NPDGamma: The Final Chapter

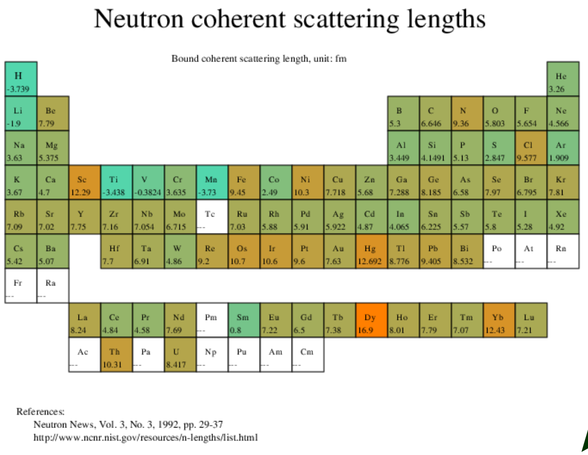
CIPANP2018

Nadia Fomin

University of Tennessee

May 30th, 2018

Strong Force



Neutron coherent scattering lengths

Bound coherent scattering length, unit: fm

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K 3.67	Ca 4.7	Sc 12.29	Ti -3.438	V -0.3824	Cr 3.635	Mn -3.73	Fe 9.45	Co 2.49	Ni 10.3	Cu 7.718	Zn 5.68	Ga 7.288	Ge 8.185	As 6.58	Se 7.97	Br 6.795	Kr 7.81
Rb 7.09	Sr 7.02	Y 7.75	Zr 7.16	Nb 7.054	Mo 6.715	Tc ---	Ru 7.03	Rh 5.88	Pd 5.91	Ag 5.922	Cd 4.87	In 4.065	Sn 6.225	Sb 5.57	Te 5.8	I 5.28	Xe 4.92
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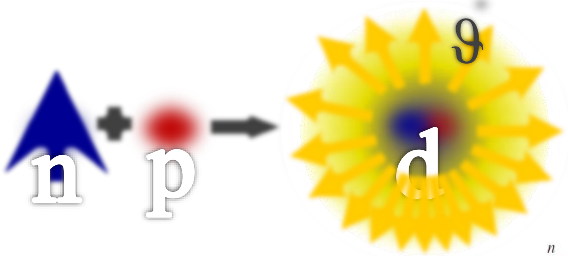
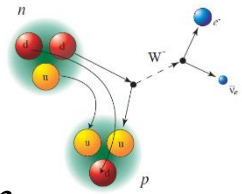
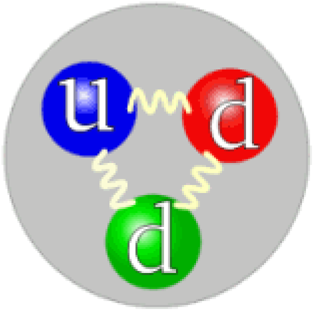




Weak Force

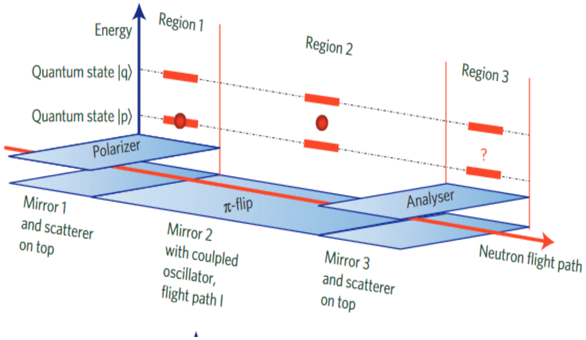
-neutron beta decay

-hadronic weak interaction

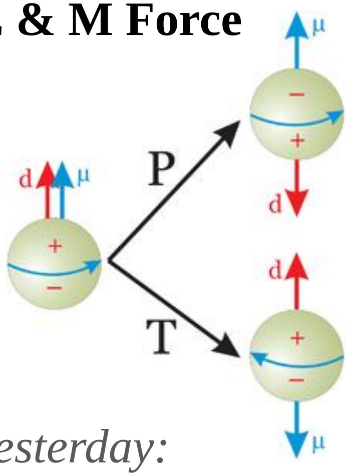


Neutron

Gravity



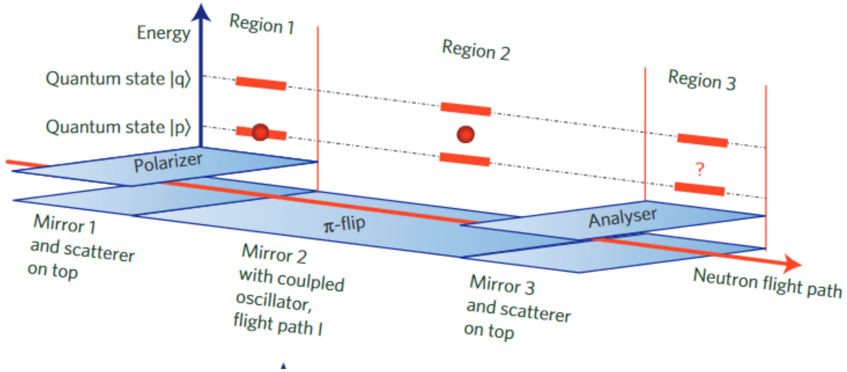
E & M Force



yesterday:
EDMs

Gravity Resonance Spectroscopy

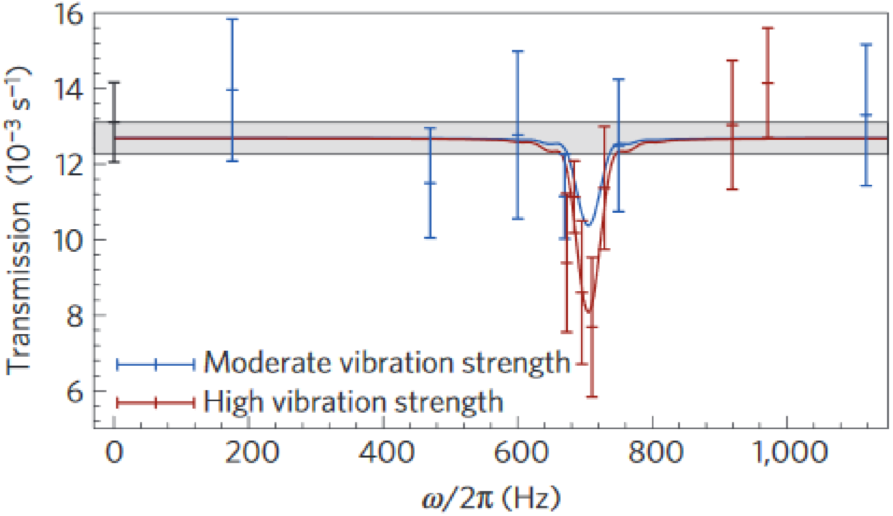
- Energy eigenstates in the gravity potential of the Earth can be probed using a new resonance-spectroscopy technique using neutrons bounced off a horizontal mirror



- Novelty: oscillating field does NOT rely on electromagnetic coupling
  1. Initial state |p> is prepared by a state selector
  2. π-pulse includes a transition into state |q>
  3. Second state selector transmits only |p> state to the detector

T. Jenke et al, Nature, Vol7, 2011

Gravity Resonance Spectroscopy

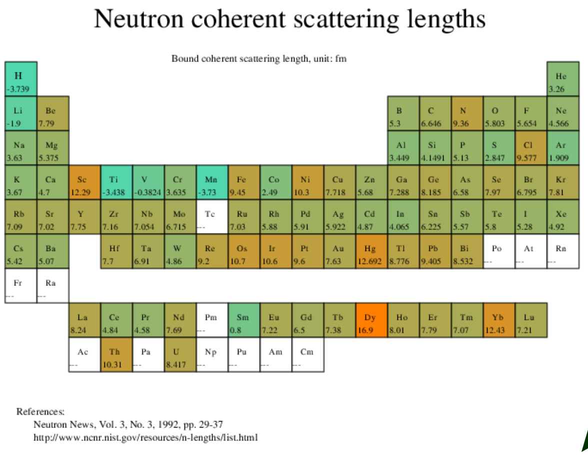


Future physics prospects:

Gravitational/inertial mass equivalence
Dark Matter searches

T. Jenke et al, Nature, Vol7, 2011

Strong Force



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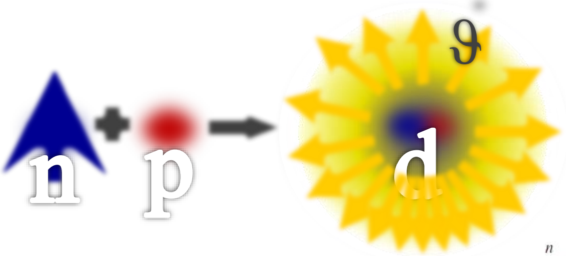
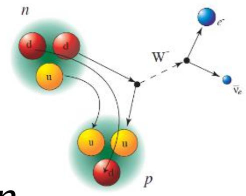
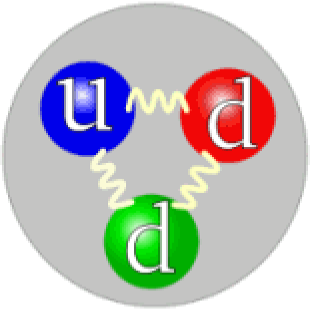




Weak Force

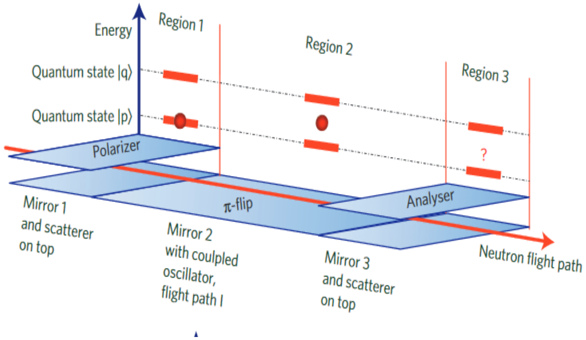
-*neutron beta decay*

-*hadronic weak interaction*



Neutron

Gravity



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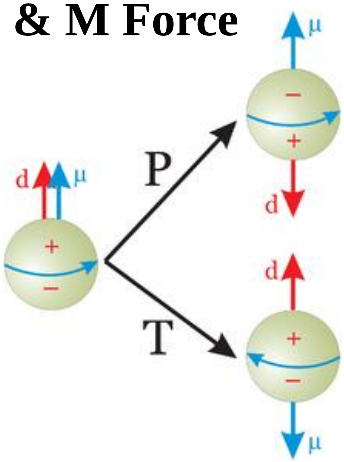


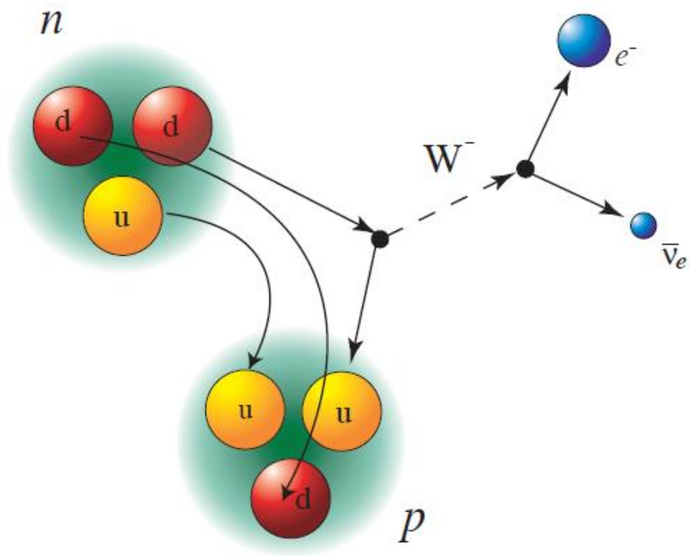
EDMs:yesterday

Free neutron β-decay

- Prototype for all weak decays of hadrons and leptons
- Input to tests of the Standard Model
- Input to Big Bang Nucleosynthesis models

V_{ud} – determined from neutron lifetime and free neutron decay

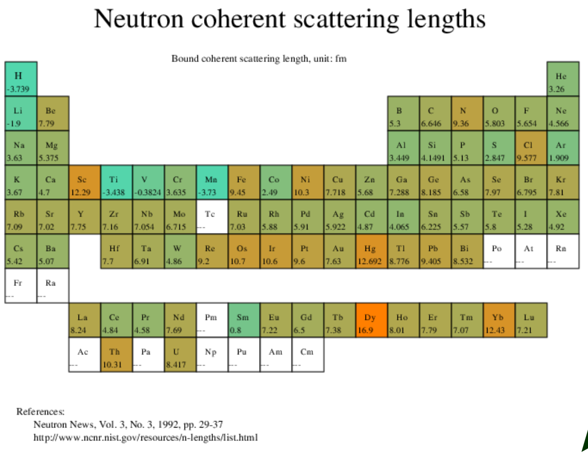
More This Afternoon:
Tests of Symmetries and the Electroweak Interaction: Parallel 4 — Beta Decays



$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{td} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

Strong Force



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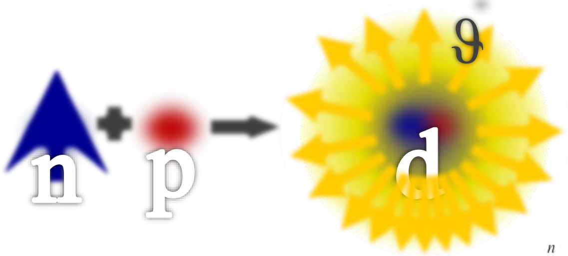

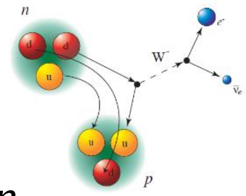

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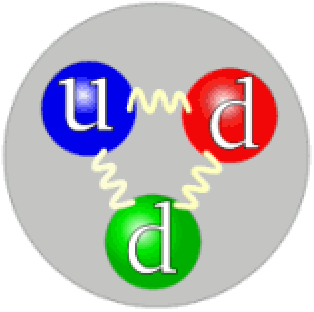

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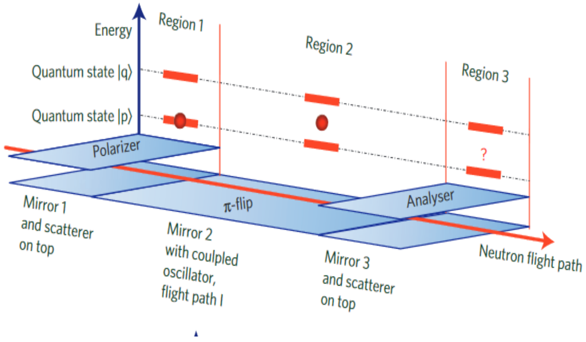

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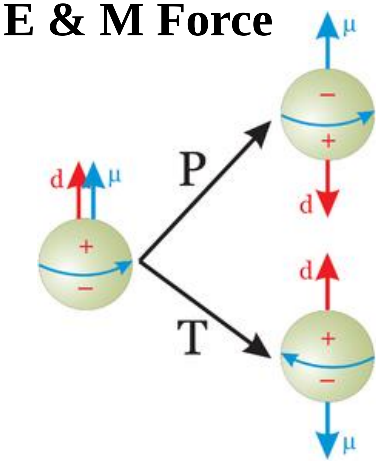
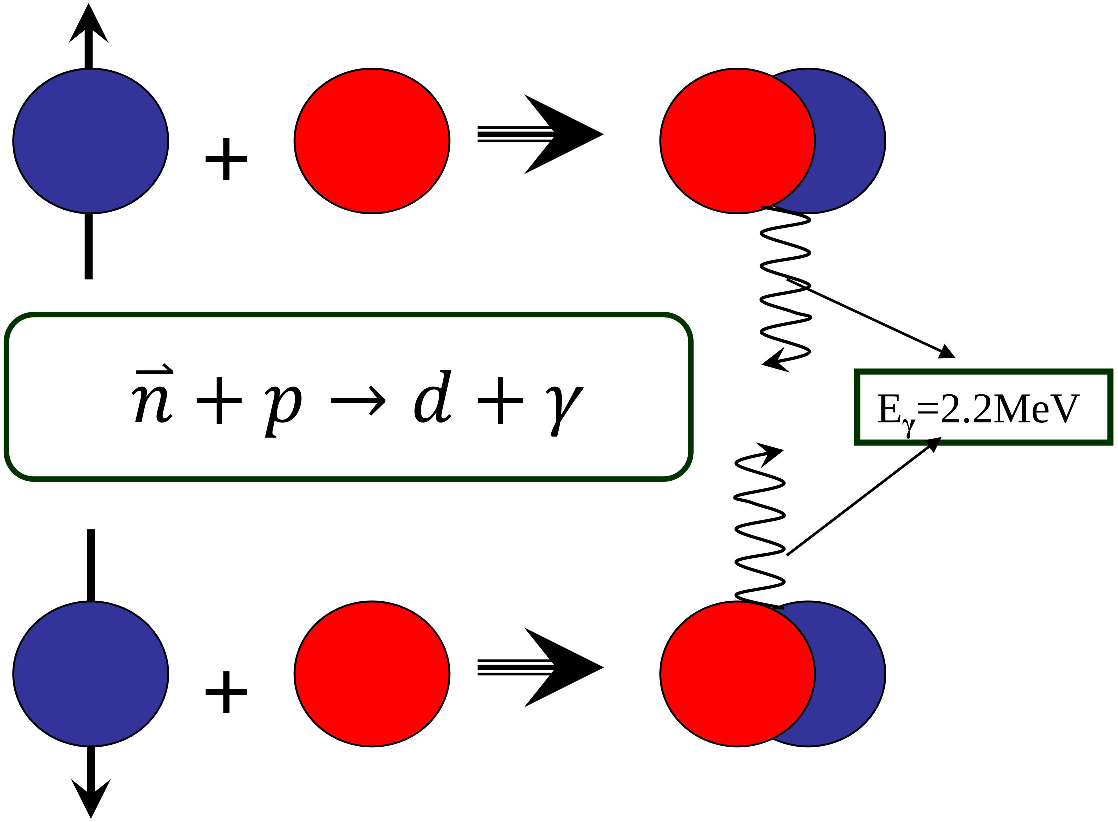


EDMs:yesterday

NPDGamma: What are we measuring?



$$\vec{n} + p \rightarrow d + \gamma$$

E_γ=2.2MeV

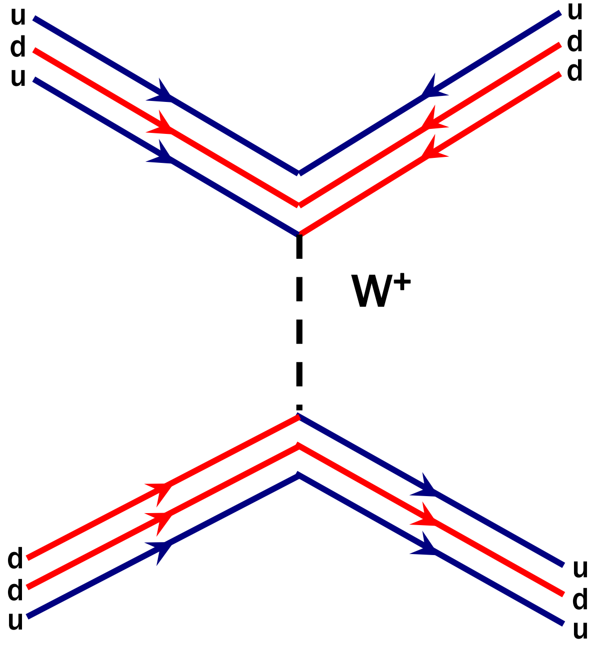
Goal: $dA = 1 \times 10^{-8}$

Why are we measuring it?

- Natural scale ~x10^{-7}, set by relative size of meson vs boson exchange amplitudes

- Weak interaction at low momentum transfer between nucleons is accessible through measurements of small parity-odd amplitudes

- Presence of strong force complicates experiments



Hadronic Weak Interaction – Theory

1. ***DDH model*** – uses valence quarks to estimate effective PV meson-nucleon coupling directly from SM via weak meson coupling constants

$$h_\pi^1, h_\rho^0, h_\rho^1, h_\rho^{1'}, h_\rho^2, h_\omega^0, h_\omega^1$$

- Observables can be written as their combinations

$$A = a_\pi^1 h_\pi^1 + a_\rho^0 h_\rho^0 + a_\rho^1 h_\rho^1 + a_\rho^2 h_\rho^2 + a_\omega^0 h_\omega^0 + a_\omega^1 h_\omega^1$$

2. *Effective Field Theory*

- comprehensive formulation by Holstein, Ramsey-Musolf, van Kolck, Zhu and Maekawa
- model-independent, consistent treatment of PC and PV interactions, theoretical error estimates
- NN potentials are expressed in terms of several parameters whose linear combinations give us 5/6 (pionless/chiral) low energy coupling constants

3. *Lattice QCD*

n+p → $\vec{d}$ + γ (isolates *ΔI=1*)   Goal: $dA = 1 \times 10^{-8}$

1. **DDH model**

$$A = -0.11 h_{\pi}^{1} + 0.001 h_{\rho}^{1} + 0.004 h_{\omega}^{1}$$

Reasonable range: $-11 < h^1_\pi < 0$ [x10^{-7}] ➡ $\boxed{h^1_\pi \sim 4.5\text{x}10^{-7}}$

2. **Effective Field Theory**

$$\boxed{A_\gamma = \frac{4}{3}\sqrt{\frac{2}{\pi}}\,\frac{M^{\frac{3}{2}}}{\kappa_1\left(1-\gamma a^{({}^1S_0)}\right)}\,g^{({}^3S_1-{}^3P_1)}}$$

3. **Lattice QCD**

$$h^1_{\pi NN} = 1.099 \pm 0.505\,{}^{+0.058}_{-0.064}\ [\text{x}10^{-7}]$$

-- *J. Wasem, PRC C85 (2012)*

Hadronic Weak Interaction – Theory

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$$h_\pi^1, h_\rho^0, h_\rho^1, h_\rho^{1'}, h_\rho^2, h_\omega^0, h_\omega^1$$

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	$n+p \rightarrow d+\gamma$ A_γ (ppm)	***$n+{}^3He \rightarrow {}^3H+p$ A_γ (ppm)***	***n-p φ_{PV} (μrad/m)***	***n-^{4}He φ_{PV} (μrad/m)***	***p-p $\Delta\sigma/\sigma$***	***p-^{4}He $\Delta\sigma/\sigma$***
h_π^1	-0.107	-0.185	-3.12	-0.97		-0.340
h_ρ^0		-0.038	-0.23	-0.32	0.079	0.140
h_ρ^1	-0.001	0.023		0.11	0.079	0.047
h_ρ^2		0.001	-0.25		0.032	
h_ω^0		-0.05	-0.23	-0.22	-0.073	0.059
h_ω^1	0.003	-0.023		0.22	0.073	0.059

n+p → $\vec{d}$ + γ (isolates *ΔI=1*) Goal: $dA = 1 \times 10^{-8}$

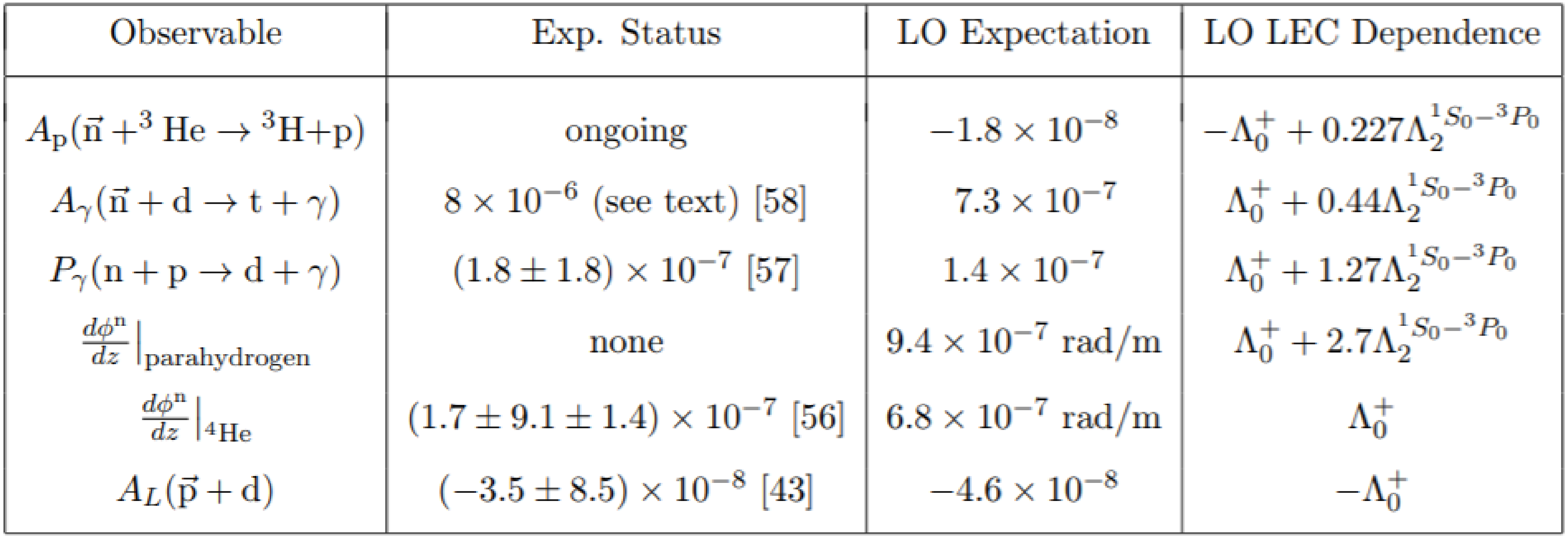
NN weak Interaction is a "test case" for our ability to trace symmetry-violating effects across strong interaction cases

1. NN weak interactions can DIRECTLY test QCD via lattice gauge theory
   → ***Calculation of the ΔI=2 NN weak amplitude on the lattice is in progress*** *(Cal-Lat collaboration)*

2. NN weak interactions can test QCD in the low energy limit using effective field theory (EFT) treatment.
   → ***New 1/N_c expansion+EFT predicts LARGE isospin dependence of NN weak amplitudes***

Stolen from M. Snow

Implications for Current and Future PV Experiments

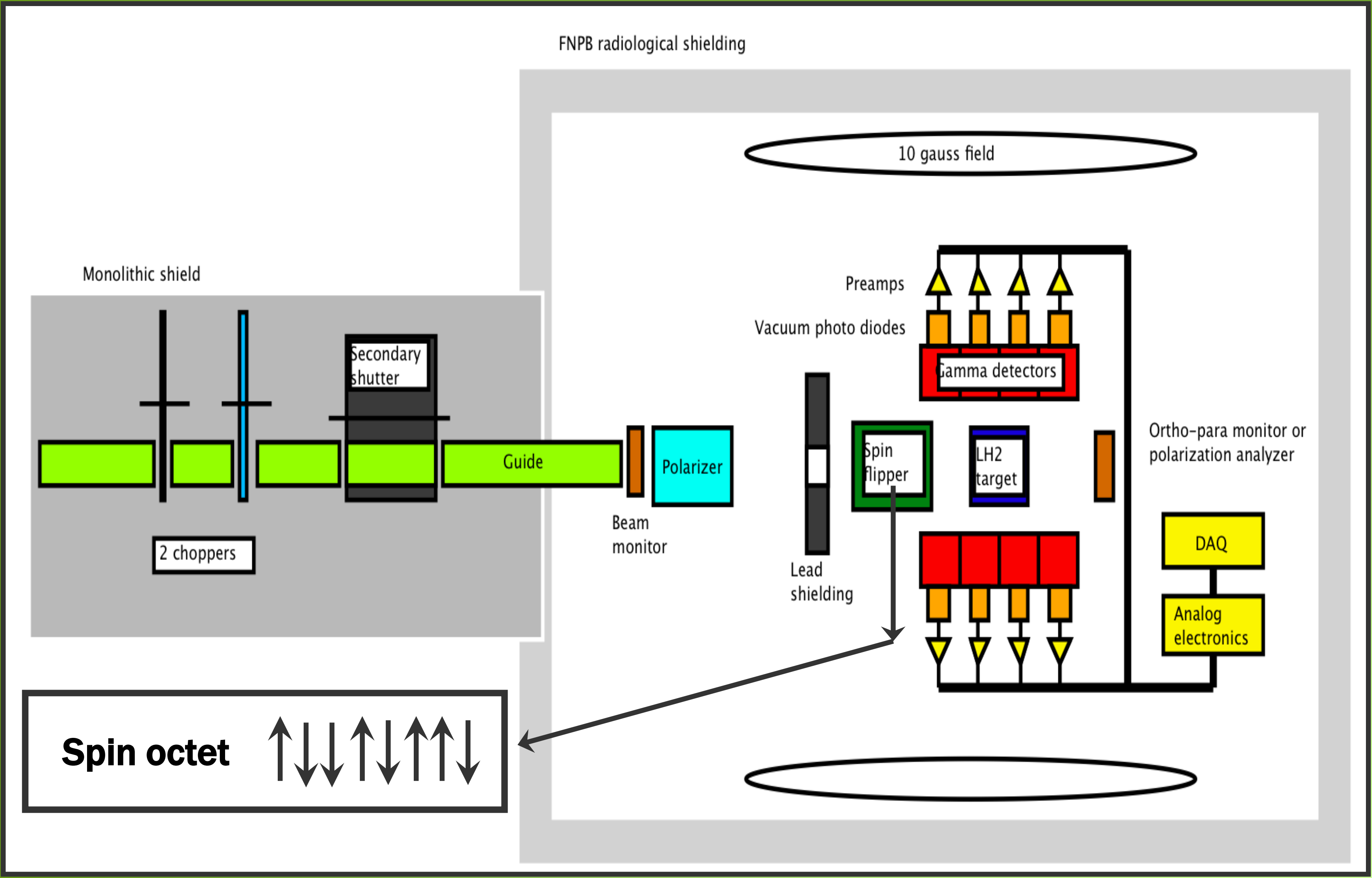


Observable	Exp. Status	LO Expectation	LO LEC Dependence
$A_p(\vec{n} + {}^3\text{He} \to {}^3\text{H}+\text{p})$	ongoing	-1.8×10^{-8}	$-\Lambda_0^+ + 0.227\Lambda_2^{{}^1S_0-{}^3P_0}$
$A_\gamma(\vec{n} + \text{d} \to \text{t} + \gamma)$	8×10^{-6} (see text) [58]	7.3×10^{-7}	$\Lambda_0^+ + 0.44\Lambda_2^{{}^1S_0-{}^3P_0}$
$P_\gamma(\text{n} + \text{p} \to \text{d} + \gamma)$	$(1.8 \pm 1.8) \times 10^{-7}$ [57]	1.4×10^{-7}	$\Lambda_0^+ + 1.27\Lambda_2^{{}^1S_0-{}^3P_0}$
$\frac{d\phi^n}{dz}\Big\vert_{\text{parahydrogen}}$	none	9.4×10^{-7} rad/m	$\Lambda_0^+ + 2.7\Lambda_2^{{}^1S_0-{}^3P_0}$
$\frac{d\phi^n}{dz}\Big\vert_{{}^4\text{He}}$	$(1.7 \pm 9.1 \pm 1.4) \times 10^{-7}$ [56]	6.8×10^{-7} rad/m	Λ_0^+
$A_L(\vec{p} + \text{d})$	$(-3.5 \pm 8.5) \times 10^{-8}$ [43]	-4.6×10^{-8}	$-\Lambda_0^+$

NN Weak Amplitudes in EFT + 1/N_c: ΔI=1 Amplitudes should be suppressed by 1/N_c^2=1/9

Gardner, Haxton, Holstein → ***Ann.Rev.Nucl.Part.Sci. 67 (2017) 69-95***

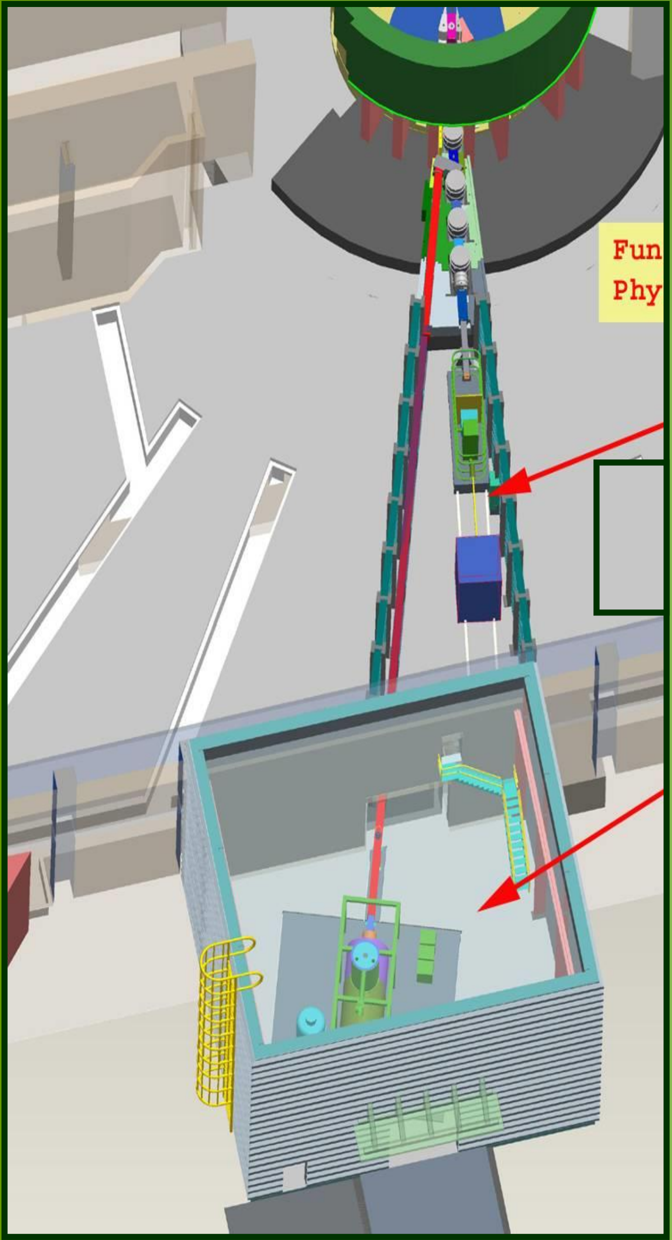
NPDGamma: How do we measure the asymmetry?

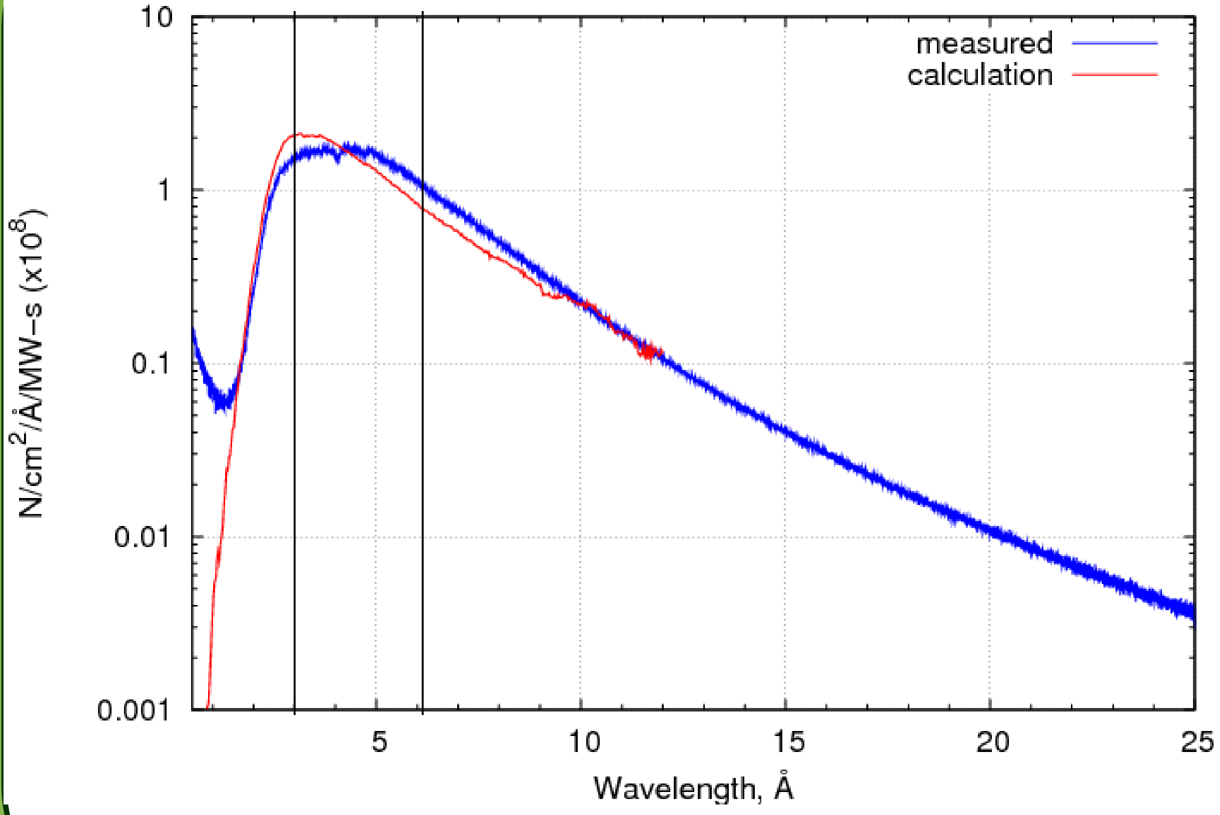


Where did we do this – SNS at ORNL

- 1.4 GeV protons, 60Hz
- Hg Spallation target → neutrons
- H_2 moderator
- 17 m SM guide, curved

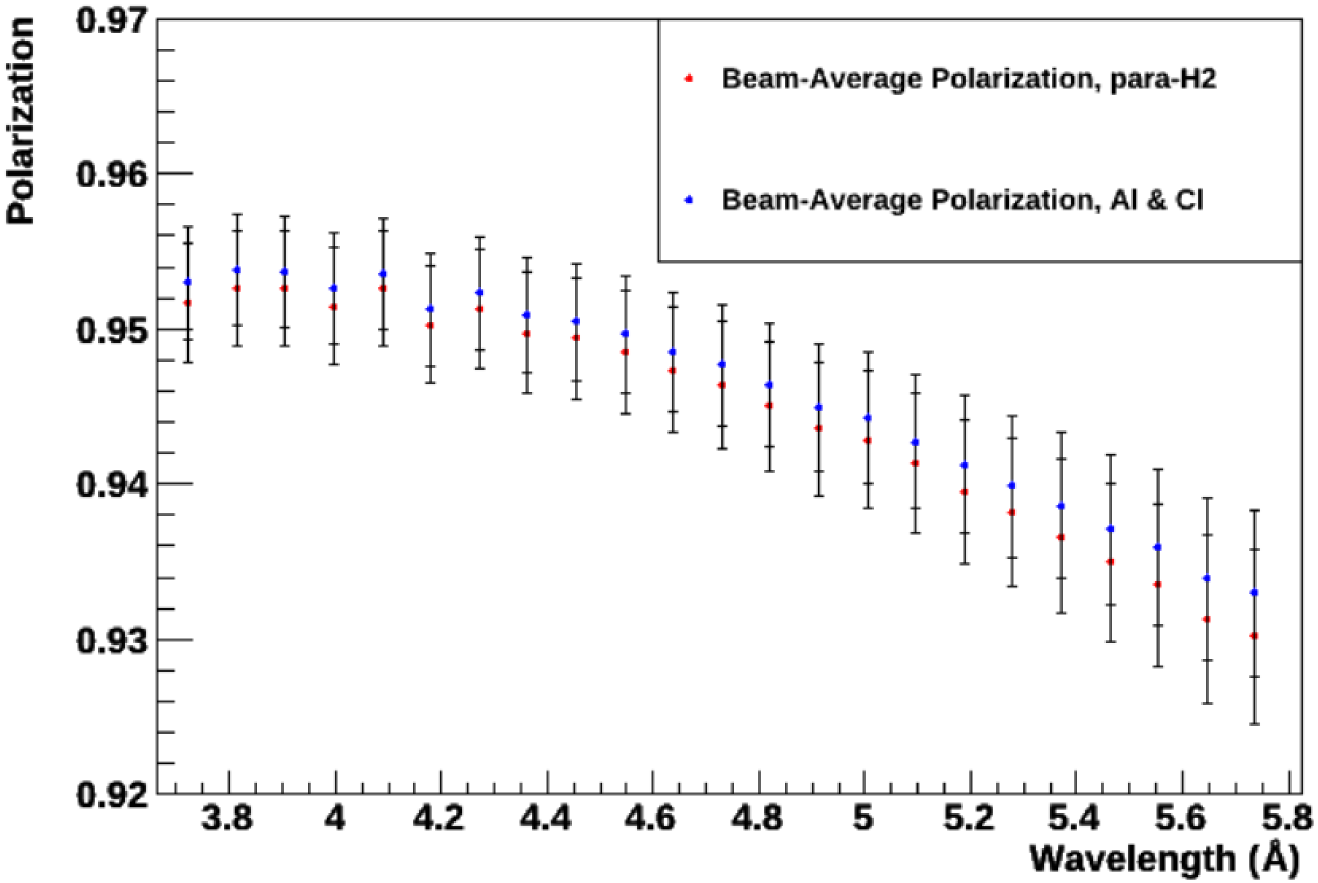
FnPB – cold beamline commissioned on Sep 12th, 2008





Nucl.Instrum.Meth. A773 (2015) 45-51

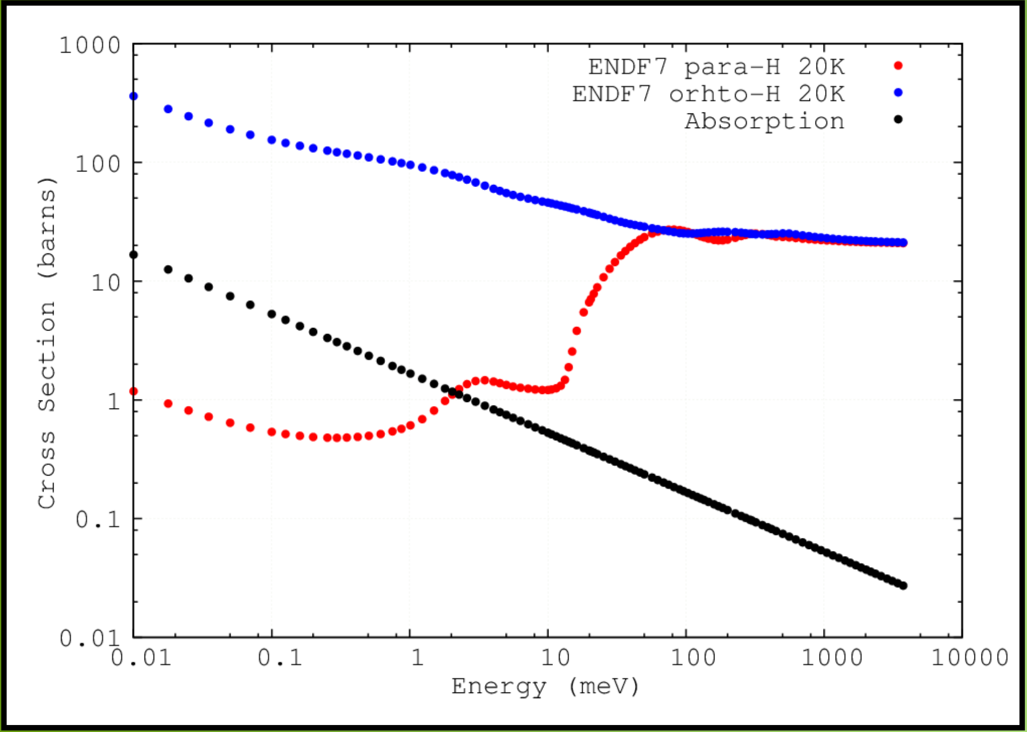
FnPB neutrons are polarized

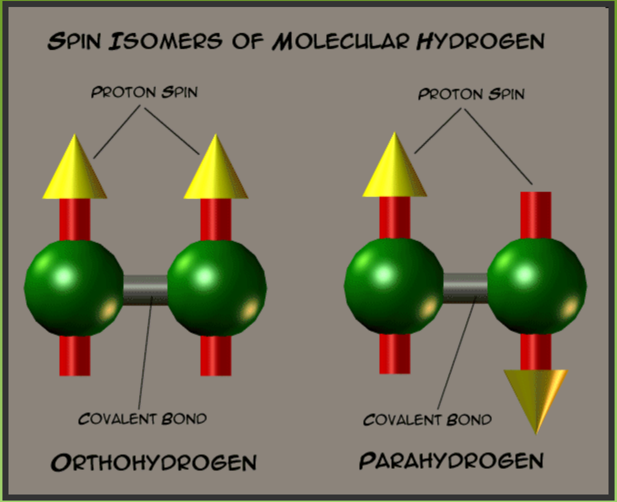


Analysis by M. Musgrave - Nucl.Instrum.Meth. A895 (2018) 19-28

LH_2 target - Parahydrogen

Orthohydrogen	*I=1 (aligned spins)*
Parahydrogen	*I=0 (anti-aligned spin)*





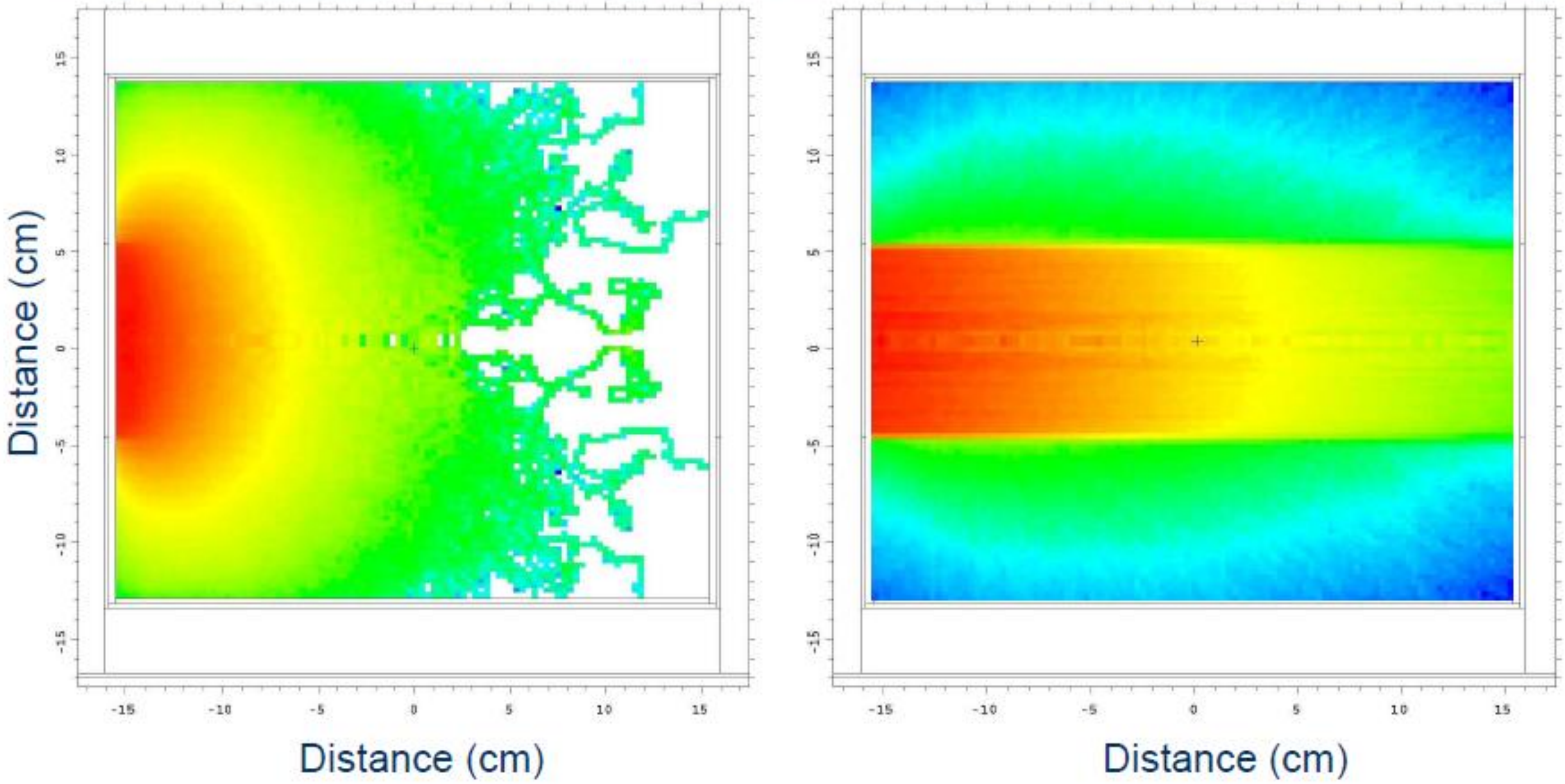
If $E_n < 14.7 meV$, cannot flip neutron spin

Para state dominates at low temperatures, helped by a catalyst (material with a solid paramagnetic surface)

- No safety issues from sensors in the hydrogen system
- Energy dependence of the neutron transmission can be used

Parahydrogen Target

MCNP calculation of neutron beam intensity in liquid hydrogen target

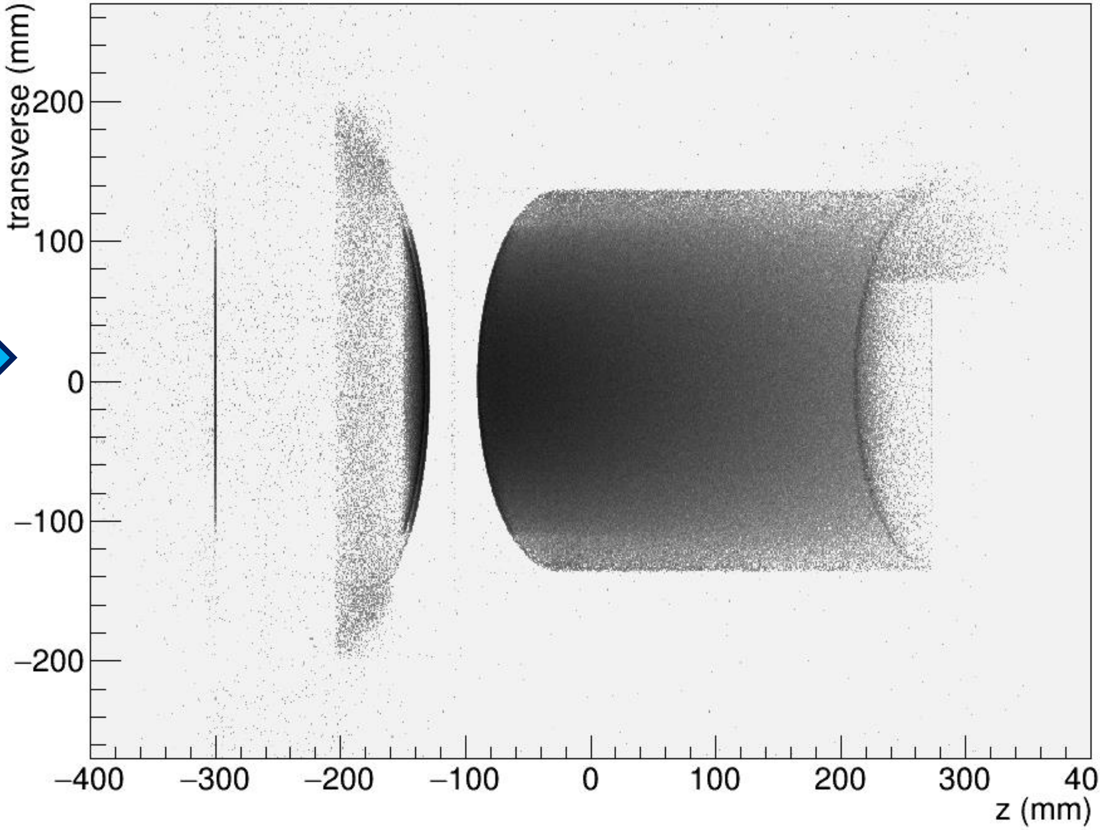


Pure Ortho - H_2

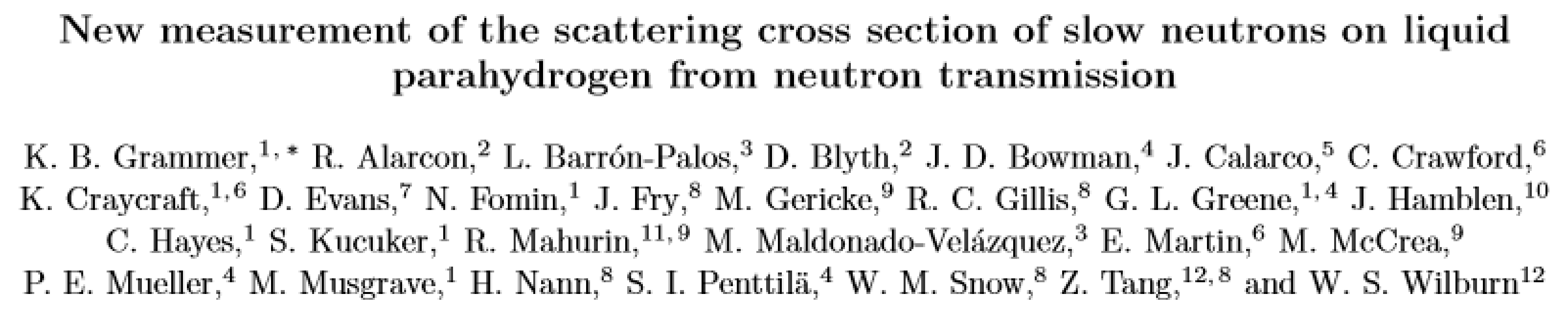
Pure Para - H_2

Neutron Capture in 3D

Cold Neutrons

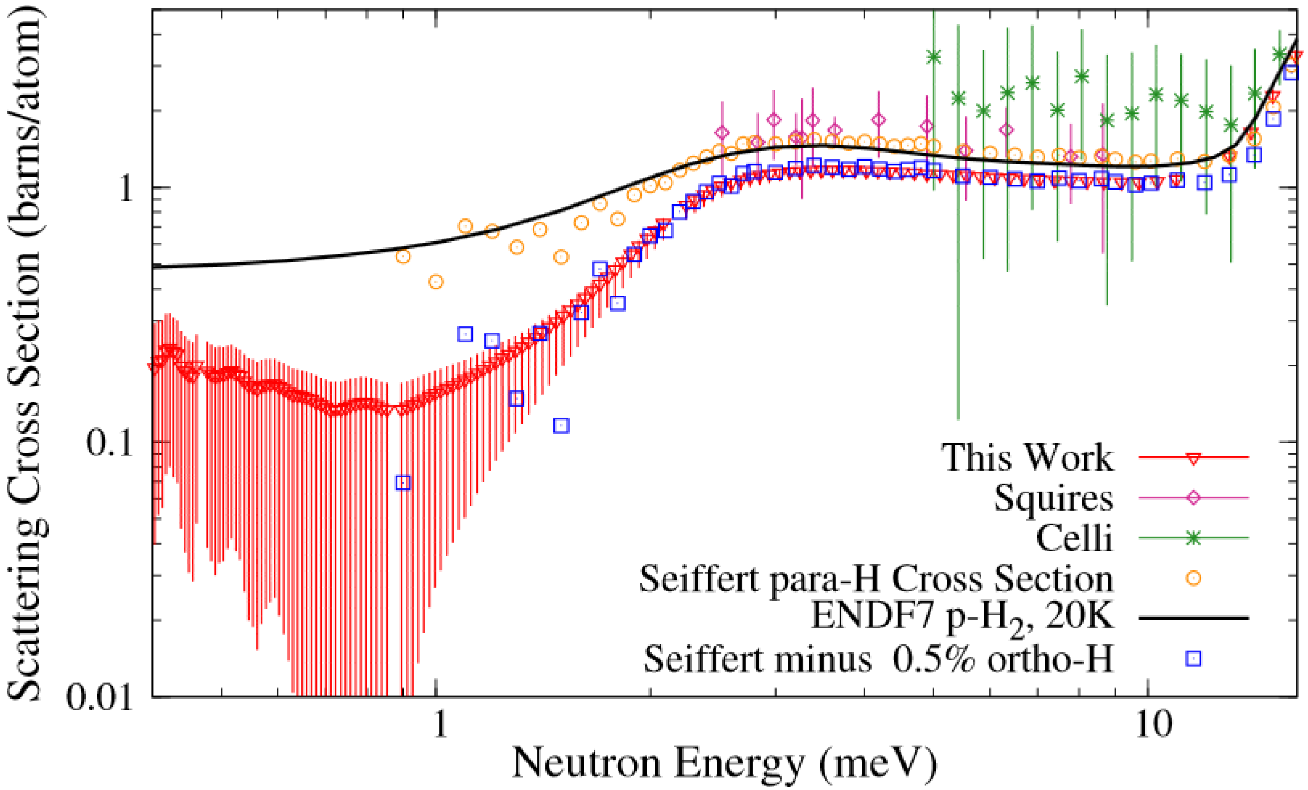


Graphics by D. Blyth



New measurement of the scattering cross section of slow neutrons on liquid parahydrogen from neutron transmission

K. B. Grammer,[1,*] R. Alarcon,[2] L. Barrón-Palos,[3] D. Blyth,[2] J. D. Bowman,[4] J. Calarco,[5] C. Crawford,[6]
K. Craycraft,[1,6] D. Evans,[7] N. Fomin,[1] J. Fry,[8] M. Gericke,[9] R. C. Gillis,[8] G. L. Greene,[1,4] J. Hamblen,[10]
C. Hayes,[1] S. Kucuker,[1] R. Mahurin,[11,9] M. Maldonado-Velázquez,[3] E. Martin,[6] M. McCrea,[9]
P. E. Mueller,[4] M. Musgrave,[1] H. Nann,[8] S. I. Penttilä,[4] W. M. Snow,[8] Z. Tang,[12,8] and W. S. Wilburn[12]



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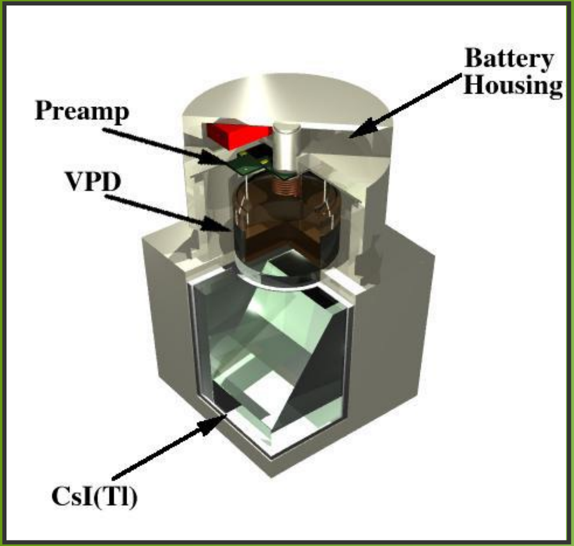
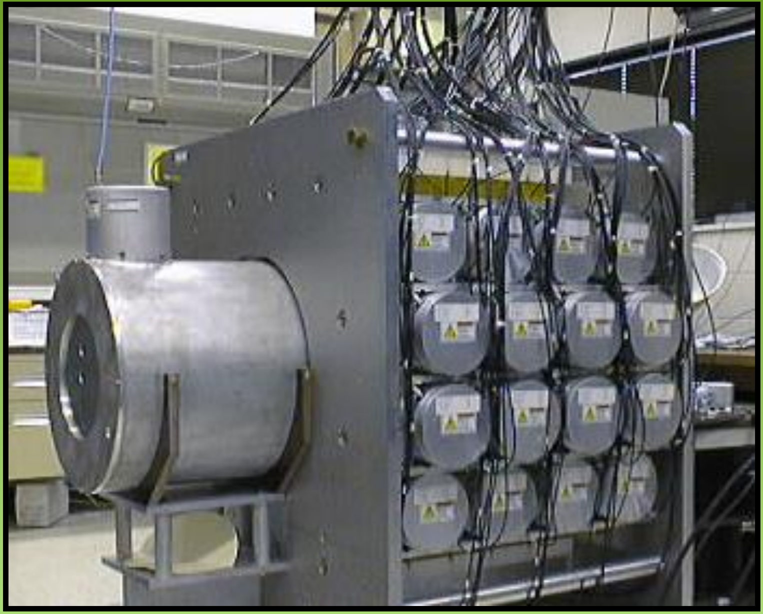
Asymmetry Extraction





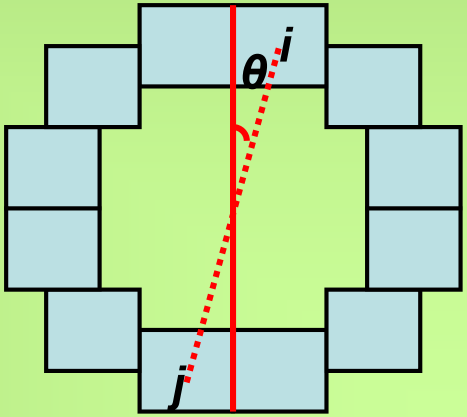
- In principle, experiment can be done with just one detector, reversing the neutron spin:

$$A_{raw} = \frac{Y^{\uparrow} - Y^{\downarrow}}{Y^{\uparrow} + Y^{\downarrow}}$$

- Add opposite detector at same angle*

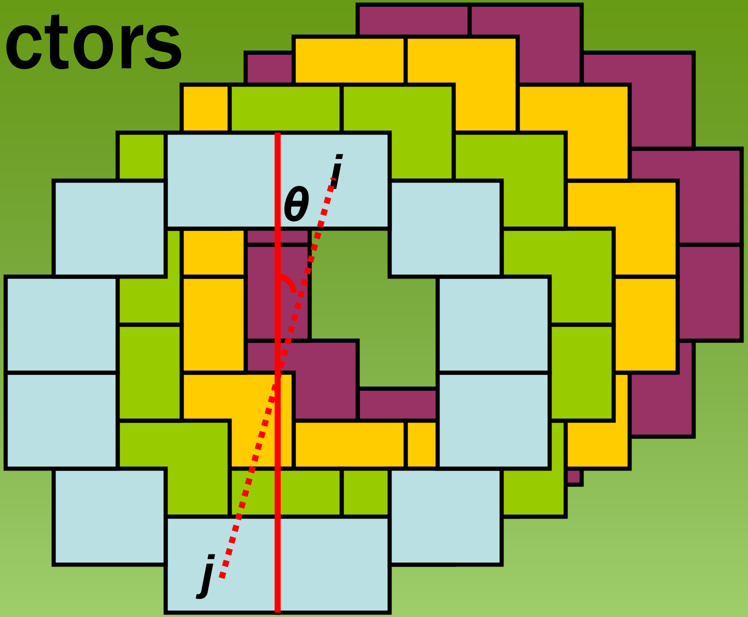
(eliminates some systematic errors):

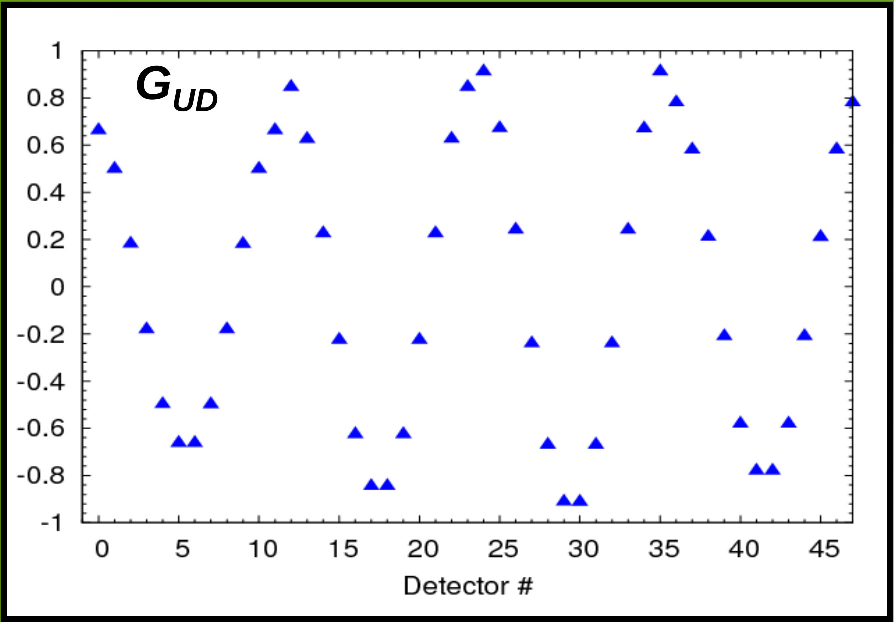
$$A_{raw} = \frac{1}{2}\left(\frac{Y_i^{\uparrow} - Y_j^{\uparrow}}{Y_i^{\uparrow} + Y_j^{\uparrow}} + \frac{Y_j^{\downarrow} - Y_i^{\downarrow}}{Y_j^{\downarrow} + Y_i^{\downarrow}} \right)$$



*Final asymmetry normalization was different

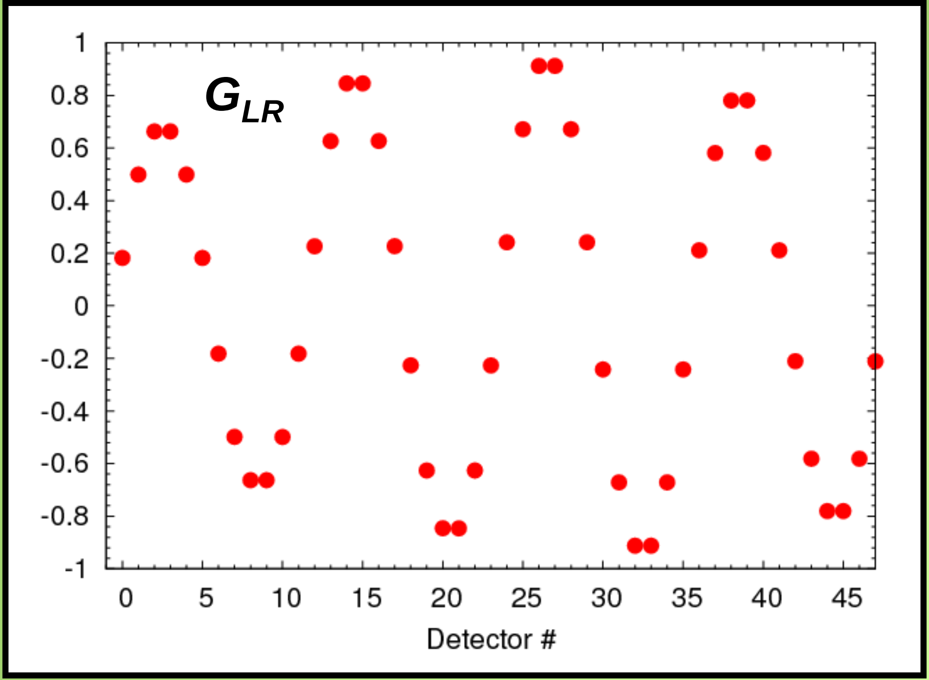
Geometrical Factors





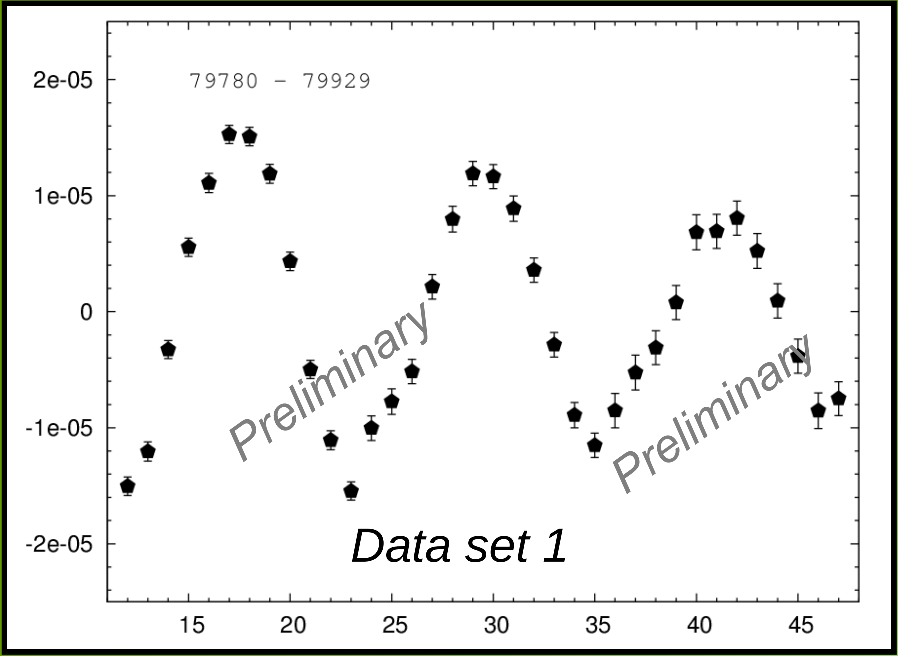
$$G_{UD}(i) = < \hat{k}_\gamma \cdot \hat{\sigma}_n > = < \hat{k}_\gamma \cdot \hat{y} >$$

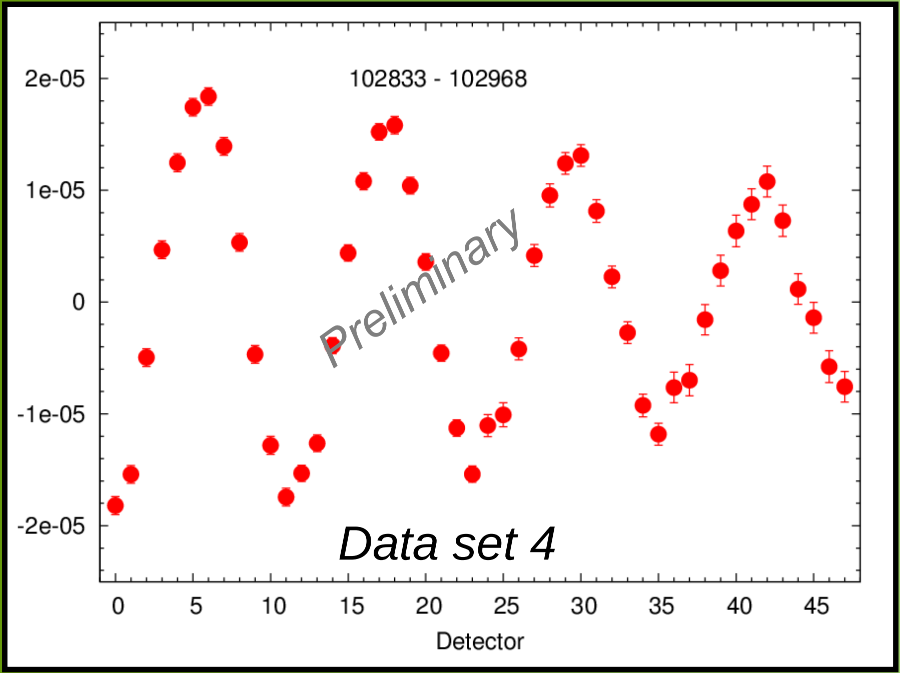
Generated via a combination of MCNPX and measurements with a gamma source



$$G_{LR}(i) = < \hat{k}_y \cdot \left(\vec{\sigma}_n \times \hat{k}_n \right) > = < \hat{k}_y \cdot \hat{x} >$$

Chlorine Asymmetry Results





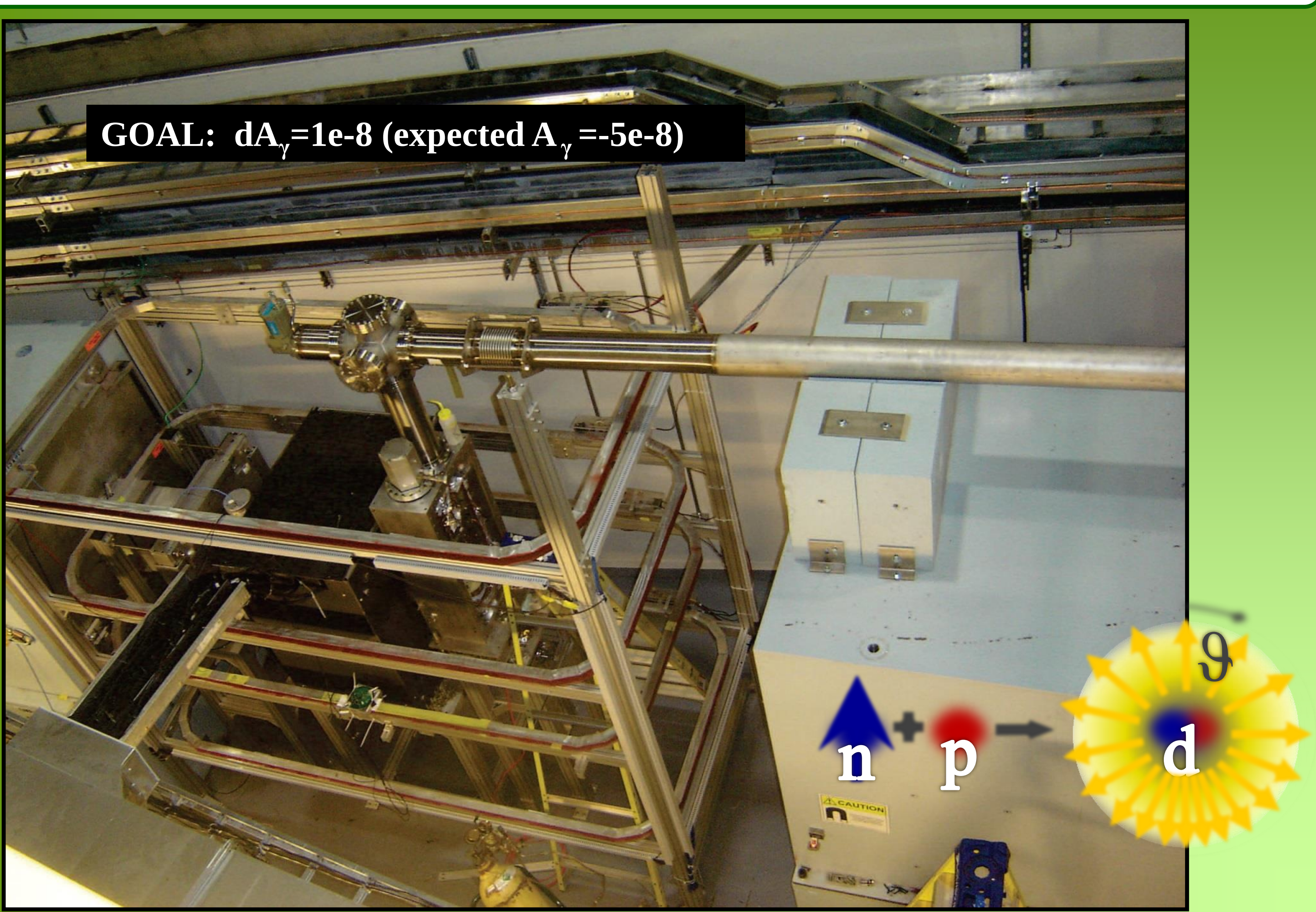
Corrections:

→ Background Subtraction
→ Beam Polarization
→ Beam Depolarization
→ RFSF Efficiency

3% Uncertainty from geometric factors

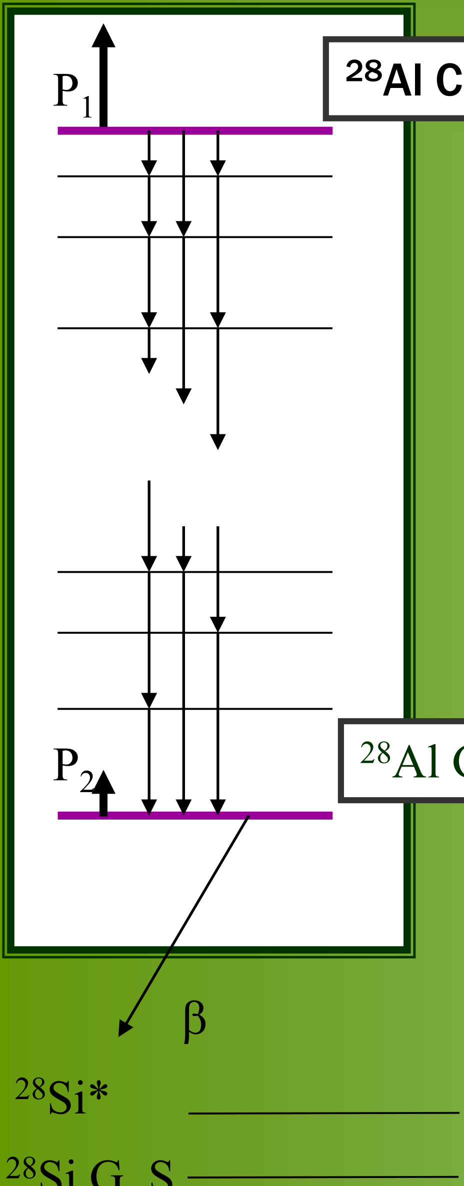
Measurement	A^{pv} (x10^{-6})
LANL	-29.1 ± 6.7
Leningrad	-27.8 ± 4.9
ILL	-21.2 ± 1.72
SNS (preliminary)	***-25.9 ± 0.6***

Production Hydrogen Configuration



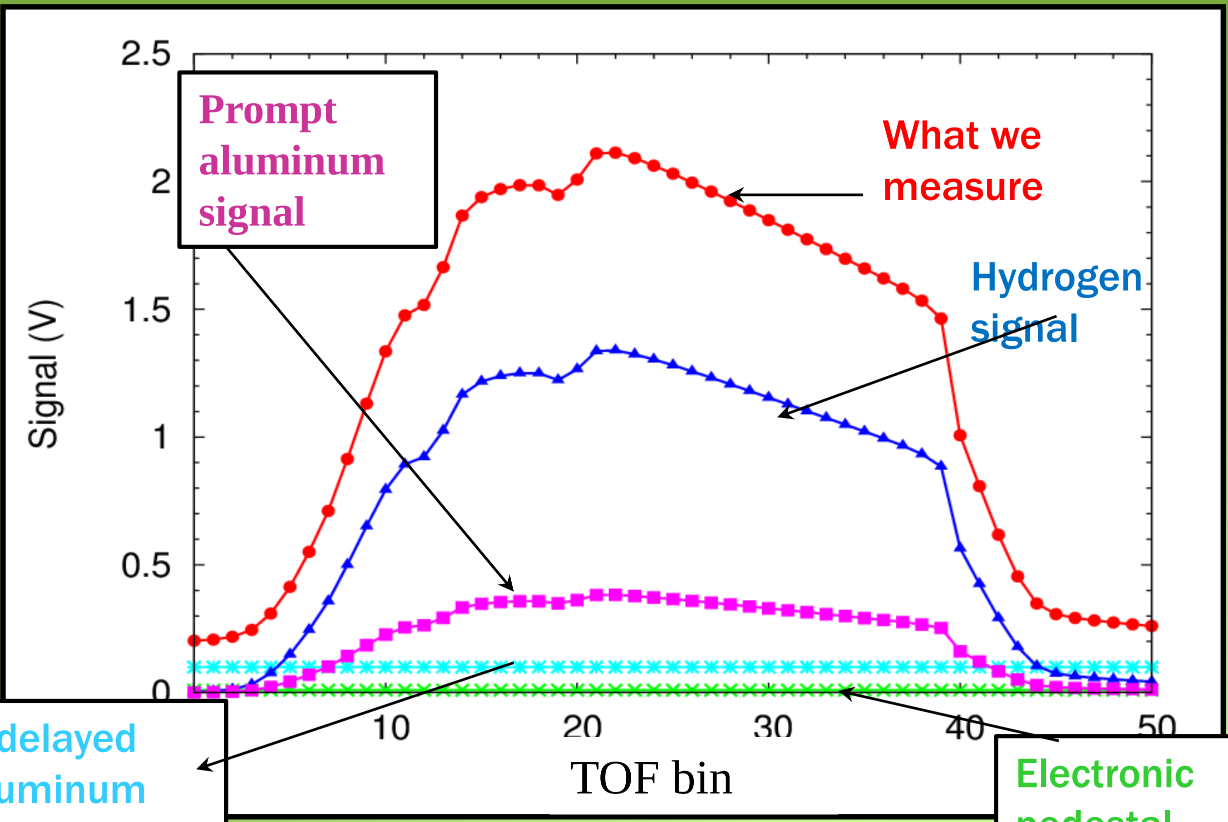
GOAL: dA_{γ}=1e-8 (expected A_{γ} =-5e-8)

What we actually measure



^{28}Al Capture State

^{28}Al G. S.



Prompt aluminum signal

What we measure

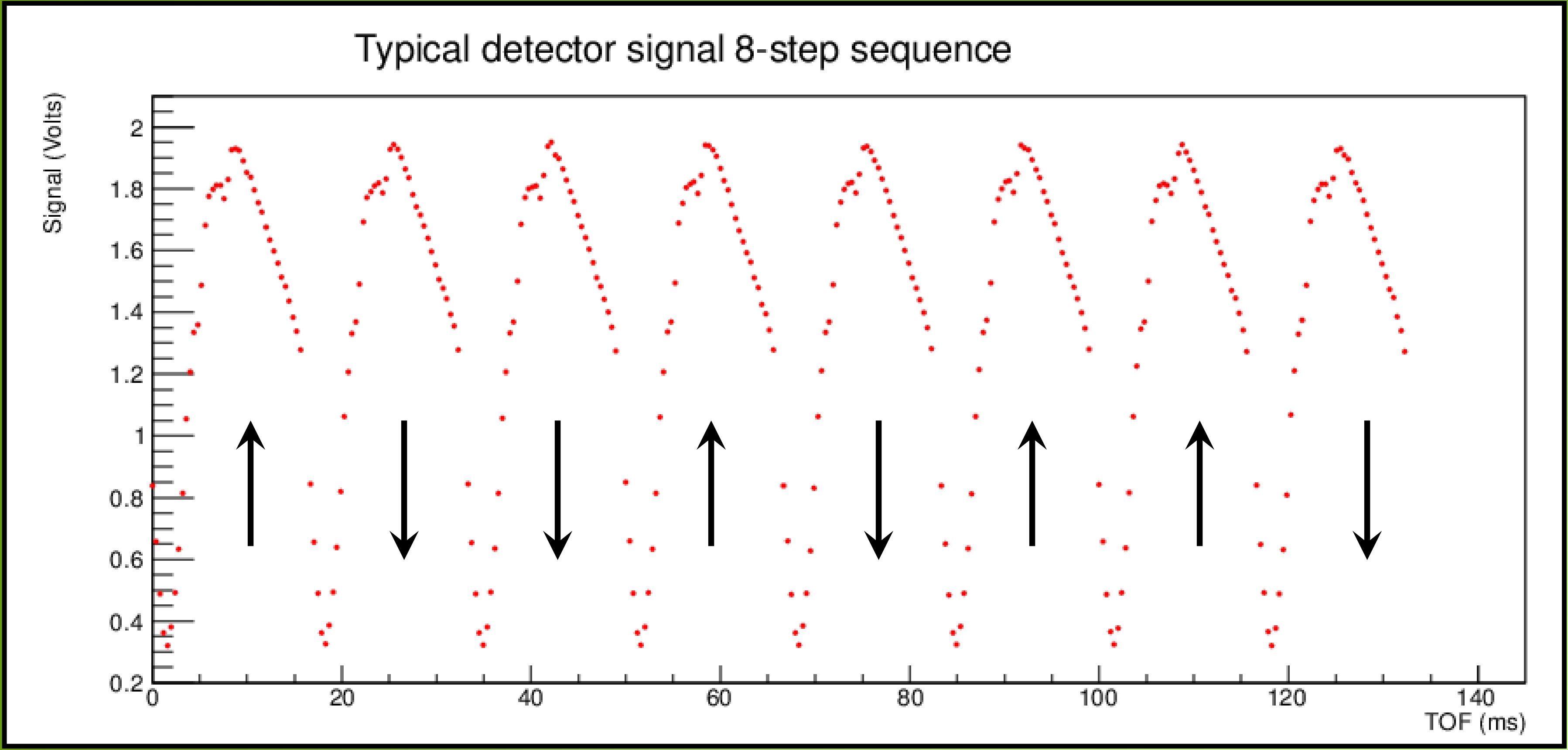
Hydrogen signal

β-delayed aluminum signal

Electronic pedestal

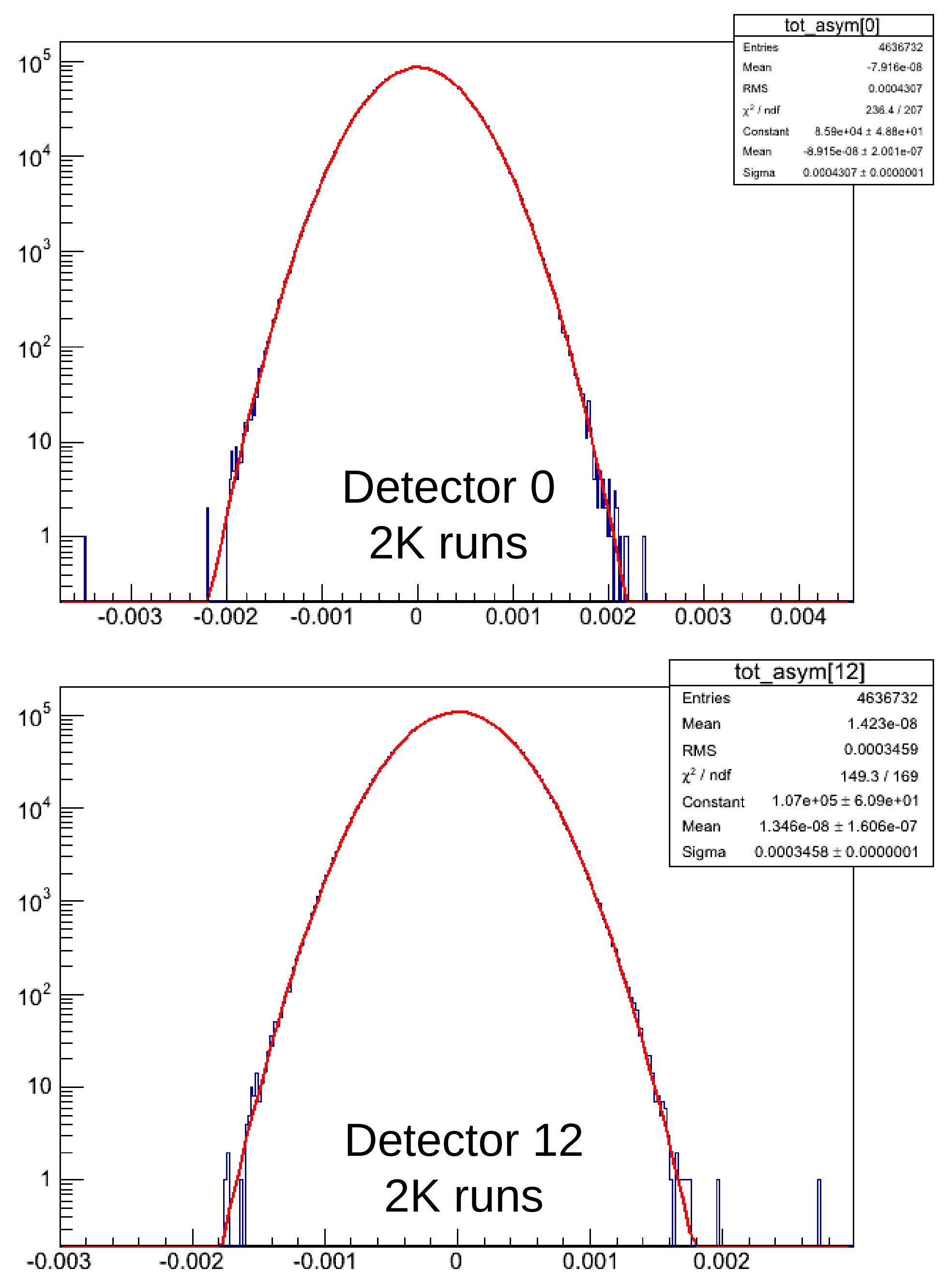
Spin octet ↑↓↓↑↓↑↑↓

Detector signals → Asymmetries



- *Runs are made up of 8-step sequences: 4 with neutron spin || B-field, 4 with neutron spin reversed*
- *Each spin sequence – 48 detector asymmetries*

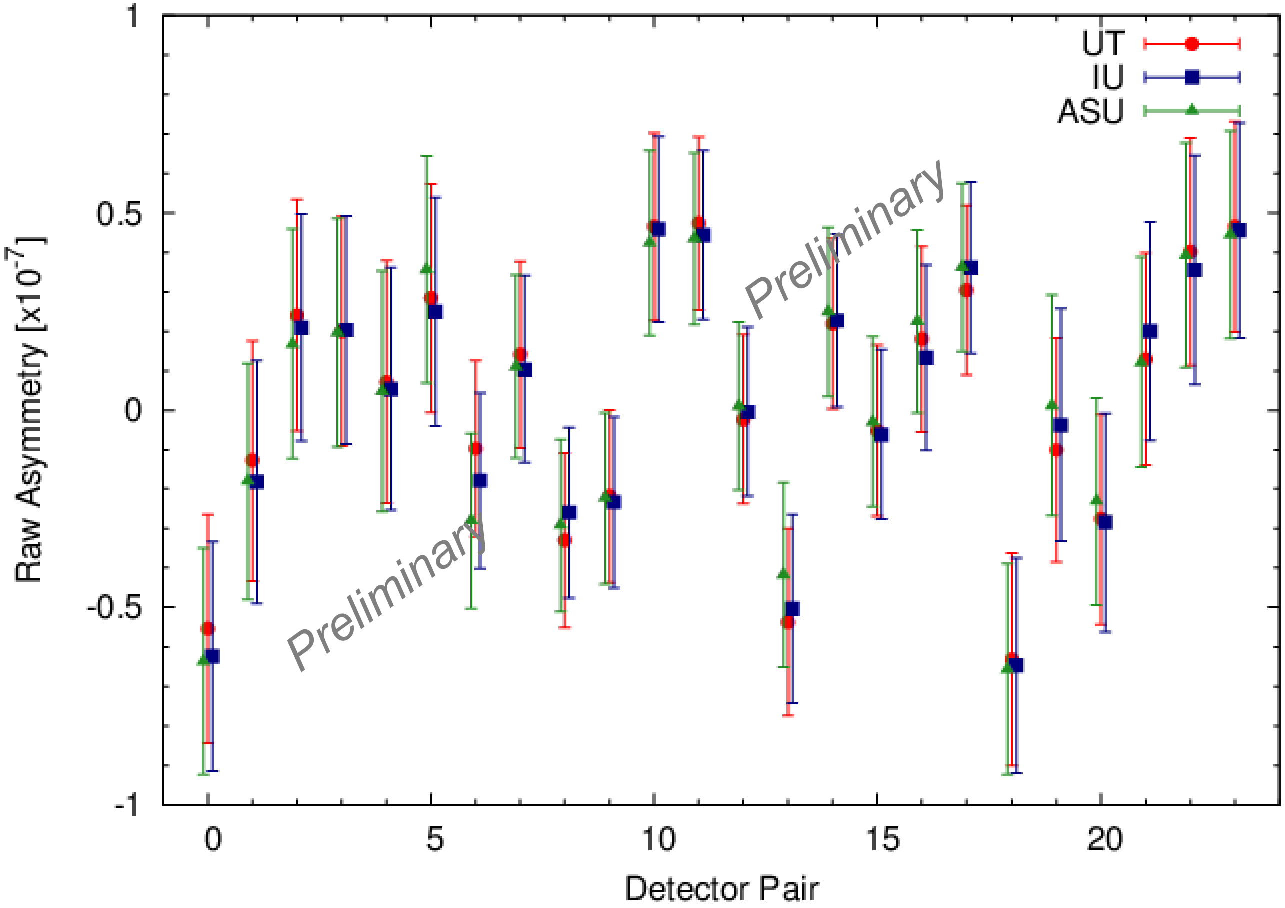
Hydrogen Data



Raw detector asymmetries with minimal cuts:

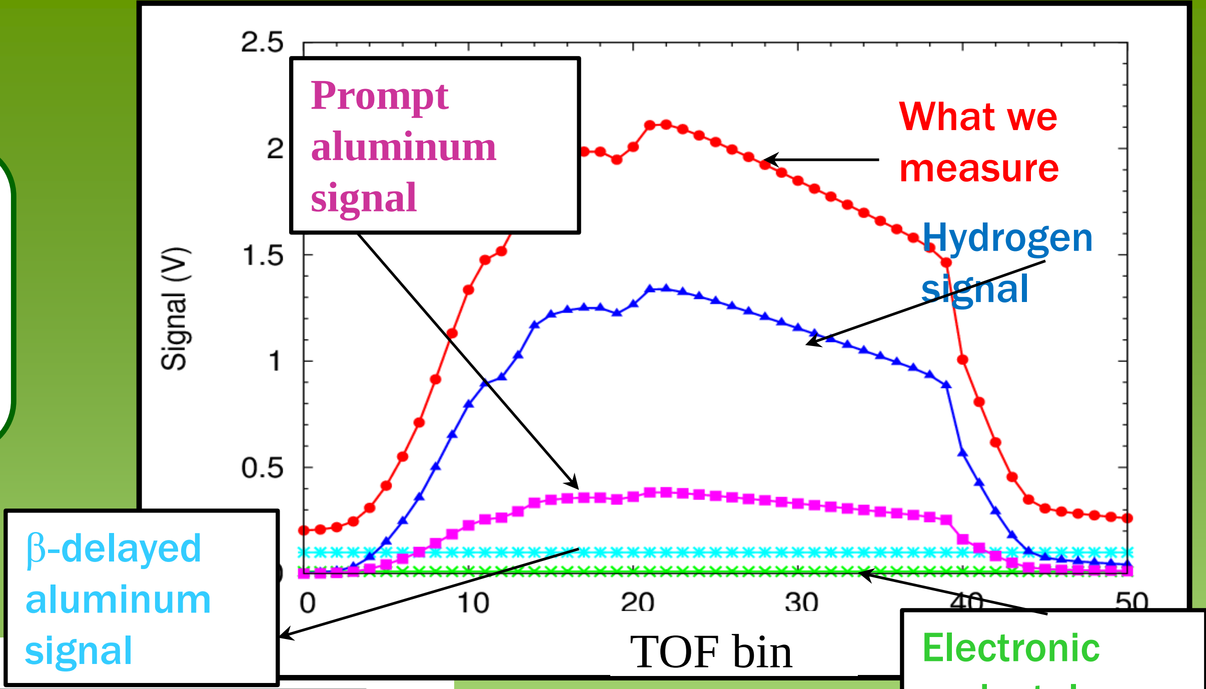
- Require beam on for several spin sequences → “good beam history”
- 1% beam stability
- No data corruption

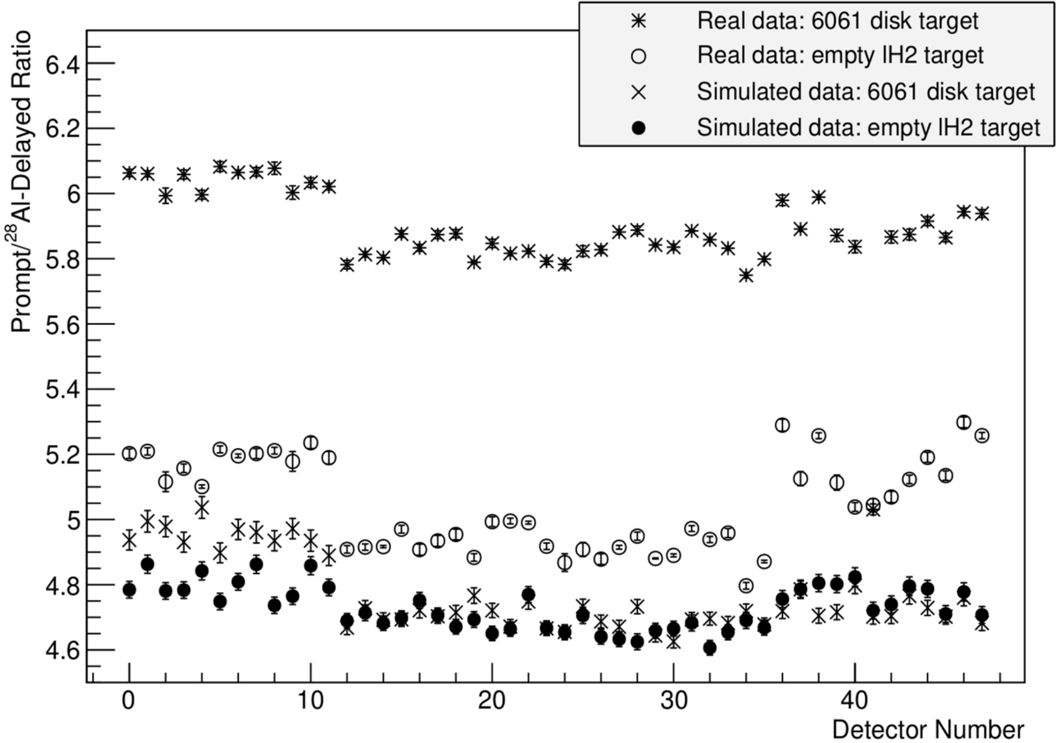
All the hydrogen data (2015)



Systematic Effects which may cause false Asym	**Size**
Additive Asymmetry (instrumental)	$< 1x10^{-9}$
Multiplicative Asymmetry (instrumental)	$< 1x10^{-9}$
Stern-Gerlach (steering of the beam)	$< 1x10^{-10}$
γ – ray circular polarization	$< 1x10^{-12}$
β – decay in flight	$< 1x10^{-11}$
Capture on ^{6}Li	$< 1x10^{-11}$
Radiative β –decay	$< 1x10^{-12}$
β - delayed Al gammas (internal + external)	$< 1x10^{-9}$
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	3 %
Polarization of overlap neutrons	0.1%
Target Position	0.03%
Statistical uncertainty in presented results	
Combined hydrogen and aluminum data	$\sim 1.3x10^{-8}$

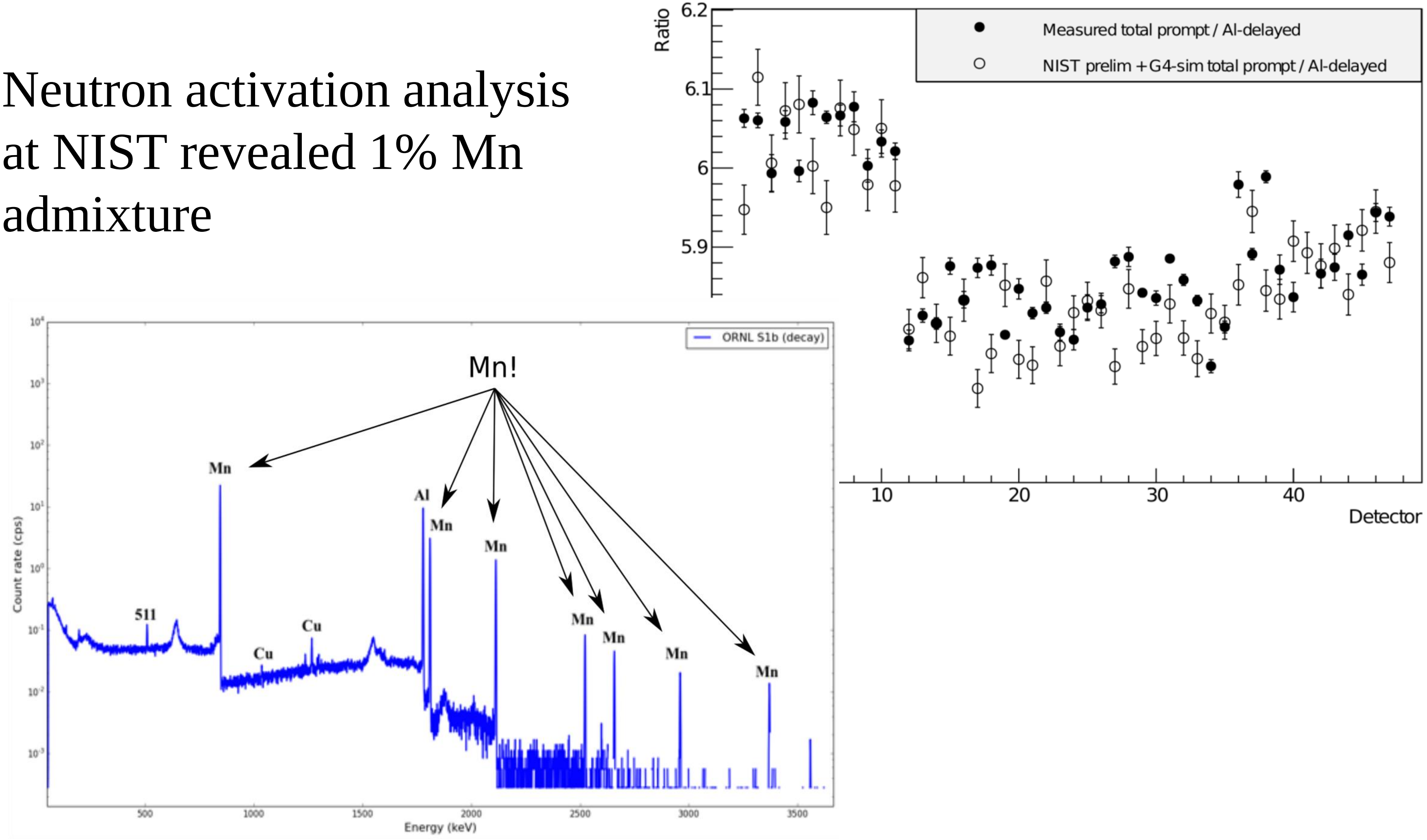
Everything was going SO well





Compositions of Cryo-vessel and Aluminum target Differ

Neutron activation analysis at NIST revealed 1% Mn admixture



Compositions of Cryo-vessel and Aluminum target Differ

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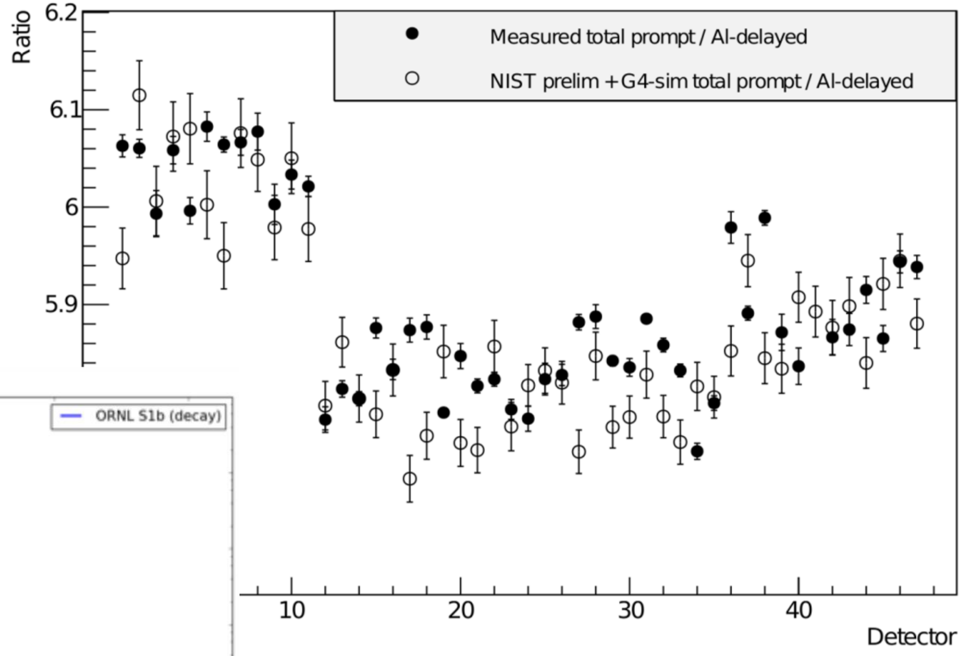
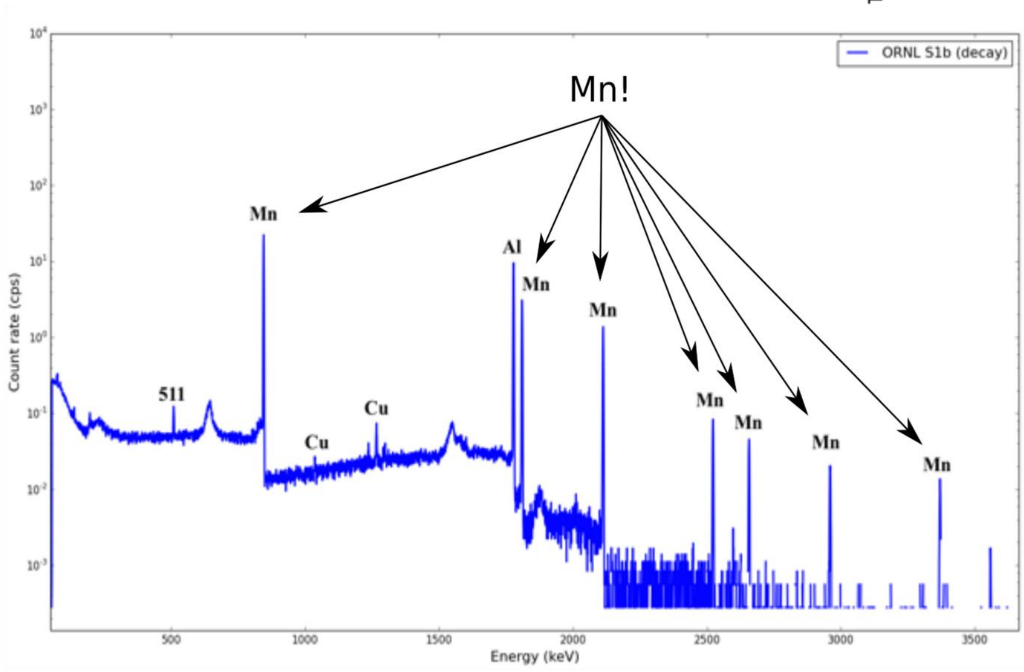




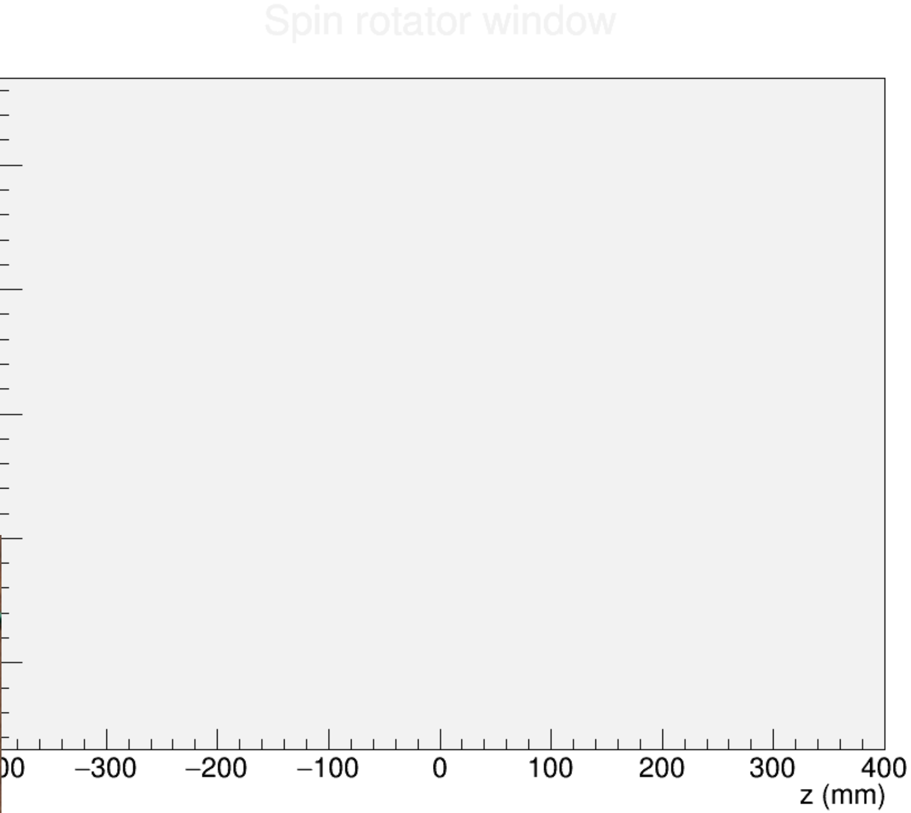
Using old Mn low-precision data:

$$A_H = -2.8 \pm 0.9\,(\mathrm{H}) \pm 4.0\,(\mathrm{Al})$$

GOAL $dA=1.34^{-8}$

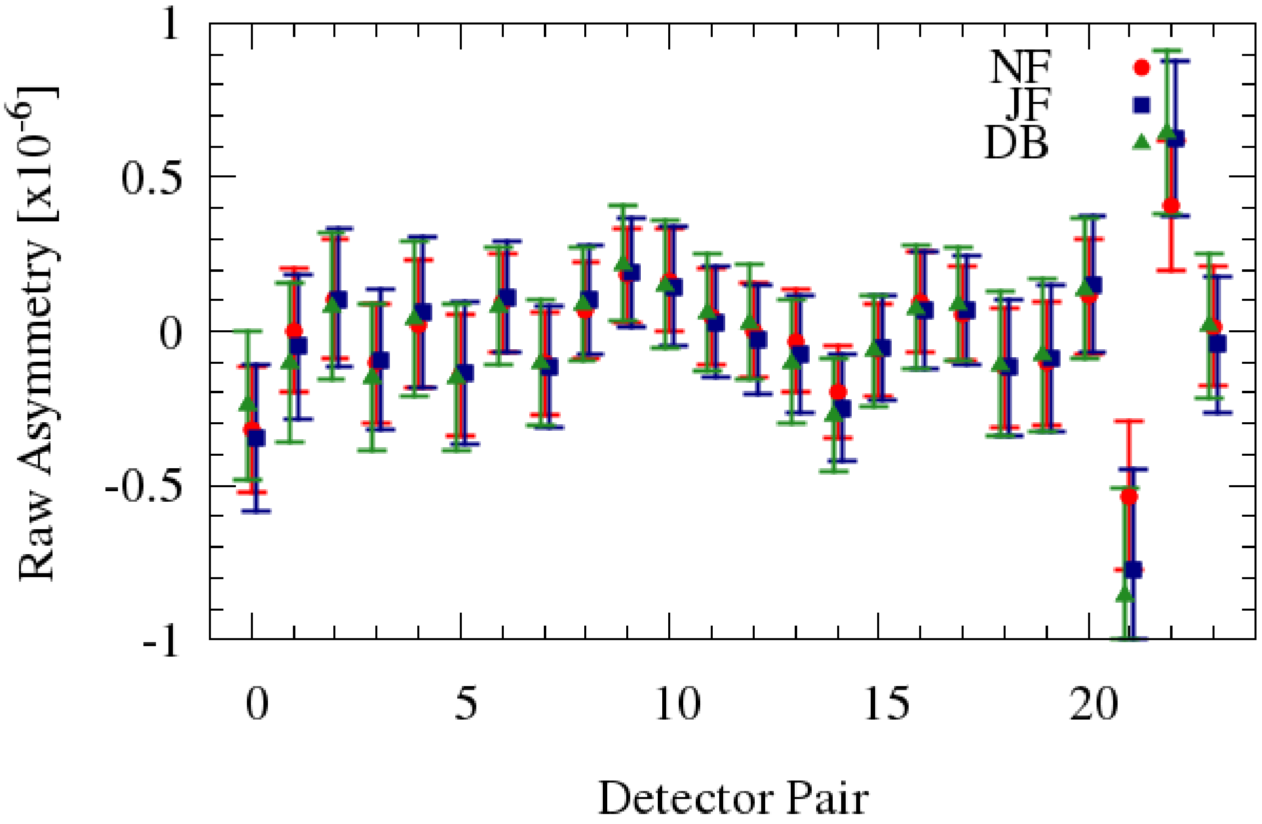
NPDGAMMA (AGAIN)

- Determine pieces of cryostat that came from single pour and assume independent
- Cut up LH_2 cryostat
- Design targets to replicate background with parahydrogen vessel full
- Composite target to mimic neutron capture on original LH_2 vessel



Graphics by D. Blyth

Aluminum 2.0 running completed (June 2016)



- New false asymmetry makes for an “exciting” data analysis
- Analysis completed, PRL submtited

Final Analysis approach

Write down:

$$\chi^2_{grand} = \chi^2_H\left(A^H_{UD}, A^H_{LR}, A^{AL}_{UD}, A^{AL}_{LR}\right) + \chi^2_{AL}\left(A^{AL}_{UD}, A^{AL}_{LR}\right)$$

Where $A^H_{UD}, A^H_{LR}, A^{AL}_{UD}, A^{AL}_{LR}$ **are free parameters**

From the data, we have

$$A^{raw}_i = P_{tot}(f^H_i A^H_i + f^{AL}_i A^{AL}_i)$$

Where f^H_i, f^{AL}_i **fractions of the total signal due to neutron capture on H or Al, respectively**

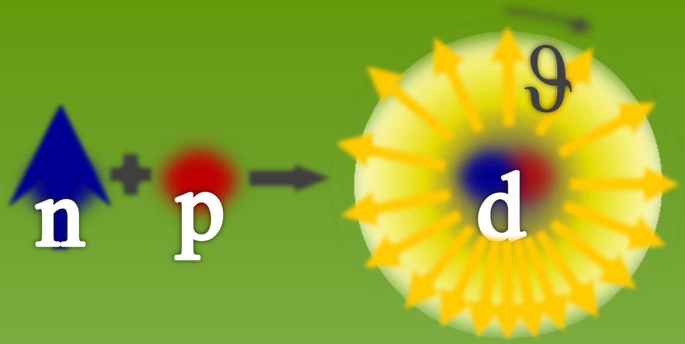
And the physics asymmetries are modified by the geometric factors for each pair via

$$A^H_i = G^H_{UD,i} A^H_{UD} + G^H_{LR,i} A^H_{LR}$$

$$A^{AL}_i = G^{AL}_{UD,i} A^{AL}_{UD} + G^{AL}_{LR,i} A^{AL}_{LR}$$

Solve for $\boldsymbol{A^H_{UD}, A^H_{LR}, A^{AL}_{UD}, A^{AL}_{LR}}$ **simultaneously using both data sets**

Final Answer?



Three analyses converged on one PV proton asymmetry

$$A^{p}_{\gamma,PV} = -3.0 \pm 1.4 \pm 0.2 [\times 10^{-8}]$$

- After 20ish years, NPDGamma has made a 1e-8 measurement of the long range component of the Hadronic Weak Interaction
  - Isolates the ΔI=1 piece of the Hadronic Weak Interaction
  - Not hindered by nuclear effects
- Future measurement at ESS?

The NPDGamma collaboration*

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[5]Thomas Jefferson National Laboratory
[6]National Institute of Standards and Technology
[7]Univeristy of Michigan, Ann Arbor
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[10]Los Alamos National Laboratory
[11]Indiana University
[12]University of Tennessee
[13]University of California at Berkeley
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[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
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[25]Western Kentucky University
[26] University of Tennessee at Chattanooga

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DOE and NSF (USA)
NSERC (CANADA)
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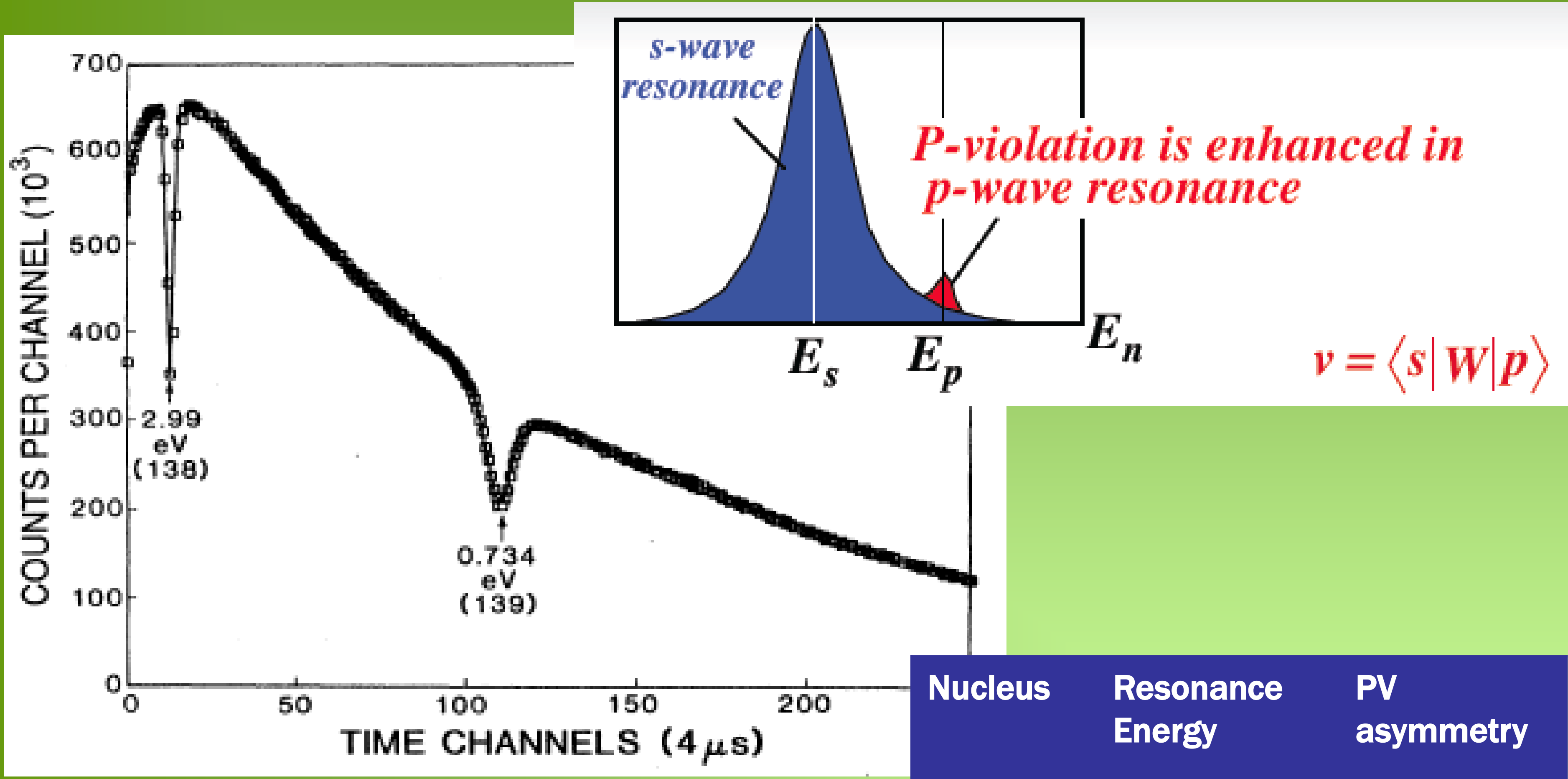
BARC (INDIA)

Parity Violation in n+ ^{139}La at 0.734 eV $\Delta\sigma/\sigma=10\%$
Standard Model P Violation Amplified by ~10^6 !



$$v = \langle s | W | p \rangle$$

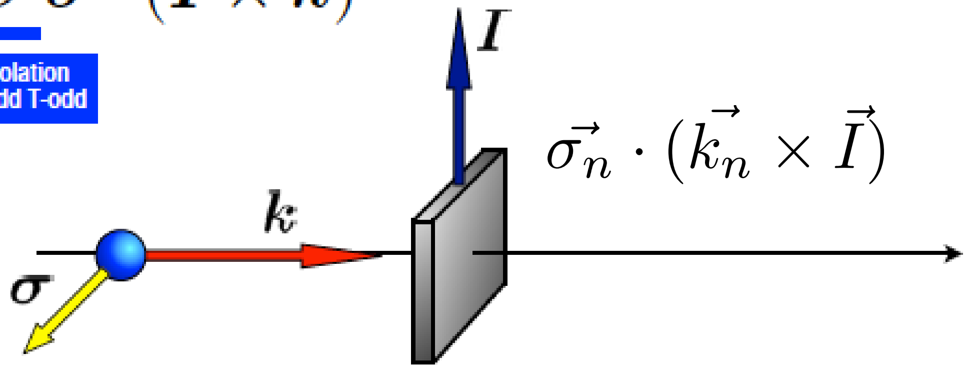
Nucleus	Resonance Energy	PV asymmetry
^{131}Xe	3.2 eV	0.043
^{139}La	0.748 eV	0.096
^{81}Br	0.88 eV	0.02

Idea is to use the observed enhancement of PV to search for a TRIV asymmetry.

Some other candidates beyond 139La exist

Forward Scattering Ampliltude

$$f = \underbrace{A'}_{\substack{\text{Spin Independent}\\ \text{P-even T-even}}} + \underbrace{B'}_{\substack{\text{Spin Dependent}\\ \text{P-even T-even}}}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + \underbrace{C'}_{\substack{\text{P-violation}\\ \text{P-odd T-even}}}\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + \underbrace{D'}_{\substack{\text{T-violation}\\ \text{P-odd T-odd}}}\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$$



$$\begin{array}{ccccc} |s\rangle & |p\rangle & |p_{1/2}\rangle & |p_{3/2}\rangle & \\ J_s E_s \Gamma_s \Gamma^n_s & J_p E_p \Gamma_p \Gamma^n_p & \Gamma^n_{p,1/2} & \Gamma^n_{p,3/2} & \langle W \rangle \end{array}$$

The enhancement of P-odd/T-odd amplitude on p-wave resonance (σ.[K X I]) is (almost) the same as for P-odd amplitude (σ.K).

Experimental observable: ratio of P-odd/T-odd to P-odd amplitudes $\lambda_{PT} = \frac{\delta\sigma_{PT}}{\delta\sigma_P}$

λ *can be measured with a statistical uncertainty of ~1 10^{-6} in 10^7 sec at MW-class spallation neutron sources. Ratio (T-odd amplitude in nucleon/strong amplitude)~10^{-13}. Statistical sensitivity up to 100X better than present neutron EDM limit. NOPTREX collaboration engaged in R&D now.*

Forward scattering neutron optics limit is null test for T (no "final state effects")