Parity Violation in Deuteron Photodisintegration

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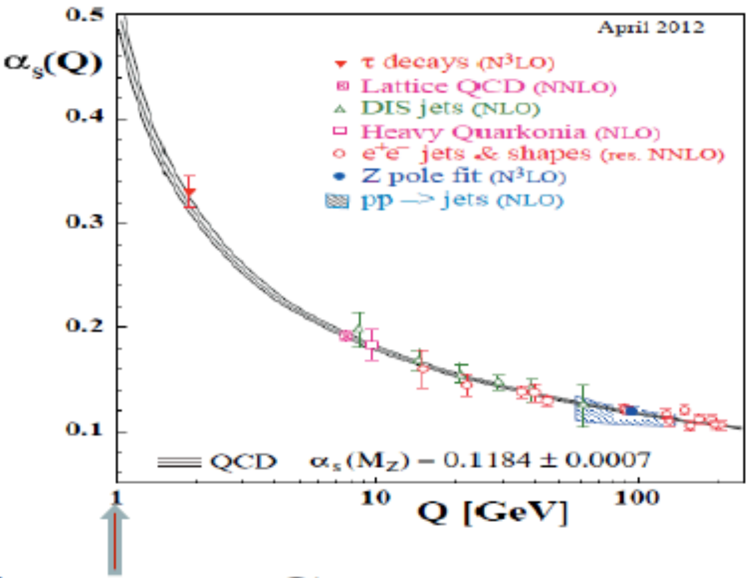
Theoretical background/recent developments
Recent experimental progress in NN weak interactions
PV in deuteron photodisintegration at HIGS2

MAIN MESSAGE: we can test QCD sector of Standard Model in the two-nucleon regime to ~20% accuracy using parity violation in quark-quark weak interactions as an “inside-out” probe

Thanks: R. P. Springer, S. Gardner, A Walker-Loud, J. Nico, C. Crawford, A. Cordon…

What kind of a probe do we need to learn about strong QCD?

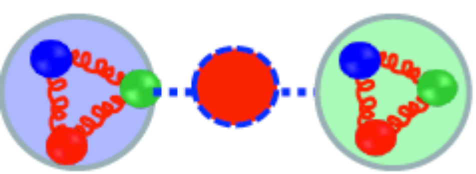
QCD coupling α_s



$\Lambda_{QCD} \approx 1GeV$

*** asymptotic freedom**
*** confinement**
*** chiral symmetry breaking**

$E_B \approx MeV$



NN interaction (meson exchange)

1. We want a "weak" probe which does not disturb the strong dynamics and leaves the system in its ground state

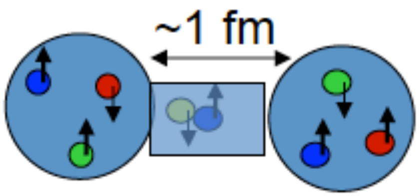
2. We want an "inside-out" probe which is understood at short distance scales

3. We want a "quark-quark" probe so that we are highly sensitive to QCD dynamics

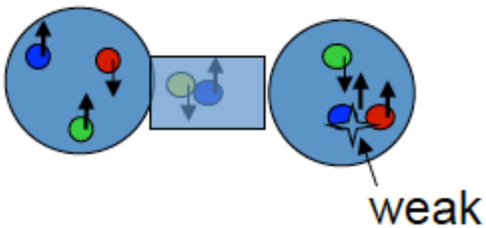
4. We want a "symmetry-violating" probe that we can see in the presence of strong dynamics

Can we understand quantitatively the evolution of strong dynamics from the q-q to the N-N level, through two nonperturbative scales?

The N-N Weak Interaction is what we want to study!



QCD (and strong NN): conserves parity



q-q weak interaction: violates parity

1. Is it "weak" enough not to disturb QCD effects? YES!

2. Is it an "inside-out" probe which is understood at short distance scales? YES! W and Z range [~1/100 fm] much smaller than nucleon

3. Is it a "quark-quark" probe? YES!

4. Is it a a "symmetry-violating" probe? YES! (QCD conserves parity, weak interaction violates parity)

So what's the problem?

Relative strength of weak / strong amplitudes in N-N system:

$$\frac{e^2}{M_W^2} / \frac{g^2}{m_\pi^2} \approx 10^{-7}$$

Too damn weak: experiments are very hard. But there is hope….

q-q Weak/NN Weak: Two Simple Facts

(1) 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.

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

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

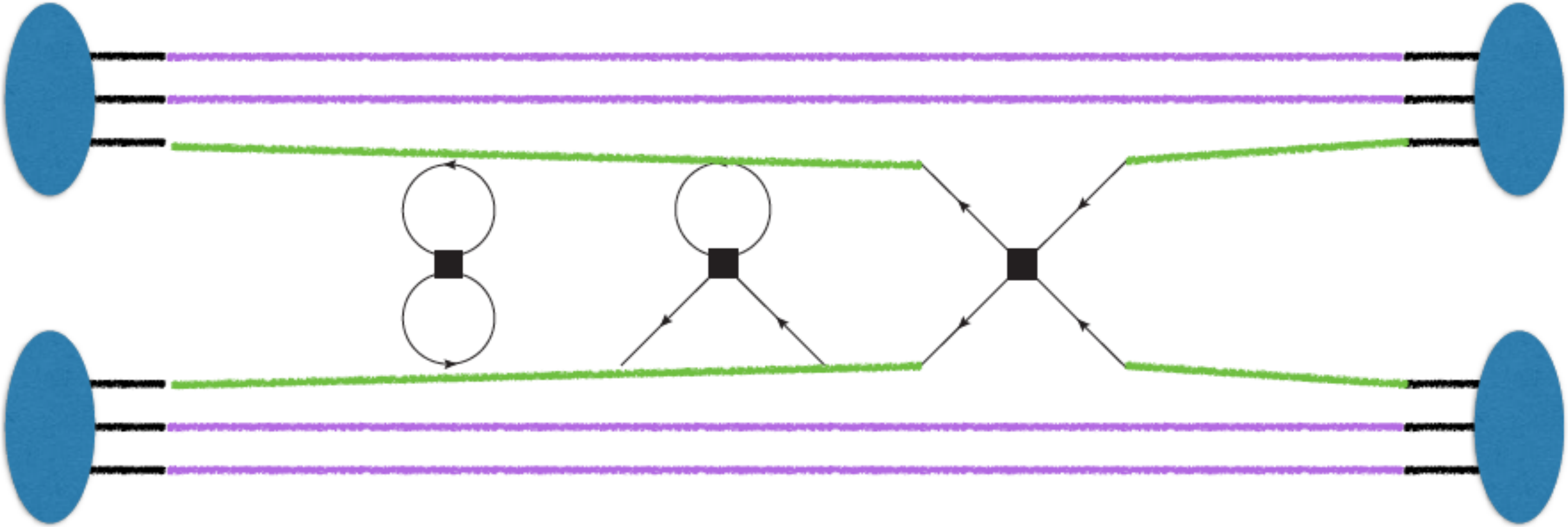
(2) If we use energies low enough that **only *S*-waves are important for strong interaction,** parity violation is dominated by ***S- P interference***, we have 5 independent NN parity-violating transition amplitudes:

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

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

Neutral currents dominate $\Delta I=1$, <u>$\Delta I=2$ only comes from one 4-quark operator</u>

LQCD Challenges for Parity Nonconservation



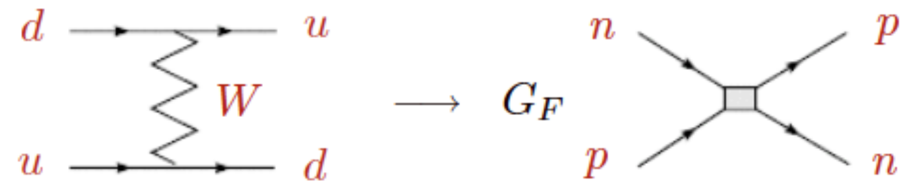
$\Delta I=0,1,2$

- The "disconnected" quark loops are numerically more expensive, and stochastically noisier
- LQCD calculations can project onto definite ΔI

The $\Delta I=2$ P-odd 4-quark operator is the easiest one to calculate on the lattice. Cal-Lat +collaborators are performing the calculation now. GOAL: 10% accuracy

A. Walker-Loud

Create low energy NN(N) EFT: down-up approach



- Use physical fields: N, γ
- Find something small to expand in: $p/\Lambda_{\not\pi}$
- Identify all operators consistent with underlying symmetry
- Determine how operators and coefficients scale
- Establish power counting
- Choose order to truncate
- Calculate observables

operators containing γ, p, n

$$\mathcal{L} = \sum_i \mathcal{C}_i(\mu)\mathcal{O}_i(\mu)$$

sum over terms
(to desired order)

coefficients include all other physics

μ dependence!

R. P. Springer

Pionless Effective Field Theory for NN Weak Interaction

$$\begin{aligned}
\mathcal{L}_{PV} = - \Big[& \mathcal{C}^{(^3S_1-^1P_1)} \left(N^T\sigma_2\,\vec{\sigma}\tau_2 N\right)^\dagger \cdot \left(N^T\sigma_2\tau_2 i\overleftrightarrow{D}N\right) \\
& + \mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)} \left(N^T\sigma_2\tau_2\vec{\tau}N\right)^\dagger \left(N^T\sigma_2\,\vec{\sigma}\cdot\tau_2\vec{\tau}i\overleftrightarrow{D}N\right) \\
& + \mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=1)}\,\epsilon^{3ab} \left(N^T\sigma_2\tau_2\tau^a N\right)^\dagger \left(N^T\sigma_2\,\vec{\sigma}\cdot\tau_2\tau^b\overleftrightarrow{D}N\right) \\
& + \mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)}\,\mathcal{I}^{ab} \left(N^T\sigma_2\tau_2\tau^a N\right)^\dagger \left(N^T\sigma_2\,\vec{\sigma}\cdot\tau_2\tau^b i\overleftrightarrow{D}N\right) \\
& + \mathcal{C}^{(^3S_1-^3P_1)}\,\epsilon^{ijk} \left(N^T\sigma_2\sigma^i\tau_2 N\right)^\dagger \left(N^T\sigma_2\sigma^k\tau_2\tau_3\overleftrightarrow{D}^j N\right)\Big] + h.c.
\end{aligned}$$

Schindler/RPS NPA 846 (2010) 51

This is a complete, low-energy realization of NN weak interactions of QCD with all the terms to lowest order in p/Λ . Once C's determined from measurement, one can then PREDICT other measurements.

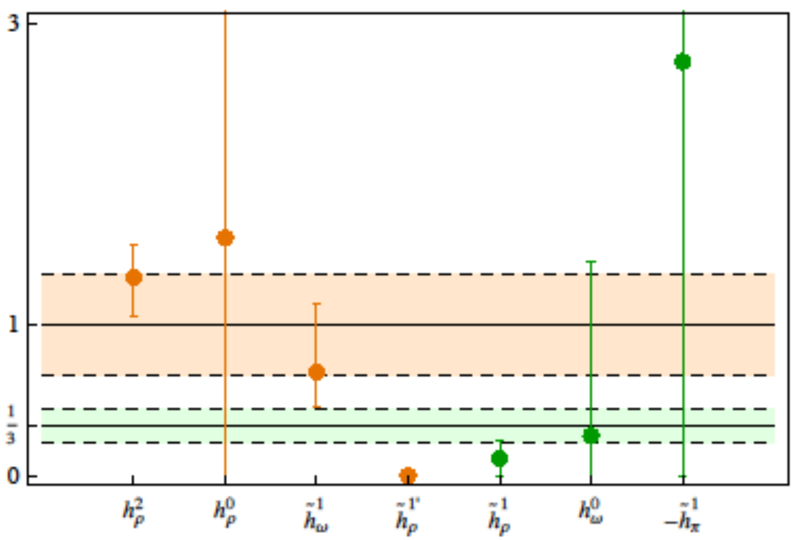
Works well for strong interactions of mesons and baryons.
We can test it in a new sector (weak NN)

R. P. Springer

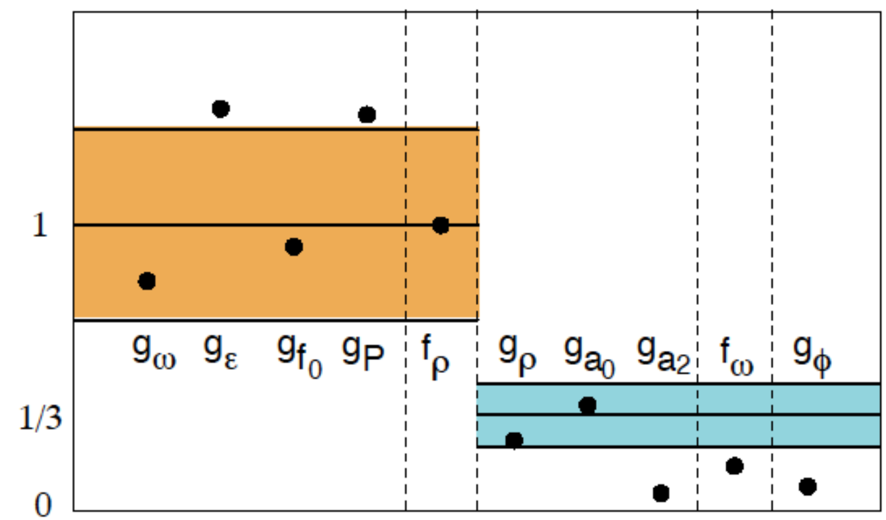
NN Weak Amplitudes in EFT+ $1/N_c$ Expansion of QCD

Large N expansion of QCD: works well for many low E observables (including strong NN couplings): what about weak NN couplings?

large N_c expansion for NN weak DDH



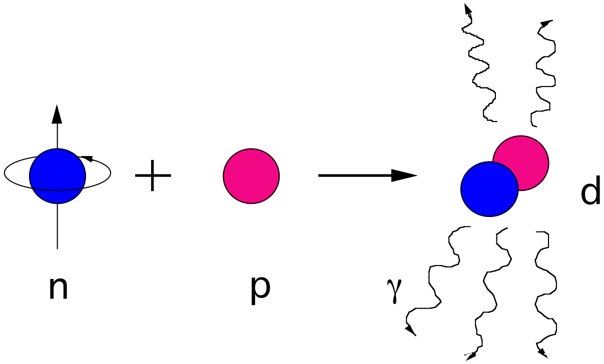
on large-N_c scaling vs Nijmegen potential



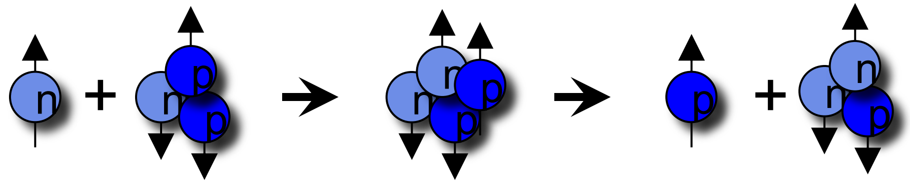
Large N_c estimates in rough agreement with data for strong NN interactions, and possibly weak NN interactions

This is good enough to guide choices for future NN weak experiments

Few-Body P-odd NN in progress: n-p, n-^{3}He, n-^{4}He

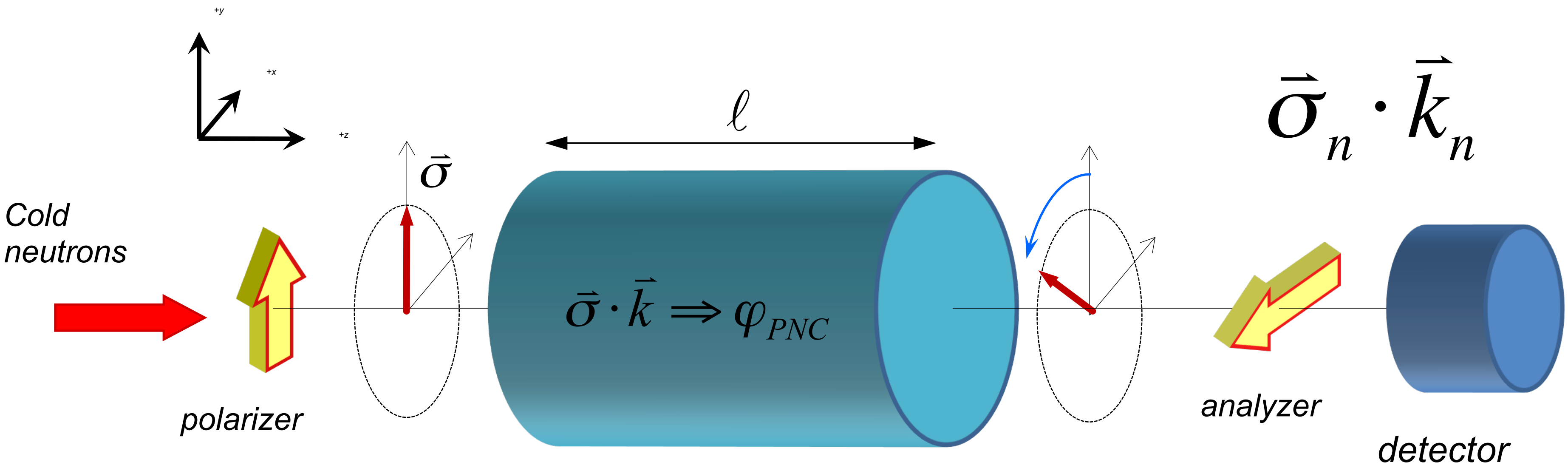


$$\vec{\sigma}_n \cdot \vec{k}_\gamma$$



$$\vec{\sigma}_n \cdot \vec{k}_p$$

$$\vec{\sigma}_n \cdot \vec{k}_n$$

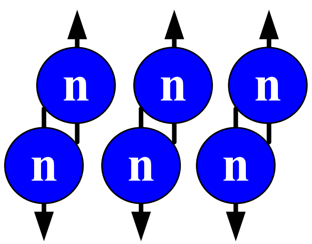


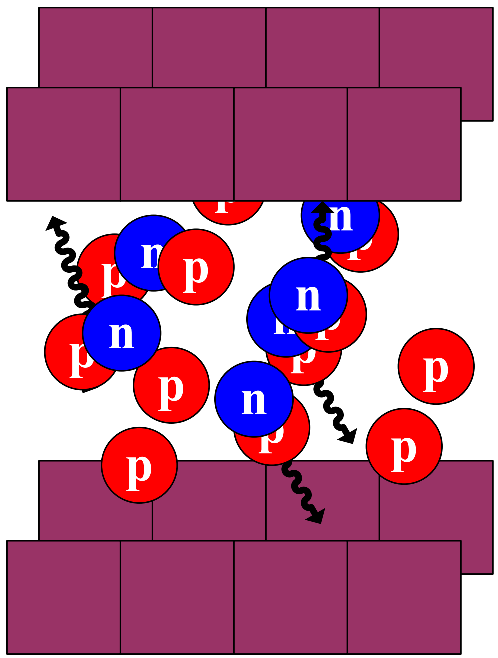
NPDγ Measurement of A_γ at Oak Ridge SNS: done

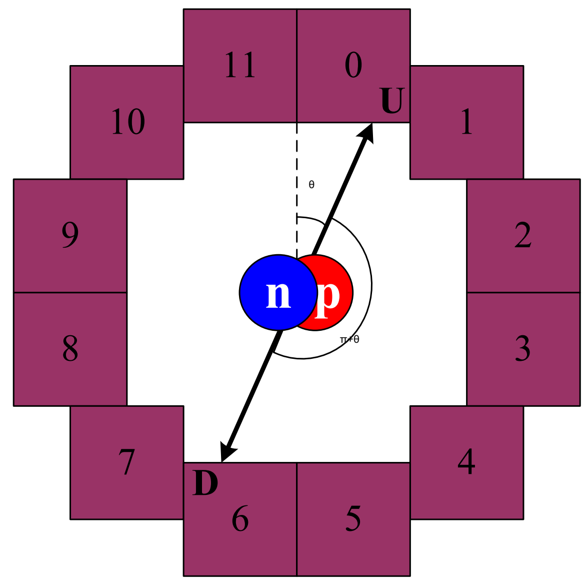
$$A_\gamma(t) P_n \cos\theta = \frac{U_\uparrow - D_\uparrow - (U_\downarrow - D_\downarrow)}{U_\uparrow + D_\uparrow + U_\downarrow + D_\downarrow}$$

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

$$A_\gamma = -0.107 f_\pi^1 - 0.001 h_\rho^1 - 0.004 h_\omega^1$$ DDH model





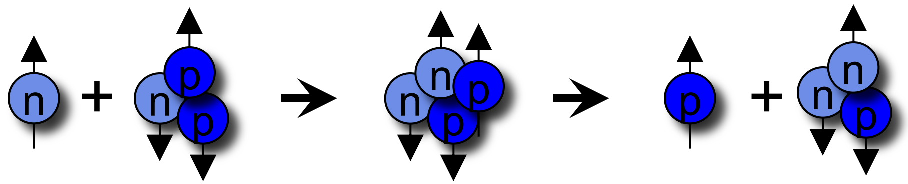


A_{np}=(-3.0 +/-1.4 [stat] +/- 0.2 [sys]) x 10^{-8}

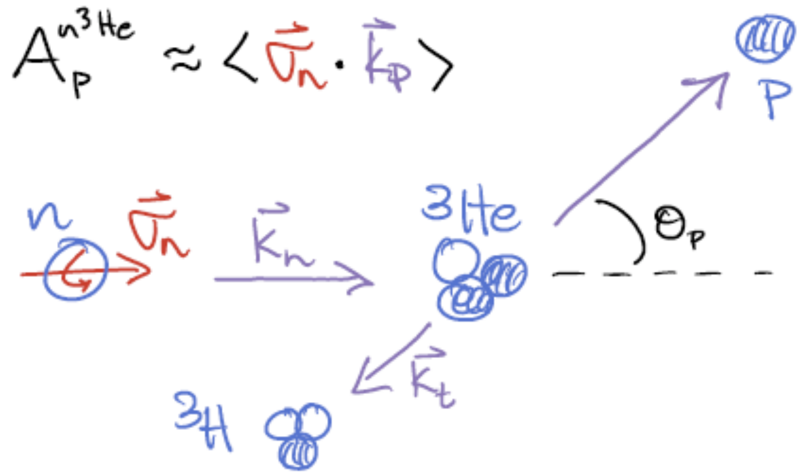
$$h_\pi^1 = (2.6 \pm 1.2(stat.) \pm 0.2(sys.)) \times 10^{-7}$$

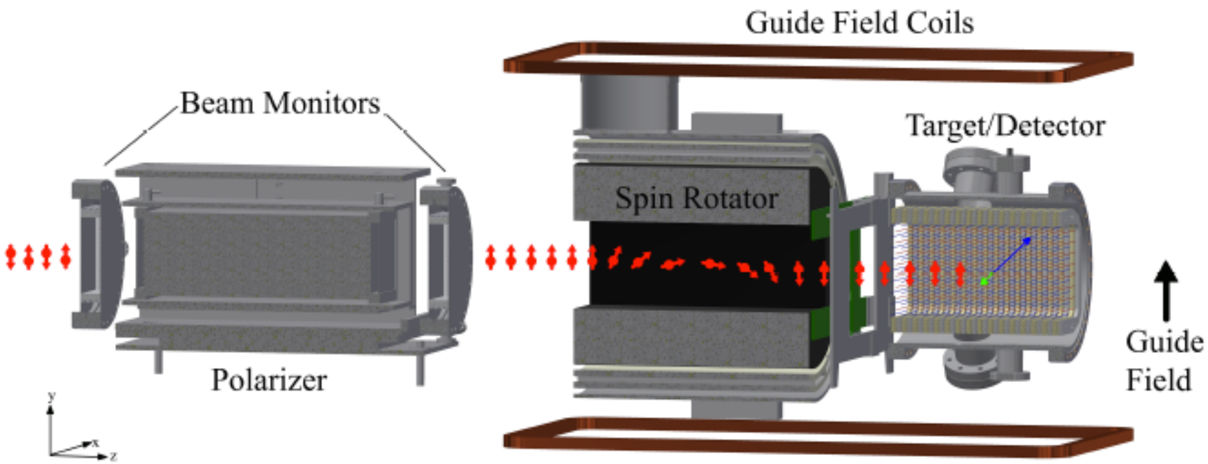
D. Blyth et al, Phys. Rev. Lett. **121**, 242002 (2018).

n-^{3}He PV measurement of A_p at Oak Ridge SNS: done



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



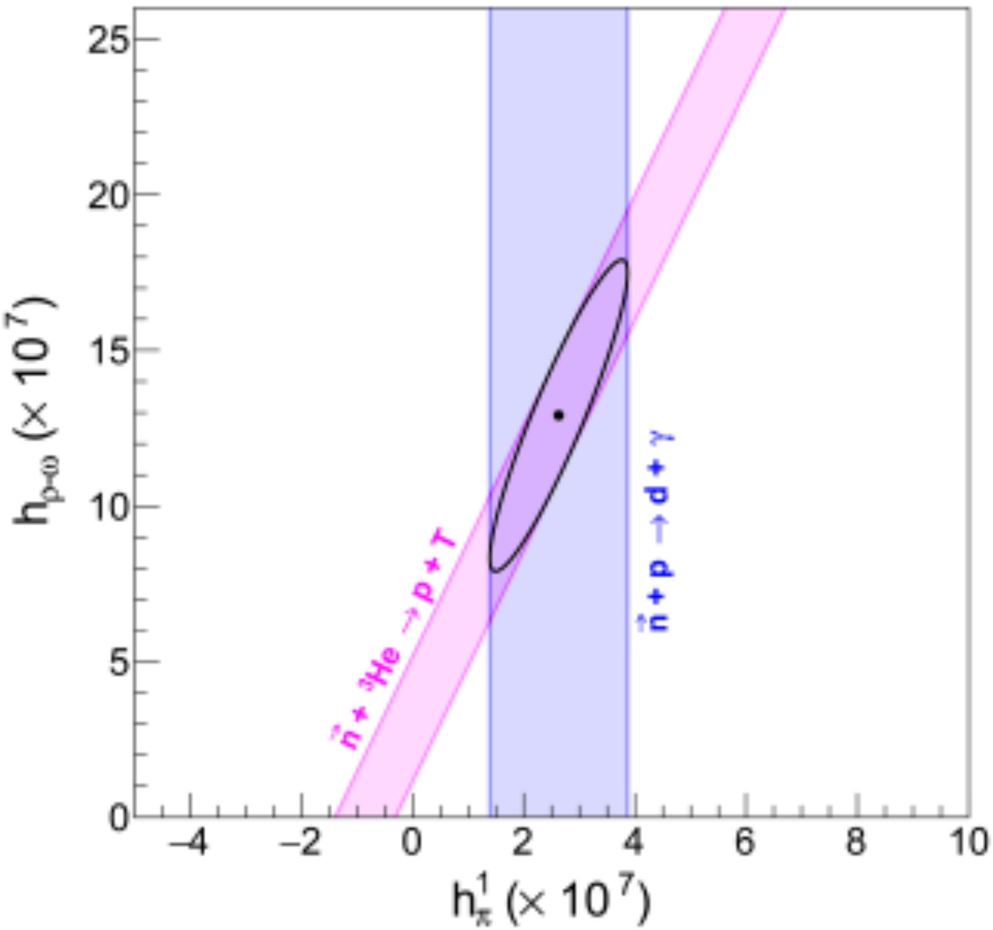


Sensitive to isoscalar couplings (ΔI=0) of the hadronic weak interaction

A_p=(1.58 +/- 0.97 [stat] +/- 0.24 [sys]) x 10^{-8}

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

NPDγ Measurement of A_γ and n-^{3}He PV measurement of A_p

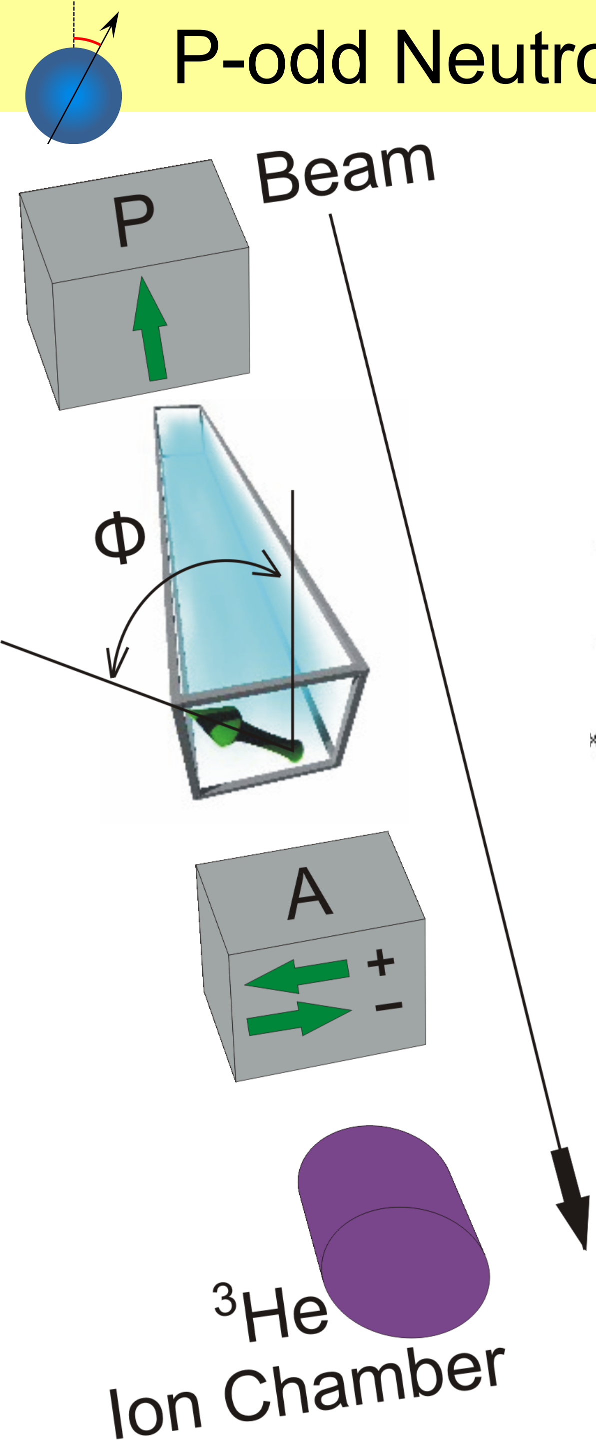


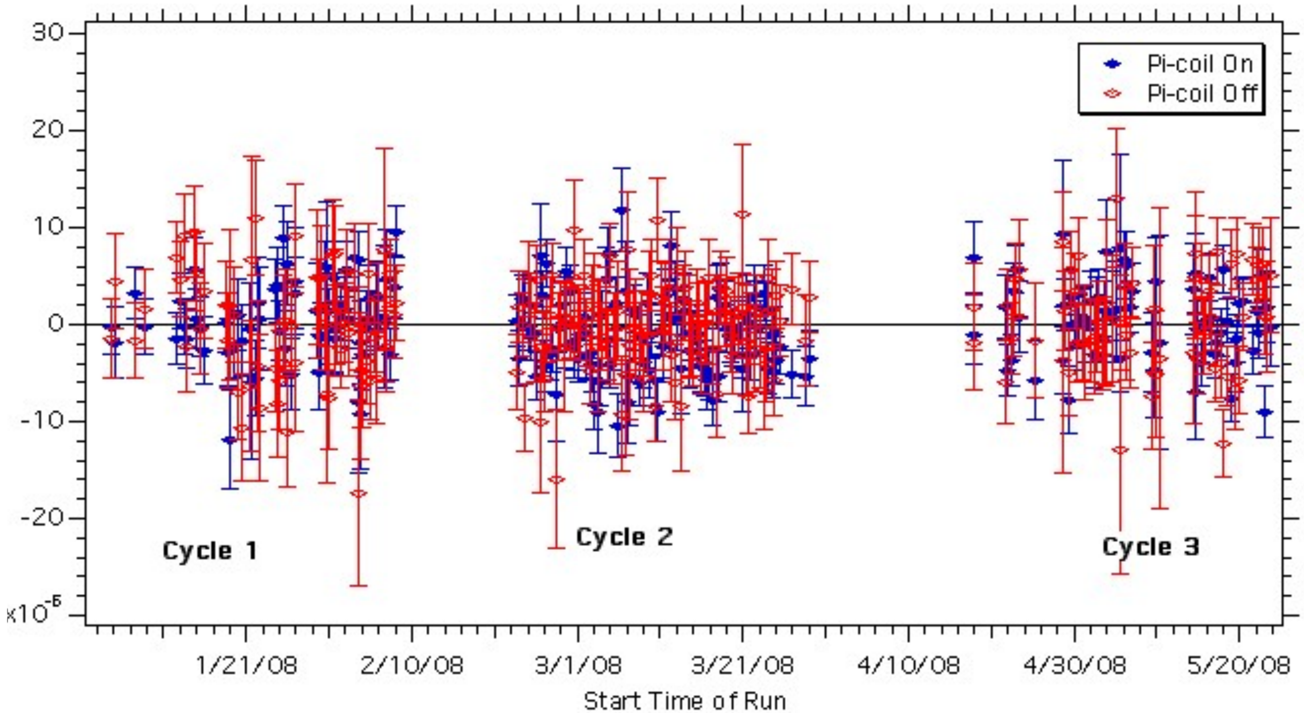
Constrains a linear combination of P-odd amplitudes

Still more work in theory and experiment is needed

$$h_{\rho-\omega} \equiv h^1_\omega + 0.46h^1_\rho - 0.46h^0_\omega - 0.76h^0_\rho - 0.02h^2_\rho$$
$$= (12.9 \pm 5.7) \times 10^{-7} \ .$$

P-odd Neutron Spin Rotation φ_{PNC} in ^{4}He at NIST





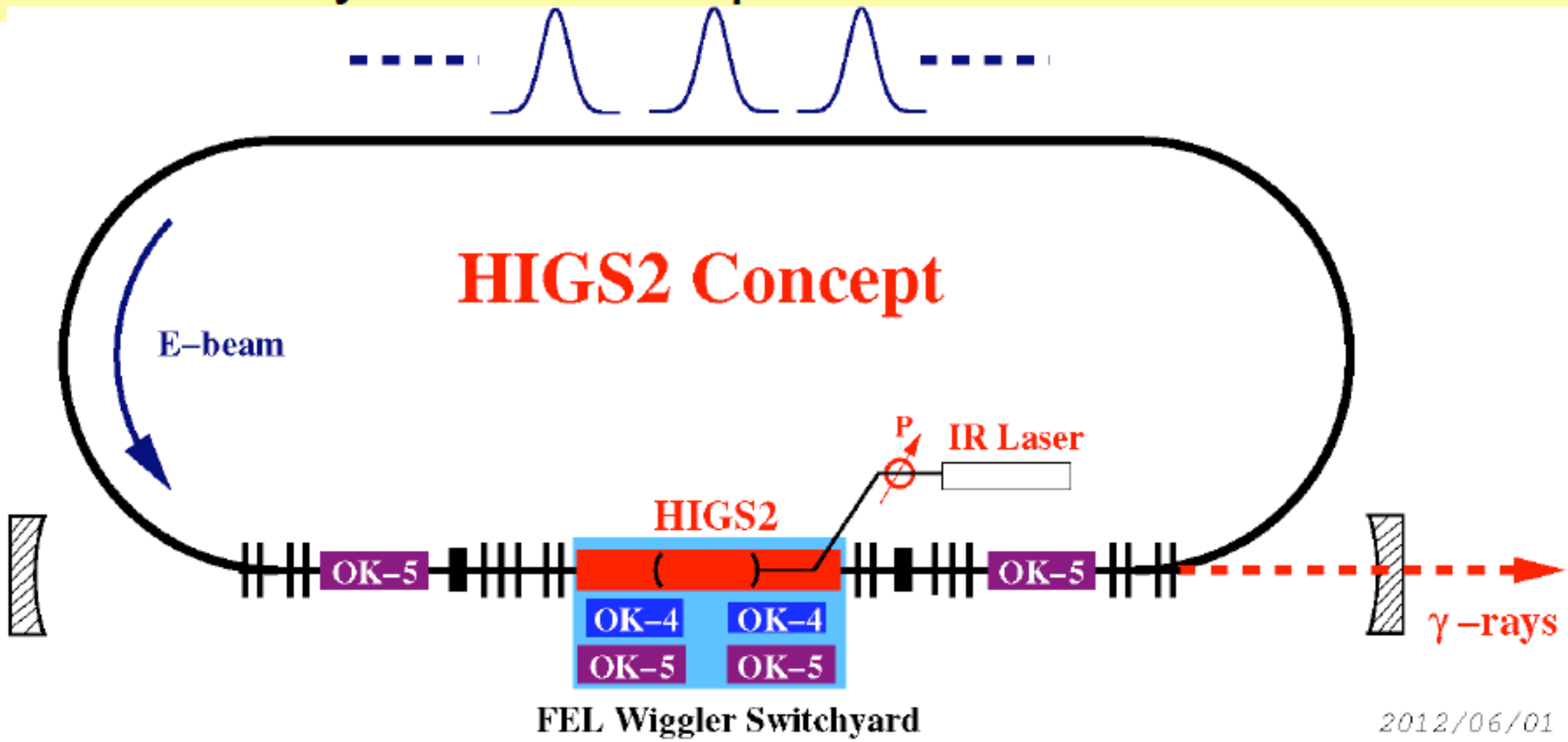
"pi-coil on" → L-R measures PNC asymmetry, L+R measures systematics
"pi-coil off" → must give zero in absence of systematics

φ_{PNC}= [+2.1 ± 8.3 (stat) ±2.9 (sys)] x 10^{-7} rad/m

W. M. Snow, et al., RSI **86**, 055101 (2015)
H. E. Swanson et al, Phys. Rev. C **100**, 015204 (2019).

In preparation for NIST, expect ~9E-7 rad/m

Parity Violation Experiments at HiGS2?



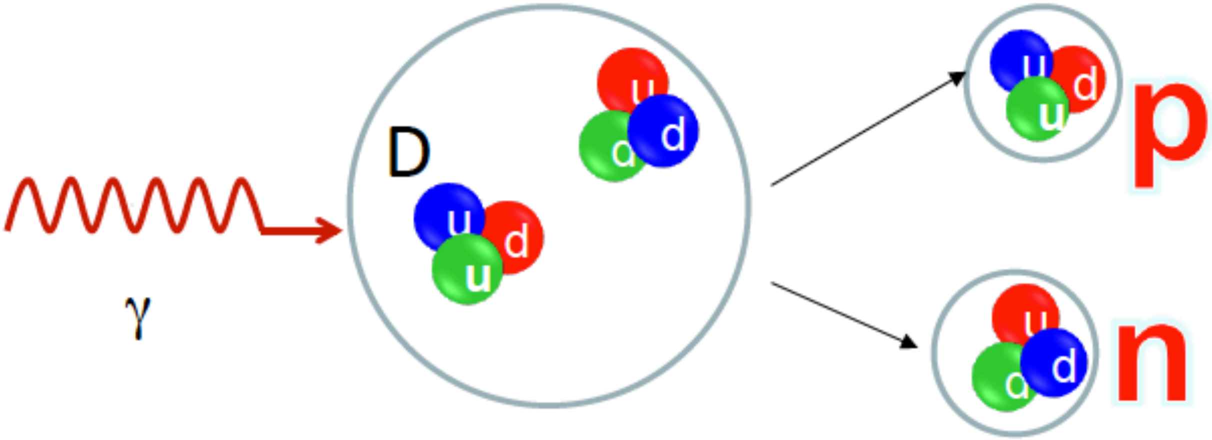
~10^{11} to 10^{12} polarized γ/sec (X100 increase in polarized gamma flux relative to HiGS1.)

Circularly polarized gammas (>~90%), fast (~100 Hz) and high-quality gamma helicity reversal possible

Controlled beam phase space: ~1% energy resolution on gamma energy (2-12 MeV)

These are attractive features in principle for parity violation experiments

Parity Violation in deuteron photodisintegration



Parity violation leads to helicity dependence of photodisintegration cross section

The neutron can escape the target and its intensity can be detected in current mode

Signal is helicity dependence of neutron current from target

Detect also scattered and transmitted gammas for normalization/systematics effect suppression

Need to supply >~10^{16} gammas just above photodisintegration threshold.

Asymmetry A_γ^L in $\vec{\gamma} d \to np$ at leading order

- Leading-order asymmetry at threshold

Helicity-dependent asymmetry

Detect either the n or p (neutron is easier)

$$A_\gamma^L = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

$$= -2\sqrt{\frac{2}{\pi}} \frac{M^{\frac{3}{2}}}{\kappa_1 \left(1 - \gamma a^{^1S_0}\right)} \left[\left(1 - \frac{2}{3}\gamma a^{^1S_0}\right) g^{(^3S_1 - ^1P_1)} + \frac{\gamma a^{^1S_0}}{3} \left(g^{(^1S_0 - ^3P_0)}_{(\Delta I=0)} - 2 g^{(^1S_0 - ^3P_0)}_{(\Delta I=2)} \right) \right],$$

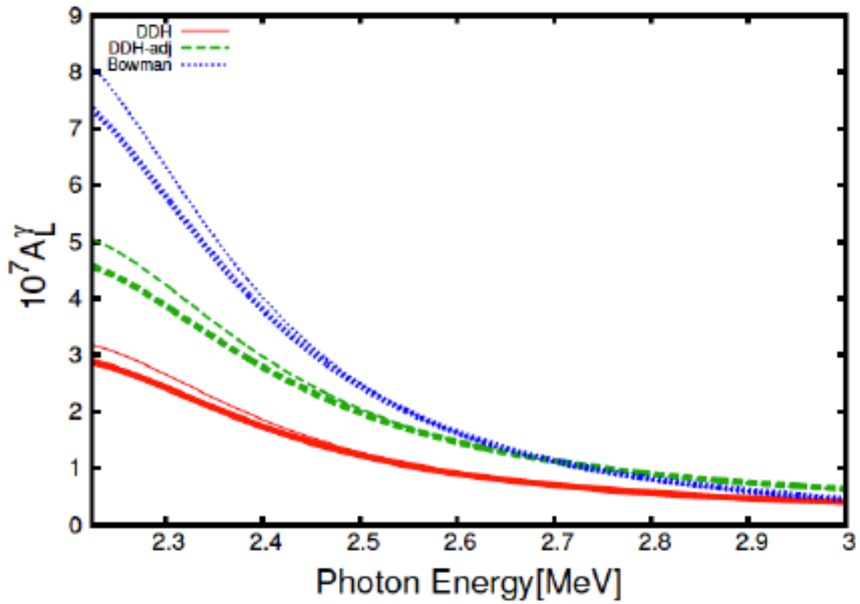
- Information independent of and complementary to $\vec{n}p \to d\gamma$

M.R. Schindler and R.P. Springer, Nucl. Phys. A **846** (2010) 51.

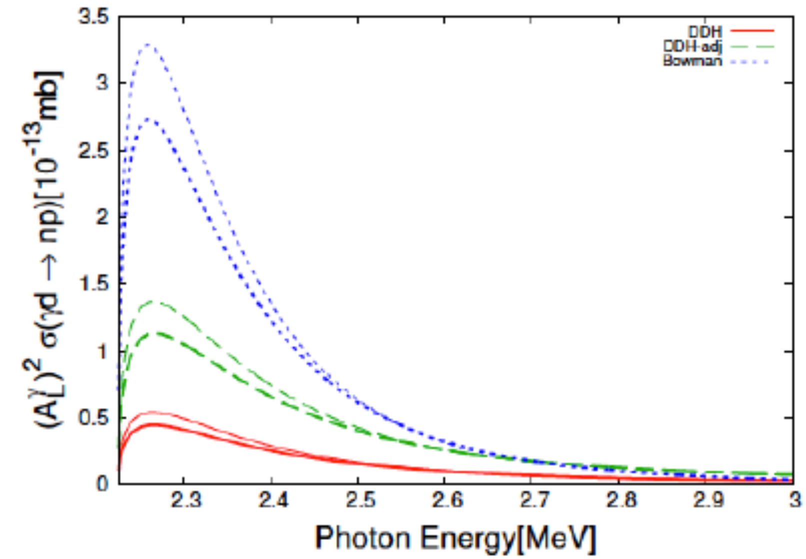
J. Vanasse and M.R. Schindler, nucl-th/ 1404.0658

Schindler, Springer (2009); Vanasse, Schindler (2014)

PV D Photodisintegration: Theory Optimization



PV asymmetry in pionless EFT under various assumptions



Statistical figure of merit for PV in deuteron photodisintegration

Remains the only known P-odd NN observable accessible to experiment which is sensitive to $\Delta I=2$ NN parity violation

Vanasse/Schindler, arXiv:1404.0658, PRC 90, 044001 (2014)

A_γ *(threshold)*$= -8.44\, h_\rho^0 + 3.63\, h_\omega^0 - 17.6\, h_\rho^2$

$\Delta I=2$ NN parity violation calculable in lattice gauge theory

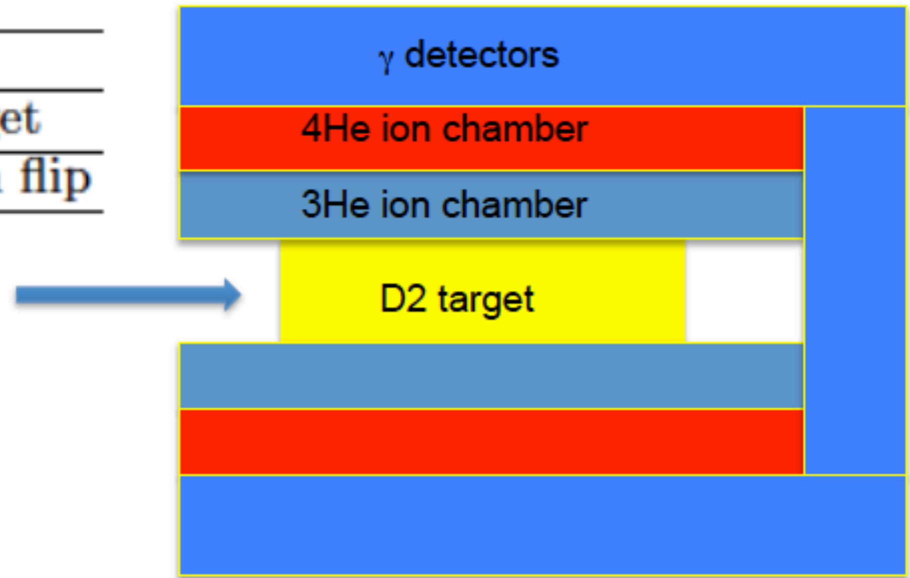
Liu/Hyun/Desplanques, arXiv:0403009

Concept of P-odd Deuteron Photodisintegration Expt.

Suggested beam parameters for PV in deuteron photodisintegration.

Parameter	Value
Energy	2.25-2.30 MeV
Flux	10^{10}
Polarization	Circular
Diameter	100 mm on target
Time Structure	10 Hz polarization flip

Circularly-polarized γ Beam from HiGS2



The neutron can be moderated in the liquid deuterium target, escape with low energy (~10 meV), and be detected efficiently in current mode in a 3He/4He ion chamber

The transmitted and scattered γs can be measured using current-mode γ detectors located behind the 3He/4He ion chamber

Cylindrical symmetry of detector array to help suppress possible systematic errors (partial analysis in Y. Li et al, Nucl. Inst. Meth. A 726, 67 (2013).)

Some relevant properties of nuclei with opposite parity doublets which can be measured at HIγS

Nucleus	J^π	T	Energy (MeV)	τ_γ	abundance (%)
^{4}He	0^+		20.1	particle unstable	100
^{4}He	0^-		21.1	particle unstable	100
^{10}B	2^-	0	5.110	particle unstable	19.4
^{10}B	2^+	1	5.163	particle unstable	19.4
^{12}C	2^+		11.16	particle unstable	99
^{12}C	2^-		11.83	particle unstable	99
^{12}C	2^+	1	16.107	particle unstable	99
^{12}C	2^-	1	16.58	particle unstable	99
^{13}C	$1/2^+$		10.996	particle unstable	1
^{13}C	$1/2^-$		11.080	particle unstable	1
^{14}N	0^+	1	8.618	particle unstable	99.6
^{14}N	0^-	1	8.79	particle unstable	99.6
^{15}N	$5/2^-$	1	10.4497	particle unstable	0.4
^{15}N	$5/2^+$	1	10.5333	particle unstable	0.4
^{19}F	$1/2^+$		0	stable	100
^{19}F	$1/2^-$		0.110	0.59 nsec	100
^{19}F	$3/2^-$		1.4585	0.05 psec	100
^{19}F	$3/2^+$		1.5541	2 fsec	100
^{21}Ne	$1/2^-$		2.7885	0.09 nsec	0.3
^{21}Ne	$1/2^+$		2.796		0.3
^{21}Ne	$5/2^+$		3.7337		0.3
^{21}Ne	$5/2^-$		3.8829	0.06 psec	0.3
^{21}Ne	$3/2^+$		4.684		0.3
^{21}Ne	$3/2^-$		4.726		0.3
^{22}Ne	2^+		4.457		9.2
^{22}Ne	2^-		5.147		9.2
^{23}Na	$1/2^+$		2.3909	0.6 psec	100
^{23}Na	$1/2^-$		2.6398	76 fsec	100
^{23}Na	$5/2^-$		3.848	0.09 psec	100
^{23}Na	$5/2^+$		3.9147	8 fsec	100
^{24}Mg	$5/2^-$		3.848	0.09 psec	100
^{24}Mg	$5/2^+$		3.9147	8 fsec	100
^{32}S	4^-		7.9500	0.09 psec	95
^{32}S	4^+		7.966		95

Parity Doublets in Light Nuclei

Parity violation is amplified by mixing of closely-spaced states of opposite parity

Theory may be doable on the HiGS2 timescale

Candidates are known

(somewhat) less demanding

Suggested beam parameters for PV in parity doublets.

Parameter	Value
Energy	1-20 MeV
Flux	10^9 at 0.1-1% FWHM
Polarization	Circular
Diameter	100 mm on target
Time Structure	10 Hz polarization flip

NN parity violation: experiment summary

- Projected HiGS2 beam properties may suffice to perform parity violation measurements, but such experiments will place VERY stringent demands on HiGS2 performance

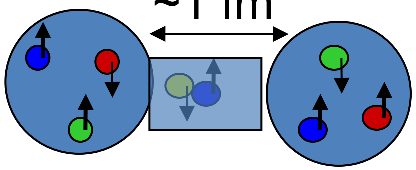
- Few precise NN weak interaction measurements in few-body systems exist. Any opportunity to measure something new is worth careful scrutiny

PV in deuteron photodisintegration: only known process with clean access to $\Delta I=2$ piece of weak NN interaction

Experience with slow neutron and γ current mode detector technology exists

P-odd effects on parity doublets at HiGS2: may be theoretically calculable on HiGS2 timescale, asymmetries larger, experiments "easier"

N- N Weak Interaction: Size is Small, but Dynamical Mechanism is Interesting

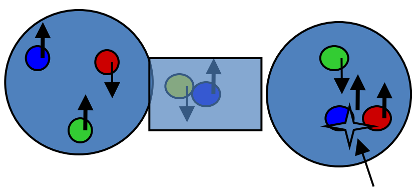


NN repulsive core → 1 fm range for NN strong force

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

interacts through NN strong force, 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



W and Z exchange probe a range [~1/100 fm] small compared to nucleon size

Relative strength of weak / strong amplitudes: $\frac{e^2}{M_W^2} / \frac{g^2}{m_\pi^2} \approx 10^{-7}$

Use **parity violation** to isolate the weak contribution to NN interaction.

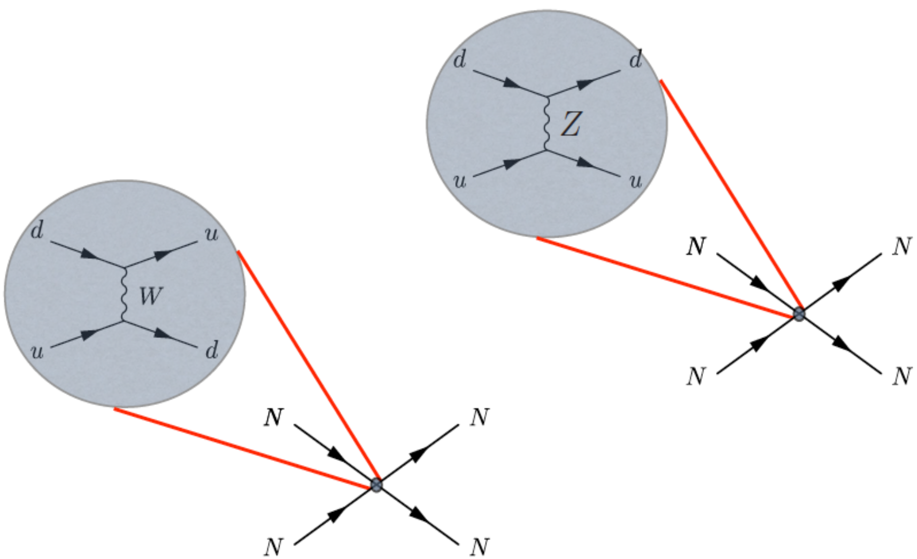
NN strong interaction at low energy largely dictated by QCD chiral symmetry.
Can be parametrized by effective field theory methods.

NN weak interaction: ΔI=0, 1, and 2, 5 S-P amplitudes

Below the W$^{\pm}$/Z^{o} mass, q-q weak interaction can be written in a current-current form (charged currents and neutral currents)

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

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

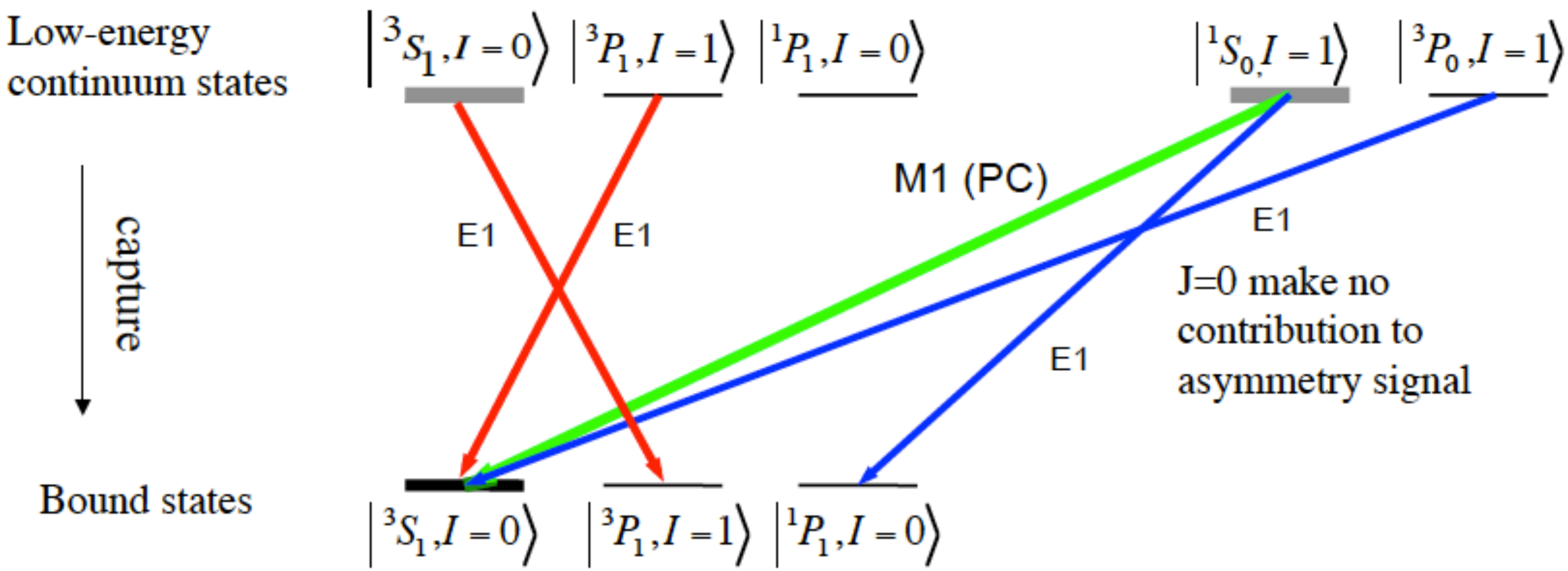


At low energy **only *S*-waves are important for strong interaction,** parity violation is dominated by ***S- P interference***,

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

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

Simple Level Diagram of *n-p* System



$\dot{n} + p \rightarrow d + \gamma$ 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 Amplitudes in EFT: 5 s-p Amplitudes, 2 lead in N_c

$$
\begin{aligned}
V_{LO}^{PNC}(\boldsymbol{r}) \;=\;& \Lambda_0^{^1S_0-^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)-\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_S}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right)\\
&+\Lambda_0^{^3S_1-^1P_1}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)+\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_S}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot i(\boldsymbol{\sigma}_1\times\boldsymbol{\sigma}_2)\right)\\
&+\Lambda_1^{^1S_0-^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\tau_{1\,z}+\tau_{2\,z})\right)\\
&+\Lambda_1^{^3S_1-^3P_1}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1+\boldsymbol{\sigma}_2)(\tau_{1\,z}-\tau_{2\,z})\right)\\
&+\Lambda_2^{^1S_0-^3P_0}\left(\frac{1}{i}\frac{\overleftrightarrow{\boldsymbol{\nabla}}_A}{2m_N}\frac{\delta^3(\boldsymbol{r})}{m_\rho^2}\cdot(\boldsymbol{\sigma}_1-\boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1\otimes\boldsymbol{\tau}_2)_{20}\right),
\end{aligned}
$$

$$
\begin{aligned}
\Lambda_0^+ \equiv \frac{3}{4}\Lambda_0^{^3S_1-^1P_1}+\frac{1}{4}\Lambda_0^{^1S_0-^3P_0} &\sim N_c\\
\Lambda_2^{^1S_0-^3P_0} &\sim N_c,
\end{aligned}
$$

$$
\begin{aligned}
\Lambda_0^- \equiv \frac{1}{4}\Lambda_0^{^3S_1-^1P_1}-\frac{3}{4}\Lambda_0^{^1S_0-^3P_0} &\sim 1/N_c\\
\Lambda_1^{^1S_0-^3P_0} &\sim \sin^2\theta_w\\
\Lambda_1^{^3S_1-^3P_1} &\sim \sin^2\theta_w
\end{aligned}
$$

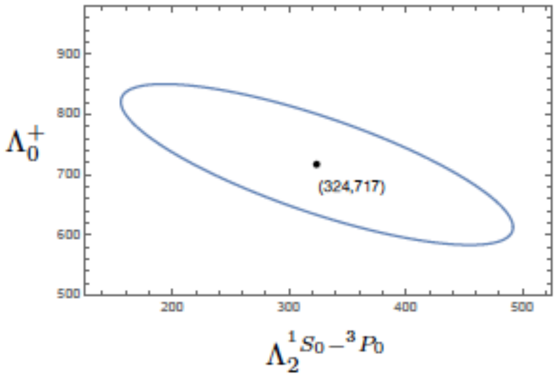
$N_c=3$

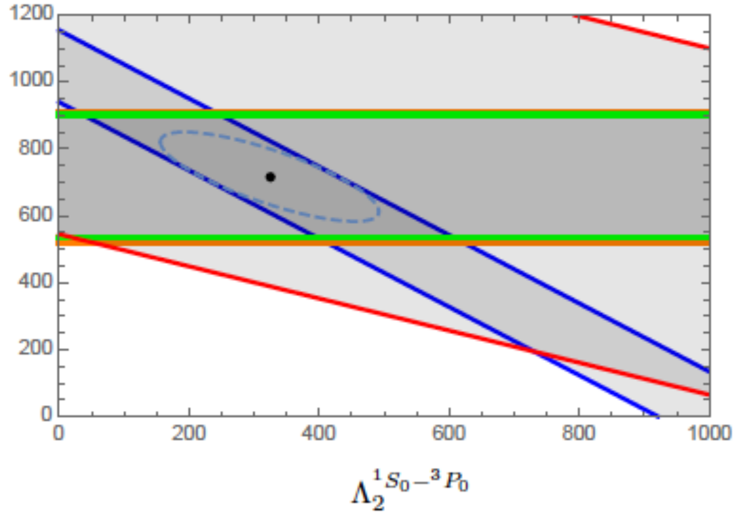
$1/N_c=1/3$

$\sin^2\theta_w\sim 1/4$

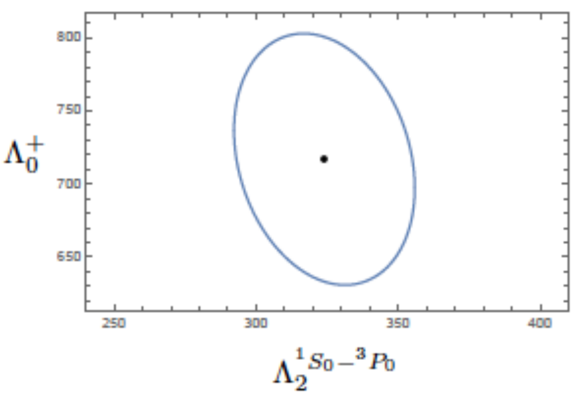
$1/N_c$ analysis: Phillips, Samart, Schat, arXiv:1410.1157, PRL 114, 062301 (2015)
Schindler, Springer, Vanasse, arXiV:1510.07598, PRC 93, 025502 (2016)

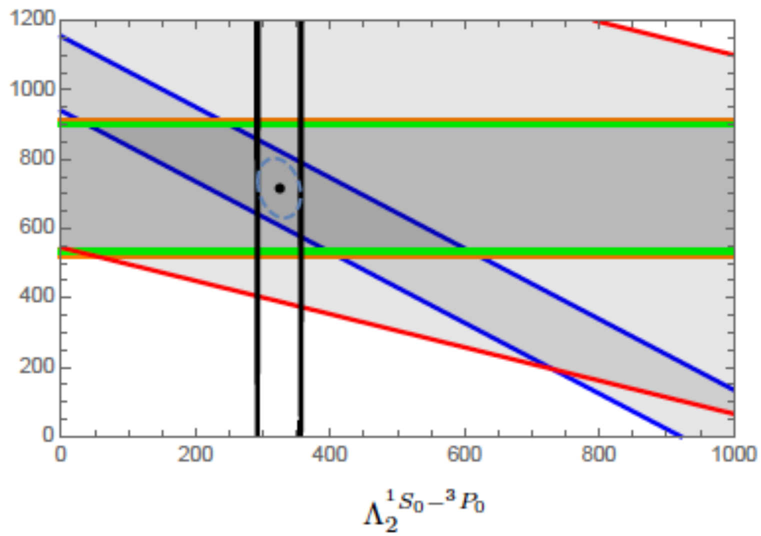
NN Weak Amplitudes in EFT+ $1/N_c$: $\Delta I=0$ and $\Delta I=2$





Constraints from existing NN parity experiments (pp, pα, ^{19}F)





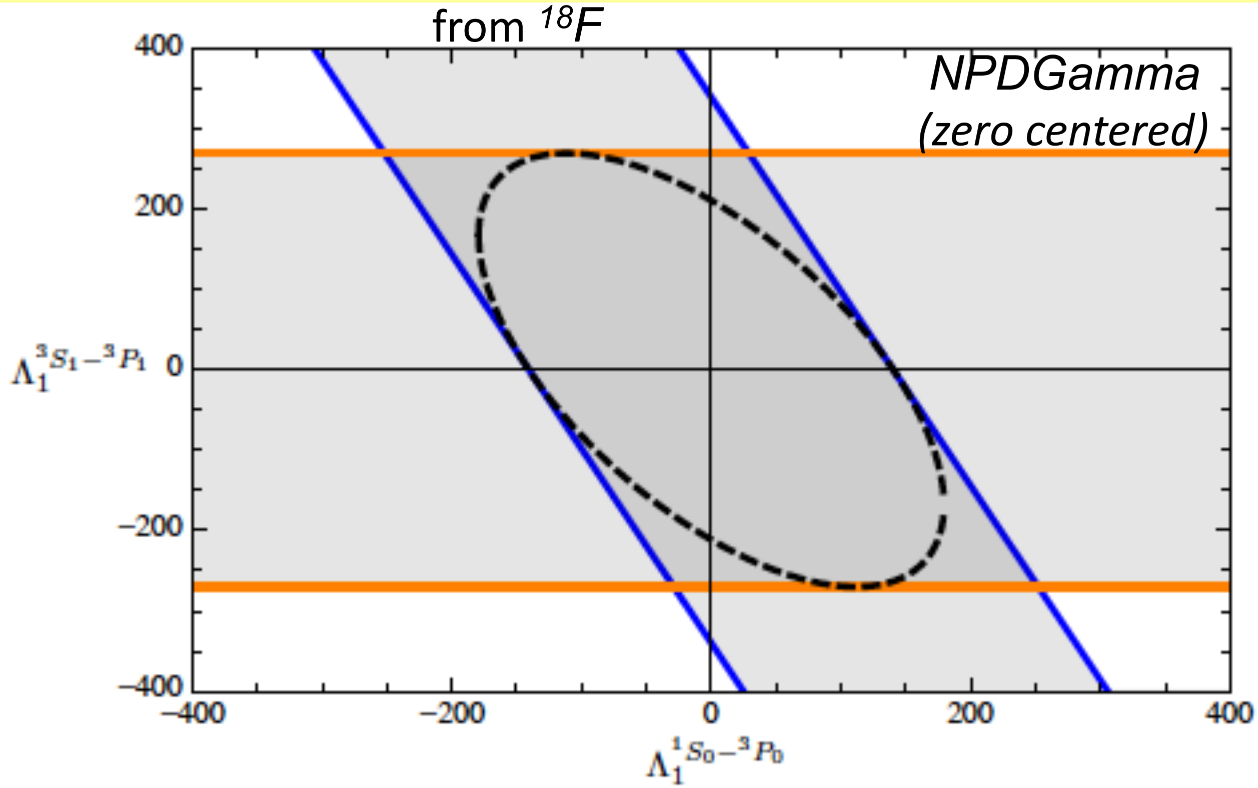
Impact of planned lattice calculation of ΔI=2 NN weak amplitude to ~10%

leading order NN weak amplitudes are constrained-> make PREDICTIONS

Other three amplitudes are suppressed by $1/N^2_c=1/9$ or $\sin^2\theta_W/N_c$ ~1/12

from Gardner, Haxton, Holstein, arXiv: 1704.02617

NN Weak Amplitudes in EFT+ $1/N_c$: ΔI=1 Amplitudes



from Gardner, Haxton, Holstein, arXiv: 1704.02617

Constraints from one existing NN parity experiment (^{18}F, ~vertical band) and NPDGamma, (horizontal band, centered at zero, width from measurement error)

This data determines the two ΔI=1 amplitudes which should be suppressed by $1/N^2_c=1/9$ or $\sin^2\theta_W/N_c$ ~1/12

^{18}F experiment is already consistent with the predicted $1/N_c$ suppression in a combination of ΔI=1 partial waves.

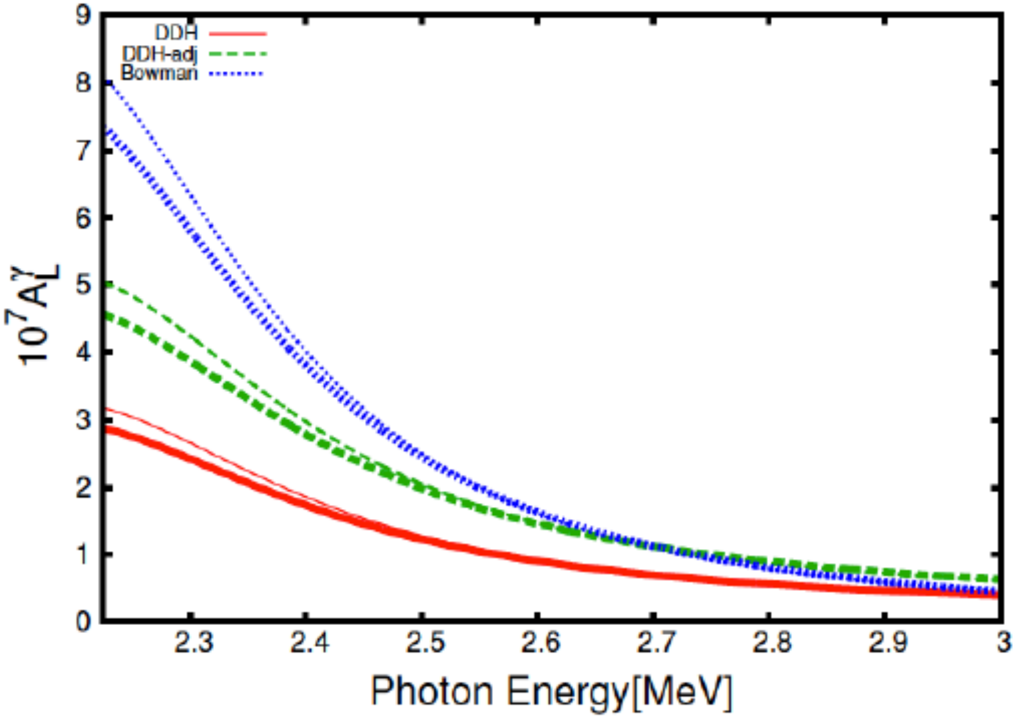
NPDGamma has determined one ΔI=1 channel

Then: we will know something about 4 out of the 5 NN weak amplitudes

Predictions of PV Asymmetry for the γ+d → n + p reaction

A_L^γ in EFT($\not\pi$): NLO results

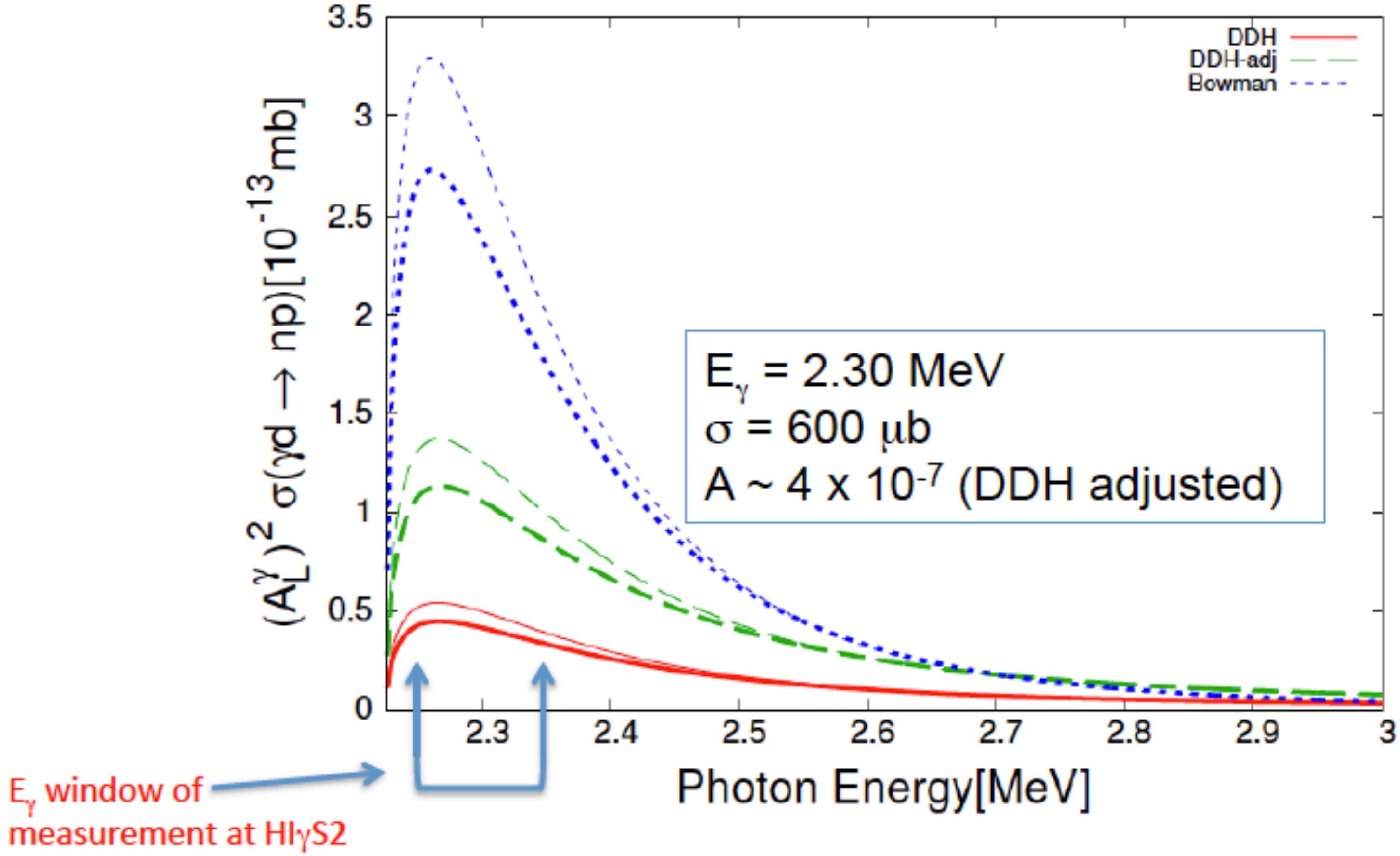
- Fix PV couplings to model estimates
- "Reasonable ranges:" A_L^γ varies over orders of magnitude and sign



Vanasse, Schindler (2014)   J. Vanasse and M.R. Schindler, nucl-th/ 1404.0658

Where to measure?

- A_L^γ max at threshold $\Rightarrow$ low count rate
- Simplified figure of merit $(A_L^\gamma)^2 \times \sigma(\gamma d \to np)$

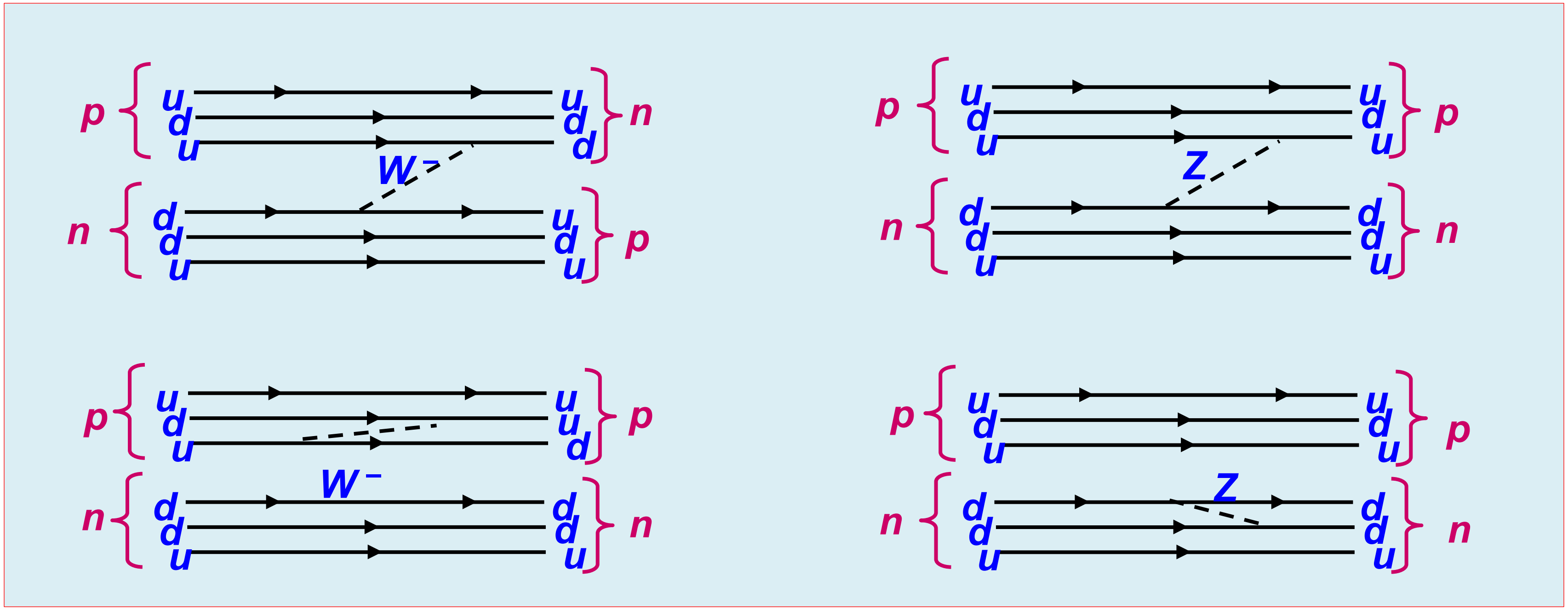


- Maximized for $\omega \approx [2.259, 2.264]$ MeV

Vanasse, Schindler (2014)

NN Weak Interaction: use EW parity violation to probe QCD

In the Standard Model, the structure of the quark-quark weak interaction is known from the electroweak sector. However, strong QCD **confines color** and **breaks chiral symmetry**, thereby strongly correlating the quarks in both the *initial* and *final* nucleon ground states.



Two aspects of qq weak interaction make it useful as **an interesting probe of QCD**:

(1) Since it is weak, it probes the nucleons in their ground states without exciting them.

(2) Since it is short-ranged compared with the size of the nucleon, NN weak amplitudes should be first-order sensitive to **quark-quark correlation effects in the nucleon.**

qq Weak → NN Weak: What can we learn?

(1) NN weak interactions can DIRECTLY test quantum chromodynamics (QCD) via lattice gauge theory.

Calculation of the ΔI=2 NN weak amplitude on the lattice is in progress (a "computational frontier" of the Standard Model).

ΔI=2 NN weak amplitude measurement can test QCD

(2) NN weak interactions can test QCD in low energy limit using effective field theory (EFT) treatment.

New 1/N_c expansion+EFT predicts LARGE isospin dependence of NN weak amplitudes.

Chiral EFT of QCD testable by slow neutron experiments

(3) NN weak interaction is a "test case" for our ability to trace symmetry-violating effects across strong interaction scales

How to use EDM/ν0ββ constraints in nucleons/nuclei to constrain physics of T violation and L violation?

Let's understand the P violation physics in QCD systems, where we know the P-odd operators from the Standard Model

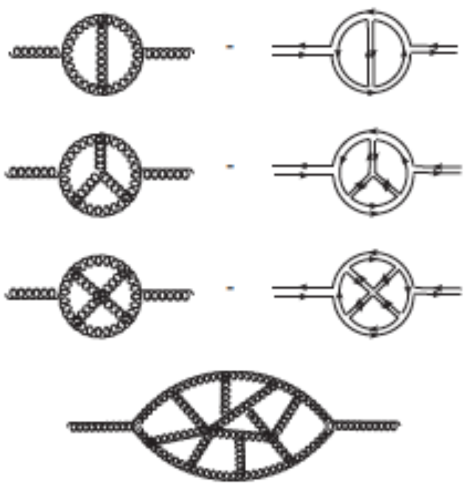
t'Hooft 1974,
Witten 1979

Large Nc limit of QCD

Planarity

Planar diagrams

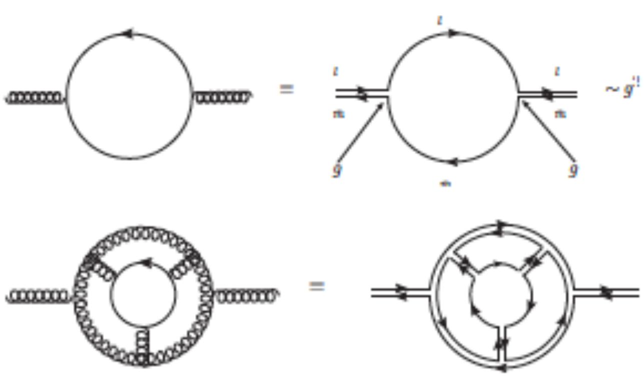
$\sim \mathcal{O}(1)$



Non-planar diagrams

$\sim 1/N_c^2$

Quark loops



$\sim 1/N_c$

Leading order Feynman diagrams in the large Nc limit are planar with a minimum number of quark loops

A. Cordon

Large N_c Implications for Future Hadronic Parity Violation Experiments: Some P-odd effects are "large"

S. Gardner, W.C. Haxton, B.R. Holstein, arXiv:1704.02617v1 (2017)

Observable	Exp. Status	LO Expectation	LO LEC Dependence
$A_p(\vec{n} + {}^3\text{He} \to {}^3\text{H} + p)$	ongoing	-1.8×10^{-8}	$-\Lambda_0^+ + 0.227\Lambda_2^{{}^1S_0-{}^3P_0}$
$A_\gamma(\vec{n} + d \to t + \gamma)$	8×10^{-6} (see text) [58]	7.3×10^{-7}	$\Lambda_0^+ + 0.44\Lambda_2^{{}^1S_0-{}^3P_0}$
$P_\gamma(n + p \to d + \gamma)$	$(1.8 \pm 1.8) \times 10^{-7}$ [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^+
$A_L(\vec{p} + d)$	$(-3.5 \pm 8.5) \times 10^{-8}$ [43]	-4.6×10^{-8}	$-\Lambda_0^+$

Only two leading-order EFT terms (Λ_0^+, Λ_2) in large N_c analysis

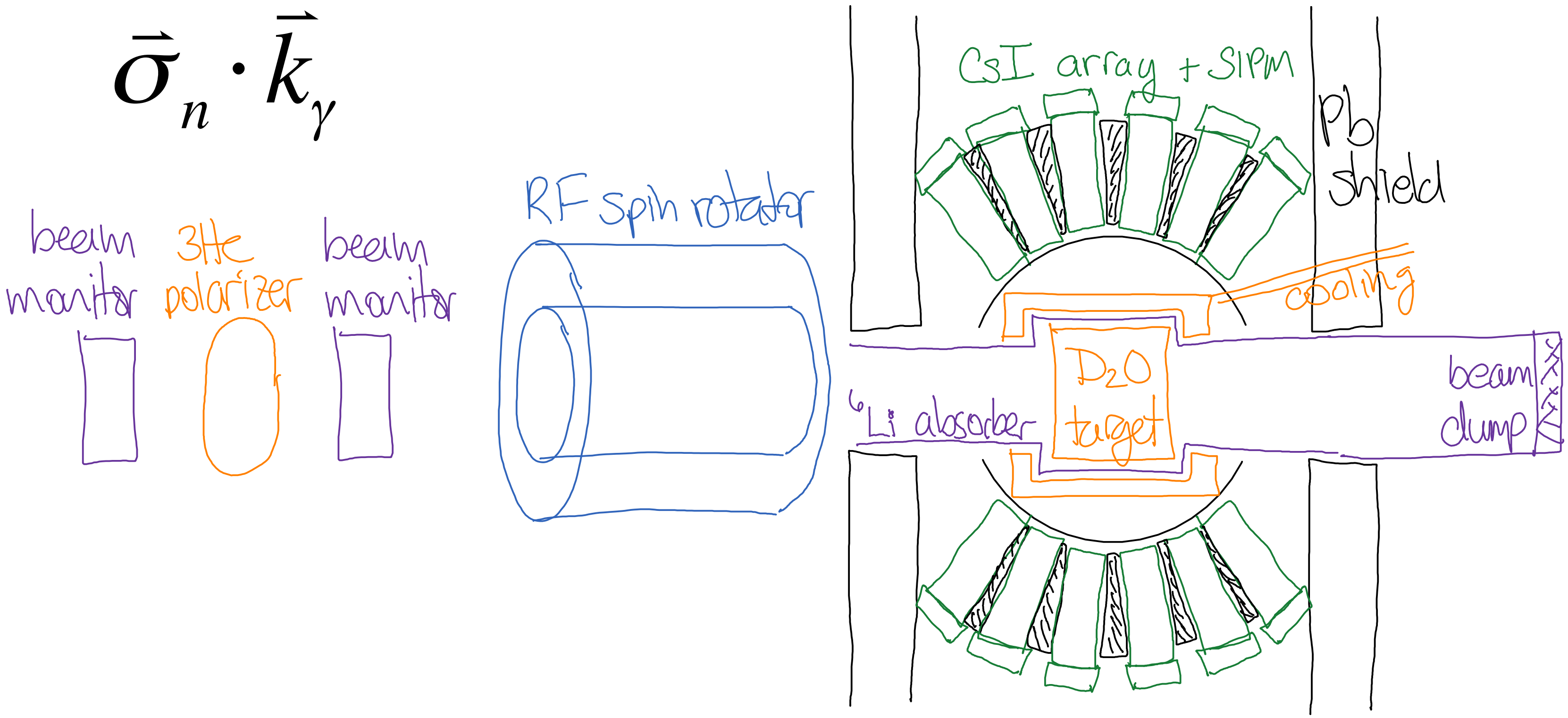
Relatively large expected P-odd asymmetries for experiments!

Measure Λ_2 to compare with lattice prediction

Measurable in future experiments at NIST, ILL, ESS, PIK,…

N+D->T+γ Parity Violation

$$\vec{\sigma}_n \cdot \vec{k}_\gamma$$



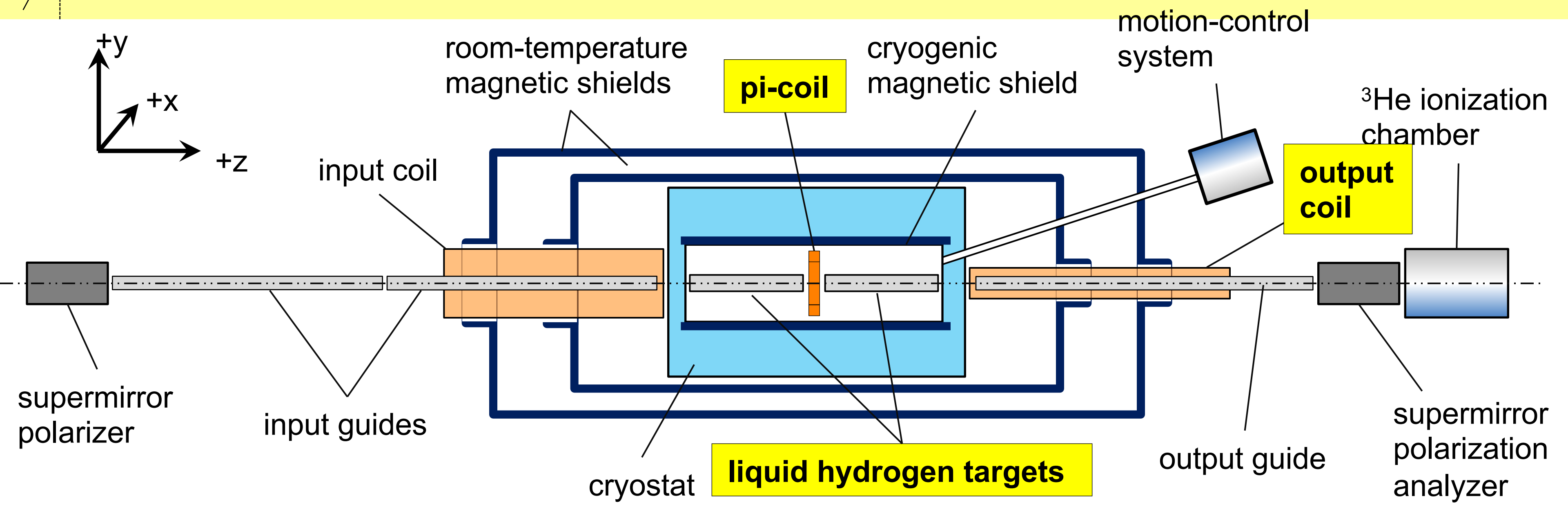
3-body system: calculation doable in pionless EFT and using Fadeev equations

PV asymmetry should be “large” (~10^{-6})

~10^{-7} statistical error on asymmetry would be possible at NIST, ILL, ESS,…

C. Crawford sketch

Liquid Parahydrogen Spin Rotation



2-body system, sensitive to ΔI=2 amplitude!

PV spin rotation angle seems to be “large” (10^{-6} rad/m) using $1/N_c$ estimate

Can use same components as for the helium spin rotation apparatus except for the cryogenic target

210 V.A. Knyaz'kov et al. / Circular polarization

$$\vec{\sigma}_\gamma \cdot \vec{k}_\gamma$$

The famous "Lobashev" n-p parity experiment

Unpolarized n-p capture, look for circular polarization of 2.2 MeV gamma

Result (1984):
Pγ=(1.8 +/- 1.8) x 10^{-7}

2-body system, sensitive to ΔI=2 amplitude!

1.4 X10^{-7} in EFT+1/N_c estimate

Now it is interesting as a QCD test

V.A. Knyaz'kov et al / Circular polarization

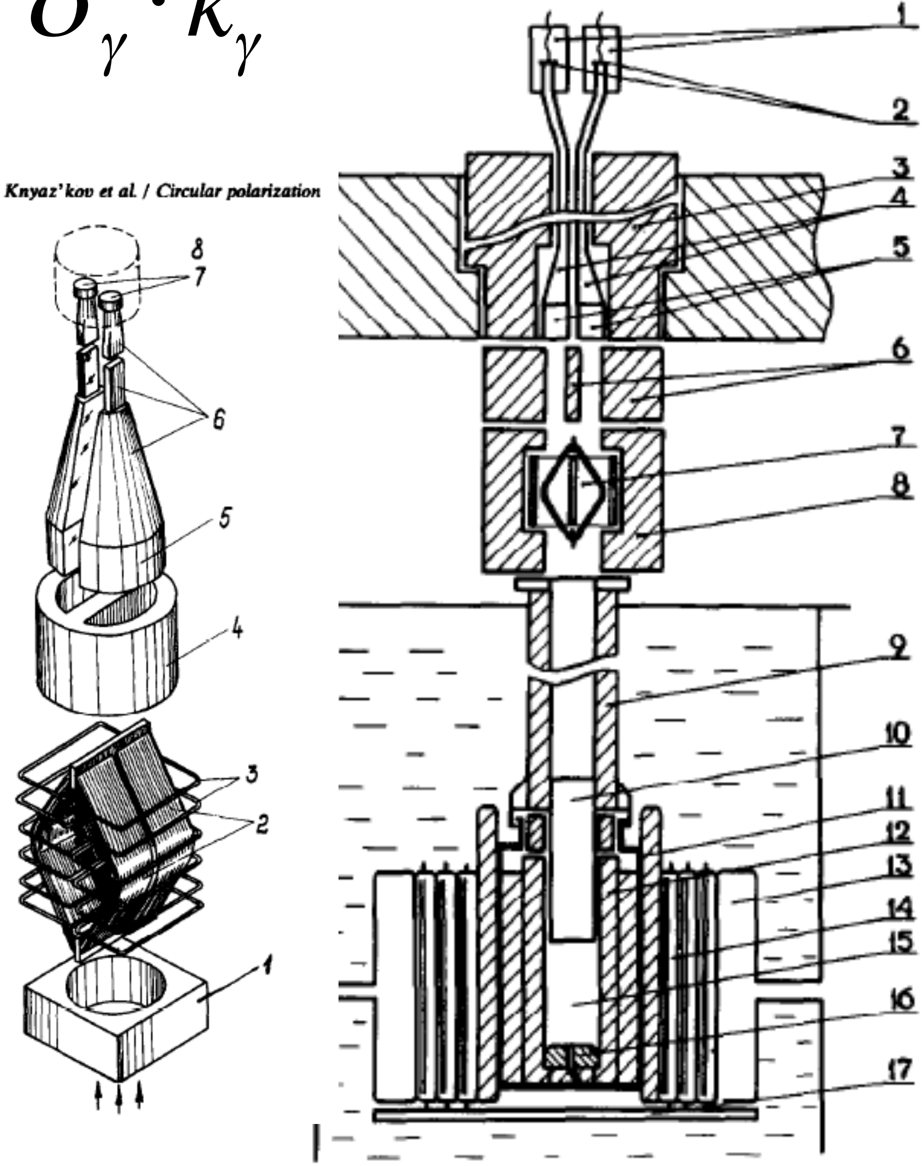


Fig. 1. Layout of installation: 1 – refrigerators; 2 – photodiodes; 3 – detector shielding; 4 – light guides; 5 – γ-ray detectors; 6 – collimator; 7 – polarimeter; 8 – polarimeter shielding; 9 – channel collimator; 10 – evacuated displacer; 11 – additional lead displacers; 12 – lead shielding of water cavity; 13 – beryllium reflector; 14 – fuel elements; 15 – target; 16 – bismuth screen; 17 – core grid.

V. N. Knyazkov et al, Nucl. Phys. A417, 209 (1984)

Conclusions

Advances in Lattice& EFT theory-> NN parity violation can test nonperturbative QCD in a qualitatively new regime

Final NPDGamma and n-^{3}He PV results public very soon

Three experiments appear within reach statistically:

(1) n-^{4}He spin rotation (EFT+1/N_c test, under construction)
(2) NDTGamma parity violation (EFT+1/N_c test, R&D needed)
(3) n-p spin rotation (sensitive to $\Delta I=2$)

Circular polarization in n-p capture ("Lobashev experiment"): can see $\Delta I=2$ piece: can we find a very intense thermal n beam somewhere?

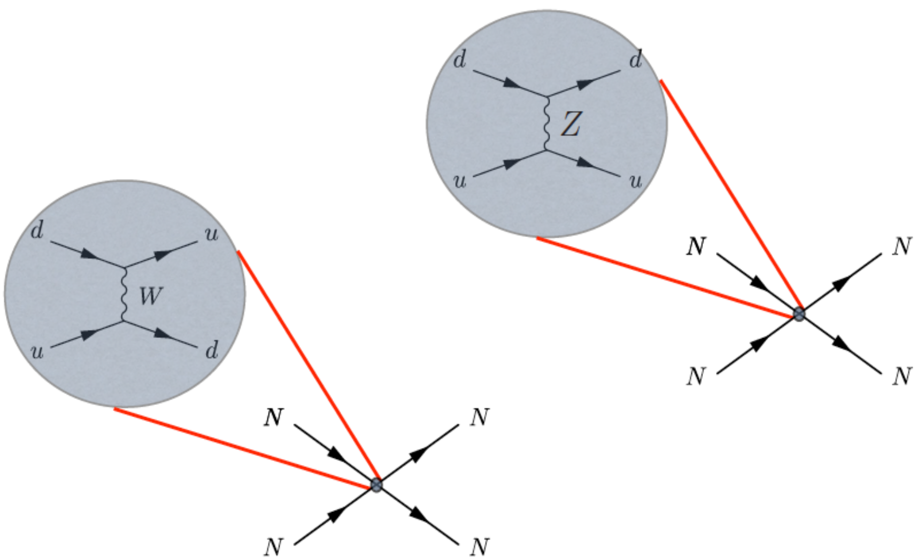
When ANNI beam at ESS beam is constructed, can get ~X5 more **POLARIZED, PULSED** cold neutrons for this physics

q-q Weak Interaction->N-N: 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.

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

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



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

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

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

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

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

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

$^{(2S+1)}L_J$ 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:**

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

QCD and Baryons in the N_c Expansion

QCD in limit $N_c \to \infty$

- Taken with $g^2 N_c$ fixed
- Simplifications
  - Color-singlet physical states
  - Mesons, glueballs: Weakly interacting $\sim 1/\sqrt{N_c}$
- Systematic expansion in $1/N_c$
- Seems to work well phenomenologically

N_c quarks

- Bound state of N_c quarks
- Completely antisymmetric in color: $\epsilon_{i_1 i_2 \cdots i_{N_c}} q^{i_1} q^{i_2} \cdots q^{i_{N_c}}$
- Baryon mass $M \sim N_c$
- $\lim N_c \to \infty$: SU(4) spin-flavor symmetry: $u\uparrow$, $u\downarrow$, $d\uparrow$, $d\downarrow$

t'Hooft 1974,
Witten 1979