Measurement of Parity-Violation in Cold Neutron Capture

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Outline

1. Hadronic Weak Interaction
   - What…
   - Why…
   - How…
2. Experiment
   - Hardware and measurements
3. Analysis and Results
   - Asymmetry, Errors
4. Summary and Outlook
   - Present and Future

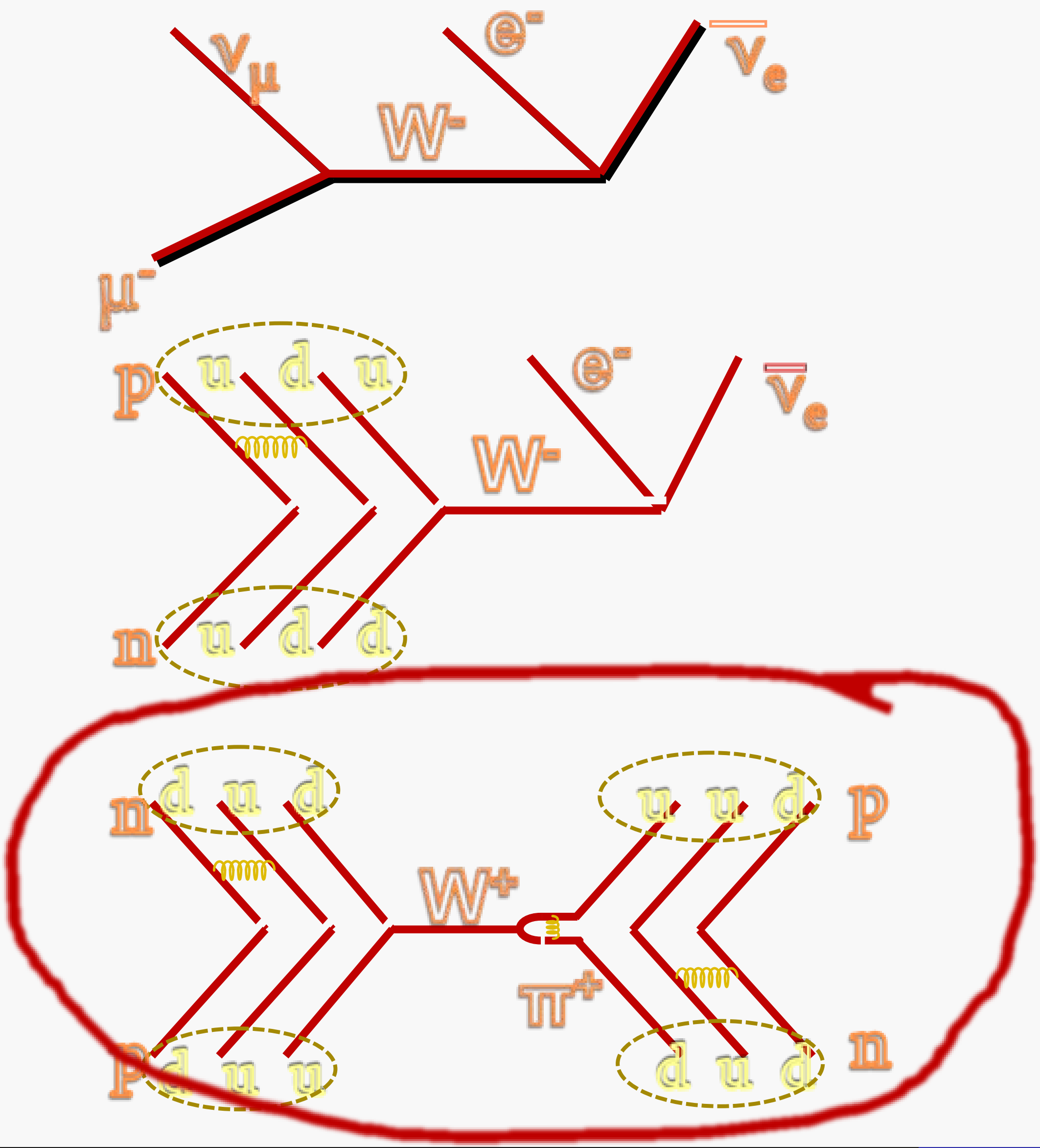
Why…

Bosons are too heavy

Study the weak interaction between hadrons

- Explore weak interaction at low energies.
- The $\Delta I = \frac{1}{2}$ rule: $\Gamma(K_s^0 \rightarrow \pi^0\pi^0) \gg \Gamma(K^+ \rightarrow \pi^+\pi^0)$.
- Probe strong interaction at low energies.

Weak Interaction



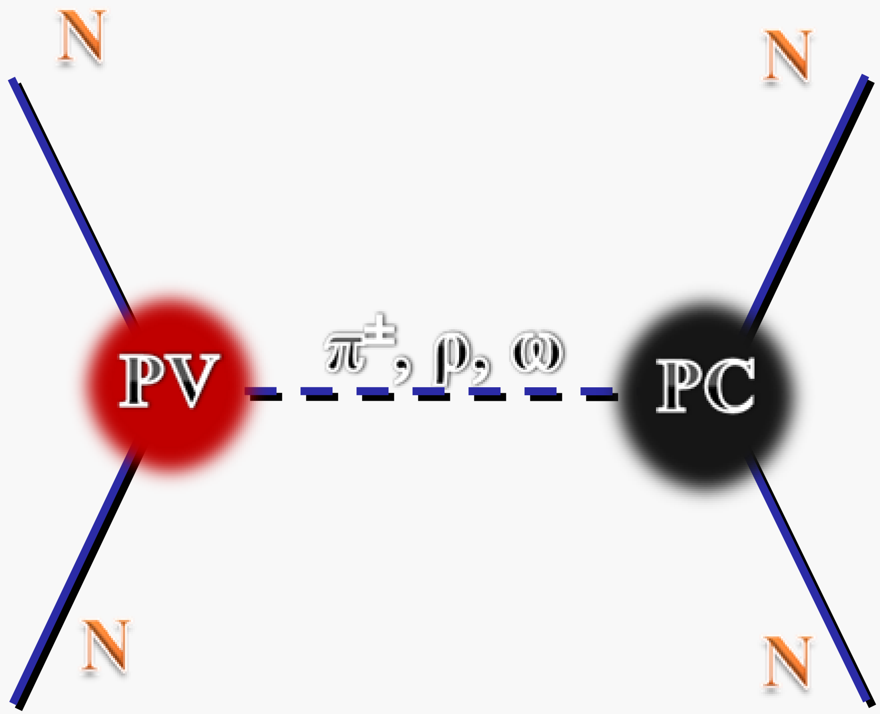
Weak processes

- $\mu \longrightarrow e^- + \upsilon_\mu + \overline{\upsilon}_e$
- $n \longrightarrow p + e^- + \overline{\upsilon}_e$
- $n + p \longrightarrow n + p$

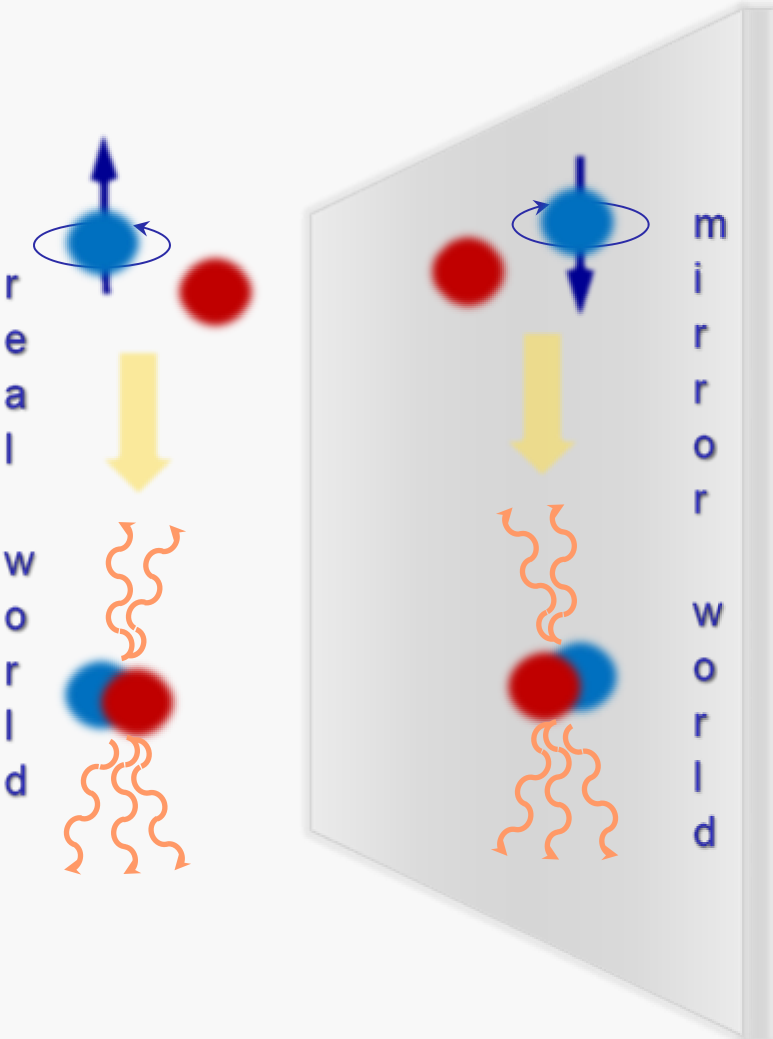
Weak Interaction

Weak vs. Strong

- $\Delta S = 0$: strong
- $\frac{STRONG}{weak} \sim 10^7$
- **Use Parity!**



Parity Violation



Parity

- P(x) = - x
- P(y) = - y
- P(z) = - z

$$P(\mathbf{s}_n) = \mathbf{s}_n$$
$$P(\mathbf{k}_\gamma) = -\mathbf{k}_\gamma$$

Study the weak interaction between hadrons

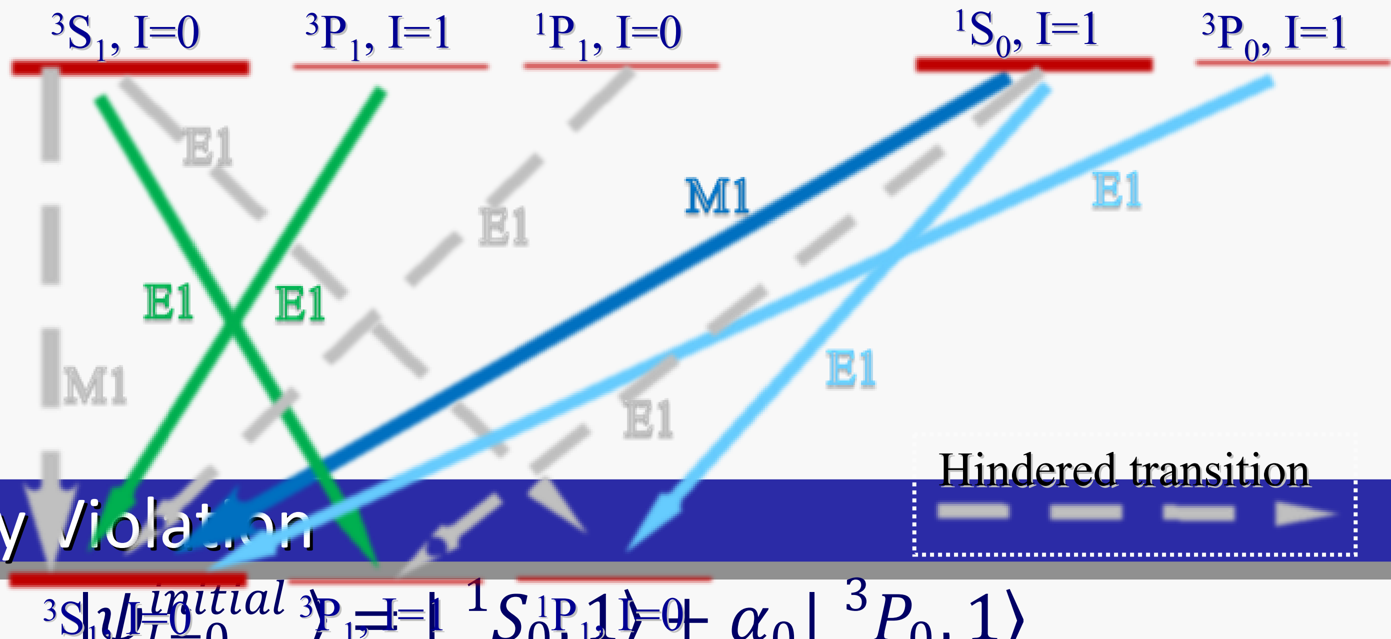
- Two nucleon system:

$$n + p \rightarrow d + \gamma$$

- $\Delta S = 0, \Delta I = 1$ channel

Why PV in $n+p \rightarrow d+\gamma$?

$n + p$ excited and ground states



Parity Violation

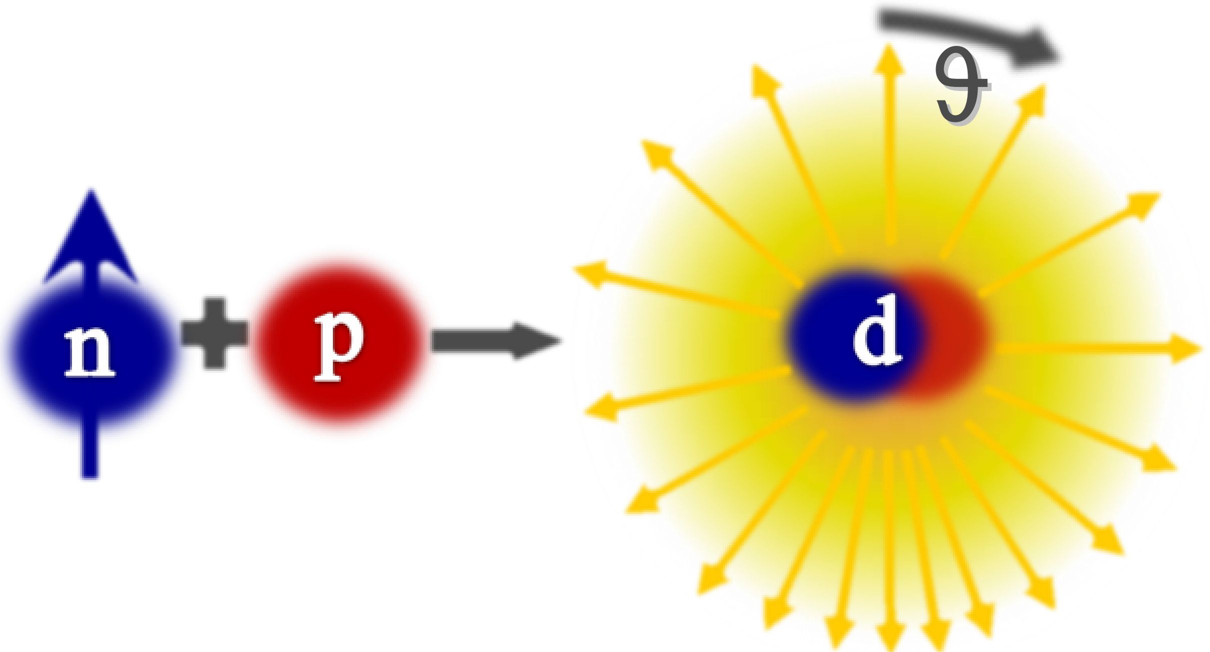
$$|\psi^{initial}_{J=0}\rangle = |\,{}^1S_0, 1\rangle + \alpha_0 |\,{}^3P_0, 1\rangle$$

$$|\psi^{initial}_{J=1}\rangle = |\,{}^3S_1, 0\rangle + \alpha_0 |\,{}^1P_1, 0\rangle + \alpha_1 |\,{}^3P_1, 1\rangle$$

$$|\psi^{final}_{J=1}\rangle = |\,{}^3S_1, 0\rangle + \alpha_0 |\,{}^1P_1, 0\rangle + \alpha_1 |\,{}^3P_1, 1\rangle$$

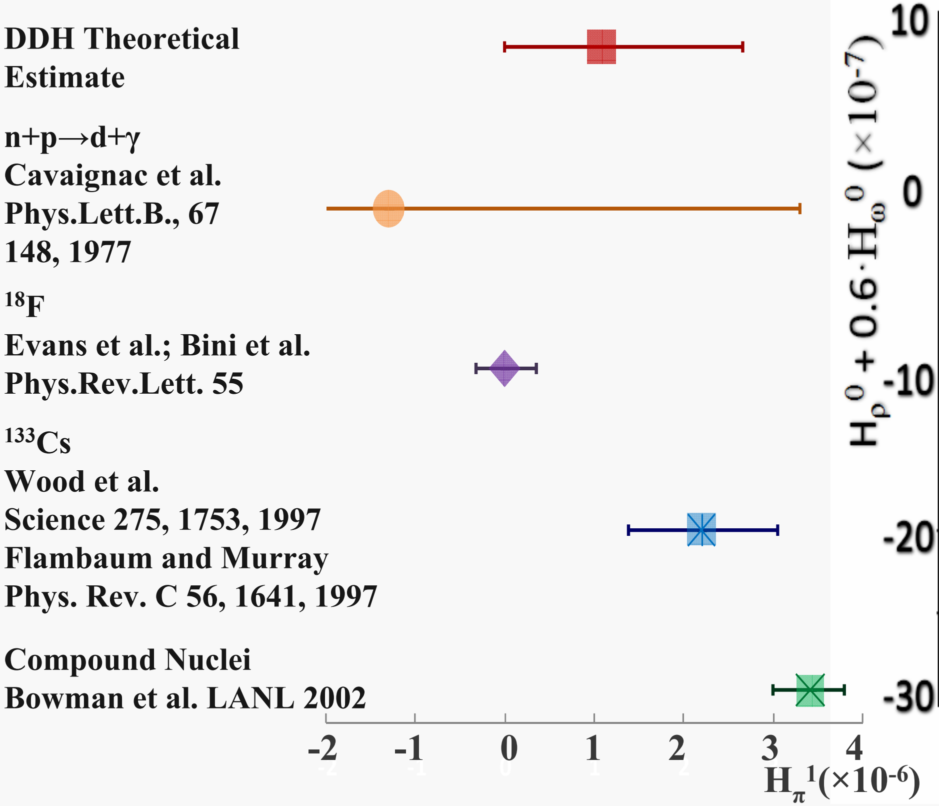
How…

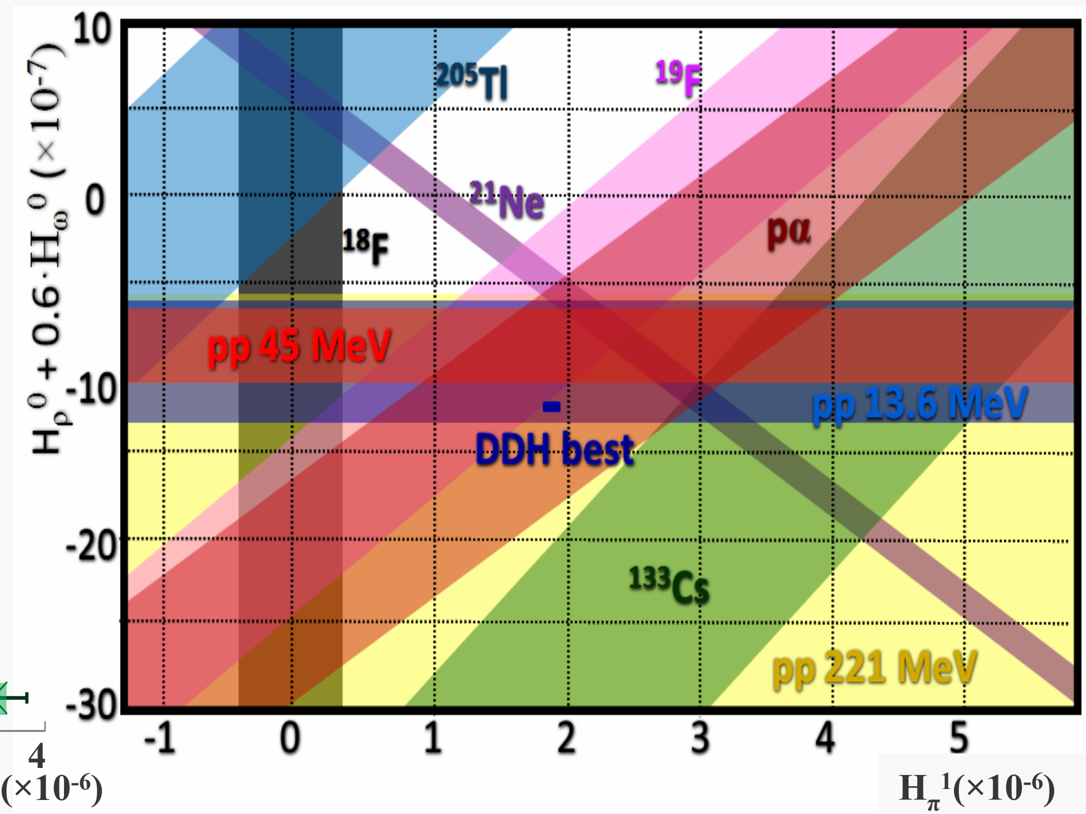
$$\frac{d\sigma}{d\Omega} = 1 + A_\gamma \cdot cos(\vartheta)$$



$$A_\gamma = 2\sqrt{2} \cdot \frac{\langle E1 \rangle}{\langle M1 \rangle}$$

H_π^1 so far…



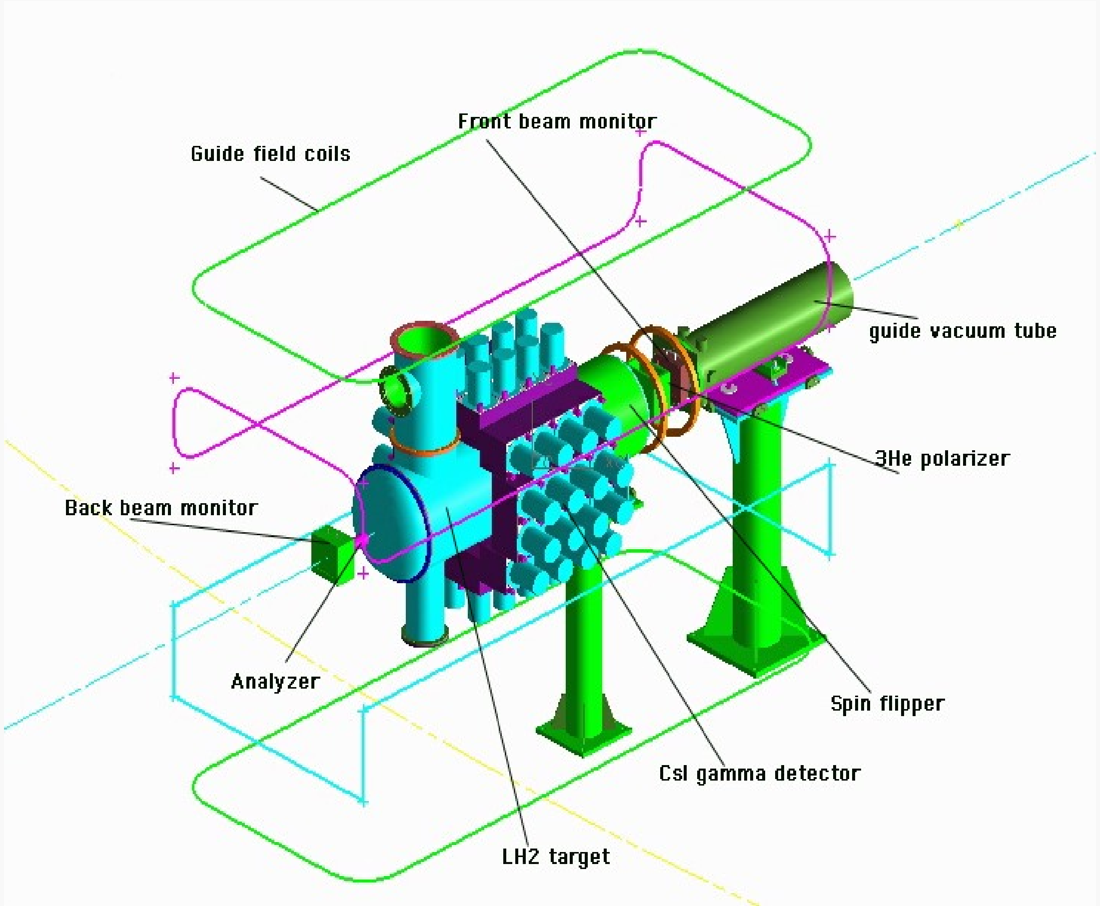


DDH: $A_\gamma = -0.045\, H_\pi^1$; $H_\pi^1, H_\rho^0, H_\rho^1, H_\rho^{1'}, H_\rho^2, H_\omega^0, H_\omega^1$

Goal: 0.5×10^{-8} *order measurement*

DDH: Desplanques, Donoghue, Holstein, Annals of Physics 124, 1980, 449.

Experiment - Overview

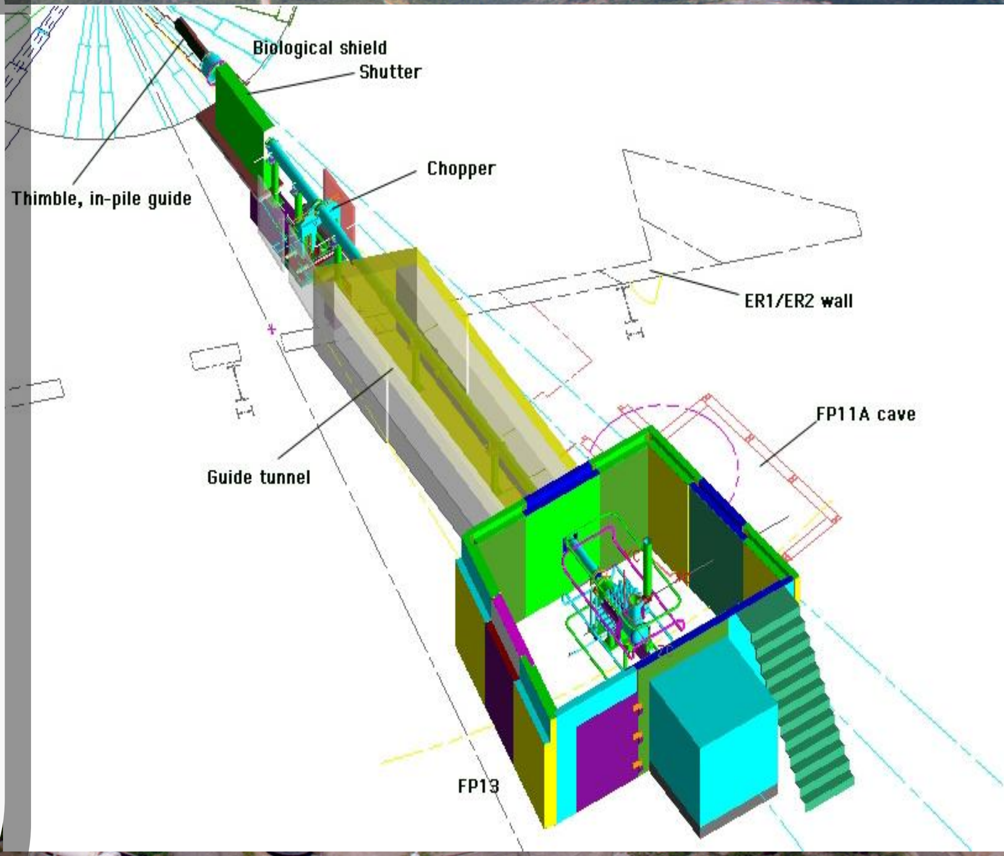


- Flight Path
- Neutron Guide
- Shielding
- Holding Field
- Beam Monitors
- Detector Array
- RF Spin Flipper
- Polarizer
- Analyzer
- Hydrogen Target
- Compound Targets

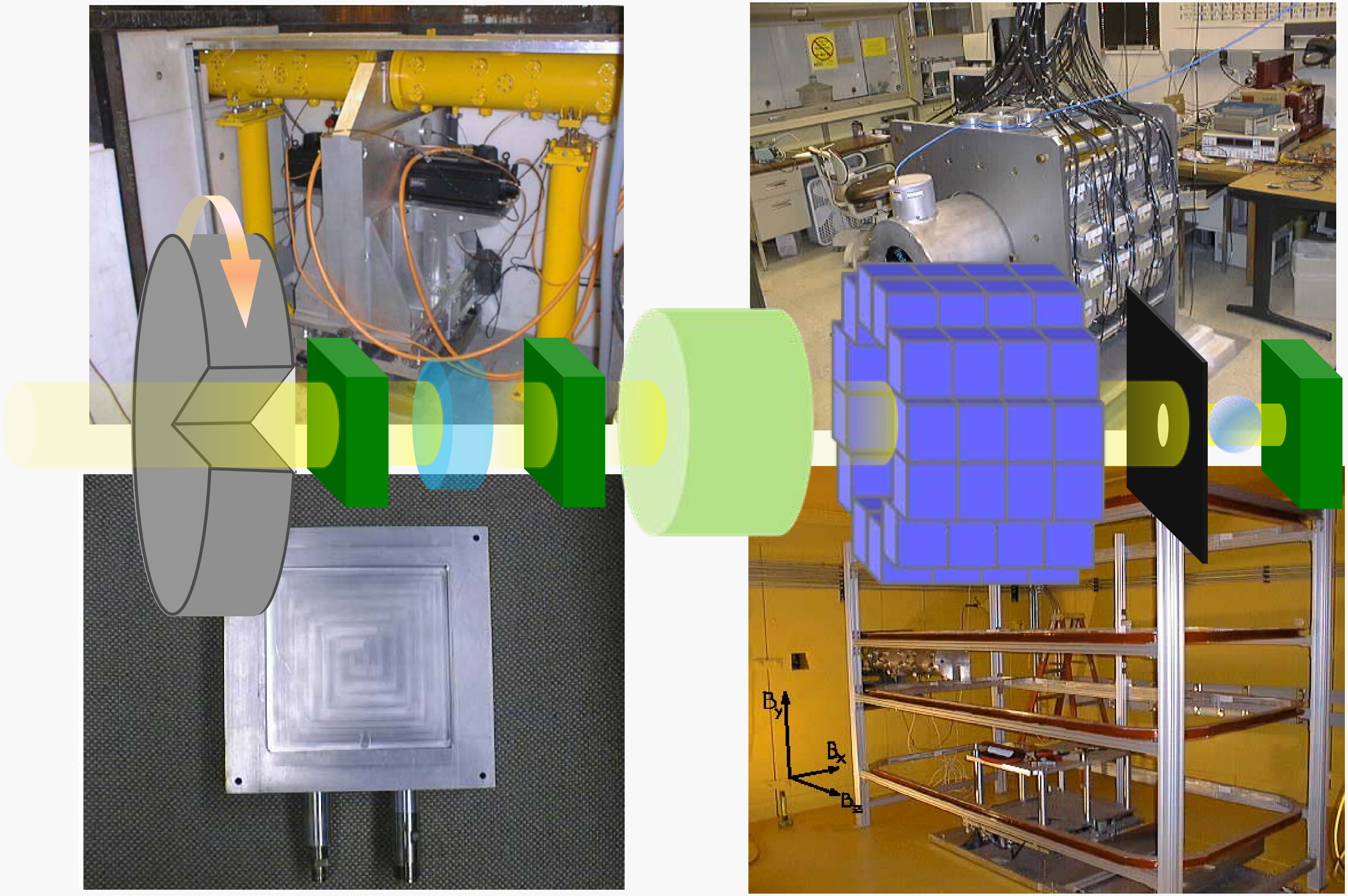
Experiment – Flight Path

Flight – Path

- 800 MeV Protons from ½ mile linac (~100μA)
- Protons hit the *W* spallation target to produce neutrons
- Neutrons are moderated by LH2 to *~100meV*
- 20Hz pulses – 50ms frames – time of flight information
- Neutrons are delivered by an ~20m “supermirror” guide



Apparatus

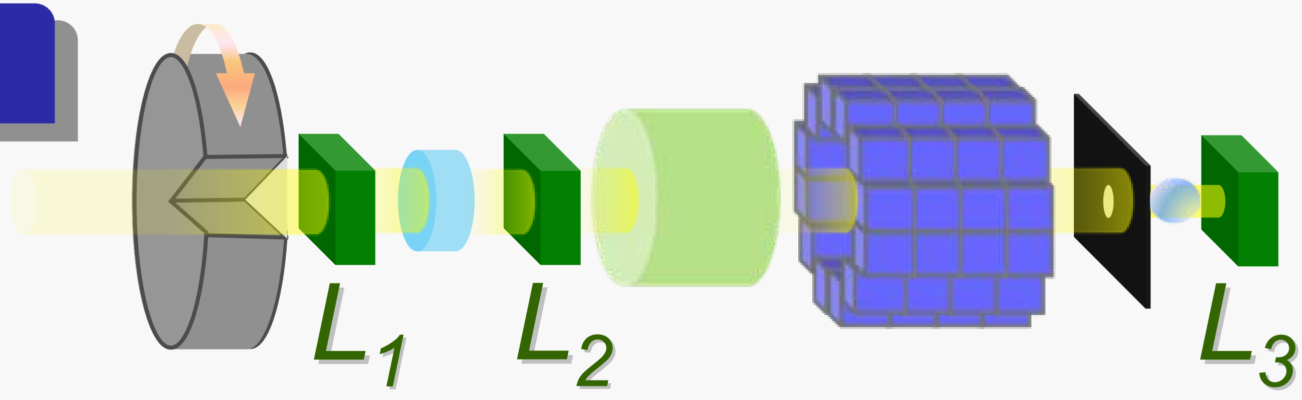


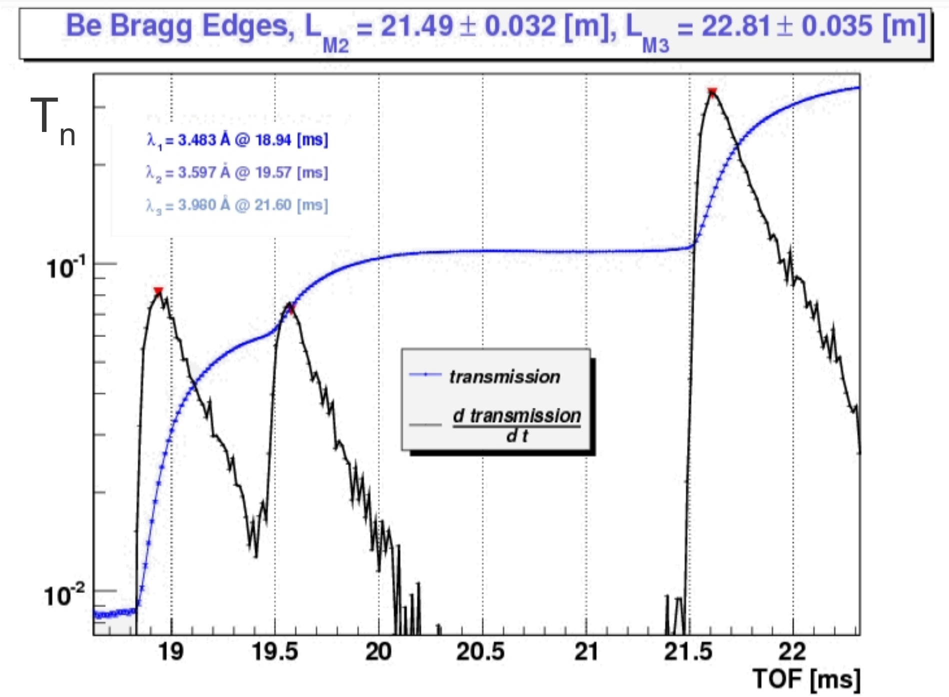
Apparatus – Flight Path Length

Bragg Transmission

$$n\lambda = 2d \cdot sin\theta$$

$$\lambda = \frac{ht}{mL}$$





Flight Path Length

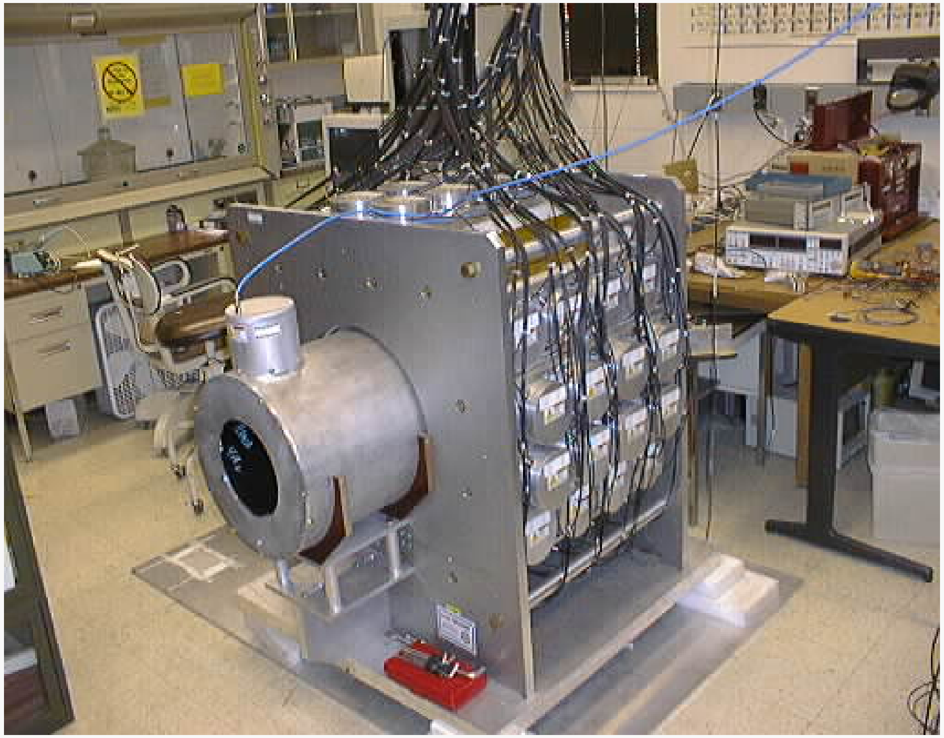
$$L_0 = 21.10 \pm 0.03\, m$$

$$L_1 = 21.11 \pm 0.03\, m$$

$$L_2 = 21.49 \pm 0.03\, m$$

$$L_3 = 22.81 \pm 0.04\, m$$

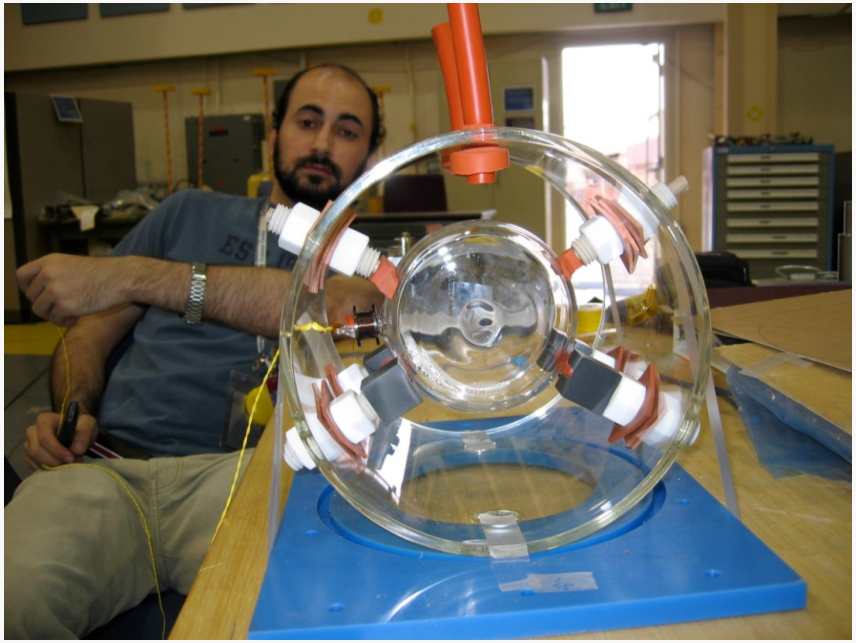
Experiment – γ-ray Detectors

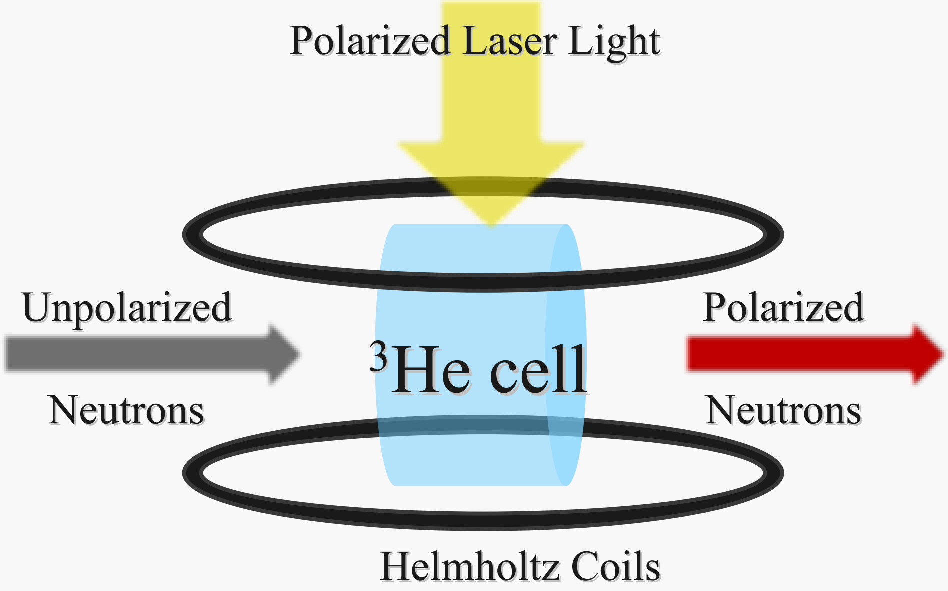


Measure Neutron Flux

- 3π acceptance
- 4 rings of $15\times15\times15$ cm^3 CsI crystals
- VPD: insensitive to magnetic field
- High event rate: use current mode
- Low-noise preamps: < 0.1 mV RMS
- Operate at counting statistics
- 95% γ's stopped in crystals
- Aligned with B_0 better than 1^o

Experiment – Polarizer





Boo-Boo

- 12 cm in diameter, 5 cm thick
- 4.9 atm·cm
- Relaxation time of 500 hrs

Typical polarization ~ 55%

Experiment – Polarizer

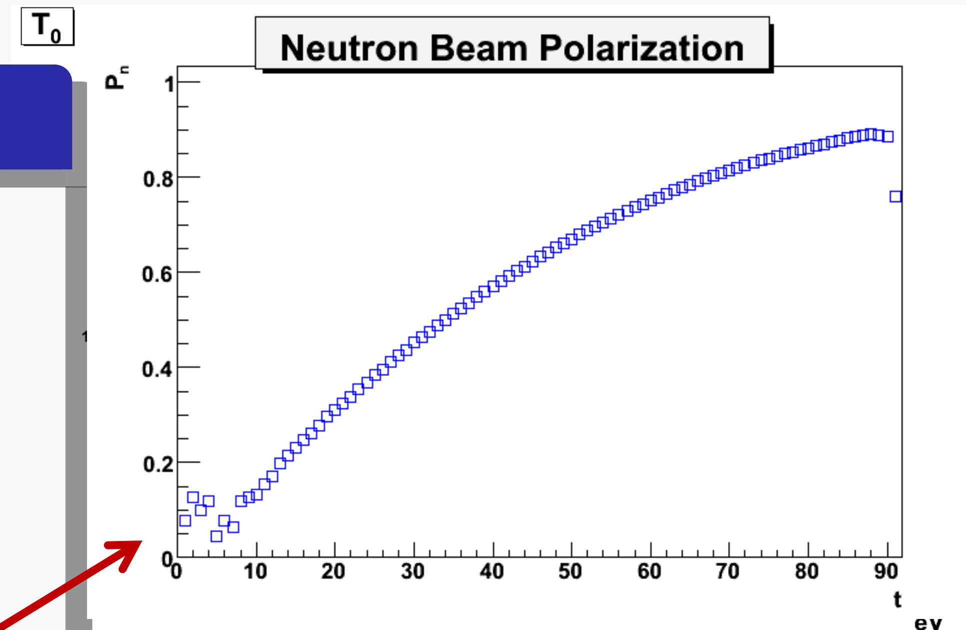
³He as a Neutron Spin Filter

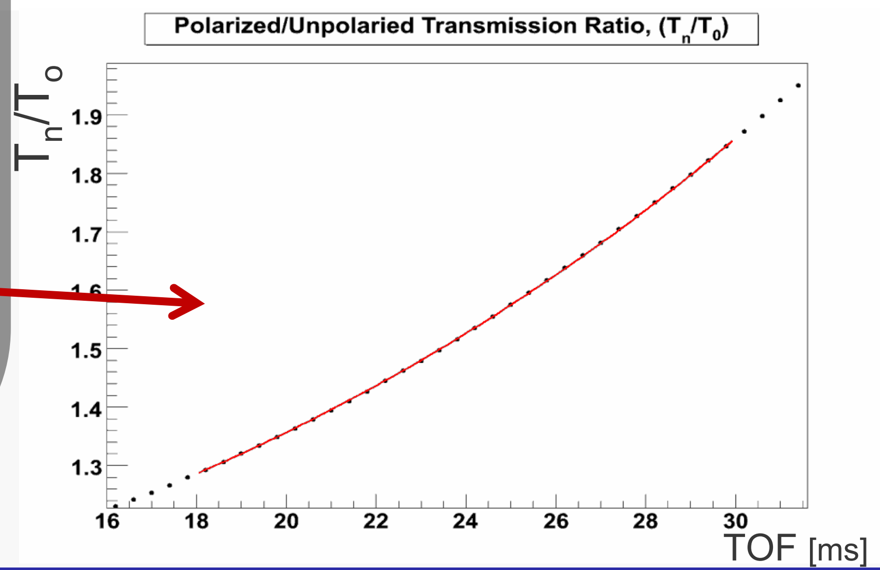
- ↑n ↑³He - 3 barns
- ↓n ↑³He - 5333 barns!
- **Transmission**

$$T_{\uparrow\downarrow} = e^{-nl\sigma\cdot(1\mp P_3)}$$

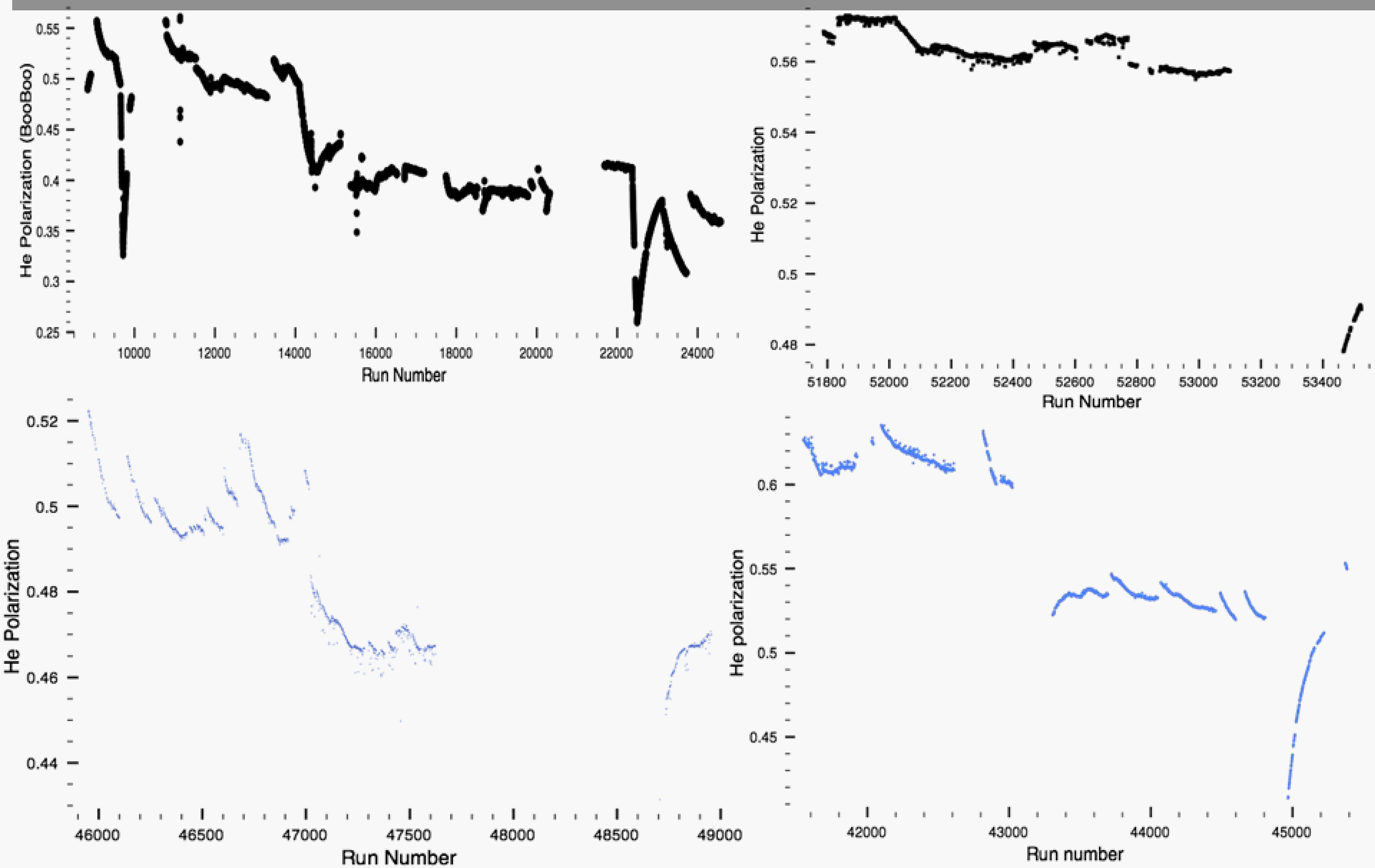
$$T_n = \cosh(nl\sigma P_3)$$

$$P_n = \sqrt{1-\left(\frac{T_0}{T_n}\right)^2}$$

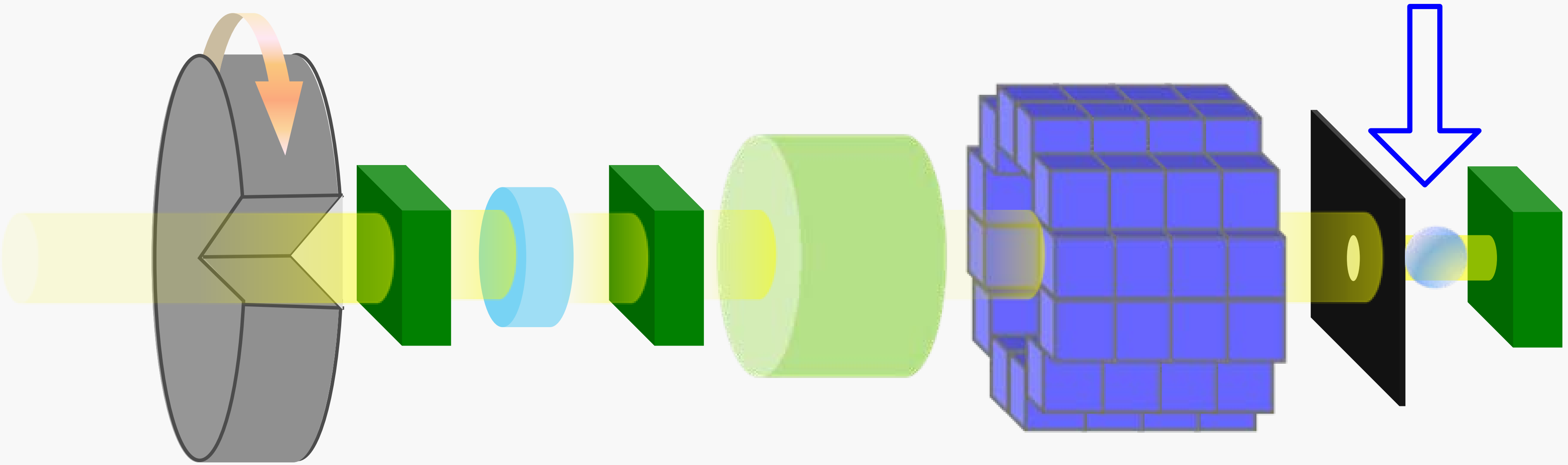




Experiment – Polarizer Performance



Experiment – Analyzer



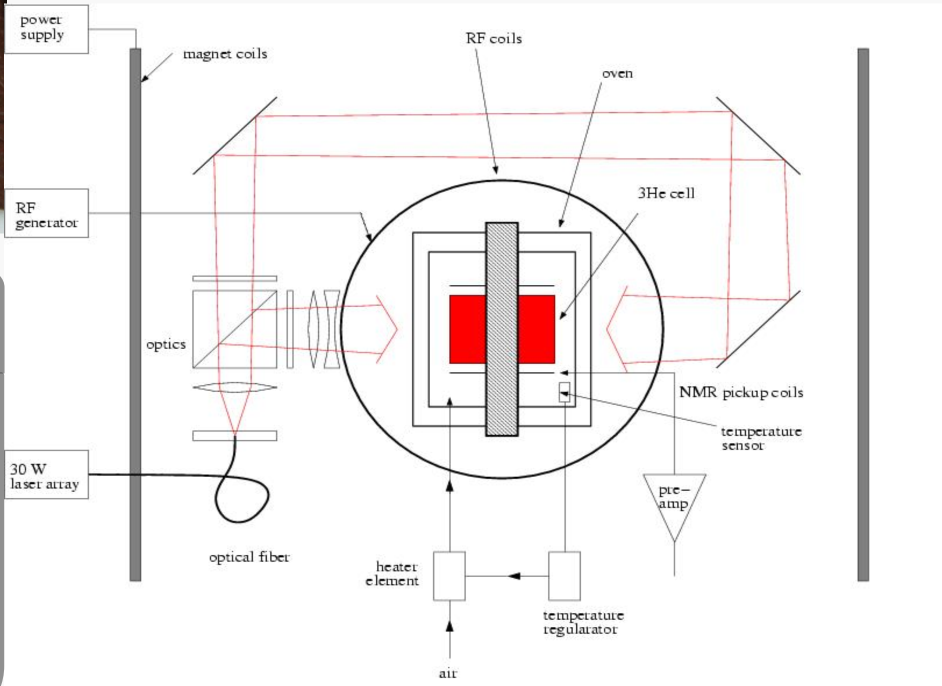
Function

- Measure Neutron Beam polarization
- Measure RFSF efficiency
- Optimize RFSF parameters

Experiment – Analyzer

Oven

- PEEK/glass components
- Uniform Temperature (165° C)



Laser Optics

- Non-metallic parts
- Polarized light from 2 sides
- 30 W Laser

Experiment – Analyzer

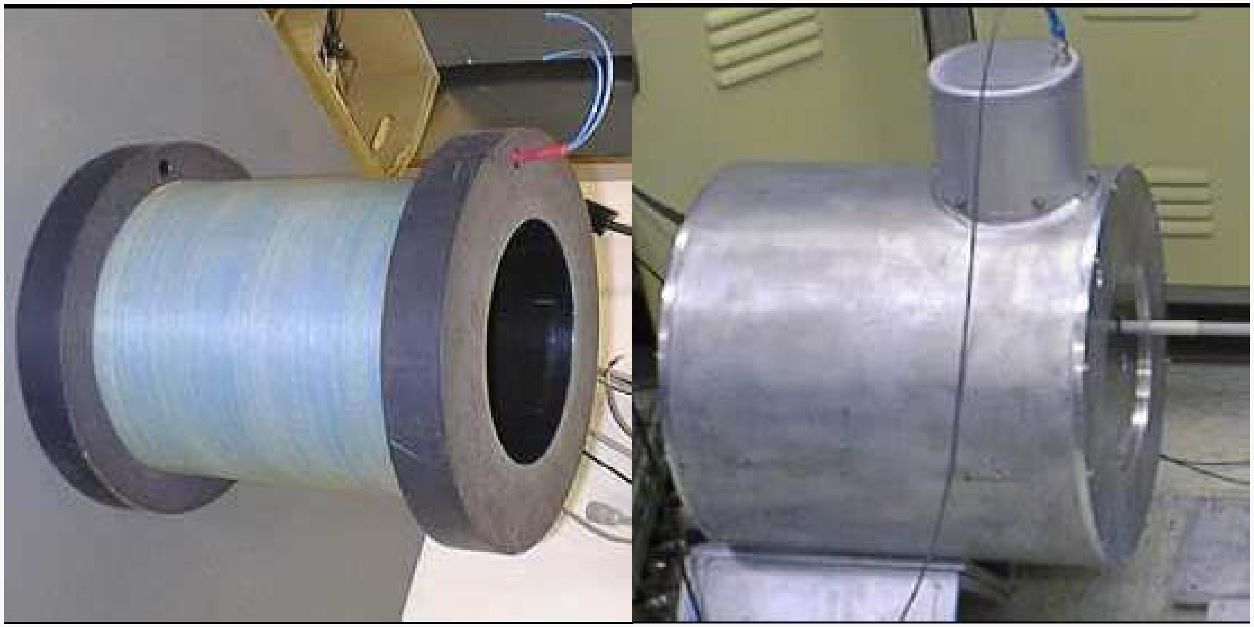
TS - 12

- 2.5 cm in diameter
- 6.2 atm.cm
- Relaxation time of 130 hrs

- Helmholtz coils create 12 Gauss field
- Running on batteries
- Loss of polarization: ~10%/hr

Typical polarization ~ 47%

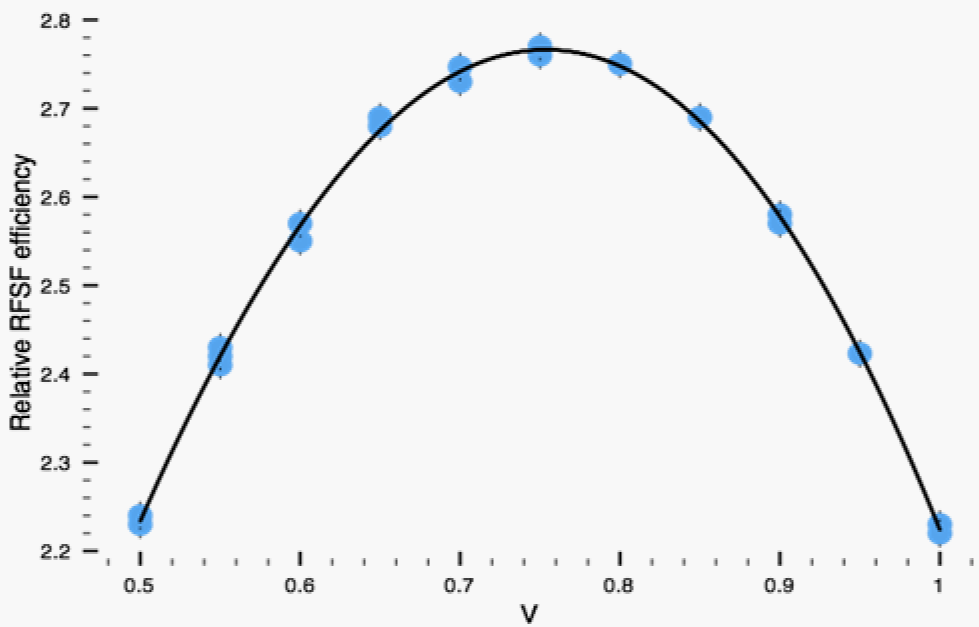
Experiment – RF Neutron Spin Flipper

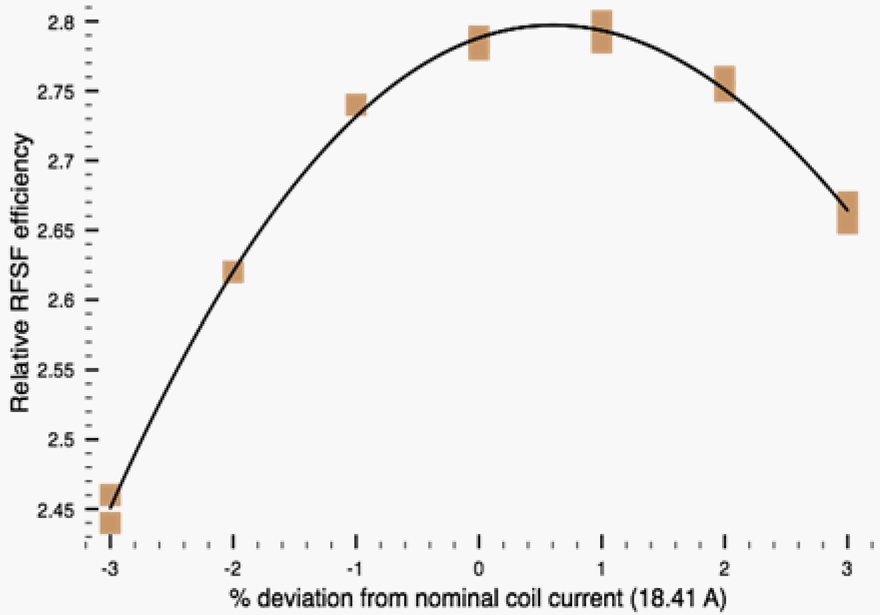


Resonant Radio Frequency Spin Rotator

- Limit systematic effects
- 2 mm Al housing enough to isolate RF field
- 20 Hz pulse pattern: ↑↓↓↑↓↑↑↓

RFSF – Parameter Optimization

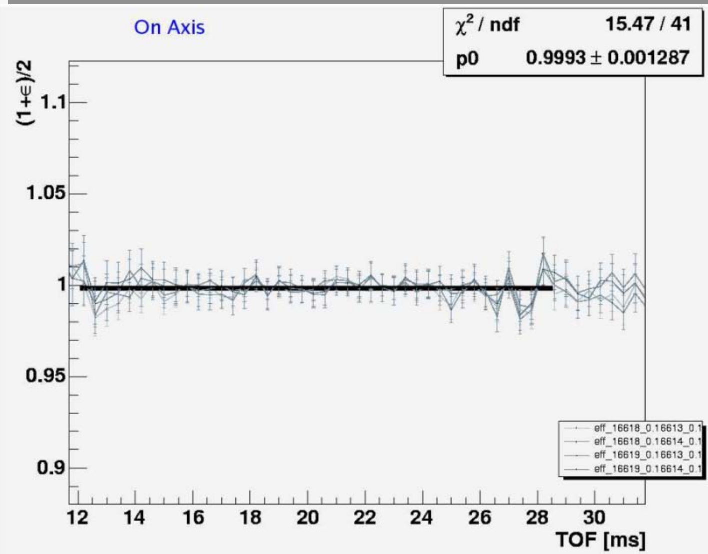


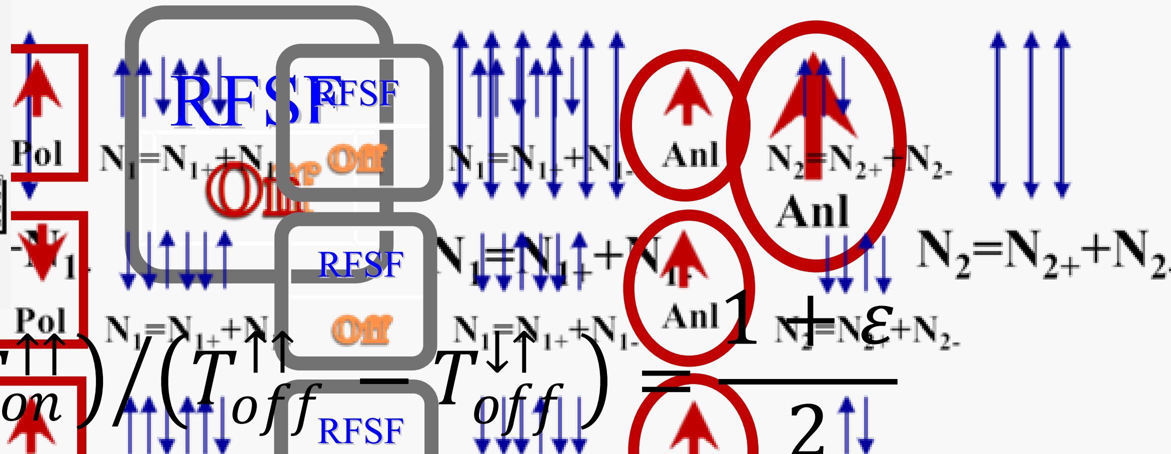


RFSF Efficiency Optimization

- Optimization is performed using the Analyzer
- Normalized population difference between ↑↓

RFSF – Efficiency





$$(T^{\uparrow\uparrow}_{off} - T^{\uparrow\uparrow}_{on})/(T^{\uparrow\uparrow}_{off} - T^{\downarrow\uparrow}_{off}) = \frac{1+\varepsilon}{2}$$

RFSF Efficiency Measurement

- NMR Flip – 100%
- Compare NMR and RFSF flips
- Scan off-axis by moving

collimator+analyzer+M3

- $\varepsilon_{\text{on axis}} = 99.69 \pm 0.12$
- $\varepsilon_{1.3\text{'' beam left}} = 94.06 \pm 0.11$
- $\varepsilon_{1.3\text{'' beam right}} = 93.83 \pm 0.11$

PV in Compound Nuclei – Not so simple, so why bother?

Reason 1.

Some materials are in the beamline – *Al, Cu, In …*

Reason 2.

Study PV in nuclear targets – has not been done for this A-range

Compound Solid Targets

σ_0 – Neutron radiative capture cross-section at 1500 m/s

σ_s – Neutron scattering cross-section

σ_{coh} - Coherent cross-section

σ_{incoh} – Incoherent cross-section

D0 – S-wave average level spacing

Sn – Neutron separation energy

Target	Isotope	σ_0	σ_s	σ_{incoh}	D0	Sn	Thickness[cm]
Sc	45	39.89	22.4	4.3	1.3	8760.5	1.82
V	51	7.33	4.8	4.783	2.7	7311.2	5.50
Co	59	54.53	6	5.04	1.1	7491.6	0.59
Ti		8.93	4.09	2.75			5.74
	48	11.50	4.1		13.0 3	8142.5 0.7	
Mn	55	19.51	2.2	0.6	2.7 0.4	7270 0.5	1.82
In		284.24	2.45	0.5			0.27
	115	296.27	2.6	0.6	.4 0.2 ev	6784.3 0.9	

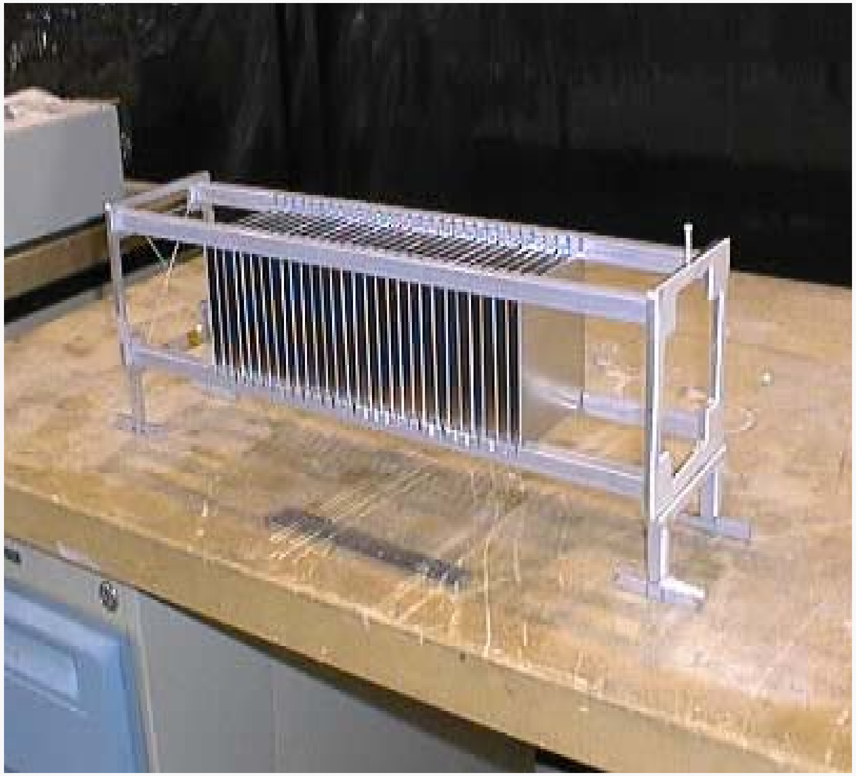
List of Solid Targets

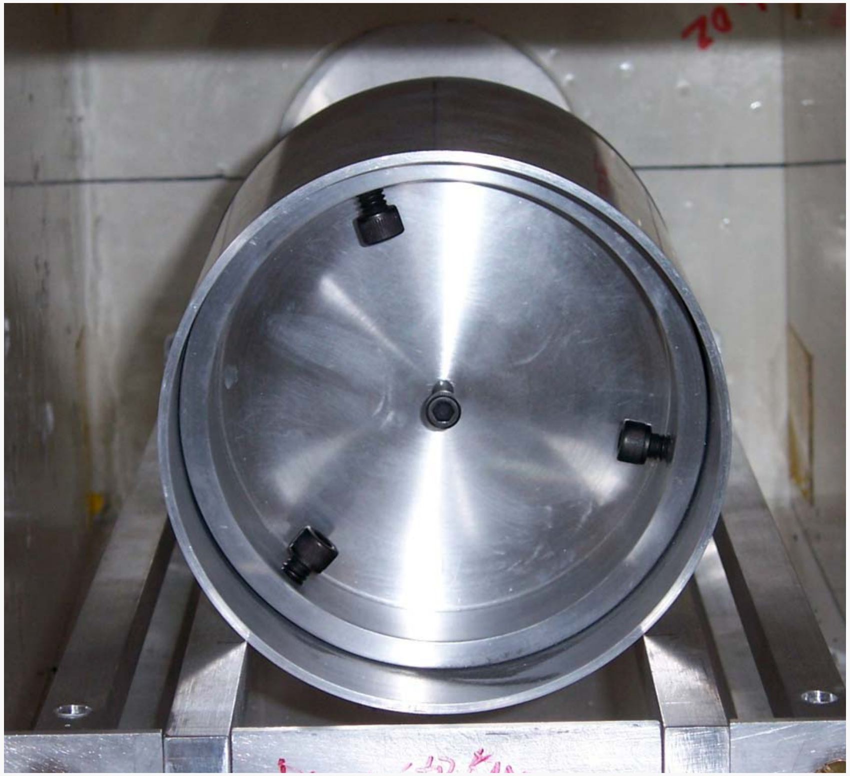
- Al
- Cu
- In
- Mn
- Ti
- V
- Co
- Cl
- Sc

Selection Criteria

- Large capture cross-section
- Small incoherent cross-section
- Small scattering cross-section
- Close level spacing

Compound Solid Targets



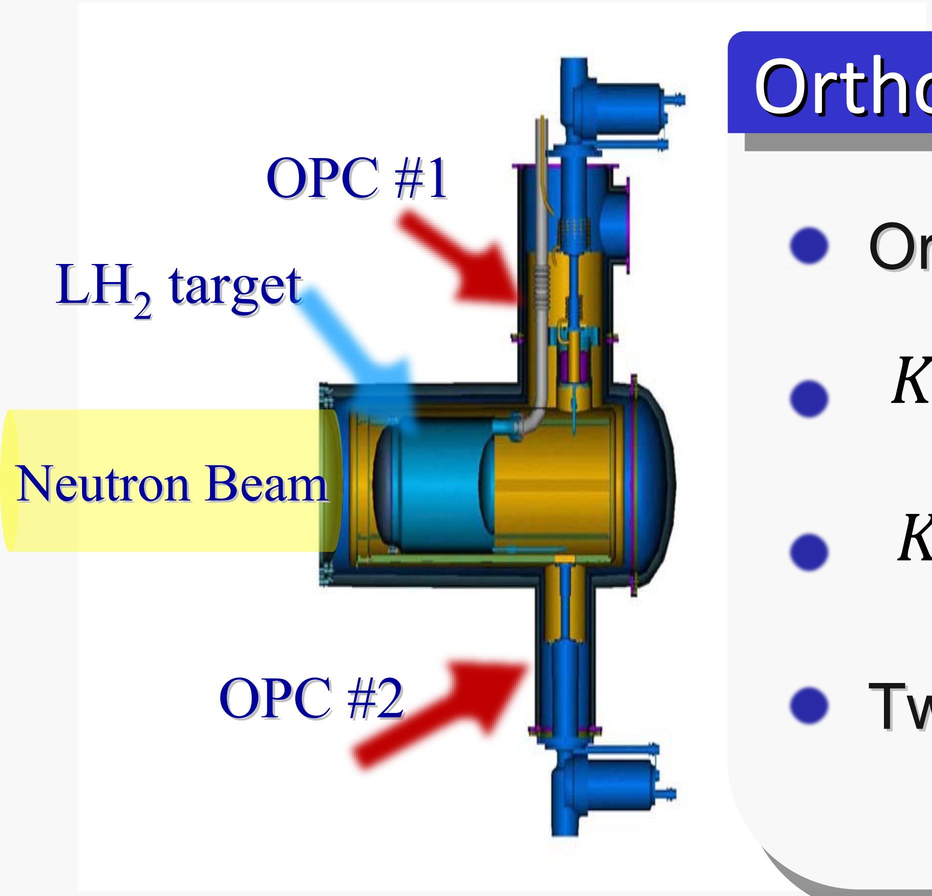


Targets – LH_2

Cross sections

- $\sigma_{cap} \ll \sigma_{scatt}$
- Para-H_2: capture and coherent scatter
- Ortho-H_2: coherent and incoherent scatter
- $\sigma_{incoh}^{ortho} = 20.052 \pm 0.014\ b$
- $\sigma_{coh}^{ortho} = 0.439 \pm 0.003\ b$

Targets – LH_2



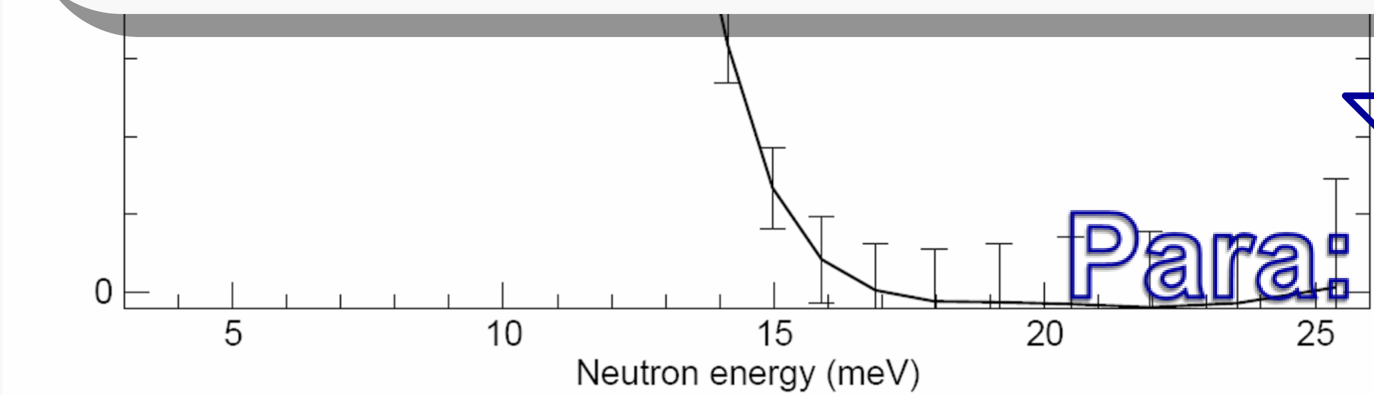
Ortho-to-Para Conversion

- Ortho-Para conversion - 1030 hrs
- $K_{natural} = 1.94 \frac{\%}{hr}$
- $K_{OPC} = 6.09 \frac{\%}{hr}$
- Two FeO_2 OPCs – 112 hrs

Targets – LH_2

Transmission Through LH_2

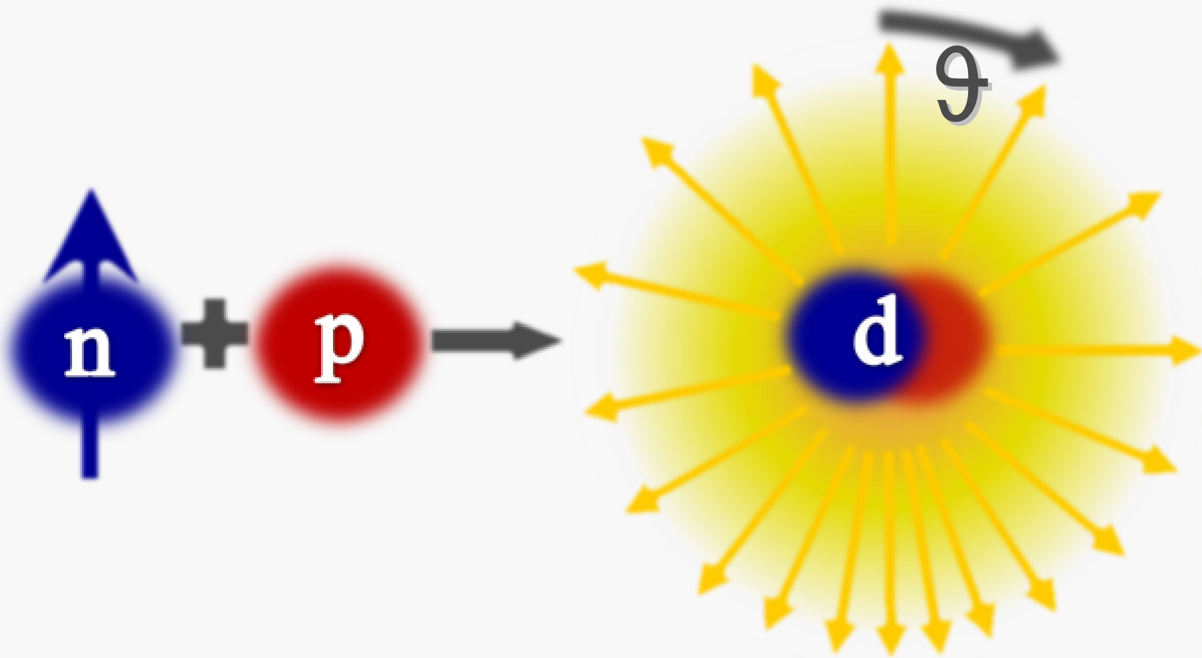
- Full measurement: $$\frac{S_{M3}^{Full}}{S_{M2}^{Full}} = \frac{K_3}{K_2} \cdot T_{other} \cdot T_{H_2}$$
- Empty measurement: $$\frac{S_{M3}^{Empty}}{S_{M2}^{Empty}} = \frac{K_3}{K_2} \cdot T_{other}$$
- Resulting in $$T_{H_2} = \frac{S_{M3}^{Full} / S_{M2}^{Full}}{S_{M3}^{Empty} / S_{M2}^{Empty}}$$



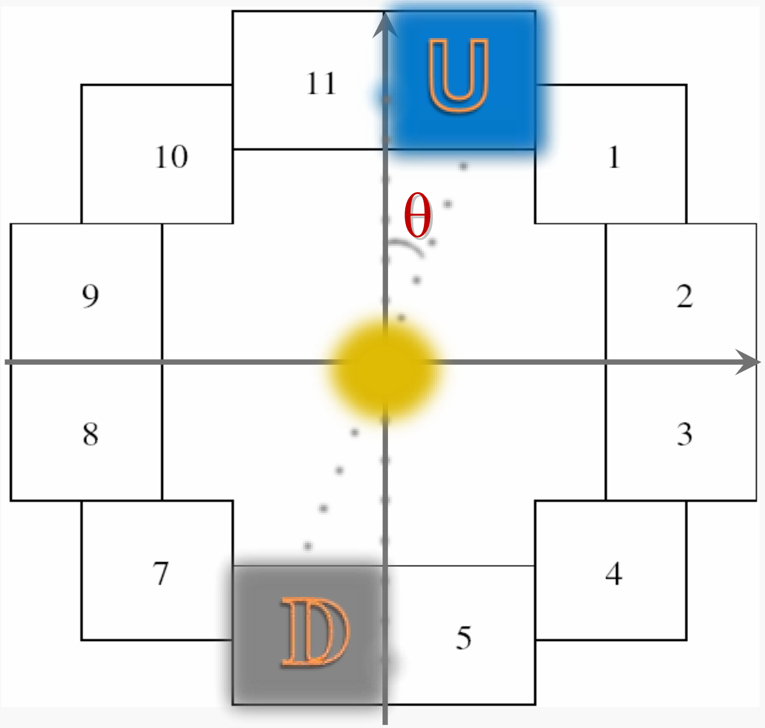
Para: 99.98%

Data Analysis

$$\frac{d\sigma}{d\Omega} = 1 + A_\gamma \cdot cos(\vartheta)$$



Data Analysis



Raw Asymmetry

$$A_\gamma^{raw} = \frac{U - D}{U + D}$$

$$A_\gamma^{raw} = A_\gamma^{UD} G_i^{UD} + A_\gamma^{LR} G_i^{LR}$$

Physics Asymmetry

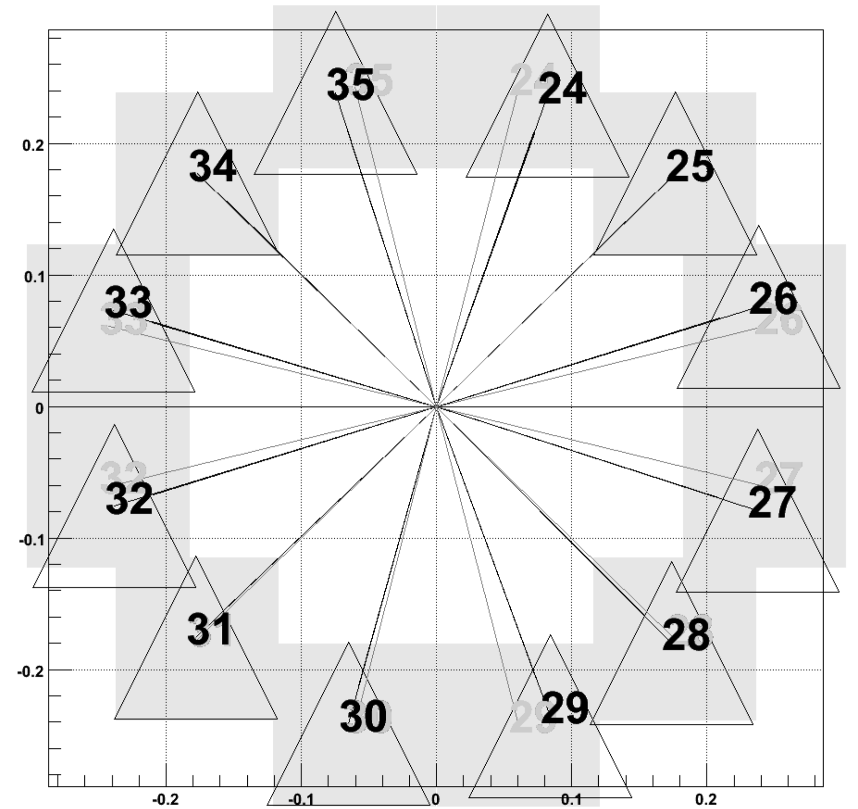
$$A_\gamma = \frac{A_\gamma^{raw}}{P(t) \cdot T(t) \cdot S(t)}$$

$$\boldsymbol{A_\gamma^{total}} = \frac{\sum_i \frac{A_\gamma^i}{\sigma_{i,\gamma}^2}}{\sum_i \frac{1}{\sigma_{i,\gamma}^2}} \pm \frac{1}{\sqrt{\sum_i \frac{1}{\sigma_{i,\gamma}^2}}}$$

Sequence Asymmetry

Detector Geometry

Reconstructed Angles



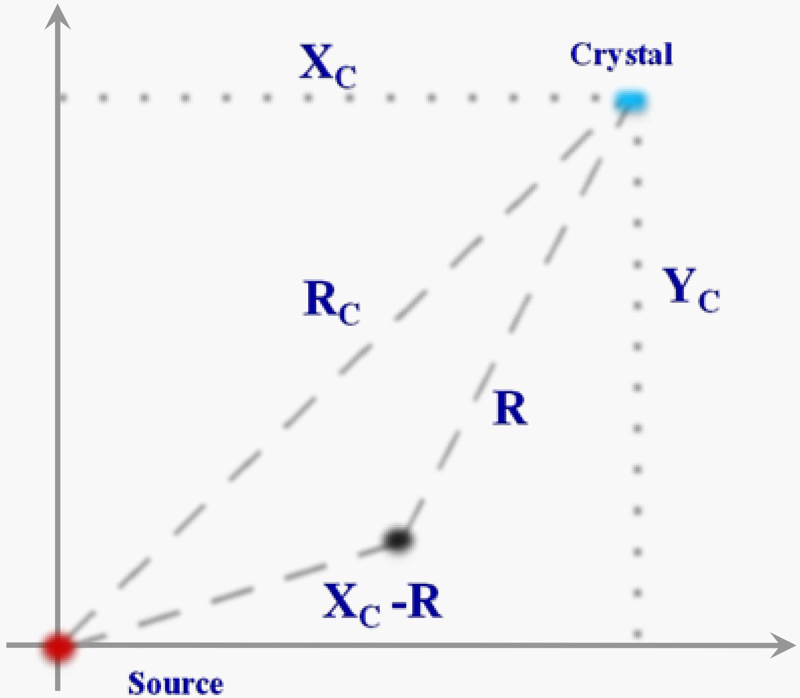


Table Motion Measurements

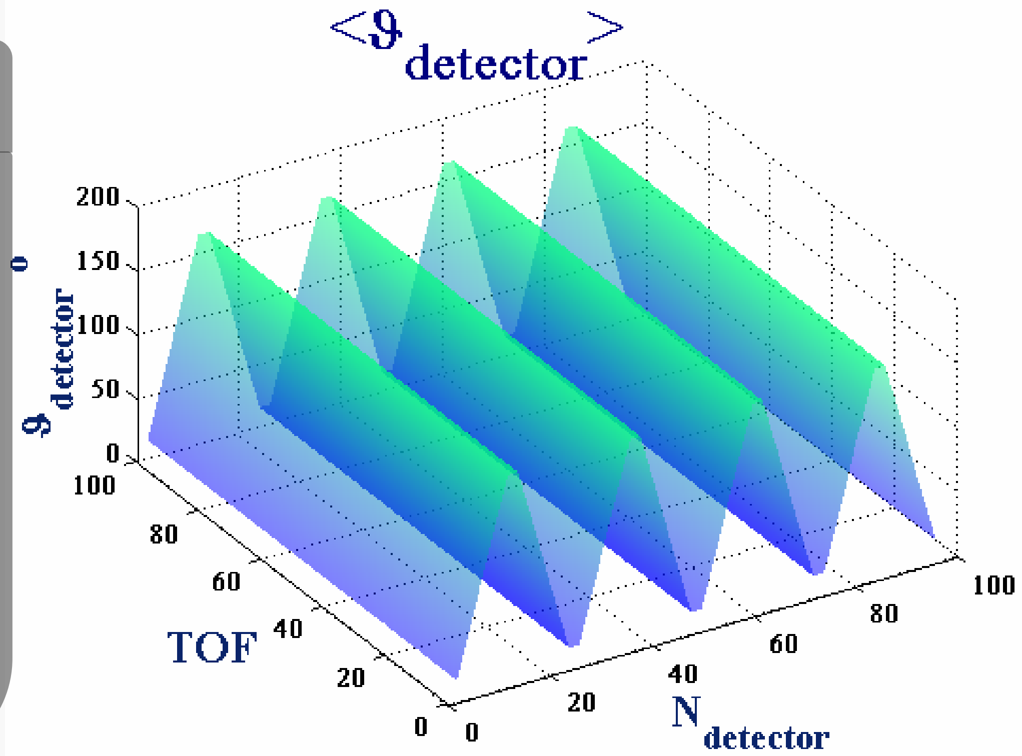
$$S(x,y) \propto \frac{1}{R^2} \Rightarrow \frac{\partial S/\partial y}{\partial S/\partial x} = tan(\vartheta)$$

Detector Geometry

Geometry Factors

- Ideally $\cos\vartheta$ and $\sin\vartheta$
- Neutron absorption probability
- Energy left by a γ in the crystal

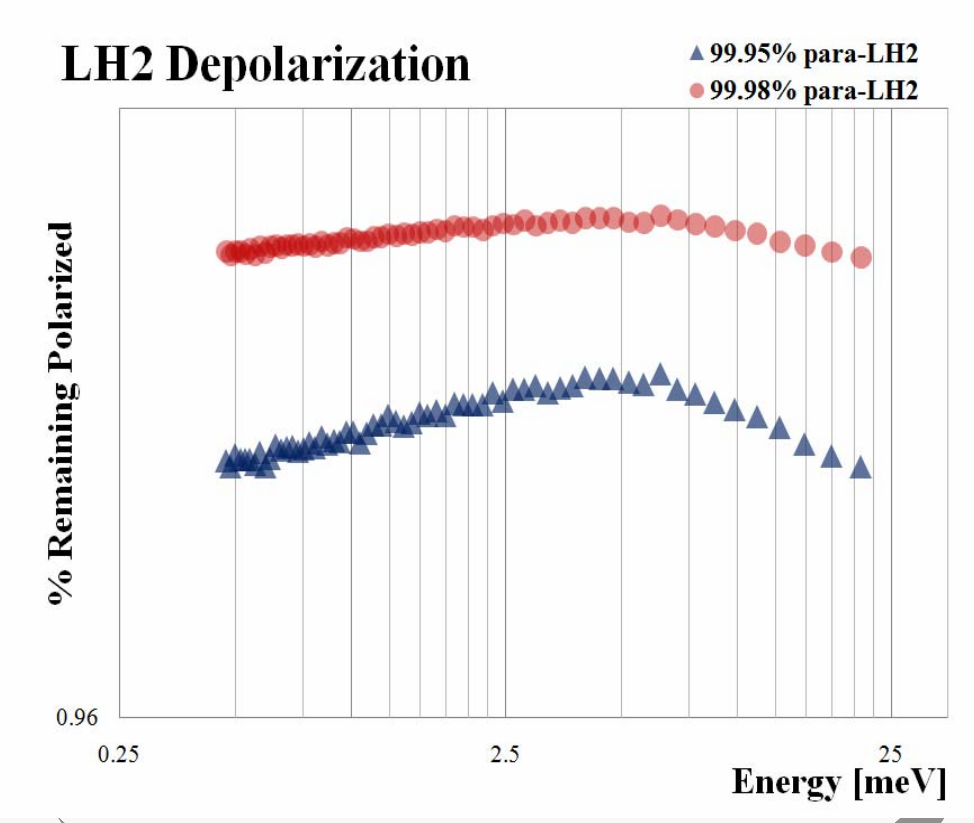
$$\vartheta' = \sin^{-1}\left[\frac{G^{i}_{LR}}{\sqrt{\left(G^{i}_{LR}\right)^{2} + \left(G^{i}_{LR}\right)^{2}}}\right]$$

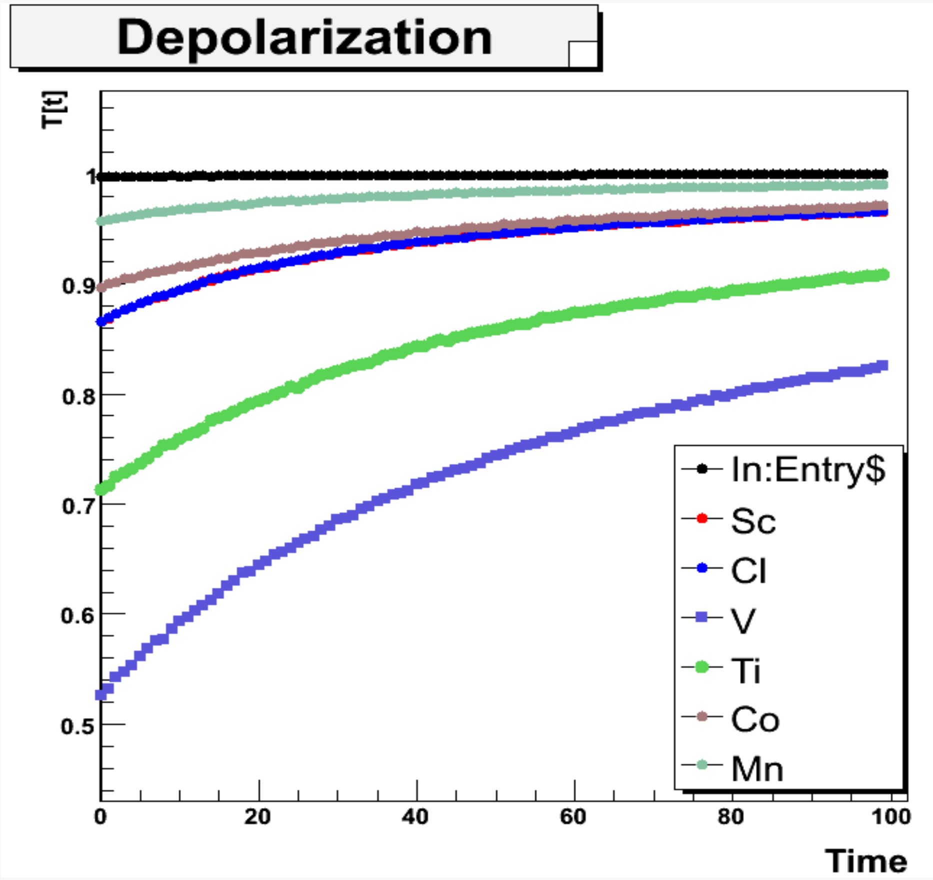


Error from Left-Right Mixing into Up-Down

$$A'^{raw}_{\gamma} = \cos\vartheta\left[A^{UD}_{\gamma} + \frac{\delta\vartheta}{2}A^{LR}_{\gamma}\right] + \sin\vartheta\left[A^{UD}_{\gamma} + \frac{\delta\vartheta}{2}A^{LR}_{\gamma}\right]$$

Depolarization in the targets

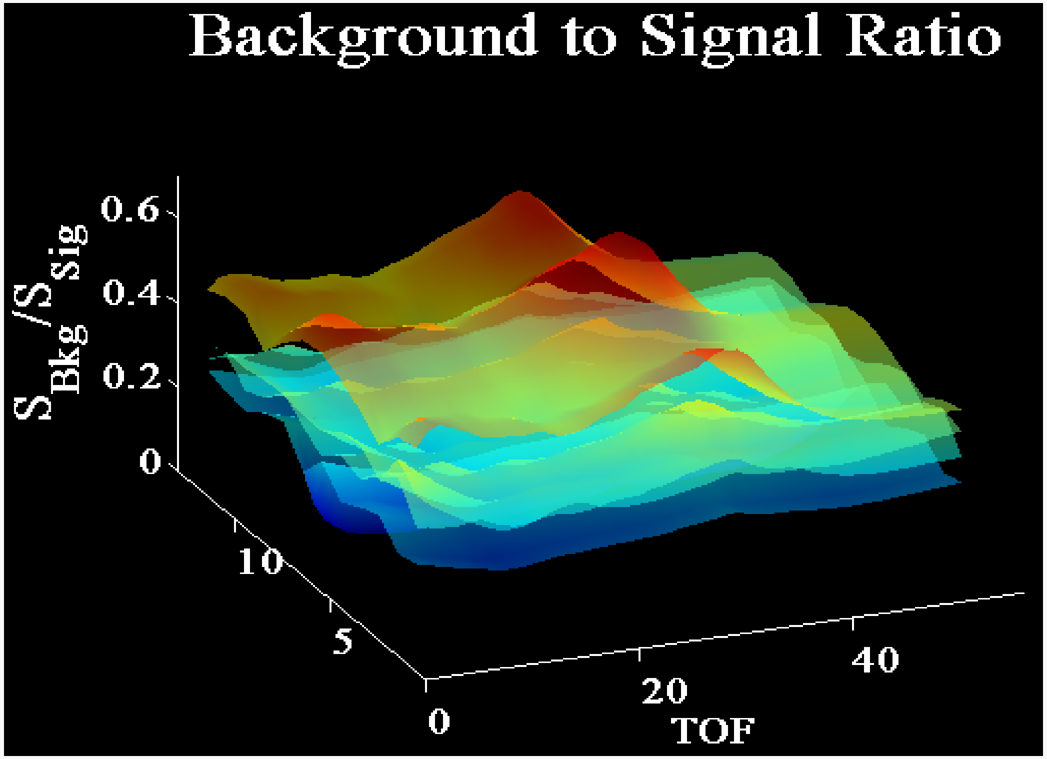




Backgrounds and false asymmetries

Sources of Backgrounds

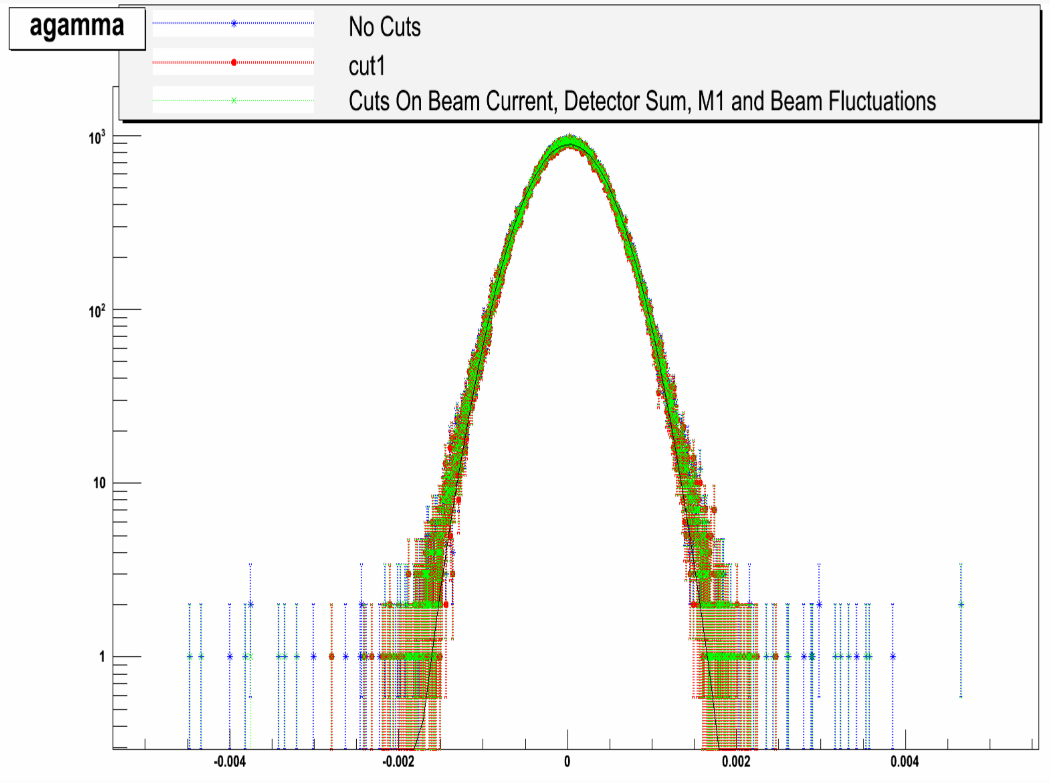
- Electronic pick-up
- Activation
- Scattered neutrons
- Frame overlap
- γ's from spallation
- Few percent for solids
- More for LH_2
- $A_{Bkg} = 0$



$$A_{sig} = \frac{A_{sig+bkg}(S_{sig} + S_{bkg})}{S_{sig}} = A_{sig+bkg}(1+\beta) - A_{bkg}\beta$$

$$\sigma_{A_{sig}} = \sqrt{(1+\beta)^2\sigma^2_{A_{sig+bkg}} + \beta^2\sigma^2_{A_{bkg}}}$$

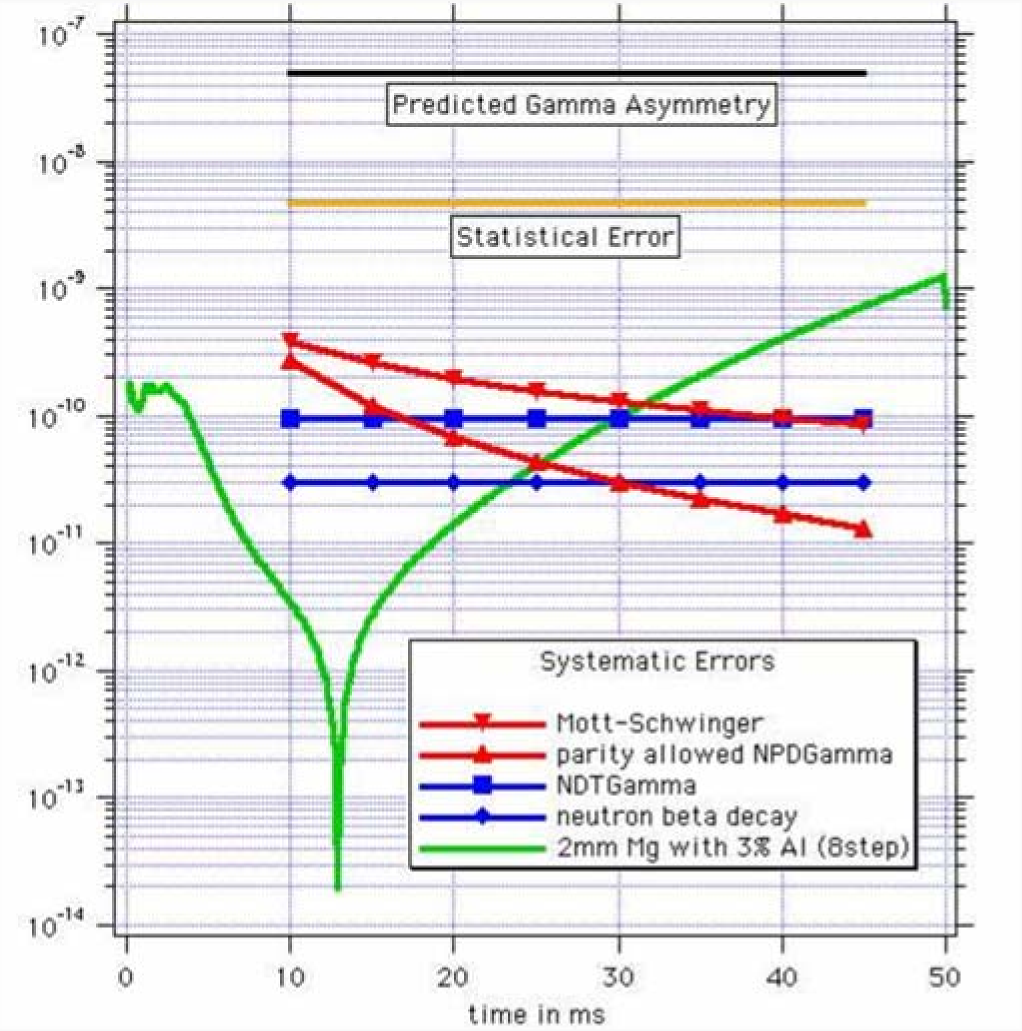
Cuts



Cuts on the Data

- Neutron beam current
- Detector sums/diff’s
- Beam fluctuations
- Detector saturation
- Valid spin sequences

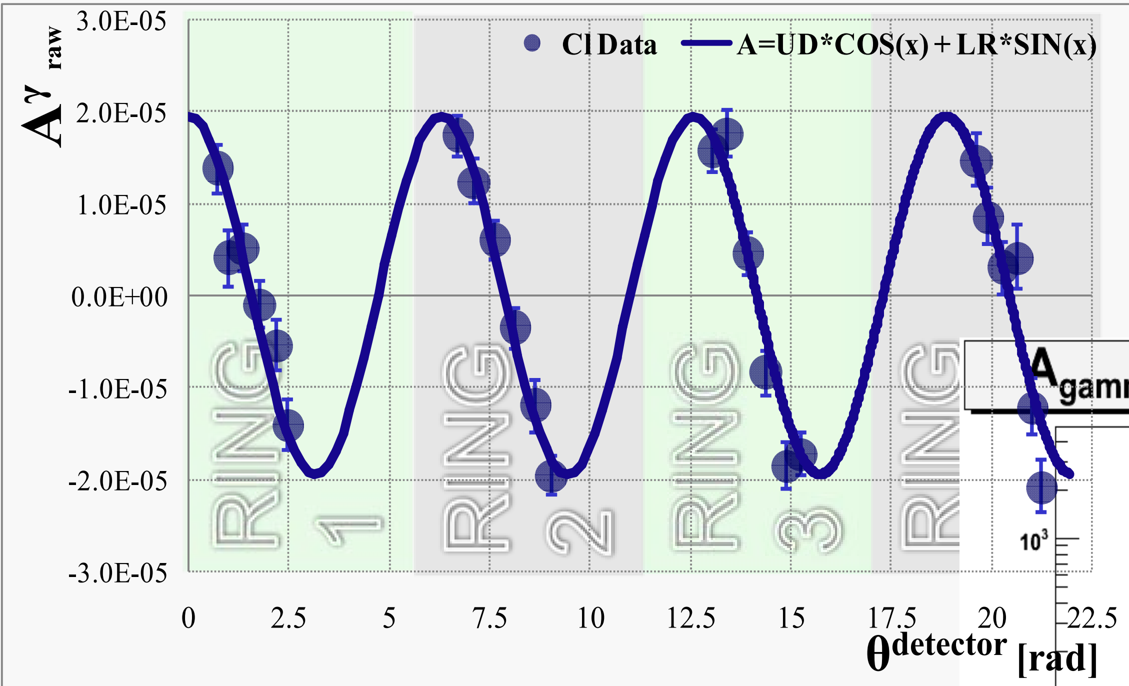
Systematics



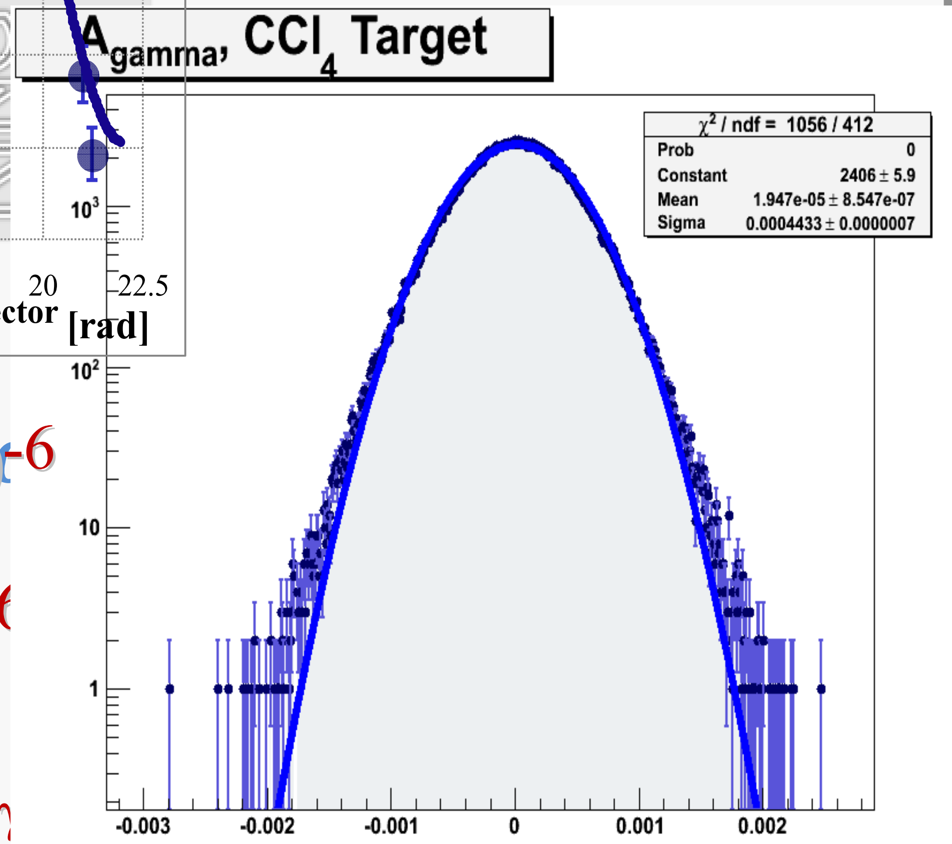
Sources

- Multiplicative noise
- Additive noise
- Non-hydrogen target A_γ
- Mott – Schwinger LR
- Stern – Gerlach steering

Asymmetry Results - Chlorine



Chlorine



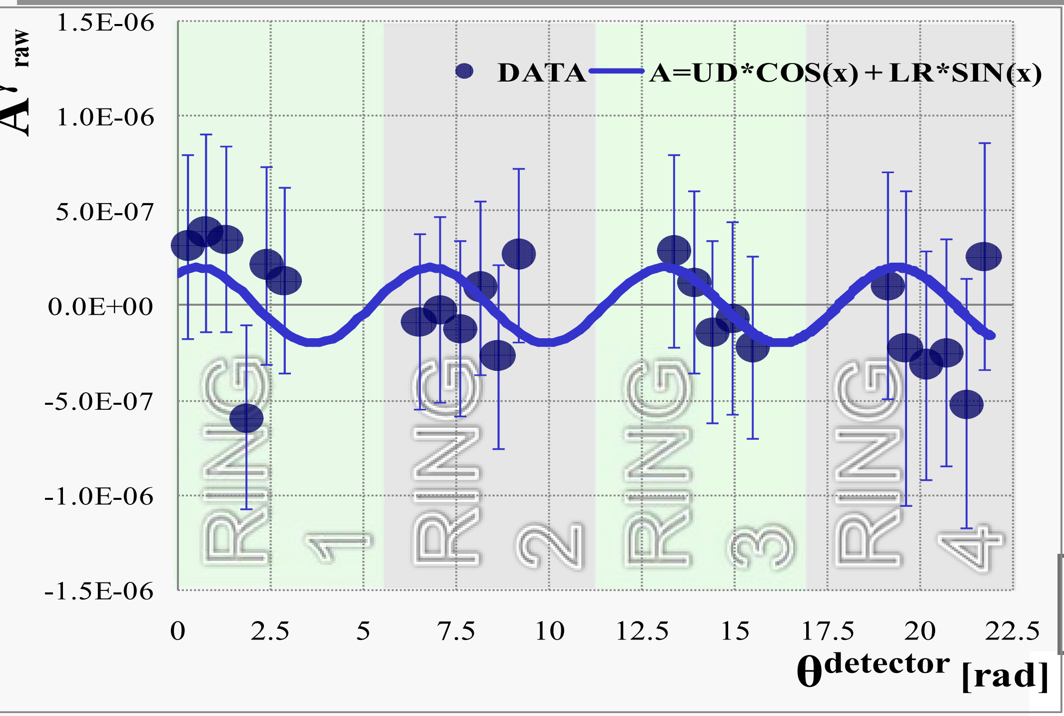
Fit to $A_\gamma^{raw} = A_\gamma^{UD}$ ...

$A_\gamma = (19.47 \pm 2.02)\times10^{-6}$

$A_\gamma^{UD} = (19.62)\times10^{-6}$

A_γ

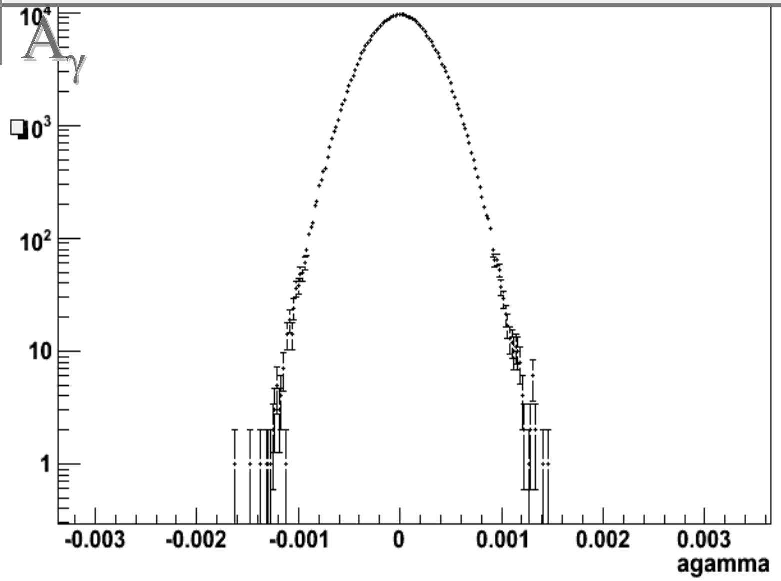
Asymmetry Results - Hydrogen



Hydrogen

- More statistics
- Better knowledge of background

Para-Hydrogen,



$$A_\gamma^{UD} = (1.7)\times 10^{-7}$$

$$A_\gamma = (0.95 \pm 2.01)\times 10^{-7}$$

$$A_\gamma^{LR} = (1.1)\times 10^{-7}$$

Results – The other targets

Targets	$A_\gamma (\times 10^{-7})$	$\sigma_{A\gamma,stat} (\times 10^{-7})$	$\sigma_{A\gamma,syst} (\times 10^{-7})$	$\sigma_{A\gamma,TOT} (\times 10^{-7})$
Co	7.7	3.5	0.7	3.6
Cu	-11.9	5.8	1.1	5.9
In	6.8	3	0.6	3.1
Mn	-5.3	7.8	0.5	7.8
Sc	7	2.8	0.7	2.9
Ti	-6.5	3	0.6	3.1
V	1.7	6.3	0.2	6.3

Summary

Cavaignac et al. Phys.Lett.B., 67 148, 1977

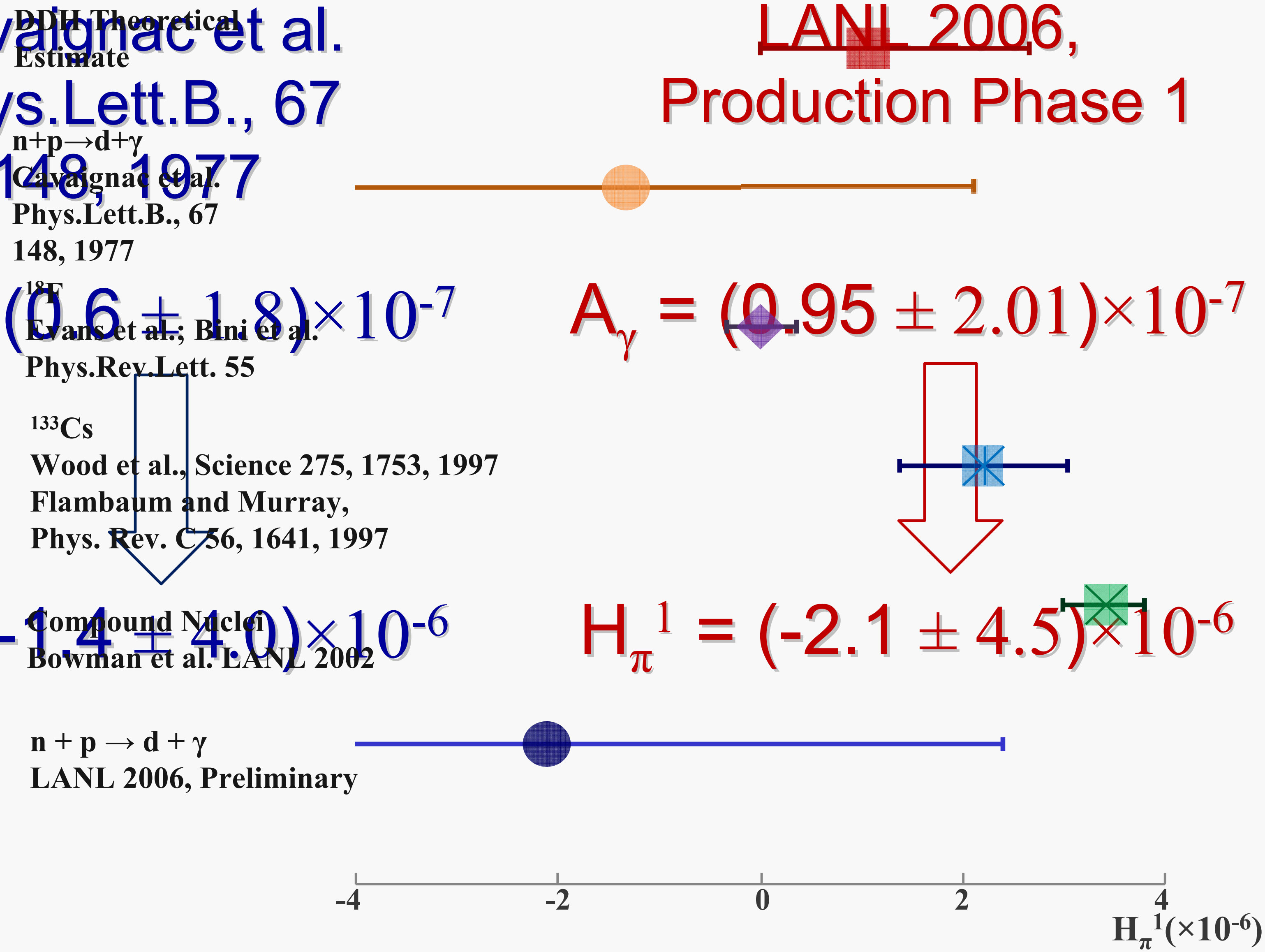
$A_\gamma = (0.6 \pm 1.8)\times 10^{-7}$

$H_\pi^1 = (-1.4 \pm 4.0)\times 10^{-6}$

LANL 2006, Production Phase 1

$A_\gamma = (0.95 \pm 2.01)\times 10^{-7}$

$H_\pi^1 = (-2.1 \pm 4.5)\times 10^{-6}$



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