{\sqrt{\sum N_i^++\sum N_i^-}}$$

$$\bar{N}^{+(-)}=\sum\frac{N_i^{+(-)}}{\eta_{LT_i}^{+(-)}}$$

$$\Delta A_{raw,corr}=2\sum Q^+\sum Q^-\sqrt{\frac{\bar{N}^{+2}\Delta\bar{N}^{-2}+\bar{N}^{-2}\Delta\bar{N}^{+2}}{\left(\sum Q^-\bar{N}^++\sum Q^+\bar{N}^-\right)^4}}$$

$$\Delta\bar{N}^{+(-)}=\sqrt{\sum\frac{N_i^{+(-)}}{\eta_{LT_i}^{+(-)2}}}$$

For $A_{corr}=sign*(A_{raw,corr})$ $\qquad \Delta A_{corr}=\Delta A_{raw,corr}$

- For combined asymmetry, combine each IHWP/target_spin setting:

$$(A_{corr})_{comb}=\frac{\sum\frac{(A_{corr})_{i_{set}}}{(\Delta A_{corr})_{i_{set}}^2}}{\sum\frac{1}{(\Delta A_{corr})_{i_{set}}^2}}$$

$$(\Delta A_{corr})_{comb}=\sqrt{\frac{1}{\sum\frac{1}{(\Delta A_{corr})_{i_{set}}^2}}}$$

Get Raw Asymmetry Notes

In order to avoid dividing by zero in the calculation:

- For each IHWP/target_spin setting, If $\sum\left(N^{+}+N^{-}\right)_{i_{set}}=0$, set:

$$\frac{\left(A_{corr}\right)}{\left(\Delta A_{corr}\right)^{2}}=0 \qquad \frac{1}{\left(\Delta A_{corr}\right)^{2}}=0$$

- If $\sum\frac{1}{\left(\Delta A_{corr}\right)_{i_{set}}^{2}}=inf$,then log: $\left(A_{corr}\right)_{comb}=0$ $\left(\Delta A_{corr}\right)_{comb}=0$

(will not plot these values)

- For HMS kine3 and SHMS kineC , calculate raw Asym before and after the Wien flip, then combine them together.

Get Phy Asymmetry

$$A_{raw} = \frac{\sum N_i^+ - \sum N_i^-}{\sum N_i^+ + \sum N_i^-}$$

$$\Delta A_{raw} = \frac{1}{\sqrt{\sum N_i^+ + \sum N_i^-}}$$

- For each IHWP/target_spin setting:

$$\bar{N}^{+(-)} = \sum \frac{N_i^{+(-)}}{P_{t_i} P_{b_i} \eta_{L T_i}^{+(-)}}$$

$$A_{phys,uncorr} = \left(\frac{\frac{\sum N_i^+ / P_{t_i} P_{b_i} \eta_{L T_i}^+}{\sum Q_i^+} - \frac{\sum N_i^- / P_{t_i} P_{b_i} \eta_{L T_i}^-}{\sum Q_i^-}}{\frac{\sum N_i^+ / P_{t_i} P_{b_i} \eta_{L T_i}^+}{\sum Q_i^+} + \frac{\sum N_i^- / P_{t_i} P_{b_i} \eta_{L T_i}^-}{\sum Q_i^-}} \right) / (D_{N2})$$

$$\Delta \bar{N}^{+(-)} = \sqrt{\sum \frac{N_i^{+(-)}}{P_{t_i}^2 P_{b_i}^2 \eta_{L T_i}^{+(-)2}}}$$

$$\Delta A_{phy_{stat}} = \frac{2}{D_{N2}} \sum Q^+ \sum Q^- \sqrt{\frac{\bar{N}^{+2} \Delta \bar{N}^{-2} + \bar{N}^{-2} \Delta \bar{N}^{+2}}{\left(\sum Q^- \bar{N}^+ + \sum Q^+ \bar{N}^-\right)^4}}$$

For $A_{phy} = sign * (A_{phy,uncorr})$ $\quad \Delta A_{phy} = \Delta A_{phy,uncorr}$

- For combined asymmetry, combine each IHWP/target_spin setting:

$$(A_{phy})_{comb} = \frac{\sum \frac{(A_{phy})_{i_{set}}}{(\Delta A_{phy})_{i_{set}}^2}}{\sum \frac{1}{(\Delta A_{phy})_{i_{set}}^2}}$$

$$(\Delta A_{phy_{stat}})_{comb} = \sqrt{\frac{1}{\sum \frac{1}{(\Delta A_{phy_{stat}})_{i_{set}}^2}}}$$

Get Physics Asymmetry

In order to avoid dividing by zero in the calculation:

- For each IHWP/target_spin setting, If $\sum (N^+ + N^-)_{i_{set}} = 0$, set:

$$\frac{(A_{phy})}{(\Delta A_{phy})^2} = 0 \qquad \frac{1}{(\Delta A_{phy})^2} = 0$$

- If $\sum \frac{1}{(\Delta A_{phy})^2_{i_{set}}} = inf$,then log: $(A_{phy})_{comb} = 0$ $(\Delta A_{phy})_{comb} = 0$

(will not plot these values)

- For HMS kine3 and SHMS kineC , calculate Asym before and after the Wien flip, then combine them together.

- D_{N2} used are the combined Nitrogen Dilution factor.

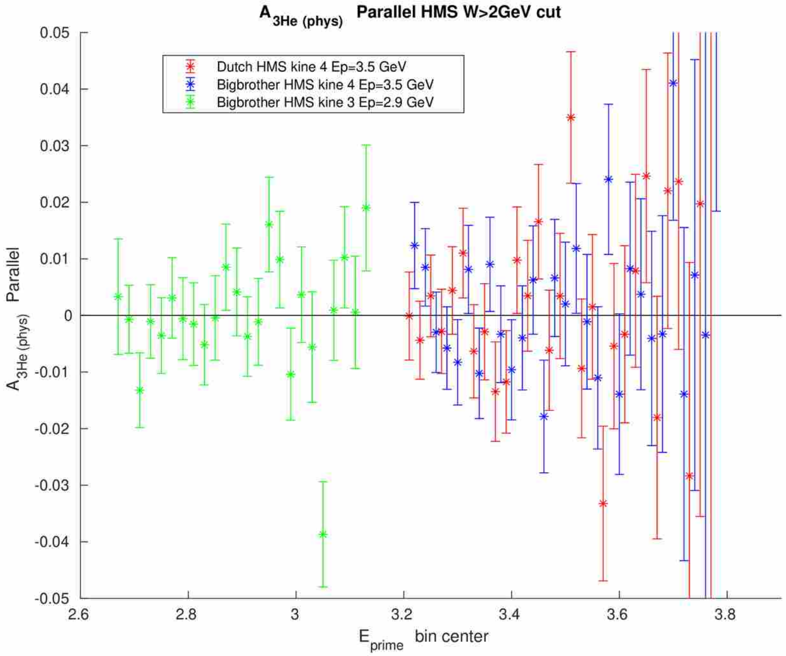
$$\Delta A_{phy_{sys}} = A_{phys} \sqrt{\left(\frac{\Delta D_{N2}}{D_{N2}}\right)^2 + \left(\frac{\Delta P_{t_{sys}}}{P_t}\right)^2 + \left(\frac{\Delta P_{b_{sys}}}{P_b}\right)^2 + \left(\frac{\Delta A_{raw_{sys}}}{A_{raw}}\right)^2}$$

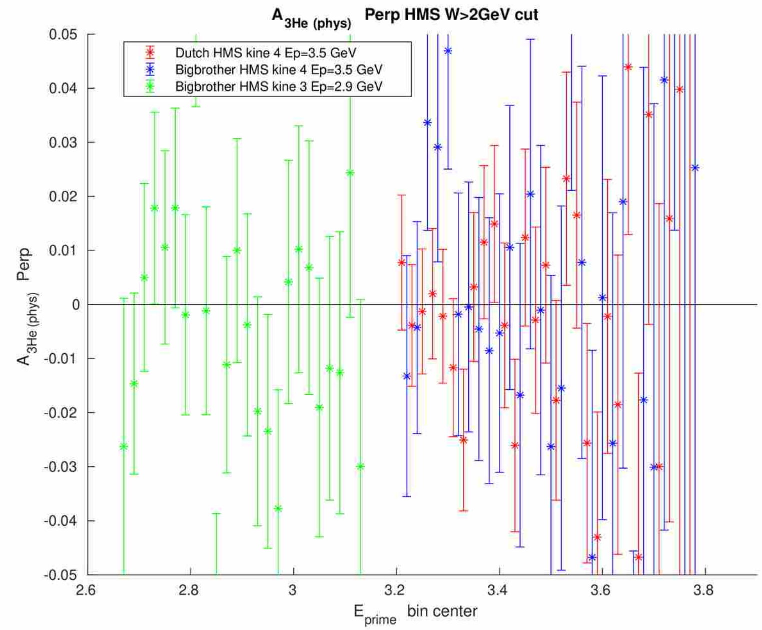
- Obtain A_{phy_sys} after combining both spec (same ΔD_{N2}, ΔP_t, ΔP_b but different ΔA_{raw_sys} for two spec)

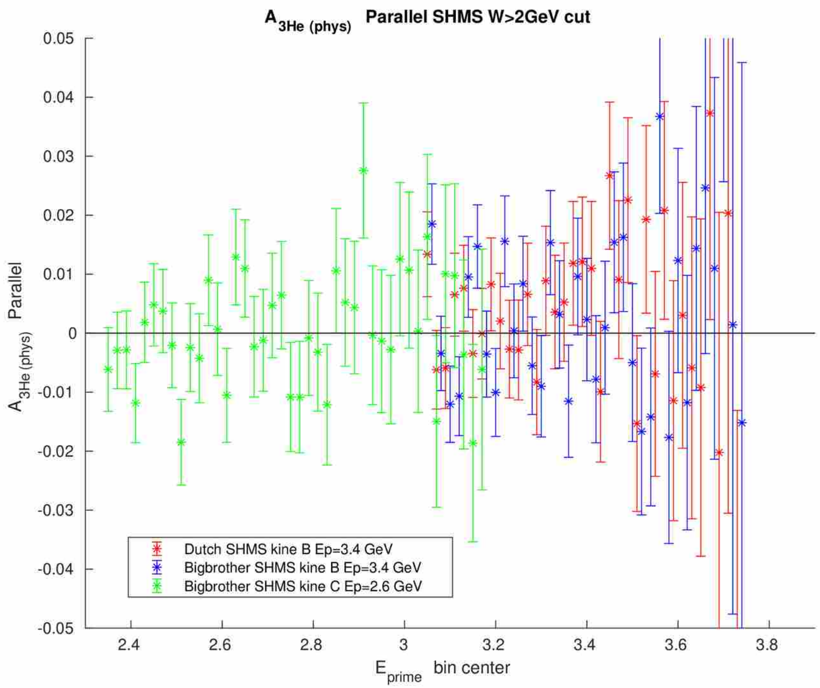
A_{Phys}^{3He} (with W>2 GeV cut; for each Cell)

- Ep bin width=20 MeV

$$A_{phy} = \frac{A_{raw}}{D_{N_2} P_b P_t}$$







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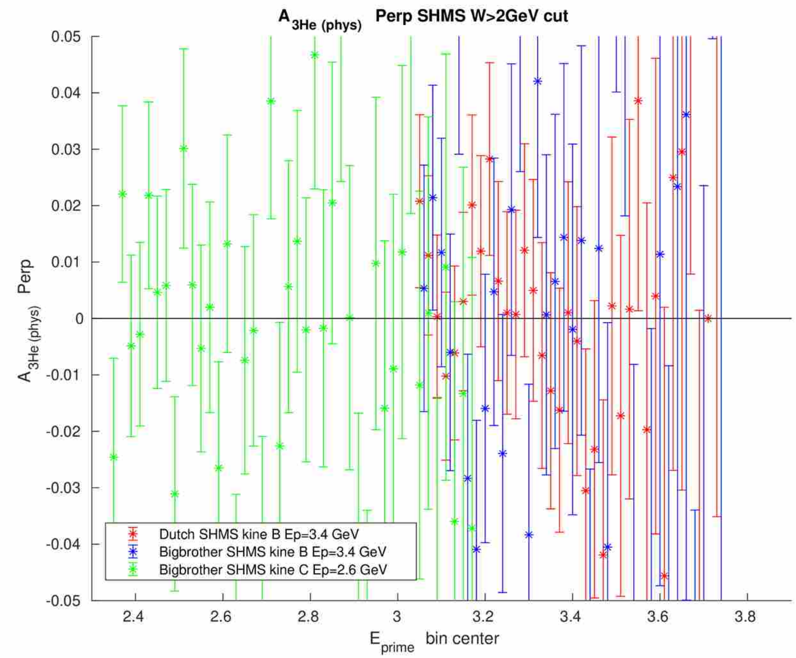
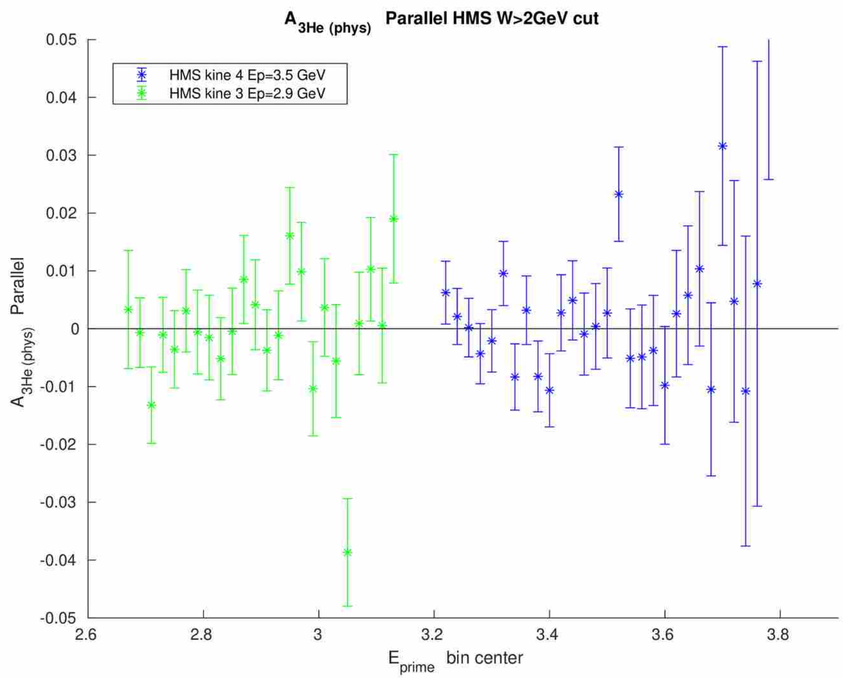
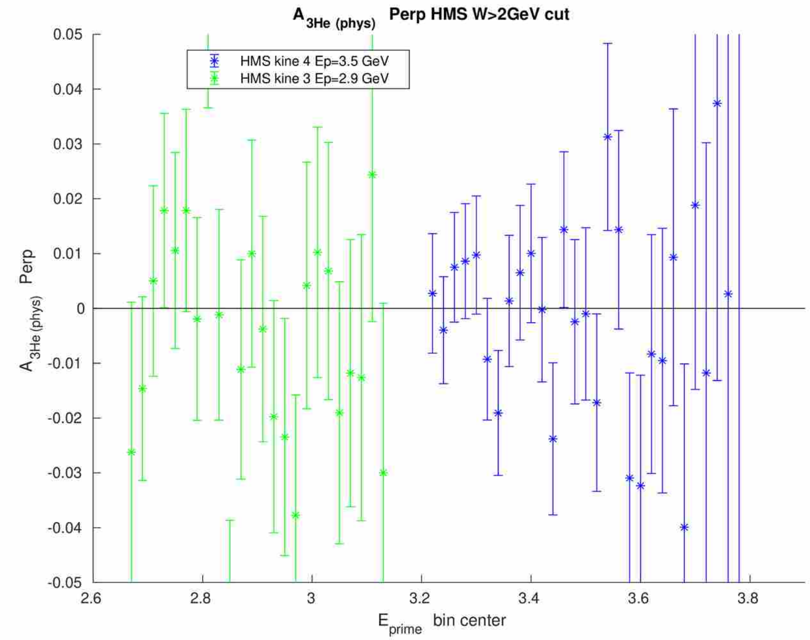


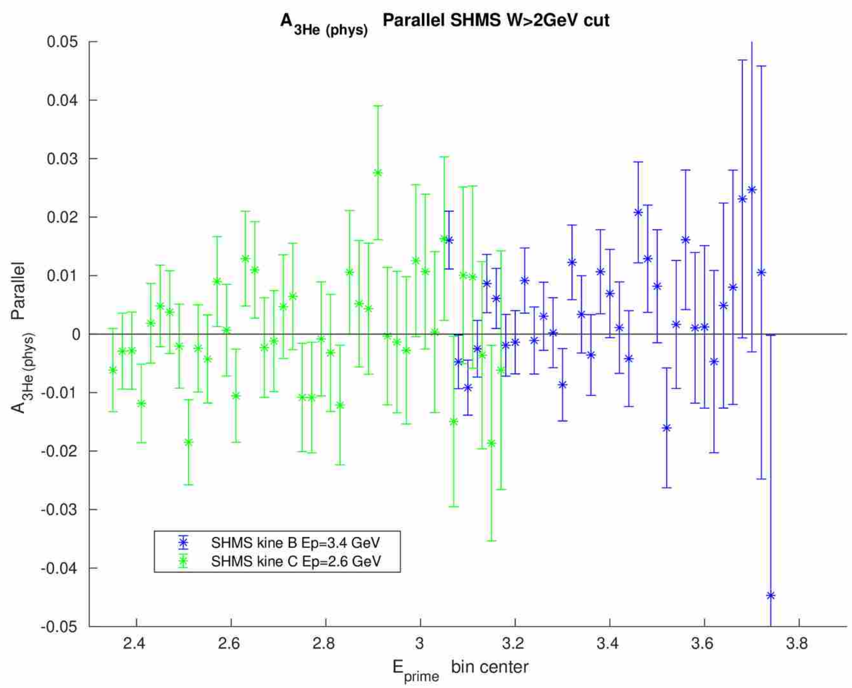
A_{Phys}^{3He}
(with W>2 GeV cut; combine two Cell)

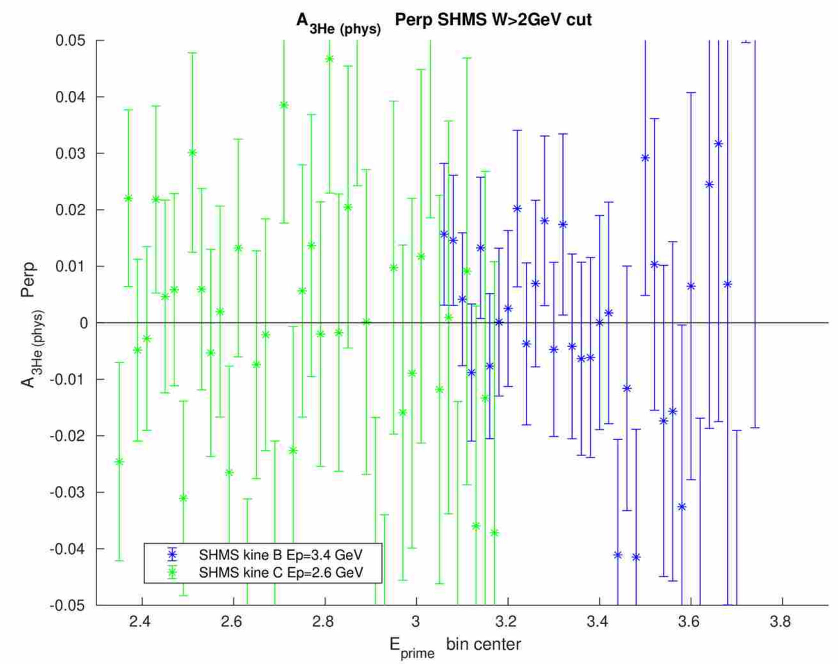
- Ep bin width=20 MeV

$$A_{phy} = \frac{A_{raw}}{D_{N_2} P_b P_t}$$









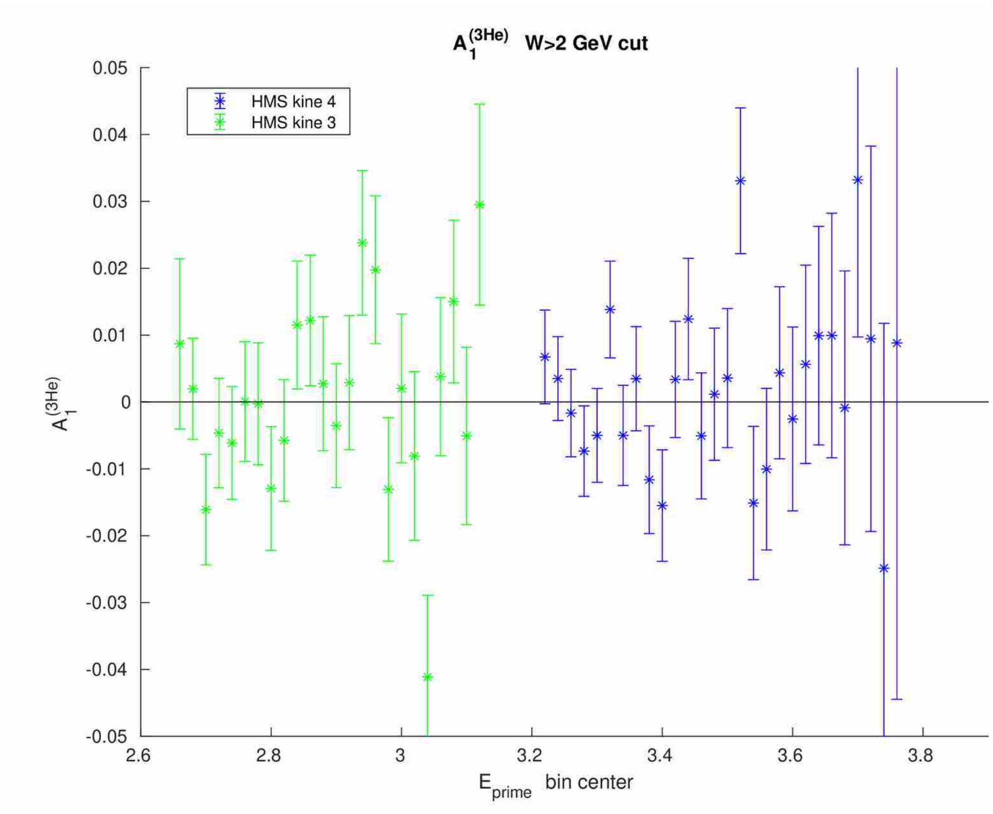
ture from

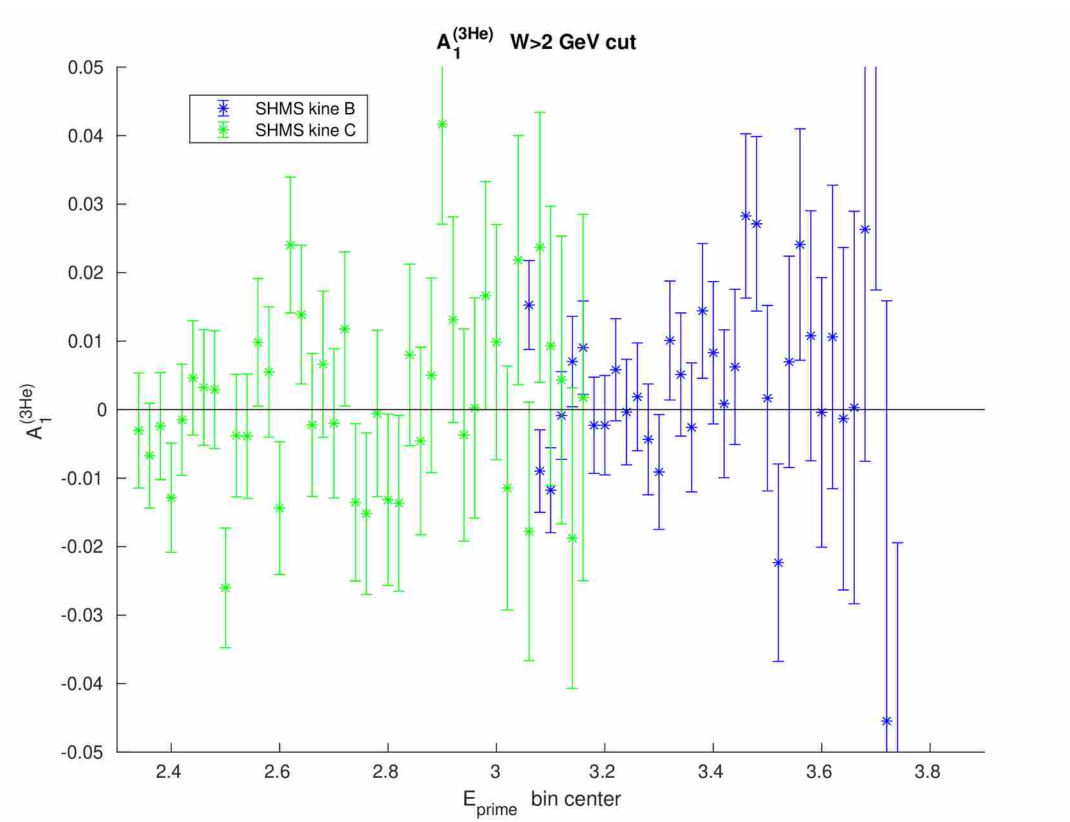
A_1^{3He}

(with W>2 GeV cut; combine two Cell)

- Ep bin width=20 MeV

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



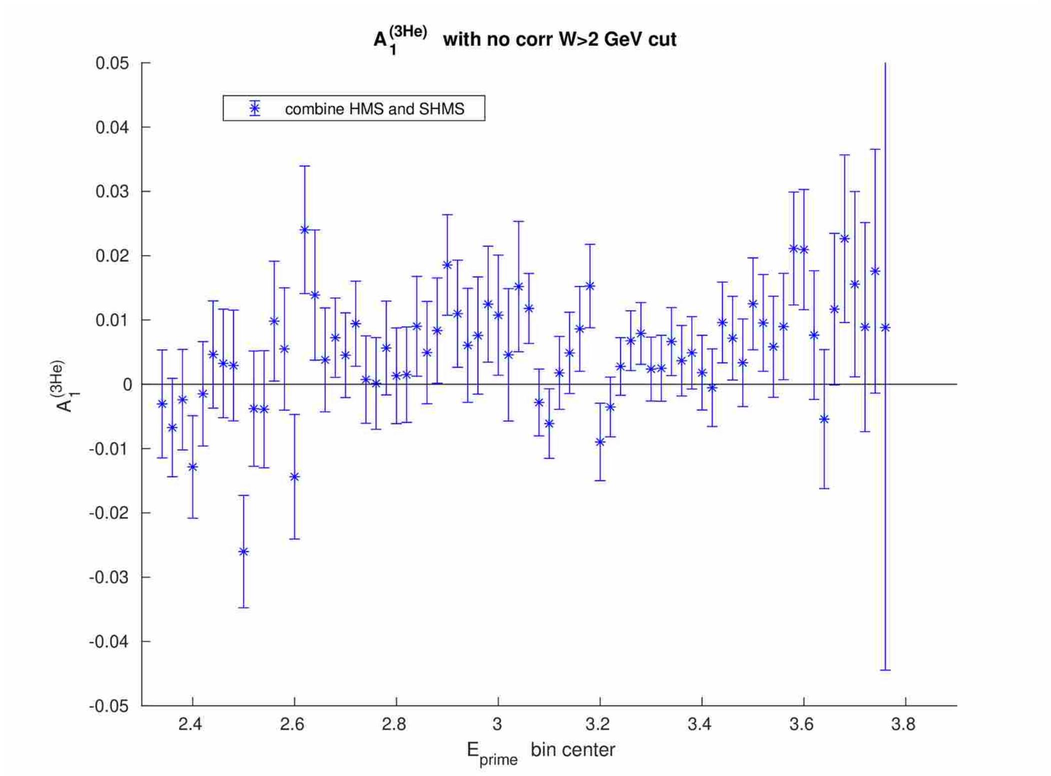


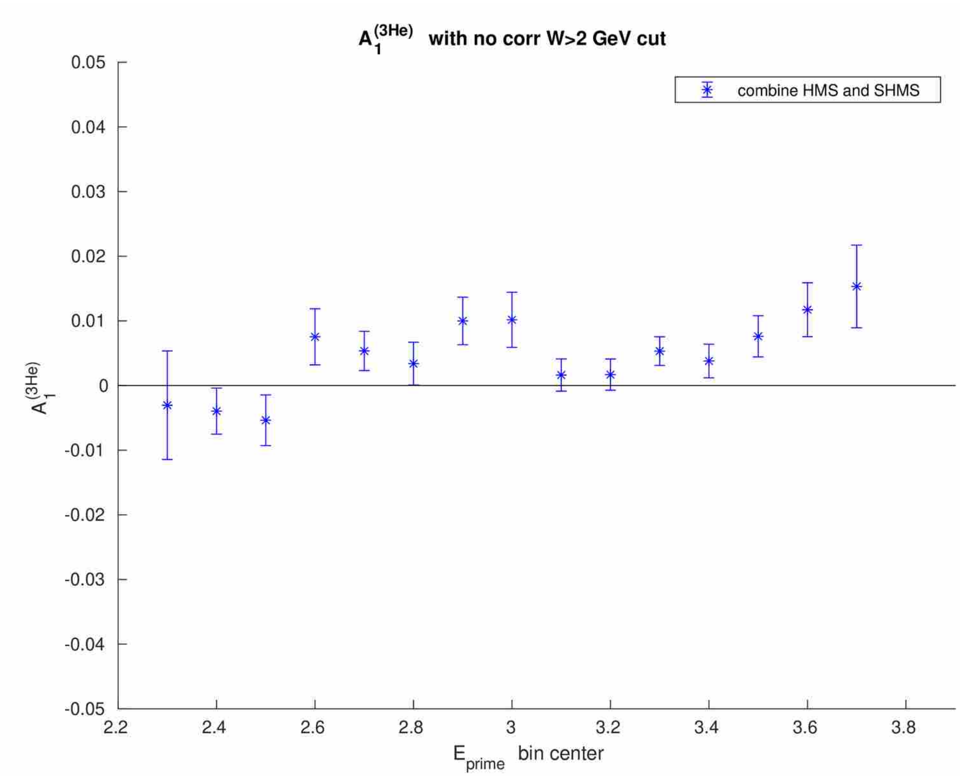
Statistical Error Propagation:

$$\Delta A_1(stat) = \sqrt{\left(\frac{\Delta A_{para}(stat)}{D(1+\eta\xi)}\right)^2 + \left(\frac{\eta \Delta A_{perp}(stat)}{d(1+\eta\xi)}\right)^2}$$

A_1^{3He}

(with W>2 GeV cut; combine two spec)





- Ep bin width=20 MeV
- Ep bin width=100 MeV

$$(A_1)_{comb} = \frac{\sum \frac{(A_1)_i}{(\Delta A_1)_i^2}}{\sum \frac{1}{(\Delta A_1)_i^2}}$$

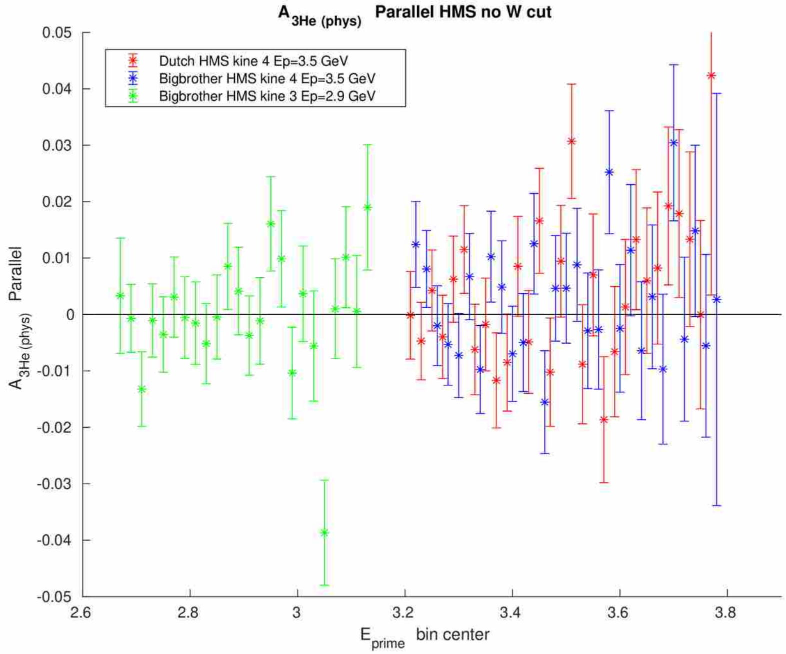
$$(\Delta A_{1_{stat}})_{comb} = \sqrt{\frac{1}{\sum \frac{1}{(\Delta A_{1_{stat}})_i^2}}}$$

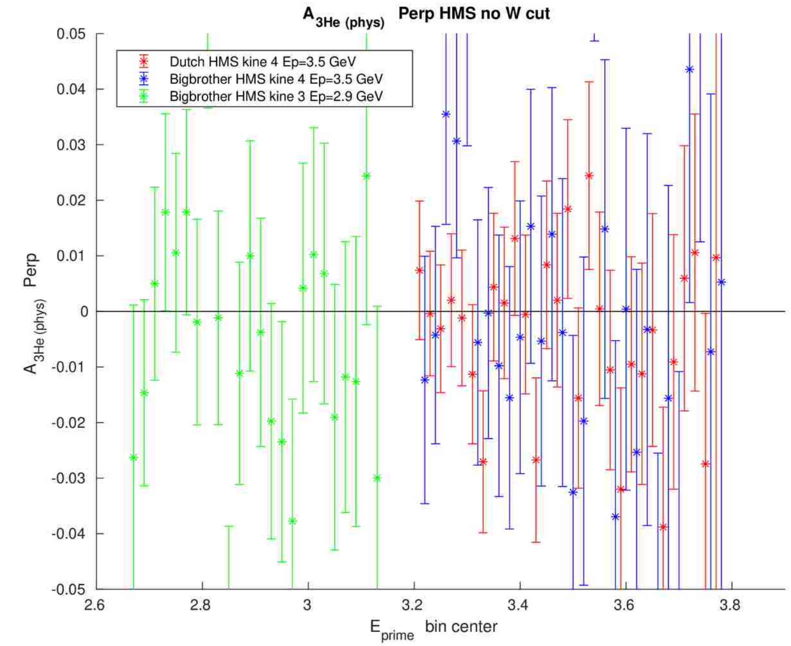
- For SHMS low mom and hi mom overlapping Ep bins combine A and dA first
- Then combine SHMS Ep bins with corresponding HMS Ep bins.
- Final step is to combine Ep_bin=20 MeV into Ep_bin=100 MeV

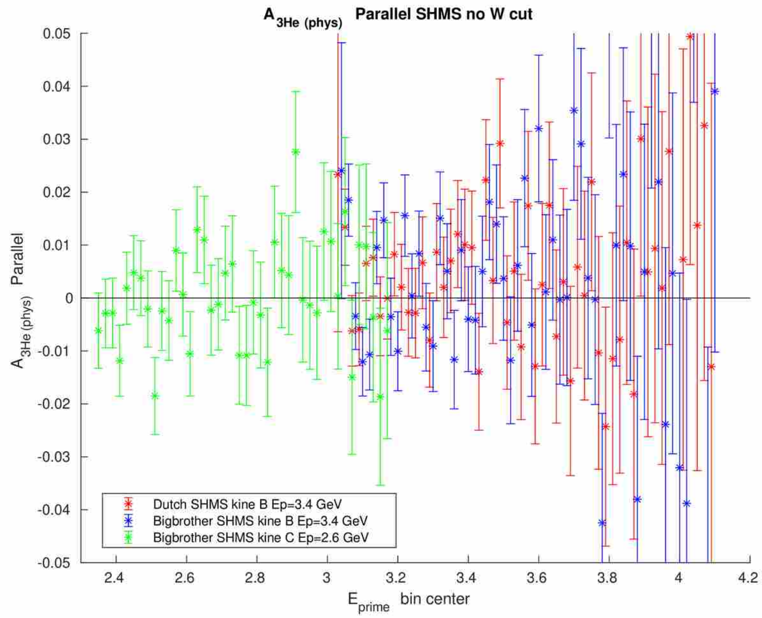
A_{Phys}^{3He} (no W cut; for each Cell)

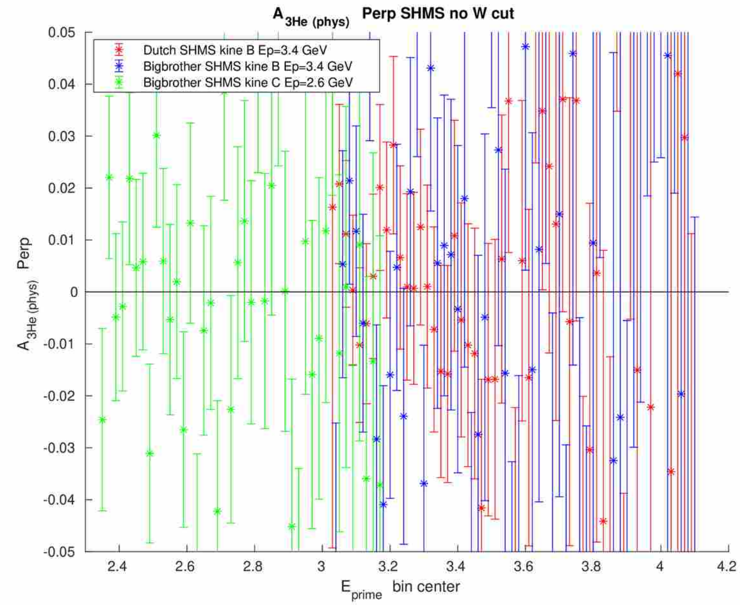
- Ep bin width=20 MeV

$$A_{phy} = \frac{A_{raw}}{D_{N_2} P_b P_t}$$





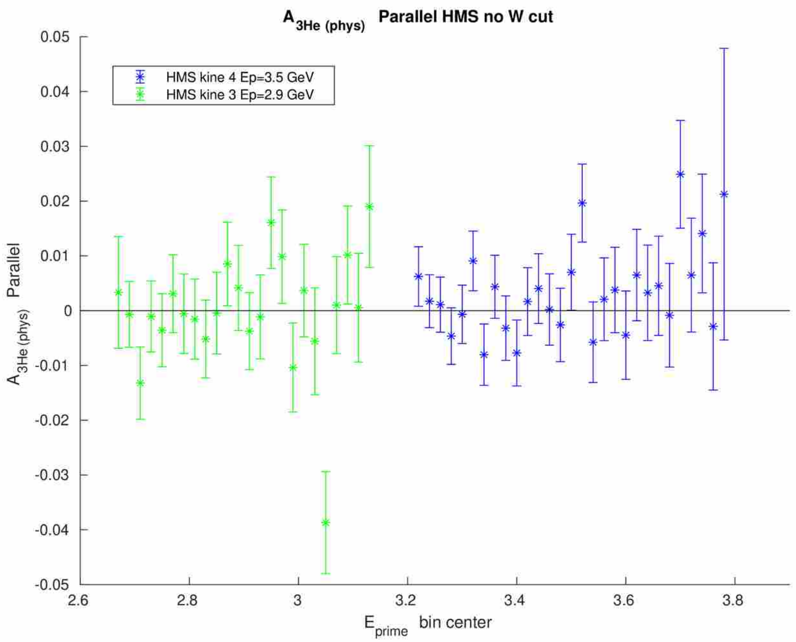


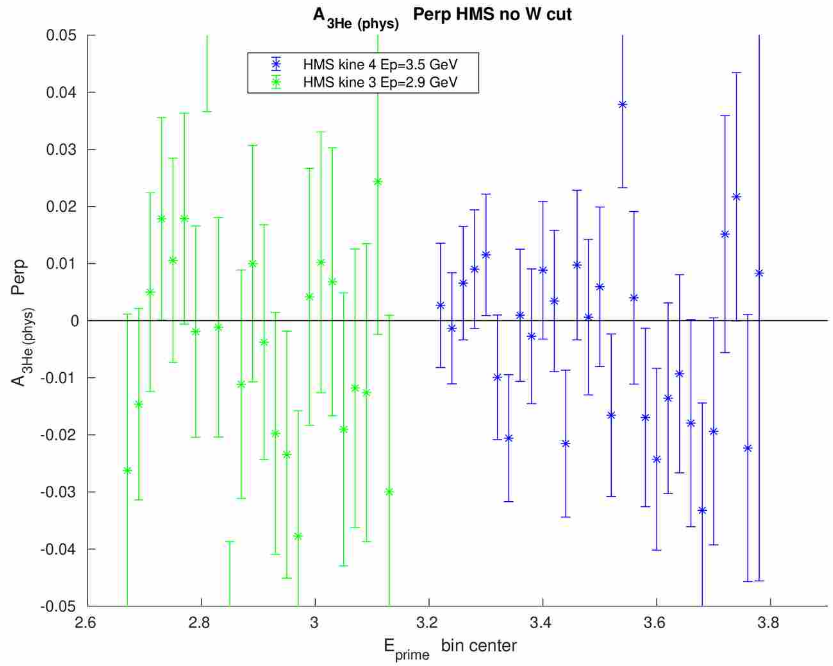


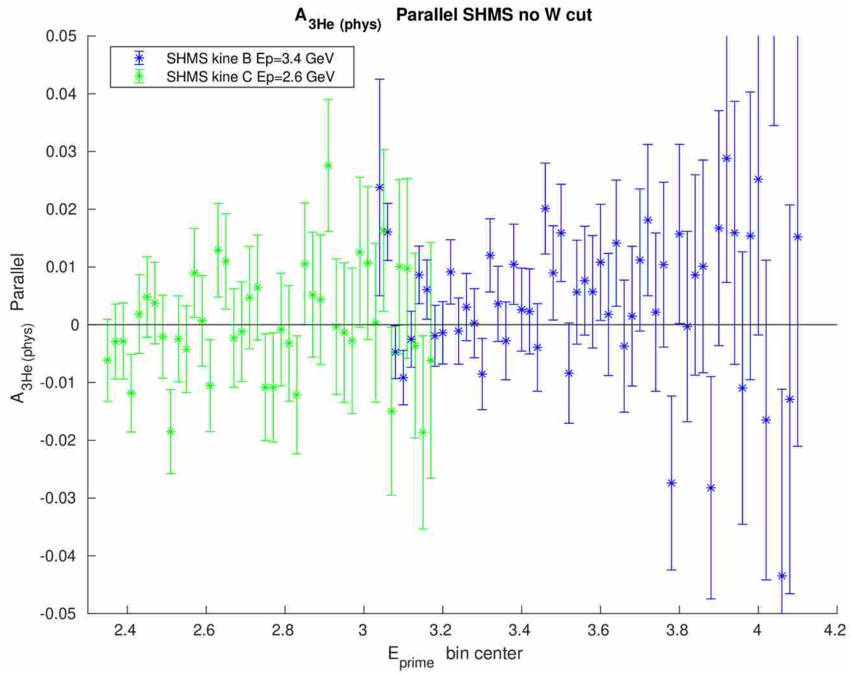
A_{Phys}^{3He} (no W cut; combine two Cell)

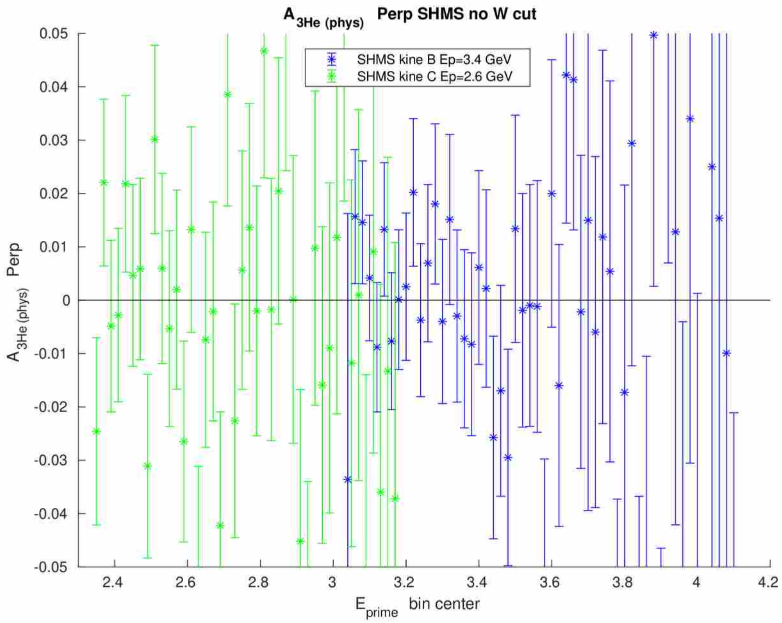
- Ep bin width=20 MeV

$$A_{phy} = \frac{A_{raw}}{D_{N_2} P_b P_t}$$









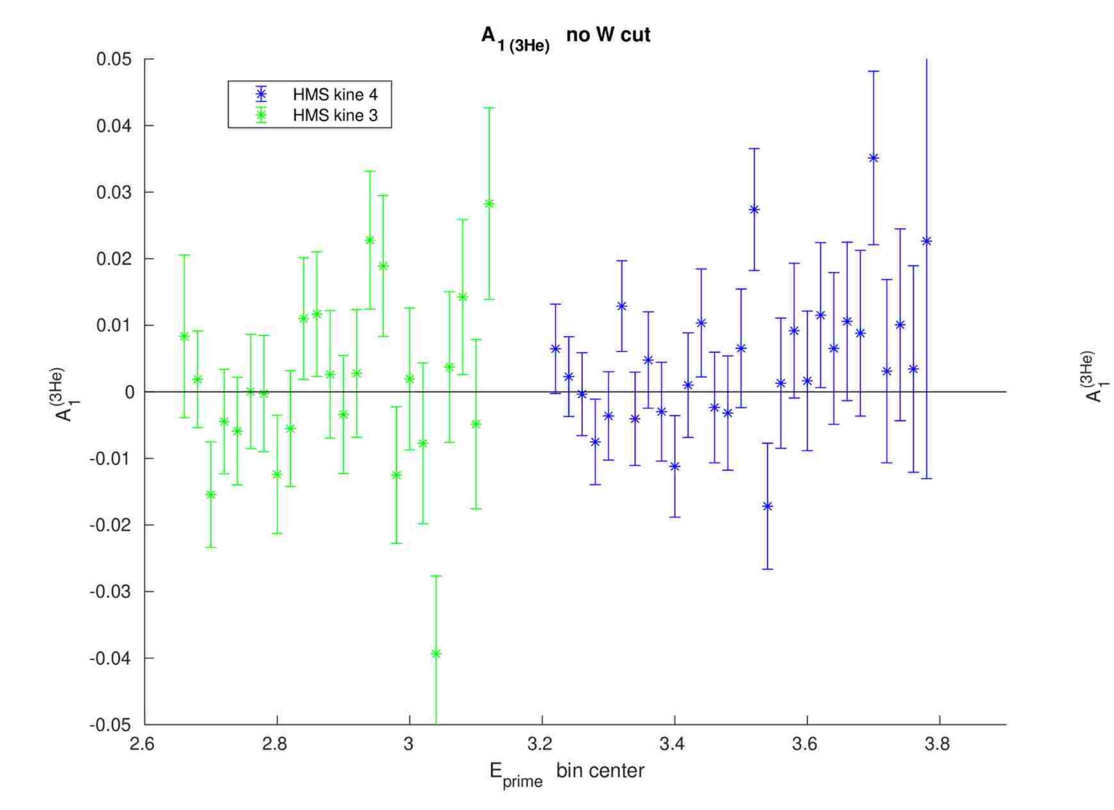
ture from in

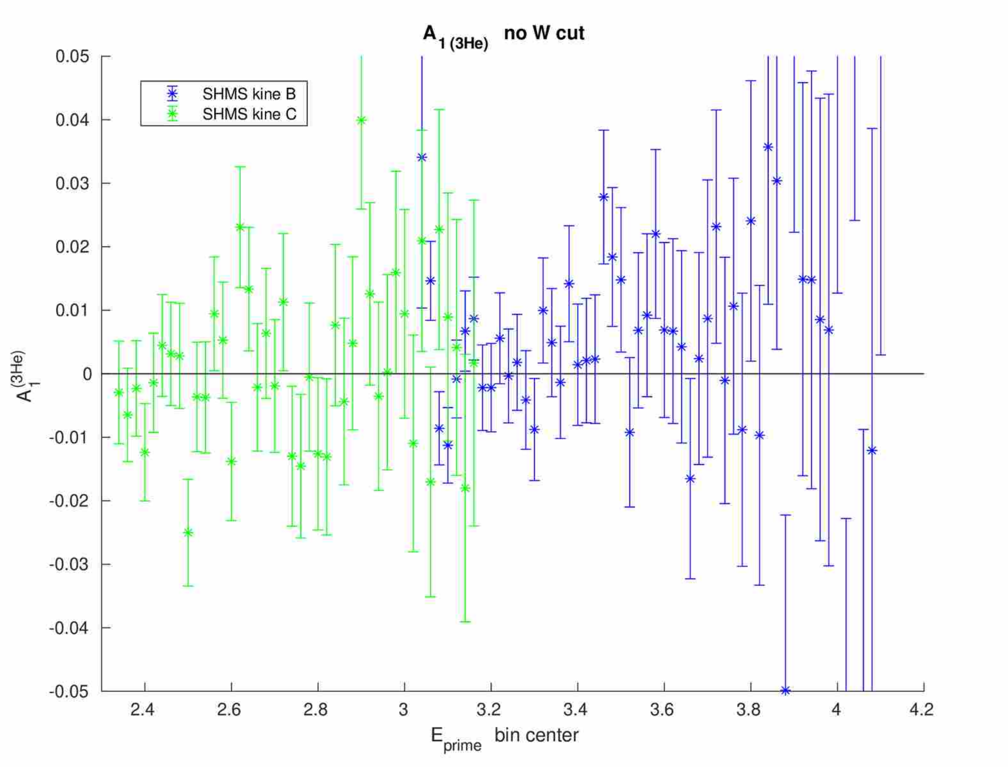
A_1^{3He}

(no W cut; combine two Cell)

- Ep bin width=20 MeV

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



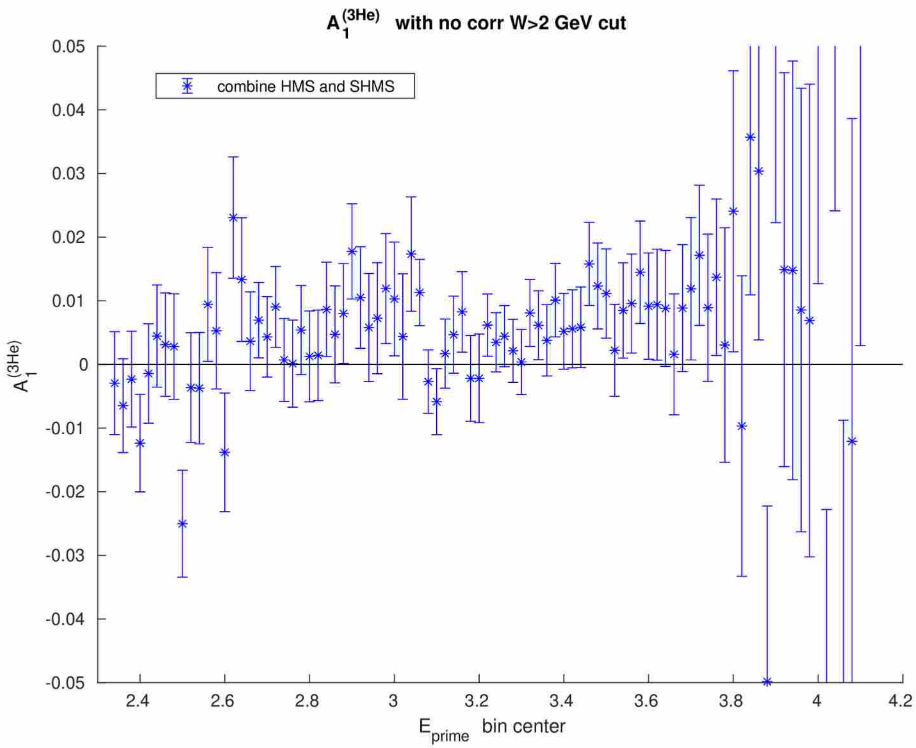


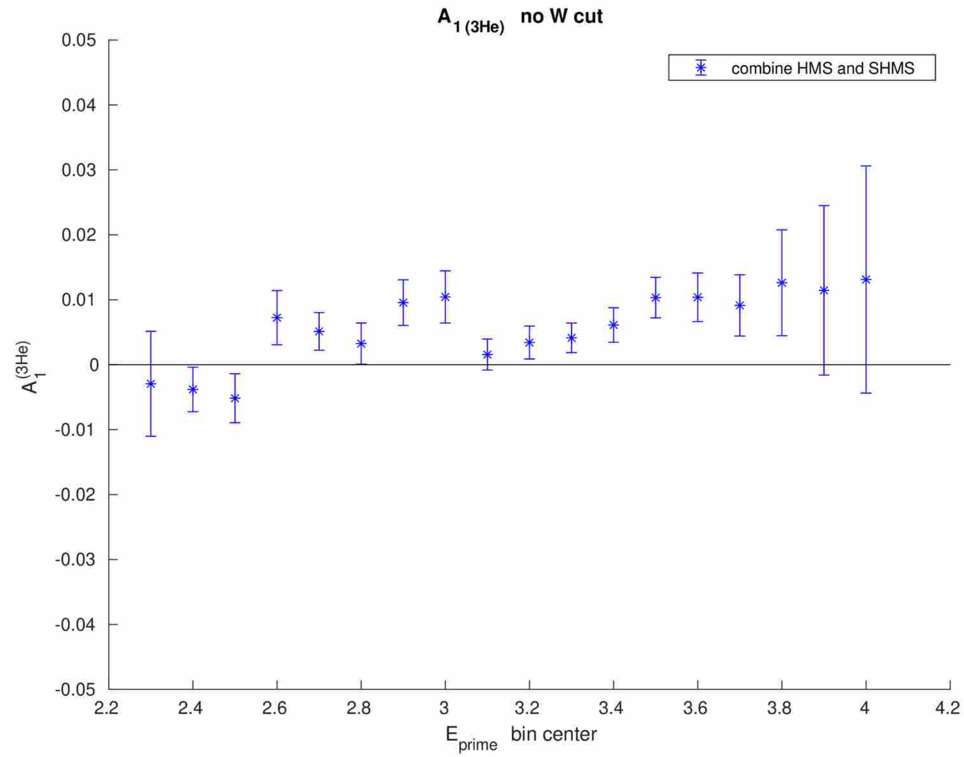
Statistical Error Propagation:

$$\Delta A_1(stat) = \sqrt{\left(\frac{\Delta A_{para}(stat)}{D(1+\eta\xi)}\right)^2 + \left(\frac{\eta \Delta A_{perp}(stat)}{d(1+\eta\xi)}\right)^2}$$

A_1^{3He}

(no W cut; combine two spec)





- Ep bin width=20 MeV

- Ep bin width=100 MeV

$$(A_1)_{comb} = \frac{\sum \frac{(A_1)_i}{(\Delta A_1)_i^2}}{\sum \frac{1}{(\Delta A_1)_i^2}}$$

$$(\Delta A_{1_{stat}})_{comb} = \sqrt{\frac{1}{\sum \frac{1}{(\Delta A_{1_{stat}})_i^2}}}$$

- For SHMS low mom and hi mom overlapping Ep bins combine A and dA first
- Then combine SHMS Ep bins with corresponding HMS Ep bins.
- Final step is to combine Ep_bin=20 MeV into Ep_bin=100 MeV

Extracting g_1/F_1 & A_1, A_2

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

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

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

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

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

Electron Beam Energy E = 10.38 GeV (fixed)

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

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

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

$$\nu = E - E' \qquad y = \nu/E$$

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

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

Nuclear Corrections & Quark Flavor Decomposition

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

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

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

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

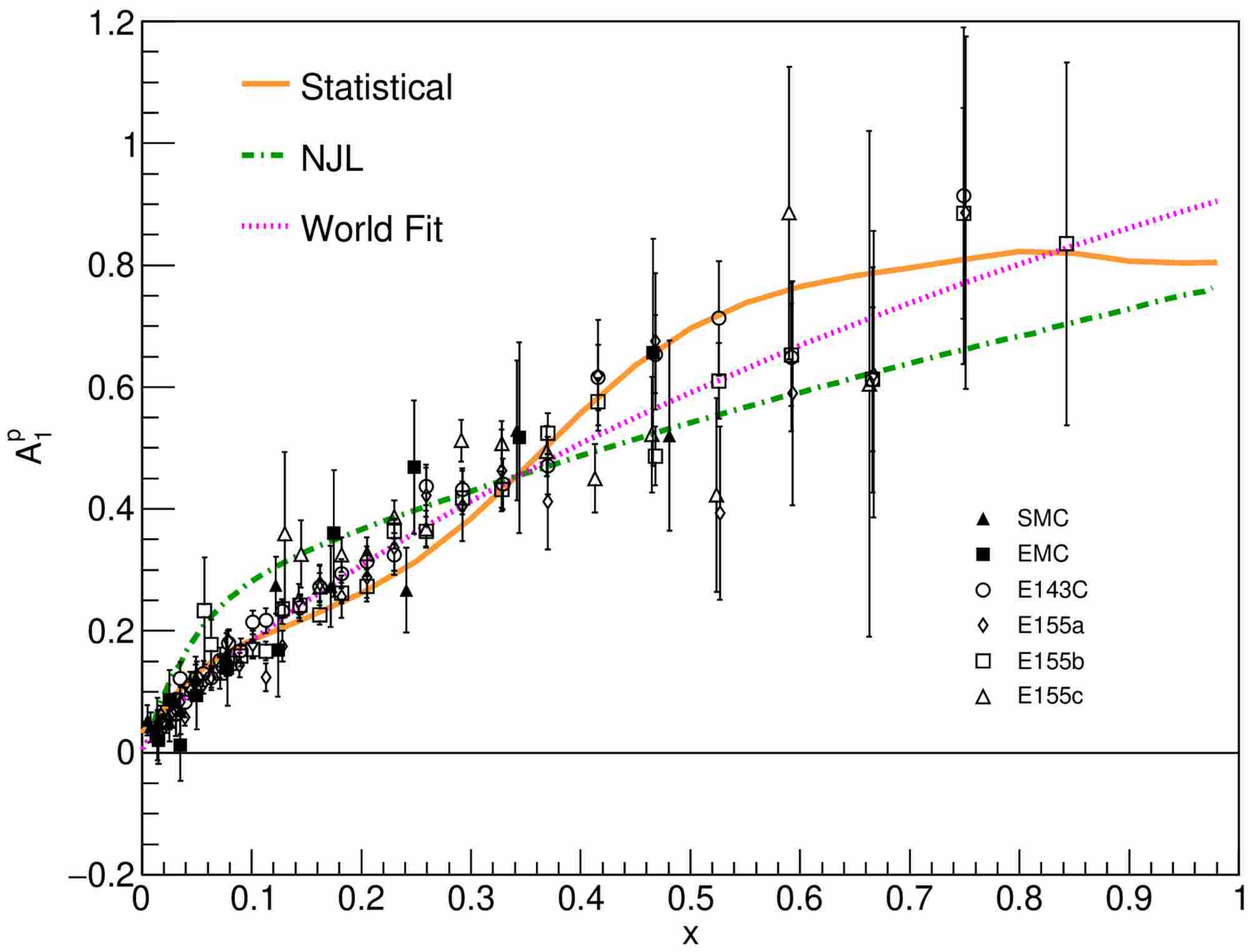
$$\frac{\Delta d + \Delta\bar{d}}{d + \bar{d}} = \frac{-1}{15}\frac{g_1^p}{F_1^p}\left(1 + \frac{4}{R^{du}}\right) + \frac{4}{15}\frac{g_1^n}{F_1^n}\left(4 + \frac{1}{R^{du}}\right)$$

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

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

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

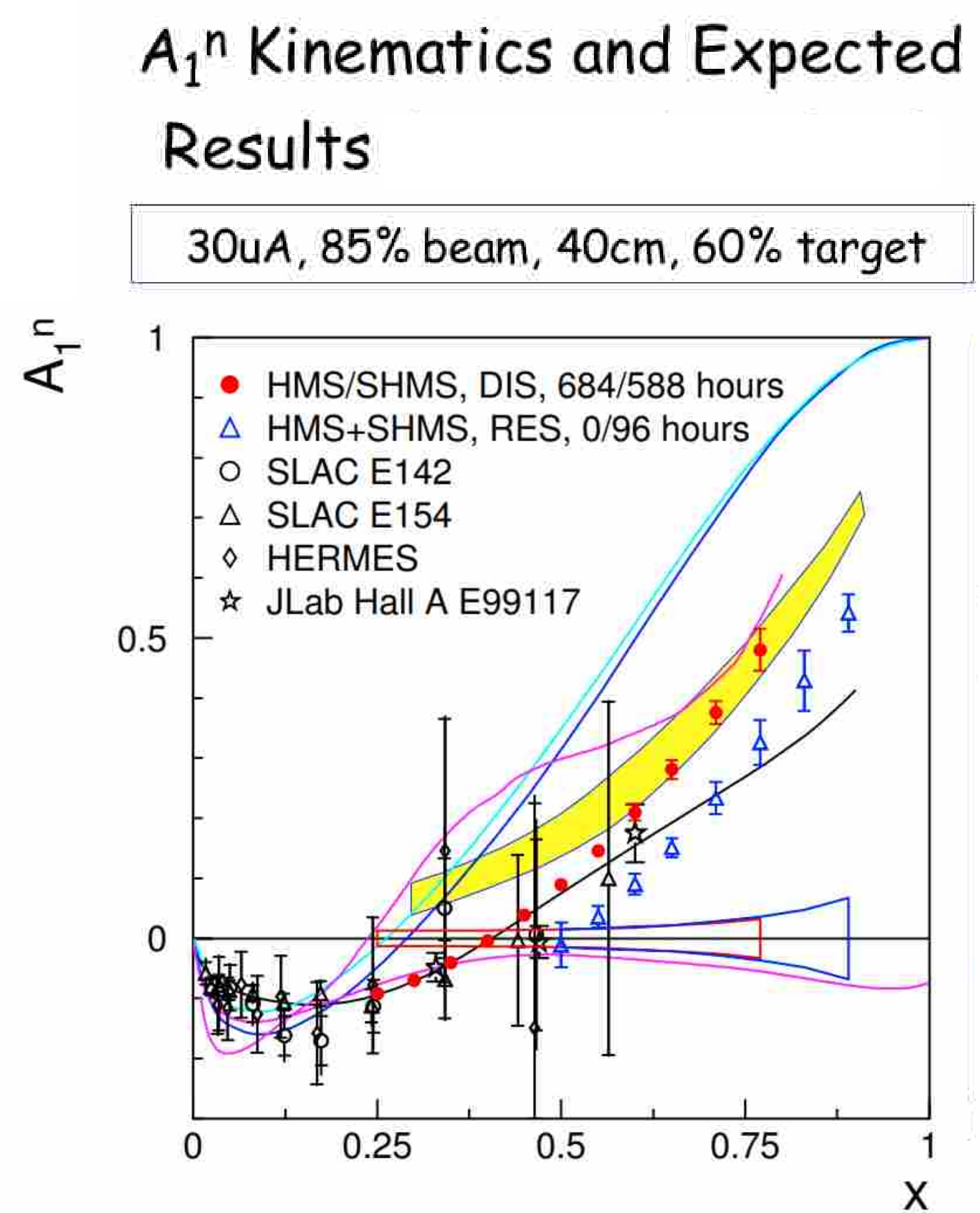
A_1^p Fit from World Data

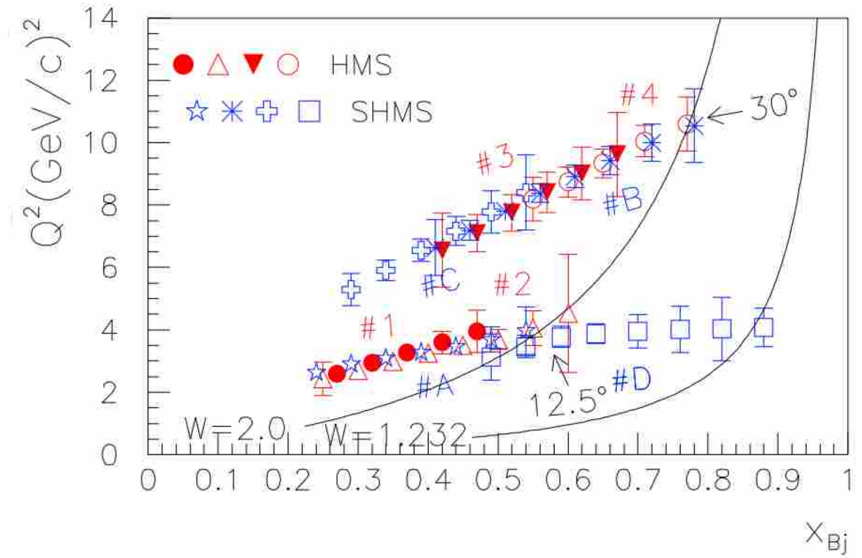


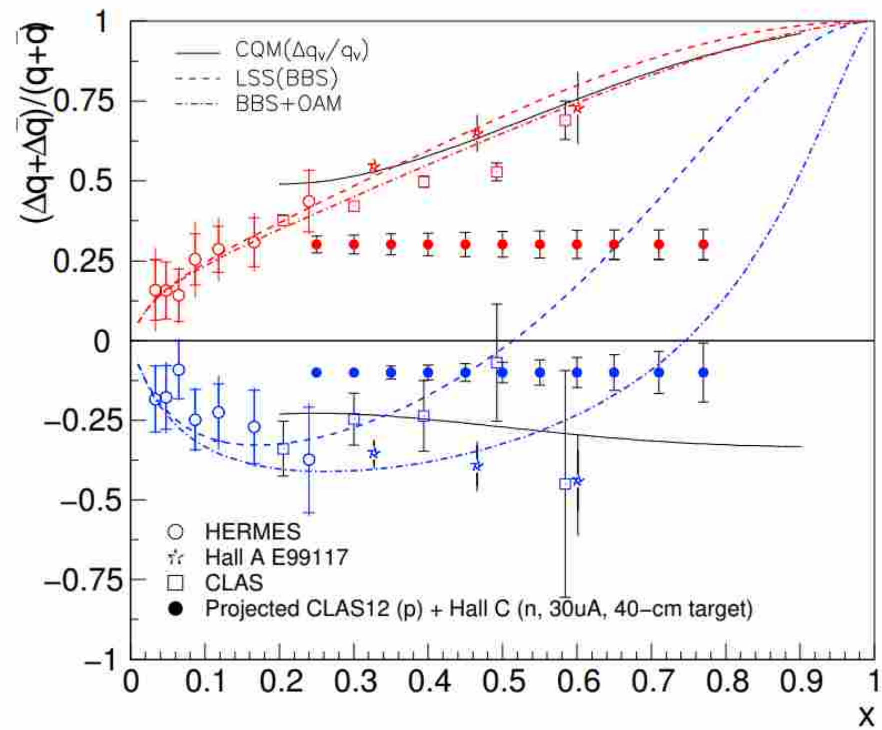
- Fit for E155, E143 at SLAC and EMC, SMC at CERN:

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

Expected Results







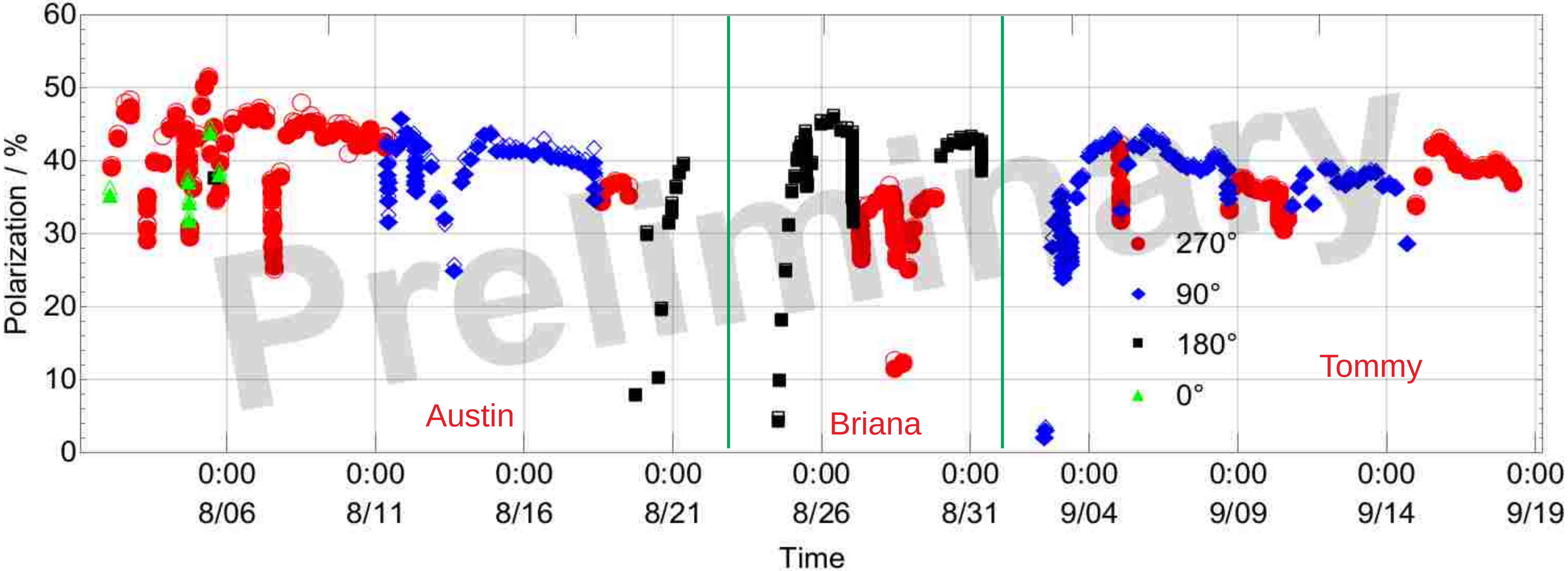
- Slide from X. Zheng ‘s March 2018 readiness review.

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_2 Dilution Study

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

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

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:

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
Bigbrother	427.182 ±0.001	293.82±0.001	100.759 ±0.001	32.602 ±0.001	0.110 ±0.001

Location	Average Temp (°C)
PC	238±2
TC	35±2
TT	38±2
Ref_N2	37±2

N_2 Dilution Study

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

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

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

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

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

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

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

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 $\sigma(Yield)_i$

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

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

N_2 Dilution Study

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

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

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

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

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

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

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

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 $\sigma(Yield)_i$

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

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

Hall C Optics Notes

Variables in replayed ROOT files

- Focal plane quantities are from drift chamber variables:

P.dc.x_fp	$x_{focal\ plane}$
P.dc.y_fp	$y_{focal\ plane}$
P.dc.xp_fp	$x'_{focal\ plane}$
P.dc.yp_fp	$y'_{focal\ plane}$

Technically, tangents of the angles:

$$x' = \frac{\mathrm{d}x}{\mathrm{d}z}$$
$$y' = \frac{\mathrm{d}y}{\mathrm{d}z}$$

Small approx, same as angle in radians

- Target reconstructed quantities are golden track variables:

P.gtr.dp	delta
P.gtr.x	x_{target}
P.gtr.y	y_{target}
P.gtr.ph	y'_{target}
P.gtr.th	x'_{target}

- Raster

P.react.x	raster x position, cm
P.react.y	raster y position, cm