Chiral effective field theory, two-body currents, and dark matter

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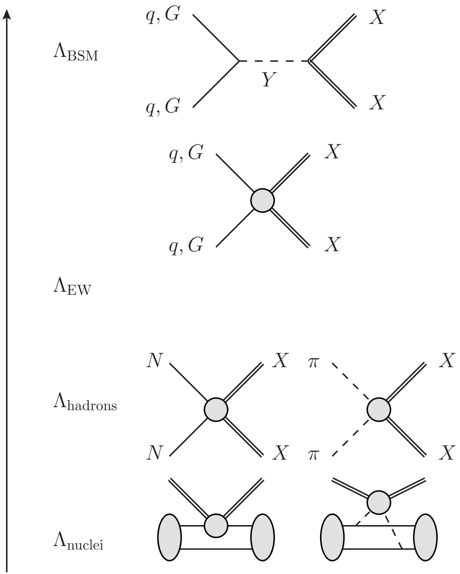
PLB 746 (2015) 410, PRD 94 (2016) 063505 with P. Klos, J. Menéndez, A. Schwenk

PRL 115 (2015) 092301, PLB 760 (2016) 74 with B. Kubis, U.-G. Meißner, J. Ruiz de Elvira

Outline

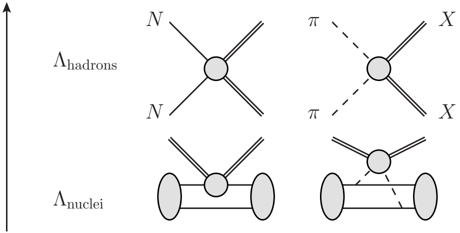
1. Direct detection of dark matter: scales
2. Chiral effective field theory
3. Corrections beyond standard nuclear response
4. Scalar channel
   - Chiral counting
   - Pion–nucleon σ-term
5. Spin-2 and coupling to the energy-momentum tensor
6. Conclusions

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



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- 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

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*

  ↪ modern theory of nuclear forces
- Long-range part related to **pion–nucleon scattering**
- KITP: tutorial Epelbaum, Nuclear EFTs – the crux of the matter Birse, Epelbaum

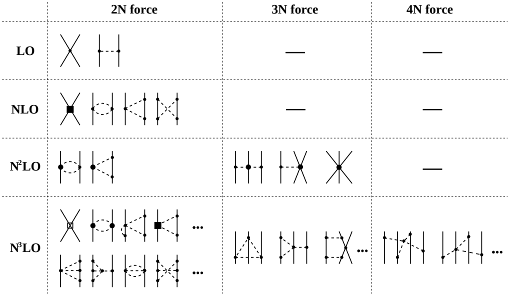
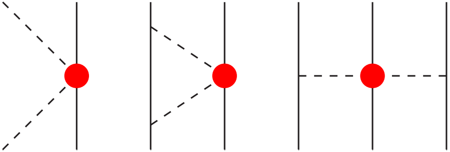


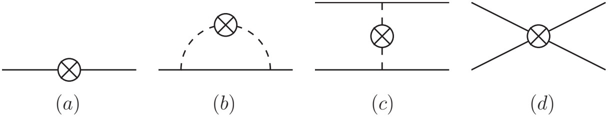
Figure taken from 1011.1343

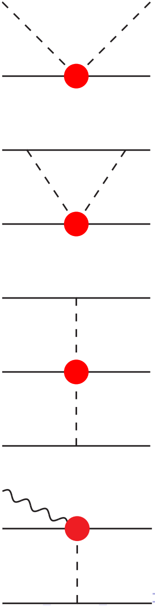


Chiral EFT: currents

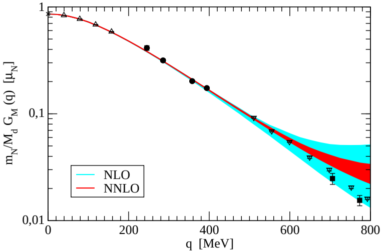
- Coupling to **external sources** $\mathcal{L}(v_\mu, a_\mu, s, p)$
- Same LECs appear in **axial current**

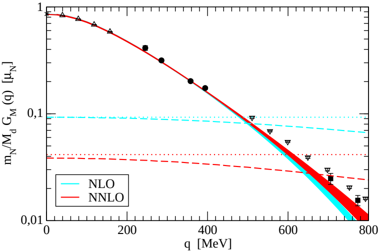
  $\hookrightarrow$ β decay, neutrino interactions, dark matter
- Vast literature for v_μ and a_μ, up to one-loop level
  - With unitary transformations: Kölling et al. 2009, 2011, Krebs et al. to appear
  - Without unitary transformations: Pastore et al. 2008, Park et al. 2003, Baroni et al. 2015
- For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



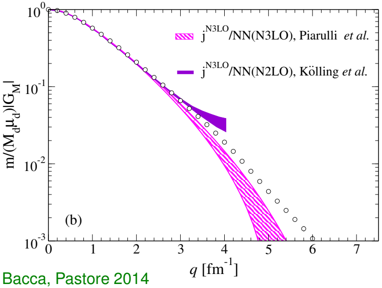


Vector current in chiral EFT: deuteron form factors, magnetic moments

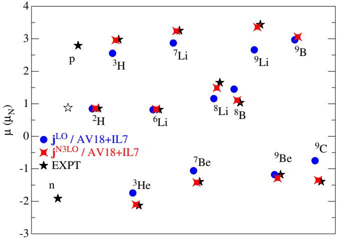




Kölling, Epelbaum, Phillips 2012

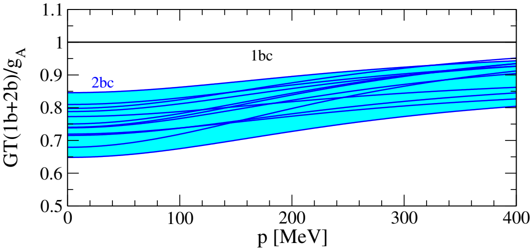


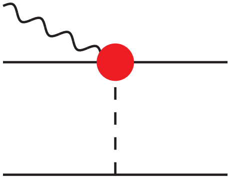
Bacca, Pastore 2014



Pastore et al. 2013

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

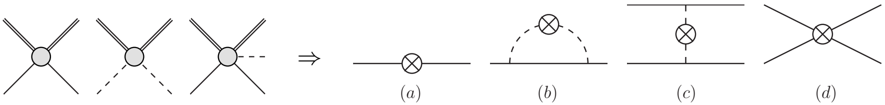




Menéndez, Gazit, Schwenk 2011

- Normal ordering over Fermi sea $\Rightarrow$ effective one-body currents
- **Two-body currents** contribute to **quenching of g_A** in Gamov–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*) Fan et al. 2010, Fitzpatrick et al. 2012, Anand et al. 2013
  - **Radius corrections** (*b*)
  - **Two-body currents** (*c*), (*d*)

Chiral counting

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

$$\mathcal{L}_\chi = \frac{1}{\Lambda^3}\sum_q \Big[C_q^{SS}\bar\chi\chi\, m_q\bar q q + C_q^{PS}\bar\chi i\gamma_5\chi\, m_q\bar q q + C_q^{SP}\bar\chi\chi\, m_q\bar q i\gamma_5 q + C_q^{PP}\bar\chi i\gamma_5\chi\, m_q\bar q i\gamma_5 q\Big]$$

$$+\frac{1}{\Lambda^2}\sum_q \Big[C_q^{VV}\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu q + C_q^{AV}\bar\chi\gamma^\mu\gamma_5\chi\,\bar q\gamma_\mu q + C_q^{VA}\bar\chi\gamma^\mu\chi\,\bar q\gamma_\mu\gamma_5 q + C_q^{AA}\bar\chi\gamma^\mu\gamma_5\chi\,\bar q\gamma_\mu\gamma_5 q\Big]$$

$$+\frac{1}{\Lambda^3}\Big[C_g^{S}\bar\chi\chi\,\alpha_s G^a_{\mu\nu}G_a^{\mu\nu}\Big]$$

- **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
  - **Phenomenological implications**: next talk by J. Menéndez

Chiral counting in scalar channel

- Leading pion–nucleon Lagrangian

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

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

WIMP	Nucleon	S
	1b	2
S	2b	3

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- Scalar coupling

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

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

WIMP	Nucleon	S
	1b	2
S	2b	3

- 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

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

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- 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

σ-term from Roy–Steiner analysis of pion–nucleon scattering

Error analysis

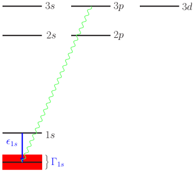
$$\sigma_{\pi N} = 59.1 \pm \underbrace{0.7}_{\text{flat directions}} \pm \underbrace{0.3}_{\text{matching}} \pm \underbrace{0.5}_{\text{systematics}} \pm \underbrace{1.7}_{\text{scattering lengths}} \pm \underbrace{3.0}_{\text{low-energy theorem}} \text{ MeV}$$

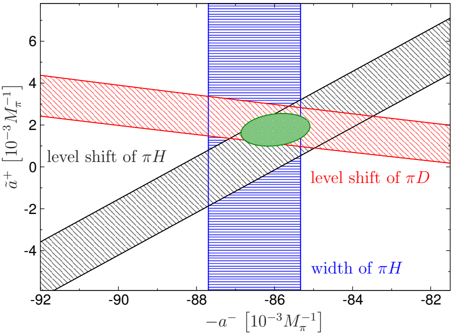
$$= 59.1 \pm 3.5 \text{ MeV}$$

- 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

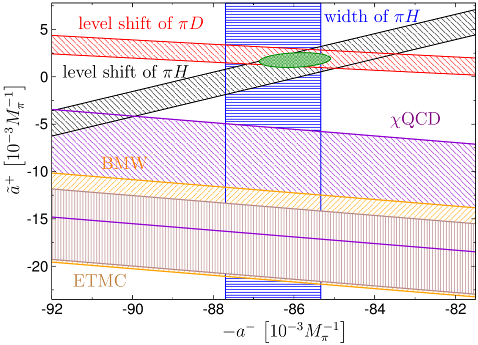
- Recent lattice calculations of $\sigma_{\pi N}$
  - BMW 1510.08013:

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

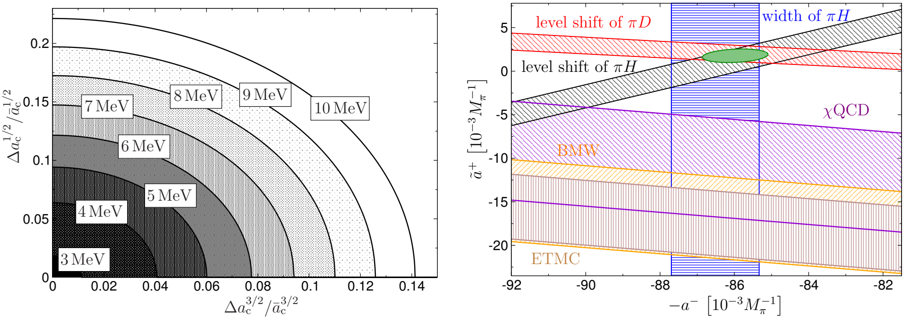
    $\sigma_{\pi N} = 44.4(3.2)(4.5)$ MeV
  - ETMC 1601.01624:

    $\sigma_{\pi N} = 37.22(2.57)\binom{+0.99}{-0.63}$ 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



- 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 $\to$ 48.5(8.0) MeV

Contact terms

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

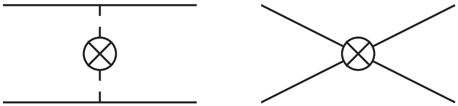
  $\hookrightarrow$ **long-range contribution dominant** (in Weinberg counting)

- Typical size **(5–10)%**

  $\hookrightarrow$ reflected by results for structure factors next talk by J. Menéndez

  $\hookrightarrow$ 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**

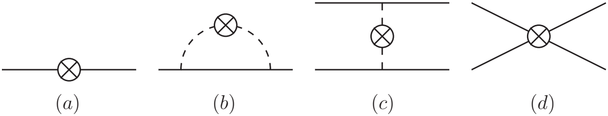
  $\hookrightarrow$ similar two-body current as in scalar case, pion pdfs, EMC effect

- 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

Conclusions



- **Chiral EFT** for WIMP–nucleon scattering
- Predicts **hierarchy** for corrections to leading coupling
- Connects nuclear and hadronic scales
- Nuclear matrix elements: tension between lattice and phenomenology for $\sigma_{\pi N}$
- Implementation into **nuclear structure factors** next talk by J. Menéndez