Nuclear structure factors for dark matter and CEνNS

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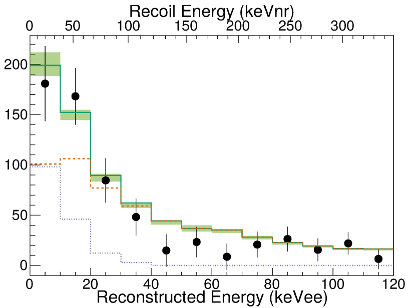
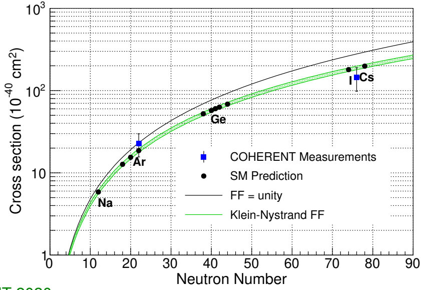
MH, Klos, Menéndez, Schwenk PRD 99 (2019) 055031

MH, Menéndez, Schwenk to appear

Recent observations of CEνNS by COHERENT

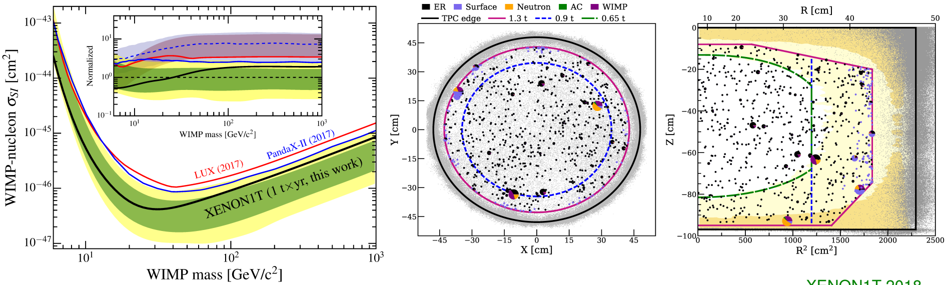




COHERENT 2020

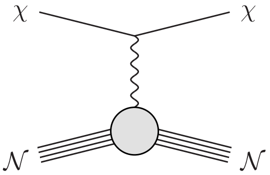
- CEνNS = coherent elastic neutrino–nucleus scattering Freedman 1974
- In SM: sensitive probe of the neutron distribution in nucleus
- Beyond SM: non-standard neutrino interactions?

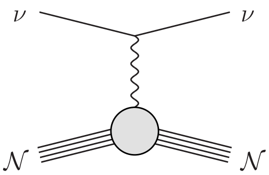
Direct detection of dark matter



XENON1T 2018

- Search for dark matter via nuclear recoils in large-scale liquid-noble-gas detectors
- Limits interpreted in terms of WIMP–nucleon cross sections





	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

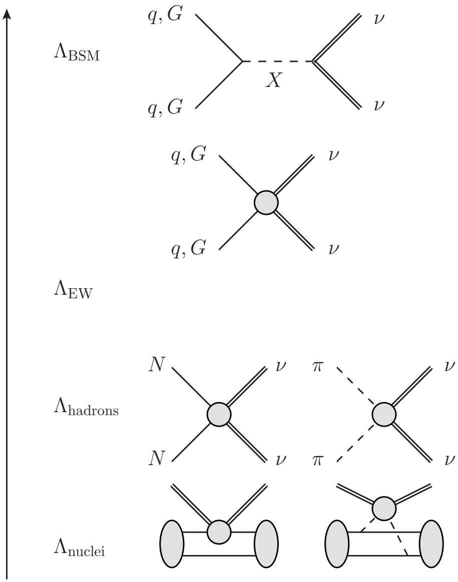
Rate $=$ BSM couplings $\otimes$ hadronic matrix elements $\otimes$ nuclear structure $\otimes$ astrophysics

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

- Same approach to CEνNS (with or without 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

Scales



1. **BSM scale** Λ_{BSM}: $\mathcal{L}_{\text{BSM}}$
2. **Effective Operators**: $\mathcal{L}_{\text{SM}} + \sum_{i,k} \frac{1}{\Lambda^i_{\text{BSM}}} \mathcal{O}_{i,k}$
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

First step: effective operators

- **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

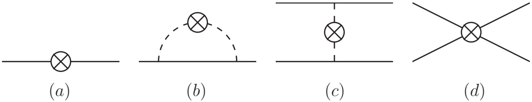
- In SM:

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

- 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**

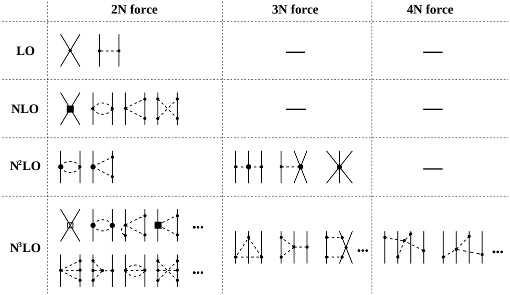
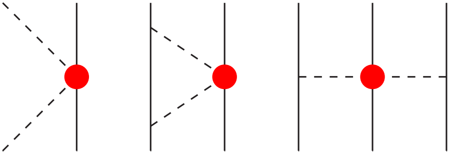
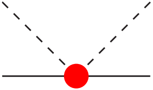


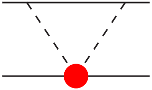
Figure taken from 1011.1343

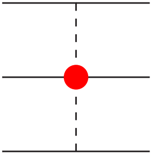


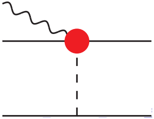
- Coupling to **external sources** $\mathcal{L}(v_\mu, a_\mu, s, p)$
- Same LECs appear in **axial-vector current**
- Two-body effects well established in β decay, magnetic moments, ...
- Formalism can be applied to other than vector and axial-vector currents

  $\hookrightarrow$ 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
- We can do better than simple parameterizations in terms of proton/neutron radii!

CEνNS cross section

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

- 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

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

- 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

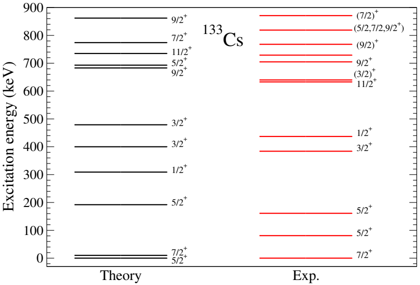
$$\langle r^2_\text{ch}\rangle = \langle r^2_p\rangle + \langle r^2_{E,p}\rangle + \frac{N}{Z}\langle r^2_{E,n}\rangle + \langle r^2_\text{rel}\rangle + \langle r^2_\text{spin-orbit}\rangle$$

- But: charge radii used to constrain parameters
- Point-neutron radii more uncertain, e.g. from coupled-cluster Payne et al. 2019

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

- Related to structure factors by

$$\langle r_p^2\rangle = -\frac{3}{Z}\frac{\text{d}}{\text{d}q^2}\big(\mathcal{F}_+^M(q^2)+\mathcal{F}_-^M(q^2)\big)\Big|_{q^2=0} \qquad \langle r_n^2\rangle = -\frac{3}{N}\frac{\text{d}}{\text{d}q^2}\big(\mathcal{F}_+^M(q^2)-\mathcal{F}_-^M(q^2)\big)\Big|_{q^2=0}$$


133Cs
Excitation energy (keV)
Theory
Exp.
9/2+
7/2+
11/2+
5/2+
9/2+
3/2+
3/2+
1/2+
5/2+
7/2+
5/2+
(7/2)+
(5/2,7/2,9/2+)
(9/2)+
9/2+
(3/2)+
11/2+
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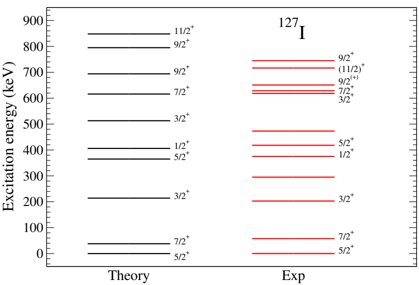
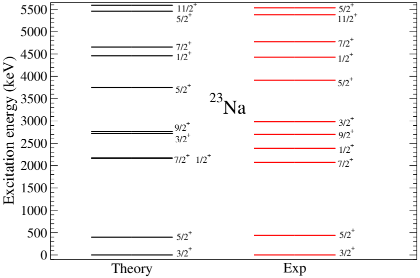
5/2+
5/2+
7/2+


127I
Excitation energy (keV)
Theory
Exp
11/2+
9/2+
9/2+
7/2+
3/2+
1/2+
5/2+
3/2+
7/2+
5/2+
9/2+
(11/2)+
9/2(+)
7/2+
3/2+
5/2+
1/2+
3/2+
7/2+
5/2+


23Na
Excitation energy (keV)
Theory
Exp
11/2+
5/2+
7/2+
1/2+
5/2+
9/2+
3/2+
7/2+ 1/2+
5/2+
3/2+
5/2+
11/2+
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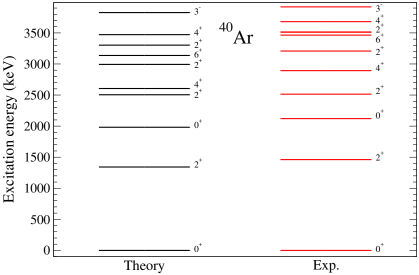
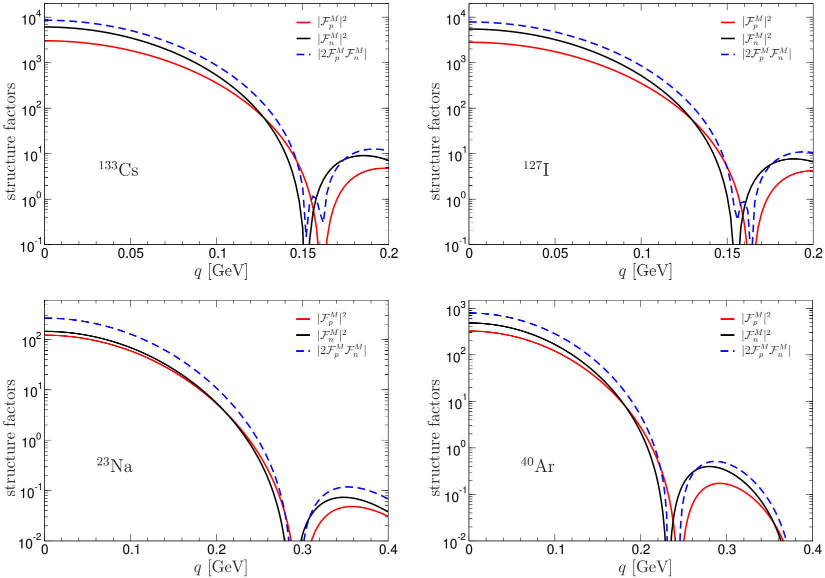
1/2+
5/2+
3/2+
9/2+
1/2+
7/2+
5/2+
3/2+


40Ar
Excitation energy (keV)
Theory
Exp.
3-
4+
2+
6+
2+
4+
2+
0+
2+
0+
3-
4+
2+
6+
2+
4+
2+
0+
2+
0+

Structure factors

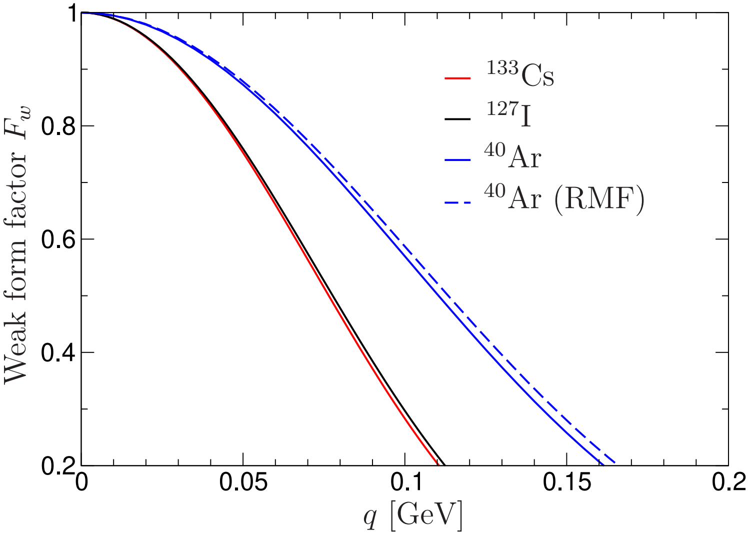


The weak form factor

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

- 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

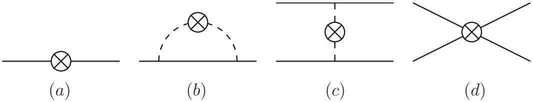
The weak form factor



A question to experiment

- Current list of isotopes MH, Menéndez, Schwenk to appear:
  - 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?**

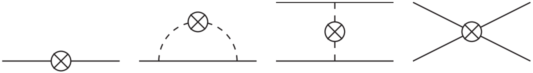
Cross section and nuclear structure factors



$$\frac{d\sigma_{\chi\mathcal{N}}}{dq^2} = \frac{1}{4\pi v^2}\bigg|\sum_{I=\pm}\Big(c_I^M - \frac{q^2}{m_N^2}\dot{c}_I^M\Big)\mathcal{F}_I^M(q^2) + c_\pi\mathcal{F}_\pi(q^2) + c_b\mathcal{F}_b(q^2) + \frac{q^2}{2m_N^2}\sum_{I=\pm}c_I^{\Phi''}\mathcal{F}_I^{\Phi''}(q^2)\bigg|^2$$
$$+ \frac{1}{4\pi v^2}\sum_{i=5,8,11}\bigg|\sum_{I=\pm}\xi_i(q, v_T^\perp)c_I^{M,i}\mathcal{F}_I^M(q^2)\bigg|^2$$
$$+ \frac{1}{v^2(2J+1)}\Big(|a_+|^2 S_{00}(q^2) + \text{Re}\,(a_+a_-^*)S_{01}(q^2) + |a_-|^2 S_{11}(q^2)\Big)$$

- Decomposition into **nuclear structure factors** $\mathcal{F}$, S_{ij} and coefficients c, a
- Three classes of contributions:
  - **(Sub-) Leading 1b responses** (a): $c_I^M\mathcal{F}_I^M(q^2)$, $c_I^{\Phi''}\mathcal{F}_I^{\Phi''}(q^2)$, $|a_\pm|^2 S_{ij}(q^2)$
  - **Radius corrections** (b): $\dot{c}_I^M\mathcal{F}_I^M(q^2)$
  - **Two-body currents** (c), (d): $c_\pi\mathcal{F}_\pi(q^2)$, $c_b\mathcal{F}_b(q^2)$
- (a)+(b) essentially **nucleon form factors**, but (c)+(d) genuinely new effects

Cross section and nuclear structure factors



(a) (b) (c) (d)

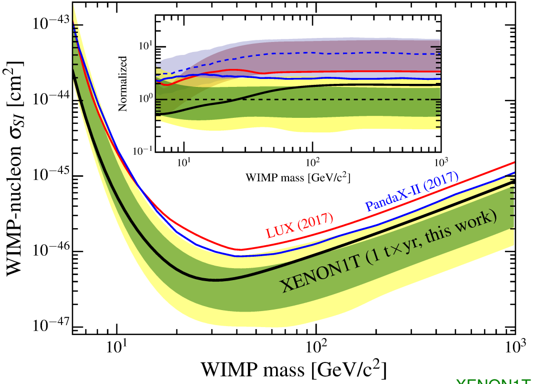
$$\frac{d\sigma_{\chi\mathcal{N}}}{dq^2} = \frac{1}{4\pi v^2}\bigg|\sum_{I=\pm}\Big(c_I^M - \frac{q^2}{m_N^2}\dot{c}_I^M\Big)\mathcal{F}_I^M(q^2) + c_\pi\mathcal{F}_\pi(q^2) + c_b\mathcal{F}_b(q^2) + \frac{q^2}{2m_N^2}\sum_{I=\pm}c_I^{\Phi''}\mathcal{F}_I^{\Phi''}(q^2)\bigg|^2$$

$$+\frac{1}{4\pi v^2}\sum_{i=5,8,11}\bigg|\sum_{I=\pm}\xi_i(q,v_T^\perp)c_I^{M,i}\mathcal{F}_I^M(q^2)\bigg|^2$$

$$+\frac{1}{v^2(2J+1)}\Big(|a_+|^2 S_{00}(q^2) + \text{Re}\,(a_+a_-^*)S_{01}(q^2) + |a_-|^2 S_{11}(q^2)\Big)$$

- Nuclear structure interpretation:
  - $\mathcal{F}_I^M(q^2)$: $\mathbb{1} \Rightarrow$ charge distribution (coherent), $\mathcal{F}_\pm^M(0) = Z \pm N$
  - $\mathcal{F}_I^{\Phi''}(q^2)$: $i\mathbf{S}_N\cdot(\mathbf{q}\times\mathbf{v}^\perp) \Rightarrow$ spin-orbit interaction (quasi-coherent)
  - $S_{ij}(q^2)$: $\mathbf{S}_\chi\cdot\mathbf{S}_N$, $\mathbf{S}_\chi\cdot\mathbf{q}\,\mathbf{S}_N\cdot\mathbf{q} \Rightarrow$ spin average (not coherent), $S_{00}(0)\pm S_{01}(0)+S_{11}(0) = \frac{(2J+1)(J+1)}{4\pi J}|\langle\mathbf{S}_{p/n}\rangle|^2$
- Coefficients: convolution of **Wilson coefficients** and **nucleon matrix elements**

$$c_\pm^M = \frac{\zeta}{2}(f_p \pm f_n) + \cdots \qquad f_N = \frac{m_N}{\Lambda^3}\sum_{q=u,d,s}C_q^{SS}f_q^N + \cdots \qquad \langle N|m_q\bar{q}q|N\rangle = m_N f_q^N$$



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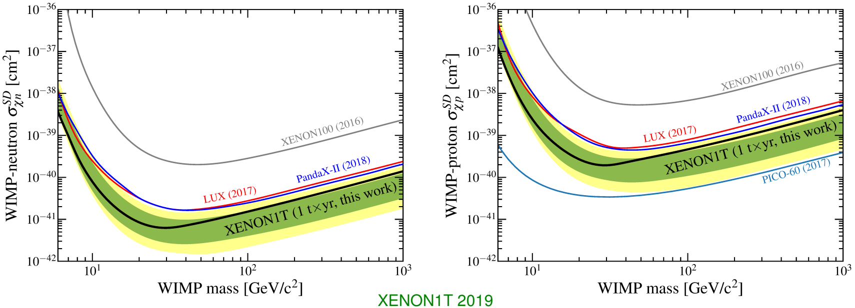
- All $c = 0$, $a = 0$ except for c_+^M: **spin-independent scattering**

$$\frac{\mathrm{d}\sigma_{\chi\mathcal{N}}}{\mathrm{d}q^2} = \frac{\sigma_{\chi N}^{\mathrm{SI}}}{4\mu_N^2 v^2}\big|\mathcal{F}_+^M(q^2)\big|^2 \qquad \sigma_{\chi N}^{\mathrm{SI}} = \frac{\mu_N^2}{\pi}\big|c_+^M\big|^2 \qquad \mu_N = \frac{m_N m_\chi}{m_N + m_\chi}$$

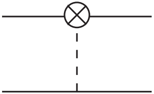
Case 2: spin-dependent scattering



XENON1T 2019

- All $c = 0$, $a_+ = \pm a_-$: **spin-dependent scattering**

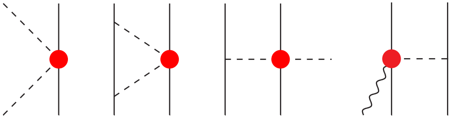
$$\frac{d\sigma_{\chi\mathcal{N}}}{dq^2} = \frac{\sigma^{\text{SD}}_{\chi N}}{3\mu_N^2 v^2}\frac{\pi}{2J+1}S_N(q^2) \qquad \sigma^{\text{SD}}_{\chi N} = \frac{3\mu_N^2}{\pi}|a_+|^2$$

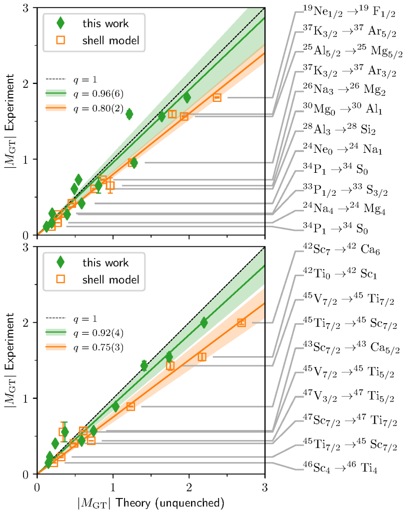


- Xe sensitive to proton spin due to **two-body currents**

  Klos, Menéndez, Gazit, Schwenk 2013

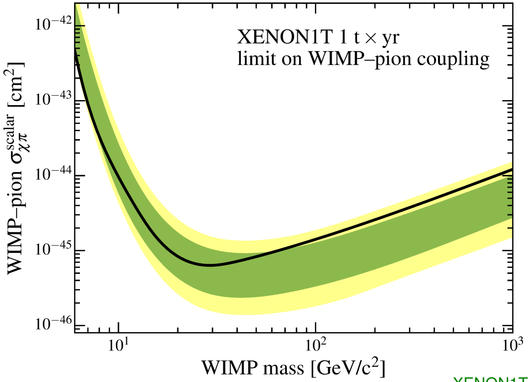
- Recent EFT developments:
  - Improved understanding of **two-body currents** in light and medium-size nuclei from ab-initio methods
  - Improved determination of **low-energy constants** MH, Ruiz de Elvira, Kubis, Meißner 2015
- Permits improved SD responses both for dark matter and CEνNS

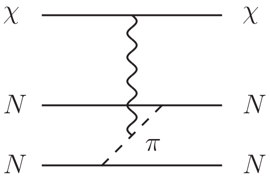




Gysbers et al. 2019

Case 3: WIMP–pion scattering





XENON1T + MH, Klos, Menéndez, Schwenk 2019

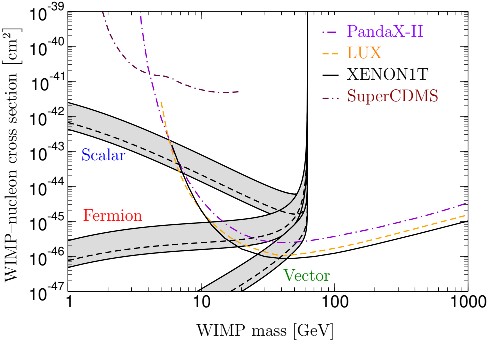
- Only c_π nonzero: **WIMP–pion scattering**

$$\frac{d\sigma_{\chi\mathcal{N}}}{dq^2} = \frac{\sigma_{\chi\pi}^{\text{scalar}}}{\mu_\pi^2 v^2}\big|\mathcal{F}_\pi(q^2)\big|^2 \qquad \sigma_{\chi\pi}^{\text{scalar}} = \frac{\mu_\pi^2}{4\pi}\big|c_\pi\big|^2 \qquad \mu_\pi = \frac{m_\chi M_\pi}{m_\chi + M_\pi}$$

- Expression in terms of cross section depends on underlying operator, here for a scalar $\bar\chi\chi\bar q q$

Higgs Portal dark matter

- **Higgs Portal**: WIMP interacts with SM via the Higgs
  - **Scalar**: $H^\dagger H S^2$
  - **Vector**: $H^\dagger H V_\mu V^\mu$
  - **Fermion**: $H^\dagger H \bar{f} f$
- If $m_h > 2m_\chi$, should happen at the LHC
  $\hookrightarrow$ limits on **invisible Higgs decays**



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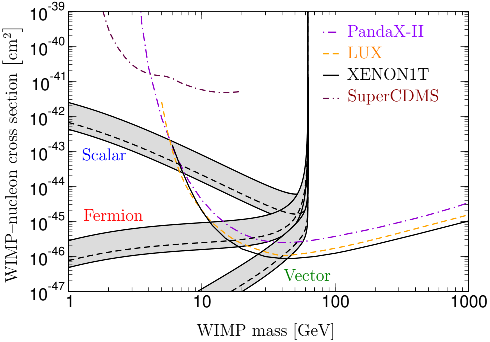
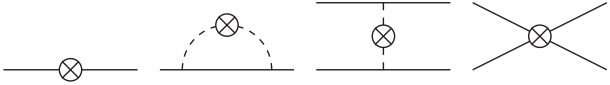


- Translation requires input for **Higgs–nucleon coupling**

$$f_N = \sum_{q=u,d,s,c,b,t} f_q^N = \frac{2}{9} + \frac{7}{9} \sum_{q=u,d,s} f_q^N + \mathcal{O}(\alpha_s) \qquad m_N f_q^N = \langle N | m_q \bar{q} q | N \rangle$$

- Issues: input for $f_N = 0.260 \ldots 0.629$ outdated, 2b currents missing

Higgs–nucleon coupling



(a) (b) (c) (d)

- **One-body contribution**

$$f_N^{1b} = 0.307(9)_{ud}(15)_s(5)_{\text{pert}} = 0.307(18)$$

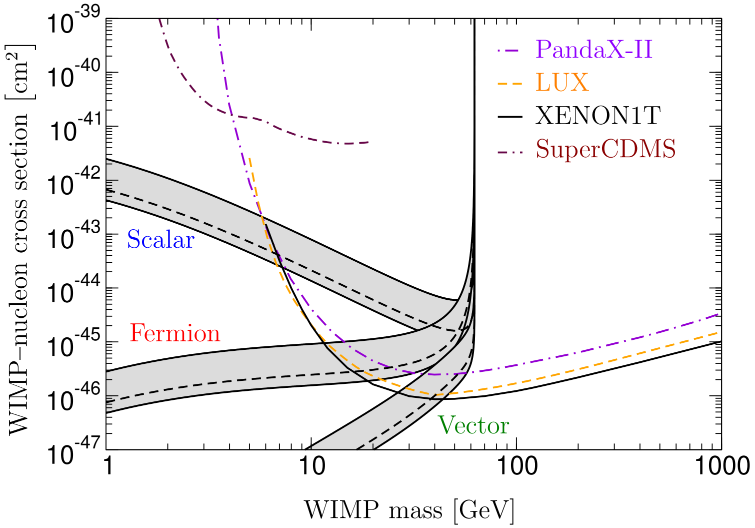
- Limits on WIMP–nucleon cross section subsume **2b effects**

  ↪ have to be included for meaningful comparison

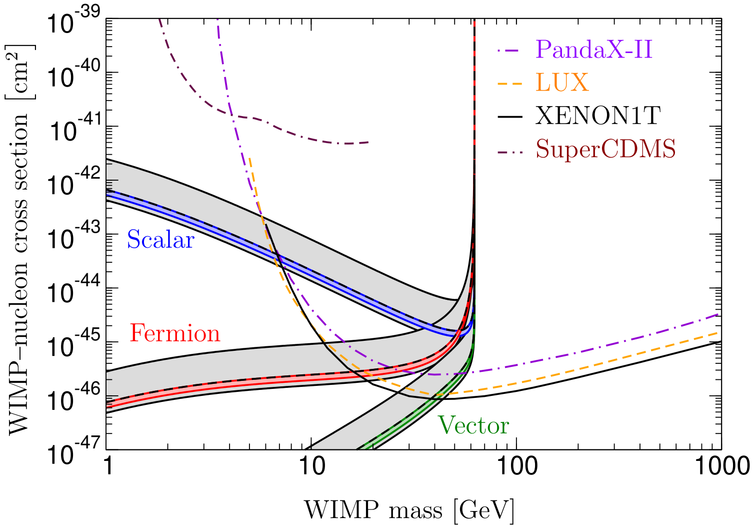
- **Two-body contribution**
  - Need s and θ^μ_μ currents
  - Treatment of θ^μ_μ tricky: several ill-defined terms combine to $\langle\Psi|T+V_{NN}|\Psi\rangle = E_{\text{b}}$
  - A cancellation makes the final result anomalously small

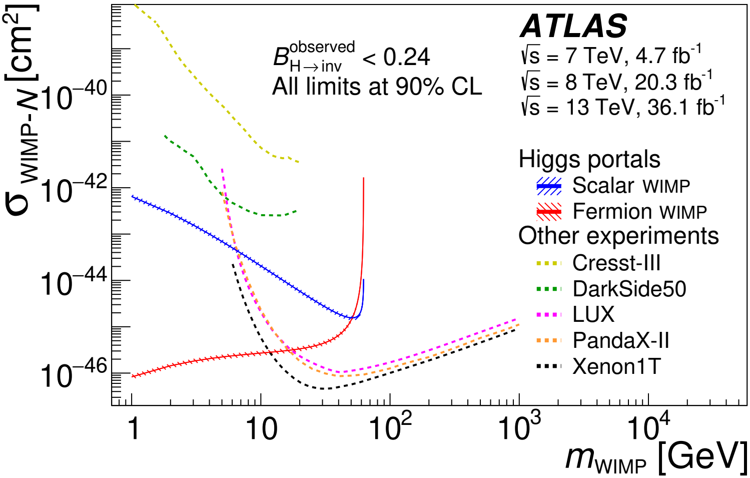
$$f_N^{2b} = \big[-3.2(0.2)_A(2.1)_{\text{ChEFT}} + 5.0(0.4)_A\big] \times 10^{-3} = 1.8(2.1)\times 10^{-3}$$

Improved limits for Higgs Portal dark matter



Improved limits for Higgs Portal dark matter




ATLAS
√s = 7 TeV, 4.7 fb-1
√s = 8 TeV, 20.3 fb-1
√s = 13 TeV, 36.1 fb-1
$B^{\text{observed}}_{H\to\text{inv}} < 0.24$
All limits at 90% CL
Higgs portals
Scalar WIMP
Fermion WIMP
Other experiments
Cresst-III
DarkSide50
LUX
PandaX-II
Xenon1T
$\sigma_{\text{WIMP-}N}$ [cm^2]
10^{-40}
10^{-42}
10^{-44}
10^{-46}
1
10
10^2
10^3
10^4
m_{WIMP} [GeV]

ATLAS 2019

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

Conclusions

- **EFT approach** to dark matter and CEνNS
- 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**

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

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

Chiral counting for neutrino–nucleus scattering

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

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