EFFECTIVE FIELD THEORIES FOR DARK MATTER DIRECT DETECTION

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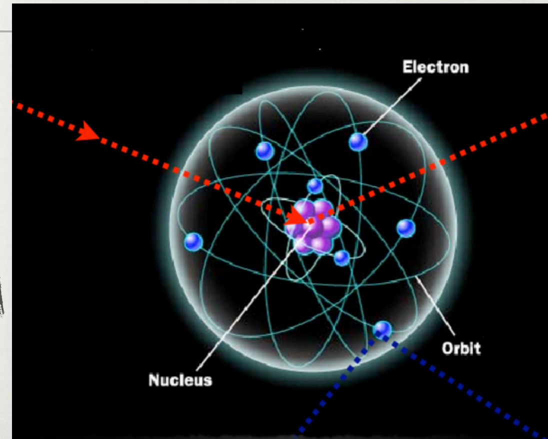
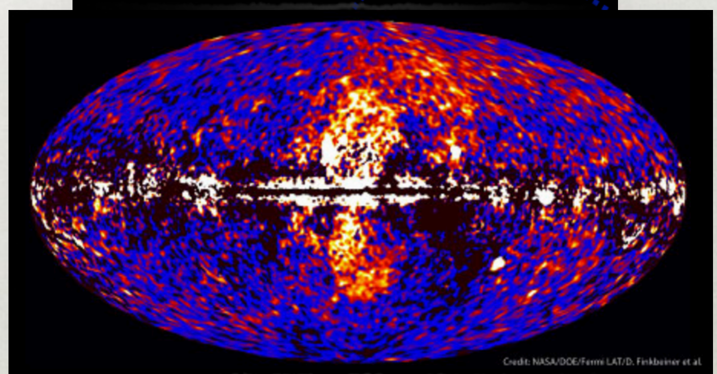
based on work with F. Bishara, J. Brod, B. Grinstein, JZ, 1611.00368, 1707.06998;1707.06998;1809.03506
J. Brod, A. Gootjes-Dreesbach, M. Tammaro, JZ, 1710.10218
J. Brod, E. Stamou, JZ, 1801.04240

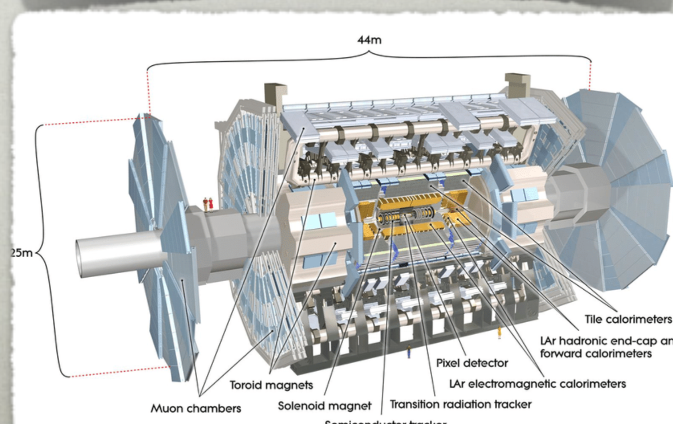
HC2NP, Tenerife, Sept 23 2019

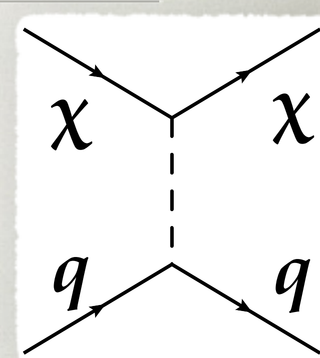
CHALLENGE #1

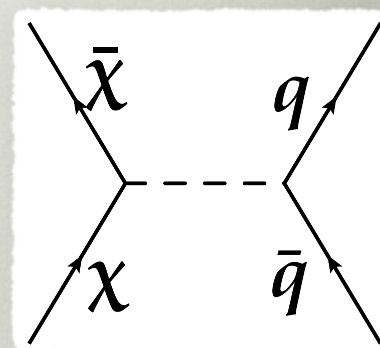
- experimental DM probes at very different energies
  - direct detection: ~200 MeV
  - indirect detection: DM mass (~ 100 GeV ?)
  - LHC production: DM mass + LHC kinem.

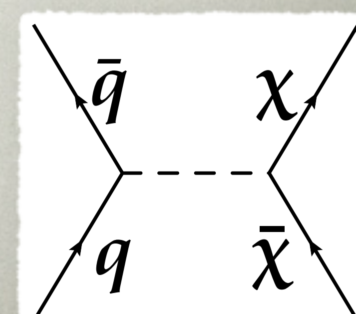












CHALLENGE #2

- we do not know how DM interacts with visible matter
- could we be missing something?
- EFTs ideal to ask "model independent" questions*

*in their domain of validity

AIM

- the aim is to be able to

  J. Brod, A. Gootjes-Dreesbach, M. Tammaro, JZ, 1710.10218

  - take any DM EFT up to dim 7 above EW scale
  - consistently give the leading expression for cross section

    F. Bishara, J. Brod, B. Grinstein, JZ, 1809.03506

  - including renormalization group running

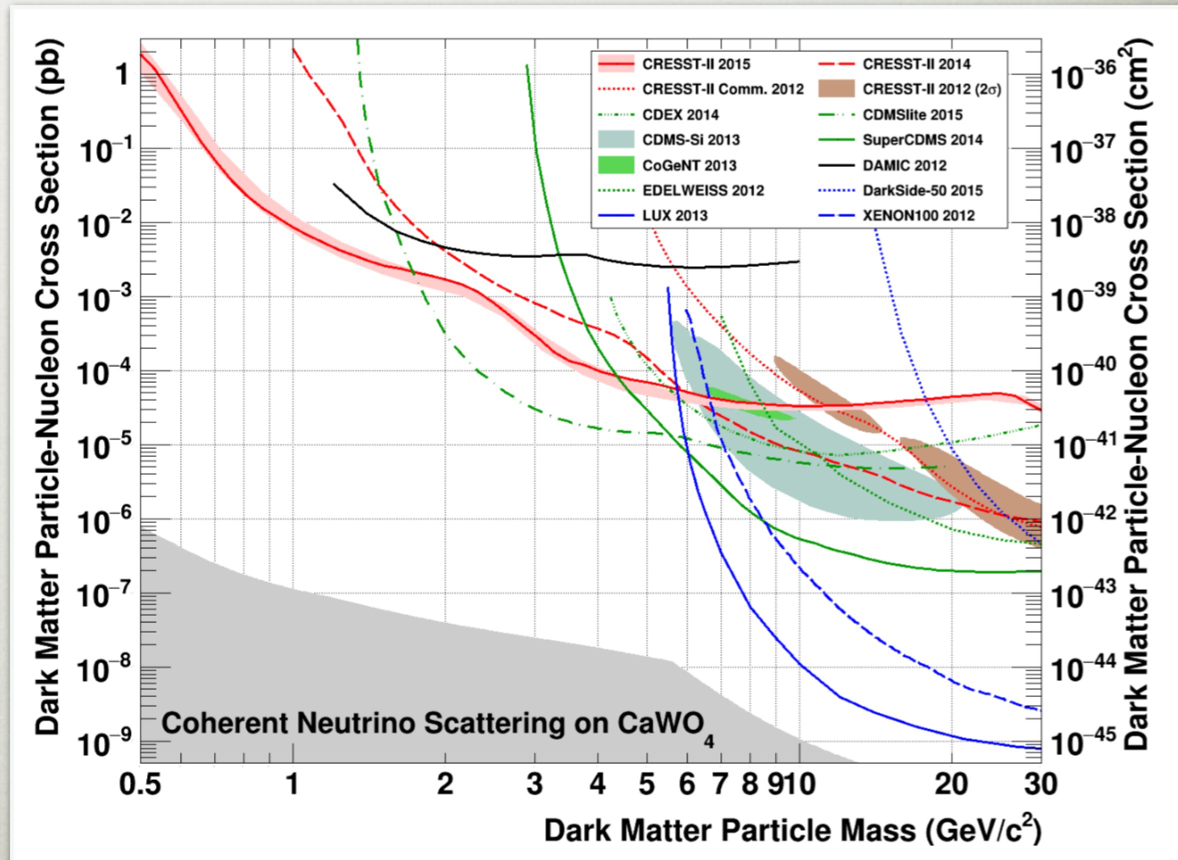
    F. Bishara, J. Brod, B. Grinstein, JZ, 1611.00368, 1707.06998

  - consistent counting, including ChPT
- most of this already available in a **Mathematica** & **Python** package **DirectDM**

  F. Bishara, J. Brod, B. Grinstein, JZ, 1708.02678

AIM

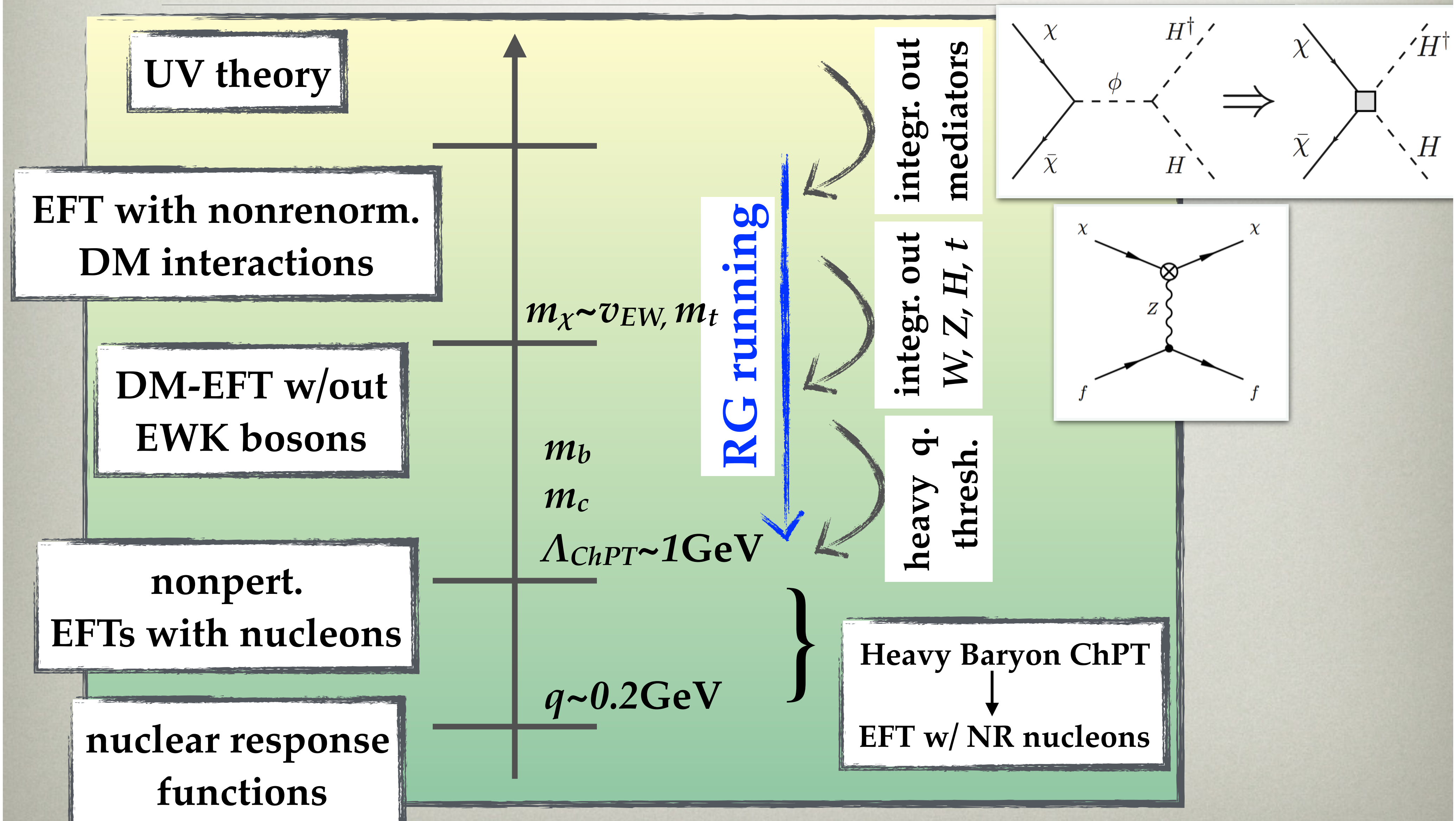
- in fact the aim is to help with two different problems
- DM-EFT ideal for:
  - comparing different DM direct detection experiments
- DM-EFT interm. step:
  - comparing direct detection with LHC and indirect detection



OUTLINE

- renormalization group running
- chiral EFT for DM direct detection
    - from quarks and gluons to nucleons

Tower of EFTs



EFT expansion

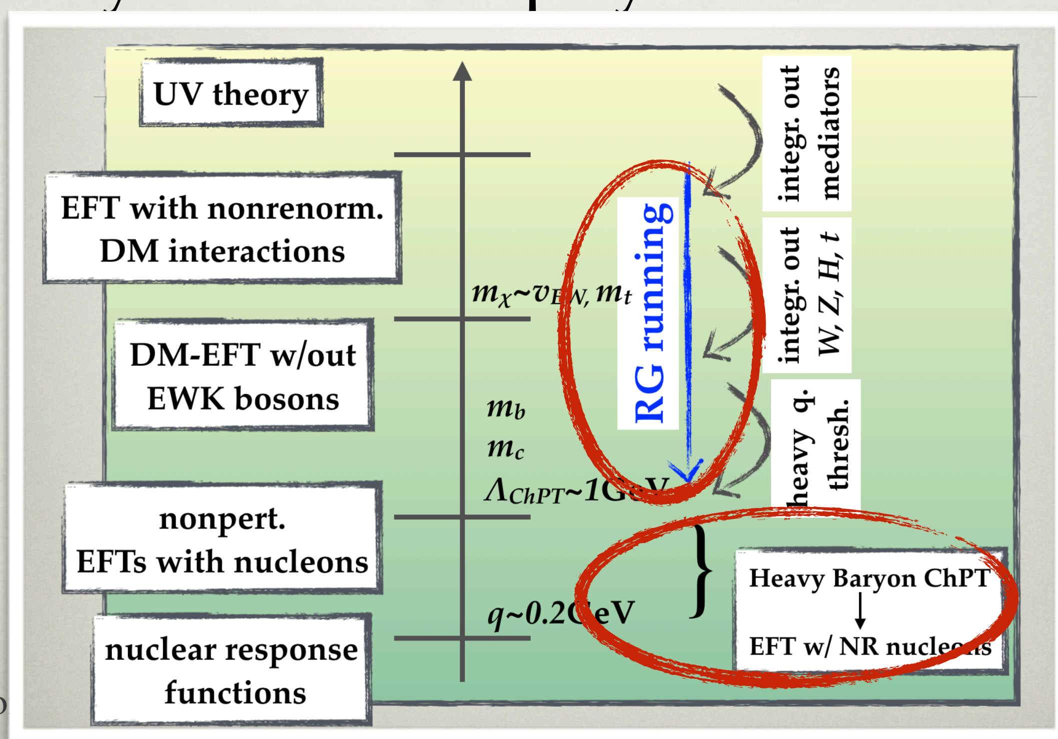
- at which mass dimension to stop?

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

- 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.

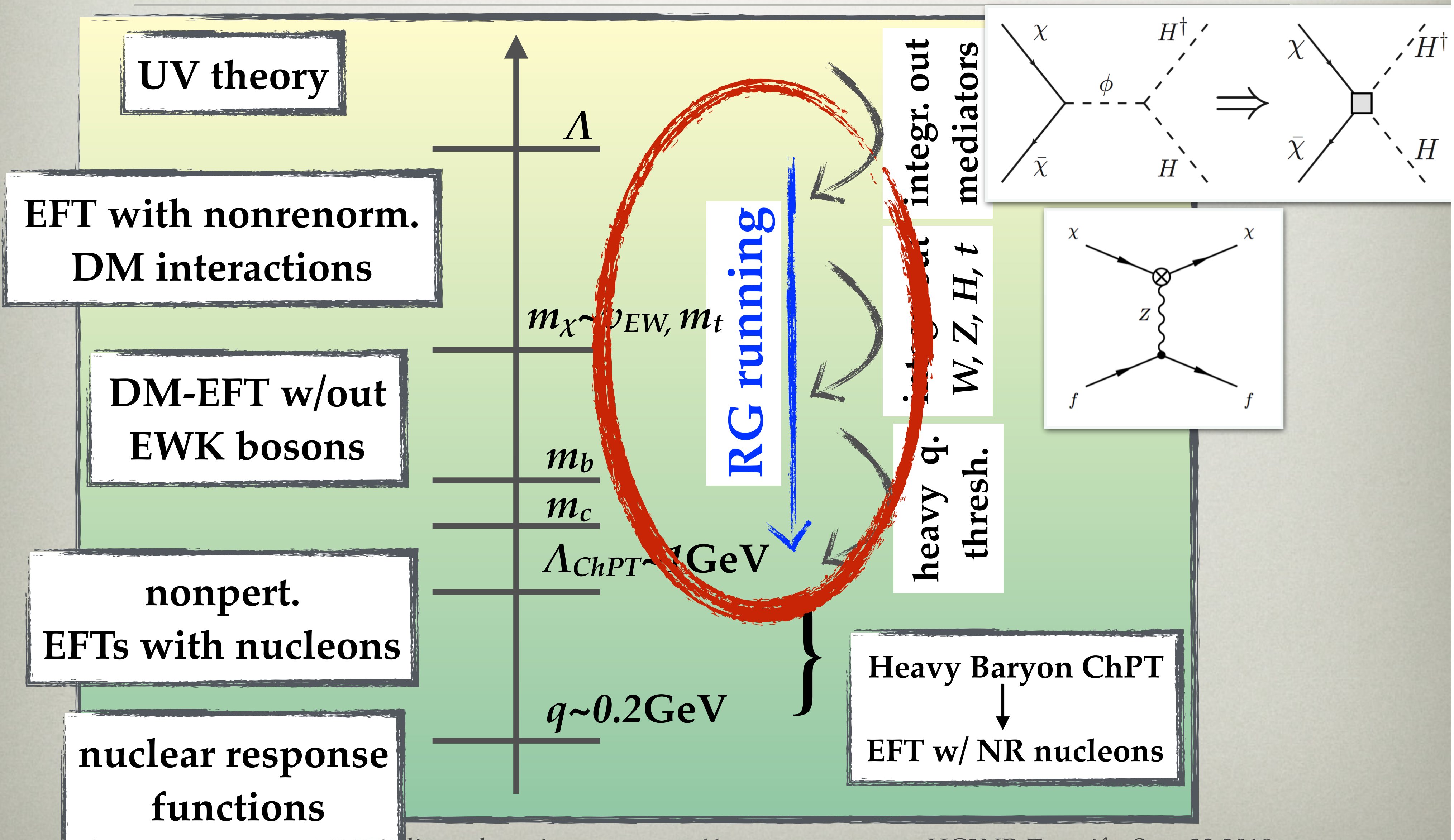
GOALS FOR TODAY

- 2 parts of the talk
  - RG running from UV to μ_{str}~2 GeV
  - matching at μ_{str}~2 GeV from relativistic theory to nuclear physics



RG RUNNING

TOWER OF EFTs



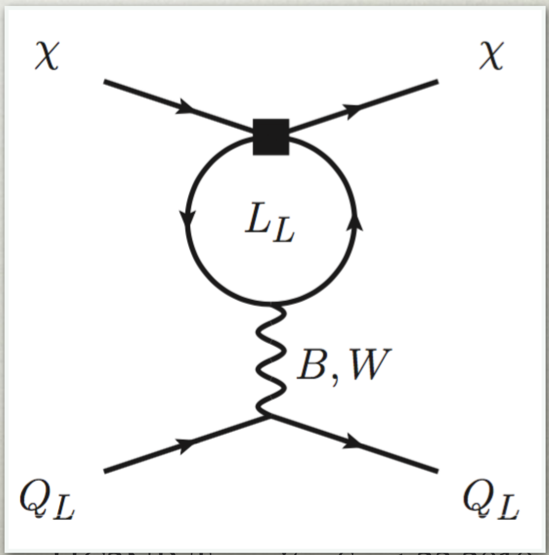
LOOP CORRECTIONS

see also D'Eramo, Procura, 1411.3342; Berlin, Robertson, Solon, Zurek, 1511.05964; Hill, Solon, 1401.3339, 1309.4092, 1409.8290;Crivellin, Haisch, 1408.5046; + many more

- mixing of operators through RGE (Renormalization Group Equations):

$$\frac{d}{d\log\mu}\mathcal{C}(\mu) = \gamma^T \mathcal{C}(\mu)$$

- Do we need to re-sum the logs?
  - $\alpha_1(\mu_{EW}) \approx 0.01$, $\alpha_2(\mu_{EW}) \approx 0.03$, $\alpha_\lambda(\mu_{EW}) \approx 0.04$, $\alpha_t(\mu_{EW}) \approx 0.08$
  - No – would need $\Lambda \sim 10^4$ TeV
- importance of RGE:
  - mixing of velocity suppressed and unsuppressed operators
  - penguin insertions mix lepton and quark operators



RG running above EW

- allow DM to carry electroweak charges
- for now: only fermion DM

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    - scalar DM in the works
- only dim5 and dim6 ops
    - dim7 to be included in the future

DIM-5 OPERATORS

- dim-5 operators:

CP even

$$Q_1^{(5)} = \frac{g_1}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\chi)B_{\mu\nu}, \quad Q_2^{(5)} = \frac{g_2}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\tilde{\tau}^a\chi)W^a_{\mu\nu},$$

$$Q_3^{(5)} = (\bar{\chi}\chi)(H^\dagger H), \qquad Q_4^{(5)} = (\bar{\chi}\tilde{\tau}^a\chi)(H^\dagger\tau^a H),$$

CP odd

$$Q_5^{(5)} = i\frac{g_1}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\gamma_5\chi)B_{\mu\nu}, \quad Q_6^{(5)} = i\frac{g_2}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\tilde{\tau}^a\gamma_5\chi)W^a_{\mu\nu},$$

$$Q_7^{(5)} = i(\bar{\chi}\gamma_5\chi)(H^\dagger H), \qquad Q_8^{(5)} = i(\bar{\chi}\tilde{\tau}^a\gamma_5\chi)(H^\dagger\tau^a H).$$

DIM-6 OPERATORS

- DM coupling to quark currents

$$Q_{1,i}^{(6)} = (\bar\chi\gamma_\mu\tilde\tau^a\chi)(\bar Q_L^i\gamma^\mu\tau^a Q_L^i),\quad Q_{5,i}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\tilde\tau^a\chi)(\bar Q_L^i\gamma^\mu\tau^a Q_L^i).$$

$$Q_{2,i}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar Q_L^i\gamma^\mu Q_L^i),\quad Q_{6,i}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar Q_L^i\gamma^\mu Q_L^i),$$

$$Q_{3,i}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar u_R^i\gamma^\mu u_R^i),\quad Q_{7,i}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar u_R^i\gamma^\mu u_R^i),$$

$$Q_{4,i}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar d_R^i\gamma^\mu d_R^i),\quad Q_{8,i}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar d_R^i\gamma^\mu d_R^i).$$

- DM coupling to lepton currents

$$Q_{9,i}^{(6)} = (\bar\chi\gamma_\mu\tilde\tau^a\chi)(\bar L_L^i\gamma^\mu\tau^a L_L^i),\quad Q_{12,i}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\tilde\tau^a\chi)(\bar L_L^i\gamma^\mu\tau^a L_L^i),$$

$$Q_{10,i}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar L_L^i\gamma^\mu L_L^i),\quad Q_{13,i}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar L_L^i\gamma^\mu L_L^i),$$

$$Q_{11,i}^{(6)} = (\bar\chi\gamma_\mu\chi)(\bar\ell_R^i\gamma^\mu\ell_R^i),\quad Q_{14,i}^{(6)} = (\bar\chi\gamma_\mu\gamma_5\chi)(\bar\ell_R^i\gamma^\mu\ell_R^i).$$

- DM coupling to Higgs currents

$$Q_{15}^{(6)} = (\bar\chi\gamma^\mu\tilde\tau^a\chi)(H^\dagger i\overleftrightarrow{D}^a{}_\mu H),\quad Q_{17}^{(6)} = (\bar\chi\gamma^\mu\gamma_5\tilde\tau^a\chi)(H^\dagger i\overleftrightarrow{D}^a{}_\mu H),$$

$$Q_{16}^{(6)} = (\bar\chi\gamma^\mu\chi)(H^\dagger i\overleftrightarrow{D}_\mu H),\quad Q_{18}^{(6)} = (\bar\chi\gamma^\mu\gamma_5\chi)(H^\dagger i\overleftrightarrow{D}_\mu H).$$

HIGHER DIM OPS?

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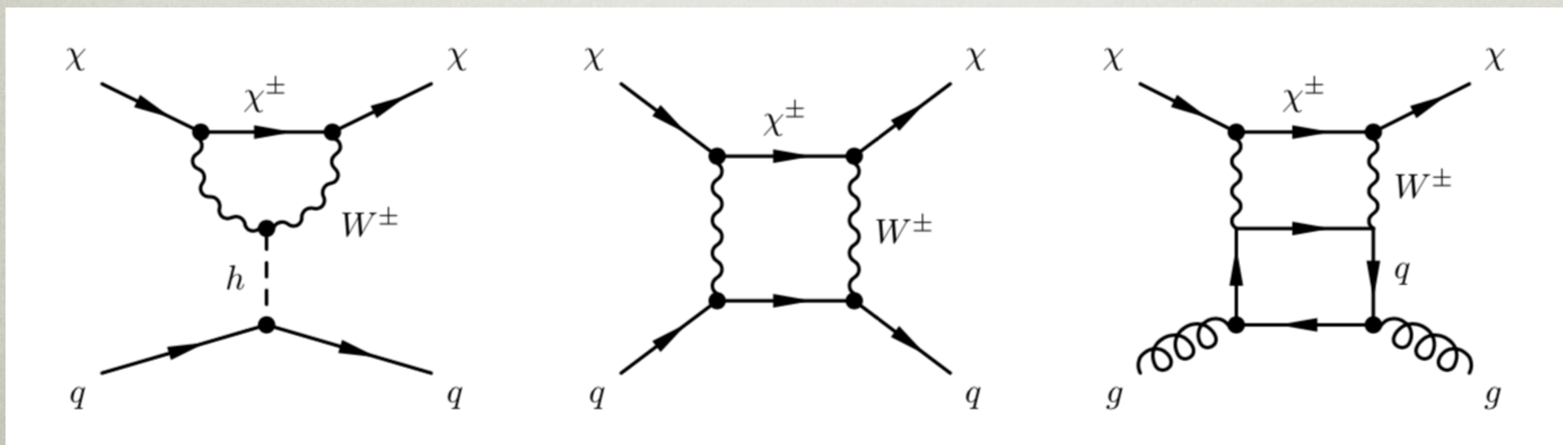
- 0-th order question:
  - since renormalizable EW interactions, do we care about higher dim ops?
- if tree level Z exchange allowed, ruled out by direct detection
- this leaves 1-loop and 2-loop as leading
- higher dim ops can dominate

Hisano et al, 1104.0228, 1007.2601



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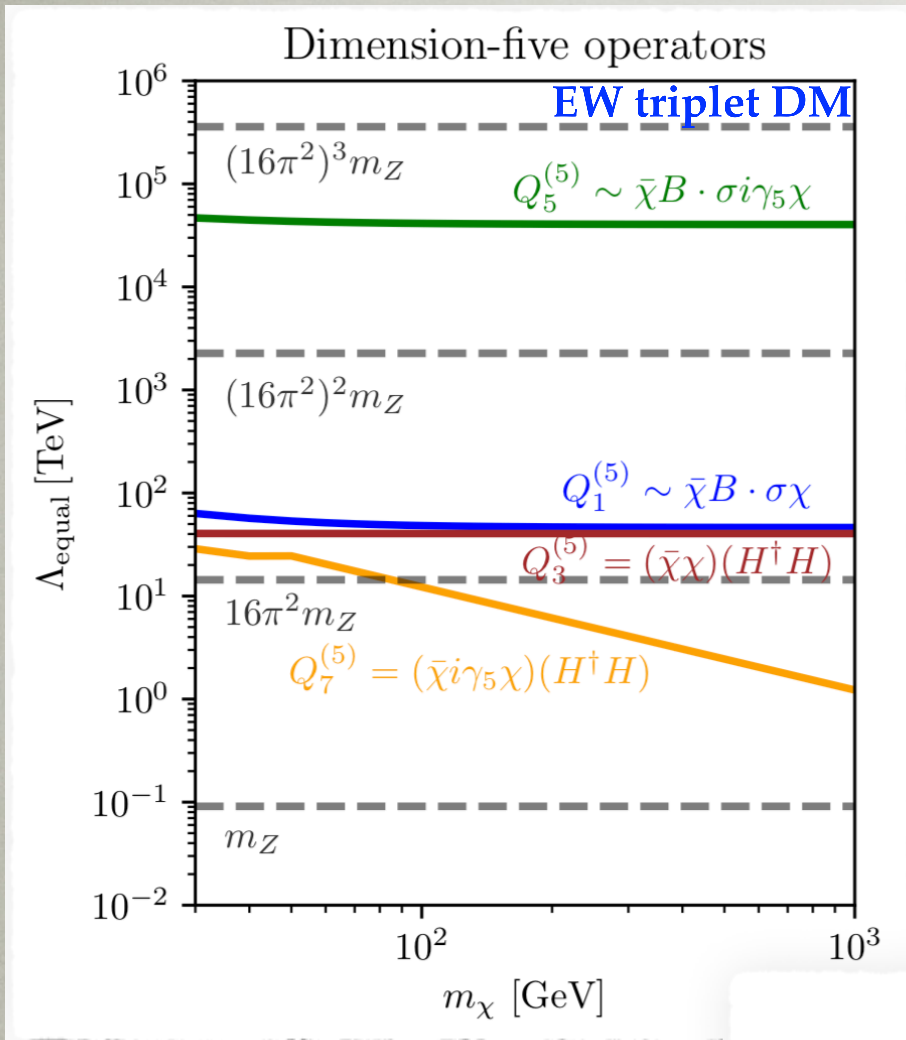

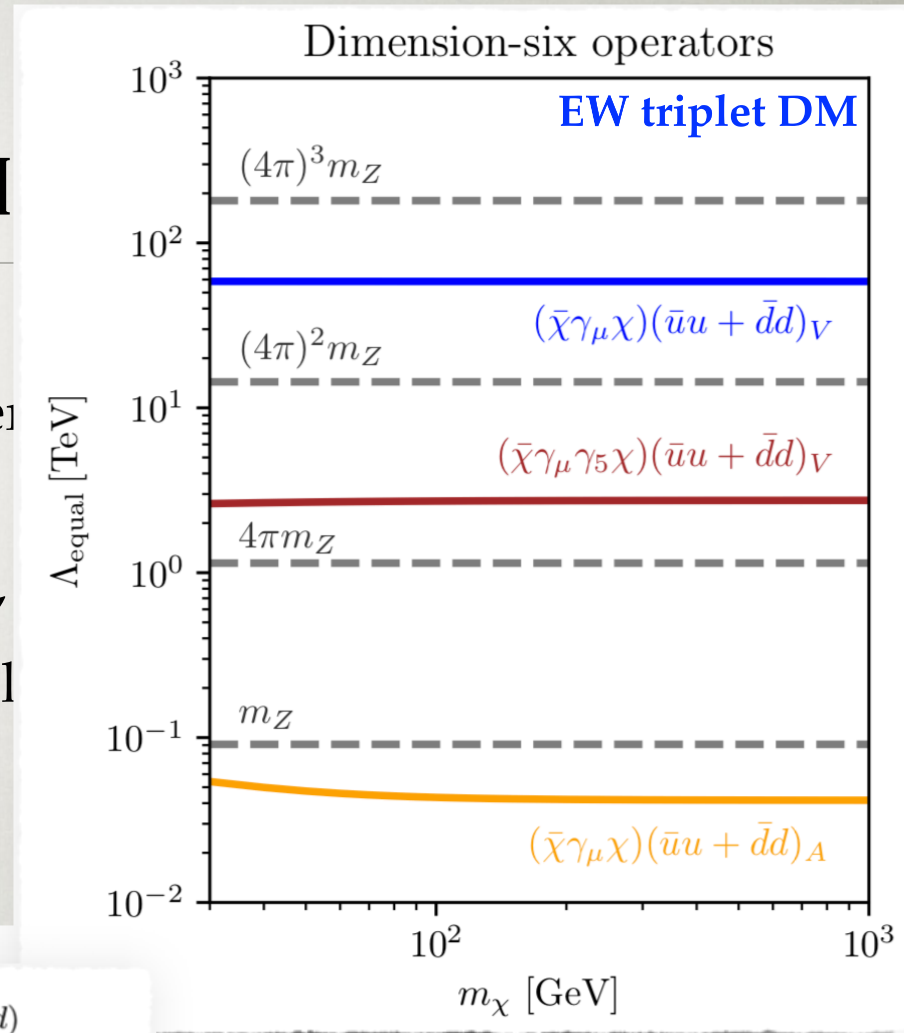

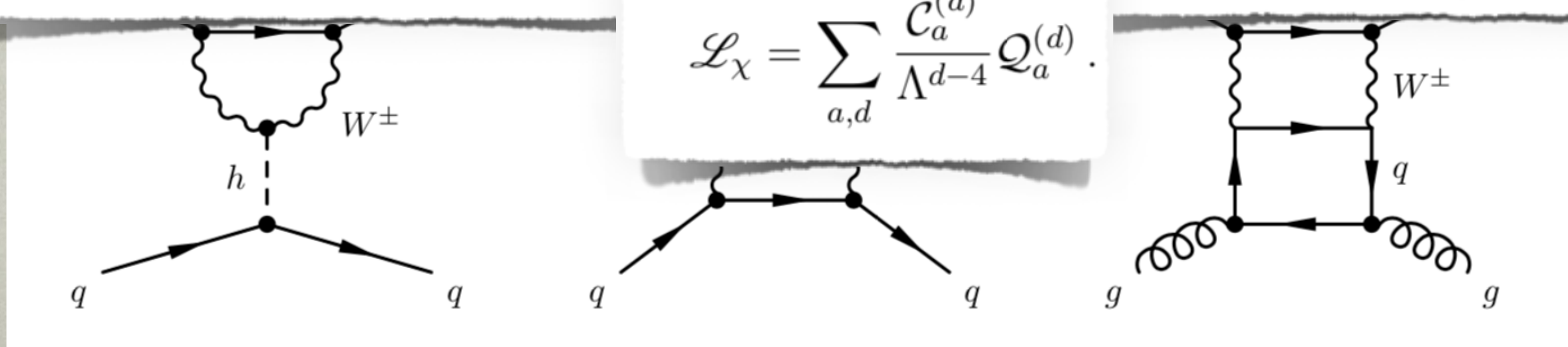

$$\mathcal{L}_\chi = \sum_{a,d} \frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}} \mathcal{Q}_a^{(d)} .$$

EFFECTS OF MIXING

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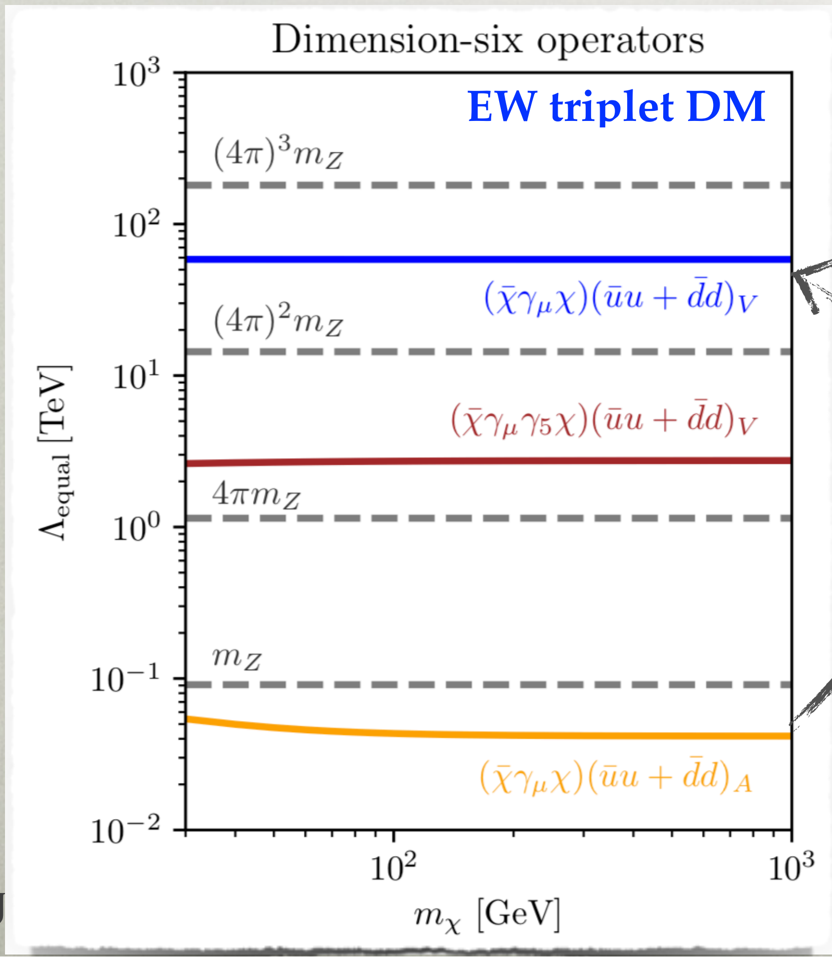
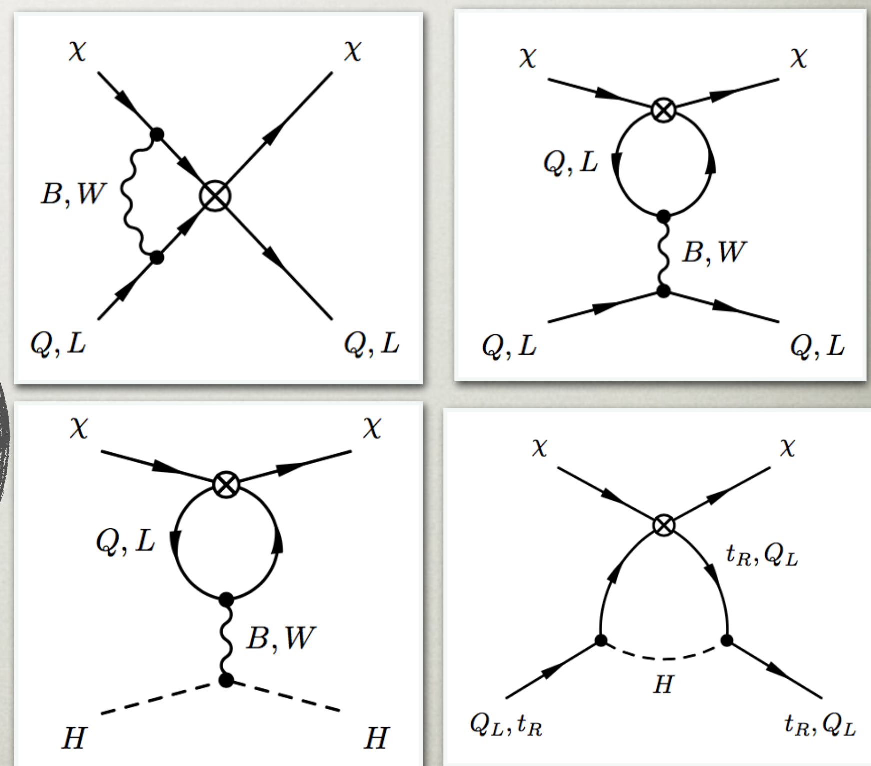
- the mixing important if from velocity suppressed ops. to unsuppressed





MIXING

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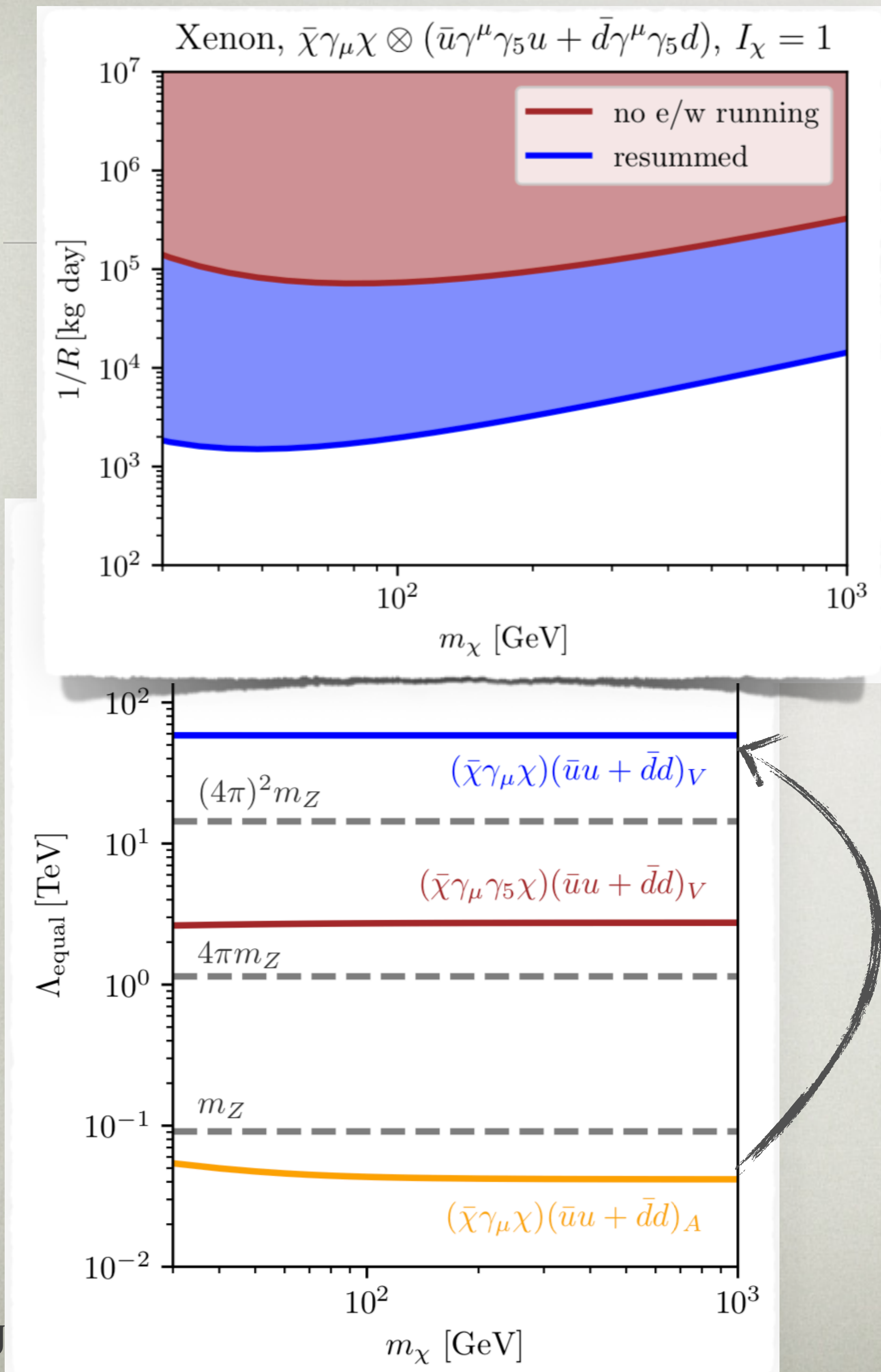
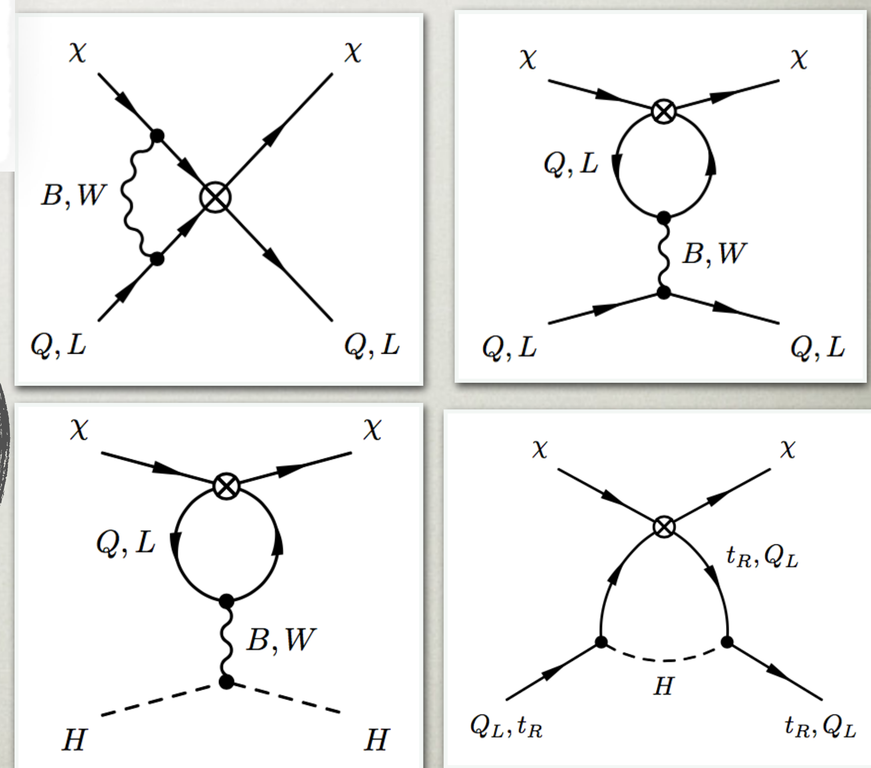
if from velocity

suppressed

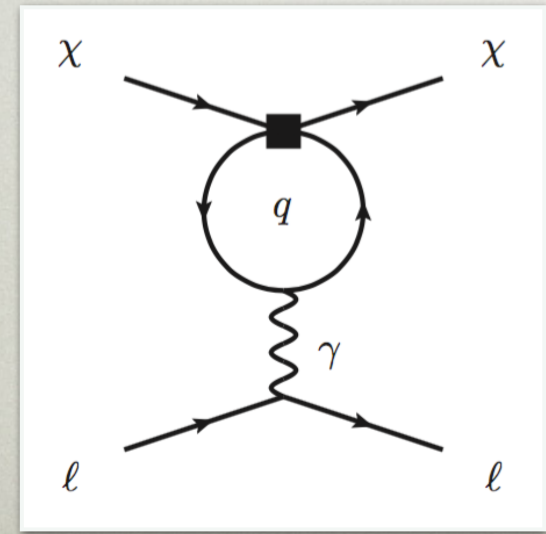


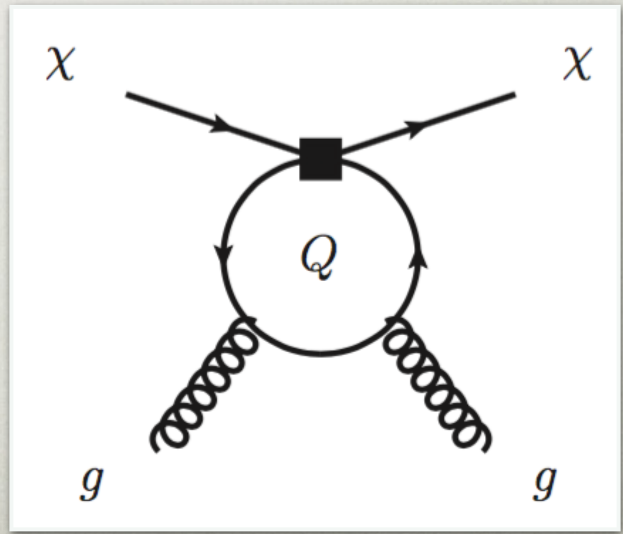


RUNNING BELOW EW

e.g., Hill, Solon, 1409.8290

- below EW: QCD / QED running is well-known
- penguin insertions mix lepton and quark ops
- matching at flavor thresholds

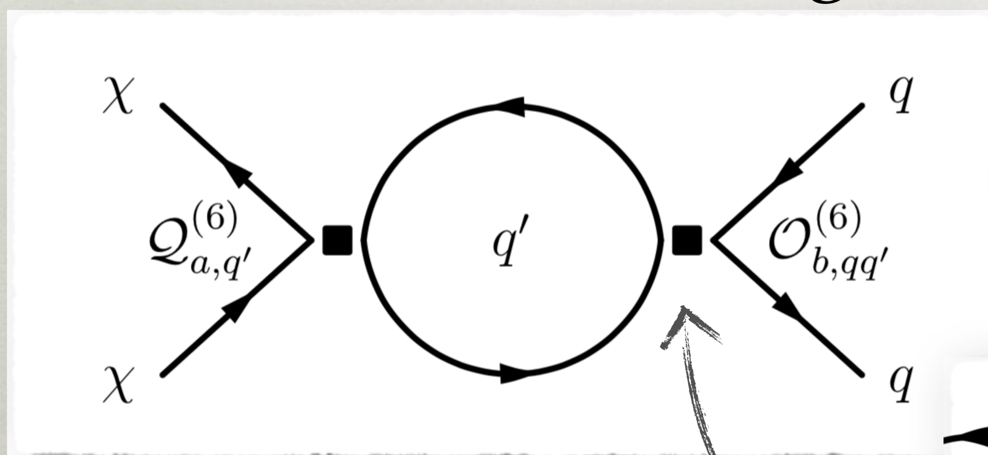


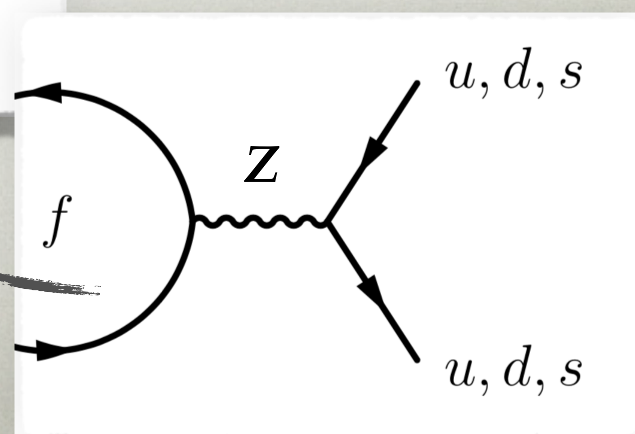


DOUBLE WEAK INSERTIONS

D'Eramo, Procura, 1411.3342; Brod, Stamou, JZ, 1801.04240

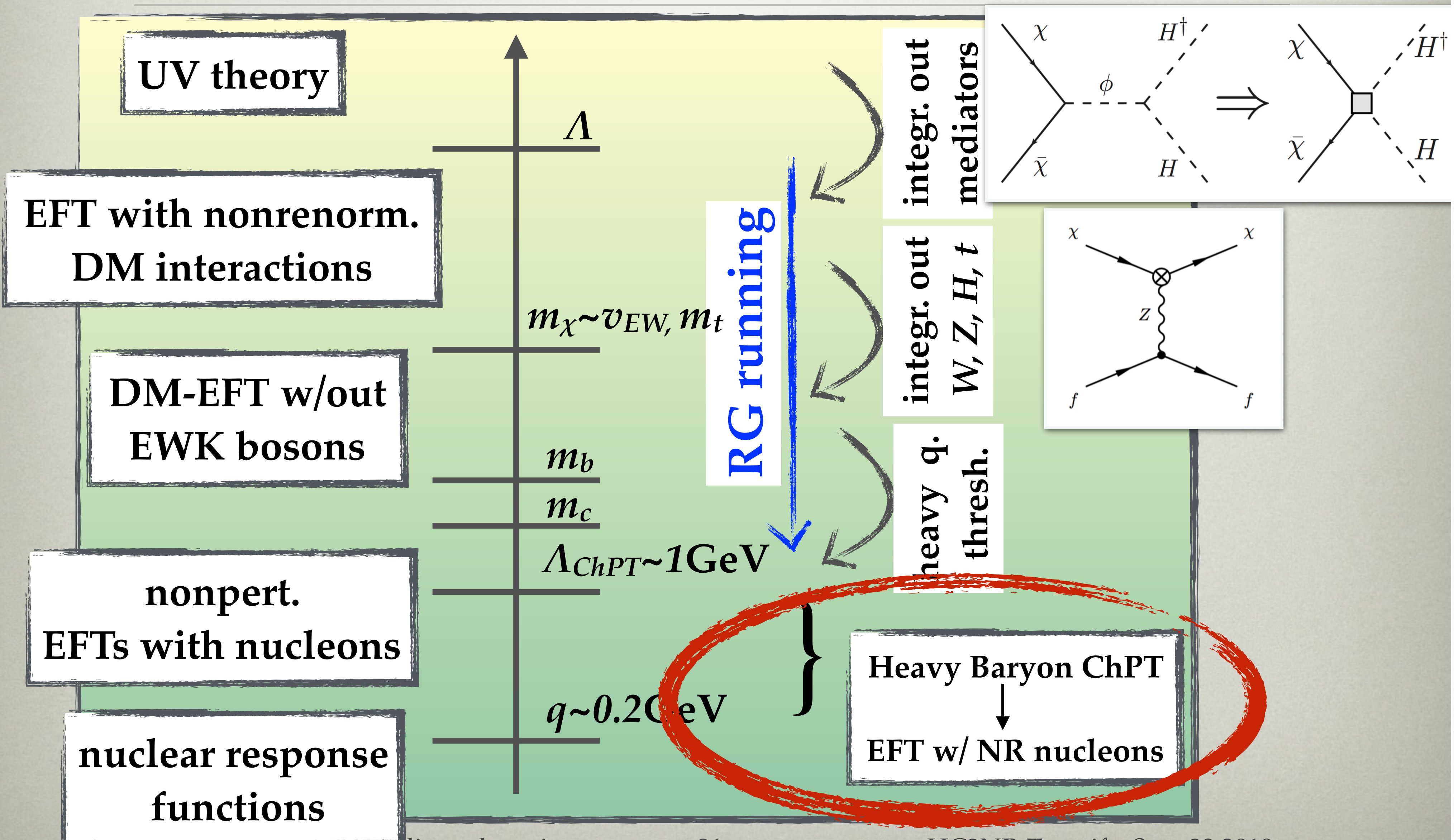
- in order to have xsecs to *O(1)* need to include double weak insertions
    - and resum QCD logs





MATCHING TO NUCLEAR PHYSICS

TOWER OF EFTs



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

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

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

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

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

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

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

relativistic theory with quarks and gluons

?

non-relativistic theory with nucleons

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

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

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

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

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

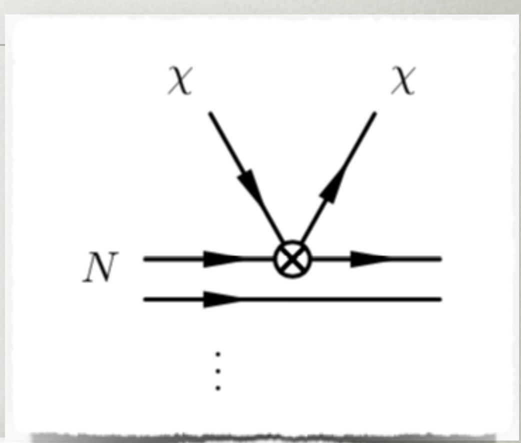
$$\mathcal{O}_{11}^N = -\Big(\vec S_\chi\cdot\frac{i\vec q}{m_N}\Big)\mathbb{1}_N\,, \qquad \mathcal{O}_{12}^N = \vec S_\chi\cdot\Big(\vec S_N\times\vec v_\perp\Big)\,,$$

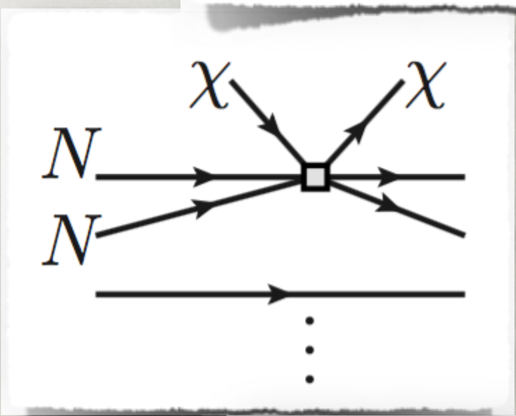
see also Cirigliano, Graesser, Ovanesyan, 1205.2695
Hoferichter, Klos, Schwenk, 1503.04811
Hoferichter, Klos, Menéndez, Schwenk, 1812.05617

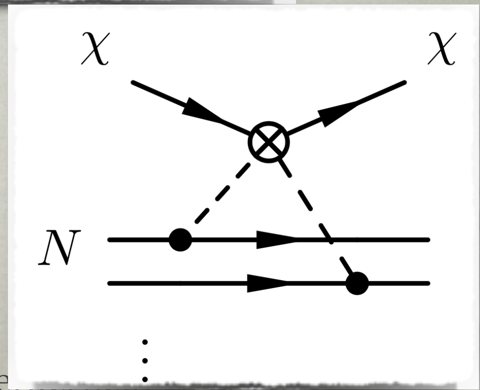
GENERAL LESSONS

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

- 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, 6, 7 EFT above EW scale requires at LO

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

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

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

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

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

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

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

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

THE INVERSE PROBLEM

- which of the NR operators can consistently switch on one by one?
- $\exists \mathcal{Q}_a^{(d)}$: only one $\mathcal{O}_i^N$ generated

assume d≤7 above EW

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

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

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

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

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

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

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

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

SINGLE NR OPERATOR?

- what is often done in global analyses of DM direct detection results
  - take only one NR operator
  - keep coefficient *q* independent

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

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

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

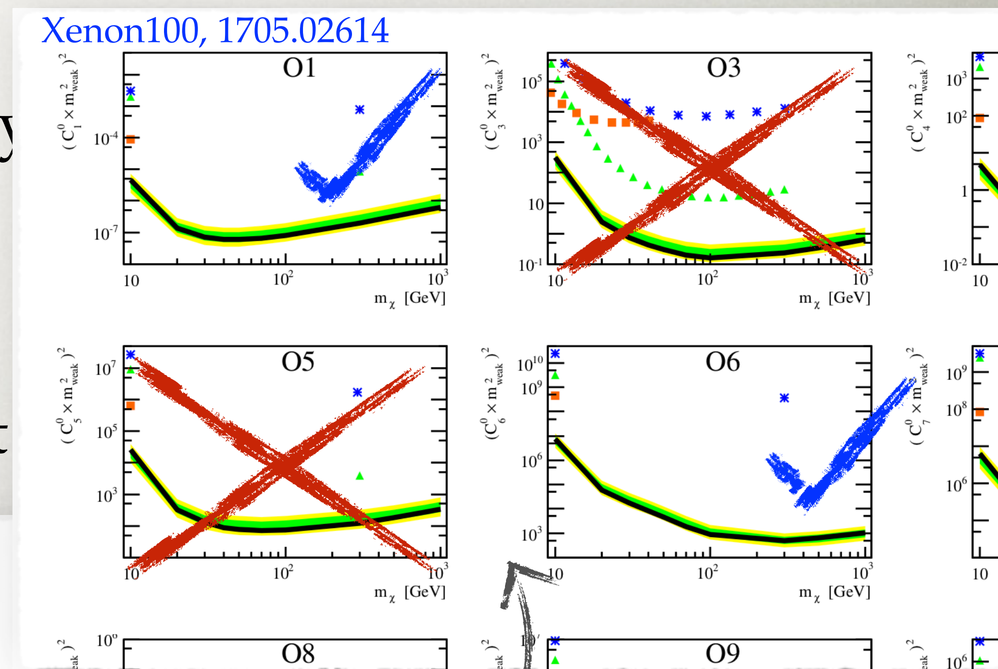
$$\mathcal{O}_7^N = \mathbb{1}_\chi \left(\vec{S}_N \cdot \vec{v}_\perp\right), \qquad \mathcal{O}_8^N = \left(\vec{S}_\chi \cdot \vec{v}_\perp\right) \mathbb{1}_N\,,$$

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

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

SINGLE NR OPERATOR?

- what is often done in global analy
  detection results
  - take only one NR operator
  - keep coefficient q independent



$$\mathcal{O}_1^N = \mathbb{1}_\chi \mathbb{1}_N \,,$$

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

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

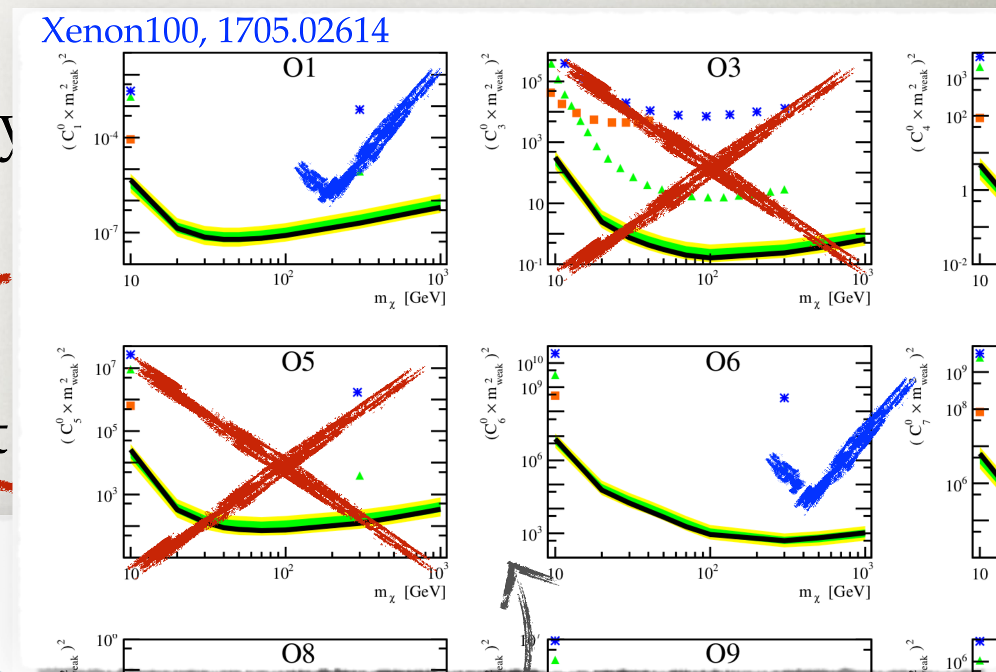
$$\mathcal{O}_7^N = \mathbb{1}_\chi \big(\vec{S}_N \cdot \vec{v}_\perp\big) \,, \qquad \mathcal{O}_8^N = \big(\vec{S}_\chi \cdot \vec{v}_\perp\big) \mathbb{1}_N \,,$$

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

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

SINGLE NR OPERATOR?

- what is often done in global analy… detection results
  - ~~take only one NR operator~~
  - ~~keep coefficient q independent~~



$$\mathcal{O}_1^N = 1_\chi 1_N \,,$$

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

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

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

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

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

AT LO IN HEAVY BARYON CHPT

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

- 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

$$J^V_{q,\mu} \sim \pi \partial_\mu \pi + \cdots\,, \qquad J^A_{q,\mu} \sim \partial_\mu \pi + \cdots\,,$$

$$J^G \sim \pi^2, \qquad J^S_q \sim m_q \pi^2 + \cdots\,, \qquad J^P_q \sim m_q \pi + \cdots\,,$$

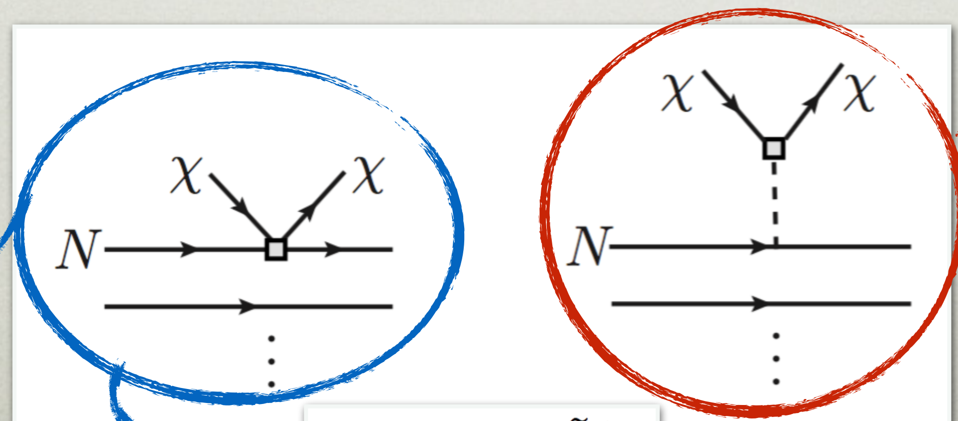
- two types of leading order diagrams

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

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

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

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



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

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

*for vector DM only left diagr. important

PION POLES

- the pion poles important for

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

$$\mathcal{Q}_{4}^{(7)} = \frac{\alpha_s}{8\pi}(\bar\chi i\gamma_5\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$$

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

$$\sim \frac{\Delta q}{m_\chi}\frac{\vec q^{\,2}}{m_\pi^2+\vec q^{\,2}}\mathcal{C}_4^{(7)}$$

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

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

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

$$\mathcal{O}_4^N = \vec S_\chi\cdot\vec S_N\,,$$

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

$$\mathcal{O}_6^N = \Big(\vec S_\chi\cdot\frac{\vec q}{m_N}\Big)\Big(\vec S_N\cdot\frac{\vec q}{m_N}\Big),$$

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

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

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

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

$$\mathcal{O}_{11}^N = -\Big(\vec S_\chi\cdot\frac{i\vec q}{m_N}\Big)\mathbb{1}_N\,,$$

$$\mathcal{O}_{12}^N = \vec S_\chi\cdot\big(\vec S_N \ldots$$

$$\sim \Delta q\frac{\vec q^{\,2}}{m_\pi^2+\vec q^{\,2}}\mathcal{C}_3^{(7)}$$

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

$$\mathcal{Q}_{3}^{(7)} = \frac{\alpha_s}{8\pi}(\bar\chi\chi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}$$

SPIN-DEPENDENT INTERACTIONS

- the classic spin-dependent interaction
  - in relativic. EFT: *A*x*A* operator

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

$$\sim \Delta q\, \mathcal{C}_{4,q}^{(6)} \quad \rightarrow \quad \mathcal{O}_4^N$$

$$\sim \frac{\Delta q}{m_\pi^2 + \vec q^{\,2}} \mathcal{C}_{4,q}^{(6)} \quad \rightarrow \quad \mathcal{O}_6^N$$

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

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

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

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

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

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

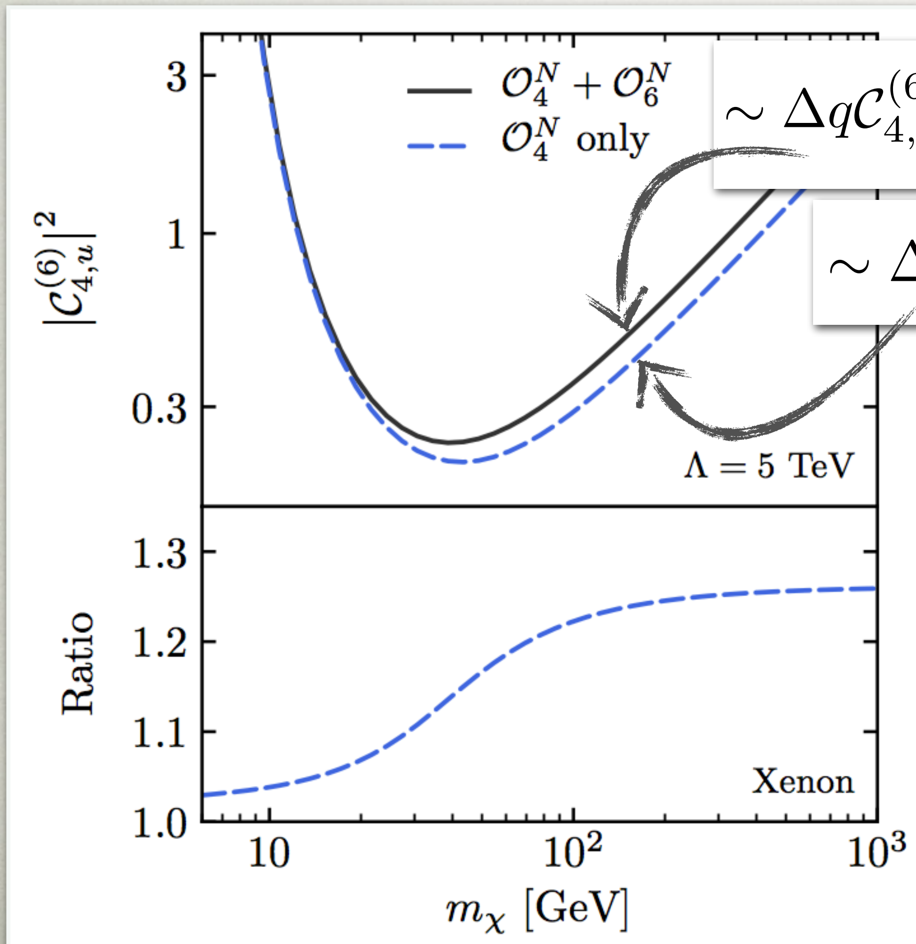
AXIAL-AXIAL

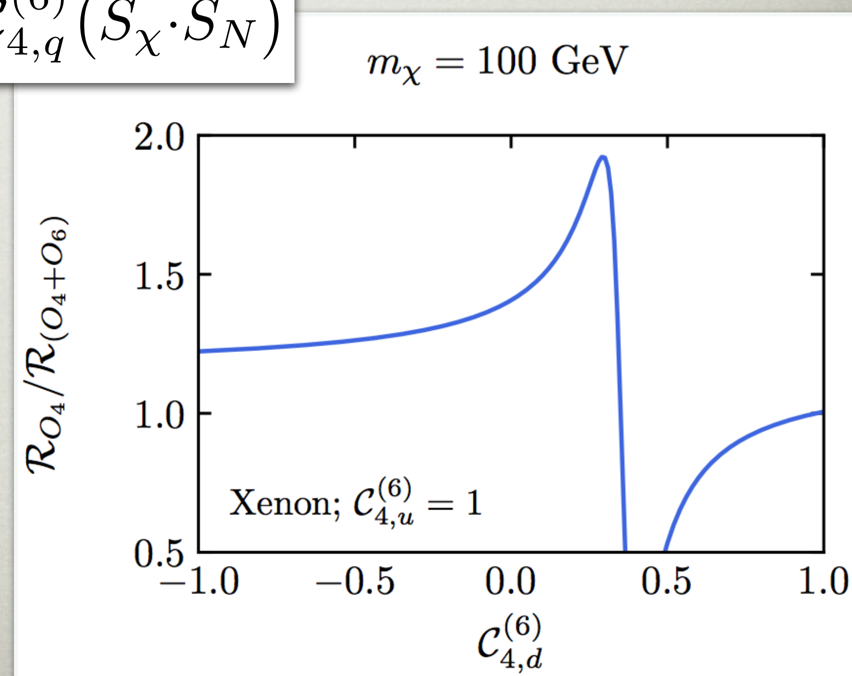
- the classic spin-dep. oper.
  - axial-axial interaction: C_{4u}=-C_{4d}

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

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

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

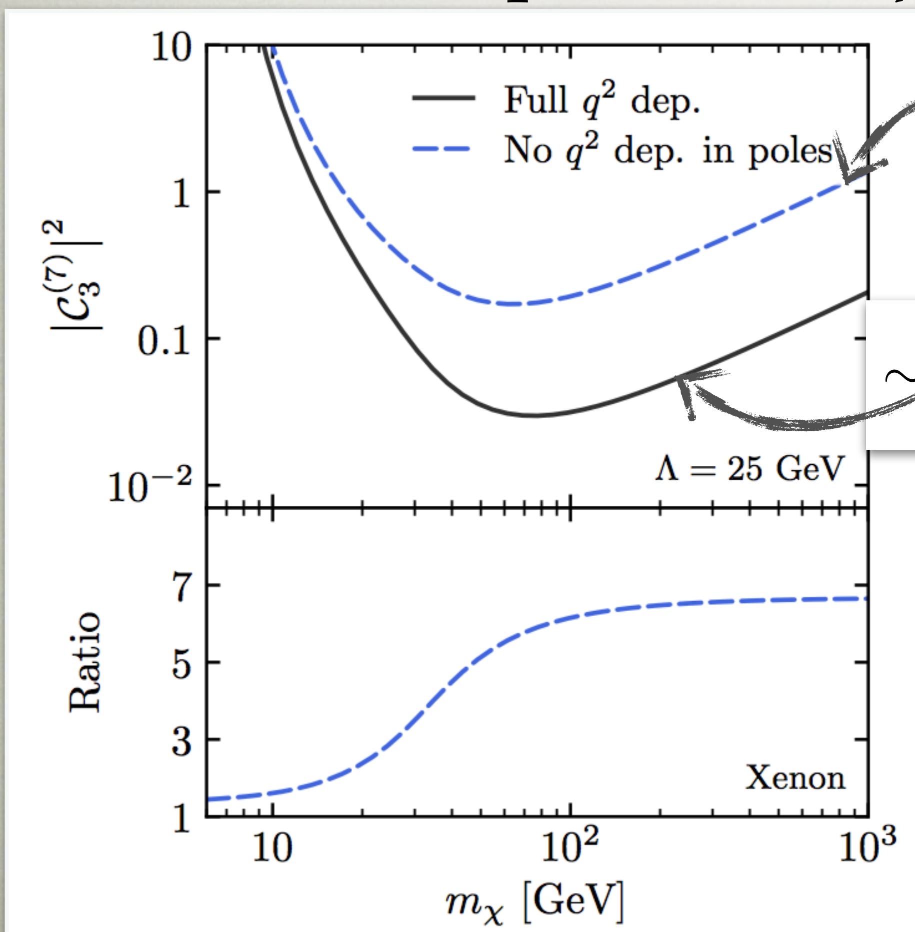




CP-odd gluonic operator

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

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



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

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

PHOTON POLES

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

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

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

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

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

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

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

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

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

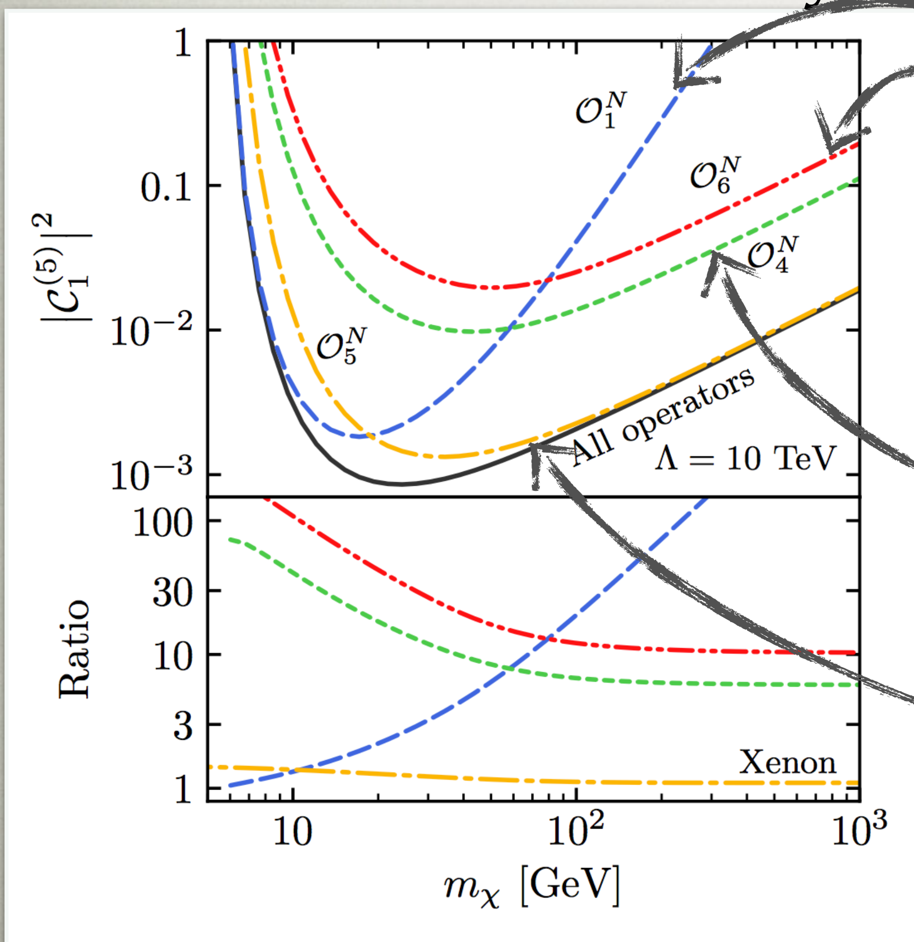
$$\mathcal{Q}_2^{(5)} = \frac{e}{8\pi^2}(\bar\chi\sigma^{\mu\nu}i\gamma_5\chi)F_{\mu\nu} \qquad \sim m_N\frac{\alpha Q_p}{\vec q^{\,2}}\mathcal{C}_2^{(5)}$$

PHOTON POLES - XENON

- for magnetic dipole interaction

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

  - two coherently enhanced operators



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

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

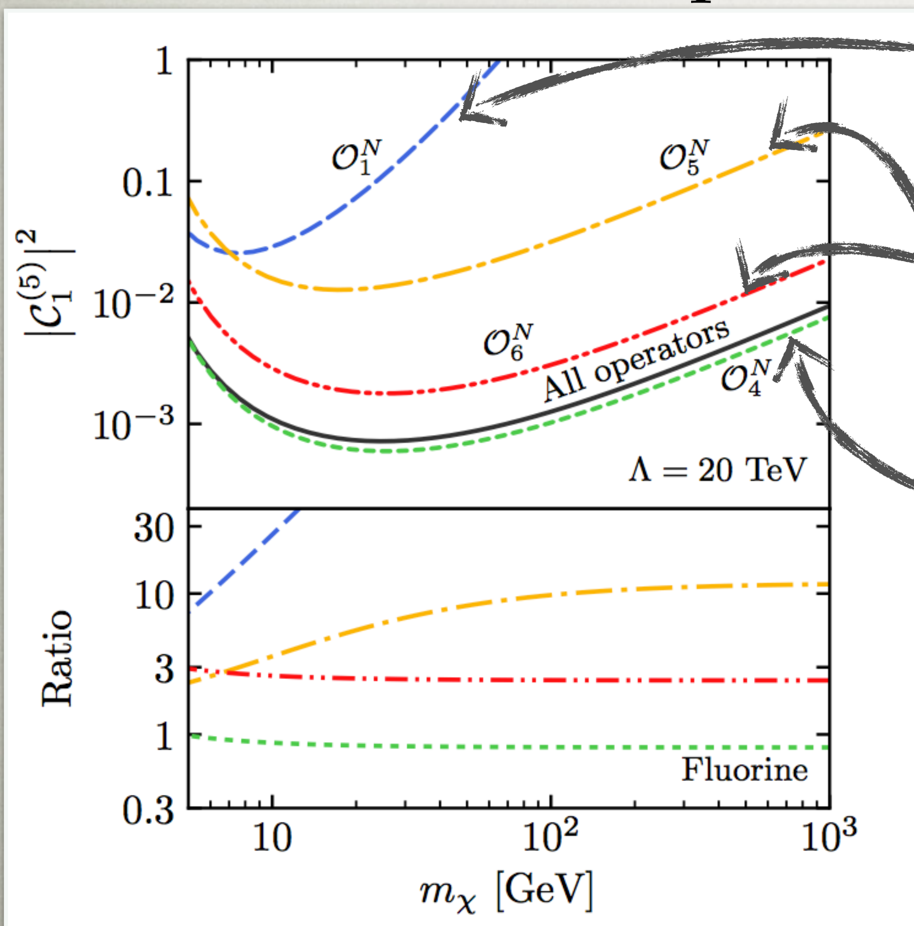
$$-\frac{2\alpha}{\pi}\frac{\mu_N}{m_N}\hat{\mathcal{C}}_1^{(5)} \qquad \mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N$$

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

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

CONCLUSIONS

- EW corrections can mix velocity supp. ops. (in NR limit) into unsupp. ones
- in general not consistent to take only a single NR operator nonzero
  - should use EFT with gluons and quarks

BACKUP SLIDES

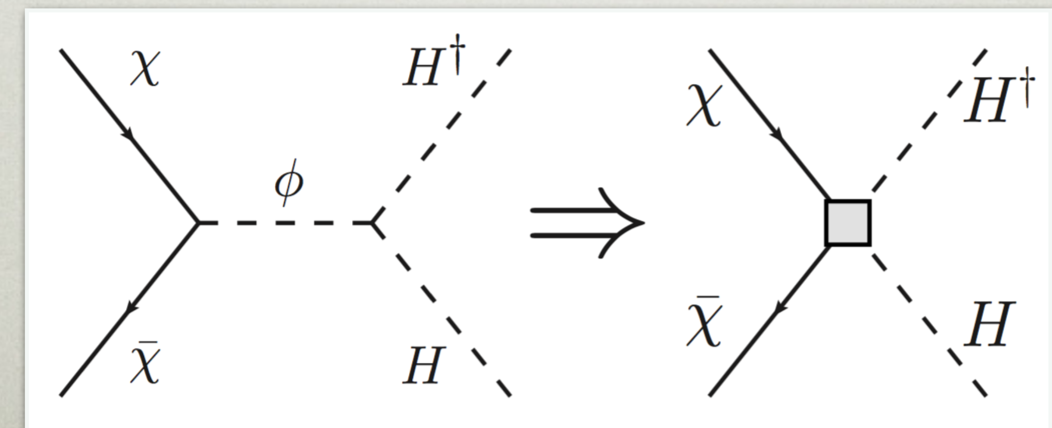
TOY EXAMPLE

- an example: scalar mediator ϕ, fermionic DM χ
- interacts with both the Higgs and DM

$$\mathcal{L}_\phi \supset \lambda_\chi \phi \bar{\chi}\chi + \mu_{H\phi}\phi H^\dagger H$$

- integrating out ϕ gives dim5 operator

$$Q_3^{(5)} = (\bar{\chi}\chi)(H^\dagger H),$$

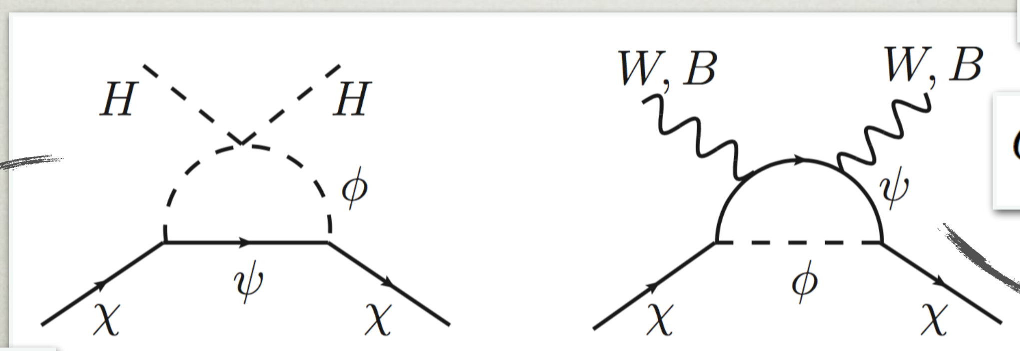


TOY EXAMPLE: LOOP ONLY

- mediators:
    - Z_2-odd electroweak singlet scalar ϕ
    - Z_2-even fermion ψ (the same EWK quantum numbers as DM)
- DM interacts with the SM only through loops
    - generate dim-5 operators

$$Q_1^{(5)} = \frac{g_1}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\chi)B_{\mu\nu},$$

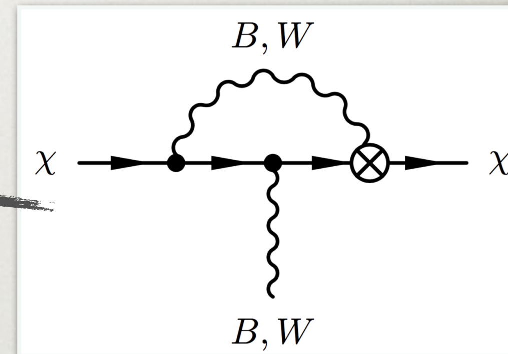
$$Q_2^{(5)} = \frac{g_2}{8\pi^2}(\bar{\chi}\sigma^{\mu\nu}\tilde{\tau}^a\chi)W^a_{\mu\nu},$$



$$Q_3^{(5)} = (\bar{\chi}\chi)(H^\dagger H),$$

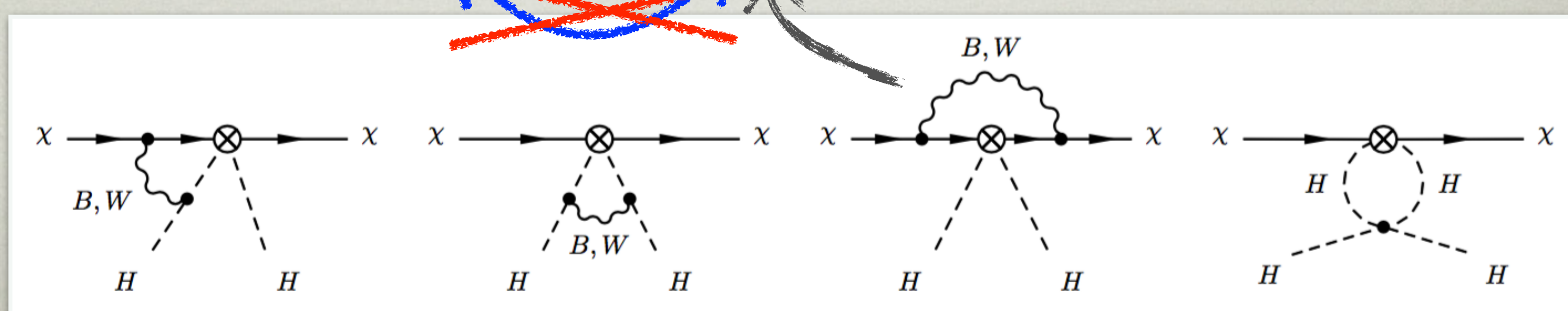
RUNNING ABOVE EW SCALE

- running above EW scale can mix velocity suppressed and unsuppressed ops.
- dim.-5 ops: only non-diag. mixing if $Y_\chi \neq 0$
  - for dipole operators
  - higgs current ops. diagonal anomal. dim.



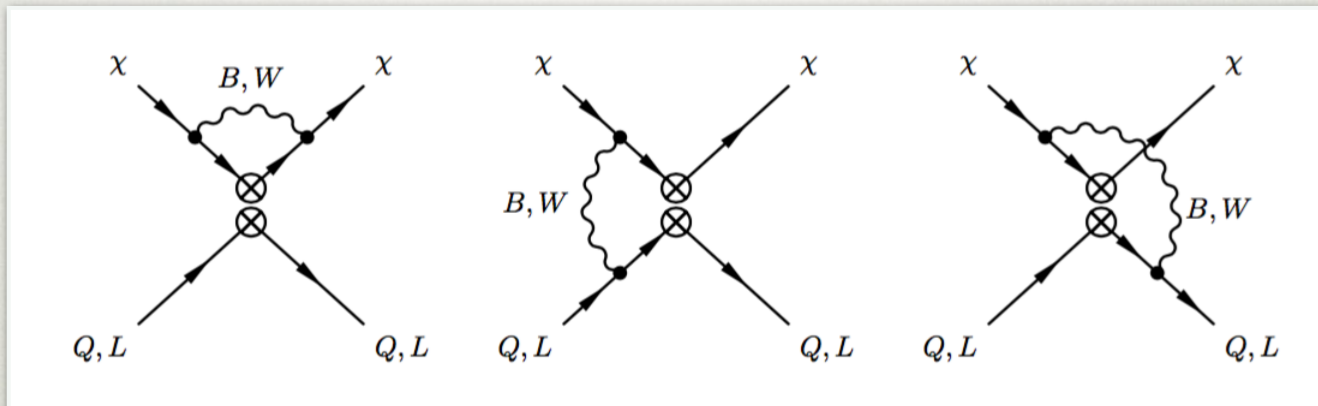
$$Q_1^{(5)} = \frac{g_1}{8\pi^2}(\bar\chi\sigma^{\mu\nu}\chi)B_{\mu\nu}, \; Q_2^{(5)} = \frac{g_2}{8\pi^2}(\bar\chi\sigma^{\mu\nu}\tilde\tau^a\chi)W^a_{\mu\nu},$$

$$Q_3^{(5)} = (\bar\chi\chi)(H^\dagger H), \qquad Q_4^{(5)} = (\bar\chi\tilde\tau^a\chi)(H^\dagger\tau^a H),$$

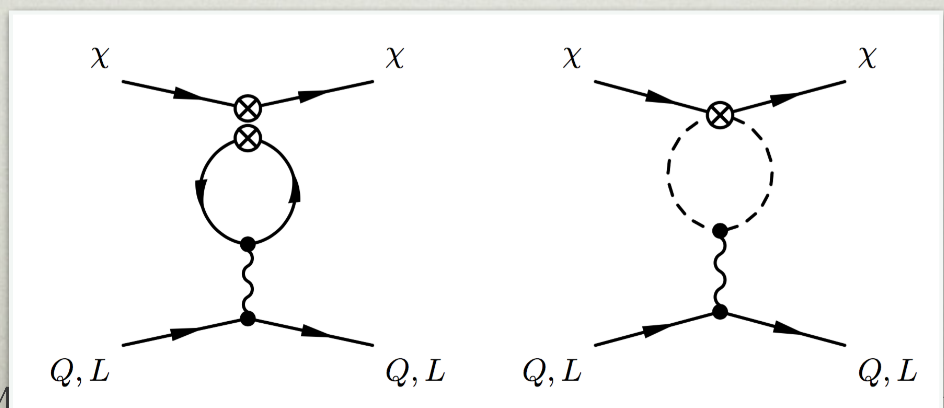


RUNNING ABOVE EW SCALE

- for dimension 6 operators
  - mixing that is present only for DM with EW charges



  - mixing that is there even for EWK neutral DM

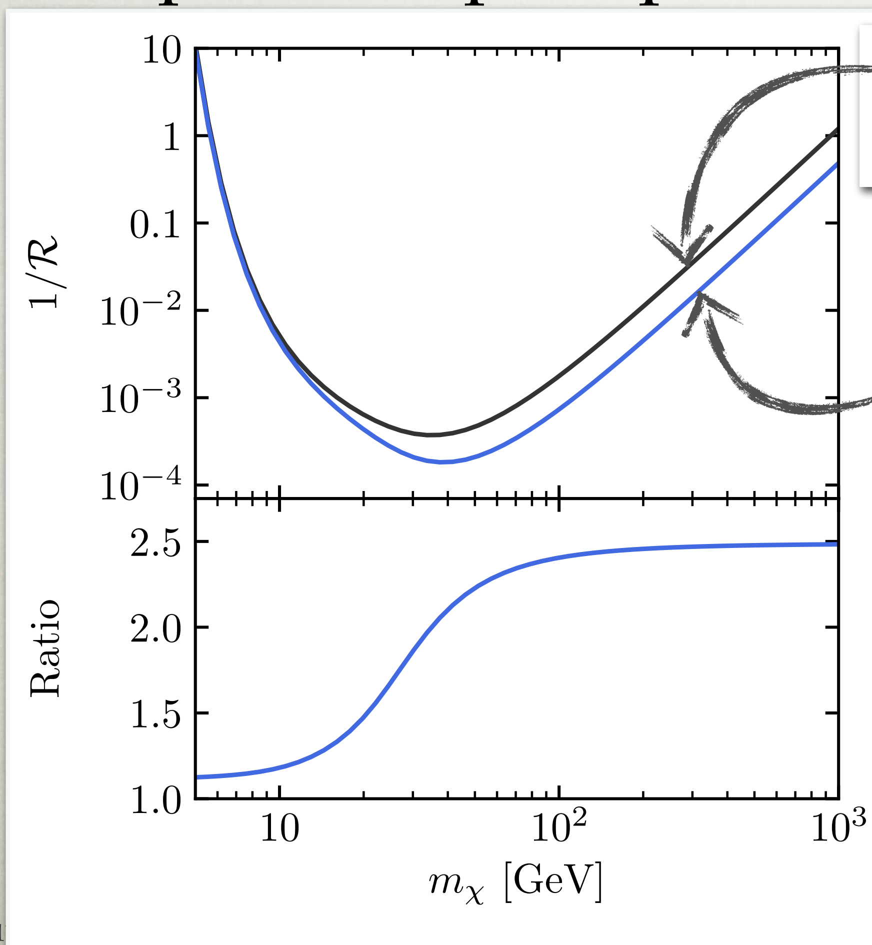


PSEUDOSCALAR-PSEUDOSCALAR

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

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

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



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

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

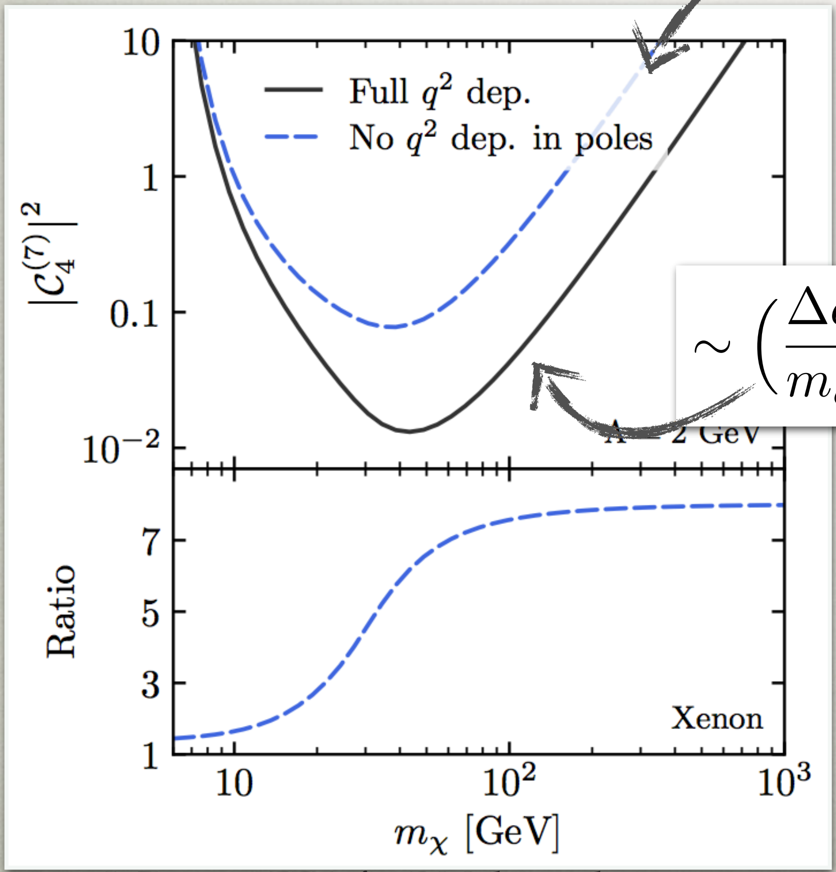
CP-odd gluonic operator

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

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

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

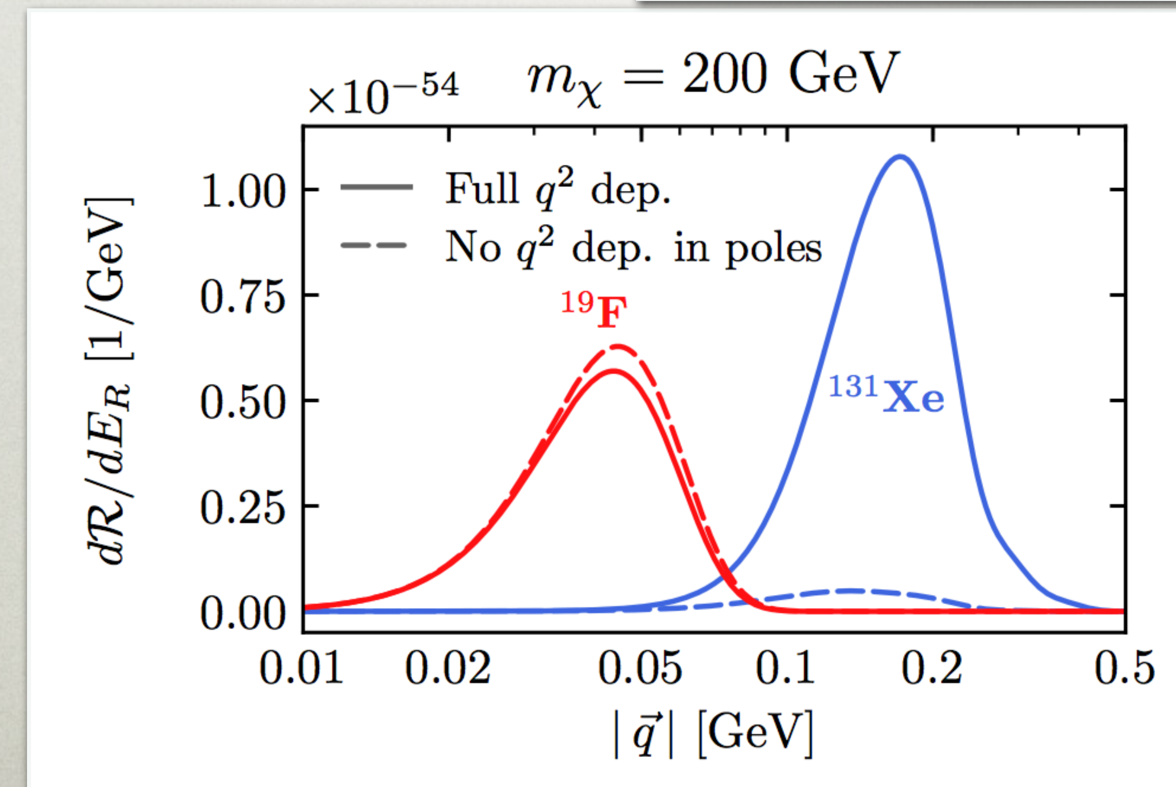
$$\sim \left(\frac{\Delta q}{m_q} + \left(\frac{1}{m_u} - \frac{1}{m_d}\right)\frac{(\Delta u - \Delta d)\vec{q}^2}{m_\pi^2 + \vec{q}^2}\right)(\vec{S}_N \cdot \vec{q})(\vec{S}_\chi \cdot \vec{q})$$



ENERGY DEPENDENCE

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

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

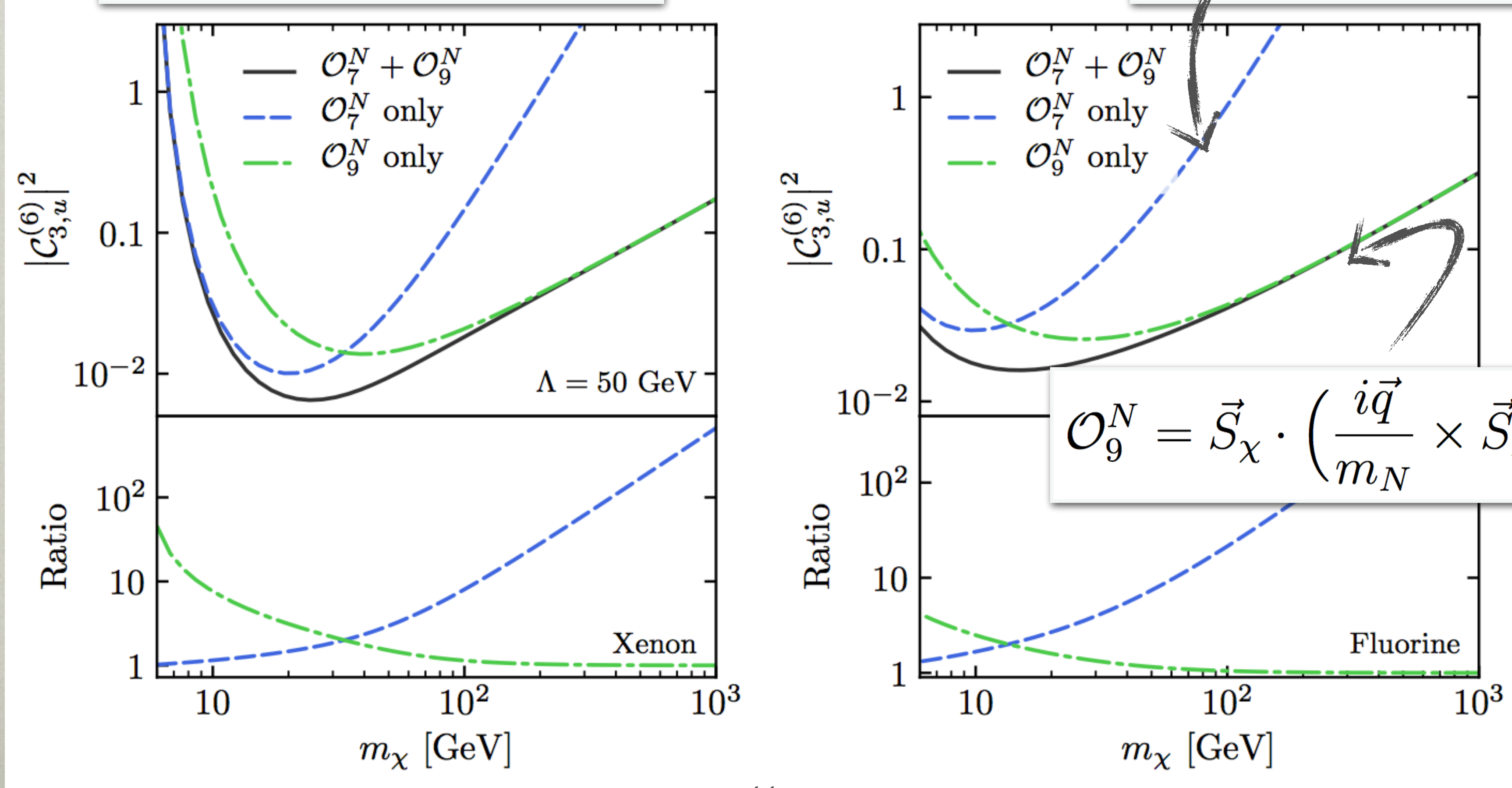


VECTOR-AXIAL

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

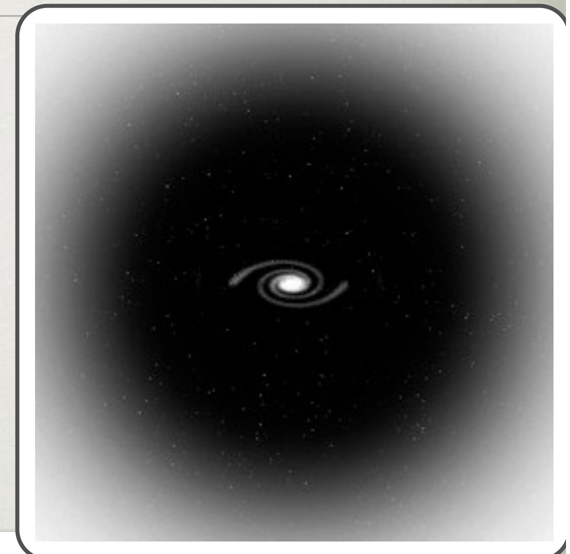
$$\mathcal{Q}_{3,q}^{(6)} = (\bar{\chi}\gamma_\mu\chi)(\bar{q}\gamma^\mu\gamma_5 q)$$

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



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

DIRECT DM DETECTION KINEMATICS



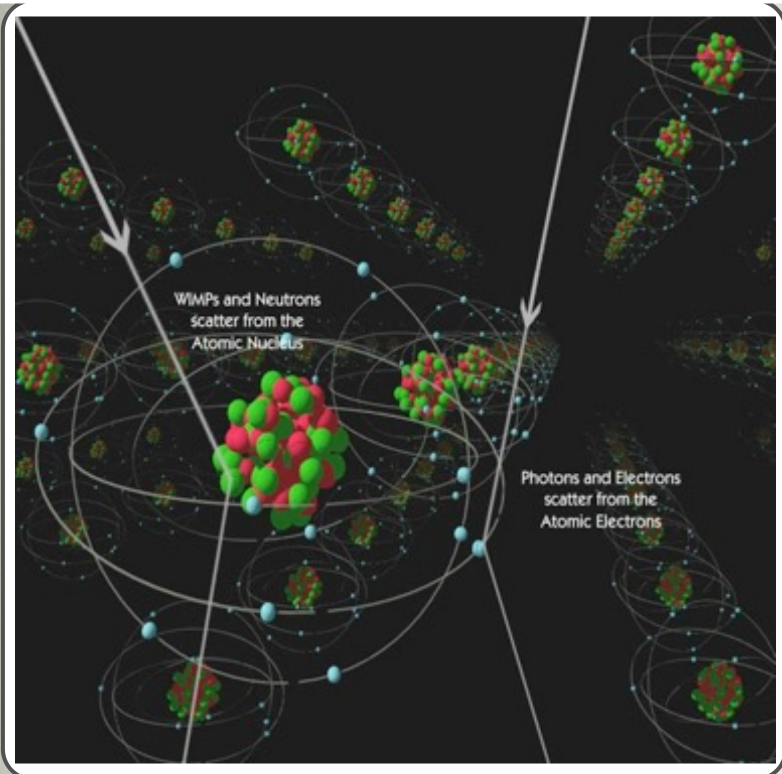
- WIMPS form DM halo
  - typical velocity $v \sim 10^{-3}$
- scatters on target nuclei $\chi N \to \chi N$
  - typical energy deposit

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

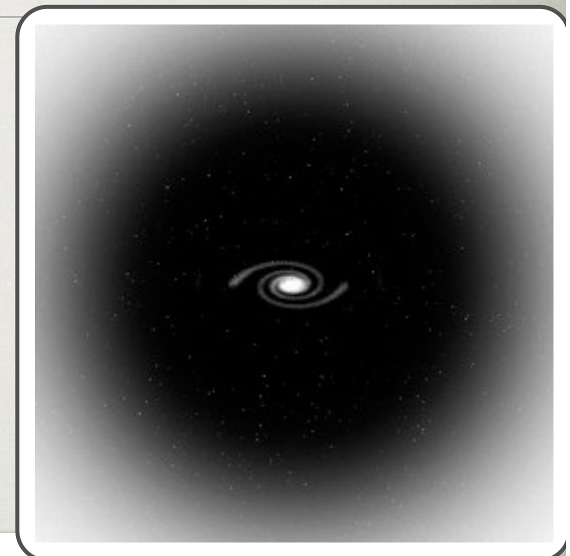
  - typical momentum exchange

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

  - this allows for treatment with ChPT
    - use Heavy Baryon ChPT to NLO



DM detection nematics



halo

$v \sim 10^{-3}$

nuclei $\chi N \to \chi N$

- typical energy deposit

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

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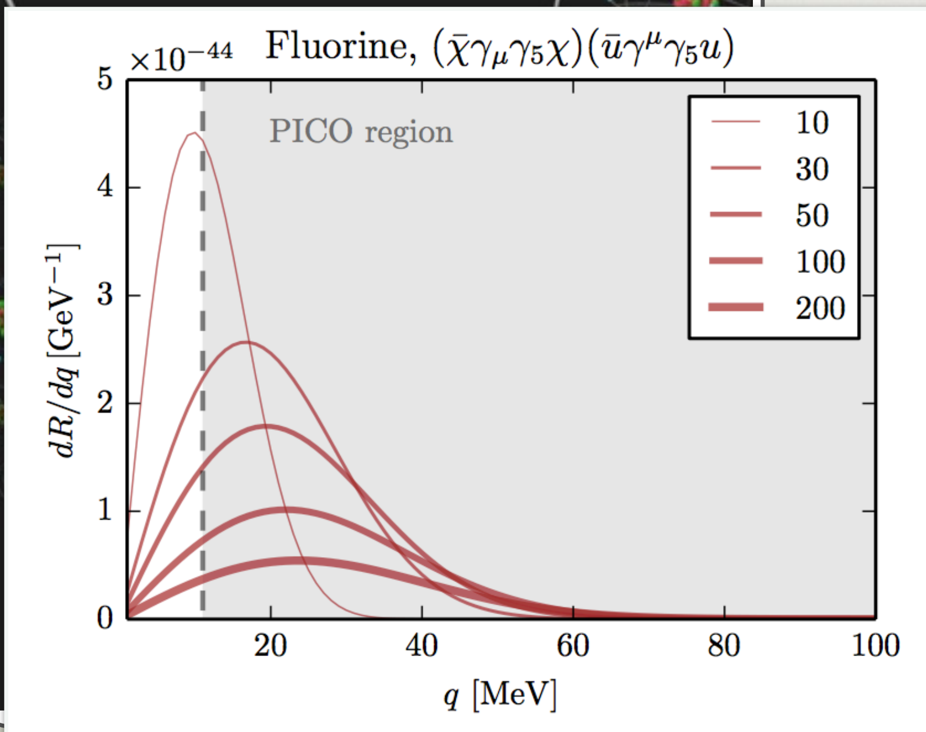

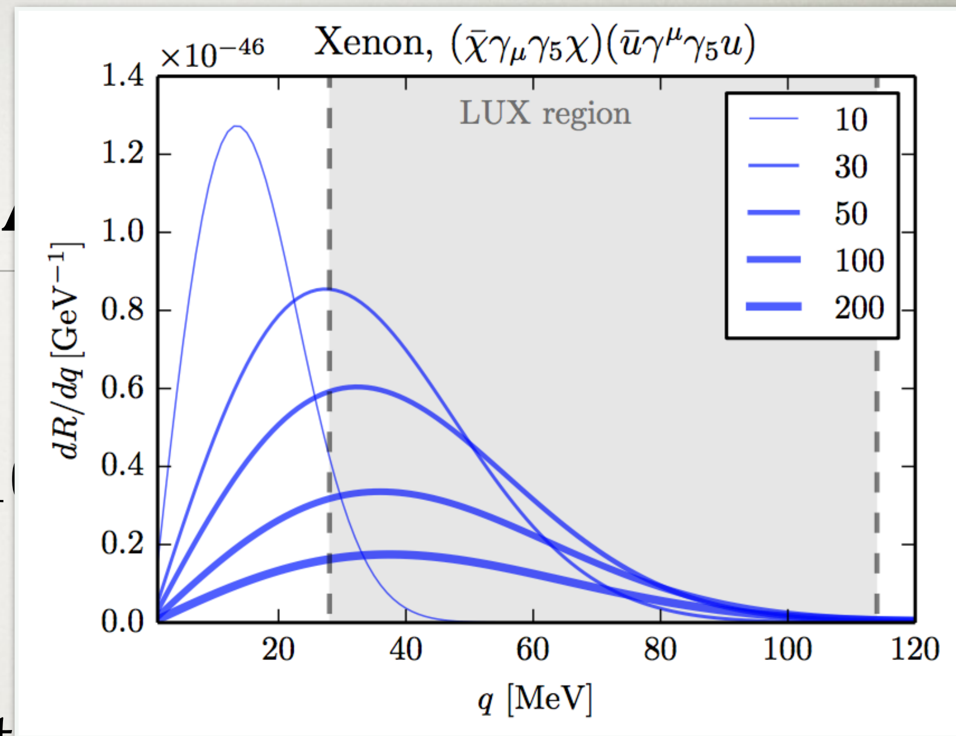

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  - use Heavy Baryon ChPT to NLO

Anand, Fitzpatrick, Haxton, 1308.6288

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

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

$$\frac{1}{2J_\chi+1}\frac{1}{2J_A+1}\sum_{\rm spins} |\mathcal{M}|^2_{\rm nucleus,NR} = \frac{\overline{|\mathcal{M}|^2}}{(4m_\chi m_A)^2} = \frac{4\pi}{2J_A+1}\sum_{\tau=0,1}\sum_{\tau'=0,1}\Big\{\Big[R_M^{\tau\tau'} W_M^{\tau\tau'}(y) + R_{\Sigma''}^{\tau\tau'} W_{\Sigma''}^{\tau\tau'}(y) + R_{\Sigma'}^{\tau\tau'} W_{\Sigma'}^{\tau\tau'}(y)\Big] + \frac{\vec{q}^2}{m_N^2}\Big[R_\Delta^{\tau\tau'} W_\Delta^{\tau\tau'}(y) + R_{\Delta\Sigma'}^{\tau\tau'} W_{\Delta\Sigma'}^{\tau\tau'}(y)\Big]\Big\},$$

W_i are nuclear response functions

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

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

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

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

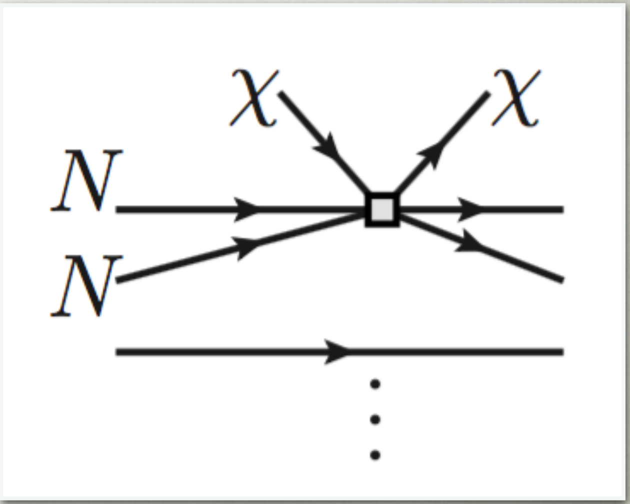
$$W_{\Sigma'}^{\tau\tau'} + W_{\Sigma''}^{\tau\tau'} = S_{\tau\tau'}, \qquad \tau, \tau' = 0, 1.$$

  - 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

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
- will address 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 $q/\Lambda_{\rm ChEFT} \sim q/m_{p,n} \sim 0.3$
- 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

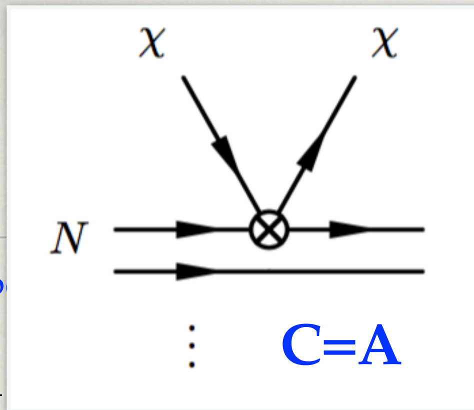
$$\epsilon_i = d_i + n_i/2 - 2,$$

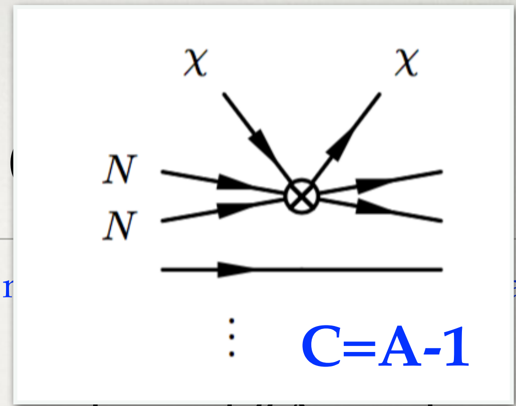
chiral dimension ~ # of derivatives

\# 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

- …consistent counting of "A-nucleon potentials"
  - expansion in $q/\Lambda_{\rm ChEFT} \sim q/m_{p,n} \sim 0.3$
- A-nucleon irreducible amplitudes scale as ~ q^ν

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

# of connected diagrams · **# of loops** · **# of vertices of type *i*** · **effective chiral dimensions**

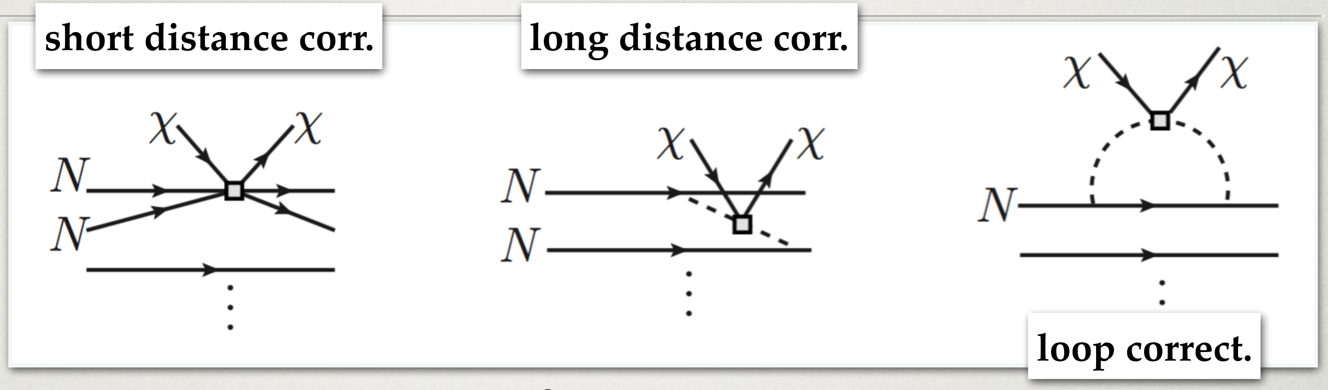
$$\epsilon_i = d_i + n_i/2 - 2,$$

chiral dimension ~ # of derivatives · **# of nucleon legs**

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

NLO CORRECTIONS

sample higher order corrections



- SD always scales as $\sim q^{\nu_{\mathrm{LO}}+3}$
- 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,
  $\sim q^{\nu_{\mathrm{LO}}+1}$ $\sim q^{\nu \mathrm{LO}+2}$

- 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 $\bar{q}q$
  - expected size in chiral EFT~$(q/\Lambda_{ChEFT}) \sim 30\%$
- short distance DM-2nucleon interaction at $O(q^3)$ (size: ~few%)

DOUBLE WEAK INSERTIONS

Brod, Stamou, JZ, 1801.04240

- QED and double weak insertions important only for dim 6 operators

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

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

- cross sections

$$\sigma \propto \left(\frac{\mathcal{C}_a^{(d)}}{\Lambda^{d-4}}\mathcal{A}[\mathcal{Q}_a^{(d)}]\right)^2$$

$$\mathcal{A}[\mathcal{Q}_{1,u(d)}^{(6)}] \sim A\,,\qquad \mathcal{A}[\mathcal{Q}_{1,s}^{(6)}] = 0\,,\qquad \mathcal{A}[\mathcal{Q}_{1,c(b)}^{(6)}] = 0\,,$$

$$\mathcal{A}[\mathcal{Q}_{2,u(d)}^{(6)}] \sim \max\left\{v_T A, \frac{q}{m_N}\right\}\,,\qquad \mathcal{A}[\mathcal{Q}_{2,s}^{(6)}] = 0\,,\qquad \mathcal{A}[\mathcal{Q}_{2,c(b)}^{(6)}] = 0\,,$$

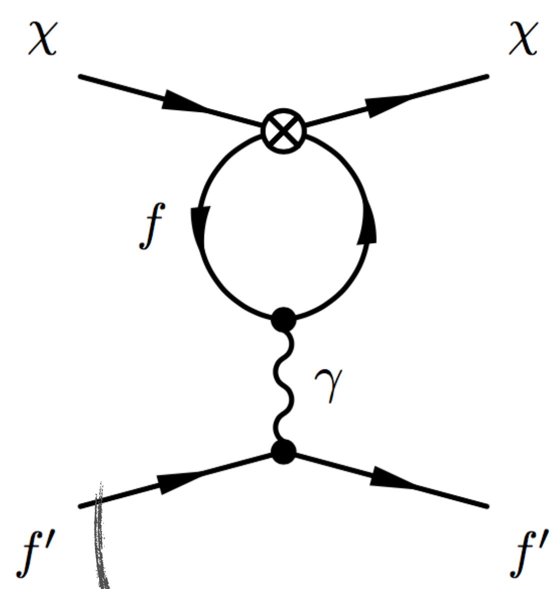
$$\mathcal{A}[\mathcal{Q}_{3,u(d)}^{(6)}] \sim \max\left\{v_T, \frac{q}{m_\chi}\right\}\,,\qquad \mathcal{A}[\mathcal{Q}_{3,s}^{(6)}] \sim \Delta s\mathcal{A}[\mathcal{Q}_{3,q}^{(6)}]\,,\qquad \mathcal{A}[\mathcal{Q}_{3,c(b)}^{(6)}] \sim \Delta c(b)\mathcal{A}[\mathcal{Q}_{3,q}^{(6)}]\,,$$

$$\mathcal{A}[\mathcal{Q}_{4,u(d)}^{(6)}] \sim 1\,,\qquad \mathcal{A}[\mathcal{Q}_{4,s}^{(6)}] \sim \Delta s\mathcal{A}[\mathcal{Q}_{4,q}^{(6)}]\,,\qquad \mathcal{A}[\mathcal{Q}_{4,c(b)}^{(6)}] \sim \Delta c(b)\mathcal{A}[\mathcal{Q}_{4,q}^{(6)}]\,,$$

$$\Delta c \approx -5\cdot 10^{-4},\ \Delta b \approx -5\cdot 10^{-5}$$

DOU… INSERTIONS

including QED corrections



Brod, Stamou, JZ, 1801.04240

- QED a… nsertions important only fo… s

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

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$$\mathcal{A}[Q_{1,s}^{(6)}] \sim \frac{\alpha}{4\pi}\mathcal{A}[Q_{1,q}^{(6)}], \qquad \mathcal{A}[Q_{1,c(b)}^{(6)}] \sim \frac{\alpha}{4\pi}\mathcal{A}[Q_{1,q}^{(6)}],$$

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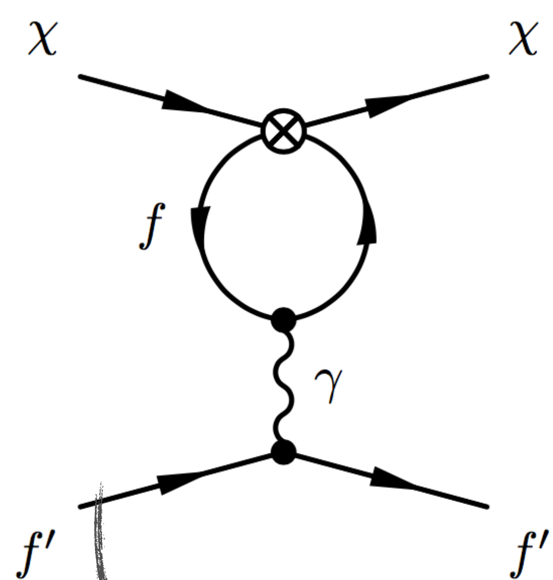
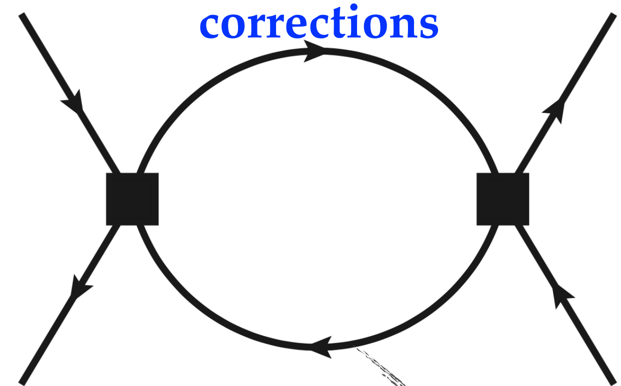


including electroweak corrections



…04240

- QED a… …inser… only fo… …s

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

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

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$$\mathcal{A}[Q_{3,c(b)}^{(6)}] \sim \frac{g_2^2}{16\pi^2}\frac{m_{c(b)}^2}{m_Z^2}A$$

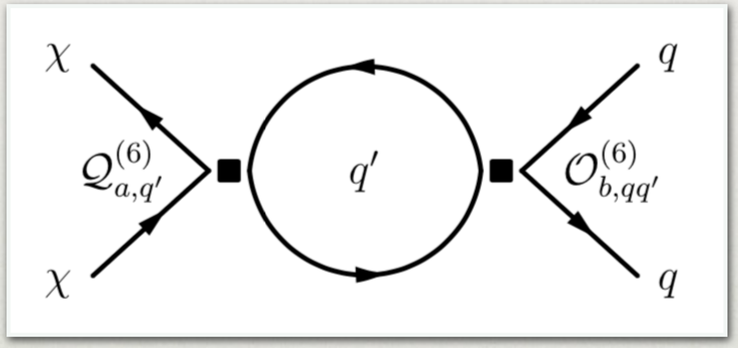
$$\mathcal{A}[Q_{4,c(b)}^{(6)}] \sim \frac{g_2^2}{16\pi^2}\frac{m_{c(b)}^2}{m_Z^2}\max\left\{v_T A, \frac{q}{m_N}\right\}$$

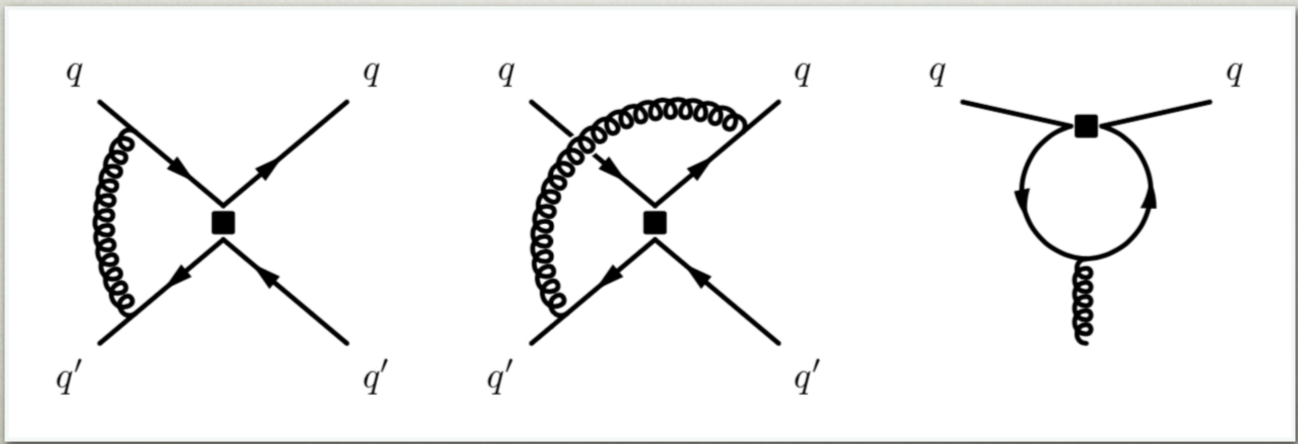
$$\Delta c \approx -5\cdot 10^{-4},\ \Delta b \approx -5\cdot 10^{-5}$$

QCD resummation

Brod, Stamou, JZ, 1801.04240

- QCD resummation for double insertions
- required since $(\alpha_s/\pi)\log(m_W/\Lambda_{had})$~$O(1)$





QCD resummation

Brod, Stamou, JZ, 1801.04240

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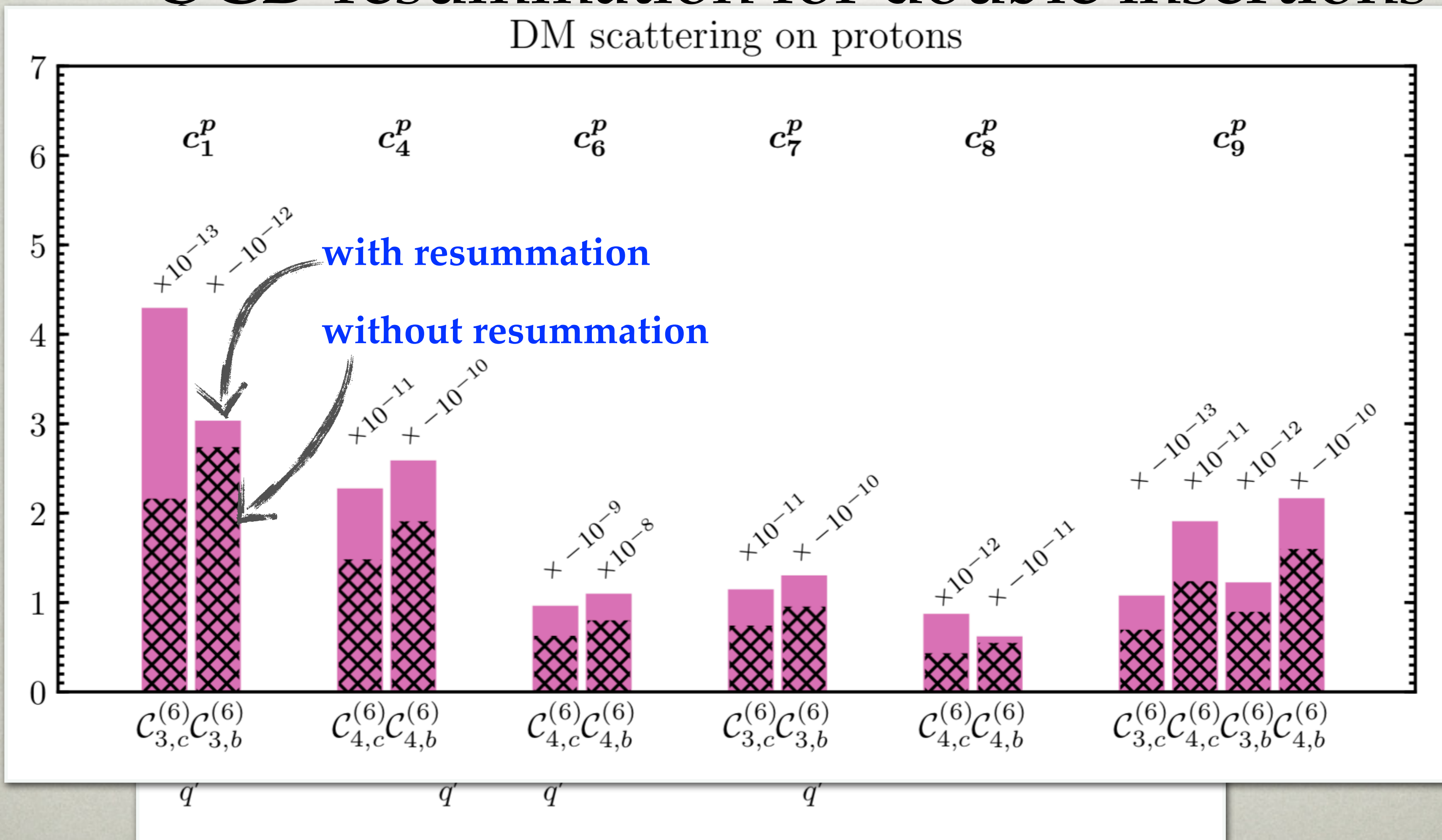

NLO - SINGLE CURRENTS

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

- for many operators two-nucleon currents highly suppressed
- are 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

$$\mathcal{Q}_{9,q}^{(7)} = m_q(\bar{\chi}\sigma^{\mu\nu}\chi)(\bar{q}\sigma_{\mu\nu}q)$$

$$\sim \frac{\Delta q}{m_q}(\vec{S}_\chi \cdot \vec{S}_N) + \frac{\vec{q}^2}{m_N m_\chi}\mathbb{1}_\chi \mathbb{1}_N$$

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

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

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

$$\mathcal{Q}_5^{(6)} = \frac{\alpha_s}{12\pi}(\varphi^*\varphi)G^{a\mu\nu}G^a_{\mu\nu}\,, \qquad \mathcal{Q}_6^{(6)} = \frac{\alpha_s}{8\pi}(\varphi^*\varphi)G^{a\mu\nu}\widetilde{G}^a_{\mu\nu}\,.$$

$$\mathcal{Q}_7^{(6)} = i\frac{e}{8\pi^2}(\partial_\mu\varphi^*\partial_\nu\varphi)F^{\mu\nu}\,,$$

relativistic theory with quarks and gluons

non-relativistic theory with nucleons

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

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

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