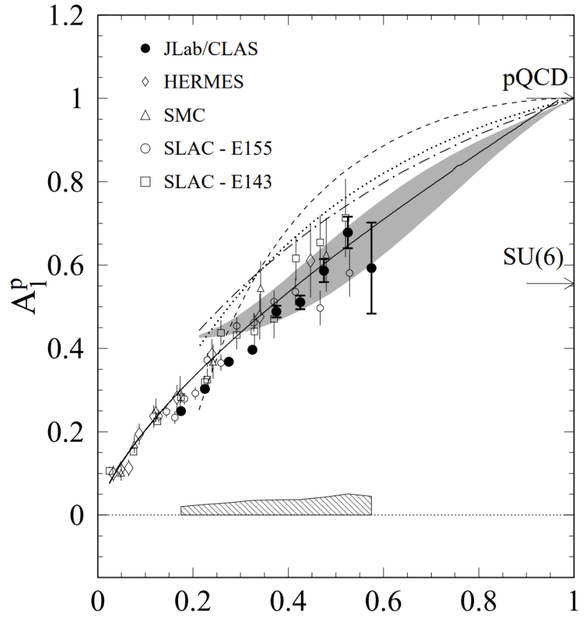
Longitudinal Spin Structure of the Proton in RG-C

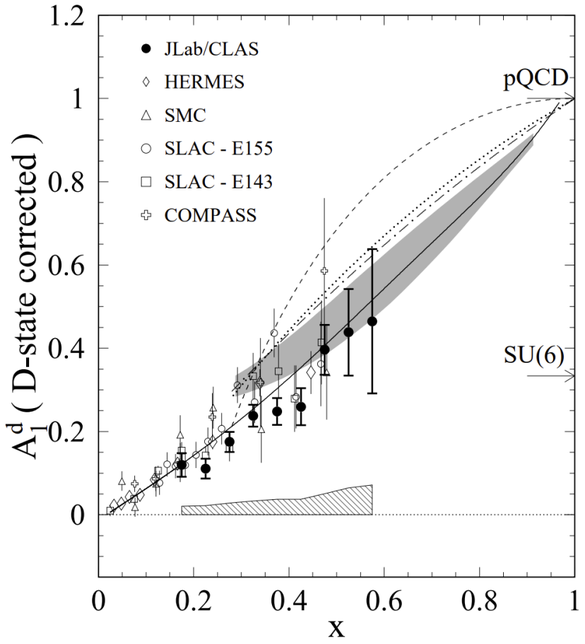
Derek Holmberg
11-18-26



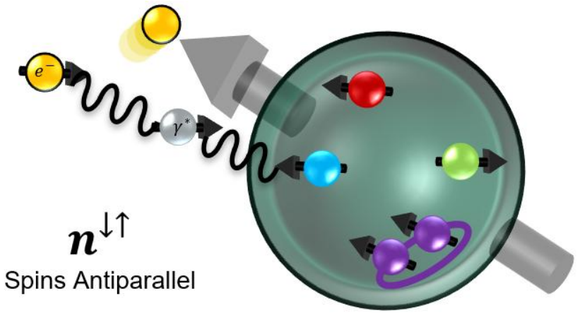
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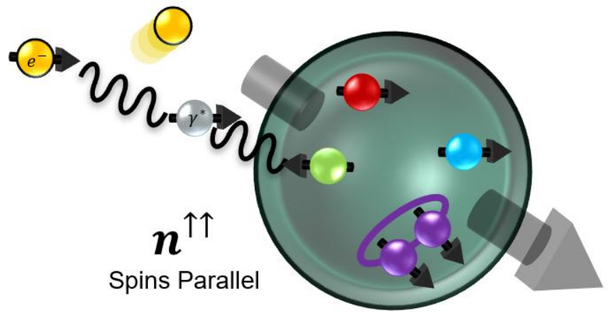
The Proton Spin Structure





The Longitudinal Spin Structure of the Nucleon:
A 12 GeV Research Proposal to Jefferson Lab (PAC 30) [Ref. 1]





- One goal of Run Group C is measuring the proton/deuteron longitudinal spin structure at large x
- Not much precise A_1 data above $x = 0.5$, leaving open possibilities of quark behavior
- Probed via polarized ep or ed DIS scattering and measuring electron double spin asymmetry $A_{||}$

$$A_{||}(x,Q^2) = \frac{N^{\downarrow\uparrow} - N^{\uparrow\uparrow}}{N^{\downarrow\uparrow} + N^{\uparrow\uparrow}} \propto D\left(A_1(x,Q^2) + \eta A_2(x,Q^2)\right)$$

A_1, A_2 = Virtual Photon Asymmetries

$$A_1(x,Q^2) = \frac{g_1 + \gamma^2 g_2}{F_1} \approx \frac{g_1}{F_1} = \frac{\sum_i e_i^2 \Delta q_i(x,Q^2)}{\sum_i e_i^2 q_i(x,Q^2)}$$

- Measurement of A_1 allows us to evaluate proton spin structure models and calculate moments, sum rules, PDFs

Run Group C Experimental Setup

- Ran from June 2022 to March 2023 for 80 PAC days (120 scheduled)
- RG-C data divided into five run periods:

Run Period	Run Range	Torus Configuration	Solenoid Configuration	Inbending or Outbending
Summer 2022	16128 – 16772	Negative	Negative	Inbending
Fall 2022 (Neg.)	16859 – 17183	Negative	Negative	Inbending
Fall 2022 (Pos.)	17188 – 17408	Negative	Positive	Inbending
Spring 2023 (Inb.)	17482 – 17768	Negative	Negative	Inbending
Spring 2023 (Outb.)	17769 – 17811	Positive	Negative	Outbending

- Inclusive DIS channel: $ep \rightarrow eX$, $ed \rightarrow eX$
- DIS electrons detected in the Forward Detector
- Most important components for e^- PID are HTCC, DCs, TOFs, ECAL
- Polarize the protons/deuterons using a frozen ammonia target

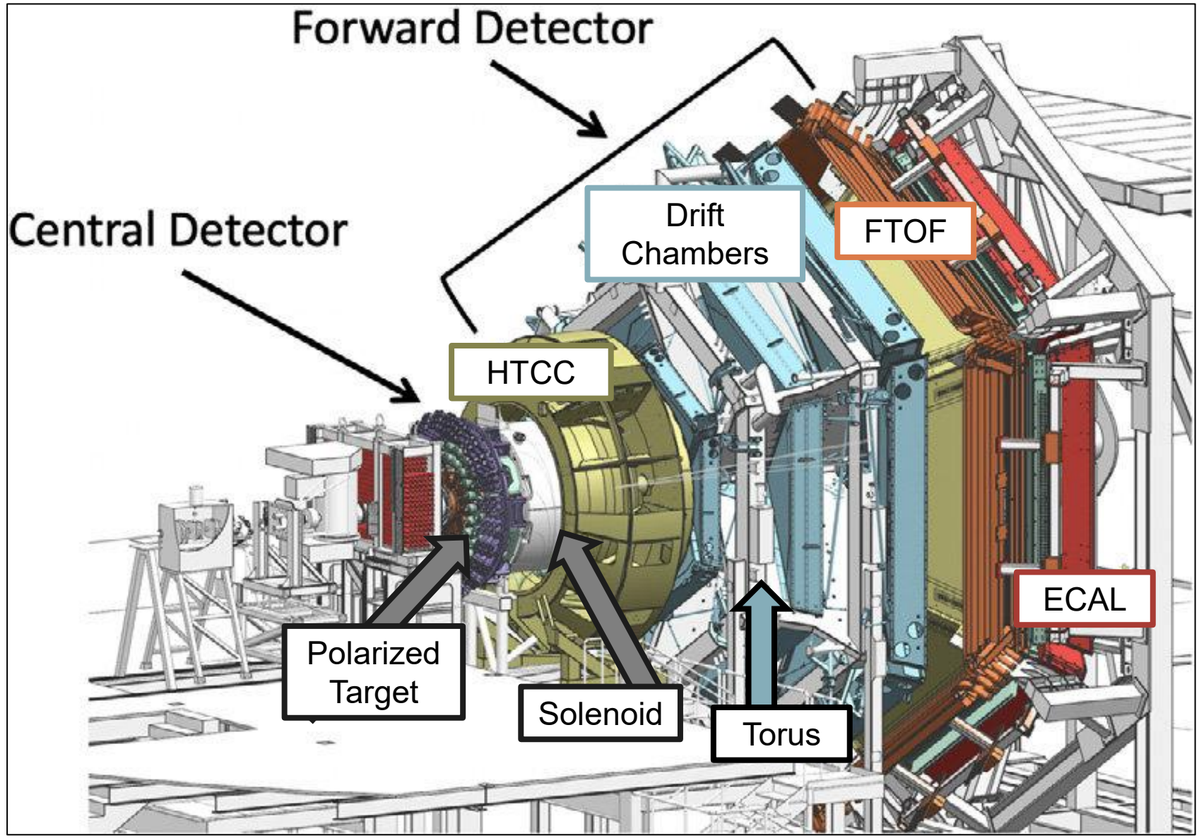
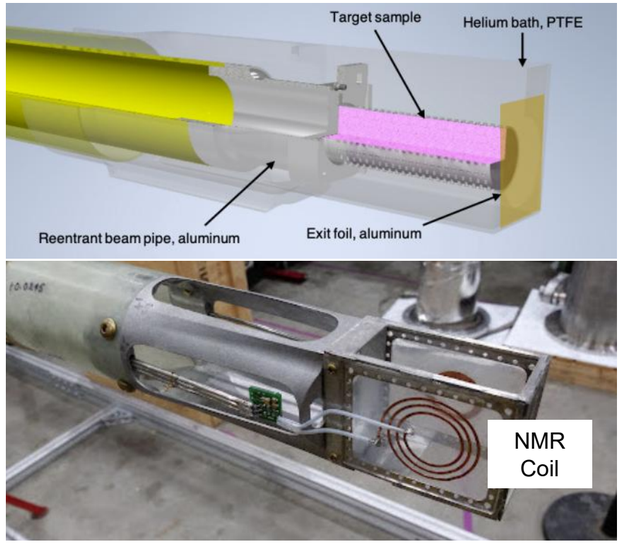


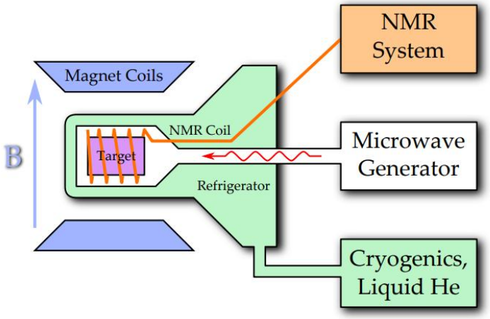
Diagram of CLAS12 Detector, Ziegler et. al. [Ref. 2]

Run Group C Experimental Setup

- Polarized protons/deuterons from the Run Group C target
- Ammonia crystals polarized via dynamic nuclear polarization (DNP)
- Cool to ~1 K in a 5 T field generated by solenoid, where free electron radicals almost completely polarize
- Using microwaves with a frequency of $\nu_{ESR} \pm \nu_{NMR}$ (~140 GHz), transfer electron polarization to the protons (or deuterons)
- ~85% for protons, ~25% for deuterons



Pictures taken from C. Keith et. al. [Ref.3]



Cell diagram taken from J. Maxwell [Ref.4]



Ammonia crystals unexposed to beam (left), crystals after beam exposure (right). Purple color from paramagnetic centers.

Extraction of $A_{1,p}$

$$A_{||}(x, Q^2) = \left(\frac{N^{\uparrow\downarrow} - L_R N^{\uparrow\uparrow}}{N^{\uparrow\downarrow} + L_R N^{\uparrow\uparrow}}\right) \frac{A_{e^+e^-}}{D_F P_b (P_t + P_{14N}) f_{RC}} + A_{RC}$$

$$A_{1,p}(x, Q^2) = A_{||}(x, Q^2)/D - \eta A_2$$

- N = counts, $L_R = F^+/F^-$ = luminosity ratio, D_F = dilution factors, P_b, P_t, P_{14N} = beam, target, nitrogen polarizations, f_{RC}, A_{RC} = radiative corrections
- The D, η, A_2 come from model values and are a small contribution to $A_{1,p}$
- **Green** quantities are mostly finished, **blue** are works in progress, **red** are yet to be determined

Finished Quantities

- Electron PID cuts
- Dilution factors D_F and systematics
- Beam-target polarizations $P_b P_t$

Works-in-Progress

- Faraday Cup charge normalization L_R
- Pair-produced electron-positron ratio correction A_{e+e-}

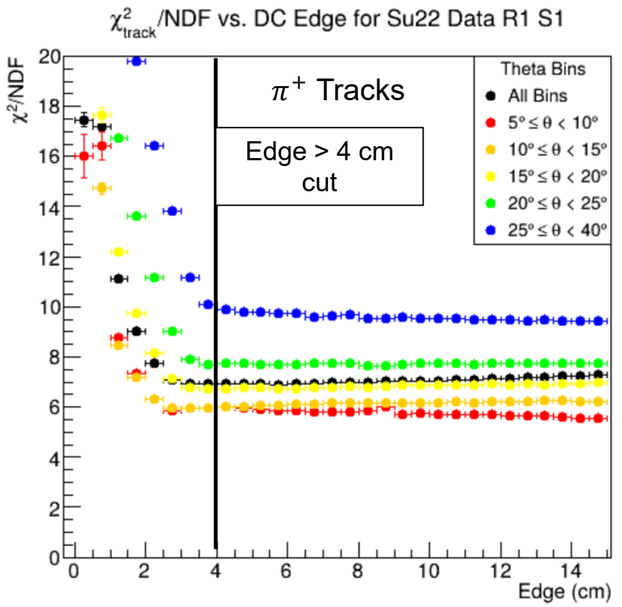
To Be Determined

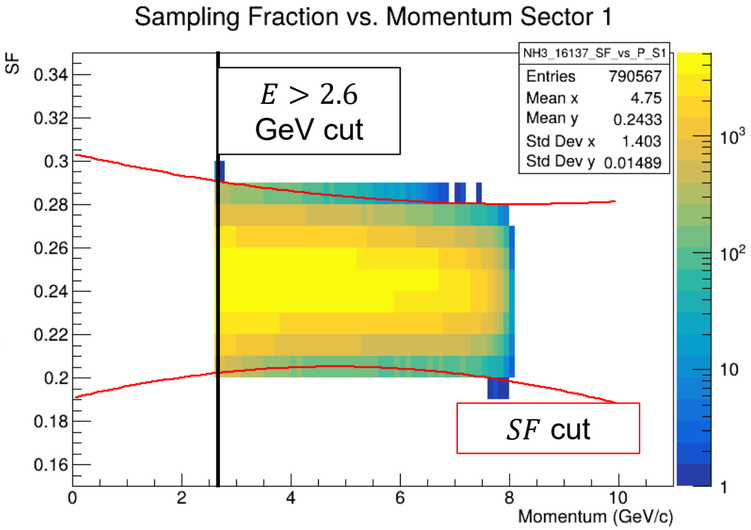
- Polarized ^{14}N correction P_{14N}
- Radiative dilution factor f_{RC}
- Radiative correction to the asymmetry A_{RC}

Electron PID Cuts

- Inclusive DIS electrons: $ep \rightarrow eX$
- e^- Event Builder PID cuts:
  - **> 60 MeV energy in PCAL**
  - **> 2 photoelectrons in HTCC**
  - **broad sampling fraction cut**
- Kinematic (DIS) cuts:
  - **E' > 2.6 GeV,**
  - $\boldsymbol{7^\circ < \theta < 40^\circ}$**,**
  - $\boldsymbol{Q^2 > 2.2\ \mathrm{GeV}^2}$**,**
  - $\boldsymbol{W > 2\ \mathrm{GeV}}$
  - **-9 cm $\leq V_Z \leq$ 1 cm (Summer)**
  - **-7.5 cm $\leq V_Z \leq$ 2.5 cm (Fall and Spring)**
- QADB cuts

- DC fiducial cuts:
  - **EdgeR1 > 4 cm**
  - **EdgeR2 > 5 cm**
  - **Edge R3 > 8 cm**
  - Based on average value of track quality χ^2_{track} versus distance to edge
- ECAL fiducial cuts
  - $\boldsymbol{lv, lw > 22.5}$ **cm for Sector 1 (runs > 16156)**
  - $\boldsymbol{lv, lw > 13.5}$ **cm for Sectors 2-6**
  - Position where sampling fraction (SF < 0.2)
- Sampling fraction cuts
  - $\boldsymbol{SF(P)_{low} < SF(P) < SF(P)_{high}}$
  - $SF(P)_{(low,high)} = a_0 + a_1 P + a_2 P^2 + a_3 P^3$
  - $SF = (E_{PCAL} + E_{ECIN} + E_{COUT})/P,\ SF \approx 0.24$ for electrons
  - SF cuts developed by Timothy Hayward

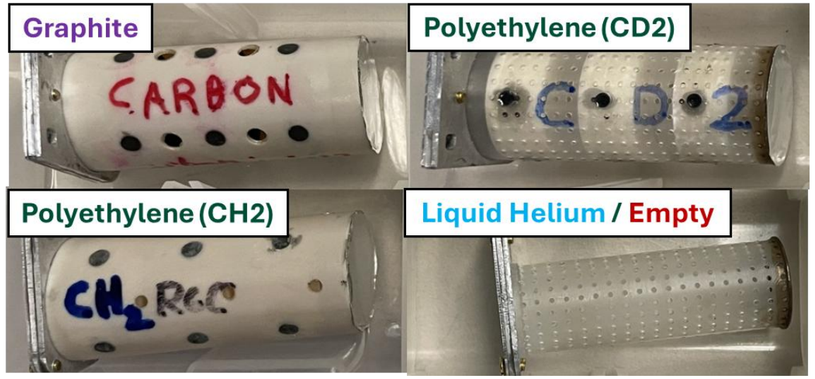




Dilution Factors and Packing Fractions

- Quantifies the scattering from unpolarized background in the ammonia targets: N, Al, He
- Defined as the yield from the hydrogen to the yield from all target material in the cell

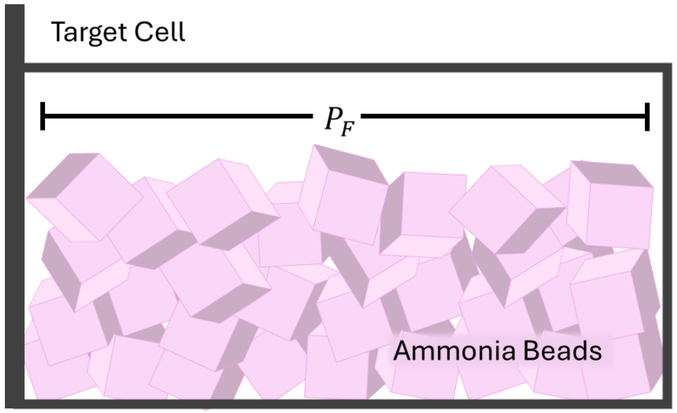
$$D_F = \frac{Y_H}{Y_{Ammonia}} = \frac{3\sigma_H \ell_A \rho_A}{(3\sigma_H + \sigma_N)\ell_A \rho_A + \sigma_{He}\ell_{He}\rho_{He} + \sigma_{Al}\ell_{Al}\rho_{Al}}$$



- Can be expressed in terms of the measured counts coming from various target types

$$D_F(x, Q^2) = \frac{(n_A - n_{MT})(n_{CH} + An_C + Bn_{MT} + Cn_F)}{n_A(n_{CH} + Dn_C + En_{MT} + Fn_F)}, \quad P_F(x, Q^2) = \frac{G(n_A - n_{MT})}{n_{CH} + Dn_C + En_{MT} + Fn_F}$$

$A \ldots G \propto \ell_i, \rho_i$ of target materials



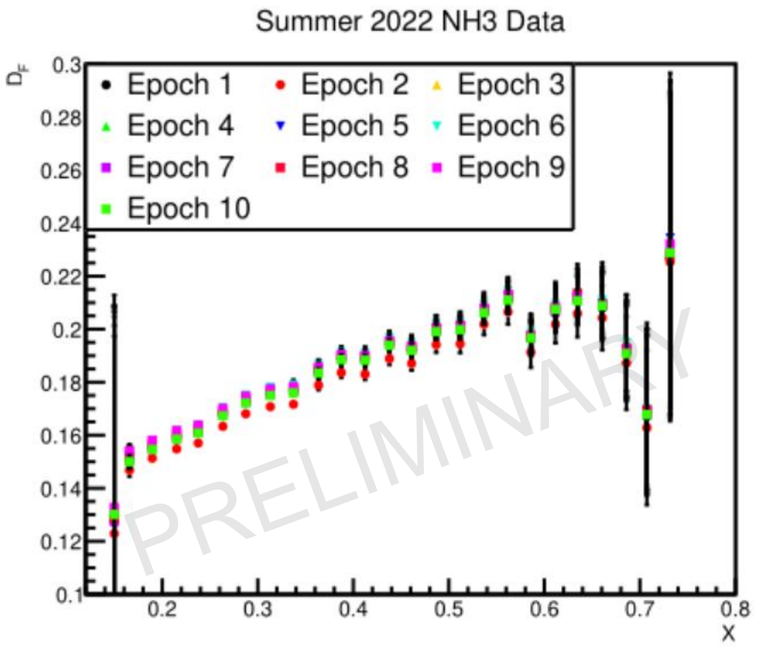
- Packing fraction $P_F \equiv$ fraction of target cell occupied by crystals

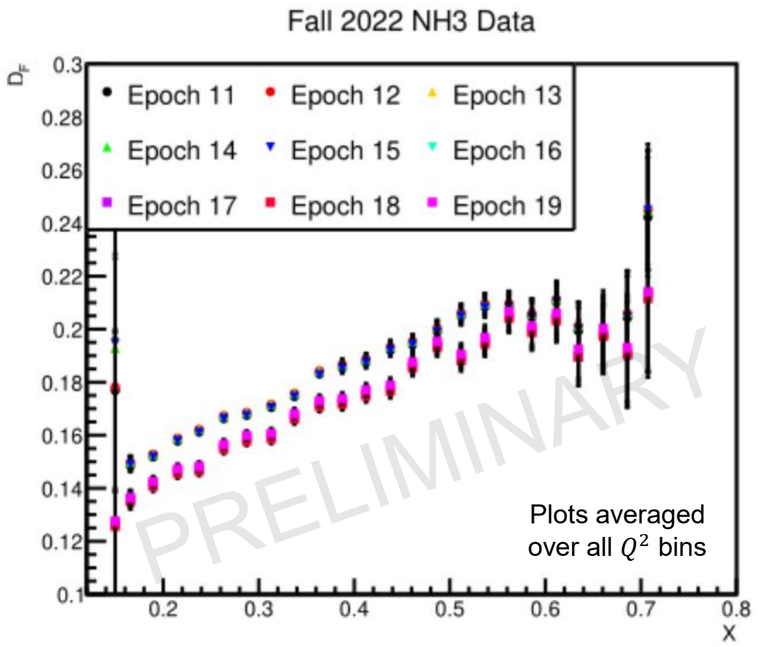
- Two approaches for calculating D_F:
  - **Data-driven approach uses measured scattering events from background targets**
  - Model-driven approach uses structure function data to directly calculate cross sections

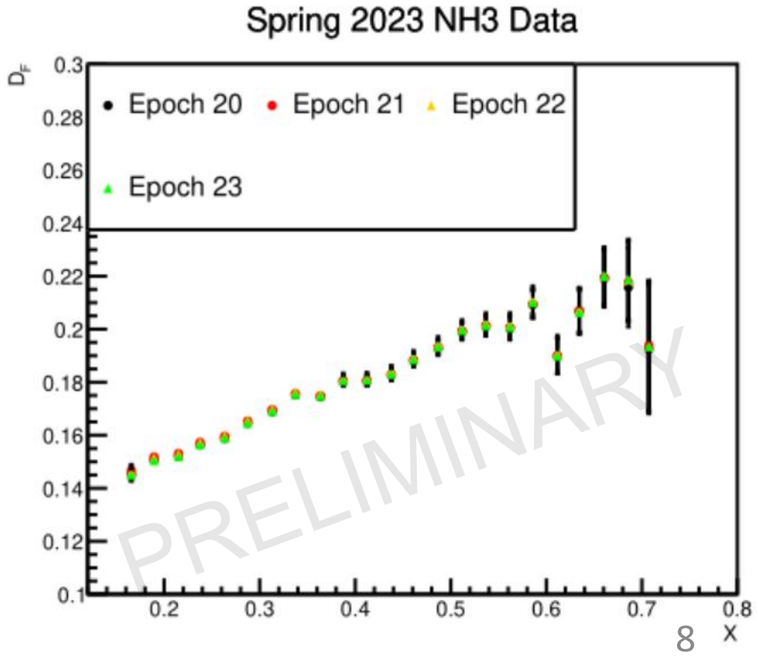
Calculating the Dilution Factor

- Run periods divided into “epochs” due to target swaps
- Radiation length corrections applied to the empty targets
- 10% difference for positive polarity solenoid data
- Systematic errors calculated from thermal contraction measurements are below 2%!

Number of NH3 Epochs by Run Period				
Summer 2022	**Fall 2022 (Neg. Sol.)**	**Fall 2022 (Pos. Sol.)**	**Spring 2023 (Inbending)**	**Spring 2023 (Outbending)**
10	5	4	4	1



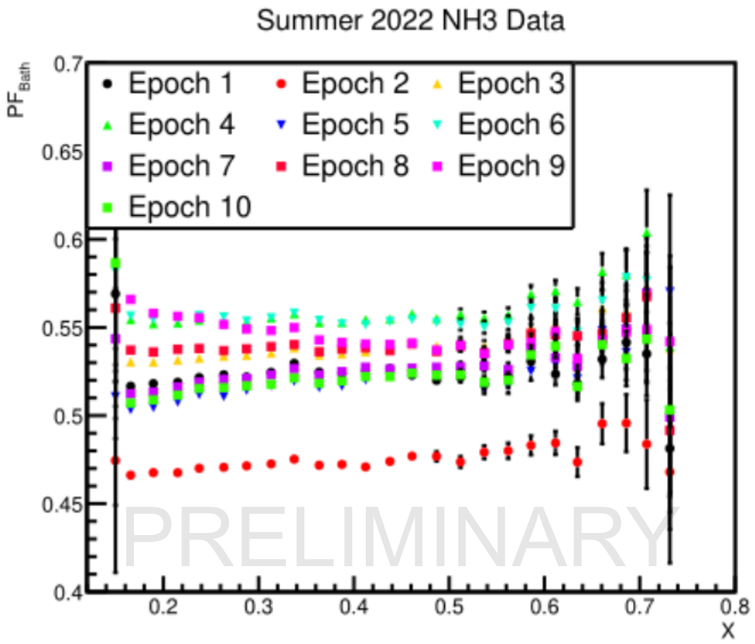


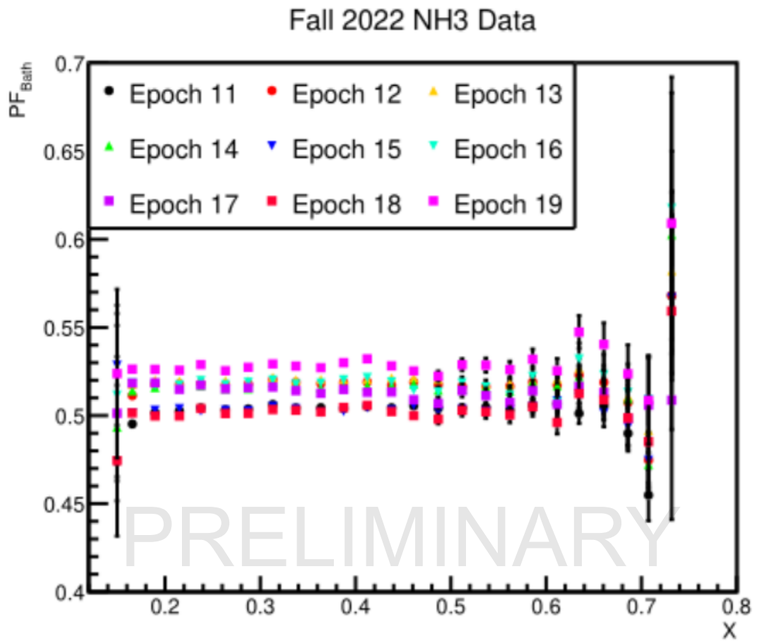


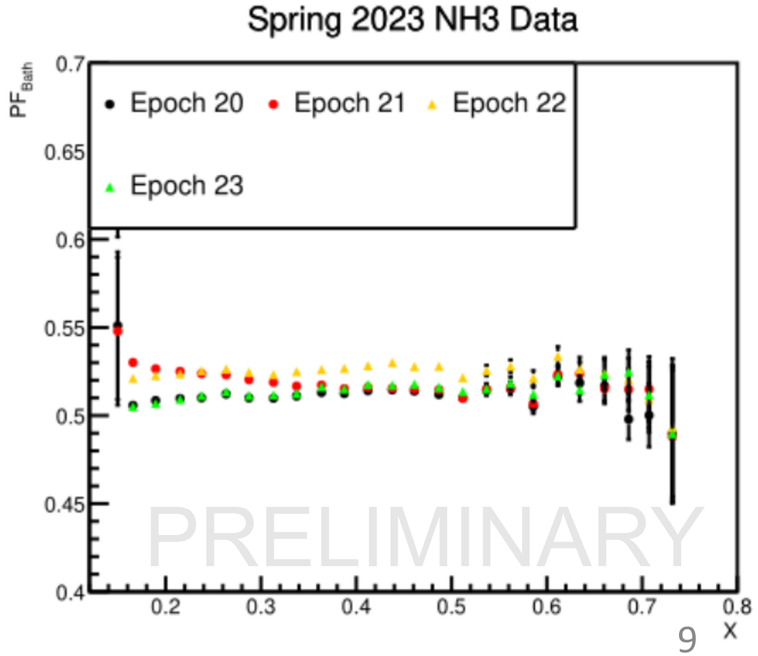
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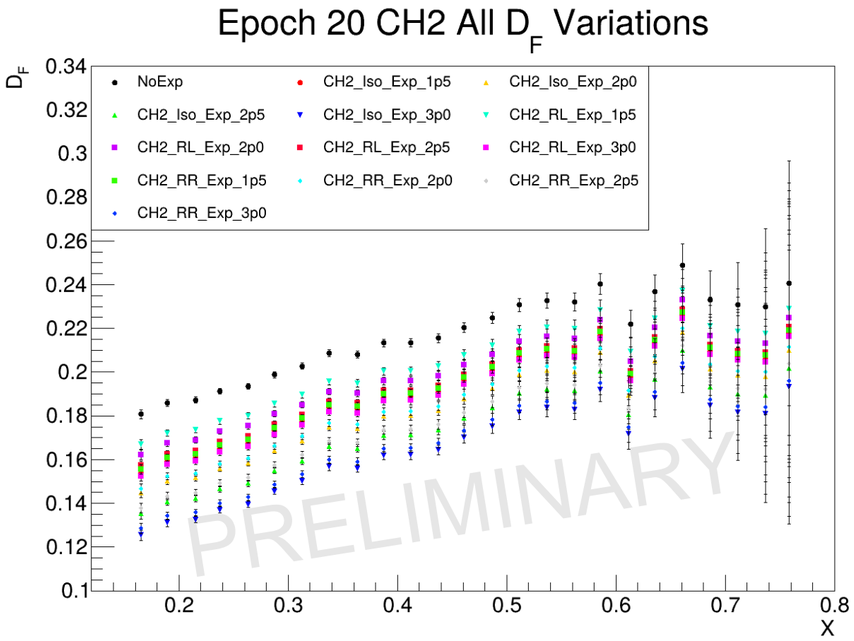


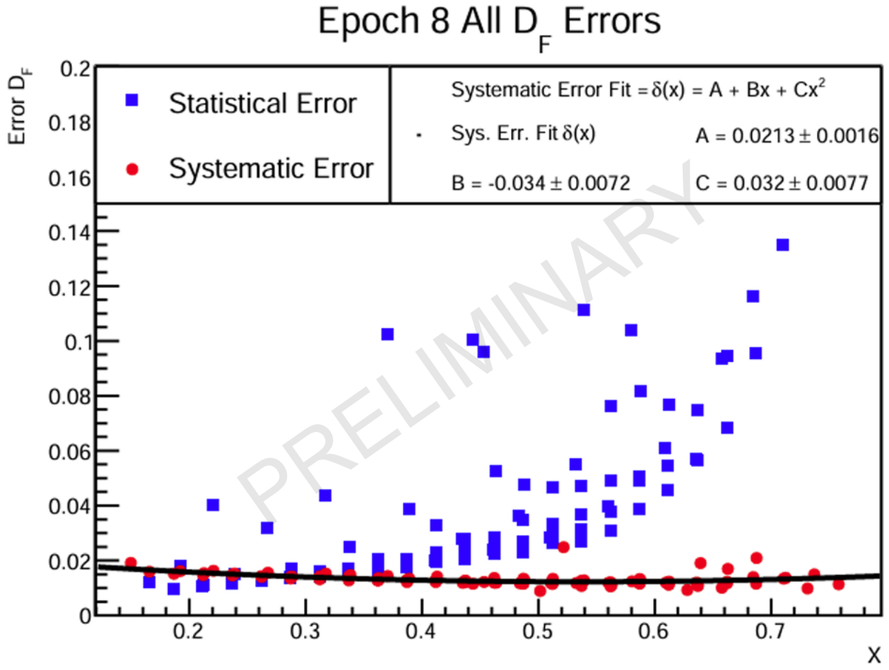


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- Systematic errors calculated from thermal contraction measurements are below 2%! Initially in the range of 6-9%
- Systematics used a variational approach based on all possible thermal contractions

Thermal Contraction Systematics		
Target Material	δ_{DF}	δ_{PF}
PE (CH_2)	$1.0 - 1.4$	0.3
Graphite	$0.8 - 1.0$	0.05
Teflon	$0.05 - 0.07$	0.016
Ammonia	0.5	4.1
Total Sys. Err.	$1.4 - 1.6$	4.1

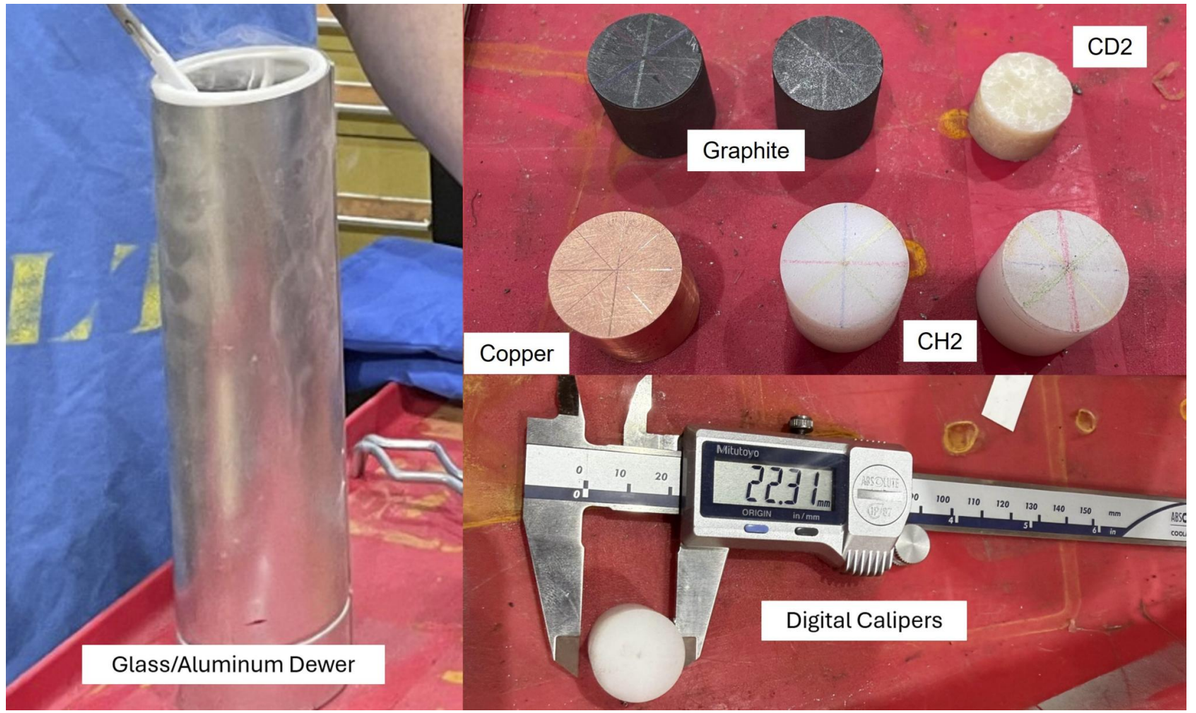




For more information on the systematics, see our summary note here

Measurement of Thermal Contraction

- Prompted a direct measurement target material samples
- Samples were made from the same extruded rods that the CH2 and graphite target foils were taken from
- Two 20mm x 20mm samples of CH2, graphite. One CD2 sample, one copy sample for comparison
- Thermal contraction measured from room temperature (~300K) to liquid nitrogen (~77K)
  1. Measured diameter and length of each sample at room temperature
  2. Immerse in liquid nitrogen until cooled, and then measure again, holding it within the liquid nitrogen vapor
- Final values of α for length and diameter taken as the average between each of the samples



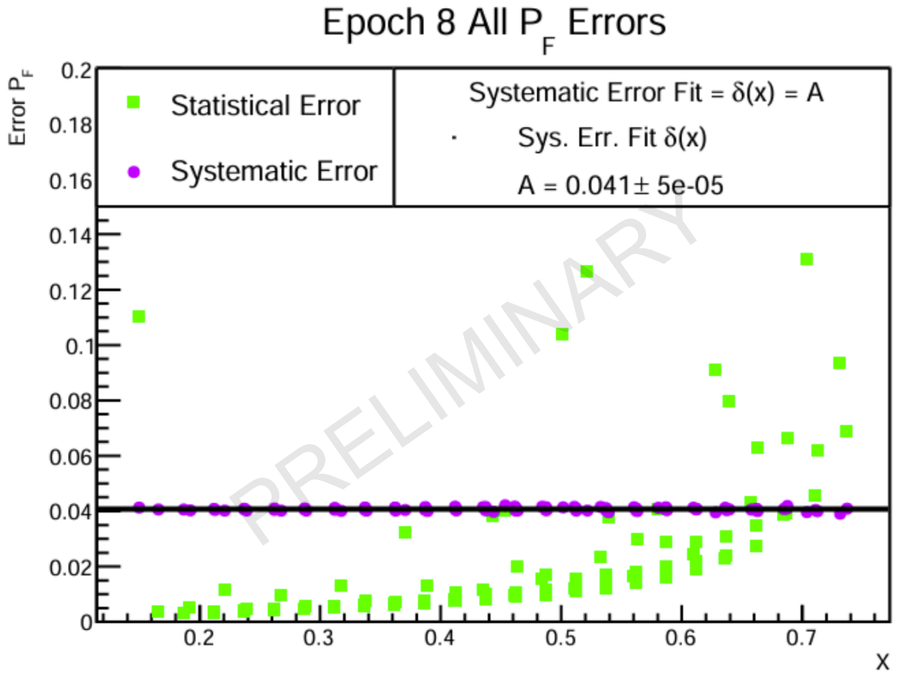
Measured Thermal Contractions			
Polyethylene (CH2)		Graphite (Carbon)	
α_D (Diameter)	α_L (Length)	α_D (Diameter)	α_L (Length)
-1.73%	-1.83%	0.16%	0.25%

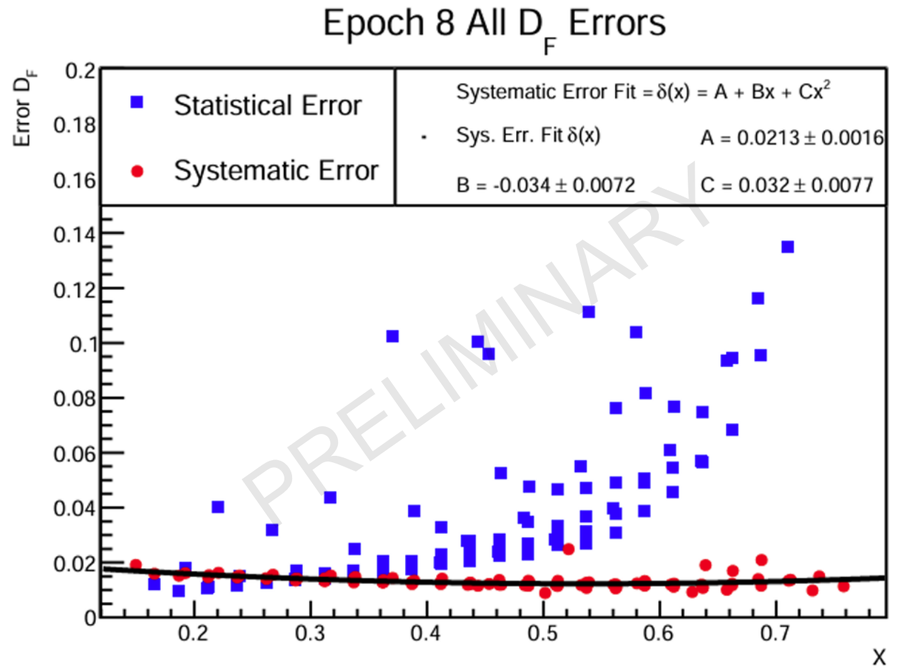
Thanks to James Maxwell, Chris Keith, and James Brock for making the samples!!!
Thanks to Sailaja, Stephen, and James Maxwell for helping take the measurements!!!

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Total Sys. Err.	$1.4 - 1.6$	4.1





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Calculation of $P_b P_t$

- The beam-target polarizations are calculated using a maximum-likelihood method and a model of the double-spin asymmetry

$$P_b P_t = \frac{\sum_{x,Q^2} D_F A_{||,model}\left(N^{\downarrow\uparrow} - N^{\uparrow\uparrow}\right)}{\sum_{x,Q^2}\left(D_F A_{||,model}\right)^2 \left(N^{\downarrow\uparrow} + N^{\uparrow\uparrow}\right)}$$

- $P_b P_t$ can be calculated using two channels, each with its own advantages

Deep inelastic scattering (DIS) channel:

- $A_{||,model} = D(A_1 + \eta A_2)$, where structure functions come from Sebastian Kuhn's fit to world data
- Very high statistics, but creates a circular dependence on the model A_1, A_2
- Precise, but not accurate

Elastic scattering channel:

- Independent from DIS channel, $A_{||,model}$ parameterized using Arrington $G_{E,M}(Q^2)$
- Lower statistics, so only the average $P_b P_t$ across a run period can be calculated
- Accurate, but not precise

- Normalize the DIS result to the elastic result to remove the circular model dependence: both precise and accurate!
- Quantified using a **Polarization Normalization Factor** PNF

Polarization Normalization Factor

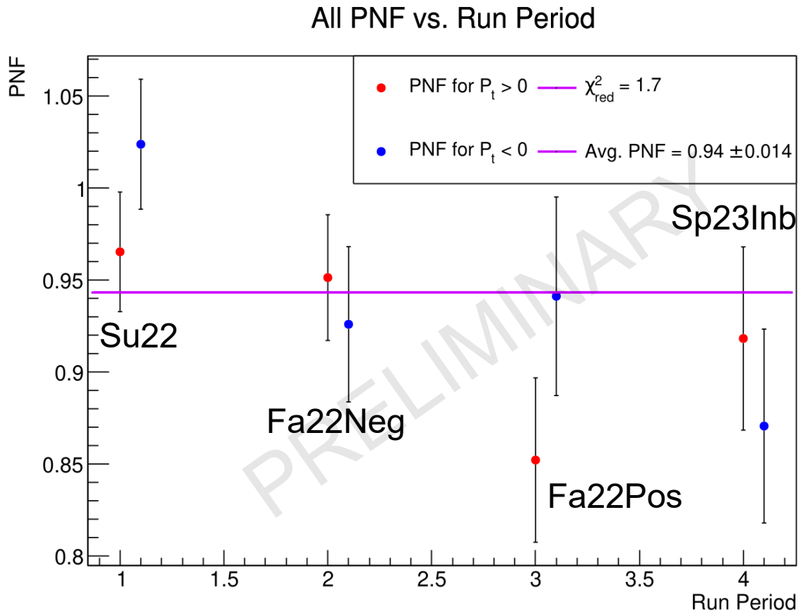
- Derive a Polarization Normalization Factor (PNF) by taking the weighted average of elastic $P_b P_t$ values to the DIS for each run $\boldsymbol{j}$

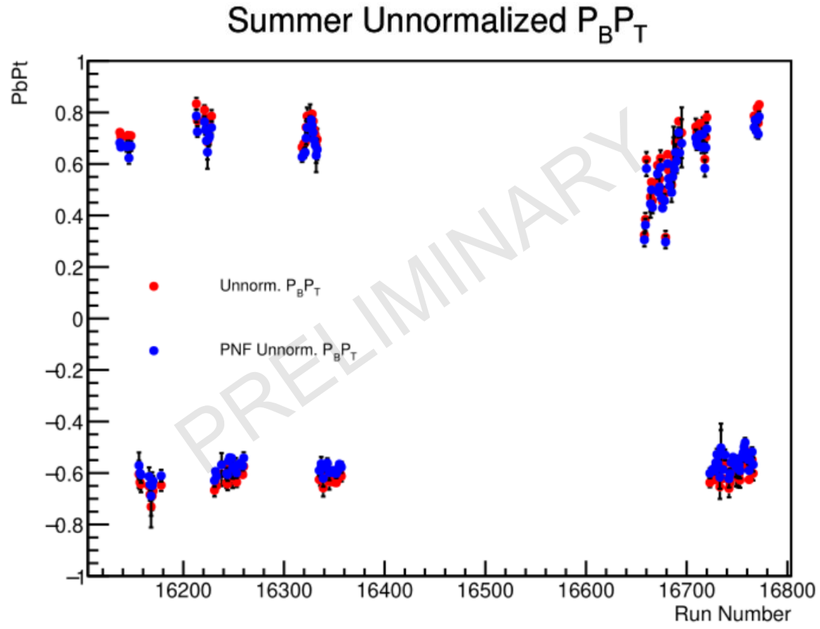
$$\boldsymbol{PNF} = \frac{\sum_{i=1}^{k} \boldsymbol{A_i d_i} \sum_{j=1}^{N_{runs}} \left(\boldsymbol{N_{ij}^{\uparrow\downarrow}} - \boldsymbol{N_{ij}^{\uparrow\uparrow}}\right)(\boldsymbol{P_b P_t})_{DIS,j}}{\sum_{i=1}^{k} (\boldsymbol{A_i d_i})^2 \sum_{j=1}^{N_{runs}} \left(\boldsymbol{N_{ij}^{\uparrow\downarrow}} + \boldsymbol{N_{ij}^{\uparrow\uparrow}}\right) \left((\boldsymbol{P_b P_t})_{DIS,j}\right)^2}$$

- Where $\boldsymbol{A, d, N}$ are the **elastic** ($ep \rightarrow e'p'$) asymmetry, dilution factor, and exclusive ep scattering counts (from Noemie Pilleux's DVCS analysis code)

- Multiply each $(\boldsymbol{P_b P_t})_{DIS} * \boldsymbol{PNF}$ for each polarization state to get corrected $P_b P_t$

- Run period average $\boldsymbol{PNF = 0.943 \pm 0.014}$





Pair Produced e^+/e^- Ratio

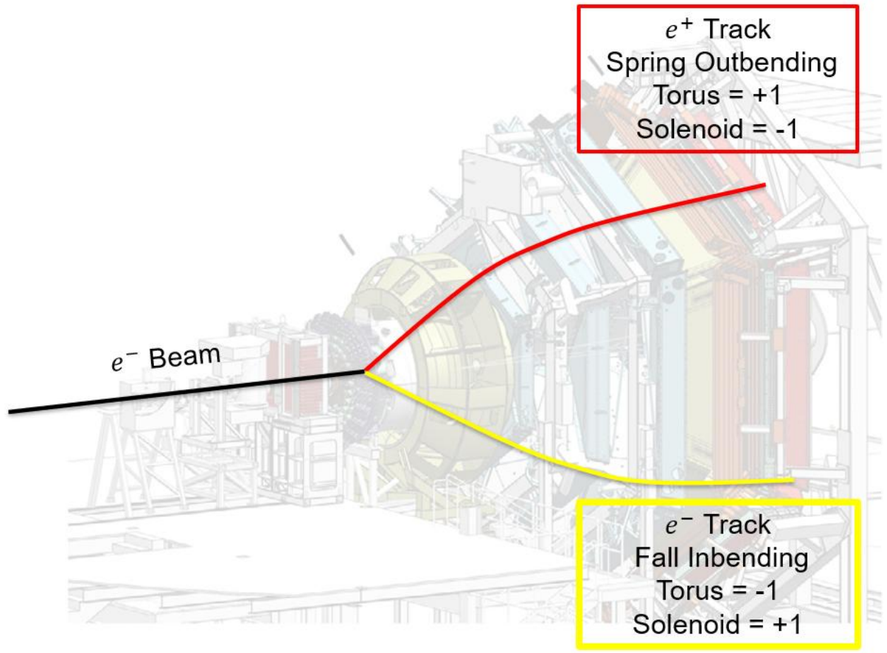
- Some e^- are generated from e^+e^- in Dalitz decays, Bethe-Heitler processes, etc., and contaminate the data at low P
- Estimate background with ratio of inbending e^+ to inbending e^- as a function of θ, P

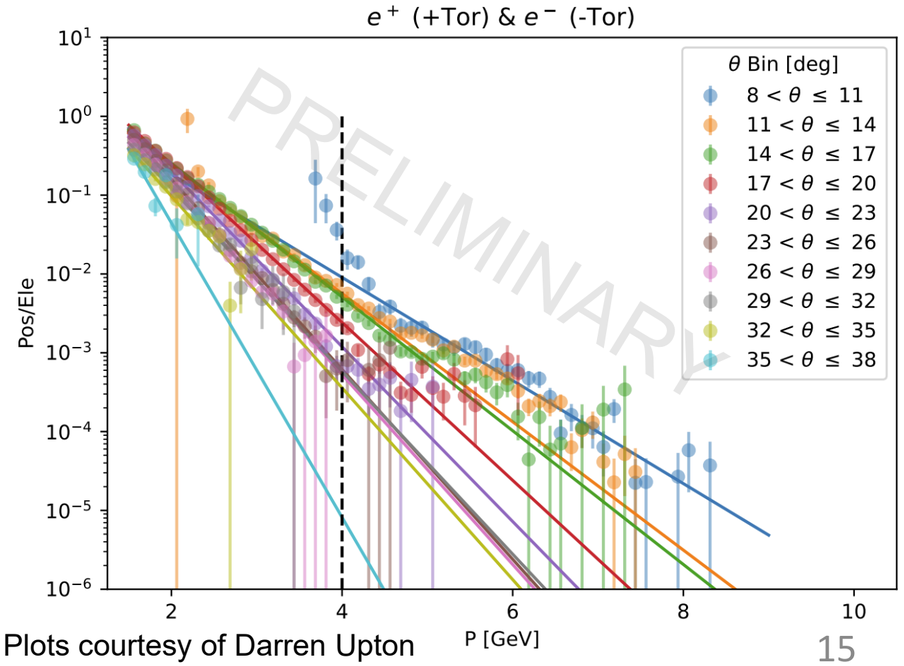
$$A_{e+e-} = \frac{1}{1 - R_{e^+}(\theta, P) - R_{\pi^+}(\theta, P)}, \qquad R_{e^+}(\theta, P) = e^{P*B_1(\theta)+B_2(\theta)}$$

$$B_i = a_i + b_i\theta + c_i\theta^2$$

Ratio Fits $B_i(\theta) = a_i + b_i\theta + c_i\theta^2$				
$B_i(\theta)$	a_i	b_i	c_i	χ^2_{red}
B_1	0.25666	−0.19508	0.0030785	3.9
B_2	−2.9804	0.52149	−0.010257	1.4

- e^+ data from the "positive" torus polarity, e^- from the "negative torus polarity
- Use boosted decision tree (BST) model for π^+ background (Mariana Tenorio-Pita's analysis)
- Check that e^+ and π^+asymmetries are minimal





Plots courtesy of Darren Upton

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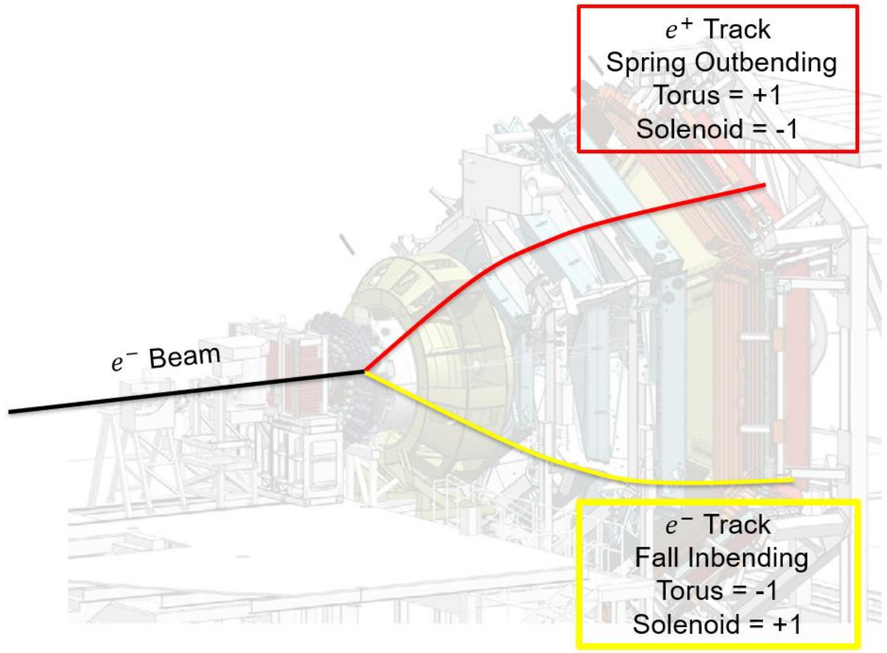
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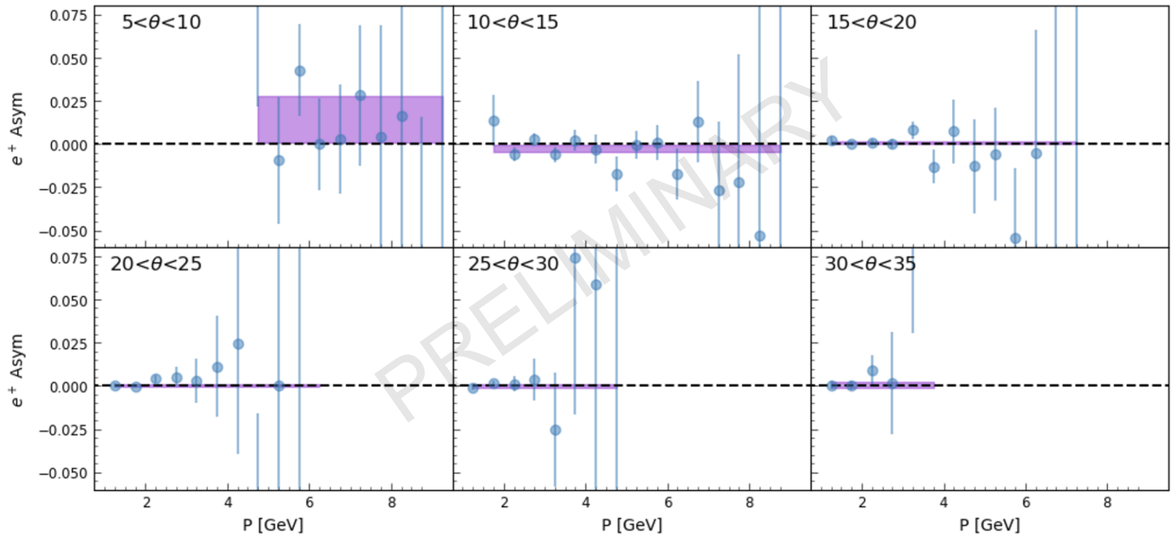
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Plots courtesy of Darren Upton

Faraday Cup Charge Asymmetries

- Beam is delivered in two helicity states: parallel and antiparallel to momentum (+,-)
- Faraday Cup (FC) measures total helicity-latched charge (HEL::scaler bank)
- Asymmetries must be normalized to the FC charge to account for charge asymmetry

$$A_{norm} = \frac{(N^+/F^+ - N^-/F^-)}{(N^+/F^+ + N^-/F^-)} \approx \left(\frac{N^+ - N^-}{N^+ + N^-}\right) - \left(\frac{F^+ - F^-}{F^+ + F^-}\right)$$

$$A_{norm} \approx A_{raw} - A_{FC}$$

- Alternatively define a luminosity ratio $L_R = F^+/F^-$

$$A_{norm} = \frac{N^+ - L_R N^-}{N^+ + L_R N^-}$$

- Raw asymmetry versus A_{FC} serves as a diagnostic tool for proper charge measurement: $A_{raw} = A_{FC} + A_{norm}$

- Deviation from a slope of 1 indicates an issue, which we saw in every run period!

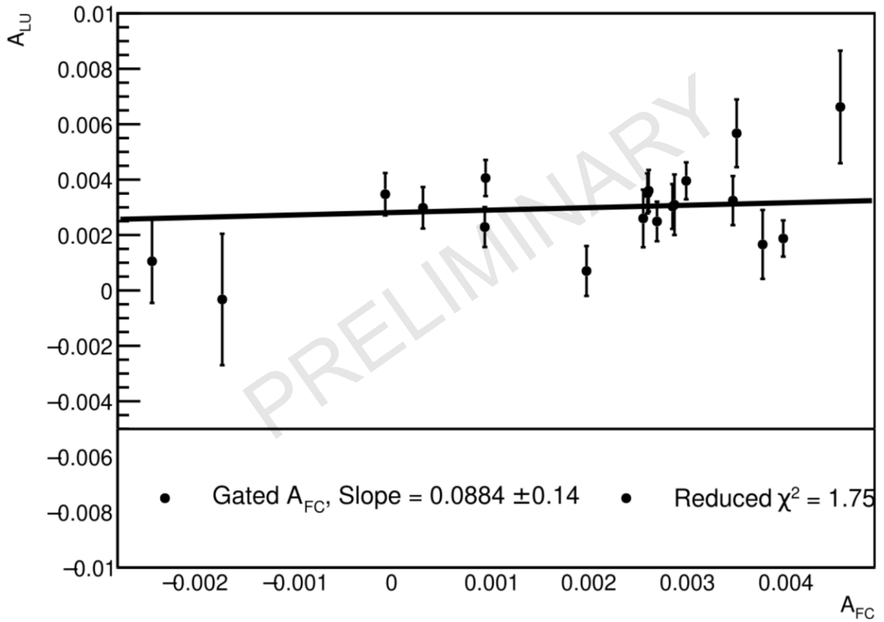
```
BANK :: NAME                HEL::scaler , ROWS      1
         fcupgated :  0.08374
             fcup :  0.08572
          slmgated :  0.00000
               slm :  0.00000
        clockgated : 32852.00000
             clock : 33330.00000
          helicity :        1
       helicityRaw :        1
```

Typical HEL::scaler bank readout

```
BANK :: NAME                HEL::scaler , ROWS      3
         fcupgated : -0.00110  0.00000  0.00000
             fcup :  0.00075  0.00000  0.00000
          slmgated : -0.00000  0.00000  0.00000
               slm :  0.00000  0.00000  0.00000
        clockgated : -1.00000  0.00000  0.00000
             clock : 33330.00000  0.00000  0.00000
          helicity :        1        1       -1
       helicityRaw :       -1        0        0
```

Erroneous HEL::scaler bank readout

Summer A_{LU} vs. A_{FC} for Unpol



Faraday Cup Charge Asymmetries

- These issues are caused by hardware issues: beam trips cause a “backup” of HEL::scaler readouts that get dumped into one output for one helicity
- HEL::scaler helicity-latched charges not entirely reliable!
- Currently working with Raffaella DeVita and Chris Dilks for alternative methods of calculating the A_{FC} from direct measurements

$$L_R = \frac{1 + A_{FC}}{1 - A_{FC}}$$

- Other methods: EPICS PVs or the number of readouts from the helicity control board electronics (“STRUCK”)
- So far, only summer data is available, but results are promising!
- All results shown today have no helicity-latched FC charge correction

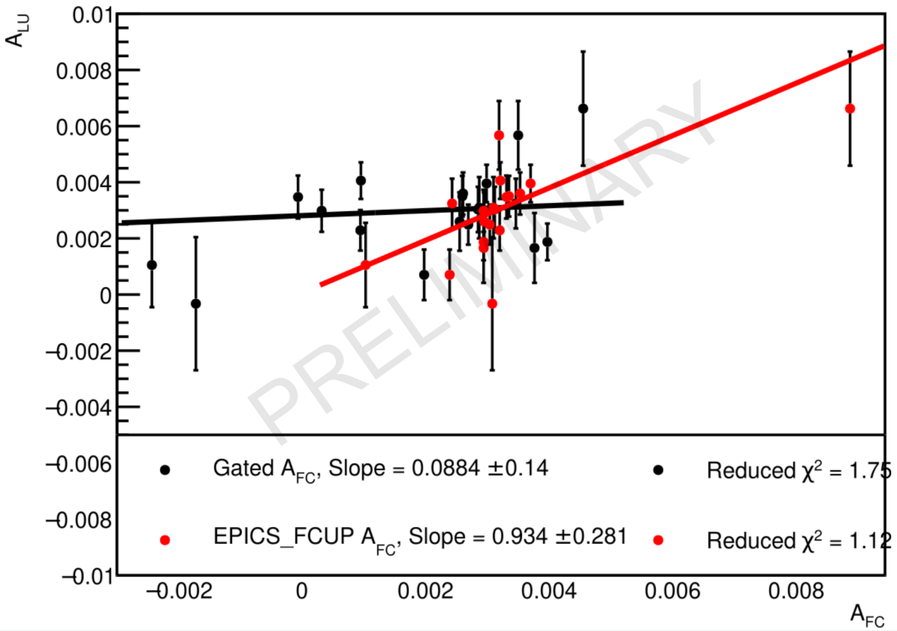
```
BANK :: NAME                HEL::scaler , ROWS      1
        fcupgated :  0.08374
             fcup :  0.08572
         slmgated :  0.00000
              slm :  0.00000
       clockgated : 32852.00000
            clock : 33330.00000
          helicity :        1
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```

Typical HEL::scaler bank readout

```
BANK :: NAME                HEL::scaler , ROWS      3
        fcupgated : -0.00110  0.00000  0.00000
             fcup :  0.00075  0.00000  0.00000
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            clock : 33330.00000  0.00000  0.00000
          helicity :        1        1       -1
       helicityRaw :       -1        0        0
```

Erroneous HEL::scaler bank readout

Summer A_{LU} vs. A_{FC} for Unpol



Preliminary Results for $A_{1,p}$

- The maximum likelihood method can also be used to combine the physical asymmetries $A_{||,meas}$ across all individual runs

$$A_{||,meas}(x,Q^2) = \frac{\sum_{i=0}^{n_{runs}} \left(N_i^{\downarrow\uparrow}(x,Q^2) - N_i^{\uparrow\uparrow}(x,Q^2)\right) D_{F,i}(x,Q^2)\boldsymbol{P_i}\,/A_{e^+e^-}}{\sum_{i=0}^{n_{runs}} \left(N_i^{\downarrow\uparrow}(x,Q^2) + N_i^{\uparrow\uparrow}(x,Q^2)\right)\left(D_{F,i}(x,Q^2)\boldsymbol{P_i}/A_{e^+e^-}\right)^2}$$

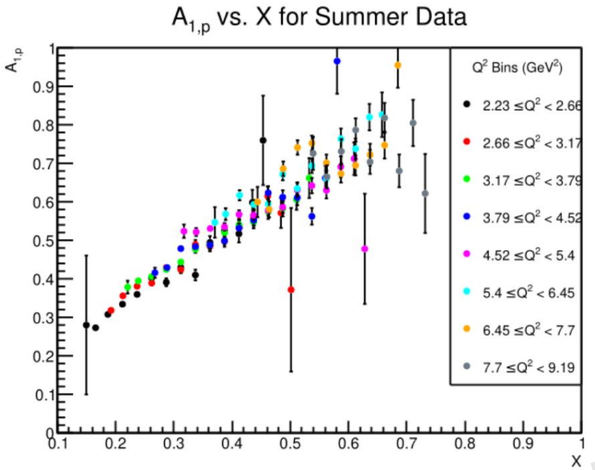
$$\sigma_{Ameas} = \sqrt{\left(\sum_{x,Q^2}(N^{\downarrow\uparrow} + N^{\uparrow\uparrow})(D_F\boldsymbol{P_i}/A_{e^+e^-})^2\right)^{-1}}$$

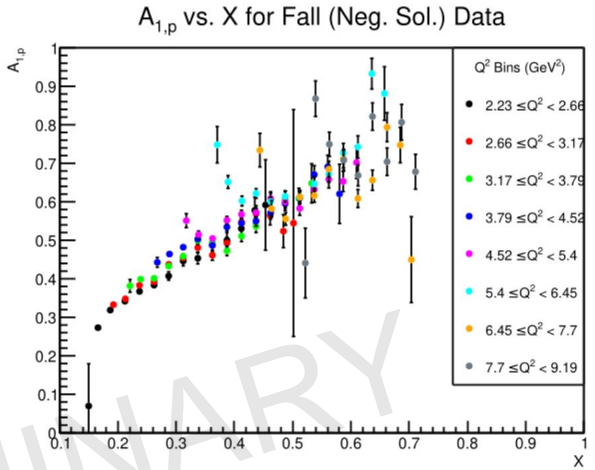
$$\boldsymbol{P_i} = (P_bP_t)_{DIS,i} * PNF$$

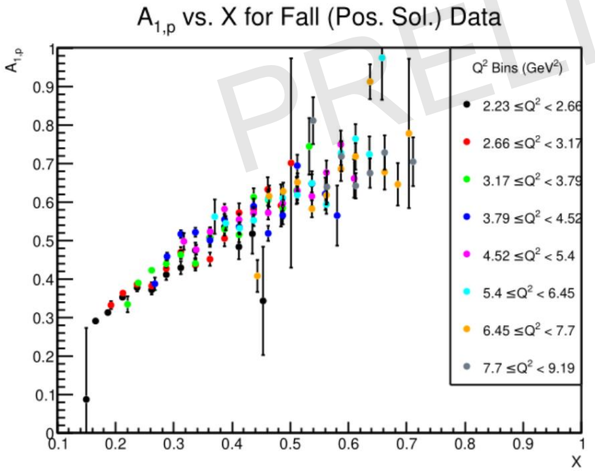
- Once data is combined, $A_{1,p}$ is extracted using model values of A_2 and R

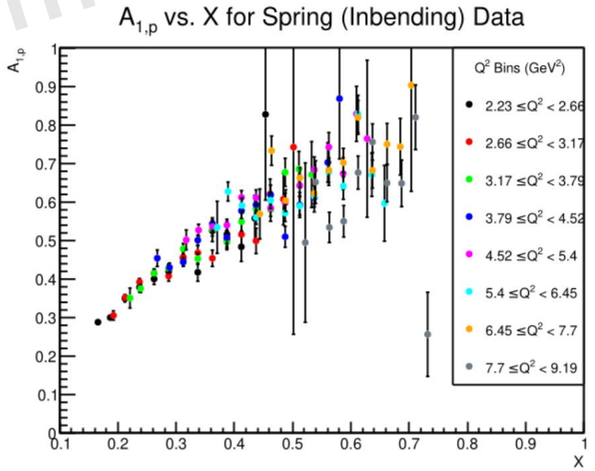
$$A_{1,p}(x,Q^2) = A_{||,phys}(x,Q^2)/D\ -\eta A_2(x,Q^2)$$

- Very preliminary results for $A_{1,p}$, showing statistical error bars and expected systematic errors
- Estimated systematic error (NH3) of 5-6% at large x, 6-11% at low x









PRELIMINARY

Preliminary Results for $A_{1,p}$

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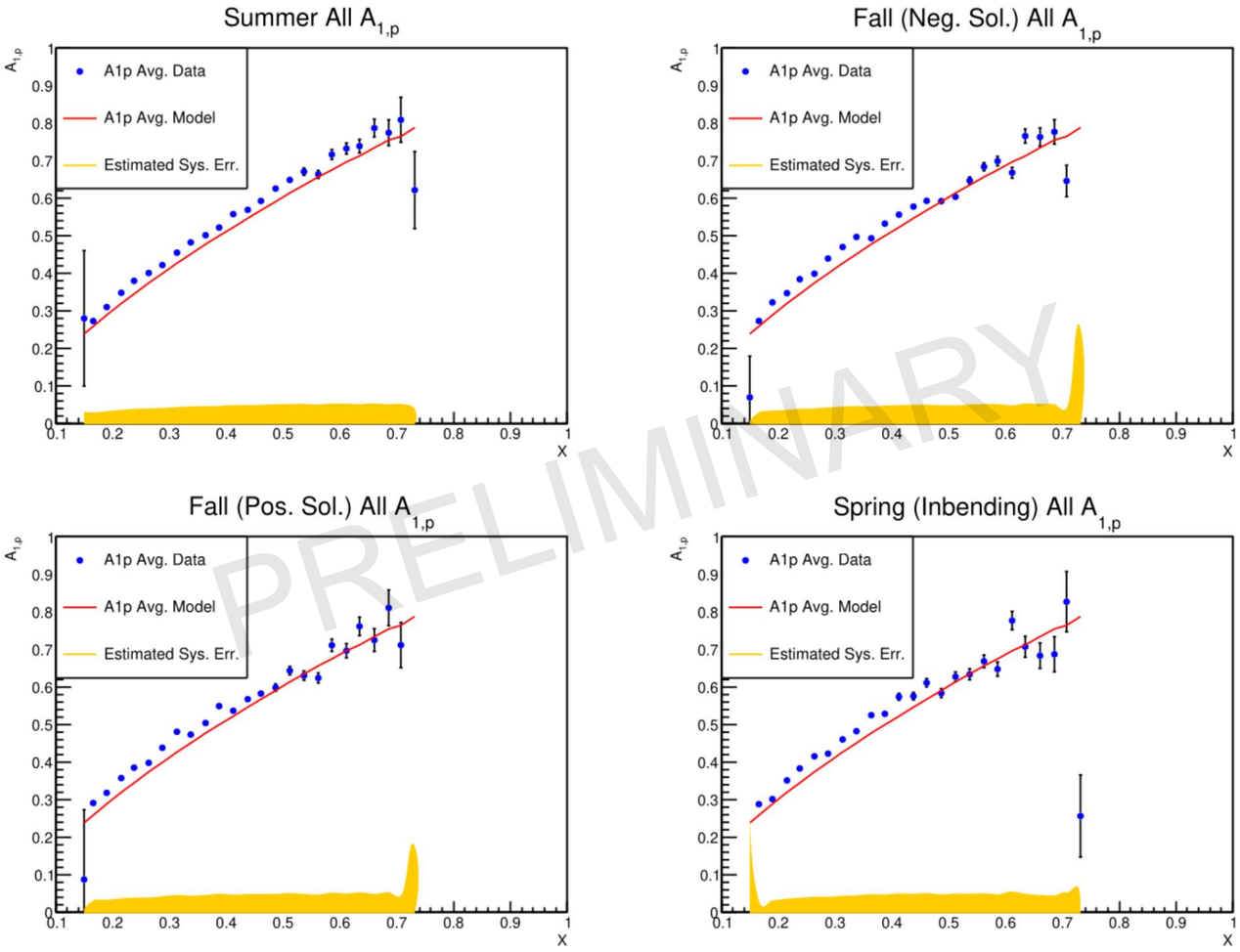
$$\sigma_{Ameas} = \sqrt{\left(\sum_{x,Q^2}(N^{\downarrow\uparrow} + N^{\uparrow\uparrow})(D_F\boldsymbol{P_i}/A_{e^+e^-})^2\right)^{-1}}$$

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PRELIMINARY

Preliminary Results for $A_{1,p}$ (June 2026)

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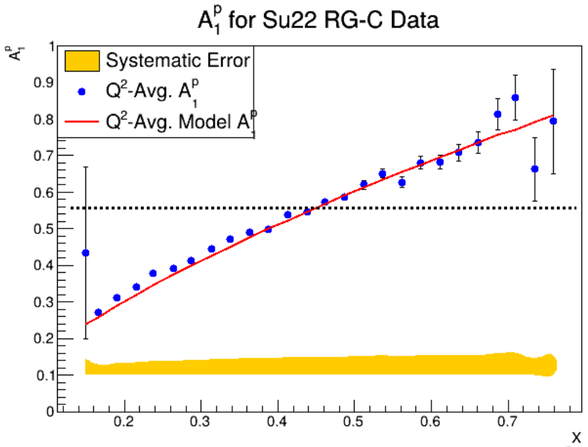
$$\sigma_{Ameas} = \sqrt{\left(\sum_{x,Q^2}(N^{\downarrow\uparrow} + N^{\uparrow\uparrow})(D_F\boldsymbol{P_i}/A_{e^+e^-})^2\right)^{-1}}$$

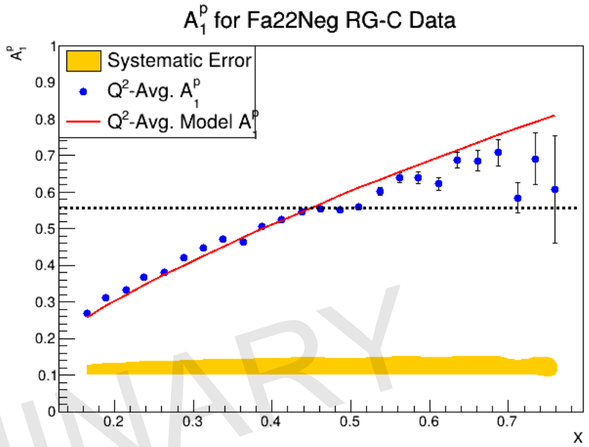
$$\boldsymbol{P_i} = (P_bP_t)_{DIS,i} * PNF$$

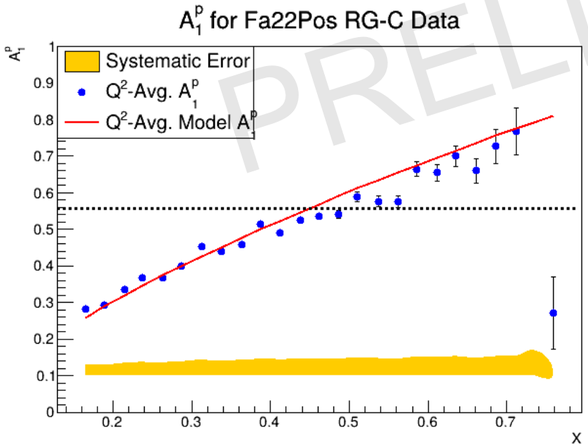
- Once data is combined, $A_{1,p}$ is extracted using model values of A_2 and R

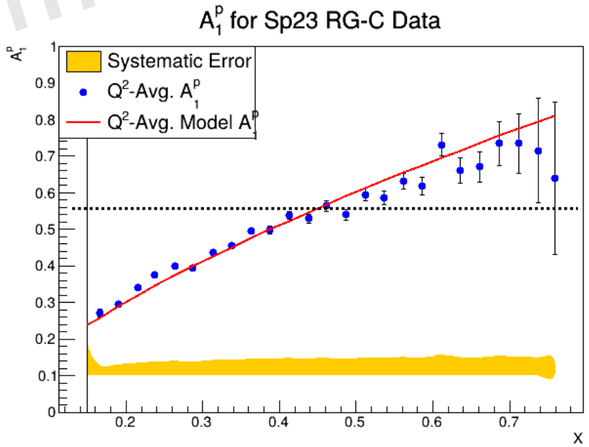
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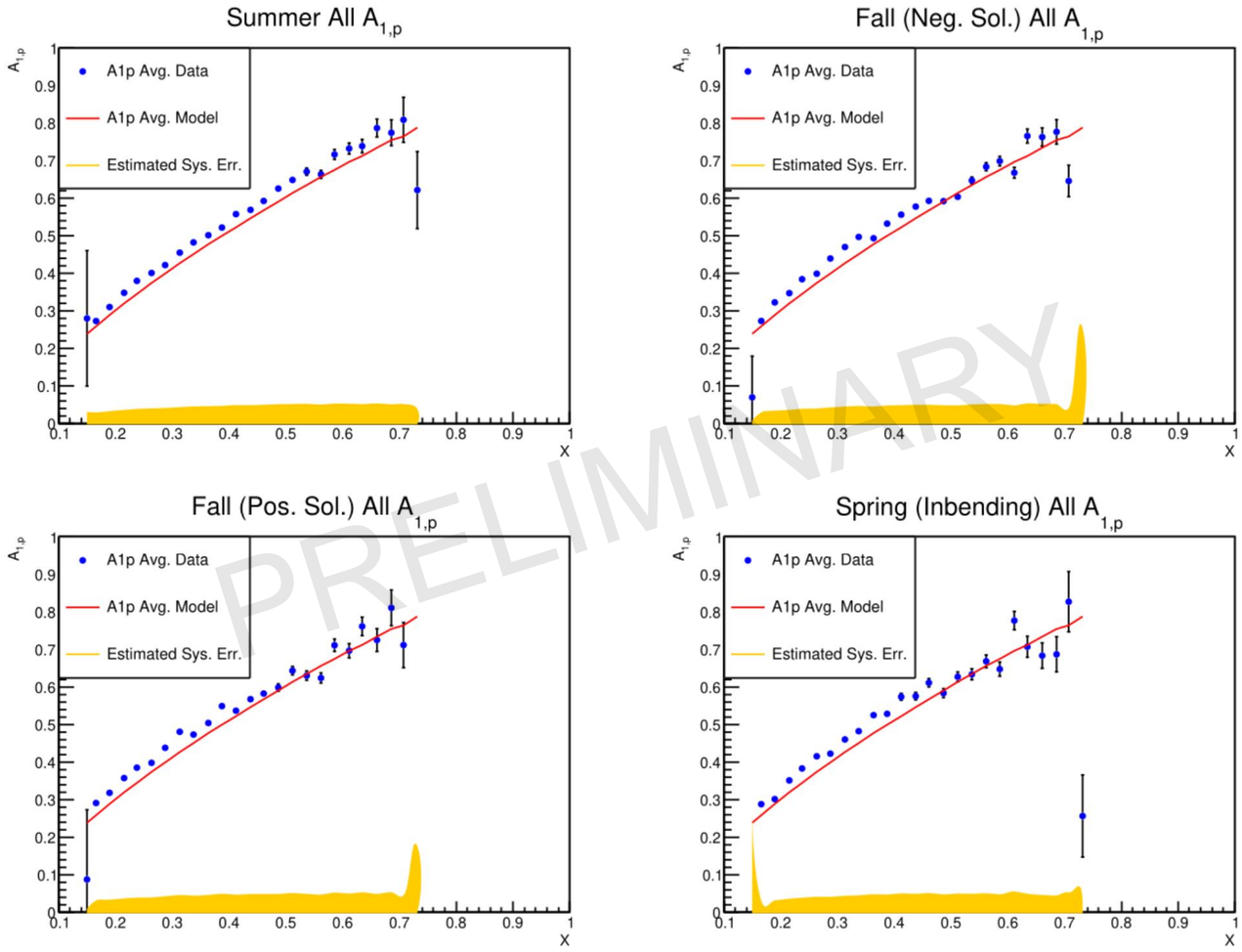
PRELIMINARY

Preliminary Results for $A_{1,p}$

- The (non-exhaustive) list of work still to be done:

1. Finalize background contributions from polarization of ^{14}N and e^+e^- pair production
2. Corrections for FC charge asymmetries
3. Radiative effects/corrections (for D_F and final results)
4. Apply momentum corrections
5. Normalization between run periods
6. Propagate systematic errors (thermal contractions, FC charge asymmetry)

Systematic Error Source	Typical Value in % of Measured Asymmetry
False asymmetries	$< 1\%$
Background subtraction	$< 1\%$
Dilution factor	3 %
Product of beam and target polarization	1% (proton) and 3% (deuteron)
Radiative corrections	3%
Unpolarized structure functions	From 1% (A_1) to 5% (g_1 for the neutron)
Asymmetry A_2	From 1% (high x) to 10% (low x)
Total for A_1^p	5-6 % at high x, 6-11% at low x
Total for A_1^d	7% at high x, 10-20% at low x



Any Questions?

References

1. M. Amarian et. al., “The Longitudinal Spin Structure of the Nucleon: A 12 GeV Research Proposal to Jefferson Lab (PAC 30)”. Link
2. V. Ziegler et. al. “The CLAS12 software framework and event reconstruction, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment”, 2020. Link
3. C. Keith et. al. “First use of a longitudinally polarized target with CLAS12”. Proceedings of 19th Workshop on Polarized Sources, Targets and Polarimetry - PoS(PSTP2022), 433, 009 (1-8). Link
4. J. Maxwell, “Polarized Targets at Jefferson Lab: Probing Nuclear Spin Structure”, New England Section, APS Meeting October 14th, 2022. Link
5. E. R. van Dorp et al., “Thermal expansion of semi-crystalline polymers: Anisotropic thermal strain and crystallite orientation”, Polymer, Volume 191, 2020, 122249, ISSN 0032-3861. Link
6. N. B. of Standards, A compilation and evaluation of mechanical, thermal, and electrical properties of selected polymers (1973). Link
7. Y. S. Touloukian et al., Thermophysical properties of matter - the tprc data series vol. 13. (1977). Link
8. N. Pilleux, “Nucleon structure studies at Jefferson Lab and the Electron-Ion Collider”, Universite Paris-Saclay, 2024. Link

Link to my GitHub code (under construction)



Image from Top Vehicles

Dilution Factors and Packing Fractions

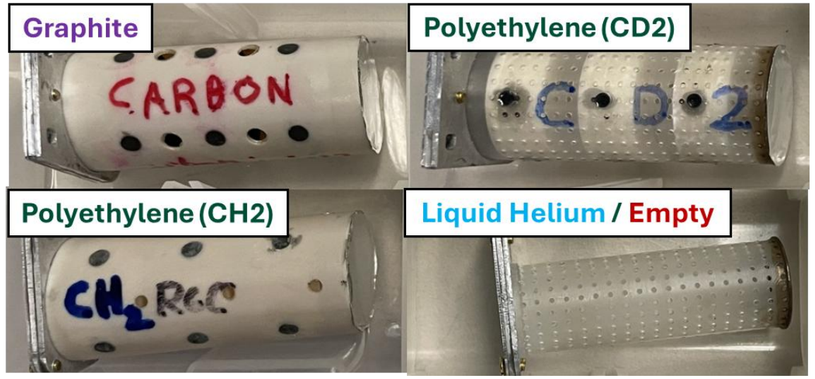
$$D_F(x,Q^2) = \frac{(n_A - n_{MT})(n_{CH} + An_C + Bn_{MT} + Cn_F)}{n_A(n_{CH} + Dn_C + En_{MT} + Fn_F)}, \quad P_F(x,Q^2) = \frac{G(n_A - n_{MT})}{n_{CH} + Dn_C + En_{MT} + Fn_F}$$

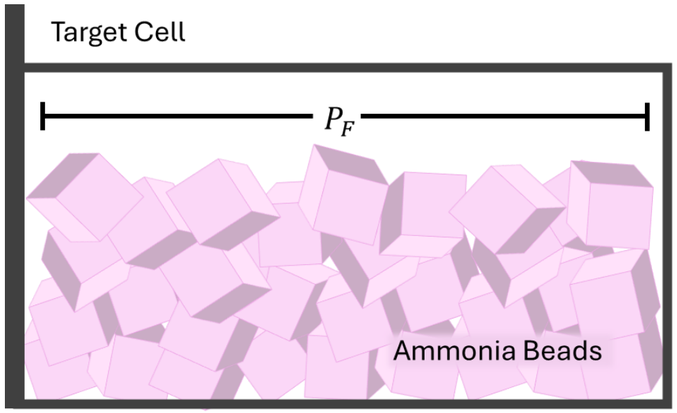
Dilution Factor / Packing Fraction Coefficients			
Coefficient	Geometry Values	Coefficient	Geometry Values
A	$-\ell_{CH}\rho_{CH}/\ell_C\rho_C$	B	$(\rho_C\ell_C L + (\rho_{CH} - \rho_C)\,\ell_C\ell_{CH} - \ell_{CH}\rho_{CH}L)\,/\,(-\ell_C\rho_C L)$
C	$(\rho_{CH} - \rho_C)\,\ell_{CH}/L\rho_C$	a	$\ell_C\ell_{CH}\,(9\rho_A\rho_C - 2\rho_{CH}\,(\rho_A + 3\rho_C))$
D	$-2\ell_{CH}\rho_{CH}/9\ell_C\rho_C$	E	$(9\ell_C\rho_C - 2\ell_{CH}\rho_{CH} - a/\,(L\rho_A))\,/\,(-9\ell_C\rho_C)$
F	$-a/\,(9\ell_C\rho_C L\rho_A)$	G	$6\ell_{CH}\rho_{CH}/9L\rho_A$

Table 1: Coefficients used to collect geometric terms for the dilution factor equation 1. Coefficients for ND3 are found by taking the subscripts $CH \to CD$ and $A \to D$ using Table 2.

Target Geometries and Thermal Corrections			
Material	Value	Material	Value
Carbon Length l_C	1.678 cm	Bath Length L	5.86 cm
CH2 Length l_{CH}	3.18 cm	CD2 Length l_{CD}	2.686 cm
Helium Density ρ_{He}	0.03623 mol/cm^3	Carbon Density ρ_C	0.1494 mol/cm^3
CH2 Density ρ_{CH}	0.06719 mol/cm^3	CD2 Density ρ_{CD}	0.06845 mol/cm^3
NH3 Density ρ_A	0.05091 mol/cm^3	ND3 Density ρ_D	0.05023 mol/cm^3

Table 2: Target geometries and densities from Ref. [1]. These are the approximate room temperature values, with the exception of the ammonia density (which is always kept at cryogenic temperatures).





Polarization Normalization Factor

- Derive a Polarization Normalization Factor (PNF) by taking the weighted average of elastic $P_b P_t$ values to the DIS for each run $\boldsymbol{j}$

- $$\boldsymbol{PNF_j = \frac{P_{el,j}}{P_{DIS,j}} = \frac{1}{(d_{el,j} A_{el,j} P_{DIS,j})} \frac{\left(N^{\uparrow\downarrow}_{el,j} - N^{\uparrow\uparrow}_{el,j}\right)}{\left(N^{\uparrow\downarrow}_{el,j} + N^{\uparrow\uparrow}_{el,j}\right)}}, \quad \boldsymbol{\sigma_{PNF,j} \approx 1/\left(A_{(||,el,j)} d_{el,j} P_{DIS,j} \sqrt{N^{\uparrow\downarrow}_{el,j} + N^{\uparrow\uparrow}_{el,j}}\right)}$$

- Where $\boldsymbol{d_{el,j}}$ are the dilution factors calculated with elastic ep scattering with exclusivity cuts
- Taking the weighted average across all runs $\boldsymbol{j}$ and kinematic bins $\boldsymbol{i}$ yields

- $$\boldsymbol{PNF = \frac{\sum_{i=1}^{k} A_{el,i} d_{el,i} \sum_{j=1}^{N runs} \left(N^{\uparrow\downarrow}_{el,ij} - N^{\uparrow\uparrow}_{el,ij}\right) P_{DIS,j}}{\sum_{i=1}^{k} \left(A_{el,i} d_{el,i}\right)^2 \sum_{j=1}^{N runs} \left(N^{\uparrow\downarrow}_{el,ij} + N^{\uparrow\uparrow}_{el,ij}\right) \left(P_{DIS,j}\right)^2}}, \quad \boldsymbol{\sigma_{PNF} = \sqrt{1/\left[\sum_{i=1}^{k} \left(A_{el,i} d_{el,i}\right)^2 \sum_{j=1}^{N runs} \left(N^{\uparrow\downarrow}_{el,j} + N^{\uparrow\uparrow}_{el,j}\right) \left(P_{DIS,j}\right)^2\right]}}$$

- Uncertainties in $d_{el,i}$ calculated separately using a variational method and added in quadrature
- PNF calculated separately for positive and negative target polarizations in each run period
- Multiply each $\boldsymbol{P_{DIS,j} * PNF}$ for each polarization state to get corrected $P_b P_t$

Calculation of Final $P_b P_t$

- The PNF are used to scale the DIS $P_b P_t$ to correct for the model bias

$$(\boldsymbol{P_b P_t})_{\boldsymbol{final}} = (\boldsymbol{P_b P_t})_{\boldsymbol{DIS}} * \boldsymbol{PNF}$$

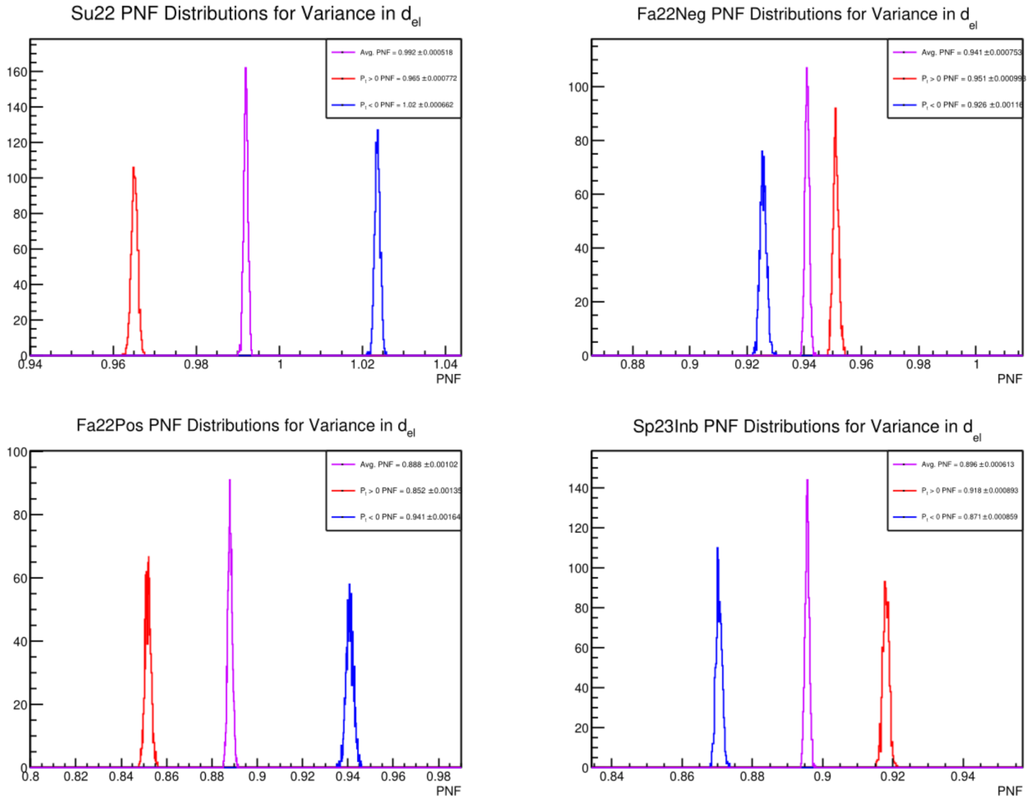
$$\boldsymbol{\delta(P_b P_t)_{final}} = \sqrt{(\boldsymbol{PNF})^2(\boldsymbol{\delta(P_b P_t)_{DIS}})^2 + \left((\boldsymbol{P_b P_t})_{\boldsymbol{DIS}}\right)^2(\boldsymbol{\delta PNF})^2}$$

- The error in the PNF from the statistical uncertainty in elastic counts $N^{\pm}$ is calculated using the previous equation which neglects errors in the DIS $P_b P_t$ and elastic d_i

$$\boldsymbol{\sigma_{PNF,N}} = \sqrt{\boldsymbol{1/\left[\sum_{i=1}^{k}\left(A_{el,i}d_{el,i}\right)^2 \sum_{j=1}^{N_{runs}}\left(N_{ij}^{+} + N_{ij}^{-}\right)\left(P_{DIS,j}\right)^2\right]}}$$

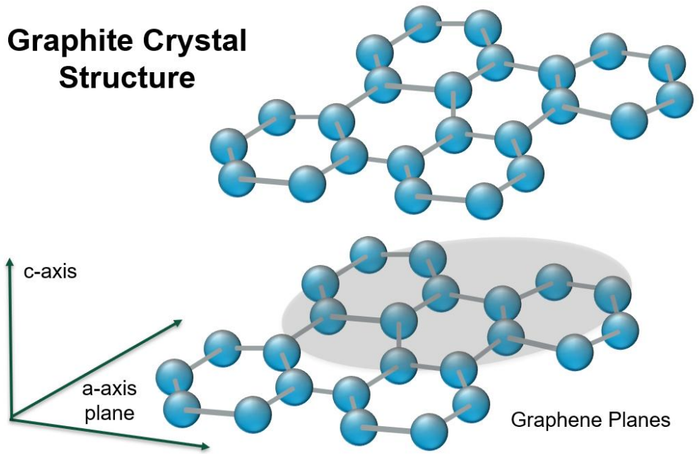
- The error from the elastic d_i are propagated using a variational approach
- Each value of the PNF is recalculated using new d_i that were varied using a Gaussian distribution around their statistical error bars
- Calculations were performed 1000 times, and the standard deviation of the PNFs is taken as the error from the elastic d_i: $\sigma_{d,el}$
- The total error in PNF is taken as the quadrature sum of the statistical and elastic errors:

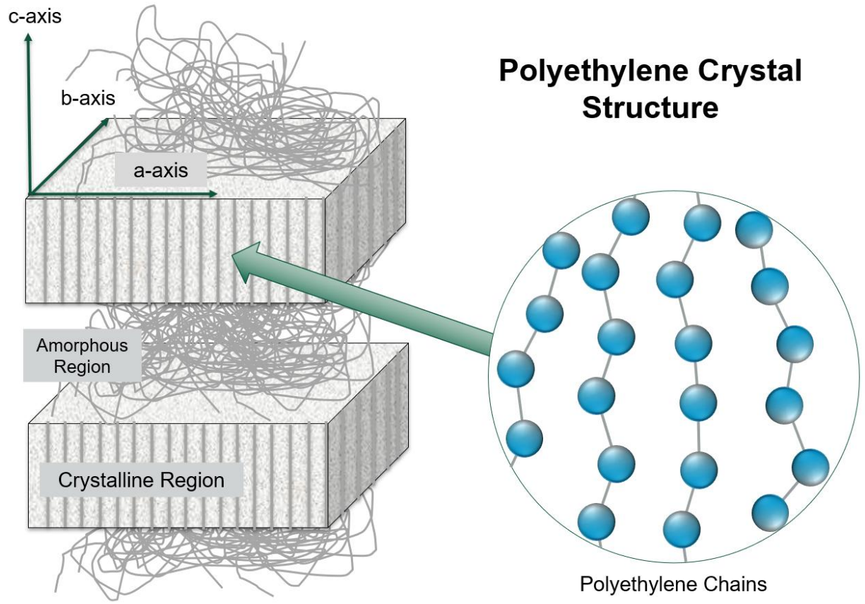
$$\boldsymbol{\delta PNF} = \sqrt{\boldsymbol{\sigma_{PNF,N}^2 + \sigma_{d,el}^2}}$$



D_F Systematics: Thermal Contractions

- Target material geometries/densities were measured at roughly room temperature (300 K)
- However, cooling the targets to ~1 K in the liquid helium bath introduces thermal contractions, which affect the D_F and P_F
- Two primary unknowns for thermal contractions: expansion constant $\boldsymbol{\alpha}$ and target anisotropic behavior $\boldsymbol{\beta}$

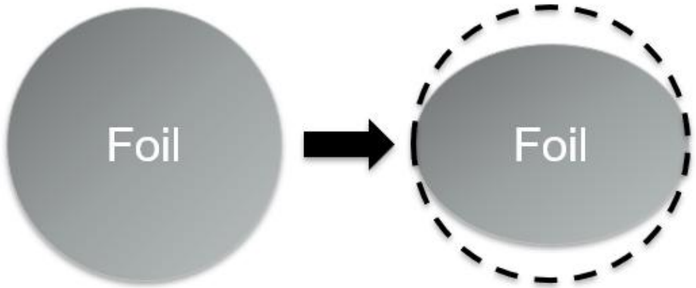




PE crystalline structure information from van Dorp et. al. [Ref. 5]

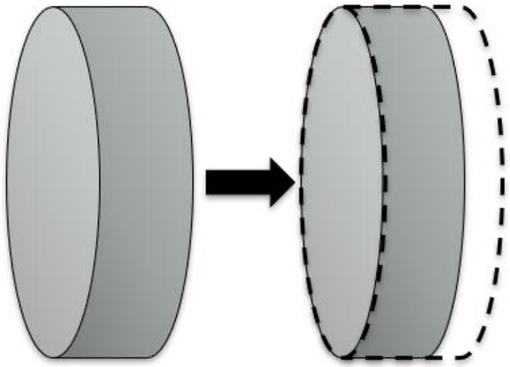
- Graphite (GR) and polyethylene (PE) targets have a crystalline structure
- Potential for anisotropic behavior during thermal contraction ⇒ different effects on areal density
- Accounted for unknown $\boldsymbol{\alpha}, \boldsymbol{\beta}$ in the systematic error

Radial Contraction (*R*)



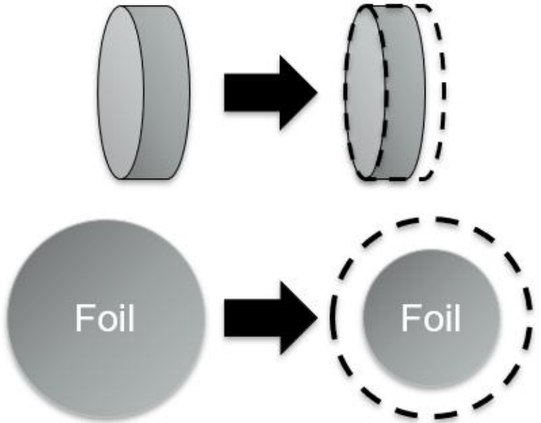
(GR)

Length Contraction (*L*)



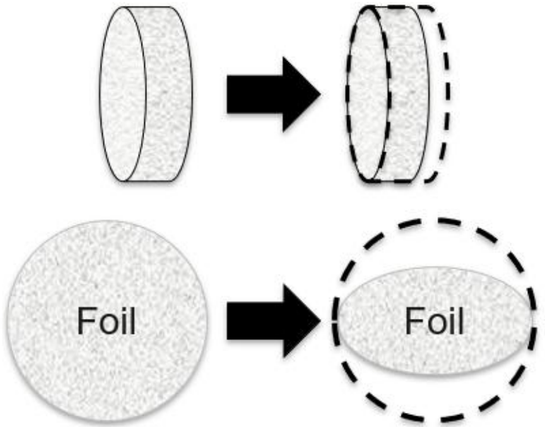
(GR)

Isotropic Contraction (*Iso*)



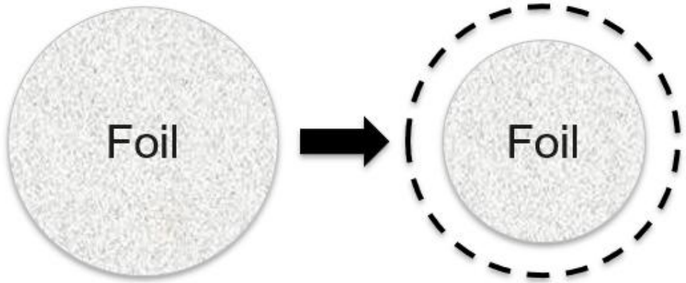
(GR)

Radius + Length Contraction (*RL*)



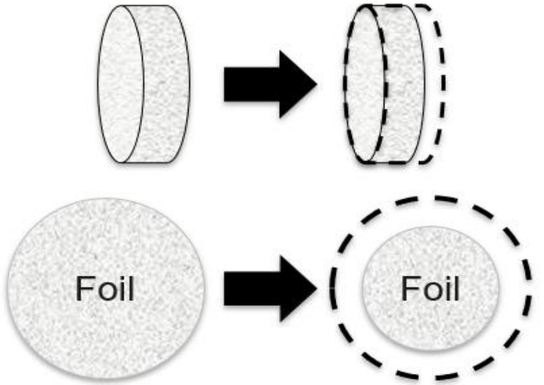
(PE)

Both Radii Contraction (*RR*)



(PE)

Isotropic Contraction (*Iso*)



(PE)

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- Potential for anisotropic behavior during thermal contraction ⇒ different effects on areal density
- Accounted for unknown $\boldsymbol{\alpha, \beta}$ in the systematic error

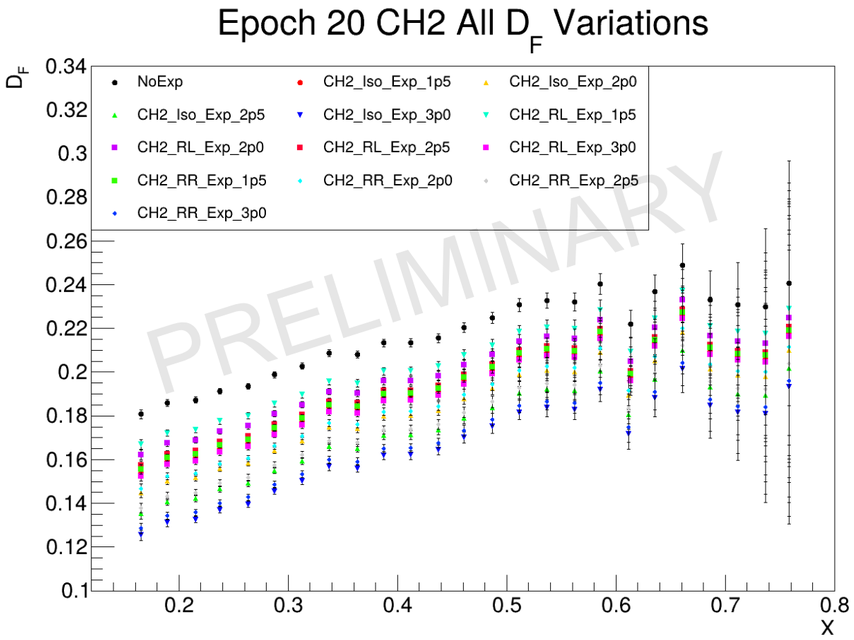
D_F Systematic Errors

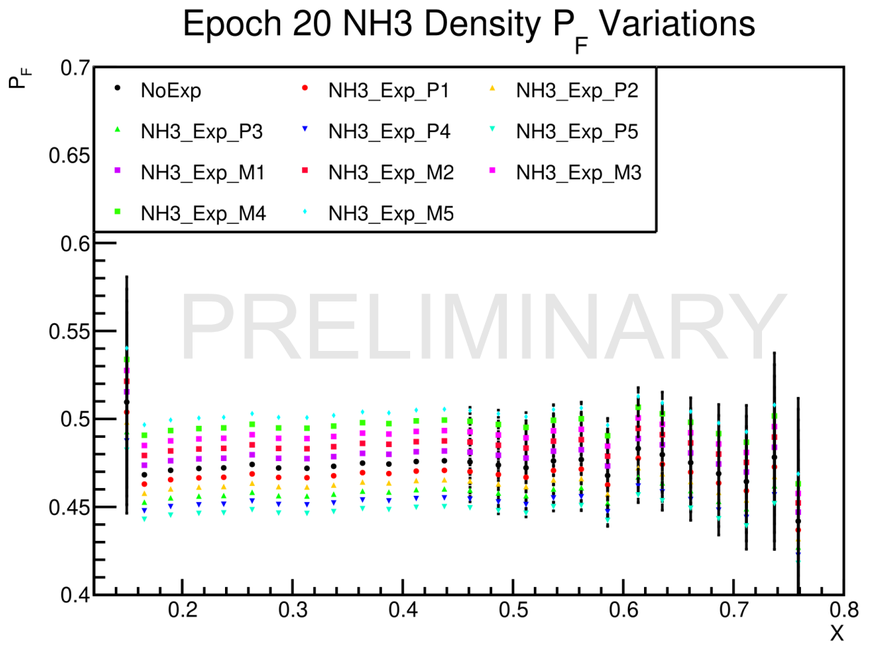
- Systematic errors in D_F and P_F determined through an iterative process of varying material contractions by $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$
  1. Holding all other material properties at their measured room temperature values, the D_F and P_F were recalculated across all variations of a material's $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$
  2. For every bin in x, Q^2 the standard deviation across all variations was calculated
  3. The standard deviation was taken as the systematic error for that bin
  4. Systematic errors were parameterized using a quadratic (for D_F) equation or a constant (for P_F)

- Very large systematic errors in D_F for CH2, from **9% at small x to 6% at large x**

Thermal Contraction Parameters By Material				
Target Material	α-Range (%)	β Configurations	δ_{sys}-Range D_F (%)	δ_{sys}-Range P_F (%)
PE (CH_2)	1.5, 2.0, 2.5, 3.0	RR, RL, Iso	6%-9%	2.2%
Graphite	0.3, 0.5, 0.7, 0.9, 1.2, 1.5	R, L, Iso	2.5%-4%	0.2%
Teflon	1.7, 1.8, 1.9, 2.0, 2.1	Iso	<0.1%	0.16%
Ammonia	$\pm1, \pm2, \pm3, \pm4, \pm5$	Iso	0.5%	4%
PE (Low Estimate)	1.5, 2.0, 2.5	RR, RL, Iso	4.5%-7%	1.8%
Graphite (Low Estimate)	0.3, 0.5, 0.7, 0.9	R, L, Iso	2%-2.5%	0.14%

Graphite and PE expansion values α taken from [Ref. 6]
Teflon expansion values taken from [Ref. 7]

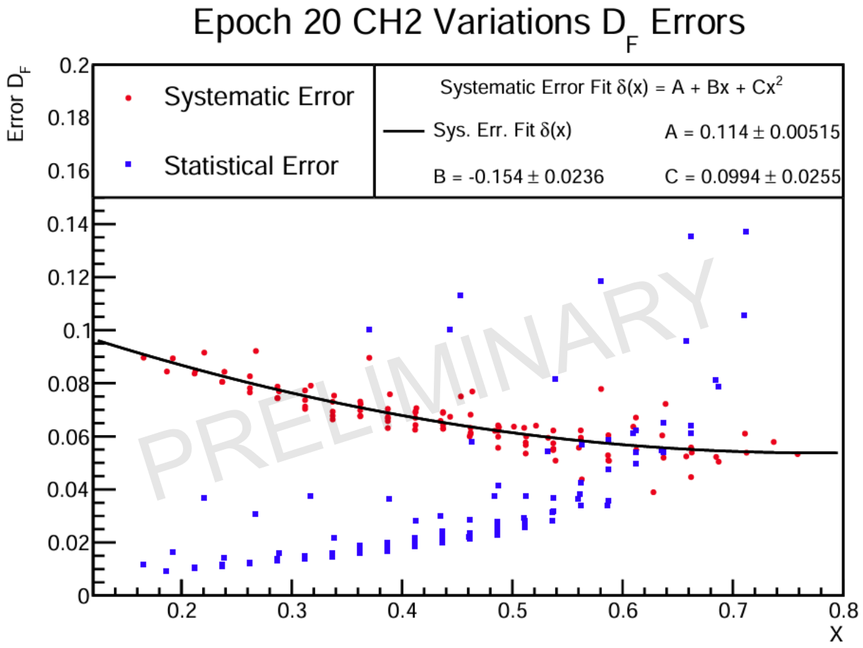


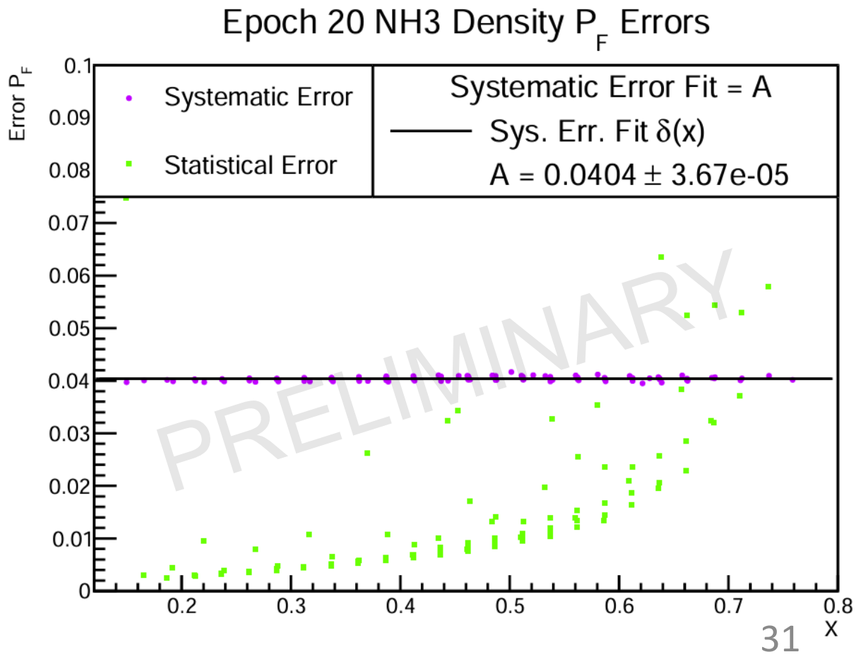


D_F Systematic Errors

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  1. Holding all other material properties at their measured room temperature values, the D_F and P_F were recalculated across all variations of a material's $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$
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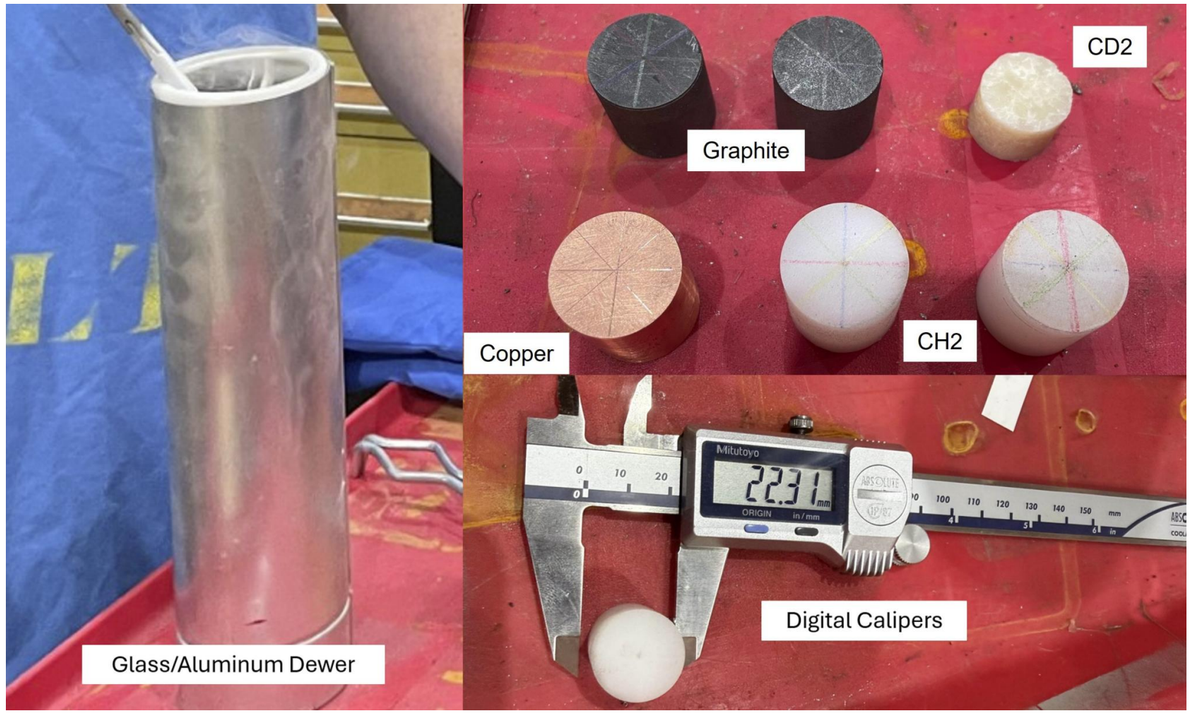


Thermal Contraction Parameters By Material				
Target Material	α-Range (%)	β Configurations	δ_{sys}-Range D_F (%)	δ_{sys}-Range P_F (%)
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Graphite	0.3, 0.5, 0.7, 0.9, 1.2, 1.5	R, L, Iso	2.5%-4%	0.2%
Teflon	1.7, 1.8, 1.9, 2.0, 2.1	Iso	<0.1%	0.16%
Ammonia	$\pm1, \pm2, \pm3, \pm4, \pm5$	Iso	0.5%	4%
PE (Low Estimate)	1.5, 2.0, 2.5	RR, RL, Iso	4.5%-7%	1.8%
Graphite (Low Estimate)	0.3, 0.5, 0.7, 0.9	R, L, Iso	2%-2.5%	0.14%

Graphite and PE expansion values α taken from [Ref. 6]
Teflon expansion values taken from [Ref. 7]

Measurement of Thermal α and β

- Prompted a direct measurement target material samples
- Samples were made from the same extruded rods that the CH2 and graphite target foils were taken from
- Two 20mm x 20mm samples of CH2, graphite. One CD2 sample, one copy sample for comparison
- Thermal contraction measured from room temperature (~300K) to liquid nitrogen (~77K)
  1. Measured diameter and length of each sample at room temperature
  2. Immerse in liquid nitrogen until cooled, and then measure again, holding it within the liquid nitrogen vapor
- Final values of α for length and diameter taken as the average between each of the two samples



Measured Thermal Contractions			
Polyethylene (CH2)		Graphite (Carbon)	
α_D (Diameter)	α_L (Length)	α_D (Diameter)	α_L (Length)
-1.73%	-1.83%	0.16%	0.25%

Thanks to James Maxwell, Chris Keith, and James Brock for making the samples!!!
Thanks to Sailaja, Stephen, and James Maxwell for helping take the measurements!!!

Measurement of Thermal α and β

- CH2 measurement saw anisotropic behavior; graphite possibly expanded slightly as it cooled
- Results extrapolated to ~1K bath temperature through $\boldsymbol{\alpha} \rightarrow \alpha/0.95, \alpha/0.9$
- Assumes that roughly 80-90% of material thermal contraction (from room temperature) occurs by liquid nitrogen temperatures [Ref. 6]
- Repeated systematic error study using smaller ranges of $\boldsymbol{\alpha}$ constrained to one $\boldsymbol{\beta}$ configuration: α, $\alpha/0.95, \alpha/0.9$
- CH2 systematics recalculated to be below 1-2% at large x

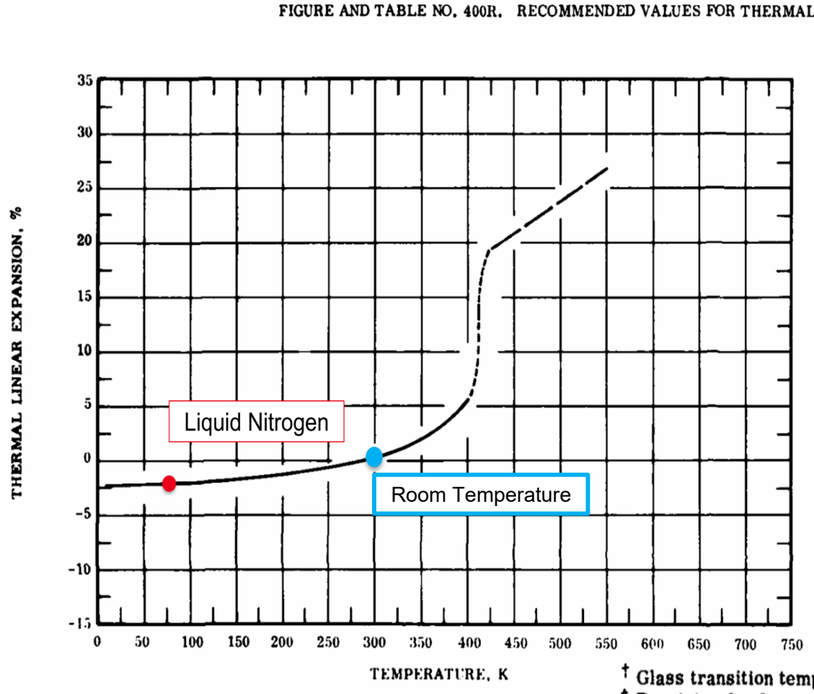


FIGURE AND TABLE NO. 400R. RECOMMENDED VALUES FOR THERMAL LINEAR EXPANSION OF POLYETHYLENE

RECOMMENDED VALUES

[Temperature, T, K; Linear Expansion, $\Delta L/L_0$, %; α, 10^{-6} K^{-1}]

T	$\Delta L/L_0$	α
10	-2.44	12
25	-2.41	23
50	-2.34	33
75	-2.25	45
100	-2.12	56
150	-1.76	82
200	-1.30	110
250	-0.67	141
293	0.00	169
325	0.75	330
350	1.60	490
375	3.10	690
400†	5.60	940
425†	19.4‡	
450	21.0‡	
500	24.1‡	
550	27.5‡	

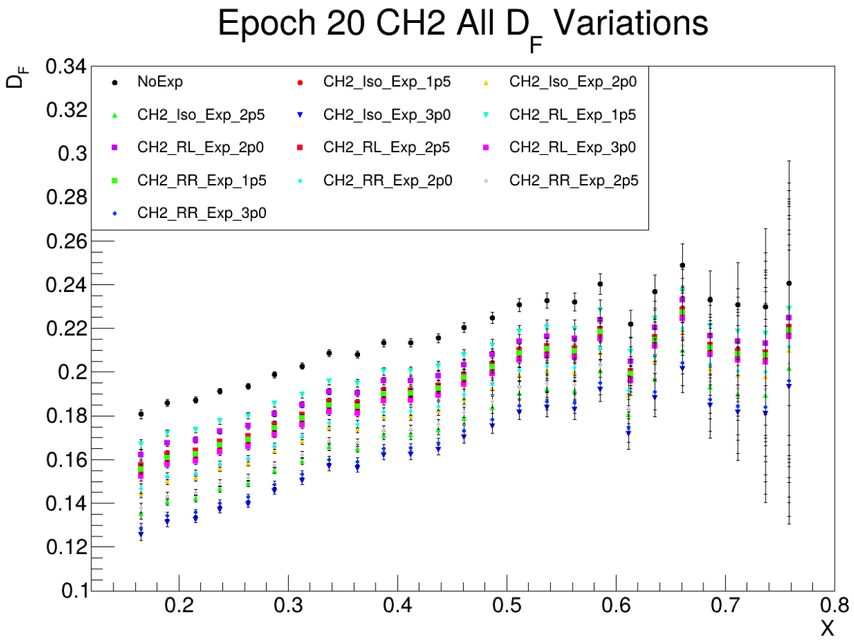
† Glass transition temperature.
‡ Provisional values.

N. B. of Standards, A compilation and evaluation of mechanical, thermal, and electrical properties of selected polymers (1973). {Ref. 6[

Measured Thermal Contractions			
Polyethylene (CH2)		Graphite (Carbon)	
α_D (Diameter)	α_L (Length)	α_D (Diameter)	α_L (Length)
-1.73%	-1.83%	0.16%	0.25%

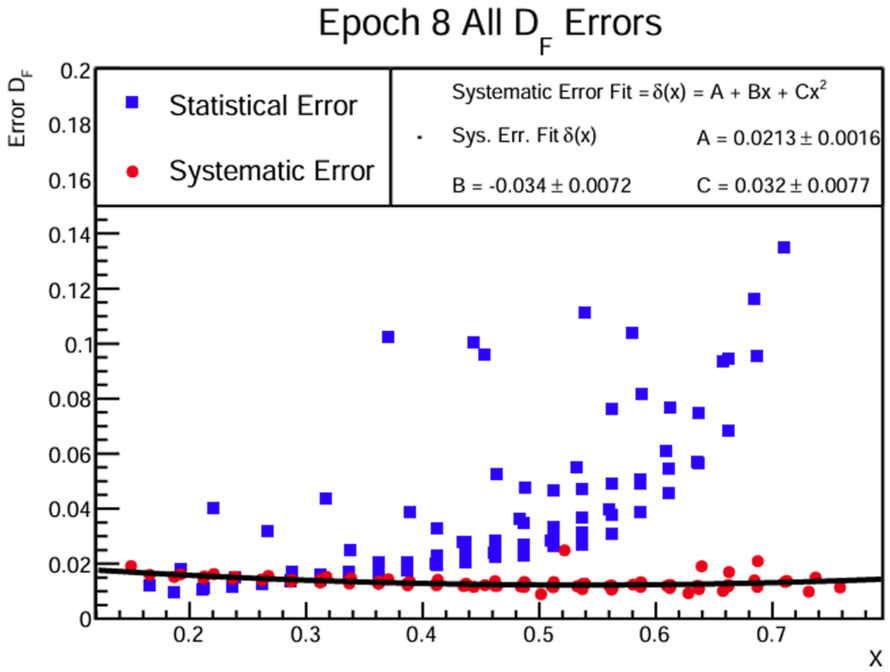
Calculating the Dilution Factor

- Run periods divided into “epochs” due to target swaps
- Radiation length corrections applied to the empty targets
- 10% difference for positive polarity solenoid data
- Systematic errors calculated from thermal contraction measurements are below 2%!
- Systematics used a variational approach based on all possible thermal contractions



Thermal Contraction Parameters By Material						
Target Material	$\alpha_D(\%)$	$\alpha_L(\%)$	α_{Iso} (%)	β Configs	δ_{DF} (%)	δ_{PF} (%)
PE (CH_2)	-1.73, -1.88	-1.83, -1.99	-1.93	DL, Iso	1.0 - 1.4	0.3
Graphite	0.11, 0.16, 0.21	0.20, 0.25, 0.30	0.0	DL, Iso	0.8 - 1.0	0.05
Teflon	-	-	-1.7,...,-2.1	Iso	0.05 - 0.07	0.016
Ammonia	-	-	±1,...,±5	Iso	0.5	4.1
Total Systematic Error $\delta_{sys} = \left(\delta^2_{CH2} + \delta^2_{Graphite} + \delta^2_{Teflon} + \delta^2_{Ammonia}\right)^{1/2}$					1.4 - 1.6	4.1

Table 7: List of all α and β used in the thermal contraction studies of the target. The α are the percent contraction measured relative to room temperature. The left columns are for the first pass analysis, the rightmost were the values used for the final systematics. “—” indicate that the values weren’t changed from the first pass. The definitions for β correspond to Figure 4.



For more information on the systematics, see our summary note here

Calculation of Elastic Dilution Factors

- Both the elastic and DIS dilution factors are calculated using the same dilution factor formula

$$d_i(x,Q^2) = \frac{(n_A - n_{MT})(n_{CH} + An_C + Bn_{MT} + Cn_F)}{n_A(n_{CH} + Dn_C + En_{MT} + Fn_F)}, \qquad P_F(x,Q^2) = \frac{G(n_A - n_{MT})}{n_{CH} + Dn_C + E_{MT} + Fn_F}$$

- Where the $A \ldots G$ collect coefficients related to target geometry
- For elastic dilution factors, extract the counts $n_i = N_i/F_i$ using the elastic exclusivity cuts from Noemie's analysis
- I modified Noemie's script to get the elastic counts n_i for each target and calculated elastic $D_{F,el}$ using the above formula

All Elastic ep Kinematic and Fiducial Cuts		
$W < 2$ GeV	$Q^2 > 0.95$ GeV^2	$SF > 0.2$
Edge Cuts for DC		
$E_{R1} > 5$ cm	$E_{R2} > 5$ cm	$E_{R3} > 10$ cm
Edge Cuts for CVT		
$E_{R1-R3} > 0$ cm	$E_{R4} > -2$ cm	$E_{R5} > -5$ cm
Edge Cuts for PCAL		
$\ell_U > 14$ cm	$\ell_V > 9$ cm	$\ell_W > 9$ cm
χ^2_{PID} Cuts		
Electron χ^2_{PID}	Proton χ^2_{PID}	
$\lvert\chi^2_{PID}\rvert < 3$	$-2.6 < \chi^2_{PID} < 3.4$	

All Elastic ep Exclusivity Cuts for NH3 and ND3	
NH3 Cuts	ND3 Cuts
$\lvert\delta P^{e^-}\rvert < 0.5$ GeV/c	$\lvert\delta P^{e^-}\rvert < 0.5$ GeV/c
$\lvert\delta P^{p}\rvert < 0.5$ GeV/c	$\lvert\delta P^{p}\rvert < 0.5$ GeV/c
$9.5 < E_B < 11.3$ GeV	$8 < E_B < 12$ GeV
$\lvert M^2_{miss}\rvert < 0.05$ GeV^2	$\lvert M^2_{miss}\rvert < 0.05$ GeV^2
$178^\circ < \Delta\phi < 181^\circ$	$175^\circ < \Delta\phi < 185^\circ$

Calculation of Elastic Dilution Factors

- Elastic double spin asymmetry modeled using

$$A_{||,el}(Q^2) = \frac{2\tau \frac{G_M}{G_E}\left(\frac{M}{E} + \frac{G_M}{G_E}\left[\frac{\tau M}{E} + (1+\tau)\tan^2(\theta/2)\right]\right)}{1 + \left(\frac{G_M}{G_E}\right)^2 \tau/\epsilon}$$

- ϵ = virtual photon polarization $= (1 + 2[1+\tau]\tan^2(\theta/2))^{-1}$, $\tau = Q^2/4M^2$, E = beam energy
- $G_{E,M}$ = Sachs form factors parameterized with Arrington model

- Applied Pilleux's exclusivity cuts for the NH3 ep events:
  - **9.5 < E^{calc}_{beam} < 11.3 GeV** ⇒ Reconstructed beam energy
  - $|MM^2_{ep\to ep}| <$ **0.05 GeV^2** ⇒ Missing mass for ep scattering
  - $178° < \Delta\phi < 181°$ ⇒ Spread of expected ϕ (assuming elastic collision)
  - $|\delta P_p| <$ **0.5 GeV/c** ⇒ Difference between expected and measured proton momentum
  - $|\delta P_{e^-}| <$ **0.5 GeV/c** ⇒ Difference between expected and measured electron momentum

- Calculate normalized P_bP_t for each run using $\boldsymbol{P} = (P_bP_t)_{DIS} * PNF$

Calculation of $A_{1,p}$

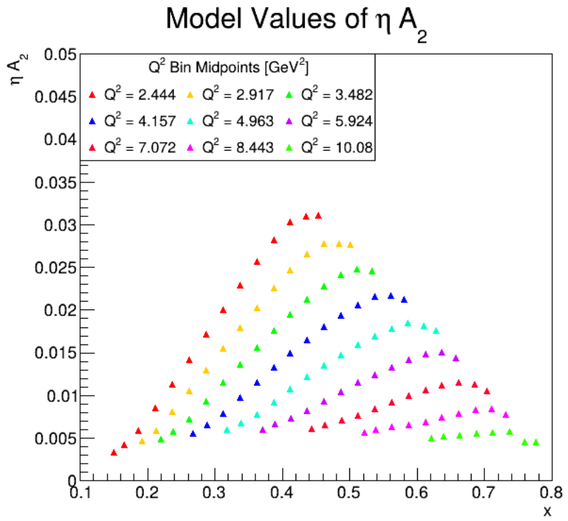
- The maximum likelihood method can also be used to combine the physical asymmetries $A_{||,meas}$ across all individual runs

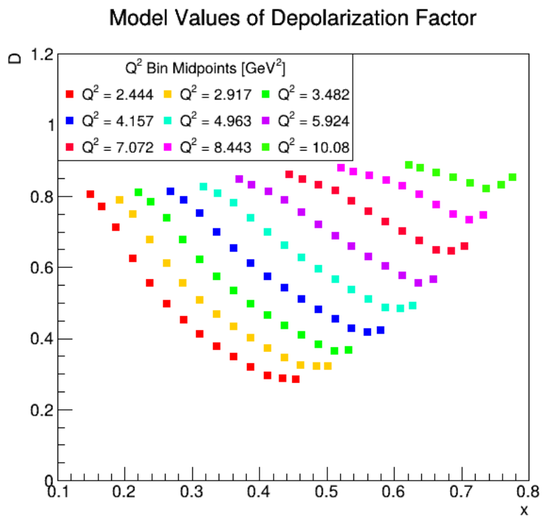
$$A_{||,meas}(x,Q^2) = \frac{\sum_{i=0}^{n_{runs}}\left(N_i^{\downarrow\uparrow}(x,Q^2) - N_i^{\uparrow\uparrow}(x,Q^2)\right)D_{F,i}(x,Q^2)\boldsymbol{P_i}}{\sum_{i=0}^{n_{runs}}\left(N_i^{\downarrow\uparrow}(x,Q^2) + N_i^{\uparrow\uparrow}(x,Q^2)\right)\left(D_{F,i}(x,Q^2)\boldsymbol{P_i}\right)^2}, \quad \sigma_{Ameas} = \sqrt{\left(\sum_{x,Q^2}(N^{\downarrow\uparrow} + N^{\uparrow\uparrow})(D_F\boldsymbol{P_i})^2\right)^{-1}}$$

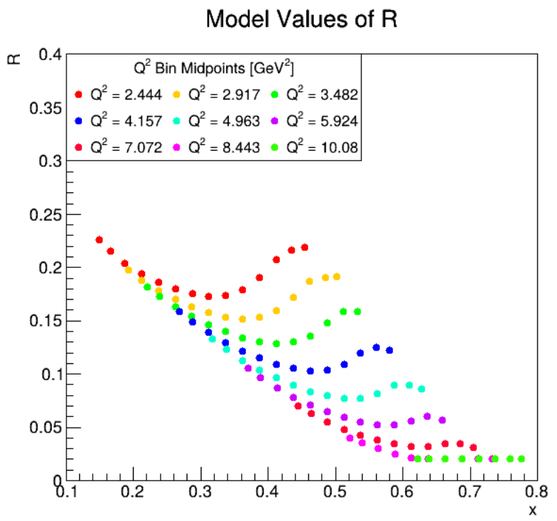
- Once data is combined, $A_{1,p}$ is extracted using model values of A_2 and R

$$A_{1,p}(x,Q^2) = A_{||,phys}(x,Q^2)/D \; -\eta A_2(x,Q^2)$$

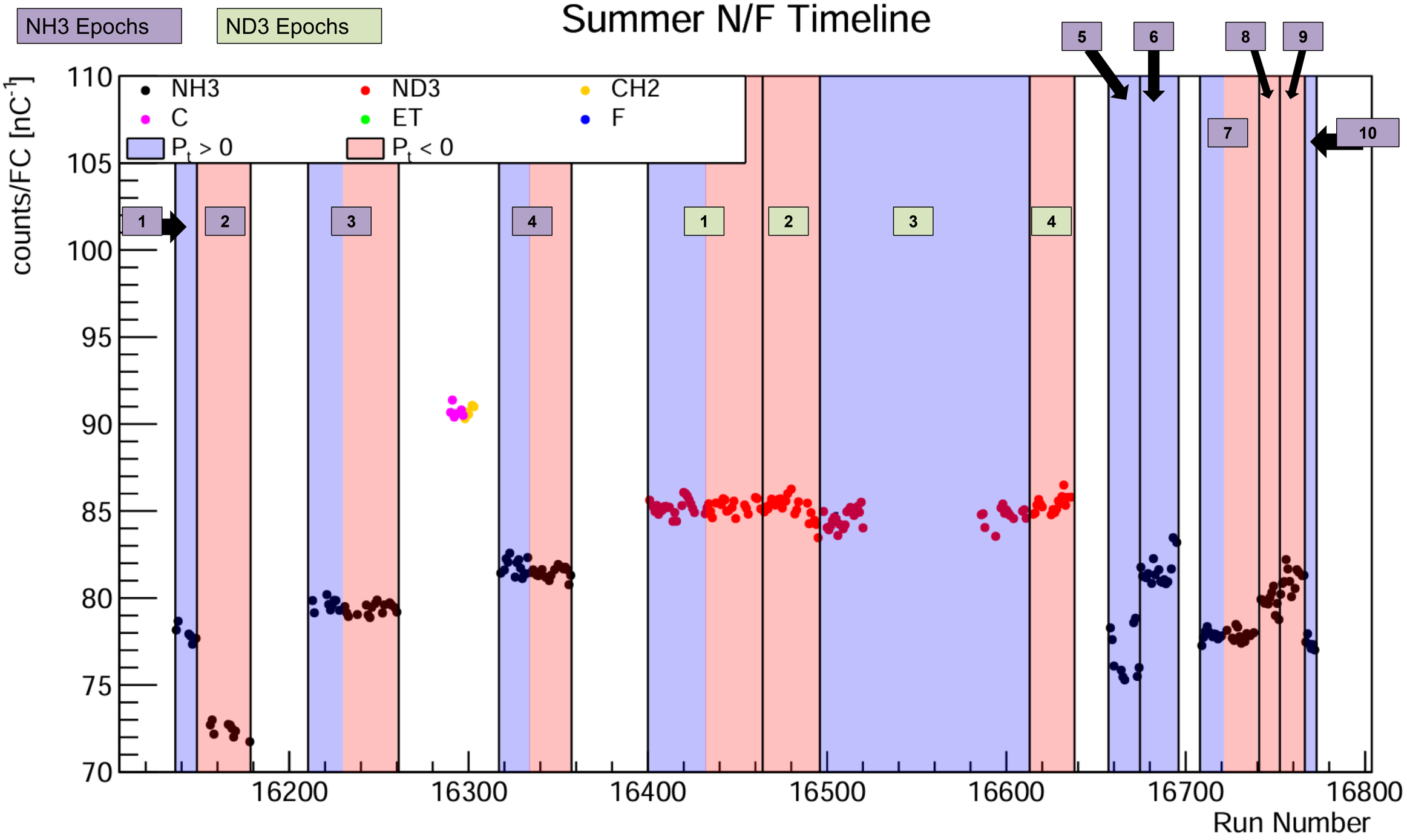
- Modeling A_2, R introduces a small systematic effect

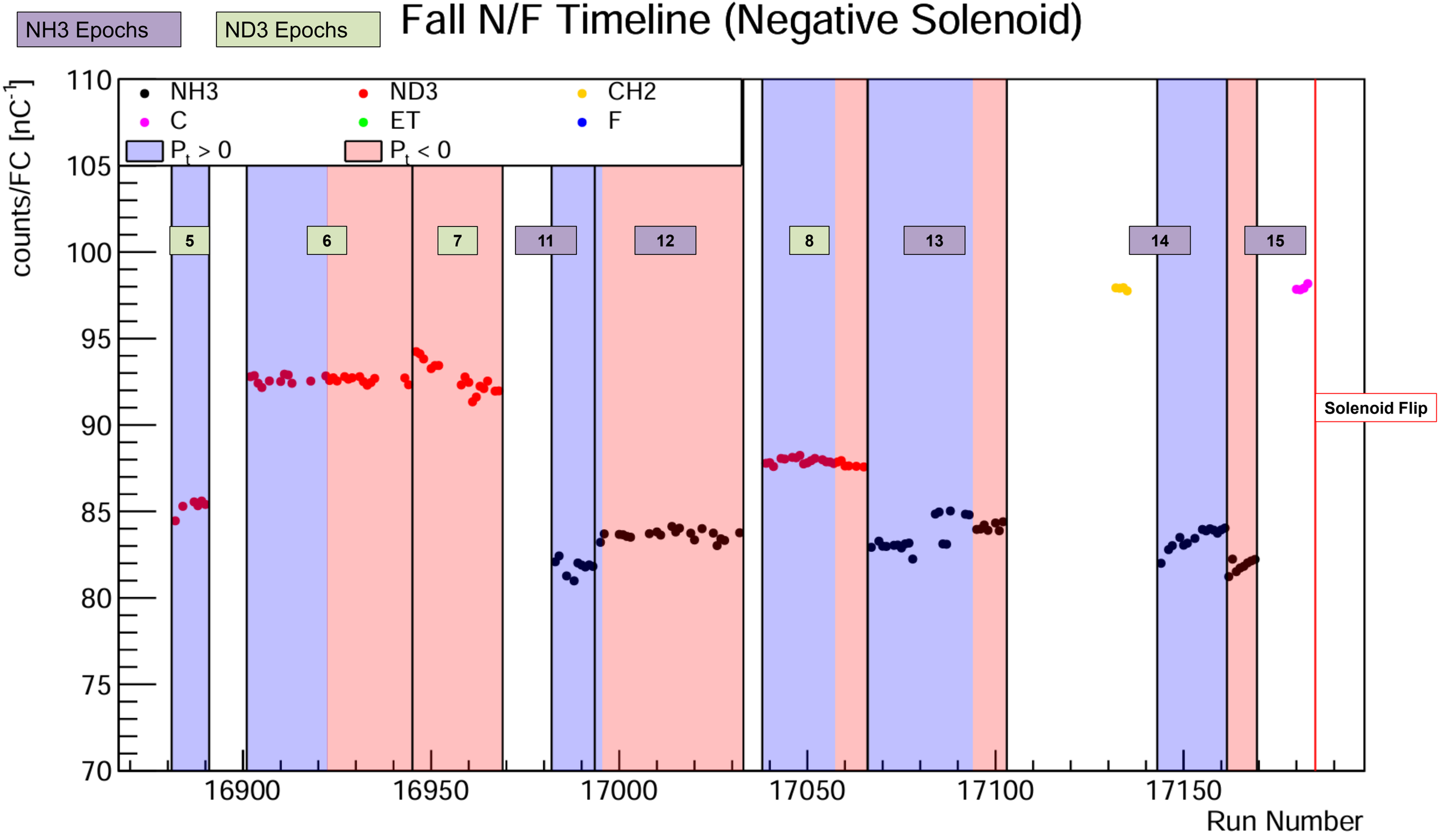


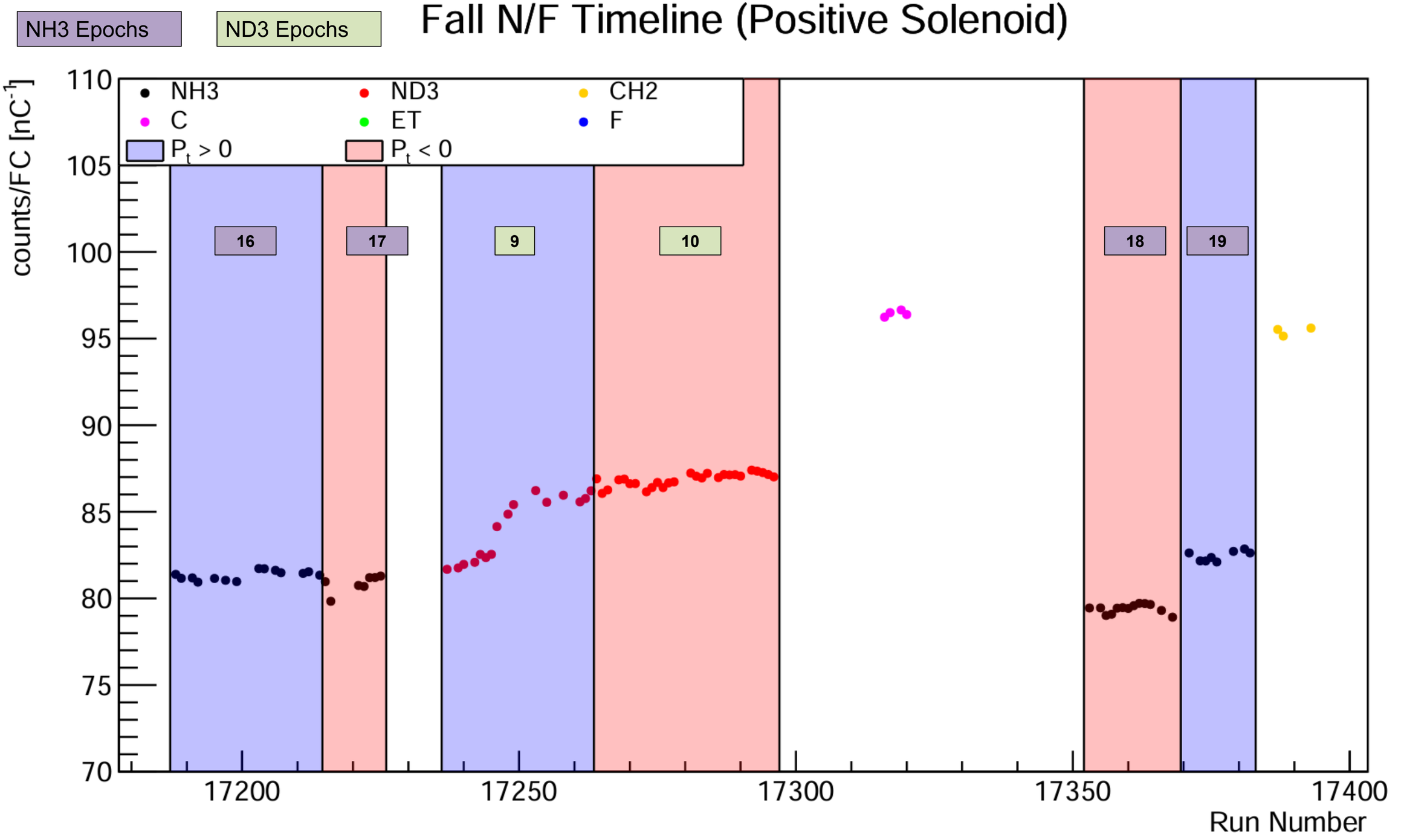




Note: The model values shown here are evaluated at the mean values of each x, Q^2 bin, ***NOT*** the bin midpoints listed in the legends.


NH3 Epochs
ND3 Epochs
Summer N/F Timeline
NH3
ND3
CH2
C
ET
F
$P_t > 0$
$P_t < 0$
counts/FC [nC^{-1}]
Run Number
1
2
3
4
5
6
7
8
9
10
110
105
100
95
90
85
80
75
70
16200
16300
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16500
16600
16700
16800

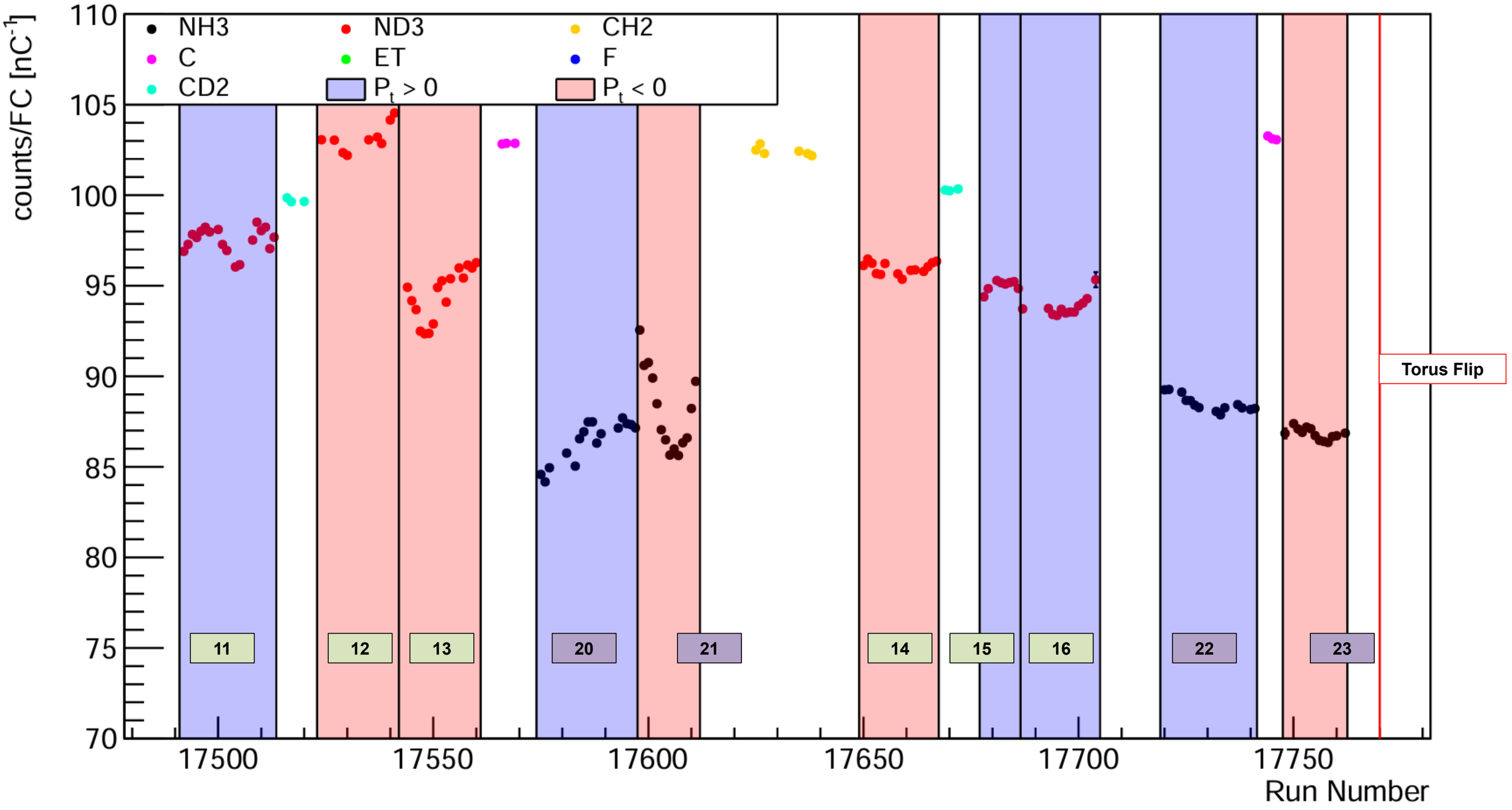

NH3 Epochs
ND3 Epochs
Fall N/F Timeline (Negative Solenoid)
counts/FC [nC^{-1}]
NH3
ND3
CH2
C
ET
F
$P_t > 0$
$P_t < 0$
5
6
7
11
12
8
13
14
15
Solenoid Flip
110
105
100
95
90
85
80
75
70
16900
16950
17000
17050
17100
17150
Run Number

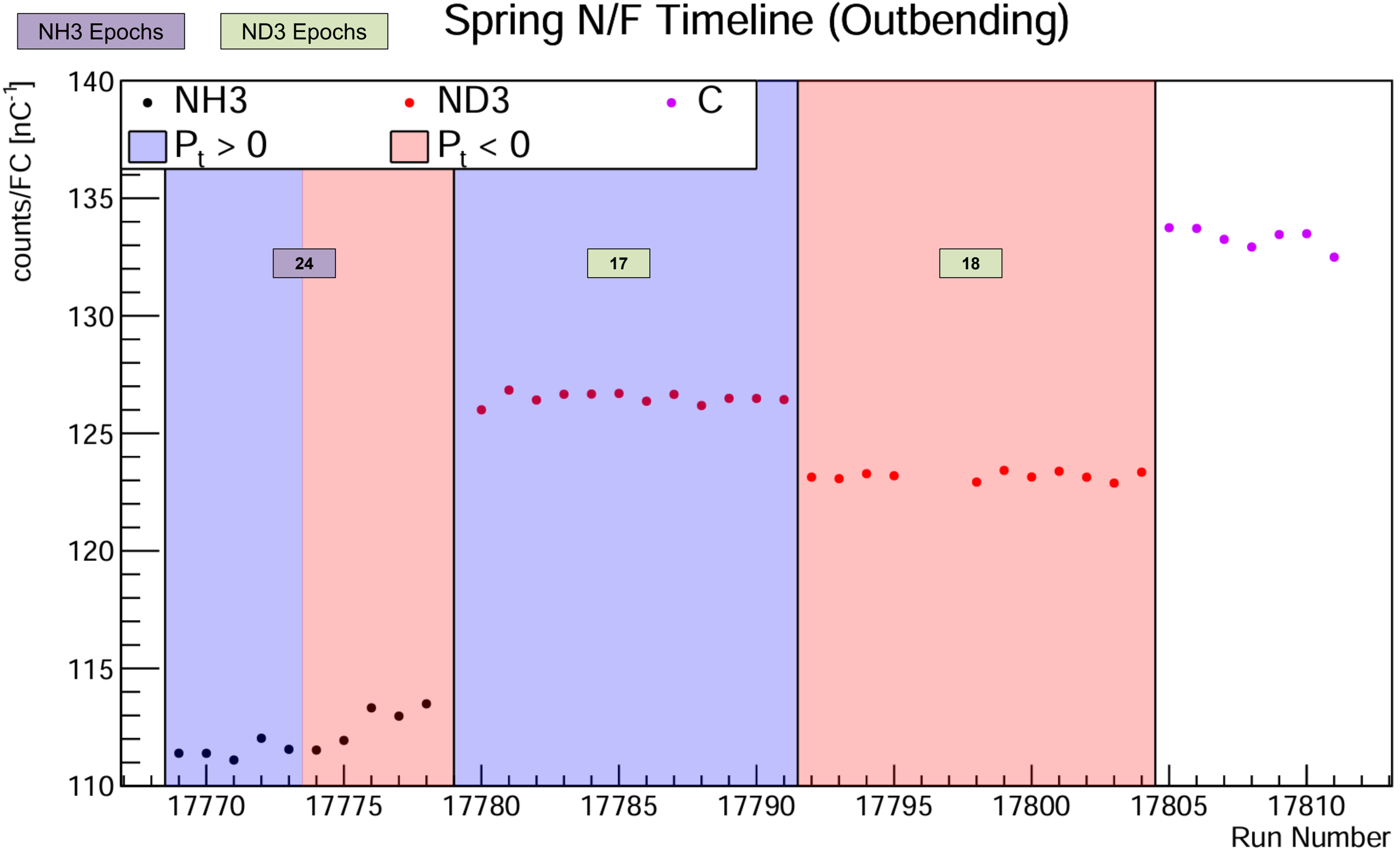

NH3 Epochs
ND3 Epochs
Fall N/F Timeline (Positive Solenoid)
NH3
ND3
CH2
C
ET
F
$P_t > 0$
$P_t < 0$
16
17
9
10
18
19
counts/FC [nC^{-1}]
110
105
100
95
90
85
80
75
70
17200
17250
17300
17350
17400
Run Number

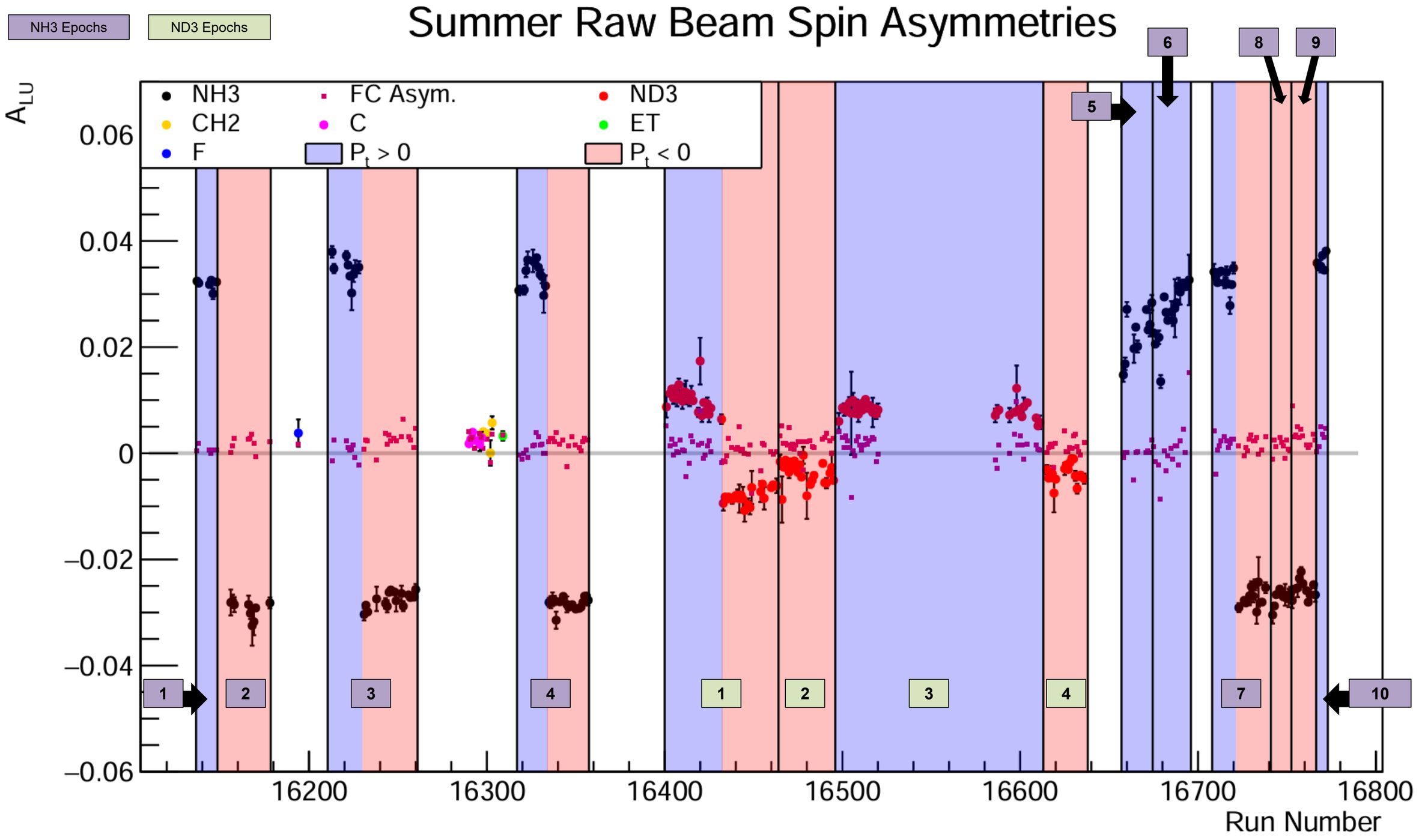
NH3 Epochs

ND3 Epochs

Spring N/F Timeline (Inbending)



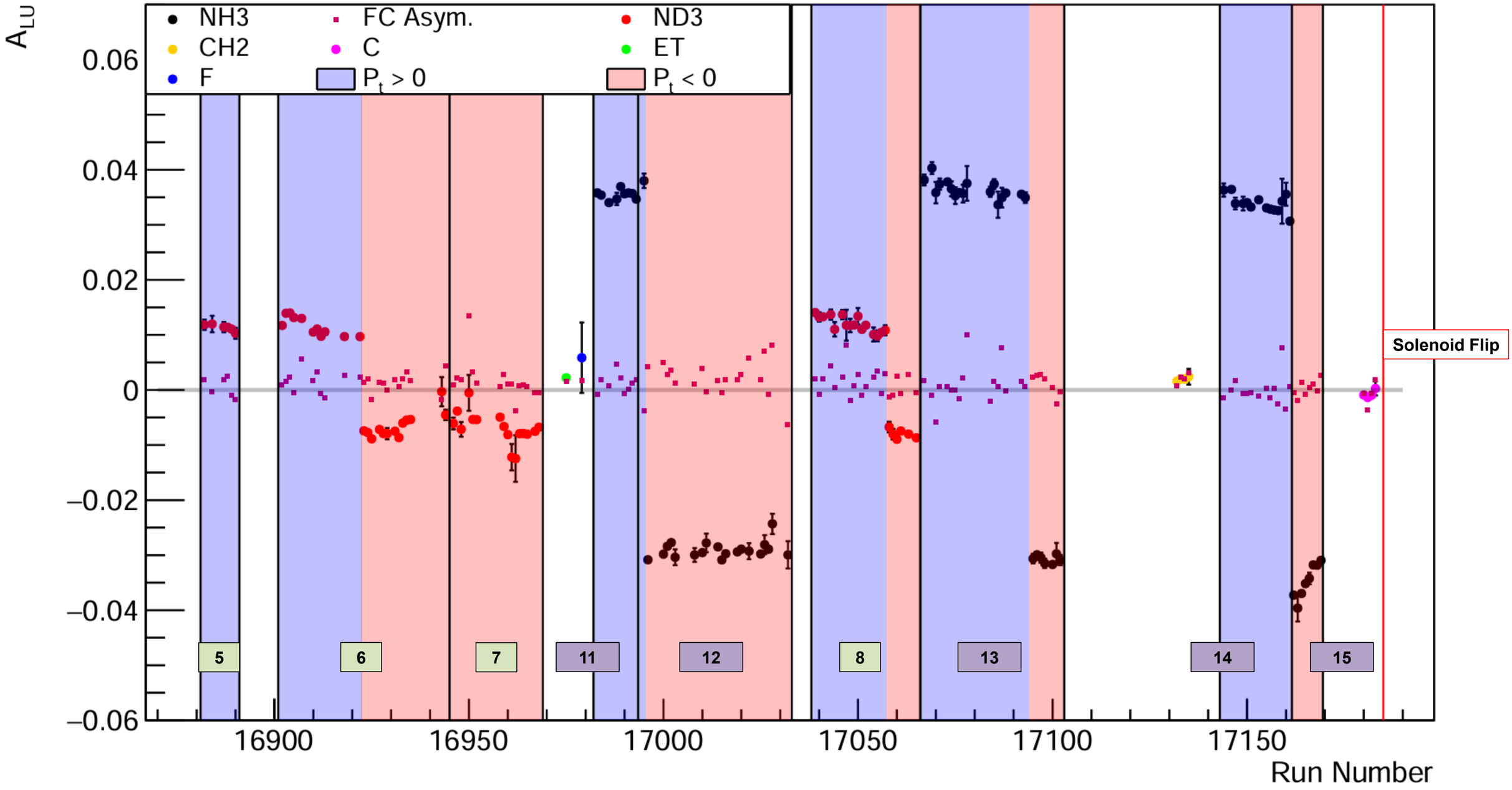

NH3 Epochs
ND3 Epochs
Spring N/F Timeline (Outbending)
NH3
ND3
C
$P_t > 0$
$P_t < 0$
24
17
18
counts/FC [nC^{-1}]
140
135
130
125
120
115
110
17770
17775
17780
17785
17790
17795
17800
17805
17810
Run Number


NH3 Epochs
ND3 Epochs
Summer Raw Beam Spin Asymmetries
NH3
CH2
F
FC Asym.
C
$P_t > 0$
ND3
ET
$P_t < 0$
A_{LU}
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
16200
16300
16400
16500
16600
16700
16800
Run Number
1
2
3
4
1
2
3
4
5
6
7
8
9
10

NH3 Epochs

ND3 Epochs

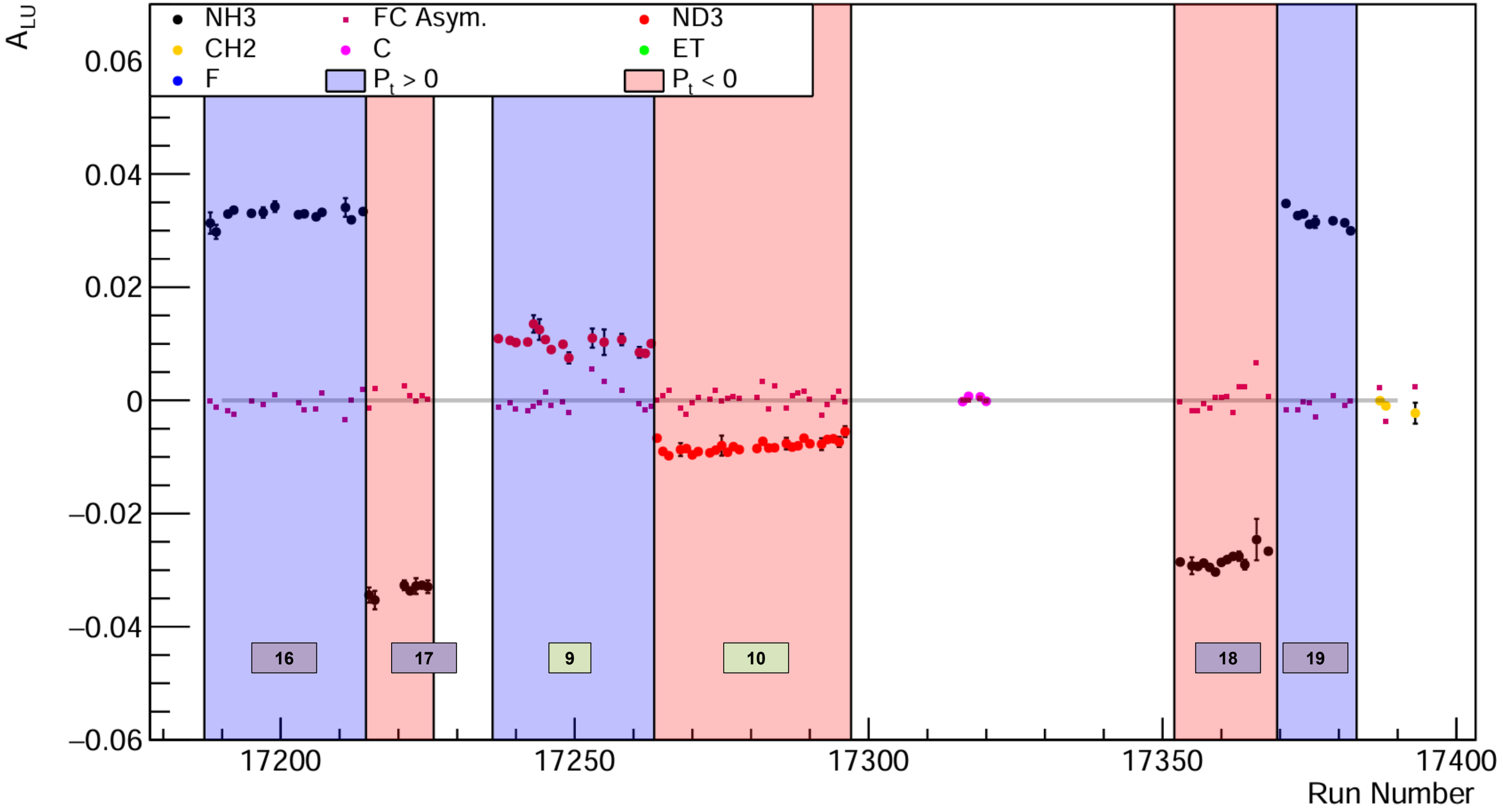
Fall Raw Beam Spin Asymmetries (Negative Solenoid)



NH3 Epochs

ND3 Epochs

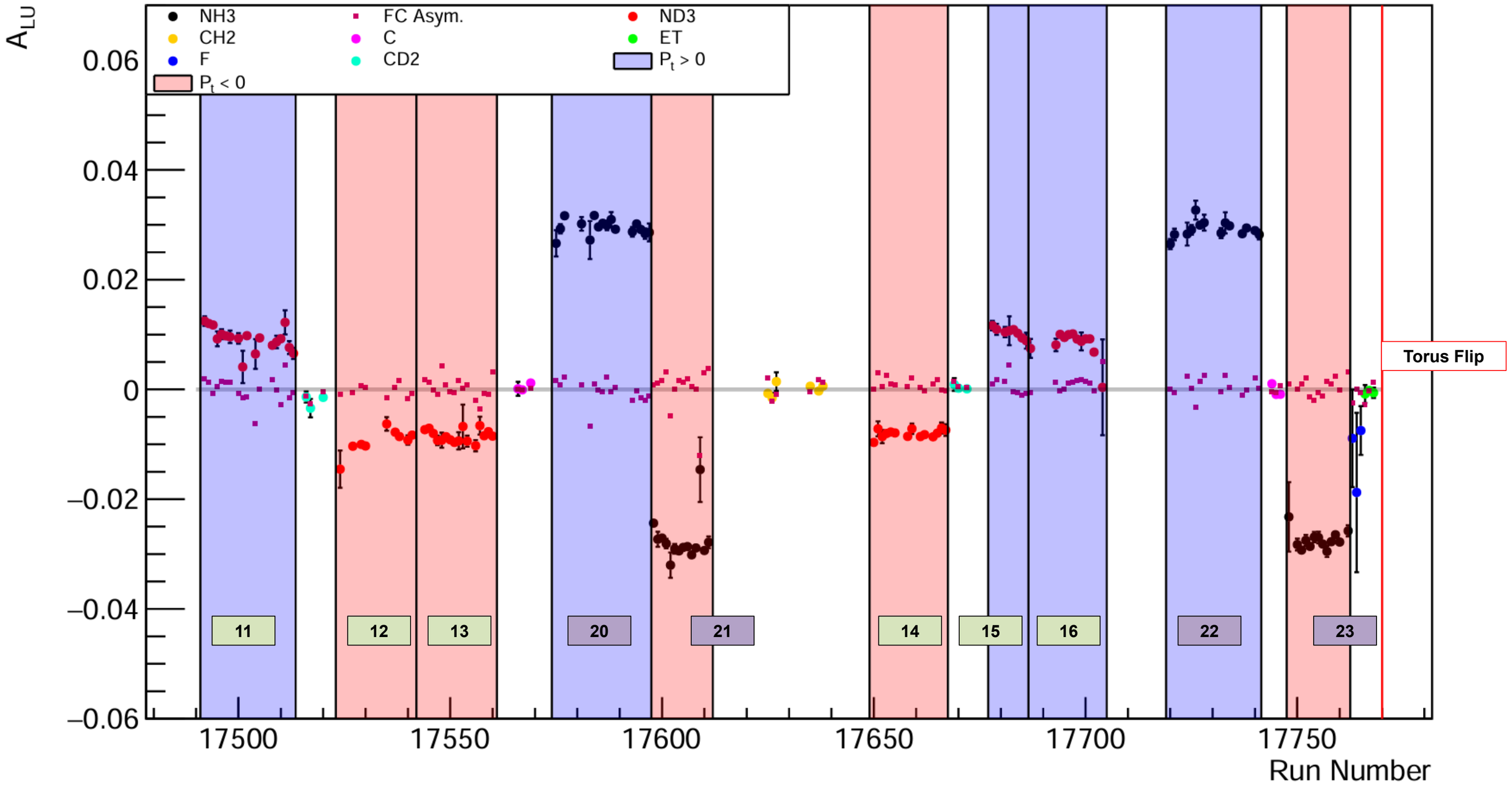
Fall Raw Beam Spin Asymmetries (Positive Solenoid)

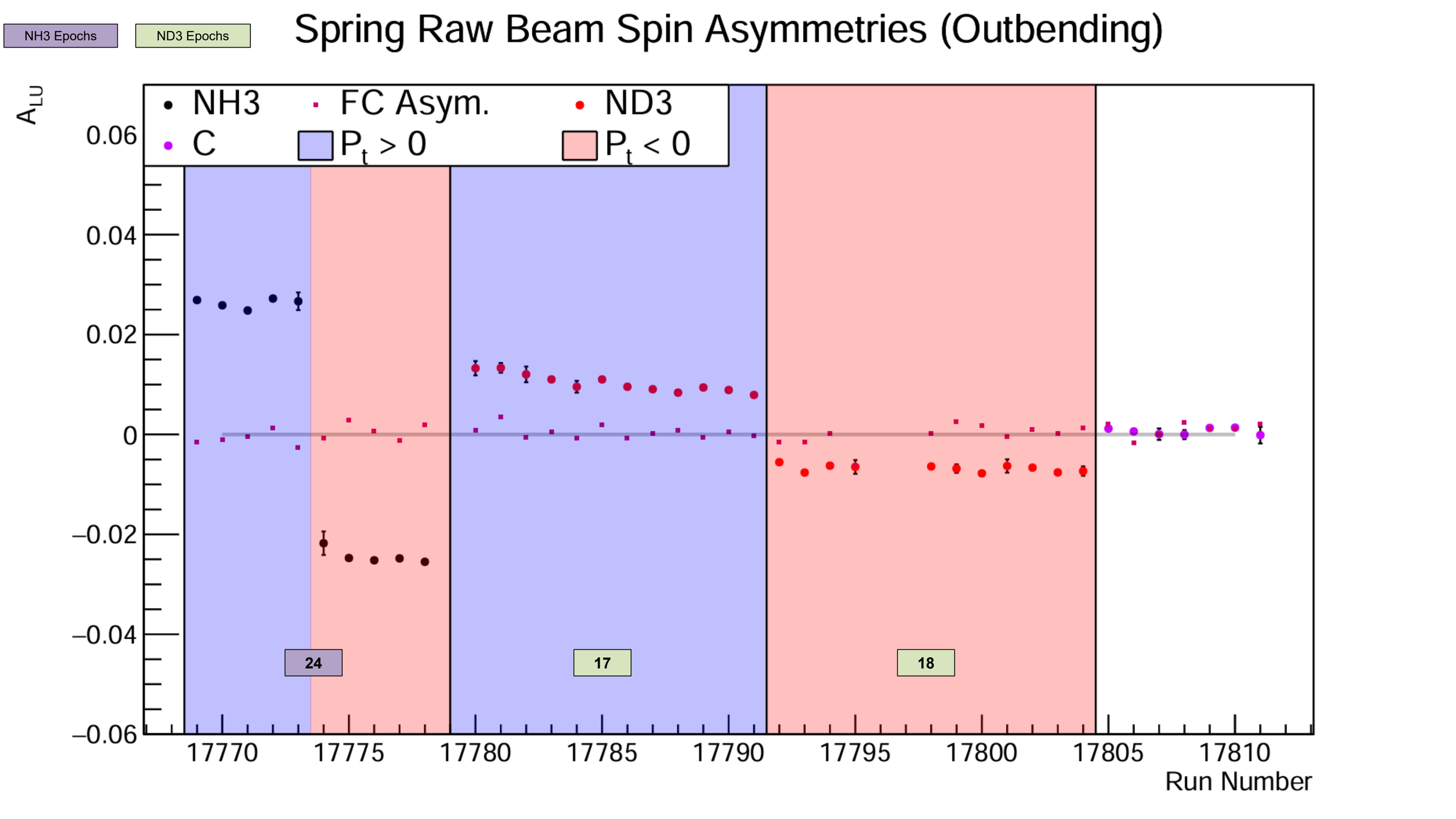


NH3 Epochs

ND3 Epochs

Spring Raw Beam Spin Asymmetries (Inbending)




NH3 Epochs
ND3 Epochs
Spring Raw Beam Spin Asymmetries (Outbending)
NH3
FC Asym.
ND3
C
$P_t > 0$
$P_t < 0$
A_{LU}
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
24
17
18
17770
17775
17780
17785
17790
17795
17800
17805
17810
Run Number