Parity Violation in Few-Nucleon Systems [1]

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Outline

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c²	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

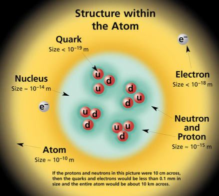
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c²	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c^2 = 1.67×10^{-27} kg.



BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c²	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c²	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

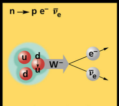
Symbol	Name	Quark content	Electric charge	Mass GeV/c²	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

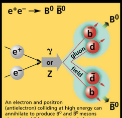
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

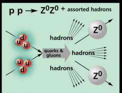
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:

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BURLE INDUSTRIES, INC.

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Classification of weak interactions

Interaction		*Charged*		*Neutral*		*Charged+Neutral*
Leptonic						
	(1)	$\mu \to e\nu\nu$ (2×10^{-5})	(4)	$\nu_\mu e \to \nu_\mu e$	(7)	$\nu_e e \to \nu_e e$ (10%)
	(2)	$\nu_\mu e \to \mu\nu_e$	(5)	$\bar{\nu}_\mu e \to \bar{\nu}_\mu e$	(8)	$\bar{\nu}_e e \to \bar{\nu}_e e$
	(3)	$\tau \to l\nu\nu$	(6)	$e^+e^- \to l^+l^-$	(9)	$e^+e^- \to \nu_e\bar{\nu}_e$
Semileptonic						
Meson	(10)	$\pi^+ \to \mu\nu,\ e\nu$ (2×10^{-4})				
		$K^+ \to \mu\nu,\ e\nu$				
		$F^+ \to \tau^+\nu$				
	(11)	$\pi^+ \to \pi^0 e\nu$				
	(12)	$K^+ \to \pi^0 l\nu$				
		$K^0_L \to \pi^\pm l\nu$				
	(13)	$D \to \begin{pmatrix}\pi\\ K\\ K^*\end{pmatrix} l\nu$				
Baryon	(14)	$\mu^- B \to B'\nu$	(17)	$eN \to eN,\ eX$ (10 − 0.1%)		
	(15)	$B \to B'l\nu$	(18)	$\nu N \to \nu N,\ \nu N\pi,\ \nu X$		
	(16)	$\nu B \to B'l$	(19)	$\bar{\nu}_e + D \to n + p + \bar{\nu}_e$		
Hadronic						
Meson	(20)	$K \to \pi\pi$ (1×10^{-3})				
	(21)	$K \to 3\pi$ (8×10^{-3})				
	(22)	$D \to KK,\ K\pi,\ K2\pi,\ K3\pi$				
	(23)	$B^{0,\pm} \to D\pi,\ DK$				
Baryon	(24)	$\Lambda \to N\pi$			(26)	$NN \to NN$ (10%)
		$\Sigma \to N\pi$				
		$\Xi \to N\pi$				
	(25)	$\Lambda_c^- \to pK^-\pi^+$				

Still fuzzy after 50 years...

Fact

Strong (and EM, too) interaction is omnipresent!

- Experimentally:
  - The signal-to-noise ratio $S/N \sim \frac{g_W^2}{M_W^2} / \frac{g_s^2}{m_\pi^2} \sim G_F\, m_\pi^2 \approx 10^{-7}$

$$A_L^{\vec{p}+p}(45\,\mathrm{MeV}) = (-1.57 \pm 0.23) \times 10^{-7}$$
$$A_L^{\vec{p}+\alpha}(46\,\mathrm{MeV}) = (-3.34 \pm 0.93) \times 10^{-7}$$
$$P_\gamma^{^{18}\mathrm{F}}(1081\,\mathrm{keV}) = (12 \pm 38) \times 10^{-5}$$
$$A_\gamma^{^{19}\mathrm{F}}(110\,\mathrm{keV}) = (-7.4 \pm 1.9) \times 10^{-5}$$
$$A_L^{\vec{n}+^{137}\mathrm{La}}(0.734\,\mathrm{eV}) = (9.8 \pm 0.3) \times 10^{-2}$$
$$A_\gamma^{^{180}\mathrm{Hf}}(501\,\mathrm{keV}) = (-1.66 \pm 0.18) \times 10^{-2}$$

- Theoretically:
  - The non-perturbative QCD at low energies
  - The difficult nuclear many-body problems

As GWS model works so well, why bother?

- The only viable venue to observe the hadronic neutral current interaction:
  FCNC is GIM suppressed.
- Provide other touchstones for strong dynamics:
  How the strong interaction modify the above interaction? Go
- Complementary to the $\Delta S = 1$ sector:
  Any similar thing to the $\Delta I = 1/2$ rule?
- Needed for better interpretation of semi-leptonic processes like:
  PV electron-nucleon/nucleus scattering Go
  Atomic PV experiments Go

S-P Amplitudes: $\langle P|H_{\not{p}}|S\rangle$ (1st-order Born Approx.)

- **Basic idea:** At low energies, only S-wave and its P-wave admixture substantially contribute to observables (Danilov 65, 71), and there are 5 independent ones (Danilov parameters):

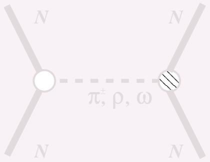
Transition	$I \leftrightarrow I'$	ΔI	n-n	n-p	p-p	Amp.	$E \longrightarrow 0$
$^3S_1 \leftrightarrow {}^1P_1$	$0 \leftrightarrow 0$	0		$\surd$		u	λ_t
$^1S_0 \leftrightarrow {}^3P_0$	$1 \leftrightarrow 1$	0	$\surd$	$\surd$	$\surd$	v^0	λ_s^0
		1	$\surd$		$\surd$	v^1	λ_s^1
		2	$\surd$	$\surd$	$\surd$	v^2	λ_s^2
$^3S_1 \leftrightarrow {}^3P_1$	$0 \leftrightarrow 1$	1		$\surd$		w	ρ_t

- **Note:** The energy dependence is determined by strong phase shifts
- **Generalization:** Approximate finite nuclei as nuclear matter, and applying the Bethe-Goldstone eqn. to obtain an effective PV interaction for many-body problems (Desplanques and Missimer 78, 80)

Meson Exchange Picture

- **Building blocks**: nucleon, mesons (pseudo-scalar and vector), and their couplings
- **Basic assumption**: the $\not{P}$ physics, which is short-ranged, is buried inside the $\not{P}$ meson-nucleon couplings
- **Low-Energy**: light mesons with $m_x < 1$ GeV
- **Barton's Thm.**: *CP* conservation excludes scalar coupling to neutral pseudoscalar mesons (*C*-even *P*-odd)

OME with $\pi^{\pm}$, ρ, and ω



$2\,m_N \times H_{\not{P}}$ based on OME

$$
\begin{aligned}
& g_\pi\, h_\pi^1/(2\sqrt{2})\,\tau_\times^z\,\vec{\sigma}_+\cdot\vec{y}_{\pi-}(\vec{r}) \\
& -g_\rho\,(h_\rho^0\,\vec{\tau}_1\cdot\vec{\tau}_2 + h_\rho^1\,\tau_+^z + h_\rho^2\,\tau^{zz})\,(\vec{\sigma}_-\cdot\vec{y}_{\rho+} + \mu_\rho\,\vec{\sigma}_\times\cdot\vec{y}_{\rho-}) \\
& -g_\omega\,(h_\omega^0\,1 + h_\omega^1\,\tau_+^z)\,(\vec{\sigma}_-\cdot\vec{y}_{\rho+} + \mu_\omega\,\vec{\sigma}_\times\cdot\vec{y}_{\rho-}) \\
& -(g_\omega\,h_\omega^1 - g_\rho\,h_\rho^1)\,\tau_-^z\,\vec{\sigma}_+\cdot\vec{y}_{\rho+} - g_\rho\,h_\rho^{\prime 1}\,\vec{\sigma}_+\cdot\vec{y}_{\rho-}
\end{aligned}
$$

with $\vec{y}_{x\pm}(\vec{r}) \equiv [\vec{p}_1 - \vec{p}_2\,,\, e^{-m_x r}/(4\pi r)]_\pm$

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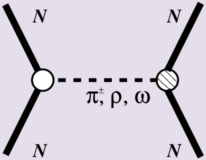

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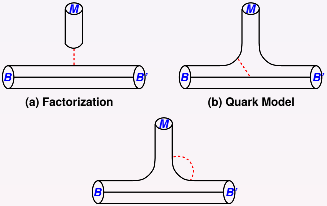
Predictions for $\not{P}$ Meson-Nucleon Couplings

$\times 10^7$	DDH Range	Best	DZ	FCDH	KM
h_π^1	$0.0 \leftrightarrow 11.4$	4.6	1.1	2.7	0.2
h_ρ^0	$-30.8 \leftrightarrow 11.4$	-11.4	-8.4	-3.8	-3.7
h_ρ^1	$-0.4 \leftrightarrow 0.0$	-0.2	0.4	-0.4	-0.1
h_ρ^2	$-11.0 \leftrightarrow -7.6$	-9.5	-6.8	-6.8	-3.3
h_ω^0	$-10.3 \leftrightarrow 5.7$	-1.9	-3.8	-4.9	-6.2
h_ω^1	$-1.9 \leftrightarrow -0.8$	-1.1	-2.3	-2.3	-1.0
$h_\rho^{\prime 1}$		0.0			-2.2



(a) Factorization (b) Quark Model (c) Sum Rule

- Calculations by DDH, DZ, FCDH are based on quark models, KM used the chiral soliton model
- $h_\rho^{\prime 1}$ term is usually ignored, so leaving 6 $\not{P}$ couplings to be checked by exps.
- QCD sum rule calculations of h_π^1 give 3×10^{-7} (HHK 98, formerly 2×10^{-8}) and 3.4×10^{-7} (Lobov 02)
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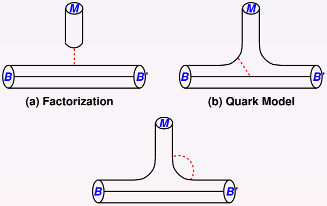

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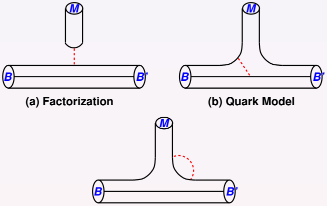

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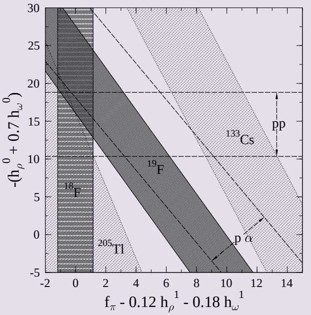
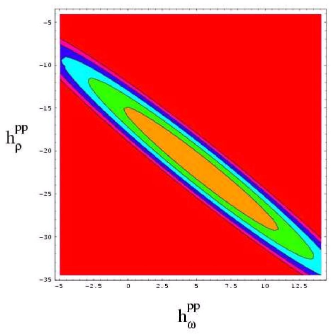
Two Major Puzzles

Is h_π^1 small?



The ^{18}F is performed by five different groups, the theoretical calculation (Haxton 85) is thought to be reliable

Is $h_\omega \equiv h_\omega^0 + h_\omega^1$ positive?



$\vec{p}p$ scattering @ 13.6, 45, and 221 MeV where A_L depends on a linear combination of h_ρ and h_ω (Carlson et al. 02)

What went wrong?

1. The experiments have problems?
   Maybe, but this should not be a theorist's answer.
2. The nuclear many-body calculations have problems?
   By first concentrating on few-nucleon systems might provide an answer.
3. The OME picture has problems?
   EFT might provide an answer.

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$H_{\not{p}}$ in EFT

In parallel to the success in the PC sector, the ChPT is extended to the PV sector at $O(Q)$ (Zhu, Maekwa, Holstein, Ramsey-Musolf, and van Kolck, 05). The benefits over or cure to the meson-exchange version include:

1. It's model-independent.
2. It's completely general and exhibits the underlying symmetries.
3. It's a systematic expansion scheme (power counting) and improvable.

Basic ingredients:

- **Chiral symmetry**: $SU(2)_L \times SU(2)_R$ (massless quarks).
- **SSB**: $SU(2)_L \times SU(2)_R \to SU(2)_V$ (eight massless Goldstone bosons: π, K, and η).
- **Scales**: $\Lambda_{\chi SB} \sim m_N \sim m_\rho \sim 1\,\mathrm{GeV}$, $m_\pi \sim f_\pi \sim 100\,\mathrm{MeV}$, so expansions in terms of $Q/\Lambda_{\chi SB}$ and m_π/m_N converges well.

Two Versions

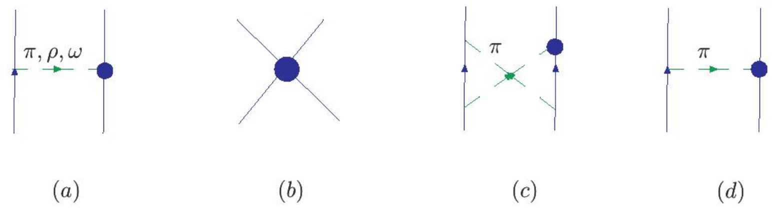
The proposed form has two versions:

Pionless: Pions are integrated out, i.e., only (b).

- Good for low energies, interaction is short-ranged.
- Has 10 LECs (superficially).

Pionful: Pions are dynamical degrees of freedom.

- Long-range int. from OPE; mid-range int. from TPE, overall is (b)+(c)+(d).
- Introduces additional 3 couplings.



$H_{\not{p}}$ in Pionless EFT

$$
\begin{aligned}
V_{\not{\pi}}^{\mathrm{PV}} = V_{1,\mathrm{SR}}^{\mathrm{PV}} &= 2/\Lambda_\chi^3 \\
&\times \Big\{ \big[C_1 + (C_2 + C_4)\,\tau_+^z + C_3\,\vec{\tau}_1 \cdot \vec{\tau}_2 + C_5\,\tau^{zz} \big]\, \vec{\sigma}_- \cdot \vec{y}_{m+} \\
&+ \big[\widetilde{C}_1 + (\widetilde{C}_2 + \widetilde{C}_4)\,\tau_+^z + \widetilde{C}_3\,\vec{\tau}_1 \cdot \vec{\tau}_2 + \widetilde{C}_5\,\tau^{zz} \big]\, \vec{\sigma}_\times \cdot \vec{y}_{m-} \\
&+ (C_2 - C_4)\,\tau_-^z\,\vec{\sigma}_+ \cdot \vec{y}_{m+} + \widetilde{C}_6\,\tau_\times^z\,\vec{\sigma}_+ \cdot \vec{y}_{m-} \Big\}
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  - Taking $m = m_\rho$ and $\widetilde{C}_{1,2}/C_{1,2} = \mu_\omega$, $\widetilde{C}_{3,4,5}/C_{3,4,5} = \mu_\rho$, $V_{1,\mathrm{SR}}^{\mathrm{PV}} \equiv V_{\rho+\omega}^{\mathrm{OME}}$, both have 6 independent parameters.

$H_{\not{p}}$ in Pionless EFT

$$
\begin{aligned}
V_{\not{\pi}}^{\mathrm{PV}} = V_{1,\mathrm{SR}}^{\mathrm{PV}} = 2/\Lambda_\chi^3 \\
&\times \Big\{ \big[C_1 + (C_2 + C_4)\,\tau_+^z + C_3\,\vec{\tau}_1\cdot\vec{\tau}_2 + C_5\,\tau^{zz} \big]\,\vec{\sigma}_-\cdot\vec{y}_{m+} \\
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$$V^{\rm PV}_{\pi-\rm ful} = V^{\rm PV}_{-1,\rm LR} + V^{\rm PV}_{1,\rm LR} + V^{\rm PV}_{1,\rm MR} + V^{\rm PV}_{1,\rm SR}$$

- $V^{\rm PV}_{-1,\rm LR}$: the normal OPE one, depends on h^1_π.
- $V^{\rm PV}_{1,\rm LR}$: from vertex corrections, add one new coupling k^{1a}_π. [2]
- $V^{\rm PV}_{1,\rm MR}$: from TPE, depends on h^1_π, has non-analytic terms ($\ln q/m_\pi$).
- $V^{\rm PV}_{1,\rm SR}$: similar structure to the pionless version, but LECs bear different meaning.
- $V^{\rm PV}_{\pi-\rm ful}$ depends on the regularization scheme which shuffles some TPE contributions into $V^{\rm PV}_{1,\rm SR}$.
- Most MECs are constrained by gauging the potential, with a transverse piece depending on a new constant $\bar{c}_\pi$ [3]

[2] Redundant (CPL and Ramsey-Musolf)
[3] Suppressed by k/m_N (CPL)

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The Approach

- Hybrid EFT
  - The general PV *NN* potential is taken from EFT consideration (not more, nor less).
  - The wave functions are obtained by potential model calculations (a temporary step until EFT reach the same accuracy.
- Numerical studies
  - Three sets of calculations are performed:
    1. bare: $f_m(r)$ is the bare Yukawa function with $m = m_\rho$.
    2. mod: $f_m(r)$ is the modified Yukawa function with $m = m_\rho$ and a dipolar cutoff $\Lambda \sim 1\text{–}2\,\mathrm{GeV}$.
    3. π-less: $f_m(r)$ is the bare Yukawa function with $m = m_\pi$.
  - Results will be expressed in terms of physical parameters, i.e., cutoff-independent.
  - Results are checked by mapping $V^{\mathrm{PV}}_{\mathrm{EFT}}$ to $V^{\mathrm{PV}}_{\mathrm{OME}}$ and compare with existing calculations.

Reduction of 10-to-5 LECs ($m = m_\rho$)

Fact

The condition $\langle P|\vec{y}_{m+}|S\rangle / \langle P|\vec{y}_{m-}|S\rangle \equiv R(E) \approx R$ has to be satisfied. (R is cutoff-dependent, in this case $m = m_\rho$.)

The results are:

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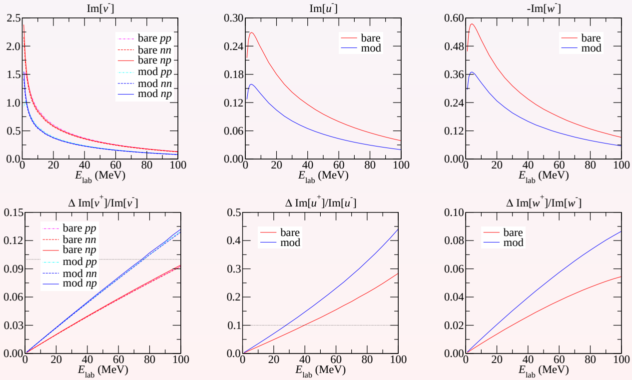

S–P dominance: limit of 10-to-5 reduction

Fact

At low energies, S-P amplitudes dominate so that
$\langle\vec{y}_{m+}\rangle/\langle\vec{y}_{m-}\rangle \approx \langle P|\vec{y}_{m+}|S\rangle/\langle P|\vec{y}_{m-}|S\rangle \approx R$
But when D-P and F-P ones come into play, this will no longer be the case.

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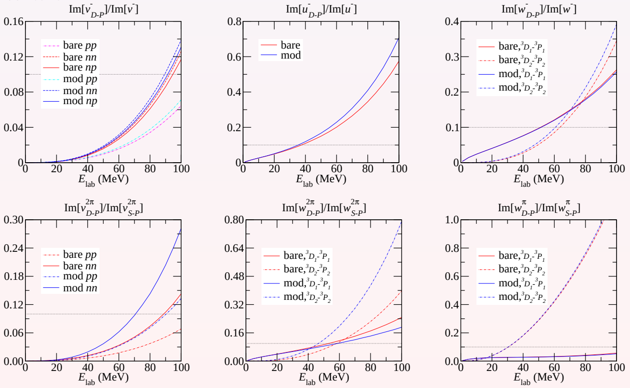

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Fact

It depends on whether pion contributions have roughly similar energy-dependence to the short-ranged interaction.

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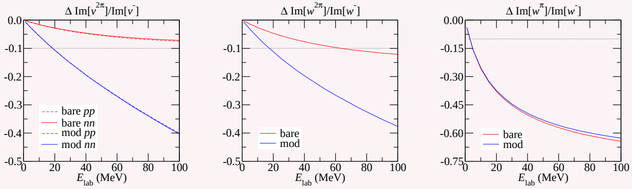

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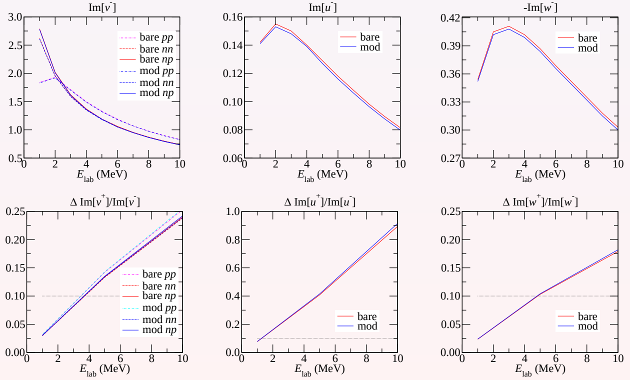


The parameters in hybrid EFT

- In pionful theory: 5 Danilov parameters $\lambda_s^{pp,np,nn}$, λ_t, ρ_t, and the OPE constant $\tilde{C}_6^{\pi} \propto h_\pi^1$. (in S–P dominant range, TPE can be effectively included in the SR int.)
- In pionless theory: 5 Danilov parameters only. (only apply to $E \lesssim 10\,\mathrm{MeV}$ and no explicit tracking of h_π^1)

bare

$$m_N\lambda_s^{pp} = 5.507\times 10^{-3}\,(\tilde{D}_v^{pp} + 0.789\,D_v^{pp} - 1.655\,\tilde{C}_2^{2\pi})$$
$$m_N\lambda_s^{nn} = 5.796\times 10^{-3}\,(\tilde{D}_v^{nn} + 0.792\,D_v^{nn} + 1.648\,\tilde{C}_2^{2\pi})$$
$$m_N\lambda_s^{np} = 5.778\times 10^{-3}\,(\tilde{D}_v^{np} + 0.809\,D_v^{np})$$
$$m_N\lambda_t = -1.462\times 10^{-3}\,(\tilde{D}_u - 2.230\,D_u)$$
$$m_N\rho_t = 3.108\times 10^{-3}\,(\tilde{D}_w + 0.604\,D_w - 1.771\,\tilde{C}_6^{2\pi})$$

mod

$$m_N\lambda_s^{pp'} = 3.628\times 10^{-3}\,(\tilde{D}_v^{pp'} + 0.849\,D_v^{pp'} - 1.260\,\tilde{C}_2^{2\pi'})$$
$$m_N\lambda_s^{nn'} = 3.809\times 10^{-3}\,(\tilde{D}_v^{nn'} + 0.853\,D_v^{nn'} + 1.237\,\tilde{C}_2^{2\pi'})$$
$$m_N\lambda_s^{np'} = 3.772\times 10^{-3}\,(\tilde{D}_v^{np'} + 0.871\,D_v^{np'})$$
$$m_N\lambda_t' = -0.867\times 10^{-3}\,(\tilde{D}_u' - 2.425\,D_u')$$
$$m_N\rho_t' = 2.003\times 10^{-3}\,(\tilde{D}_w' + 0.664\,D_w' - 1.586\,\tilde{C}_6^{2\pi'})$$

Results

$A_L^{\vec{p}p}$ @ 13.6 and 45 MeV

$$\begin{aligned} A_L^{\vec{p}p}(13.6\,\text{MeV}) &= -0.449\, m_N \lambda_s^{pp} && \text{(bare)} \\ &= -0.445\, m_N \lambda_s^{pp\prime} && \text{(mod)} \\ A_L^{\vec{p}p}(45\,\text{MeV}) &= -0.795\, m_N \lambda_s^{pp} && \text{(bare)} \\ &= -0.771\, m_N \lambda_s^{pp\prime} && \text{(mod)} \end{aligned}$$

$\vec{n}_{\text{th.}}$ spin rotation in hydrogen (in m/rad)

$$\begin{aligned} \frac{d\phi_n^{\vec{n}p}}{dz} & \\ &= 2.500\, m_N \lambda_s^{np} - 0.571\, m_N \lambda_t + 1.412\, m_N \rho_t + 0.286\, \widetilde{C}_6^{\pi} \\ &= 2.500\, m_N \lambda_s^{np\prime} - 0.571\, m_N \lambda_t^{\prime} + 1.412\, m_N \rho_t^{\prime} + 0.284\, \widetilde{C}_6^{\pi} \end{aligned}$$

P_γ in $n + p \to d + \gamma$

$$\begin{aligned} P_\gamma^{np}(\text{th.}) &= -0.161\, m_N \lambda_s^{np} + 0.670\, m_N \lambda_t && \text{(bare)} \\ &= -0.161\, m_N \lambda_s^{np\prime} + 0.669\, m_N \lambda_t^{\prime} && \text{(mod)} \end{aligned}$$

A_γ in $\vec{n} + p \to d + \gamma$

$$\begin{aligned} A_\gamma^{\vec{n}p}(\text{th.}) &= -0.093\, m_N \rho_t - 0.272\, \widetilde{C}_6^{\pi} && \text{(bare)} \\ &= -0.093\, m_N \rho_t^{\prime} - 0.270\, \widetilde{C}_6^{\pi\prime} && \text{(mod)} \end{aligned}$$

The Search Program in Few-Nucleon Systems

Gather as many observables in FB systems and see if a consistent picture of low-energy hadronic PV can be reached.

Observables	Theory	Experiment ($\times 10^7$)
$A_L^{\vec{p}p}(13.6\,\mathrm{MeV})$	$-0.45\,\lambda_s^{pp}\,m_N$	-0.93 ± 0.21 (Bonn)
$A_L^{\vec{p}p}(45\,\mathrm{MeV})$	$-0.78\,\lambda_s^{pp}\,m_N$	-1.57 ± 0.23 (SIN)
$\frac{d}{dz}\phi_n^{\vec{n}p}(\mathrm{th.})\vert_{\mathrm{rad/m}}$	$\left[2.50\,\lambda_s^{np} - 0.57\,\lambda_t + 1.41\,\rho_t\right]\,m_N + 0.29\,\widetilde{C}_6^{\pi}$	SNS
$P_\gamma^{np}(\mathrm{th.})$	$\left[-0.16\,\lambda_s^{np} + 0.67\,\lambda_t\right]\,m_N$	(1.8 ± 1.8), SNS?
$A_L^{\vec{\gamma}d}(1.32\,\mathrm{keV})$	Same as above	HIGS? IASA? Spring-8?
$A_\gamma^{\vec{n}p}(\mathrm{th.})$	$-0.09\,\rho_t\,m_N - 0.27\,\widetilde{C}_6^{\pi}$	LANSCE→SNS
$\frac{d}{dz}\phi_n^{\vec{n}d}(\mathrm{th.})$	To be done	SNS?
$A_\gamma^{\vec{n}d}(\mathrm{th.})$	$\left[0.59\,\lambda_s^{nn} + 0.51\,\lambda_s^{np} + 1.18\,\lambda_t + 1.42\,\rho_t\right]\,m_N$ *	(0.6 ± 2.1), SNS?
$A_L^{\vec{p}\alpha}(46\,\mathrm{MeV})$	$\left[-0.48\,\lambda_s^{pp} - 0.24\,\lambda_s^{np} - 0.54\,\lambda_t - 1.07\,\rho_t\right]\,m_N$ *	-3.3 ± 0.9 (SIN)
$\frac{d}{dz}\phi_n^{\vec{n}\alpha}(\mathrm{th.})\vert_{\mathrm{rad/m}}$	$\left[1.2\,\lambda_s^{nn} + 0.6\,\lambda_s^{np} + 1.34\,\lambda_t - 2.68\,\rho_t\right]\,m_N$ *	(8 ± 14), NIST→SNS

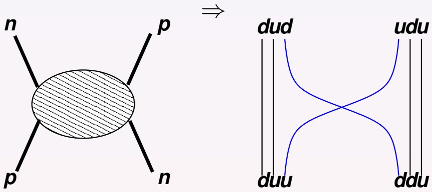
1. Few-body calculations (*) need to be updated.
2. FNPB @ SNS will be the key facility.
3. $\vec{p}\,\alpha$ may be a problem for S–P analysis.

In conclusion:

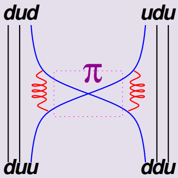
- The strangeness-conserving hadronic weak interaction is the last piece of the jigsaw for a complete test of the standard electroweak theory; at the same time, it provides another window for examining strong interaction dynamics which is complementary to PC observables or its strangeness-non-conserving counterpart.
- An EFT formulation of PV nucleon-nucleon interaction anticipates six independent parameters for the low-energy processes in which S-P amplitudes dominate the observables.
- Theory and experiment of nuclear few-body physics are mature enough to make new progress. With FNPB at SNS being the key facility to trigger a renaissance of study on hadronic PV, one hopes to see a more consistent picture resulting from these efforts.

N–N Interactions in Terms of q–q Interactions

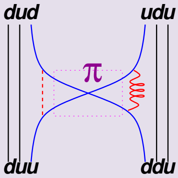
How to calculate $\langle n,p|V_{NN}|p,n\rangle = \langle n,p|(\bar{q}'_1\,\Gamma_1\,q_1)\,G(q)\,(\bar{q}'_2\,\Gamma_2\,q_2)|n,p\rangle$?



Parity-Conserving



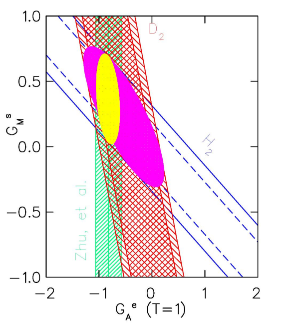
Parity-Violating



Return

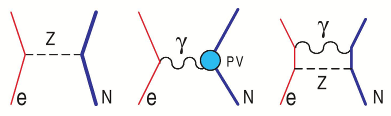
PV electron scattering

SAMPLE exp.



- backward angle, sensitive to G_M and G_A^e
- non-zero strangeness?!

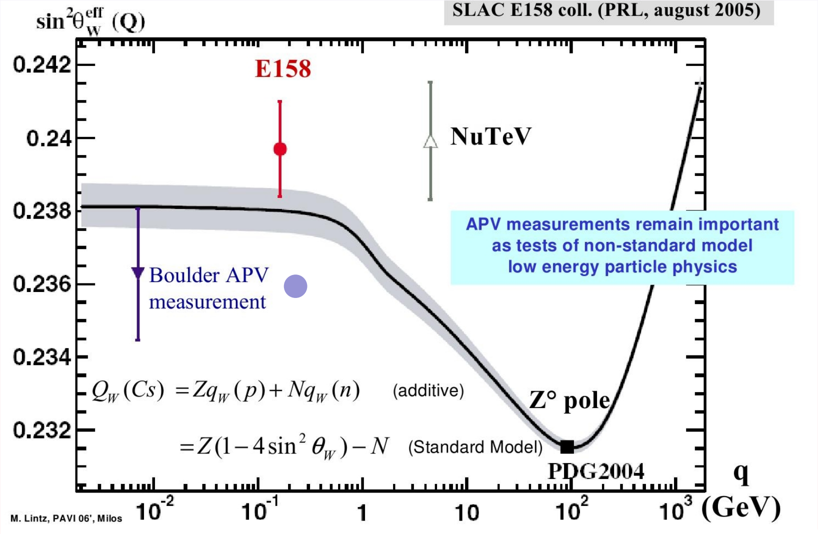
Diagrams



- dominated by Z^0 exchange $e(A)–N(V) > e(V)–N(A)$
- radiative corrections $\sim \alpha$
- 2. anapole form factor (axial)
- 3. box diagram

Return

Constraining $\sin^2\theta_W$ at very low energy



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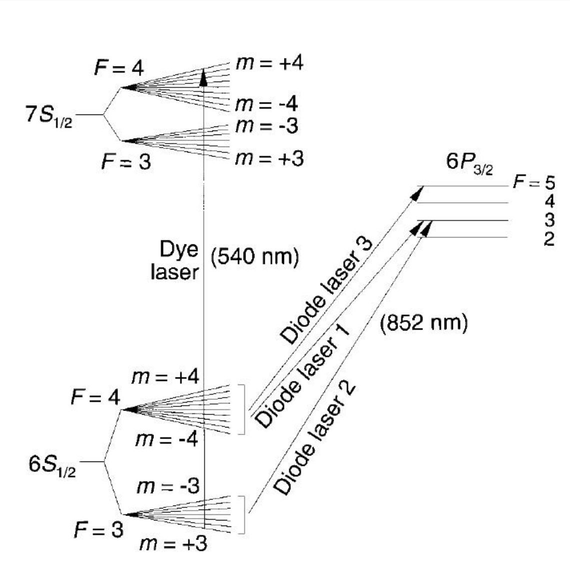
^{133}Cs experiment (Colorado)



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