Chiral effective field theory for direct detection

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Astro-, Particle, and Nuclear Physics of Dark Matter Direct Detection

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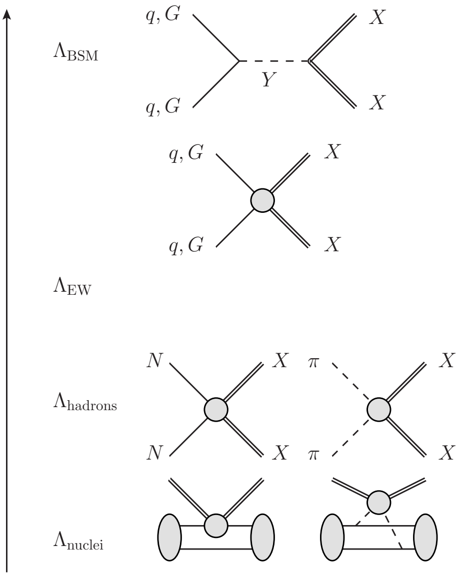
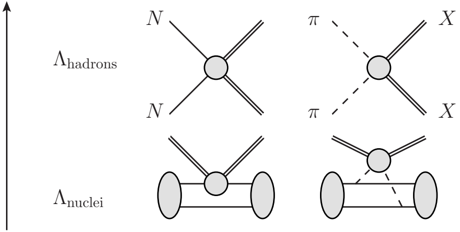
Outline

Direct detection of dark matter: 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**
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

Direct detection of dark matter: scales



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

- Typical WIMP–nucleon **momentum transfer**

$$|\mathbf{q}_{\text{max}}| = 2\mu_{\mathcal{N}\chi}|\mathbf{v}_{\text{rel}}| \sim 200\,\text{MeV} \qquad |\mathbf{v}_{\text{rel}}| \sim 10^{-3} \qquad \mu_{\mathcal{N}\chi} \sim 100\,\text{GeV}$$

- QCD constraints: spontaneous breaking of chiral symmetry

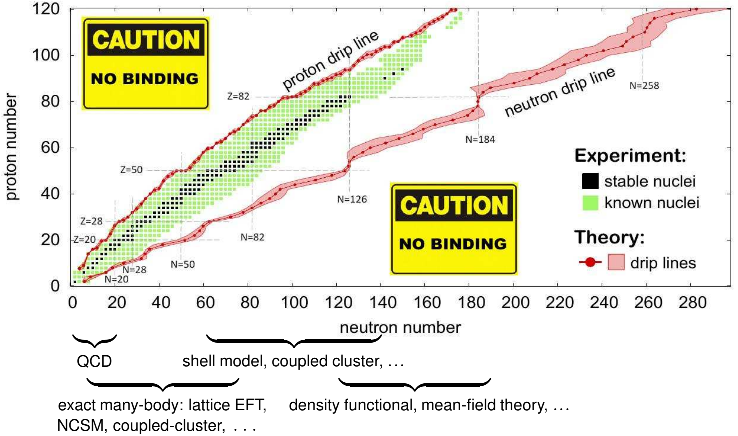
  $\Rightarrow$ **Chiral effective field theory for WIMP–nucleon scattering**

  Prézeau et al. 2003, Cirigliano et al. 2012, 2013, Menéndez et al. 2012, Klos et al. 2013, MH et al. 2015

- In NREFT Fan et al. 2010, Fitzpatrick et al. 2012, Anand et al. 2013 need to **match to QCD** to extract information on BSM physics $\Rightarrow$ "the" EFT approach not unique!

- Neither ChEFT nor NREFT valid for WIMP masses $\lesssim 1\,\text{GeV}$

Nuclear Physics from first principles



long-range plan 2015

- Finding missing nuclei: mission of **FRIB**
- Piecewise overlap of **ab-initio** and various **many-body** methods $\Rightarrow$ match to QCD
- Consistent *NN* interactions key at various stages

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 $3N$

$\hookrightarrow$ modern theory of nuclear forces

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

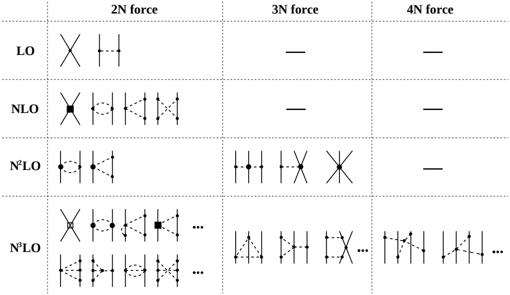
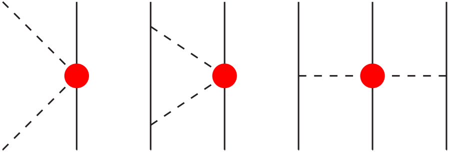


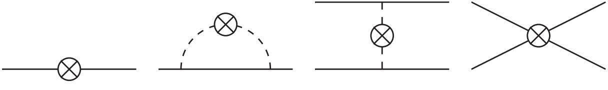
Figure taken from 1011.1343



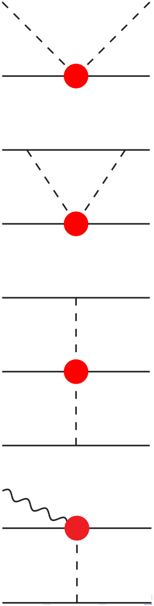
Chiral EFT: currents

- Coupling to **external sources** $\mathcal{L}(v_\mu, a_\mu, s, p)$
- Same LECs appear in **axial current**

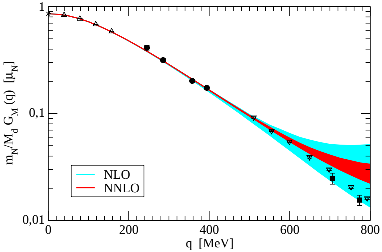
  $\hookrightarrow$ β decay, neutrino interactions, dark matter
- Vast literature for v_μ and a_μ, up to one-loop level
  - With unitary transformations: Kölling et al. 2009, 2011, Krebs et al. 2016
  - Without unitary transformations: Pastore et al. 2008, Park et al. 2003, Baroni et al. 2015
- For **dark matter** further currents: s, p, tensor, spin-2, θ^μ_μ

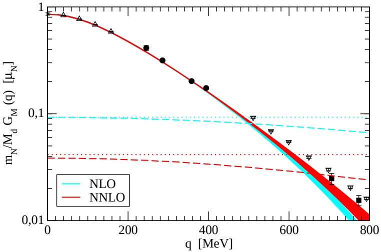


(a) (b) (c) (d)

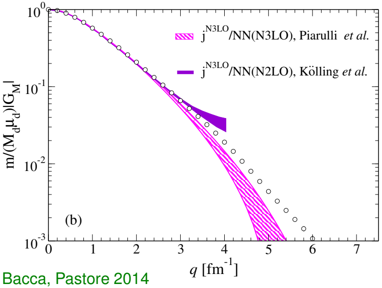


Vector current in chiral EFT: deuteron form factors, magnetic moments

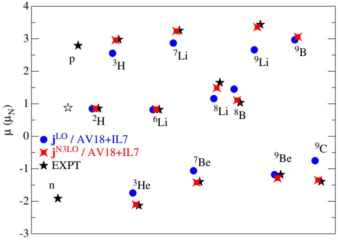




Kölling, Epelbaum, Phillips 2012

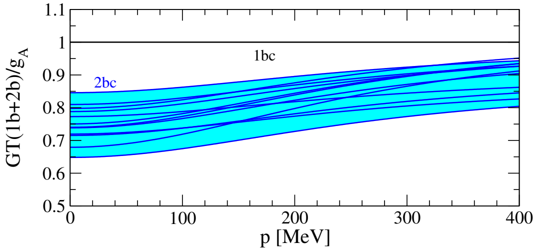


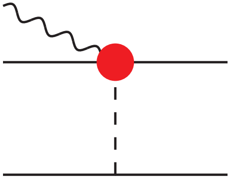
Bacca, Pastore 2014



Pastore et al. 2013

Axial-vector current in chiral EFT: ν-less double β decay

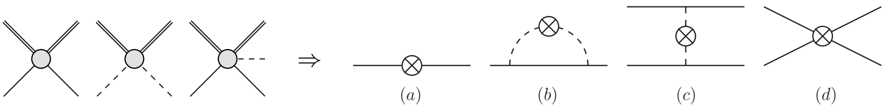




Menéndez, Gazit, Schwenk 2011

- Normal ordering over Fermi sea $\Rightarrow$ effective one-body currents
- **Two-body currents** contribute to **quenching of g_A** in Gamow–Teller operator $g_A \boldsymbol{\sigma}\tau^-$

Direct detection and chiral EFT



- Expansion around **chiral limit** of QCD

  $\hookrightarrow$ simultaneous expansion in momenta and quark masses

- Three classes of corrections:
  - **Subleading one-body responses** (*a*)
  - **Radius corrections** (*b*)
  - **Two-body currents** (*c*), (*d*)
- NREFT covers (*a*), but misses (*b*)–(*d*)
  - (*b*): modifies coefficient of $\mathcal{O}_i$ by momentum-dependent factor
  - (*c*), (*d*): do not match directly onto NREFT, need **normal ordering** next talk by P. Klos

$$\langle N^\dagger N\rangle N^\dagger N \to \mathcal{O}_i^{\text{eff}}$$

Chiral counting

- Starting point: **effective WIMP Lagrangian** Goodman et al. 2010

$$\mathcal{L}_\chi = \frac{1}{\Lambda^3}\sum_q \Big[C_q^{SS}\bar\chi\chi\, m_q\bar q q + C_q^{PS}\bar\chi i\gamma_5\chi\, m_q\bar q q + C_q^{SP}\bar\chi\chi\, m_q\bar q i\gamma_5 q + C_q^{PP}\bar\chi i\gamma_5\chi\, m_q\bar q i\gamma_5 q\Big]$$
$$+ \frac{1}{\Lambda^2}\sum_q \Big[C_q^{VV}\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu q + C_q^{AV}\bar\chi\gamma^\mu\gamma_5\chi\,\bar q\gamma_\mu q + C_q^{VA}\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu\gamma_5 q + C_q^{AA}\bar\chi\gamma^\mu\gamma_5\chi\,\bar q\gamma_\mu\gamma_5 q\Big]$$
$$+ \frac{1}{\Lambda^3}\Big[C_g^{S}\bar\chi\chi\,\alpha_s G_{\mu\nu}^a G_a^{\mu\nu}\Big]$$

- **Chiral power counting**

$$\partial = \mathcal{O}(p), \qquad m_q = \mathcal{O}(p^2) = \mathcal{O}(M_\pi^2), \qquad a_\mu, v_\mu = \mathcal{O}(p), \qquad \frac{\partial}{m_N} = \mathcal{O}(p^2)$$

$\hookrightarrow$ construction of effective Lagrangian for nucleon and pion fields

$\hookrightarrow$ organize in terms of **chiral order ν**, $\mathcal{M} = \mathcal{O}(p^\nu)$

Chiral counting: summary

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	—	$4+2$

- $+2$ from NR expansion of WIMP spinors, terms can be dropped if $m_\chi \gg m_N$
- Red: all terms up to $\nu = 3$
- Two-body currents: *AA* Menéndez et al. 2012, Klos et al. 2013, *SS* Prézeau et al. 2003, Cirigliano et al. 2012, but **new currents in *AV* and *VA* channel** 1503.04811

Matching to nonrelativistic EFT

- Operator basis in NREFT Fan et al. 2010, Fitzpatrick et al. 2012, Anand et al. 2013

$$\mathcal{O}_1 = \mathbb{1} \qquad \mathcal{O}_2 = (\mathbf{v}^\perp)^2 \qquad \mathcal{O}_3 = i\mathbf{S}_N \cdot (\mathbf{q} \times \mathbf{v}^\perp) \qquad \mathcal{O}_4 = \mathbf{S}_\chi \cdot \mathbf{S}_N$$

$$\mathcal{O}_5 = i\mathbf{S}_\chi \cdot (\mathbf{q} \times \mathbf{v}^\perp) \qquad \mathcal{O}_6 = \mathbf{S}_\chi \cdot \mathbf{q}\, \mathbf{S}_N \cdot \mathbf{q} \qquad \mathcal{O}_7 = \mathbf{S}_N \cdot \mathbf{v}^\perp \qquad \mathcal{O}_8 = \mathbf{S}_\chi \cdot \mathbf{v}^\perp$$

$$\mathcal{O}_9 = i\mathbf{S}_\chi \cdot (\mathbf{S}_N \times \mathbf{q}) \qquad \mathcal{O}_{10} = i\mathbf{S}_N \cdot \mathbf{q} \qquad \mathcal{O}_{11} = i\mathbf{S}_\chi \cdot \mathbf{q}$$

- Matching to chiral EFT ($f_N, \ldots$: Wilson coefficients + nucleon form factors)

$$\mathcal{M}^{SS}_{1,\text{NR}} = \mathcal{O}_1 f_N(t) \qquad \mathcal{M}^{SP}_{1,\text{NR}} = \mathcal{O}_{10} g_5^N(t) \qquad \mathcal{M}^{PP}_{1,\text{NR}} = \frac{1}{m_\chi}\mathcal{O}_6 h_5^N(t)$$

$$\mathcal{M}^{VV}_{1,\text{NR}} = \mathcal{O}_1\Big(f_1^{V,N}(t) + \frac{t}{4m_N^2} f_2^{V,N}(t)\Big) + \frac{1}{m_N}\mathcal{O}_3 f_2^{V,N}(t) + \frac{1}{m_N m_\chi}\Big(t\mathcal{O}_4 + \mathcal{O}_6\Big) f_2^{V,N}(t)$$

$$\mathcal{M}^{AV}_{1,\text{NR}} = 2\mathcal{O}_8 f_1^{V,N}(t) + \frac{2}{m_N}\mathcal{O}_9\Big(f_1^{V,N}(t) + f_2^{V,N}(t)\Big)$$

$$\mathcal{M}^{AA}_{1,\text{NR}} = -4\mathcal{O}_4 g_A^N(t) + \frac{1}{m_N^2}\mathcal{O}_6 g_P^N(t) \qquad \mathcal{M}^{VA}_{1,\text{NR}} = \Big\{-2\mathcal{O}_7 + \frac{2}{m_\chi}\mathcal{O}_9\Big\} h_A^N(t)$$

- Conclusions
  - $\mathcal{O}_2$, $\mathcal{O}_5$, and $\mathcal{O}_{11}$ do not appear at $\nu = 3$, not all $\mathcal{O}_i$ independent
  - 2b operators of similar or even greater importance than some of the 1b operators

Example: chiral counting in scalar channel

- Leading pion–nucleon Lagrangian

$$\mathcal{L}_{\pi N}^{(1)} = \bar{\Psi}\left[i\gamma_\mu\left(\partial^\mu - i v^\mu\right) - m_N + \frac{g_A}{2}\gamma_\mu\gamma_5\left(2a^\mu - \frac{\partial^\mu \boldsymbol{\pi}}{F_\pi}\right) + \cdots\right]\Psi$$

$\hookrightarrow$ **no scalar source**!

WIMP	Nucleon	S
	1b	2
S	2b	3

Example: chiral counting in scalar channel

- Leading pion–nucleon Lagrangian

$$\mathcal{L}_{\pi N}^{(1)} = \bar{\Psi}\Big[i\gamma_\mu\big(\partial^\mu - i v^\mu\big) - m_N + \frac{g_A}{2}\gamma_\mu\gamma_5\Big(2a^\mu - \frac{\partial^\mu \boldsymbol{\pi}}{F_\pi}\Big) + \cdots\Big]\Psi$$

$\hookrightarrow$ **no scalar source**!

- Scalar coupling

$$f_N = \frac{m_N}{\Lambda^3}\sum_{q=u,d,s} C_q^{SS} f_q^N + \cdots \qquad \langle N|m_q\bar{q}q|N\rangle = f_q^N m_N$$

	Nucleon	S
WIMP		
	1b	2
S	2b	3

$\hookrightarrow$ for $q = u, d$ related to **pion–nucleon σ-term** $\sigma_{\pi N}$

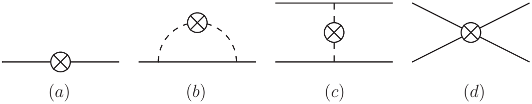
- Chiral expansion

$$\sigma_{\pi N} = -4c_1 M_\pi^2 - \frac{9g_A^2 M_\pi^3}{64\pi F_\pi^2} + \mathcal{O}(M_\pi^4) \qquad \dot{\sigma} = \frac{5g_A^2 M_\pi}{256\pi F_\pi^2} + \mathcal{O}(M_\pi^2)$$

$\hookrightarrow$ slow convergence due to strong $\pi\pi$ rescattering

$\hookrightarrow$ use phenomenology for the full scalar form factor!

QCD constraints for subleading nuclear corrections



- One-body operators: known **nuclear form factors**

  $\hookrightarrow$ determines **radius corrections** (*b*)

- **Axial Ward identity** relates $g^N_{A,P}(t)$ and

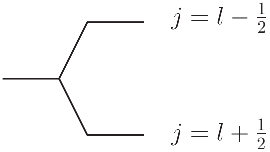
$$\mathcal{M}^{AA}_{1,\mathrm{NR}} = -4\mathcal{O}_4 g^N_A(t) + \frac{1}{m_N^2}\mathcal{O}_6 g^N_P(t)$$

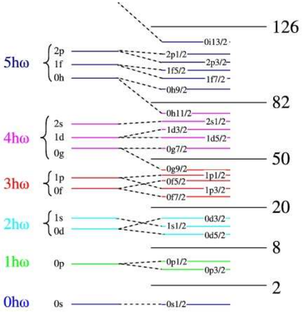
  $\hookrightarrow$ fixed combination of $\mathcal{O}_{4,6}$ in (*a*)

- $\mathcal{O}_{10}$ only appears in *SP* channel $\Rightarrow$ not coherent and vanishes at $\mathbf{q} = 0$

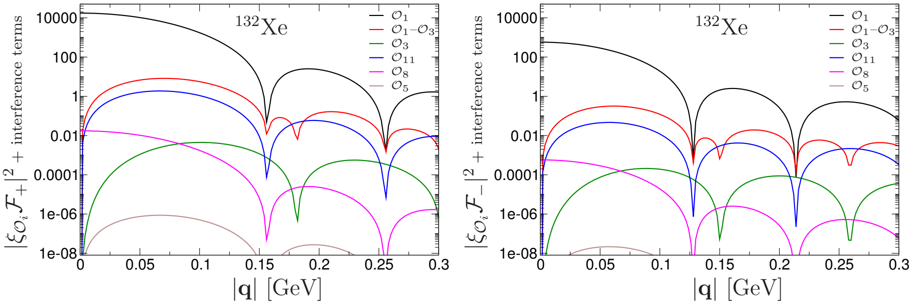
Coherence effects

- 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–$\Phi'' \leftrightarrow \mathcal{O}_1$–$\mathcal{O}_3$
- Further coherent M-responses from $\mathcal{O}_5$, $\mathcal{O}_8$, $\mathcal{O}_{11}$, but no interference with $\mathcal{O}_1$ due to sum over $\mathbf{S}_\chi$



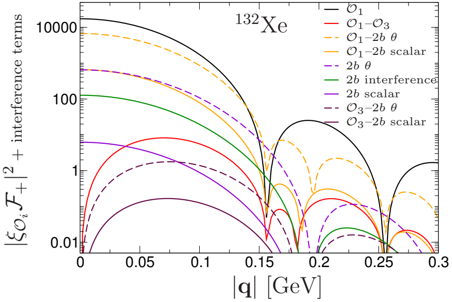


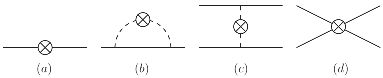
Consequences for the structure factors



- $\xi_{\mathcal{O}_i}$ kinematic factors for $\mathcal{O}_i$, e.g. $\xi_{\mathcal{O}_1} = 1$, $\xi_{\mathcal{O}_3} = \frac{\mathbf{q}^2}{2m_N^2}$
- $\mathcal{O}_{11}$ assumes $m_\chi = 2\,\text{GeV}$

  $\hookrightarrow$ much stronger suppressed for heavy WIMPs
- Structure factors imply **hierarchy** as long as coefficients do not differ strongly



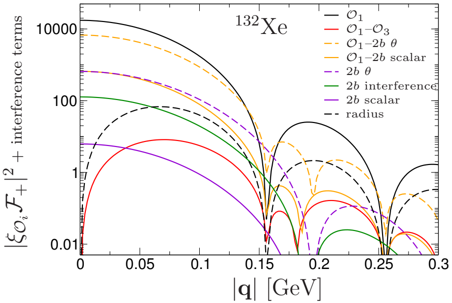


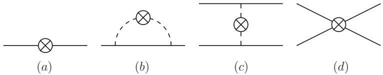
- Finite at $|\mathbf{q}| = 0$
- Most important next to IS and IV $\mathcal{O}_1$
- Sensitive to **new combination of Wilson coefficients**, e.g. for scalar channel

$$f_N = \frac{m_N}{\Lambda^3}\bigg(\sum_{q=u,d,s} C_q^{SS} f_q^N - 12\pi f_Q^N C_g'^S\bigg) \qquad f_\pi = \frac{M_\pi}{\Lambda^3}\sum_{q=u,d}\bigg(C_q^{SS} + \frac{8\pi}{9}C_g'^S\bigg)f_q^\pi \qquad f_\pi^\theta = -\frac{M_\pi}{\Lambda^3}\frac{8\pi}{9}C_g'^S$$

- Typically (5–10)% effect, enhanced whenever cancellations occur: **blind spots**, **heavy WIMP limit**

Radius corrections

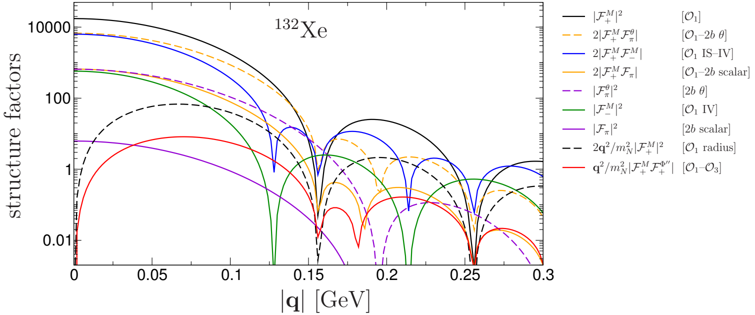




- Set scale as $\mathbf{q}^2/m_N^2$
- Strong suppression at small $|\mathbf{q}|$, but potentially relevant later
- Yet another new combination

$$\dot{f}_N = \frac{m_N}{\Lambda^3}\left(\sum_{q=u,d,s} C_q^{SS}\dot{f}_q^N - 12\pi\dot{f}_Q^N C_g'^S\right)$$

Full set of coherent contributions



- Parameterize cross section as

$$\frac{d\sigma^{SI}_{\chi\mathcal{N}}}{d\mathbf{q}^2} = \frac{1}{4\pi\mathbf{v}^2}\bigg|\Big(c_+^M - \frac{\mathbf{q}^2}{m_N^2}\dot{c}_+^M\Big)\mathcal{F}_+^M(\mathbf{q}^2) + \Big(c_-^M - \frac{\mathbf{q}^2}{m_N^2}\dot{c}_-^M\Big)\mathcal{F}_-^M(\mathbf{q}^2)$$

$$+ c_\pi\mathcal{F}_\pi(\mathbf{q}^2) + c_\pi^\theta\mathcal{F}_\pi^\theta(\mathbf{q}^2) + \frac{\mathbf{q}^2}{2m_N^2}\Big[c_+^{\Phi''}\mathcal{F}_+^{\Phi''}(\mathbf{q}^2) + c_-^{\Phi''}\mathcal{F}_-^{\Phi''}(\mathbf{q}^2)\Big]\bigg|^2$$

- Single-nucleon cross section: $\sigma^{SI}_{\chi N} = \mu_N^2|c_+^M|^2/\pi$
- c related to Wilson coefficients and nucleon form factors

Comparison to NREFT

- For the **leading corrections** all $\mathcal{O}_i$ but $\mathcal{O}_3$ are small

  $\hookrightarrow$ not necessary to keep 2×14 parameters in first step

- But: some new parameters for two-body effects and radius corrections

  $\hookrightarrow$ cover **coherent responses** (+ SD), same order in chiral counting

- Nucleon operators: $\mathbb{1}$, $\mathbf{S}_N$, $\mathbf{v}^\perp$, $\mathbf{v}^\perp \times \mathbf{q}$, $\mathbf{v}^\perp \cdot \mathbf{q} = 0$

  $\hookrightarrow$ only $\mathbf{v}^\perp \to \boldsymbol{\nabla}$ can produce new coherent (nuclear) effect

- Similarly to SD searches: define subleading "cross sections"

  $\hookrightarrow$ pion–WIMP scattering

- NREFT only first step in chain of EFTs

  $\hookrightarrow$ need **matching to QCD** to make connection to BSM, ChEFT one crucial step

Analysis strategies

- Parameters ($\zeta = 1(2)$ for Dirac (Majorana)):

$$c_\pm^M = \frac{\zeta}{2}\Big[f_p \pm f_n + f_1^{V,p} \pm f_1^{V,n}\Big] \qquad c_\pi = \zeta f_\pi \qquad c_\pi^\theta = \zeta f_\pi^\theta \qquad c_\pm^{\Phi''} = \frac{\zeta}{2}\Big(f_2^{V,p} \pm f_2^{V,n}\Big)$$

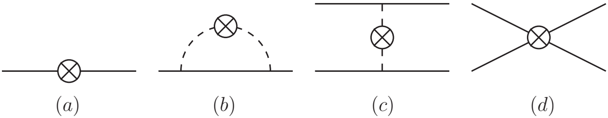
$$\dot{c}_\pm^M = \frac{\zeta m_N^2}{2}\bigg[\dot{f}_p \pm \dot{f}_n + \dot{f}_1^{V,p} \pm \dot{f}_1^{V,n} + \frac{1}{4m_N^2}\Big(f_2^{V,p} \pm f_2^{V,n}\Big)\bigg]$$

- Couplings

$$f_N = \frac{m_N}{\Lambda^3}\bigg(\sum_{q=u,d,s} C_q^{SS} f_q^N - 12\pi f_Q^N C_g^{\prime S}\bigg) \qquad f_\pi = \frac{M_\pi}{\Lambda^3}\sum_{q=u,d}\bigg(C_q^{SS} + \frac{8\pi}{9}C_g^{\prime S}\bigg) f_q^\pi \qquad f_\pi^\theta = -\frac{M_\pi}{\Lambda^3}\frac{8\pi}{9}C_g^{\prime S}$$

- Conclusions
  - Different c probe **different linear combinations** of Wilson coefficients
  - Ideally: global analysis of different experiments
  - **One-operator-at-a-time strategy**: producing limits e.g. on c_-^M and c_π in addition to c_+^M would provide additional information on BSM parameter space
  - **QCD constraints**: when considering $\mathcal{O}_3$ should also keep radius corrections

Conclusions



- **Chiral EFT** for WIMP–nucleon scattering
- Predicts **hierarchy** for corrections to leading coupling
- Connects nuclear and hadronic scales
- More on implementation into **nuclear structure factors** next talk by P. Klos

Status of the phenomenological determination of $\sigma_{\pi N}$

- **Karlsruhe/Helsinki** partial-wave analysis KH80 Höhler et al. 1980s

  $\hookrightarrow$ comprehensive analyticity constraints, old data

- Formalism for the extraction of $\sigma_{\pi N}$ via the **Cheng–Dashen low-energy theorem**

  Gasser, Leutwyler, Locher, Sainio 1988, Gasser, Leutwyler, Sainio 1991

  $\hookrightarrow$ "canonical value" $\sigma_{\pi N} \sim 45\,\text{MeV}$, based on KH80 input

- **GWU/SAID** partial-wave analysis Pavan, Strakovsky, Workman, Arndt 2002

  $\hookrightarrow$ much larger value $\sigma_{\pi N} = (64 \pm 8)\,\text{MeV}$

- ChPT fits vary according to PWA input Fettes, Meißner 2000

  (same problem in different regularizations (w/ and w/o Δ) Alarcón et al. 2012)

Status of the phenomenological determination of $\sigma_{\pi N}$

- **Karlsruhe/Helsinki** partial-wave analysis KH80 Höhler et al. 1980s

  $\hookrightarrow$ comprehensive analyticity constraints, old data

- Formalism for the extraction of $\sigma_{\pi N}$ via the **Cheng–Dashen low-energy theorem**

  Gasser, Leutwyler, Locher, Sainio 1988, Gasser, Leutwyler, Sainio 1991

  $\hookrightarrow$ "canonical value" $\sigma_{\pi N} \sim 45\,\text{MeV}$, based on KH80 input

- **GWU/SAID** partial-wave analysis Pavan, Strakovsky, Workman, Arndt 2002

  $\hookrightarrow$ much larger value $\sigma_{\pi N} = (64 \pm 8)\,\text{MeV}$

- ChPT fits vary according to PWA input Fettes, Meißner 2000

  (same problem in different regularizations (w/ and w/o Δ) Alarcón et al. 2012)

- Our work: two new sources of information on low-energy πN scattering
  - Precision extraction of **πN scattering lengths** from **hadronic atoms**
  - **Roy-equation constraints**: analyticity, unitarity, crossing symmetry

  1506.04142,1510.06039

Error analysis

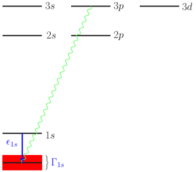
$$\sigma_{\pi N} = 59.1 \pm \underbrace{0.7}_{\text{flat directions}} \pm \underbrace{0.3}_{\text{matching}} \pm \underbrace{0.5}_{\text{systematics}} \pm \underbrace{1.7}_{\text{scattering lengths}} \pm \underbrace{3.0}_{\text{low-energy theorem}} \text{ MeV}$$

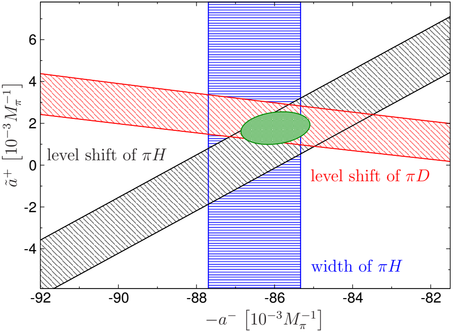
$$= 59.1 \pm 3.5 \text{ MeV}$$

- Crucial result: relation between $\sigma_{\pi N}$ and **πN scattering lengths**

$$\sigma_{\pi N} = 59.1\,\text{MeV} + \sum_{I_s} c_{I_s} \Delta a_{0+}^{I_s}$$

- **Pionic atoms**: $\pi^- p/d$ bound states





A new σ-term puzzle

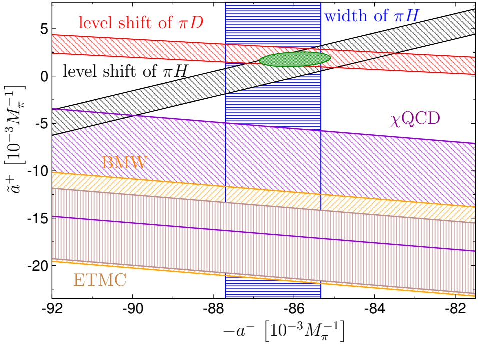
- Recent lattice calculations of $\sigma_{\pi N}$
  - BMW 1510.08013:

    $\sigma_{\pi N} = 38(3)(3)$ MeV
  - χQCD 1511.09089:

    $\sigma_{\pi N} = 44.4(3.2)(4.5)$ MeV
  - ETMC 1601.01624:

    $\sigma_{\pi N} = 37.22(2.57)\left(^{+0.99}_{-0.63}\right)$ MeV
  - RQCD 1603.00827:

    $\sigma_{\pi N} = 35(6)$ MeV



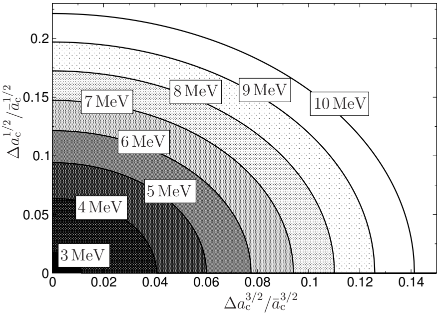
- Similar puzzle in lattice calculation of

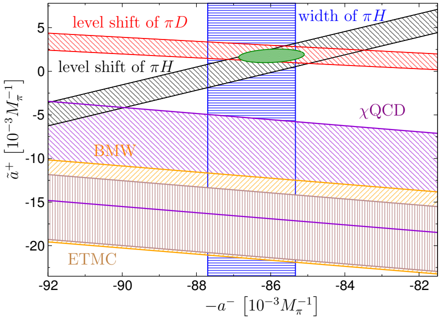
  $K \to \pi\pi$ RBC/UKQCD 1505.07863, also 3σ level

- Both puzzles with profound implications for BSM searches:

  scalar nucleon couplings, *CP* violation in K_0–$\bar{K}_0$ mixing

A new σ-term puzzle





- πN: lattice calculation of $a^{1/2}$, $a^{3/2}$

  $\hookrightarrow$ test input for πN scattering lengths

- Preliminary BMW update from lattice 2016: 38(3)(3) MeV $\rightarrow$ 48.5(8.0) MeV

Contact terms

- Scalar source also suppressed for $(N^\dagger N)^2$

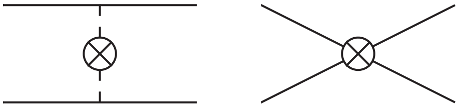
  $\hookrightarrow$ **long-range contribution dominant** (in Weinberg counting)

- Typical size **(5–10)%**

  $\hookrightarrow$ reflected by results for structure factors

  $\hookrightarrow$ more important in case of cancellations

- Contact terms $\leftrightarrow$ nuclear σ-terms Beane et al. 2014



Spin-2 and coupling to the energy-momentum tensor

- Effective Lagrangian truncated at dim-7, but if WIMP heavy $m_\chi/\Lambda = \mathcal{O}(1)$

  $\hookrightarrow$ heavy-WIMP EFT Hill, Solon 2012, 2014

$$\mathcal{L} = \frac{1}{\Lambda^4}\bigg\{\sum_q C_q^{(2)}\bar{\chi}\gamma_\mu i\partial_\nu\chi\frac{1}{2}\bar{q}\Big(\gamma^{\{\mu}iD_-^{\nu\}} - \frac{m_q}{2}g^{\mu\nu}\Big)q + C_g^{(2)}\bar{\chi}\gamma_\mu i\partial_\nu\chi\Big(\frac{g_{\mu\nu}}{4}G^a_{\lambda\sigma}G_a^{\lambda\sigma} - G_a^{\mu\lambda}G^\nu_{a\lambda}\Big)\bigg\}$$

  $\hookrightarrow$ leading order: **nucleon pdfs**

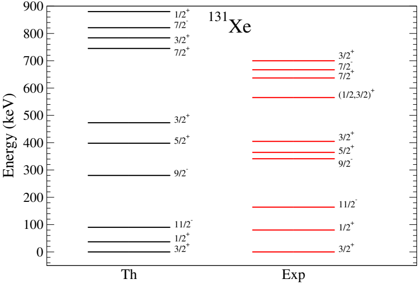
  $\hookrightarrow$ similar two-body current as in scalar case, pion pdfs, EMC effect

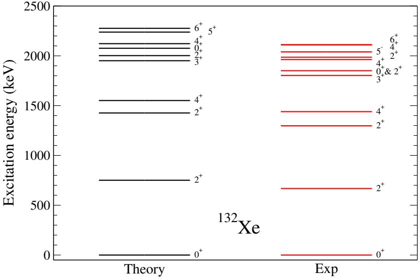
- Coupling of trace anomaly θ^μ_μ to $\pi\pi$

$$\theta^\mu_\mu = \sum_q m_q\bar{q}q + \frac{\beta_{\text{QCD}}}{2g_s}G^a_{\mu\nu}G_a^{\mu\nu} \quad\Leftrightarrow\quad \langle\pi(p')|\theta_{\mu\nu}|\pi(p)\rangle = p_\mu p'_\nu + p'_\mu p_\nu + g_{\mu\nu}\big(M_\pi^2 - p\cdot p'\big)$$

  $\hookrightarrow$ probes gluon Wilson coefficient C_g^S

Spectra and shell-model calculation





- **Shell-model diagonalization** for Xe isotopes with ^{100}Sn core
- **Uncertainty estimates**: currently phenomenological shell-model interaction

  ↪ chiral-EFT-based interactions in the future