The n-^{3}He Experiment: A new era in Hadronic Parity Violation

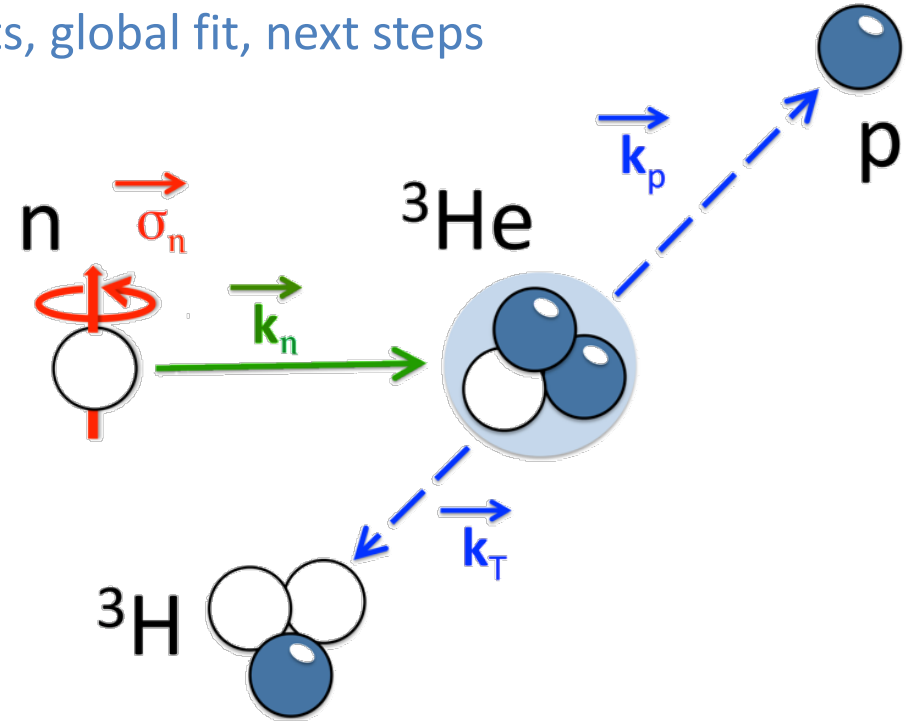
Christopher Crawford, Univ. Kentucky, for the n-^{3}He collaboration

Physics of Fundamental Symmetries and Interactions - PSI2019

PSI, Villigen, Switzerland 2019-10-22

Overview

- Hadronic Parity Violation
  - Hadronic Weak Interaction (HWI) formalisms
- n-^{3}He Experimental Setup
  - RF spin rotator, active target/ion chamber
- Data analysis
  - Results, global fit, next steps

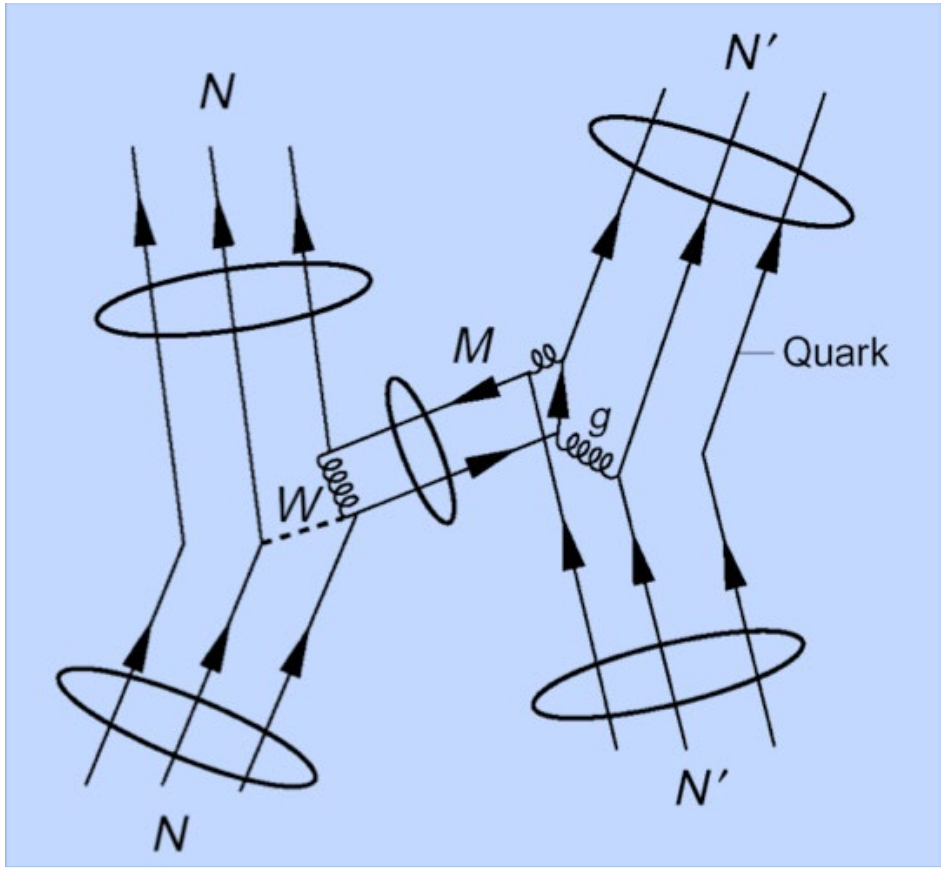


$$A_p \approx \vec{s}_n \cdot \vec{k}_p$$

Is a parity odd pseudoscalar!

Motivation the studying the HWI

- Least understood weak interaction
  - EW: Quarks & Leptons, Semileptonic, Hadronic
  - Complicated by nuclear structure
  - Strongly suppressed by $M_\pi^{2/}M_W^2 \sim 10^{-7}$
  - Unique PV signature
- Orthogonal probe of QCD structure
  - test of QCD structure in $\Delta S = 0$ sector ($\Delta I=1/2$ rule not understood)
  - Study the NC in hadronic systems – forbidden by $\Delta S = 1$ by GIM mechanism
  - W,Z range = 0.002 fm – probe of short-range quark correlations in QCD nonperturbative regime
  - Nuclear and atomic PV test of nuclear structure models
  - physics input to PV electron scattering experiments
  - $0\nu\beta\beta$ decay – matrix elements of 4-quark operators
  - Same formalism used for Hadronic TRIV (complementary to EDM)



Relation between HPV and EDMs

- Tree level diagrams

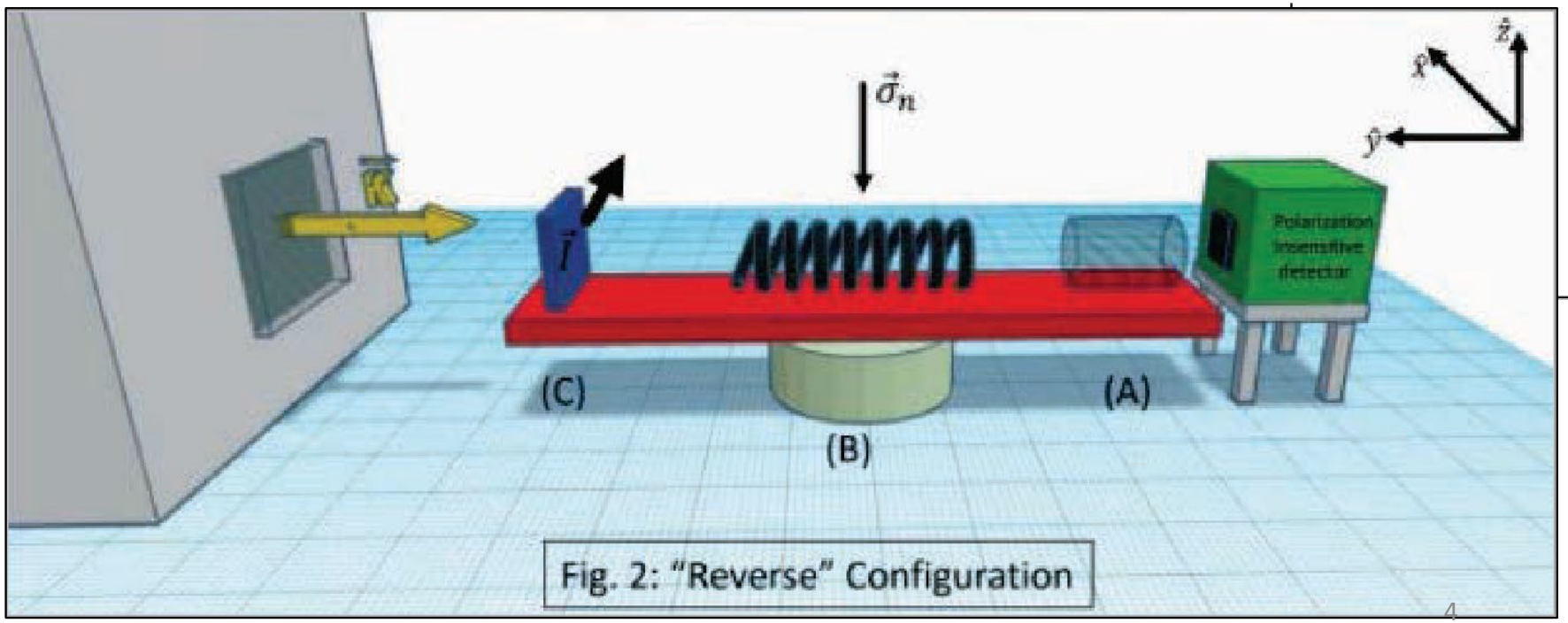
Bowman, Gudkov,
PRC 90, 065503 (2014)

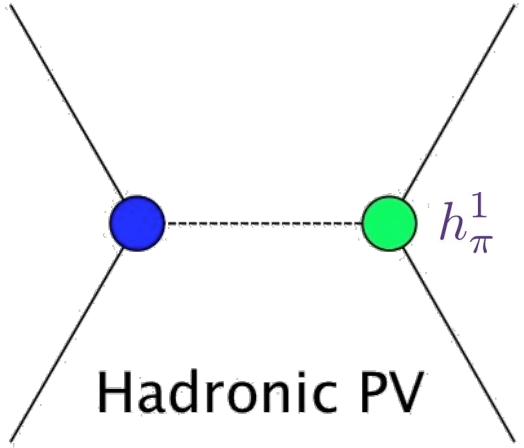
$$\frac{d\sigma_{TP}}{d\sigma_P} = k_0 \frac{\bar{g}_\pi^0}{h_\pi^1} + k_1 \frac{\bar{g}_\pi^1}{h_\pi^1}$$

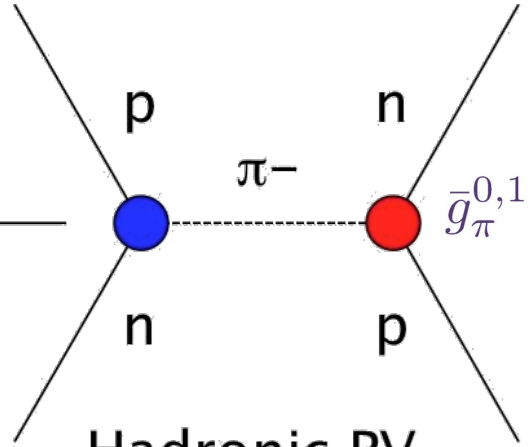
P even T even

P odd T even

P odd T odd



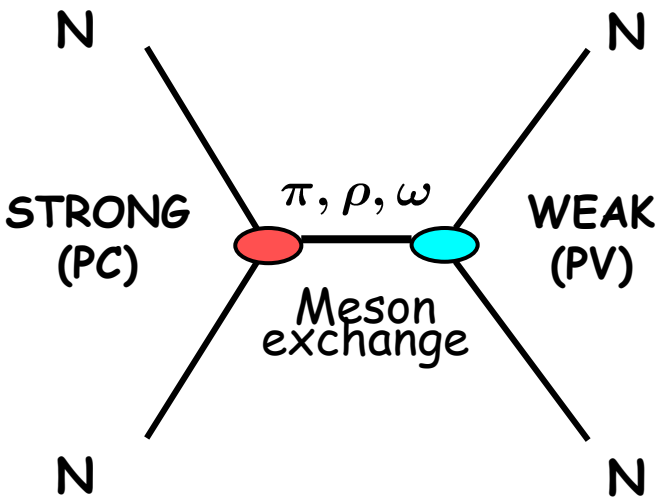




Hadronic PV and TV

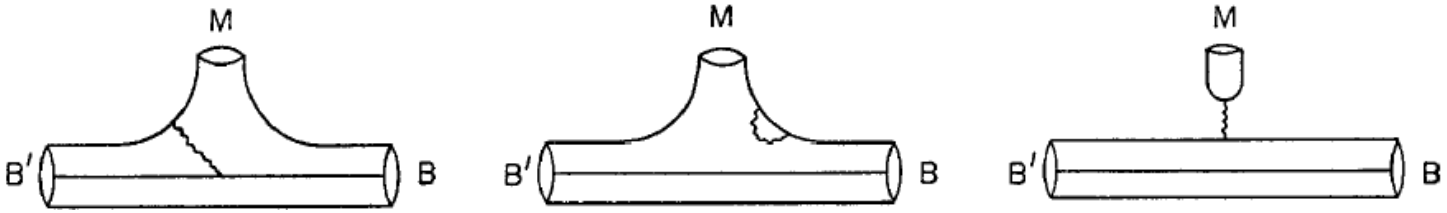
DDH Meson-exchange potential

PV meson exchange



$$\frac{e^2}{M_W^2} / \frac{g^2}{m_\pi^2} \approx 10^{-7}$$

isospin	f_π	$h_\rho^{\prime 1}$	$h_\rho^{0,1,2}$	$h_\omega^{0,1}$
$\Delta I = 0$			$(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$	(1)
$\Delta I = 1$	$\frac{i}{2}(\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2)^3$		$\frac{1}{2}(\boldsymbol{\tau}_1 \pm \boldsymbol{\tau}_2)^3$	$\frac{1}{2}(\boldsymbol{\tau}_1 \pm \boldsymbol{\tau}_2)^3$
$\Delta I = 2$			$\frac{1}{2\sqrt{6}}(3\tau_1^3\tau_2^3 - \boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$	
range	$J = 0$		$J = 1$	$J = 1$
m_π	$(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)\left[\frac{\boldsymbol{p}_1 - \boldsymbol{p}_2}{2M}, \frac{e^{-m_\pi r}}{4\pi r}\right]$			
$m_\rho = m_\omega$	$(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)\left[\frac{\boldsymbol{p}_1 - \boldsymbol{p}_2}{2M}, \frac{e^{-m_\rho r}}{4\pi r}\right]$		$(\boldsymbol{\sigma}_1 \pm \boldsymbol{\sigma}_2)\left\{\frac{\boldsymbol{p}_1 - \boldsymbol{p}_2}{2M}, \frac{e^{-m_\rho r}}{4\pi r}\right\}$	
			$i(\boldsymbol{\sigma}_1 \times \boldsymbol{\sigma}_2)\left[\frac{\boldsymbol{p}_1 - \boldsymbol{p}_2}{2M}, \frac{e^{-m_\rho r}}{4\pi r}\right]$	



Desplanques, Donoghue, Holstein, Annals of Physics **124**, 449 (1980)

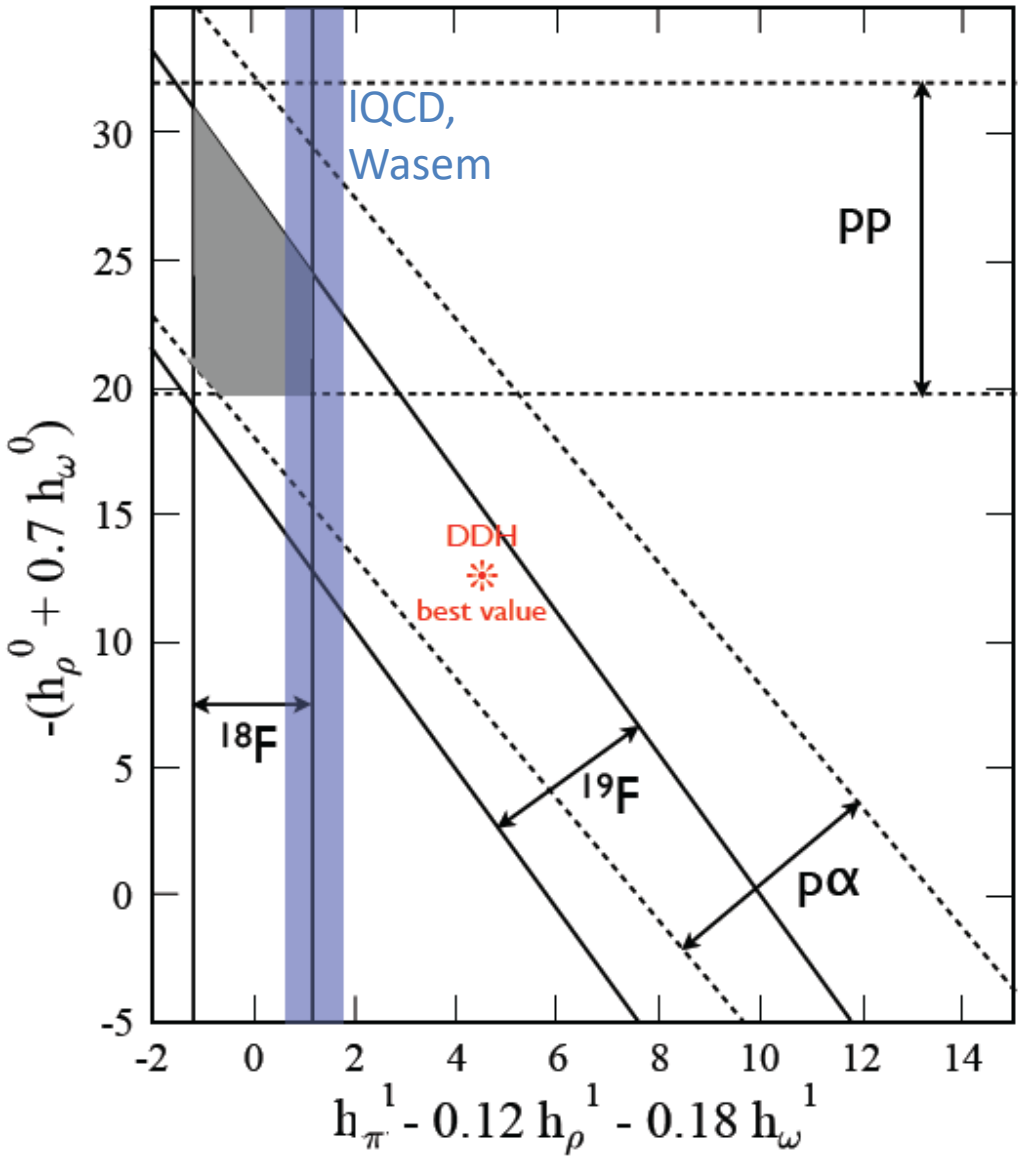
Wasem, Phys. Rev. C **85** (2012) 022501

1st Lattice QCD result of f_π !!

Few-body HWI PV Observables

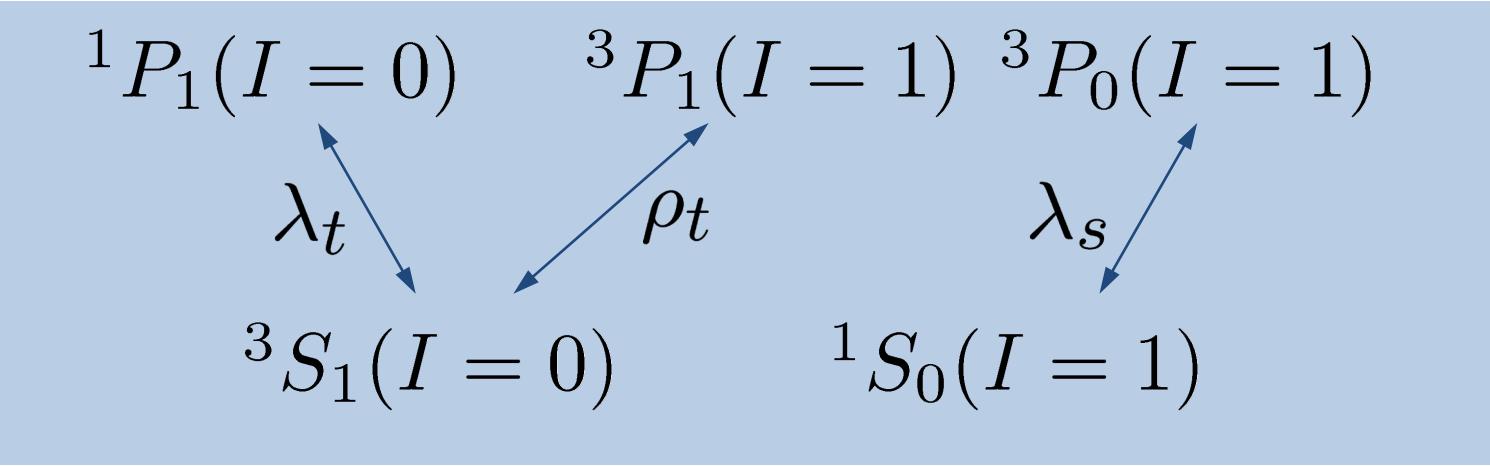
- Long. analyzing power in elastic scattering
  - pp (15,45, 220 MeV), pd, pα
- Circular polarization, n + p –> d + γ
- Gamma asymmetry, n + p –> d + γ
  - Desplanques, NP A 335, 147 (1980)
  - PV mixing in final bound state
    + PV transition amplitudes
  - Dominated by long range h^1_π
- n + ^{3}He –> p + ^{3}H reaction
  - Viviani, et al, PRC 82, 044001 (2010)
  - 4-body wave functions + P_{odd} operators
  - Sensitive to $h^1_\pi, h^0_\rho, h^0_\omega$
- n + ^{4}He spin rotation

observables are LINEAR in weak couplings



Danilov parameters / EFT

- Elastic NN scattering
  S-P transition amplitudes
  $S_z = \pm 1/2$ $I_3 = \pm 1/2$
  antisymmetric in L, S, I
  conservation of J
- Equivalent to pion-less Effective Field Theory (EFT) in the low energy limit



Coeff	DDH	Girlanda	Zhu
$\Lambda_0^{^1S_0-^3P_0}$ DDH	$-g_\rho h_\rho^0(2+\chi_V) - g_\omega h_\omega^0(2+\chi_S)$	$2(\mathcal{G}_1+\tilde{\mathcal{G}}_1)$	$2(\mathcal{C}_1+\tilde{\mathcal{C}}_1+\mathcal{C}_3+\tilde{\mathcal{C}}_3)$
$\Lambda_0^{^3S_1-^1P_1}$ DDH	$g_\omega h_\omega^0 \chi_S - 3g_\rho h_\rho^0 \chi_V$	$2(\mathcal{G}_1-\tilde{\mathcal{G}}_1)$	$2(\mathcal{C}_1-\tilde{\mathcal{C}}_1-3\mathcal{C}_3+3\tilde{\mathcal{C}}_3)$
$\Lambda_1^{^1S_0-^3P_0}$ DDH	$-g_\rho h_\rho^1(2+\chi_V) - g_\omega h_\omega^1(2+\chi_S)$	$\mathcal{G}_2$	$(\mathcal{C}_2+\tilde{\mathcal{C}}_2+\mathcal{C}_4+\tilde{\mathcal{C}}_4)$
$\Lambda_1^{^3S_1-^3P_1}$ DDH	$\frac{1}{\sqrt{2}} g_{\pi NN} h_\pi^1 \left(\frac{m_\rho}{m_\pi}\right)^2 + g_\rho(h_\rho^1 - h_\rho^{1\prime}) - g_\omega h_\omega^1$	$2\mathcal{G}_6$	$(2\tilde{\mathcal{C}}_6+\mathcal{C}_2-\mathcal{C}_4))$
$\Lambda_2^{^1S_0-^3P_0}$ DDH	$-g_\rho h_\rho^2(2+\chi_V)$	$-2\sqrt{6}\mathcal{G}_5$	$2\sqrt{6}(\mathcal{C}_5+\tilde{\mathcal{C}}_5)$

C.-P. Liu, P.R.C. **75**, 065501 (2007)

Haxton & Holstein, P.P.N.P. **7**, 1851 (2013)

Large N_c expansion

- Two leading order amplitudes

$$\Lambda_0^+ \equiv \frac{3}{4}\Lambda_0^{^3S_1-^1P_1} + \frac{1}{4}\Lambda_0^{^1S_0-^3P_0} \sim N_c$$

$$\Lambda_2^{^1S_0-^3P_0} \sim N_c \sin^2\theta_w$$

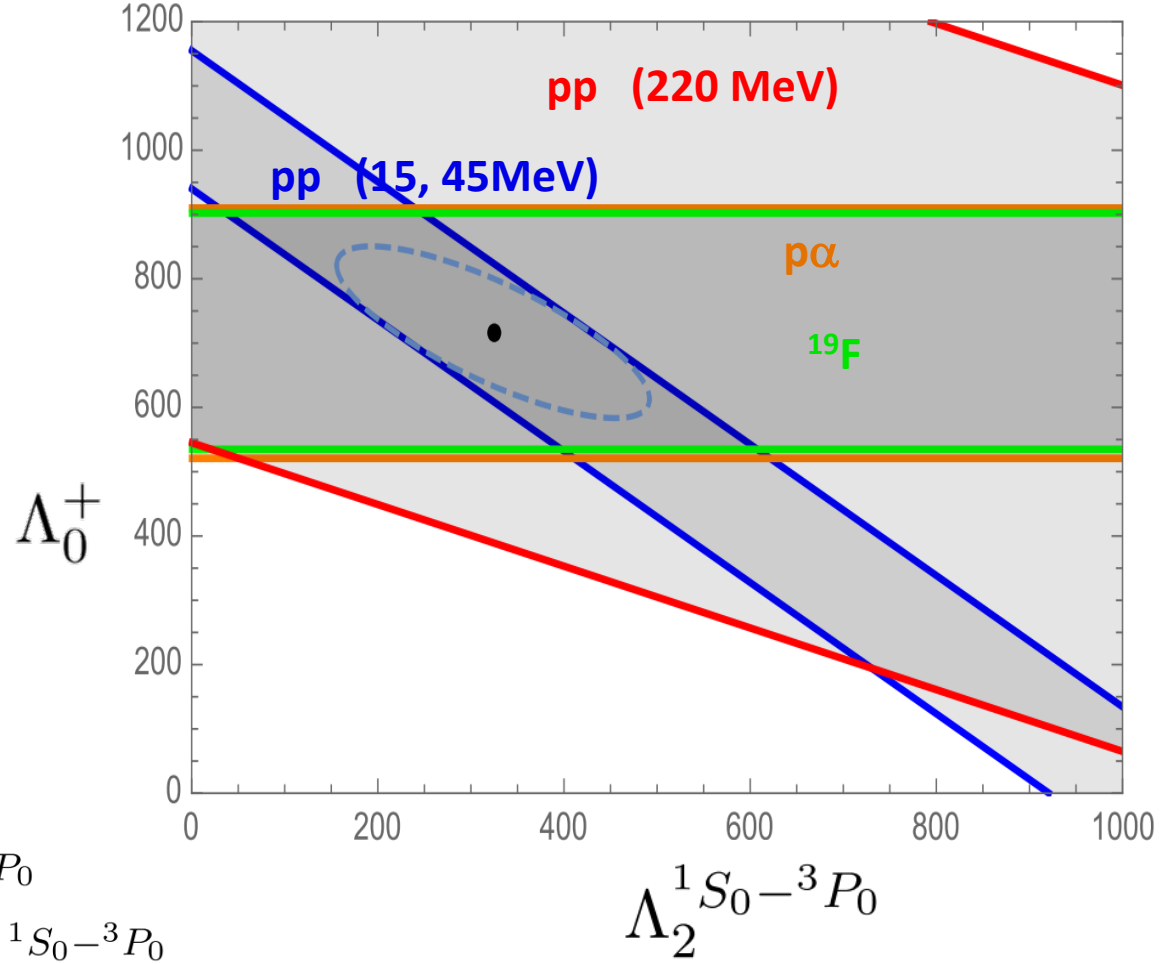
- Others suppressed by N_c^2

$$\Lambda_0^- \equiv \frac{1}{4}\Lambda_0^{^3S_1-^1P_1} - \frac{3}{4}\Lambda_0^{^1S_0-^3P_0} \sim 1/N_c$$

$$\Lambda_1^{^1S_0-^3P_0} \sim \sin^2\theta_w$$

$$\Lambda_1^{^3S_1-^3P_1} \sim \sin^2\theta_w$$

- New paradigm for experiments
  - NPDG tests the smallness of $\Lambda_1^{^1S_0-^3P_0}$
  - n^3He an orthogonal constraint on Λ_0^+ , $\Lambda_2^{^1S_0-^3P_0}$.

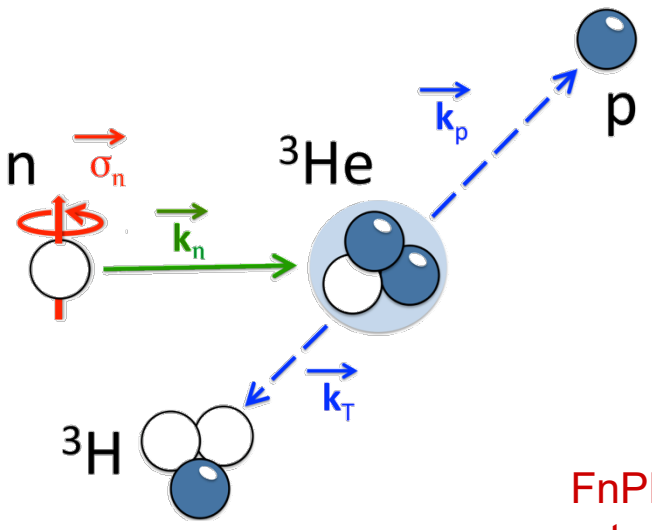


Phillips, Samart, Schat, PRL **114**, 062301 (2015)

Schindler, Springer, Vanasse, PRC **93**, 025502 (2016)

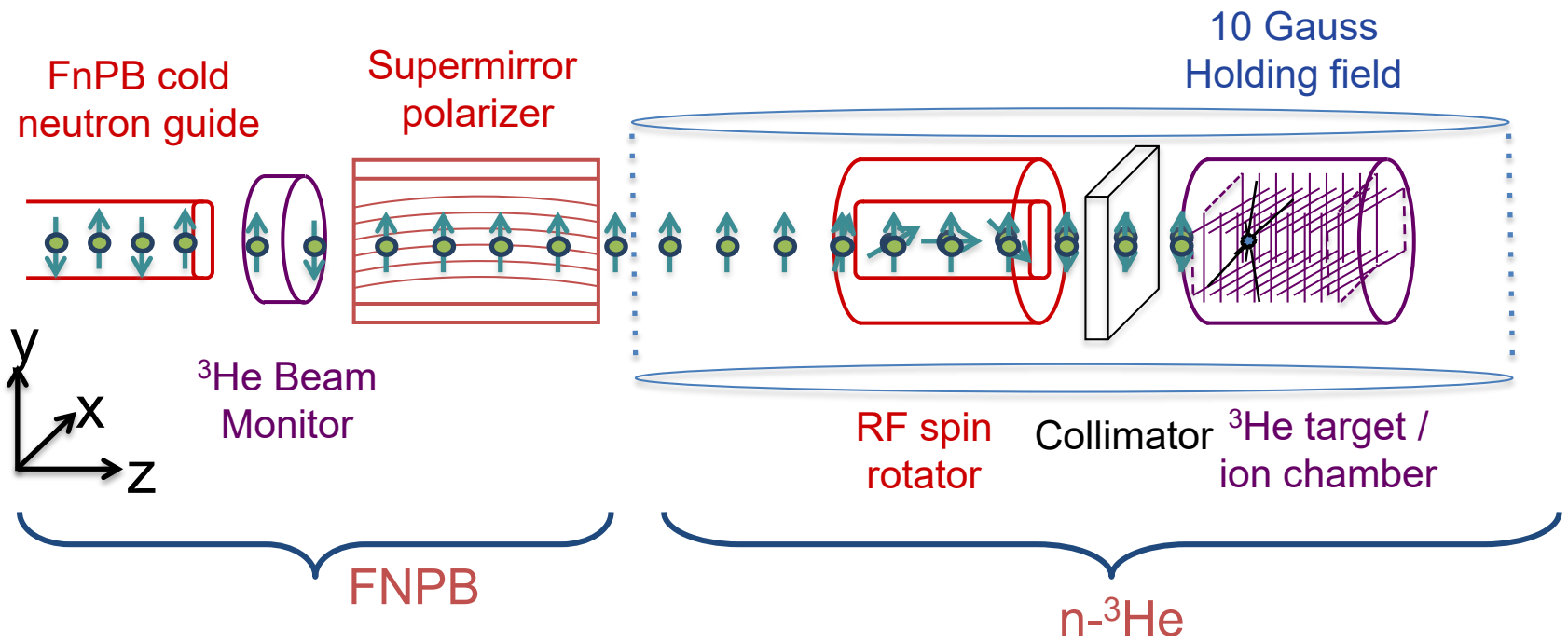
Gardner, Haxton, Holstein, ARNPS **67**, 69 (2017)

n-^{3}He Experimental setup



$$\sigma_\pm = \sigma_0(1 \pm A_{PC}\,\underbrace{\hat{\boldsymbol{k}}_n \times \hat{\boldsymbol{\sigma}}_n \cdot \hat{\boldsymbol{k}}_p}_{G_{\mathrm{LR}}} \pm A_{PV}\,\underbrace{\hat{\boldsymbol{\sigma}}_n \cdot \hat{\boldsymbol{k}}_p}_{G_{\mathrm{UD}}})$$

$$P_n A_{\substack{\mathrm{PC}\\ \mathrm{PV}}} G_{\substack{\mathrm{LR}\\ \mathrm{UD}}} = \frac{Y_+ - Y_-}{Y_+ + Y_-}$$

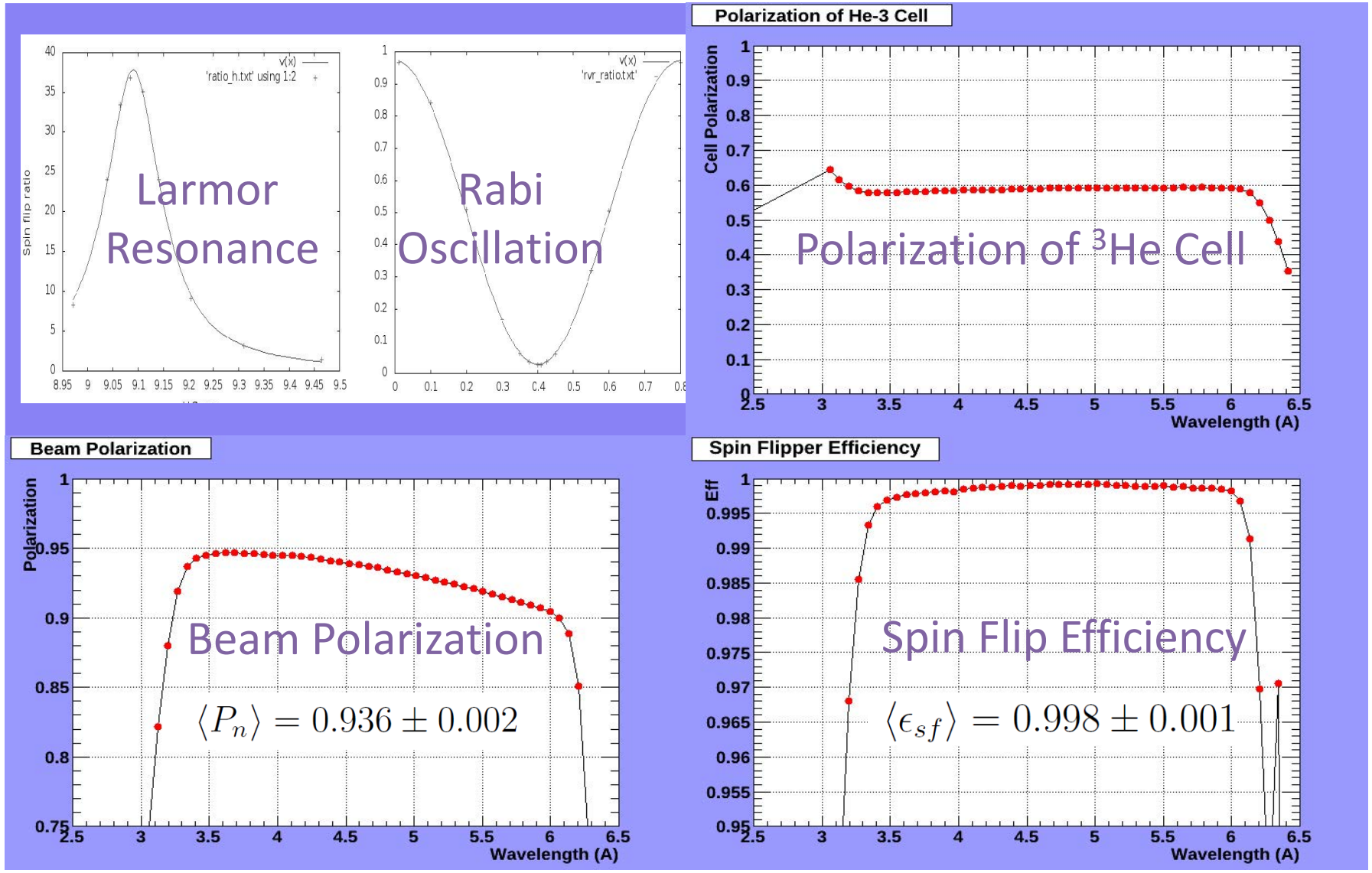


Transverse RF spin rotator

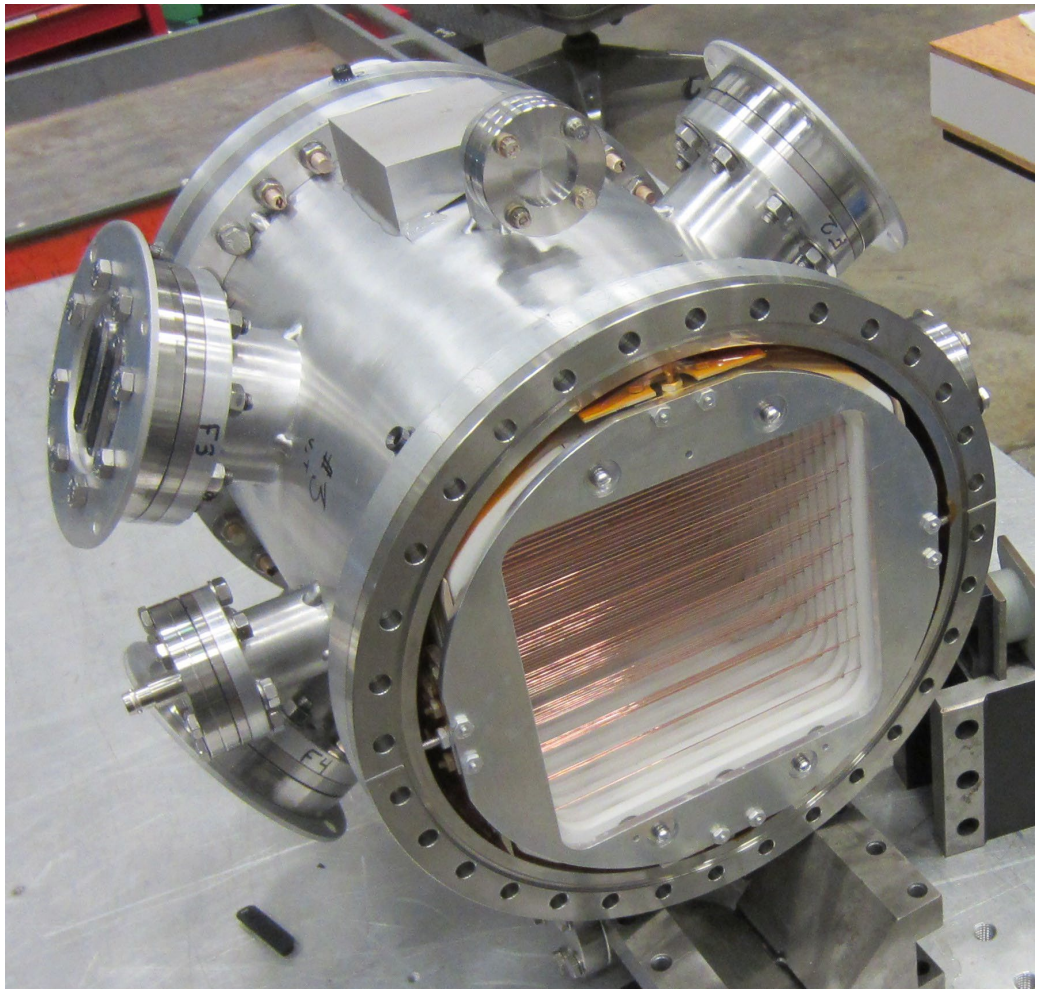
- Double-cosine-theta coil
  - Fringeless transverse RF field
  - Longitudinal OR transverse
  - Designed using scalar potential

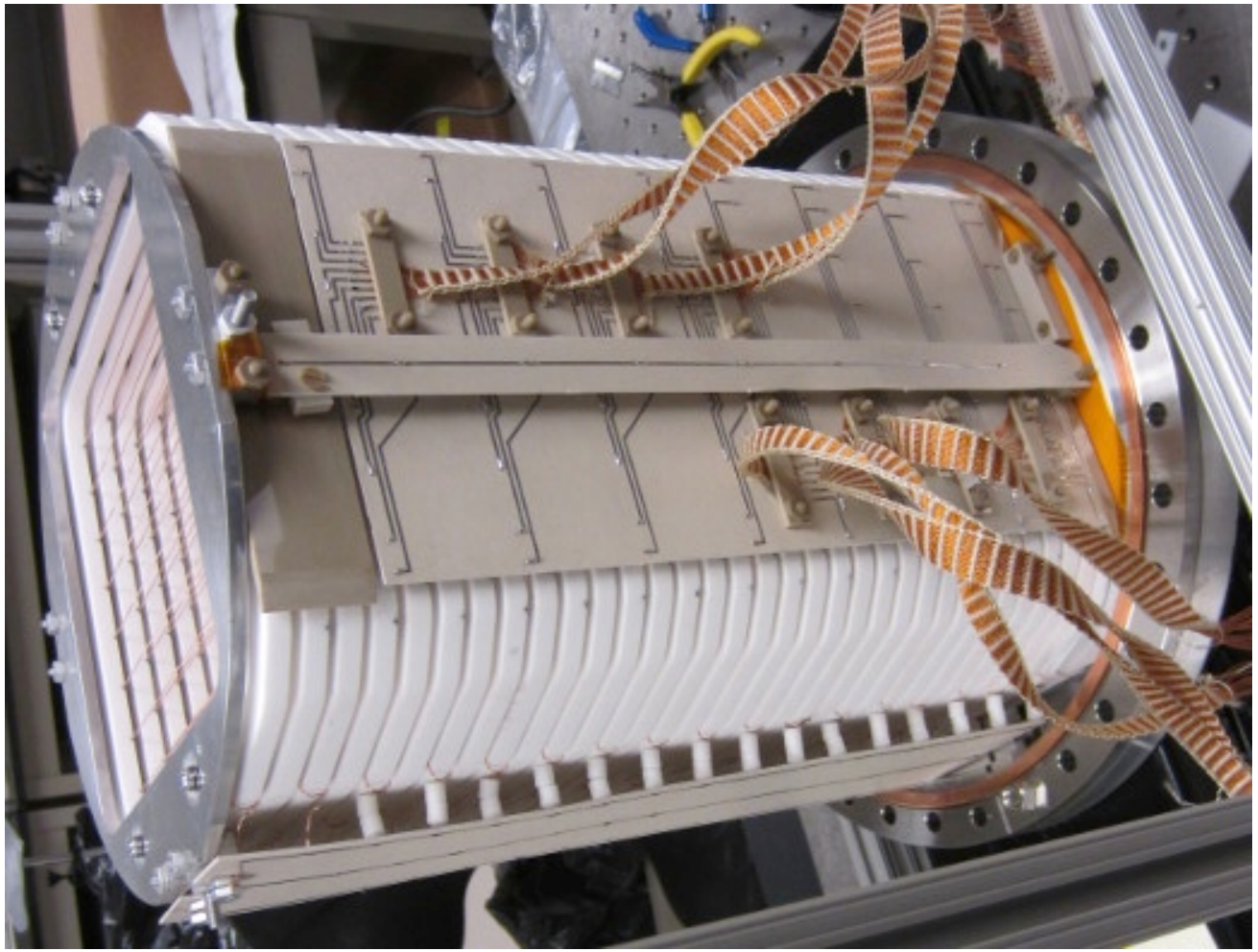
Univ. Kentucky / Univ. Tennessee

^{3}He transmission polarimetry



Active target / ion chamber





- ^{3}He serves as both target and ionization gas
- 16 mCi tritium over life of experiment

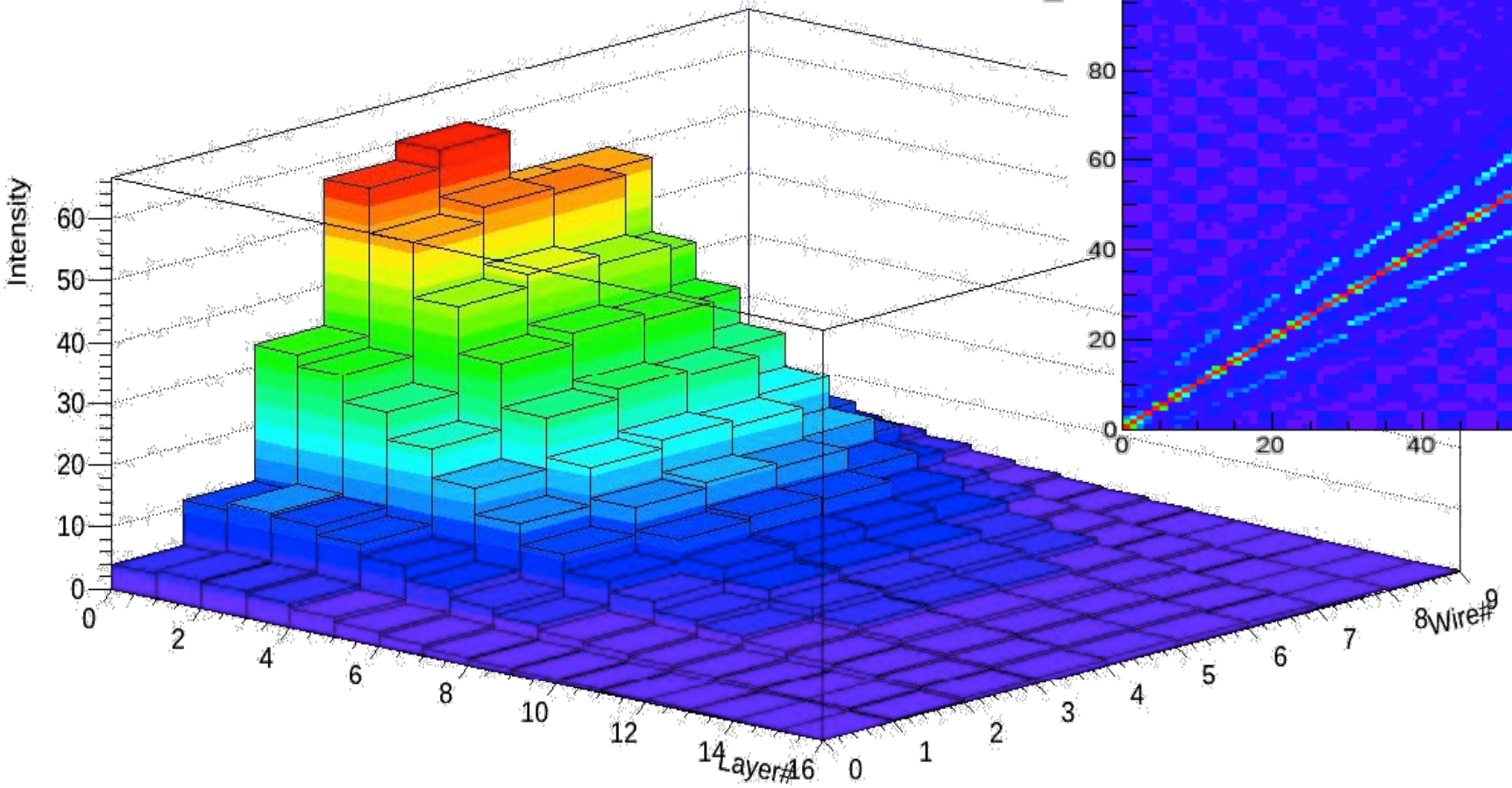
University of Manitoba

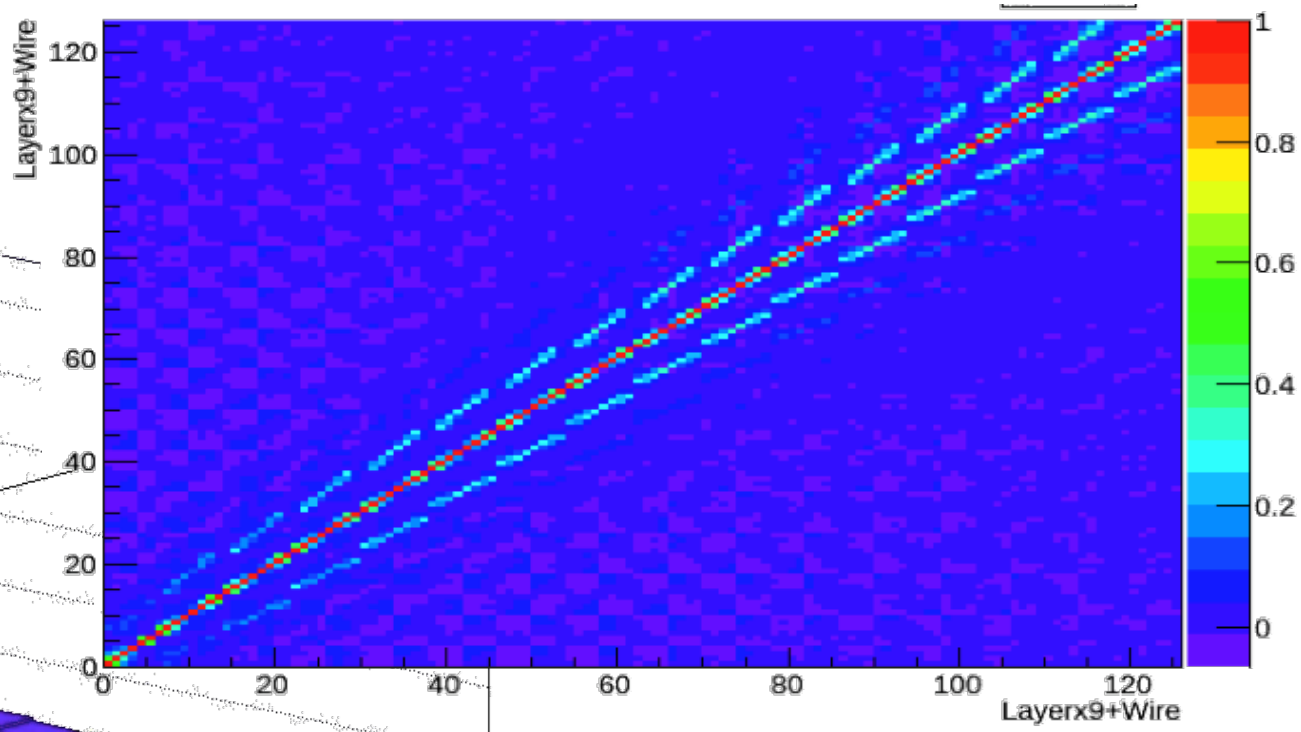
- Macor frames with 9 x 16 sense wires, 8 x 17 HV wires
- 12” x 0.9 mm CF aluminum windows
- All aluminum chamber except for knife edges

Ion chamber yield from neutron beam

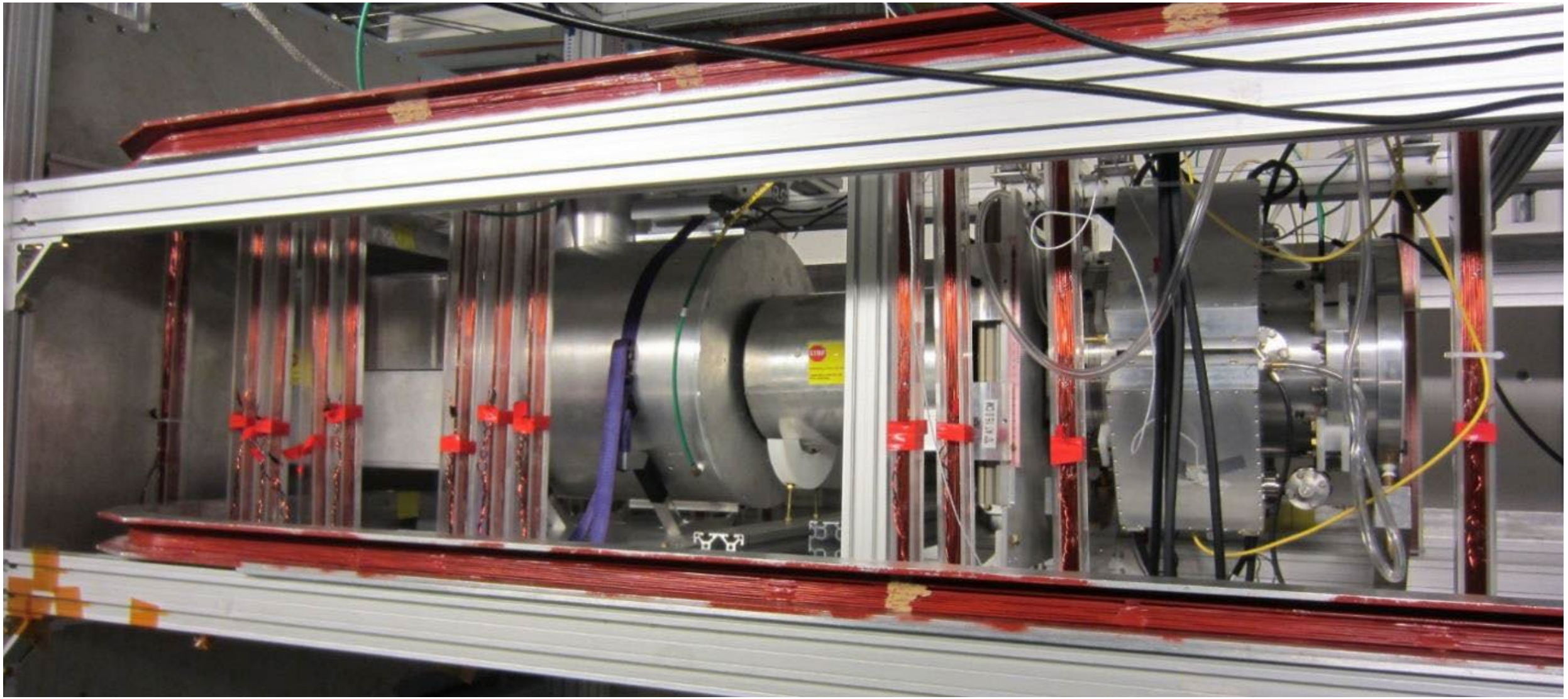
- Detector yield in individual wire cells

Correlation matrix





n-^{3}He in the FnPB

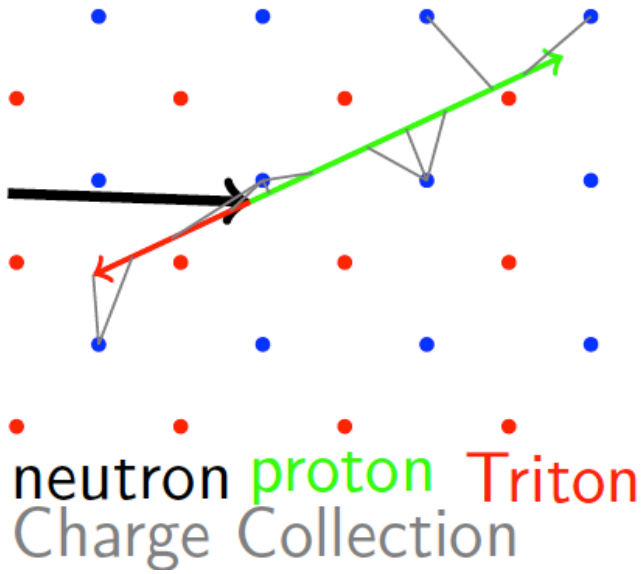


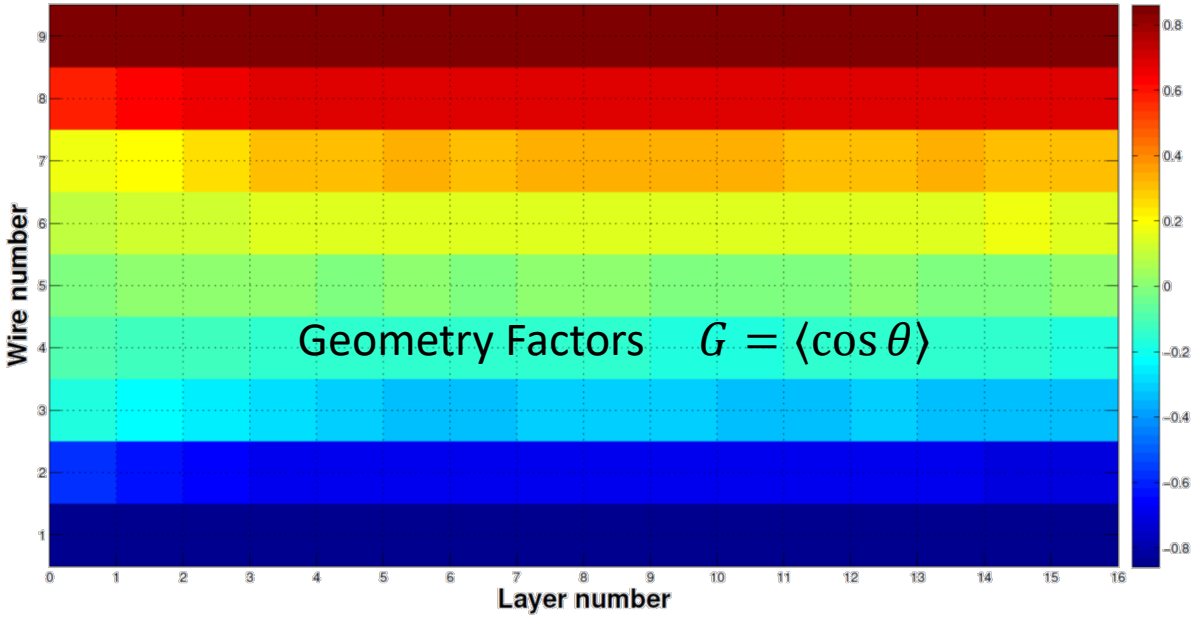
Asymmetry extraction

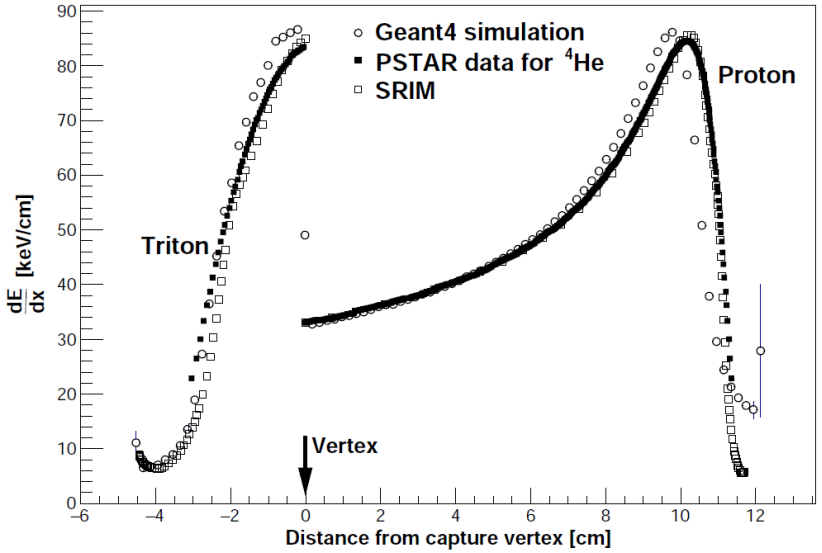
- PV physics asymmetry
  - Extracted from weighted average of single-wire spin asymmetries

$$Y_{\pm} = Y_0(1 \pm P A_p \langle \cos\theta \rangle)$$

$$A_p = \frac{1}{P\langle \cos\theta \rangle} \frac{Y_+ - Y_-}{Y_+ + Y_-}$$

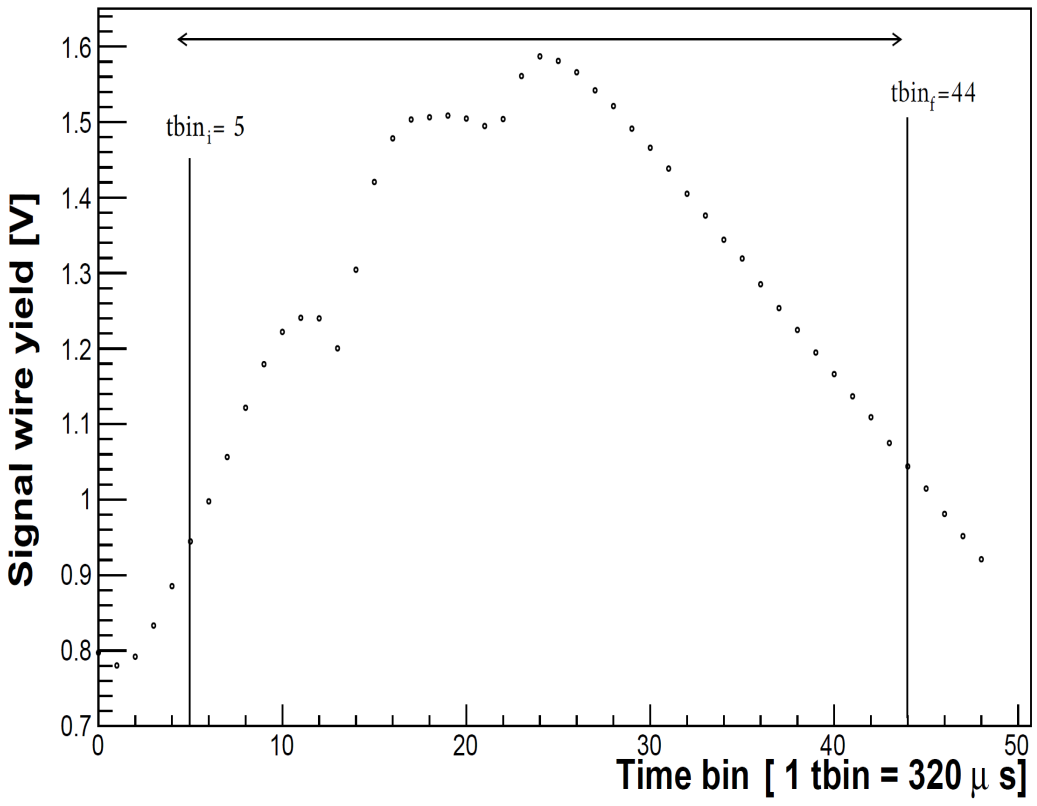


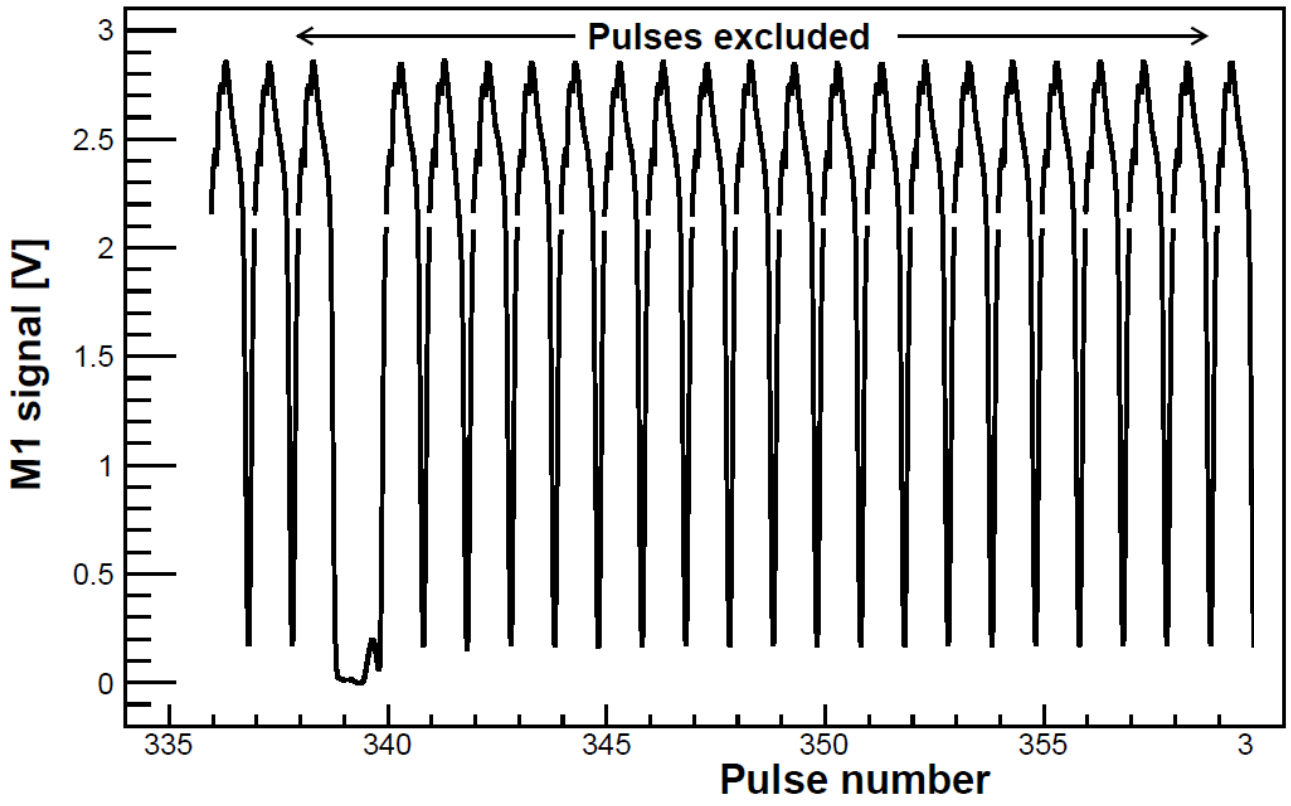




Data selection

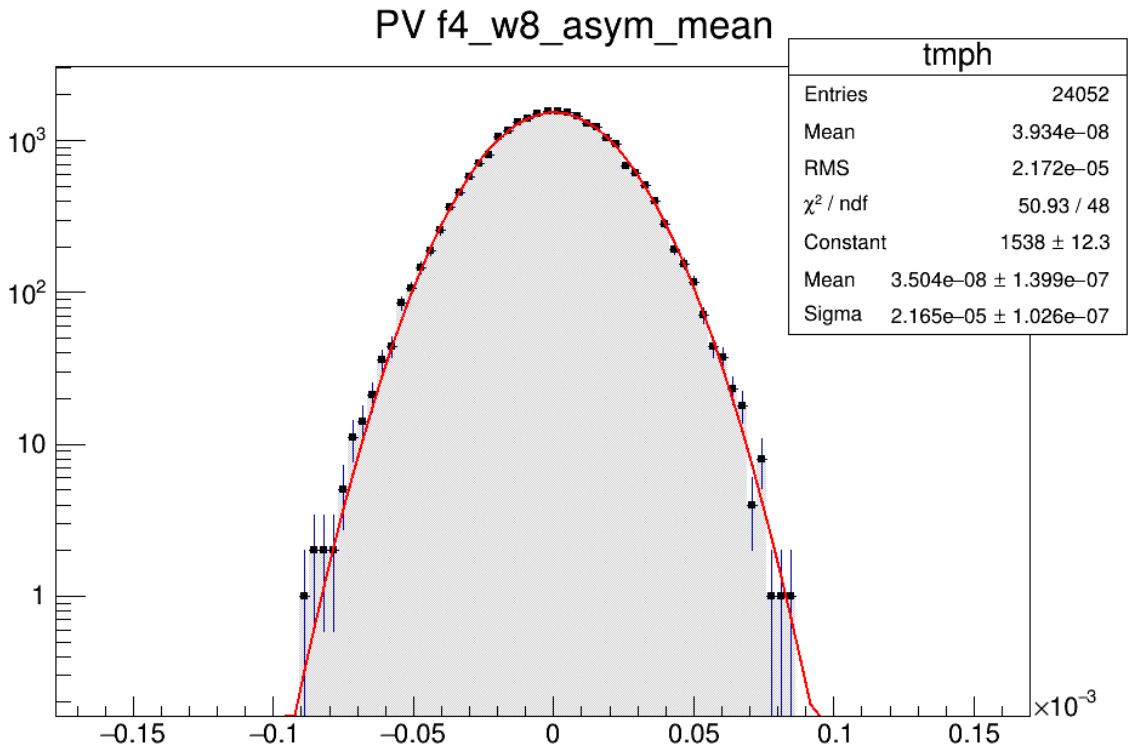
- cut on time-of-flight
  - chopper opening/closing, RFSF ramping)
- cut on dropped pulses
  - require complete 600 pulse sequence + previous

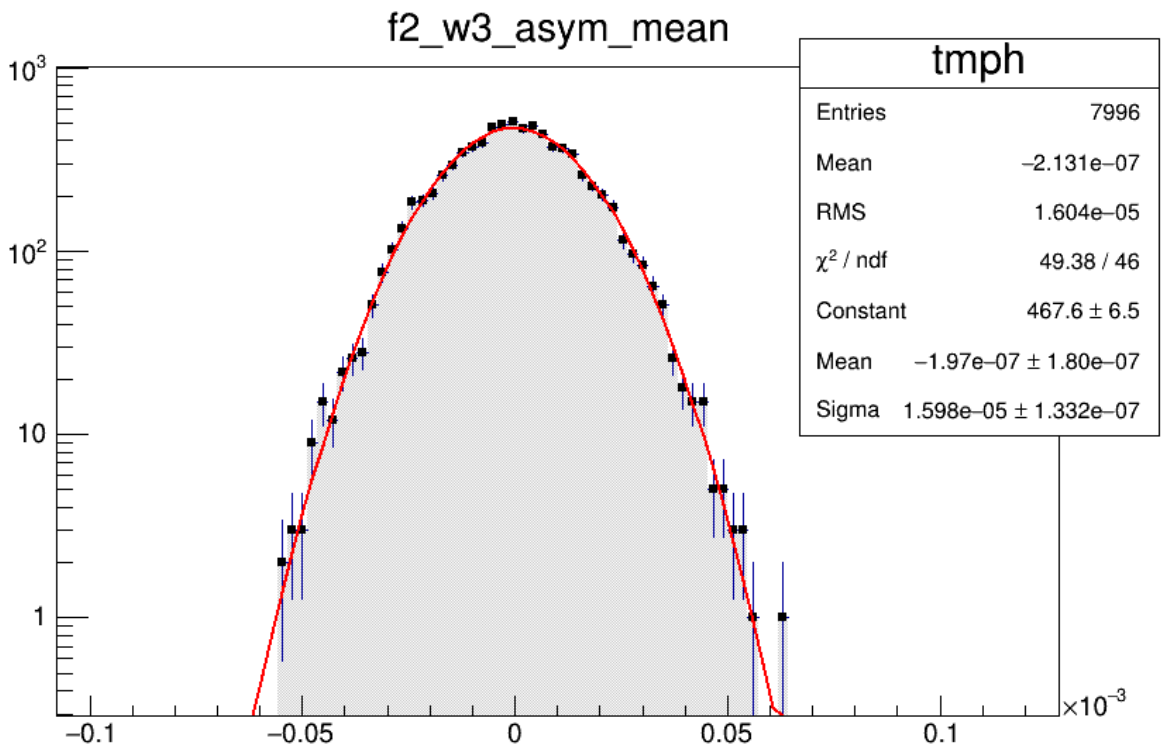




Individual raw wire asymmetries

Example 600-pulse sequence asymmetry distributions.



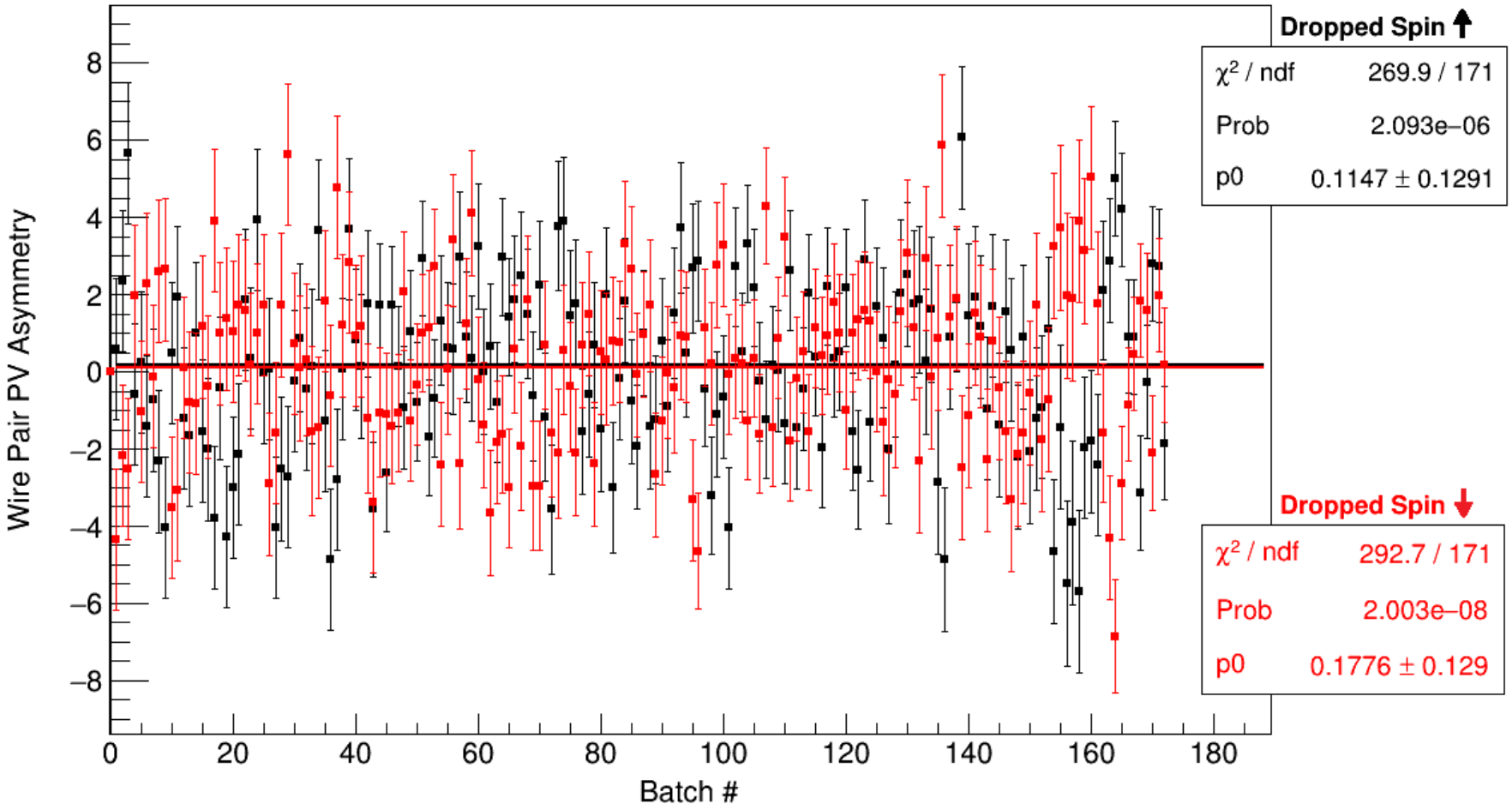


PV asymmetry 31854 runs (~8 minute long)
good pulses: 690937760
pulses cut: 78335992 (10%)

PC asymmetry 1110 runs
good pulses: 22529520
pulses cut: 4468923 (17%)

Final Results

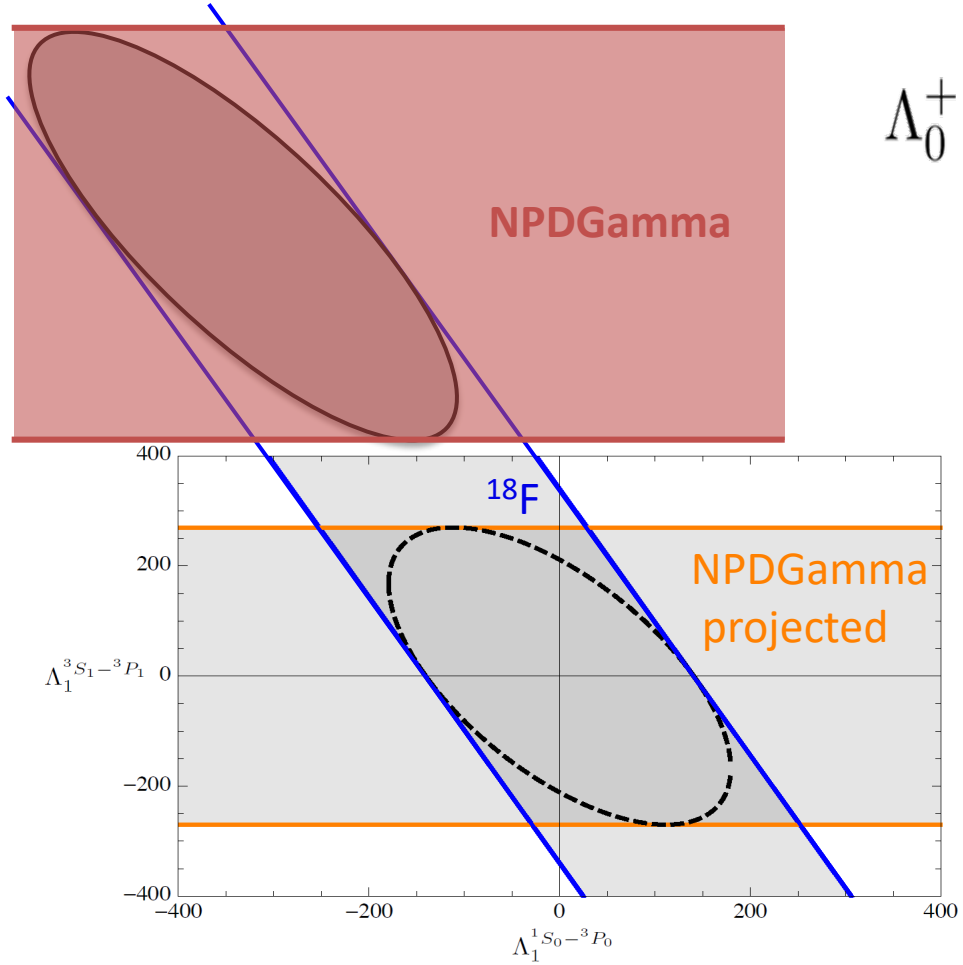
- $A_{PV} = \ 15.3 \pm 9.7\ (\mathrm{stat}) \pm 2.5\ (\mathrm{sys})\ \ \mathrm{ppb}$ (goal: 20 ppb)
- $A_{PC} = -437 \pm 59\ (\mathrm{stat}) \pm 4.3\ (\mathrm{sys})\ \ \mathrm{ppb}$



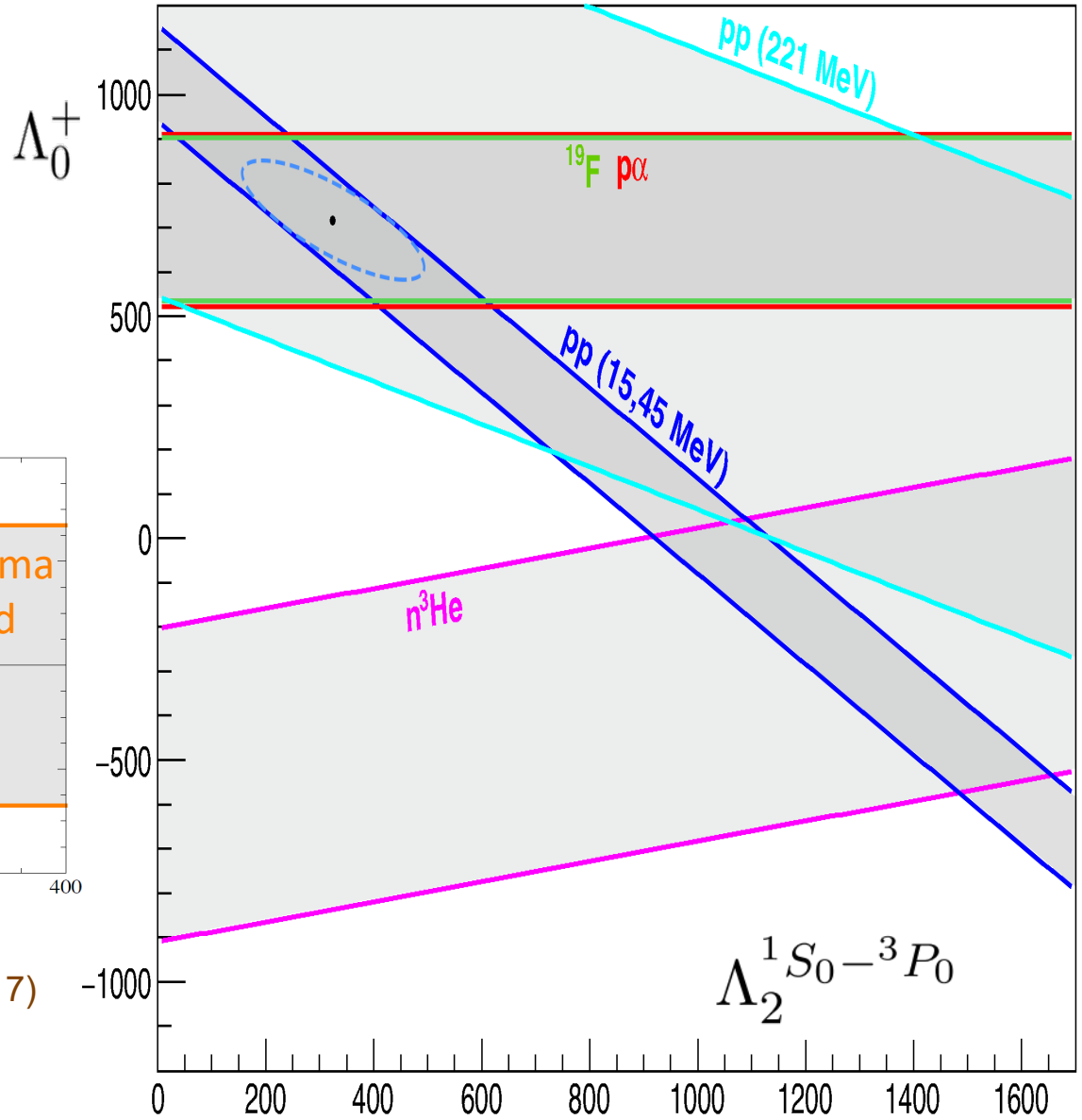
Systematic Effects

	Source	Comment	PV Correction/uncert.	PC Correction/uncert.
Corrections	Frame twist correction 0 to 20 mrad front to back of chamber	**Additive correction** due to measured twist in the frames. Implemented in the simulation geometry used to determine the geometry factors.	$\sim 2 \times 10^{-9}$	$\sim 5 \times 10^{-9}$
	Residual 3He polarization	**Additive correction** estimate from thermal polarization and 3He removal	$< 6 \times 10^{-11}$	0
	beta/gamma background from capture	**Additive correction,** simulated signal fraction $< 0.5\%$ Small dE/dx (~ 100 times smaller) Ionization prob. 10^{-4} relative to capture	$<< 10^{-10}$	same
	In flight beta decay	**Additive correction** (using NPDGamma estimate)	$<< 10^{-10}$	same
	Stern-Gerlach steering	**Additive correction** (2 mG/cm field grad., small chamber volume)	$< 10^{-10}$	same
	Mott-Schwinger	**Additive correction** for left-right E&M and Strong elastic scattering (published calculation)	$\sim 6 \times 10^{-11}$	$\sim 3 \times 10^{-9}$
	Electronic false asymmetry	**Additive correction,** measured from beam-off runs every week	0	same
	Polarization	**Multiplicative correction** from measured beam polarization.	0.936 ± 0.002	same
	Spin-flip efficiency	**Multiplicative correction** from measured spin flip efficiency	0.998 ± 0.001	same
	Total Corrections (white fields only)		$\sim 2.1 \times 10^{-9}$	$\sim 8 \times 10^{-9}$
Systematic Uncertainties	Chamber-field alignment	3 mrad field to chamber vertical axis misalignment pitch, roll, yaw	$\pm 0.04 \times 10^{-9}$	1.25×10^{-9}
	Geometry Factor	Pressure and position uncertainty	1.5×10^{-9}	3×10^{-9}
	Electronic false asymmetry	Measured from beam-off runs every week	$\pm 1.0 \times 10^{-9}$	same
	Total systematic uncertainty (white fields only)		$\sim 2.54 \times 10^{-9}$	$\sim 4.25 \times 10^{-9}$

Extraction of couplings



Gardner, Haxton, Holstein, ARNPS **67**, 69 (2017)



Global Fit to 10 Parity Violating Observables [10^{-7}]

$$f_\pi = 2.9 \pm 1.6$$
$$f_\rho^0 = -14.1 \pm 11.7$$
$$f_\rho^1 = 5.3 \pm 9.1$$
$$f_\rho^2 = -21.5 \pm 27.9$$
$$f_\omega^0 = 0.6 \pm 10.3$$

$\chi 2$/DOF= 7.3471/5

(David Bowman)

DDH reasonable range:

	min	'best'	max
f_π	0.	4.6	11.4
f_ρ^0	-30.8	-11.4	11.4
f_ρ^1	-0.38	-0.19	0
f_ρ^2	-11.	-9.5	7.6
f_ω^0	-10.3	-1.9	5.7
f_ω^1	-1.9	-1.1	-0.8

Conclusion

Hadronic Parity Violation

- We are close to a full complement of few-body HPV observables:

  old: **pp** (15, 45, 220 MeV) , **pα**

  new: **NPDGamma**, **n^{3}He**

  upcoming: **^{4}He NSR-III** (NIST-NGC)

  future possible measurements with low energy neutrons:
  NPDGamma circular polarization
  NDTGamma (counting mode)

- Tested newly proposed hierarchy in large N_c limit
- An obtainable goal is to extract HWI couplings, AND to test the self-consistency of the HWI formalisms using only few-body observables

Thank you!

n-3He Collaboration

U.S. DEPARTMENT OF ENERGY

National Science Foundation

NSERC CRSNG

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- Paul Mueller
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- Jack Thomison

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- Latiful Kabir
- Aaron Sprow

Western Kentucky University
- Ivan Novikov

University of Manitoba
- Michael Gericke
- Mark McCrea
- Carlos Olguin

Universidad Nacional Autónoma de México
- Libertad Baron
- Jose Favela

University of New Hampshire
- John Calarco

University of South Carolina
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- Matthias Schindler
- Young-Ho Song

University of Tennessee
- Nadia Fomin
- Geoff Greene
- Serpil Kucuker
- Chris Hayes
- Chris Coppola
- Irakli Garishvili
- Eric Plemons

University of Tennessee at Chattanooga
- Josh Hamblen
- Caleb Wickersham

University of Virginia
- S. Baessler

Sensitivities of few-body reactions

Process	Observable	Expt($\times 10^{-7}$)	h^1_π	h^0_ρ	h^1_ρ	h^2_ρ	h^0_ω	h^1_ω
$\vec{n} + p \to d + \gamma$	$A_\gamma \equiv \vec{\sigma}_n \cdot \vec{k}_\gamma$	-1.2 ± 2.1	-0.11		-0.001			+0.004
$\vec{n} + d \to t + \gamma$	$A_\gamma \equiv \vec{\sigma}_n \cdot \vec{k}_\gamma$	42 ± 38	0.69	-0.33	0.99	0.05	-0.22	-0.05
$\vec{n} + {}^3He \to p + T$	$A_p \equiv \vec{\sigma}_n \cdot \vec{k}_p$	–	-0.185	-0.038	0.023	-0.0011	-0.023	0.050
$\vec{n} + {}^4He \to n + {}^4He$	ϕ_{PV}	1.7 ± 9.2	-0.97	-0.32	0.11		-0.22	0.22
$\vec{p} + p \to p + p$ (13.6 MeV)	$A_L \equiv \vec{\sigma}_p \cdot \vec{k}_p$	-0.93 ± 0.21		0.042	0.042	0.017	0.046	0.046
$\vec{p} + p \to p + p$ (45 MeV)	$A_L \equiv \vec{\sigma}_p \cdot \vec{k}_p$	-1.57 ± 0.23		0.074	0.074	0.032	0.067	0.067
$\vec{p} + p \to p + p$ (221 MeV)	$A_L \equiv \vec{\sigma}_p \cdot \vec{k}_p$	0.84 ± 0.34		-0.03	-0.03	-0.012		
$\vec{p} + {}^4He \to p + {}^4He$	A_L	-3.34 ± 0.93	-0.34	0.14	0.047		0.059	0.059
${}^{18}F$ decay	P_γ	1200 ± 3680	4385		-492			-833
${}^{19}F$ decay	A_γ	-740 ± 190	-94.2	34.1	-10.2		19.4	-16.9

Adelberger, Haxton,
A.R.N.P.S. **35,** 501 (1985)

Viviani (PISA), [n-^{3}He]
P.R.C. 82, 044001 (2010)

n-^{3}He EFT calculation

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

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

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

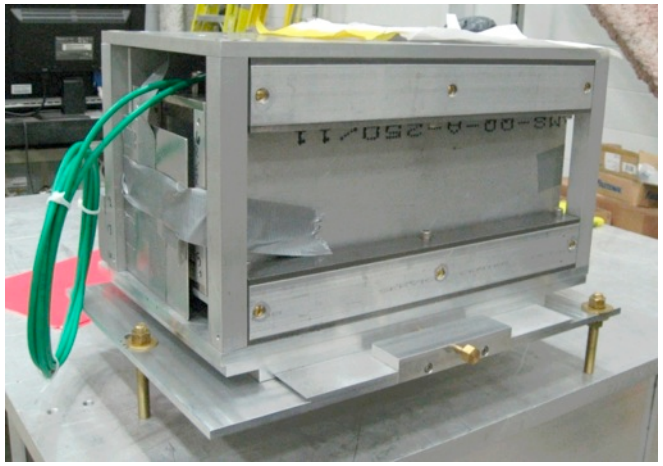
$$A_{PV}(th.) \approx 3.5 \times 10^{-8} \quad (\Lambda = 600 \text{ MeV})$$

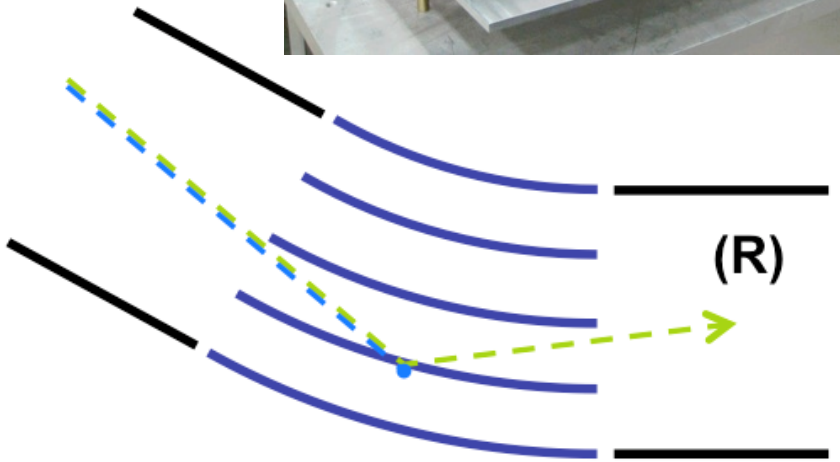
EFT coefficients	Λ = 500 MeV	Λ = 600 MeV
a_0	-0.1444	-0.1293
a_1	0.0061	0.0081
a_2	0.0226	0.0320
a_3	-0.0199	-0.0161
a_4	-0.0174	-0.0156
a_5	-0.0005	-0.0001

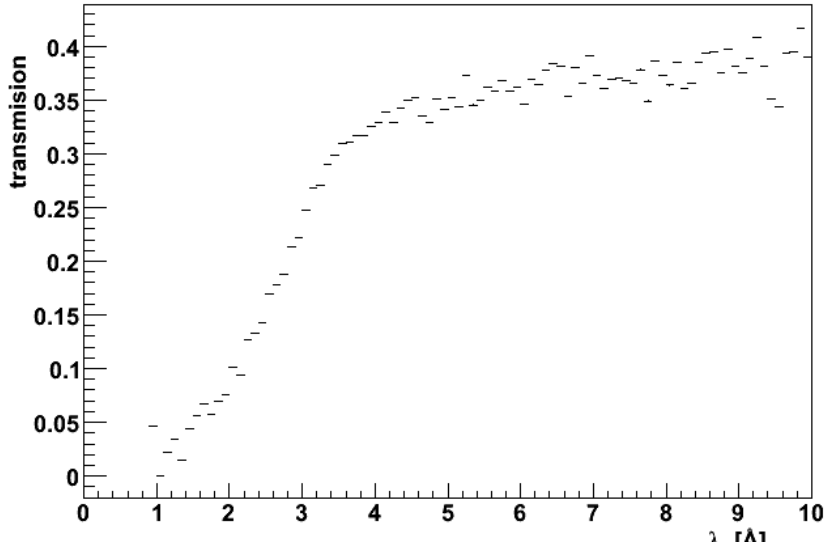
M. Viviani, et al. Phys. Rev. C **89**, 064004 (2014)

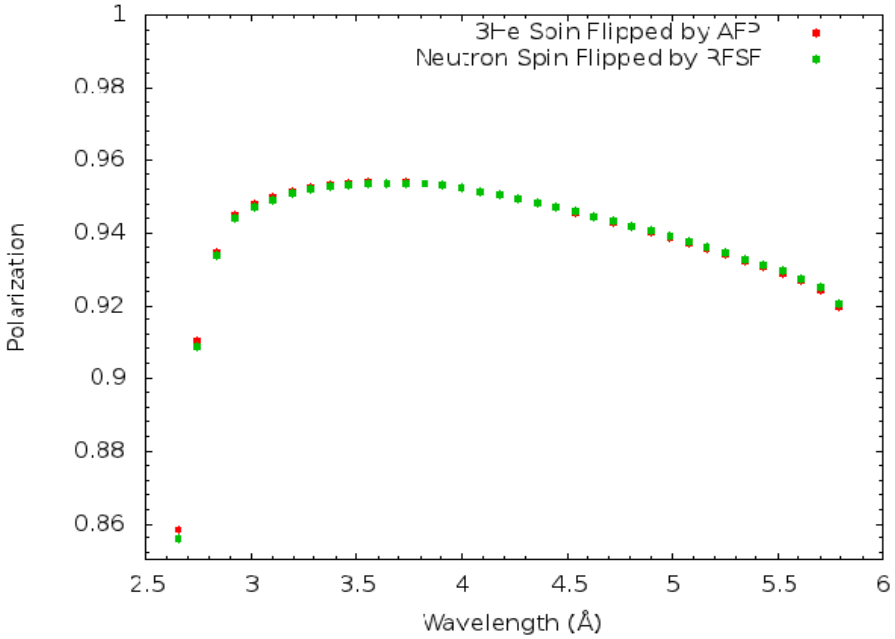
FnPB supermirror polarizer

T=25.8% transmission
P=95.3% polarization
N=2.2£10^{10} n/s output flux (chopped)







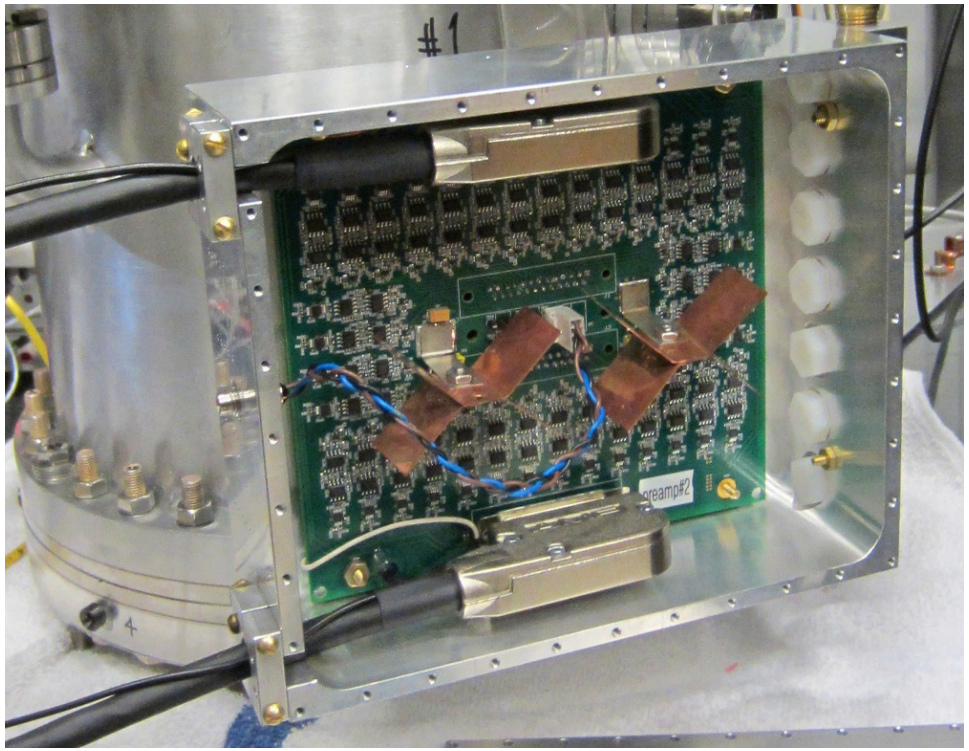


S. Balascuta

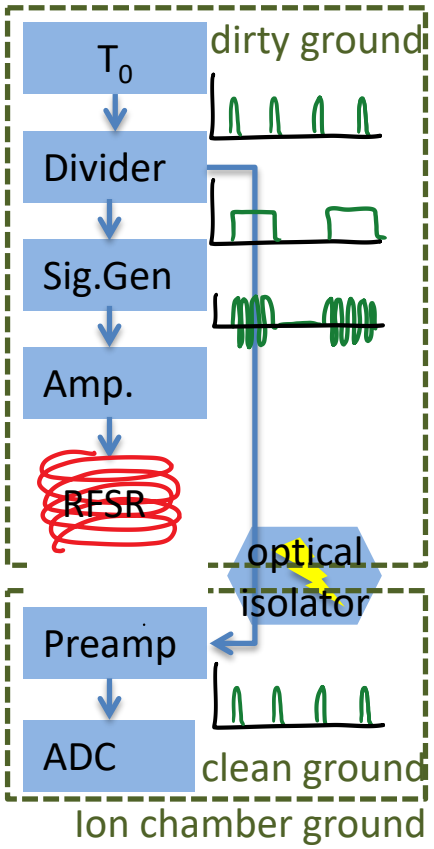
Readout electronics

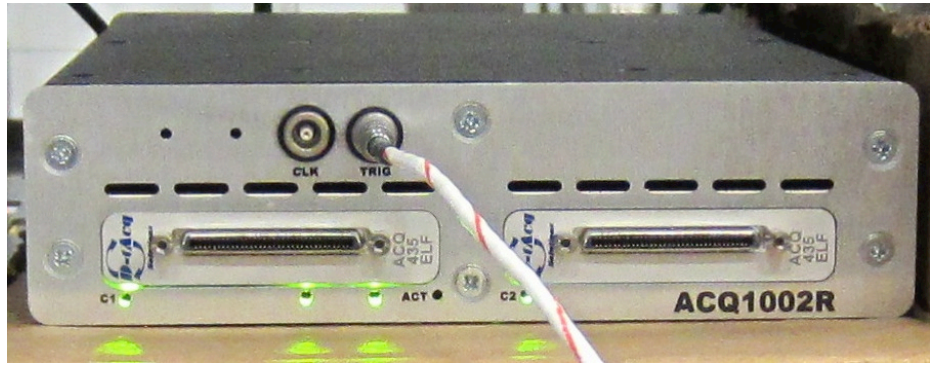
- Ionization read out in current mode
  - 144 channels read out simultaneously
  - Low-noise I-V preamplifiers mounted on chamber
  - 24-bit, 100 kS/s, 48 channel Δ-Σ ADC FMC modules

Oak Ridge National Lab, Univ. Kentucky, Univ. Tennessee



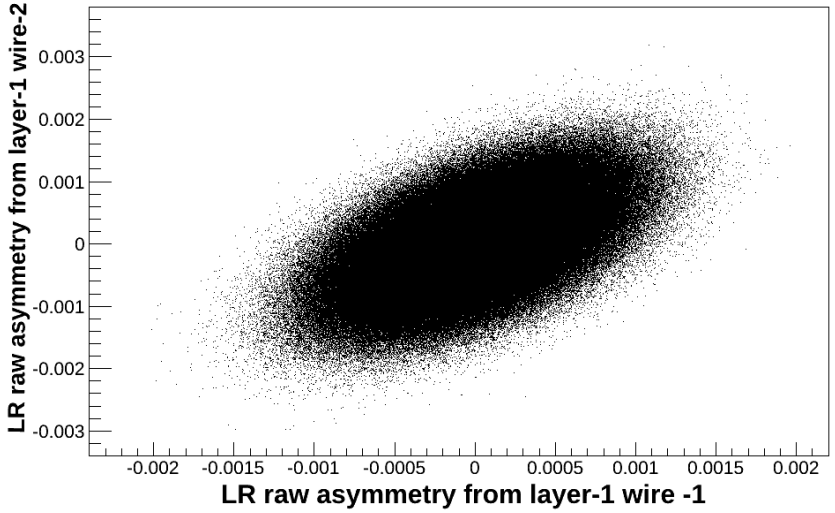
Electronic Tests:
Instrumental
false asymmetry
measurements:
$\delta A_{in} < 10^{-9}$

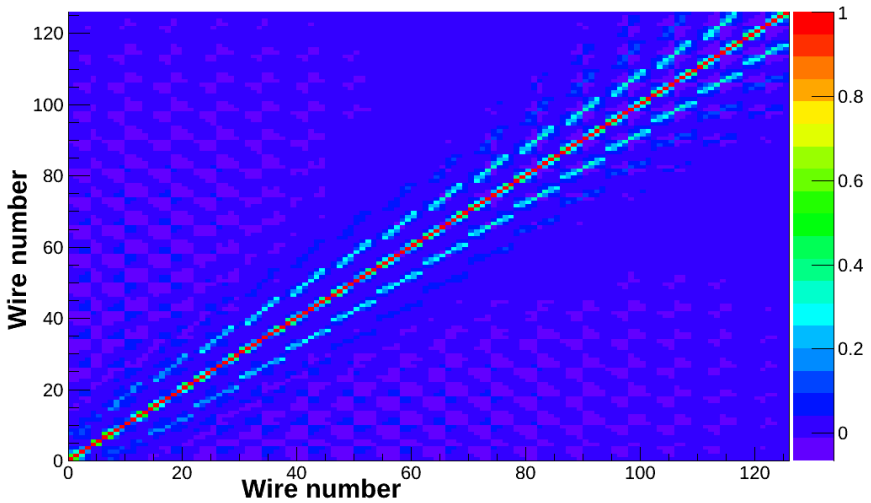




Covariance weighted averages

- Individual wire asymmetries are not independent
  - each proton/tritons ionizes gas in multiple cells in wire chamber

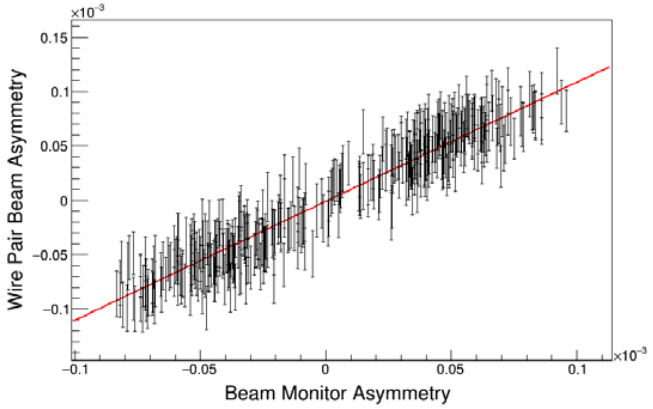


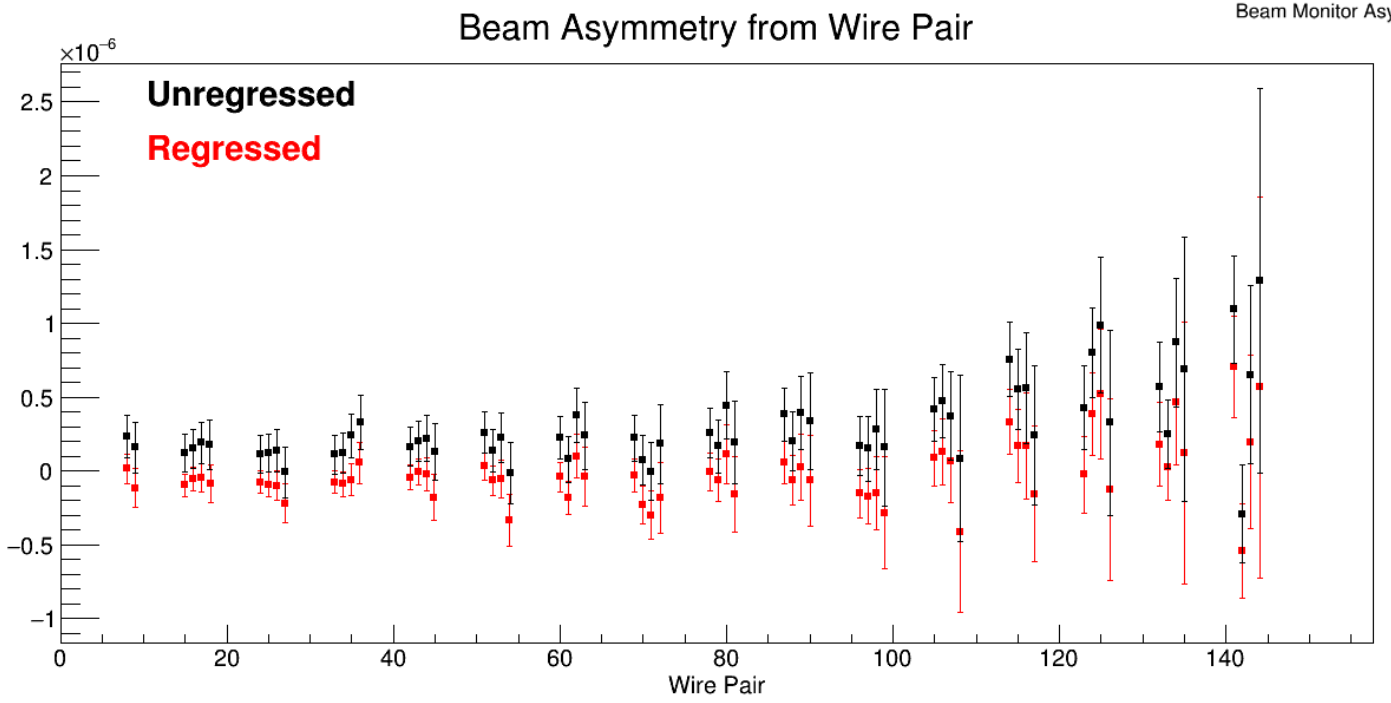


- Two identical methods of properly weighting for covariance
  - direct calculation: $w_i = Var\left(A_i^p\right)^{-1} \rightarrow \sum_j Cov\left(A_i^p, A_j^p\right)^{-1}$
  - diagonalization: $S^T \cdot Cov\left(A_i^p, A_j^p\right) \cdot S = diag(\sigma_i)$
    - asymmetry modes are statistically independent

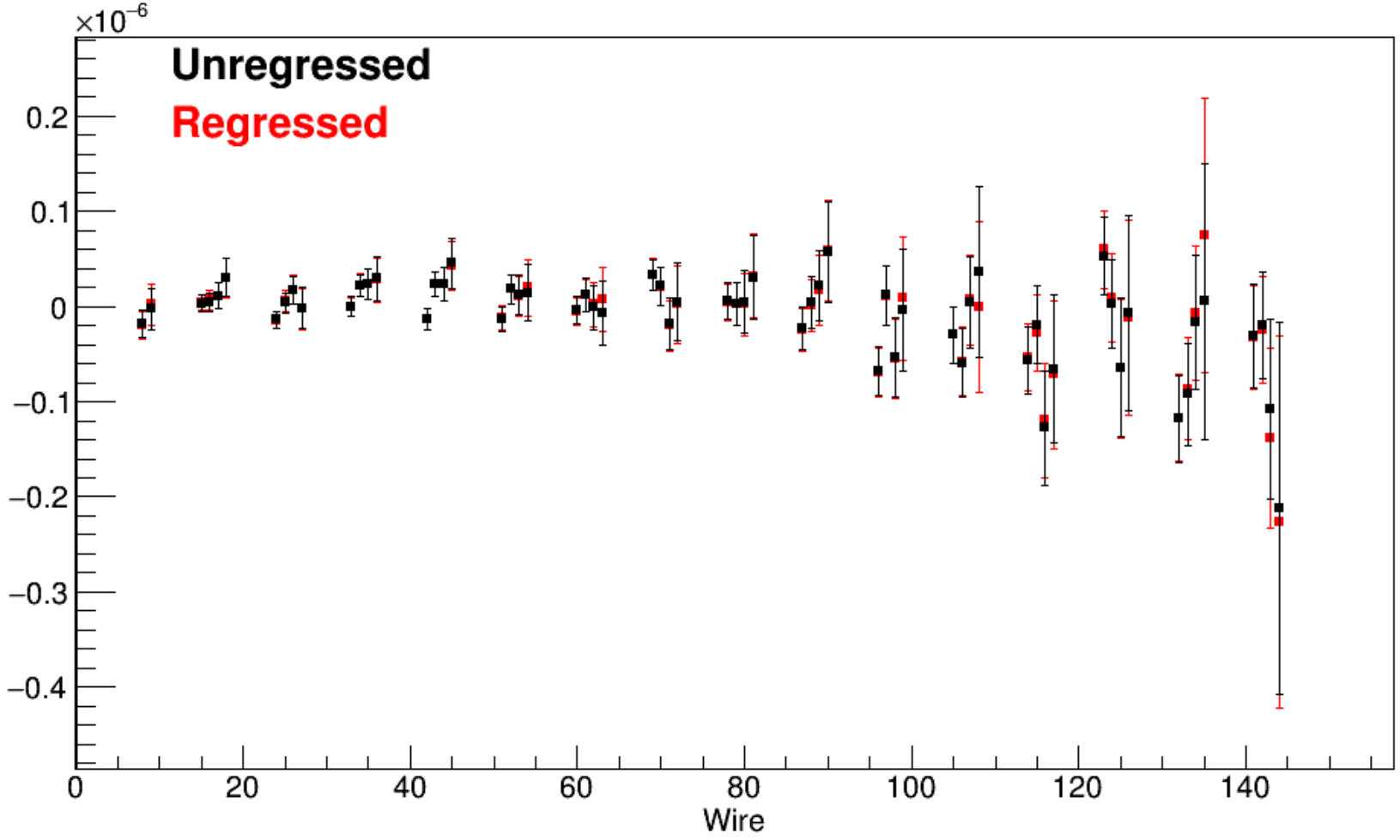
Regression for Beam Asymmetry

- correlation between detector pair beam monitor asymmetries
- tested by beam asymmetry measured in individual wires





Corrected PV Wire Pair Asymmetries



Corrected PV Wire Pair Asymmetries