Pionless Effective Field Theory and low-energy few-nucleon parity violation

Goal: Encode all low-energy parity-violation measurements (existing and expected) on few-nucleon systems in terms of a few simple rules/parameters: unbiased and systematic, based upon standard model symmetries and power counting only.

Start with *very* low energy, for two and three nucleons, and see if we can understand those systems. $E \lesssim 10 \text{ MeV}$

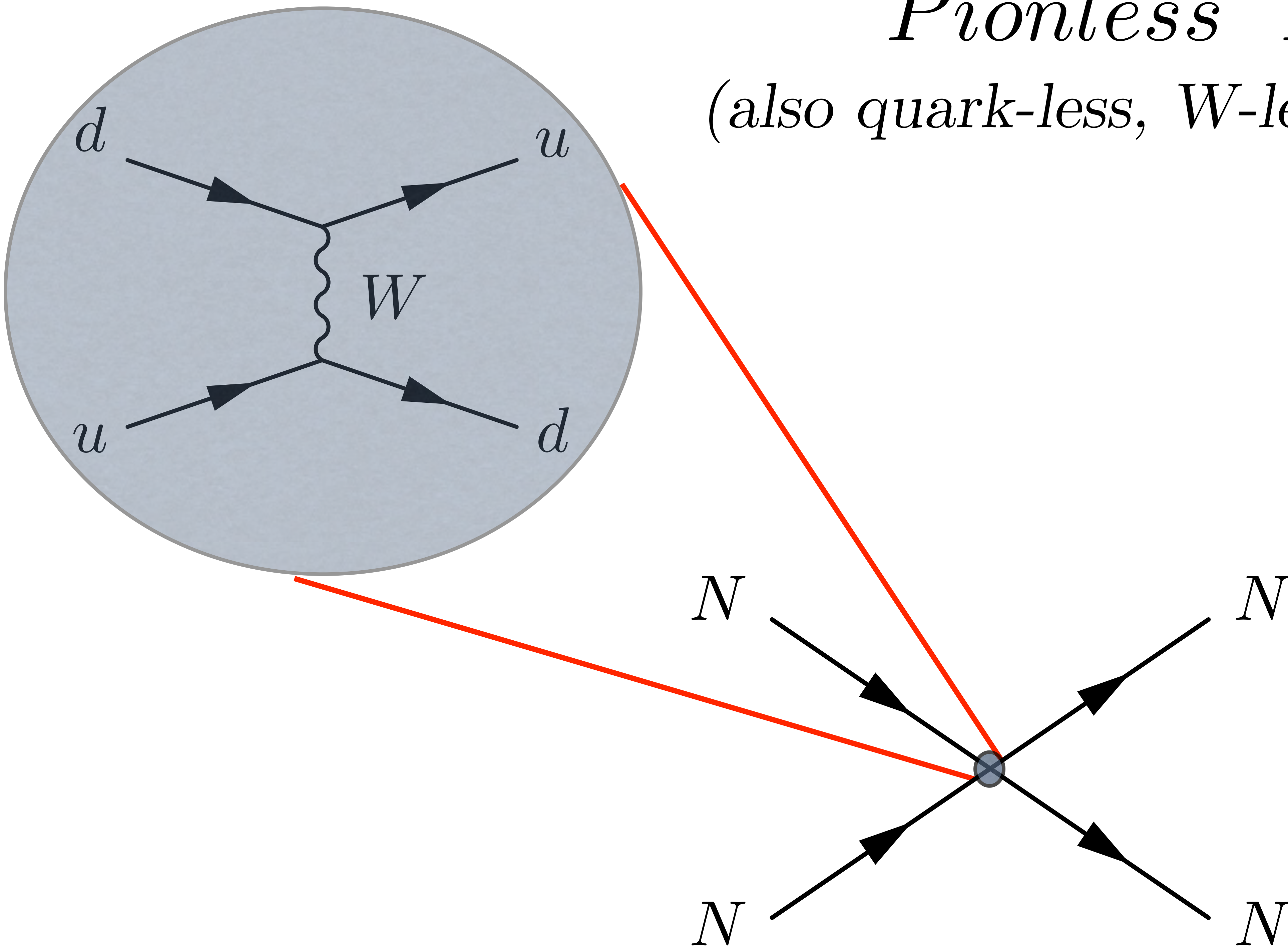
Experimental challenge: $\sim 10^{-7}$ signal

Input: EFT and large N_C -> Output: future experimental focus

Hadronic Parity Nonconservation KITP Santa Barbara
March 15-16, 2018 R P Springer

Pionless EFT

(also quark-less, W-less, and Z-less)

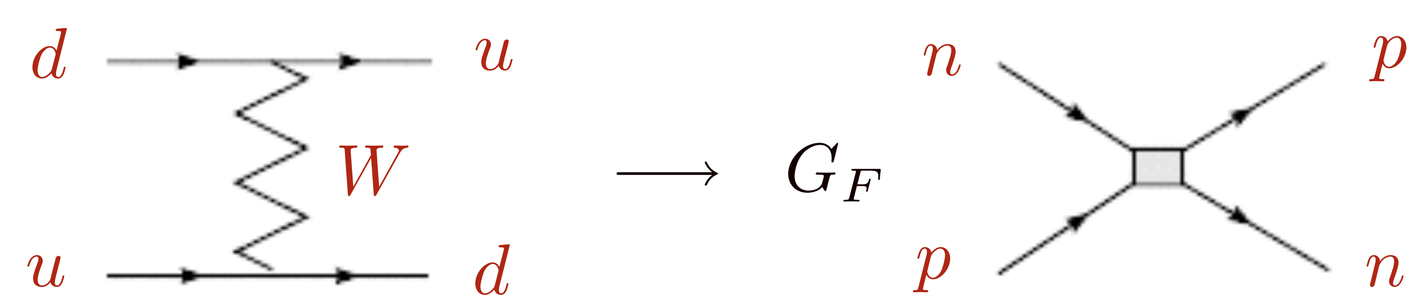


If the symmetries are correct and the power counting is correct, results include those of the underlying theory (e.g., QCD/PV) — but unknown parameters specify which underlying theory.

Creating an EFT

$C(\mu)$ is not an observable

Top-down procedure
(not to scale)



(GeV)

180 ——— t,Z,W,b,c,s,d,u,γ, ν

run ↓ match

$$\sum_i^{n_{\not{t}}} C_i^{\not{t}}(\mu)\mathcal{O}_i^{\not{t}}(\mu)$$

90 ——— Z,W,b,c,s,d,u,γ, ν

run ↓ match

$$\sum_i^{n_{\not{W}}} C_i^{\not{W}}(\mu)\mathcal{O}_i^{\not{W}}(\mu)$$

$$C_i^{\not{W}}(\mu = 80) \neq C_i^{\not{W}}(\mu = 10)$$

5 ——— b,c,s,d,u,γ, ν

~~run~~ ↓ match ⋮

$$\sum_i^{n_{\not{b}}} C_i^{\not{b}}(\mu)\mathcal{O}_i^{\not{b}}(\mu)$$

$$C_i^{\not{b}} \neq C_i^{\not{W}}$$

$$n_{\not{b}} \neq n_{\not{W}}$$

1 ——— nucleons, pions, . . . , γ, ν

~~run~~ ↓ ~~match~~

0.01 ——— nonrelativistic nucleons, γ, ν

~~match~~

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

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

operators containing γ, p, n

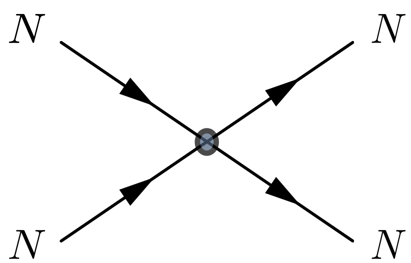
sum over terms (to desired order)

coefficients include all other physics

μ dependence!

Two Nucleon Parity Conserving Interaction Terms

$$\mathcal{L} = N^\dagger\left(iD_0 + \frac{\vec{D}^2}{2M}\right)N + \frac{e}{2M}N^\dagger(\kappa_0 + \kappa_1\tau_3)\sigma\cdot BN$$



$$-\frac{1}{8}\mathcal{C}_0^{(^1S_0)}(N^T\tau_2\tau_a\sigma_2N)^\dagger(N\tau_2\tau_a\sigma_2N)$$

$$-\frac{1}{8}\mathcal{C}_0^{(^3S_1)}(N^T\tau_2\sigma_2\sigma_iN)^\dagger(N\tau_2\sigma_2\sigma_iN) + \cdots$$

(Observables: mag. mom., scatt lengths)

$$P_a(^1S_0) = \frac{1}{\sqrt{8}}\tau_2\tau_a\sigma_2 \;; \qquad P_i(^3S_1) = \frac{1}{\sqrt{8}}\tau_2\sigma_2\sigma_i$$

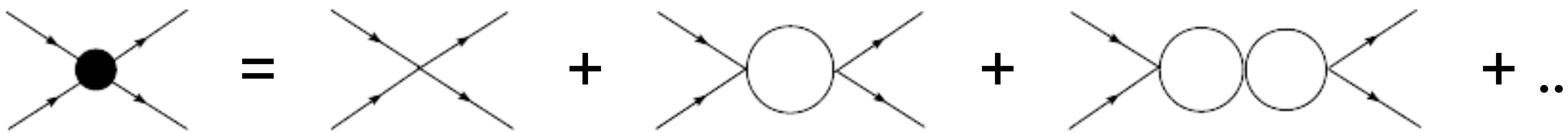
$$D_\mu N = \partial_\mu N + i\frac{e}{2}(1+\tau_3)A_\mu N$$

isospin doublet $N = \begin{pmatrix} p \\ n \end{pmatrix}$

$\sigma \sim$ Pauli for spin

$\tau \sim$ Pauli for I-spin

Parity Conserving NN



$$A \quad = \quad \mathcal{C} \quad + \quad i\mathcal{C}^2 \frac{Mp}{4\pi} \quad + \quad \mathcal{C}^3 \left(\frac{Mp}{4\pi}\right)^2 \quad + \cdots$$

$$A = \frac{4\pi}{M}[-a + ia^2 p + \frac{1}{2}(a^3 - a^2 r_0)p^2 + \cdots]$$

does not converge

$$a^{(^1S_0)} \sim -\frac{1}{8\ \mathrm{MeV}} \qquad a^{(^3S_1)} \sim \frac{1}{36\ \mathrm{MeV}}$$

Both S-wave scattering lengths anomalously large => momentum expansion fails => reorganize to treat C's nonperturbatively

$$A = -\frac{4\pi}{M}\frac{1}{1/a + ip} + \cdots$$

$$\mathcal{C}(\mu) = \frac{4\pi}{M}\frac{1}{-\mu + 1/a}$$

EM effects easily included

Kaplan/Savage/Wise
v. Kolck

$np \to d\gamma$ Parity Conserving

(See Vanasse for 3N examples)

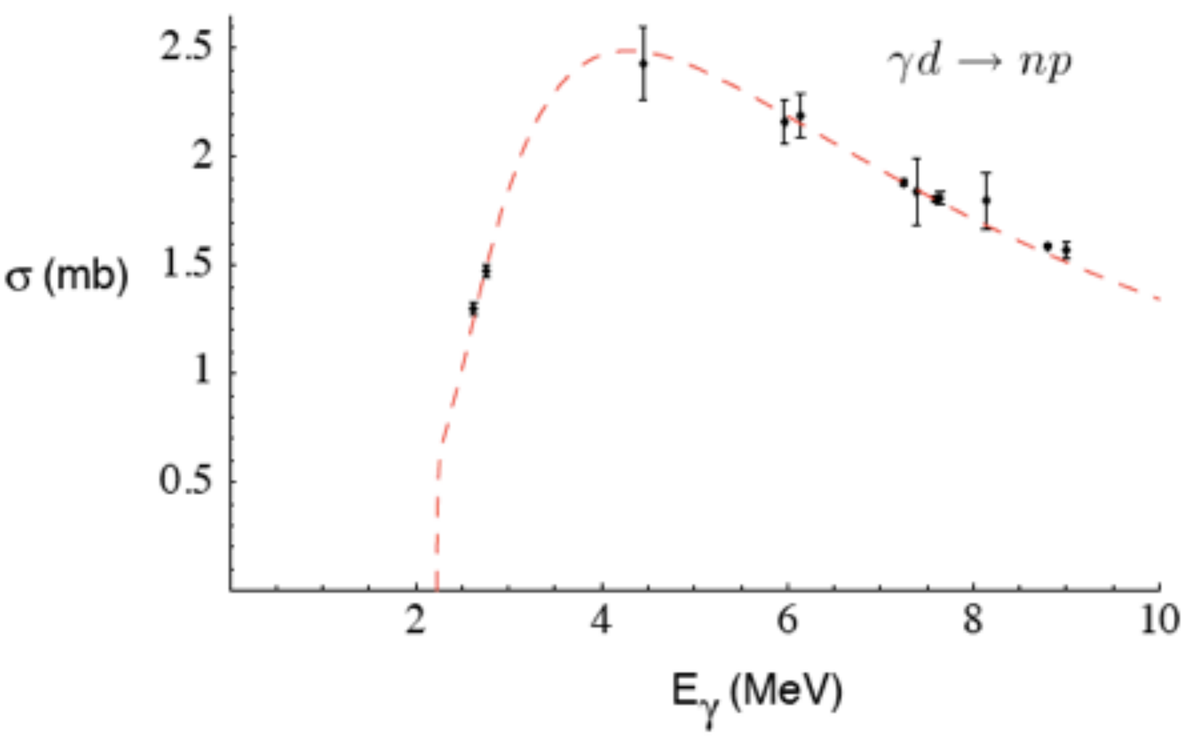
Rupak NPA 678, 405 (2000)

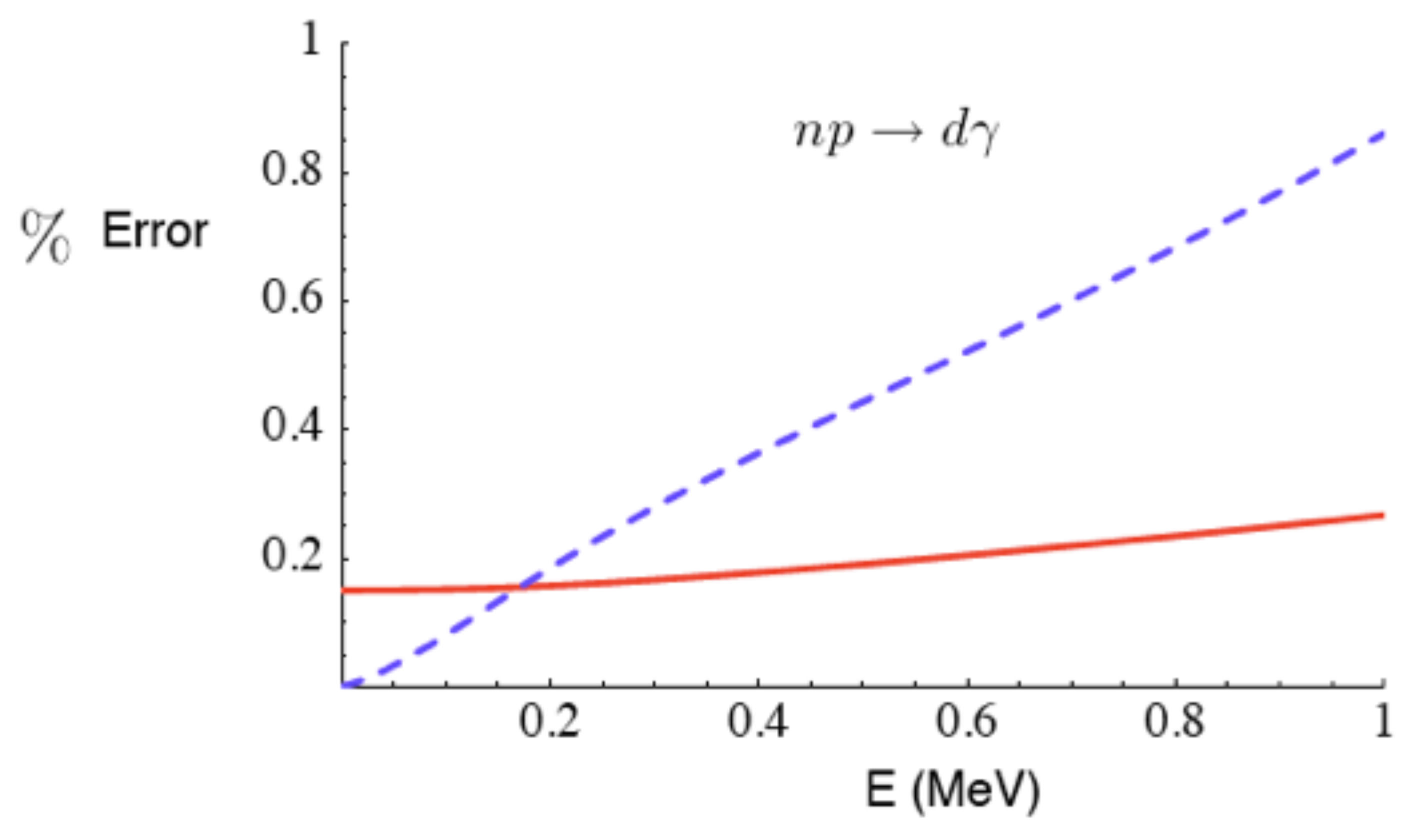
$\mathrm{E1}_V$ to $\mathrm{N^4LO}$

$$\frac{C_2}{2}\left[(N^T \mathcal{O}_i^{(2)} N)\left(N^T P_i N\right) + \mathrm{h.c}\right] \qquad P_i = \frac{1}{\sqrt{8}}\sigma_2\sigma_i\tau_2$$

$$\mathcal{O}_i^{(2)} = \frac{1}{4}\left[\overleftarrow{D}^2 P_i - 2\overleftarrow{D}P_i\overrightarrow{D} + P_i\overrightarrow{D}^2\right] \qquad D_\mu = \partial_\mu N + ie\frac{1+\tau_3}{2}A_\mu N$$

$$\frac{e}{2M}N^\dagger(\kappa_0 + \tau_3\kappa_1)\vec{\sigma}\cdot\vec{B}N$$





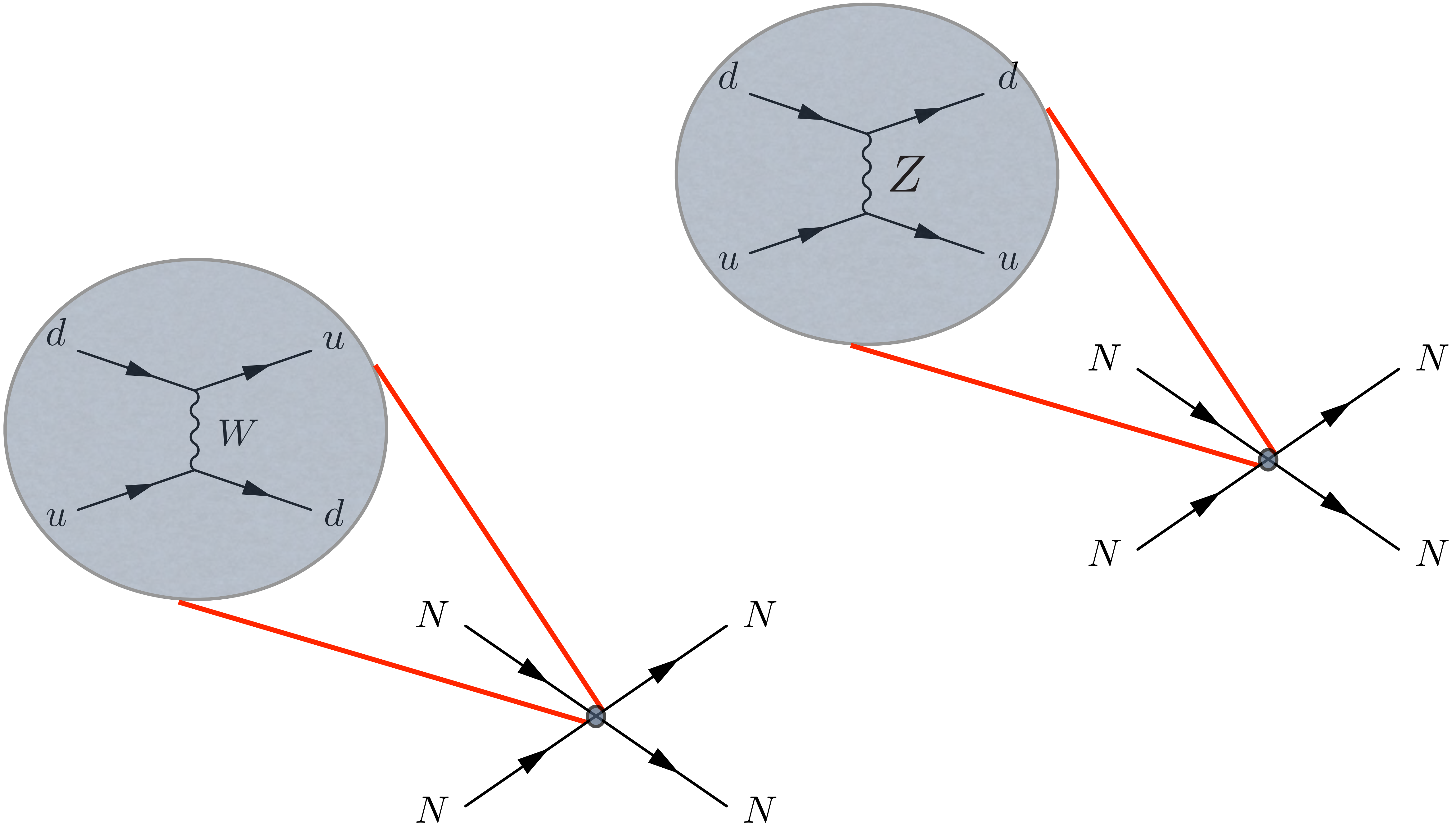
Five parity-violating EFT$_{\not\pi}$ low-energy constants

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

Schindler/RPS NPA 846 (2010) 51

cf. Danilov parameters, Zhu et al. NPA 748 (2005) 435,
Girlanda PRC 77 (2008) 067001.

What are these coefficients?



Standard model of weak interactions in quark sector

$$\mathcal{L} = \frac{g}{2\sqrt{2}} \left(\overline{u} \quad \overline{c} \quad \overline{t}\right) \gamma^\mu (1-\gamma_5)\, V \begin{pmatrix} d \\ s \\ b \end{pmatrix} W^+_\mu \; + \; \text{h.c.} \; + \; [Z] \; + \cdots$$

$$\rightarrow \mathcal{H} = \frac{G_F}{\sqrt{2}} \left([J^\nu_{(cc)}]^\dagger J_{(cc)\nu} + [J^\nu_{(nc)}]^\dagger J_{(nc)\nu} \right)$$

light quarks:

$I = 1$

$$V \sim \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix}$$

$$J^\nu_{(cc)} \sim \cos\theta_c \overline{u}_L \gamma^\nu d_L + \sin\theta_c \overline{u}_L \gamma^\nu s_L$$

$I(s) = 0$ $\qquad$ $I = 1/2$ $\qquad$ from $SU(2)_L \times U(1)_Y$

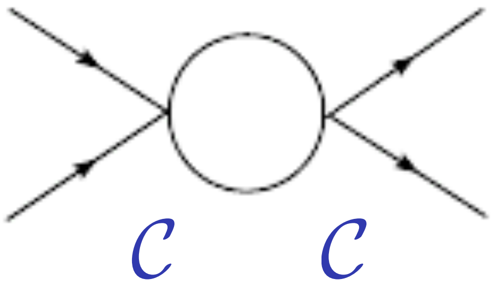
$$J^\nu_{(nc)} \sim \overline{u}_L \gamma^\nu u_L - \overline{d}_L \gamma^\nu d_L - \overline{s}_L \gamma^\nu s_L - 4\sin^2\theta_W J^\nu_{EM}$$

$$J^\nu_{nc} \sim J^{\nu,(I=1)}_{nc} + J^{\nu,(I=0)}_{nc} \qquad J^\nu_{(EM)} \sim \sum_{f=u,d,s} \overline{f} \gamma^\nu Q_f f$$

$$\Delta S = 0 \rightarrow \mathcal{H}^{\Delta I=2} + \mathcal{H}^{\Delta I=1} + \mathcal{H}^{\Delta I=0} \qquad \frac{\text{weak}}{\text{strong}} \sim G_F m_\pi^2 \sim 10^{-7}$$

must rely on parity violation to distinguish the weak portion among nucleons

Scaling of Operators



strong-strong

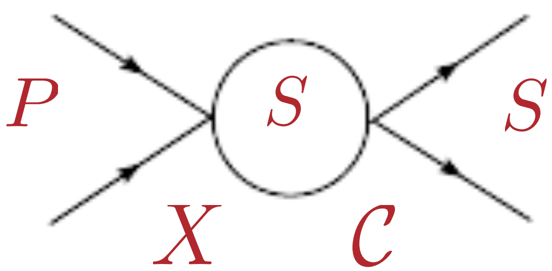
$$\frac{Q^5}{Q^2 Q^2} \sim Q$$

$$\mathcal{C} = \mathcal{C}^{(^1S_0)}, \mathcal{C}^{(^3S_1)}$$

$$a = a(^1S_0), a(^3S_1)$$

$$\mu \frac{d}{d\mu}\mathcal{C} = \frac{M\mu}{4\pi}\mathcal{C}^2$$

$$\mathcal{C}(\mu) = \frac{4\pi}{M}\frac{1}{-\mu + 1/a}$$



weak-strong

$$\mu \frac{d}{d\mu}X(\mu) = \frac{M\mu}{4\pi}\mathcal{C}(\mu)X(\mu)$$

$$X(\mu) = X(0)\frac{1/a}{-\mu + 1/a}$$

$$X = X^{(^1S_0)}, X^{(^3S_1)}$$

NN Parity Violating Observables

- $\vec{p} + p \to p + p$ $\qquad A_L = \frac{\sigma^+(\theta) - \sigma^-(\theta)}{\sigma^+(\theta) + \sigma^-(\theta)}$

$$A_L^{\vec{p}p}(E = 13.6\mathrm{MeV}) = (-0.93 \pm 0.21) \times 10^{-7}$$

P.D.Eversheim *et al.* PLB **256** (1991) 11.

- nn/np analyzing power

- $n + p \to d + \vec{\gamma}$ $\qquad P_\gamma = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-} \sim -2\frac{E1(PV)}{M1(PC)}$

$$P_\gamma^{\mathrm{exp}} = (1.8 \pm 1.8) \times 10^{-7}$$

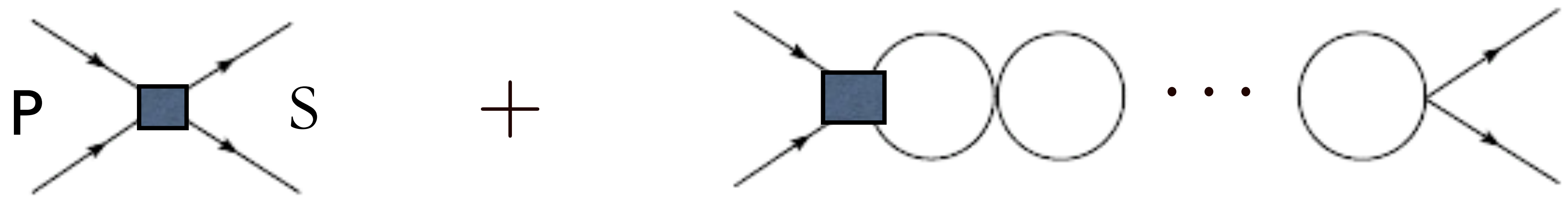
V.A. Knyazkov *et al.* NPA **197** 241 (1972)

- $\vec{n} + p \to d + \gamma$ $\qquad \frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = 1 + A_\gamma \cos\theta$

NPDGamma Oak Ridge SNS

$A_\gamma^{\mathrm{exp}} \lesssim 10^{-8}$ http://meetings.aps.org/link/BAPS.2015.APR.S6.2).

NN Analyzing Power



$$A_L^{nn} = \frac{8M}{\pi} p \left(\mathcal{C}^{(\Delta I=0)}_{(^1S_0 - ^3P_0)} - \mathcal{C}^{(\Delta I=1)}_{(^1S_0 - ^3P_0)} + \mathcal{C}^{(\Delta I=2)}_{(^1S_0 - ^3P_0)} \right) \left(\frac{1}{a^{^1S_0}} - \mu \right)$$

$$A_L^{pp} = \frac{8M}{\pi} p \left(\mathcal{C}^{(\Delta I=0)}_{(^1S_0 - ^3P_0)} + \mathcal{C}^{(\Delta I=1)}_{(^1S_0 - ^3P_0)} + \mathcal{C}^{(\Delta I=2)}_{(^1S_0 - ^3P_0)} \right) \left(\frac{1}{a^{^1S_0}} - \mu \right)$$

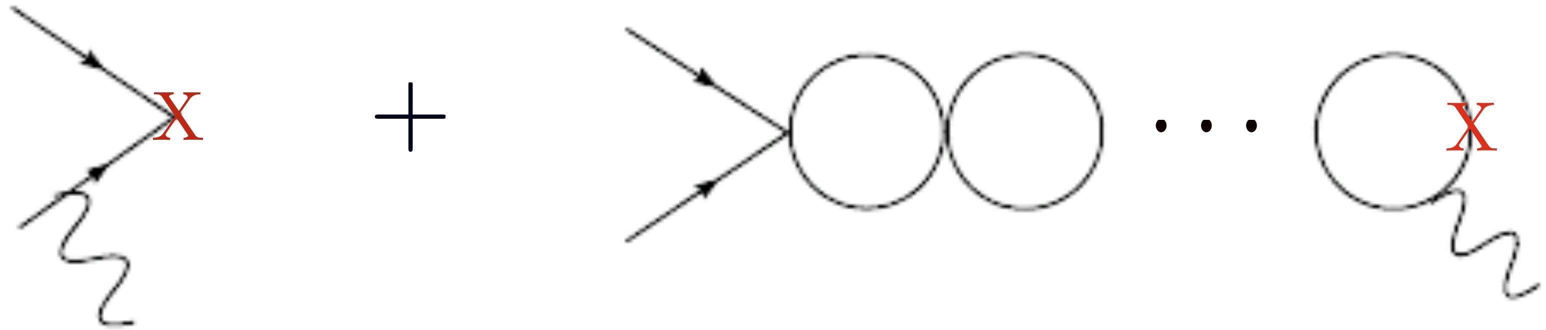
$$A_L^{np} = \frac{8M}{\pi} p \frac{\frac{d\sigma^{(^1S_0)}}{d\Omega}}{\frac{d\sigma^{(^1S_0)}}{d\Omega} + 3\frac{d\sigma^{(^3S_1)}}{d\Omega}} \left(\mathcal{C}^{(\Delta I=0)}_{(^1S_0 - ^3P_0)} - 2\mathcal{C}^{(\Delta I=2)}_{(^1S_0 - ^3P_0)} \right) \left(\frac{1}{a^{(^1S_0)}} - \mu \right)$$

$$+ \frac{8M}{\pi} p \frac{\frac{d\sigma^{(^3S_1)}}{d\Omega}}{\frac{d\sigma^{(^1S_0)}}{d\Omega} + 3\frac{d\sigma^{(^3S_1)}}{d\Omega}} \left(\mathcal{C}_{(^3S_1 - ^1P_1)} - 2\mathcal{C}_{(^3S_1 - ^3P_1)} \right) \left(\frac{1}{a^{(^3S_1)}} - \mu \right)$$

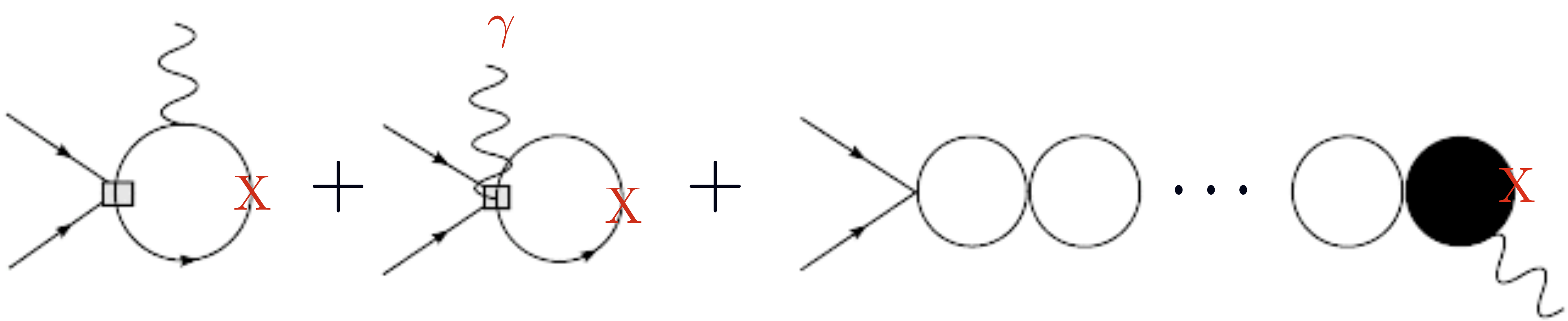
Phillips/Schindler/RPS NPA 822 (2009) 1

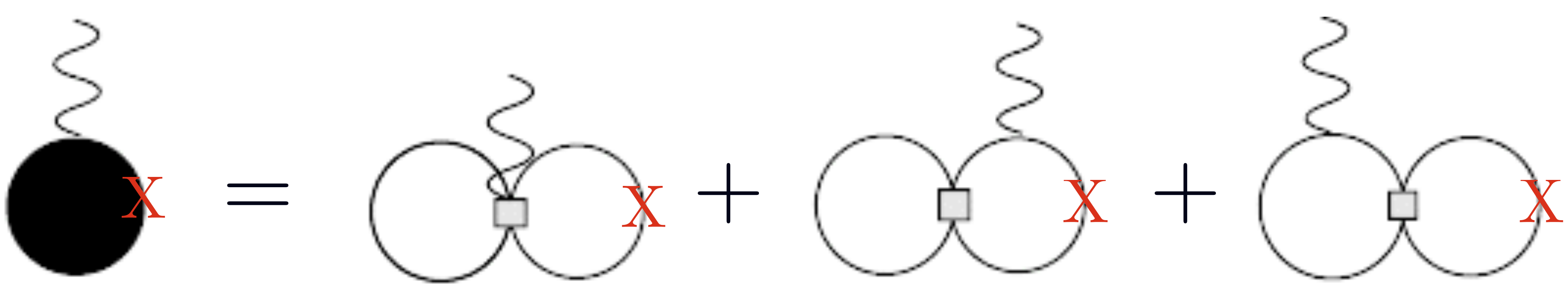
$$\vec{n} + p \to d + \gamma \quad \text{and} \quad n + p \to d + \overset{\circlearrowleft}{\gamma}$$

strong piece:
M1



weak piece:





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

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} = 1 + A_\gamma \cos\theta \qquad A_\gamma = -\frac{2}{B}\mathrm{Re}\frac{M1^* E1}{|M1|^2}$$

$$= \frac{32}{3}\frac{M}{\kappa_1(1-\gamma a^{(^1S_0)})}\frac{\mathcal{C}^{(^3S_1-^3P_1)}}{\mathcal{C}_0^{(^3S_1)}}$$

$$np \to \overset{\circlearrowleft}{\gamma} d$$

$$P_\gamma = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} \qquad = -16\frac{M}{\kappa_1(1-\gamma a^{(^1S_0)})}\cdot$$

$$\left[\left(1-\frac{2}{3}\gamma a^{(^1S_0)}\right)\frac{\mathcal{C}^{(^3S_1-^1P_1)}}{\mathcal{C}_0^{^3S_1}} + \left(\frac{\gamma a^{(^1S_0)}}{3}\right)\frac{\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=0)} - 2\mathcal{C}^{(^1S_0-^3P_0)}_{(\Delta I=2)}}{\mathcal{C}_0^{(^1S_0)}}\right]$$

Schinder/RPS NA846 (2010) 51.

LO Extraction of PV low energy constants

$$pp \to \mathcal{C}^{(\Delta I=0)}_{(^1S_0-^3P_0)}\ ,\ \mathcal{C}^{(\Delta I=1)}_{(^1S_0-^3P_0)}\ ,\ \mathcal{C}^{(\Delta I=2)}_{(^1S_0-^3P_0)}$$

$$nn \to \mathcal{C}^{(\Delta I=0)}_{(^1S_0-^3P_0)}\ ,\ \mathcal{C}^{(\Delta I=1)}_{(^1S_0-^3P_0)}\ ,\ \mathcal{C}^{(\Delta I=2)}_{(^1S_0-^3P_0)}$$

(in different combination)

$$np\ (^1S_0) \to \mathcal{C}^{(\Delta I=0)}_{(^1S_0-^3P_0)}\ ,\ \mathcal{C}^{(\Delta I=2)}_{(^1S_0-^3P_0)}$$

$$np\ (^3S_1) \to \mathcal{C}_{(^3S_1-^1P_1)}\ ,\ \mathcal{C}_{(^3S_1-^3P_1)}$$

$$(\vec{n}p \to d\gamma) \to \mathcal{C}_{(^3S_1-^3P_1)}$$

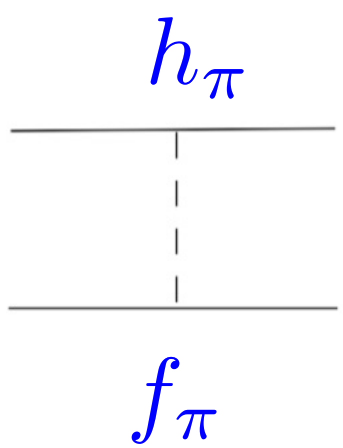
$$(np \leftrightarrow d\overset{\circlearrowleft}{\gamma}) \to \mathcal{C}_{(^3S_1-^1P_1)}\ ,\ \mathcal{C}^{(\Delta I=0)}_{(^1S_0-^3P_0)}\ ,\ \mathcal{C}^{(\Delta I=2)}_{(^1S_0-^3P_0)}$$

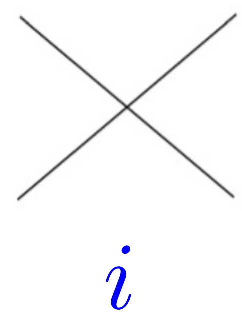
$$n \text{ rotation off } d \to \mathcal{C}_{(^3S_1-^3P_1)}, \mathcal{C}_{(^3S_1-^1P_1)}, \mathcal{C}^{(\Delta I=0)}_{(^1S_0-^3P_0)}, \mathcal{C}^{(\Delta I=1)}_{(^1S_0-^3P_0)}$$

Griesshammer/Schindler/RPS Eur.Phys.J. A48 (2012) 7

Compare to Pionful Description needed for higher energies

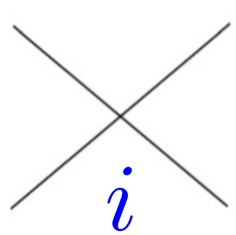
Pionful PV NN interaction $\sum_i C_i^{\pi}(\mu)\mathcal{O}_i^{\pi}(\mu)$



$+ \sum_i C_i^{\pi}$ 

i=5 pionful PV LECs

Pionless PV NN interaction $\sum_i C_i^{\not\pi}(\mu)\mathcal{O}_i^{\not\pi}(\mu)$

$\sum_i C_i^{\not\pi}$ 

i=5 pionless PV LECs

$$C_i^{\not\pi}(\mu) \neq C_i^{\pi}(\mu)$$

Imposing LO large N$_c$ symmetry

$$pp \rightarrow \mathcal{C}^{(\Delta I=0)}_{(^1S_0-^3P_0)}\ ,\ \cancel{\mathcal{C}^{(\Delta I=1)}_{(^1S_0-^3P_0)}}\ ,\ \mathcal{C}^{(\Delta I=2)}_{(^1S_0-^3P_0)} \quad \rightarrow \mathcal{C}_{(^3S_1-^1P_1)}, \mathcal{C}^{(\Delta I=2)}_{(^1S_0-^3P_0}$$

$$nn \rightarrow \mathcal{C}^{(\Delta I=0)}_{(^1S_0-^3P_0)}\ ,\ \cancel{\mathcal{C}^{(\Delta I=1)}_{(^1S_0-^3P_0)}}\ ,\ \mathcal{C}^{(\Delta I=2)}_{(^1S_0-^3P_0)} \quad \rightarrow \mathcal{C}_{(^3S_1-^1P_1)}, \mathcal{C}^{(\Delta I=2)}_{(^1S_0-^3P_0}$$

$$np\ (^1S_0) \rightarrow \mathcal{C}^{(\Delta I=0)}_{(^1S_0-^3P_0)}\ ,\ \mathcal{C}^{(\Delta I=2)}_{(^1S_0-^3P_0)} \quad \rightarrow \mathcal{C}_{(^3S_1-^1P_1)}, \mathcal{C}^{(\Delta I=2)}_{(^1S_0-^3P_0}$$

$$np\ (^3S_1) \rightarrow \mathcal{C}_{(^3S_1-^1P_1)}\ ,\ \cancel{\mathcal{C}_{(^3S_1-^3P_1)}} \quad \rightarrow \mathcal{C}_{(^3S_1-^1P_1)}$$

$$(\vec{n}p \rightarrow d\gamma) \rightarrow \cancel{\mathcal{C}_{(^3S_1-^3P_1)}}$$

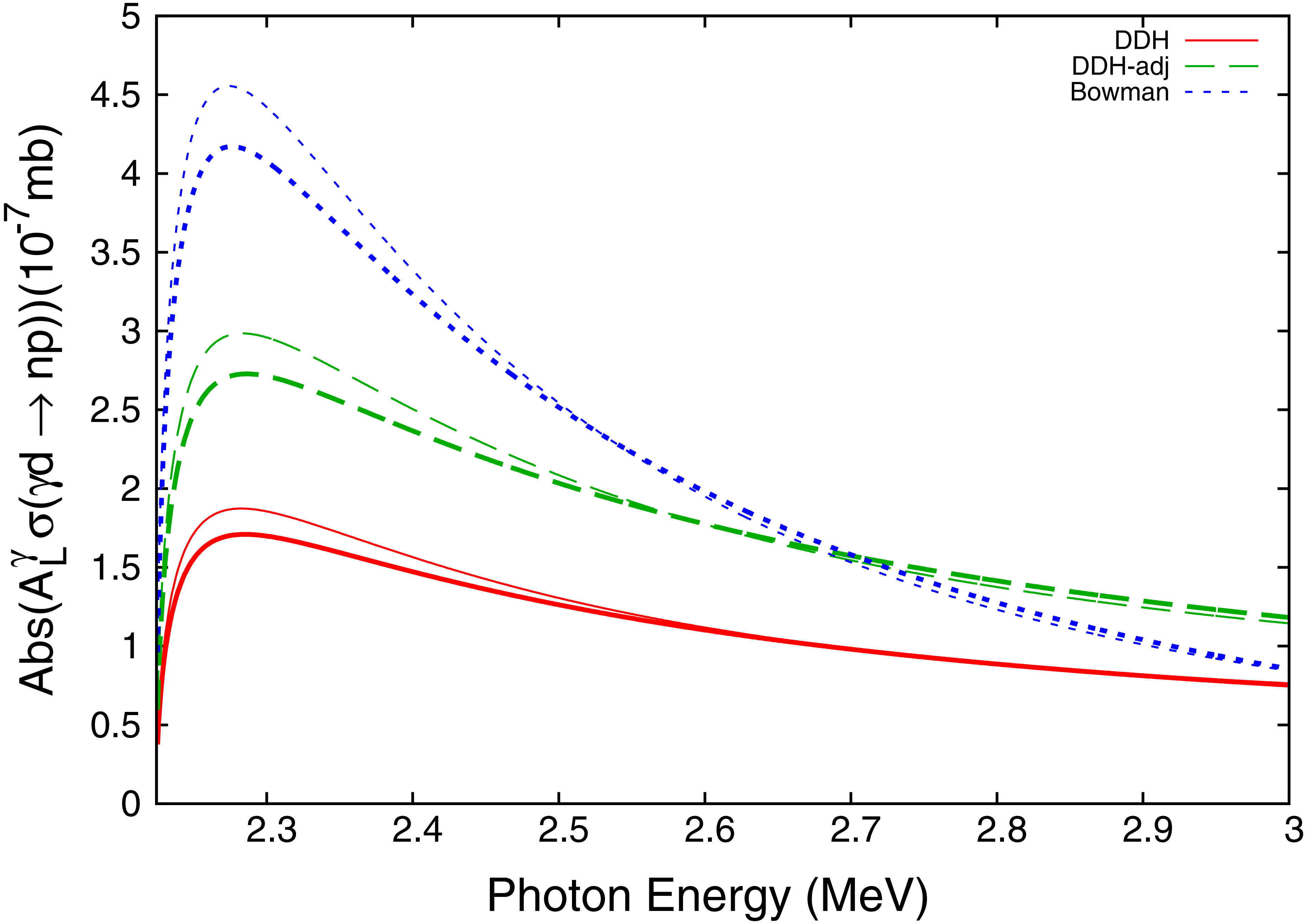
$$(np \leftrightarrow d\overset{\circlearrowleft}{\gamma}) \rightarrow \mathcal{C}_{(^3S_1-^1P_1)}\ ,\ \mathcal{C}^{(\Delta I=0)}_{(^1S_0-^3P_0)}\ ,\ \mathcal{C}^{(\Delta I=2)}_{(^1S_0-^3P_0)} \rightarrow \mathcal{C}_{(^3S_1-^1P_1)}, \mathcal{C}^{(\Delta I=2)}_{(^1S_0-^3P_0}$$

$$n \text{ rotation off } d \rightarrow \cancel{\mathcal{C}_{(^3S_1-^3P_1)}}, \mathcal{C}_{(^3S_1-^1P_1)}, \mathcal{C}^{(\Delta I=0)}_{(^1S_0-^3P_0)}, \cancel{\mathcal{C}^{(\Delta I=1)}_{(^1S_0-^3P_0)}}$$

$$\rightarrow \mathcal{C}_{(^3S_1-^1P_1)}$$

$\overset{\circlearrowleft}{\gamma} d \to np$

Vanasse/Schindler PRC,90,044001



NSAC Implementation (2013)

``Parity-violation measurements offer another way to probe the short-distance behavior of the nuclear force and its relation to QCD...An experiment [of $\vec{\gamma} d \to np$] is being discussed at the High Intensity Gamma Source at ...(TUNL)...if an upgrade to higher flux is carried out.”

See Viviani Talk

$\vec{n} + {}^3He \rightarrow p + {}^3H$

Oak Ridge Spallation Neutron Source
(Bowman, Gericke, Crawford)
expected to 10^{-8}

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

depends upon 4 EFT$_{\not\pi}$ LECs (not $\Delta I = 2$)

hybrid prediction $\sim 10^{-8} - 10^{-7}$
(Viviani, Schiavilla, Girlanda, Kievsky, Marcucci, PRC 82, 0440001 (2010))

Future Possibilities for PV Measurement, cont.

spin rotation: $\vec{n} + {}^4He$

Snow et al, PRC 83, 022501(R) 2011:
$\frac{d\phi}{dz} = (1.7 \pm 9.1 \pm 1.4) \times 10^{-7}$ rad/m

NIST goal: 10^{-7} rad/m

Sensitive to same parameters as $\vec{n} + {}^3He$

Model potential: $\sim 10^{-6}$ rad/m

(Dmitriev, Flambaum, Sushkov, Telitson, PLB 125, 1 (1983))

Summary and Outlook

- $\text{EFT}_{\not\pi}$ well established for parity conserving NN(N)
- More bodies on the horizon
- PV NN(N) is promising; more calcs in progress
- Well-suited for large N_C restrictions
- 5 PV LECs (before large N_C)
- Importance of $\Delta I = 2$ (lattice?)
- Measurement needed: HIGS2 $\vec{\gamma} d \rightarrow np$ $(\vec{\gamma} + {}^3H \rightarrow nd)$
- Expected: SNS $\vec{n} + {}^3He$
- Planned: NIST $\vec{n} + {}^4He$
- Future for theory: pions needed to extend energy range