Final Results from the n3He experiment: Parity violation in cold neutron capture on ^{3}He.

Spokespersons
D. Bowman (ORNL), C. Crawford (U. Kentucky), M. Gericke (U. Manitoba)

Project Manager
S. Penttila (ORNL)

S. Baessler (UVA), L. Barrón (UNAM),

J. Calarco (U. New Hampshire), V. Cianciolo (ORNL), C. Coppola (U. Tennessee),

N. Fomin (U. Tennessee), I. Garishvili (U. Tennessee),

G. Greene (ORNL), J. Hamblen (U. Tennessee Chattanooga),

C. Hayes (U. Tennessee), K. Latiful (U Kentucky), M. McCrea (U. Manitoba),

A.R. Morales (UNAM), P. Mueller (ORNL), I. Novikov (Western Kentucky), C. Wickersham (U. Tennessee Chattanooga)

The n³He Observable

The experiment measures the parity violating directional asymmetry in the number of emitted protons, as a function of neutron spin, in the reaction

$$\vec{n} + {}^{3}He \rightarrow T + p + 764\ keV$$

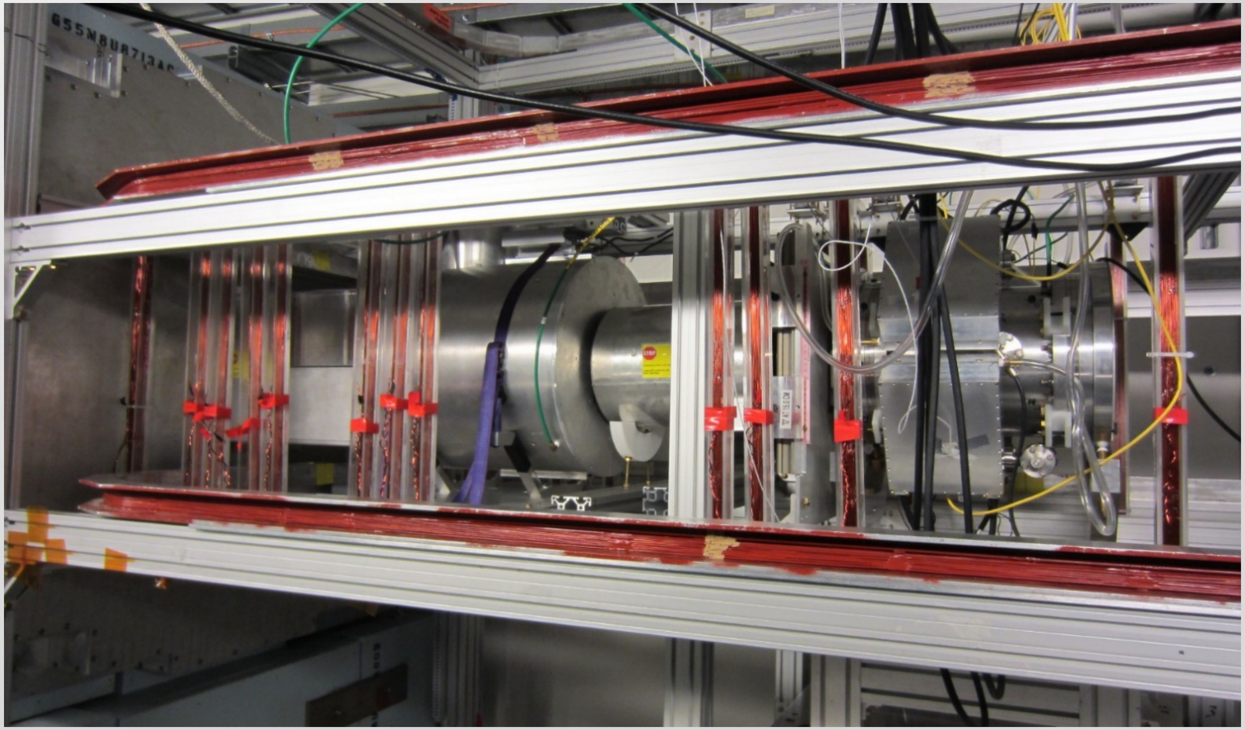
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_c \left(1 + A_{PV}\cos\theta_{\vec{s}_n\cdot\vec{k}_p} + A_{PC}\cos\phi_{\vec{s}_n\times\vec{k}_n\cdot\vec{k}_p}\right)$$

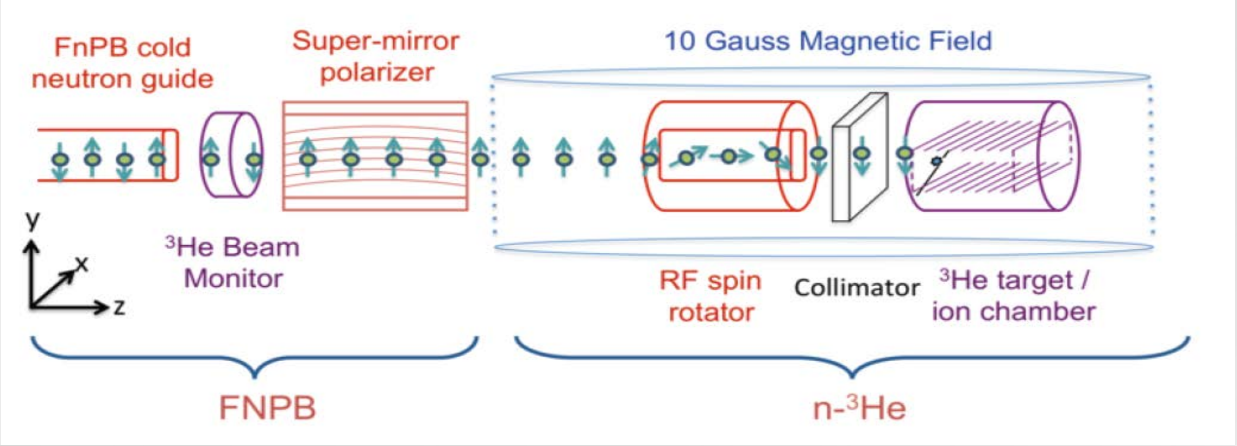
$$A_{PV}^{exp} = f_{exp}\left(A_{PV}\cos\theta_{\vec{s}_n\cdot\vec{k}_p} + A_{PC}\cos\phi_{\vec{s}_n\times\vec{k}_n\cdot\vec{k}_p}\right)$$

Proposal Goal:

- Measure the up-down PV spin asymmetry to $\sim 2\times10^{-8}$
- Measure the left right PC spin asymmetry to $\sim 5\times10^{-8}$

The n³He Setup





n^3He Motivation

Parity violating processes between nucleons can be used as a tool to study the hadronic weak interaction (HWI) as well as how it is modified by the strong interactions from the Standard Model prediction.

1. Study how the symmetries of QCD characterize the HWI in strongly interacting systems

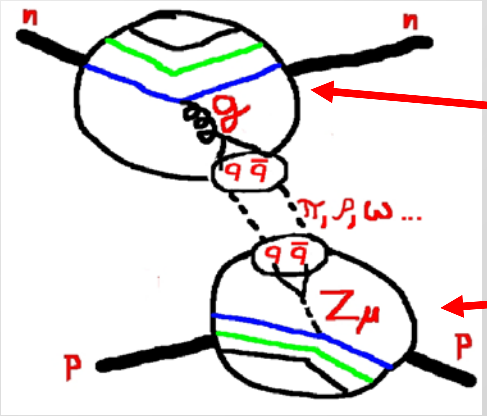
   The HWI is just a residual effect of the q-q weak interaction for which the range is set by the mass of the Z,W bosons which is much smaller than the size of nucleons, as determined by QCD dynamics.

   ➡ HWI probes short range qq correlations

2. Shed light on the puzzles in the $\Delta S=1$ sector of the HWI

Hadronic Weak Interaction

Basic dynamic picture:



For the pion:

$$H_{PC} = ig_{\pi NN}\int d^3x\,\overline{\psi}_i(x)\gamma^5\psi_j(x)\left(\vec{\tau}\cdot\vec{\phi}(x)\right)$$

$$H_{PNC} = \frac{h_\pi^1}{\sqrt{2}}\int d^3x'\,\overline{\psi}_i(x')\psi_j(x')\left(\vec{\tau}\times\vec{\phi}(x')\right)$$

$$\langle f|V_{PNC}|i\rangle = \langle N_f N_f|H_{PC}\frac{1}{E_0 - H_0 + i\varepsilon}H_{PNC}|N_i N_i\rangle \rightarrow \frac{ig_{\pi NN}h_\pi^1}{\sqrt{32M}}\left[\vec{\tau}_1\times\vec{\tau}_2\right]_z\left[\vec{\sigma}_1+\vec{\sigma}_2\right]\cdot\left[\vec{p},\frac{e^{-mr}}{4\pi r}\right]$$

Weak π-Nucleon Coupling potential

Problem: We don't know how to form nucleon wavefunctions based on fundamental degrees of freedom (except maybe now from LQCD - talk by Andre Walker-Loud) …

n^3He Effective Theory

- Full four-body calculation of strong scattering wave functions
- Evaluation of the weak matrix elements in terms of the DDH potential:

$$A_{PV} = a_\pi^1 h_\pi^1 + a_\rho^0 h_\rho^0 + a_\rho^1 h_\rho^1 + a_\rho^2 h_\rho^2 + a_\omega^0 h_\omega^0 + a_\omega^1 h_\omega^1$$

DDH Weak Coupling	(A^p_Z) $n^3He \rightarrow tp$
a_π^1	-0.189
a_ρ^0	-0.036
a_ρ^1	0.019
a_ρ^2	-0.0006
a_ω^0	-0.0334
a_ω^1	0.0413

$$A_{PV}(th.) \approx (-9.4 \rightarrow 2.5) \times 10^{-8}$$

M. Viviani, R. Schiavilla, Phys. Rev. C. 82 044001 (2010)
L. Girlanda et al. Phys. Rev. Lett. 105 232502 (2010)

n^3He Effective Theory

- Full four-body calculation of strong scattering wave functions
- Evaluation of the weak matrix elements in terms of χPT EFT:

$$A_{PV} = a_0 h_\pi^1 + a_1 C_1 + a_2 C_2 + a_3 C_3 + a_4 C_4 + a_5 C_5$$

$$A_{PV}(th.) \approx 1.7 \times 10^{-8} \qquad \Lambda = 500\ MeV$$

$$A_{PV}(th.) \approx 3.5 \times 10^{-8} \qquad \Lambda = 600\ MeV$$

EFT coefficients	Λ = 500 MeV	Λ = 600 MeV
a_0	-0.1444	-0.1293
a_1	0.0061	0.0081
a_2	0.0226	0.0320
a_3	-0.0199	-0.0161
a_4	-0.0174	-0.0156
a_5	-0.0005	-0.0001

M. Viviani, et al. Phys. Rev. C 89, 064004 (2014)

n^3He Effective Theory

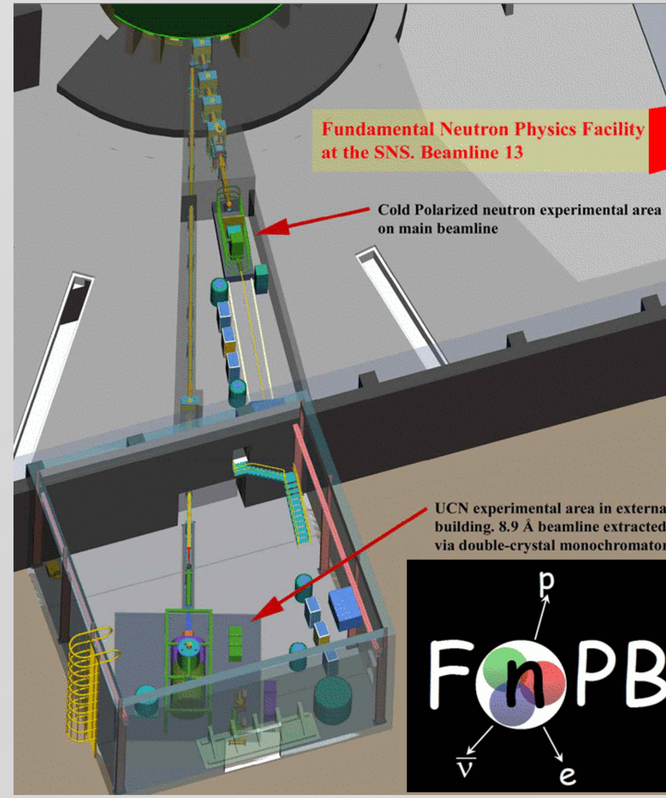
- **New approach to HWI: Large Nc expansion formalism**

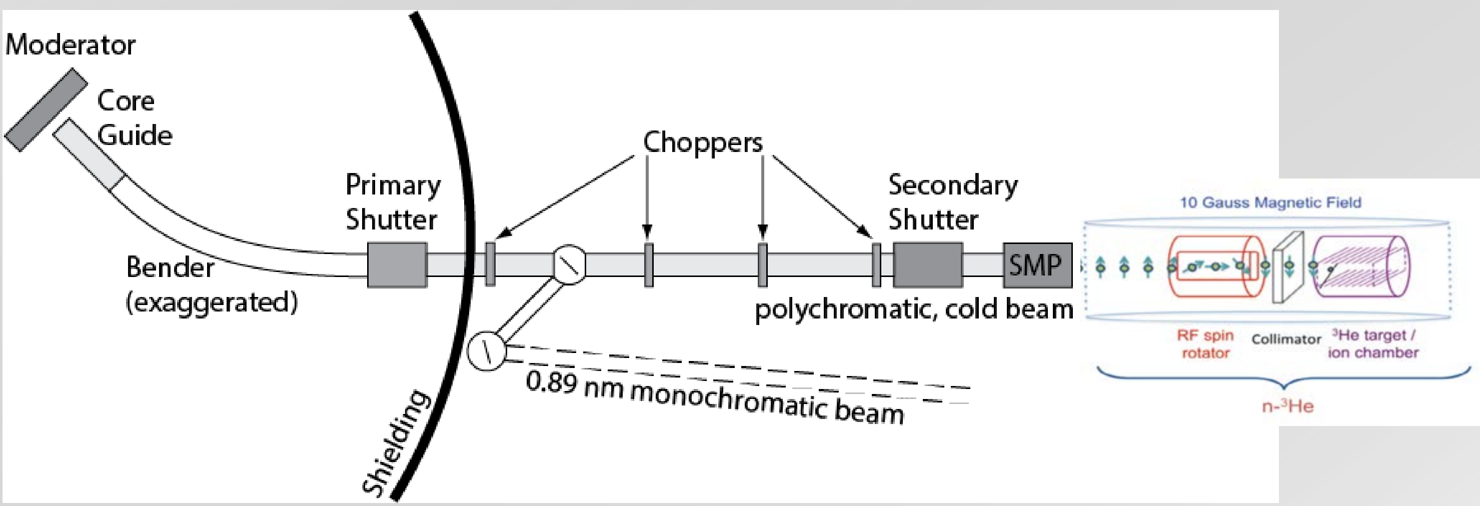
Susan Gardner, Wick Haxton, Barry Holstein:
arXiv:1704.02617v1 [nucl-th] 9 Apr 2017

Wick's talk next …

The Fundamental Neutron Physics Beam (FnPB)

- LH2 moderator
- 17 m long guide ~ 20 m to experiment
- one polyenergetic cold beam line
- one monoenergetic (0.89 nm) beam line
- ~ 40 m to nEDM UCN source
- 4 frame overlap choppers
- 60 Hz pulse repetition





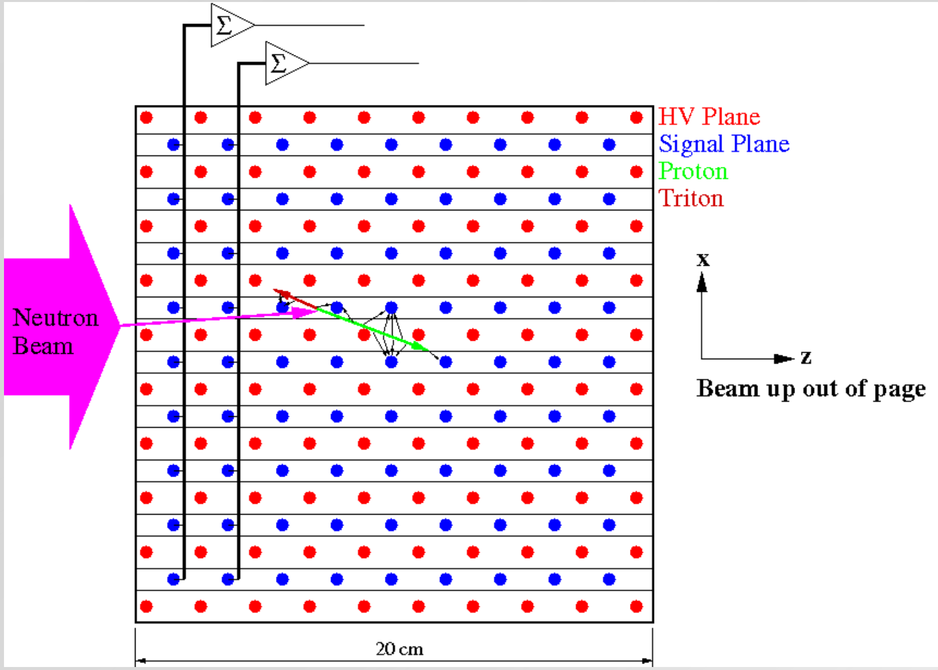
n^3He Principle of Measurement

Measure the asymmetry in the number of outgoing protons in a ^3He wire chamber as a function of neutron spin:

$\vec{\sigma}_n \cdot \vec{k}_T$ Directional PV asymmetry in the number of tritons

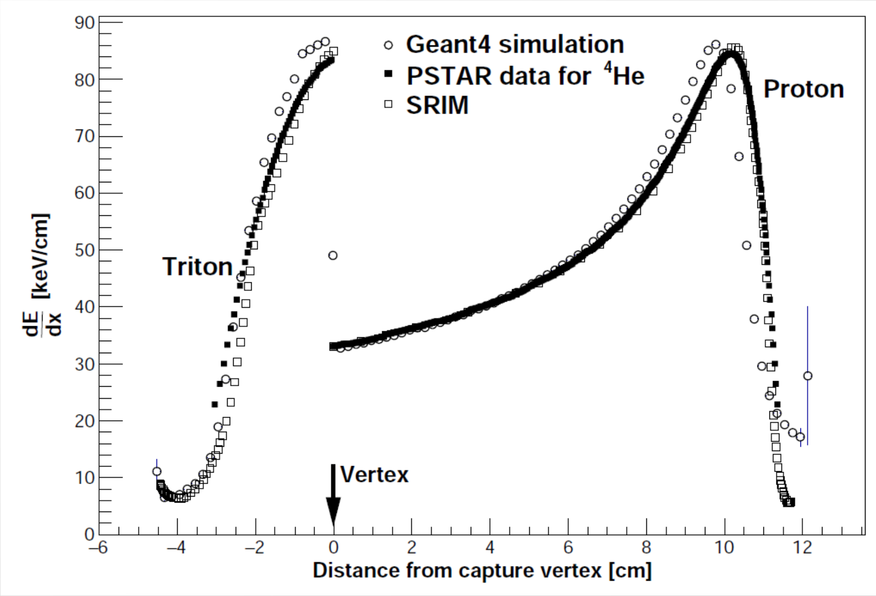
$\vec{\sigma}_n \cdot \vec{k}_p$ Directional PV asymmetry in the number of protons

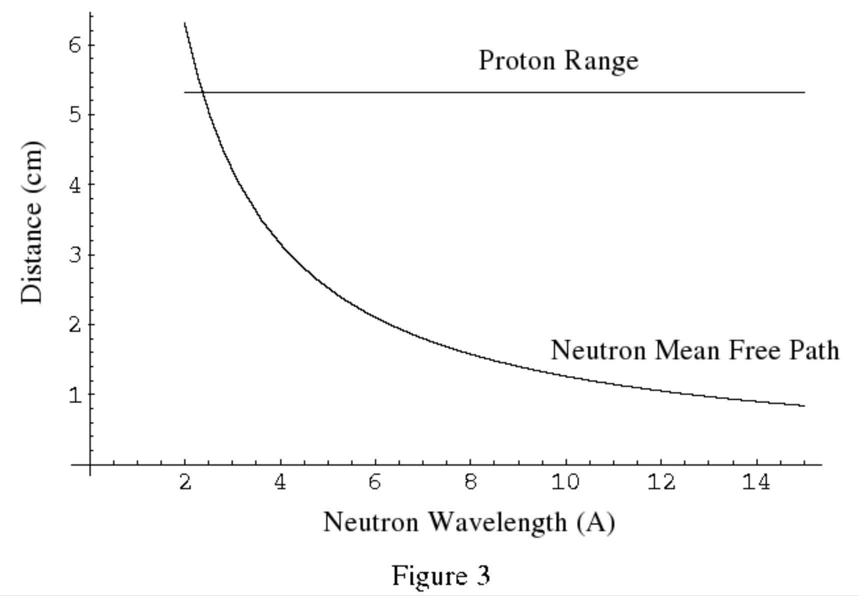
- Active target
- Exploit the much larger track length of the protons
- Wires run vertical or horizontal



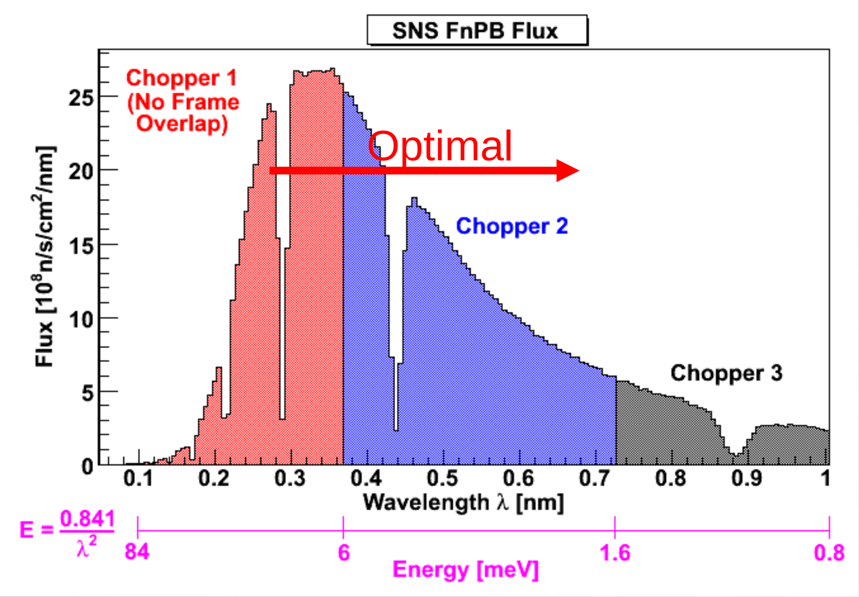
$$\vec{n} + {}^3\mathrm{He} \rightarrow \mathrm{p} + \mathrm{t} + 764\ \mathrm{keV}$$

n³He Principle of Measurement



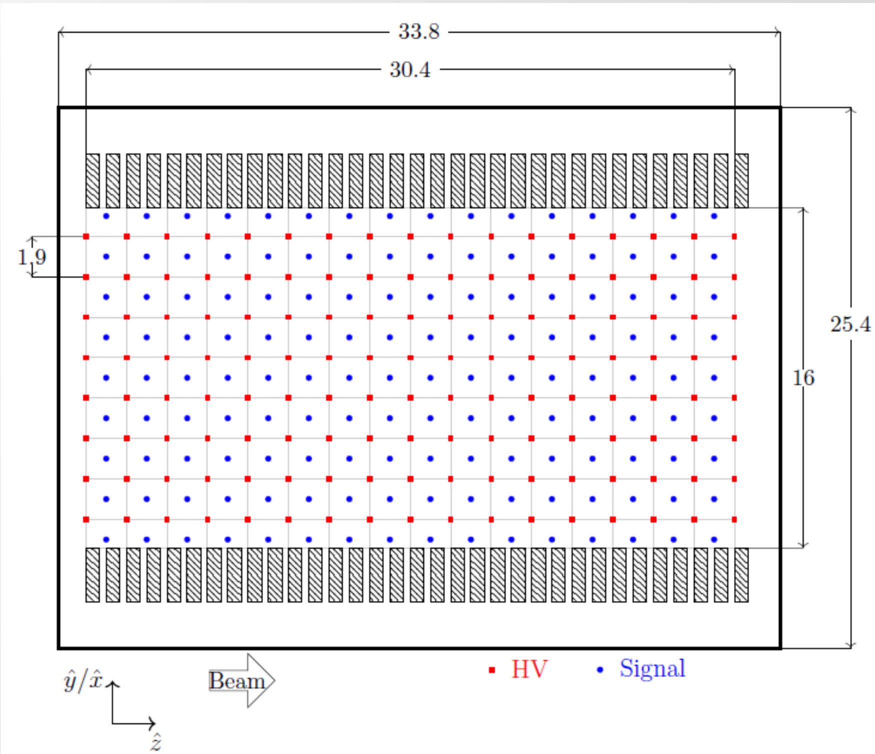


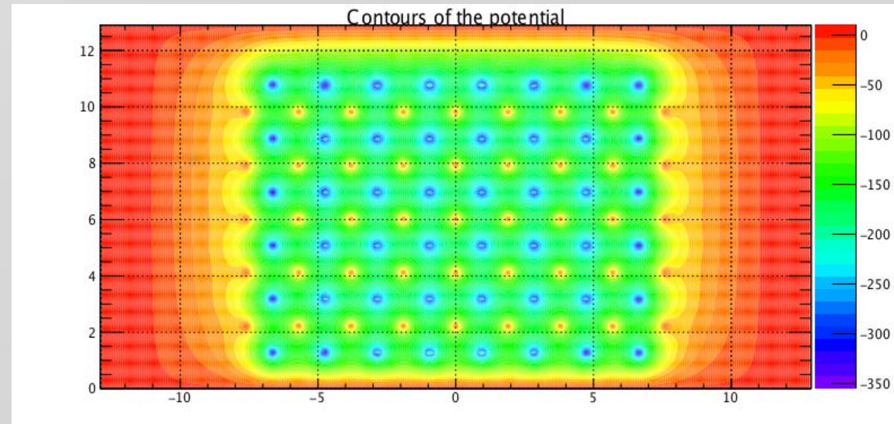
- Chamber filled with Helium 3
- Want to let protons range out
- Proton range r_p~10 cm
- Neutron mfp should be < r_p / 2
- Optimize wavelength range
- Maximize neutron beam intensity



n^{3}He Principle of Measurement

Split the ^{3}He target volume into 144 equally spaced cells using wires:





From Mark McCrea Ph.D. thesis.

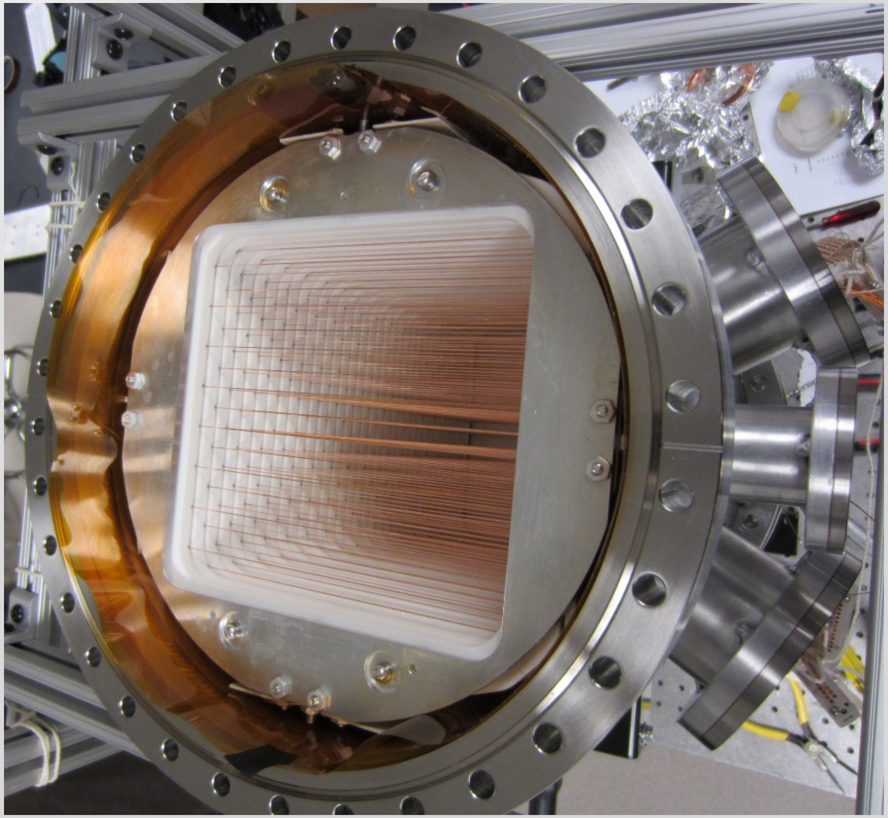
$$A_{raw} = \left(\frac{Y^{\uparrow} - Y^{\downarrow}}{Y^{\uparrow} + Y^{\downarrow}} \right)$$

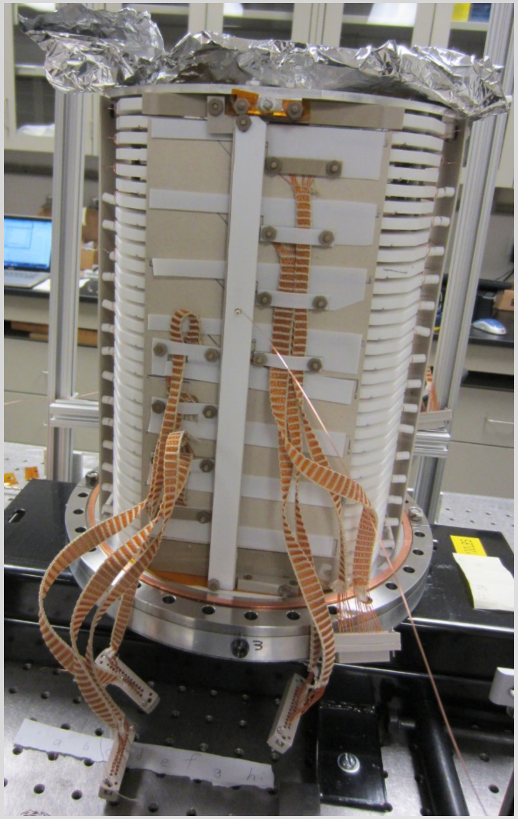
The asymmetry is determined either from the yield of a single wire for two different spin states, or

from the yield of two opposite (conjugate) wire pairs in the same spin state.

n^3He Principle of Measurement

Target-Detector Chamber:

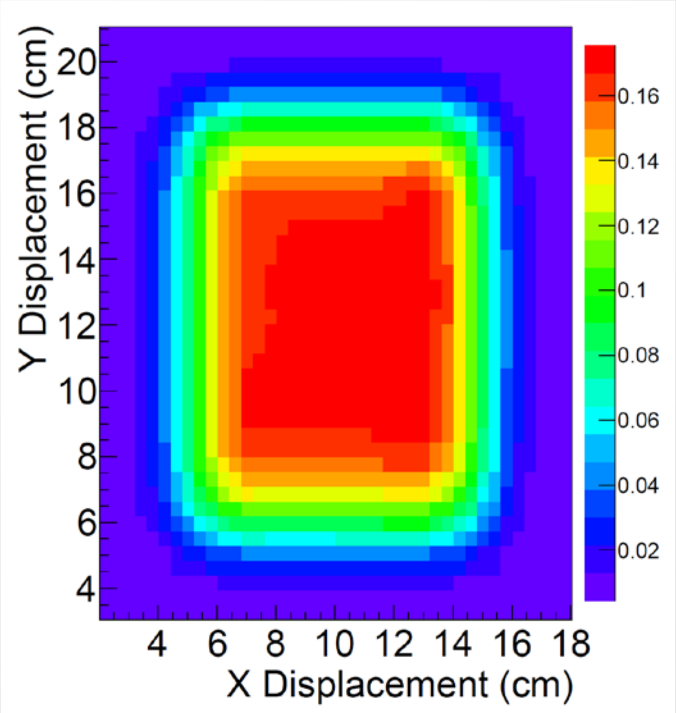


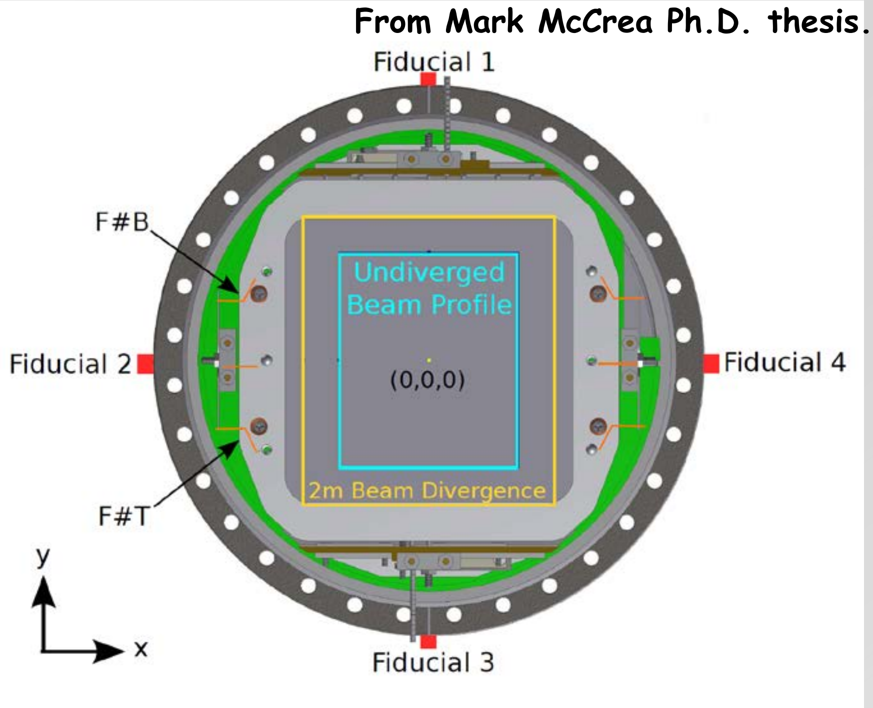


From Mark McCrea Ph.D. thesis.

n^3He Principle of Measurement

Beam Profile:



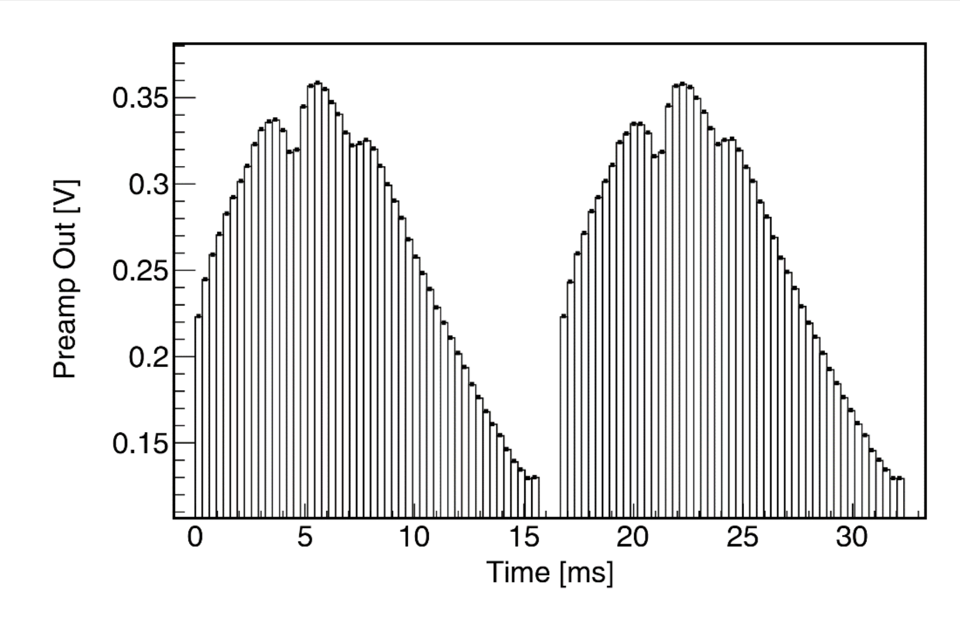


The size of the wire frame was designed to cover the beam profile including beam divergence.

n^3He Principle of Measurement

Wire signal:

Two consecutive pulses:



Each neutron pulse window signal yield is divided into 49 TOF bins of 0.32 ms width.

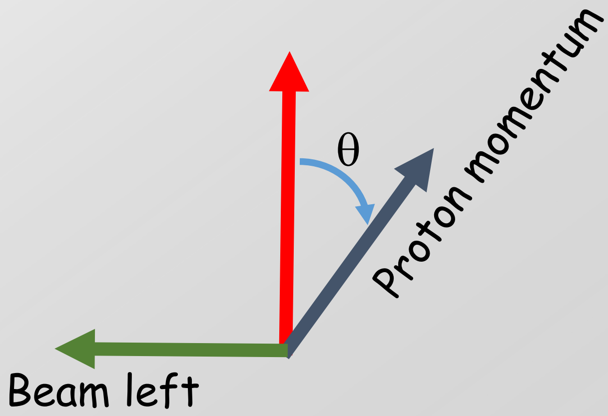
We usually integrate over the a TOF range within each pulse to get the wire yield.

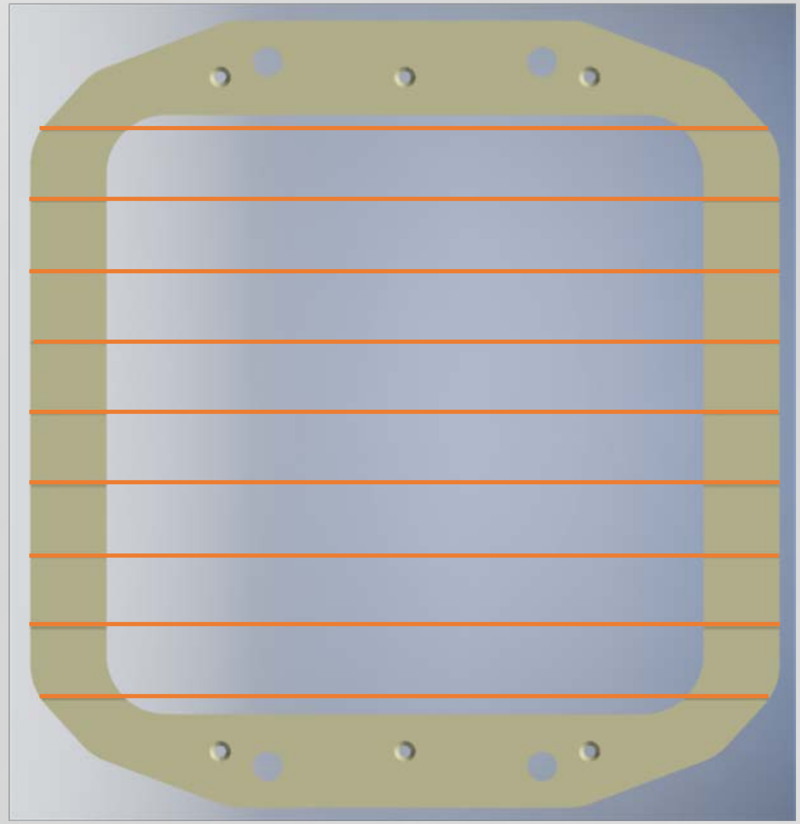
n³He Principle of Measurement

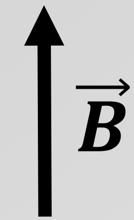
Parity Violating measurement (Up-Down) setup:

Neutron polarization up or down

Beam direction into page







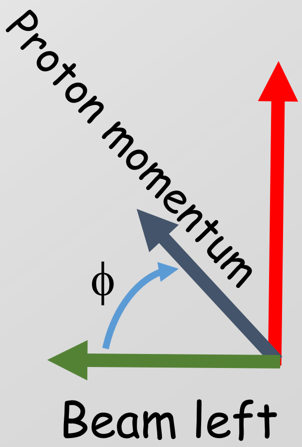
$$A_{PV}^{exp} = f_{exp}\left(A_{PV} \cos\theta_{\vec{s}_n \cdot \vec{k}_p} + A_{PC} \cancel{\cos}\, \phi_{\vec{s}_n \times \vec{k}_n \cdot \vec{k}_p} \right)$$

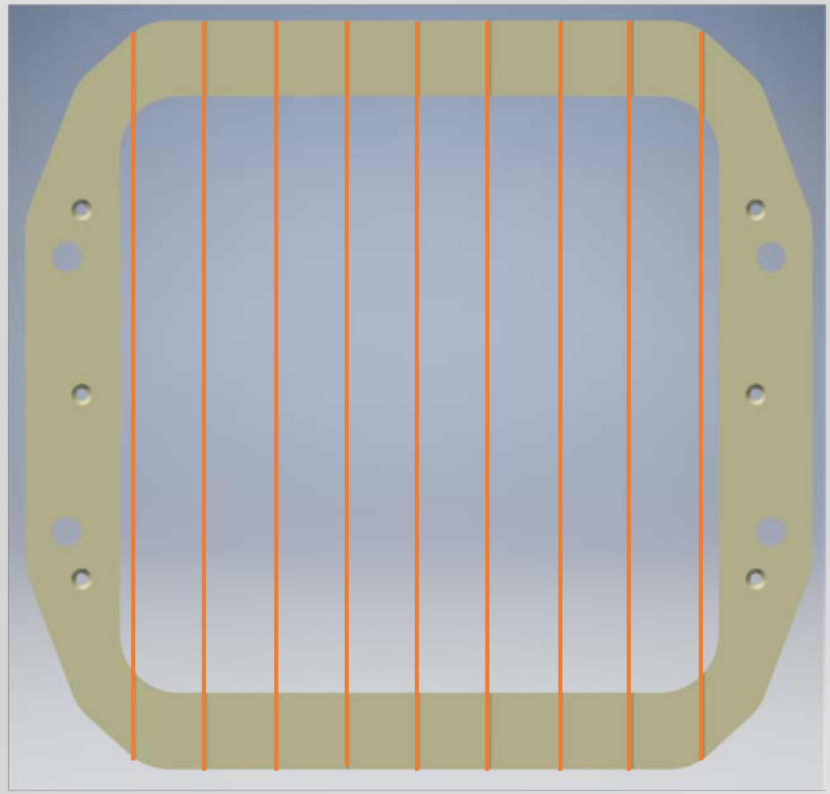
n^3He Principle of Measurement

Parity Conserving (Left-Right) measurement setup:

Neutron polarization up or down

Beam direction into page

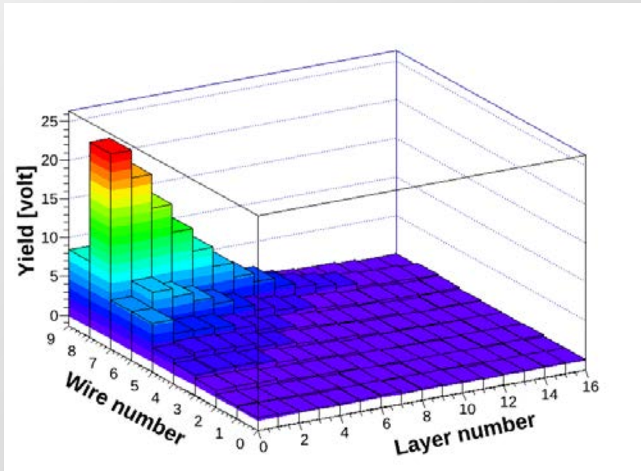


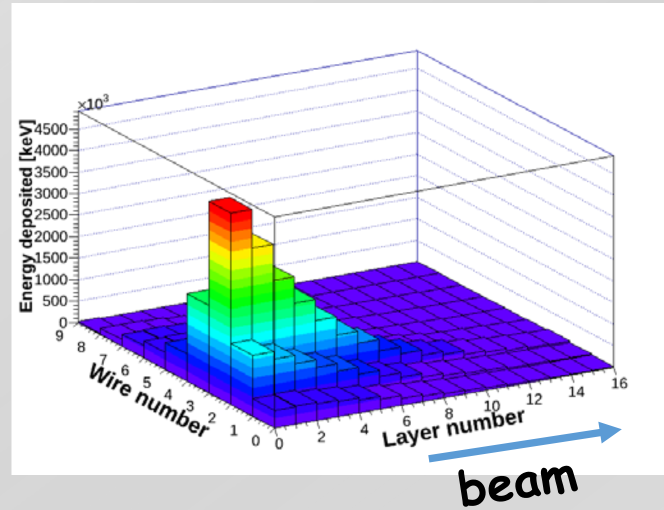


$$A_{PV}^{exp} = f_{exp}\left(\xcancel{A_{PV}\cos\theta_{\vec{s}_n\cdot\vec{k}_p}} + A_{PC}\cos\phi_{\vec{s}_n\times\vec{k}_n\cdot\vec{k}_p} \right)$$

n^3He Principle of Measurement

Finite geometry correction factors:

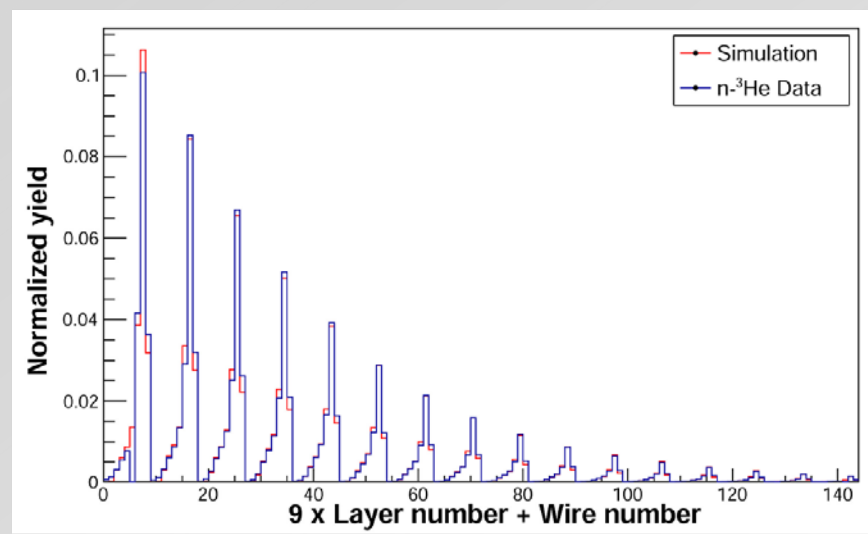




Comparisons between data and Simulation were used to verify the geometry effect of the chamber and the beam.

$$\cos\theta_{\vec{s}_n\cdot\vec{k}_p} \rightarrow G_{UD}$$

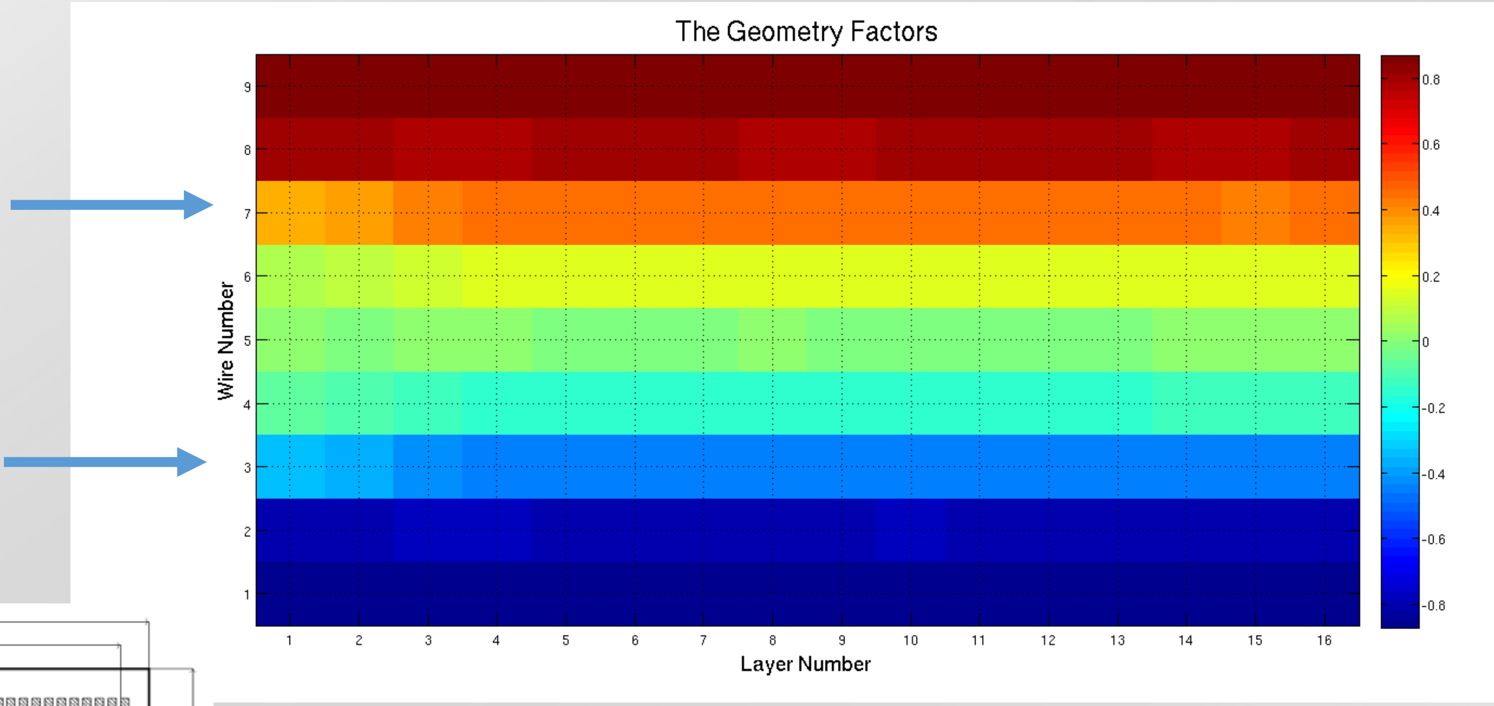
$$\cos\phi_{\vec{s}_n\times\vec{k}_n\cdot\vec{k}_p} \rightarrow G_{LR}$$

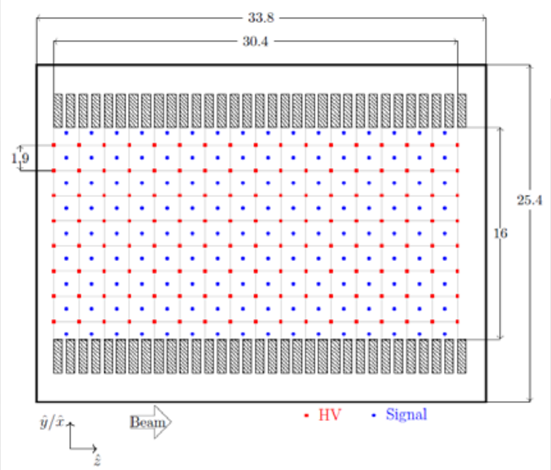


n^3He Principle of Measurement

Finite geometry correction factors:

Conjugate wire pair rows





$$A_{PV}^{exp} = f_{exp}\left(A_{PV}G_{UD} + A_{PC}G_{LR}\right)$$

n^3He Analysis

Detector wire yield:
$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_c \left(1 + A_{PV}\cos\theta_{\vec{s}_n\cdot\vec{k}_p} + A_{PC}\cos\phi_{\vec{s}_n\times\vec{k}_n\cdot\vec{k}_p}\right)$$

$$\Rightarrow \quad Y^{\pm} = Y_0\left(1 \pm \varepsilon P A_{PV} G_{UD} \pm \varepsilon P A_{PC} G_{LR}\right) \text{ per wire}$$

Raw asymmetry: $A_{raw} = \left(\frac{Y^+ - Y^-}{Y^+ + Y^-}\right)$ (theoretically: $\varepsilon P A_{PC/PV} = \left(\frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}\right)$)

Things that one has to take care off:

- Pedestals and possible electronic false asymmetries

$$Y_i^{\pm} \rightarrow Y_i^{\pm} + p_i^{\pm}$$

- Beam fluctuations and associated false asymmetries

$$Y_i^{o} \rightarrow g_i I^{\pm}$$

- Correlations between wires

n^3He Analysis

Incorporating the pedestal and neutron beam intensity variations in the analysis:

Single wire asymmetry (with normalized yields):

$$A_{i,raw} = \varepsilon P G_i A_{PV} + \frac{1}{2}\left(\frac{p_i^+}{Y_i^{o+}} - \frac{p_i^-}{Y_i^{o-}}\right)$$

Wire pair asymmetry (un-normalized yields):

$$A_{u-d,raw} = \frac{Y_u^- - Y_u^-}{Y_u^- + Y_u^-} - \frac{Y_d^- - Y_d^-}{Y_d^- + Y_d^-} \approx 2\varepsilon P G_u A_{PV} + \frac{\tilde{p}_u^+ - \tilde{p}_u^-}{Y_u^{o+} + Y_u^{o-}} - \frac{\tilde{p}_d^+ - \tilde{p}_d^-}{Y_d^{o+} + Y_d^{o-}}$$

We can measure the beam intensity asymmetry and the pedestal asymmetry:

$$A_{i,ped} = \frac{p_i^+ - p_i^-}{Y_i^{o+} + Y_i^{o-}} \qquad A_{Beam} = \frac{Y_i^{o+} - Y_i^{o-}}{Y_i^{o+} + Y_i^{o-}} = \frac{I^+ - I^-}{I^+ + I^-}$$

n^3He Analysis

Incorporating the pedestal and neutron beam intensity variations in the analysis:

Single wire asymmetry (with normalized yields):

$$A_{i,raw} = \varepsilon P G_i A_{PV} - \frac{\tilde{p}_i^+}{Y_i^{o+}} A_{Beam} + A_{i,ped} + A_{i,ped} A_{Beam} + \mathcal{O}\left(A_{Beam}^2\right) + \ldots$$

$$\Rightarrow \quad A_{i,raw} \approx \varepsilon P G_i A_{PV} - \frac{\tilde{p}_i^+}{Y_i^{o+}} A_{Beam} + A_{i,ped}$$

Wire pair asymmetry (un-normalized yields):

$$A_{u-d,raw} \approx 2\varepsilon P G_u A_{PV} + A_{u,ped} - A_{d,ped}$$

➡ **The wire pair asymmetry should be less sensitive to beam intensity variations.**

n^3He Analysis

Some data statistics:

- PV asymmetry

  31854 runs (~8 minute long)

  Number of good pulses: 690937760

  Number of pulses cut: 78335992 (10%)

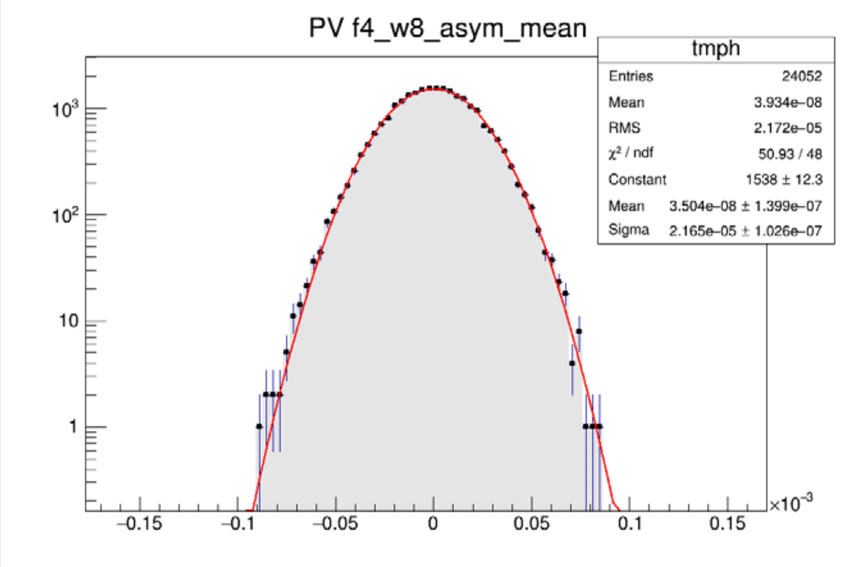
- PC asymmetry

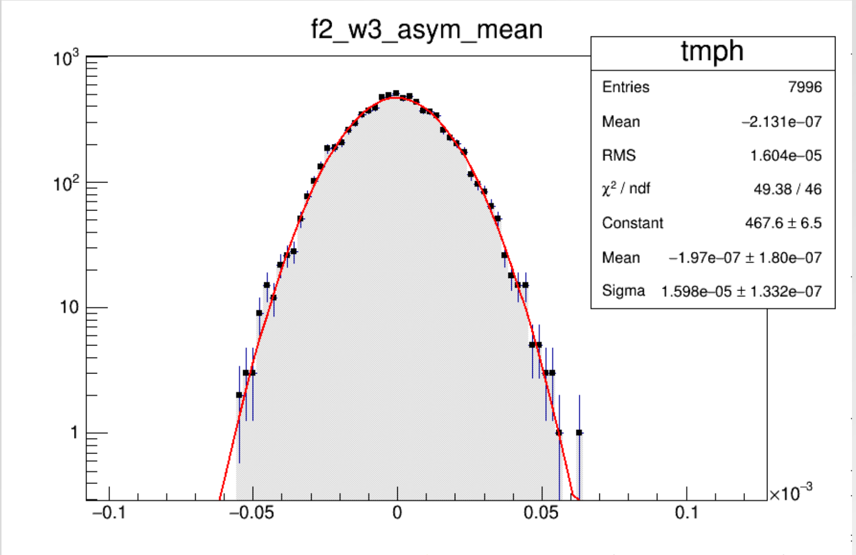
  1110 runs

  Number of good pulses: 22529520

  Number of pulses cut: 4468923 (17%)

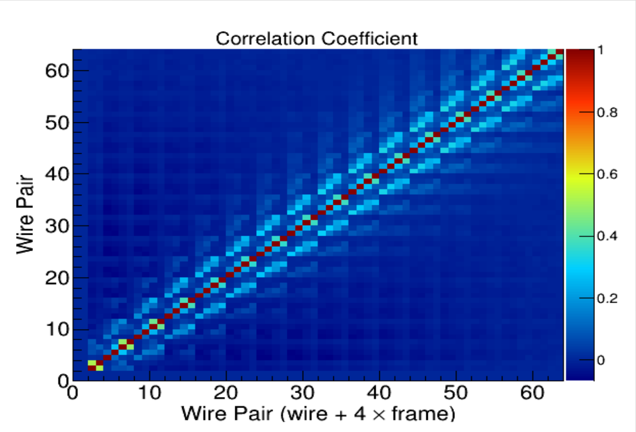
Right: Example of asymmetry distributions for specific wires.

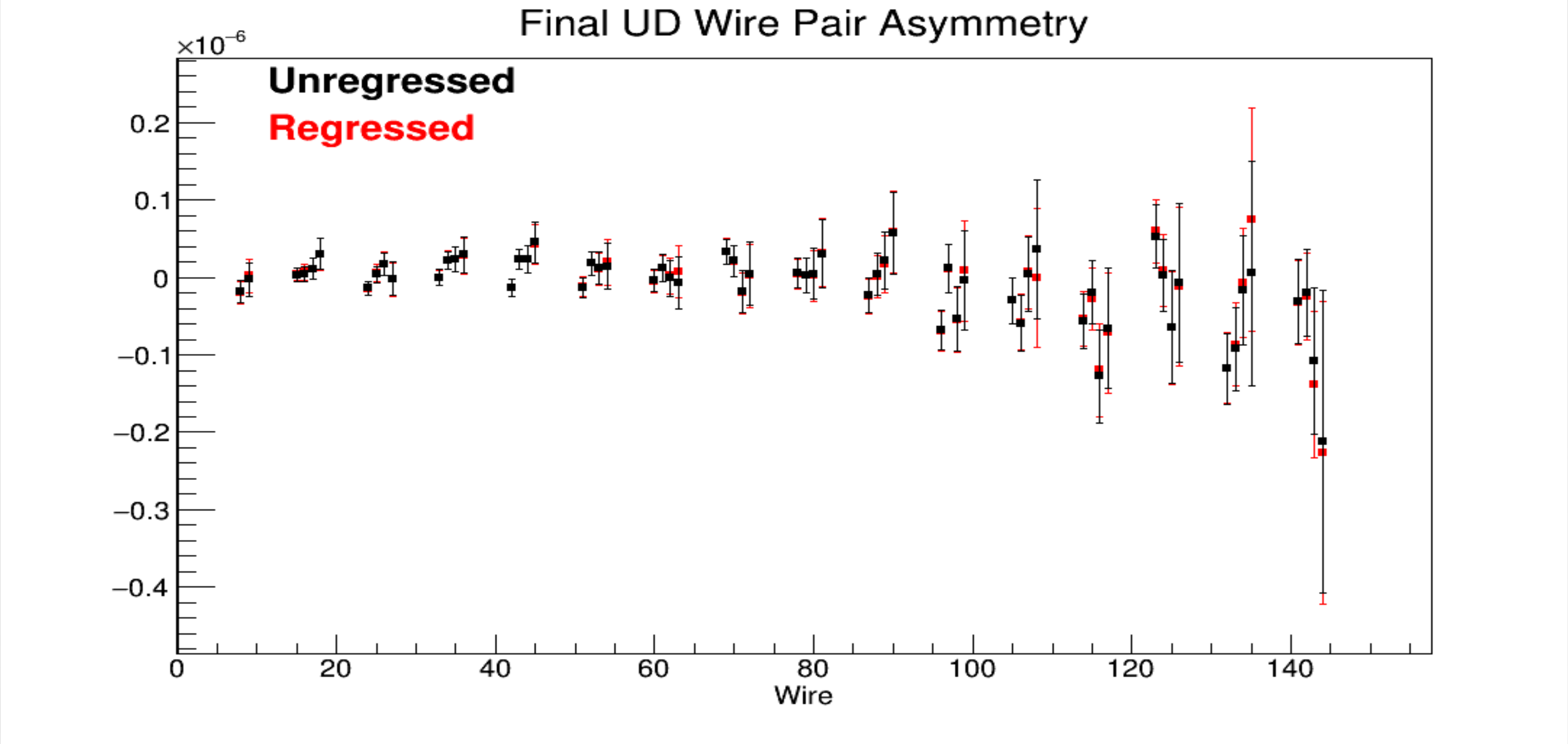




n^{3}He Analysis

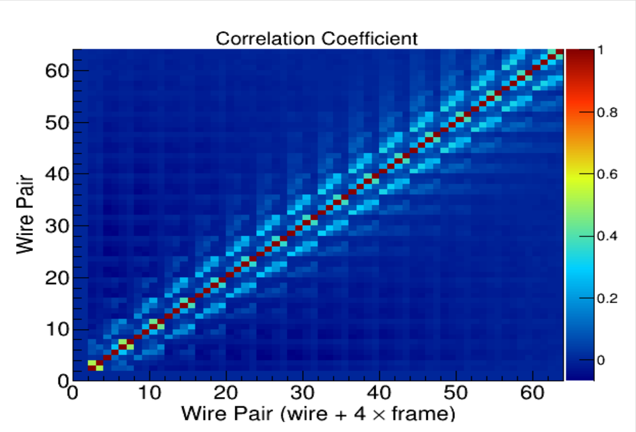
Corrected PV (UD) asymmetry:

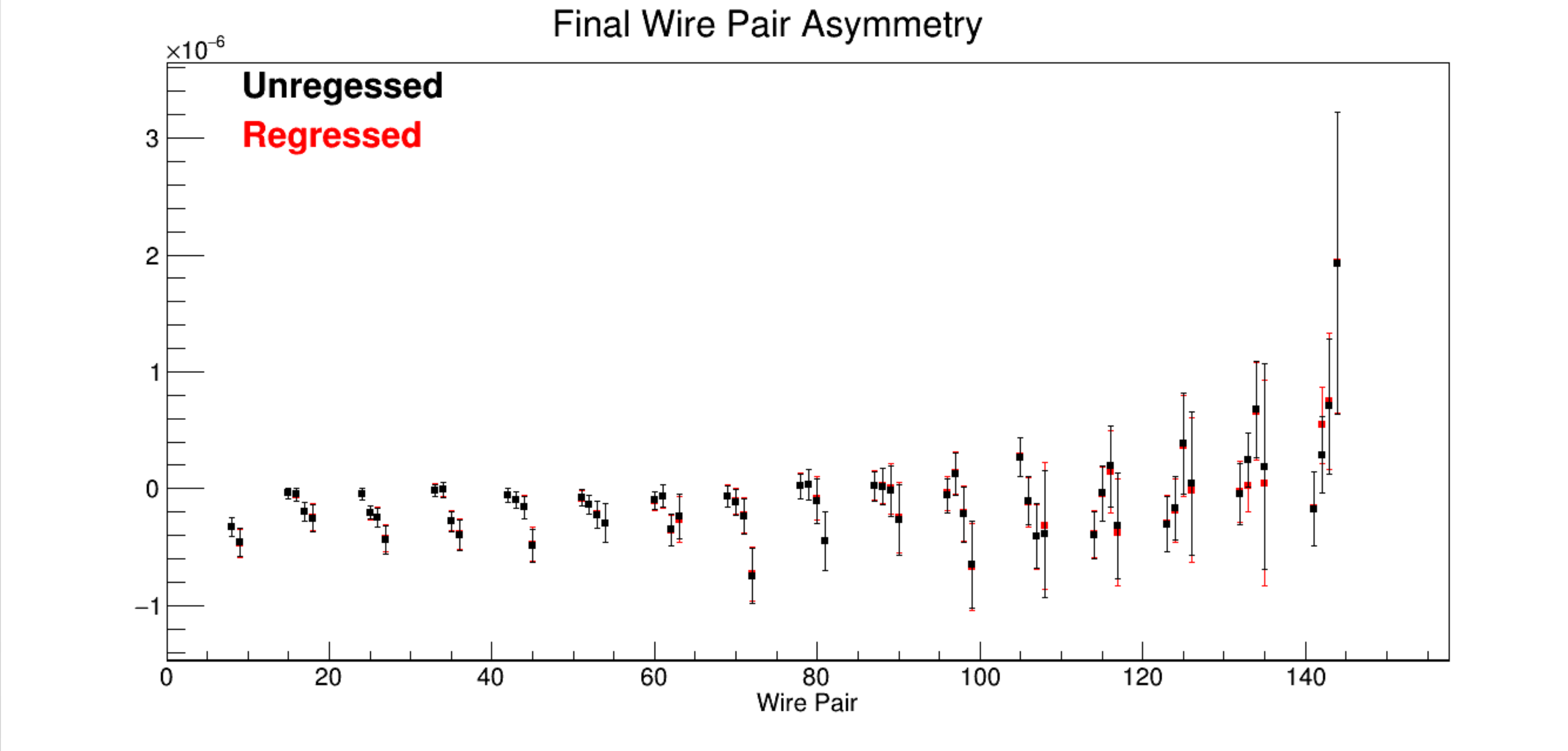




n^{3}He Analysis

Corrected PC (LR) asymmetry:



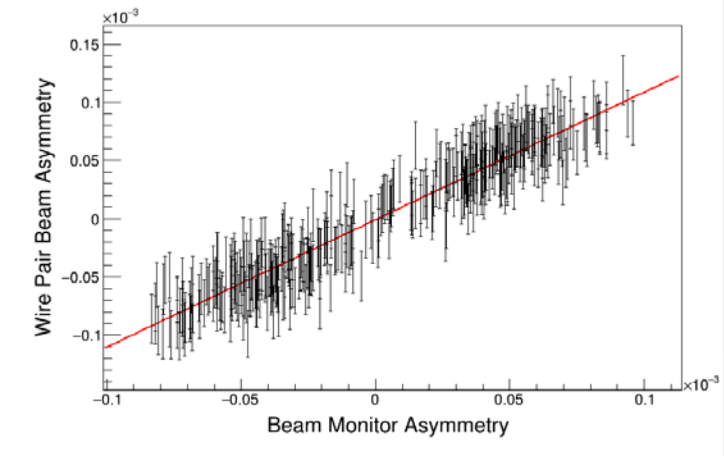


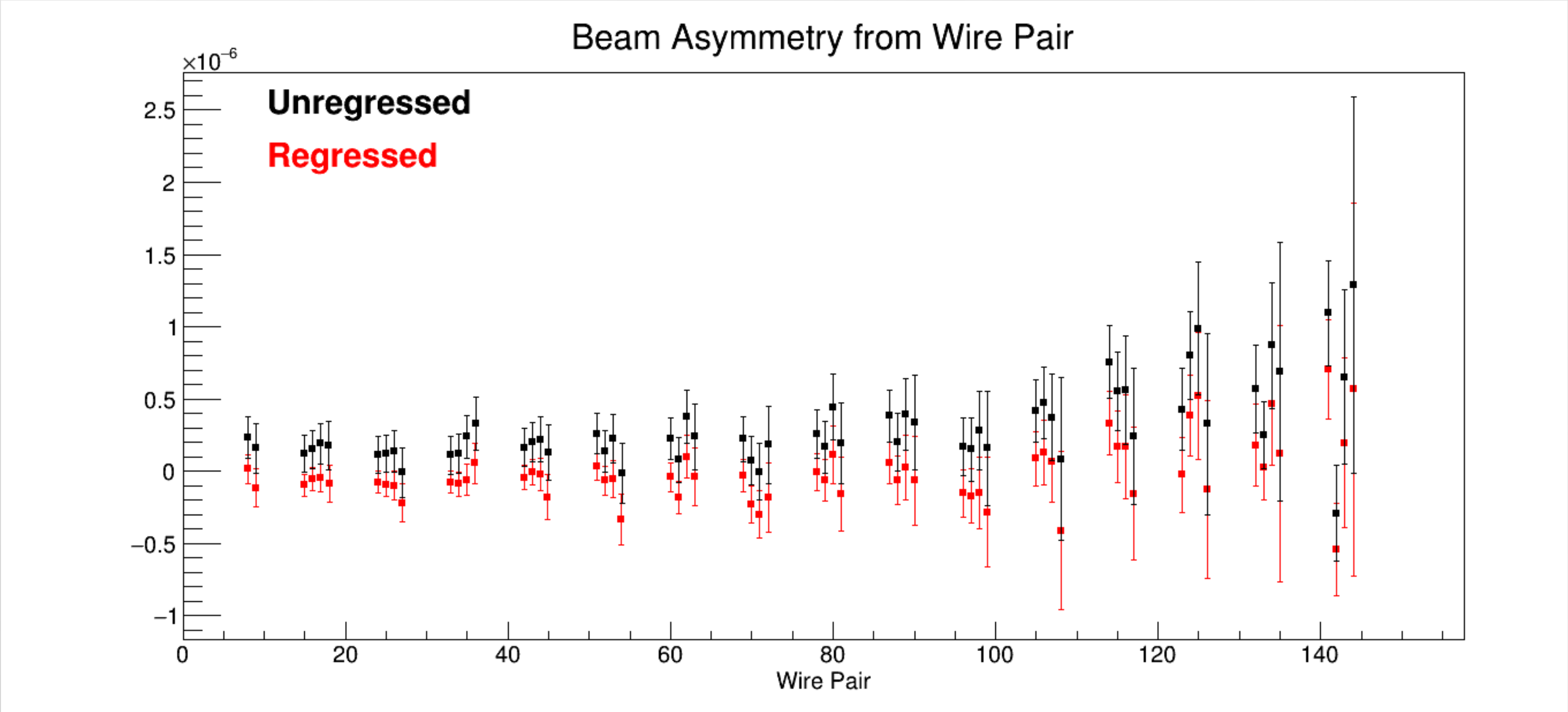
n³He Analysis

Corrected wire pair beam asymmetry:

$$A_{u+d,raw} = \frac{Y_u^- - Y_u^-}{Y_u^- + Y_u^-} + \frac{Y_d^- - Y_d^-}{Y_d^- + Y_d^-}$$

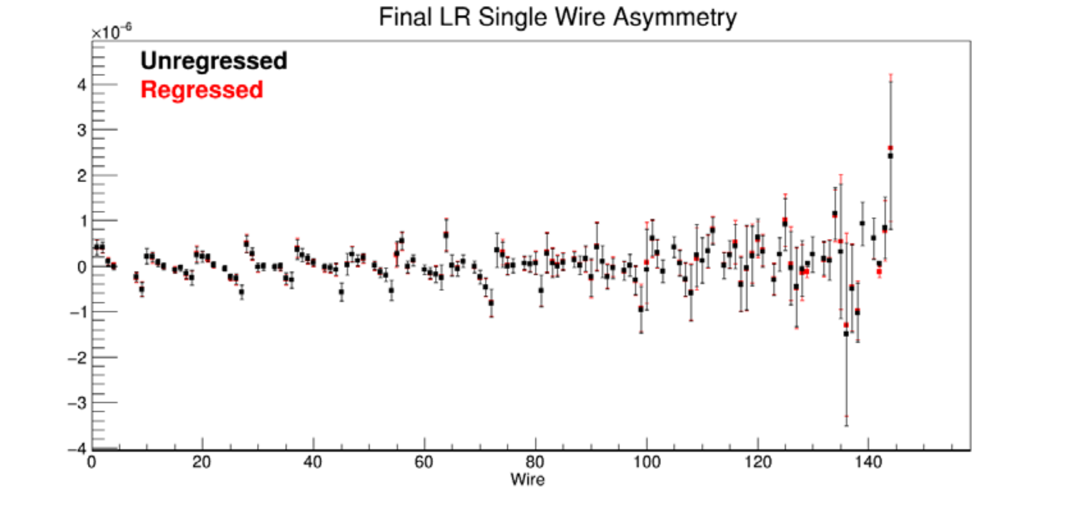
$$A_{u+d,raw} \approx 2A_{Beam} + A_{u,ped} - A_{d,ped}$$



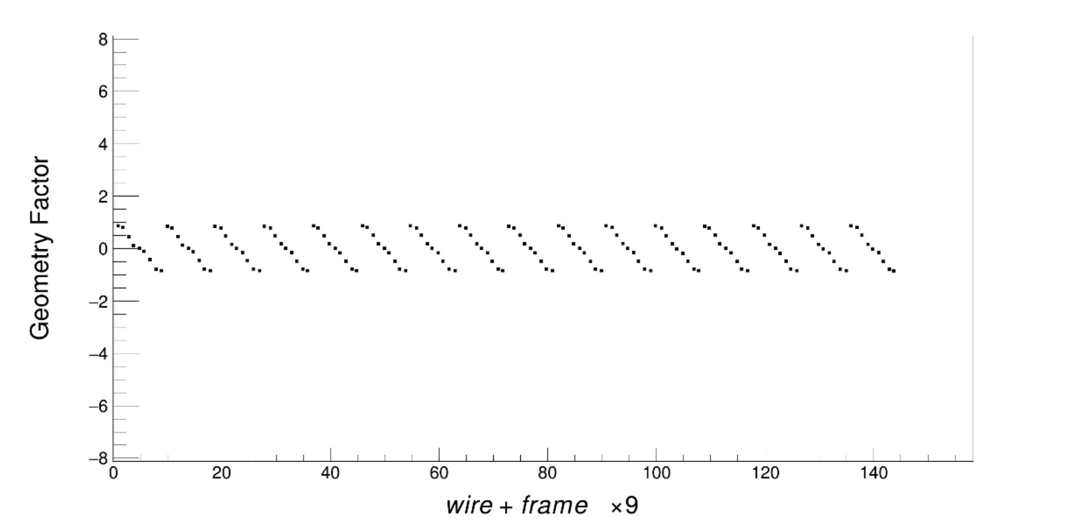


n^3He Analysis

Uncorrected
PC (LR) asymmetry:



Compare with simulated form factor structure:

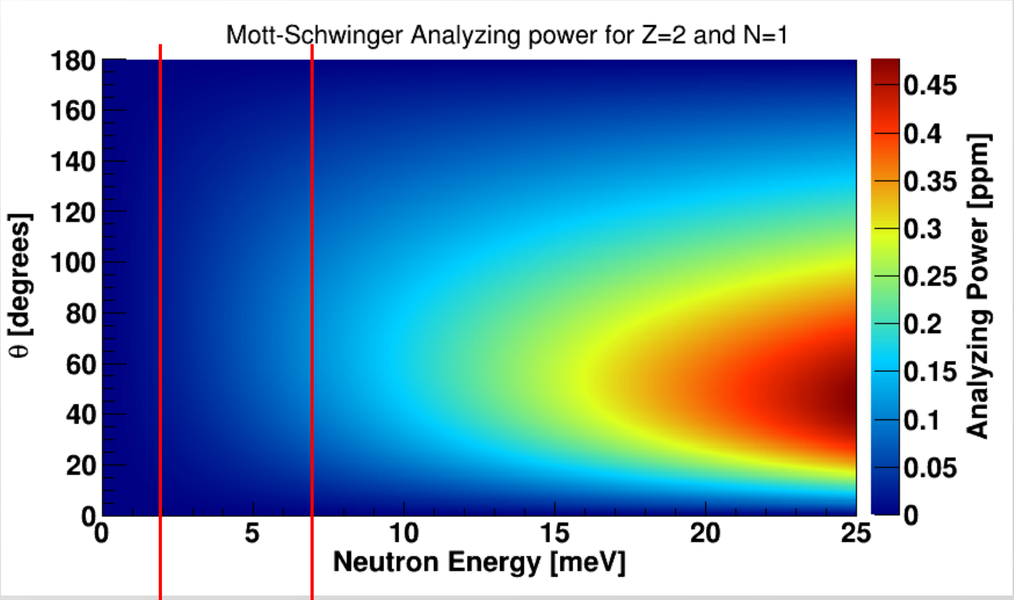


n^3He Systematic Effects / background

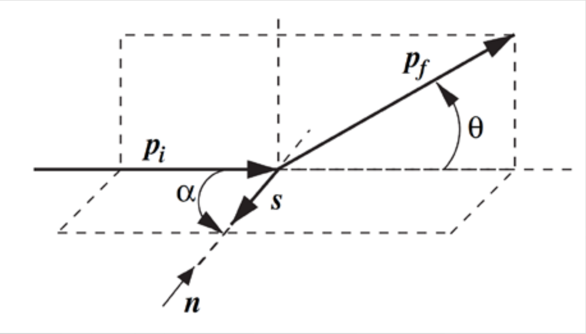
Source	**Comment**	**PV Correction**
beta/gamma background from capture	Simulated signal fraction $< 0.5\%$ Small dE/dx (~ 100 times smaller) Interaction prob. 10^{-4} relative to capture	$< 10^{-10}$
In flight beta decay	(using NPDGamma estimate)	$< 10^{-11}$
Stern-Gerlach steering	2 mG/cm field grad., small chamber volume	$< 10^{-10}$
Chamber-field alignment	3 mrad field to vertical, 0-20 mrad frame twist (leakage of PC into PV)	$\sim 1 \times 10^{-9}$
Mott-Schwinger	next slide	$< 10^{-11}$
Polarization		0.936 ± 0.002
Spin-flip efficiency		0.998 ± 0.001
Electronic false asymmetry	Measured from beam-off runs every week	$< 10^{-9}$

n^3He Systematic Effects

Mott-Schwinger Correction: M. T. GERICKE, J. D. BOWMAN, AND M. B. JOHNSON Phys. Rev. C 78, 044003 (2008)



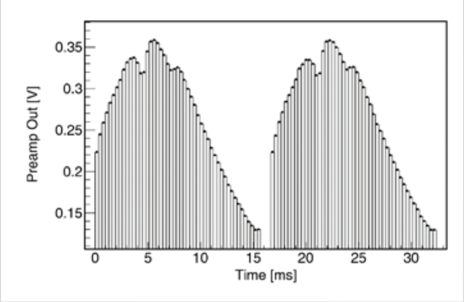
E&M spin-orbit and strong elastic (parity conserving) left-right asymmetry



$$H = V_s - \vec{\mu}_n \cdot \left(\vec{E} \times \vec{v}/c^2\right)$$

Integration over energy and angle range.

Weighted by the Detector spectrum



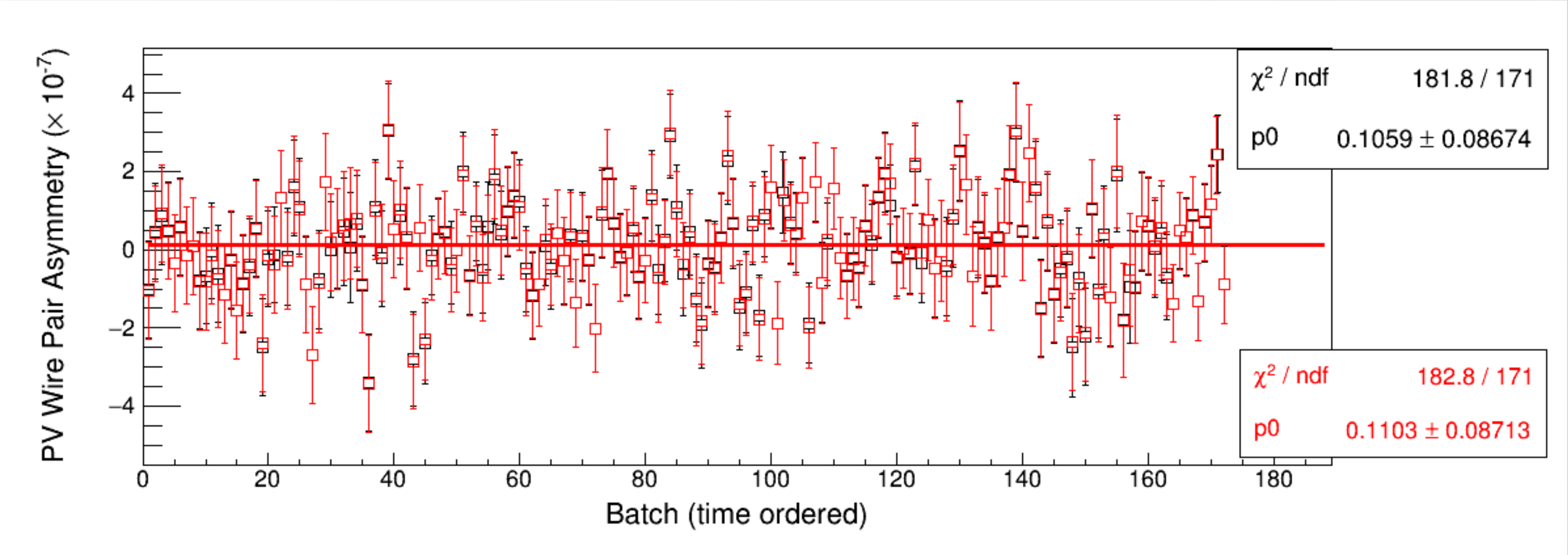
$$A_{false} = \frac{\sigma_s}{\sigma_c} A_{MS} \leq 3\ ppb$$

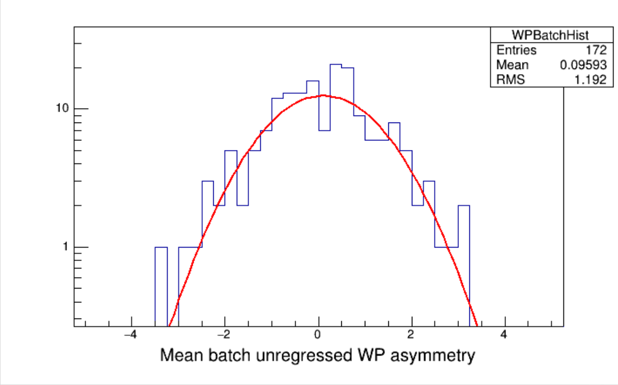
$$\sigma_c = \frac{(5327 \pm 10)v_o}{v}\ barn$$

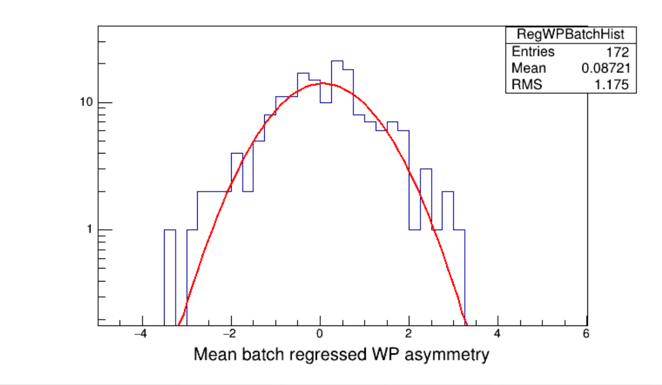
$$\sigma_s \approx 1.0\ \pm 0.7\ barn$$

n^{3}He Final Results

PV asymmetry:



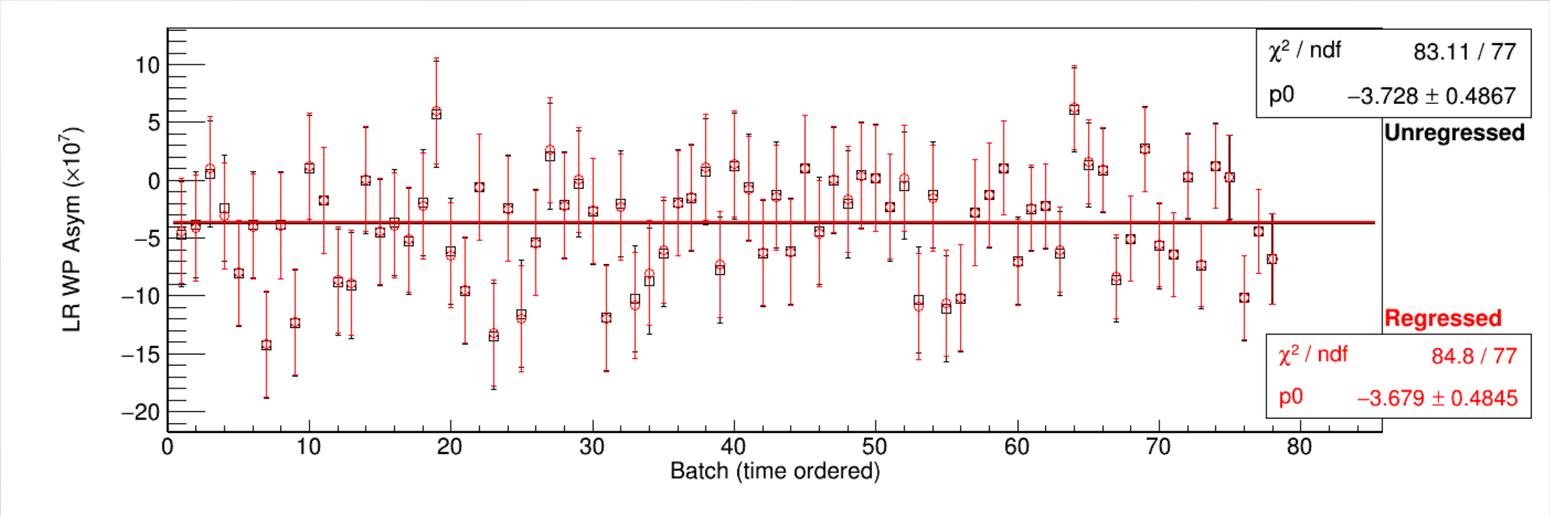


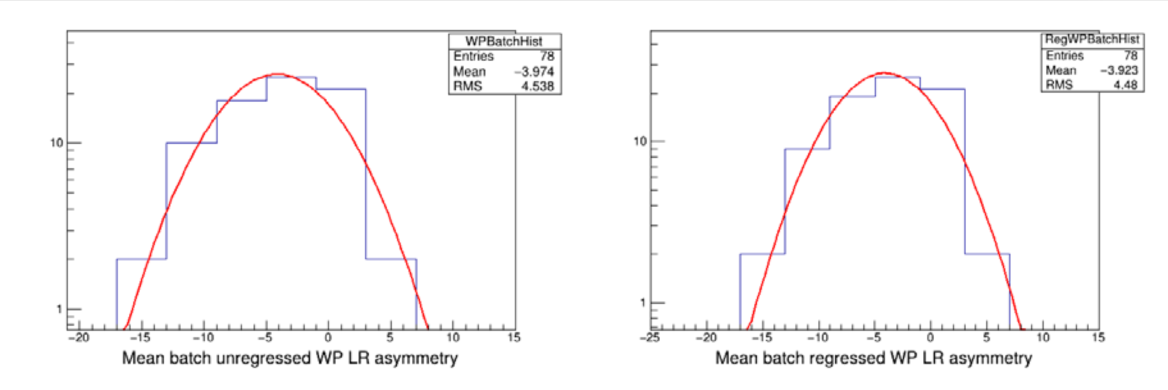


Corrected asymmetry: $A_{PV} = 11.7 \pm 9.3(stat) \pm 1.0(sys)$ ppb

n^3He Final Results

PC asymmetry:

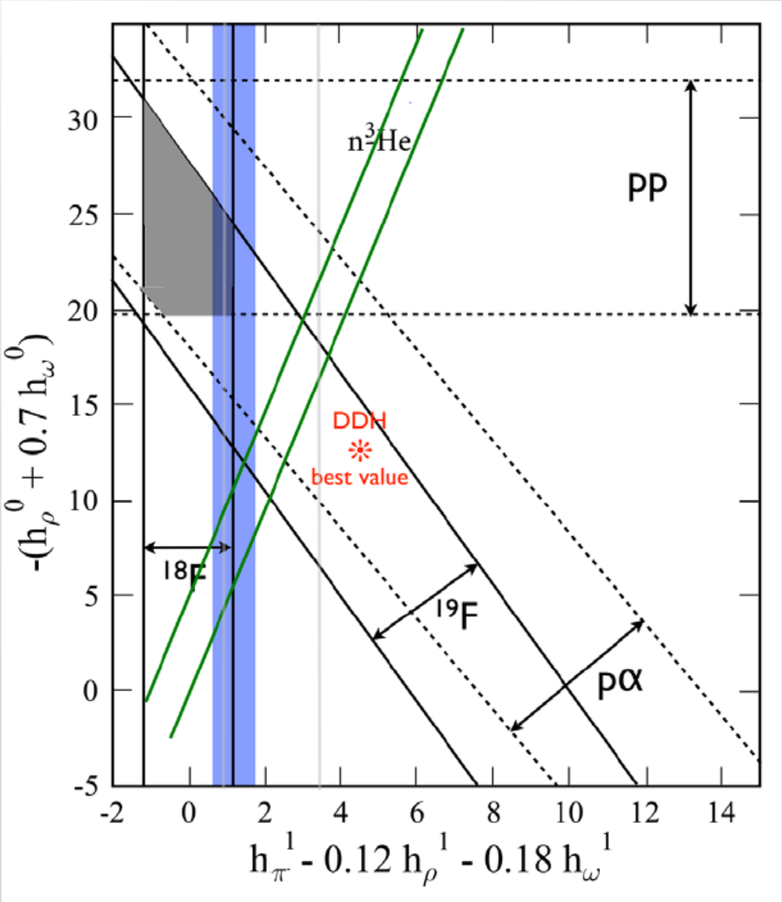


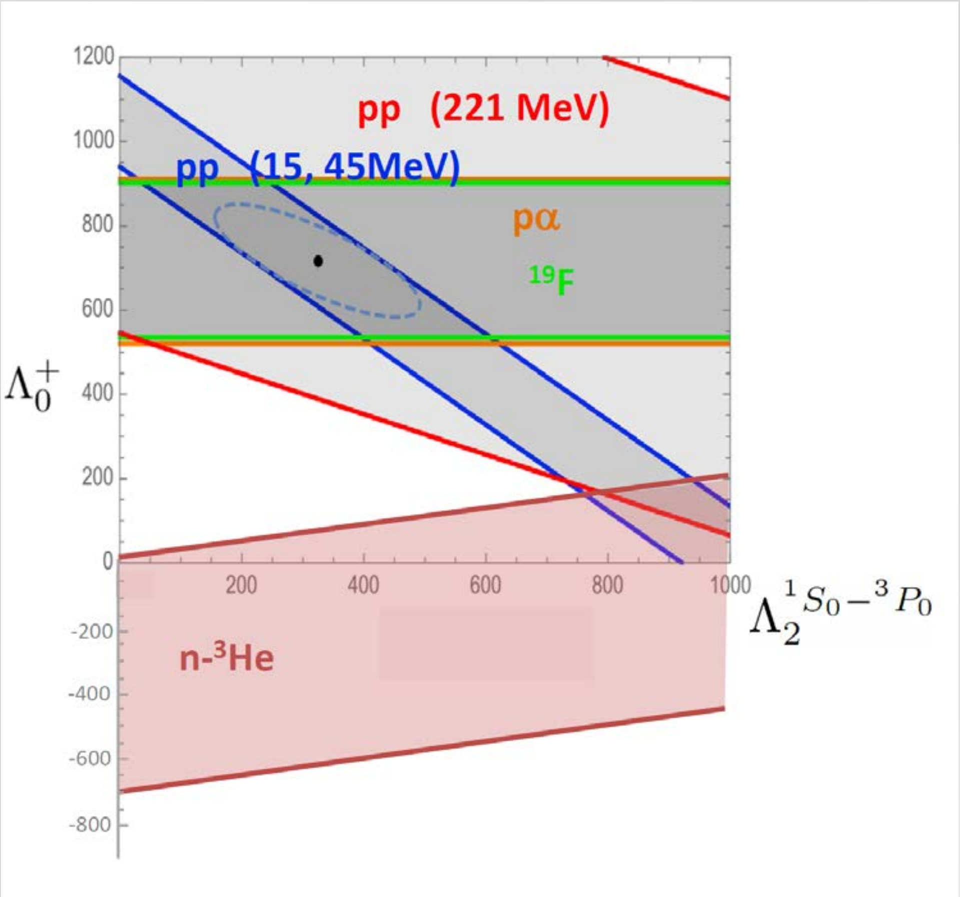


Corrected asymmetry: $A_{PC} = -394 \pm 51(stat) \pm 3.0(sys)$ ppb

n^3He Final Results

Constraints from this experiment:





Summary

• Proposal	2008
• Development and Construction	2010 - 2014
• Installation	Fall 2014
• Commissioning	Fall 2014 – January 2015
• Production Data Taking	February – December 2015
• Analysis	Completed
• Publications	In progress

Thank you