Physics of NN parity violation

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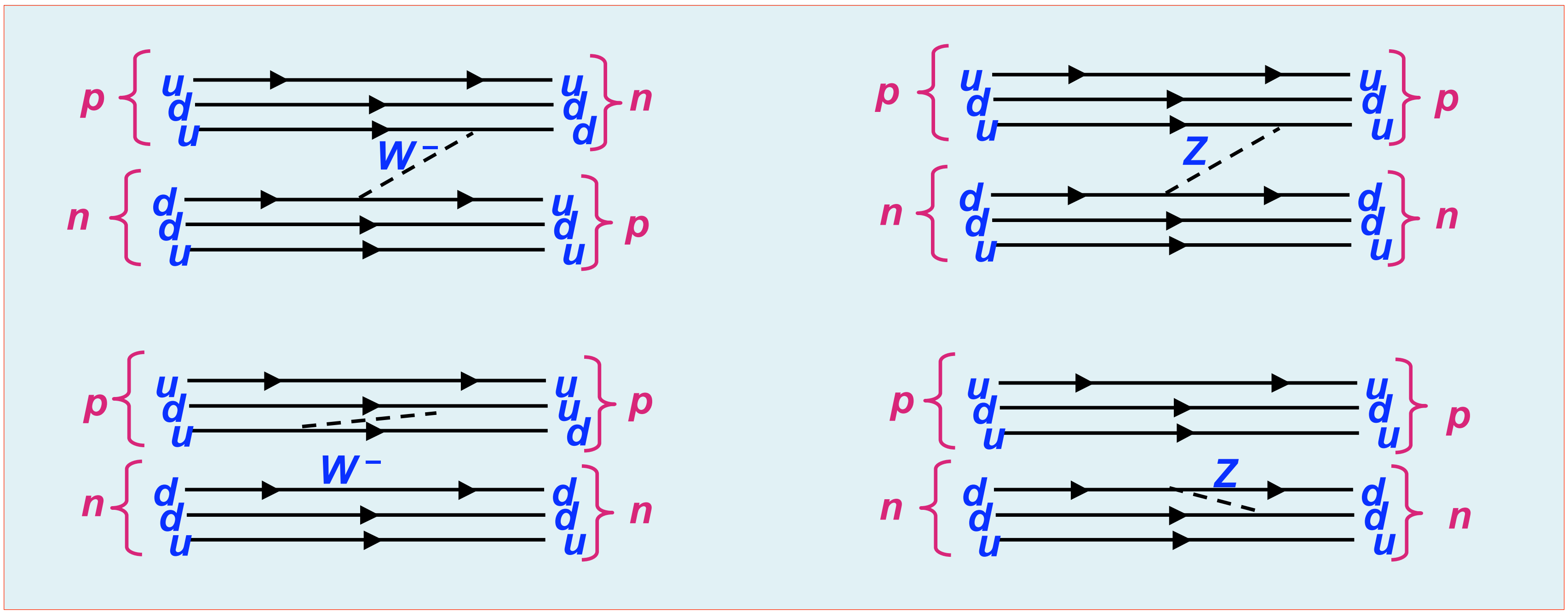
1. Theoretical background/present experimental status
2. Neutron experiment in progress: NPDGamma
3. Proposed neutron experiments:(a) n+3He, (b) n+4He
4. Experimental bounds on “long-range” neutron parity violation

NN Weak Interaction: the nucleons are the "problem"

In the Standard Model, the structure of the quark-quark weak interaction is known from the electroweak sector.

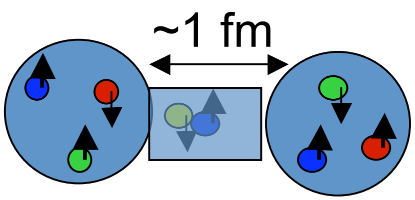
However, quarks in both the *initial* and *final* states are confined by QCD.



QCD confines/correlates the quarks, thereby making perturbative calculation of the amplitude impossible.

Furthermore, the physical picture for the interaction mechanism above is wrong

N-N Weak Interaction: Size and Mechanism

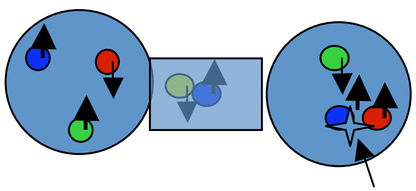


NN repulsive core → 1 fm range for NN strong force

$|N\rangle = |qqq\rangle + |qqqq\bar{q}\rangle + \cdots$ = valence + sea quarks + gluons + …

NN strong force at low energy mediated by mesons $|m\rangle = |q\bar{q}\rangle + |q\bar{q}q\bar{q}\rangle + \cdots$

QCD possesses only vector quark-gluon couplings → conserves parity



Both W and Z exchange possess much smaller range [~1/100 fm]

Relative strength of weak / strong amplitudes: $\left(\frac{e^2}{m_W{}^2}\right)\Big/\left(\frac{g^2}{m_\pi{}^2}\right) \approx 10^{-6}$

NN weak amplitudes first-order sensitive to qq correlations

Weak interaction violates parity. Use parity violation to isolate the weak contribution to the NN interaction.

Hadronic Parity Violation Theory?

There is no quantitative theory for NN parity violation.

The reason why there is no theory is because such a theory would need to understand subnucleon-range quark-quark correlation effects and their long-range manifestation in a two nucleon system. We have no such understanding at present.

From all of our previous experience with strongly interacting many-body systems, we know that it is very important to understand the ground state of the theory and build excitations upon it. In QCD the first part is equivalent to understanding the mechanism of confinement and chiral symmetry breaking.

If the (strongly interacting) ground state is not boring it is typically highly correlated. The QCD ground state is not boring.

Lattice gauge theory? There is hope…

What to do in the meantime? Classify

NN Weak Interaction: Isospin Dependence

The quark-quark weak interaction at energies below the W and Z mass can be written in a current-current form, with contributions from charged and neutral currents

$$M_{CC} = \frac{g^2}{2M_W^2} J^{\dagger}_{\mu,CC} J^{\mu}_{CC}; M_{NC} = \frac{g^2}{\cos^2\theta_W M_Z^2} J^{\dagger}_{\mu,NC} J^{\mu}_{NC}$$

$$J^{\mu}_{CC} = \bar{u}\frac{-1}{2}\gamma^{\mu}(1-\gamma^5)\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} d \\ s \end{pmatrix}; J^{\mu}_{NC} = \sum_{q=u,d} \bar{q}\frac{-1}{2}\gamma^{\mu}(c_V^q - c_A^q\gamma^5)q$$

Possible isospin changes from qq weak interactions:

Charged current: ΔI=0,2 (~ V^2_{ud}), ΔI=1 (~ V^2_{us})

Neutral current: ΔI=0,1,2.

The ΔI=1 terms comes only from the quark-quark neutral currents in the absence of strange quarks due to small size of V_{us}

These terms are about the same size, so any large differences in different isospin channels presumably would come from QCD dynamics.

Between electroweak scale and QCD scale one can perturbatively calculate RG evolution of the 4-quark operators; DONE at LO (Dai91) and for Δ I=1 at NLO (Tiburzi 2012)

Theoretical Approaches to NN Weak Interaction

- Kinematic: 5 S→P transition amplitudes in elastic NN scattering (*Danilov*)
- QCD effective field theory: χ perturbation theory, incorporates low energy symmetries of QCD (Kaplan, Savage, Wise, *Liu, Holstein, Musolf, Zhu,Phillips,Springer, Schindler,…)*
- Dynamical models: meson exchange model for NN weak interaction

(effect of qq weak interactions parametrized by ~6 couplings), QCD sum rules, Skyrme models, chiral quark models, ADS/CFT-based models (*Desplanques, Donoghue, Holstein, Meissner, Hwang, Gazit,…)*

- Standard Model; lattice gauge theory: a target for exoscale computing (*Beane & Savage, Wasem*)

Strong NN amplitudes are now well-enough known to relate parity violation measurements in few body systems to the weak NN interaction (Pieper, Wiringa, Nollett, Schiavilla, Carlson, Paris, Kievsky, Viviani…).

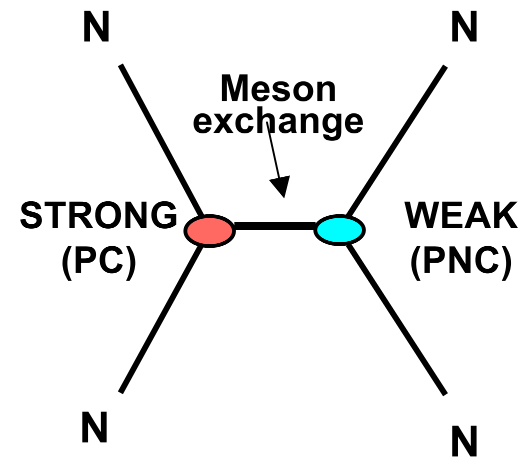
It is also known that, as expected, P-odd NNN interactions are small compared to P-odd NN interactions (Schindler)

Meson Exchange/NN Weak Effective Field Theories

Meson exchange model: exchange of light mesons (π, ρ, ω) with one strong interaction vertex and one weak interaction vertex (Desplanques, Donoghue, Holstein 1980)

Effective Field Theory approach: most general formulation for NN weak interaction consistent with QCD symmetries (Zhu et al 2005)

Pionless EFT (equivalent to 5 S-P transition amplitudes). Calculations in progress (Phillips, Schindler, Springer 2009, Springer,Schindler 2013)



Partial wave transition	I ⇔ I'	ΔI	n-n	n-p	p-p	Hybrid EFT coupling	Pionless EFT coupling	Exchanged Meson
$^3S_1 \Leftrightarrow {}^3P_1$	0 ⇔ 1	1		✓		$m\rho_t$, C^π [~ f_π]	$C(^3S_1 - {}^3P_1)$	$\pi^\pm$, ρ, ω°
$^3S_1 \Leftrightarrow {}^1P_1$	0 ⇔ 0	0		✓		$m\lambda_t$	$C(^3S_1 - {}^1P_1)$	ρ, ω°
$^1S_0 \Leftrightarrow {}^3P_0$	1 ⇔ 1	0	✓	✓	✓	$m\lambda_s^{nn}$	$C(^1S_0 - {}^3P_0, \Delta I=0)$	ρ, ω°
$^1S_0 \Leftrightarrow {}^3P_0$	1 ⇔ 1	1	✓		✓	$m\lambda_s^{np}$	$C(^1S_0 - {}^3P_0, \Delta I=1)$	ρ, ω°
$^1S_0 \Leftrightarrow {}^3P_0$	1 ⇔ 1	2	✓	✓	✓	$m\lambda_s^{pp}$	$C(^1S_0 - {}^3P_0, \Delta I=2)$	ρ

Weak NN interaction: a target for petascale computing (S. Beane)

- High-impact NP from petascale computing (in Pflop-yrs)

1. The emergence of two-body forces from QCD (LRP,ch2,p31)
   Two-body interactions: NN, YN and YY (~ 1)
2. Hadronic parity violation (LRP,ch2,p91)
   Parity-violating πN coupling constant (~ 1)
3. Deuteron axial charge (LRP,ch2,p91)
   Two-body with currents: axial charge, E&M properties *etc.* (~ 10)
4. The hadron spectrum (LRP,ch2,p30) ★
   πN phase shifts!, σ-terms, *etc.* (~ 1)

⋆ more later in this session!

Lattice Calculations of NN Weak Amplitudes from Standard Model Now Becoming Possible

NT-

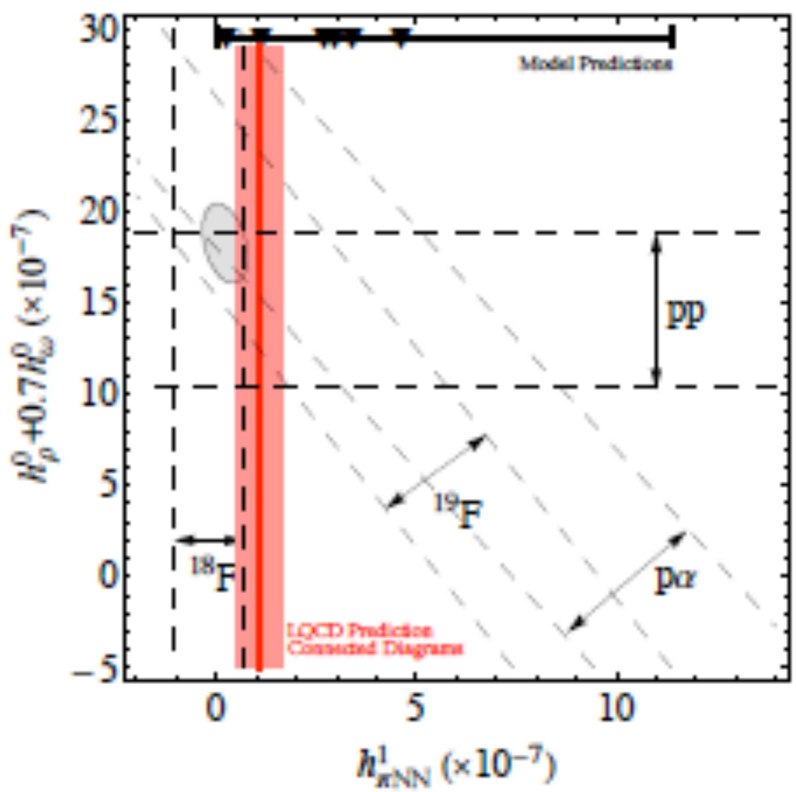
Lattice QCD Calculation of Nuclear Parity Violation

Joseph Wasem*
Lawrence Livermore National Laboratory, L-414, 7000 East Ave., Livermore, CA 94550, USA

We present the first lattice QCD calculation of the leading-order momentum-independent parity violating coupling between pions and nucleons, $h^1_{\pi NN}$. The calculation performs measurements on

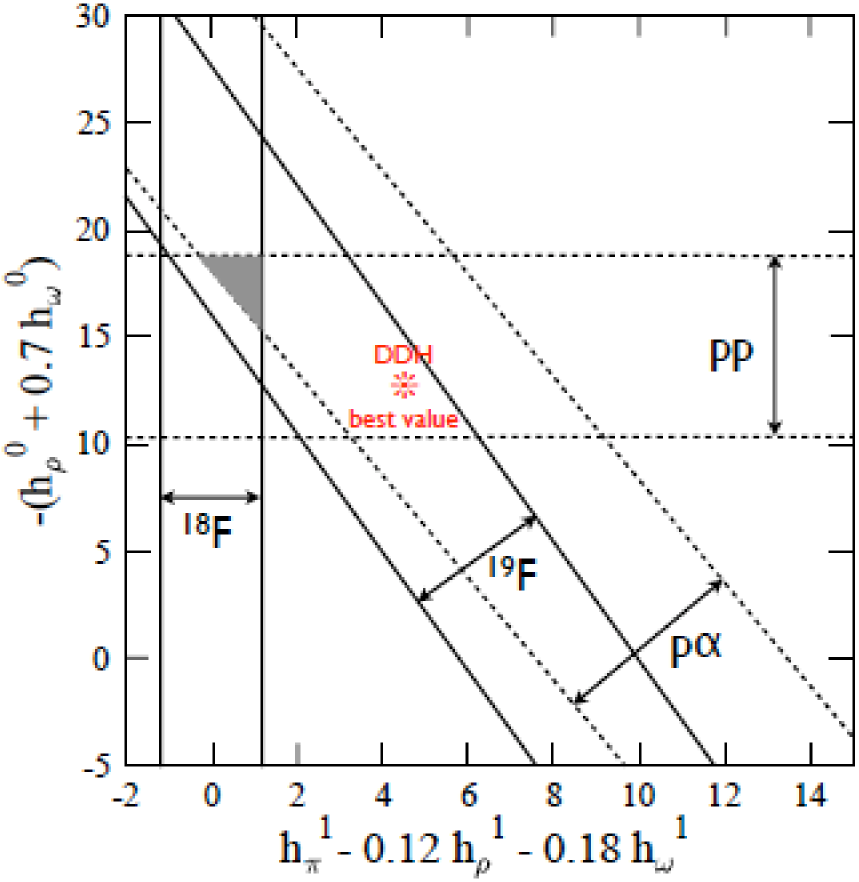
arXiv: 1108.1151 (2012)

- Calculation of NN weak amplitudes is just now becoming possible using lattice gauge theory
- Result: h_π=(1.1 +/- 0.5)x 10^{-7}
- Prospects for lattice calculation for Δ I=2 from the lattice: next talk?

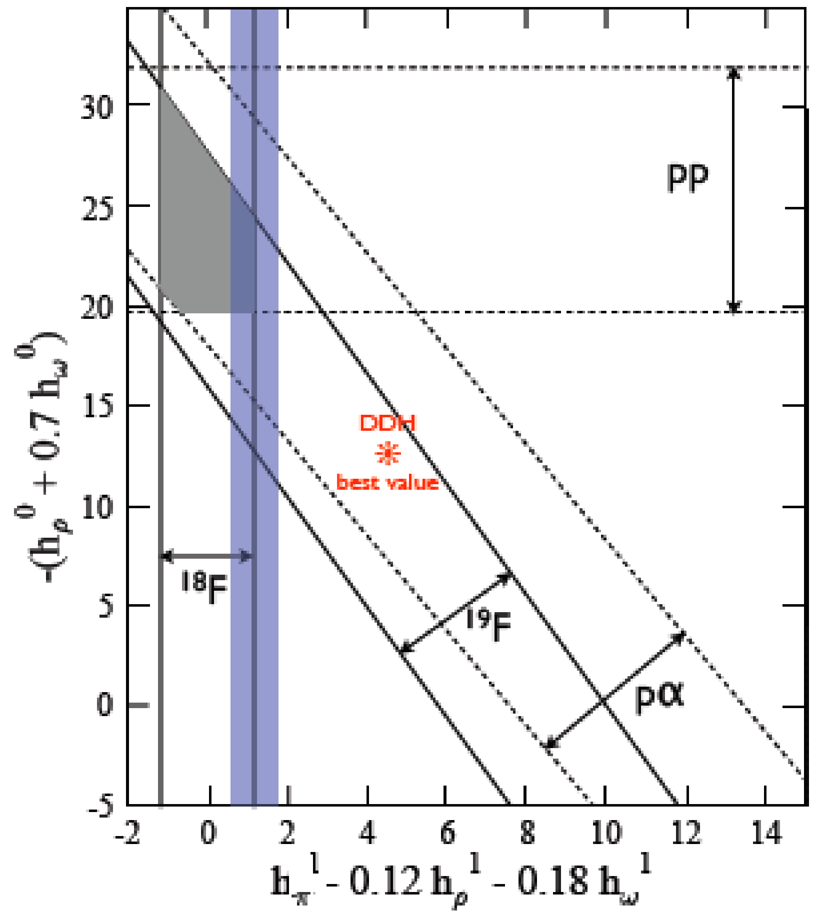


Haxton and Holstein 2013: reanalysis of pp parity violation

Corrected pp analysis for inconsistent treatment of strong NN couplings
Result: isoscalar linear combination goes up by ~50%

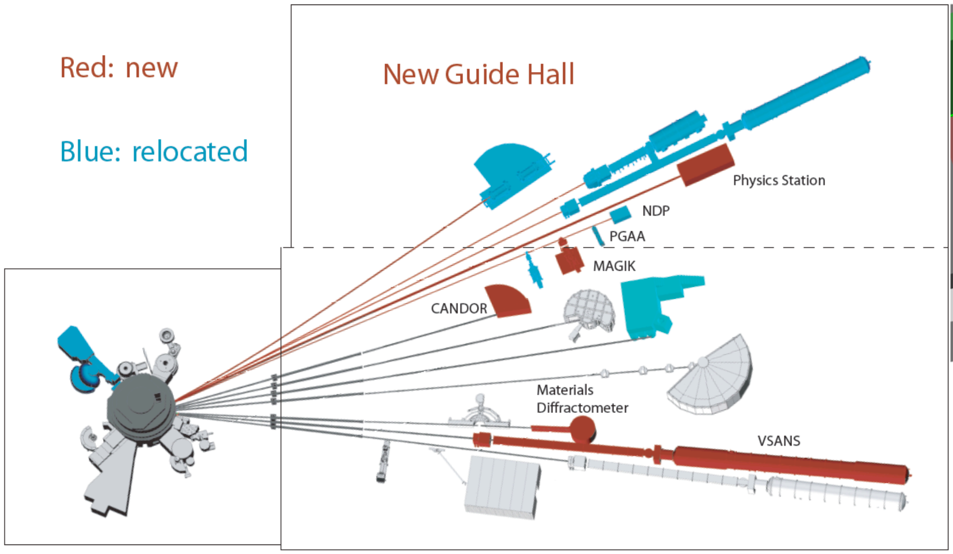


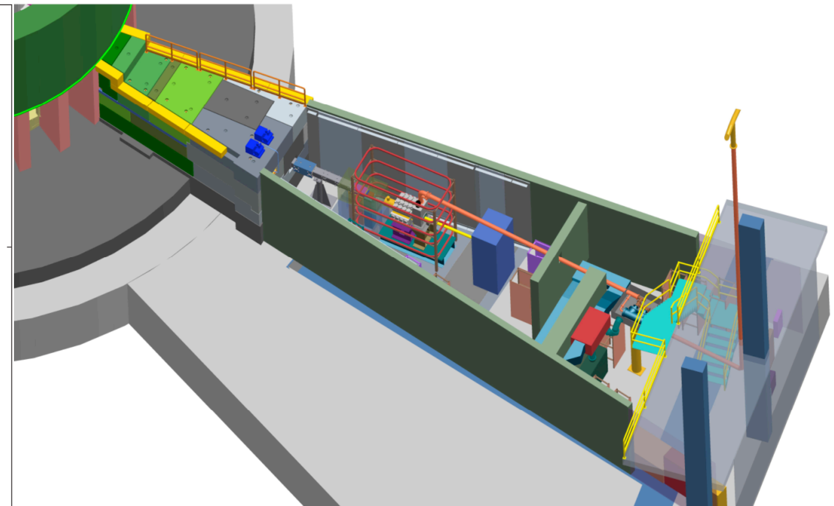
Haxton/Musolf ~2005



Haxton/Holstein 2013

Nuclear/Particle/Astrophysics with Slow Neutrons: New Beams in US





NIST Center for Neutron Research
Gaithersburg MD
Most intense reactor-based US slow neutron source, new beam #2 intensity in the world in 2014

Spallation Neutron Source
Oak Ridge National Lab (TN)
Most intense pulsed spallation neutron source in the world.
Now in operation

~X10 increase in polarized slow neutron flux relative to previous comparable beams.

The NPDGamma collaboration

P. Alonzi[3], R. Alacron[1], R. Allen[4], S. Balascuta[1], L. Barron-Palos[2], S. Baeßler[3,4], A. Barzilov[25], J.D. Bowman[4], M. Bychkov[3], J.R. Calarco[9], R.D. Carlini[5], W.C. Chen[6], T.E. Chupp[7], C. Crawford[8], M. Dabaghyan[9], N. Fomin[10], S.J. Freedman[13], E. Frlež[3], T.R. Gentile[6], M.T. Gericke[14] R.C. Gillis[11], K. Grammer[12], G.L. Greene[4,12], J. Hamblen[26], F. W. Hersman[9], T. Ino[15], G.L. Jones[16], S. Kucucker[12], B. Lauss[17], W. Lee[18], M. Leuschner[11], W. Losowski[11], E. Martin[8], R. Mahurin[14], M. McCrea[14], Y. Masuda[15], J. Mei[11], G.S. Mitchell[19], P. Mueller[4], S. Muto[15], M. Musgrave[12], H. Nann[11], I. Novikov[25], S. Page[14], D.Počanic[3], S.I. Penttila[4], D. Ramsay[14,20], A. Salas Bacci[10], S. Santra[21], P.-N. Seo[3], E. Sharapov[23], M. Sharma[7], T. Smith[24], W.M. Snow[11], Z. Tang[11], W.S. Wilburn[10] , V. Yuan[10]

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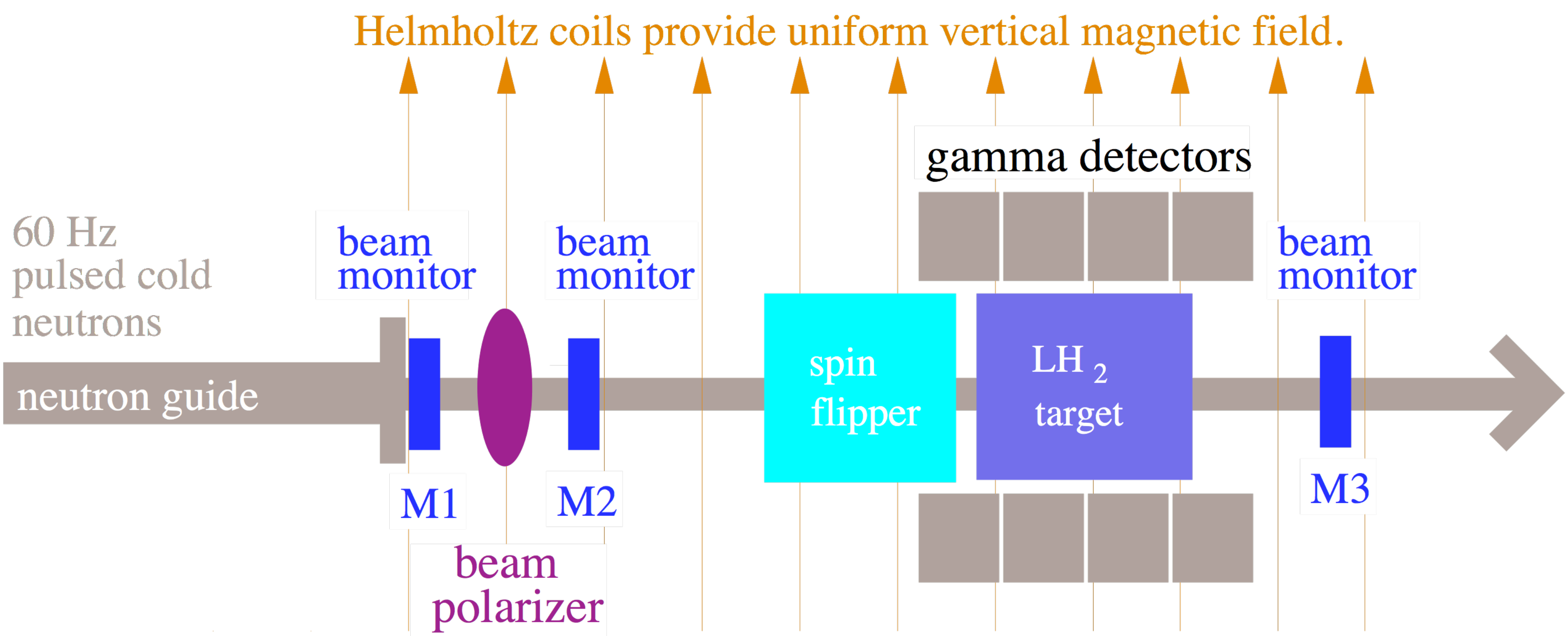
The NPDGamma experiment

$$\frac{d\sigma}{d\Omega} \propto \frac{1}{4\pi}\left(1 + A_\gamma \cos\theta\right)$$

A_γ – P-odd asymmetry in the gammas emitted from polarized slow neutron capture on protons.

GOAL: 10 ppb stat error on A_γ ,<1 ppb sys error



Hadronic Weak Interaction Models

1. **DDH model** – uses valence quarks to calculate effective PV meson-nucleon coupling directly from SM via 7 weak meson coupling constants

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

$f_\pi \sim 4.5\text{x}10^{-7}$ DDH best guess

$A_\gamma \approx -0.11 f_\pi^1$

- Observables can be written as their combinations

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

Meson exchange

2. Lattice QCD [J. Wasem, PRC (2012)]

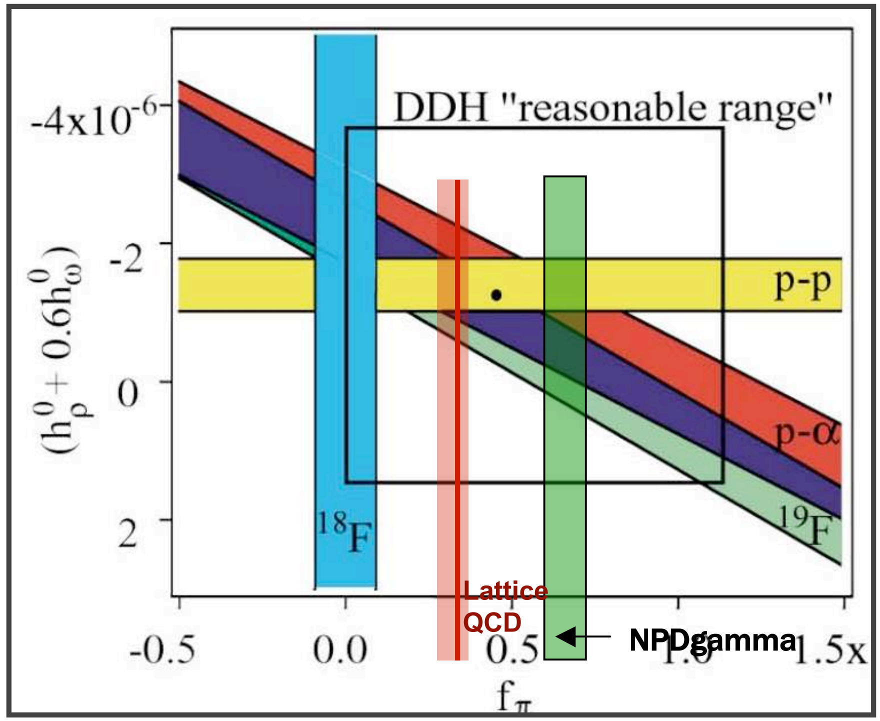
•Result: $f_\pi=(1.1 +/- 0.5)\text{x } 10^{-7}$

3. Effective Field Theory (hybrid and pure)
– model-independent

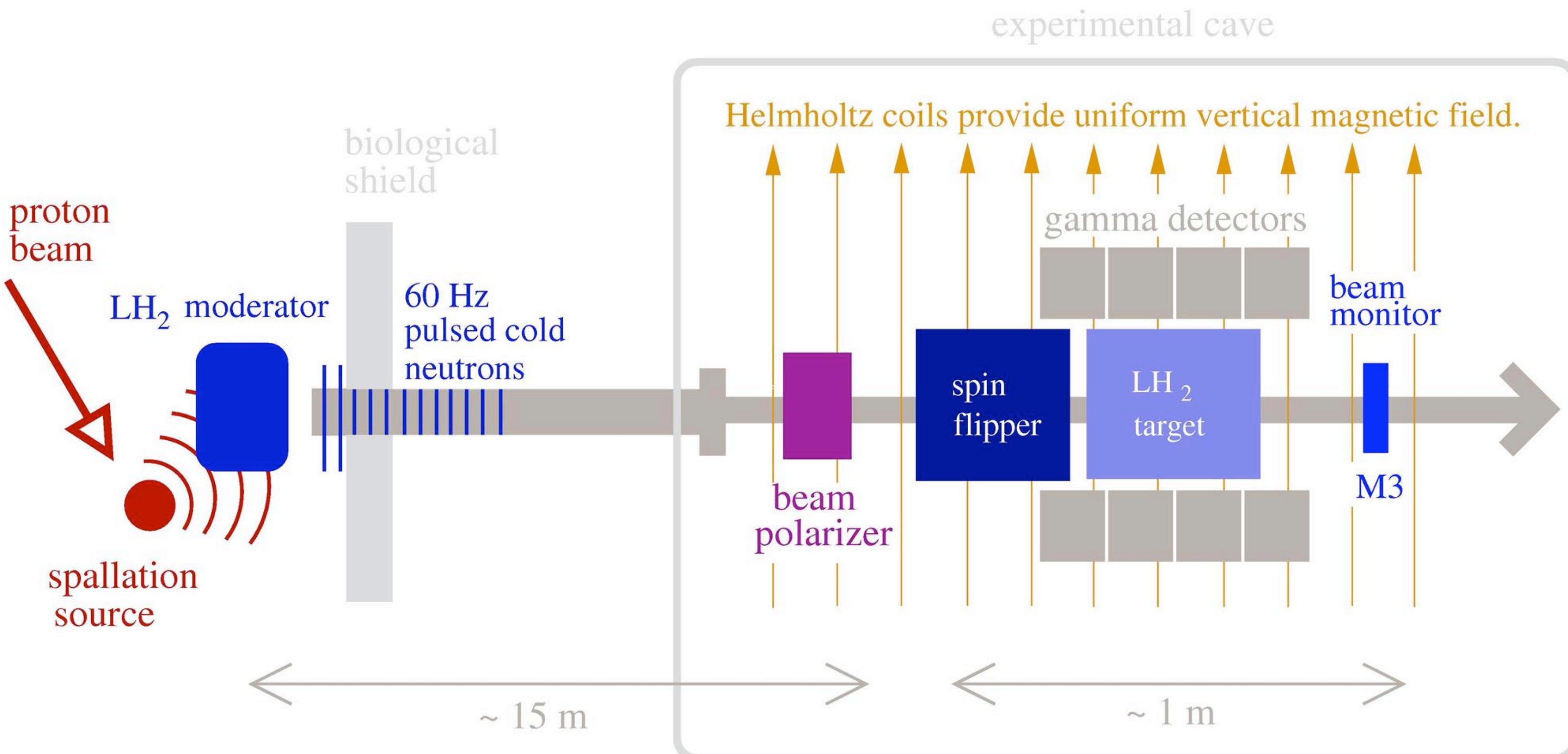
- connect to 5 parity-odd S-P NN amplitudes

$$A_\gamma^{\vec{n}p} \approx -0.27\tilde{C}_6^\pi - 0.09 m_N \rho_t$$ hybrid

$$A_\gamma^{\vec{n}p} \approx \tilde{C}^{3S1->3P1}$$ pionless

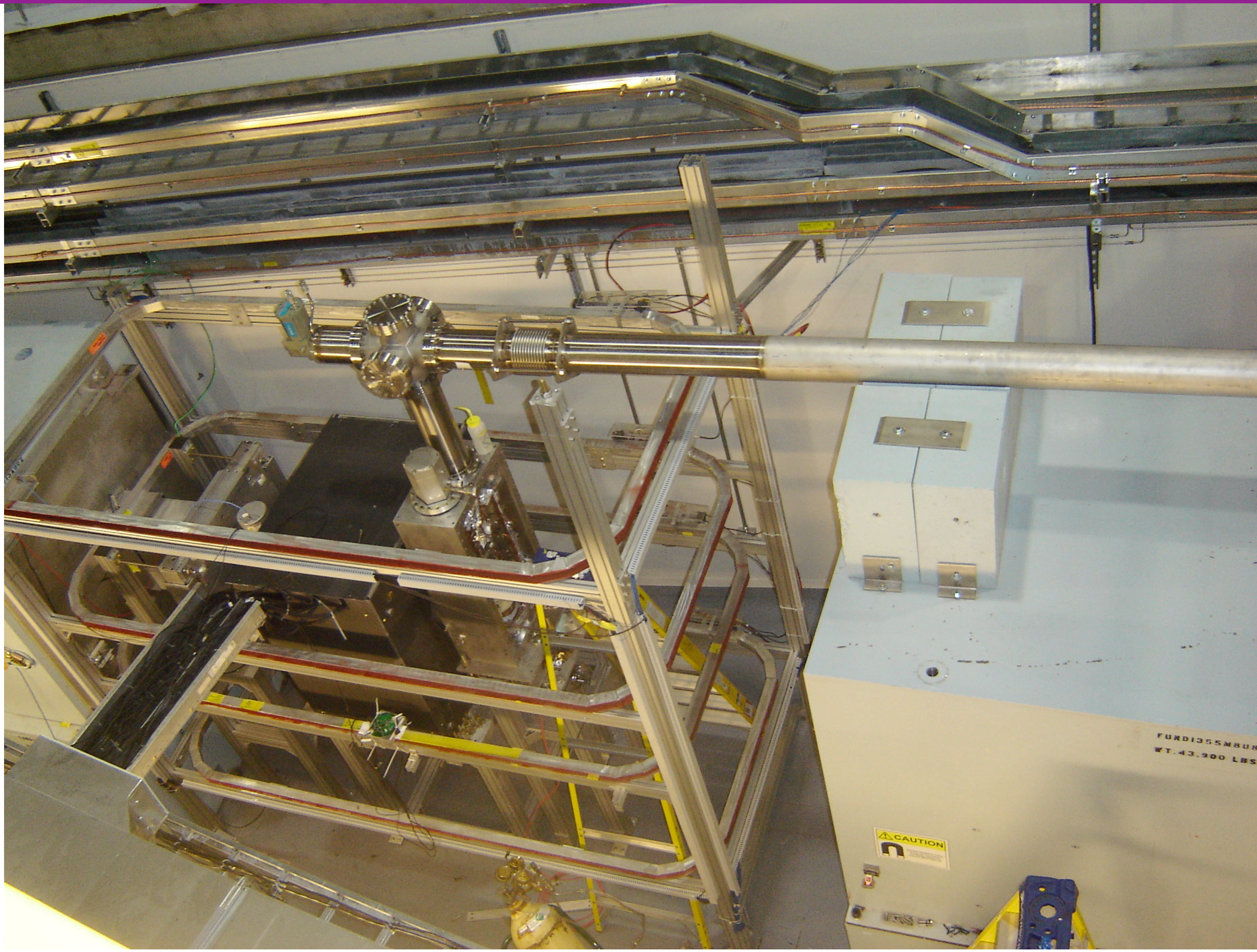


PV Gamma Asymmetry in Polarized Neutron Capture

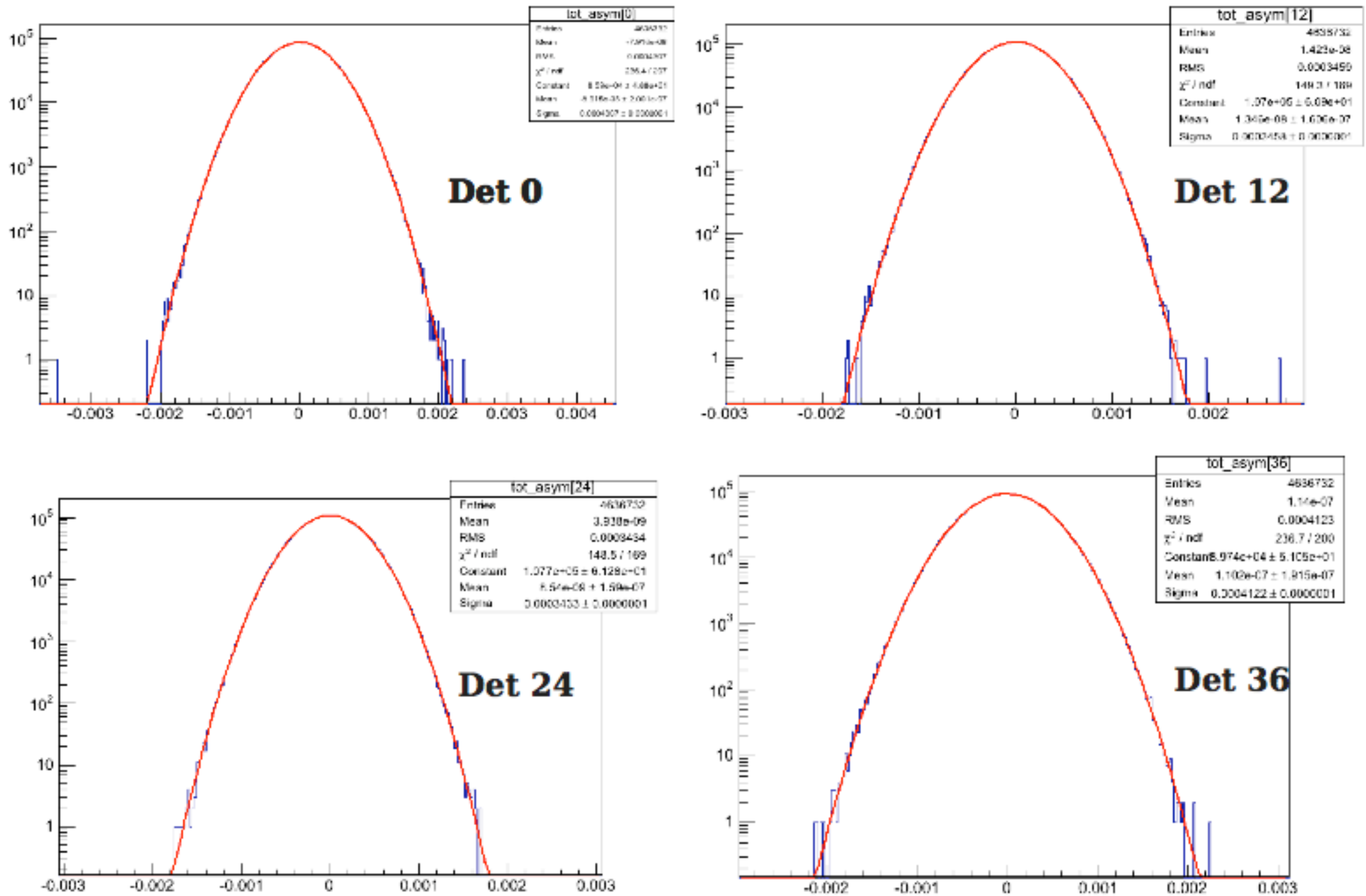


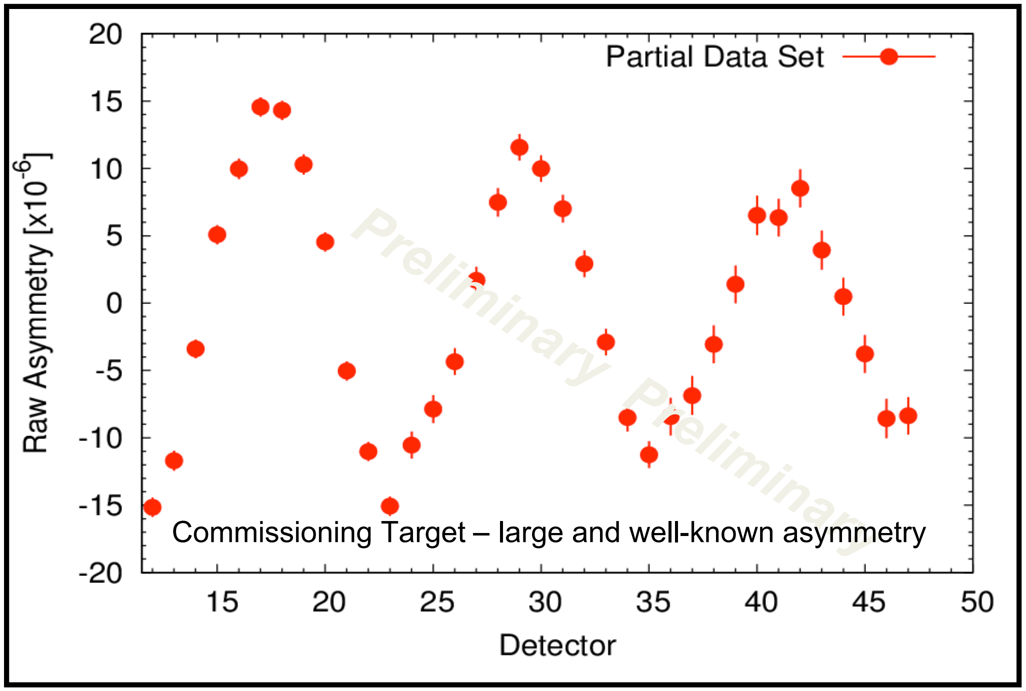
- Pulsed neutron source important for control of systematic errors
- Liquid parahydrogen target (16 liters), current mode CsI array
- Goal at SNS: 1×10^{-8} for A_γ in n+p->D+ϒ
- STATUS: now taking data at SNS: statistical error of better than 20 ppb with data in hand.
- Need to separately measure P-odd asymmetry from aluminum
- Scheduled to end in ~mid-2014

NPDGamma Apparatus at SNS



H1 Asymmetries, after cuts



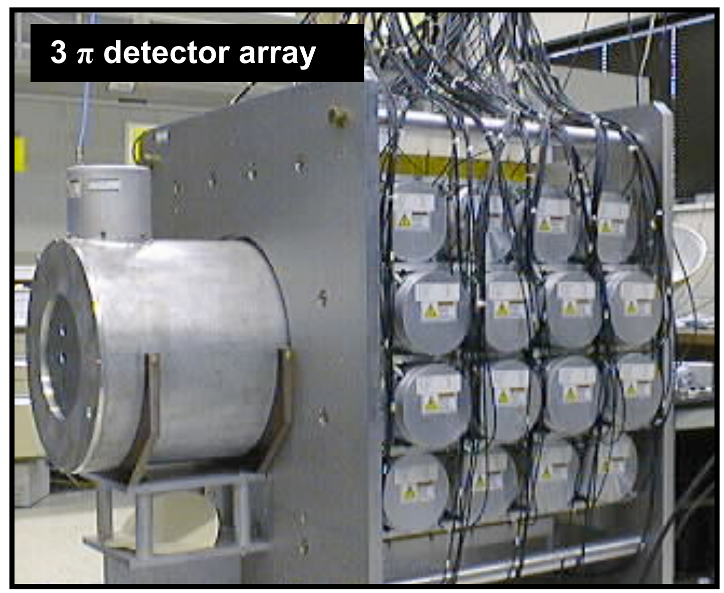


Ability of apparatus to measure parity violation confirmed using n capture on 35Cl (possesses ~20 ppm P-odd asymmetry)

CsI gamma array operated in current mode

Systematic errors bounded from several auxiliary measurements at LANSCE and SNS

Need to measure and correct for possible aluminum P-odd asymmetry



n-3He and n-4He Parity Violation: ~orthogonal to p-4He

The PV longitudinal analyzing power in p-^{4}He scattering at 40 MeV has been measured:

$$A_L(p,4He) = [-3.3 +/- 0.9] \times 10^{-7}$$

Lang et al. PRC ***34*** *1545 (1986)*

It was calculated in the DDH framework:

$$A_L\left(p,{}^4\mathrm{He}\right) = -\left(0.34 f_\pi - 0.06 h_\omega^0 - 0.06 h_\omega^1 - 0.14 h_\rho^0 - 0.05 h_\rho^1\right)$$

The calculation for the n-^{4}He spin rotation (*isospin mirror system*):

$$\phi_{PV}\left(\vec{n},{}^4\mathrm{He}\right) = -\left(0.97 f_\pi + 0.22 h_\omega^0 - 0.22 h_\omega^1 + 0.32 h_\rho^0 - 0.11 h_\rho^1\right)\mathrm{rad/m}$$

Dmitriev et al. Phys Lett ***125*** *1 (1983)*

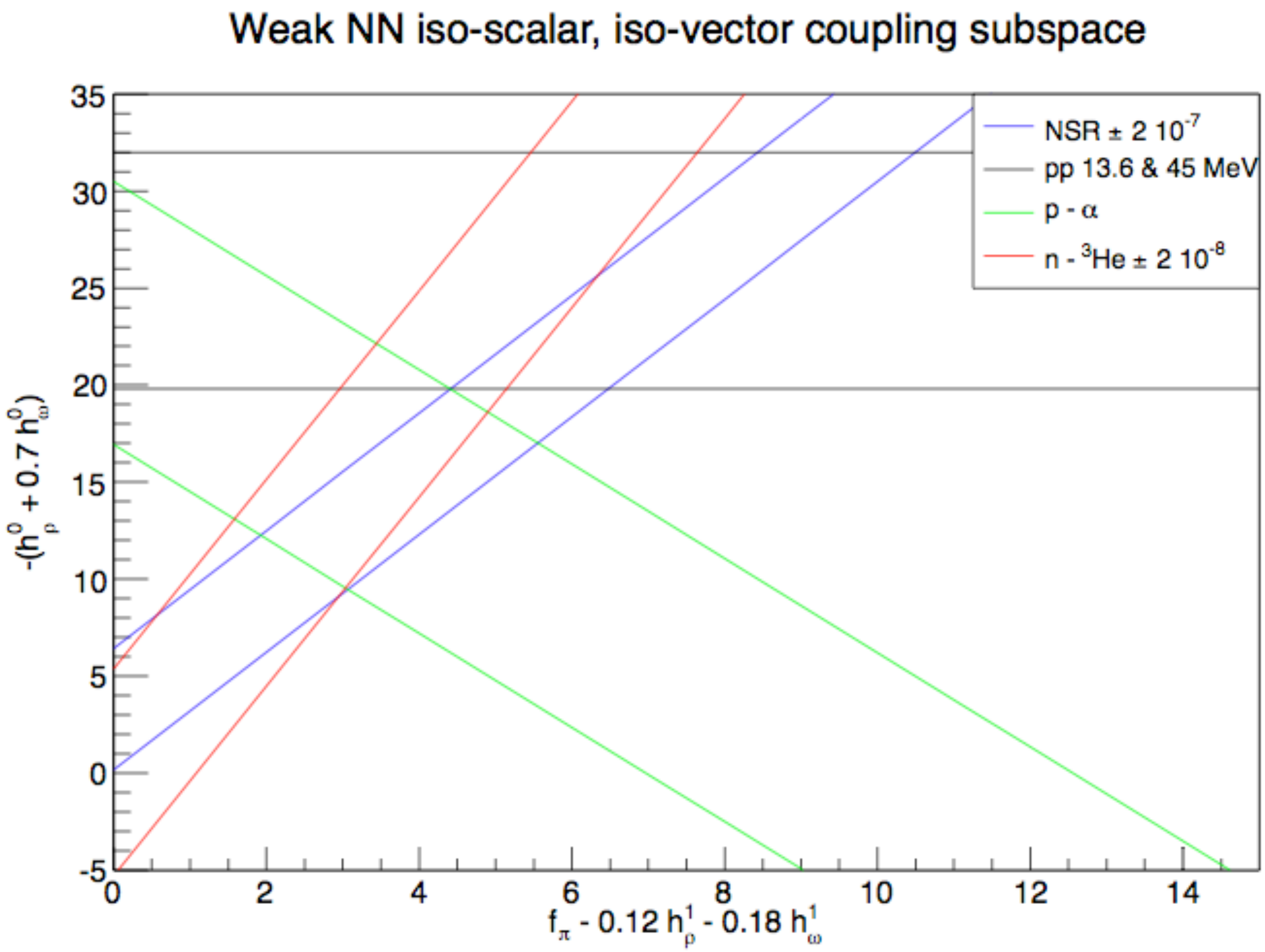
The calculation for the n-^{3}He correlation:

$$A_{PV}\left(\vec{n},{}^3\mathrm{He}\right) = \left(-.19 f_\pi - .023 h_\omega^0 - .038 h_\rho^0 + .023 h_\rho^1 + .05 h_\omega^1\right)$$

Vivani et al. PRC ***82*** *044001 (2010)*

These expressions are proportional (up to signs of coefficients) from isospin. Also n-3He and n-4He observables constrain a similar linear combination of amplitudes. This makes n-3He/n-^{4}He and p-^{4}He combination more powerful in constraining weak NN

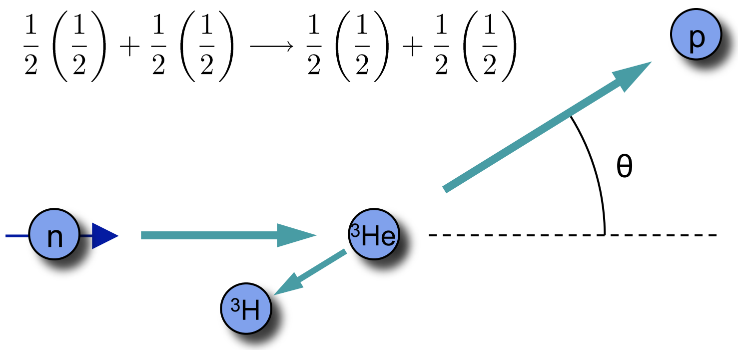
Constraints from n-3He and n-4He experiments



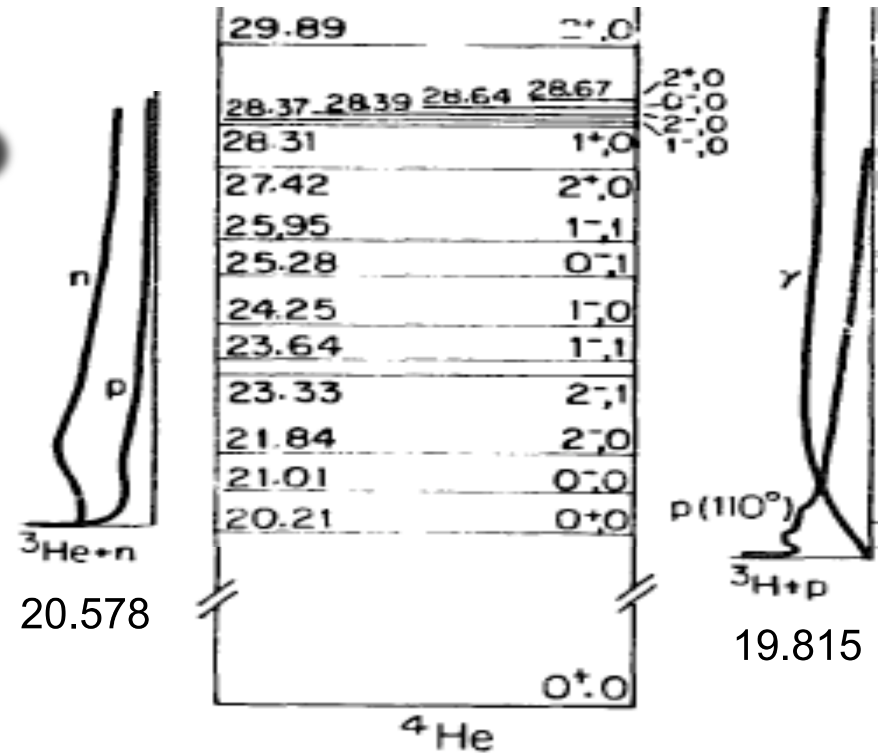
n-^{3}He PV Asymmetry

$$\vec{\mathrm{n}} + {}^3\mathrm{He} \rightarrow \mathrm{p} + \mathrm{t} + 764\ \mathrm{keV}$$

$$\mathrm{S(I)}:\ \tfrac{1}{2}\left(\tfrac{1}{2}\right) + \tfrac{1}{2}\left(\tfrac{1}{2}\right) \rightarrow \tfrac{1}{2}\left(\tfrac{1}{2}\right) + \tfrac{1}{2}\left(\tfrac{1}{2}\right)$$



Tilley, Weller, Hale, Nucl. Phys. A541, 1 (1992)



PV observables:

$\sigma_n \cdot k_n$ ~ k_n very small for low-energy neutrons

$\sigma_n \cdot k_p$, $\sigma_n \cdot k_t$ - the same asymmetry - must discriminate between back-to-back proton-triton

$$N = N_0 \frac{d\Omega}{4\pi}\left(1 \pm P_n A_p \cos\theta\right)$$

- sensitive to I=0 and I=1 couplings
- PV A ~ 1.1 x 10^{-7} (Viviani)
- PC A ~ 1.7 x 10^{-6} (Hale)

GOAL: $\delta A = 1.3 \times 10^{-8}$

UK UNIVERSITY OF KENTUCKY

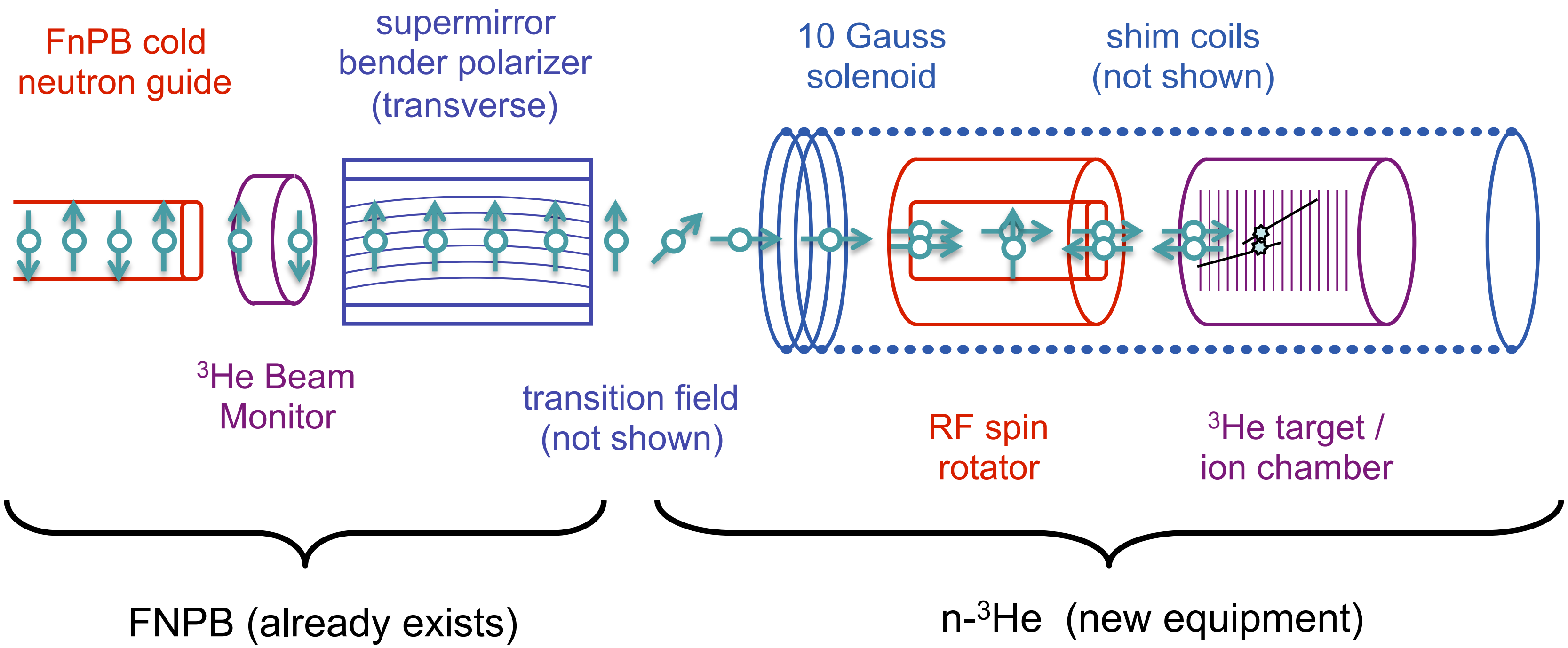
Theoretical calculations

- Gerry Hale (LANL) PC $A_y(90) = -1.7 \pm 0.3 \times 10^{-6}$
  - R matrix calculation of PC asymmetry, nuclear structure, and resonance properties
- Vladimir Gudkov (USC) PV $A = -(1 - 4) \times 10^{-7}$
  - PV reaction theory
  - Gudkov, PRC 82, 065502 (2010)
- Michele Viviani *et al.* (INFN Pisa) PV $A = -1.14 \times 10^{-7}$
  - Full 4-body calc. of strong scattering wave functions $J^\pi = 0^+, 0^-, 1^+, 1^-$
  - Eval. of weak $\langle J^- | V_{PV} | J^+ \rangle$ matrix elements in terms of DDH potential
  - Work in progress on calculation of EFT low energy coefficients
  - Viviani, Schiavilla, Girlanda, Kievsky, Marcucci, PRC 82, 044001 (2010)

	C_π^1	C_ρ^0	C_ρ^1	C_ρ^2	C_ω^0	C_ω^1
AV18	−0.1892(86)	−0.0364(40)	+0.0193(9)	−0.0006(1)	−0.0334(29)	+0.0413(10)
AV18/UIX	−0.1853(150)	−0.0380(70)	+0.0230(18)	−0.0011(1)	−0.0231(56)	+0.0500(20)

$$a_z = h_\pi^1\, C_\pi^1 + h_\rho^0\, C_\rho^0 + h_\rho^1\, C_\rho^1 + h_\rho^2\, C_\rho^2 + h_\omega^0\, C_\omega^0 + h_\omega^1\, C_\omega^1$$

Experimental setup



- longitudinal holding field – suppressed PC asymmetry
- RF spin flipper – negligible spin-dependent neutron velocity
- ^{3}He ion chamber – both target and detector
- record ionization signal in each wire; spin asymmetry -> A_p

n-^{4}He Spin Rotation Collaboration

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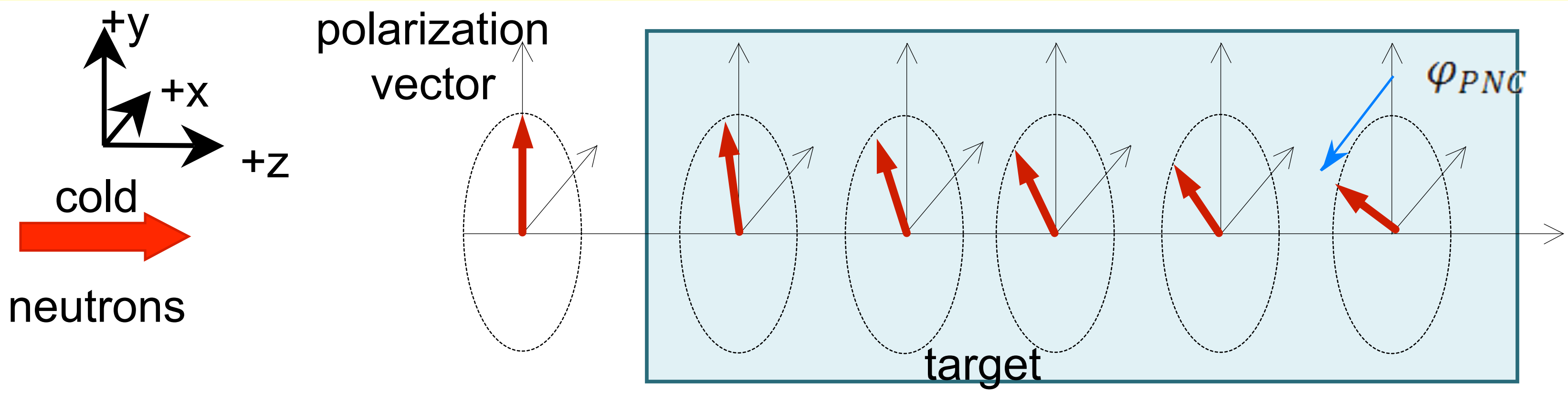
Gettysburg College [2]
The George Washington University [3]
University of Washington [4]
North Carolina State University / TUNL [5]
North Carolina Central University [6]
National Institute of Standards and Technology (NIST) [7]
Joint Institute for Nuclear Research, Dubna, Russia [8]
Al-Farabi Khazakh National University [9]

NSF PHY-0457219, NSF PHY-0758018
DOE

A Parity-Violating Observable: Neutron Spin Rotation



$$f(0) = f_{PC} + f_{PNC}(\vec{\sigma} \cdot \vec{k})$$

neutron index of refraction in target dependent on incident neutron helicity

transversely-polarized neutrons corkscrew due to the NN weak interaction

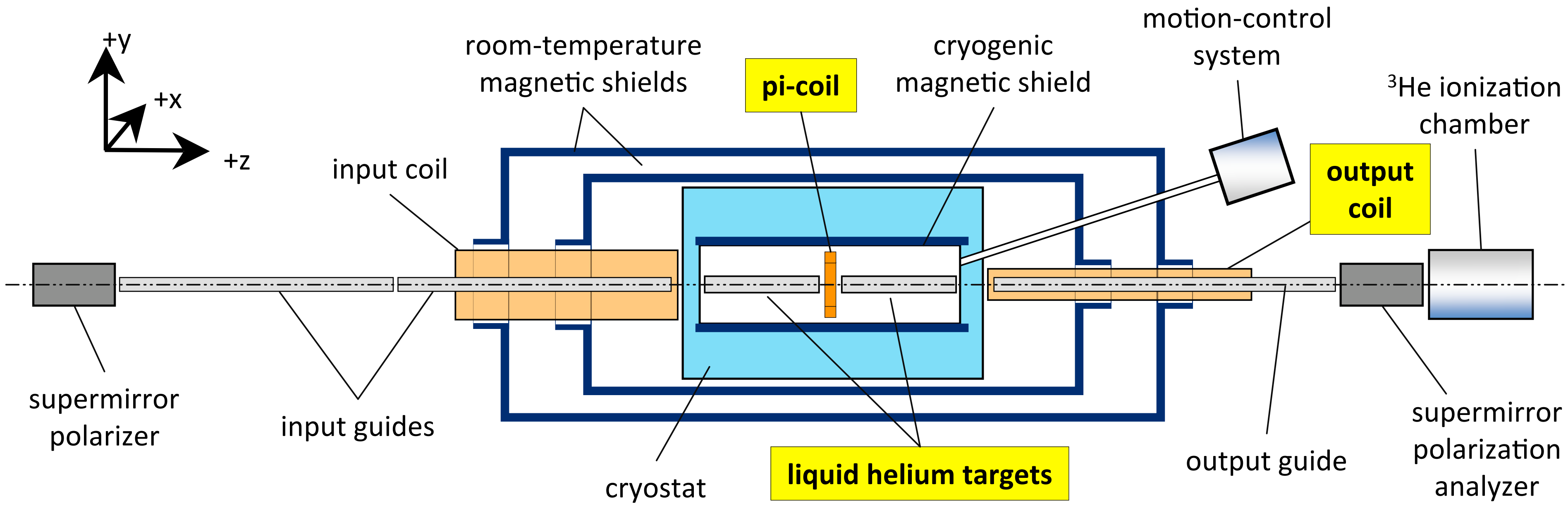
$$|+y\rangle = \frac{1}{\sqrt{2}}(|+z\rangle + |-z\rangle) \Rightarrow \frac{1}{\sqrt{2}}\left(e^{-i(\phi_{PC}+\phi_{PNC})}|+z\rangle + e^{-i(\phi_{PC}-\phi_{PNC})}|-z\rangle\right)$$

PNC spin rotation angle is independent of incident neutron energy

$$\varphi_{PNC} = \phi_+ - \phi_- = 2\phi_{PNC} = 4\pi l \rho f_{PNC}$$

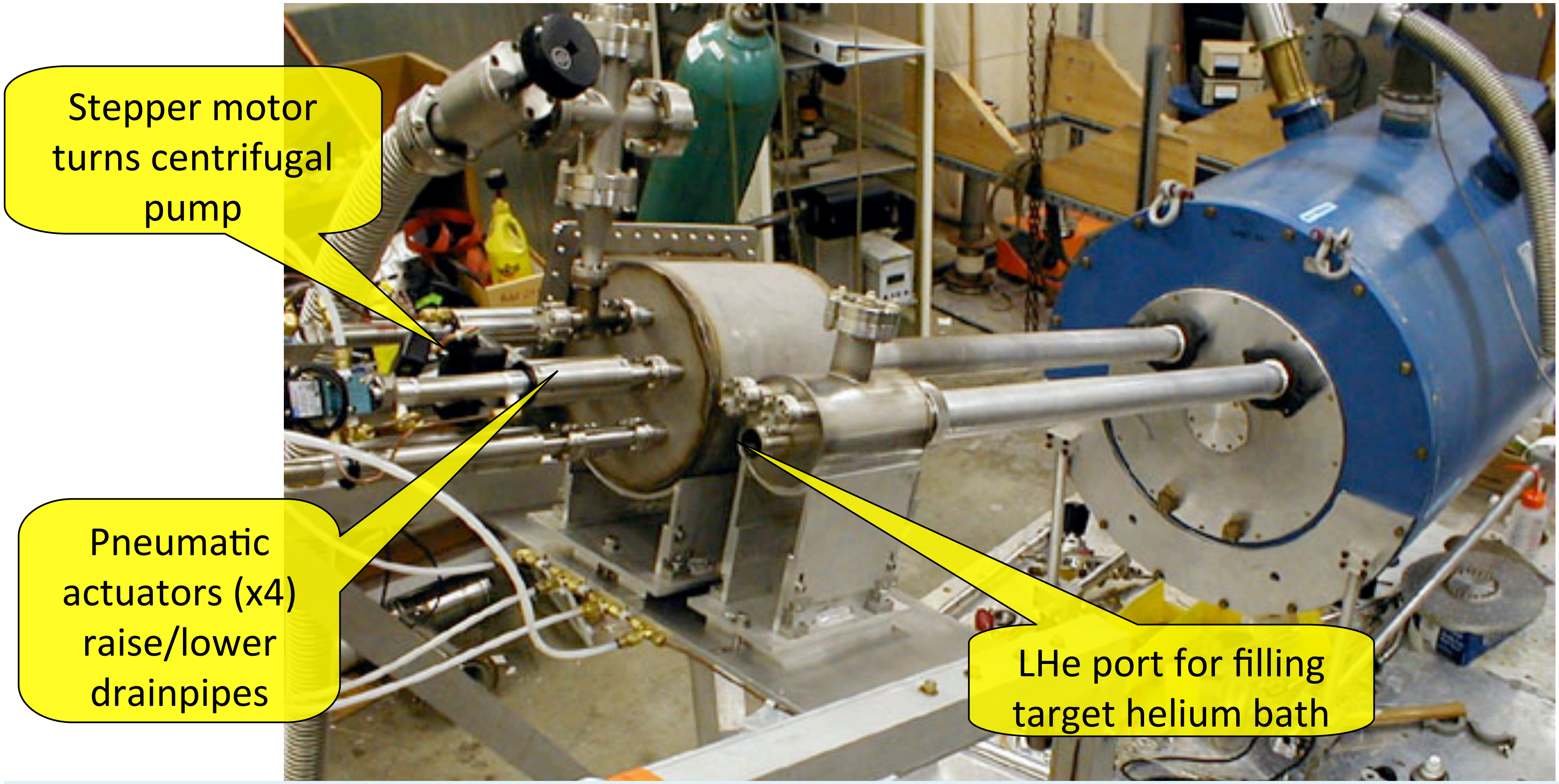
Parity Violation in Neutron Spin Rotation

Apparatus measures the horizontal component of neutron spin generated in the liquid target starting from a vertically-polarized beam



$$|\uparrow> = \frac{1}{\sqrt{2}}(|+> + |->) \rightarrow \frac{1}{\sqrt{2}}(e^{i\phi_+}|+> + e^{i\phi_-}|->)$$

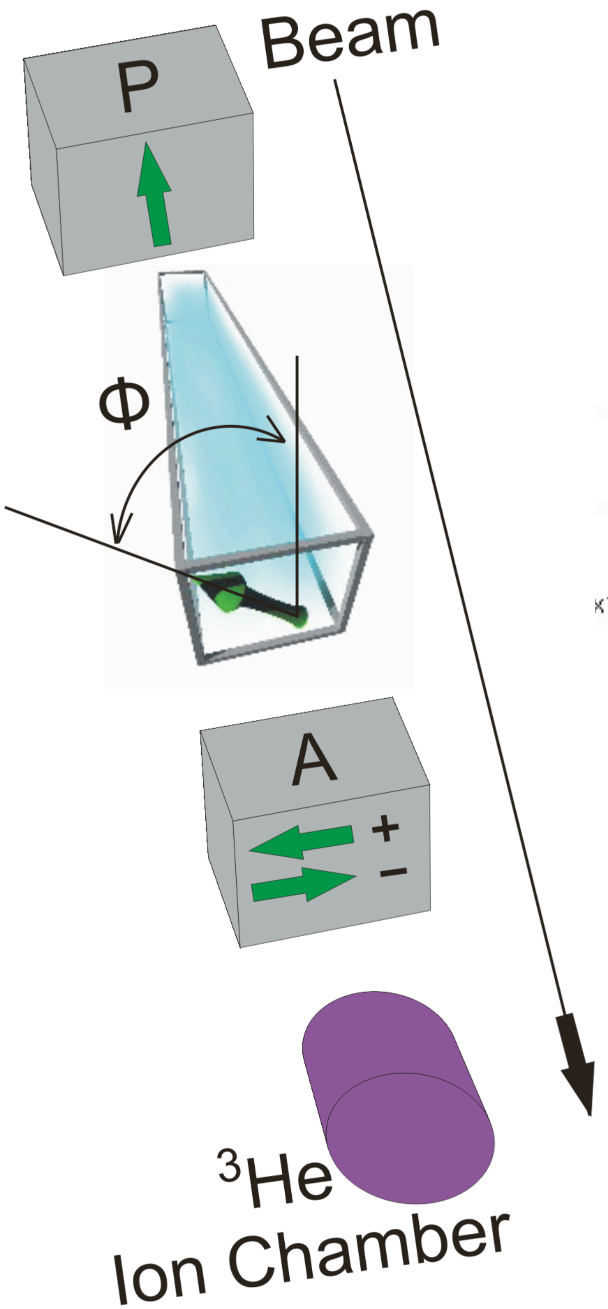
Liquid Helium Cryostat and Motion Control

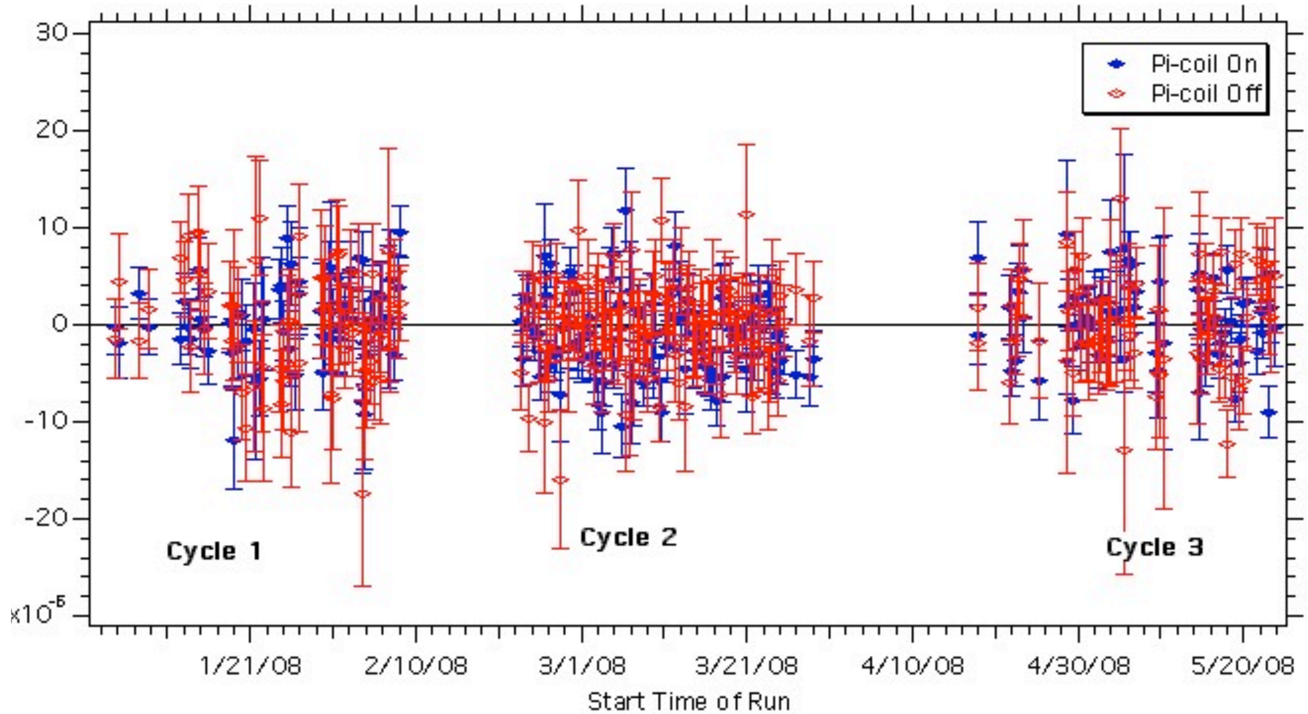


- Nonmagnetic movement of liquid helium.
- Cryogenic target of 4K helium, volume~10 liters

C. D. Bass et al, Nucl. Inst. Meth. A612, 69-82 (2009).

Neutron Spin Rotation in n+4He





Transversely polarized neutrons corkscrew due to weak interaction

ϕ_{PNC}= [+1.7 ± 9.1 (stat) ±1.4 (sys)] x 10^{-7} rad/m

W. M. Snow et al., Phys. Rev. C83, 022501(R) (2011).

PLAN: experiment to be repeated at NIST, ~1 x 10^{-7} rad/m goal

New interactions with ranges from millimeters to microns… "Who ordered that?"

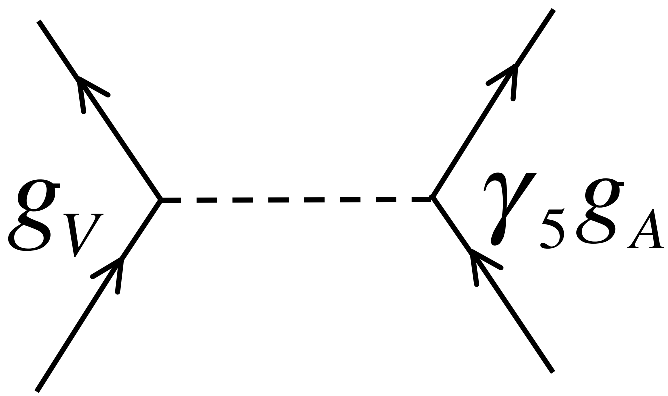
1. Weakly-coupled, long-range interactions are a generic consequence of spontaneously broken continuous symmetries (Goldstone theorem)
2. Specific theoretical ideas (axions, extra dimensions for gravity) imply new interactions at ~mm-μm scales
3. Dimensional analysis: dark energy->100 microns

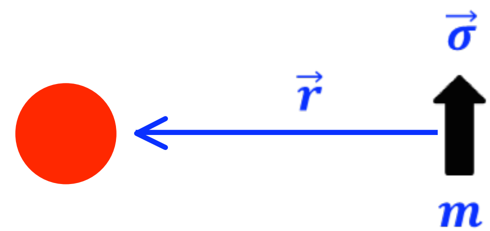
Not so many precision experiments have been conducted to search for new interactions over "mesoscopic" ranges, esp. spin-dependent ones

Comptes Rendus Physique 12, 755-778 (2011)
J. Jaeckel and A. Ringwald, Ann. Rev. Nucl. Part. Sci. **60, 405 (2010).**

Example of a nonstandard P-odd interaction from spin 1 boson exchange:

[Dobrescu/Mocioiu 06, general construction of interaction between nonrelativistic fermions]

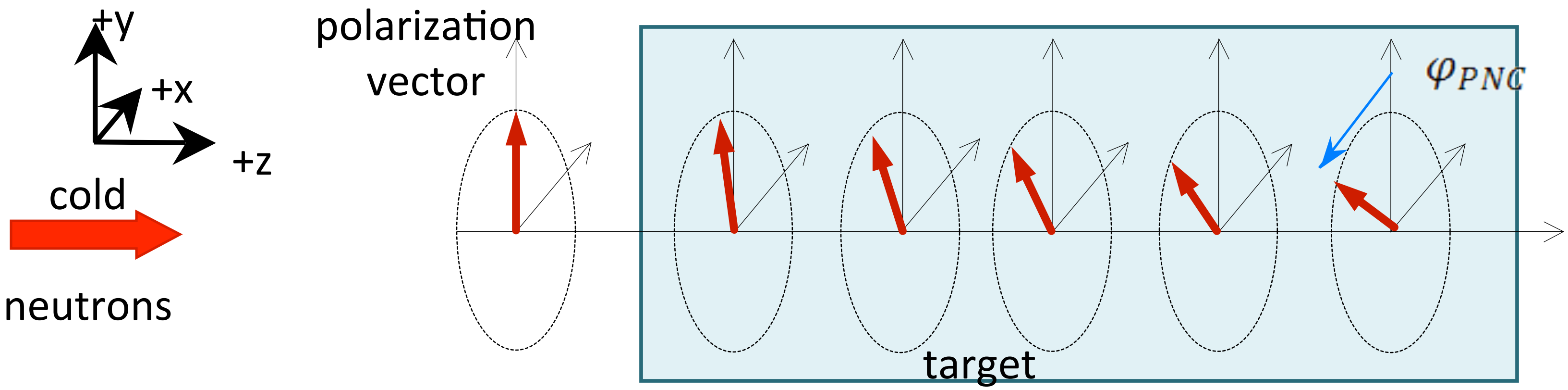




$$V(\vec{\sigma},\vec{r},\vec{v}) = \frac{\hbar}{8\pi mc^2} g_A g_V \vec{\sigma} \bullet \vec{v} \frac{1}{r} e^{-\frac{r}{\lambda}}$$

- Induces an interaction between polarized and unpolarized matter
- Violates P symmetry
- Not very well constrained over "mesoscopic" ranges(millimeters to microns)
- Best investigated using a beam of polarized particles

Neutron Spin Rotation: A Parity-Odd Observable in Neutron Optics



$$f(0) = f_{strong} + f_{P-odd}(\vec{\sigma} \cdot \vec{p})$$

$$f_{P-odd} = g_A g_V \lambda^2$$

Forward scattering amplitude of neutron in matter sensitive to all neutron-matter interactions

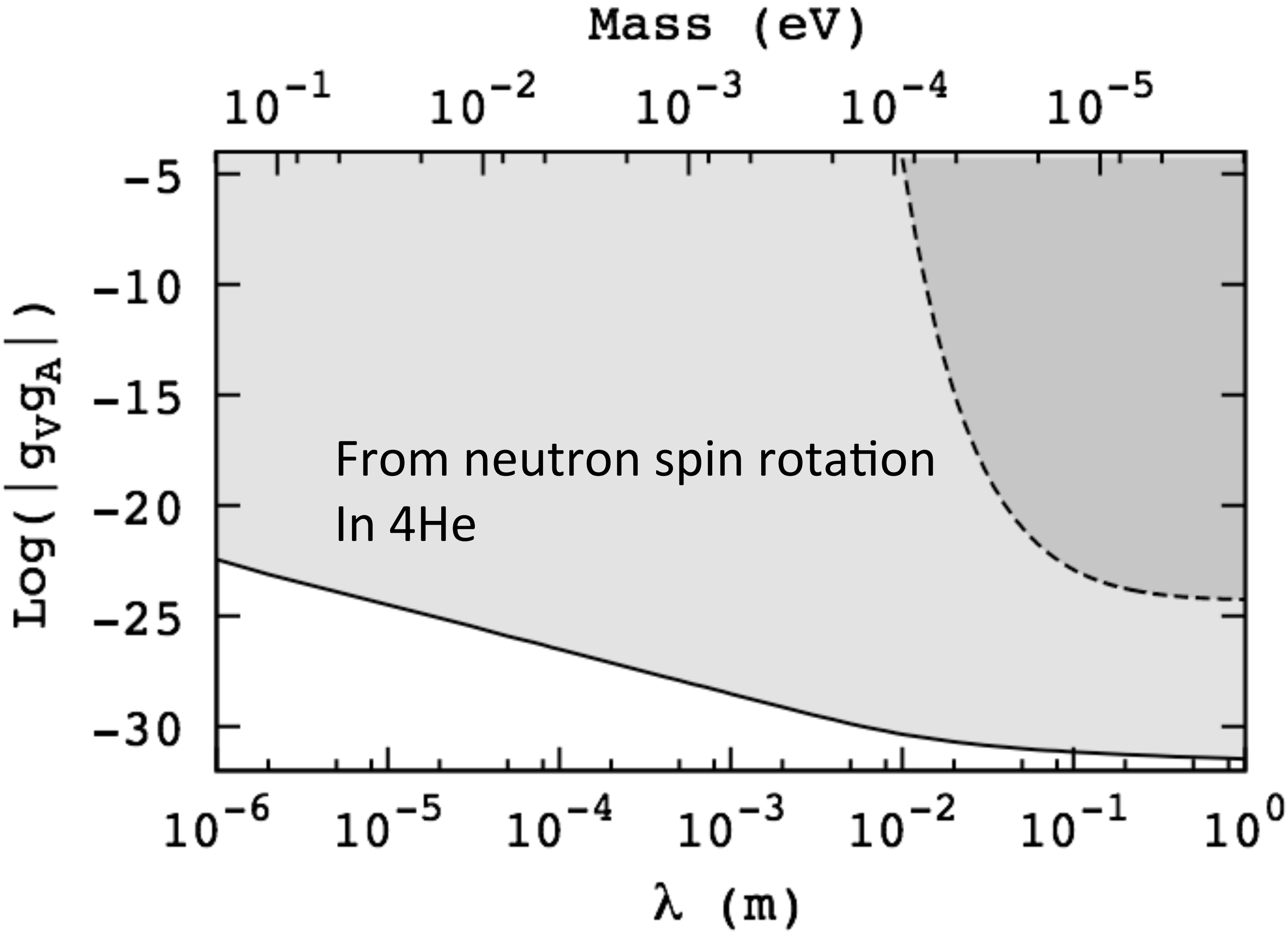
$$\phi_{\pm} = \phi_{strong} \pm \phi_{P-odd}$$

Parity violation gives helicity-dependent phase shift and therefore rotation of plane of polarization vector

$$\frac{d\phi_{P-odd}}{dL} = 4 g_A g_V \rho \lambda^2$$

An upper bound on $f_{P\text{-odd}}$ places a constraint on possible new P-odd interactions between nucleons over a broad set of distance scales

Constraints on exotic V-A interactions



H. Yan, and W. M. Snow, PRL 110, 082003 (2013).
Also: much stronger constraints now above ~1 cm from Eot_Wash+ other data [E. G. Adelberger and T. A. Wagner, PRD 88, 031101 (2013)]

NN parity violation: experiment summary

NPDGamma: on track to get ~10 ppb error on P-odd asymmetry

n-3He P-odd asymmetry and n-4He P-odd spin rotation:
~orthogonal to already-measured p-4He in isoscalar/isovector coupling space

Status:

n-3He parity violation experiment at SNS:
"readiness review" in ~Jan. 2014
n-4He parity violation experiment at NIST:
"readiness review" in ~Jan. 2014

γ-D P-odd photodisintegration: under analysis for HiGS2

Outlook for NN Weak Interaction Theory+Experiment

Only one NN weak EFT coupling is determined from existing experiments from p-p

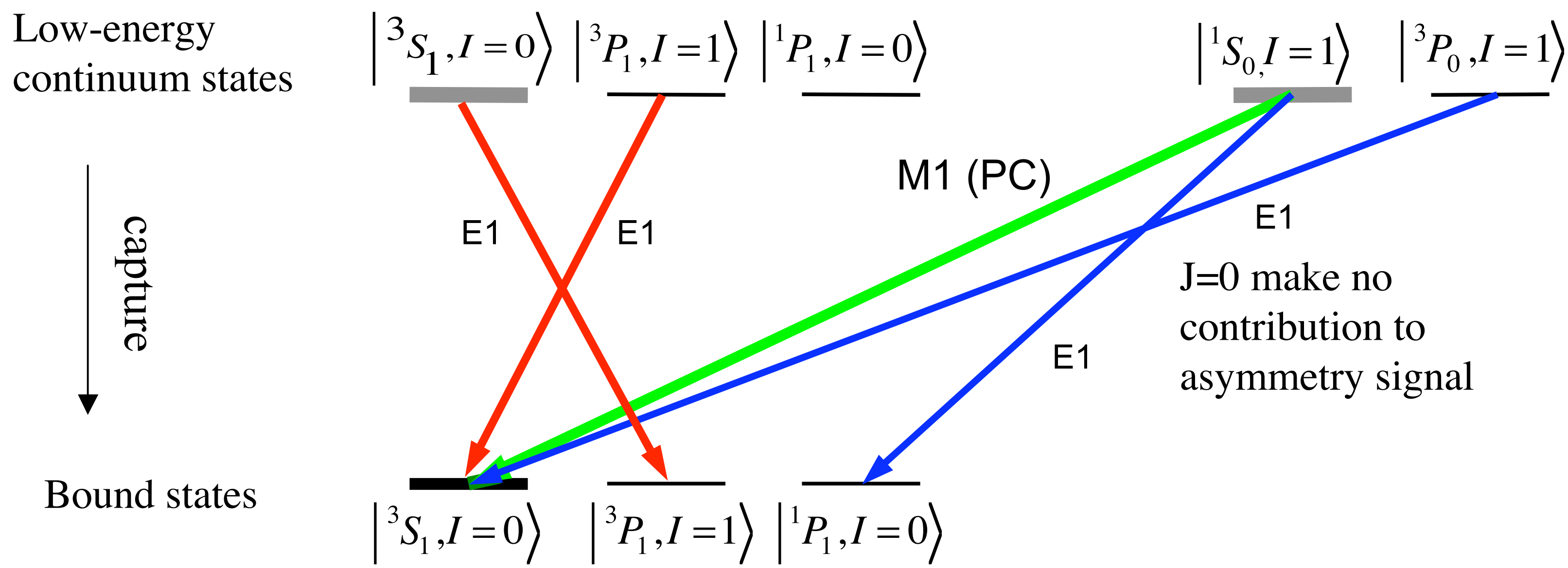
Asymmetry measurement in n+p->D+gamma will fix a second NN weak EFT coupling($^3S_1 \Leftrightarrow {}^3P_1$ $\Delta I=1$)

Asymmetry in n+p->D+gamma/weak isovector NN coupling a goal for lattice gauge theory/exoscale computing

Beams at NIST and SNS can be used to see parity violation in spin rotation experiments [~1E-7 rad/m statistical accuracy in n-^{4}He] and in inelastic asymmetries and analyzing powers [~1E-8 in n+p->D+gamma and n+3He->3H+p]

Theoretical work is needed to extend weak NN calculations to few nucleon systems (n-D, n-3He, n-^{4}He, p-^{4}He), investigate region of EFT validity, and make use of existing data in p-4He and experiments planned in n-3He and n-4He

Simple Level Diagram of *n-p* System



$\vec{n} + p \rightarrow d + \gamma$ is primarily sensitive to the $\Delta I = 1$ component of the weak interaction

- Weak interaction mixes in *P* waves to the singlet and triplet *S*-waves in initial and final states.
- Parity conserving transition is $M1$.
- Parity violation arises from mixing in *P* states and interference of the $E1$ transitions.
- A_γ is coming from ${}^3S_1$ - ${}^3P_1$ mixing and interference of $E1$-$M1$ transitions in $\Delta I = 1$ channel.

Mixing amplitudes:

$\langle {}^3S_1 | V_W | {}^3P_1 \rangle; \Delta I = 1$

$\langle {}^3S_1 | V_W | {}^1P_1 \rangle; \Delta I = 0$

$\langle {}^1S_0 | V_W | {}^3P_0 \rangle; \Delta I = 2$

NN Weak Interaction: 5 Independent Elastic Scattering Amplitudes at Low Energy

Using isospin symmetry applied to NN elastic scattering we get the usual Pauli-allowed L,S,J combinations:

I_{tot} = 1 *(isospin-S)*:

Space-S (even L) ⊗ spin-A (S_{tot} = 0) ⇒ $^1S_0$, $^1D_2$, $^1G_4$, …

or Space-A (odd L) ⊗ spin-S (S_{tot} = 1) ⇒ $^3P_{0,1,2}$, $^3F_{2,3,4}$, …

I_{tot} = 0 *(isospin-A)*:

Space-A (odd L) ⊗ spin-A (S_{tot} = 0) ⇒ $^1P_1$, $^1F_3$, …

Space-S (even L) ⊗ spin-S (S_{tot} = 1) ⇒ $^3S_1$, $^3D_{1,2,3}$, $^3G_{3,4,5}$, …

$^{(2S+1)}L_J$ notation, with L=0,1,2,3,4,… denoted as S,P,D, F,G,…

If we use energies low enough that **only *S*-waves are important for strong interaction,** parity violation is dominated by ***S- P interference***,

Then we have 5 independent NN parity-violating transition amplitudes:

$^3S_1 \Leftrightarrow {}^1P_1$($\Delta$I=0, np); $^3S_1 \Leftrightarrow {}^3P_1$($\Delta$I=1, np); $^1S_0 \Leftrightarrow {}^3P_0$($\Delta$I=0,1,2; nn,pp,np)

Spin-dependent macroscopic interactions between nonrelativistic fermions meditated by light bosons

$$\mathcal{O}_1 = 1 \ ,$$

$$\mathcal{O}_2 = \vec{\sigma} \cdot \vec{\sigma}\,' \ ,$$

$$\mathcal{O}_3 = \frac{1}{m^2} (\vec{\sigma} \cdot \vec{q})\ (\vec{\sigma}\,' \cdot \vec{q}) \ ,$$

$$\mathcal{O}_{4,5} = \frac{i}{2m^2} (\vec{\sigma} \pm \vec{\sigma}\,') \cdot \left(\vec{P} \times \vec{q}\right) \ ,$$

$$\mathcal{O}_{6,7} = \frac{i}{2m^2} \left[\left(\vec{\sigma} \cdot \vec{P}\right) (\vec{\sigma}\,' \cdot \vec{q}) \pm (\vec{\sigma} \cdot \vec{q}) \left(\vec{\sigma}\,' \cdot \vec{P}\right) \right] \ ,$$

$$\mathcal{O}_8 = \frac{1}{m^2} \left(\vec{\sigma} \cdot \vec{P}\right) \left(\vec{\sigma}\,' \cdot \vec{P}\right) \ .$$

$$\mathcal{O}_{9,10} = \frac{i}{2m} (\vec{\sigma} \pm \vec{\sigma}\,') \cdot \vec{q} \ ,$$

$$\mathcal{O}_{11} = \frac{i}{m} (\vec{\sigma} \times \vec{\sigma}\,') \cdot \vec{q} \ ,$$

$$\mathcal{O}_{12,13} = \frac{1}{2m} (\vec{\sigma} \pm \vec{\sigma}\,') \cdot \vec{P} \ ,$$

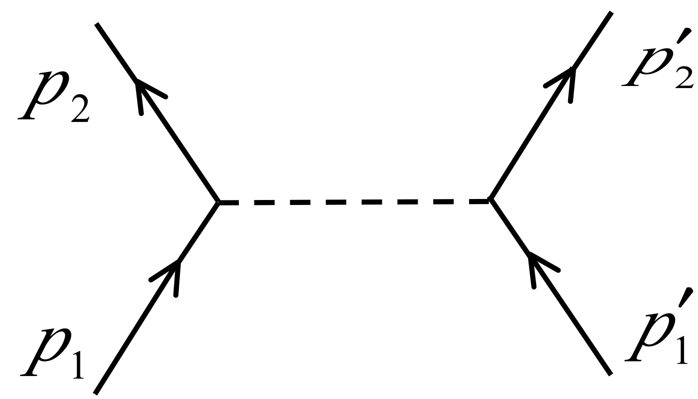
$$\mathcal{O}_{14} = \frac{1}{m} (\vec{\sigma} \times \vec{\sigma}\,') \cdot \vec{P} \ ,$$

$$\mathcal{O}_{15} = \frac{1}{2m^3} \left\{ \left[\vec{\sigma} \cdot \left(\vec{P} \times \vec{q}\right)\right] (\vec{\sigma}\,' \cdot \vec{q}) + (\vec{\sigma} \cdot \vec{q}) \left[\vec{\sigma}\,' \cdot \left(\vec{P} \times \vec{q}\right)\right] \right\}$$

$$\mathcal{O}_{16} = \frac{i}{2m^3} \left\{ \left[\vec{\sigma} \cdot \left(\vec{P} \times \vec{q}\right)\right] \left(\vec{\sigma}\,' \cdot \vec{P}\right) + \left(\vec{\sigma} \cdot \vec{P}\right) \left[\vec{\sigma}\,' \cdot \left(\vec{P} \times \vec{q}\right)\right] \right\} .$$

$$\vec{q} \equiv \vec{p}_2 - \vec{p}_1$$

$$\vec{P} \equiv \frac{1}{2} (\vec{p}_1 + \vec{p}_2) \ .$$



- 16 independent scalars can be formed: 8 P-even, 8 P-odd
- 15/16 depend on spin
- Traditional “fifth force” searches constrain O_1

B. Dobrescu and I. Mocioiu, J. High Energy Phys. 11,005 (2006)

Parity-odd Nonrelativistic Potentials between Fermions

$$\mathcal{V}_{9,10} = -\frac{1}{2m\,r^2}\,(\vec{\sigma} \pm \vec{\sigma}\,') \cdot \hat{\vec{r}} \left(1 - r\frac{d}{dr}\right) y(r) \ ,$$

$$\mathcal{V}_{11} = -\frac{1}{m\,r^2}\,(\vec{\sigma} \times \vec{\sigma}\,') \cdot \hat{\vec{r}} \left(1 - r\frac{d}{dr}\right) y(r) \ ,$$

$$\mathcal{V}_{12,13} = \frac{1}{2r}\,(\vec{\sigma} \pm \vec{\sigma}\,') \cdot \vec{v}\, y(r) \ ,$$

$$\mathcal{V}_{14} = \frac{1}{r}\,(\vec{\sigma} \times \vec{\sigma}\,') \cdot \vec{v}\, y(r) \ ,$$

$$\mathcal{V}_{15} = -\frac{3}{2m^2\,r^3}\left\{\left[\vec{\sigma} \cdot \left(\vec{v} \times \hat{\vec{r}}\right)\right]\left(\vec{\sigma}\,' \cdot \hat{\vec{r}}\right) + \left(\vec{\sigma} \cdot \hat{\vec{r}}\right)\left[\vec{\sigma}\,' \cdot \left(\vec{v} \times \hat{\vec{r}}\right)\right]\right\} \times \left(1 - r\frac{d}{dr} + \frac{1}{3}r^2\frac{d^2}{dr^2}\right) y(r) \ ,$$

$$\mathcal{V}_{16} = -\frac{1}{2m\,r^2}\left\{\left[\vec{\sigma} \cdot \left(\vec{v} \times \hat{\vec{r}}\right)\right](\vec{\sigma}\,' \cdot \vec{v}) + (\vec{\sigma} \cdot \vec{v})\left[\vec{\sigma}\,' \cdot \left(\vec{v} \times \hat{\vec{r}}\right)\right]\right\}\left(1 - r\frac{d}{dr}\right) y(r)$$

B. Dobrescu and I. Mocioiu, J. High Energy Phys. 11,005 (2006)

Comparison with (p,^{4}He) PV in EFT

In terms of pionless EFT couplings:

$$\phi_{\mathrm{PV}}(n\,^4\mathrm{He}) = (0.85\lambda_s^{nn} - 0.43\lambda_s^{np} + 0.95\lambda_t - 1.89\rho_t) = (1.7 +/- 8.3)\times 10^{-7}$$

$$A_L(p\,^4\mathrm{He}) = -0.48\lambda_s^{pp} - 0.24\lambda_s^{np} - 0.54\lambda_t - 1.07\rho_t) = -(3.3 +/- 0.9)\times 10^{-7}$$

$$A_L(pp,13MeV) = -0.48\lambda_s^{pp} = -(0.9 +/- 0.2)\times 10^{-7}$$

Eversheim et al, Phys Lett B ***256*** *11 (1991)*

$$P_\gamma(np) = 0.63\lambda_t - 0.16\lambda_s^{np} = (1.8 +/- 1.8)\times 10^{-7}$$

npDγ

The same constraint expressed in terms of the Danilov parameters :

$$1.95\lambda_t + 0.85\lambda_s^{nn} = (6.0 +/- 8.3)\times 10^{-7}$$

q-q Weak Interaction: Isospin Dependence

At energies below the $W^{\pm}$ and Z^{o} mass, the q-q weak interaction can be written in a current-current form, with contributions from charged currents and neutral currents.

$$M_{CC} = \frac{g^2}{2M_W^2} J^{\dagger}_{\mu,CC} J^{\mu}_{CC}; M_{NC} = \frac{g^2}{\cos^2\theta_W M_Z^2} J^{\dagger}_{\mu,NC} J^{\mu}_{NC}$$

$$J^{\mu}_{CC} = \bar{u}\frac{-1}{2}\gamma^{\mu}(1-\gamma^5)\begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}\begin{pmatrix} d \\ s \end{pmatrix}; J^{\mu}_{NC} = \sum_{q=u,d} \bar{q}\frac{-1}{2}\gamma^{\mu}(c_V^q - c_A^q\gamma^5)q$$

Looks like neutral currents dominate Δ I=1

Between electroweak scale and QCD scale one can perturbatively calculate RG evolution of the 4-quark operators

DONE at LO (Dai91) and for Δ I=1 at NLO (Tiburzi 2012)

possible isospin changes from q-q weak interactions	
	Δ I
charged current	0, 2 : ($\sim V^2_{ud}$) 1 : ($\sim V^2_{us}$)
neutral current	0, 1, 2

(n,^{4}He) and (p,^{4}He) PV Theory

n-^{4}He spin rotation has been calculated in DDH framework

$$\phi_{PV}\left(\vec{n},{}^4\mathrm{He}\right)=-\left(0.97 f_\pi+0.22h_\omega^0-0.22h_\omega^1+0.32h_\rho^0-0.11h_\rho^1\right)\mathrm{rad/m}$$

*Dmitriev et al. Phys Lett **125** 1 (1983)*

The PV longitudinal analyzing power in *p*-^{4}He scattering at 40 MeV (*isospin mirror system!*) has been measured:

$$A_L(p,4He)=[-3.3+/-0.9]\times 10^{-7}$$

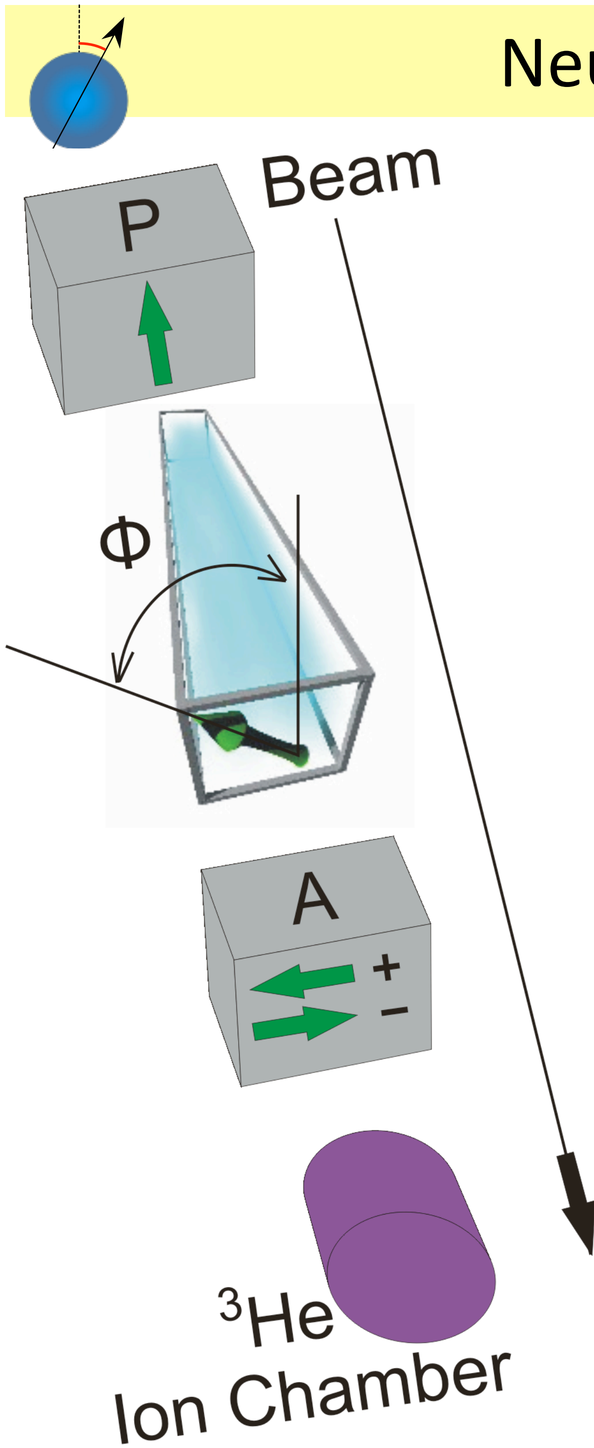
It was also calculated in the DDH framework:

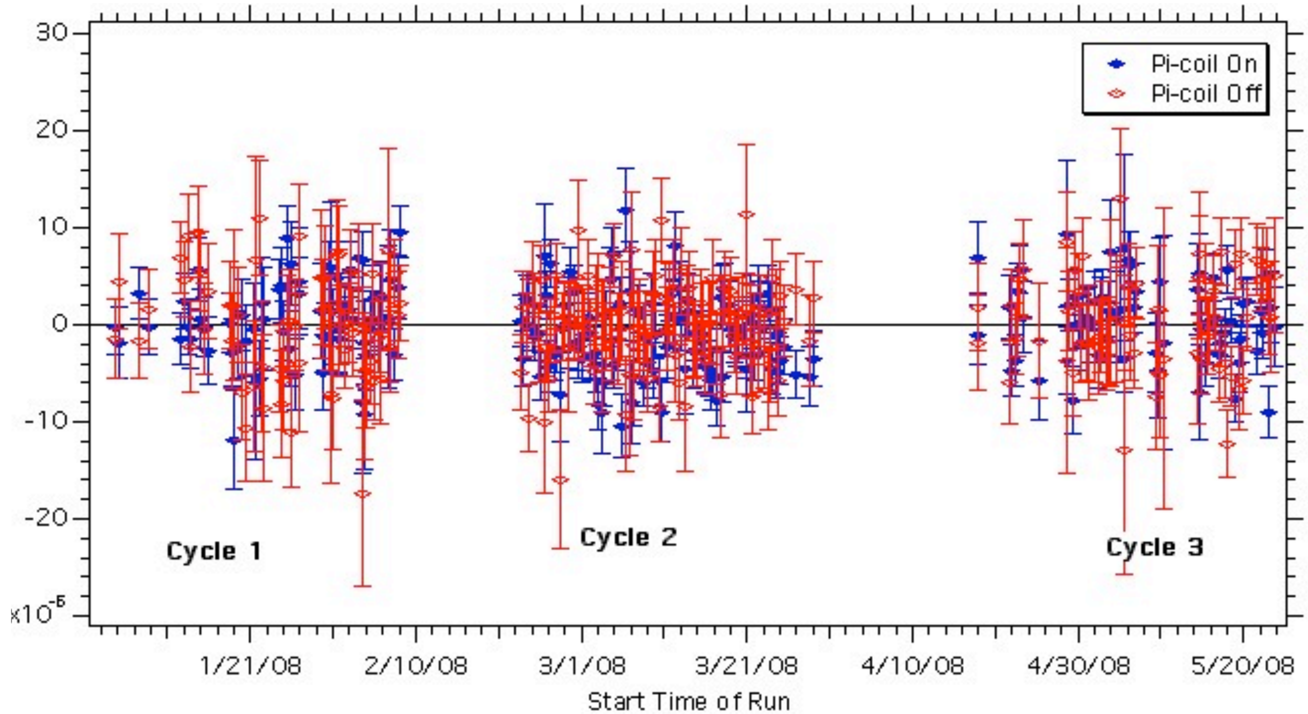
$$A_L\left(p,{}^4\mathrm{He}\right)=-\left(0.34 f_\pi-0.06h_\omega^0-0.06h_\omega^1-0.14h_\rho^0-0.05h_\rho^1\right)$$

*Lang et al. PRC **34** 1545 (1986)*

Calculations are old and in DDH framework; need GFMC methods/conversion to EFT
Can EFT treatment even be applied to *p*-^{4}He? Is 40 MeV too high?
New calculations in progress (*Carlson, Wiringa, Nollett, Schiavilla, Pieper*)

Neutron Spin Rotation in n+4He





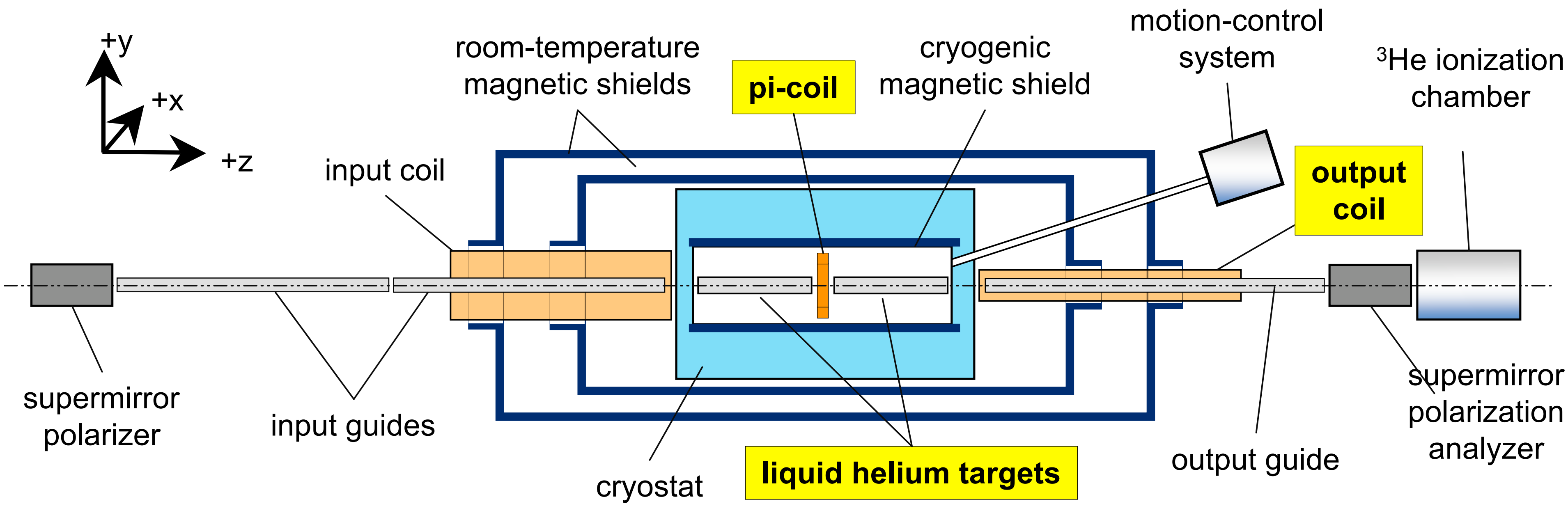
Transversely polarized neutrons corkscrew due to parity violation

ϕ_{PNC}= [+1.7 ± 9.1 (stat) ±1.4 (sys)] x 10^{-7} rad/m

W. M. Snow et al., Phys. Rev. C83, 022501(R) (2011).

Sets upper bound on any P-odd neutron coupling to protons, neutrons, electrons in 4He

Apparatus Improvements



If we stay with 5 cm x 5 cm beam, can reuse B shields, target, cryostat, ion chamber, motion control, and (maybe) coils

Pi-coil: measure/reconstruct?
Input/output guides: glass->supermirrors (IU $$$ exists)
New polarizer/analyzer (NIST?)
Target motion improved — Chris will discuss
Change location of cryo shield (IU $$$ exists)
Continuous liquid helium fill of cryostat/target (IU $$$ exists)
Better B shielding/compensation