THEORY OF THE SCATTERING CROSS SECTION

for DM direct detection

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based on work with F. Bishara, J. Brod, B. Grinstein, JZ, 1611.00368, 1707.06998;1707.06998;+
J. Brod, A. Gootjes-Dreesbach, M. Tammaro, JZ, 1710.10218
J. Brod, E. Stamou, JZ, 1801.04240

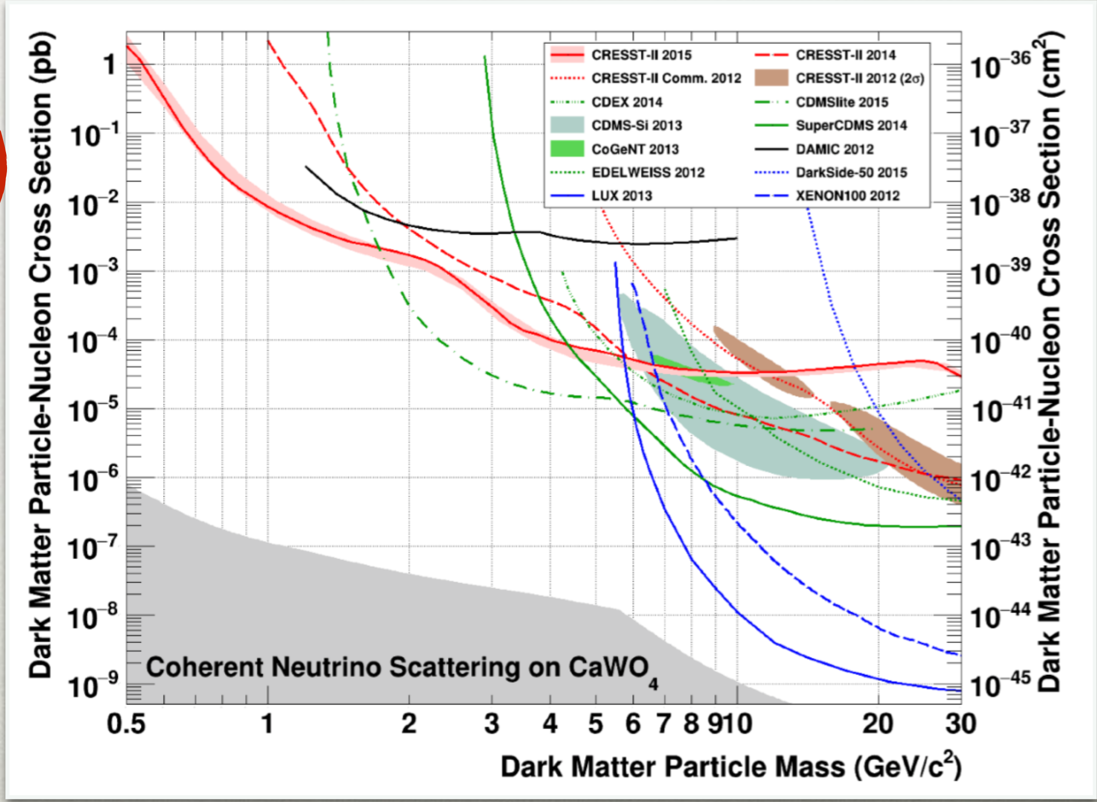
Dark Matter at the Dawn of Discovery?, Heidelberg, Apr 14 2018

MOTIVATION

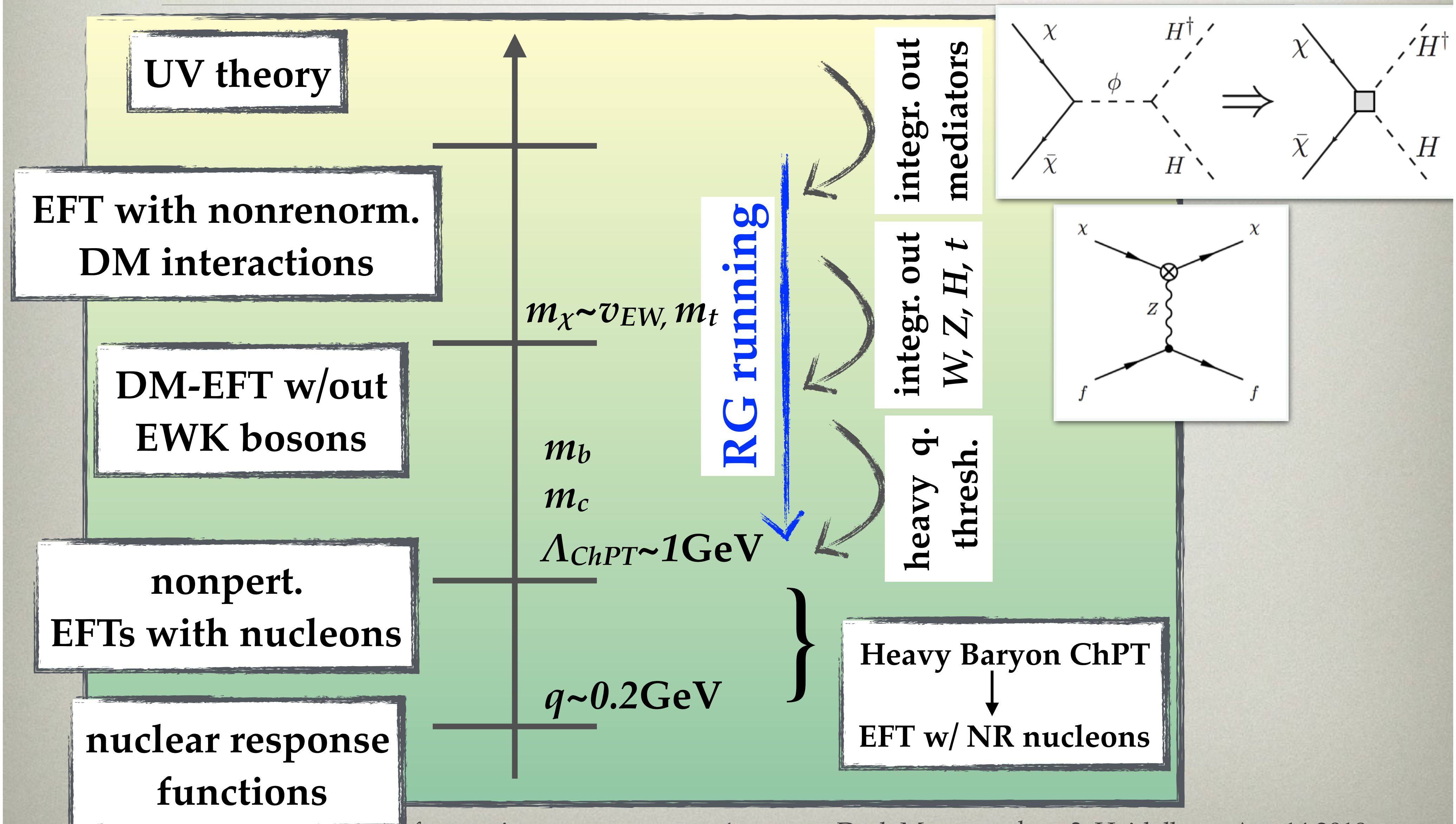
- DM candidate at EW scale in many solutions to the hierarchy problem
    - the dominant interactions with the SM may be unconventional
- can parametrize our ignorance by using EFT for DM interactions

MOTIVATION

- two immediate questions if signal of DM
  - comparing different DM direct detection experiments
  - comparing direct detection with LHC and indirect detection



TOWER OF EFTS



EFT expansion

- at which mass dimension to stop?

$$\mathcal{L}_{\rm EW} = \sum_{a,d} \frac{C_a^{(d)}}{\Lambda^{d-4}} Q_a^{(d)}$$

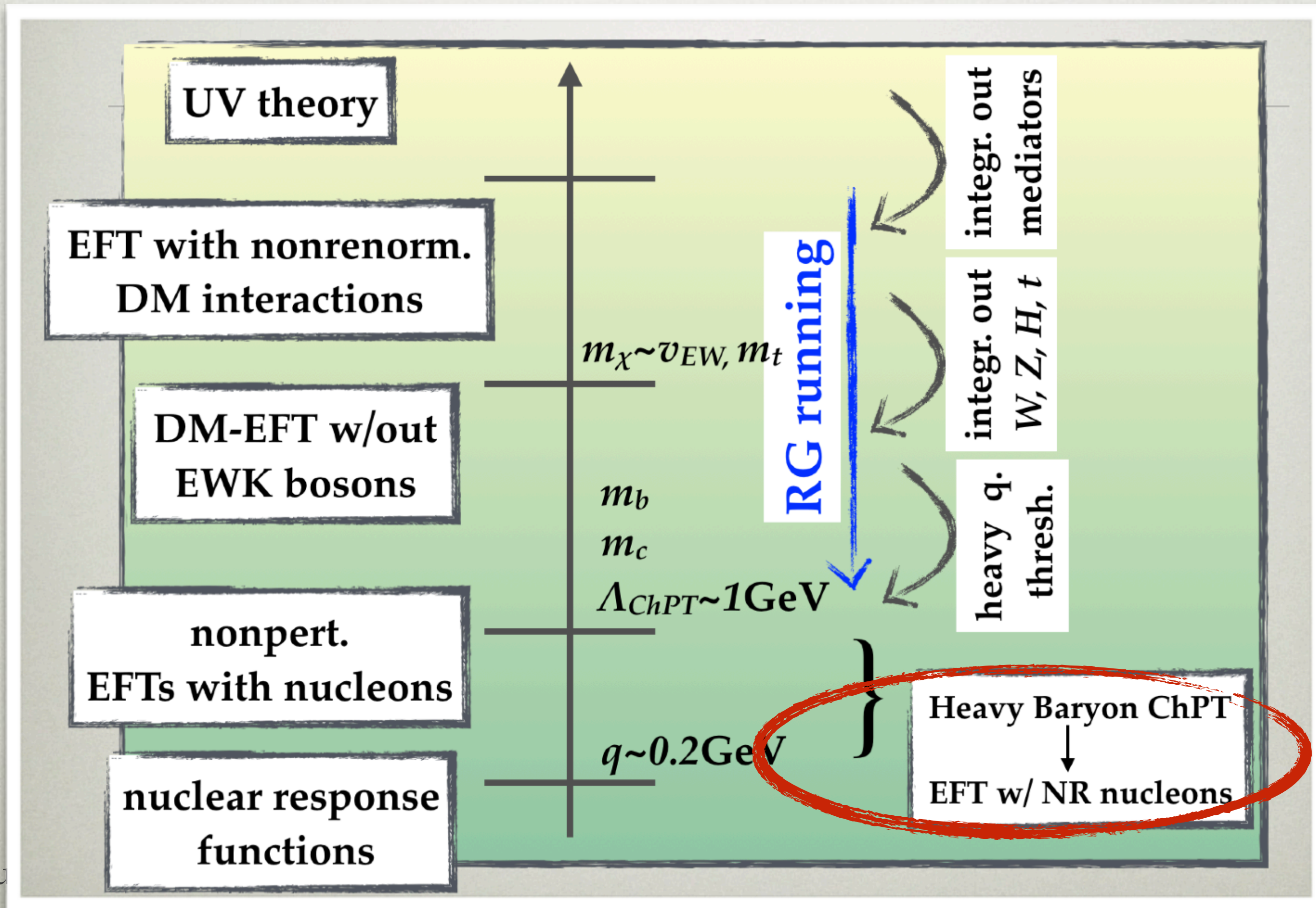
- at dimension 7 all chiral/Lorentz structures without derivatives
  - probably captures leading behaviour in most theories of DM
- already a large set of operators
  - above EW, if Dirac fermion DM in general EW multiplet
    - 8 dim-5 ops., 18 dim-6 ops., 100 dim-7 ops.
    - this not counting flavor multiplicities
  - at μ_{str}~2 GeV smaller set
    - 2 dim-5 ops., 4 dim-6 ops., 22 dim-7 ops.

AIM

- the aim is to be able to
  - take any DM EFT up to dim 7 above EW scale
    J. Brod, A. Gootjes-Dreesbach, M. Tammaro, JZ, 1710.10218
  - consistently give the leading expression for cross section
  - includes renormalization group running
  - consistent counting, including ChPT
    F. Bishara, J. Brod, B. Grinstein, JZ, 1611.00368, 1707.06998
- part of this already available in a **Mathematica** & **Python** package **DirectDM** F. Bishara, J. Brod, B. Grinstein, JZ, 1708.02678

GOAL FOR TODAY

- matching at μ_{str}~2 GeV from relativistic theory to nuclear physics



$$\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\bar\chi\sigma^{\mu\nu}\chi)F_{\mu\nu}\,, \qquad \mathcal{Q}_2^{(5)} = \frac{e}{8\pi^2}(\bar\chi\sigma^{\mu\nu}i\gamma_5\chi)F_{\mu\nu}$$

$$\mathcal{Q}_{1,q}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar q\gamma^\mu q), \qquad \mathcal{Q}_{2,q}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar q\gamma^\mu q),$$

$$\mathcal{Q}_{3,q}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar q\gamma^\mu\gamma_5 q)\,, \qquad \mathcal{Q}_{4,q}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar q\gamma^\mu\gamma_5 q)\,,$$

$$\mathcal{Q}_1^{(7)} = \frac{\alpha_s}{12\pi}(\bar\chi\chi)G^{a\mu\nu}G^a_{\mu\nu}\,, \qquad \mathcal{Q}_2^{(7)} = \frac{\alpha_s}{12\pi}(\bar\chi i\gamma_5\chi)G^{a\mu\nu}G^a_{\mu\nu}\,,$$

$$\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\bar\chi\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,, \qquad \mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar\chi i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,,$$

$$\mathcal{Q}_{5,q}^{(7)} = m_q(\bar\chi\chi)(\bar q q)\,, \qquad \mathcal{Q}_{6,q}^{(7)} = m_q(\bar\chi i\gamma_5\chi)(\bar q q)\,,$$

$$\mathcal{Q}_{7,q}^{(7)} = m_q(\bar\chi\chi)(\bar q i\gamma_5 q)\,, \qquad \mathcal{Q}_{8,q}^{(7)} = m_q(\bar\chi\gamma_5\chi)(\bar q\gamma_5 q)\,.$$

relativistic theory with quarks and gluons

?

non-relativistic theory with nucleons

$$\mathcal{O}_1^N = \mathbb{1}_\chi\mathbb{1}_N\,, \qquad \mathcal{O}_2^N = (v_\perp)^2\,\mathbb{1}_\chi\mathbb{1}_N\,,$$

$$\mathcal{O}_3^N = \mathbb{1}_\chi\,\vec S_N\cdot\Big(\vec v_\perp\times\frac{i\vec q}{m_N}\Big)\,, \qquad \mathcal{O}_4^N = \vec S_\chi\cdot\vec S_N\,,$$

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DIRECT DM DETECTION KINEMATICS

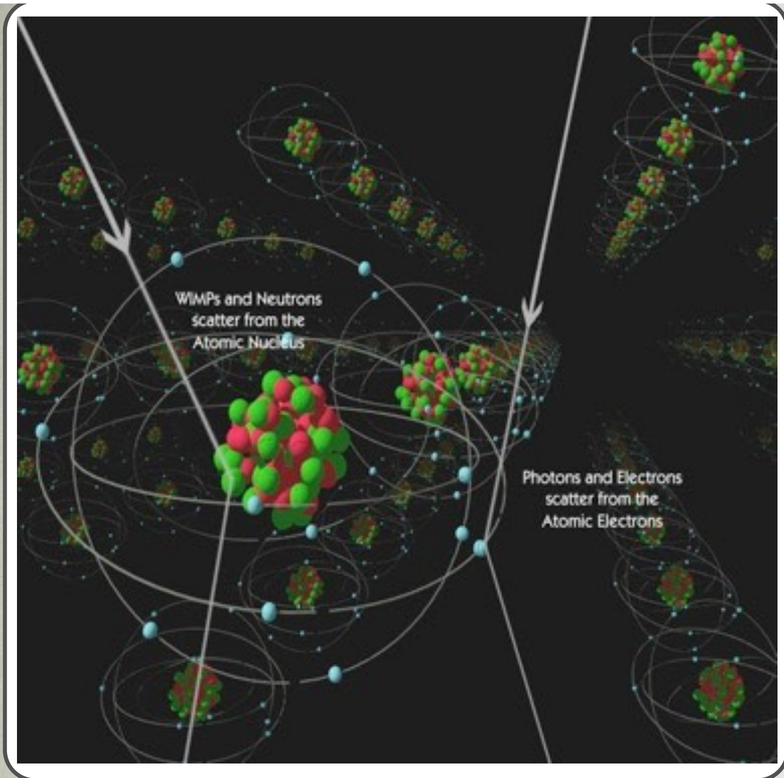
- WIMPS form DM halo
  - typical velocity $v \sim 10^{-3}$
- scatters on target nuclei $\chi N \to \chi N$
  - typical energy deposit

$$E_d = 2\frac{\mu_\chi^2}{M_A}v^2 \sim 2\text{keV}\left(\frac{120GeV}{M_A}\right)\left(\frac{\mu_\chi}{10\text{GeV}}\right)^2\left(\frac{v}{10^{-3}}\right)^2$$

  - typical momentum exchange

$$q_{\rm max} \sim 200 \text{ MeV}.$$

  - this allows for treatment with ChPT, expansion in q/Λ_{ChEFT}



DM detection
nematics

- M halo
- y $v \sim 10^{-3}$
- t nuclei $\chi N \to \chi N$
- typical energy deposit

$$E_d = 2\frac{\mu_\chi^2}{M_A}v^2 \sim 2\text{keV}\Big(\frac{120GeV}{M_A}\Big)\Big(\frac{\mu_\chi}{10\text{GeV}}\Big)^2\Big(\frac{v}{10^{-3}}\Big)^2$$

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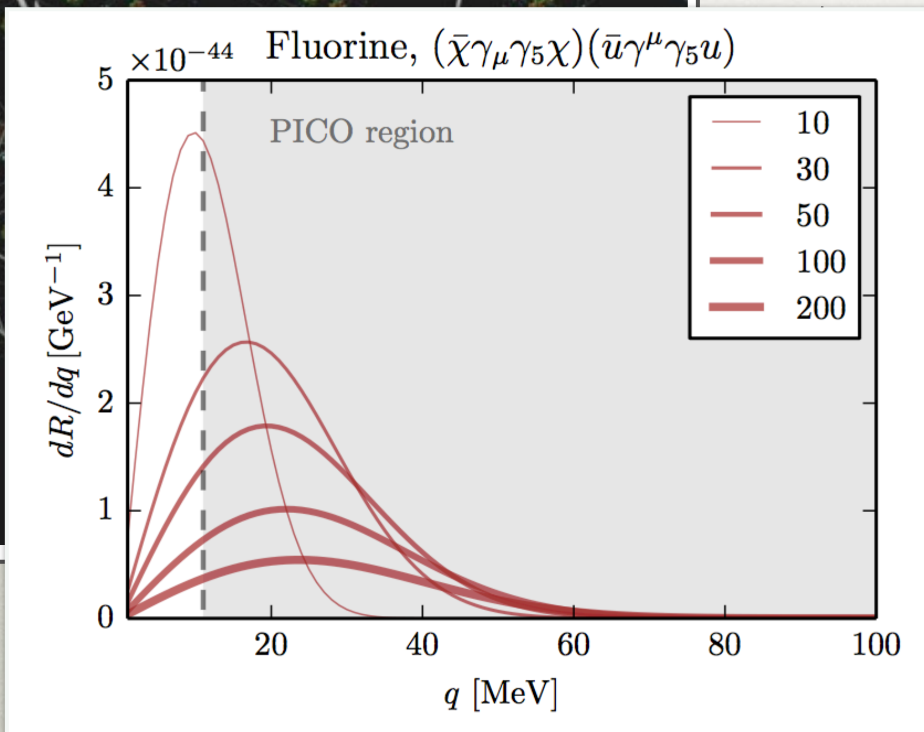
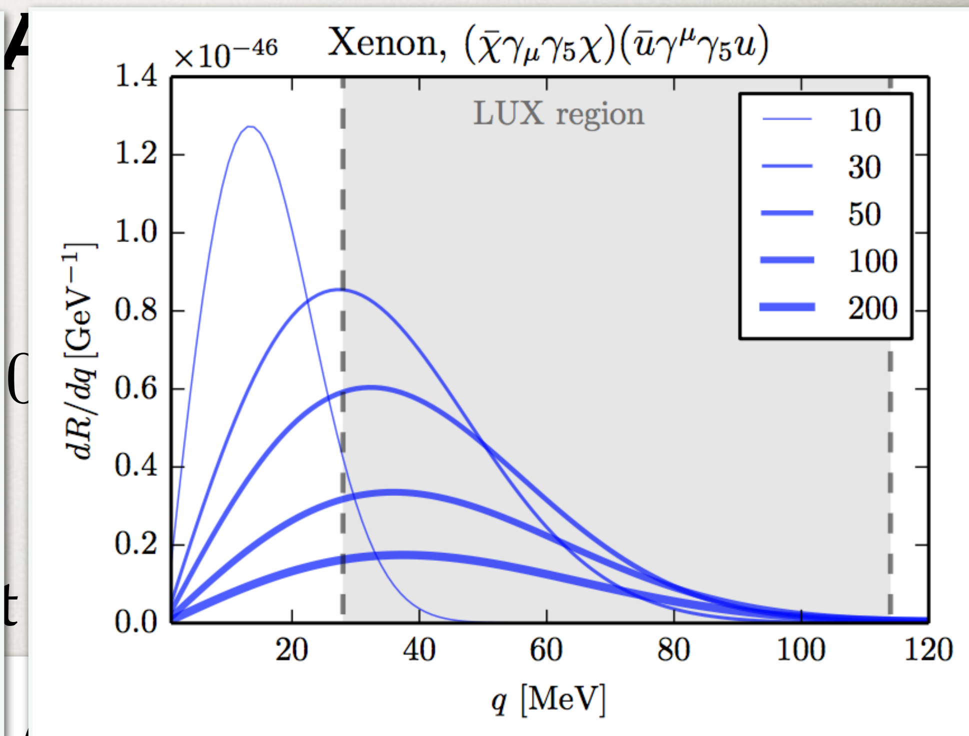
DM DETECTION





$$E_d = 2\frac{\ldots}{M_A}v^2 \sim 2\text{keV}\left(\frac{\ldots}{M_A}\right)\left(\frac{\ldots}{10\text{GeV}}\right)\left(\frac{\ldots}{10^{-3}}\right)$$

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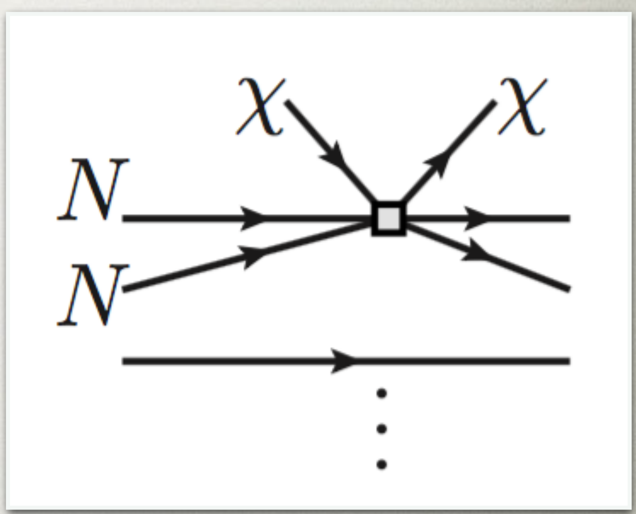
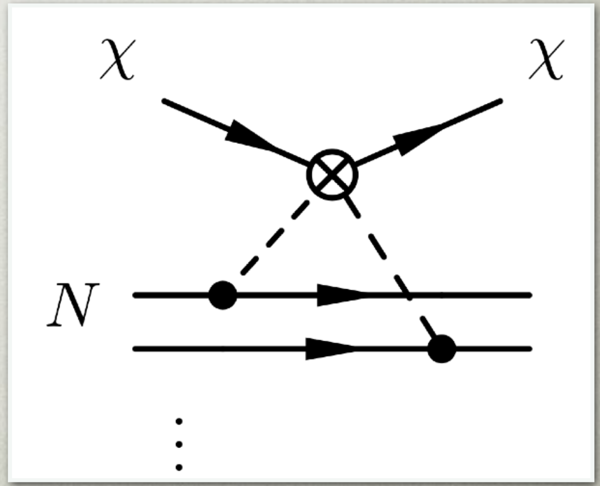
GENERAL LESSONS

- chirally leading contributions due to DM scattering on a single nucleon current
  - DM coupling to four-nucleon ops. always $O(q^3)$ suppressed
  - long distance contribs. only $O(q)$ suppr. for scalar couplings
- not all NR ops. generated
- switching on just one NR oper. at a time not justified





ALL OPERATORS?

- do we need all the operators? F. Bishara, J. Brod, B. Grinstein, JZ, 1611.00368; 1707.06998
    - 15 operators with up to 2 derivatives
    - general dim 5 and 6 EFT above EW scale requires at LO

$$\mathcal{O}_{2b}^N = (\vec{S}_N \cdot \vec{v}_\perp)(\vec{S}_\chi \cdot \vec{v}_\perp)$$

$$\mathcal{O}_1^N = \mathbb{1}_\chi \mathbb{1}_N \,, \qquad \mathcal{O}_2^N = (v_\perp)^2 \mathbb{1}_\chi \mathbb{1}_N \,,$$

$$\mathcal{O}_3^N = \mathbb{1}_\chi \, \vec{S}_N \cdot \Big(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\Big) \,, \qquad \mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N \,,$$

$$\mathcal{O}_5^N = \vec{S}_\chi \cdot \Big(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\Big) \mathbb{1}_N \,, \qquad \mathcal{O}_6^N = \Big(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\Big)\Big(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\Big) \,,$$

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$$\mathcal{O}_9^N = \vec{S}_\chi \cdot \Big(\frac{i\vec{q}}{m_N} \times \vec{S}_N\Big) \,, \qquad \mathcal{O}_{10}^N = -\mathbb{1}_\chi \Big(\vec{S}_N \cdot \frac{i\vec{q}}{m_N}\Big) \,,$$

$$\mathcal{O}_{11}^N = -\Big(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N}\Big) \mathbb{1}_N \,, \qquad \mathcal{O}_{12}^N = \vec{S}_\chi \cdot \Big(\vec{S}_N \times \vec{v}_\perp\Big) \,,$$

$$\mathcal{O}_{13}^N = -\Big(\vec{S}_\chi \cdot \vec{v}_\perp\Big)\Big(\vec{S}_N \cdot \frac{i\vec{q}}{m_N}\Big) \,, \qquad \mathcal{O}_{14}^N = -\Big(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N}\Big)\Big(\vec{S}_N \cdot \vec{v}_\perp\Big) \,,$$

- do we need the *O(q²)* terms? Can we stop at *O(q²)*?

LO DIAGRAMS

- quark and gluon currents hadronize as

nucleon currents

$$\tilde{J}^V_{q,\mu} \sim v^\mu_B \bar{N} N + \cdots\,, \qquad \tilde{J}^A_{q,\mu} \sim S_\mu \bar{N} N + \cdots\,,$$
$$\tilde{J}^S_q \sim m_q \bar{N} N + \cdots\,, \qquad \tilde{J}^P_q \sim m_q \bar{N} N \pi + \cdots\,,$$
$$\tilde{J}^G \sim \bar{N} N + \cdots\,, \qquad \tilde{J}^\theta \sim q^\mu S_\mu \bar{N} N + \cdots\,,$$

meson currents

$$J^V_{q,\mu} \sim \pi \partial_\mu \pi + \cdots\,, \qquad J^A_{q,\mu} \sim \partial_\mu \pi + \cdots\,,$$
$$J^G \sim \pi^2, \qquad J^S_q \sim m_q \pi^2 + \cdots\,, \qquad J^P_q \sim m_q \pi + \cdots\,,$$

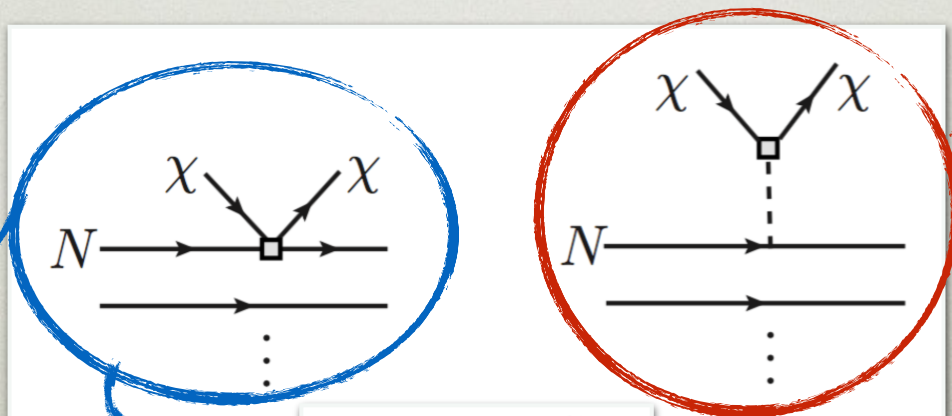
- two types of leading order diagrams

$\bar{q}\gamma_\mu q \to \tilde{J}^V_{q,\mu}$,

$\bar{q}q \to \tilde{J}^S_q$,

$GG \to \tilde{J}^G$,

$G\tilde{G} \to \tilde{J}^\theta$



$i\bar{q}\gamma_5 q \to \tilde{J}^P_q$,

$\bar{q}\gamma_\mu\gamma_5 q \to \tilde{J}^A_{q,\mu}$,

*for vector DM only left diagr. important

COMPARISON

F. Bishara, J. Brod, B. Grinstein, JZ, 1611.00368; 1707.06998

see also, e.g., Cirelli, Del Nobile, Panci, 1307.5955;
Hill, Solon, 1409.8290;

- what is new?
  - for most NR operators the results agree with previous literature

$$\mathcal{O}_1^N = \mathbb{1}_\chi \mathbb{1}_N\,, \qquad \mathcal{O}_2^N = (v_\perp)^2 \mathbb{1}_\chi \mathbb{1}_N\,,$$

$$\mathcal{O}_3^N = \mathbb{1}_\chi \vec{S}_N \cdot \Big(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\Big)\,, \qquad \mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N\,,$$

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COMPARISON

see also Hoferichter, Klos, and Schwenk, 1503.04811

- what is new?
  - re-amphasising the importance of (pion) pole enhanced contribs.

$$\mathcal{O}_1^N = \mathbb{1}_\chi \mathbb{1}_N\,, \qquad \mathcal{O}_2^N = (v_\perp)^2 \mathbb{1}_\chi \mathbb{1}_N\,,$$

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PION POLES

- the pion poles important for

$$\mathcal{Q}_{4,q}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar q\gamma^\mu\gamma_5 q) \quad\to\quad \sim \frac{\Delta q}{m_\pi^2+\vec q^{\,2}}\mathcal{C}_{4,q}^{(6)} \quad\to\quad \mathcal{O}_6^N$$

$$\mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar\chi i\gamma_5\chi)G^{a\mu\nu}\widetilde G^a_{\mu\nu} \quad\to\quad \sim \frac{\Delta q}{m_\chi}\frac{\vec q^{\,2}}{m_\pi^2+\vec q^{\,2}}\mathcal{C}_4^{(7)} \quad\to\quad \mathcal{O}_6^N$$

$$\mathcal{Q}_{8,q}^{(7)} = m_q(\bar\chi\gamma_5\chi)(\bar q\gamma_5 q) \quad\to\quad \sim \frac{\Delta q}{m_\chi}\frac{m_\pi^2}{m_\pi^2+\vec q^{\,2}}\mathcal{C}_{8,q}^{(7)} \quad\to\quad \mathcal{O}_6^N$$

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COMPARISON

- what is new?
  - consistent chiral counting
  - for instance: *A*x*A* operator

$$\mathcal{Q}^{(6)}_{4,q} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)$$

$$\sim \Delta q\, \mathcal{C}^{(6)}_{4,q}$$

$$\sim \frac{\Delta q}{m_\pi^2 + \vec{q}^{\,2}}\mathcal{C}^{(6)}_{4,q}$$

$$\mathcal{O}_1^N = \mathbb{1}_\chi \mathbb{1}_N\,, \qquad \ldots = (v_\perp)^2\, \mathbb{1}_\chi \mathbb{1}_N\,,$$

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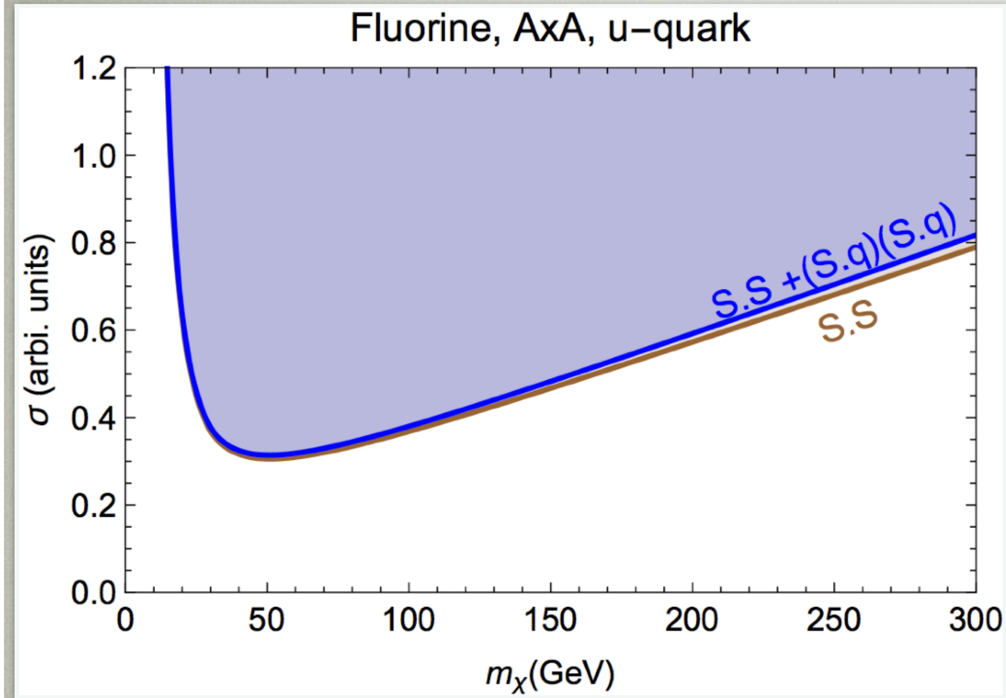

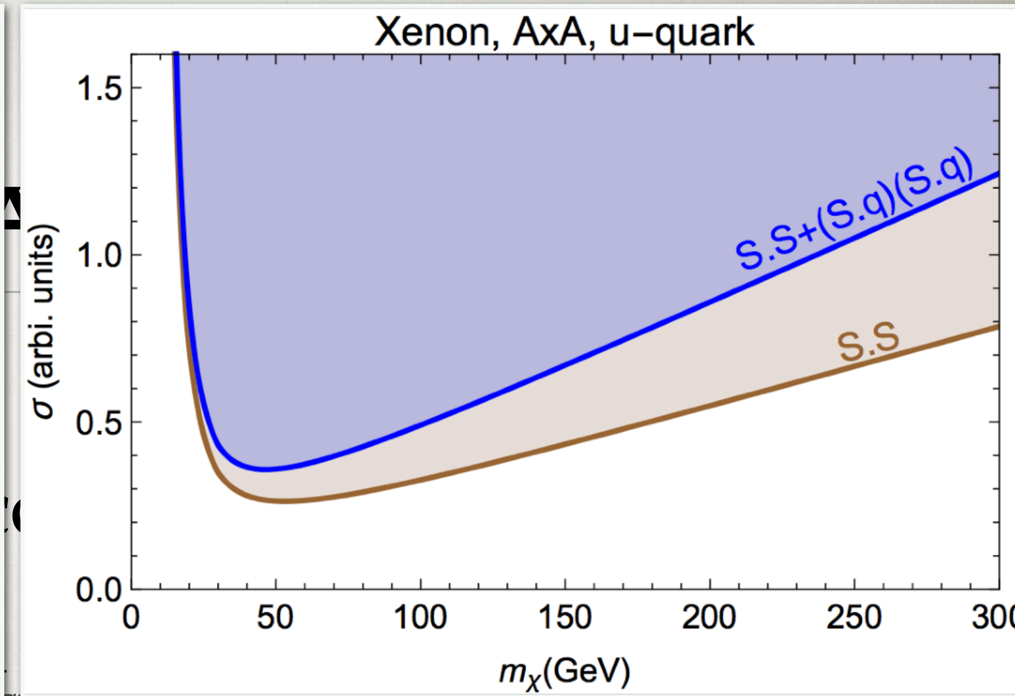

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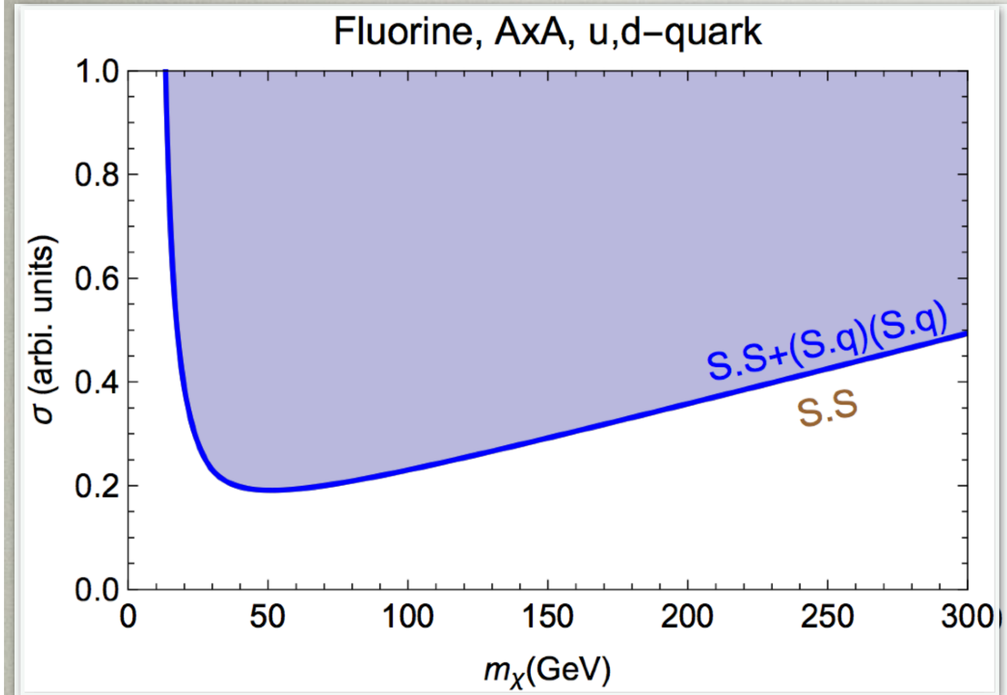

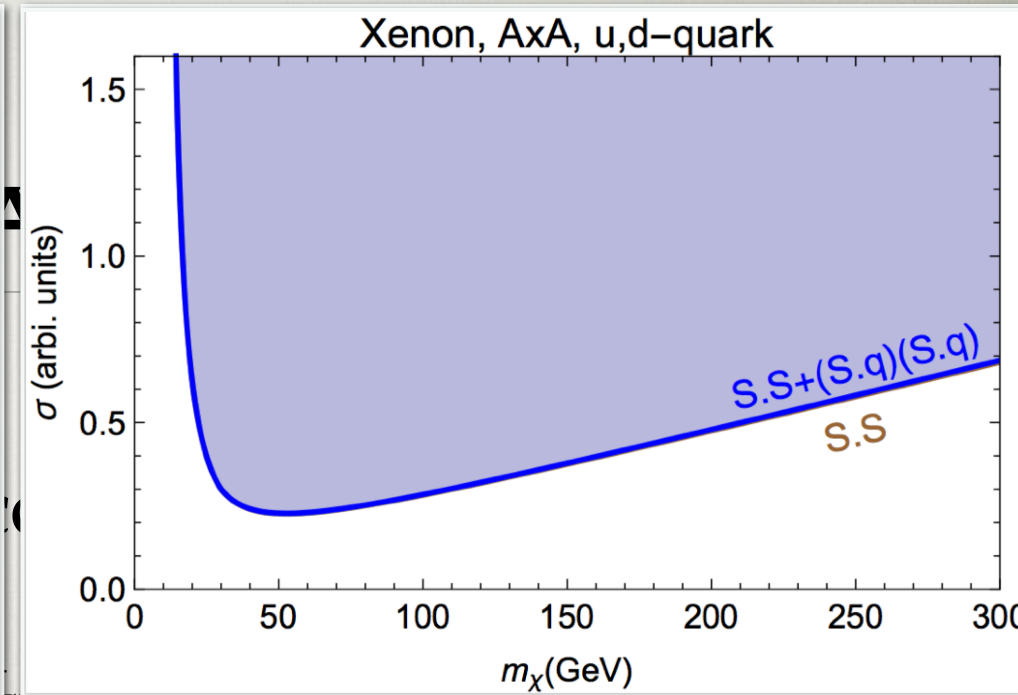

$$\sim \Delta q \, \mathcal{C}_{4,q}^{(6)}$$

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$$\mathcal{O}_3^N = \mathbb{1}_\chi \, \vec{S}_N \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N} \right) , \qquad \mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N \,,$$

$$\mathcal{O}_5^N = \vec{S}_\chi \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N} \right) \mathbb{1}_N \,, \qquad \mathcal{O}_6^N = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left(\vec{S}_N \cdot \frac{\vec{q}}{m_N} \right) ,$$

$$\mathcal{O}_7^N = \mathbb{1}_\chi \left(\vec{S}_N \cdot \vec{v}_\perp \right) , \qquad \mathcal{O}_8^N = \left(\vec{S}_\chi \cdot \vec{v}_\perp \right) \mathbb{1}_N \,,$$

$$\mathcal{O}_9^N = \vec{S}_\chi \cdot \left(\frac{i\vec{q}}{m_N} \times \vec{S}_N \right) , \qquad \mathcal{O}_{10}^N = -\mathbb{1}_\chi \left(\vec{S}_N \cdot \frac{i\vec{q}}{m_N} \right) ,$$

$$\mathcal{O}_{11}^N = -\left(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N} \right) \mathbb{1}_N \,, \qquad \mathcal{O}_{12}^N = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}_\perp \right) ,$$

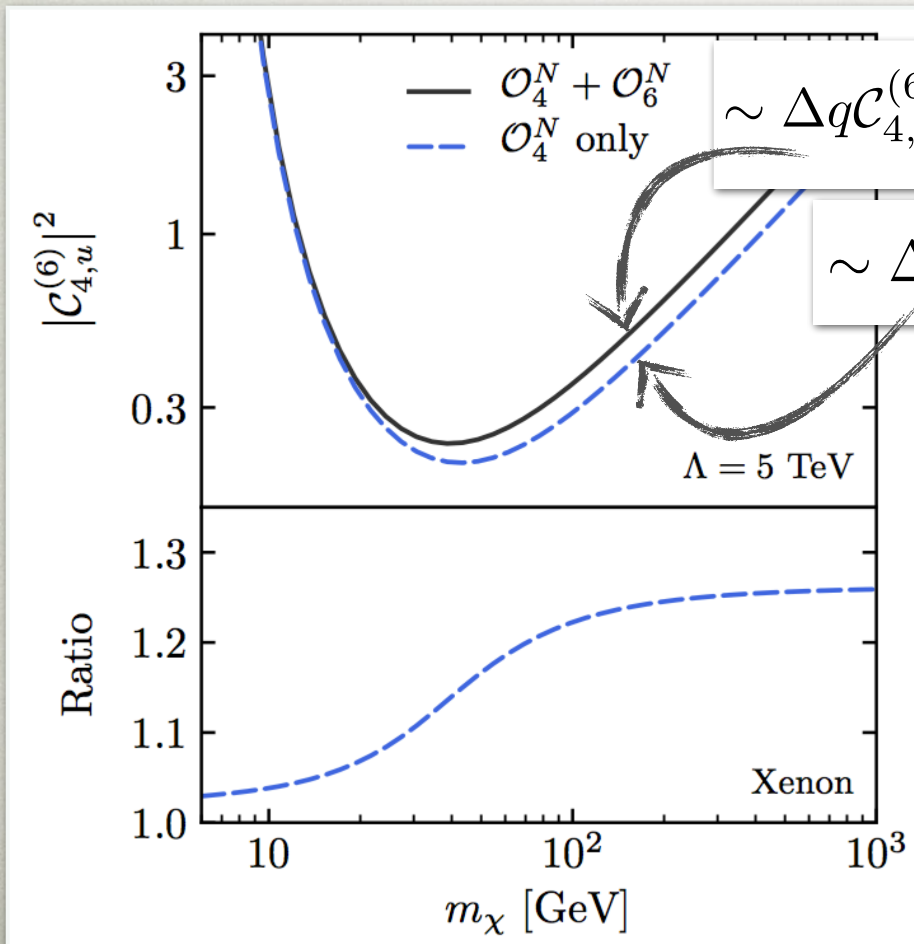
AXIAL-AXIAL

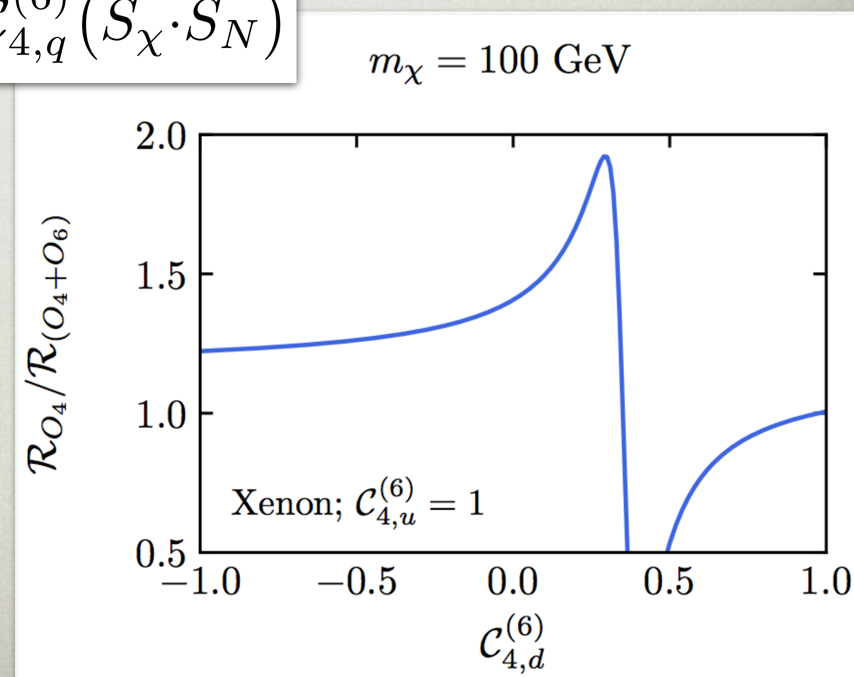
- some further examples
  - axial-axial interaction: C_{4u}=-C_{4d}

$$\mathcal{Q}_{4,q}^{(6)} = (\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma^\mu\gamma_5 q)$$

$$\sim \Delta q \mathcal{C}_{4,q}^{(6)} \big(\vec{S}_\chi \cdot \vec{S}_N\big) + \frac{\Delta q}{m_\pi^2 + \vec{q}^2} \mathcal{C}_{4,6}^{(6)} \big(\vec{S}_\chi \cdot \vec{q}\big)\big(\vec{S}_N \cdot \vec{q}\big)$$

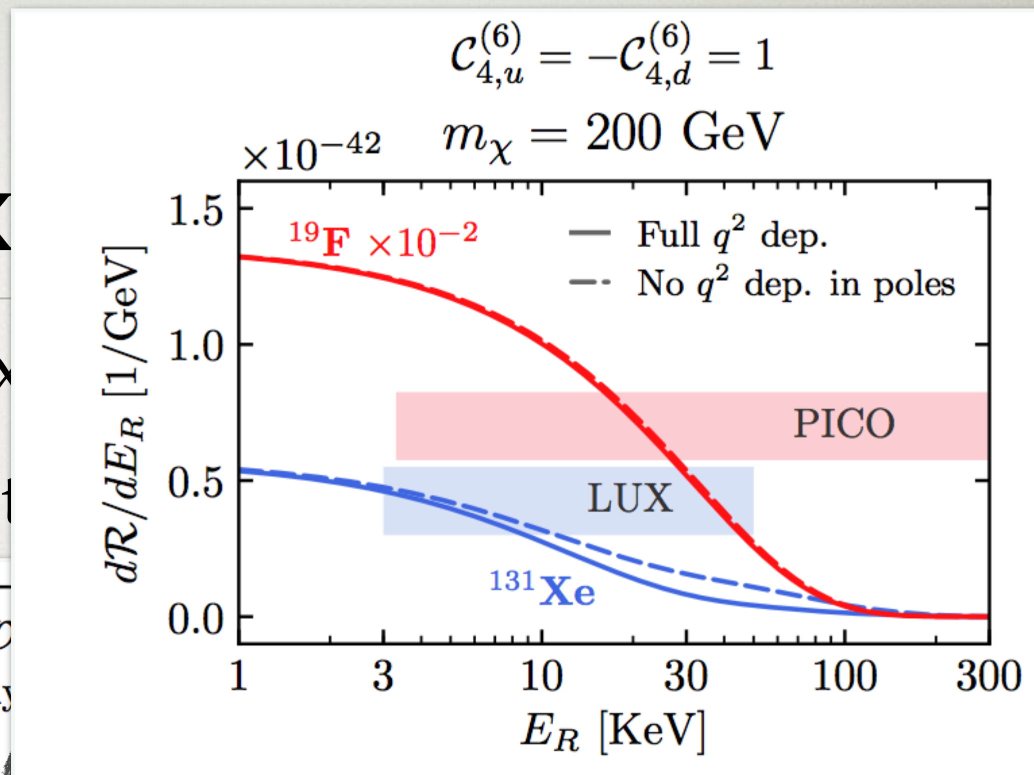
$$\sim \Delta q \mathcal{C}_{4,q}^{(6)} \big(\vec{S}_\chi \cdot \vec{S}_N\big)$$





AX

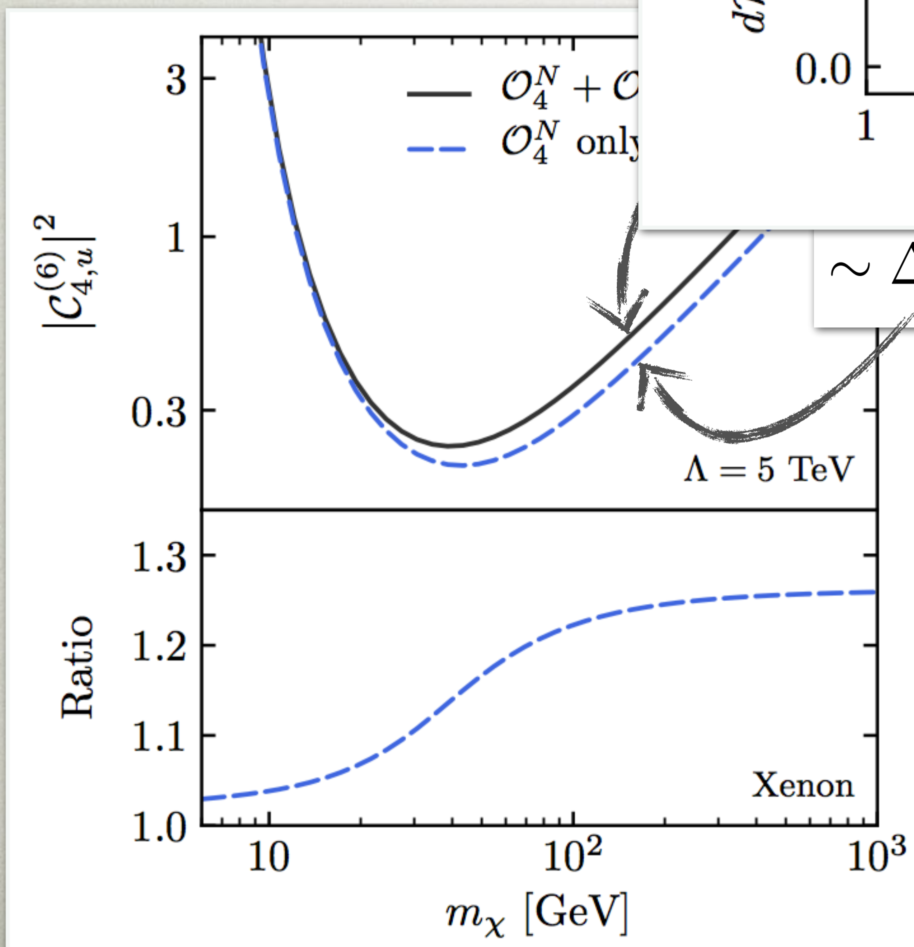
- some further ex
  - axial-axial int

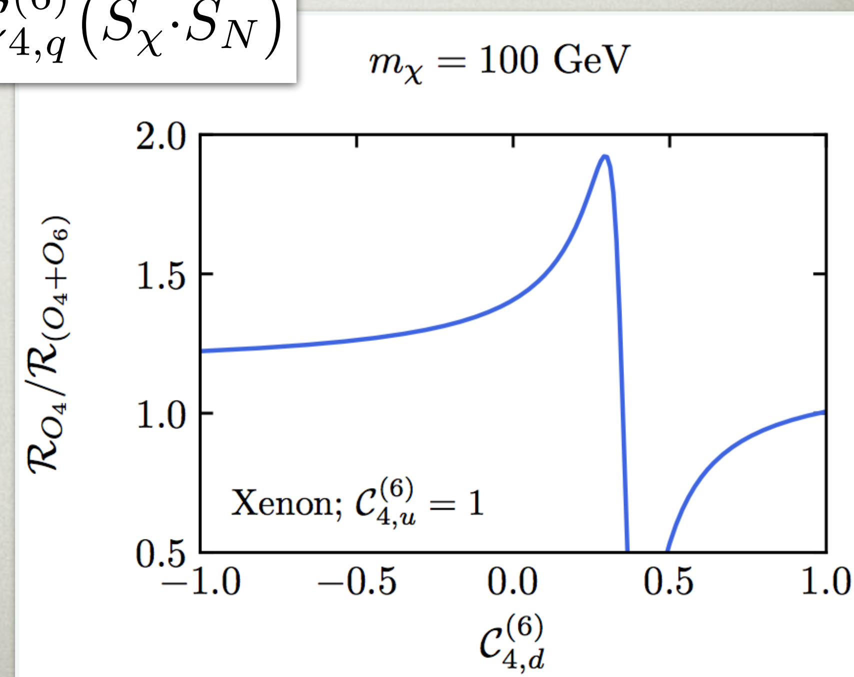


$\gamma_5 q)$

$(\vec{S}_N \cdot \vec{q})$

$\sim \Delta q \mathcal{C}^{(6)}_{4,q} \left(\vec{S}_\chi \cdot \vec{S}_N\right)$



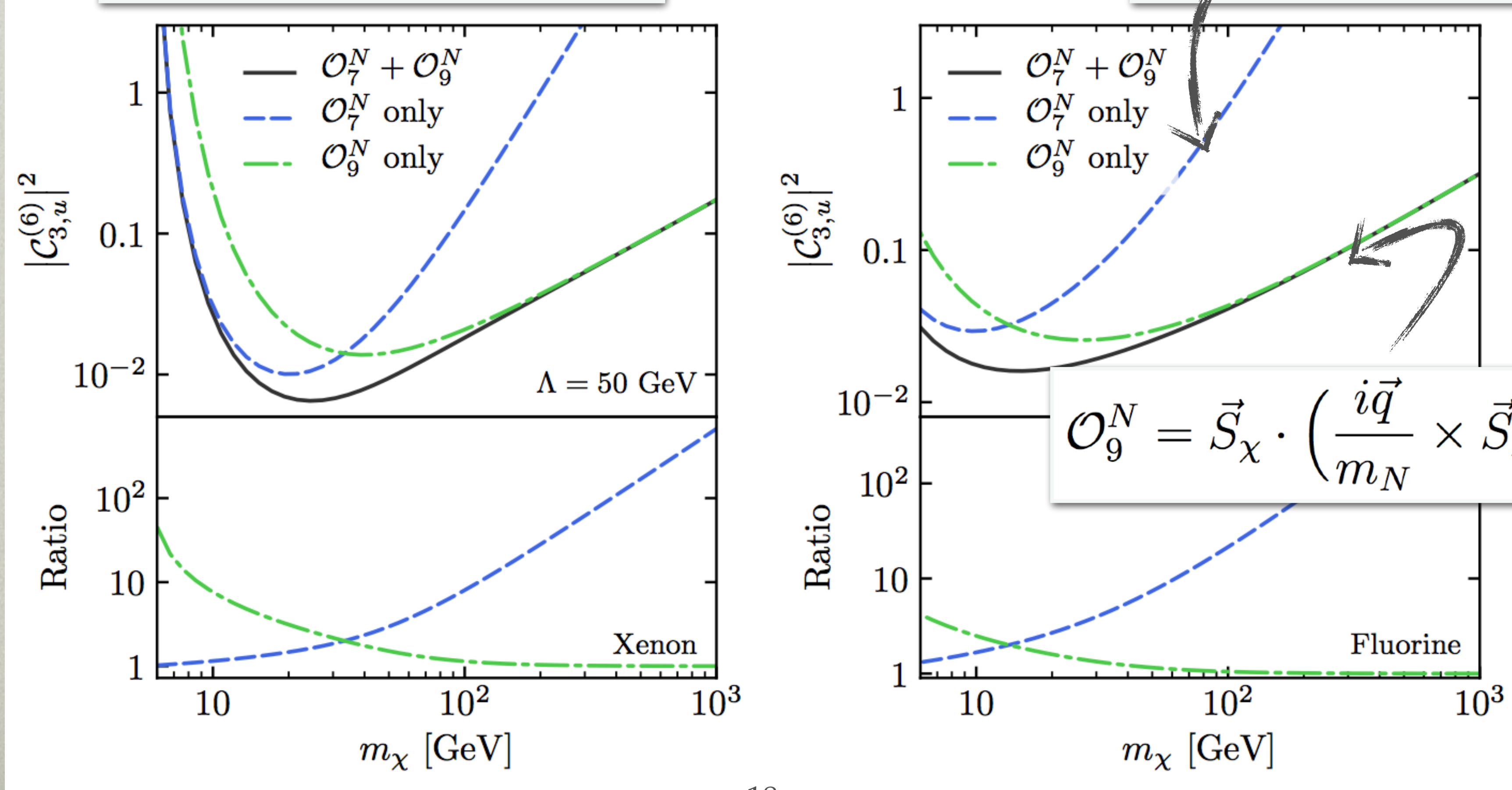


VECTOR-AXIAL

- vector-axial interaction: $C_{3u}=C_{3d}=C_{3s}=1$

$$\mathcal{Q}_{3,q}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar q\gamma^\mu\gamma_5 q)$$

$$\mathcal{O}_7^N = \mathbb{1}_\chi\left(\vec S_N\cdot\vec v_\perp\right)$$

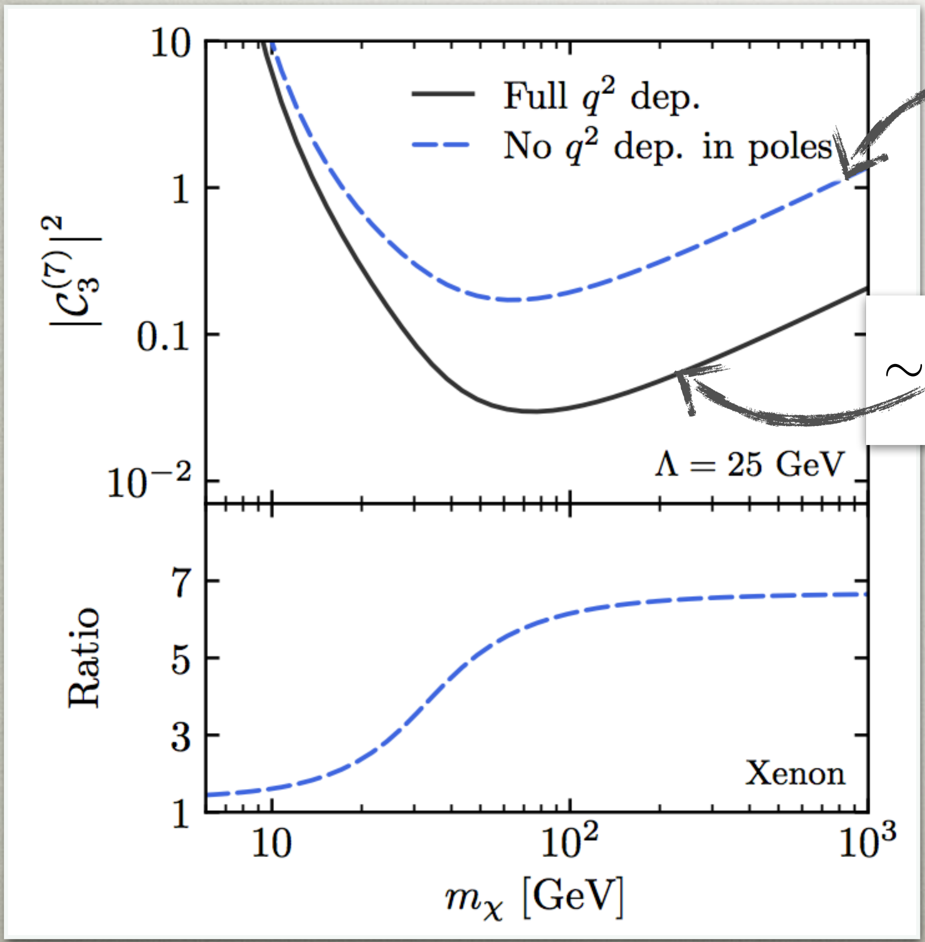


$$\mathcal{O}_9^N = \vec S_\chi\cdot\left(\frac{i\vec q}{m_N}\times\vec S_N\right)$$

CP-odd gluonic operator

- SxCP-odd gluonic operator
  - compare with *q→0* limit

$$\mathcal{Q}_3^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi}\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$$



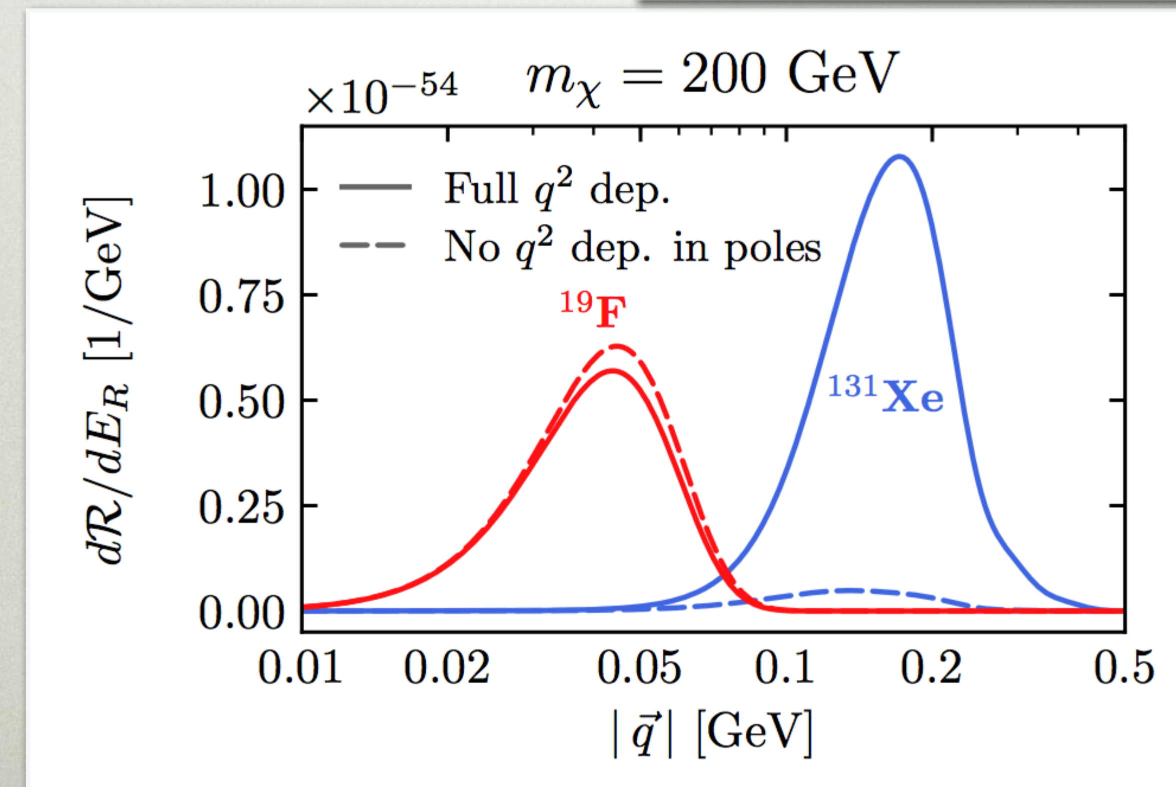
$$\sim \frac{\Delta q}{m_q}(\vec{S}_N \cdot \vec{q})$$

$$\sim \left(\frac{\Delta q}{m_q} + \left(\frac{1}{m_u} - \frac{1}{m_d}\right)\frac{(\Delta u - \Delta d)\vec{q}^2}{m_\pi^2 + \vec{q}^2}\right)(\vec{S}_N \cdot \vec{q})$$

ENERGY DEPENDENCE

- The differential event rate as a function of the momentum transfer as an example: $Q_4^{(7)}$

$$\mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi} i\gamma_5 \chi) G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$$



PHOTON POLES

- due to photon poles also need $O(q^2)$ ops

$$\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\bar\chi\sigma^{\mu\nu}\chi)F_{\mu\nu}$$

$$\sim \frac{\alpha\mu_p}{m_N}\mathcal{C}_1^{(5)} \qquad \sim m_N\frac{\alpha\mu_p}{\vec q^{\,2}}\mathcal{C}_1^{(5)}$$

$$\sim \frac{\alpha Q_p}{m_\chi}\mathcal{C}_1^{(5)} \qquad \sim m_N\frac{\alpha Q_p}{\vec q^{\,2}}\mathcal{C}_1^{(5)}$$

$$\mathcal{O}_1^N = \mathbb{1}_\chi\mathbb{1}_N\,, \qquad \mathcal{O}_2^N = (v_\perp)^2\,\mathbb{1}_\chi\mathbb{1}_N\,,$$

$$\mathcal{O}_3^N = \mathbb{1}_\chi\,\vec S_N\cdot\Big(\vec v_\perp\times\frac{i\vec q}{m_N}\Big)\,, \qquad \mathcal{O}_4^N = \vec S_\chi\cdot\vec S_N\,,$$

$$\mathcal{O}_5^N = \vec S_\chi\cdot\Big(\vec v_\perp\times\frac{i\vec q}{m_N}\Big)\mathbb{1}_N\,, \qquad \mathcal{O}_6^N = \Big(\vec S_\chi\cdot\frac{\vec q}{m_N}\Big)\Big(\vec S_N\cdot\frac{\vec q}{m_N}\Big)$$

$$\mathcal{O}_7^N = \mathbb{1}_\chi\big(\vec S_N\cdot\vec v_\perp\big)\,, \qquad \mathcal{O}_8^N = \big(\vec S_\chi\cdot\vec v_\perp\big)\mathbb{1}_N\,,$$

$$\mathcal{O}_9^N = \vec S_\chi\cdot\Big(\frac{i\vec q}{m_N}\times\vec S_N\Big)\,, \qquad \mathcal{O}_{10}^N = -\mathbb{1}_\chi\Big(\vec S_N\cdot\frac{i\vec q}{m_N}\Big)\,,$$

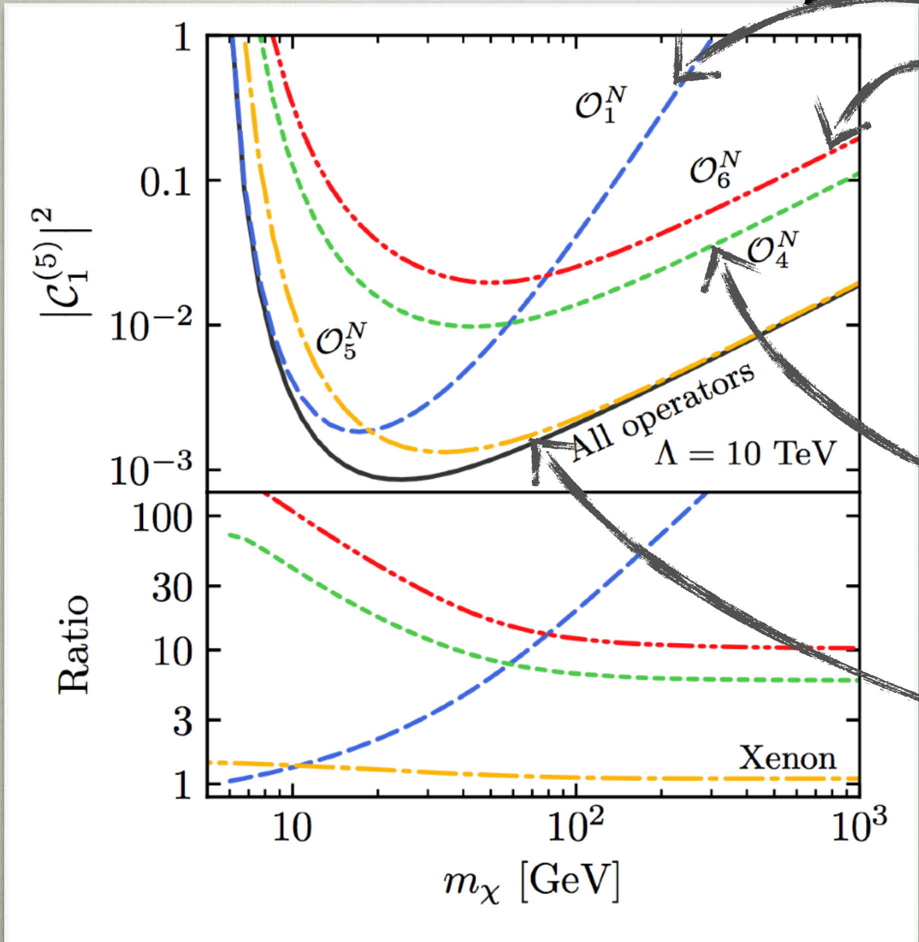
$$\mathcal{O}_{11}^N = -\Big(\vec S_\chi\cdot\frac{i\vec q}{m_N}\Big)\mathbb{1}_N\,, \qquad \mathcal{O}_{12}^N = \vec S_\chi\cdot\big(\vec S_N\times\vec v_\perp\big)\,,$$

$$\mathcal{Q}_2^{(5)} = \frac{e}{8\pi^2}(\bar\chi\sigma^{\mu\nu}i\gamma_5\chi)F_{\mu\nu} \qquad \sim m_N\frac{\alpha Q_p}{\vec q^{\,2}}\mathcal{C}_2^{(5)}$$

PHOTON POLES - XENON

- for magnetic dipole interaction
  - two coherently enhanced operators

$$\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu}$$



$$-\frac{\alpha Q_p}{2\pi m_\chi}\hat{\mathcal{C}}_1^{(5)} \qquad \mathcal{O}_1^N = \mathbb{1}_\chi \mathbb{1}_N$$

$$\frac{2\alpha}{\pi}\frac{\mu_N m_N}{\vec{q}^2}\hat{\mathcal{C}}_1^{(5)} \qquad \mathcal{O}_6^N = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$

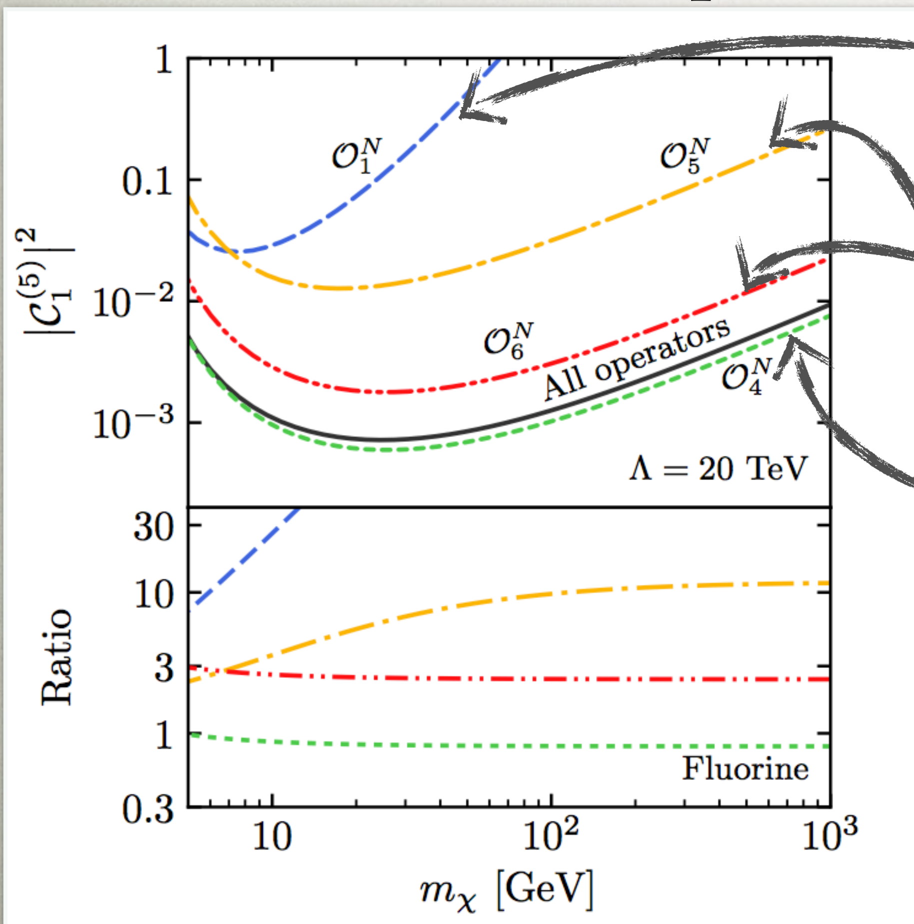
$$-\frac{2\alpha}{\pi}\frac{\mu_N}{m_N}\hat{\mathcal{C}}_1^{(5)} \qquad \mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N$$

$$\frac{2\alpha Q_p m_N}{\pi \vec{q}^2}\hat{\mathcal{C}}_1^{(5)} \qquad \mathcal{O}_5^N = \vec{S}_\chi \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\right)\mathbb{1}_N$$

PHOTON POLES - FLUORINE

- magnetic dipole interaction
  - both SD operators important

$$\mathcal{Q}_1^{(5)} = \frac{e}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\chi)F_{\mu\nu}$$



$$-\frac{\alpha Q_p}{2\pi m_\chi}\hat{\mathcal{C}}_1^{(5)} \qquad \mathcal{O}_1^N = \mathbb{1}_\chi \mathbb{1}_N$$

$$\frac{2\alpha}{\pi}\frac{\mu_N m_N}{\vec{q}^2}\hat{\mathcal{C}}_1^{(5)} \qquad \mathcal{O}_6^N = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right)$$

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NLO - SINGLE CURRENTS

F. Bishara, J. Brod, B. Grinstein, JZ, 1611.00368; 1707.06998

- for many operators two-nucleon currents highly suppressed
- are O(q^2) corrections to single currents ever important?
  - part of it captured by form factors for LO operators
  - but also new operators generated
- example: tensor-tensor operator

$$\mathcal{Q}_{9,q}^{(7)} = m_q(\bar\chi\sigma^{\mu\nu}\chi)(\bar q\sigma_{\mu\nu}q) \quad \to \quad \sim \frac{\Delta q}{m_q}(\vec S_\chi\cdot\vec S_N) + \frac{\vec q^{\,2}}{m_N m_\chi}\mathbb{1}_\chi\mathbb{1}_N$$

LO spin-dep.

NLO spin-indep.
coherently enhanced ~A^2

  - numerical factors make it small, though

SCALAR DARK MATTER

- analysis for scalar DM easier
- no DM spin ⇒ no cancellations in products of J_χx(leading chiral J_q)
- for P_q and A_q currents the contribs. are enhanced by pion poles

$$\mathcal{Q}_{1,q}^{(6)} = (\varphi^* i\overset{\leftrightarrow}{\partial}_\mu \varphi)(\bar{q}\gamma^\mu q), \qquad \mathcal{Q}_{2,q}^{(6)} = (\varphi^* i\overset{\leftrightarrow}{\partial}_\mu \varphi)(\bar{q}\gamma^\mu\gamma_5 q),$$

$$\mathcal{Q}_{3,q}^{(6)} = m_q(\varphi^*\varphi)(\bar{q}q)\,, \qquad \mathcal{Q}_{4,q}^{(6)} = m_q(\varphi^*\varphi)(\bar{q}i\gamma_5 q)\,,$$

$$\mathcal{Q}_{5}^{(6)} = \frac{\alpha_s}{12\pi}(\varphi^*\varphi)G^{a\mu\nu}G^a_{\mu\nu}\,, \qquad \mathcal{Q}_{6}^{(6)} = \frac{\alpha_s}{8\pi}(\varphi^*\varphi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,.$$

$$\mathcal{Q}_{7}^{(6)} = i\frac{e}{8\pi^2}(\partial_\mu\varphi^*\partial_\nu\varphi)F^{\mu\nu}\,,$$

relativistic theory with quarks and gluons

non-relativistic theory with nucleons

$$Q_{1,p}^{(0)} = (\varphi_v^*\varphi_v)(\bar{p}_v p_v),$$

$$Q_{1,p}^{(1)} = (\varphi_v^*\varphi_v)(\bar{p}_v i q\cdot S_N p_v),$$

$$Q_{2,p}^{(1)} = m_N(\varphi_v^*\varphi_v)(\bar{p}_v\, v_\perp\cdot S_N\, p_v),$$

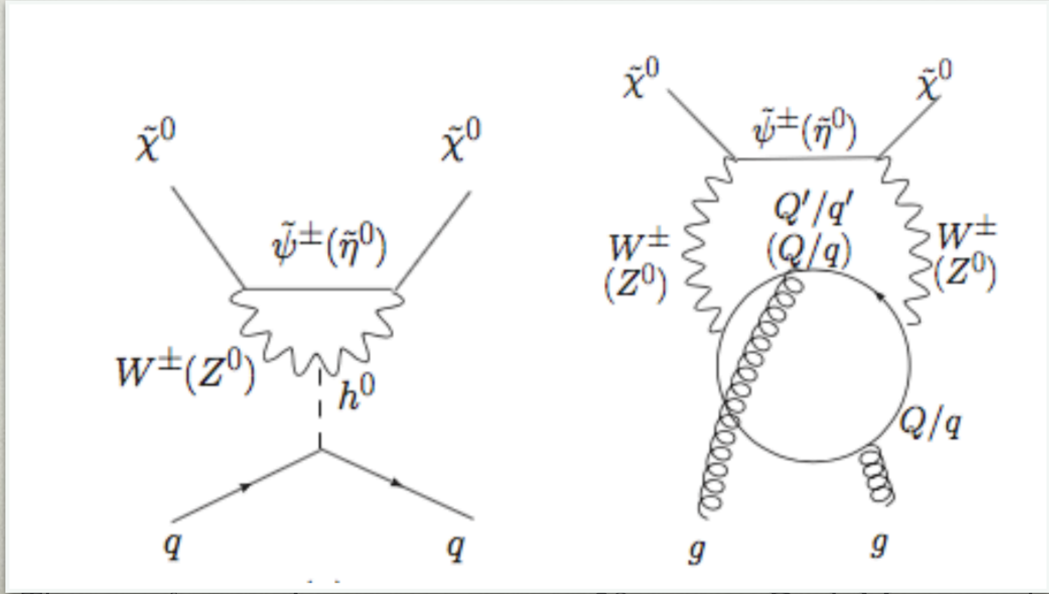
CONCLUSIONS

- presented LO + partial NLO matching from DM interacting with gluons and quarks to nuclear physics
- not always consistent to take single NR operators
- one should use EFT with gluons and quarks to consistently compare direct detection experiments

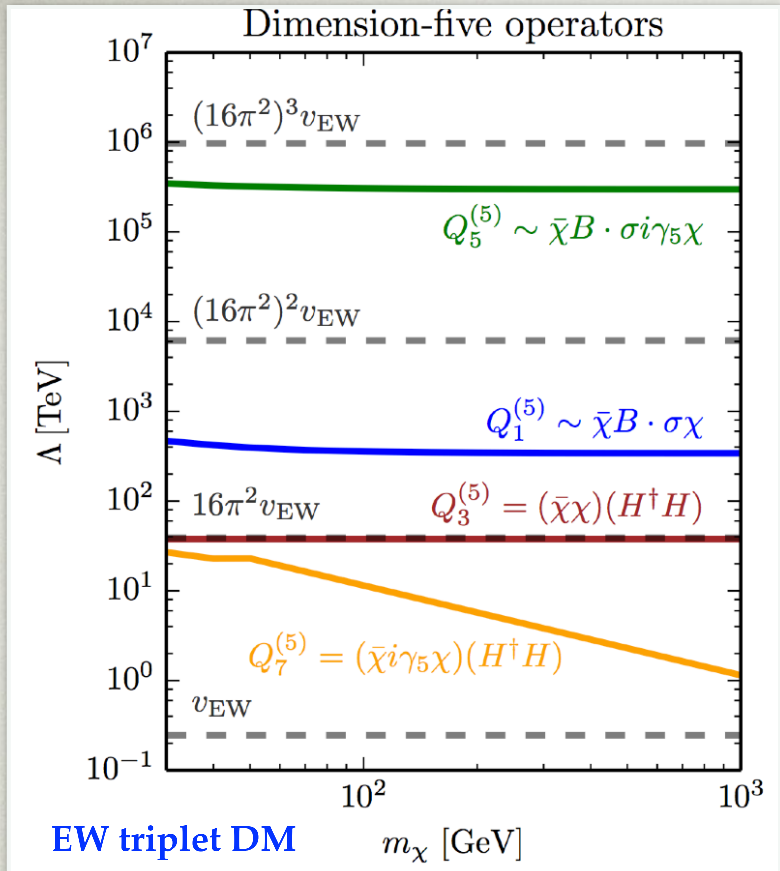
BACKUP SLIDES

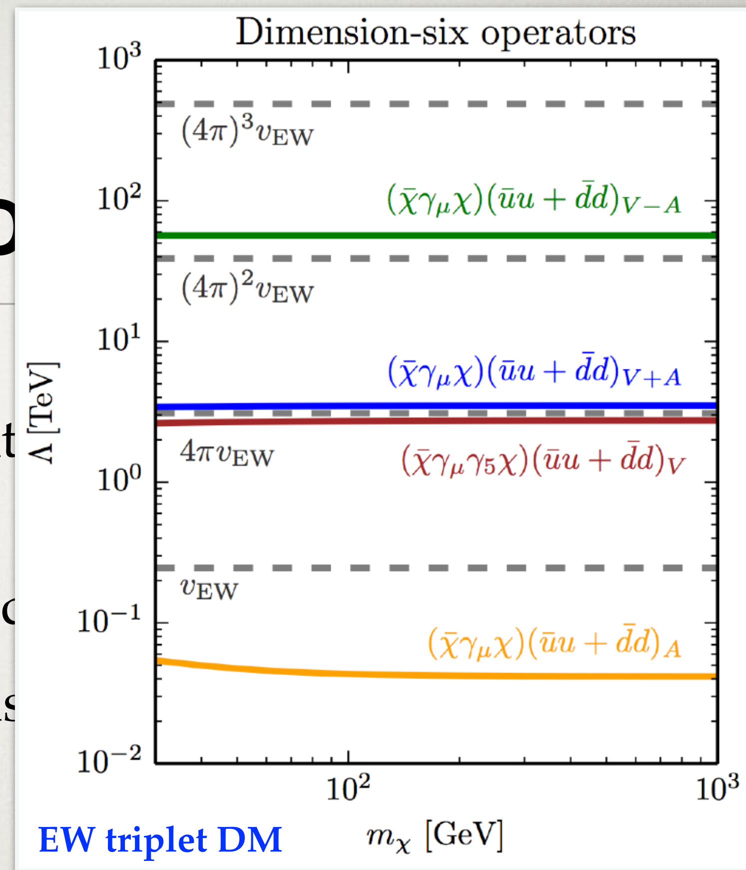
HIGHER DIM OPS?

- 0-th order question:
    - since renormalizable EW interactions, do we care about higher dim ops?
- if tree level Z exchange allowed, ruled out by direct detection
- this leaves 1-loop and 2-loop as leading
- higher dim ops can dominate

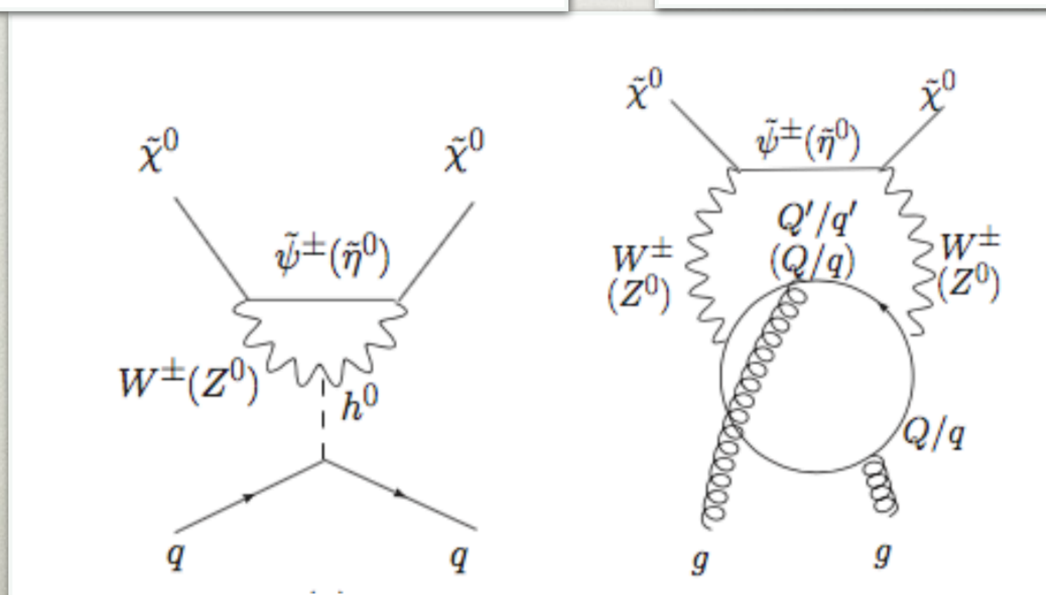


Hisano et al, 1104.0228, 1007.2601



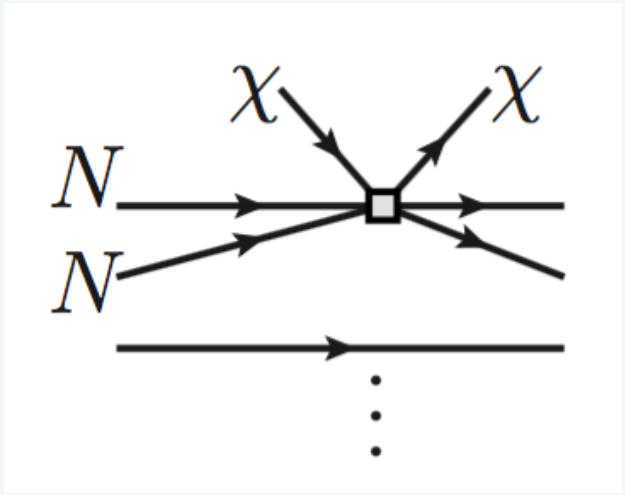


Hisano et al, 1104.0228, 1007.2601



Heavy Baryon ChPT

- assumption in the formalism for nuclear response functions
  - DM scatters on single nucleon
- how justified is this assumption?
  - how large are contributions from DM coupling to four-nucleon operators
- can be addressed using
  - Heavy Baryon Chiral Perturbation Theory (HBChPT)
  - ChEFT of nuclear forces
  - proton and neutron treated as heavy, $m_{p,n} \gg q \sim 200$MeV



HBChPT counting

Weinberg, NPB363, 3 (1991); Kaplan, Savage, Wise, nucl-th/9605002; Cirigliano, Graesser, Ovanesyan, 1205.2695

- HBChPT allows for consistent counting of "A-nucleon potentials"
  - expansion in $q/\Lambda_{\text{ChEFT}} \sim q/m_{p,n} \sim 0.3$
- A-nucleon irreducible amplitudes scale as $\sim q^{\nu}$

$$\nu = 4 - A - 2C + 2L + \sum_i V_i \epsilon_i + \epsilon_\chi,$$

effective chiral dimensions

# of connected diagrams

# of loops

# of vertices of type *i*

$$\epsilon_i = d_i + n_i/2 - 2,$$

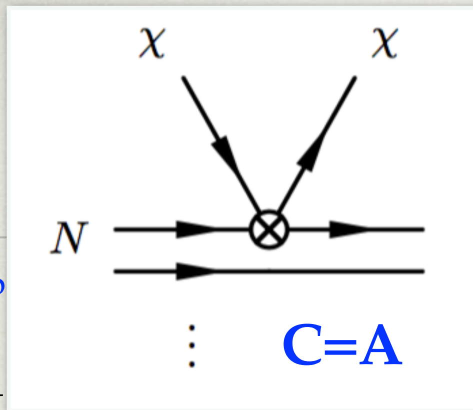
chiral dimension ~ # of derivatives

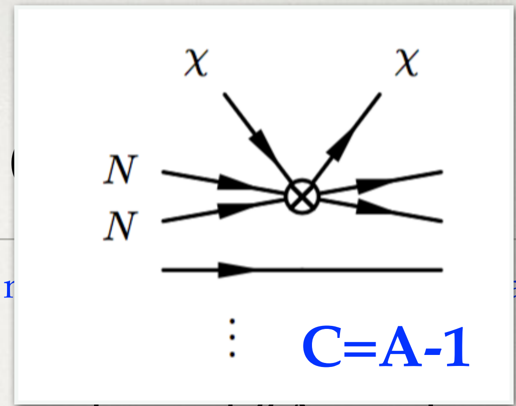
# of nucleon legs

  - more nucleon legs in a vertex more suppressed
- gives scaling for LO and NLO potentials

hPT

Weinb , Savage, Wise, r aesser, Ovanesyan, 1205.2695





- HBChPT allows for consistent counting of "A-nucleon potentials"
  - expansion in $q/\Lambda_{\text{ChEFT}} \sim q/m_{p,n} \sim 0.3$
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effective chiral dimensions

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# of loops

# of vertices of type *i*

$$\epsilon_i = d_i + n_i/2 - 2,$$

chiral dimension ~ # of derivatives

# of nucleon legs

  - more nucleon legs in a vertex more suppressed
- gives scaling for LO and NLO potentials

A COMPLICATION

- the external currents are due to nonrelativistic fermions (WIMPs)
- need to match on Heavy DM Effective Theory (HDMET)
  - expansion in $1/m_\chi$
  - similar to HQET for heavy quarks
  - matching trivial if one works to tree level
- after contracting with hadronic currents leading terms in chiral counting vanish for $J_\chi^V \cdot \tilde{J}_q^A, J_\chi^V \cdot \tilde{J}_q^A$
- the J_χ^P starts at $1/m_\chi$

$$J_\chi^V \cdot \tilde{J}_q^V \sim J_\chi^S \tilde{J}^G \sim (\bar{\chi}_v \chi_v)\,(\bar{N}N), \qquad J_\chi^A \cdot \tilde{J}_q^A \sim (\bar{\chi}_v S_\chi \chi_v)\cdot(\bar{N} S_N N),$$

$$J_\chi^A \cdot \tilde{J}_q^V \sim J_\chi^P \tilde{J}^G \sim (\bar{\chi}_v \partial\cdot S_\chi \chi_v)\,(\bar{N}N), \qquad J_\chi^V \cdot \tilde{J}_q^A \sim J_\chi^S \tilde{J}^\theta \sim (\bar{\chi}_v \chi_v)\,(\bar{N}\partial\cdot S_N N),$$

$$J_\chi^S \tilde{J}_q^S \sim m_q(\bar{\chi}_v \chi_v)\,(\bar{N}N), \quad J_\chi^S \tilde{J}_q^P \sim m_q(\bar{\chi}_v \chi_v)\,(\bar{N}N)\pi, \quad J_\chi^P \tilde{J}^\theta \sim (\bar{\chi}_v \partial\cdot S_\chi \chi_v)\,(\bar{N}\partial\cdot S_N N),$$

$$J_\chi^P \tilde{J}_q^S \sim (\bar{\chi}_v \partial\cdot S_\chi \chi_v) m_q(\bar{N}N), \qquad J_\chi^P \tilde{J}_q^P \sim (\bar{\chi}_v \partial\cdot S_\chi \chi_v) m_q(\bar{N}N)\pi,$$

NUCLEAR RESPONSE

- for nuclear response we use the formalism of Anand, Fitzpatrick, Haxton
- match onto ops. with NR nucleons
- only this subset of NR operators is generated
- xsec prop. to

$$\mathcal{O}_1^N = \mathbb{1}_\chi \mathbb{1}_N\,, \qquad \mathcal{O}_2^N = (v_\perp)^2\, \mathbb{1}_\chi \mathbb{1}_N\,,$$

$$\mathcal{O}_3^N = \mathbb{1}_\chi\, \vec{S}_N \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\right), \qquad \mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N\,,$$

$$\mathcal{O}_5^N = \vec{S}_\chi \cdot \left(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\right) \mathbb{1}_N\,, \qquad \mathcal{O}_6^N = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\right)\left(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\right),$$

$$\mathcal{O}_7^N = \mathbb{1}_\chi \left(\vec{S}_N \cdot \vec{v}_\perp\right), \qquad \mathcal{O}_8^N = \left(\vec{S}_\chi \cdot \vec{v}_\perp\right) \mathbb{1}_N\,,$$

$$\mathcal{O}_9^N = \vec{S}_\chi \cdot \left(\frac{i\vec{q}}{m_N} \times \vec{S}_N\right), \qquad \mathcal{O}_{10}^N = -\mathbb{1}_\chi \left(\vec{S}_N \cdot \frac{i\vec{q}}{m_N}\right),$$

$$\mathcal{O}_{11}^N = -\left(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N}\right) \mathbb{1}_N\,, \qquad \mathcal{O}_{12}^N = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}_\perp\right),$$

Wilson coeffs. in R_i

***W_i* are nuclear response functions**

$$\frac{1}{2J_\chi+1}\frac{1}{2J_A+1}\sum_{\text{spins}} |\mathcal{M}|^2_{\text{nucleus,NR}} = \frac{\overline{|\mathcal{M}|^2}}{(4m_\chi m_A)^2} =$$

$$\frac{4\pi}{2J_A+1}\sum_{\tau=0,1}\sum_{\tau'=0,1}\Big\{\Big[R_M^{\tau\tau'} W_M^{\tau\tau'}(y) + R_{\Sigma''}^{\tau\tau'} W_{\Sigma''}^{\tau\tau'}(y) + R_{\Sigma'}^{\tau\tau'} W_{\Sigma'}^{\tau\tau'}(y)\Big]$$

$$+\frac{\vec{q}^2}{m_N^2}\Big[R_\Delta^{\tau\tau'} W_\Delta^{\tau\tau'}(y) + R_{\Delta\Sigma'}^{\tau\tau'} W_{\Delta\Sigma'}^{\tau\tau'}(y)\Big]\Big\},$$

$$\vec{v}_T^{\perp} = \vec{v} - \vec{q}/(2\mu_{\chi A}),$$

$$R_M^{\tau\tau'} = (4m_\chi m_N)^2\Big[c_{\text{NR},1}^\tau c_{\text{NR},1}^{\tau'} + \frac{1}{4}\Big(\frac{\vec{q}^2}{m_N^2}\vec{v}_T^{\perp 2} c_{\text{NR},5}^\tau c_{\text{NR},5}^{\tau'} + \vec{v}_T^{\perp 2} c_{\text{NR},8}^\tau c_{\text{NR},8}^{\tau'} + \frac{\vec{q}^2}{m_N^2} c_{\text{NR},11}^\tau c_{\text{NR},11}^{\tau'}\Big)\Big],$$

NUCLEAR RESPONSE FUNCTIONS

- $W_M(q)$: from vector operator
  - in $q \to 0$ limit counts nucleons ⇒ spin-indep. (coherent) scattering
- $W_{\Sigma''}$ and $W_{\Sigma'}$: longit. and transverse axial ops.
  - related to conventional spin form factors

$$S_{00,11} = \frac{1}{4\pi} \sum_{\text{spins}} |\langle \vec{S}_p \pm \vec{S}_n \rangle|^2,$$

$$S_{01} = \frac{1}{2\pi} \sum_{\text{spins}} |\langle \vec{S}_p \rangle|^2 - |\langle \vec{S}_n \rangle|^2,$$

$$W_{\Sigma'}^{\tau\tau'} + W_{\Sigma''}^{\tau\tau'} = S_{\tau\tau'}, \qquad \tau, \tau' = 0, 1.$$

  - measure the nucleon spin content of the nucleus
- W_Δ : vector transverse magnetic operators
  - nucleon angular momentum content of the nucleus
- (very) rough scaling:

$$W_M \sim \mathcal{O}(A^2), \qquad W_{\Sigma'}, W_{\Sigma''}, W_\Delta, W_{\Delta\Sigma'} \sim \mathcal{O}(1)$$

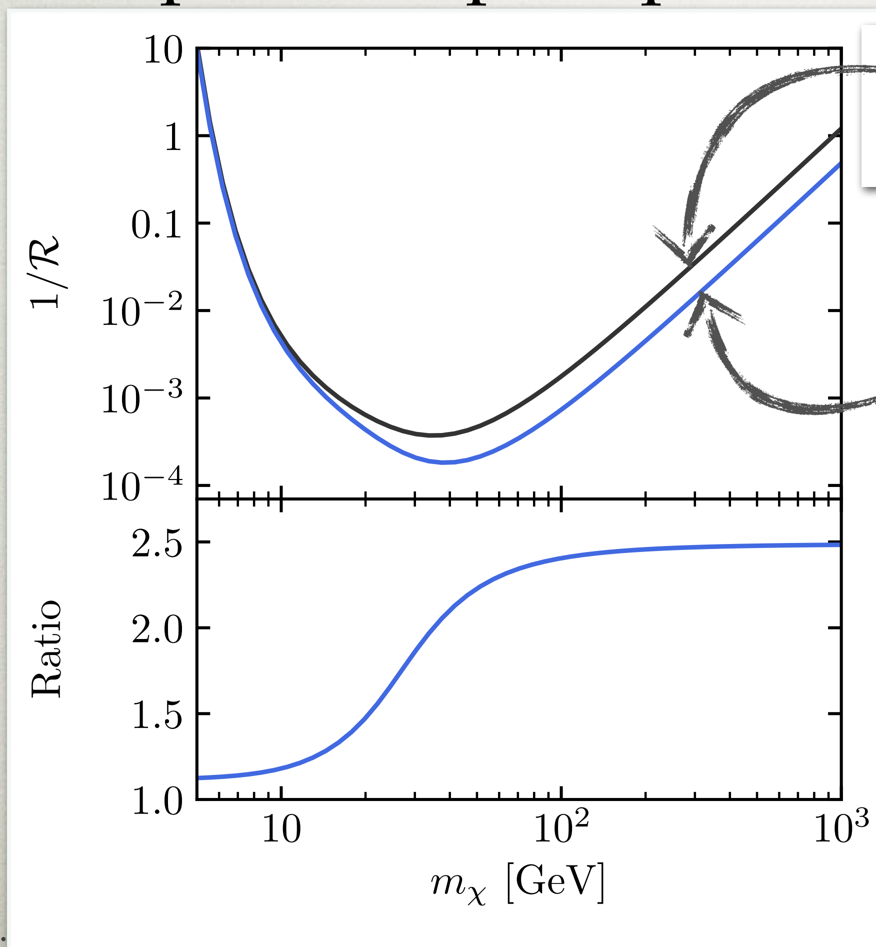
- in general three more response functions
  - these not generated to the order we work

PSEUDOSCALAR-PSEUDOSCALAR

- PS-PS operator C_{8u}=-C_{8d}=-C_{8s}

$$\mathcal{Q}^{(7)}_{8,q} = m_q(\bar{\chi}\gamma_5\chi)(\bar{q}\gamma_5 q)$$

  - compare full pion pole with $q \rightarrow 0$ limit



$$\sim \frac{\Delta q}{m_\chi}\mathcal{C}^{(7)}_{8,q}\frac{m_\pi^2}{m_\pi^2+\vec{q}^{\,2}}(\vec{S}_\chi\cdot\vec{q})(\vec{S}_N\cdot\vec{q})$$

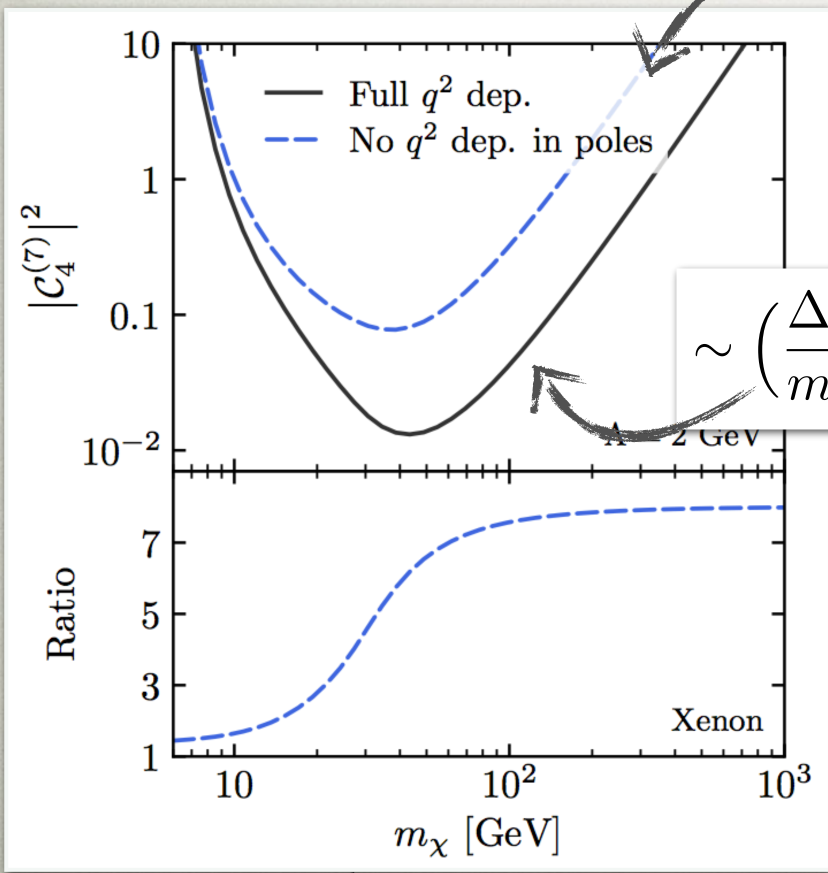
$$\sim \frac{\Delta q}{m_\chi}\mathcal{C}^{(7)}_{8,q}(\vec{S}_\chi\cdot\vec{q})(\vec{S}_N\cdot\vec{q})$$

CP-odd gluonic operator

- PSxCP-odd gluonic operator
  - compare with $q \to 0$ limit

$$\mathcal{Q}_4^{(7)} = \frac{\alpha_s}{8\pi}(\bar{\chi} i \gamma_5 \chi) G^{a\mu\nu} \widetilde{G}^a_{\mu\nu}$$

$$\sim \frac{\Delta q}{m_q}(\vec{S}_N \cdot \vec{q})(\vec{S}_\chi \cdot \vec{q})$$



$$\sim \left(\frac{\Delta q}{m_q} + \left(\frac{1}{m_u} - \frac{1}{m_d}\right)\frac{(\Delta u - \Delta d)\vec{q}^2}{m_\pi^2 + \vec{q}^2}\right)(\vec{S}_N \cdot \vec{q})(\vec{S}_\chi \cdot \vec{q})$$

ALL OPERATORS?

- do we need all the operators?
  - general dim 5 and 6 EFT require for LO description:

$$\mathcal{O}_1^N = \mathbb{1}_\chi \mathbb{1}_N\,, \qquad \mathcal{O}_2^N = (v_\perp)^2\, \mathbb{1}_\chi \mathbb{1}_N\,,$$

$$\mathcal{O}_3^N = \mathbb{1}_\chi\, \vec{S}_N \cdot \Big(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\Big)\,, \qquad \mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N\,,$$

$$\mathcal{O}_5^N = \vec{S}_\chi \cdot \Big(\vec{v}_\perp \times \frac{i\vec{q}}{m_N}\Big)\, \mathbb{1}_N\,, \qquad \mathcal{O}_6^N = \Big(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N}\Big)\Big(\vec{S}_N \cdot \frac{\vec{q}}{m_N}\Big),$$

$$\mathcal{O}_7^N = \mathbb{1}_\chi\, \big(\vec{S}_N \cdot \vec{v}_\perp\big)\,, \qquad \mathcal{O}_8^N = \big(\vec{S}_\chi \cdot \vec{v}_\perp\big)\, \mathbb{1}_N\,,$$

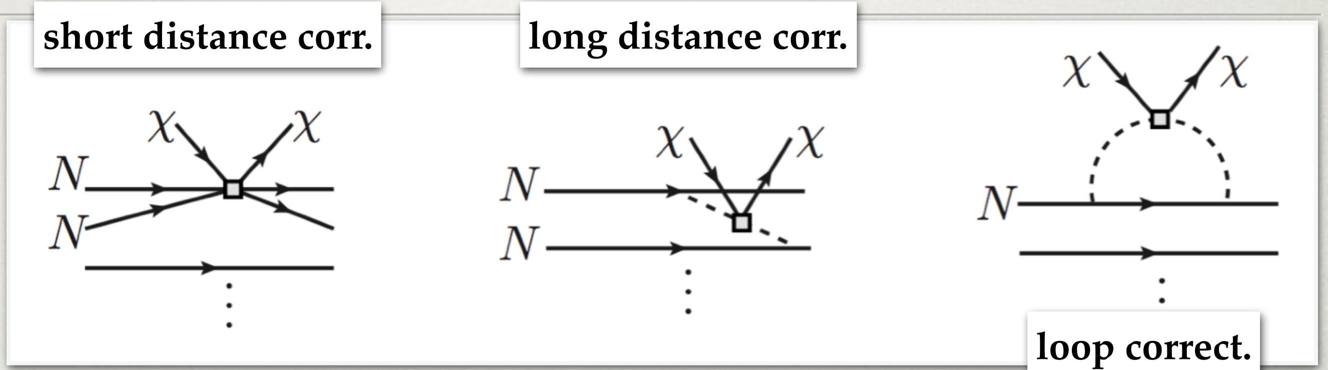
$$\mathcal{O}_9^N = \vec{S}_\chi \cdot \Big(\frac{i\vec{q}}{m_N} \times \vec{S}_N\Big)\,, \qquad \mathcal{O}_{10}^N = -\mathbb{1}_\chi\, \Big(\vec{S}_N \cdot \frac{i\vec{q}}{m_N}\Big)\,,$$

$$\mathcal{O}_{11}^N = -\Big(\vec{S}_\chi \cdot \frac{i\vec{q}}{m_N}\Big)\, \mathbb{1}_N\,, \qquad \mathcal{O}_{12}^N = \vec{S}_\chi \cdot \Big(\vec{S}_N \times \vec{v}_\perp\Big)\,,$$

  - using the rough scalings $A\sim100$, $q/m_N\sim0.1$, $v_T\sim10^{-3}$
  - allow for fine-tuning to get VxA, AxV structures
    - then 2 derivative ops. can be LO
  - due to pion poles 2 derivative ops. can be of LO size

NLO CORRECTIONS

sample higher order corrections



- SD always scales as $\sim q^{\nu_{\rm LO}+3}$
- only for $J_\chi^A \cdot \tilde{J}_q^V$, $J_\chi^S \tilde{J}_q^S$, $J_\chi^P \tilde{J}_q^S$ and $J_\chi^V \cdot \tilde{J}_q^A$ LD parametrically larger,
  $\sim q^{\nu_{\rm LO}+1}$ $\qquad \sim q^{\nu{\rm LO}+2}$

- we work to LO, results have relative $O(q/\Lambda_{ChEFT}) \sim 30\%$ accuracy
  - at this order: DM couples only to single nucleon currents
- at $O(q)$ LD DM interaction with two nucleons, e.g., for $\bar{q}q$
  - calculable using HBChPT, expected size $\sim(q/\Lambda_{ChEFT}) \sim 30\%$
- short distance DM-2nucleon interaction at $O(q^3)$ (size: ~few%)