Fundamental physics with low-energy neutrons

Hadronic Weak Interaction (HWI)

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Why is the HWI interesting?

- One of the most poorly understood sectors in the SM

- Weak couplings between quarks and $W^{\pm}$ and Z bosons well described in the electroweak theory

- No first-principles calculation of weak couplings between nucleons due to the non-perturbative nature of QCD at low energies

- NN weak interactions are very sensitive to quark-quark correlations in the nucleon, offering a unique regime to test the standard electroweak model

- Quantitative understanding of the NN weak amplitudes in combination with PV measurements in heavy nuclei ($\vec{s} \cdot \vec{k}$ and $\vec{s} \cdot \vec{s}'$ correlations, P_γ, anapolar moments, PV in neutron-nucleus resonances, etc.) can provide benchmarks for nuclear structure theory

"Fundamental Neutron Physics: a White Paper on Progress and Prospects in the US", arXiv:2308.09059v1 (2023)

Theoretical description of the HWI

One-meson exchange model (DDH)

- Model dependent
- Six weak NN couplings:

$h_\pi^1, h_\rho^0, h_\rho^1, h_\rho^2, h_\omega^0$ and h_ω^1

- Desplanques, Donoghue, Holstein, Ann. Phys. (N.Y.) 124, 449 (1980)
- Haxton, Holstein, Prog.Part.Nucl. Phys.71, 185 (2013)

$\not\pi$- and χ- EFT

- Consistent with symmetries of QCD
- In $\not\pi$-EFT, five low-energy constants: $\Lambda_0^{^1S_0-^3P_0}$, $\Lambda_0^{^3S_1-^1P_1}$, $\Lambda_1^{^1S_0-^3P_0}$, $\Lambda_1^{^3S_1-^1P_1}$, $\Lambda_2^{^1S_0-^3P_0}$
- In χ-EFT also 5 LEC + π and 2π-exchange

- S.L. Zhu et al.,Nucl. Phys.A748 (2005)435
- L.Girlanda, Phys.Rev.C77 (2008)067001
- D.R. Phillips et al., ,Nucl. Phys.A822 (2009)
- M. Viviani, R. Schiavilla, Phys. Rev. C 82044001 (2010)
- L.Girlanda et al. Phys. Rev. Lett. 105 232502(2010)
- M.Viviani, et al. Phys. Rev. C89, 064004 (2014)

Theoretical description of the HWI

Table 2
The coefficients of the S–P PNC potential of Eq. (36) in the DDH potential, Girlanda, and Zhu descriptions. Note that multiplicative factors of $2m_N m_\rho^2$ and $2m_N m_\rho^2/\Lambda_\chi^3$ must be applied to the Girlanda and Zhu entries, respectively, to obtain the dimensionless coefficients Λ, e.g., $\Lambda_{0\,\mathrm{DDH}}^{^1S_0-^3P_0} = 2(\mathcal{G}_1 + \tilde{\mathcal{G}}_1)[2m_N m_\rho^2] = 2(\mathcal{C}_1 + \tilde{\mathcal{C}}_1 + \mathcal{C}_3 + \tilde{\mathcal{C}}_3)[2m_N m_\rho^2/\Lambda_\chi^3]$.

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

Haxton, Holstein, Prog. Part. Nucl. Phys. 71, 187 (2013)

Theoretical description of the HWI

Lattice gauge theory

- Existing calculation for the $\Delta I = 1, {}^3S_1 - {}^1P_1$ component and new calculation in progress
- Current attempts to calculate the $\Delta I = 2$

Wassem, PRC 85 (2012) 022501

Other approaches

- $1/N_c$ expansion
- Factorization approximation for nucleon-meson matrix elements

Phillips, Samart, Schat, PRL 114 (2015) 062301

Schindler, Springer, Vanasse, PRC 93 (201 6) 0 5502

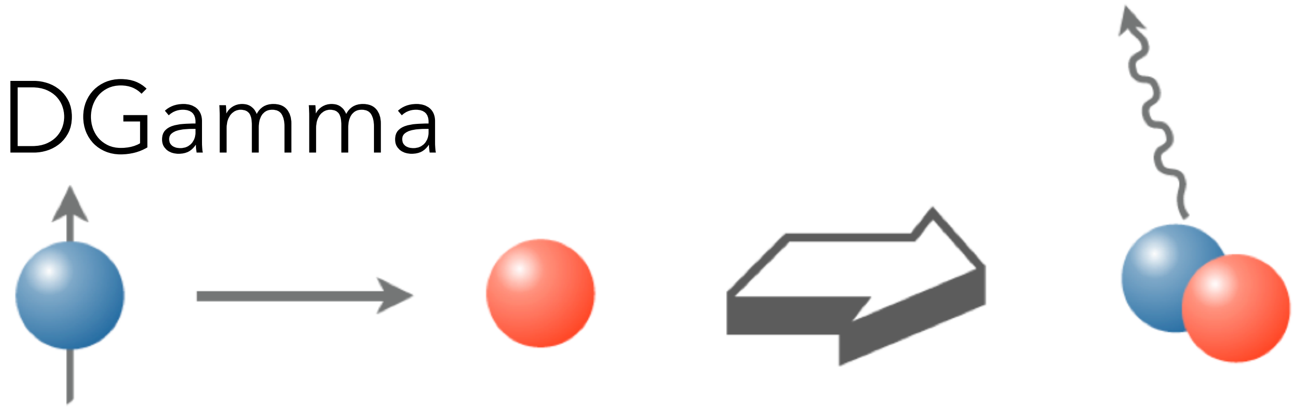
Gardner, Haxton, Holstein, ARNPS 67, 6 (2017)

Richardson, Schindler, Springer, Ann. Ren. Nucl. Part. Sci. 72 (2023) 123

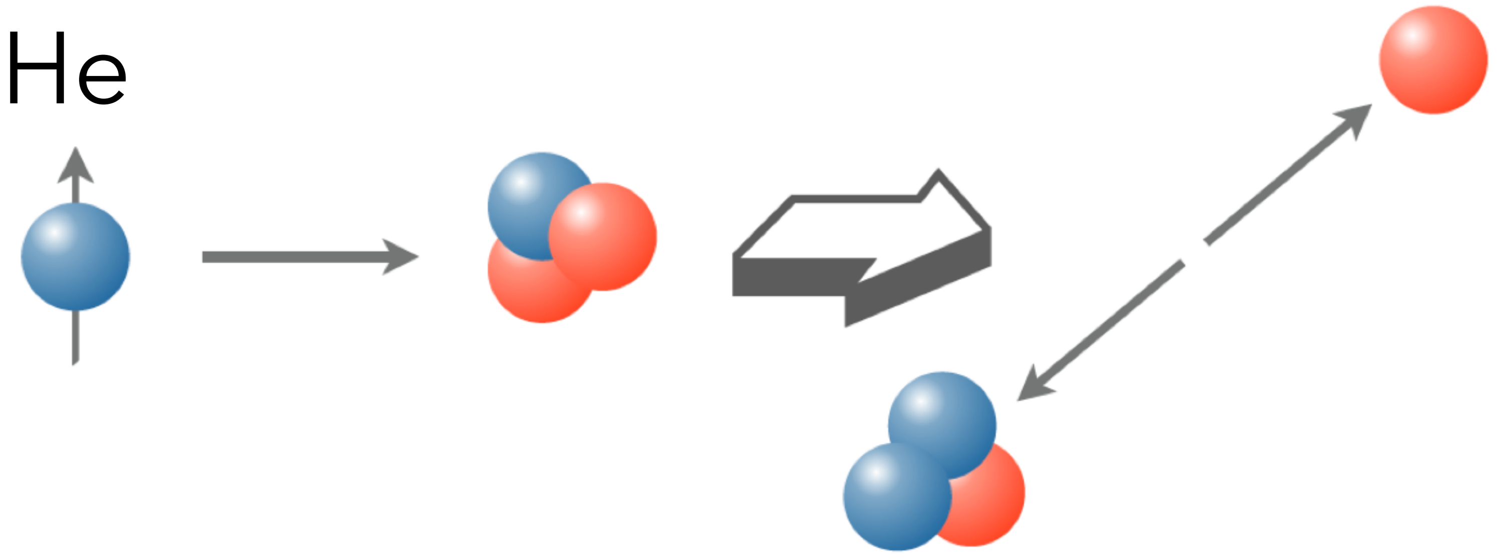
Muralidhara, Gardner, Phys. Lett. B 849 (2024) 138428

Experimental study of the HWI

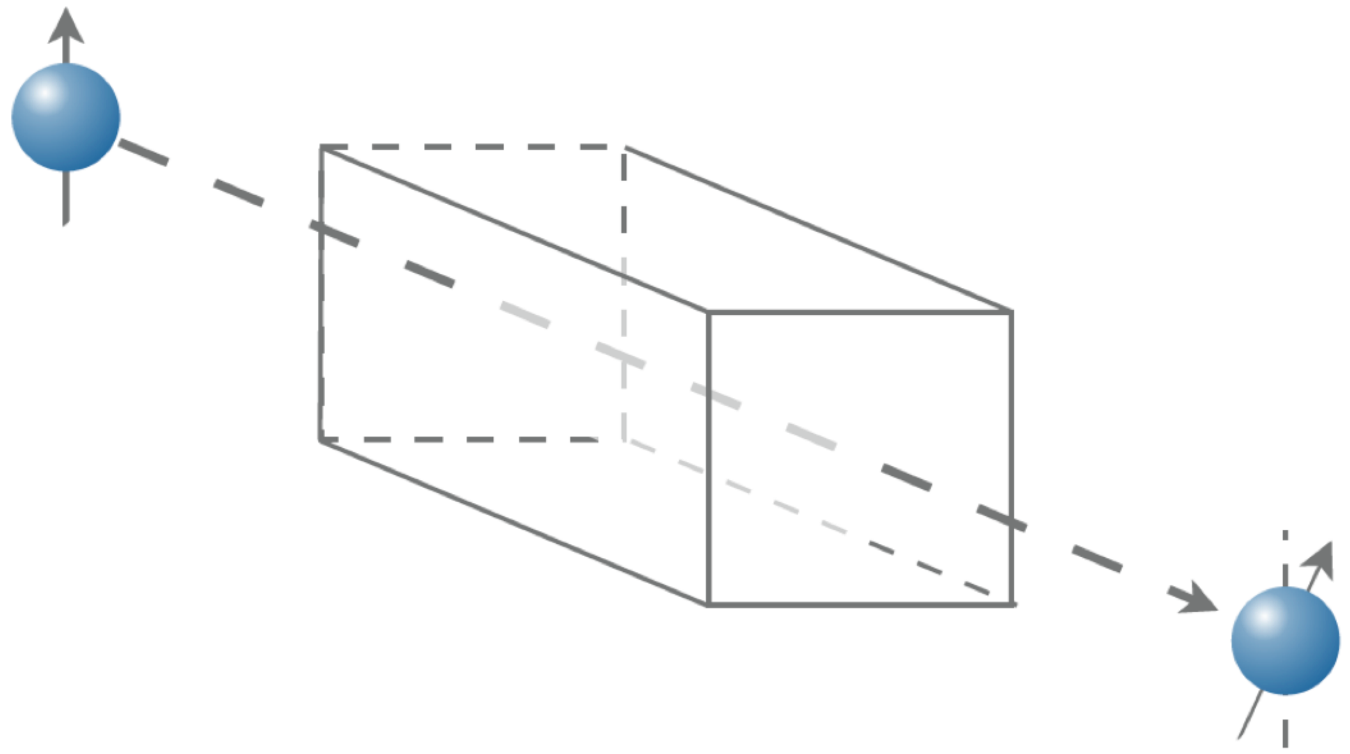
NPDGamma



n-^{3}He



Neutron Spin Rotation (NSR)



Using DDH "best values"
observables are $\sim 10^{-7} - 10^{-6}$

system	$\vec{n} + p \rightarrow d + \gamma$	$\vec{n} + {}^3He \rightarrow p + {}^3H$	$\vec{n} - {}^4He$
correlation	$\vec{s}_n \cdot \vec{k}_\gamma$	$\vec{s}_n \cdot \vec{k}_p$	$\vec{s}_n \cdot \vec{s}_n'$
observable	$A_\gamma\ (\times 10^{-7})$	$A_p\ (\times 10^{-7})$	$d\varphi/dz\ (\mu rad/m)$
h_π^1	-0.107	-0.185	-0.97
h_ρ^0	–	-0.038	-0.32
h_ρ^1	-0.001	0.023	0.11
h_ρ^2	–	-0.001	–
h_ω^0	–	-0.023	-0.22
h_ω^1	0.003	0.050	0.22

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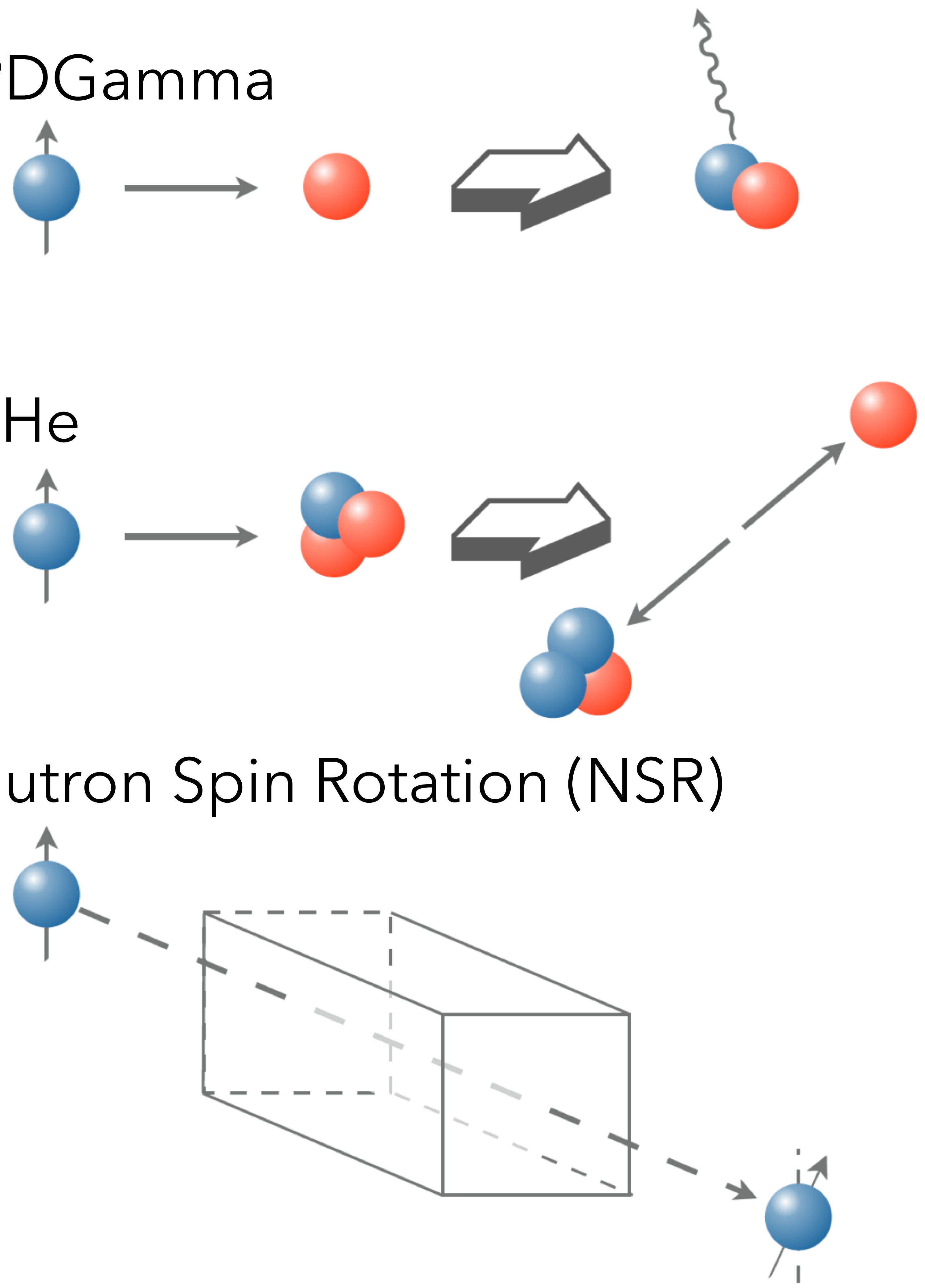

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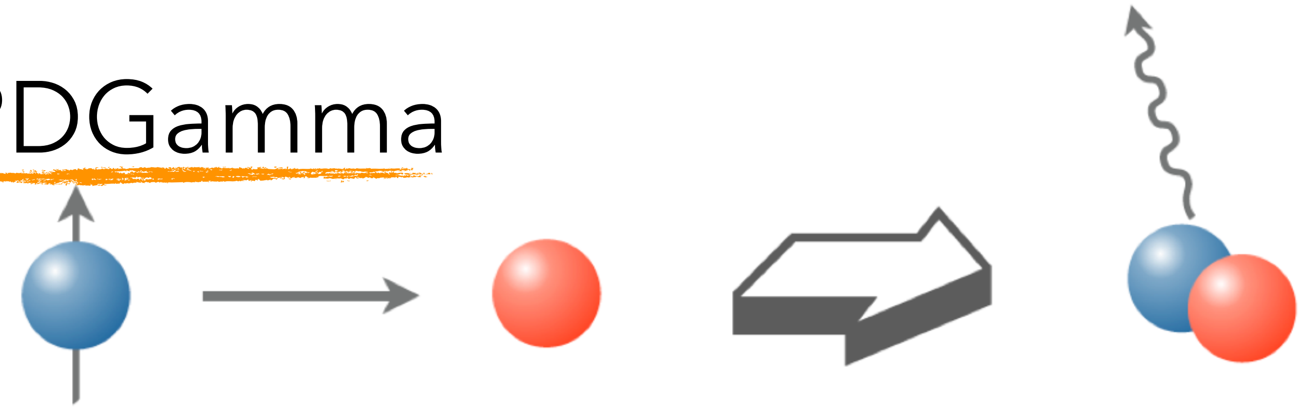
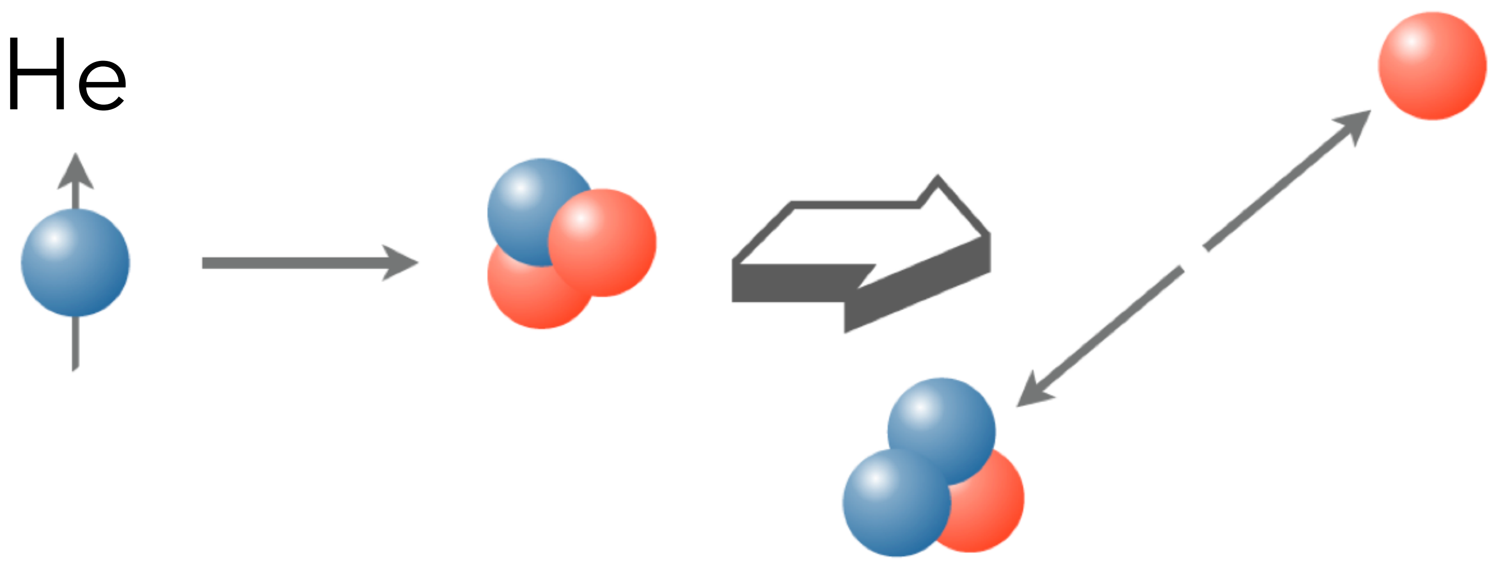


n-^{3}He



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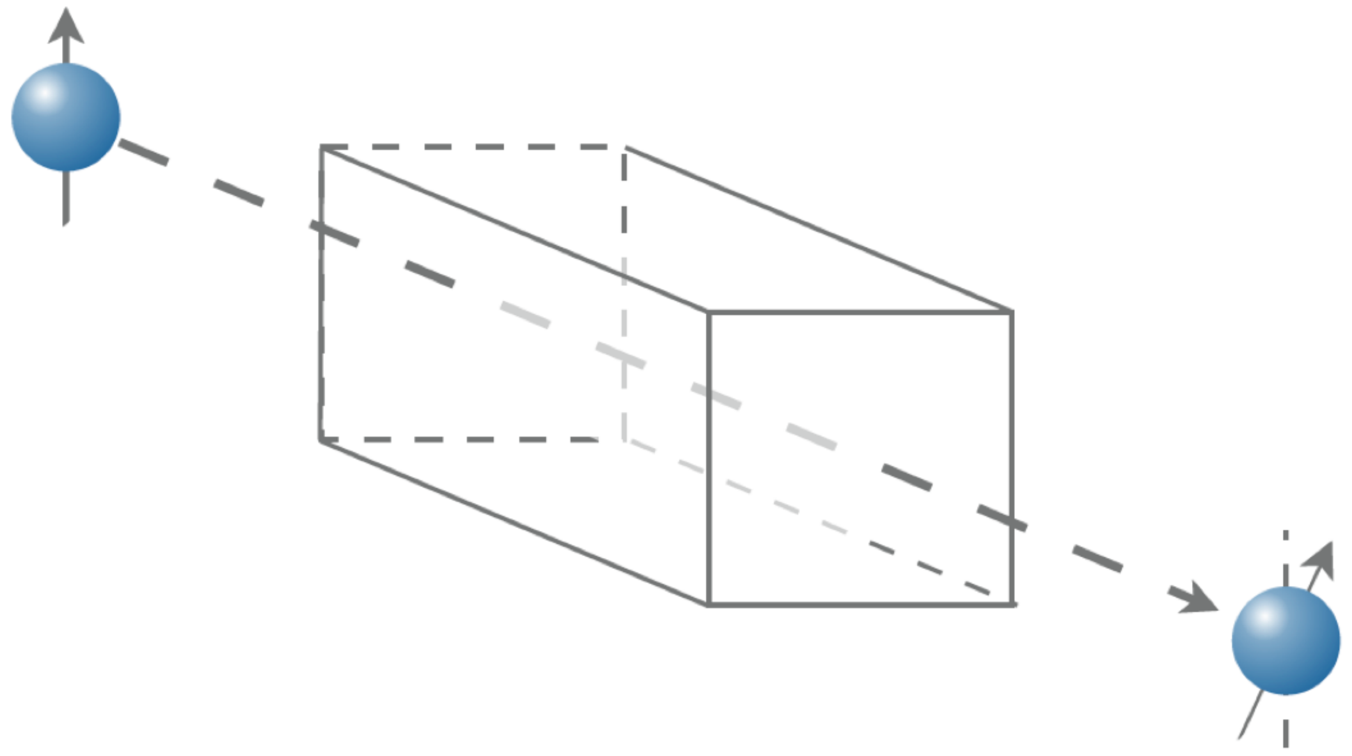

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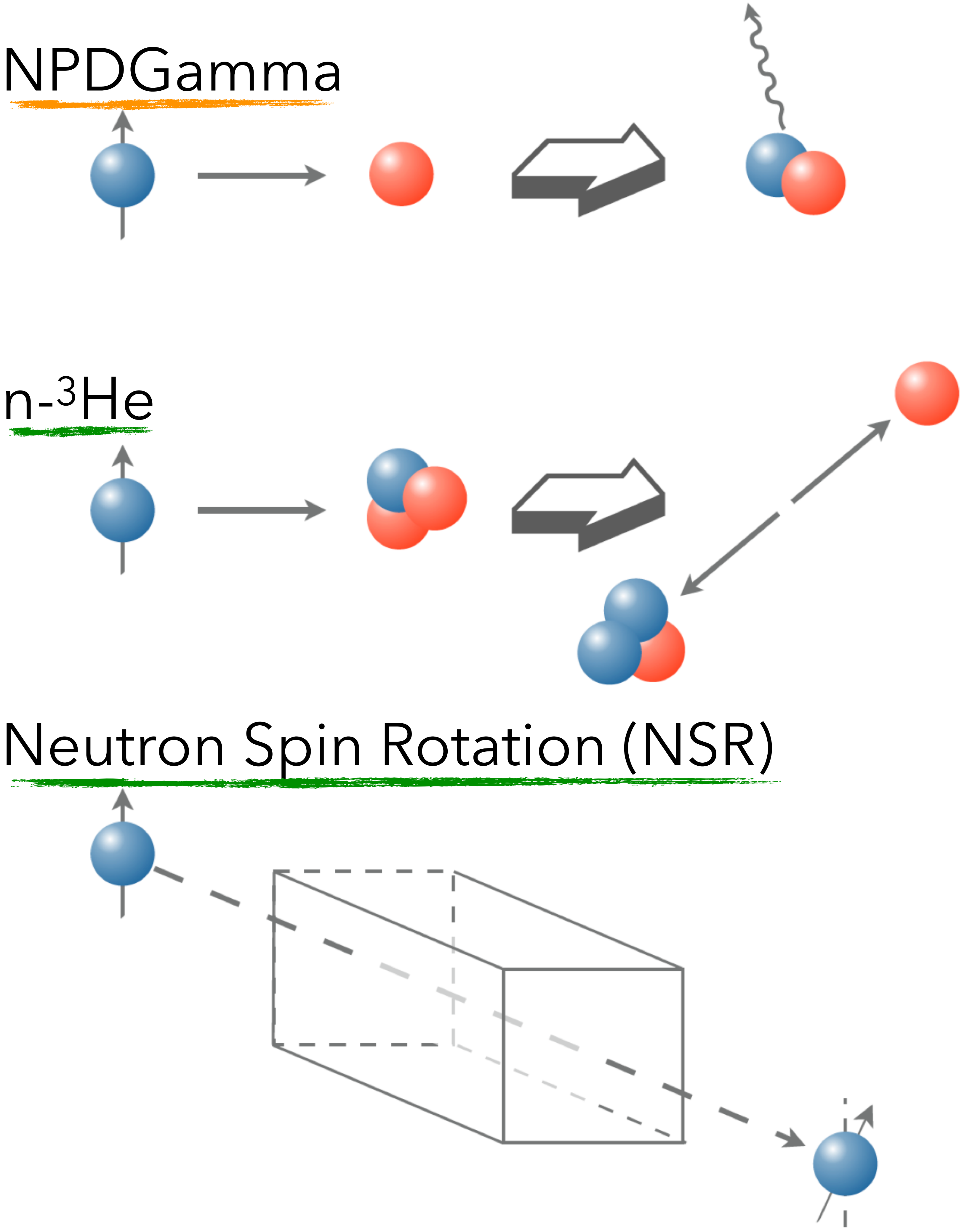

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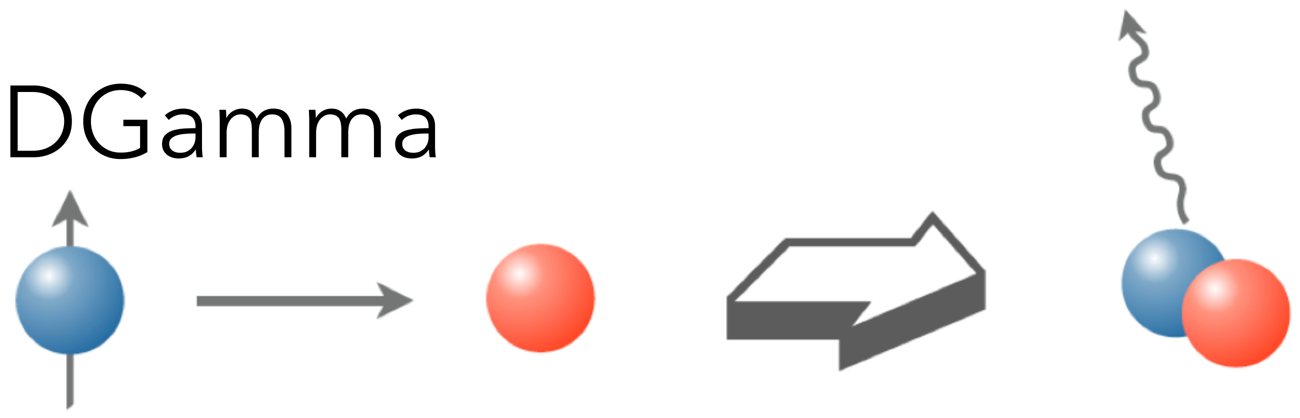
Experimental study of the HWI

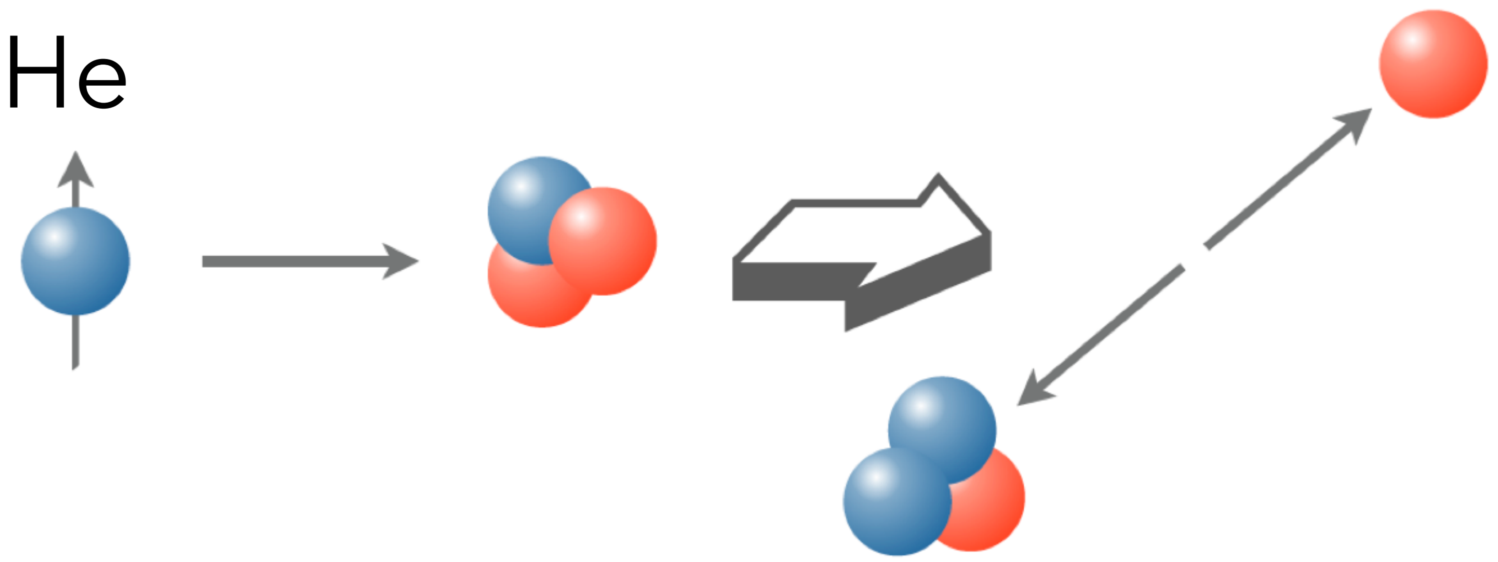
NPDGamma



$$A_\gamma = [-3 \pm 1.3(\text{stat}) \pm 0.2(\text{sys})] \times 10^{-8}$$

- D. Blyth *et al.* (NPDGamma Collaboration), “First observation of P-odd γ-asymmetry in polarized neutron capture on hydrogen”, Phys. Rev. Lett. 121, 242002 (2018).

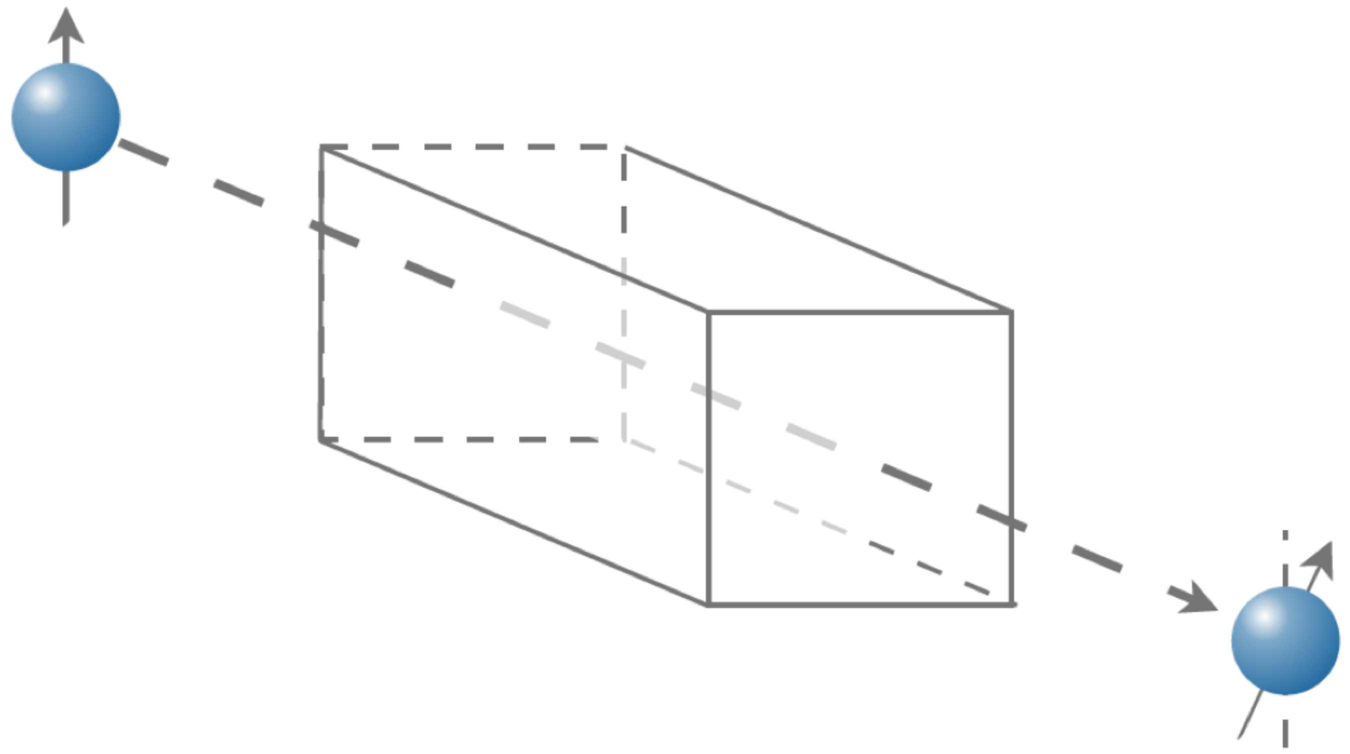
n-³He



$$A_p = [1.55 \pm 0.97(\text{stat}) \pm 0.24(\text{sys})] \times 10^{-8}$$

- M.T. Gericke *et al.* (n3He Collaboration), “First precision measurement of the parity violating asymmetry in cold neutron capture on 3He”, Phys. Rev. Lett. 125, 131803 (2020).

Neutron Spin Rotation (NSR)



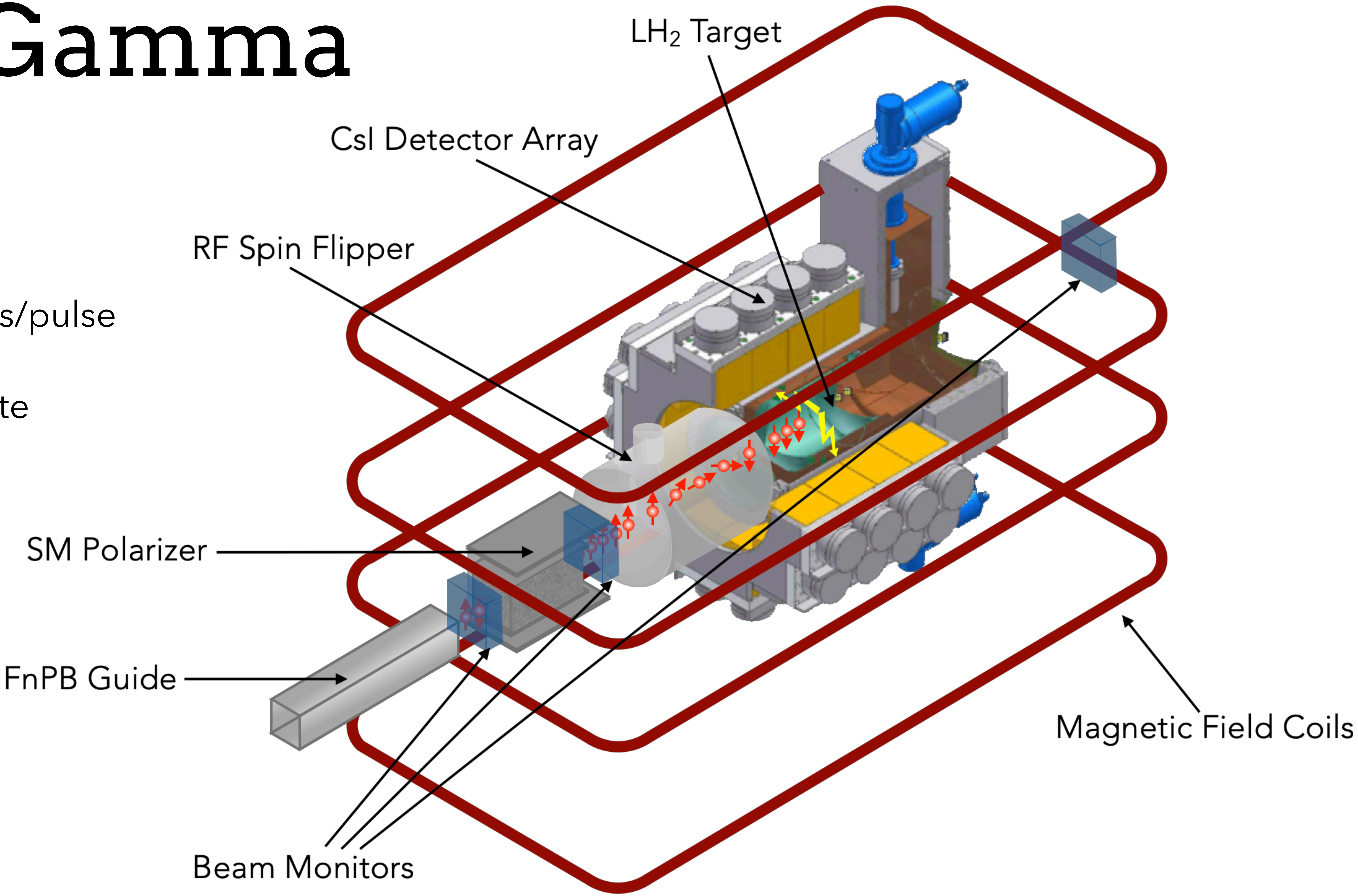
$$\frac{d\phi}{dz} = [1.7 \pm 9.1(\text{stat}) \pm 1.4(\text{sys})] \times 10^{-7} \text{ rad/m}$$

- W.M. Snow *et al.*, “Upper bound on parity-violating neutron spin rotation in 4He”, Phys. Rev. C 83, 022501(R) (2011).

NPDGamma

5x10^7 neutrons/pulse

60 Hz pulse rate



Status of weak NN couplings

$A_p = -0.185h_\pi^1 - 0.038h_\rho^0 - 0.023h_\omega^0 + 0.23h_\rho^1 + 0.05h_\omega^1 - 0.001h_\rho^2$
(n-^{3}He)

$A_\gamma = -0.107h_\pi^1$ (NPDGamma)

Using the experimental results

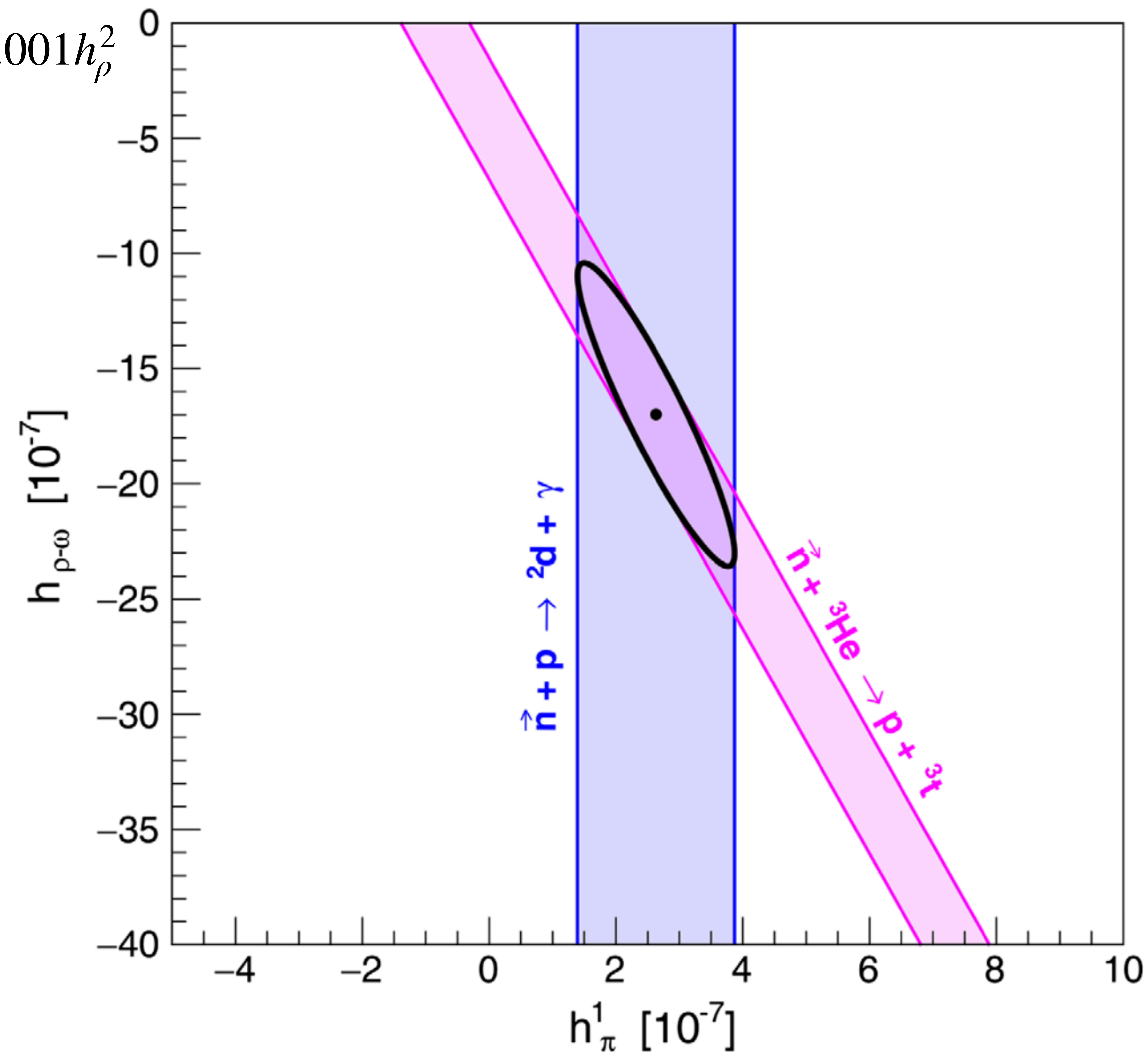
$A_\gamma = [-3 \pm 1.3(\text{stat}) \pm 0.2(\text{sys})] \times 10^{-8}$

➡ $h_\pi^1 = (2.6 \pm 1.2) \times 10^{-7}$

and $A_p = [1.55 \pm 0.97(\text{stat}) \pm 0.24(\text{sys})] \times 10^{-8}$

➡ $h_{\rho-\omega} \equiv h_\rho^0 + 0.605h_\omega^0 - 0.605h_\rho^1 - 1.316h_\omega^1 + 0.026h_\rho^2$

$= (-1.7 \pm 6.56) \times 10^{-7}$



M.T. Gericke *et al.* (n3He Collaboration), Phys. Rev. Lett. 125, 131803 (2020).

Potential for improvement

- NPDGamma and n-^{3}He results are not limites by systematics:
  $A_\gamma = [-3 \pm 1.3(\text{stat}) \pm 0.2(\text{sys})] \times 10^{-8}$
  $A_p = [1.55 \pm 0.97(\text{stat}) \pm 0.24(\text{sys})] \times 10^{-8}$
  and systematic uncertainties can be further reduced

- NPDGamma was the more time consuming: ~4300 hours life time with average beam power about 1 MW at SNS for the LH_2 running gave a statistical error of 1.3×10^{-8}

- Other potentials sources? Need a pulsed beam to study transient effects but not necessarily a pulsed source

- VCN instead of CN? Capture cross section increases by a factor between ~4 - 90 when going from 3 meV to 0.2 meV - 0.4 µeV

Other possible experiments

- Neutron P-odd spin rotation in hydrogen, with sensitivity to the $\Delta I = 2$ NN weak amplitude

- Parity-odd gamma asymmetry in $\vec{n} + d \rightarrow t + \gamma$ (NDTGamma), where calculations in terms of two-body NN weak amplitudes are possible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