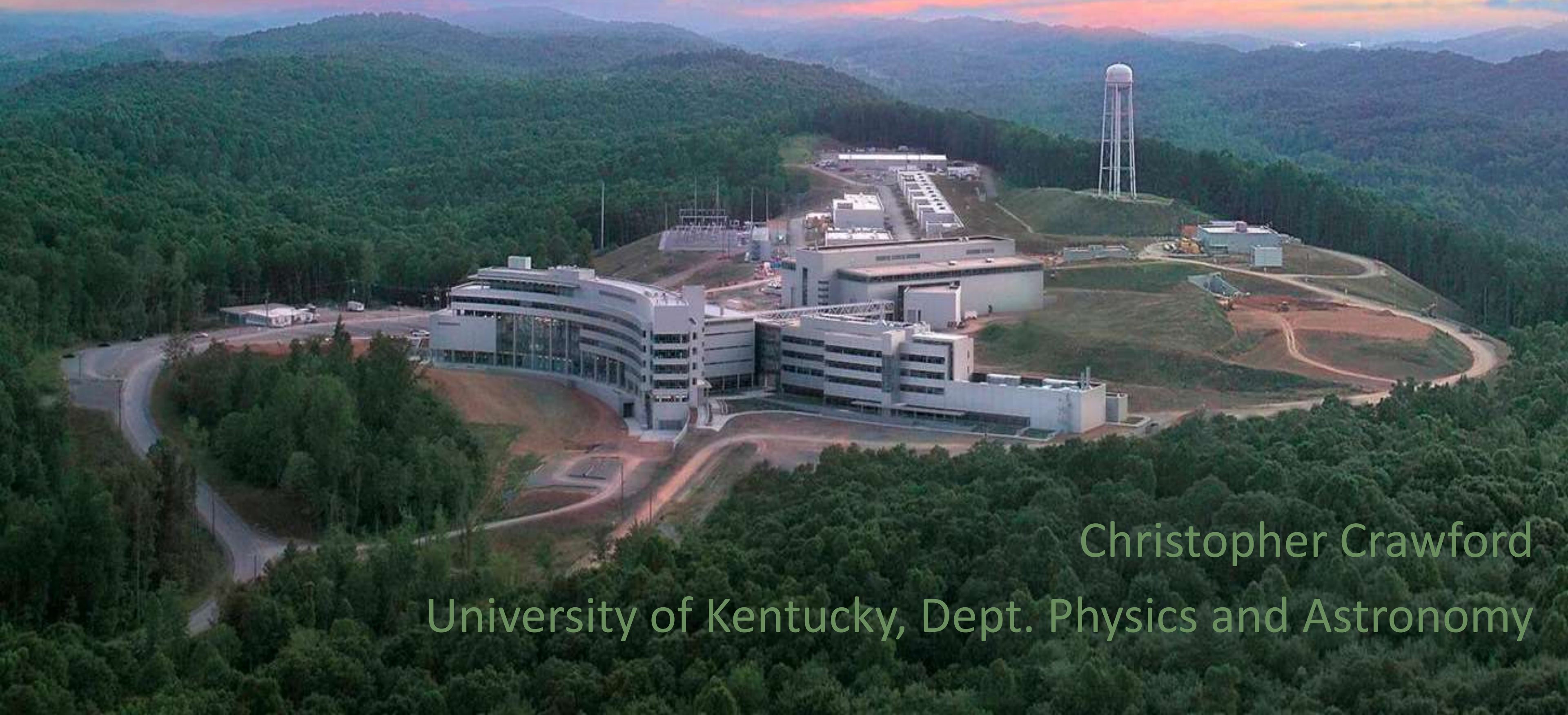
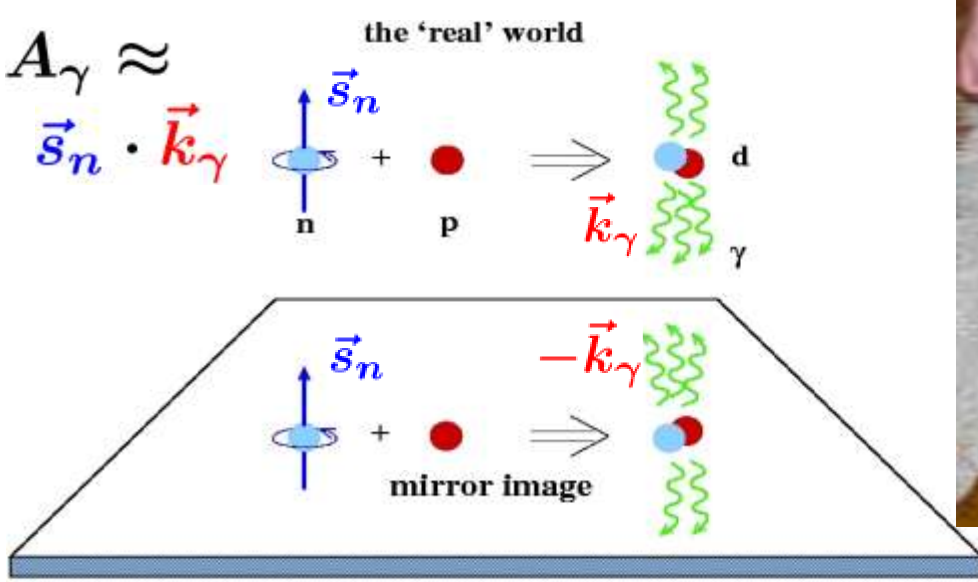
New Results from the NPDGamma Parity Violation Experiment at the Spallation Neutron Source



Christopher Crawford
University of Kentucky, Dept. Physics and Astronomy

Hadronic Parity Violation – Outline

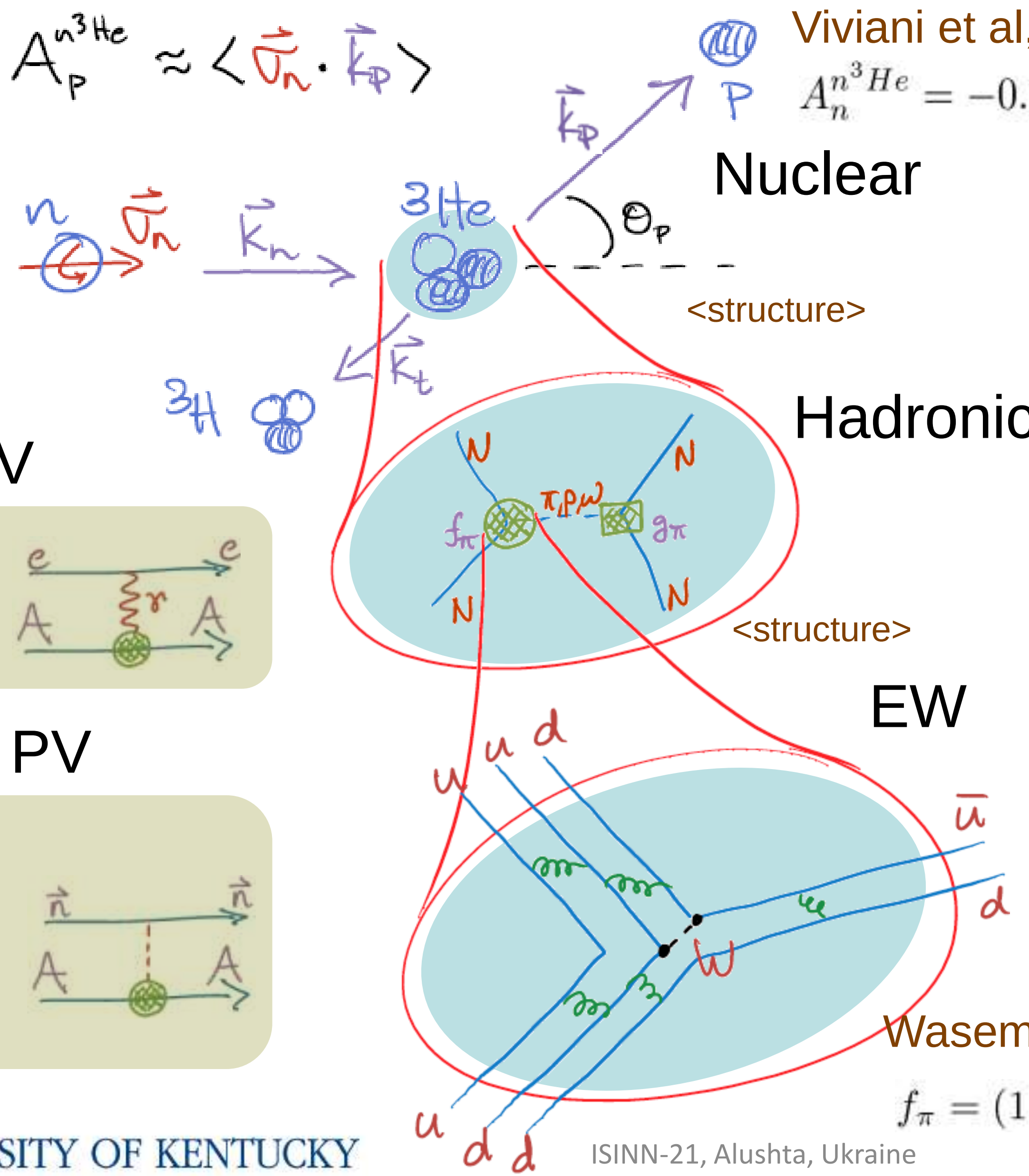
- Hadronic Parity Violation
  - Hadronic Weak Interaction
  - Existing HPV Data
- New Experiments at the SNS
  - NPDGamma experiment
  - n-^{3}He experiment



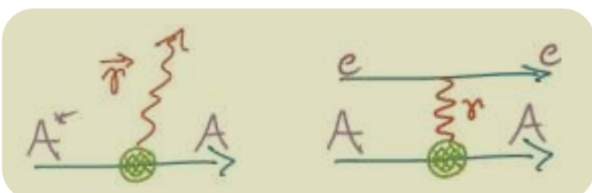
Hadronic Weak Interaction in a nutshell

Viviani et al, PRC 82 (2010), 044001

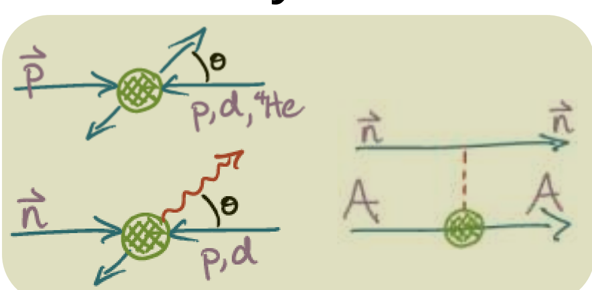
$$A_n^{n^3He} = -0.189 f_\pi - 0.036 h_\rho^0 - 0.033 h_\omega^0$$

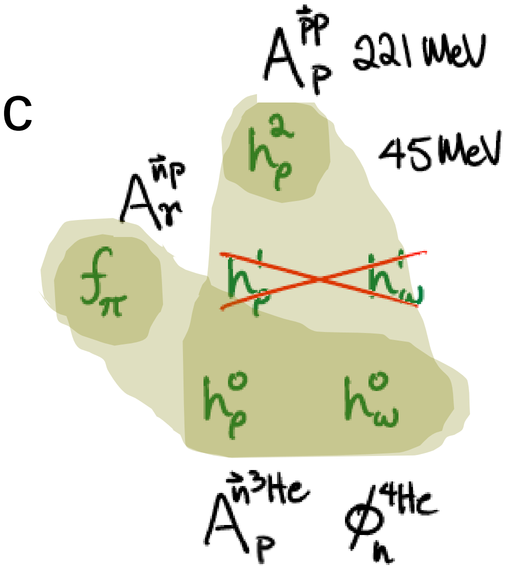


Nuclear PV



Few-body PV



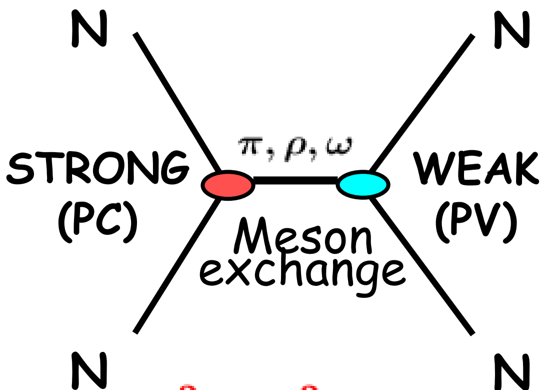


Wasem, PRC 85 (2012), 022501

$$f_\pi = (1.099 \pm 0.505^{+0.058}_{-0.064}) \times 10^{-7}$$

DDH Potential

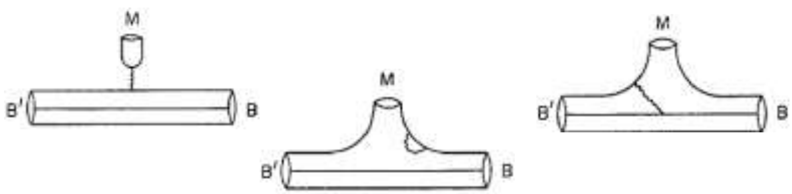
PV meson exchange



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

isospin	f_π	h'^1_ρ	$h^{0,1,2}_\rho$	$h^{0,1}_\omega$
$\Delta I = 0$			$(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$	(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	$(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)\left[\frac{\boldsymbol{p}_1 - \boldsymbol{p}_2}{2M}, \frac{e^{-m_\pi r}}{4\pi r}\right]$		
$m_\rho = m_\omega$	$(\boldsymbol{\sigma}_1 + \boldsymbol{\sigma}_2)\left[\frac{\boldsymbol{p}_1 - \boldsymbol{p}_2}{2M}, \frac{e^{-m_\rho r}}{4\pi r}\right]$	$(\boldsymbol{\sigma}_1 \pm \boldsymbol{\sigma}_2)\left\{\frac{\boldsymbol{p}_1 - \boldsymbol{p}_2}{2M}, \frac{e^{-m_\rho r}}{4\pi r}\right\}$	
		$i(\boldsymbol{\sigma}_1 \times \boldsymbol{\sigma}_2)\left[\frac{\boldsymbol{p}_1 - \boldsymbol{p}_2}{2M}, \frac{e^{-m_\rho r}}{4\pi r}\right]$	

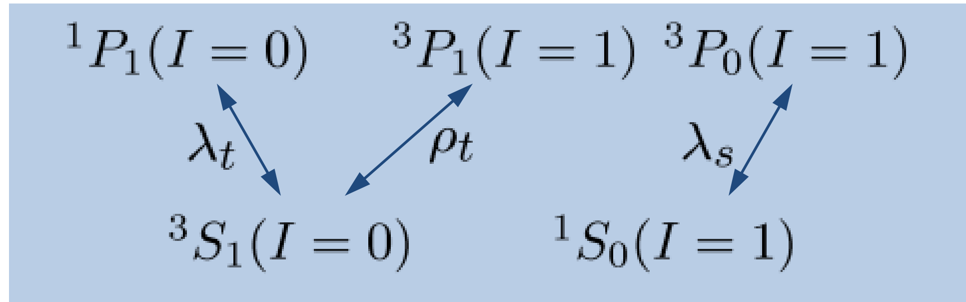


Cabibbo model	Reasonable range	"Best" value
f_π	$0 \to 1$	0.5
h_ρ^0	$15 \to -64$	-25
h_ρ^1	$0 \to -0.7$	-0.4
h_ρ^2	-58	-58
h_ω^0	$6 \to -22$	-6
h_ω^1	$0 \to -2$	-1

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

Danilov parameters / EFT

- Elastic NN scattering
  S-P transition (PV)
  S=1/2+1/2 , I=1/2+1/2
  Antisymmetric in L, S, I
  Conservation of J
- Equivalent to Effective Field Theory (EFT) in low energy limit



$$
\begin{array}{lcl}
\lambda_t & \propto & (C_1 - 3C_3) - (\tilde{C}_1 - 3\tilde{C}_3) \\
\lambda_s^0 & \propto & (C_1 + C_3) + (\tilde{C}_1 + \tilde{C}_3) \\
\lambda_s^1 & \propto & (C_2 + C_4) + (\tilde{C}_2 + \tilde{C}_4) \\
\lambda_s^2 & \propto & -\sqrt{8/3}(C_5 + \tilde{C}_5) \\
\rho_t & \propto & \frac{1}{2}(C_2 - C_4) + C_6 \quad .
\end{array}
$$

$$^3S_1 \longrightarrow {}^1P_1, \quad I=0$$

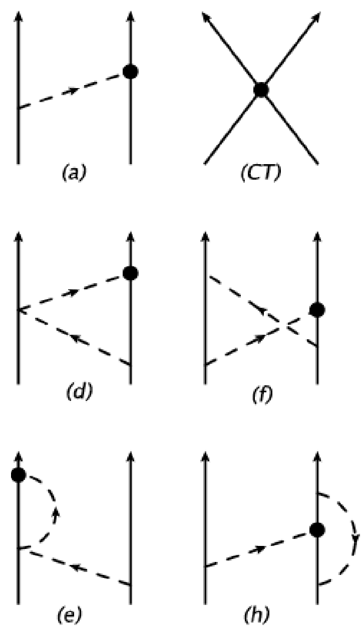
$$^1S_0 \longrightarrow {}^3P_0, \quad I=1$$

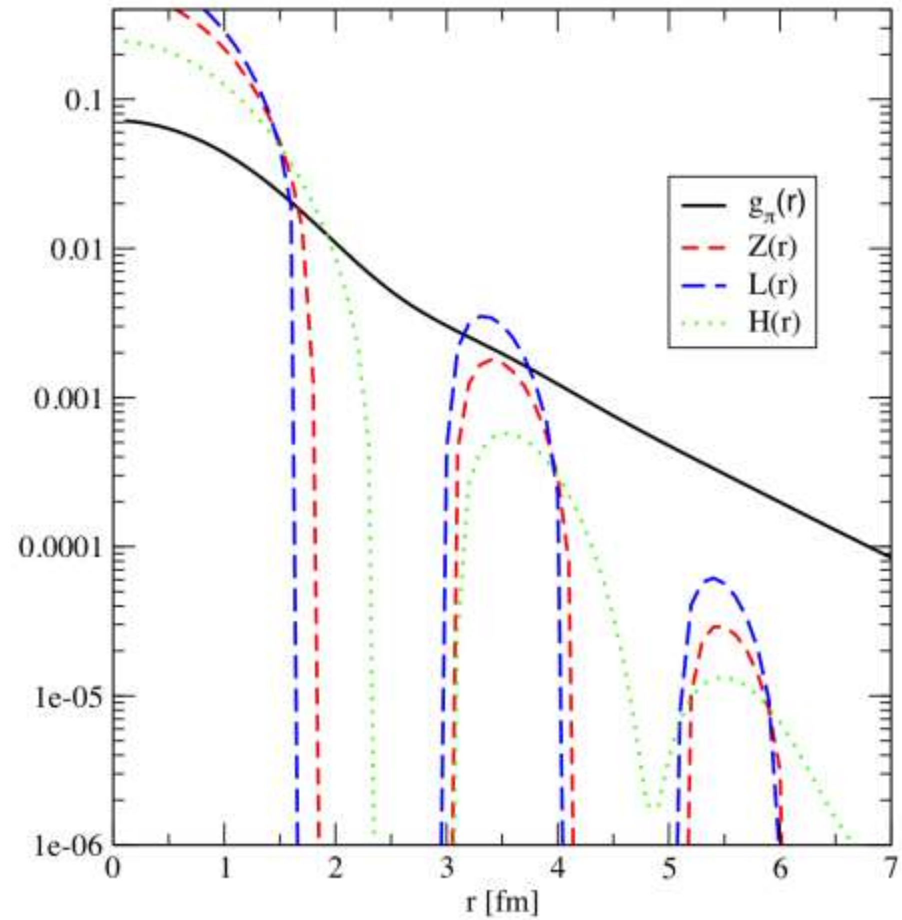
$$^3S_1 \longrightarrow {}^3P_1, \quad I=1 \rightarrow 0$$

C.-P. Liu, PRC 75, 065501 (2007)

EFT NN potential revisited to NNLO

- Viviani et al., preliminary (PAVI 11)
  - (a) Q^0 h^1_π $g_\pi(r)$
  - (CT) Q^1 $C_{1,2,3,4,5}$ Z(r)
  - (b,c) Q^2 zero
  - (e,h) Q^2 renorm./absorb in h^1_π
  - (d), Q^2 $h^1_{\pi+}C_3$ (triangle) L(r)
  - (f,g,g') Q^2 h^1_π (box) H(r)+L(r)





A_z^{n3He} (prelim) using N3LO (Emtem & Macheleidt) + 3N N2LO (Navratil)

Λ = 500: $\mathbf{a_0}$=-0.15 $\mathbf{a_1}$=.026 $\mathbf{a_2}$=.021 $\mathbf{a_3}$=0.11 $\mathbf{a_4}$=-.043 $\mathbf{a_5}$=-.0022

Existing HPV data

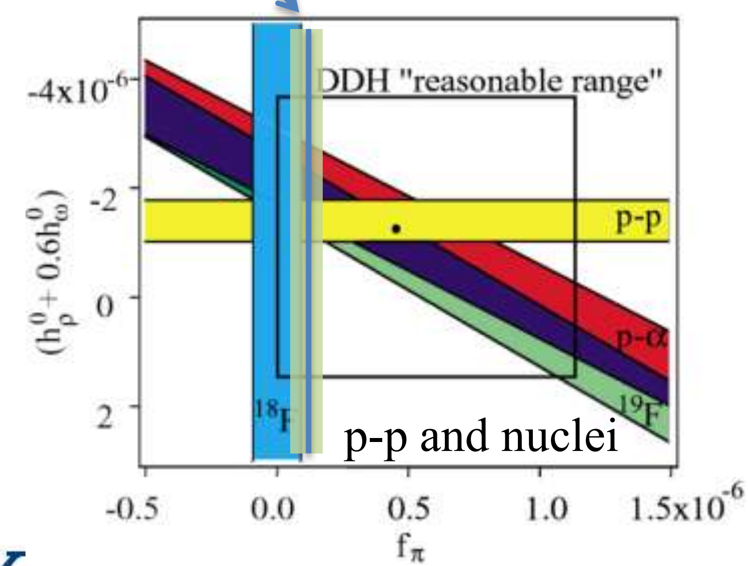
- p-p scat. 15, 45 MeV A_z^{pp}
- p-α scat. 46 MeV $A_z^{p\alpha}$
- p-p scat. 220 MeV A_z^{pp}
- n+p$\rightarrow$d+γ circ. pol. P_γ^d
- n+p$\rightarrow$d+γ asym. A_γ^d
- n-α spin rot. $d\phi^{n\alpha}/dz$

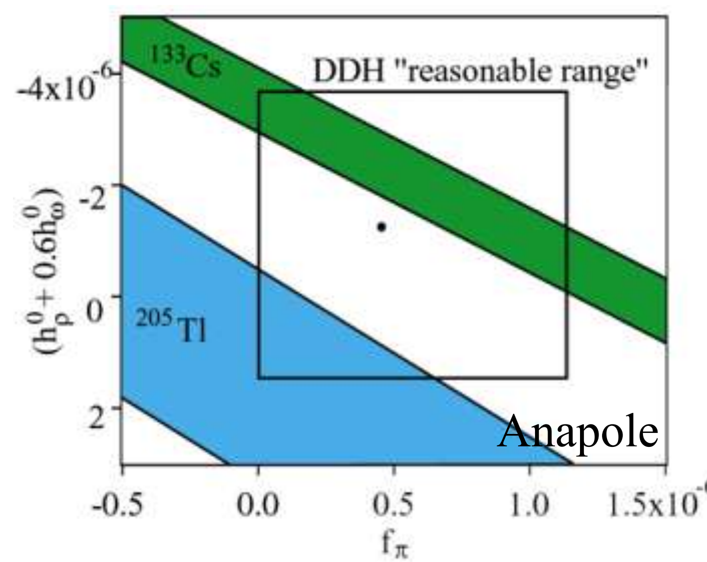
- ^{18}F asym. $\Delta I = 1$
- ^{19}F, ^{41}K, ^{175}Lu, ^{181}Ta asym.
- ^{21}Ne (even-odd)
- ^{133}Cs, ^{205}Tl anapole moment

GOAL – resolve coupling constants from few-body PV experiments only

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

$h^1_{\pi NN} = (1.099 \pm 0.505^{+0.058}_{-0.064})\ x10^{-7}$





Extraction of DDH couplings

	np A_γ	nD A_γ	n^{3}He 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_ρ^0		-0.50	-0.14	-0. 23	-0.32	0.08	0.14
h_ρ^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

E. G. Adelberger and W. C. Haxton. Parity Violation in the Nucleon-Nucleon Interaction. *Ann. Rev. Nucl. Part. Sci.*, 35:501–558, 1985.

n-^{3}He: M. Viviani (PISA), Phys. Rev. C **82** (2010) 044001

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

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[13]University of California at Berkeley
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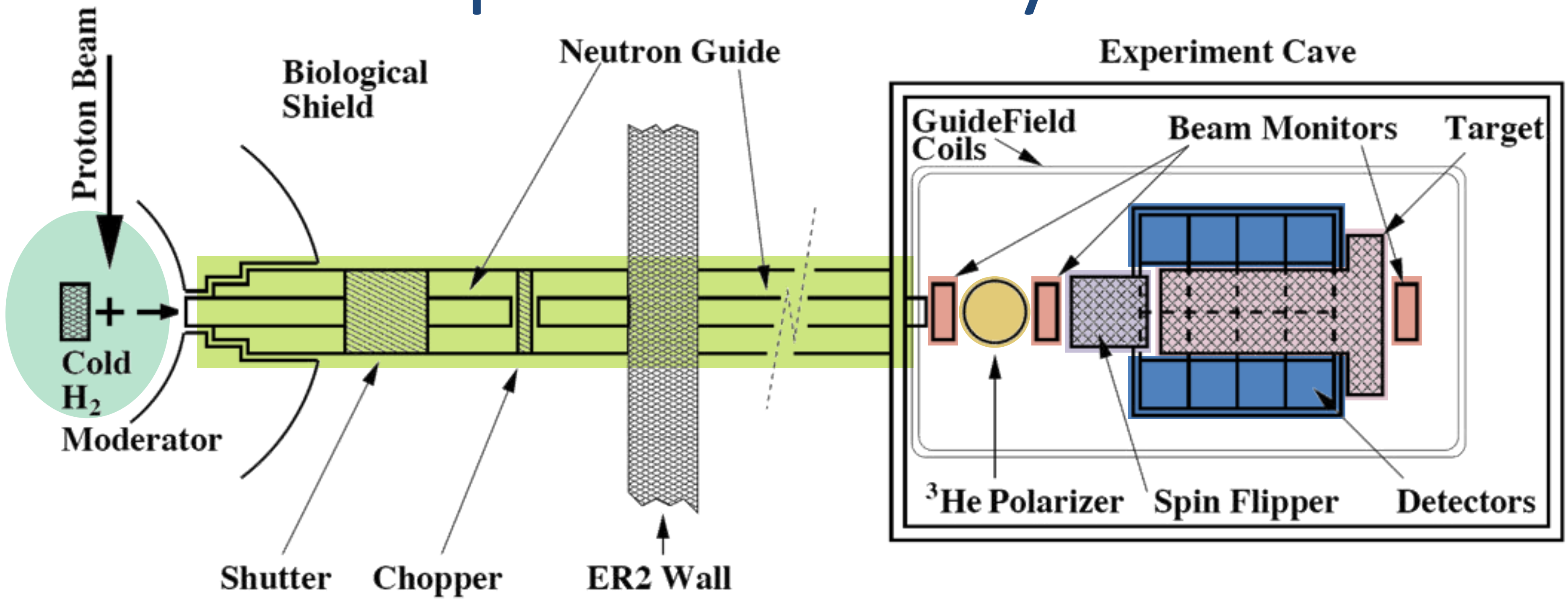
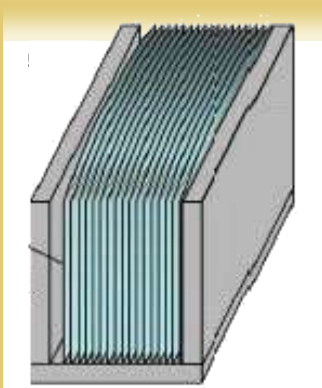
[16]Hamilton College
[17]Paul Scherer Institute, Switzerland
[18]Spallation Neutron Source
[19]University of California at Davis
[20]TRIUMF, Canada
[21]Bhabha Atomic Research Center, India
[22]Duke University
[23]Joint Institute of Nuclear Research, Dubna, Russia
[24]University of Dayton

Experimental Layout



Supermirror Polarizer



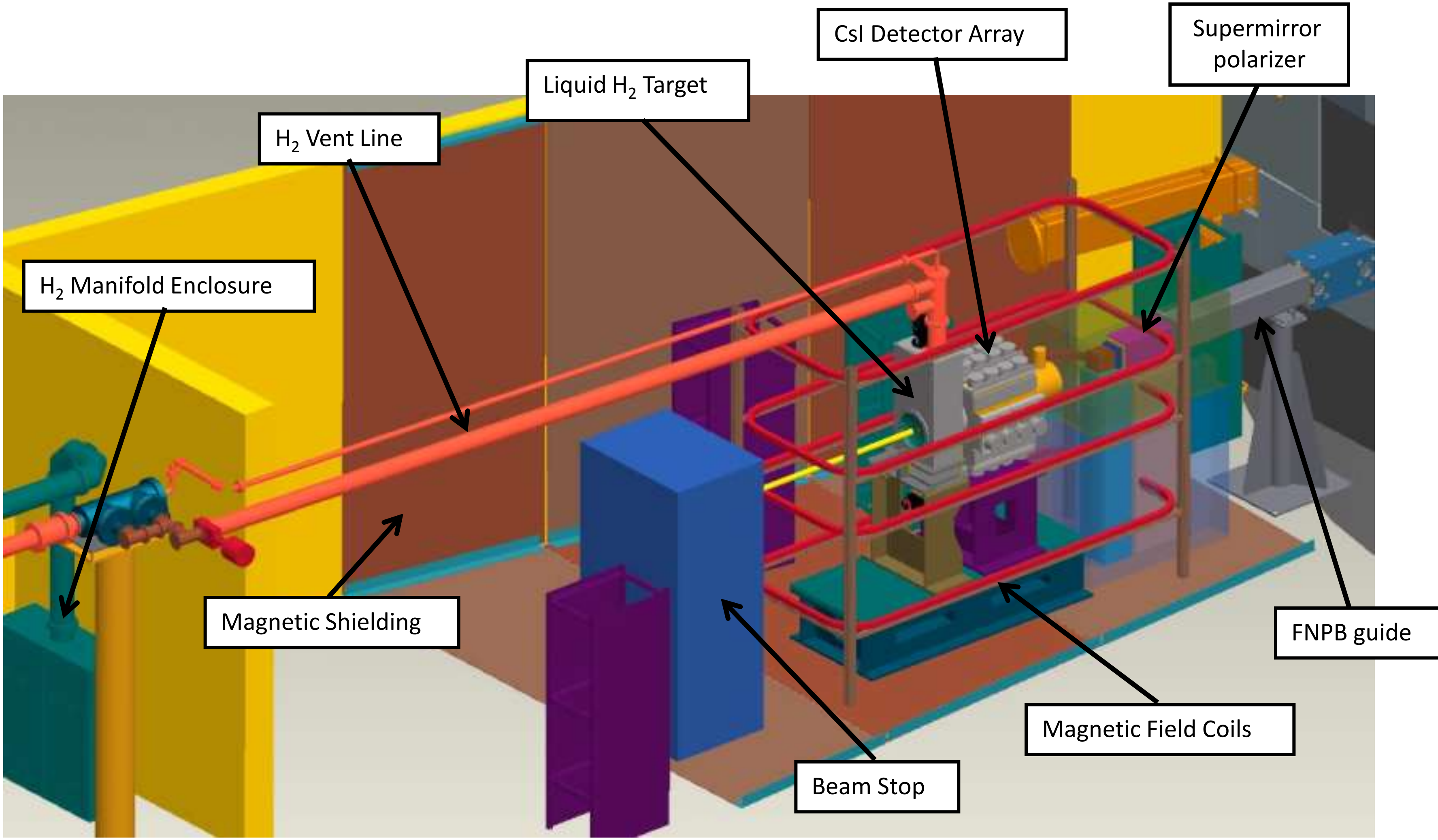
Beam Monitors

RF Spin Rotator

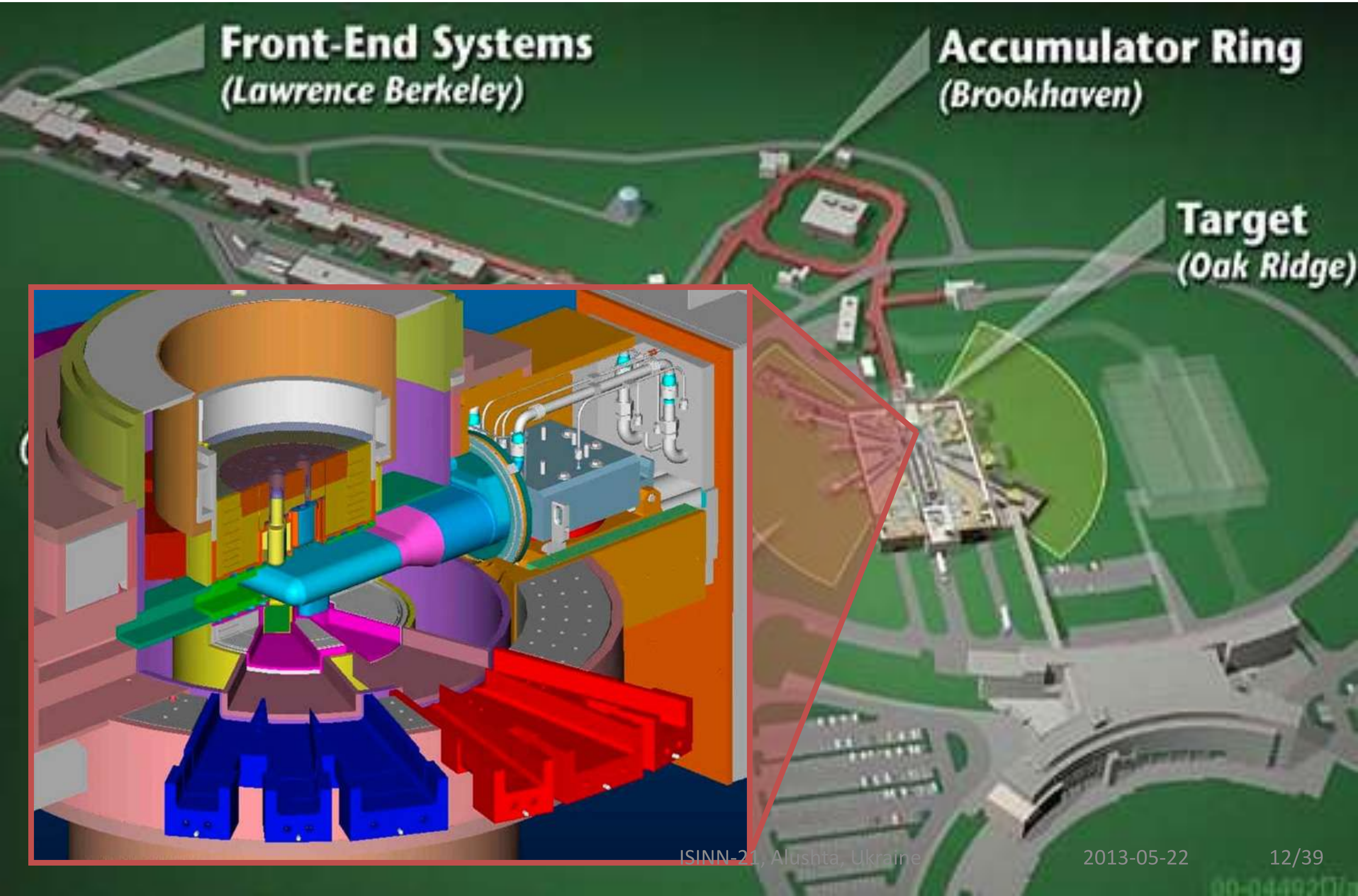
LH_2 Target

Gamma Detectors

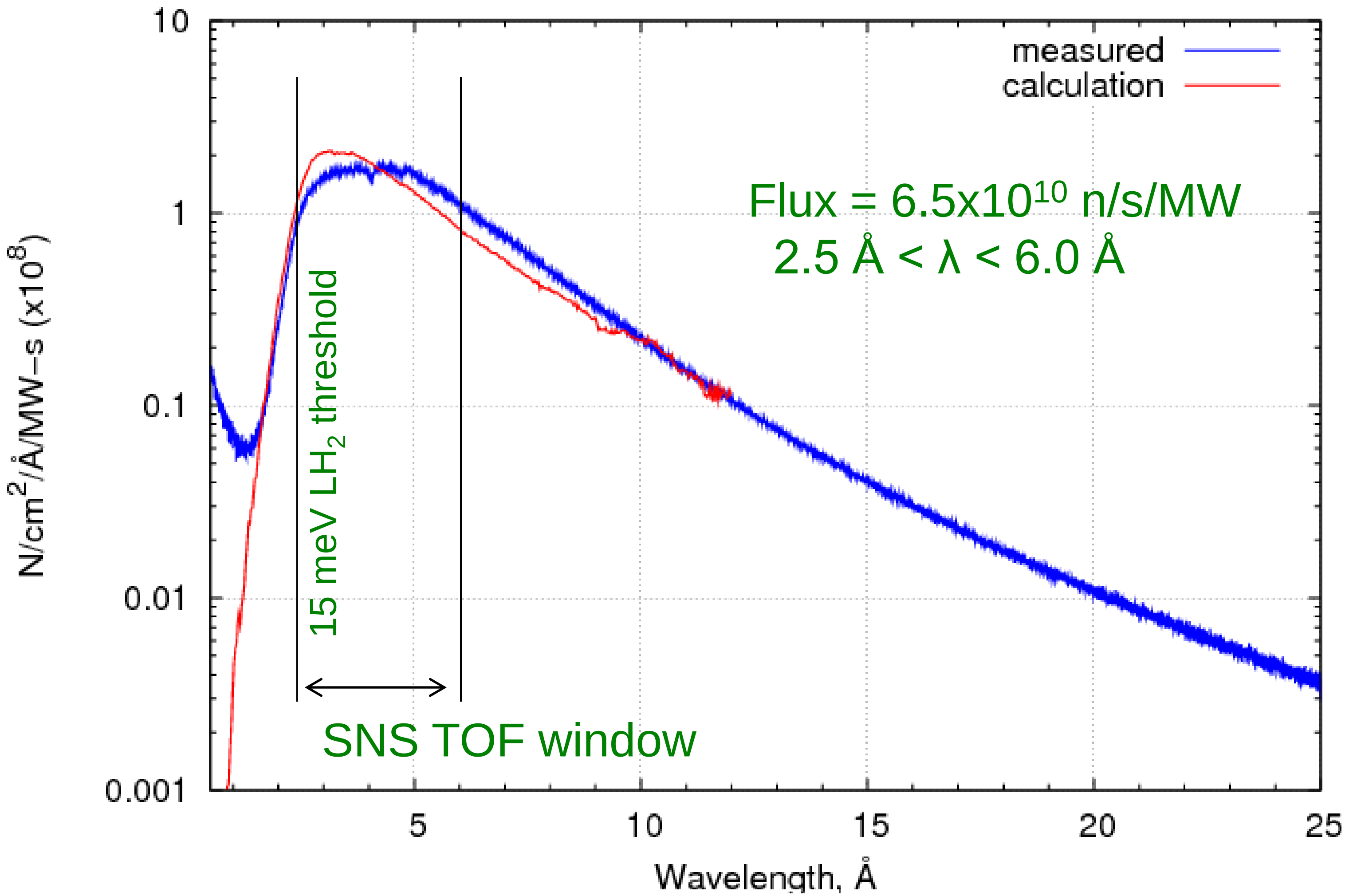
Experimental setup at the FnPB



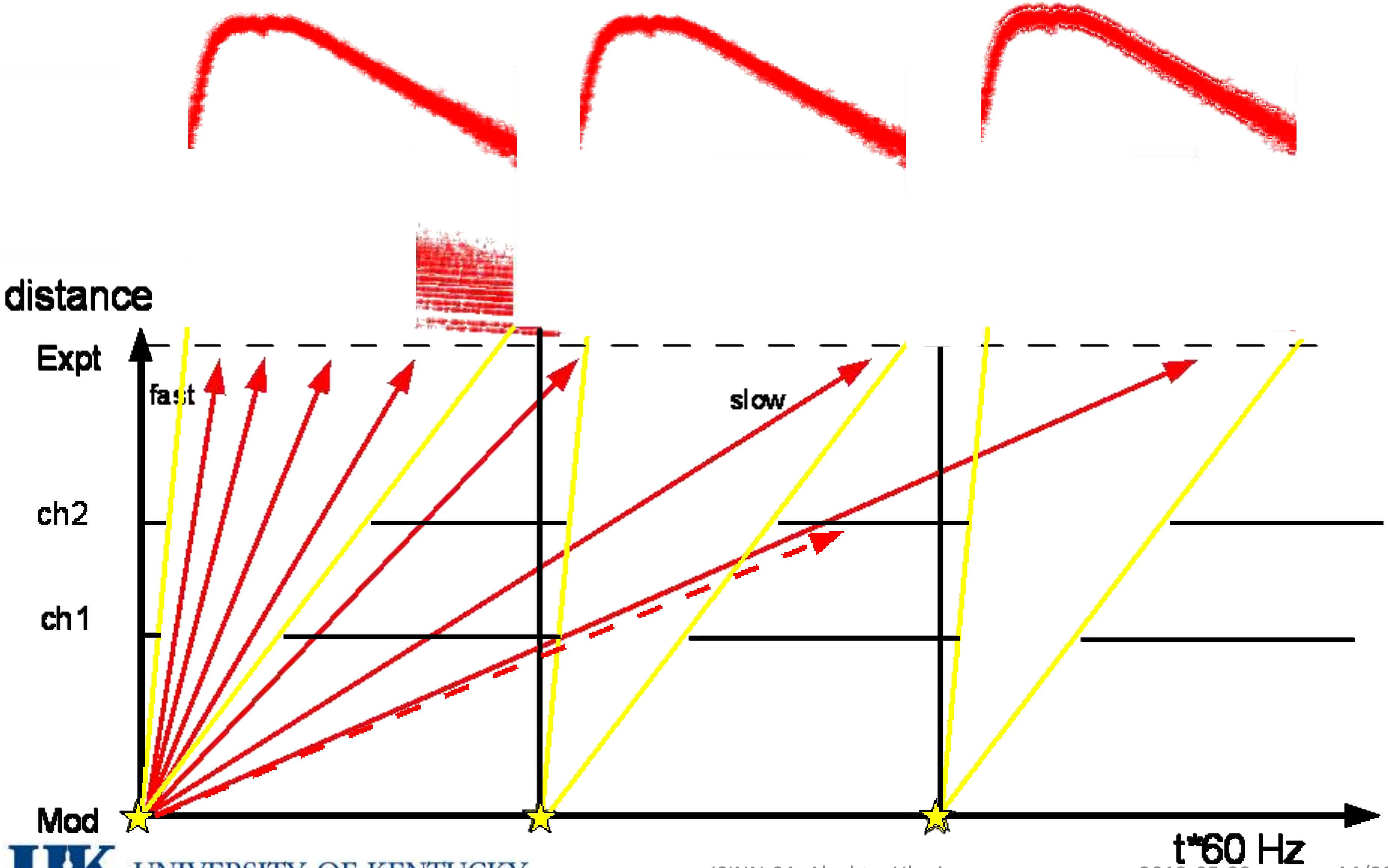
Spallation neutron source



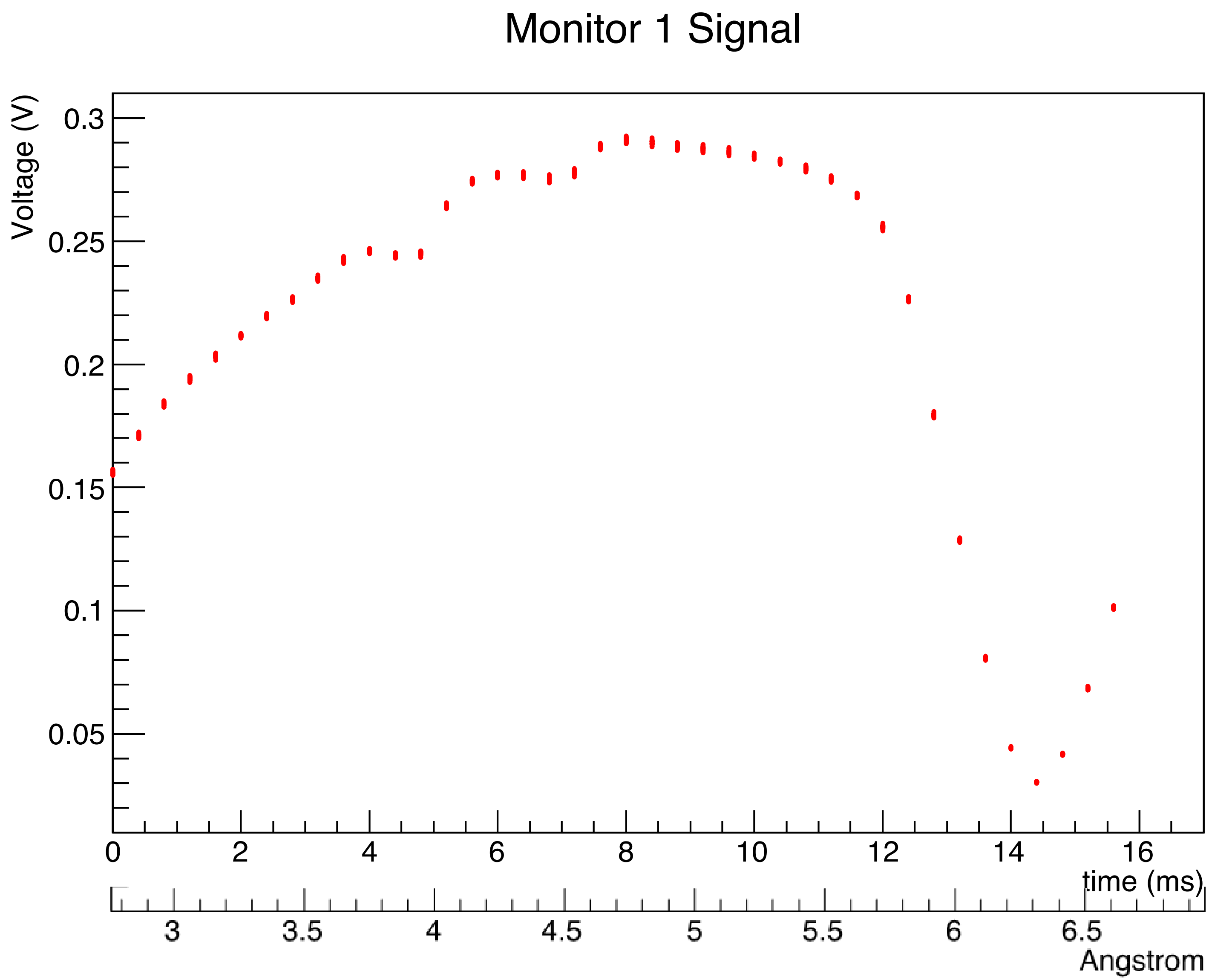
Neutron Flux at the SNS FnPB



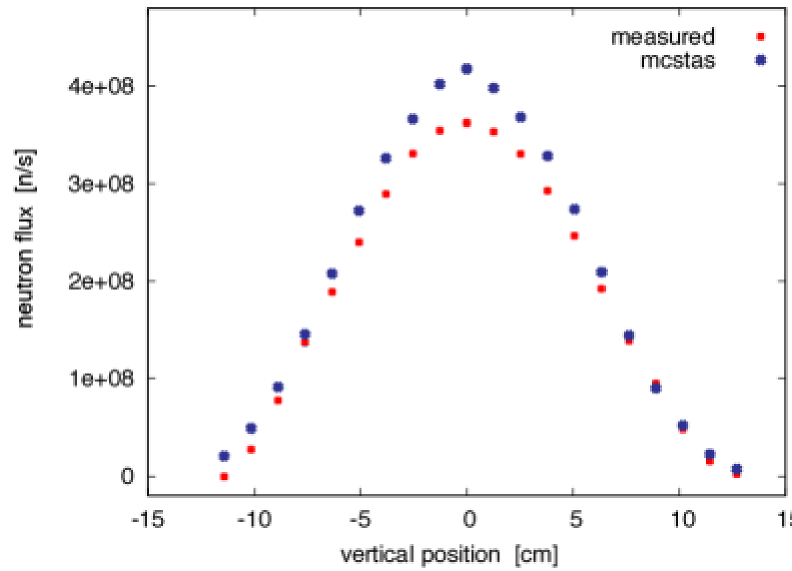
Time-of-flight choppers

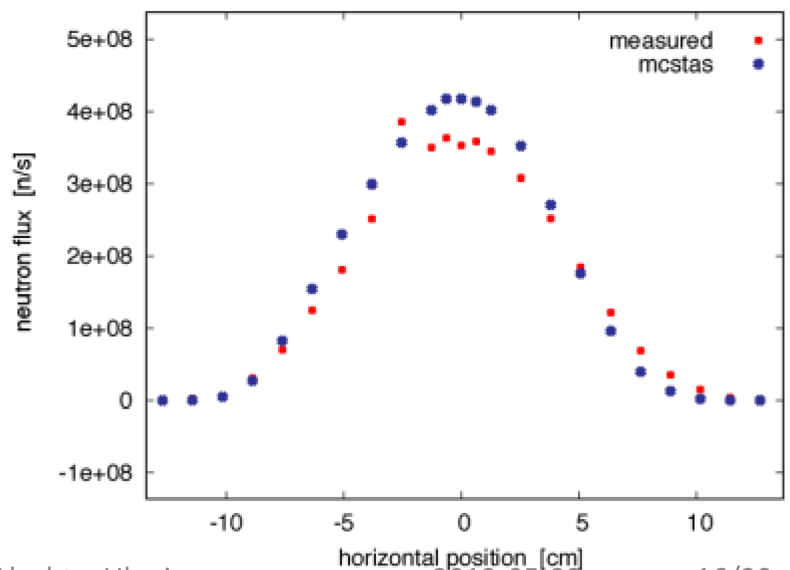


Chopped & folded spectrum

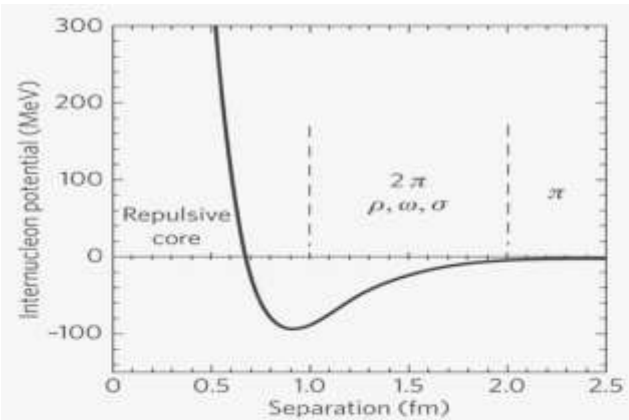


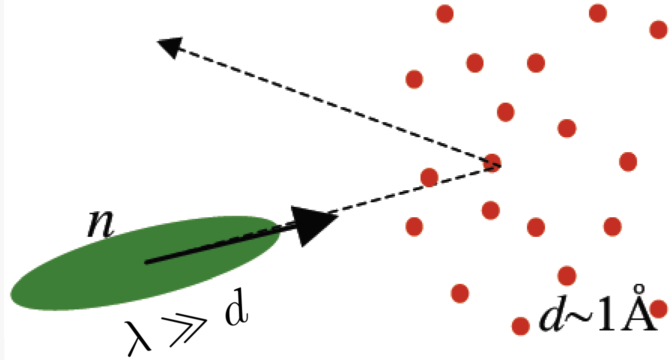
Measurement of Beam Flux and Profile



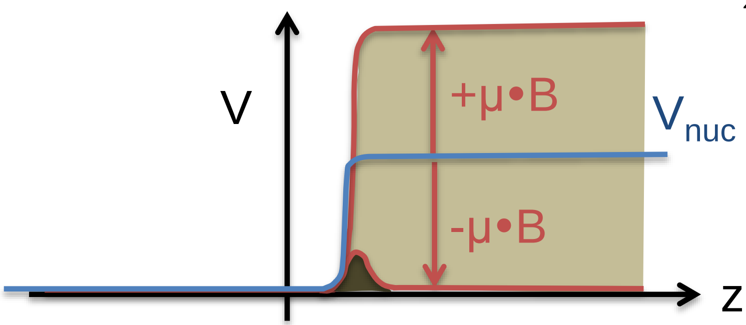


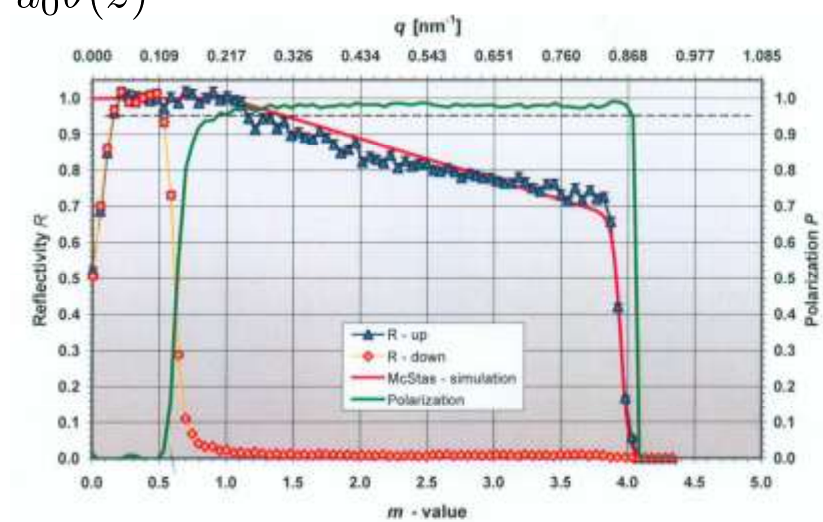
Nuclear interaction: neutron optics





- Fermi potential: $V_i(\boldsymbol{r}) = \dfrac{2\pi\hbar^2}{m_n} b\,\delta(\boldsymbol{r} - \boldsymbol{r}_i)$ $\quad b = b_{coh} + ib_{abs}$
- Optical potential: $V(\boldsymbol{r}) = \sum_i V_i(\boldsymbol{r}) \approx u_0\theta(z)$
- Index of refraction: $n = 1 - \dfrac{\lambda^2 b\rho}{2\pi}$

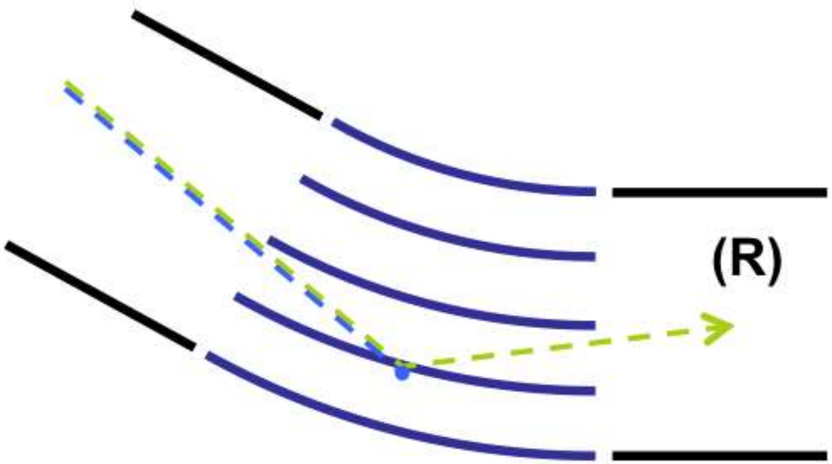


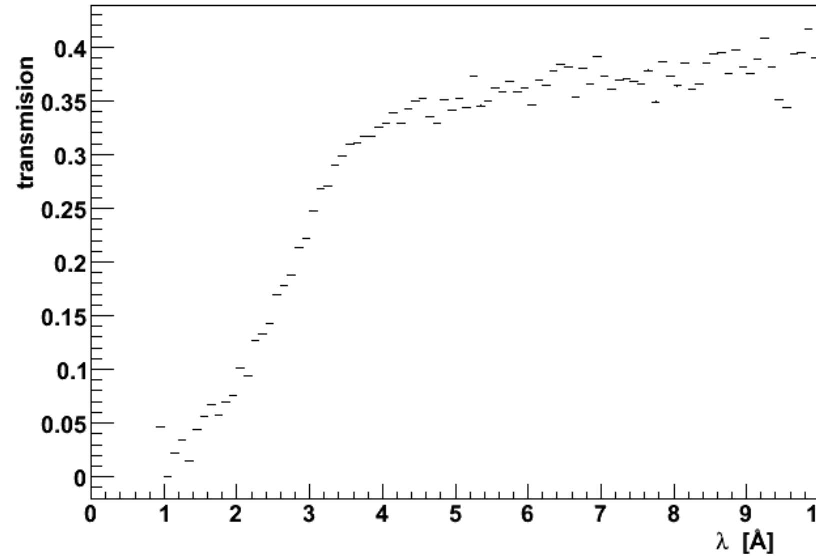


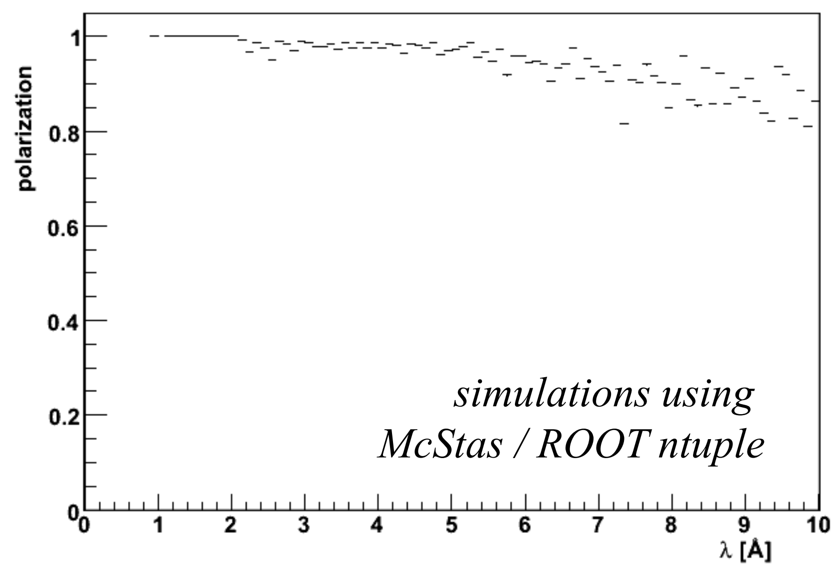
FnPB supermirror polarizer

Fe/Si on boron float glass, no Gd

m = 3.0	critical angle
n = 45	channels
r = 9.6 m	radius of curvature
l = 40 cm	length
d = 0.3mm	vane thickness
T=25.8%	transmission
P=95.3%	polarization
N=2.2£10^{10} n/s	output flux (chopped)

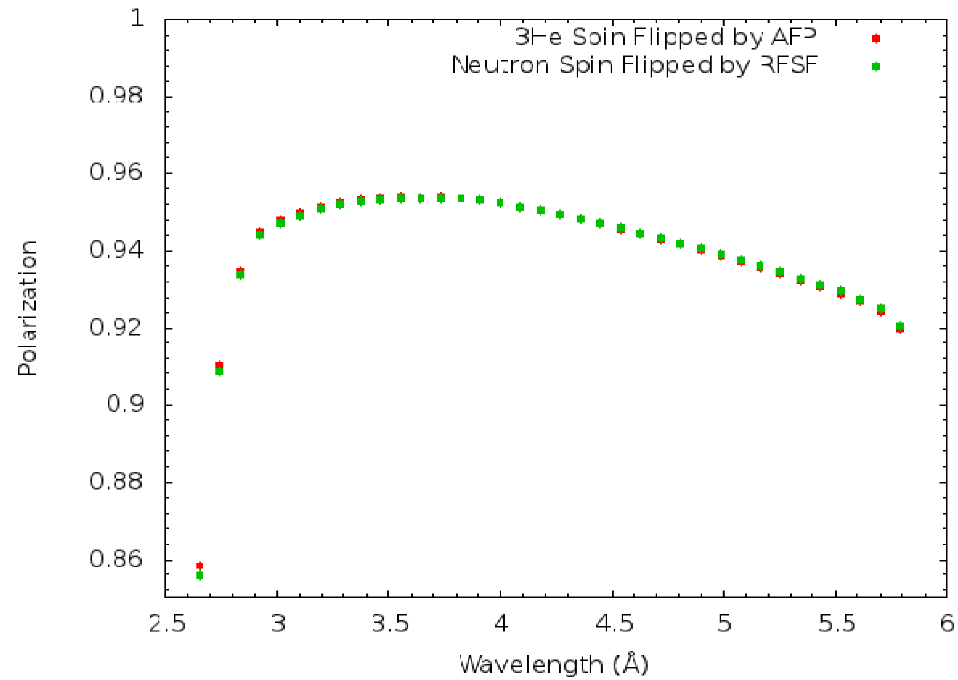


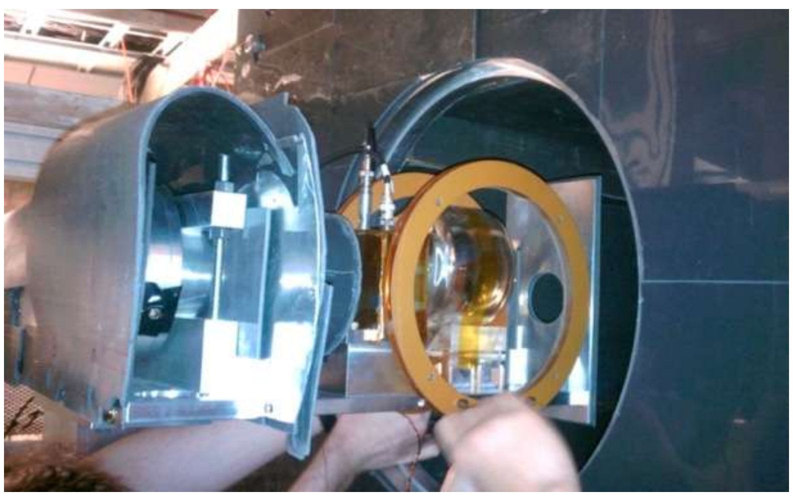


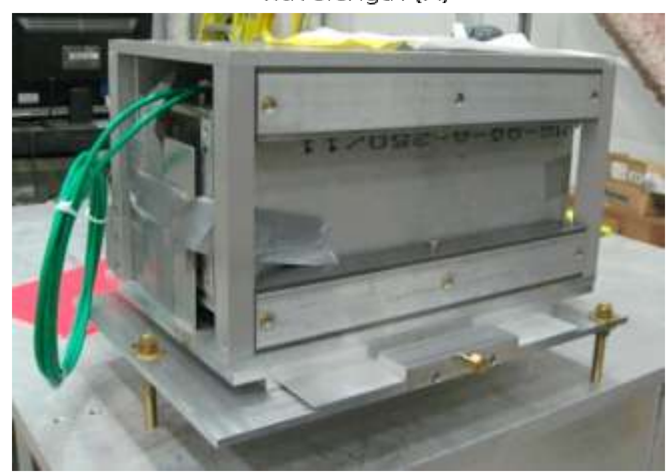


S. Balascuta, .., CBC, *et al.,* Nucl. Instr. Meth. **A671** 137 (2012)

Polarimetry – ^{3}He spin filter

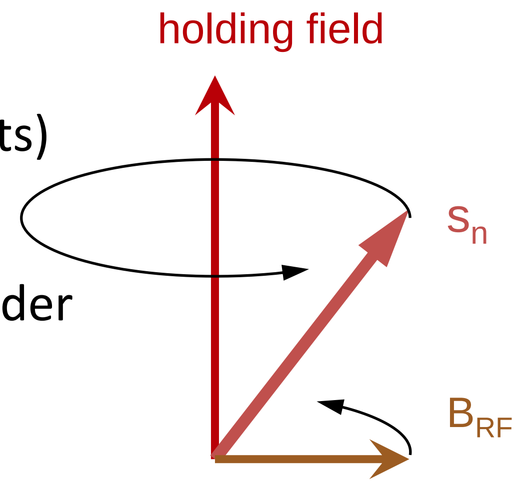


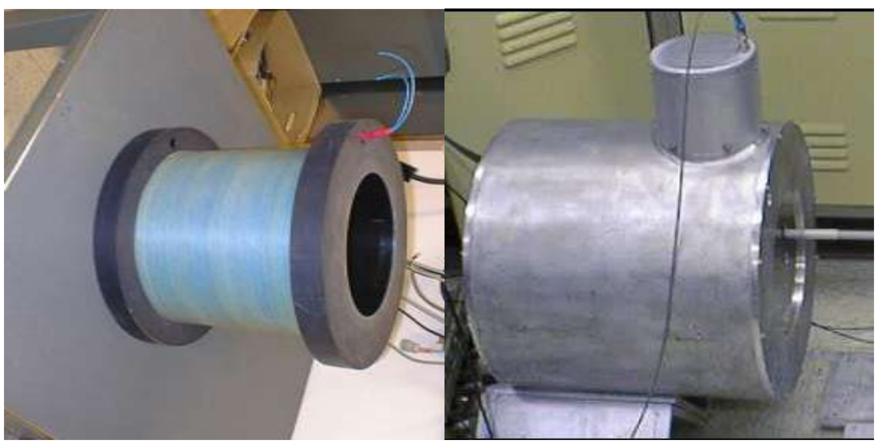


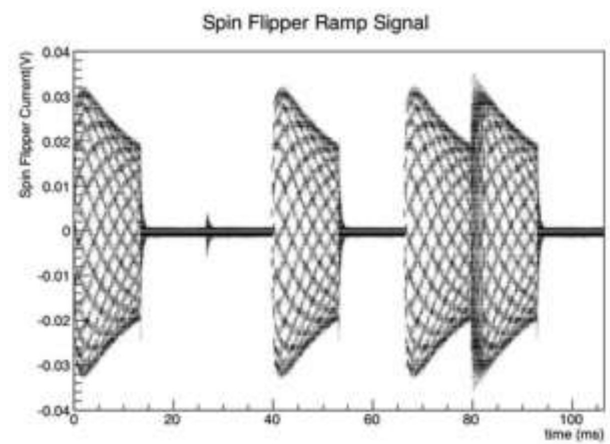


Longitudinal RF spin rotator

- Resonant RF spin rotator,
  - 1/t RF amplitude tuned to velocity of neutrons
  - Affects spin only – NOT velocity! (no static gradients)
- essential to reduce instrumental systematics
  - spin sequence: ↑↓↓↑ ↓↑↑↓ cancels drift to 2nd order
  - danger: must isolate fields from detector
  - false asymmetries: additive & multiplicave



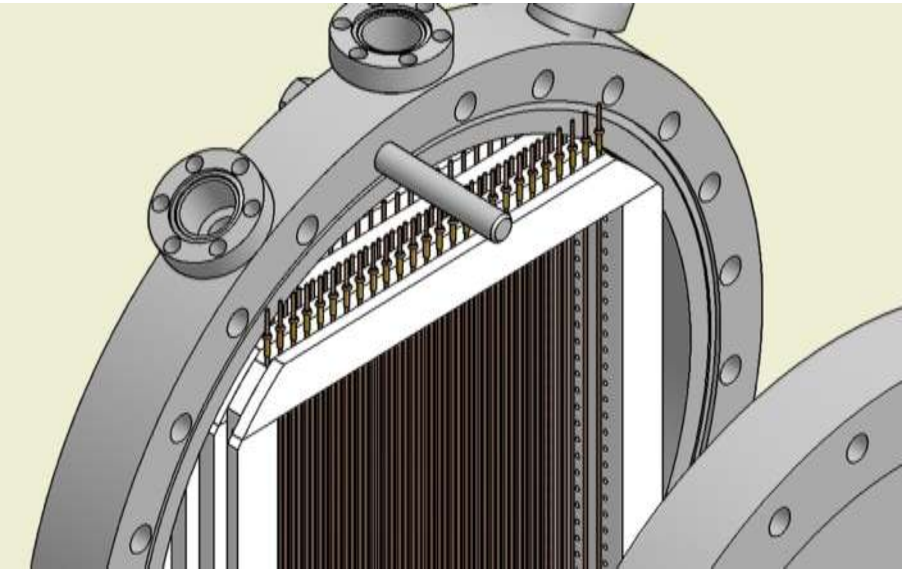




↓↑↑↓↑↓↓↑

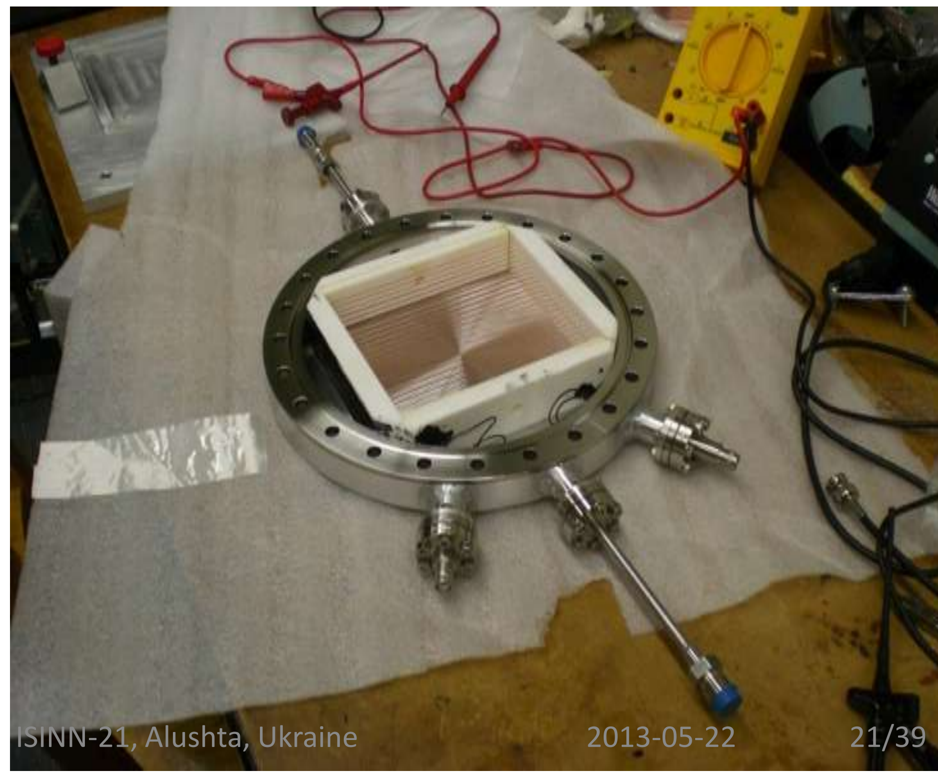
P. Neo-Seo, .., CBC, *et al.* Phys. Rev. ST Accel. Beams **11** 084701 (2008)

Neutron beam monitors

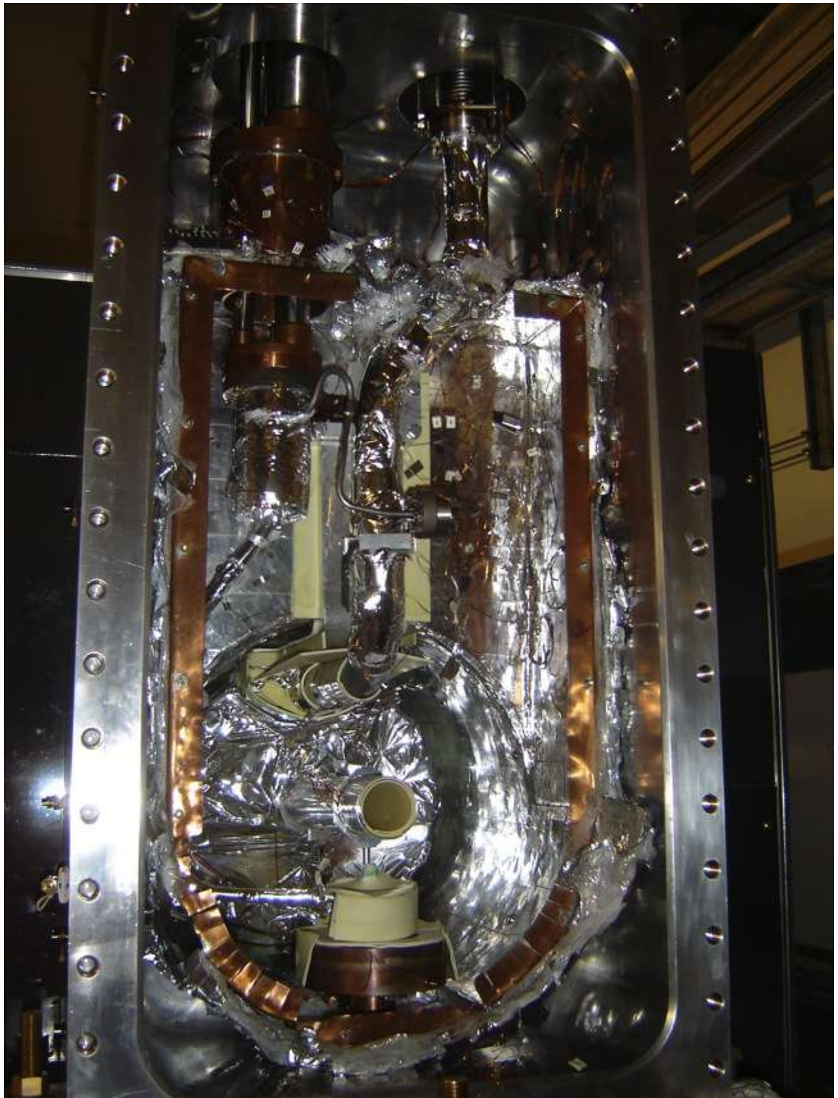


- Purpose:
  - Neutron Flux monitor
  - Neutron Polarimetry (in conjunction with ^{3}He analyzer)
  - Monitor ortho/para ratio in the target

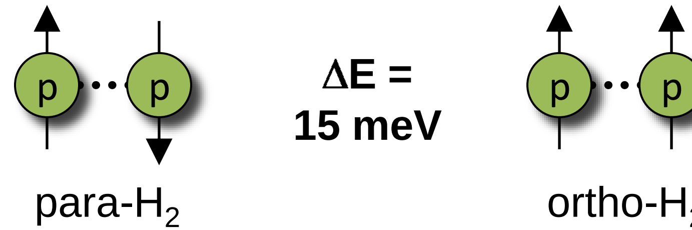
- Improvements:
  - Larger beam cross section
  - Wires electrodes instead of plate
    Reduced absorption and scattering of beam
    Reduced microphonic noise pickup
- Similar chamber being constructed for n-^{3}He exp.

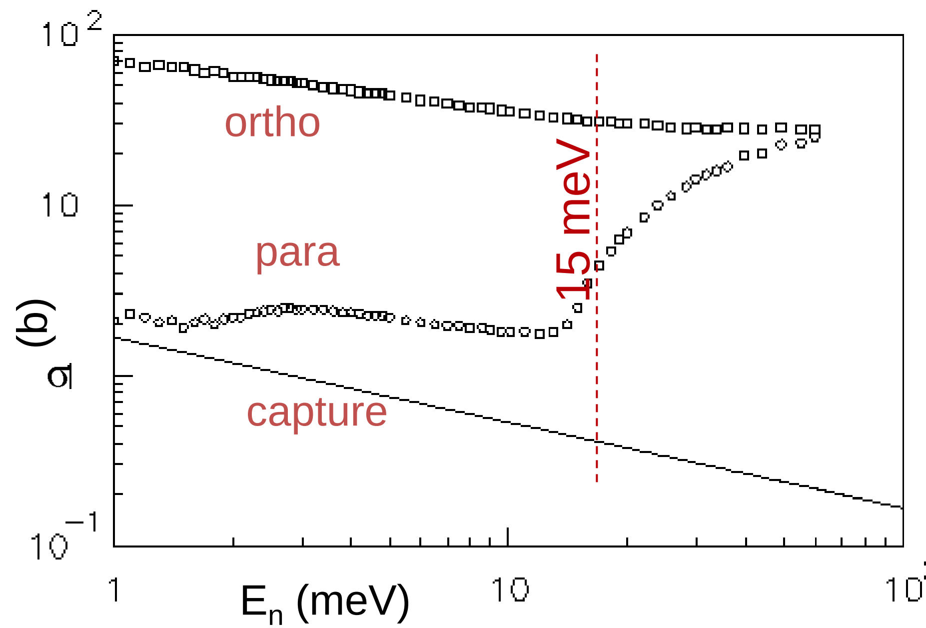


16L liquid para-hydrogen target



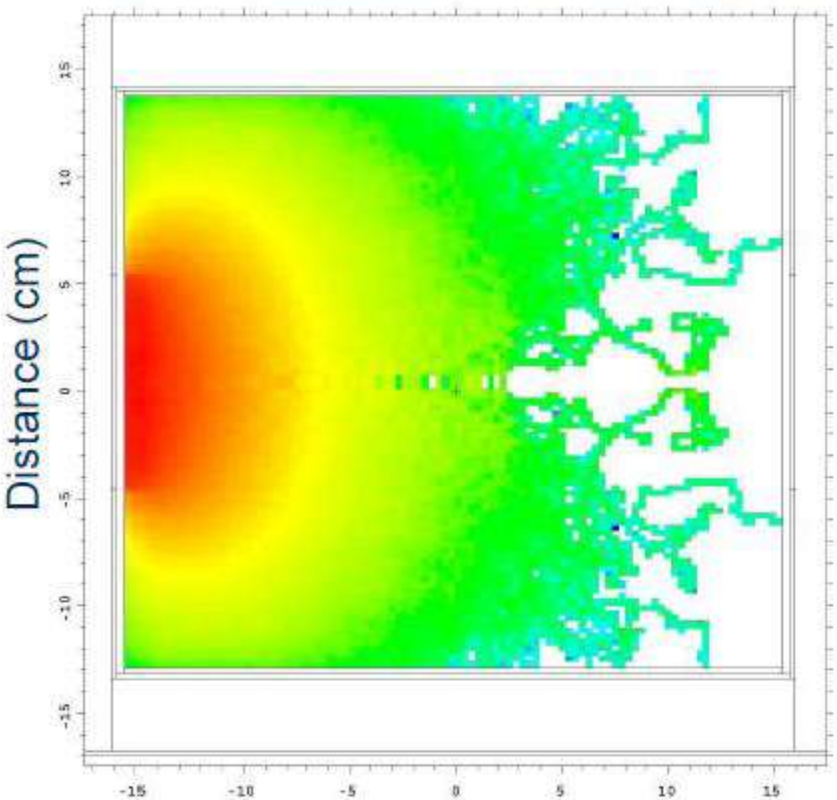
- 30 cm long → 1 interaction length
- 99.97% para → 1% depolarization
- Improvements: pressure-stamped vessel
  thinner windows





Ortho vs. Para H_2 neutron scattering

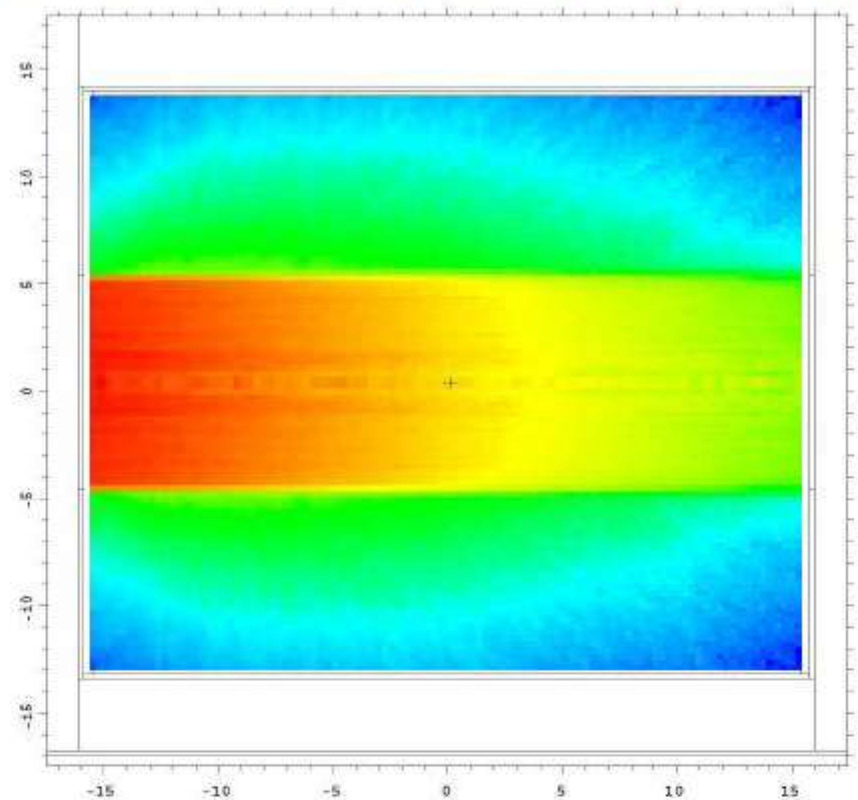
MCNP calculation of neutron beam intensity in liquid hydrogen target



Distance (cm)

Pure Ortho - H_2

Simulation by
Kyle Grammer

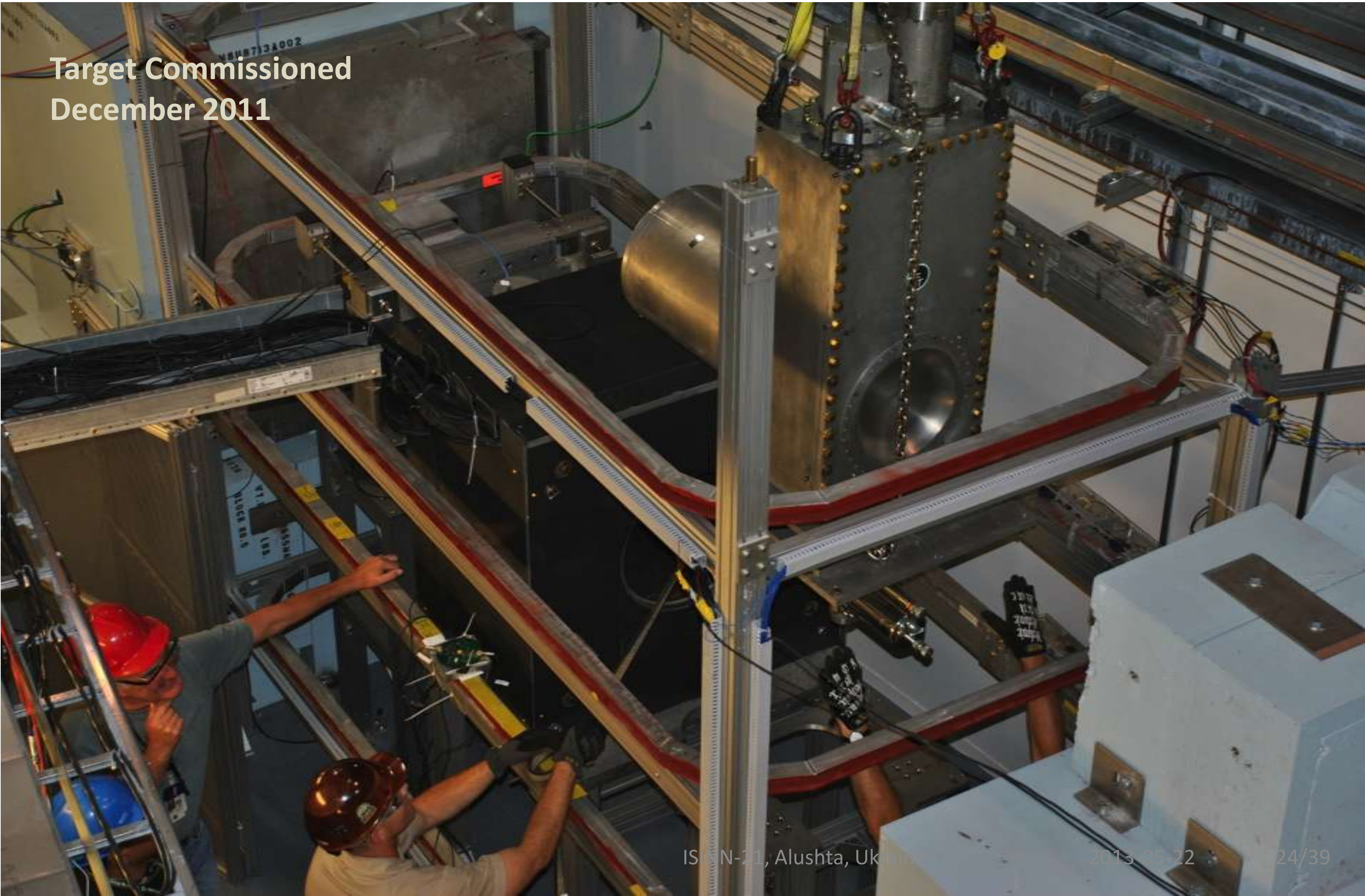


Distance (cm)

Pure Para - H_2

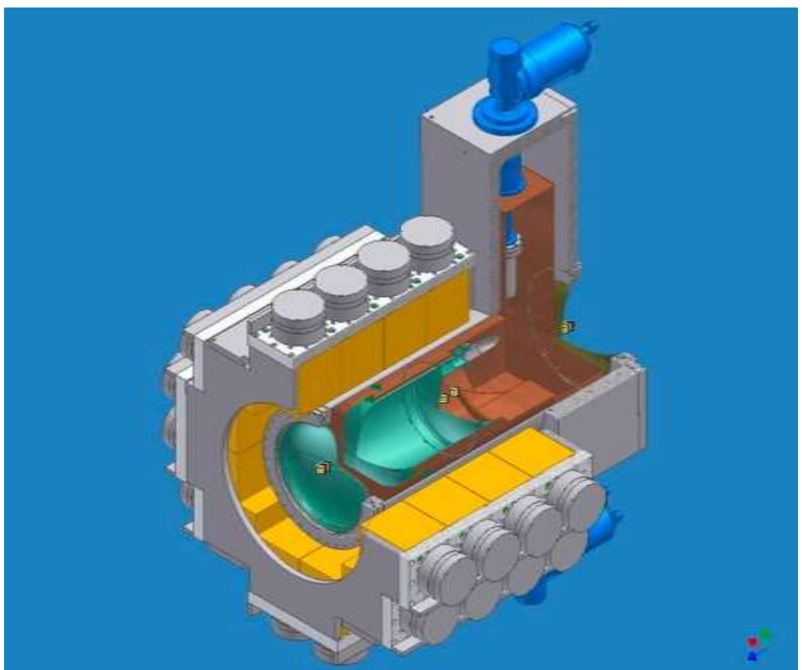
L. Barron-Palos, .., CBC, *et al.,* Nucl. Instr. Meth. **A671** 137 (2012)

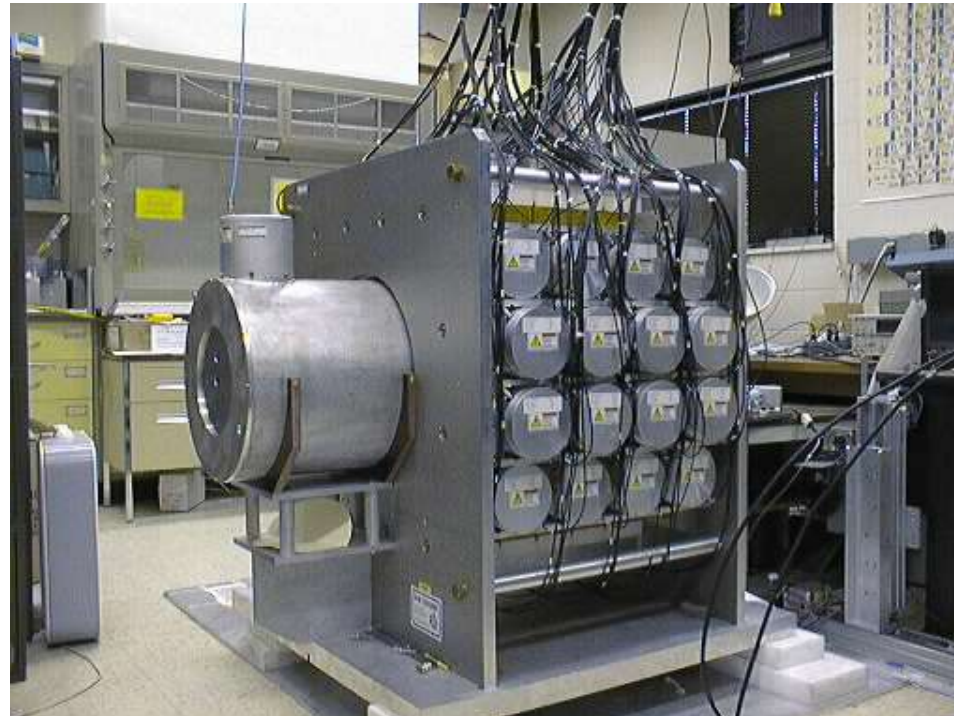
Installation of the LH_2 target in the FnPB

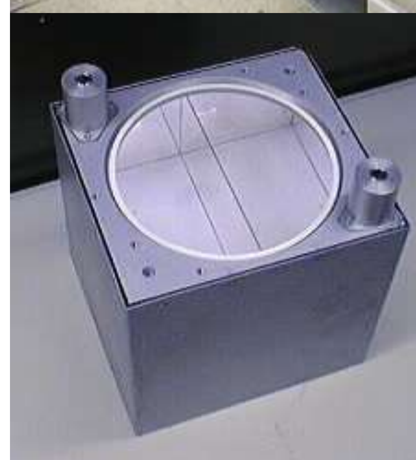


CsI(Tl) Detector Array

- 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





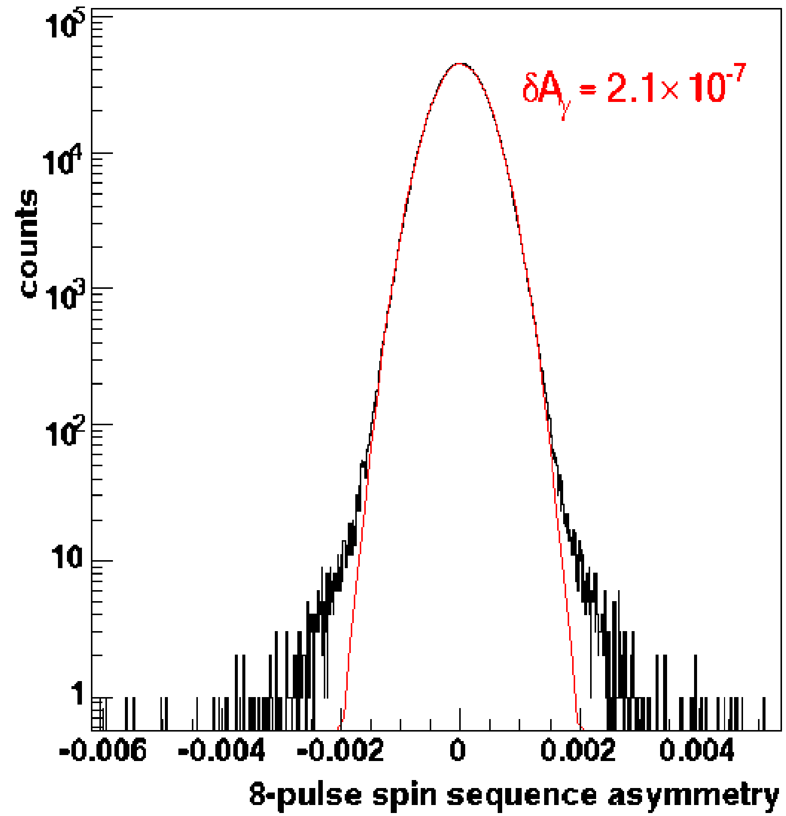


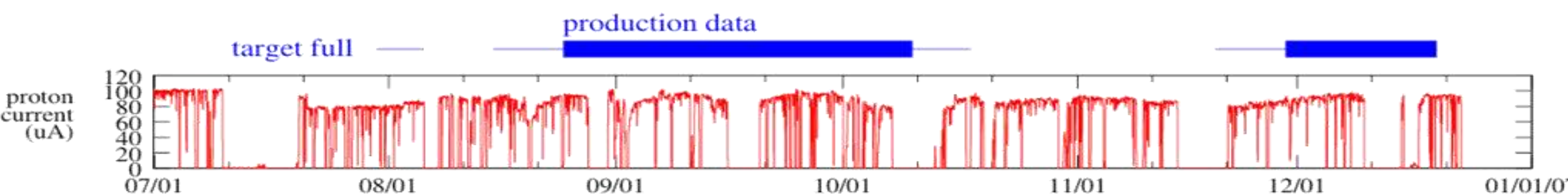
LH_2 run at LANSCE – Fall 2006

$A_{\gamma,UD}$=(-1.2   2.1 ± 0.2) x10^{-7}

$A_{\gamma,LR}$=(-1.8 ± 1.9 ± 0.2) x10^{-7}

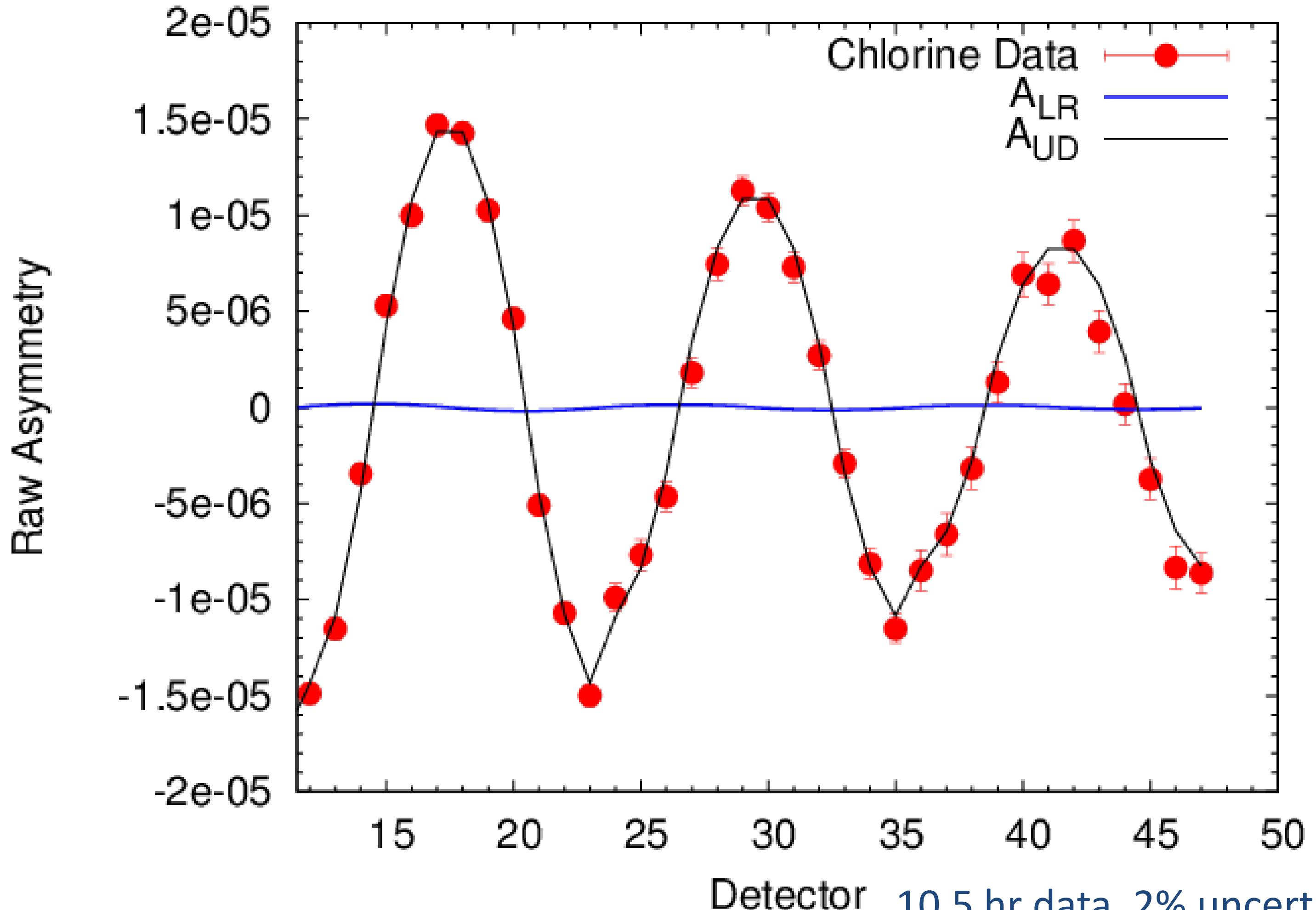
- Number of good runs
  5401 / 750 h
- Average delivered proton current
  89 A at 80 kW
- Average beam pol. (3He spin filter)
  55 +/- 7.5 %
- Spin-flip efficiency
  98 +/- 0.8%
- Para-hydrogen fraction in LH2 target
  99.98 %
- Beam depolarization in target
  2 %
- Data loss (cuts, bad events)
  ~1 %





M. Gericke, .., CBC, *et al.,* Phys. Rev. C **83** 015505 (2011)

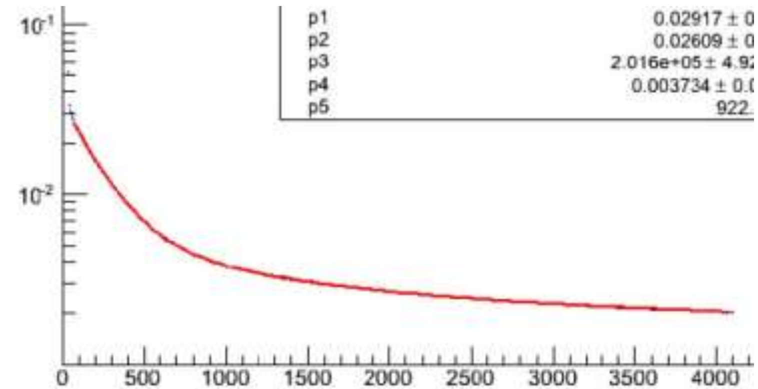
Chlorine PV asymmetry

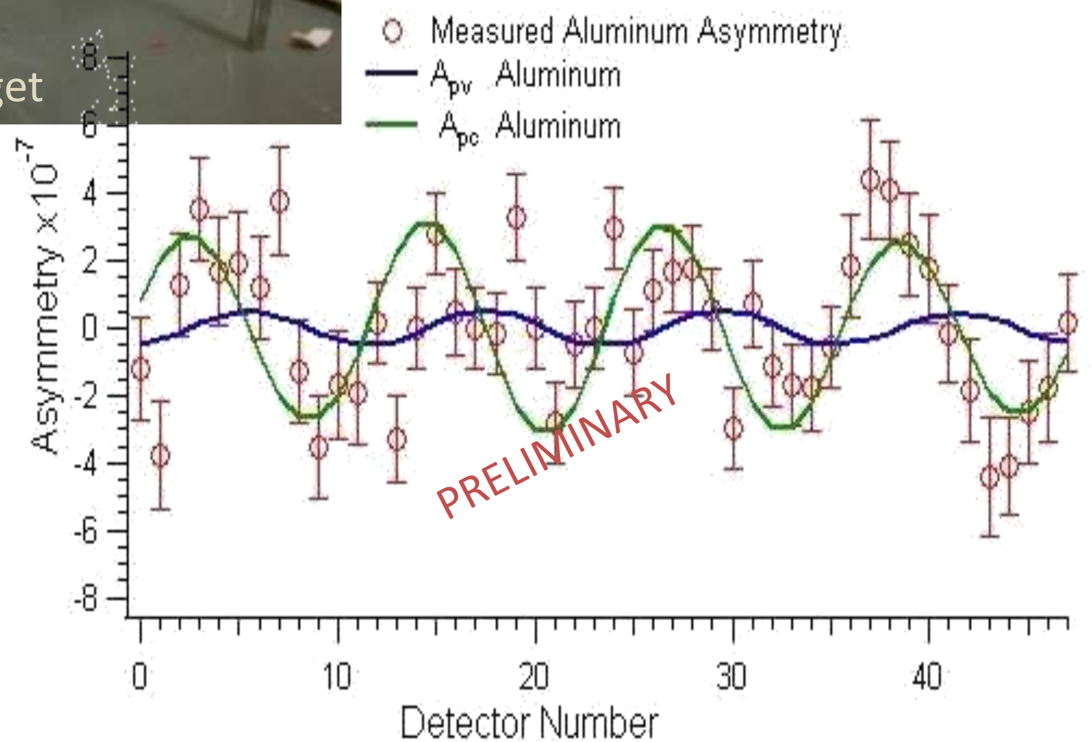


10.5 hr data, 2% uncertainty

Integrated test of complete system

Aluminum Asymmetry





- Dominant systematic effect
  - 25% background at LANL
  - Al thickness reduced by 50%
- Fit beta-delayed gammas
  - Lifetime ¿ = 27 min
- Must measure ±A = 3£ 10^{-8}
- Preliminary data

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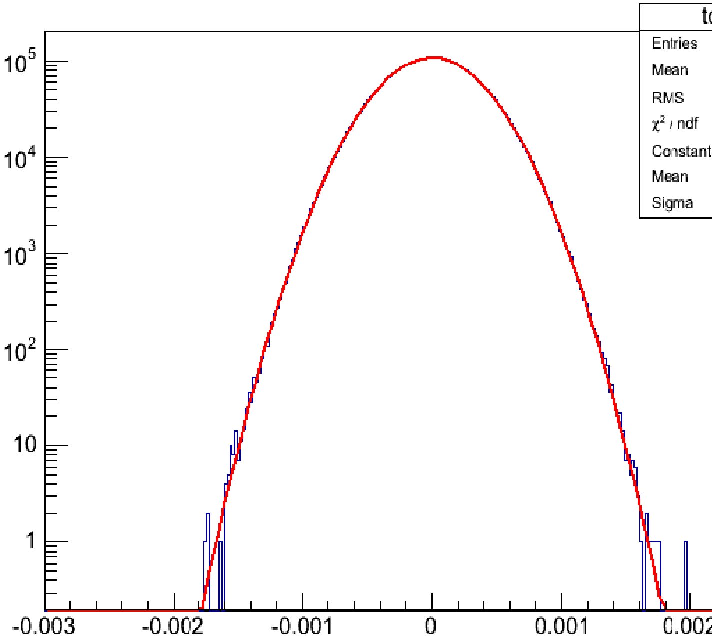
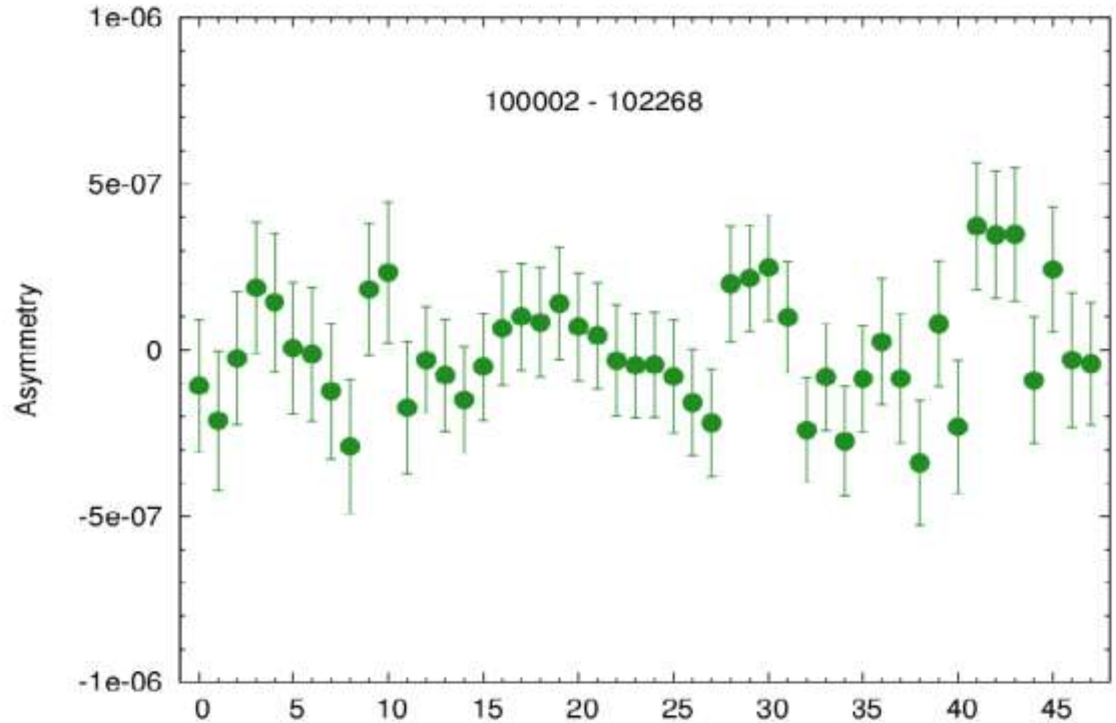
Recent Hydrogen Data



- 200 hr. of data from Fall 2012



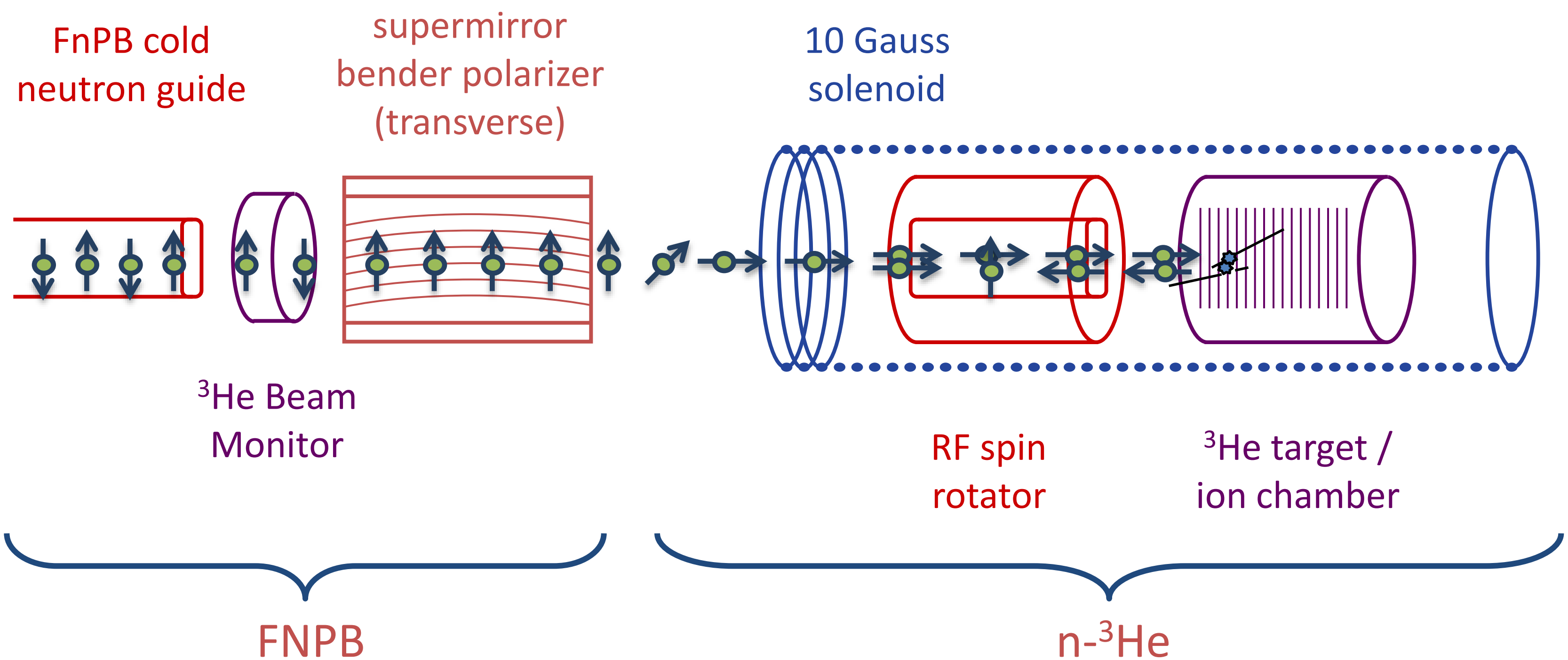
- Preliminary result:

A_{UD} = (-7.14 ± 4.4) x 10^{-8} A_{LR} = (-0.91 ± 4.3) x 10^{-8}

Systematic & Statistical Uncertainties

Systematic Effects which may cause false Asym	Size
Additive Asymmetry (instrumental)	$< 1\times10^{-9}$
Multiplicative Asymmetry (instrumental)	$< 1\times10^{-9}$
Stern-Gerlach (steering of the beam)	$< 1\times10^{-10}$
γ – ray circular polarization	$< 1\times10^{-12}$
β – decay in flight	$< 1\times10^{-11}$
Capture on ^{6}Li	$< 1\times10^{-11}$
Radiative β –decay	$< 1\times10^{-12}$
β - delayed Al gammas (internal + external)	$< 1\times10^{-9}$
Uncertainties in applied corrections	
Neutron beam polarization uncertainty	< 2%
RFSF efficiency uncertainty	~ 0.5%
Depolarization of the neutron beam	< 0.5% (target-dependent)
Uncertainty in geometric factors	1%
Polarization of overlap neutrons	0.1%
Target Position	0.03%
Statistical uncertainty in presented results	
Combined hydrogen and aluminum data	$\sim 4.5\times10^{-8}$

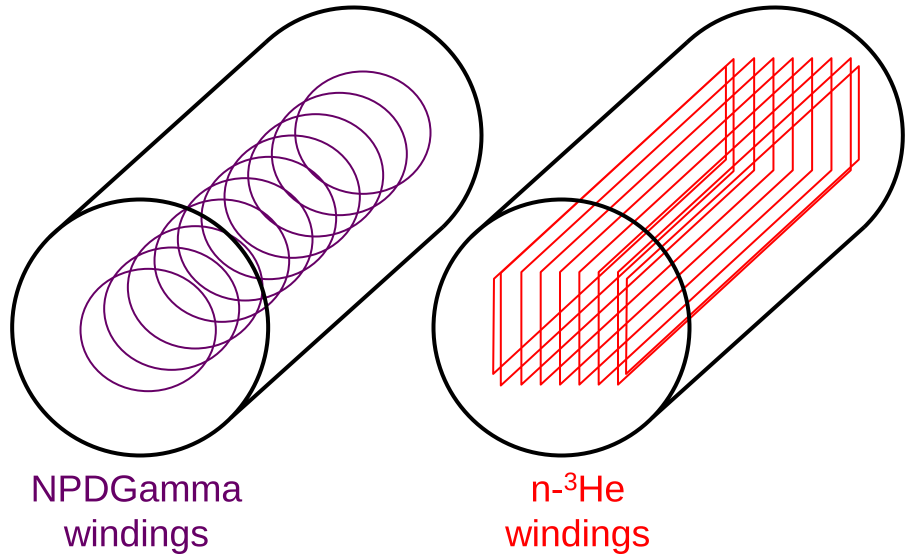
Experimental setup at the FnPB

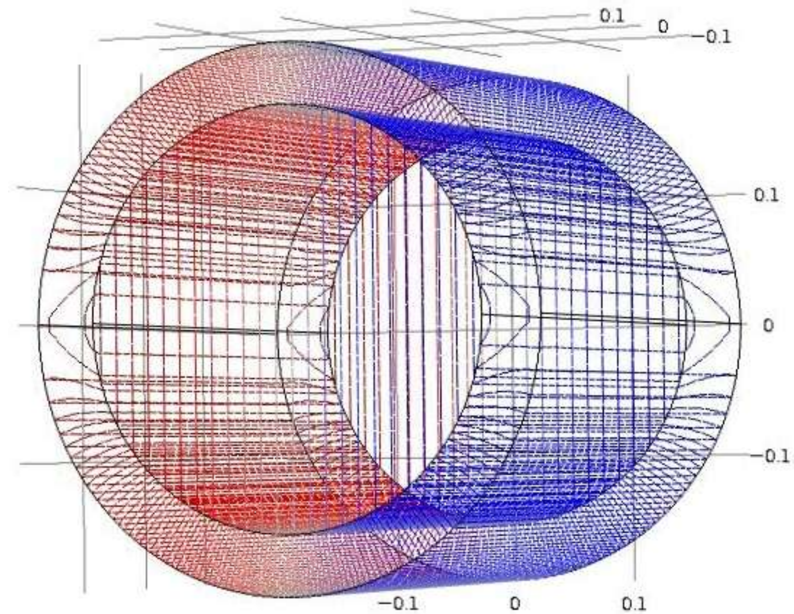


- longitudinal holding field – suppressed PC nuclear asymmetry
  $A=1.7 \times 10^{-6}$ (Hales) $s_n \bullet k_n \times k_p$ suppressed by two small angles
- RF spin flipper – negligible spin-dependence of neutron velocity
- ^{3}He ion chamber – both target and detector

Transverse RFSR for n-^{3}He Expt.

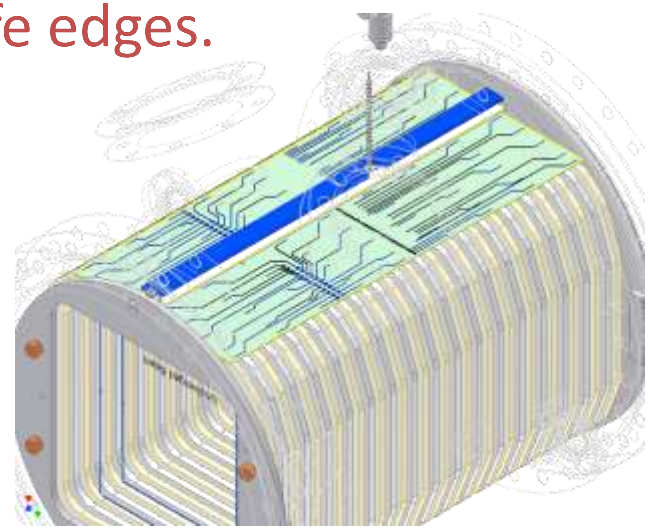
- extension of NPDGamma design
  - Resonant RF spin rotator
  - TEM RF waveguide
- new resonator for n-^{3}He expt.
  - Transverse horizontal RF B-field
  - Longitudinal / transverse flipping
  - No fringe field - 100% efficiency
  - Compact geometry – efficient
  - matched to NPDG electronics





n-^{3}He target / ion chamber

- Chamber all aluminum except for the knife edges.
  - 4 feedthrough ports (153 readout channels)
  - 2 HV ports + 2 gas inlets/outlets
  - 12 inch aluminum windows (0.9 mm thick).
- Macor wire frames
  - Platinum-gold thick film wire solder pads
- Filled with 1 atm of 3He



Asymmetry Measurement – Statistics

- PV Physics asymmetry is extracted from weighted average of single-wire spin asymmetries

- Two Monte Carlo simulations:
  1. a code based on GEANT4
  2. a stand-alone code including wire correlations

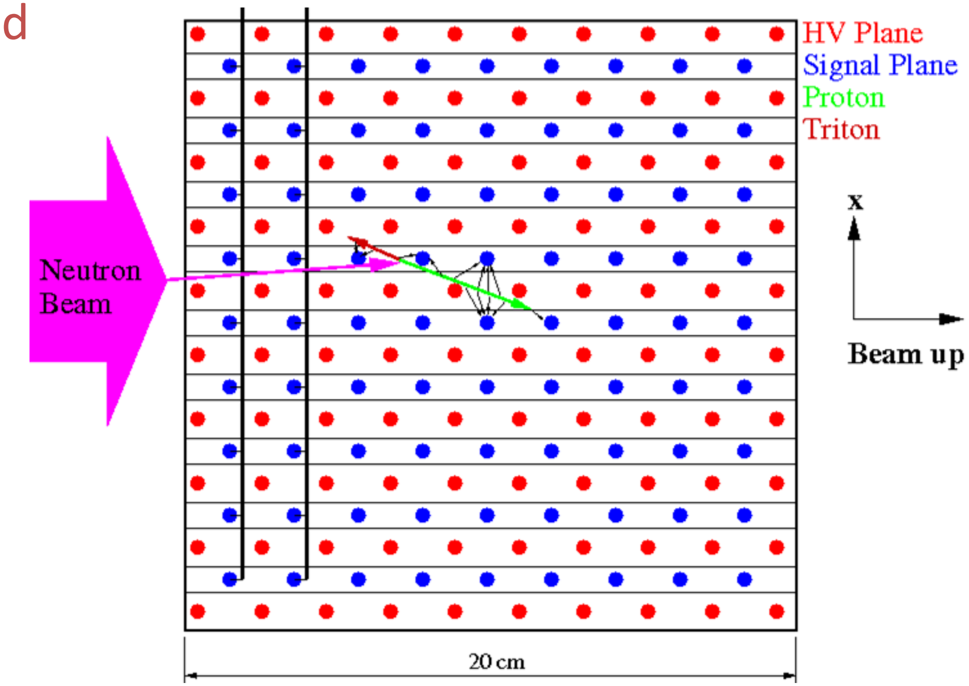
$$\delta A = \frac{\sigma_d}{P\sqrt{N}} = 1.6 \times 10^{-8}$$

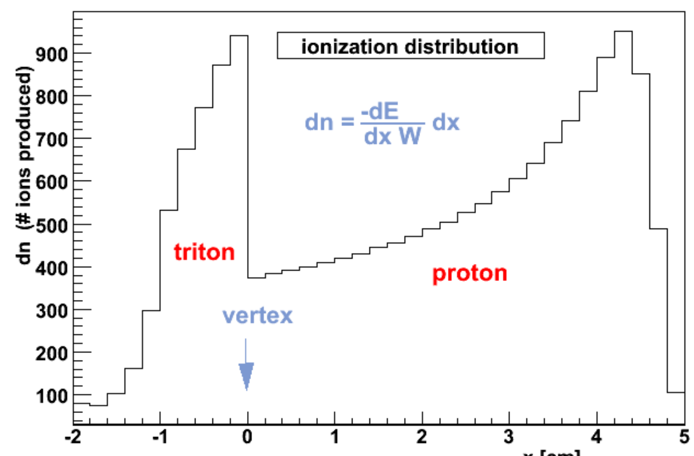
N = $1.5\mathrm{x}10^{10}$ n/s flux (chopped)
x 10^{7} s (116 days)

P = 96.2% neutron polarization

σ_d = 6 detector inefficiency

- 15% measurement in 1 beam cycle (without contingency), assuming A_z= 1.15 x 10^{-7}





Systematic Uncertainties

- Beam fluctuations, polarization, RFSF efficiency:

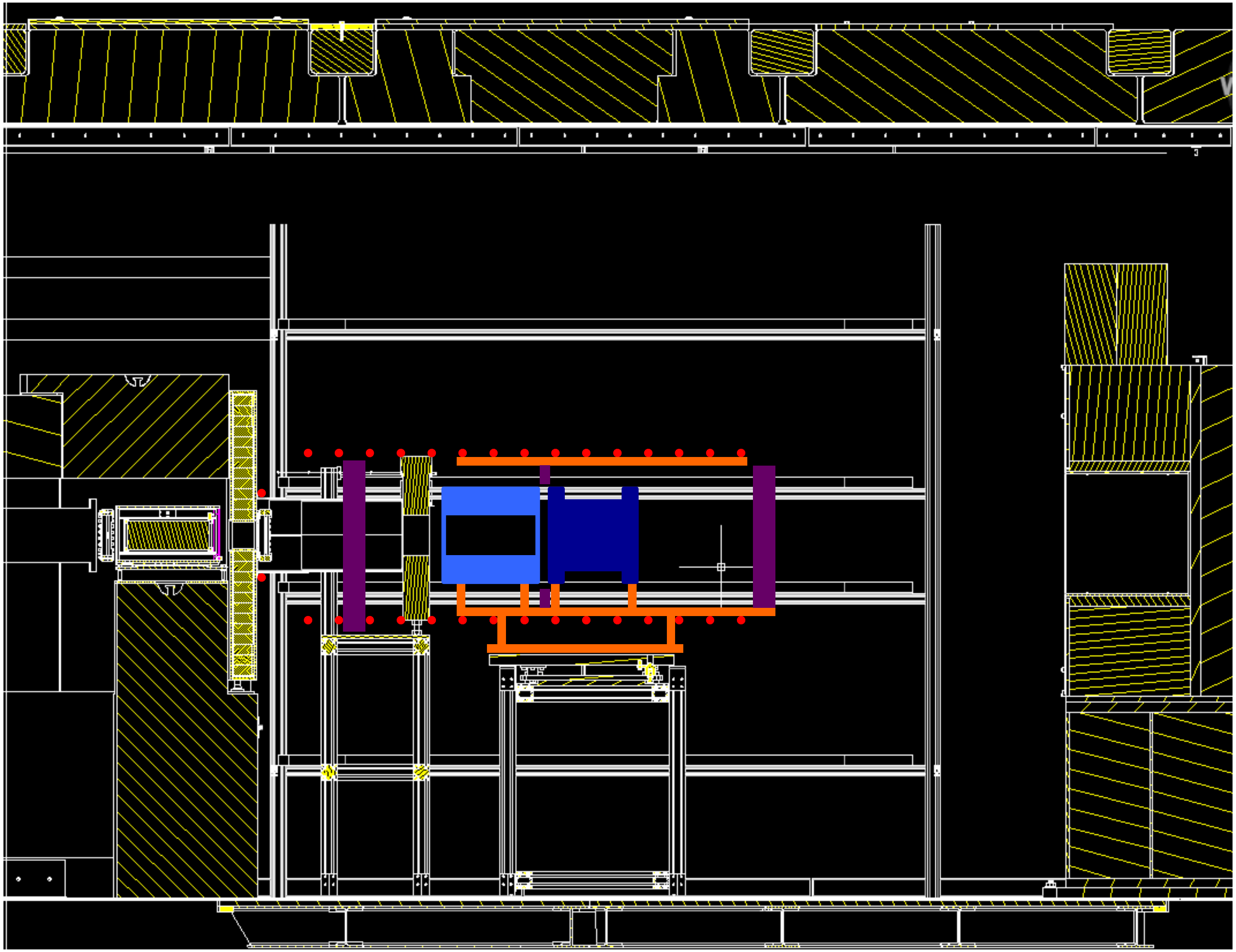
$$A_{exp} = \frac{A_b + PA}{1 + A_p PA}$$

- $k_n r \sim 10^{-5}$ 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 ° or n d -> t °,
  n-^{3}He is very insensitive to gammas (only Compton electrons)

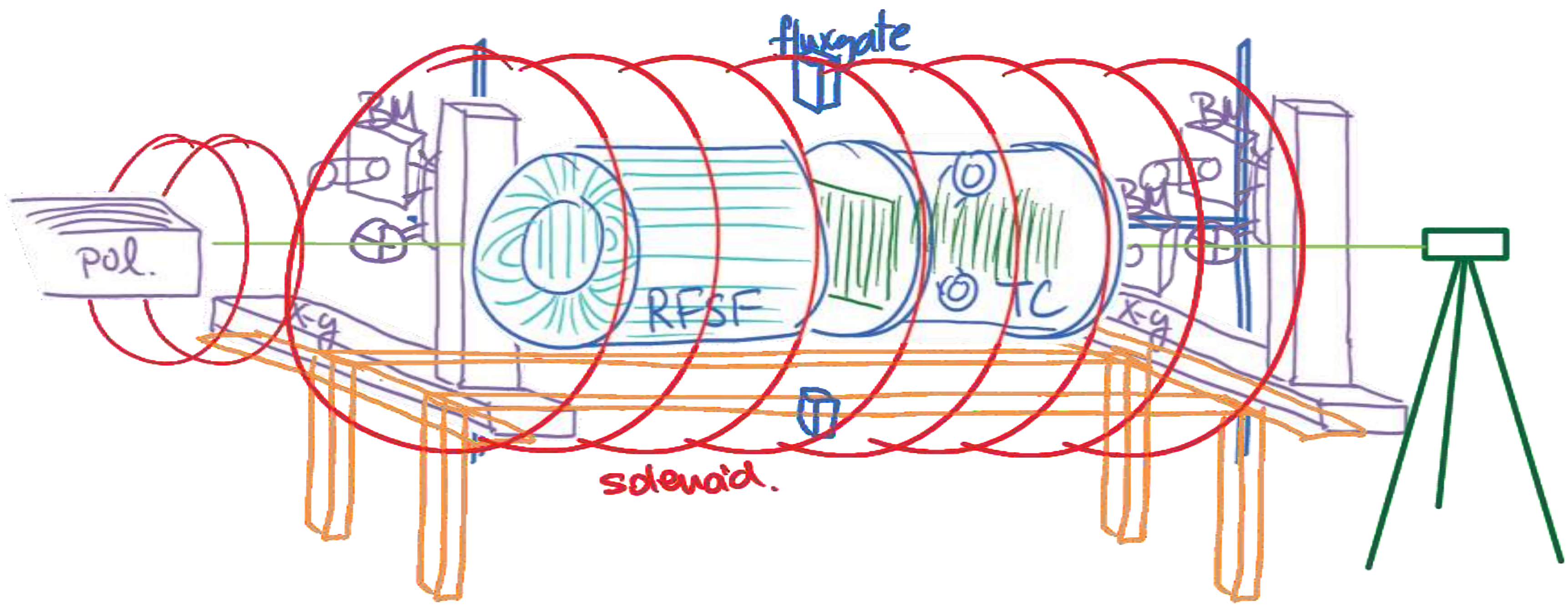
Invariant	Parity	Size	Comments
$\vec{\sigma}_n \cdot \vec{k}_p$	Odd	3×10^{-7}	Nuclear capture asymmetry
$\vec{\sigma}_n \cdot (\vec{k}_n \times \vec{k}_p)$	Even	2×10^{-10}	Nuclear capture asymmetry
	Even	6×10^{-12}	Mott-Schwinger scattering
$\vec{\sigma}_n \cdot \vec{B}$	Even	1×10^{-10}	Stern-Gerlach 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

$A_p^{\vec{n}^3He}$

Assembly in the FnPB cave



Commissioning / run plan



1. Scan beam profile upstream and transfer centroid to crosshairs
2. Scan beam profile downstream
3. Align theodolite to crosshairs
4. Align B-field to theodolite
5. Field map in RFSR/Target region
6. Align the position / angle of target with theodolite / autocollimator
7. Tune RSFR / measure polarization
8. Measure physics asymmetry

Summary

- NPDGamma is the cleanest measurement of $f_{1/4}$ coupling
- Preliminary result: $\pm A = 4.4\times10^{-8}$
- Expect $\pm A = 1\times10^{-8}$ by June 2014

- n-^{3}He is the last measurement needed to characterize the Hadronic Weak Interaction
- 15% projected uncertainty will be the most accurate HWI experiment in a few-body system
- FnPB beam time scheduled from June 2014 – Dec 2015

n-3He collaboration

Institution	Researcher	Category	2013 Effort
Duke University, Triangle Universities Nuclear Laboratory			
	Pil-Neo Seo	Research Staff	10
Istituto Nazionale di Fisica Nucleare, Sezione di Pisa			
	Michele Viviani	Research Staff	15
Oak Ridge National Laboratory			
	Seppo Penttilä	Research Staff	50
	David Bowman	Research Staff	20
	TBD	Postdoc	20
University of Kentucky			
	Chris Crawford	Faculty	35
	TBD	Grad Student	100
Western Kentucky University			
	Ivan Novikov	Faculty	70
	TBD * 2	Undergraduate	100
University of Manitoba			
	Michael Gericke	Faculty	30
	Shelley Page	Faculty	10
	WTH. Van Oers	Faculty	10
	Rob Mahurin	Postdoc	20
	V. Tvaskis	Postdoc	10
	Mark McCrea	Grad Student	100
	D. Harrison	Grad Student	100
Universidad Nacional Autónoma de México			
	Libertad Baron	Faculty	30
	TBD	Grad Student	100
University of New Hampshire			
	John Calarco	Faculty	50
University of South Carolina			
	Vladimir Gudkov	Faculty	5
	Young-Ho Song	Postdoc	5
	TBD	Grad Student	10
Univeristy of Tennessee			
`	Geoff Greene	Faculty	10
	Nadia Fomin	Faculty	
	S. Kucuker	Postdoc	20
Univeristy of Tennessee at Chattanooga			
`	Josh Hamblen	Faculty	30
University of Virginia			

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Justin Tomey
Will Bates
Edward Goodman
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Alec Gilbert

Dustin Doss
Joseph Natter
Deborah Ferguson
Rebecca Schladt
Mykalin Jones