The NPDGamma Experiment

First Observation of the Parity-Violating Asymmetry in Polarized Cold Neutron Capture on Hydrogen

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For the NPDGamma Collaboration

XIII Quark Confinement and the Hadron Spectrum

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Observable:

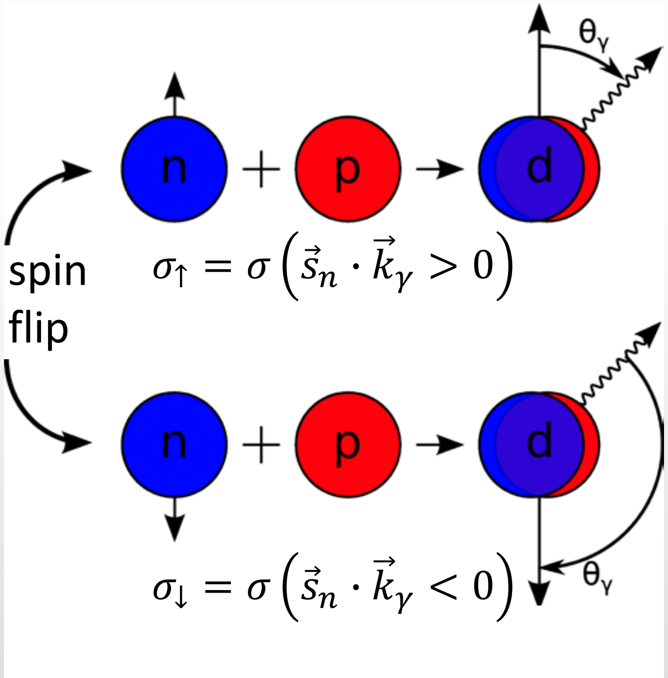
NPDGamma measured the radiative neutron capture cross-section as a function of neutron spin:

The observable is the parity-vilating up-down asymmetry in the angular distribution of gamma rays with respect to the neutron spin direction

$$A_{meas} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} = C\big(A_{\gamma PV}\cos(\theta_\gamma) + A_{\gamma PC}\sin(\theta_\gamma)\big)$$

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

$$\sigma \propto \left|\langle\psi_f|\boldsymbol{E1}|\psi_i\rangle + \langle\psi_f|\boldsymbol{M1}|\psi_i\rangle\right|^2$$



We get parity-odd ***E1*** transitions between parity admixed initial and final states:

$$|\psi_{i,f}\rangle = |\psi_0\rangle + \frac{\langle\psi_1|V_{PNC}|\psi_0\rangle}{\Delta E}|\psi_1\rangle$$

$$H = H_s + V_{PNC}$$

The form of V_{PNC} is model dependent (see later …)

Observable:

To lowest order in L and V_{PNC} , the surviving transitions are:

Parity even $\langle I=0,{}^3S_1|\boldsymbol{M1}|I=1,{}^1S_0\rangle$

Parity odd $a_1\langle I=0,{}^3S_1|\boldsymbol{E1}|I=1,{}^3P_1\rangle$

Parity odd $a_1\langle I=1,{}^3P_1|\boldsymbol{E1}|I=0,{}^3S_1\rangle$

$$a_1=\frac{\langle\psi_1|V_{PNC}|\psi_0\rangle}{\Delta E}$$

The corresponding asymmetry is:

$$A_{\gamma PV}=-2\sqrt{2}\frac{\langle\boldsymbol{E1}\rangle}{\langle\boldsymbol{M1}\rangle}$$

This asymmetry has not been seen in this simple system, but there is no reason why it shouldn't be there.

So how big is it?

Various models (meson exchange, $EFT(\cancel{\pi})$, χPT, Large N_C, LQCD (?)) predict the size to be

$$A_{\gamma PV}\sim -50\;ppb$$

But which model does a reasonable job at explaining why it is so small?

NPDGamma goal was a 10% measurement → Very challenging …

Experiment History:

NPDGamma has a long history:

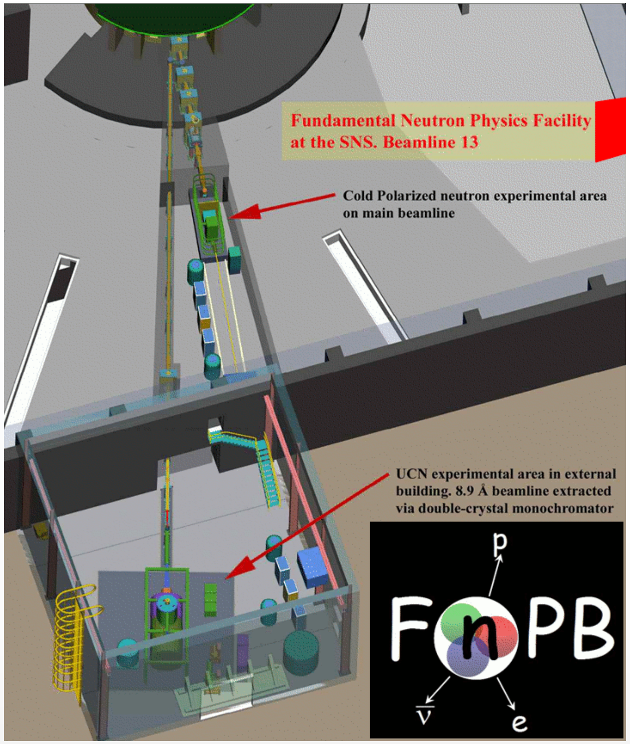
- First hardware development started in the late 1990s
- First phase measurement at LANL in 2006
    - Too little statistics (low beam power)
    - Beam pulse frequency not ideal $\Rightarrow$ systematic effects
- Move to ORNL and reconstruct 2009 – 2011
- Run between 2011-2013 and 2016
- Final analysis completed
- In publication mode (**arXiv:1807.10192**)

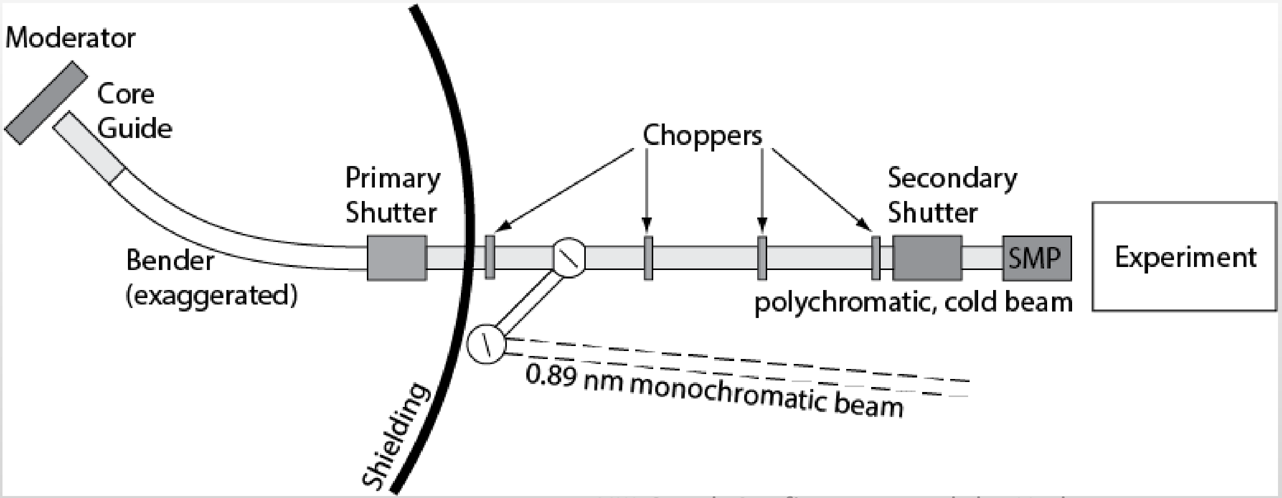
Experiment Layout:

Experiment Layout:

ORNL Spallation Neutron Source (SNS)
Fundamental neutron physics beam (FnPB) line

- LH2 moderator
- 17 m long guide ~ 20 m to experiment
- one polyenergetic cold beam line
- one monoenergetic (0.89 nm) beam line
- ~ 40 m to nEDM UCN source
- 4 frame overlap choppers
- 60 Hz pulse repetition





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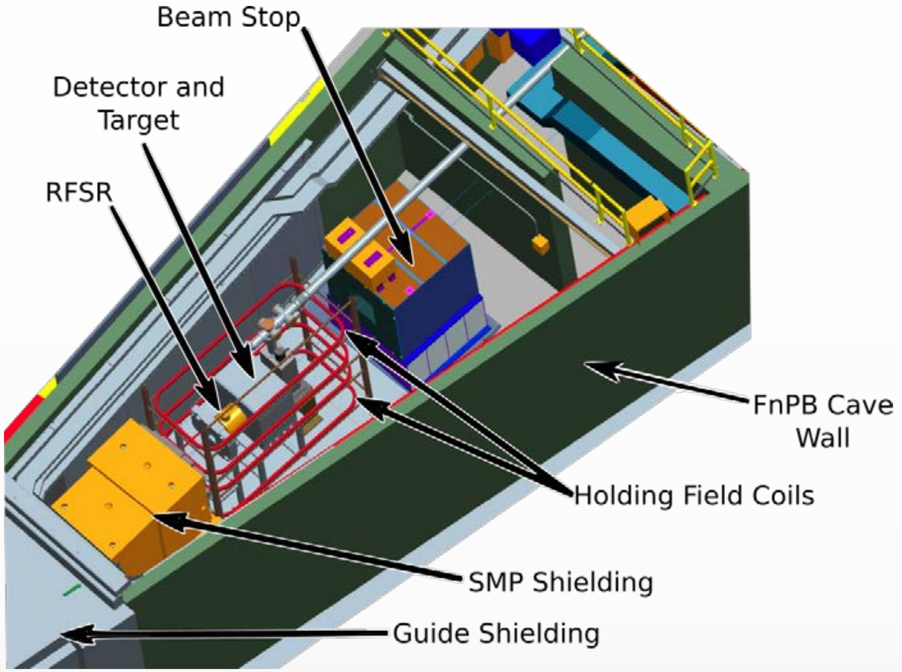
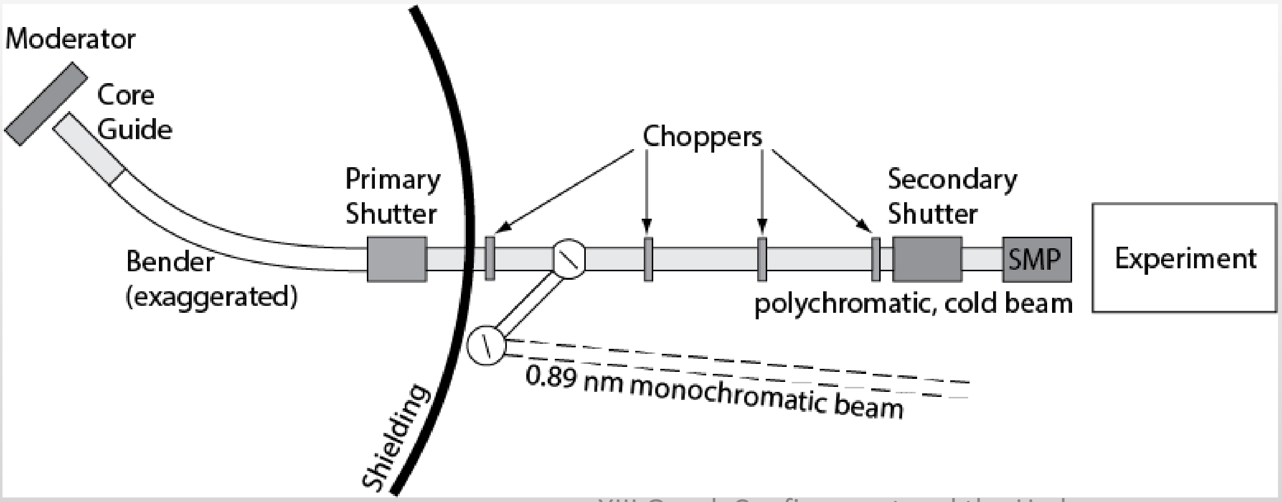
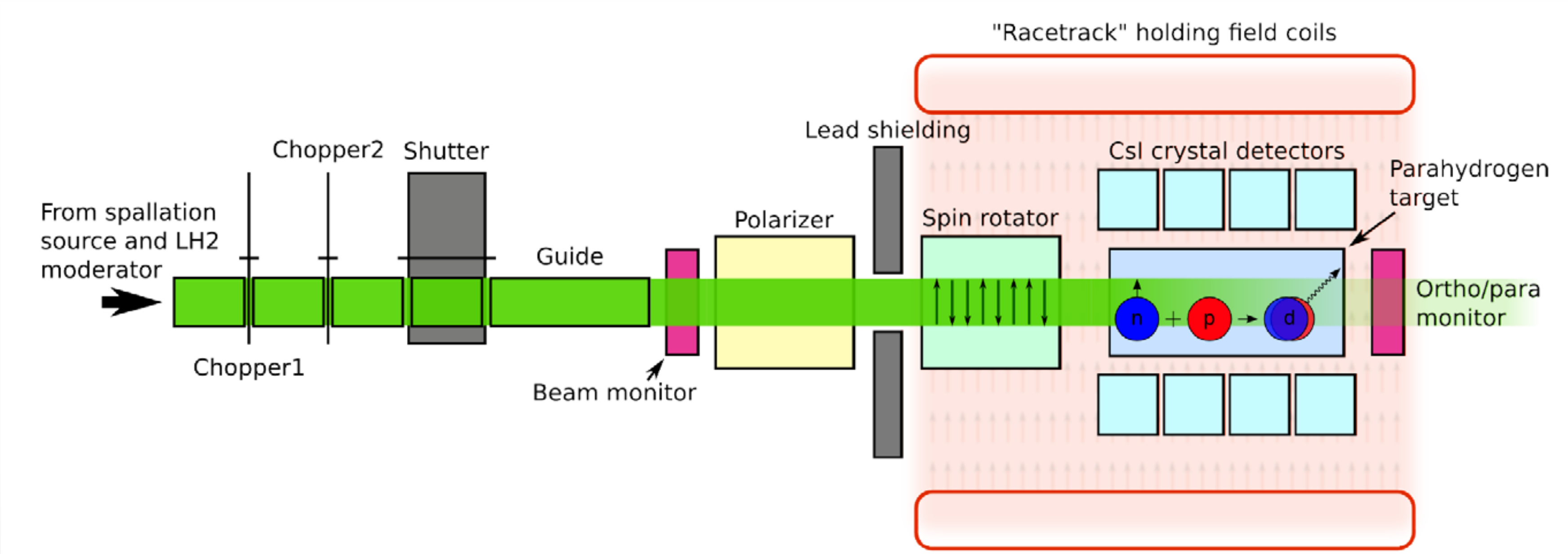




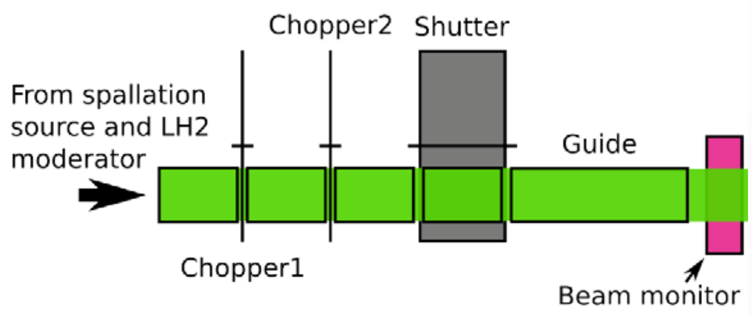
Experiment Layout:

NPDGamma Setup:

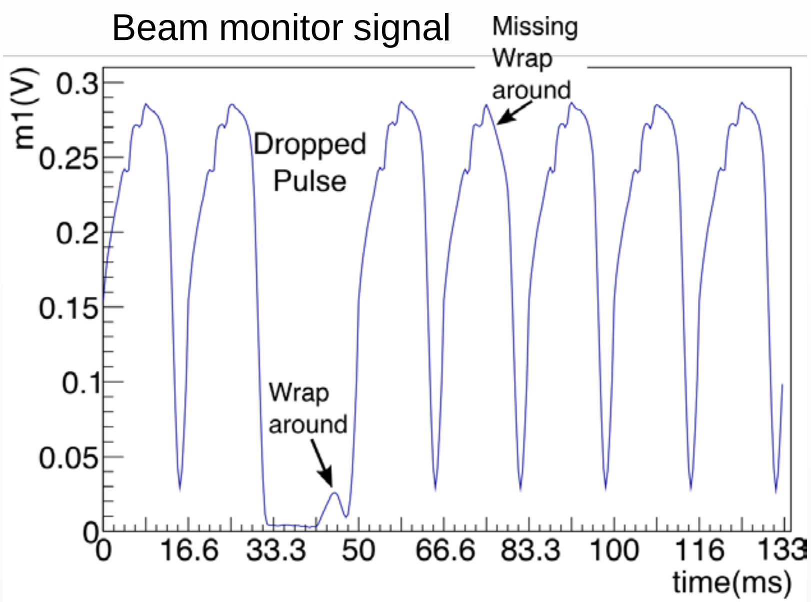


Experiment Layout:

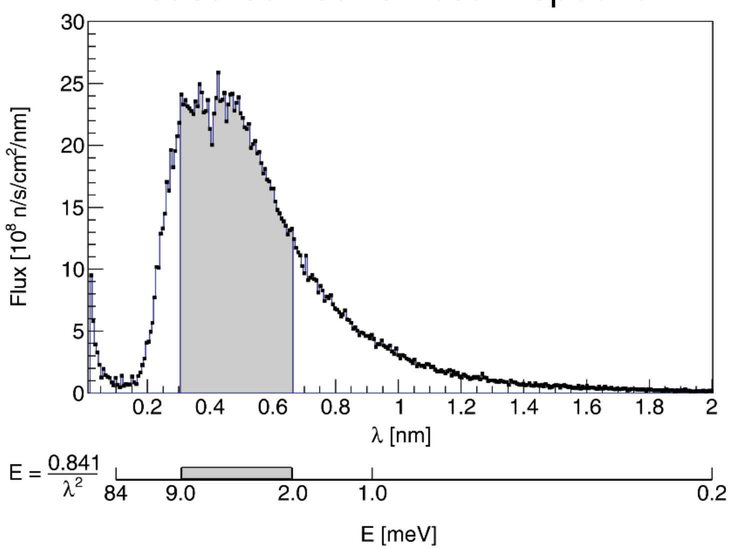
Beam spectrum and chopped pulses

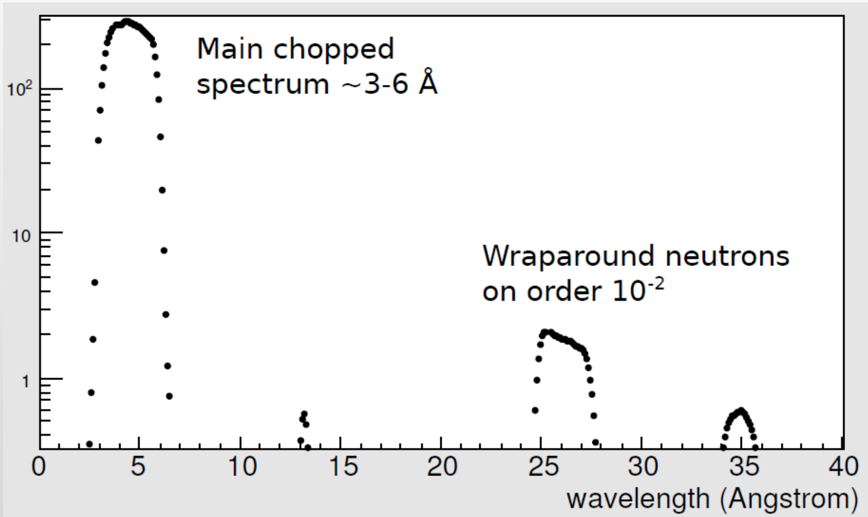


Beam monitor signal



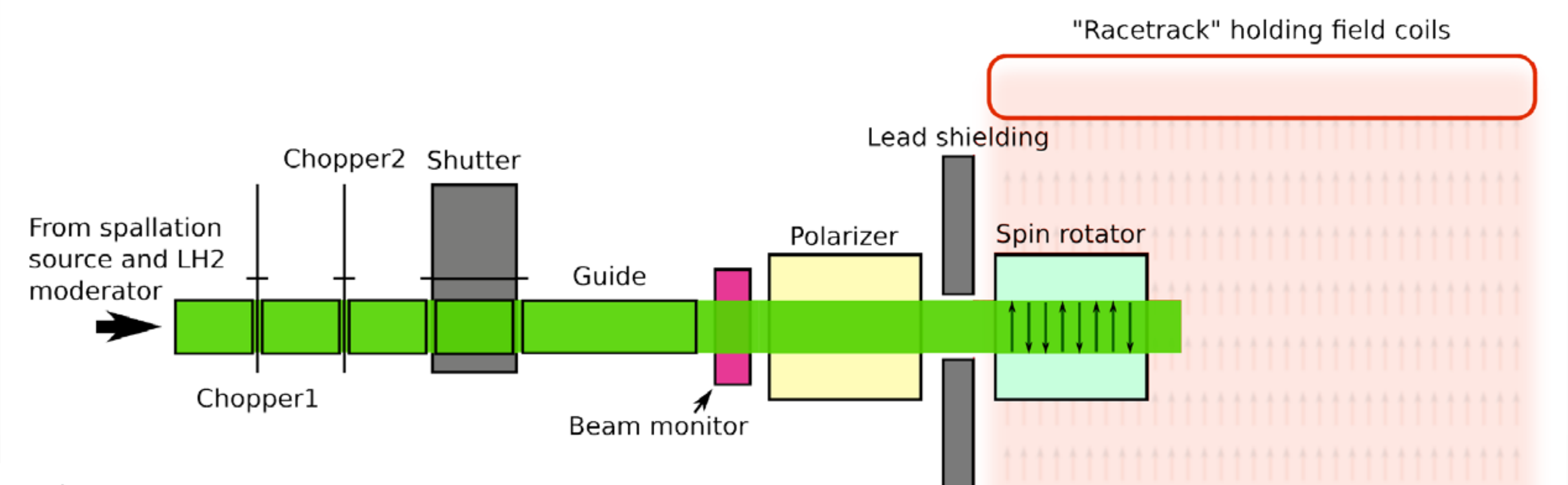
Measured neutron beam spectrum

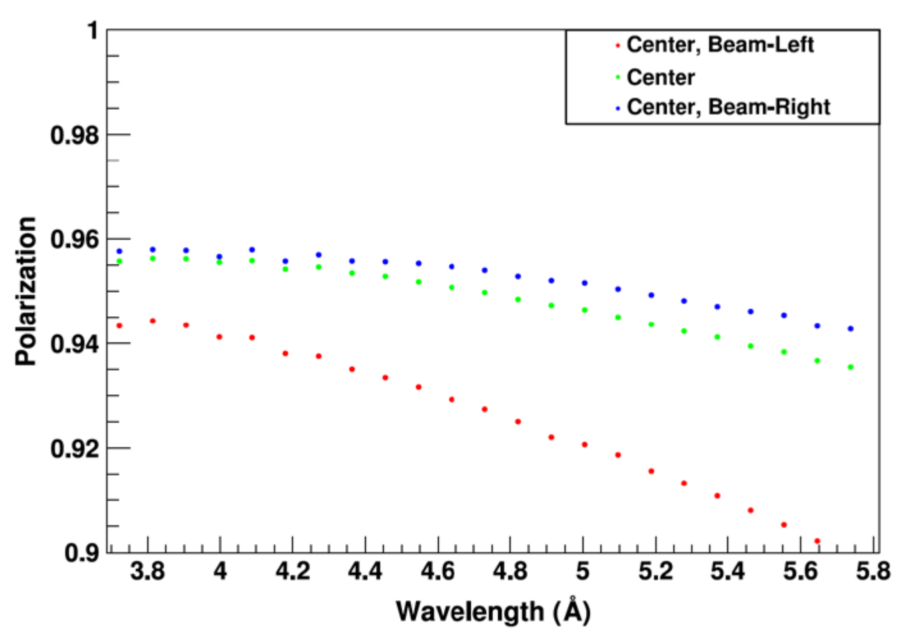


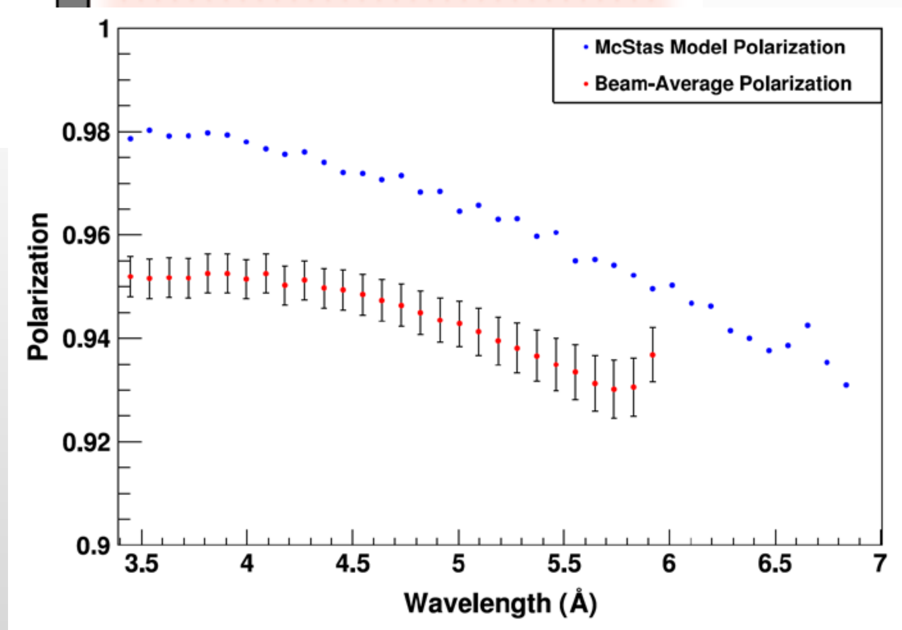


Experiment Layout:

Beam polarization (NIM, A 895 (2018) 19–28)

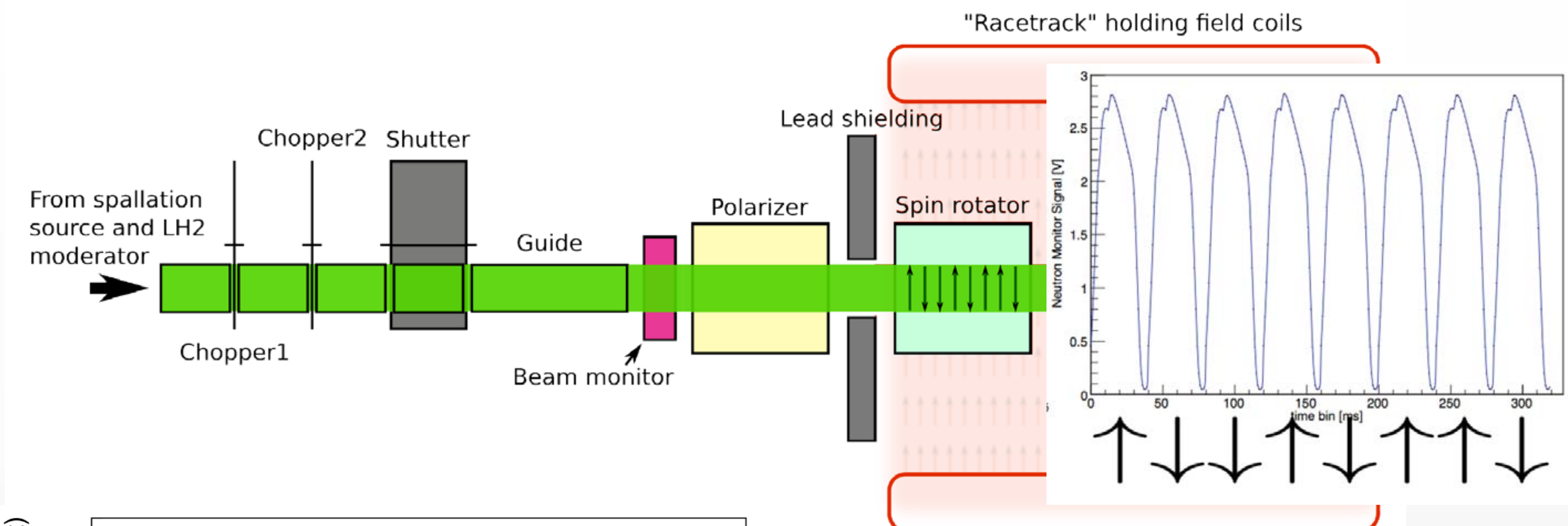


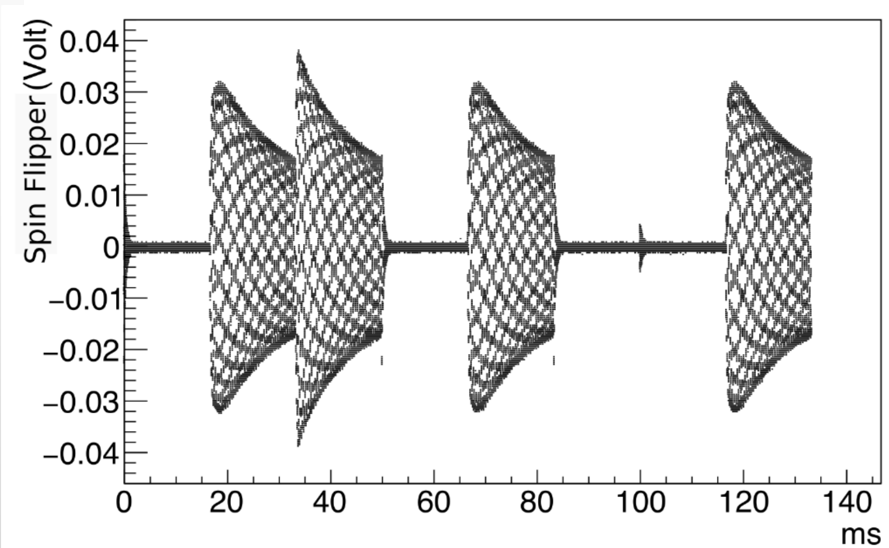


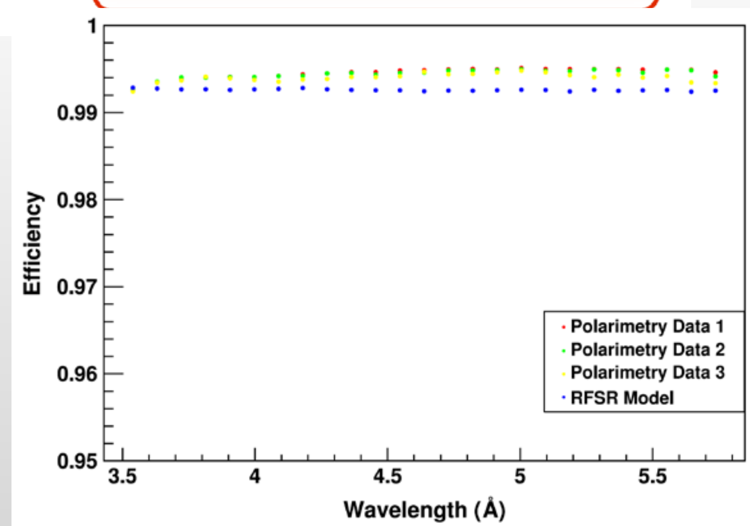


Experiment Layout:

Spin rotator

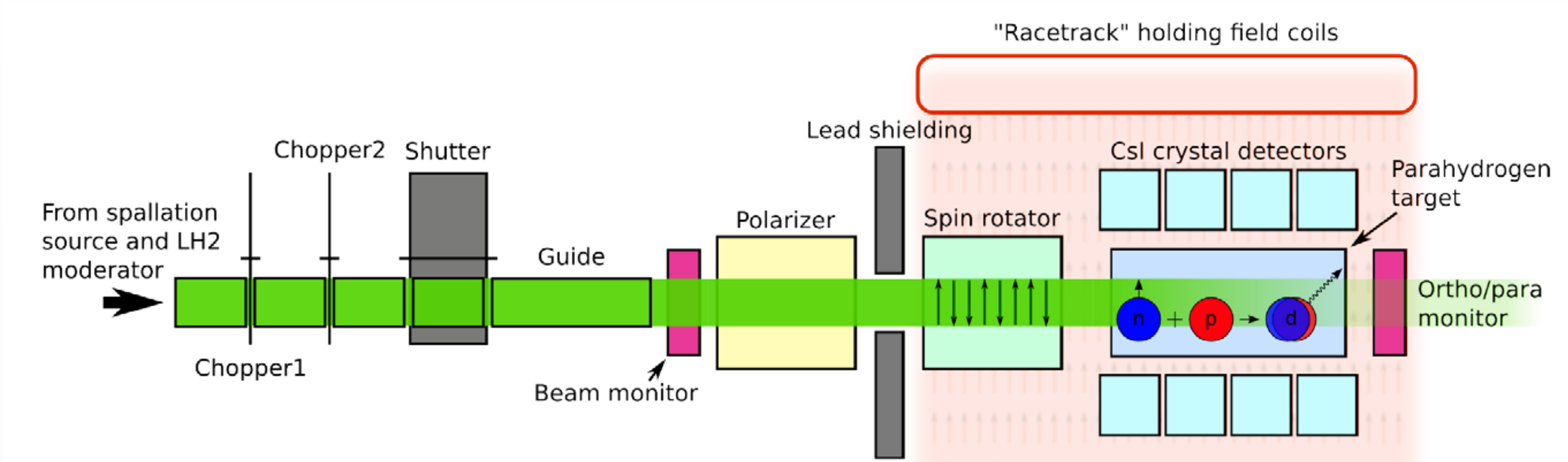


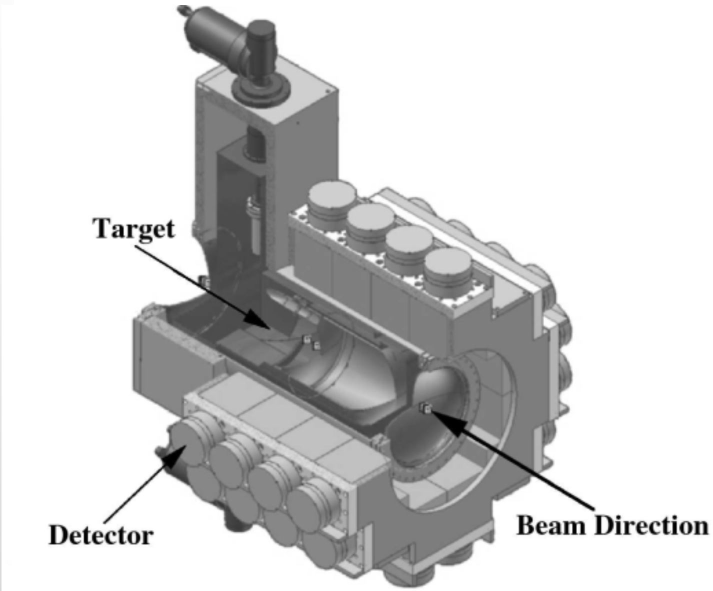


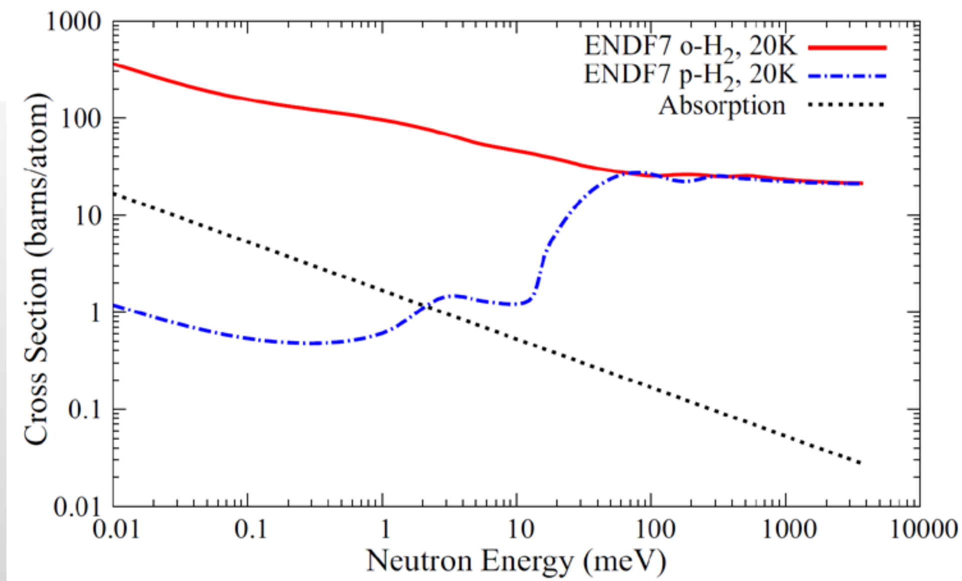


Experiment Layout:

NPDGamma Target (PhysRev B 91, 180301(R) (2015)



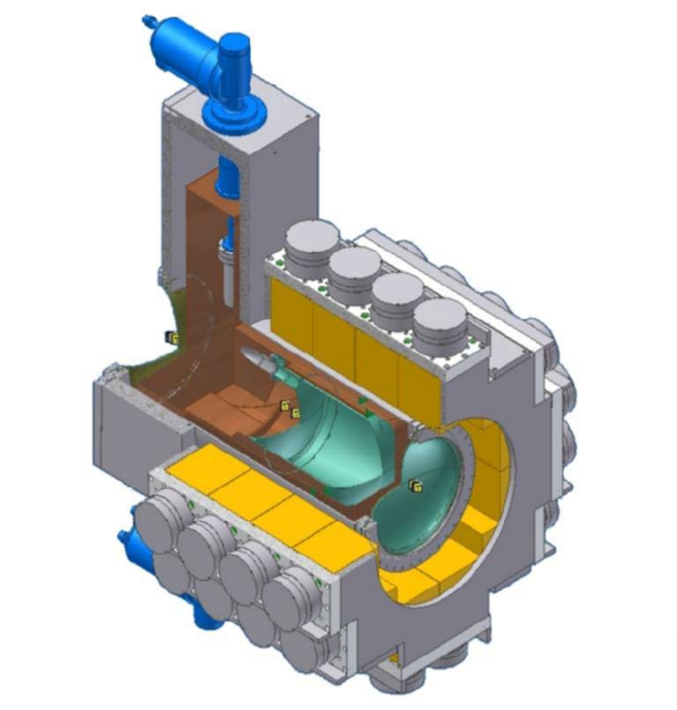


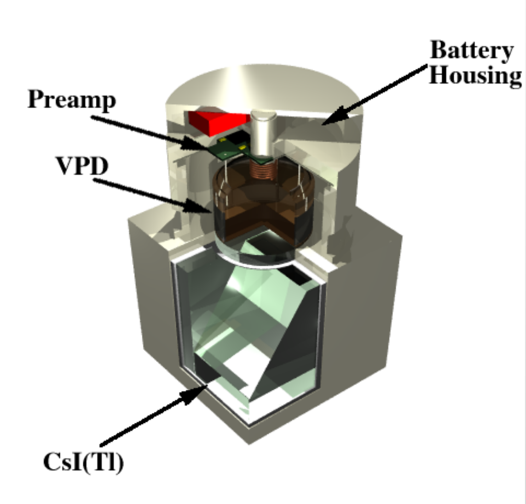


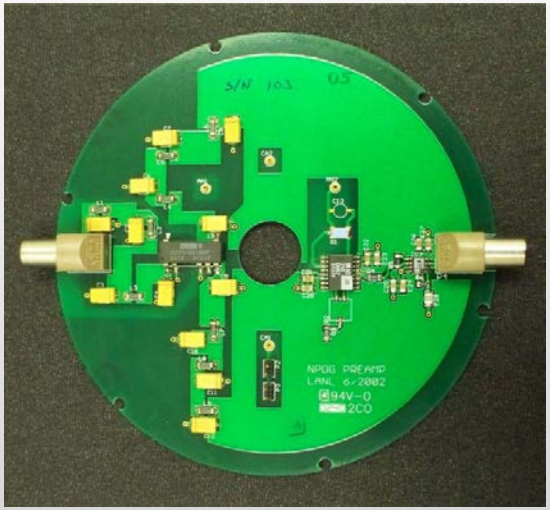
Experimental Layout:

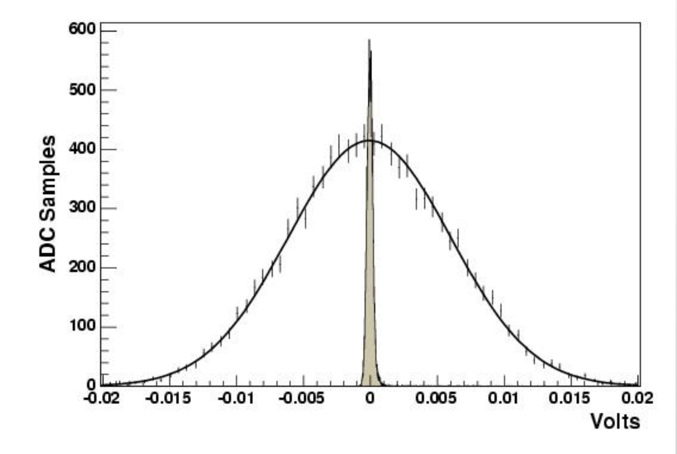
NPDGamma Detector (NIM A 540, 328 (2005)

- Consists of 4 rings with 12 detectors each
- CsI(Tl) scintillator crystals coupled to 3 inch vacuum photodiodes
- Covers a solid angle of ~ 3π
- Rate per detector ~ 100 MHz
- Operated in current mode
- Gain provided by low noise solid state preamplifiers.

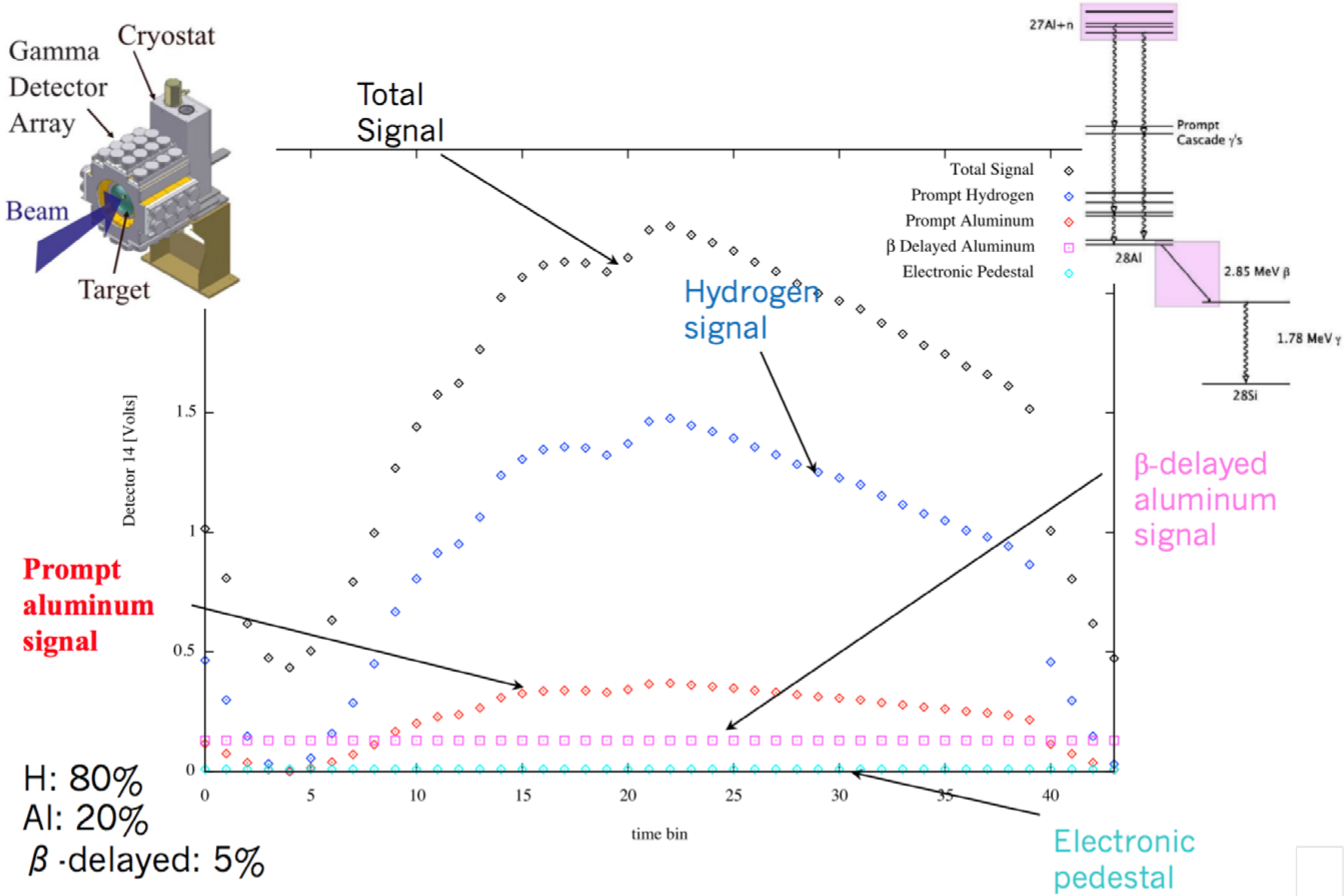








Detector Signal and Background:



H: 80%
Al: 20%
β -delayed: 5%

Analysis Procedure:

Raw asymmetries are measured simultaneously for each detector pair to filter pulse to pulse intensity fluctuations and for a valid spin sequence of eight pulses

↑↓↓↑↓↑↑↓

to suppress detector gain drifts up to second order.

Point target and detector: $\frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi}\left(1 + A_{\gamma PV}\cos(\theta_\gamma)\right)$

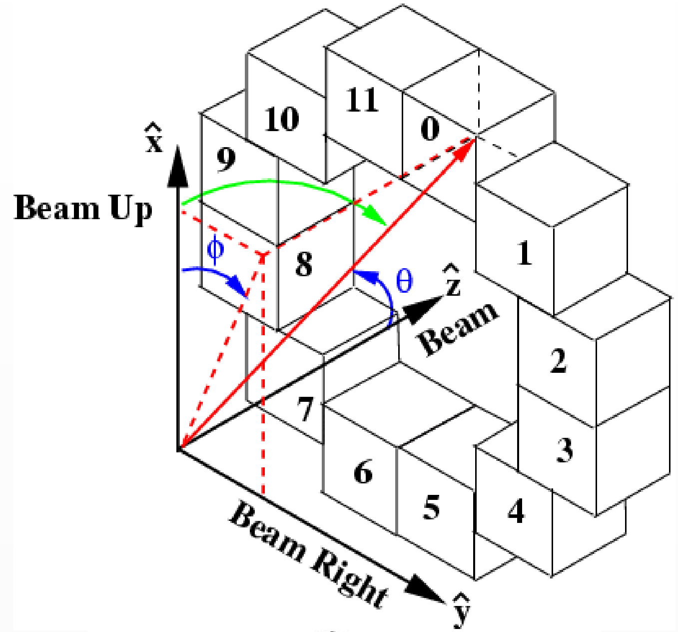
Acceptance corrected: $\cos(\theta_\gamma) \Rightarrow G_d(\langle z, \theta, \phi \rangle)$

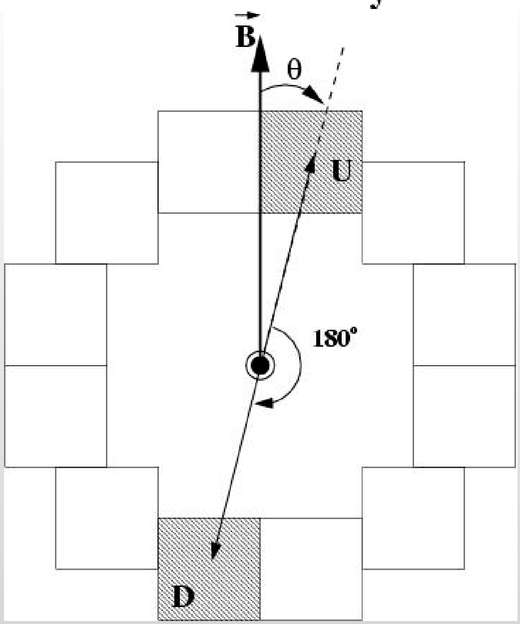
Detector yield: $Y_d = \frac{V_d}{4\pi}\left(1 + A_{\gamma PV}\, G_d\, P_n\, R_n\, S_n\right)$

Detector pair asymmetry:

$$A_{meas} = \frac{\sqrt{\alpha} - 1}{\sqrt{\alpha} + 1} \qquad \alpha \equiv \frac{Y_d^{\uparrow}}{Y_d^{\downarrow}} \cdot \frac{Y_{d+6}^{\uparrow}}{Y_{d+6}^{\downarrow}}$$

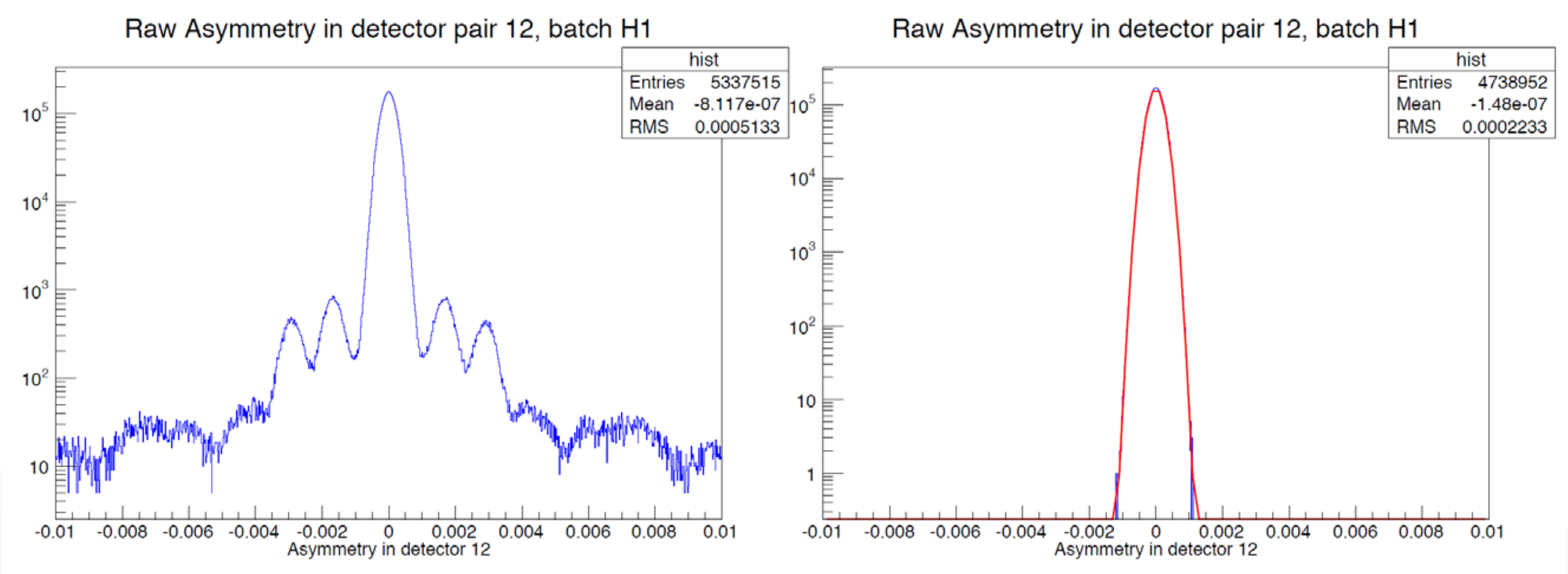
Geometric mean detector pair asymmetry removes beam and pedestal variations.





Analysis Procedure:

Beam monitor data and dropped pulse cuts:



About 15% of data is removed by cuts

Varying cuts does not affect the asymmetry

Cuts are independent of polarization

Extraction of Physics Asymmetry:

Take into account aluminum background fraction and independently measured aluminum asymmetry for each detector pair.

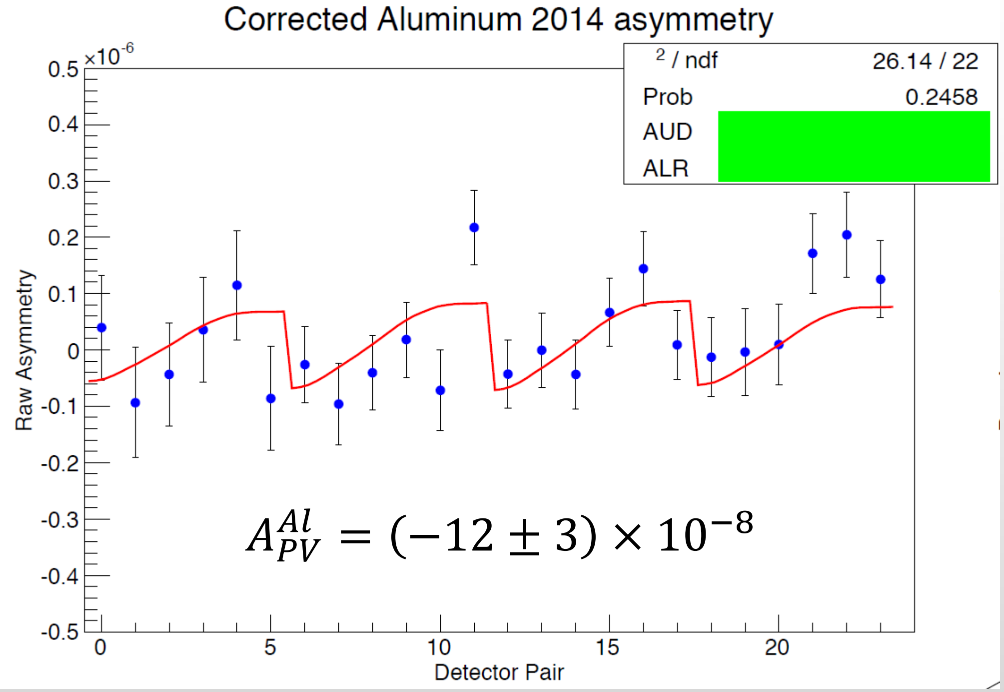
Also take into account the parity-conserving left-right asymmetry.

$$A_p^{meas} = f_H P_{tot}^H \left(G_{UD,p}^H A_{\gamma PV}^H + G_{LR,p}^H A_{\gamma PC}^H \right) + f_{Al} P_{tot}^{Al} \left(G_{UD,p}^{Al} A_{\gamma PV}^{Al} + G_{LR,p}^H A_{\gamma PC}^{Al} \right)$$

Combine the beam polarization, spin rotation efficiency, and depolarization into one P_{tot}

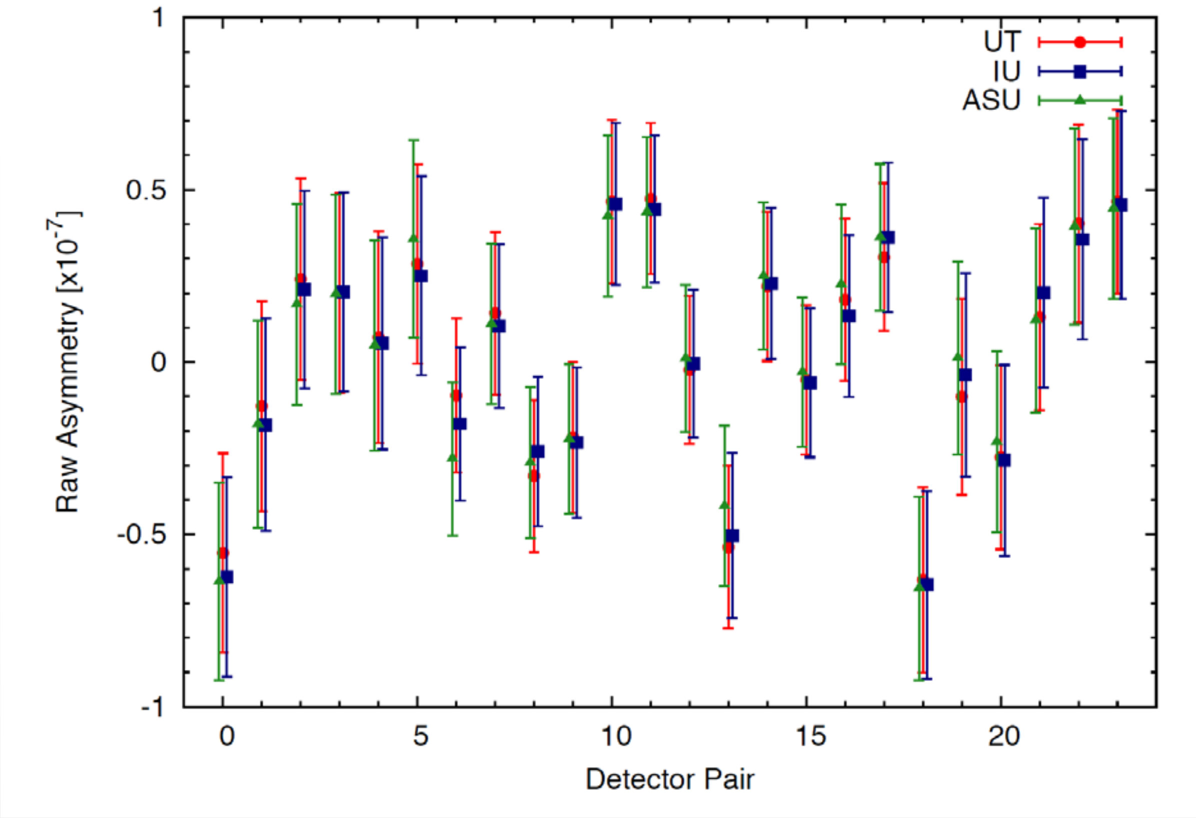
Subtract the measured Aluminum PV and PC asymmetries

Plot the pair asymmetries and extract the PV and PC asymmetries from a fit to the data.



Final Result for the Hydrogen Asymmetry:

Three independent analysis approaches were pursued, with independent cut methodologies.



$$\boxed{A_{PV}^{H} = \left(-3.0 \pm 1.4\ (stat) \pm 0.2\ (sys)\right) \times 10^{-8}}$$

Goals of $\Delta S = 0$ HWI studies:

1. Answer how the symmetries of QCD characterize the HWI in strongly interacting systems

   The HWI is just a residual effect of the q-q weak interaction for which the range is set by the mass of the Z,W bosons which is much smaller than the size of nucleons, as determined by QCD dynamics.

   $\Rightarrow$ HWI probes short range qq correlations at low energy

   Best hope for the future are possible calculations in LQCD

2. Try to shed some light on the puzzles in the $\Delta S = 1$ sector of the HWI

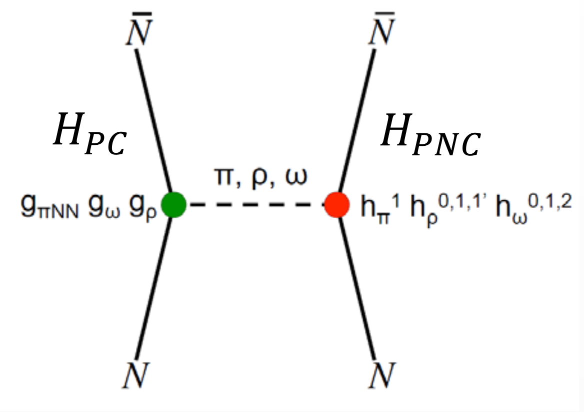
Overview:

- Meson exchange model: PV potential π, ρ, and ω ! with strong and weak vertex. Leads to 7 Weak couplings
  - B. Desplanques, J. F. Donoghue, and B. R. Holstein, Annals of Physics, 124 (1980)
  - W. C. Haxton and B. R. Holstein, Progress in Particle and Nuclear Physics, 2013
- $EFT(\not{\pi})$, χEFT: 5 LEC constants, model independent
  - S. L. Zhu et al., Nucl. Phys. A748 (2005) 435
  - L. Girlanda, Phys. Rev. C77 (2008) 067001
  - D. R. Phillips, M. R. Schindler, and R. P. Springer, Nucl. Phys. A822 (2009) 1
- $1/N_C$ expansions: $N_C \rightarrow$ large gives hierarchy of couplings
  - D. Phillips, D. Samart, and C. Schat, PRL 114 (2015) 062301
  - M. R. Schindler, R. P. Springer, and J. Vanasse, PRC 93 (2016) 025502
  - Gardner, Haxton, Holstein, ARNPS 67, 69 (2017)
- LQCD calculations of HWI couplings
  - J. Wasem Phys. Rev. C85 (2012) 022501 (problems with this calculation)
  - A. Walker-Loud – expensive, but forthcoming re-calculation of pion coupling in NN

Meson exchange picture (DDH - B. Desplanques, J. F. Donoghue, and B. R. Holstein):

- Low energy NN interaction in terms of the lowest energy mesons in which the pseudoscalar π meson and ρ and ω vector mesons couple a weak vertex to a strong vertex

- To relate to observables, need to calculate matrix elements. DDH used quark model, SU(6) symmetry, and non-leptonic hyperon decays to make estimates of the couplings



e.g. pion coupling: $H_{PC} = ig_{\pi NN} \int d\boldsymbol{x}\, \bar{\psi}\gamma_5\psi\, \boldsymbol{\tau}\cdot\boldsymbol{\phi}$ $\quad H_{PNC} = \frac{h_\pi^1}{\sqrt{2}} \int d\boldsymbol{x}\, \bar{\psi}\psi\, \boldsymbol{\tau}\times\boldsymbol{\phi}$

$$\langle f|V_{PNC}|i\rangle = \left\langle N_{f1}N_{f2}\middle| H_{PC}\frac{1}{E_o - H_o + i\varepsilon} H_{PNC} \middle| N_{i1}N_{i2}\right\rangle + \text{h.c.}$$

$$\Rightarrow \frac{ih_\pi^1 g_{\pi NN}}{m_N\sqrt{36}}(\boldsymbol{\tau}_1\times\boldsymbol{\tau}_2)_z(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)\left[\boldsymbol{p}_1-\boldsymbol{p}_2, \frac{e^{-m_n \boldsymbol{r}}}{4\pi\,\boldsymbol{r}}\right]$$

Weak pion-nucleon coupling

Meson exchange picture (DDH - B. Desplanques, J. F. Donoghue, and B. R. Holstein):

$$
\begin{aligned}
V_{DDH}^{PV}(\vec{r}) = {} & i\frac{h_\pi^1 g_{\pi NN}}{\sqrt{2}}\left(\frac{\boldsymbol{\tau_1}\times\boldsymbol{\tau_2}}{2}\right)_z(\boldsymbol{\sigma_1}+\boldsymbol{\sigma_2})\cdot\left[\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\pi(\boldsymbol{r})\right] \\
& - g_\rho\left(h_\rho^0\boldsymbol{\tau_1}\cdot\boldsymbol{\tau_2} + h_\rho^1\left(\frac{\boldsymbol{\tau_1}\times\boldsymbol{\tau_2}}{2}\right)_z + \frac{h_\rho^2}{2\sqrt{6}}((3\boldsymbol{\tau_1}\cdot\boldsymbol{\tau_2})_z - \boldsymbol{\tau_1}\cdot\boldsymbol{\tau_2})\right) \\
& \times\left((\boldsymbol{\sigma_1}-\boldsymbol{\sigma_2})\cdot\left\{\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\rho(\boldsymbol{r})\right\} + i(1+\chi_V)\boldsymbol{\sigma_1}\times\boldsymbol{\sigma_2}\cdot\left[\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\rho(\boldsymbol{r})\right]\right) \\
& - g_\omega\left(h_\omega^0 + h_\omega^1\left(\frac{\boldsymbol{\tau_1}\times\boldsymbol{\tau_2}}{2}\right)_z\right) \\
& \times\left((\boldsymbol{\sigma_1}-\boldsymbol{\sigma_2})\cdot\left\{\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\omega(\boldsymbol{r})\right\} + i(1+\chi_S)\boldsymbol{\sigma_1}\times\boldsymbol{\sigma_2}\cdot\left[\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\omega(\boldsymbol{r})\right]\right) \\
& + \left(\frac{\boldsymbol{\tau_1}\times\boldsymbol{\tau_2}}{2}\right)_z(\boldsymbol{\sigma_1}+\boldsymbol{\sigma_2})\cdot\Big) g_\rho h_\rho^1\left\{\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\rho(\boldsymbol{r})\right\} - g_\omega h_\omega^1\left\{\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\omega(\boldsymbol{r})\right\}\Big) \\
& - i g_\rho h_\rho^{1'}\left(\frac{\boldsymbol{\tau_1}\times\boldsymbol{\tau_2}}{2}\right)_z(\boldsymbol{\sigma_1}+\boldsymbol{\sigma_2})\cdot\left[\frac{\boldsymbol{p_1}-\boldsymbol{p_2}}{2m_N}, w_\rho(\boldsymbol{r})\right]
\end{aligned}
$$

$$O_{PV} = a_\pi^1 h_\pi^1 + a_\rho^0 h_\rho^0 + a_\rho^1 h_\rho^1 + a_\rho^2 h_\rho^2 + a_\omega^0 h_\omega^0 + a_\omega^1 h_\omega^1$$

Theory and Implications:

Meson exchange picture (DDH - B. Desplanques, J. F. Donoghue, and B. R. Holstein):

$$O_{PV} = a_\pi^1 h_\pi^1 + a_\rho^0 h_\rho^0 + a_\rho^1 h_\rho^1 + a_\rho^2 h_\rho^2 + a_\omega^0 h_\omega^0 + a_\omega^1 h_\omega^1$$

E. G. Adelberger and W. C. Haxton, Ann. Rev. Nucl. Part. Sci. 35, 501 (1985).

DDH Weak Coupling	(A_γ) $np \to d\gamma$	(A_γ) $nd \to t\gamma$	(ϕ_{PV}) n-p (μrad/m)	(ϕ_{PV}) n-α (μrad/m)	p-p	p-α	(A^p_Z) $n^3He \to tp$
a_π^1	-0.107	-0.92	-3.12	-0.97	0	-0.340	-0.189
a_ρ^0	0	-0.50	-0.23	-0.32	0.079	0.140	-0.036
a_ρ^1	-0.001	0.103	0	0.11	0.079	0.047	0.019
a_ρ^2	0	0.053	-0.25	0	0.032	0	0.0006
a_ω^0	0	-0.160	-0.23	-0.22	-0.073	0.059	-0.033
a_ω^1	0.003	0.002	0	0.22	0.073	0.059	0.041

Theory and Implications:

Meson exchange picture (DDH - B. Desplanques, J. F. Donoghue, and B. R. Holstein)

For NPDGamma

Prediction:

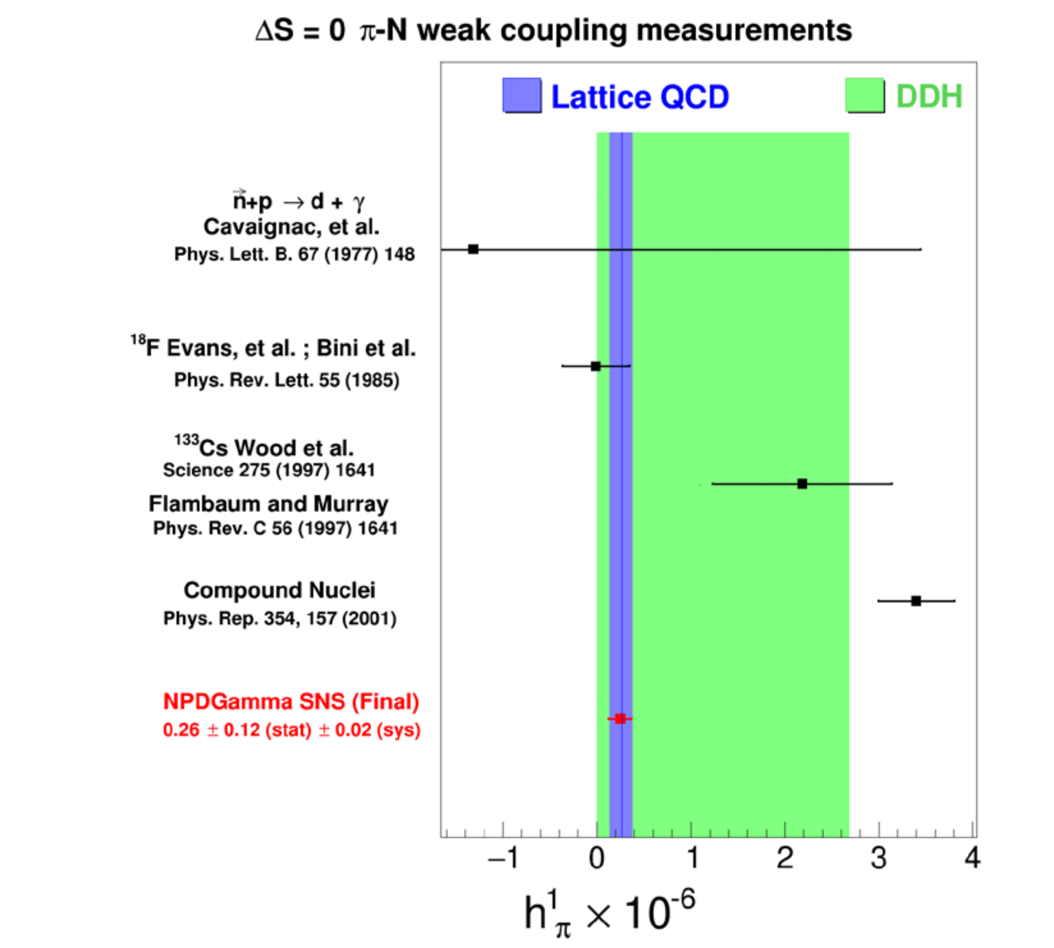
$$\boxed{A^H_{PV} \approx -0.107 h_\pi^{\Delta I=1} \approx -5 \times 10^{-8}}$$

Asymmetry result:

$$\boxed{A^H_{PV} = (-3.0 \pm 1.4 \pm 0.2) \times 10^{-8}}$$

Leads to a determination of the coupling

$$\boxed{h^1_\pi = (0.26 \pm 0.12 \pm 0.02) \times 10^{-6}}$$



Note: LQCD

J. Wasem PRC C 85 (2012)

Result is being recalculated

Effective field theories (pion-less) D. R. Phillips, M. R. Schindler, and R. P. Springer, Nucl. Phys. A822 (2009) 1

- Choose the lowest mass hadrons possible: pions
- Below pion production, can choose photons and nucleons (instead of gluons, which are in bound states) as the only dynamical degrees of freedom, non-relativistic

$$\begin{aligned}\mathcal{L}_{PV} = -\Big[& \mathcal{C}^{({}^3S_1-{}^1P_1)} \left(N^T\sigma^2\vec{\sigma}\tau^2 N\right)^\dagger \cdot \left(N^T\sigma^2\tau^2 i\overleftrightarrow{D} N\right) \\ & + \mathcal{C}^{({}^1S_0-{}^3P_0)}_{(\Delta I=0)} \left(N^T\sigma^2\tau^2\vec{\tau}N\right)^\dagger \left(N^T\sigma^2\vec{\sigma}\cdot\tau^2\vec{\tau} i\overleftrightarrow{D} N\right) \\ & + \mathcal{C}^{({}^1S_0-{}^3P_0)}_{(\Delta I=1)} \epsilon_{3ab} \left(N^T\sigma^2\tau^2\tau^a N\right)^\dagger \left(N^T\sigma^2\vec{\sigma}\cdot\tau^2\tau^b\overleftrightarrow{D} N\right) \\ & + \mathcal{C}^{({}^1S_0-{}^3P_0)}_{(\Delta I=2)} \mathcal{I}_{ab} \left(N^T\sigma^2\tau^2\tau^a N\right)^\dagger \left(N^T\sigma^2\vec{\sigma}\cdot\tau^2\tau^b i\overleftrightarrow{D} N\right) \\ & + \mathcal{C}^{({}^3S_1-{}^3P_1)} \epsilon_{ijk} \left(N^T\sigma^2\sigma^i\tau^2 N\right)^\dagger \left(N^T\sigma^2\sigma^k\tau^2\tau^3\overleftrightarrow{D}^j N\right)\Big] + \text{H.c.}\,,\end{aligned}$$

- 5 LECs. Currently can only do calculations in few-body systems

Theory and Implications:

Effective field theories (pion-less) D. R. Phillips, M. R. Schindler, and R. P. Springer, Nucl. Phys. A822 (2009) 1

- Schindler et al. Showed that the two terms are related to one another by a factor of 3 up to $\mathcal{O}(1/N_C^2)$ corrections. So we go from 5 to 4 LECs

$$\mathcal{C}^{({}^3S_1-{}^1P_1)} = 3\,\mathcal{C}^{({}^1S_0-{}^3P_0)}_{(\Delta I=0)}$$

- In the large N_C formalism (M. R. Schindler, R. P. Springer, and J. Vanasse, PRC 93 (2016) 025502)
M. Schindler and R. Springer, Prog. Part. Nucl. Phys. 72, 1 (2013).

$$\begin{aligned}
\mathcal{C}^{({}^3S_1-{}^1P_1)} &\sim N_c\ ,\\
\mathcal{C}^{({}^1S_0-{}^3P_0)}_{(\Delta I=0)} &\sim N_c\ ,\\
\mathcal{C}^{({}^1S_0-{}^3P_0)}_{(\Delta I=1)} &\sim N_c^0 \sin^2\theta_W\ ,\\
\mathcal{C}^{({}^1S_0-{}^3P_0)}_{(\Delta I=2)} &\sim N_c\ ,\\
&\boxed{\mathcal{C}^{({}^3S_1-{}^3P_1)} \sim N_c^0 \sin^2\theta_W}\ .
\end{aligned}$$

From NPDGamma $$\boxed{\frac{C^{{}^3S_1-{}^3P_1}}{C_0} = (-7.4 \pm 3.5 \pm 0.5)\times 10^{-11}\ \ MeV^{-1}}$$

In the large N_C formalism Gardner, Haxton, Holstein, ARNPS 67, 69 (2017)

$$\begin{aligned} V_{\rm LO}^{\rm PNC}(\boldsymbol{r}) = \Lambda_0^{^1\mathrm{S}_0-^3\mathrm{P}_0} & \left(\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2) - \frac{1}{i}\frac{\overleftrightarrow{\nabla}_S}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right) \\ + \Lambda_0^{^3\mathrm{S}_1-^1\mathrm{P}_1} & \left(\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2) + \frac{1}{i}\frac{\overleftrightarrow{\nabla}_S}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right) \\ + \Lambda_1^{^1\mathrm{S}_0-^3\mathrm{P}_0} & \left(\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\tau_{1z}+\tau_{2z})\right) \\ + \Lambda_1^{^3\mathrm{S}_1-^3\mathrm{P}_1} & \left(\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)(\tau_{1z}-\tau_{2z})\right) \\ + \Lambda_2^{^1\mathrm{S}_0-^3\mathrm{P}_0} & \left(\frac{1}{i}\frac{\overleftrightarrow{\nabla}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1\otimes\boldsymbol{\tau}_2)_{20}\right), \end{aligned}$$

$\Lambda_1^{^3S_1-^3P_1}$	$\frac{1}{\sqrt{2}}g_{\pi NN}h_\pi^1\left(\frac{m_\rho}{m_\pi}\right)^2 + g_\rho(h_\rho^1 - h_\rho^{1\prime}) - g_\omega h_\omega^1$	$2\mathcal{G}_6$	$\sim \sin^2\theta_w$

$$h_\rho^0 \sim \sqrt{N_c}, \quad h_\rho^2 \sim \sqrt{N_c}$$

$$\frac{h_\rho^{1\prime}}{\sin^2\theta_W} \lesssim \sqrt{N_c}, \quad \frac{h_\omega^1}{\sin^2\theta_W} \sim \sqrt{N_c}$$

$$\frac{h_\rho^1}{\sin^2\theta_W} \lesssim \frac{1}{\sqrt{N_c}}, \quad \frac{h_\pi^1}{\sin^2\theta_W} \lesssim \frac{1}{\sqrt{N_c}}, \quad h_\omega^0 \sim \frac{1}{\sqrt{N_c}}$$

From NPDGamma

$$\boxed{\Lambda_1^{^3S_1-^3P_1} = 810 \pm 380 \times 10^{-7}}$$

Summary:

- NPDGamma performed a high statistics measurement of the parity-violating gamma asymmetry in neutron proton capture.
- First time observed a non-zero value for the effect
- Together with other few-body HWI measurements (p-p, p-α, n^{3}He, etc.) can constrain couplings in various theories that attempt to explain the lower energy hadronic weak interaction, in the strong-coupling regime
- PRL with results will come out soon

Thank you!