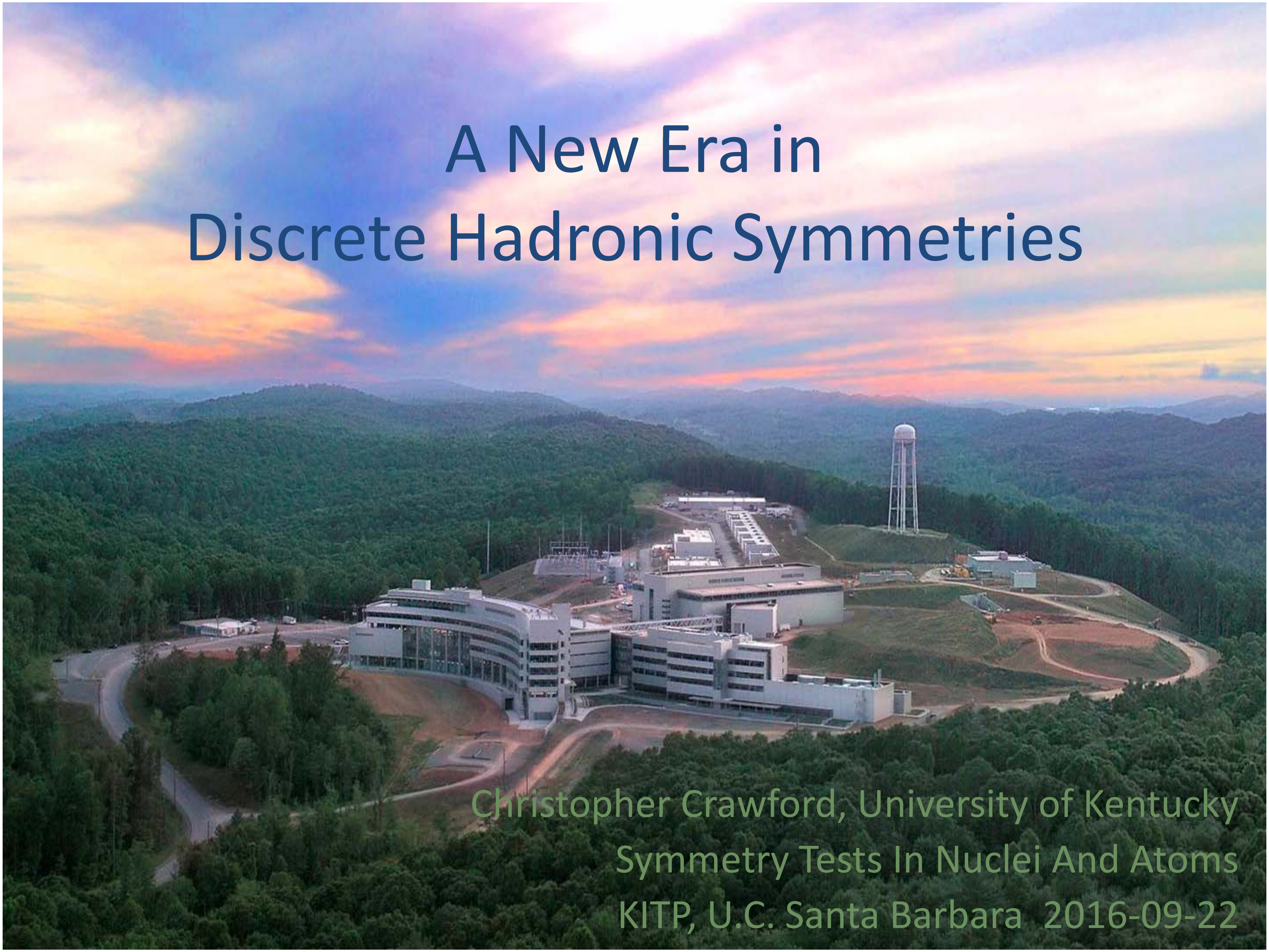
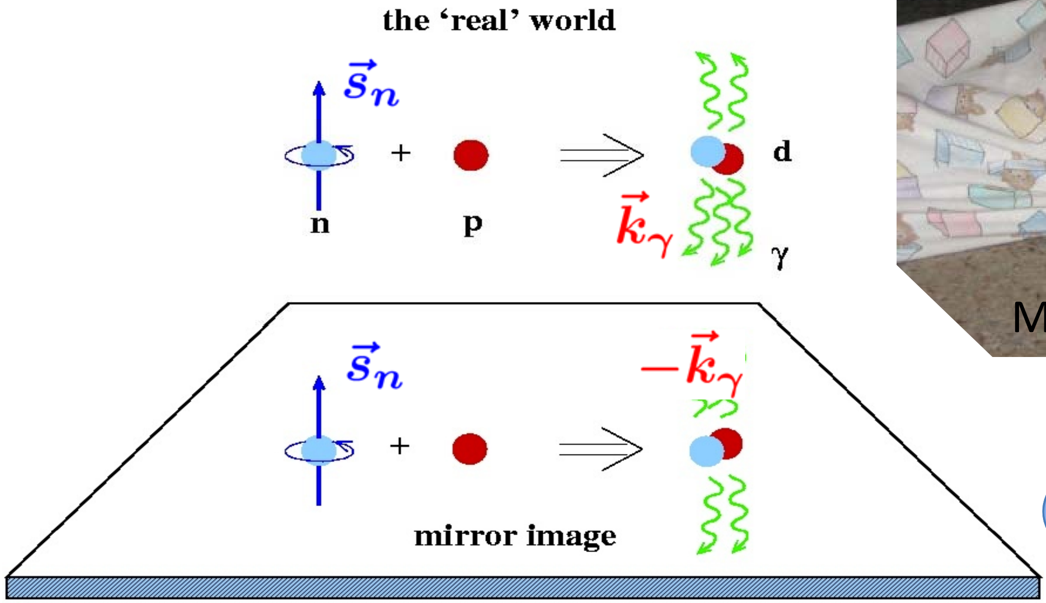


A New Era in Discrete Hadronic Symmetries

Christopher Crawford, University of Kentucky
Symmetry Tests In Nuclei And Atoms
KITP, U.C. Santa Barbara 2016-09-22

Outline

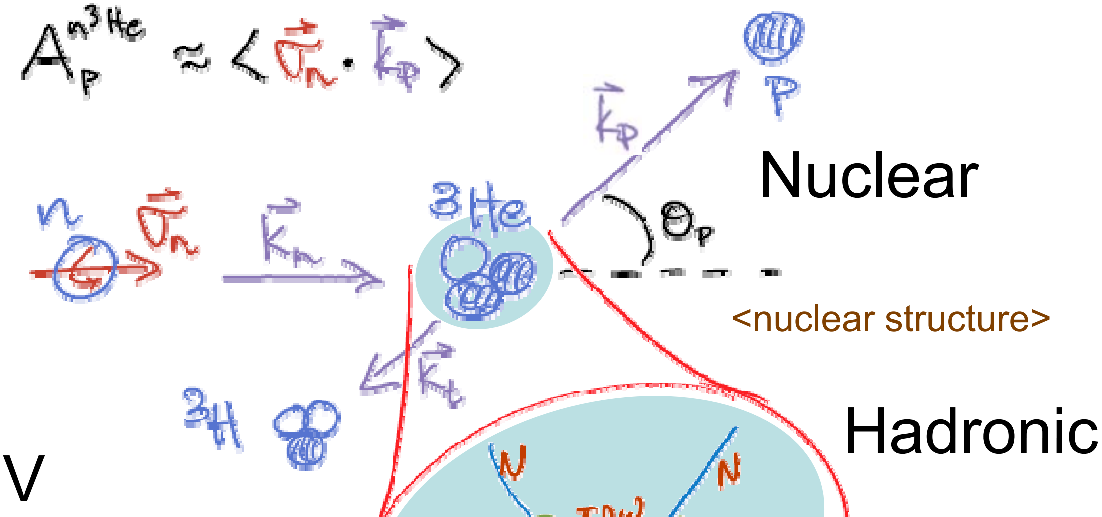
- Hadronic Parity Violation
  - Hadronic Weak Interaction (HWI) formalism
- NPDGamma Experiment
- n-^{3}He Experiment
- Future directions
  - Beyond HWI …



$$A_\gamma \approx \vec{s}_n \cdot \vec{k}_\gamma$$

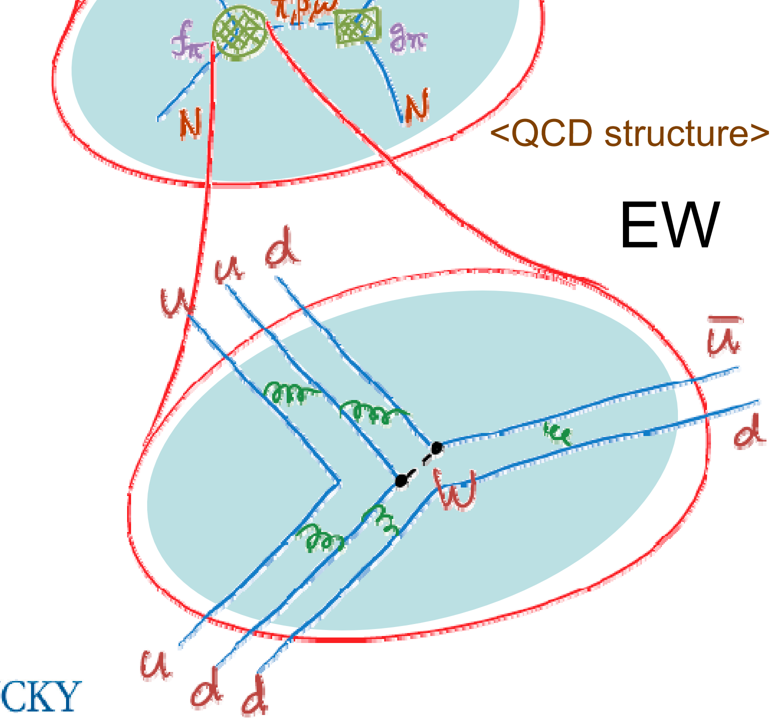
Is a parity odd pseudoscalar!

Hadronic Weak Interaction in a nutshell



Nuclear

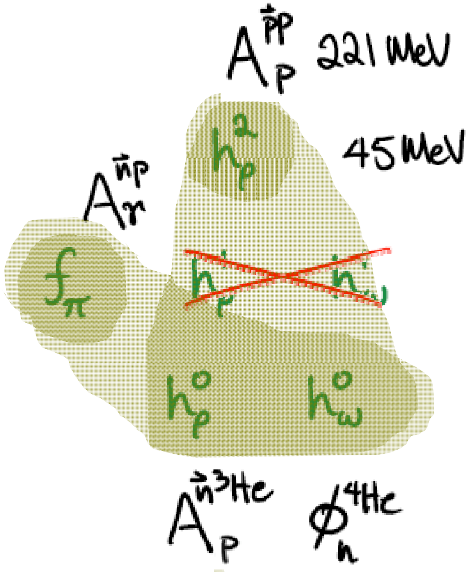
<nuclear structure>



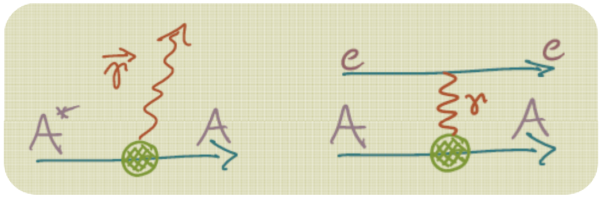
Hadronic

<QCD structure>

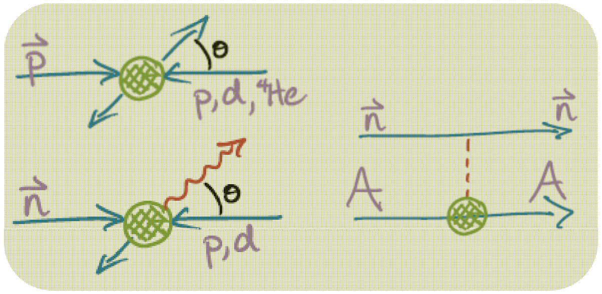
EW



Nuclear PV



Few-body PV



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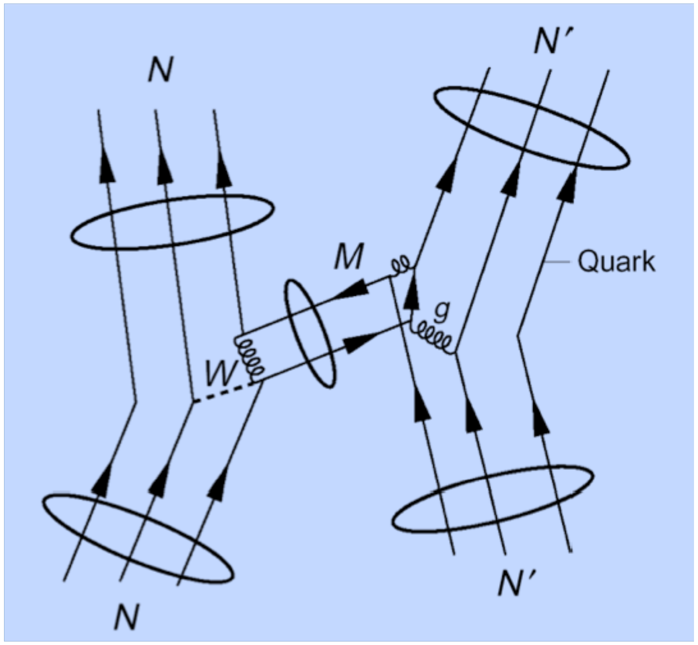
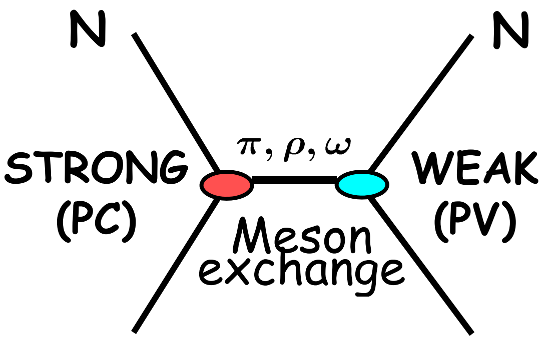
Motivation the studying the HWI

- 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 ΔS = 0 sector (ΔI=1/2 rule not understood)
  - Study the NC in hadronic systems – forbidden by ΔS = 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
  - 0νββ decay – matrix elements of 4-quark operators
  - Same formalism used for Hadronic TRIV (complementary to EDM)

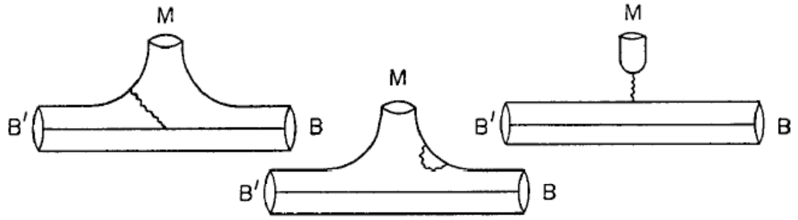


DDH Meson-exchange potential

PV meson exchange



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

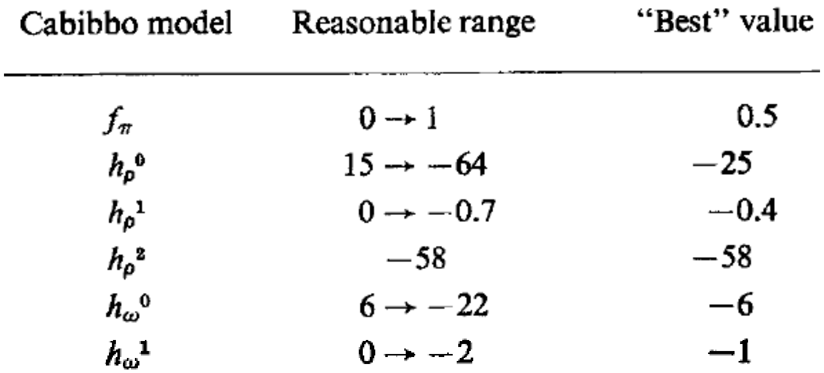


Desplanques, Donoghue, Holstein,
Annals of Physics **124**, 449 (1980)

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

1st Lattice QCD result of f_π !!

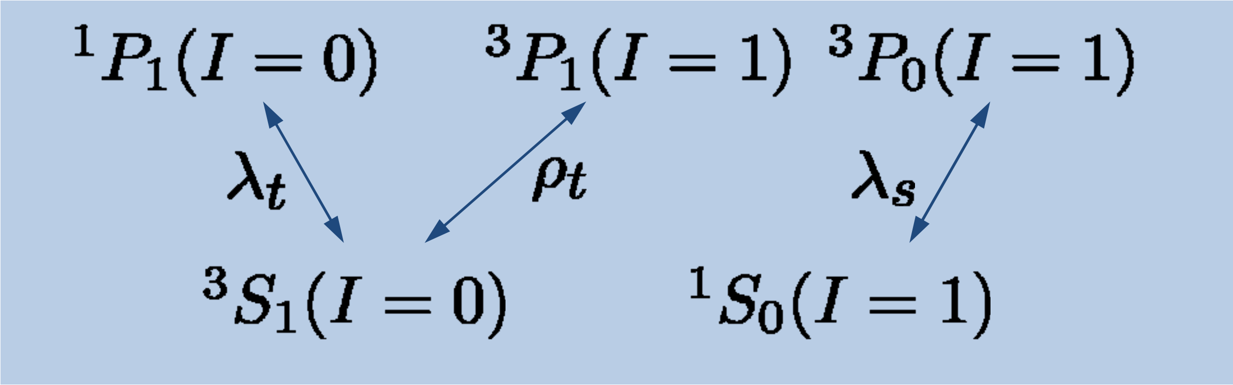
isospin	f_π	$h_\rho^{\prime 1}$	$h_\rho^{0,1,2}$	$h_\omega^{0,1}$
$\Delta I = 0$			$(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$	(1)
$\Delta I = 1$	$\frac{i}{2}(\boldsymbol{\tau}_1 \times \boldsymbol{\tau}_2)^3$		$\frac{1}{2}(\boldsymbol{\tau}_1 \pm \boldsymbol{\tau}_2)^3$	$\frac{1}{2}(\boldsymbol{\tau}_1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



Cabibbo model	Reasonable range	"Best" value
f_π	0 → 1	0.5
h_ρ^0	15 → −64	−25
h_ρ^1	0 → −0.7	−0.4
h_ρ^2	−58	−58
h_ω^0	6 → −22	−6
h_ω^1	0 → −2	−1

Danilov parameters / EFT

- Elastic NN scattering
  at low energy (<40 MeV)
  S-P transition (PV)
  $S_z = \pm 1/2 \quad I_3 = \pm 1/2$
  Antisymmetric in L, S, I
  Conservation of J
- Equivalent to pion-less
  Effective Field Theory (EFT)
  in the low energy limit



$^1P_1(I=0)$ $\quad$ $^3P_1(I=1)$ $\quad$ $^3P_0(I=1)$

λ_t $\quad$ ρ_t $\quad$ λ_s

$^3S_1(I=0)$ $\quad$ $^1S_0(I=1)$

C.-P. Liu, P.R.C. **75**, 065501 (2007)
Haxton & Holstein, P.P.N.P. **7**, 1851 (2013)

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

Few-body HWI PV Observables

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

PV observables are LINEAR in weak couplings

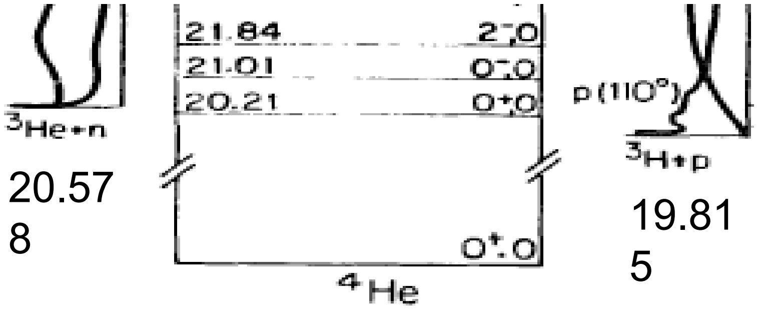
$|{}^3S, I=0\rangle$ $|{}^3P, I=1\rangle$ $|{}^1P, I=0\rangle$ $|{}^1S\ \ I=1\rangle$ $|{}^3P\ \ I=1\rangle$

$P_1\rangle$

$P_1\rangle$

$P_0\rangle$

$|{}^3S_1, I=0\rangle$ $|{}^3P_1, I=1\rangle$ $|{}^1P_1, I=0\rangle$



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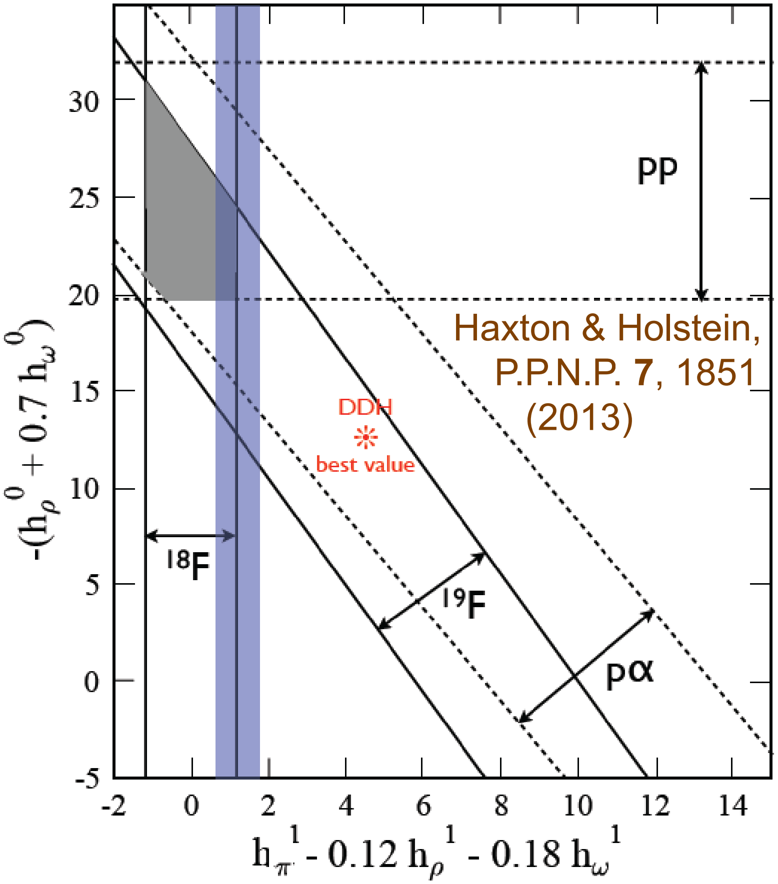
DDH Extraction

	np A_γ	nD A_γ	n^3He A_p	np ϕ	nα ϕ	pp A_z	pα A_z
f_π	-0.11	0.92	-0.18	-3.12	-0.97		-0.34
h_r^0		-0.50	-0.14	-0. 23	-0.32	0.08	0.14
h_r^1	-0.001	0.10	0.027		0.11	0.08	0.05
h_ρ^2		0.05	0.0012	-0.25		0.03	
h_ω^0		-0.16	-0.13	-0. 23	-0.22	-0.07	0.06
h_ω^1	-0.003	-0.002	0.05		0.22	0.07	0.06

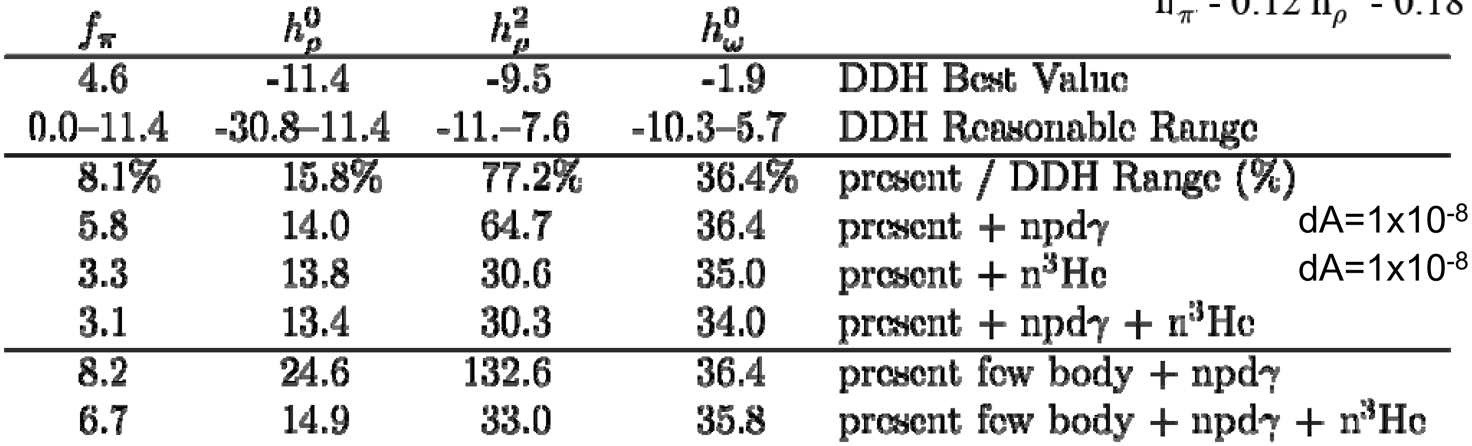
Adelberger, Haxton,
A.R.N.P.S. **35,** 501 (1985)

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



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

- How do NPDG, n-^{3}He contribute?



f_π	h_ρ^0	h_ρ^2	h_ω^0		
4.6	-11.4	-9.5	-1.9	DDH Best Value	
0.0–11.4	-30.8–11.4	-11.–7.6	-10.3–5.7	DDH Reasonable Range	
8.1%	15.8%	77.2%	36.4%	present / DDH Range (%)	
5.8	14.0	64.7	36.4	present + npdγ	dA=1x10^{-8}
3.3	13.8	30.6	35.0	present + n^{3}He	dA=1x10^{-8}
3.1	13.4	30.3	34.0	present + npdγ + n^{3}He	
8.2	24.6	132.6	36.4	present few body + npdγ	
6.7	14.9	33.0	35.8	present few body + npdγ + n^{3}He	

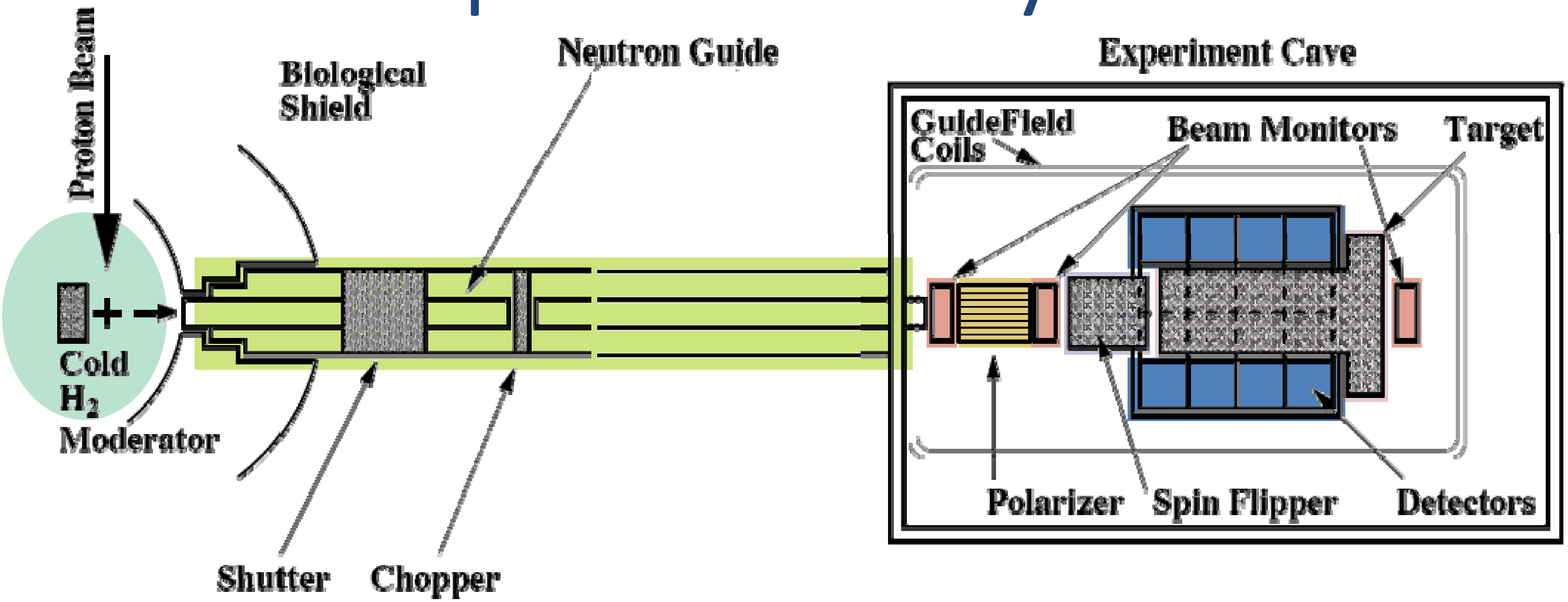
NPDGamma Collaboration

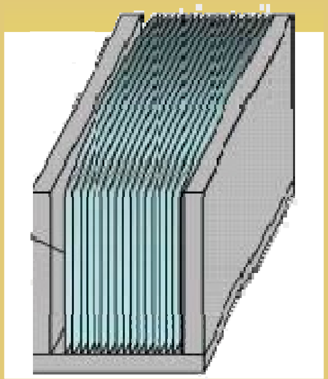
R. Alarcon[1], R. Allen[18], L.P. Alonzi[3], E. Askanazi[3], S. Baeßler[3], S. Balascuta[1], L. Barron-Palos[2], A. Barzilov[27], W. Berry[8], C. Blessinger[18], D. Blythe[1], D. Bowman[4], M. Bychkov[3], J. Calarco ,R. Carlini[5], W. Chen[6], T. Chupp[7], C. Crawford[8], M. Dabaghyan[9], A. Danagoulian[10], M. Dawkins[11], D. Evans[3], J. Favela[2], N. Fomin[12], W. Fox[11], E. Frlez[3], S. Freedman[13], J. Fry[11], C. Fu[11], C. Garcia[2], T. Gentile[6], M. Gericke[14] C. Gillis[11], K Grammer[12], G. Greene[4,12], J Hamblen[26], C. Hayes[12], F. Hersman[9], T. Ino[15], E. Iverson[4], G. Jones[16], K. Latiful[8], K. Kraycraft[8], S. Kucuker[12], B. Lauss[17], Y. Li[30], W. Lee[18], M. Leuschner[11], W. Losowski[11], R. Mahurin[12], M. Maldonado-Velazquez[2], E. Martin[8], Y. Masuda[15], M. McCrea[14], J. Mei[11], G. Mitchell[19], S. Muto[15], H. Nann[11], I. Novikov[25], S. Page[14], D. Parsons[26], S. Penttila[4], D. Pocinic[3], D. Ramsay[14,20], A. Salas-Bacci[3], S. Santra[21], S. Schroeder[3], P.-N. Seo[22], E. Sharapov[23], M. Sharma[7], T. Smith[24], W. Snow[11], J. Stuart[26], Z. Tang[11], J. Thomison[18], T. Tong[18], J. Vanderwerp[11], S. Waldecker[26], W. Wilburn[10], W. Xu[30], V. Yuan[10], Y. Zhang[29]

[1]Arizona State University
[2]Universidad Nacional Autonoma de Mexico
[3]University of Virginia
[4]Oak Ridge National Laboratory
[5]Thomas Jefferson National Laboratory
[6]National Institute of Standards and Technology
[7]Univeristy of Michigan, Ann Arbor
[8]University of Kentucky
[9]University of New Hampshire
[10]Los Alamos National Laboratory
[11]Indiana University
[12]University of Tennessee, Knoxville
[13]University of California at Berkeley
[14]University of Manitoba, Canada
[15]High Energy Accelerator Research Organization (KEK), Japan
[16]Hamilton College
[17]Paul Scherer Institute, Switzerland
[18]Spallation Neutron Source, ORNL
[19]University of California at Davis
[20]TRIUMF, Canada
[21]Bhabha Atomic Research Center, India
[22]Duke University
[23]Joint Institute of Nuclear Research, Dubna, Russia
[24]University of Dayton
[25]Western Kentucky University
[26]University of Tennessee at Chattanooga
[27]Univeristy of Nevada at Los Vegas
[28]University of California, Davis
[29]Lanzhou University
[30]Shanghai Institute of Applied Physics

http://npdgamma.com

Experimental Layout




Supermirror Polarizer

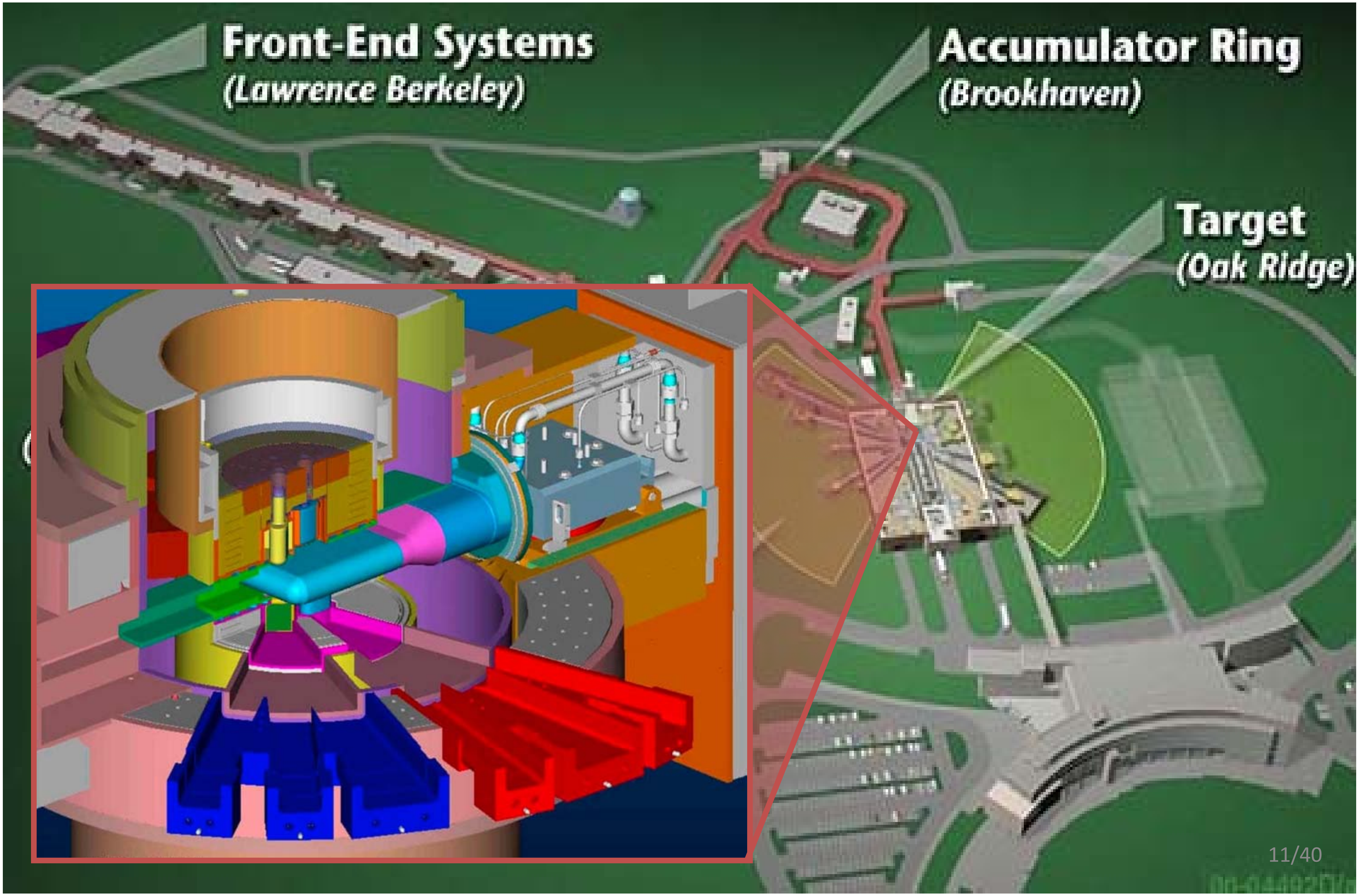

Beam Monitors


RF Spin Rotator

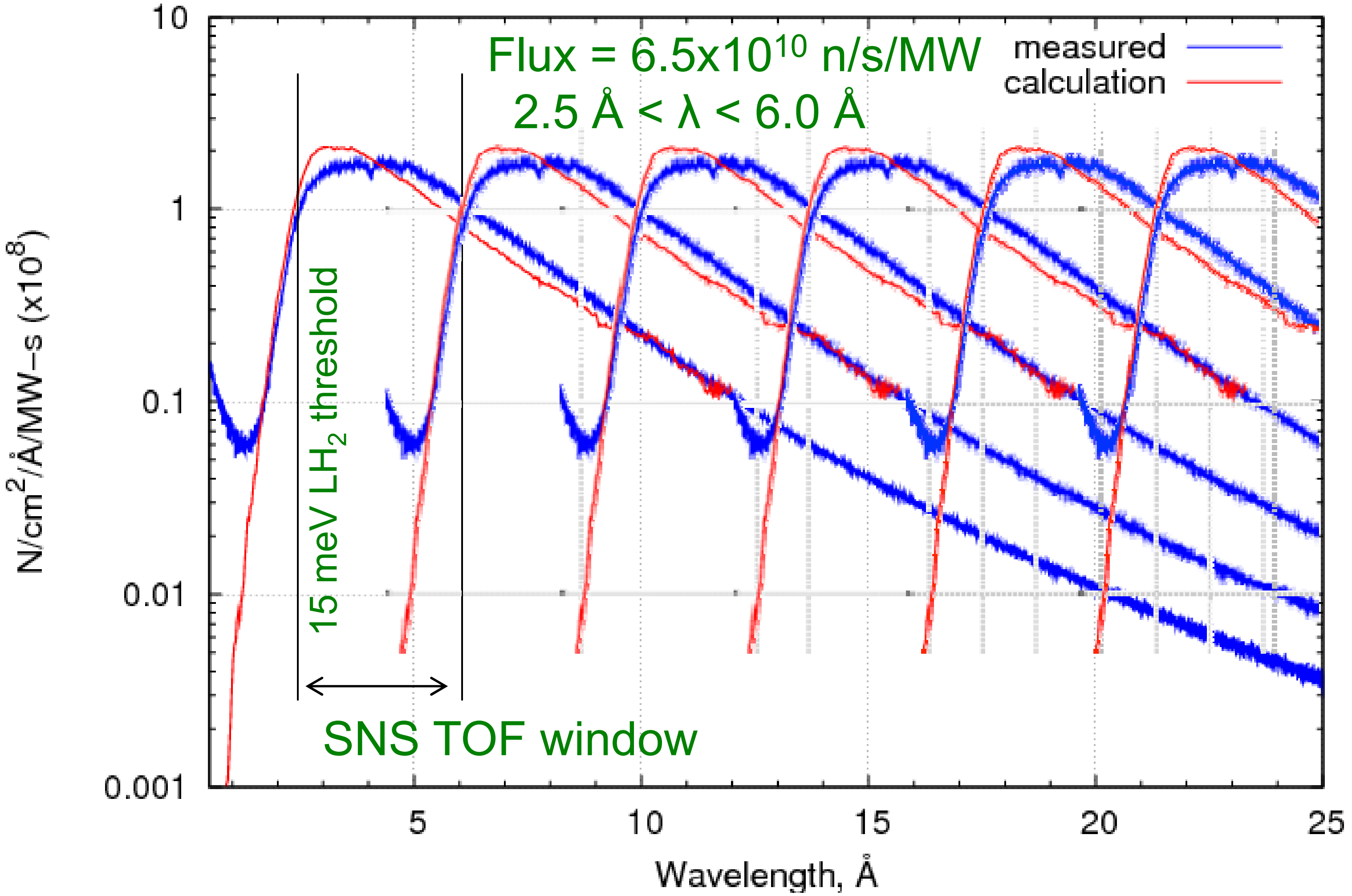

LH_2 Target


Gamma Detectors

Spallation neutron source



Neutron Flux at the SNS FnPB



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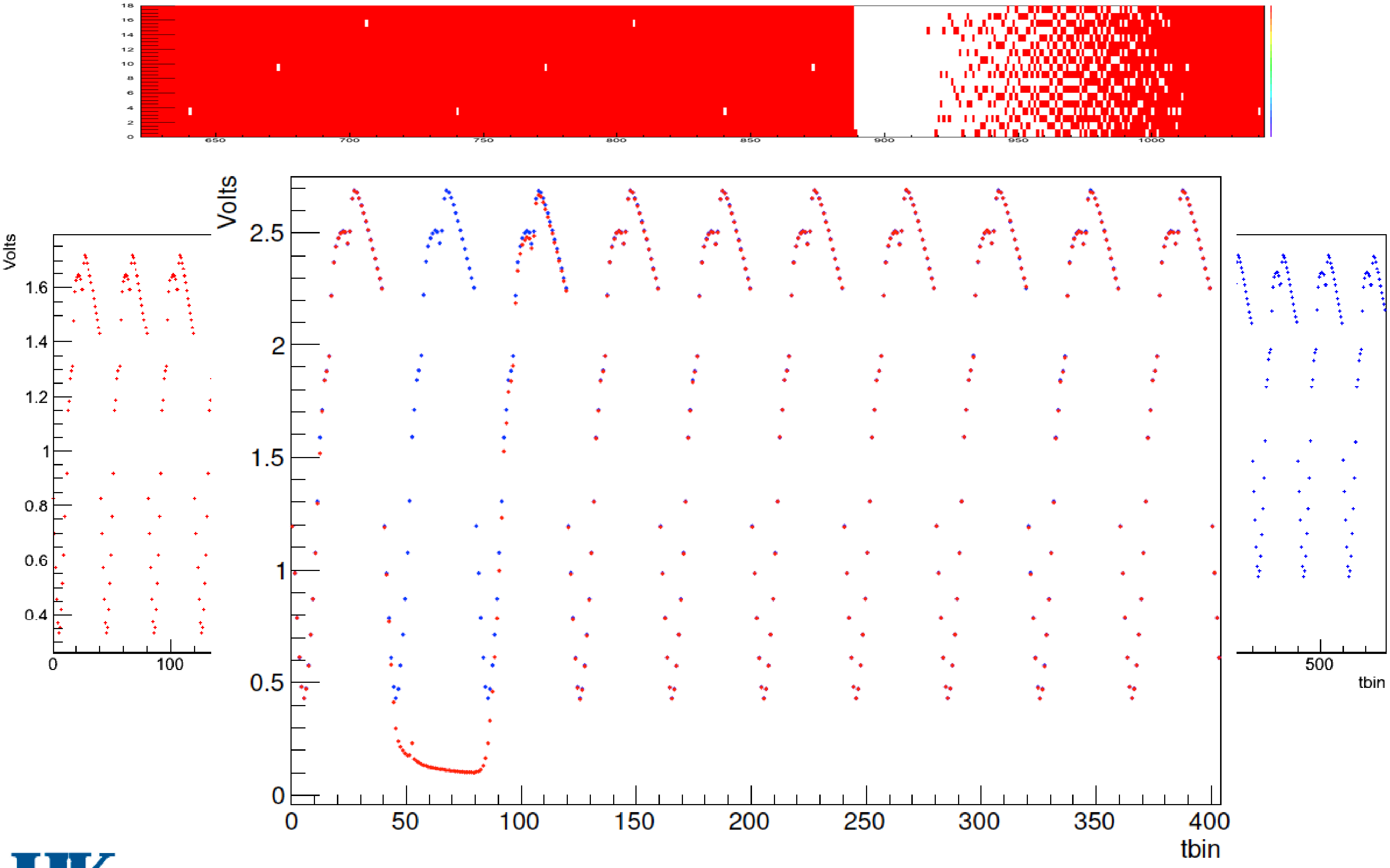
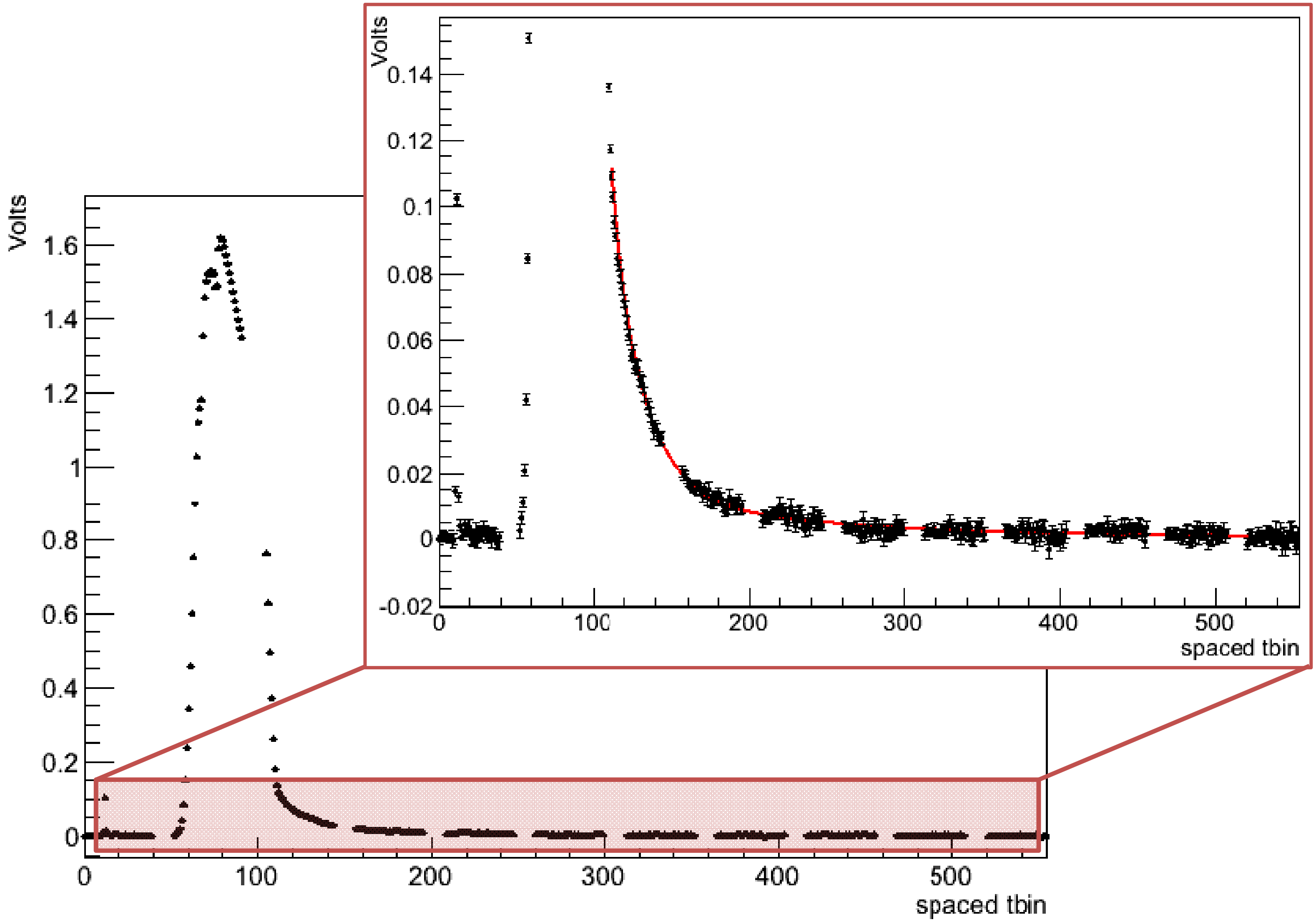
Unfolding single-pulse spectrum



Single neutron *“Negative image”* pulse



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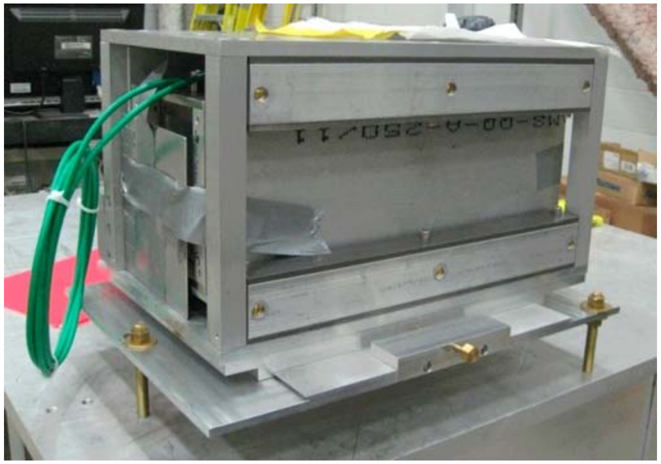
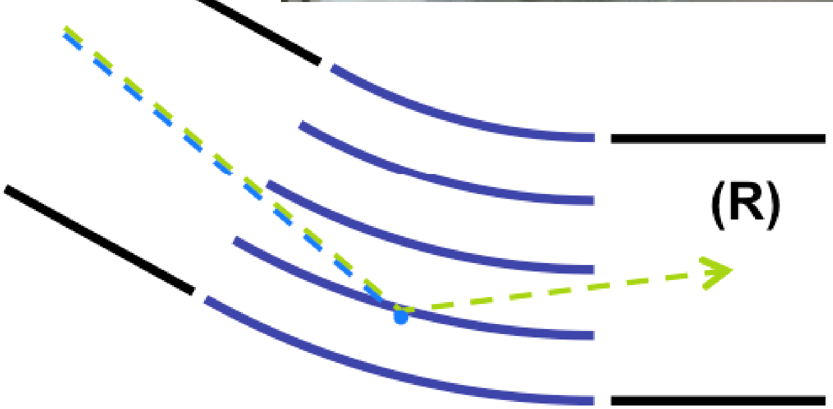
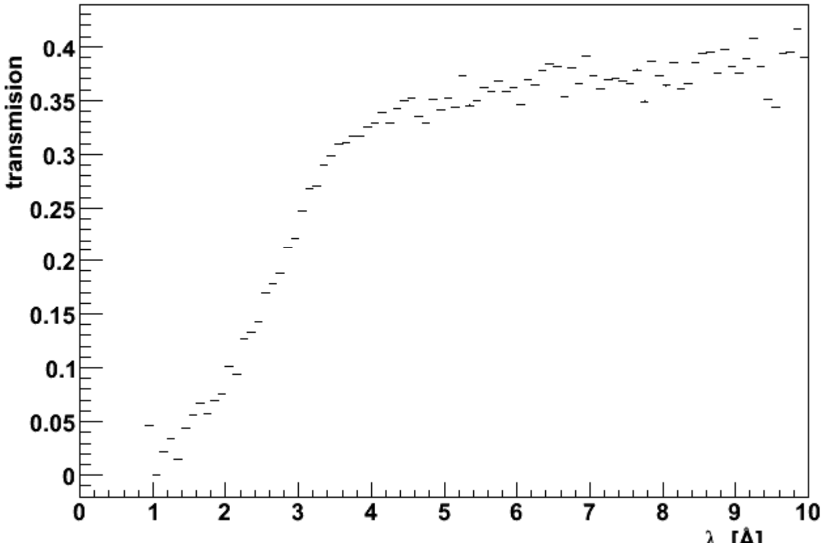
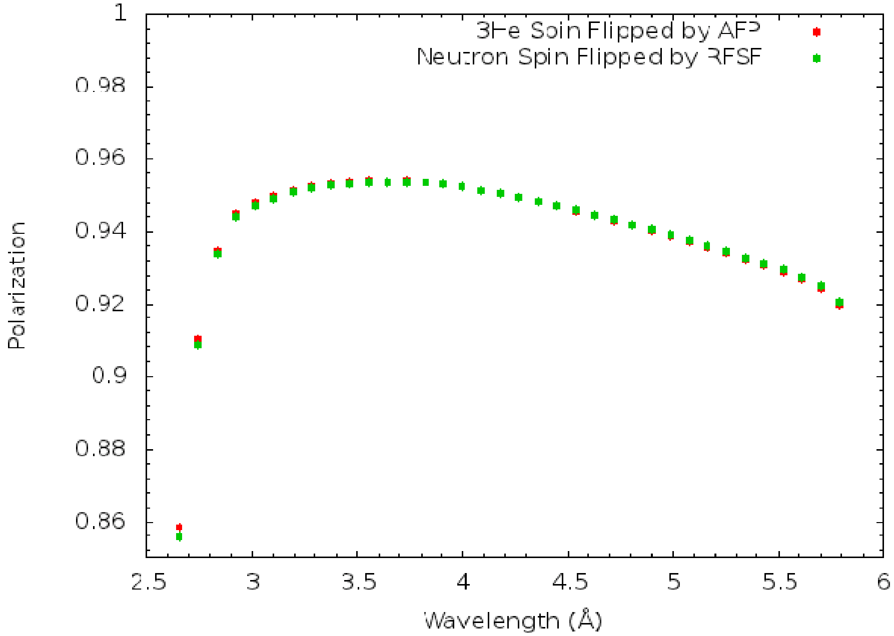
FnPB supermirror polarizer

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





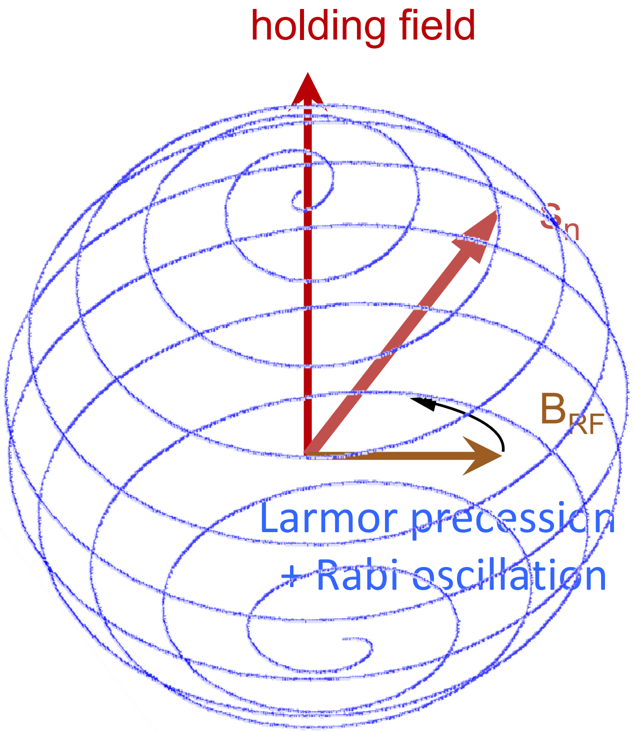


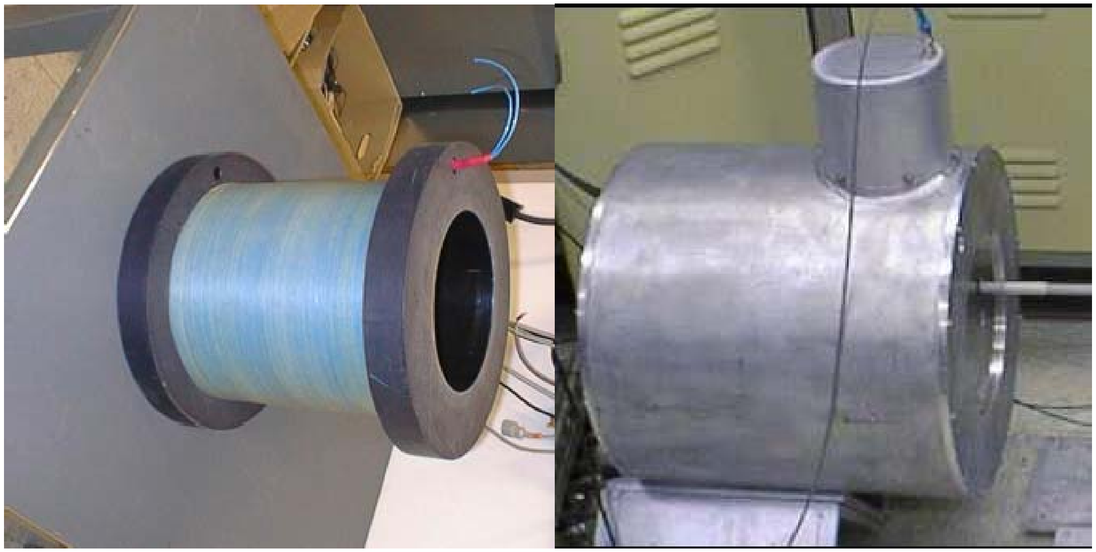


S. Balascuta

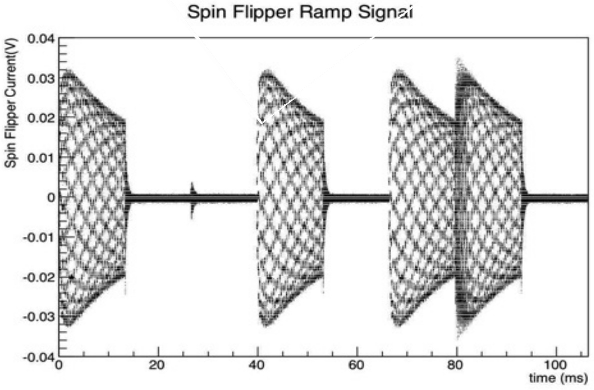
Resonant RF spin rotator

- Resonant RF spin rotator,
  - 1/t RF amplitude tuned to velocity of neutrons
  - Affects spin only–NOT velocity (no static gradient)
- essential to reduce instrumental systematics
  - danger: must isolate spin state from the detector
  - false asymmetries: additive & multiplicave

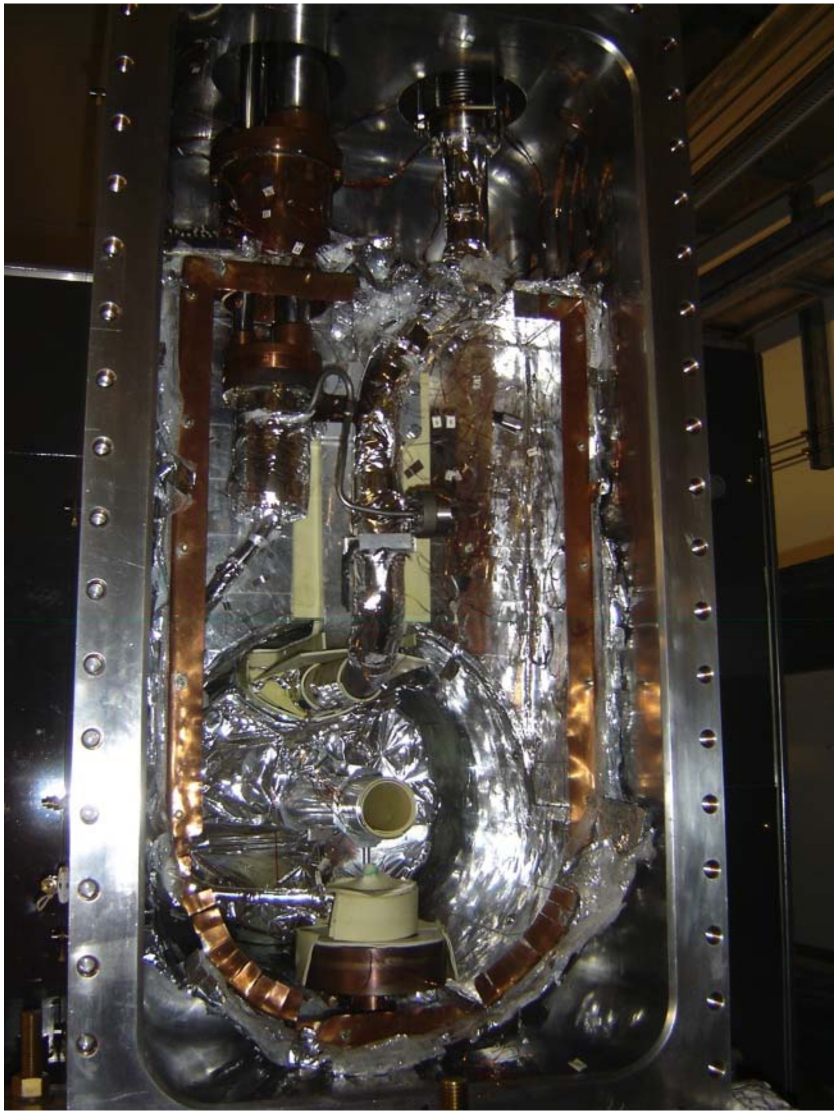




P. Neo-Seo, *et al.* Phys. Rev. ST Accel. Beams **11** 084701 (2008)



16L liquid para-hydrogen target

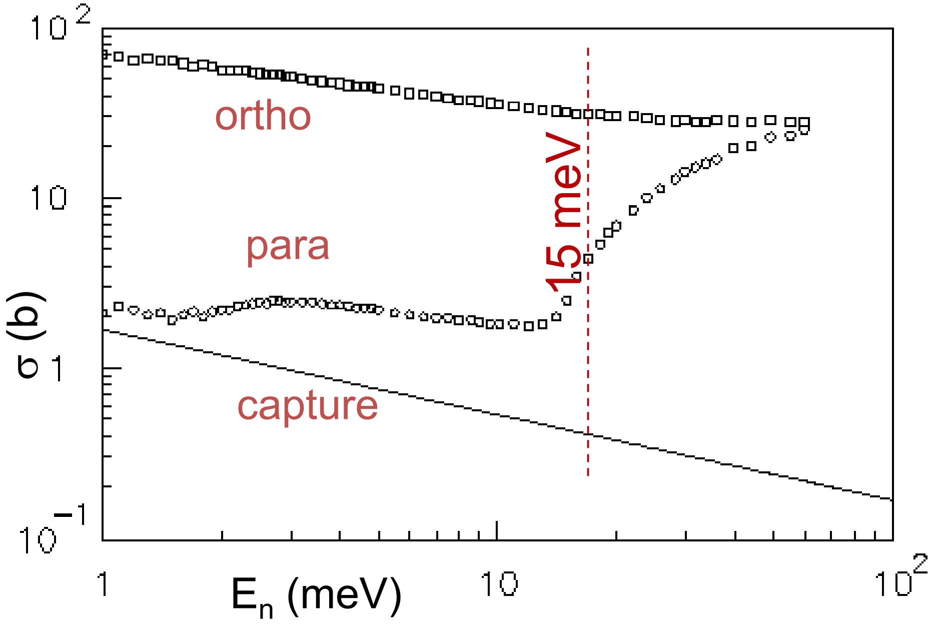


- 30 cm long → 1 interaction length
- 99.97% para → 1% depolarization
- Improvements: pressure-stamped vessel
  thinner windows

para-H_2

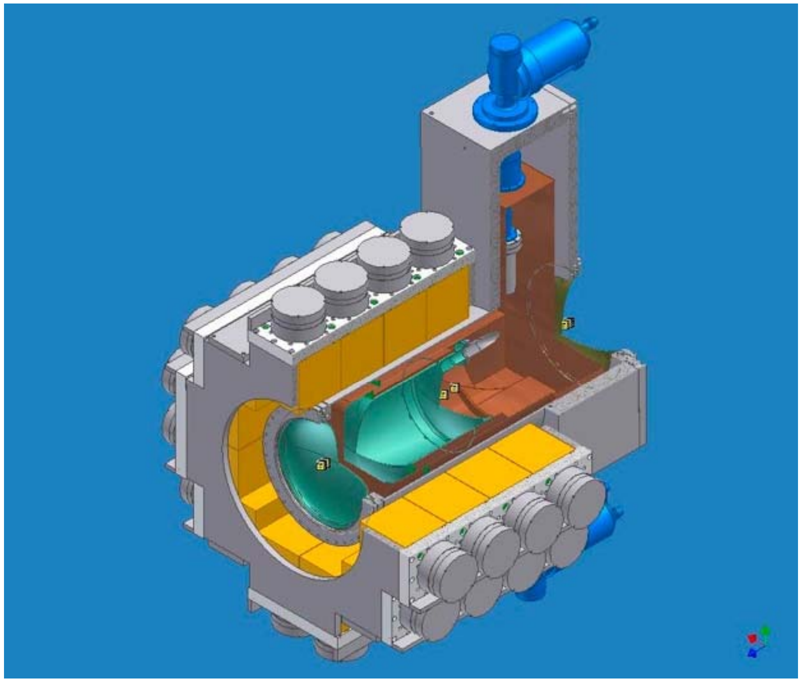
ΔE = 15 meV

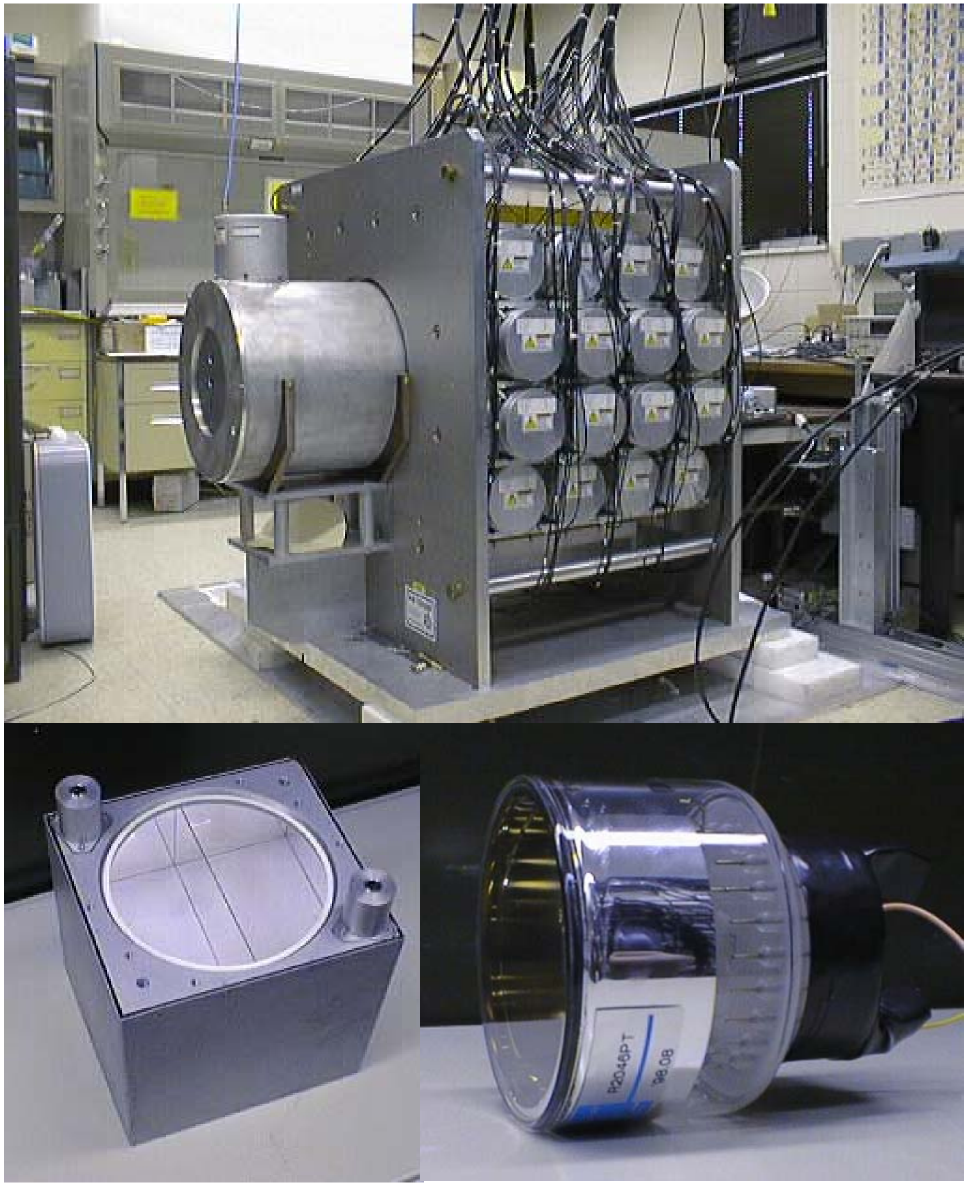
ortho-H_2



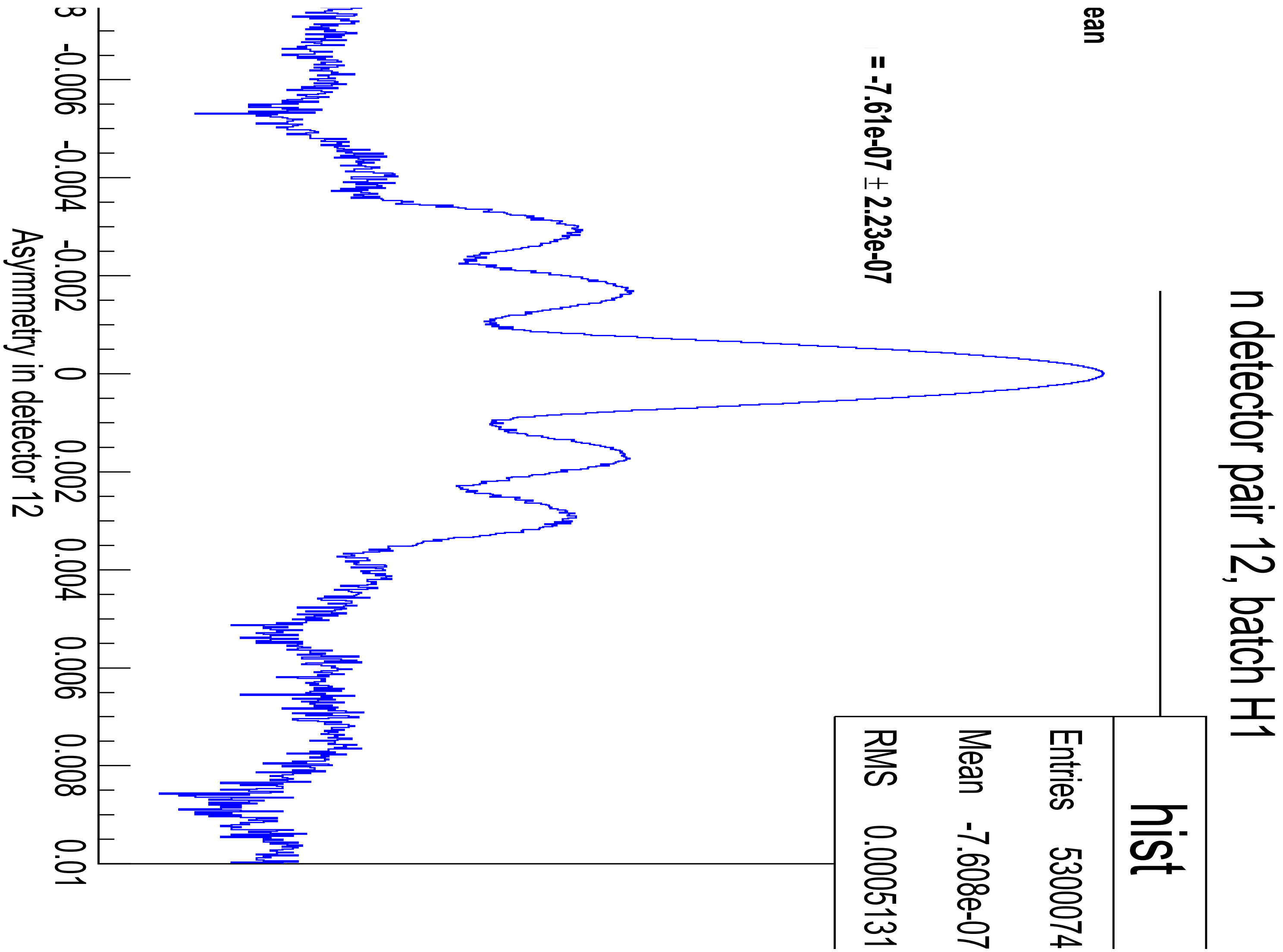
CsI(Tl) Detector Array

- 4 rings of 12 detectors each
  - 15 x 15 x 15 cm^3 each
- VPD’s insensitive to B field
- detection efficiency: 95%
- current-mode operation
  - 5 x 10^7 gammas/pulse
  - counting statistics limited





Detector asymmetry without cuts



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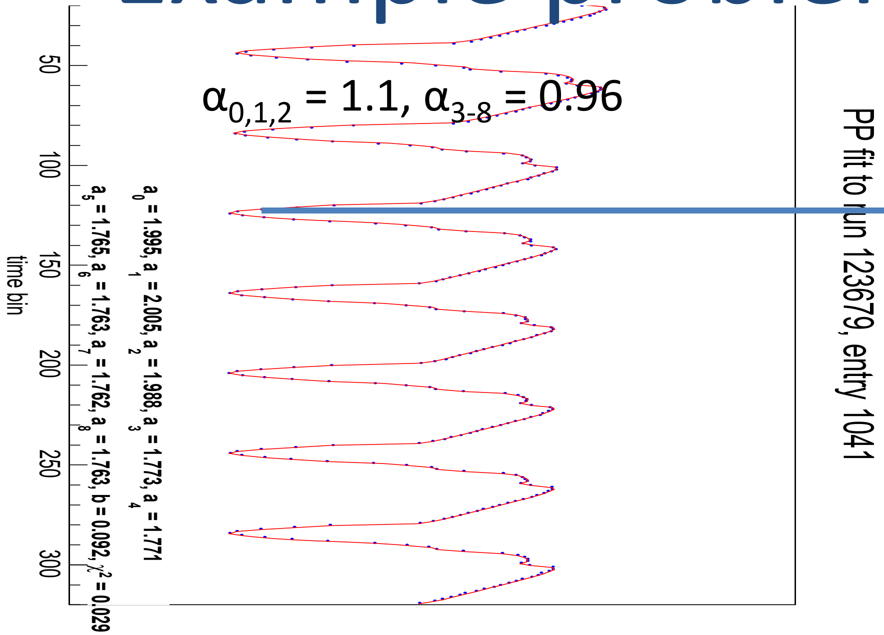
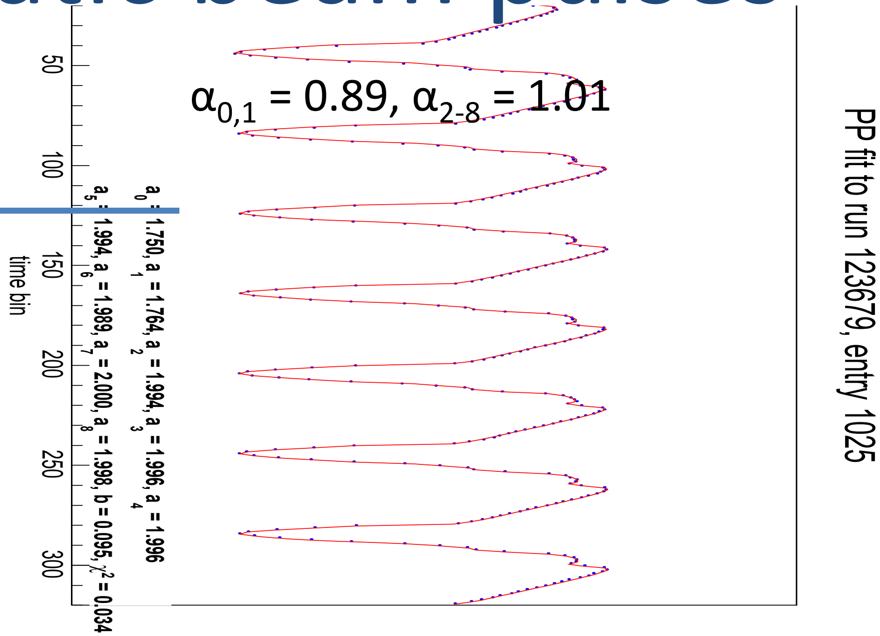
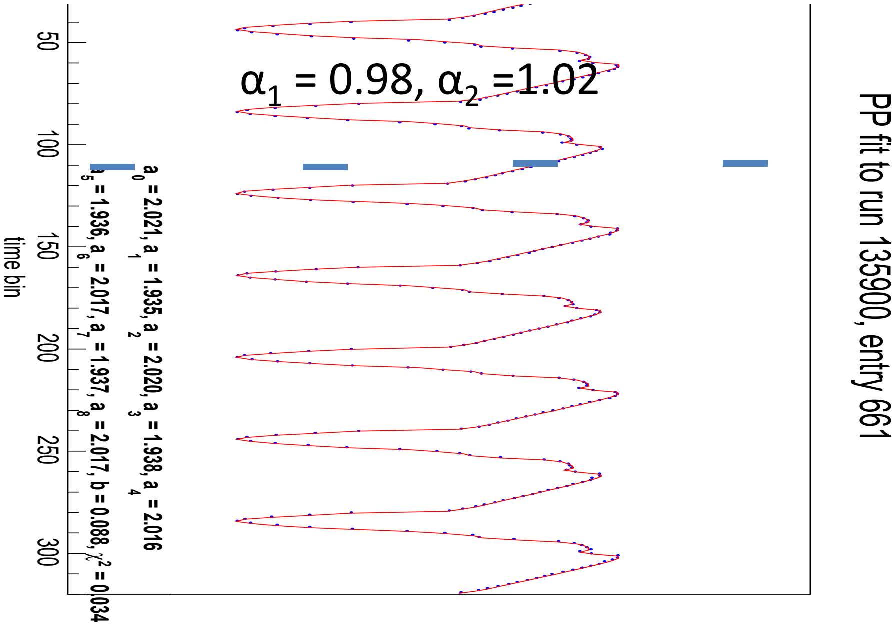
Example problematic beam pulses



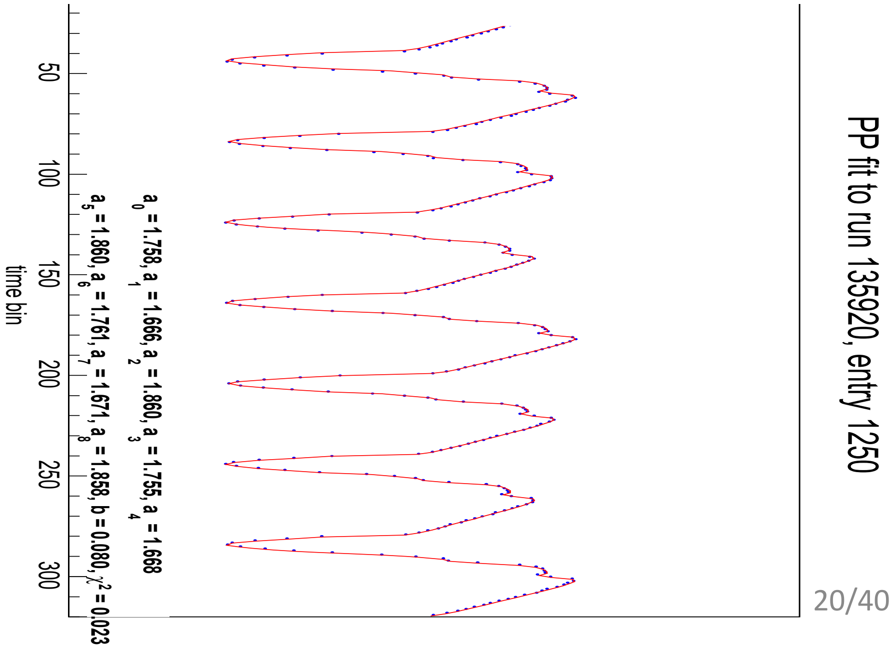
$\alpha_{0,1,2}$ = 1.1, $\alpha_{3\text{-}8}$ = 0.96



$\alpha_{0,1}$ = 0.89, $\alpha_{2\text{-}8}$ = 1.01

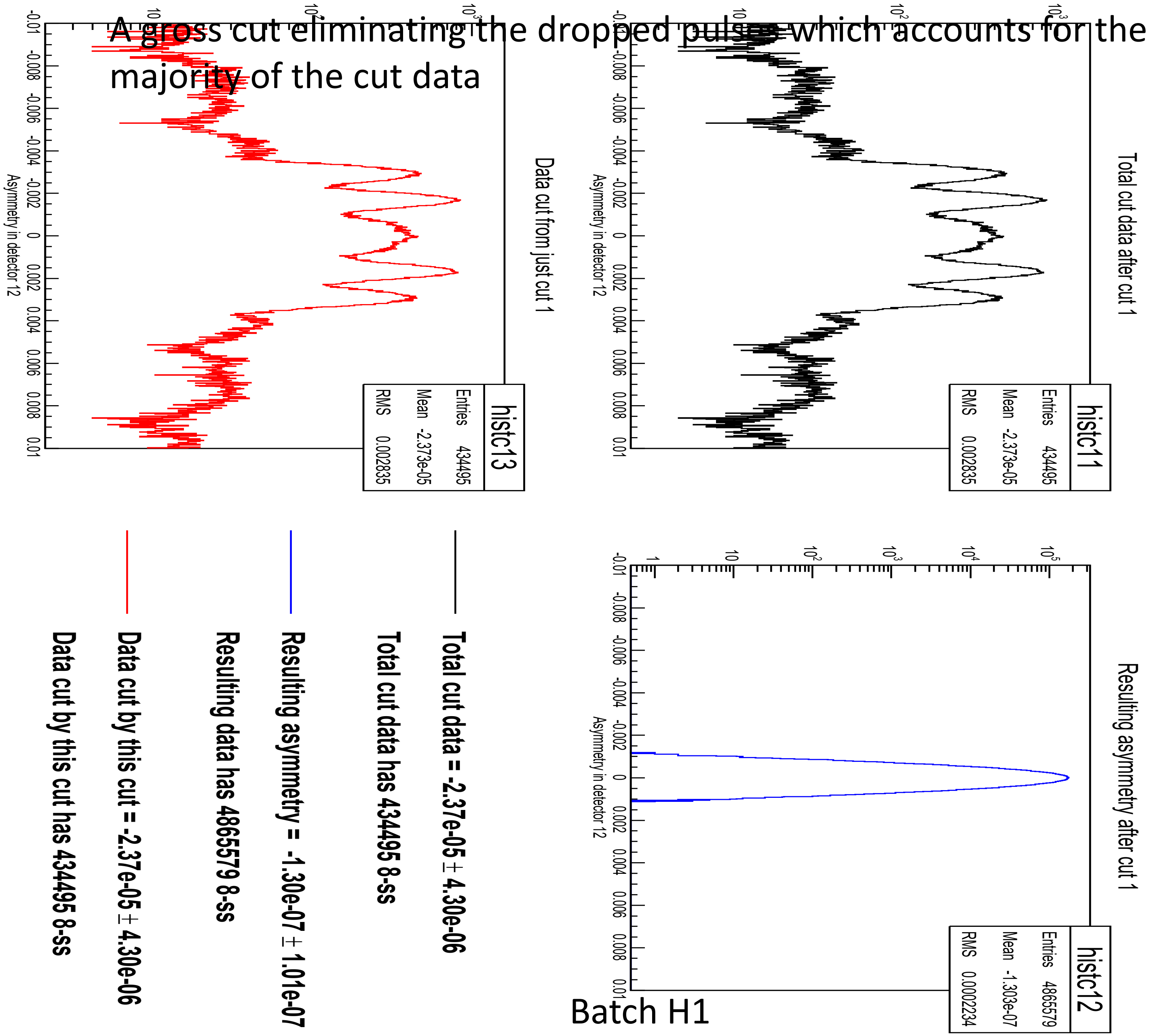


α_1 = 0.98, α_2 =1.02



Cut 1: Minimum amplitude

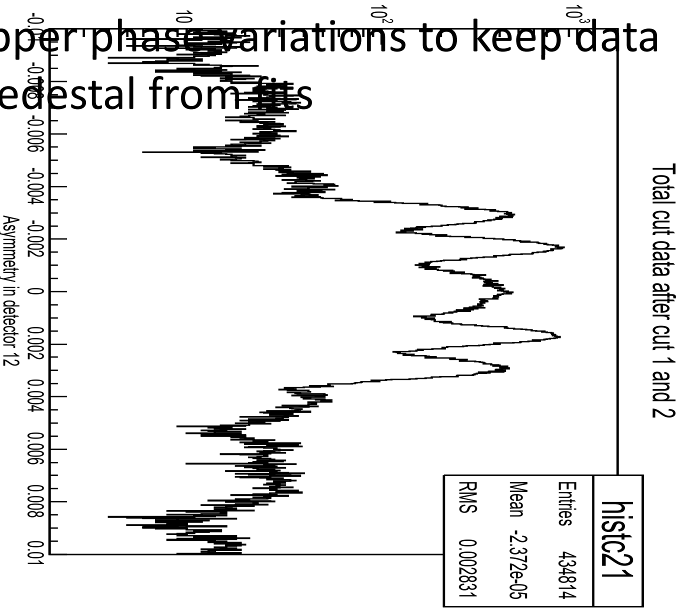
A gross cut eliminating the dropped pulses which accounts for the majority of the cut data

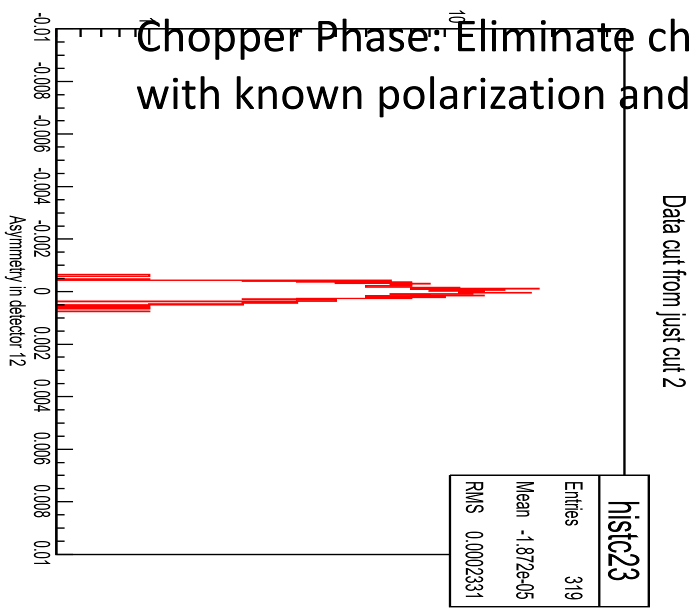


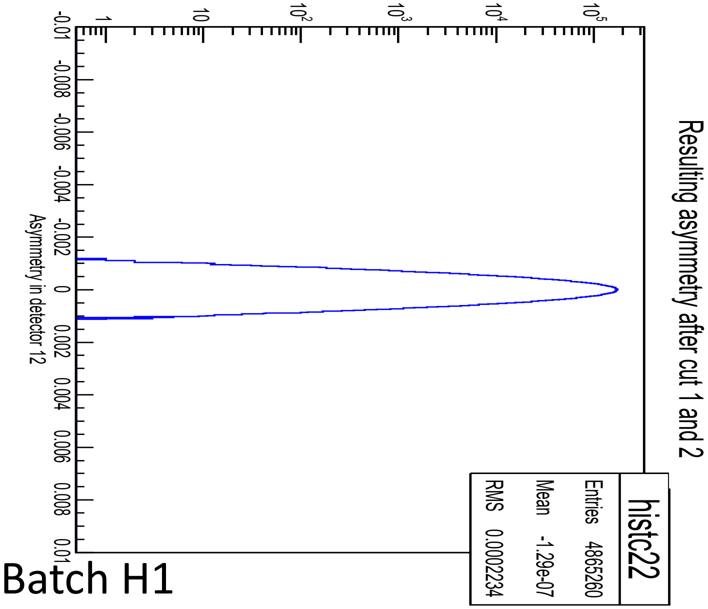
Batch H1

Cut 2: Chopper Phases

- Chopper Phase: Eliminate chopper phase variations to keep data with known polarization and pedestal from fits


Total cut data after cut 1 and 2


Data cut from just cut 2


Resulting asymmetry after cut 1 and 2

Batch H1

Total cut data = -2.37e-05 ± 4.29e-06

Total cut data has 434814 8-ss

Resulting asymmetry = -1.29e-07 ± 1.01e-07

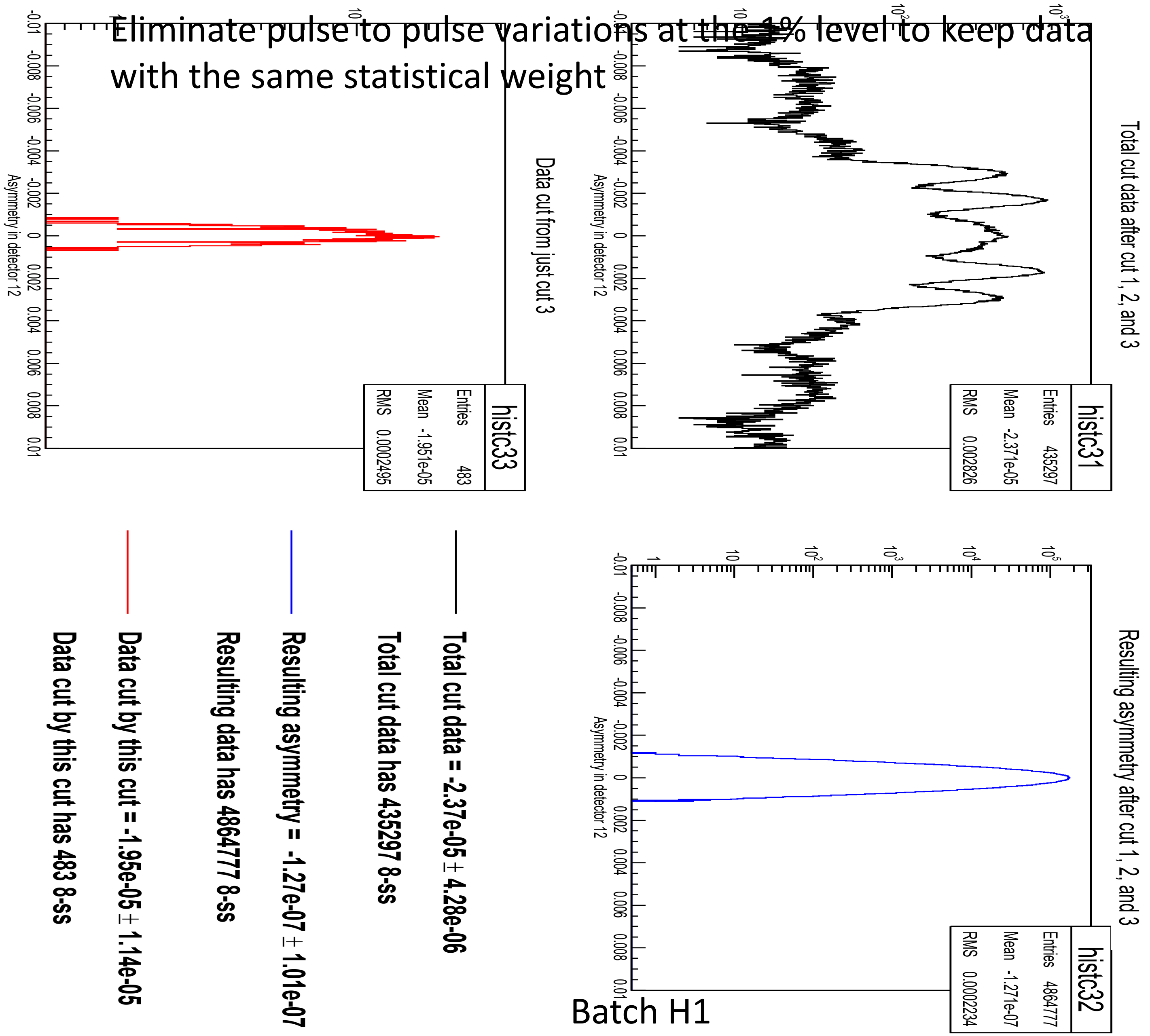
Resulting data has 4865260 8-ss

Data cut by this cut = -1.87e-05 ± 1.31e-05

Data cut by this cut has 319 8-ss

Cut 3: Pulse to Pulse Stability

Eliminate pulse to pulse variations at the 1% level to keep data with the same statistical weight



Total cut data = -2.37e-05 ± 4.28e-06

Total cut data has 435297 8-ss

Resulting asymmetry = -1.27e-07 ± 1.01e-07

Resulting data has 4864777 8-ss

Data cut by this cut = -1.95e-05 ± 1.14e-05

Data cut by this cut has 483 8-ss

Batch H1

Background Sub. & Geometry Factors

$$A_\gamma^{np} = \frac{A_{LH_2}}{P_n \epsilon_{sf} C_d} - F_{BG}\frac{A_{Al}}{P_n^{Al}\epsilon_{sf}^{Al}C_d^{Al}}$$

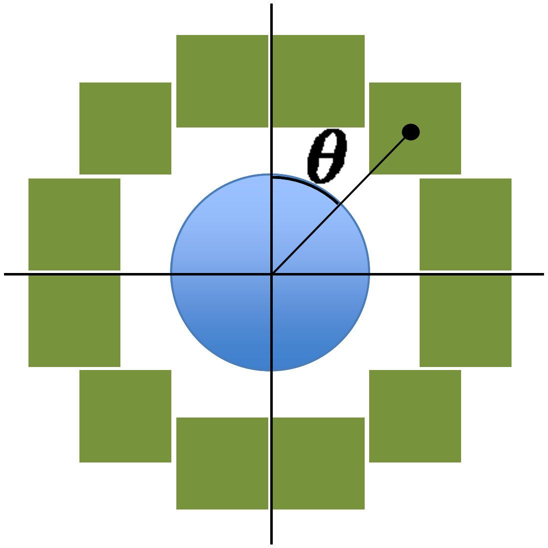
Aluminum asymmetry

neutron pol.

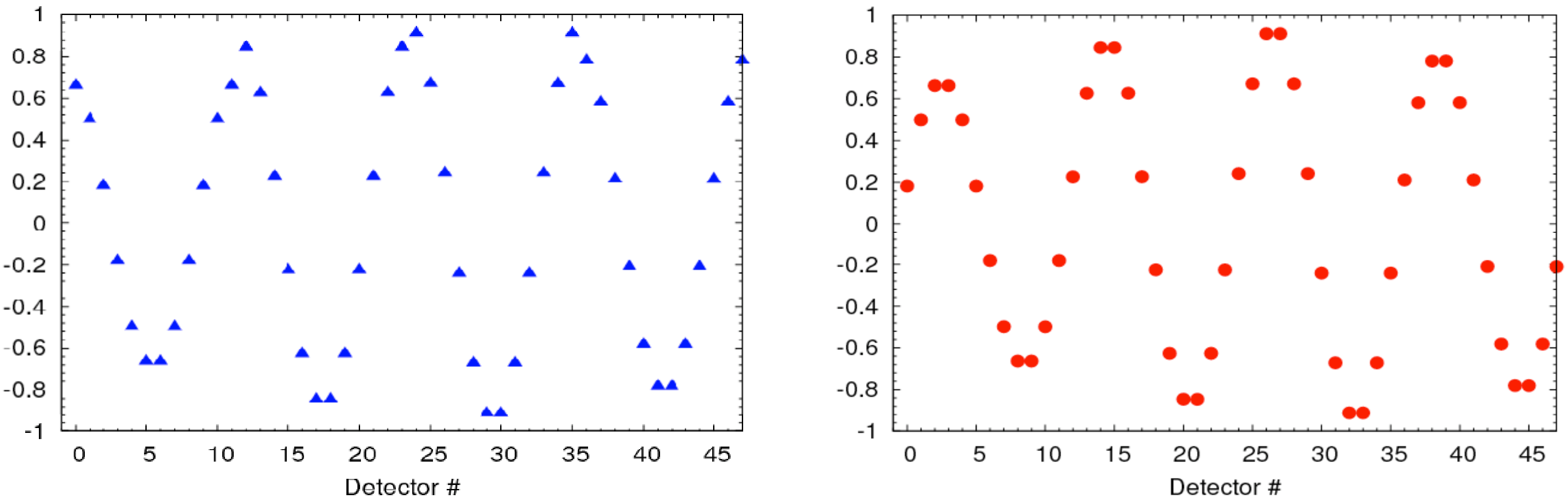
RFSF eff.

target depol.

Aluminum background



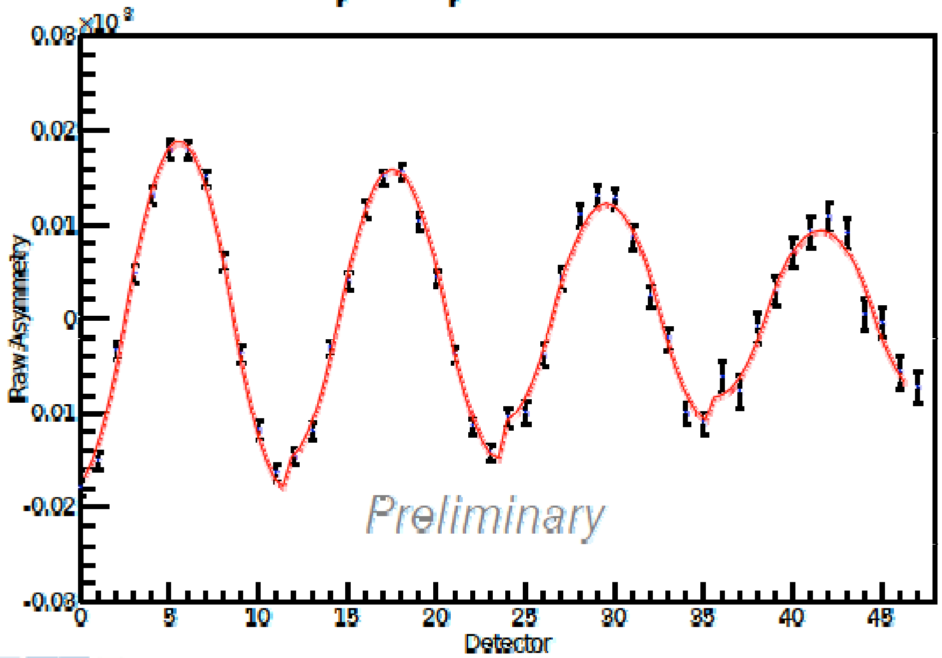
$$A_\gamma^{np} = A_\gamma^{PV}\underbrace{G_{UD}}_{\langle s_n\cdot k_\gamma = \cos\theta\rangle} + A_\gamma^{PC}\underbrace{G_{LR}}_{\langle s_n\cdot k_n\times k_\gamma = \sin\theta\rangle} + A_{offset}$$

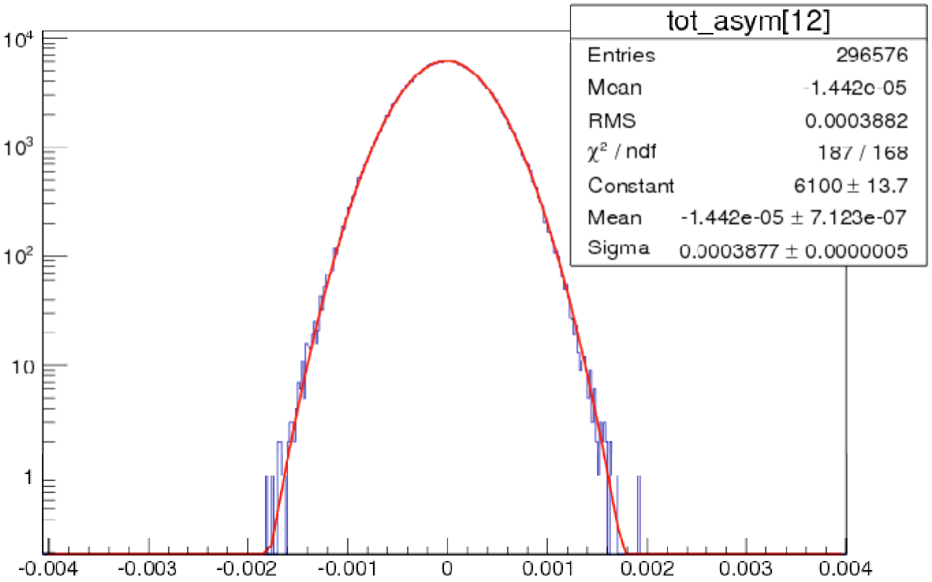


Chlorine PV asymmetry

- Data set
  - To verify sensitivity & geometry factors
  - 40 hr. over 4 run periods
- Corrections
  - Background Subtraction
  - Beam Polarization / Depolarization
  - RFSF Efficiency

Chlorine asymmetry for runs 102833 - 102968



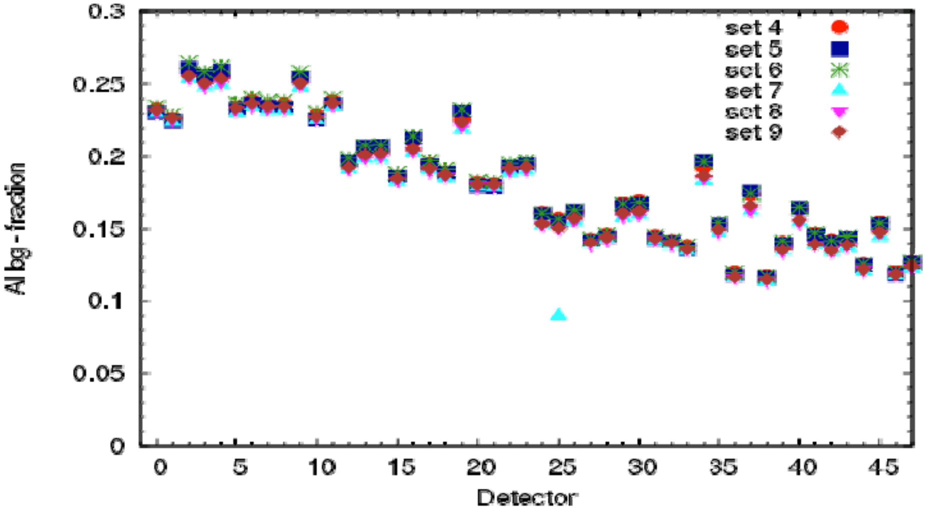


Prev. Measurement	Asymmetry ($\times10^{-6}$)
LANL	-29.1 ± 6.7
Leningrad	-27.8 ± 4.9
ILL	-21.2 ± 1.72

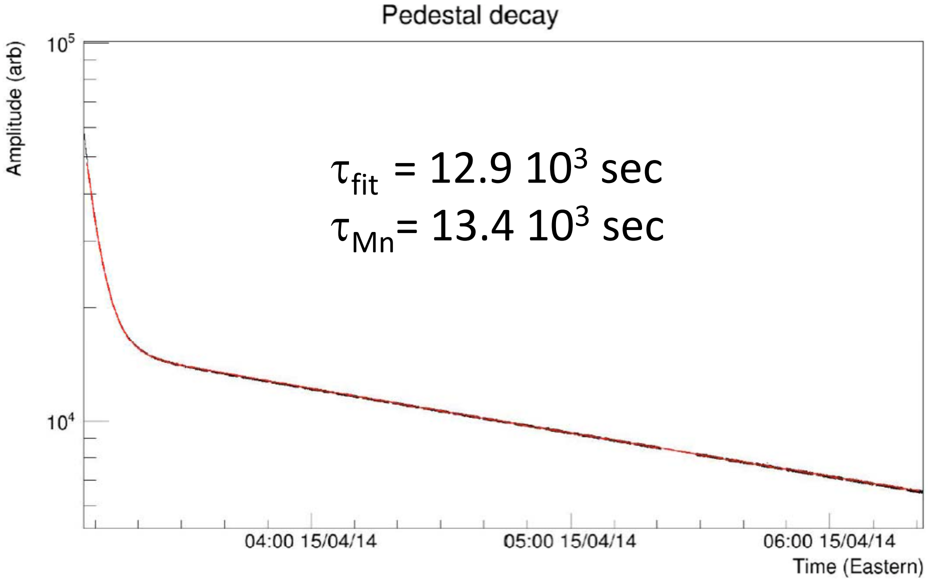
$$A_{UD} = 25.9 \pm 0.6 \times 10^{-6}$$

$$A_{LR} = 0.06 \pm 0.6 \times 10^{-6}$$

Aluminum Asymmetry



- Dominant systematic effect
- 15–25% background at SNS
  after thinning windows and adding extra neutron shielding in cryostat
- Extracted from decay amplitude
  Lifetime τ = 27 min
- Additional τ = 3 hr amplitude
  was the first indication of Mn in the background target (not in 6061)
- Confirmed by neutron activation analysis at NIST



τ_{fit} = 12.9 10^3 sec
τ_{Mn}= 13.4 10^3 sec

Result for Hydrogen asymmetry

All asymmetries
In units of 10^{-8}

- Unsubtracted PV asymmetries

A_{LH} = - 4.0 ± 0.9
A_{Al} = - 9.8 ± 2.3

- Window subtraction assuming disk and cryostat the same

A_H = - 3.1 ± 1.3

This is a 2.4σ effect

- Correction for Mn asymmetry

$A_{6061} = A_{3004} - A_{Mn} = -9.5 \pm 19.$

The large uncertainty in A_{6061} comes from the large experimental uncertainty in the Mn asymmetry, which gives 20% of the prompt yield.

- Window subtraction with Mn correction:

A_H = - 2.8 ± 0.9 (stat. LH) ± 4.0 (stat. Al)

This was an urgent call for reduction the background contribution!

2016 Al Background Run

To reduce systematic errors due to Aluminum background we cut up all pieces that neutrons interacted with:

- SF window
- cryostat windows
- LH2 vessel entry dome
- LH2 vessel side walls.

Their contributions to final Al signal were estimated with MCNP and data were collected correspondingly.

PV data collected for 10 weeks from February to June 2016.

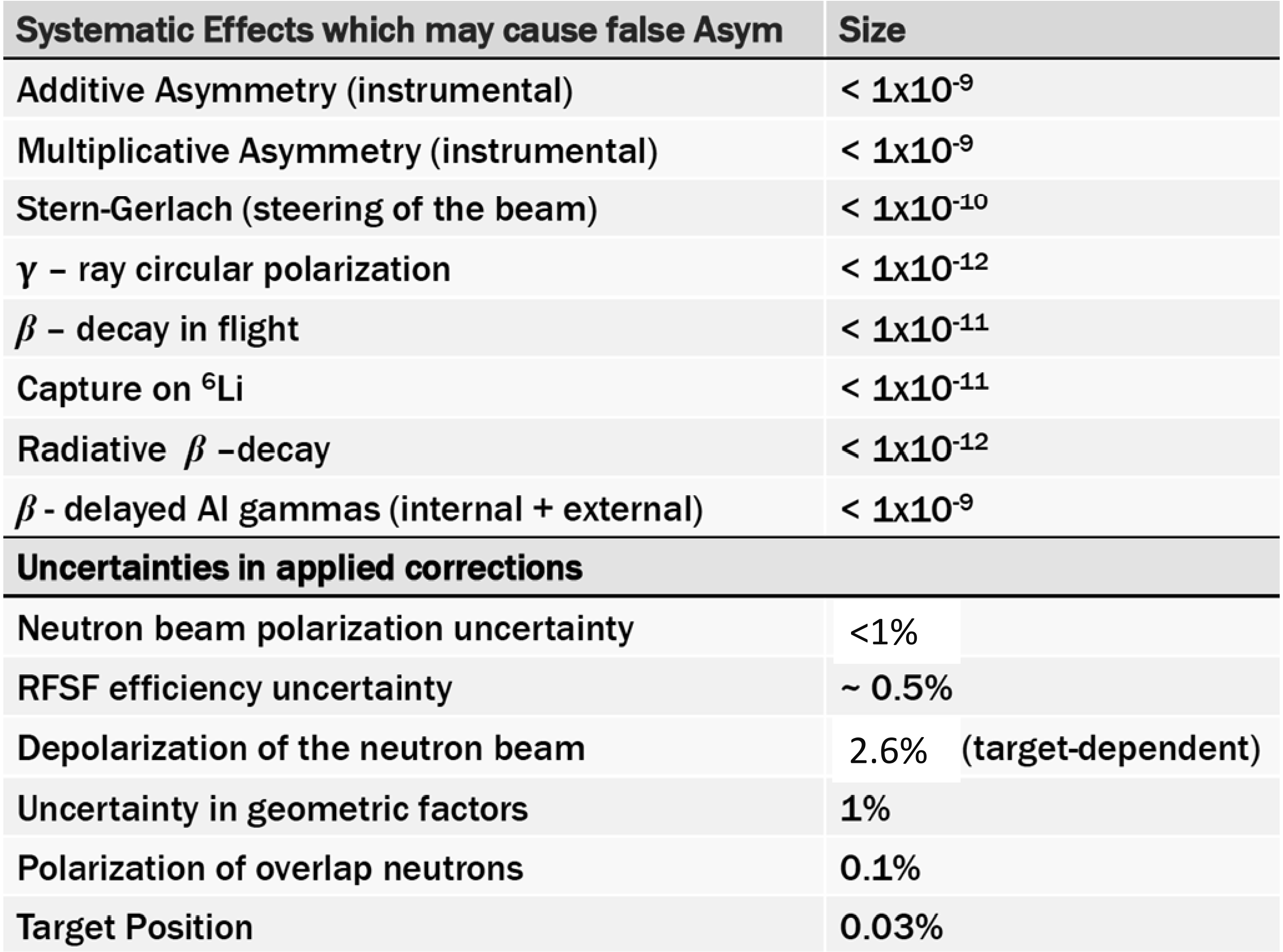
Data analysis is in the final stage:

$\delta A_{Al} = 2.3 \times 10^{-8}$

Impact on hydrogen asymmetry:

$$\delta A_{Al} = 1.3 \times 10^{-8}$$

Systematic & Statistical Uncertainties



Systematic Effects which may cause false Asym	Size
Additive Asymmetry (instrumental)	$< 1\text{x}10^{-9}$
Multiplicative Asymmetry (instrumental)	$< 1\text{x}10^{-9}$
Stern-Gerlach (steering of the beam)	$< 1\text{x}10^{-10}$
γ – ray circular polarization	$< 1\text{x}10^{-12}$
β – decay in flight	$< 1\text{x}10^{-11}$
Capture on ^{6}Li	$< 1\text{x}10^{-11}$
Radiative β –decay	$< 1\text{x}10^{-12}$
β - delayed Al gammas (internal + external)	$< 1\text{x}10^{-9}$
Uncertainties in applied corrections	
Neutron beam polarization uncertainty	<1%
RFSF efficiency uncertainty	~ 0.5%
Depolarization of the neutron beam	2.6% (target-dependent)
Uncertainty in geometric factors	1%
Polarization of overlap neutrons	0.1%
Target Position	0.03%

n-^{3}He Collaboration

R. Alarcon[1], S. Baeßler[3], S. Balascuta[1], L. Barron-Palos[2], A. Barzilov[7], D. Bowman[4], J. Calarco[9], V. Cianciolo[4], C. Crawford[5], J. Favela[2], N. Fomin[4,13], I. Garishvili[13], M. Gericke[6], C. Gillis[8], G. Greene[4,13], V. Gudkov[11], J. Hamblen[12], C. Hayes[13], E. Iverson[4], K. Latiful[5], S. Kucuker[13], M. Maldonado-Velazquez[2], M. McCrea[6], I. Novikov[15], C. Olguin[6], S. Penttila[4], E. Plemons[12], A. Ramirez[2], P.-N. Seo[14], Y. Song[11], A. Sprow[5], J. Thomison[4], T. Tong[4], M. Viviani[10], C. Wichersham[12]

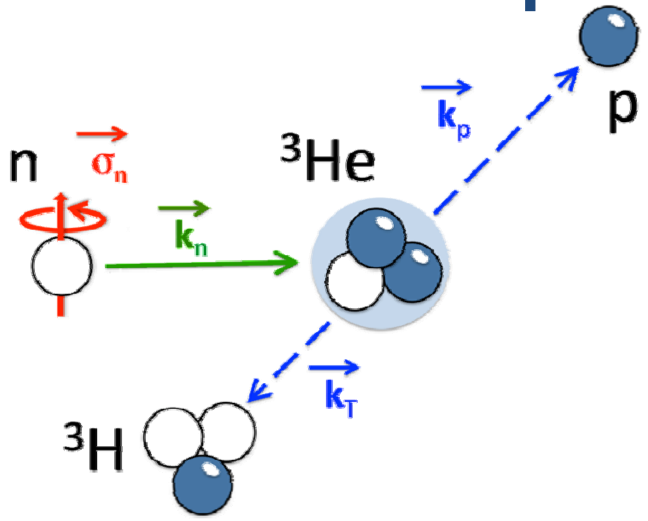
[1]Arizona State University
[2]Universidad Nacional Autonoma de Mexico
[3]University of Virginia
[4]Oak Ridge National Laboratory
[5]University of Kentucky
[6]University of Manitoba, Canada
[7]Univeristy of Nevada at Los Vegas
[8]Indiana University
[9]University of New Hampshire
[10]Instituto Nazionale di Fisica Nucleare, Sezione di Pisa
[11]University of South Carolina
[12]University of Tennessee at Chattanooga
[13]University of Tennessee, Knoxville
[14]Duke University
[15]Western Kentucky University

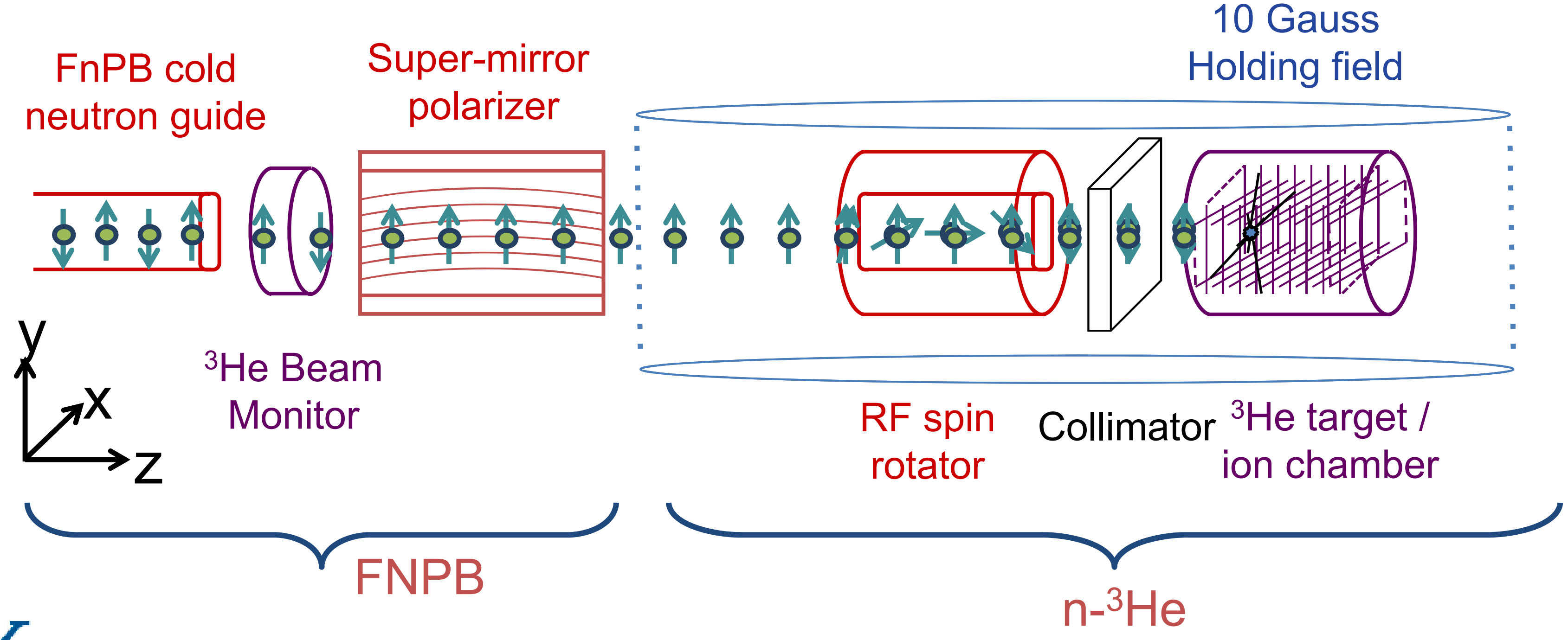
https://n3he.wikispaces.com

n-^{3}He Experimental setup

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

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





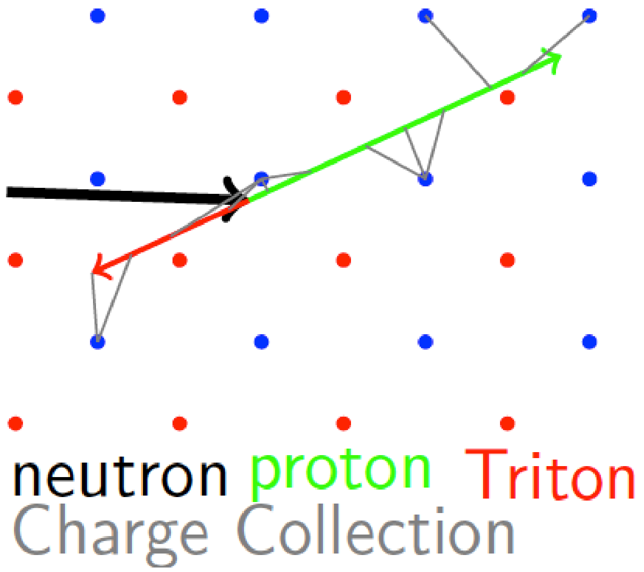
Asymmetry extraction – statistics

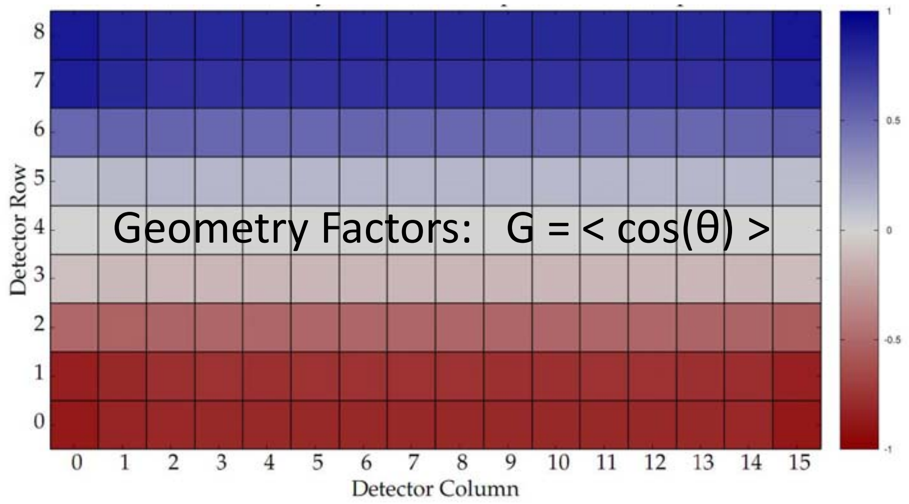
- PV physics asymmetry
  - Extracted from weighted average of single-wire spin asymmetries

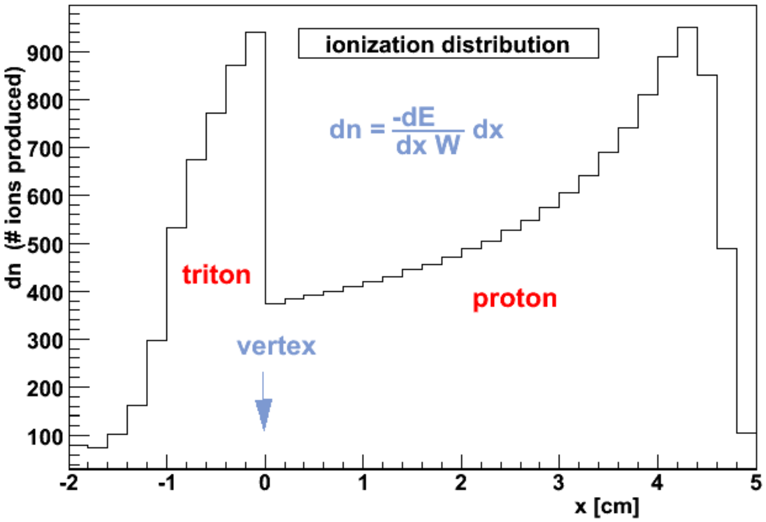
$$Y_{\pm} = Y_0(1 \pm P A_p \langle\cos\theta\rangle)$$

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

$$\delta A = \frac{\sigma_d}{P\sqrt{N}} \qquad 2.9 < \sigma_d < 6$$




Geometry Factors: G = < cos(θ) >

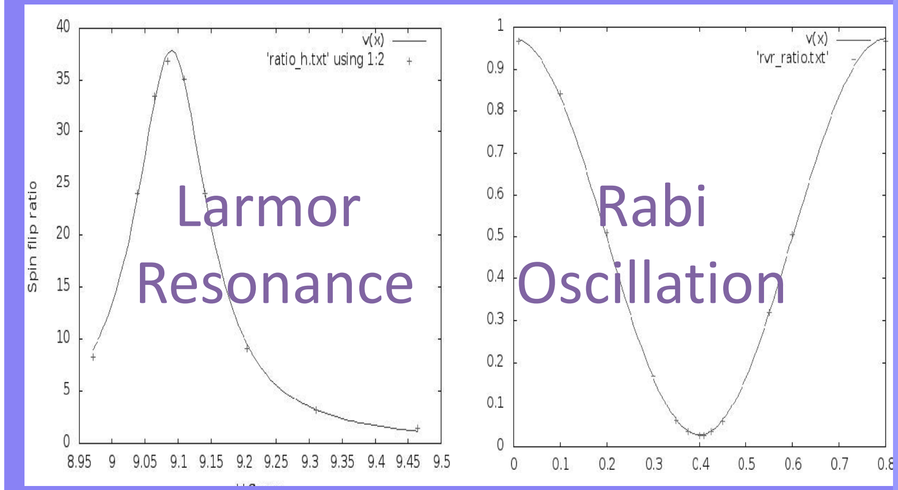


Transverse RF Spin Rotator

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

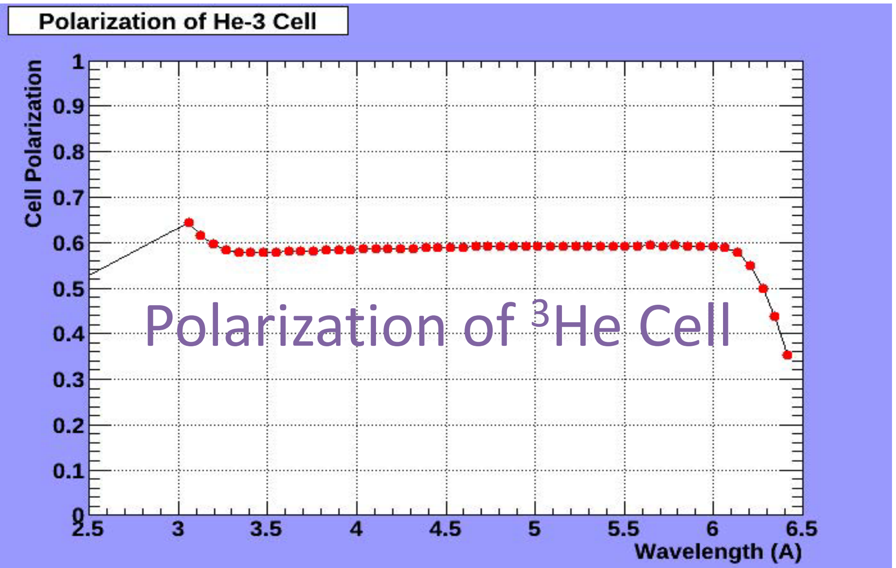
Univ. Kentucky / Univ. Tennessee

^{3}He transmission polarimetry

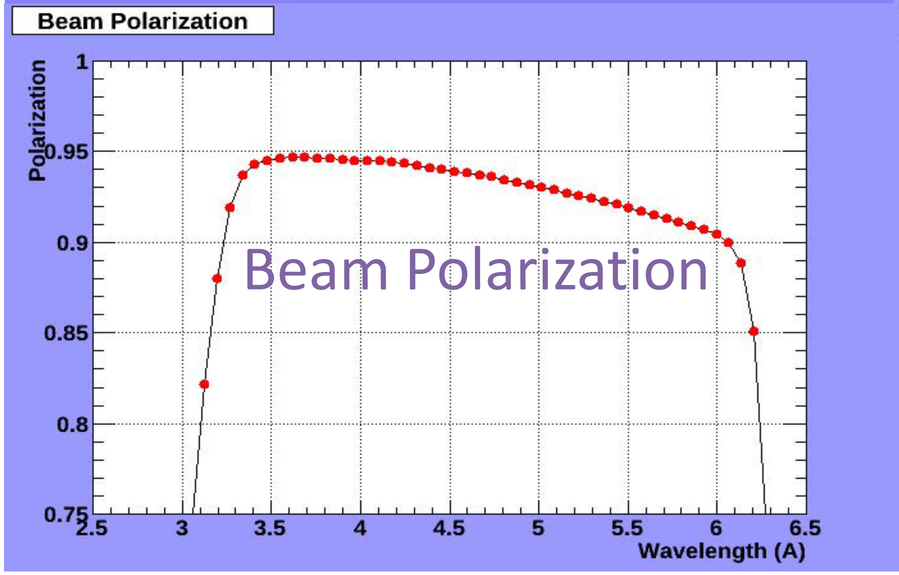


Larmor Resonance

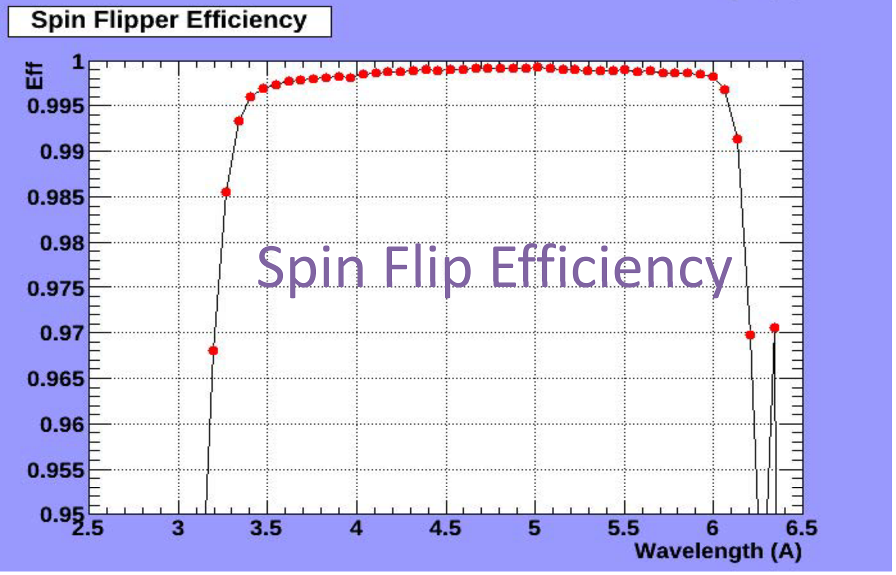
Rabi Oscillation



Polarization of ^{3}He Cell



Beam Polarization

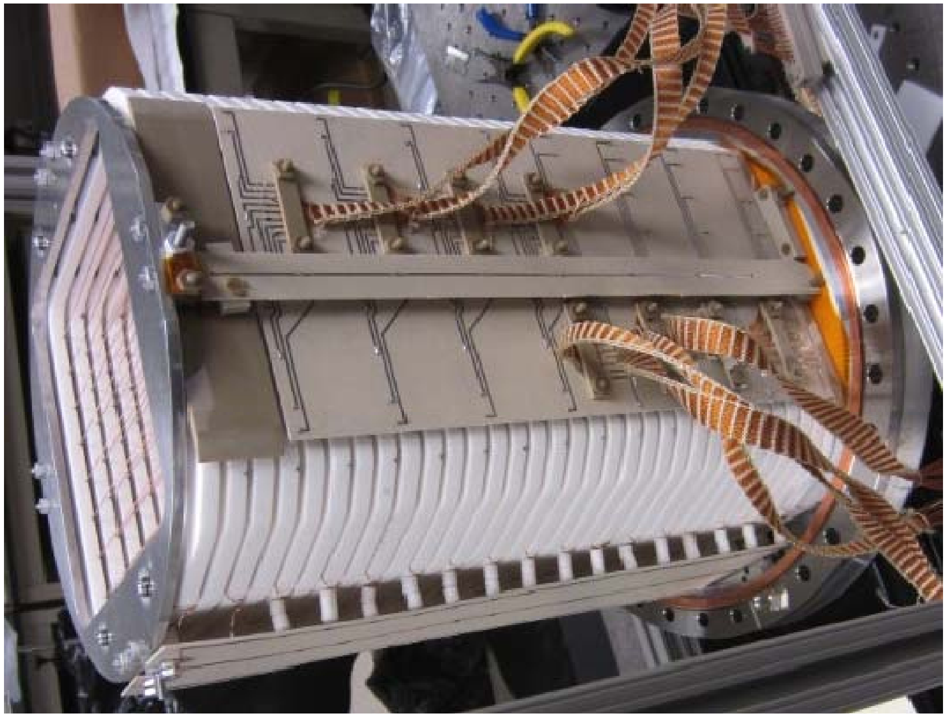


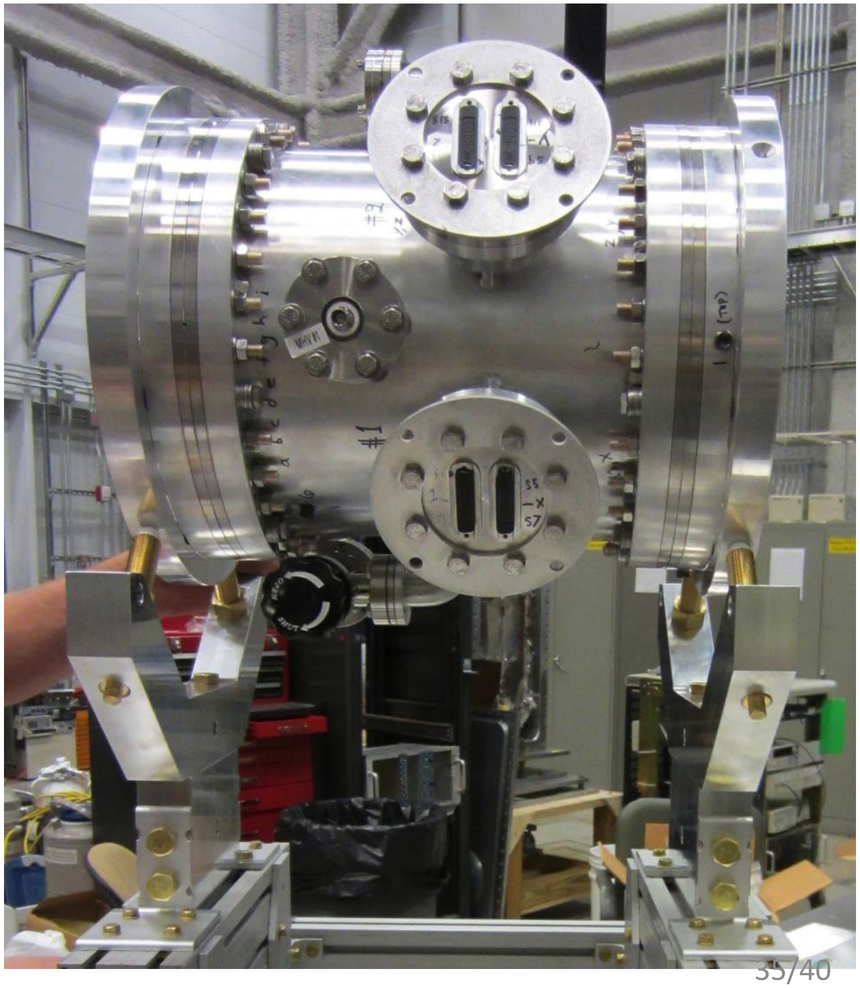
Spin Flip Efficiency

Active Target / Ion Chamber

- ^{3}He for both target and ionization gas
  - Macor frames with 9 x 16 sense wires, 8 x 17 HV wires
  - All aluminum chamber except for knife edges
  - 12” x 0.9 mm CF aluminum windows
  - 16 mCi tritium over life of experiment

University of Manitoba

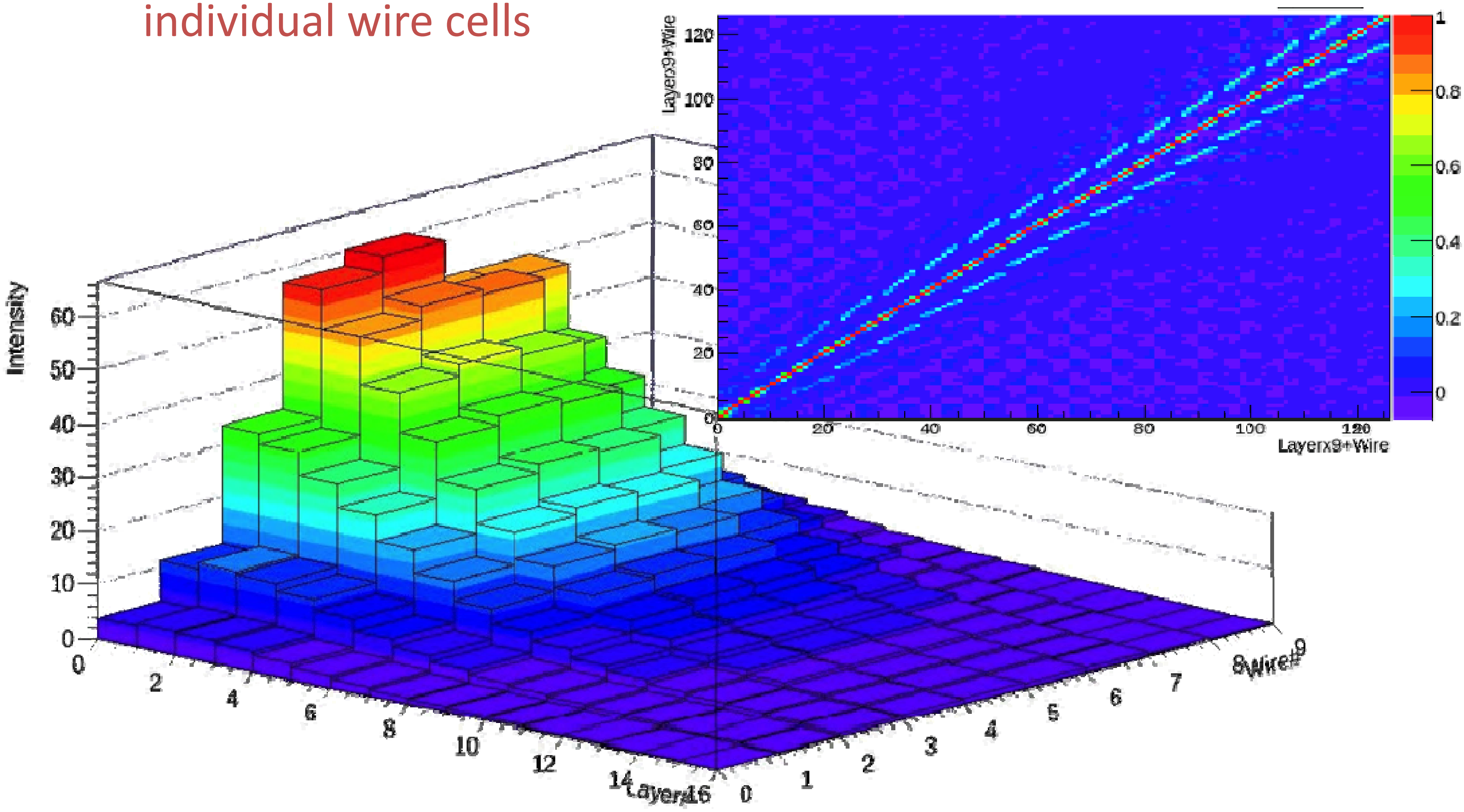




Ion chamber yield from neutron beam

- Detector yield in individual wire cells

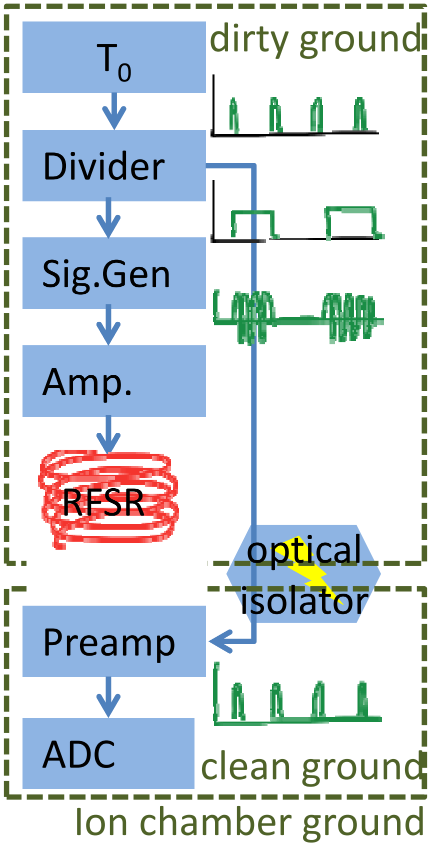
Correlation matrix



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



dirty ground

T_0

Divider

Sig.Gen

Amp.

RFSR

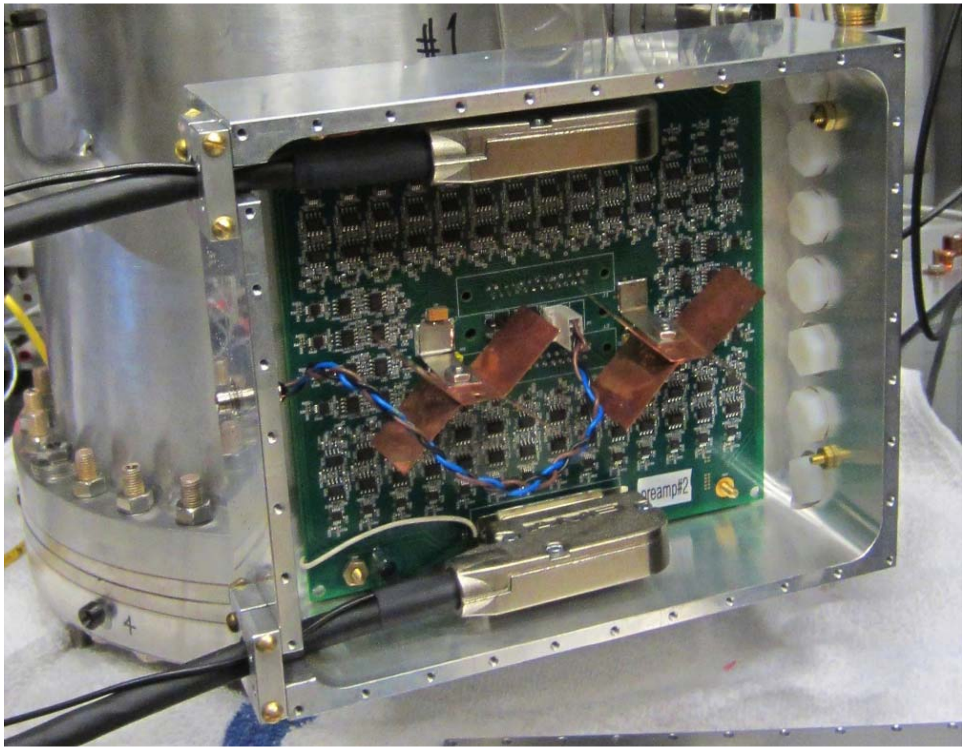
optical isolator

Preamp

ADC

clean ground

Ion chamber ground

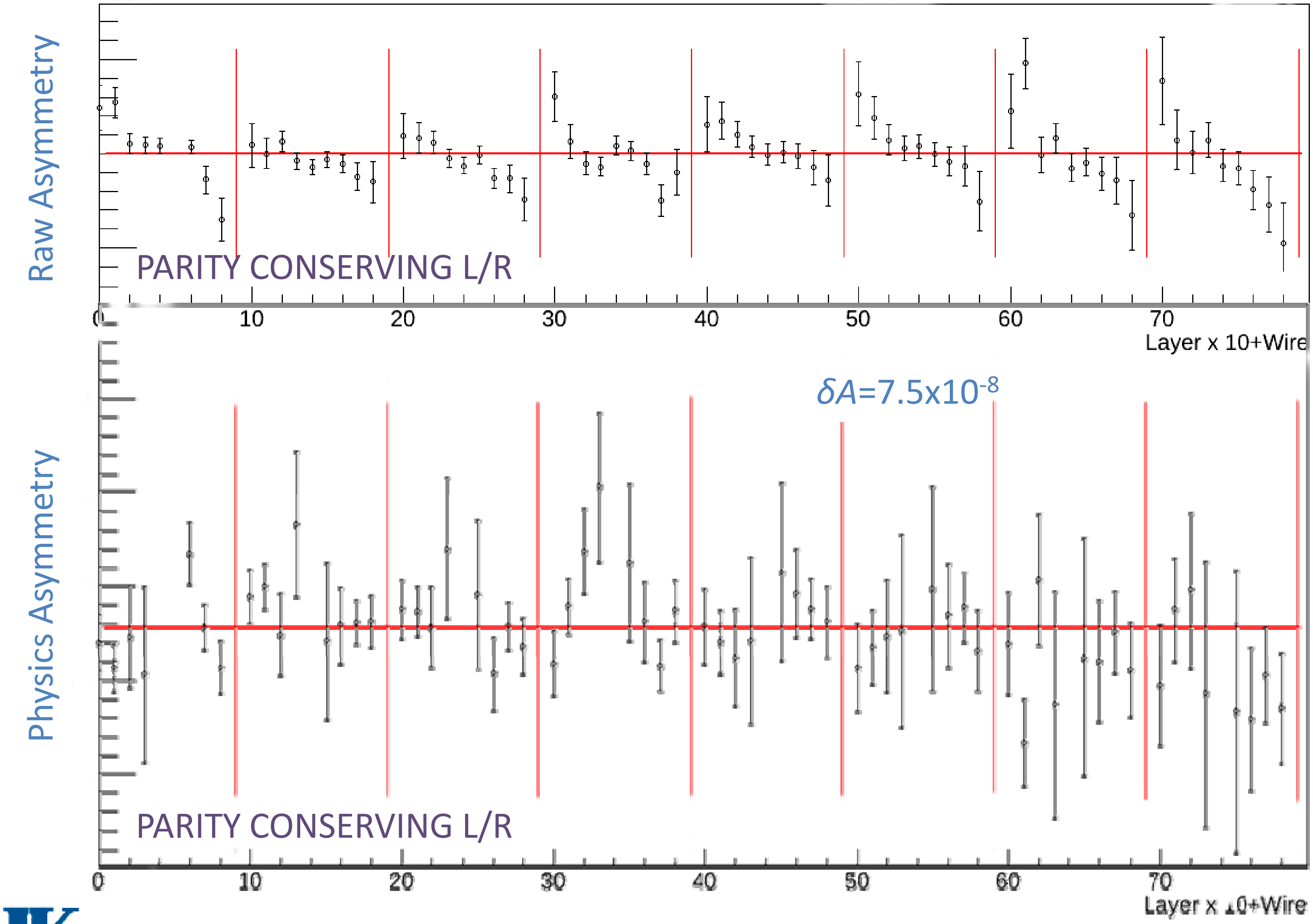


Electronic Tests:

Instrumental false asymmetry measurements:

$\delta A_{in}<(.12\pm.07)\text{x}10^{-8}$

Preliminary L/R asymmetries



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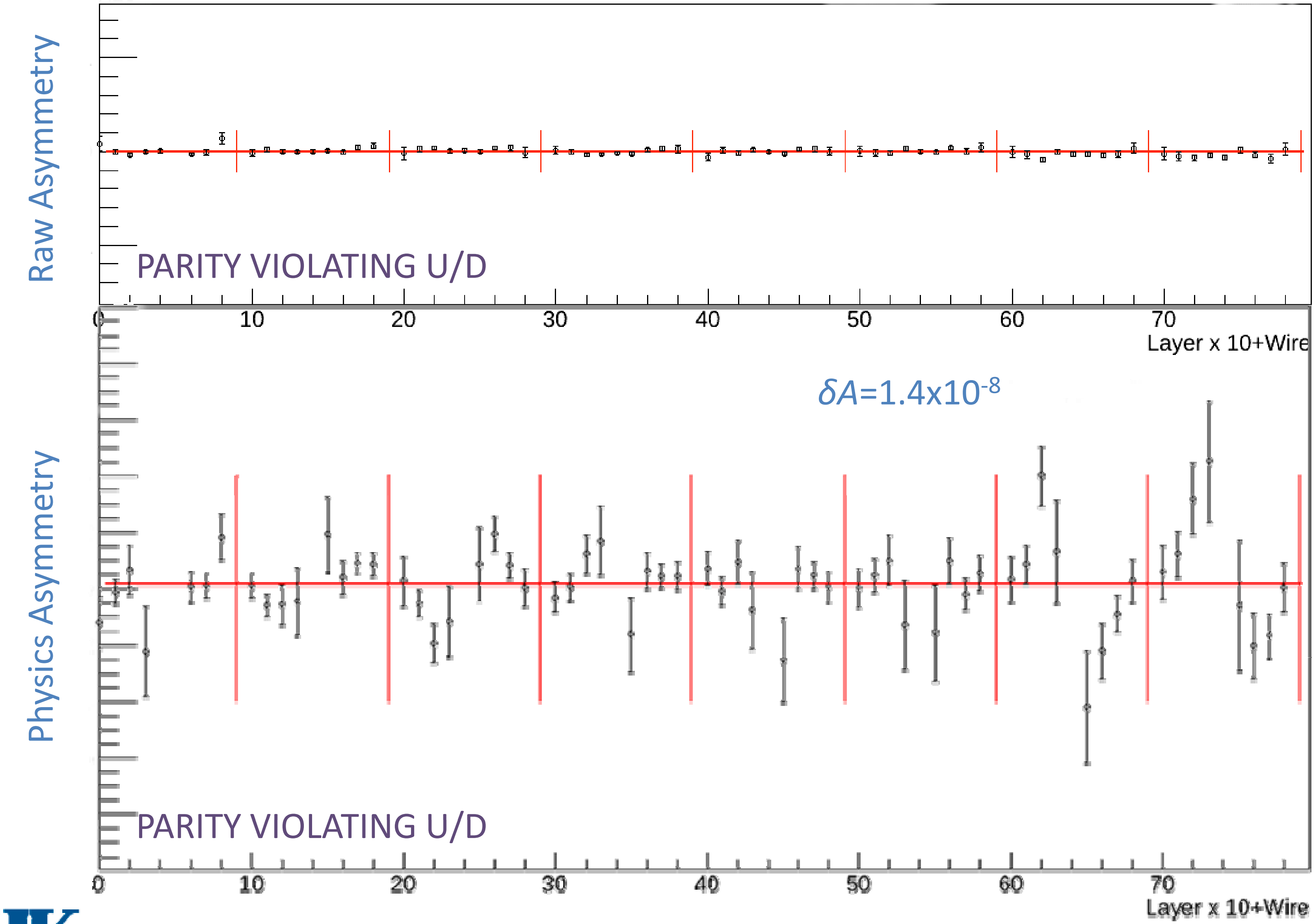
Preliminary U/D asymmetries

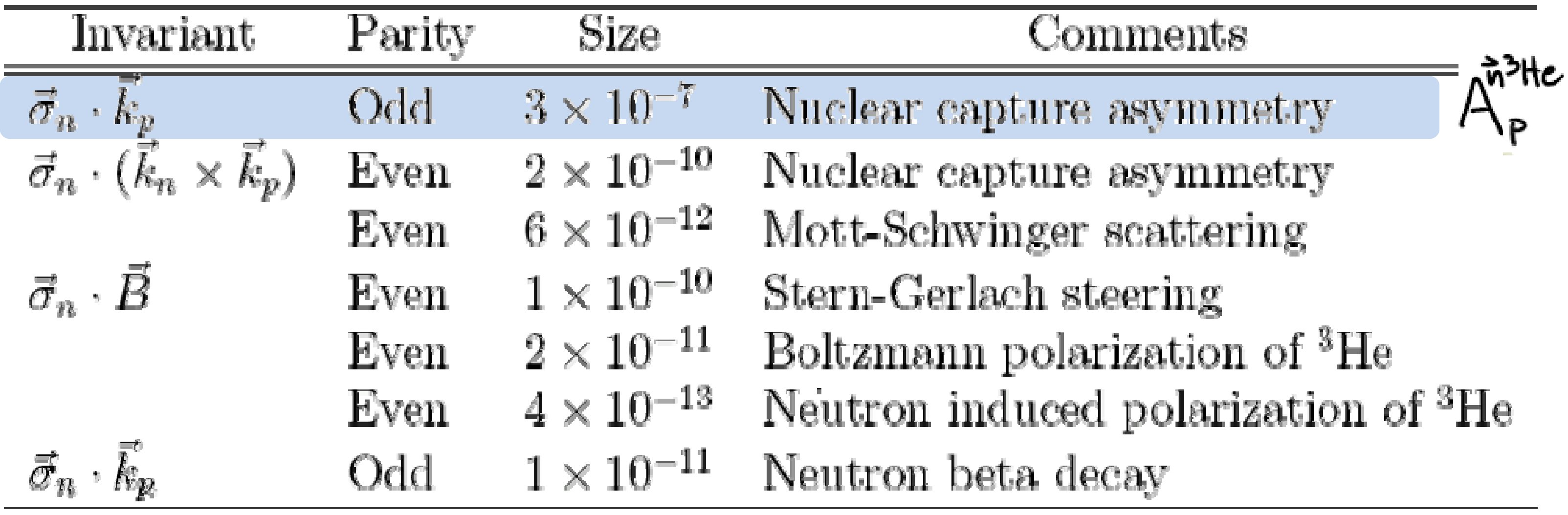


δA=1.4x10^{-8}

Systematic uncertainties

- Beam fluctuations, polarization, RFSF efficiency:
- $k_n r \sim 10^{-5}$ small for cold neutrons
- PC asymmetries minimized with longitudinal polarization
- Alignment of field, beam, and chamber to 10 mrad is achievable
- Unlike n p –> d γ or n d –> t γ,
  n-^{3}He is very insensitive to gammas (only Compton electrons)

$$A_{exp} = \frac{A_b + PA}{1 + A_p PA}$$



Invariant	Parity	Size	Comments
$\vec{\sigma}_n \cdot \vec{k}_p$	Odd	3×10^{-7}	Nuclear capture asymmetry
$\vec{\sigma}_n \cdot (\vec{k}_n \times \vec{k}_p)$	Even	2×10^{-10}	Nuclear capture asymmetry
	Even	6×10^{-12}	Mott-Schwinger scattering
$\vec{\sigma}_n \cdot \vec{B}$	Even	1×10^{-10}	Stern-Gerlach steering
	Even	2×10^{-11}	Boltzmann polarization of ^{3}He
	Even	4×10^{-13}	Neutron induced polarization of ^{3}He
$\vec{\sigma}_n \cdot \vec{k}_p$	Odd	1×10^{-11}	Neutron beta decay

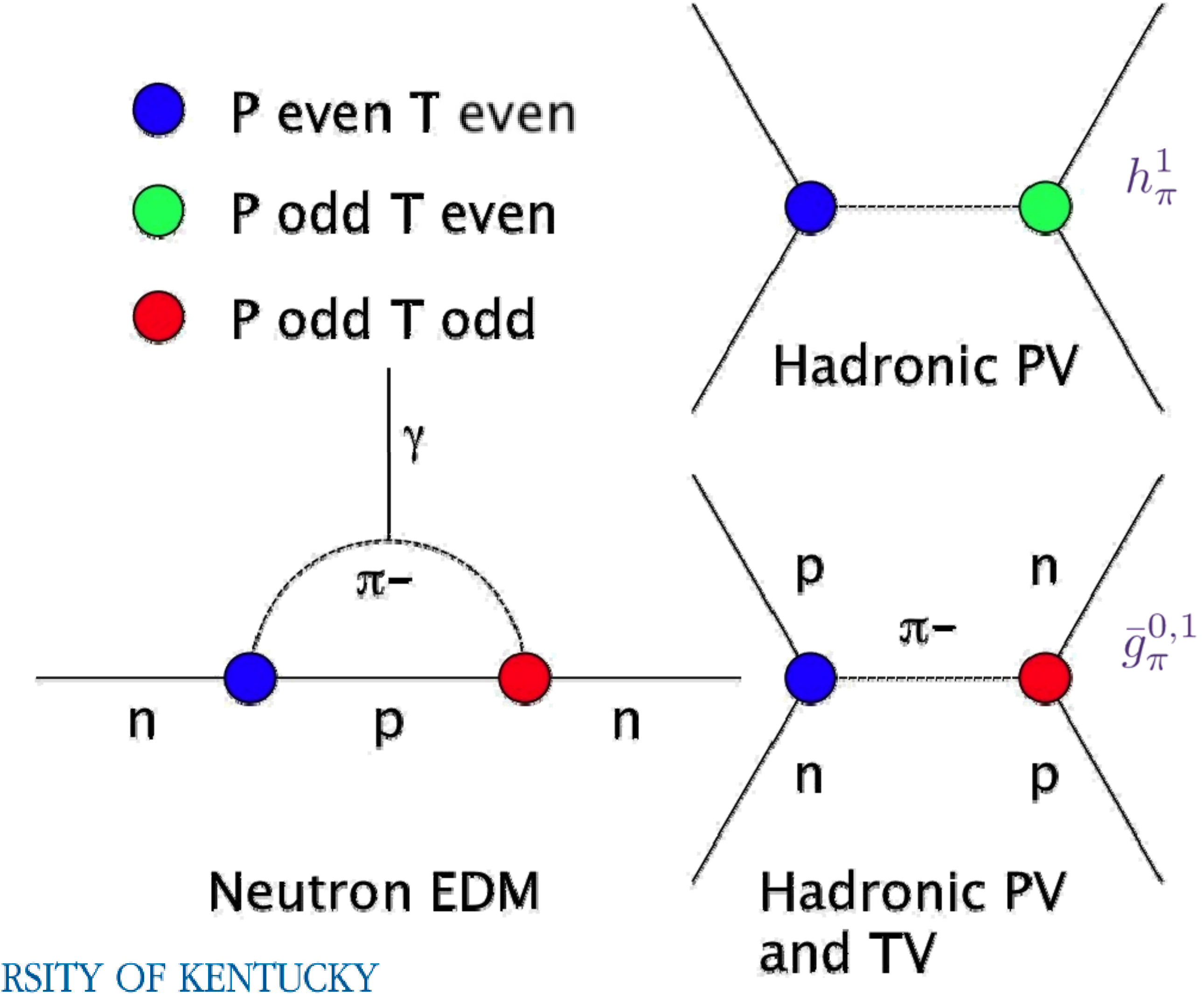
$A_P^{\vec{n}\,{}^3He}$

Relation between HPV and EDMs

- Tree level diagrams

Bowman, Gudkov, PRC 90, 065503 (2014)

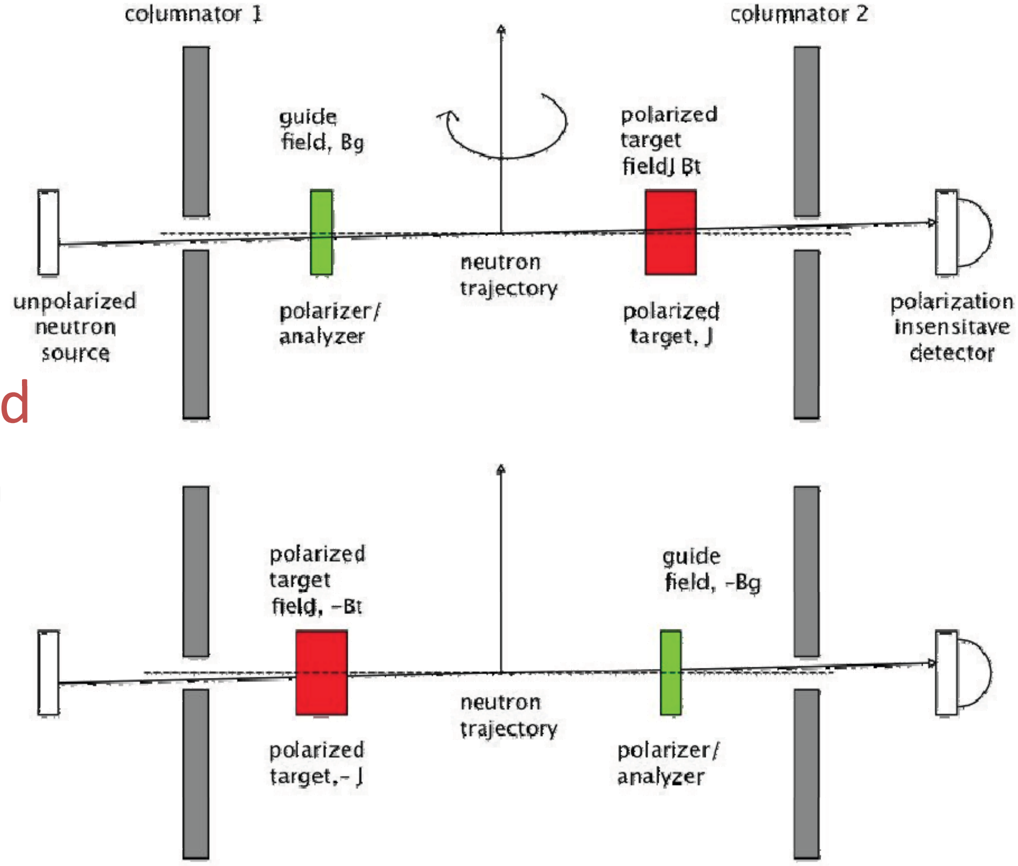
$$\frac{d\sigma_{TP}}{d\sigma_P} = k_0 \frac{\bar{g}_\pi^0}{h_\pi^1} + k_1 \frac{\bar{g}_\pi^1}{h_\pi^1}$$



Future HWI symmetry measurements

- T-violating neutron transmission (0°) through polarized nuclei
  - Amplification factors of 10^5–10^6 in heavy nuclei: ^{139}La, ^{131}Xe, and ^{81}Br
  - Complementary with searches for EDMs
  - Alignment errors cancel by rotating both target and analyzer

Bowman, Gudkov, PRC **90**, 065503 (2014)



- LANSCE beam time awarded
  - To investigate TOF resolution
  - 48 m beamline with single-crystal monochromator

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Conclusion

Hadronic Parity Violation

- We are very close to a full complement of few-body HPV observables
- Using **pp** (45MeV), **pp** (220 MeV), **NPDGamma**, **n-^{3}He**, **NSR-III**, we can test the self-consistency of HWI formalisms

NPDGamma Experiment

- Sensitive to long-range h^1_π
- Estimated sensitivity δA=1.3x10^{-8}
- Finalizing Al background analysis

n-3He Experiment

- Finalizing geometry factors
- Sensitive to h^1_π, also h^0_ρ, h^0_ω
- Estimated sensitivity δA=1.4x10^{-8}

On the horizon …

- Time-reversal invariance violation

Thank you!

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