CEνNS in effective field theory

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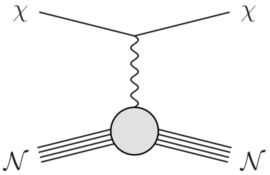
Magnificent CEνNS 2019

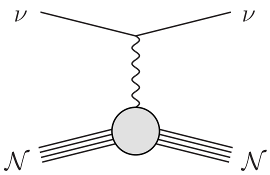
Chapel Hill, November 9, 2019

MH, Klos, Menéndez, Schwenk PRD 99 (2019) 055031

MH, Menéndez, Schwenk to appear

Weak Elastic Scattering with Nuclei





	WIMP–nucleus scattering	**neutrino–nucleus scattering**
kinematics	elastic, χ non-relativistic	elastic, ν relativistic
mediator	BSM	Z, BSM?
quantum numbers	unknown	$V-A$, others?
momentum transfer q	$\lesssim 200\,\text{MeV}$	$\lesssim 50\,\text{MeV}$

$\hookrightarrow$ need very similar nuclear responses (“**structure factors**”)

Weak Elastic Scattering with Nuclei: EFT approach

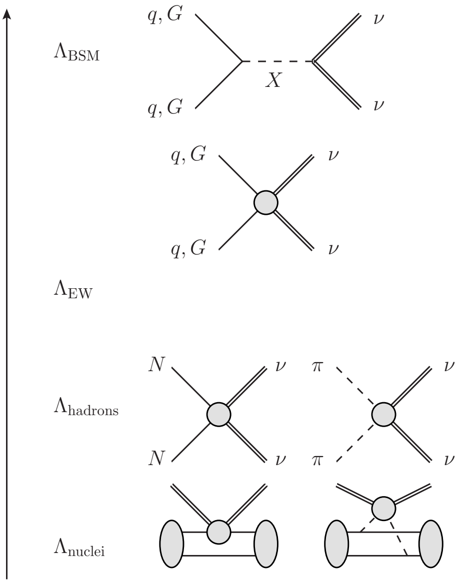
EFT approach to dark matter

Rate $=$ BSM couplings $\otimes$ hadronic matrix elements $\otimes$ nuclear structure $\otimes$ astrophysics

$\hookrightarrow$ most efficiently addressed in **effective field theory**

- This talk: same approach to CEνNS (with SM prediction for the Wilson coefficients)
- Will assume a **heavy mediator**, e.g. Z in SM
- Light BSM physics can be added to set of BSM operators, e.g. light Z'
  $\hookrightarrow$ requires same hadronic/nuclear input

Coherent elastic neutrino–nucleus scattering: scales



1. **BSM scale** $\Lambda_{\rm BSM}$: $\mathcal{L}_{\rm BSM}$
2. **Effective Operators**: $\mathcal{L}_{\rm SM} + \sum_{i,k} \frac{1}{\Lambda^i_{\rm BSM}} \mathcal{O}_{i,k}$
3. Integrate out **EW physics**

   (start here if only SM)
4. **Hadronic scale**: nucleons and pions

   $\hookrightarrow$ effective interaction Hamiltonian H_I
5. **Nuclear scale**: $\langle \mathcal{N} | H_I | \mathcal{N} \rangle$

   $\hookrightarrow$ nuclear wave function

- **Vector** and **axial-vector operators**

$$\mathcal{L}_q^{\text{SM}} = -\frac{G_F}{\sqrt{2}} \sum_{q=u,d} \Big(C_q^V \bar{\nu}\gamma^\mu(1-\gamma_5)\nu\, \bar{q}\gamma_\mu q + C_q^A \bar{\nu}\gamma^\mu(1-\gamma_5)\nu\, \bar{q}\gamma_\mu\gamma_5 q \Big)$$

$\hookrightarrow$ can add more operators in BSM case

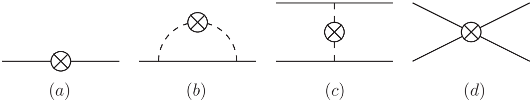
- In SM:

$$C_u^V = \frac{1}{2} - \frac{4}{3}\sin^2\theta_W \qquad C_d^V = -\frac{1}{2} + \frac{2}{3}\sin^2\theta_W \qquad C_u^A = -\frac{1}{2} \qquad C_d^A = \frac{1}{2}$$

- Related to typical CEνNS notation by

$$C_q^V - C_q^V\big|_{\text{SM}} = \epsilon_{ee}^{qV} = \epsilon_{ee}^{qL} + \epsilon_{ee}^{qR} \qquad C_q^A - C_q^A\big|_{\text{SM}} = -\epsilon_{ee}^{qA} = \epsilon_{ee}^{qR} - \epsilon_{ee}^{qL}$$

Second step: hadronic matrix elements



- **Single-nucleon level**: vector and axial-vector form factors

  $\hookrightarrow$ charge radii, magnetic moments, ...

- **Beyond single-nucleon level**: pion-exchange diagrams $\leftrightarrow$ two-body currents

$\hookrightarrow$ can all be addressed systematically in **chiral effective field theory**

Chiral EFT: a modern approach to nuclear forces

- Traditionally: meson-exchange potentials
- Chiral effective field theory
  - Based on **chiral symmetry** of QCD
  - **Power counting**
  - **Low-energy constants**
  - Hierarchy of multi-nucleon forces
  - Consistency of *NN* and 3*N*

$\hookrightarrow$ modern theory of nuclear forces

- Long-range part related to **pion–nucleon scattering**

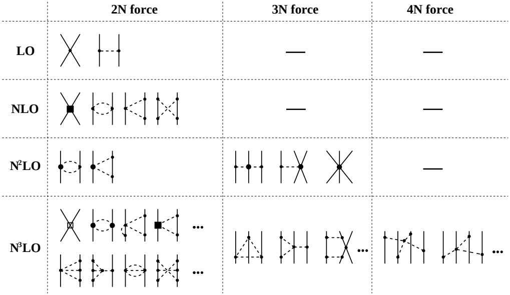
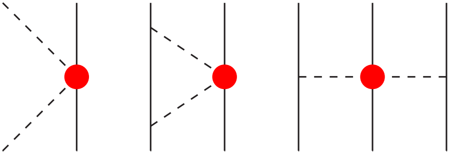


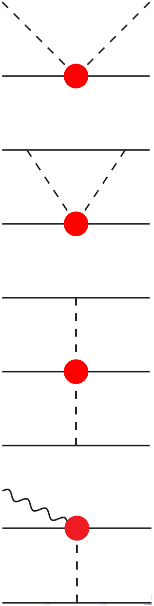
Figure taken from 1011.1343



Chiral EFT: currents

- Coupling to **external sources** $\mathcal{L}(v_\mu, a_\mu, s, p)$
- Same LECs appear in **axial-vector current**
- Two-body effects well established in β decay, magnetic moments, ...
- Formalism can be applied to other than vector and axial-vector currents

  $\hookrightarrow$ sizable two-body effect for a **scalar current**



Third step: nuclear structure factors

- **Nuclear matrix element** of the single-nucleon and few-nucleon amplitudes
- Ideally: based on nuclear interactions from chiral EFT

  $\hookrightarrow$ "ab-initio" calculation Coupled-cluster calculation for ^{40}Ar, Payne et al. 2019
- Not yet available for heavier nuclei, challenge to get charge radii right
- Therefore: here us **nuclear shell model** with phenomenological interactions
- Alternative: **relativistic mean field** methods see previous talk by J. Piekarewicz

  $\hookrightarrow$ difference some measure of nuclear structure uncertainty
- We can do better than simple parameterizations in terms of proton/neutron radii!

CEνNS cross section

$$\frac{d\sigma_{\nu\mathcal{N}}}{dT} = \frac{G_F^2 m_A}{2\pi}\Bigg[\bigg(2 - \frac{m_A T}{E_\nu^2}\bigg)\bigg|\bigg(g_V^0 - \dot{g}_{V,1}^0 q^2 - \frac{g_V^0 + 2g_{V,2}^0}{8m_N^2}q^2\bigg)\mathcal{F}_+^M(q^2) + \bigg(g_V^1 - \dot{g}_{V,1}^1 q^2 - \frac{g_V^1 + 2g_{V,2}^1}{8m_N^2}q^2\bigg)\mathcal{F}_-^M(q^2)$$
$$+ \frac{g_V^0 + 2g_{V,2}^0}{4m_N^2}q^2\mathcal{F}_+^{\Phi''}(q^2) + \frac{g_V^1 + 2g_{V,2}^1}{4m_N^2}q^2\mathcal{F}_-^{\Phi''}(q^2)\bigg|^2$$
$$+ \bigg(2 + \frac{m_A T}{E_\nu^2}\bigg)\frac{2\pi}{2J+1}\Big((g_A^0)^2 S_{00}^{\mathcal{T}}(q^2) + g_A^0 g_A^1 S_{01}^{\mathcal{T}}(q^2) + (g_A^1)^2 S_{11}^{\mathcal{T}}(q^2)\Big)\Bigg]$$

- Notation:
  - Momentum transfer $q^2 = 2m_A T$ with target mass m_A, $T \in [0, 2E_\nu^2/(m_A + 2E_\nu)]$
  - g_V^0, $\dot{g}_V^0$, g_A^0 etc.: combination of Wilson coefficients and hadronic matrix elements
    $\hookrightarrow$ "**matching relations**"
  - $\mathcal{F}_\pm^M(q^2)$: isoscalar/isovector charge distribution
  - $S_{ij}^{\mathcal{T}}(q^2)$: only transverse part $\mathcal{T}$ contributes in spin-dependent response
  - Interference term neglected: $T/E_\nu \lesssim 2E_\nu/m_A$ tiny

CEνNS cross section

$$\frac{d\sigma_{\nu\mathcal{N}}}{dT} = \frac{G_F^2 m_A}{2\pi}\Bigg[\bigg(2-\frac{m_A T}{E_\nu^2}\bigg)\bigg|\bigg(g_V^0 - \dot{g}_{V,1}^0 q^2 - \frac{g_V^0+2g_{V,2}^0}{8m_N^2}q^2\bigg)\mathcal{F}_+^M(q^2) + \bigg(g_V^1 - \dot{g}_{V,1}^1 q^2 - \frac{g_V^1+2g_{V,2}^1}{8m_N^2}q^2\bigg)\mathcal{F}_-^M(q^2)$$

$$+\frac{g_V^0+2g_{V,2}^0}{4m_N^2}q^2\mathcal{F}_+^{\Phi''}(q^2) + \frac{g_V^1+2g_{V,2}^1}{4m_N^2}q^2\mathcal{F}_-^{\Phi''}(q^2)\bigg|^2$$

$$+\bigg(2+\frac{m_A T}{E_\nu^2}\bigg)\frac{2\pi}{2J+1}\Big((g_A^0)^2 S_{00}^{\mathcal{T}}(q^2) + g_A^0 g_A^1 S_{01}^{\mathcal{T}}(q^2) + (g_A^1)^2 S_{11}^{\mathcal{T}}(q^2)\Big)\Bigg]$$

- Subleading contributions
  - Radius and relativistic corrections included
  - Quasi-coherent $\mathcal{F}_I^{\Phi''}(q^2)$ spin-orbit response Serot 1978
  - Two-body corrections kinematically suppressed for vector response, but relevant for axial vector

Charge radii and neutron skin

	^{23}Na	^{40}Ar	^{74}Ge	^{132}Xe	^{127}I	^{133}Cs
$\sqrt{\langle r^2\rangle_{\text{ch}}}$ [fm] (th)	3.00	3.43	4.08	4.77	4.73	4.79
(exp)	2.9936(21)	3.427(3)	4.0742(12)	4.7808(49)	4.7500(81)	4.8041(46)
$\sqrt{\langle r_n^2\rangle}-\sqrt{\langle r_p^2\rangle}$ [fm]	0.04	0.11	0.17	0.28	0.26	0.27
shell-model interaction	SDPF.SM	RG	GCN	USDB	GCN	GCN

- Excellent agreement for charge radii

$$\langle r^2_{\text{ch}}\rangle = \langle r^2_p\rangle + \langle r^2_{E,p}\rangle + \frac{N}{Z}\langle r^2_{E,n}\rangle + \langle r^2_{\text{rel}}\rangle + \langle r^2_{\text{spin-orbit}}\rangle$$

- But: charge radii used to constrain parameters

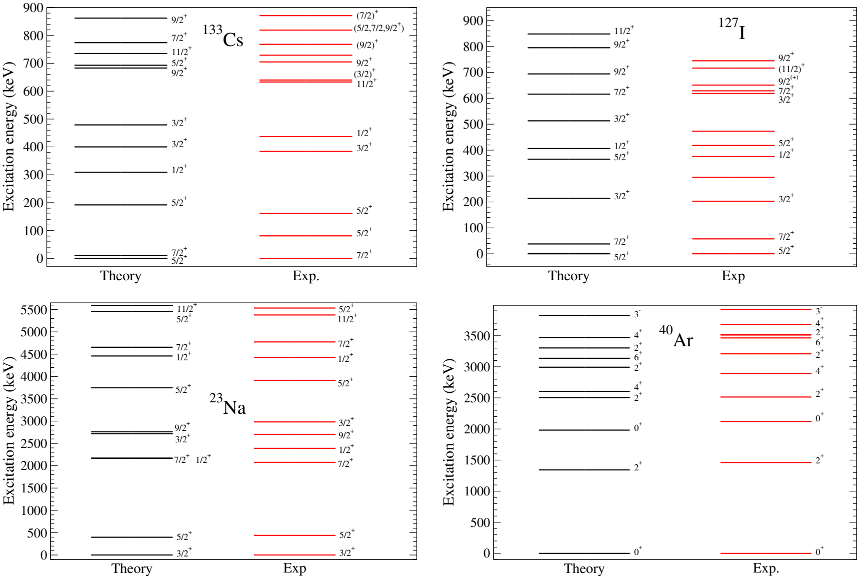
- Point-neutron radii more uncertain, e.g. from coupled-cluster Payne et al. 2019

$$\sqrt{\langle r^2_n\rangle} - \sqrt{\langle r^2_p\rangle}\Big|_{^{40}\text{Ar}} = 0.035\ldots 0.09\text{ fm}$$

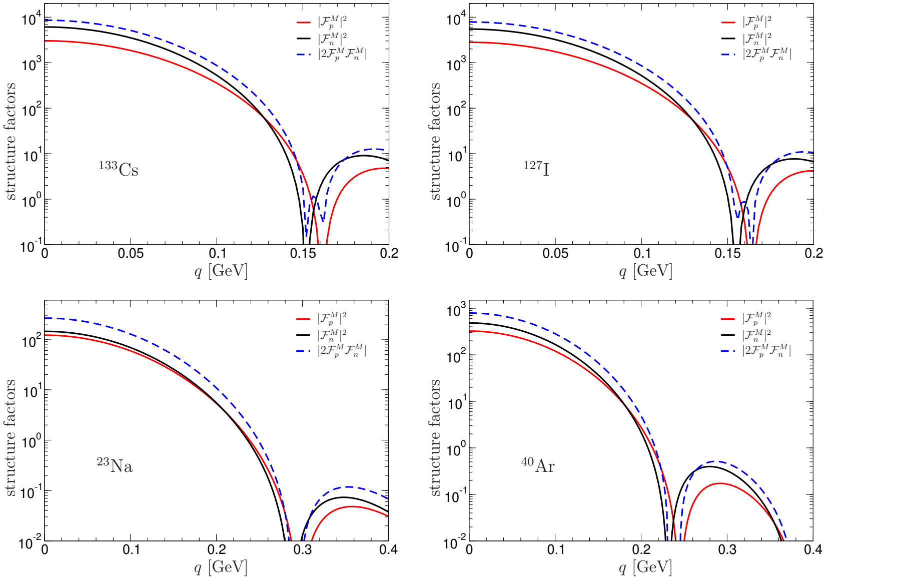
- Related to structure factors by

$$\langle r^2_p\rangle = -\frac{3}{Z}\frac{\mathrm{d}}{\mathrm{d}q^2}\big(\mathcal{F}^M_+(q^2)+\mathcal{F}^M_-(q^2)\big)\Big|_{q^2=0} \qquad \langle r^2_n\rangle = -\frac{3}{N}\frac{\mathrm{d}}{\mathrm{d}q^2}\big(\mathcal{F}^M_+(q^2)-\mathcal{F}^M_-(q^2)\big)\Big|_{q^2=0}$$

Spectra



Structure factors

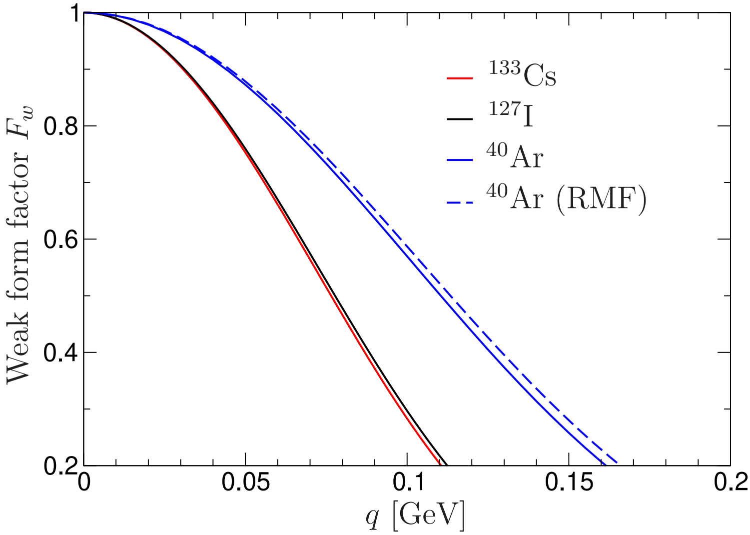


The weak form factor

$$\frac{d\sigma_{\nu\mathcal{N}}}{dT} = \frac{G_F^2 m_A}{4\pi}\left(1 - \frac{m_A T}{2E_\nu^2}\right) Q_w^2 \big|F_w(q^2)\big|^2 \qquad Q_w = N - (1 - 4\sin^2\theta_W)Z$$

- In the SM define so-called **weak form factor** $F_w(q^2)$
- Q_w does not actually factorize
- $F_w(q^2)$ depends on $\mathcal{F}_\pm^M, \mathcal{F}_+^{\Phi''}(q^2)$, with coefficients determined by the Wilson coefficients and hadronic matrix elements
- Once Wilson coefficients are changed away from the SM, **the form factor will change**!
- EFT decomposition allows one to keep track of these changes

The weak form factor



A question to experiment

- Current list of isotopes:
  - Cesium: ^{133}Cs
  - Iodine: ^{127}I
  - Argon: ^{40}Ar
  - Sodium: ^{23}Na
  - Germanium: ^{70,72,73,74,76}Ge
  - Xenon: ^{128,129,130,131,132,134,136}Xe
- **Should we consider anything else?**

Conclusions

- **EFT approach** to CEνNS generalizes the weak form factor
- Separation into
  - **Wilson coefficients**
  - **Hadronic matrix elements**
  - **Nuclear structure factors**
- Two-body corrections kinematically suppressed for leading, coherent response
- Axial-vector part similar, but not identical to spin-dependent dark matter
- Cannot just use the weak form factor for when constraining BSM (weak charge does not factorize)
- Can systematically include non-standard interactions in **chiral EFT**

ChiralEFT4DM: a PYTHON package for dark matter

- ChiralEFT4DM: PYTHON package for dark matter structure factors

  `https://theorie.ikp.physik.tu-darmstadt.de/strongint/ChiralEFT4DM.html`

- Includes:
  - (Quasi-) Coherent structure factors for F, Si, Ar, Ge, Xe
  - Nucleon matrix elements and matching relations for spin-$1/2$ and spin-0 WIMP
  - 1b and 2b responses up to third chiral order
  - S, P, V, A, T, θ_μ^μ, and spin-2 effective operators that can lead to a coherent response
  - Convolution with Standard Halo Model

Chiral counting for neutrino–nucleus scattering

WIMP	Nucleon	V: t	V: $\mathbf{x}$	A: t	A: $\mathbf{x}$
V	1b	0	$1+2$	2	$0+2$
	2b	4	$2+2$	2	$4+2$
	2b NLO	—	—	5	$3+2$
A	1b	$0+2$	1	$2+2$	0
	2b	$4+2$	2	$2+2$	4
	2b NLO	—	—	$5+2$	3

WIMP	Nucleon	S	P
S	1b	2	1
	2b	3	5
	2b NLO	—	4
P	1b	$2+2$	$1+2$
	2b	$3+2$	$5+2$
	2b NLO	—	$4+2$

Chiral counting for neutrino–nucleus scattering

ν	Nucleon	V t	V $\mathbf{x}$	A t	A $\mathbf{x}$
V	1b	0	1	2	0
	2b	4	2	2	4
	2b NLO	—	—	5	3
A	1b	0	1	2	0
	2b	4	2	2	4
	2b NLO	—	—	5	3

ν	Nucleon	S	P
S	1b	2	1
	2b	3	5
	2b NLO	—	4
P	1b	2	1
	2b	3	5
	2b NLO	—	4

Chiral counting for neutrino–nucleus scattering

ν	Nucleon	V t	V **x**	A t	A **x**
V	1b	0	1	2	0
	2b	4	2	2	4
	2b NLO	—	—	5	3
A	1b	0	1	2	0
	2b	4	2	2	4
	2b NLO	—	—	5	3

ν	Nucleon	S	P
S	1b	2	1
	2b	3	5
	2b NLO	—	4
P	1b	2	1
	2b	3	5
	2b NLO	—	4

- **Standard interactions**: *AA* as for dark matter, vector 2b
- **Non-standard interactions**: potentially large corrections for scalar 2b currents

Coherence effects

- Six distinct nuclear responses
  Fitzpatrick et al. 2012, Anand et al. 2013
  - $M \leftrightarrow \mathcal{O}_1 \leftrightarrow$ SI
  - $\Sigma', \Sigma'' \leftrightarrow \mathcal{O}_4, \mathcal{O}_6 \leftrightarrow$ SD
  - $\Phi'' \leftrightarrow \mathcal{O}_3 \leftrightarrow$ quasi-coherent, spin-orbit operator
  - $\Delta, \tilde{\Phi}'$: not coherent
- **Quasi-coherence** of Φ''
  - Spin-orbit splitting
  - Coherence until mid-shell
  - About 20 coherent nucleons in Xe
  - Interference M–$\Phi'' \leftrightarrow \mathcal{O}_1$–$\mathcal{O}_3$
- Coherent 2b currents:
  - Scalar $\propto N + Z$
  - Vector $\propto N - Z$

$\hookrightarrow$ concentrate on scalar case