

Dark Matter Overview (EFTs for Unified Searches)

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Motivation

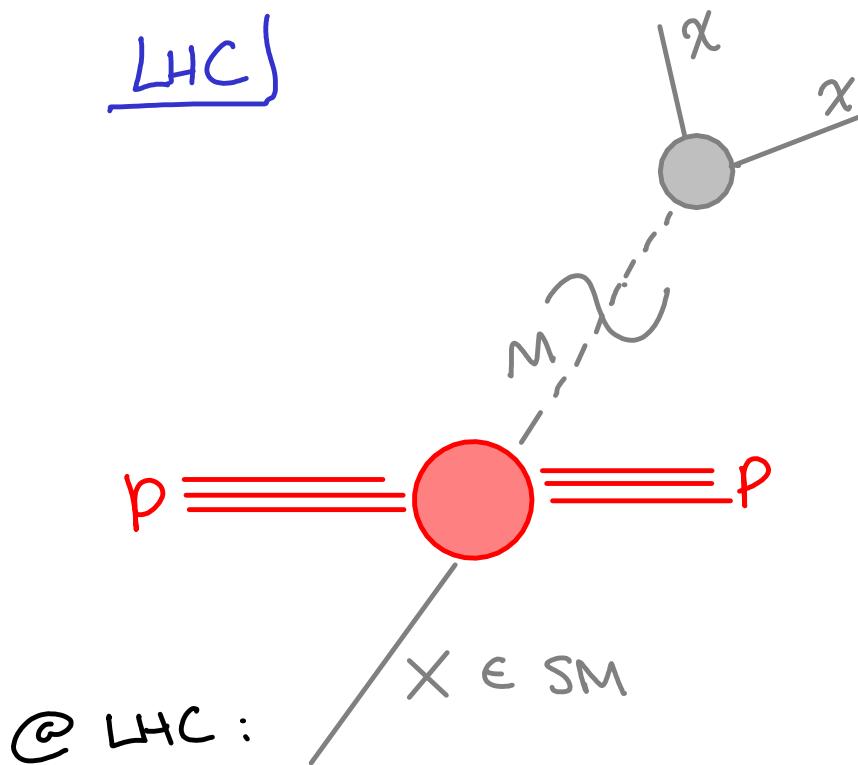
- There is overwhelming observational evidence for the existence of DM due to its gravitational interactions
- But, we know that there is (particle) physics beyond the SM – can this also include particle DM?
- If DM is also a particle, a variety of searches currently exist to look for it – complementarity between these searches would be key to success

① How can one compare results from different DM search strategies?

② For direct detection of DM, are all relevant effects accounted for in a consistent way?

💡 Both questions can be answered in the context of DM effective field theory (DMEFT)!

LHC vs. Direct Detection



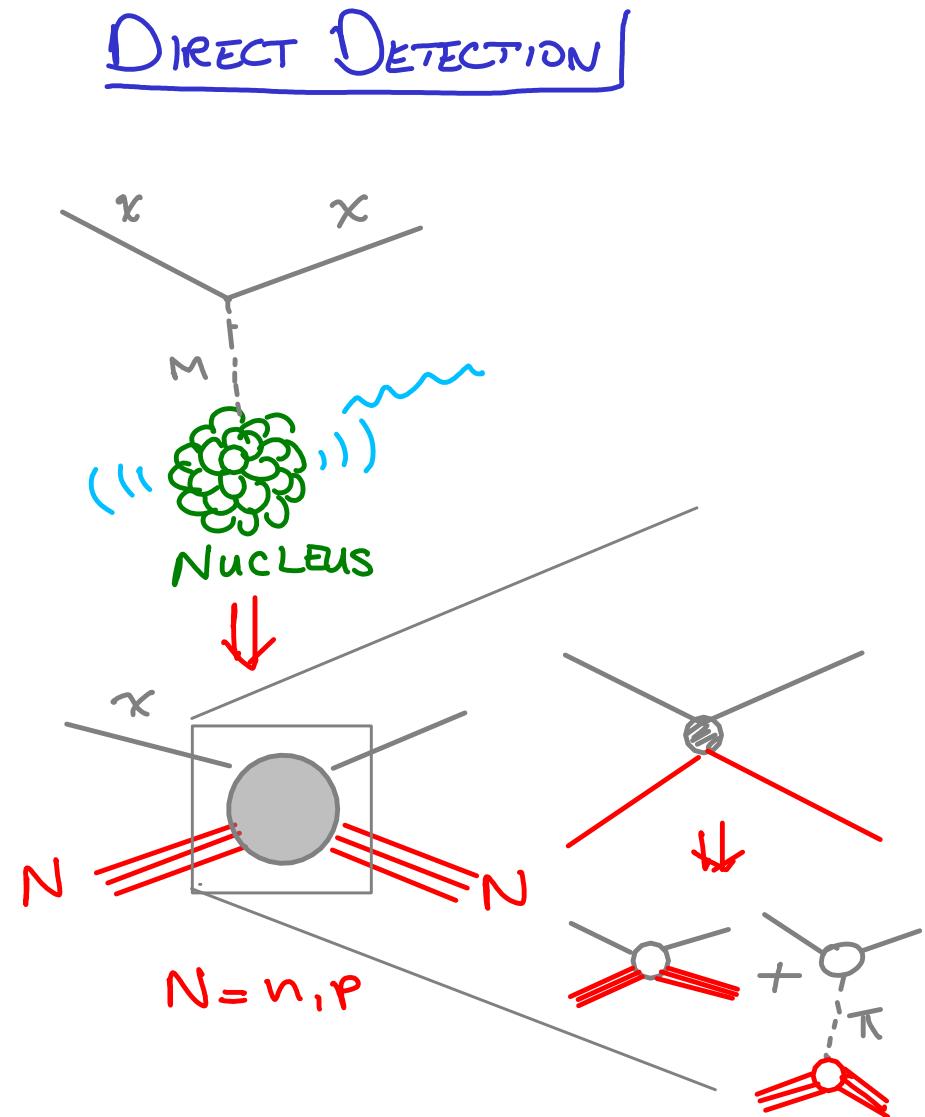
@ LHC :

1) PRODUCE MEDIATOR
DIRECTLY

2) ~~EX~~ SIGNATURES

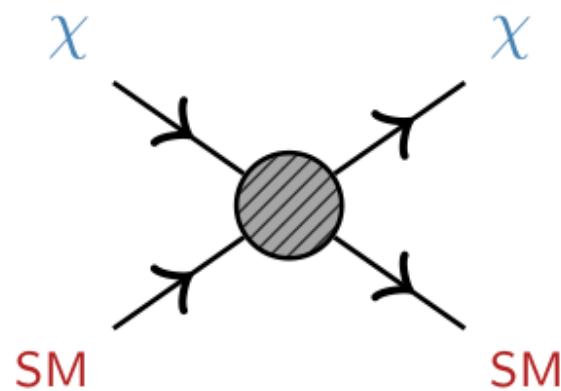
↳ MONO- χ

↳ ETC.

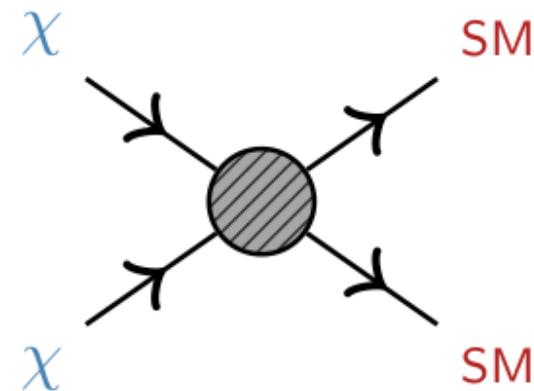


Many scales in the search for DM

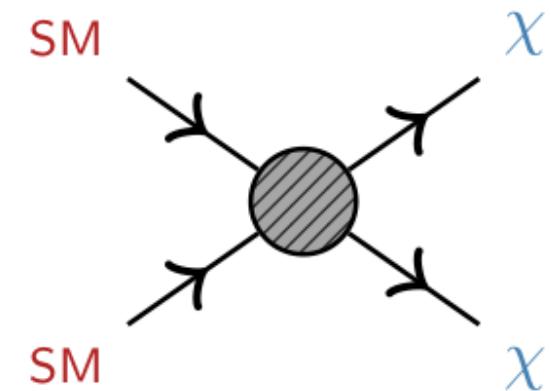
Direct Detection



Indirect Detection



Collider Searches



$$q^{(\max)}$$

~ 200 [MeV]

$$m_\chi \sim v_{\text{EW}}$$

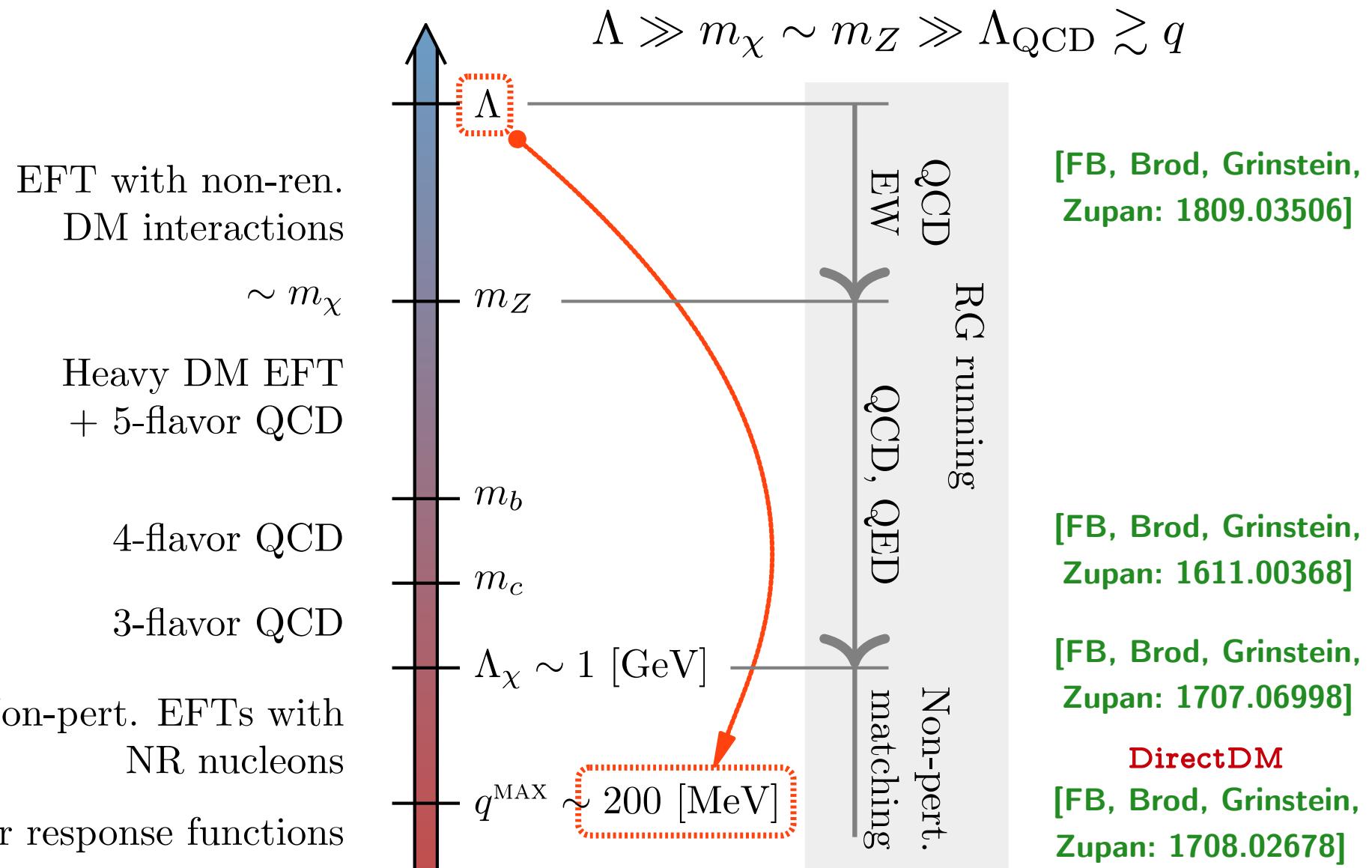
~ 100 [GeV]

$$\sqrt{\hat{s}}$$

\sim [TeV]

Assuming heavy mediators between DM and SM \Rightarrow another scale $\Lambda \sim$ mass of the mediator(s) $> m_Z$

A tower of EFTs



See also e.g.: Fan, Reece, Wang [1008.1591]; Hill & Solon [1309.4092, 1401.3339, 1409.8290]; Crivellin, D'Eramo, Procura [1402.1173]; D'Eramo, Procura [arXiv:1411.3342]; Hoferichter, Klos, Schwenk [1503.04811]; Berlin, Robertson, Solon, Zurek [1511.05964]; Hoferichter, Klos, Menendez, Schwenk [1605.08043]; D'Eramo, Kavanagh, Panci [1605.04917]; + ...

Nucleon matrix elements

- Typically use form factors for expectation value of quark currents between nucleon states

Hill, Solon [1409.8290]; Hoferichter, Klos, Schwenk [1503.04811]

$$\langle N' | \bar{q} \gamma^\mu q | N \rangle = \bar{u}'_N \left[F_1^{q/N}(q^2) \gamma^\mu + \frac{i}{2m_N} F_2^{q/N}(q^2) \sigma^{\mu\nu} q_\nu \right] u_N ,$$

$$\langle N' | \bar{q} \gamma^\mu \gamma_5 q | N \rangle = \bar{u}'_N \left[F_A^{q/N}(q^2) \gamma^\mu \gamma_5 + \frac{1}{2m_N} F_{P'}^{q/N}(q^2) \gamma_5 q^\mu \right] u_N ,$$

- **But**, full momentum dependence is not known for all form factors
- **And**, how important are two-nucleon interactions?
- Compute form factors systematically using **chiral expansion**

Chiral expansion

- Use Heavy Baryon Chiral Perturbation Theory (HBChPT)
 $\because m_{p,n} \gg (q \lesssim 200 \text{ MeV})$
[Jenkins & Manohar, Phys.Lett. B255 (1991) 558]; see also Hoferichter, Klos, Schwenk [1503.04811]

- Expansion parameter $\lesssim \frac{q^{\text{MAX}}}{\Lambda_\chi} \sim \frac{q^{\text{MAX}}}{4\pi f_\pi} \sim \mathcal{O}(20\%)$
- Treat DM currents as $SU(3)_L \times SU(3)_R$ spurions
- Can write hadronization of quark currents explicitly as

$$\bar{u}i\gamma_5 u \rightarrow B_0 f m_u \left(\pi^0 + \frac{1}{\sqrt{3}}\eta \right) + \dots$$
$$\bar{u}\gamma^\mu u \rightarrow v^\mu (2\bar{p}_v p_v + \bar{n}_v n_v) + \dots$$

- Hadronic physics is encoded in a few Low Energy Constants: f_π , g_A , $\sigma_{\pi N}$, ...

NREFT

- NR basis built out of Galilean-invariant operators up to quadratic order in momentum transfer
Fitzpatrick, Haxton, Katz, Lubbers, Xu [1203.3542]
- Leads to six nuclear responses calculated in shell model

V \otimes A

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

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

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

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

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

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

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

A \otimes

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

$$\mathcal{O}_4^N = \vec{S}_\chi \cdot \vec{S}_N ,$$

$$\mathcal{O}_6^N = \left(\vec{S}_\chi \cdot \frac{\vec{q}}{m_N} \right) \left(\vec{S}_N \cdot \frac{\vec{q}}{m_N} \right) ,$$

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

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

$$\mathcal{O}_{12}^N = \vec{S}_\chi \cdot \left(\vec{S}_N \times \vec{v}_\perp \right) ,$$

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

Nuclear response

- In general, there are 6 nuclear responses [1308.6288]
- Only 4 are generated in our setup

Response	Property	Long wavelength behavior
W_M	spin-independent	counts nucleons (coherent scattering)
$W_{\Sigma', \Sigma''}$	spin-dependent	nucleon spin content of nucleus
W_Δ	nuclear ang. mom.	nucleon ang. mom. content of nucleus

- Rough scaling

$$W_M \sim \mathcal{O}(A^2),$$

$$W_{\Sigma'}, W_{\Sigma''}, W_\Delta, W_{\Delta\Sigma'} \sim \mathcal{O}(1)$$

Nuclear response

- The direct detection cross-section is proportional to

$$\sigma_{\text{DD}} \propto \frac{4\pi}{2J_A + 1} \sum_{\tau=0,1} \sum_{\tau'=0,1} \left\{ \left[R_M^{\tau\tau'} W_M^{\tau\tau'}(y) + R_{\Sigma''}^{\tau\tau'} W_{\Sigma''}^{\tau\tau'}(y) + R_{\Sigma'}^{\tau\tau'} W_{\Sigma'}^{\tau\tau'}(y) \right] \right.$$

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

- Where, R_i contain the Wilson coefficients and W_i are the nuclear response functions.

- For example,

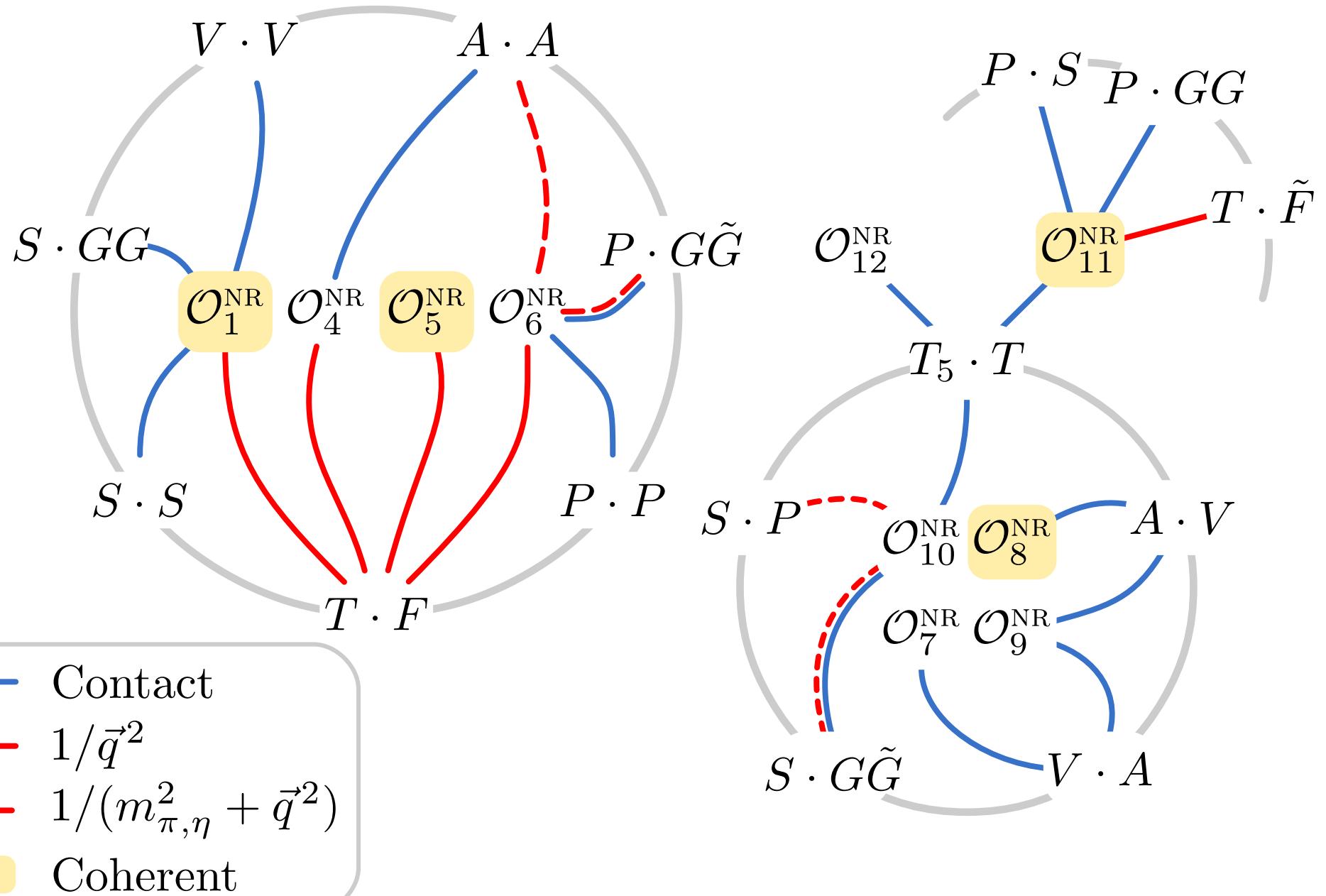
$$R_{\Sigma''}^{\tau\tau'} = (4m_\chi m_N)^2 \frac{1}{16} \left[c_{\text{NR},4}^\tau c_{\text{NR},4}^{\tau'} + \frac{\vec{q}^2}{m_N^2} (c_{\text{NR},4}^\tau c_{\text{NR},6}^{\tau'} + c_{\text{NR},6}^\tau c_{\text{NR},4}^{\tau'}) + \frac{\vec{q}^4}{m_N^4} c_{\text{NR},6}^\tau c_{\text{NR},6}^{\tau'} \right]$$

 $c_{\text{NR},4}^p \supset -4 (\Delta u_p \hat{\mathcal{C}}_{4,u}^{(6)} + \Delta d_p \hat{\mathcal{C}}_{4,d}^{(6)} + \Delta s \hat{\mathcal{C}}_{4,s}^{(6)})$

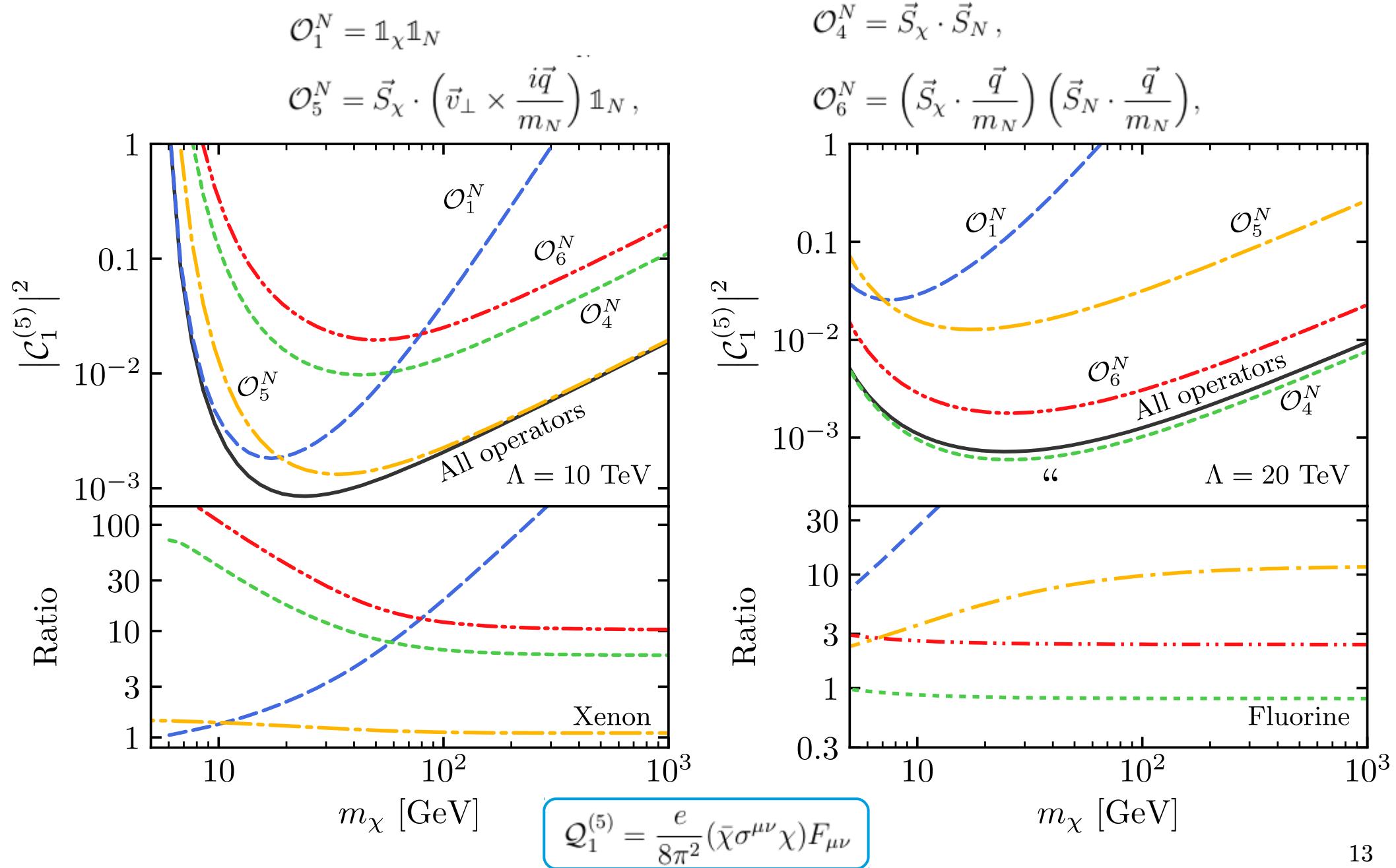
 **Interference!**

 $c_{\text{NR},6}^p \supset m_N^2 \frac{2g_A}{m_\pi^2 + \vec{q}^2} (\hat{\mathcal{C}}_{4,u}^{(6)} - \hat{\mathcal{C}}_{4,d}^{(6)})$

Matching at a glance



Interference between NR operators



The DirectDM package

DirectDM: a tool for dark matter direct detection

`DirectDM` is a program that matches Wilson coefficients of a relativistic EFT onto a Galilean-invariant non-relativistic EFT valid at the nuclear scale. The program is available as a `Mathematica` and a `python` package.

The `Mathematica` package is available from: github.com/DirectDM/directdm-mma

The `python3` package is available from: github.com/DirectDM/directdm-py



<https://directdm.github.io/>

- Compute the matching and running automatically
- Seamlessly interfaces to `DMFormFactor` package by Anand, Fitzpatrick, & Haxton [1308.6288] to calculate the scattering rates using their nuclear response fns
- Can also use `DDCalc` [1705.07920] to recast limits and compute DD cross-section <https://github.com/patscott/ddcalc>

Summary

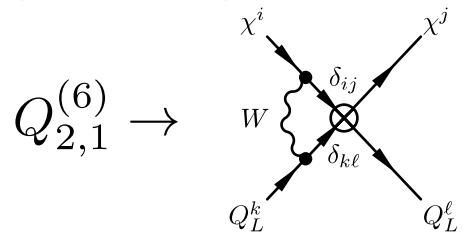
- ▶ There is overwhelming observational evidence for the existence of DM
- ▶ It is reasonable to posit that it is a particle in nature ⇒ discover the model and disentangle the structure of the dark sector
- ▶ To this end, need different probes at different scales which is a classic setup for EFTs
- ▶ A public code, `DirectDM`, that implements the tower of EFTs for this purpose
 - Next week -

Thank you!

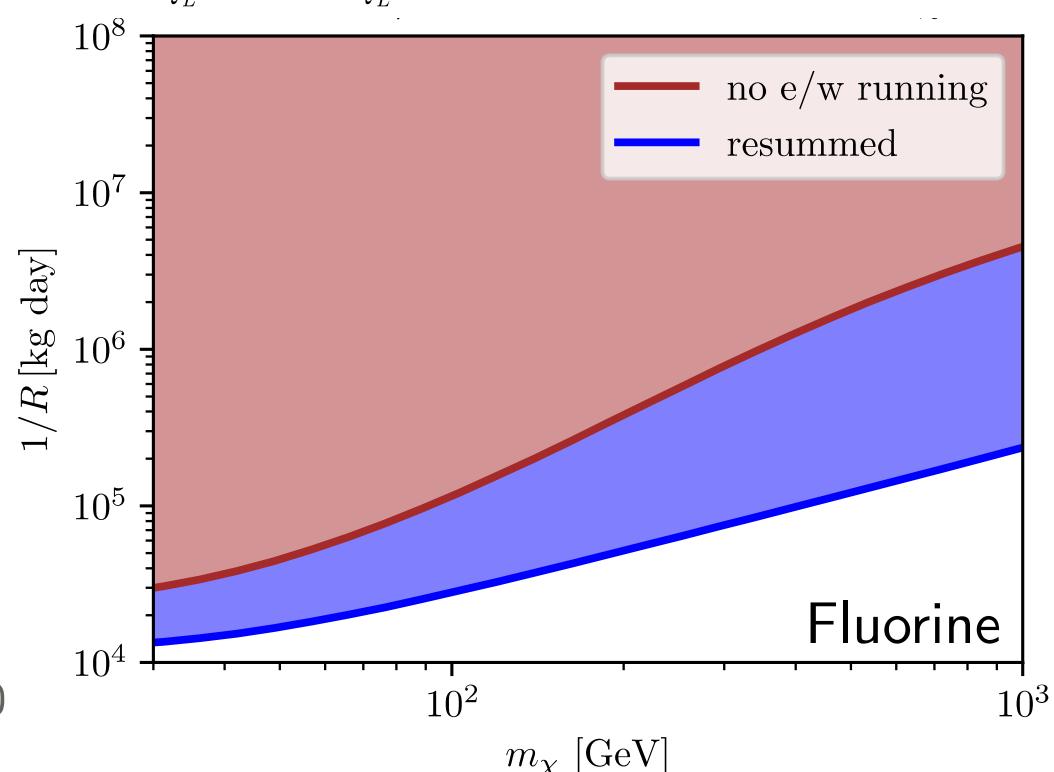
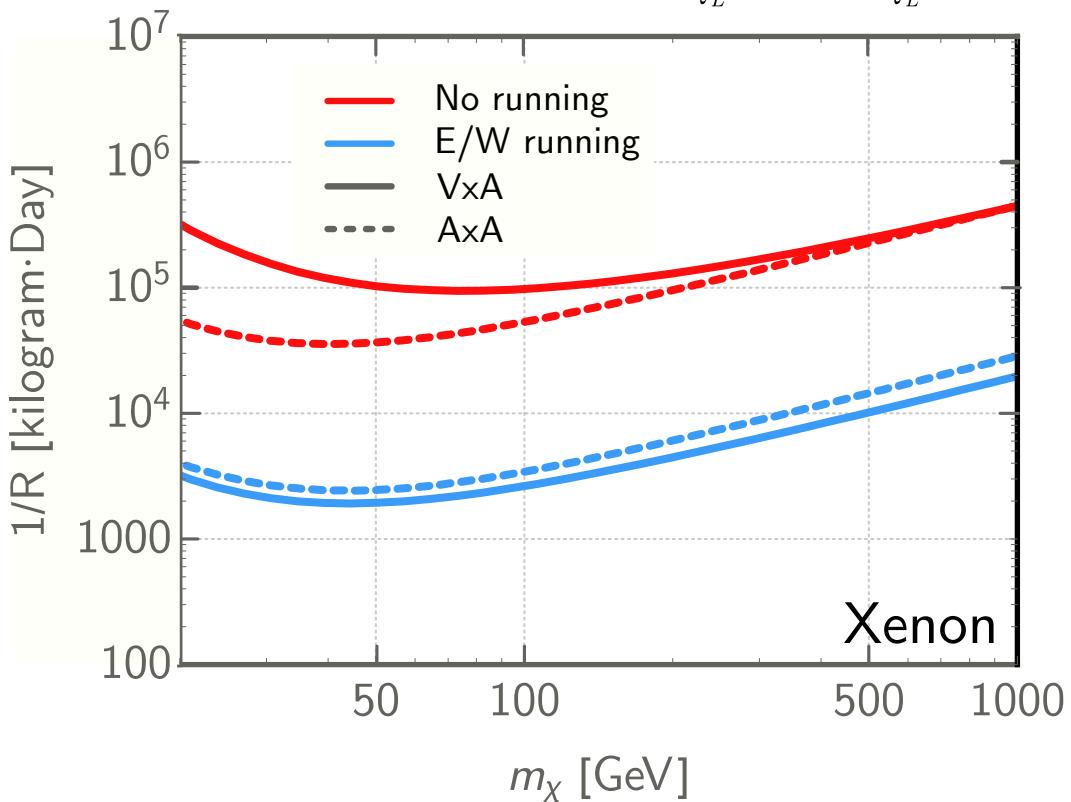
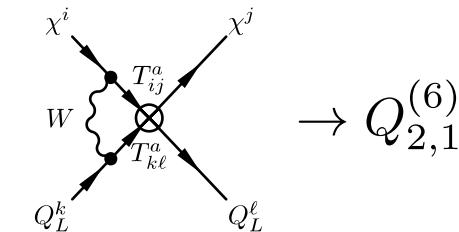
Axial quark coupling 1st gen.

$I_\chi = 1; Y_\chi = 0$

$$- C_{2,1}^{(6)}(\Lambda) = C_{3,1}^{(6)}(\Lambda) = C_{4,1}^{(6)}(\Lambda)$$



$$- Q_{2,1}^{(6)} + Q_{3,1}^{(6)} + Q_{4,1}^{(6)} = (\bar{\chi} \gamma_\mu \chi) (\bar{u} \gamma^\mu \gamma_5 u + \bar{d} \gamma^\mu \gamma_5 d)$$



$$Q_{2,i}^{(6)} = (\bar{\chi} \gamma_\mu \chi) \left(\bar{Q}_L^i \gamma^\mu Q_L^i \right),$$

$$Q_{3,i}^{(6)} = (\bar{\chi} \gamma_\mu \chi) \left(\bar{u}_R^i \gamma^\mu u_R^i \right),$$

$$Q_{4,i}^{(6)} = (\bar{\chi} \gamma_\mu \chi) \left(\bar{d}_R^i \gamma^\mu d_R^i \right)$$

$$Q_{5,i}^{(6)} = (\bar{\chi} \gamma_\mu \gamma_5 \tilde{\tau}^a \chi) \left(\bar{Q}_L^i \gamma^\mu \tau^a Q_L^i \right)$$

$\Lambda = 1 \text{ TeV}$

Axial quark coupling 1st gen.

$$I_\chi = 1; Y_\chi = 0$$

Schematically, the RGE solution looks like

$$\vec{C}(M_W) \sim \exp \left[- \int_{g(M_W)}^{g(\Lambda)} \frac{\gamma(g')^T}{\beta(g')} dg' \right] \cdot \vec{C}(\Lambda)$$

$$[\gamma_1^{(0)}]_{Q_{1,i \dots 8,i}^{(6)} \times Q_{1,i \dots 8,i}^{(6)}} = \begin{pmatrix} 0 & 0 & 0 & 0 & -Y_\chi & 0 & 0 & 0 \\ 0 & \frac{2}{3}d_\chi Y_\chi^2 + \frac{2}{9} & \frac{8}{9} & -\frac{4}{9} & 0 & -Y_\chi & 0 & 0 \\ 0 & \frac{4}{9} & \frac{2}{3}d_\chi Y_\chi^2 + \frac{16}{9} & -\frac{8}{9} & 0 & 0 & 4Y_\chi & 0 \\ 0 & -\frac{2}{9} & -\frac{8}{9} & \frac{2}{3}d_\chi Y_\chi^2 + \frac{4}{9} & 0 & 0 & 0 & -2Y_\chi \\ -Y_\chi & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -Y_\chi & 0 & 0 & 0 & \frac{2}{9} & \frac{8}{9} & -\frac{4}{9} \\ 0 & 0 & 4Y_\chi & 0 & 0 & \frac{4}{9} & \frac{16}{9} & -\frac{8}{9} \\ 0 & 0 & 0 & -2Y_\chi & 0 & -\frac{2}{9} & -\frac{8}{9} & \frac{4}{9} \end{pmatrix}$$

$$[\gamma_2^{(0)}]_{Q_{1,i \dots 8,i}^{(6)} \times Q_{1,i \dots 8,i}^{(6)}} = \begin{pmatrix} \frac{8}{9}\mathcal{J}_\chi d_\chi - 4 & 0 & 0 & 0 & 0 & -3\mathcal{J}_\chi & 0 & 0 \\ 0 & 0 & 0 & 0 & -12 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -3\mathcal{J}_\chi & 0 & 0 & -4 & 0 & 0 & 0 \\ -12 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

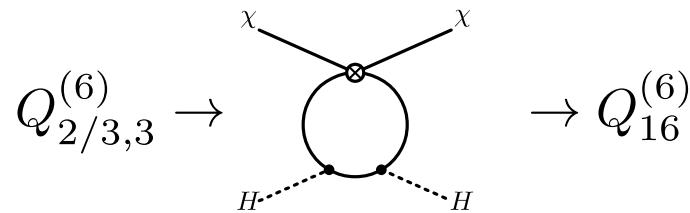
$$\mathcal{J}_\chi = I_\chi(I_\chi + 1)$$

Axial quark coupling 3rd gen.

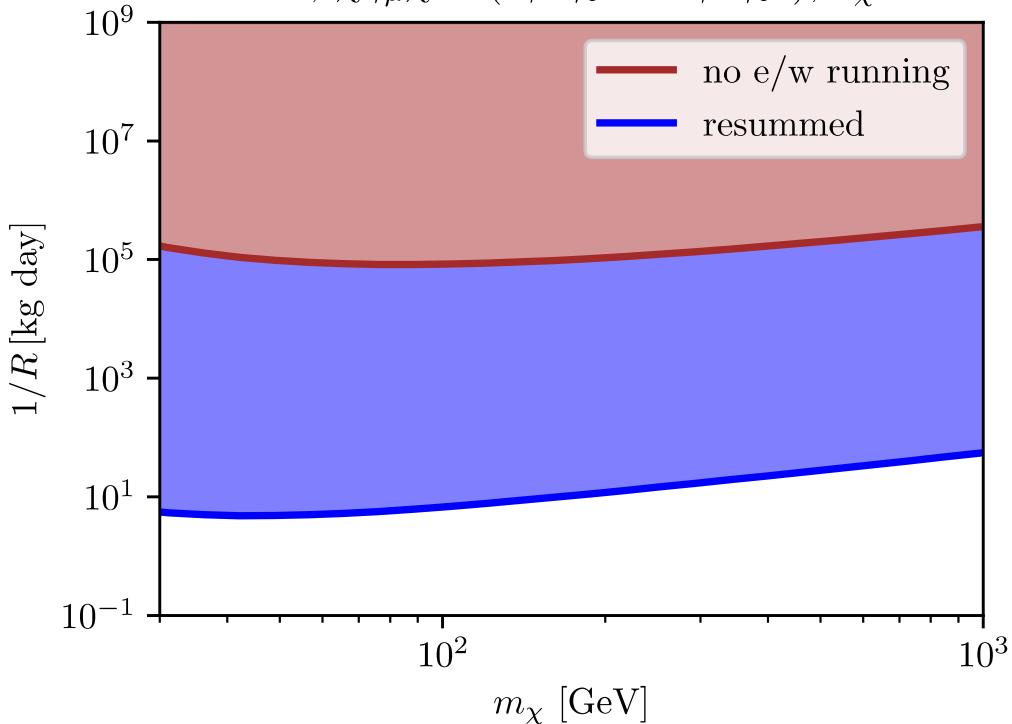
$I_\chi = 1; Y_\chi = 0$

$$-C_{2,3}^{(6)}(\Lambda) = C_{3,3}^{(6)}(\Lambda) = C_{4,3}^{(6)}(\Lambda)$$

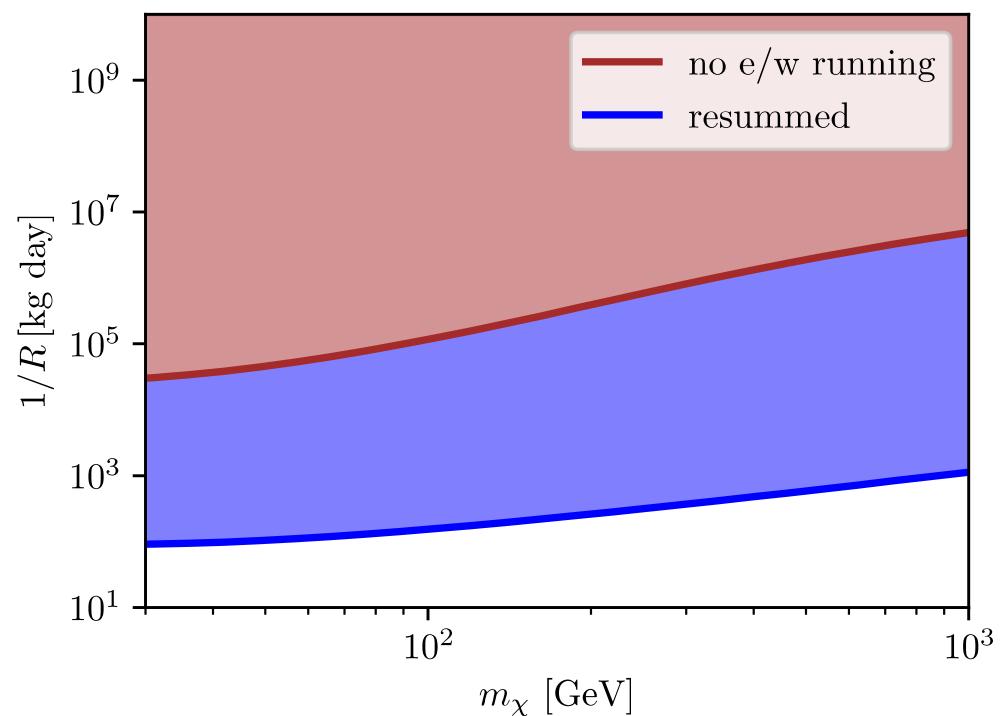
$$-Q_{2,3}^{(6)} + Q_{3,3}^{(6)} + Q_{4,3}^{(6)} = (\bar{\chi}\gamma_\mu\chi)(\bar{t}\gamma^\mu\gamma_5 t + \bar{b}\gamma^\mu\gamma_5 b)$$



Xenon, $\bar{\chi}\gamma_\mu\chi \otimes (\bar{t}\gamma^\mu\gamma_5 t + \bar{b}\gamma^\mu\gamma_5 b)$, $I_\chi = 1$



Fluorine, $\bar{\chi}\gamma_\mu\chi \otimes (\bar{t}\gamma^\mu\gamma_5 t + \bar{b}\gamma^\mu\gamma_5 b)$, $I_\chi = 1$



$$Q_{2,i}^{(6)} = (\bar{\chi}\gamma_\mu\chi) \left(\overline{Q}_L^i \gamma^\mu Q_L^i \right),$$

$$Q_{3,i}^{(6)} = (\bar{\chi}\gamma_\mu\chi) \left(\overline{u}_R^i \gamma^\mu u_R^i \right),$$

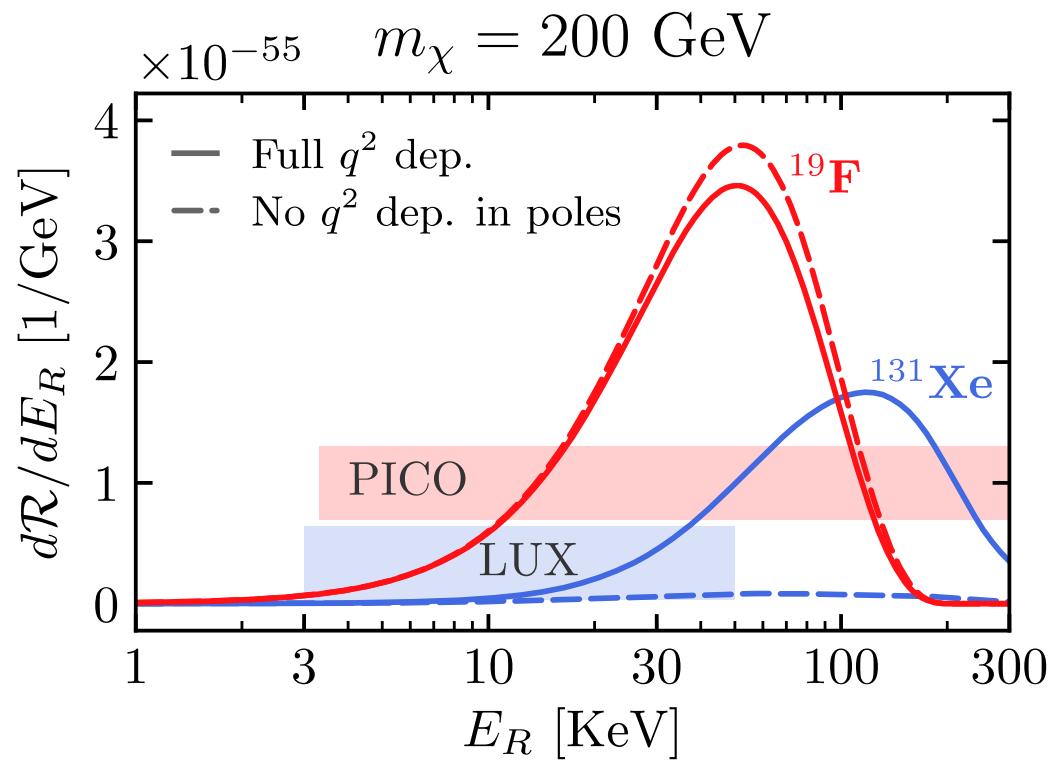
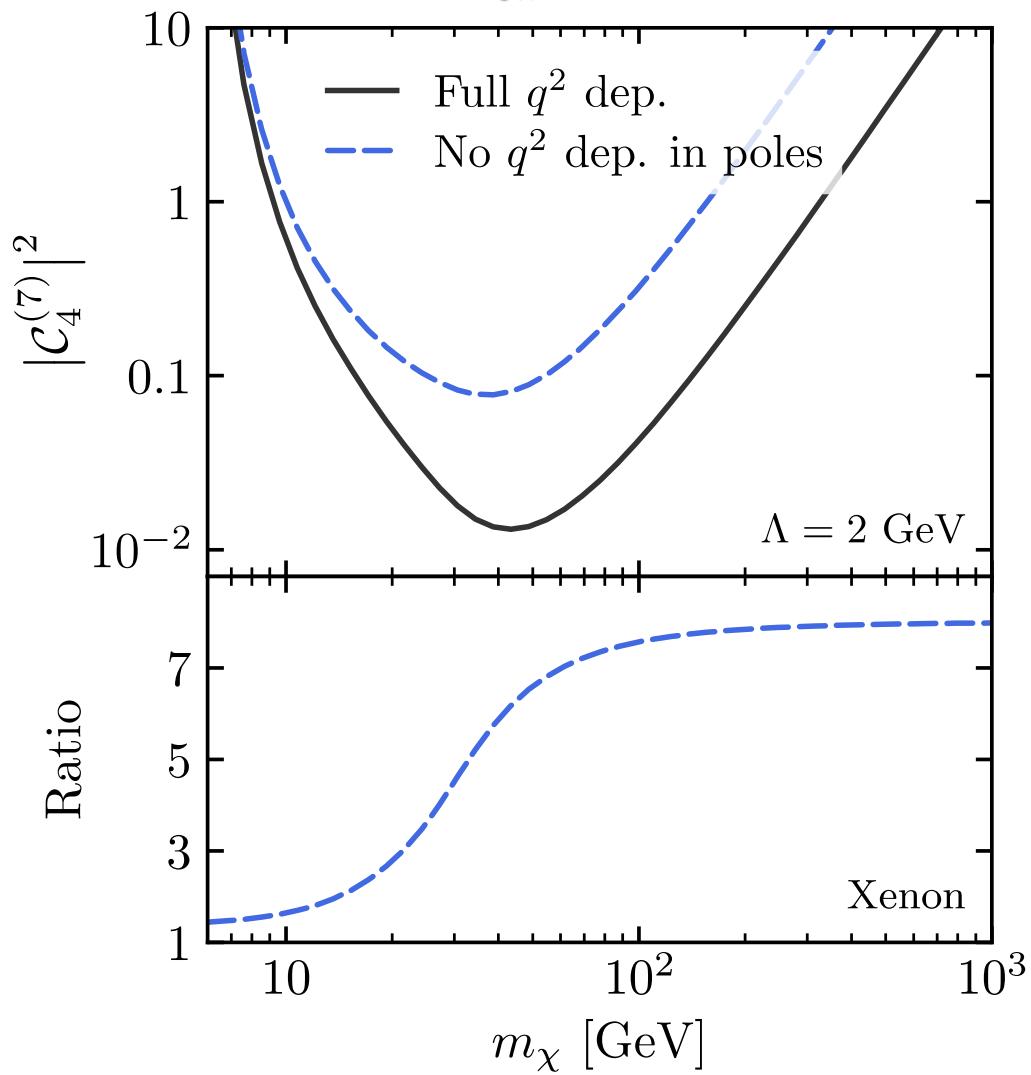
$$Q_{4,i}^{(6)} = (\bar{\chi}\gamma_\mu\chi) \left(\overline{d}_R^i \gamma^\mu d_R^i \right)$$

$$Q_{16}^{(6)} = (\bar{\chi}\gamma^\mu\chi) \left(H^\dagger i \overset{\leftrightarrow}{D}_\mu H \right)$$

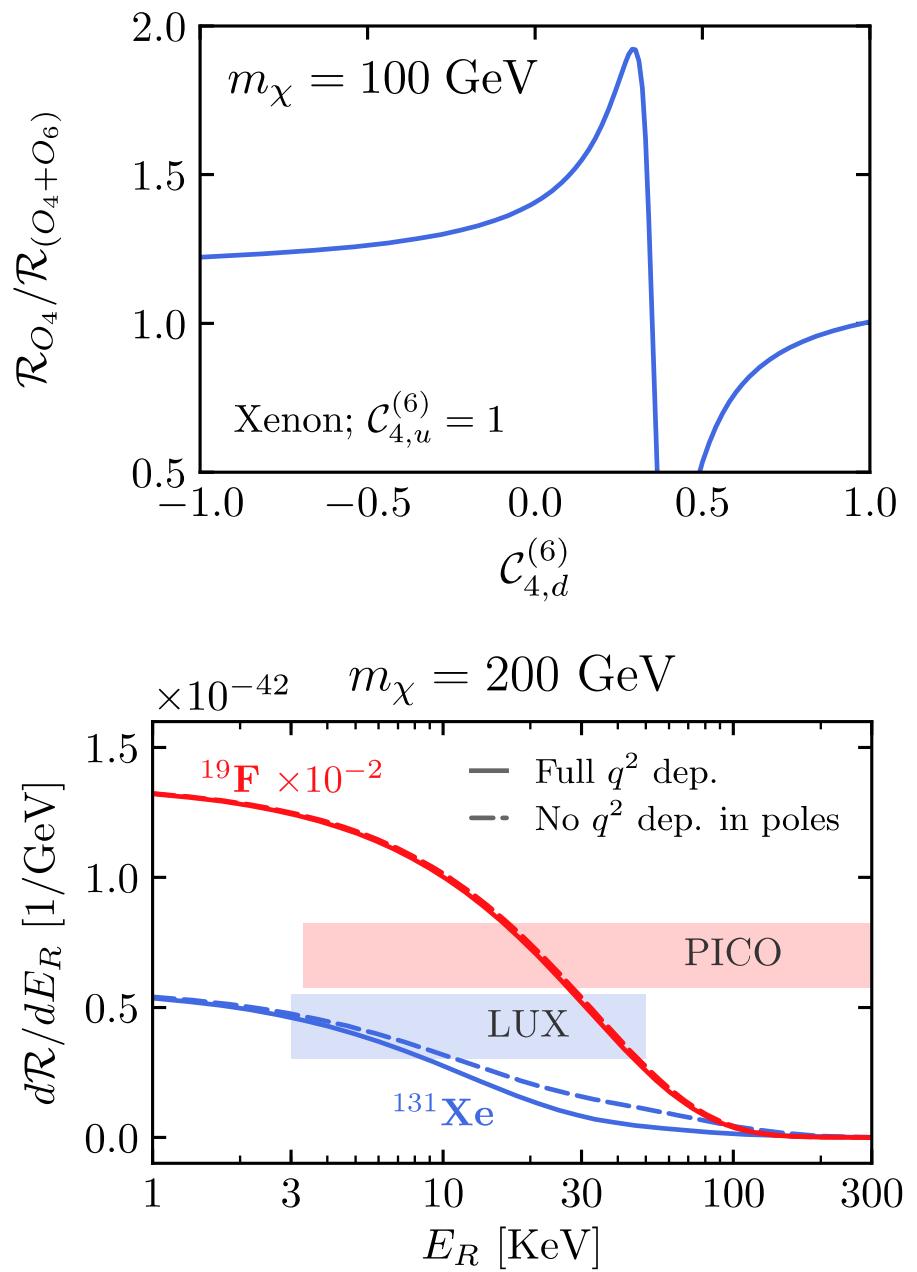
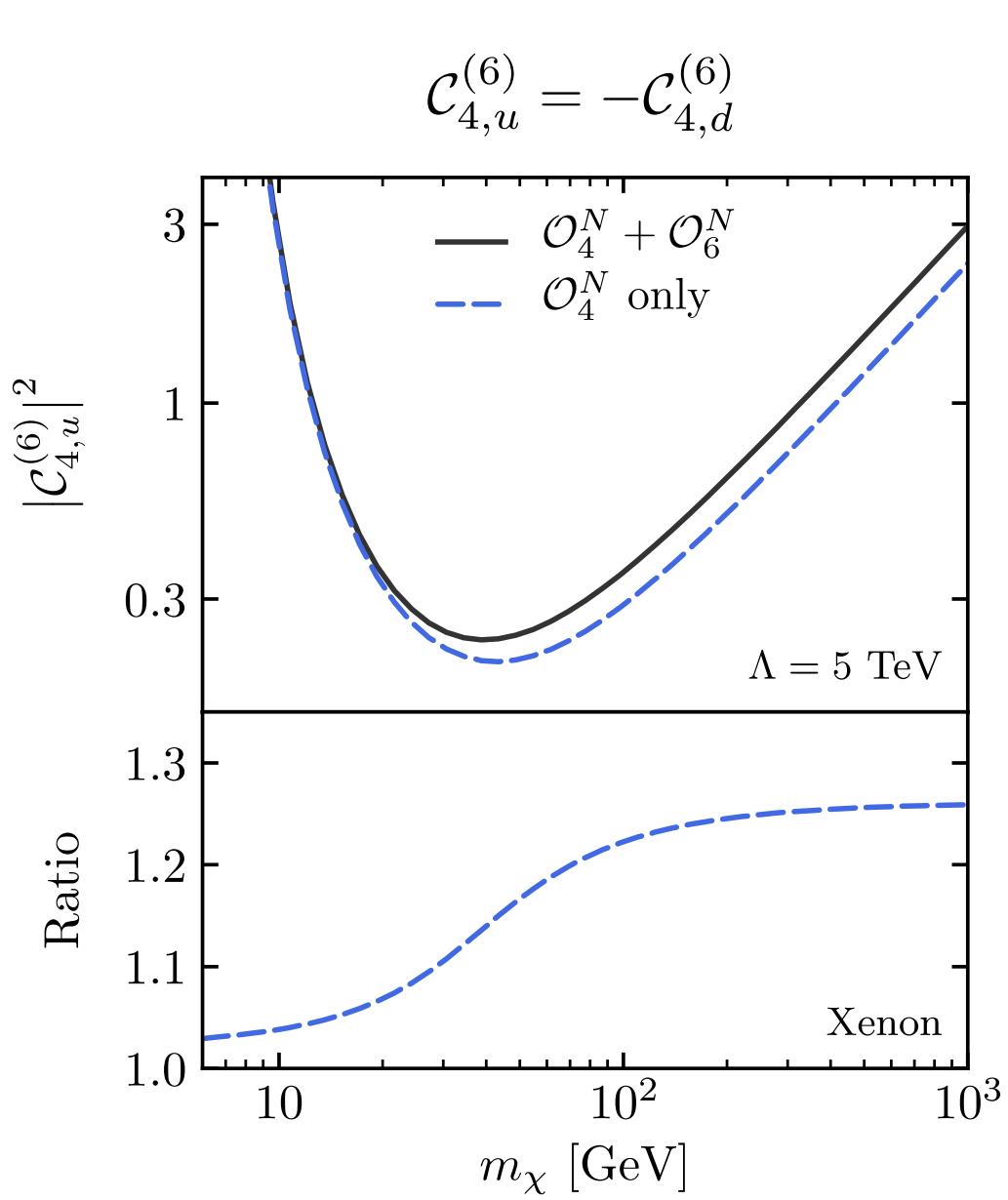
$\Lambda = 1$ TeV

Pion exchange

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



Example: $A \otimes A$



DMEFT above EW scale

DIMENSION 5:

$$\frac{g_1}{8\pi^2} (\bar{\chi} \sigma^{\mu\nu} [1 \oplus i\gamma_5] \chi) B_{\mu\nu}, \quad \frac{g_2}{8\pi^2} (\bar{\chi} \sigma^{\mu\nu} \tilde{\tau}^a \chi) W_{\mu\nu}^a,$$

$$(\bar{\chi}_\alpha [1 \oplus i\gamma_5] \chi_\beta) (H_\rho^\dagger H_\sigma) (\delta_{\alpha\beta} \delta_{\rho\sigma} \oplus \tilde{\tau}_{\alpha\beta}^a \tau_{\rho\sigma}^a)$$

DIMENSION 6: $\Gamma_\mu \in \{\gamma_\mu, \gamma_\mu \gamma_5\}$, $F^i \in \{Q_L^i, L_L^i\}$, $f^i \in \{u_R^i, d_R^i, \ell_R^i\}$

$$(\bar{\chi}_\alpha \Gamma_\mu \chi_\beta) (\bar{F}^i \gamma^\mu F^i) (\delta_{\alpha\beta} \delta_{\rho\sigma} \oplus \tilde{\tau}_{\alpha\beta}^a \tau_{\rho\sigma}^a),$$

$$(\bar{\chi}_\alpha \Gamma_\mu \chi_\beta) (\bar{f}^i \gamma^\mu f^i) \delta_{\alpha\beta},$$

$$(\bar{\chi}_\alpha \Gamma_\mu \chi_\beta) (H_\rho^\dagger i \overset{\leftrightarrow}{D}^\mu H_\sigma) (\delta_{\alpha\beta} \delta_{\rho\sigma} \oplus \tilde{\tau}_{\alpha\beta}^a \tau_{\rho\sigma}^a),$$

$$^{**} (\bar{\chi}_\alpha \Gamma_\mu \chi_\beta) (\bar{\chi}_\rho \gamma^\mu \chi_\sigma) (\delta_{\alpha\beta} \delta_{\rho\sigma} \oplus \tilde{\tau}_{\alpha\beta}^a \tilde{\tau}_{\rho\sigma}^a)$$

Full basis has $8 + 8 \times 3 + 6 \times 3 + 4 + 4 = 54$ operators.

****** Only 4 operators if we neglect DM-DM self-mixing. Otherwise, each Lorentz structure comes with $2I_\chi + 1$ operators.

DMEFT below EW scale

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

$$\mathcal{Q}_{10,q}^{(7)} = m_q (\bar{\chi} i\sigma^{\mu\nu} \gamma_5 \chi) (\bar{q} \sigma_{\mu\nu} q).$$

Low energy limit – DM currents

- In our setup, $m_\chi \gg \Lambda_\chi$, and so should treat DM as a heavy field
 \rightarrow HDMET à la HQET with $\chi(x) = e^{-im_\chi v \cdot x} (\chi_v(x) + X_v(x))$
 Hill, Solon [1111.0016; 1409.8290]
- Tree-level matching then gives

$$\bar{\chi}\chi \rightarrow \bar{\chi}_v\chi_v + \dots ,$$

$$\bar{\chi}i\gamma_5\chi \rightarrow \frac{1}{m_\chi}\partial_\mu(\bar{\chi}_v S_\chi^\mu \chi_v) + \dots ,$$

$$\bar{\chi}\gamma^\mu\chi \rightarrow v^\mu \bar{\chi}_v\chi_v + \frac{1}{2m_\chi}\bar{\chi}_v i_\perp^\mu \chi_v + \frac{1}{2m_\chi}\partial_\nu(\bar{\chi}_v \sigma_\perp^{\mu\nu} \chi_v) + \dots ,$$

$$\bar{\chi}\gamma^\mu\gamma_5\chi \rightarrow 2\bar{\chi}_v S_\chi^\mu \chi_v - \frac{i}{m_\chi} v^\mu \bar{\chi}_v S_\chi \cdot \chi_v + \dots ,$$

$$\bar{\chi}\sigma^{\mu\nu}\chi \rightarrow \bar{\chi}_v \sigma_\perp^{\mu\nu} \chi_v + \frac{1}{2m_\chi} \left(\bar{\chi}_v i v^{[\mu} \sigma_\perp^{\nu]\rho} \chi_v - v^{[\mu} \partial^{\nu]} \bar{\chi}_v \chi_v \right) + \dots ,$$

$$\bar{\chi}\sigma^{\mu\nu}i\gamma_5\chi \rightarrow 2\bar{\chi}_v S_\chi^{[\mu} v^{\nu]} \chi_v + \dots ,$$

Spurions and the chiral rotation

$$\mathcal{L} = \mathcal{L}_{\text{QCD}}^0 + s_G \frac{\alpha_s}{12\pi} G_{\mu\nu}^a G^{a\mu\nu} + \theta \frac{\alpha_s}{8\pi} G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \bar{q} [\gamma^\mu (\nu_\mu + \gamma_5 a_\mu) - s + i\gamma_5 p] q$$

- The spurions s_G , θ , ν_μ , a_μ , s , and p contain the DM currents
- The θ spurion can be moved by a chiral transformation exp
Georgi, Kaplan, Randall [Phys. Lett. B169 (1986) 73]

$$\beta(x) = \frac{\theta(x)}{2} \frac{\mathcal{M}_q^{-1}}{\text{Tr}(\mathcal{M}_q^{-1})}$$

- The effect is that it now contributes to the axial and pseudo-scalar spurions

$$a'_\mu = a_\mu + \frac{\partial_\mu \theta}{2} \frac{\mathcal{M}_q^{-1}}{\text{Tr}(\mathcal{M}_q^{-1})}, \quad p' = p + \theta \frac{\mathcal{M}^{-1}}{\text{Tr}(\mathcal{M}_q^{-1})}$$

Chiral power counting

- Interested in A -nucleon irreducible amplitudes with one insertion of DM current, $M_{A,\chi}$, which scale as [Weinberg, NPB363, 3 (1991); Kaplan, Savage, Wise, nucl-th/9605002; Cirigliano, Graesser, Ovanesyan, 1205.2695]

$$M_{A,\chi} \sim q^\nu$$

where

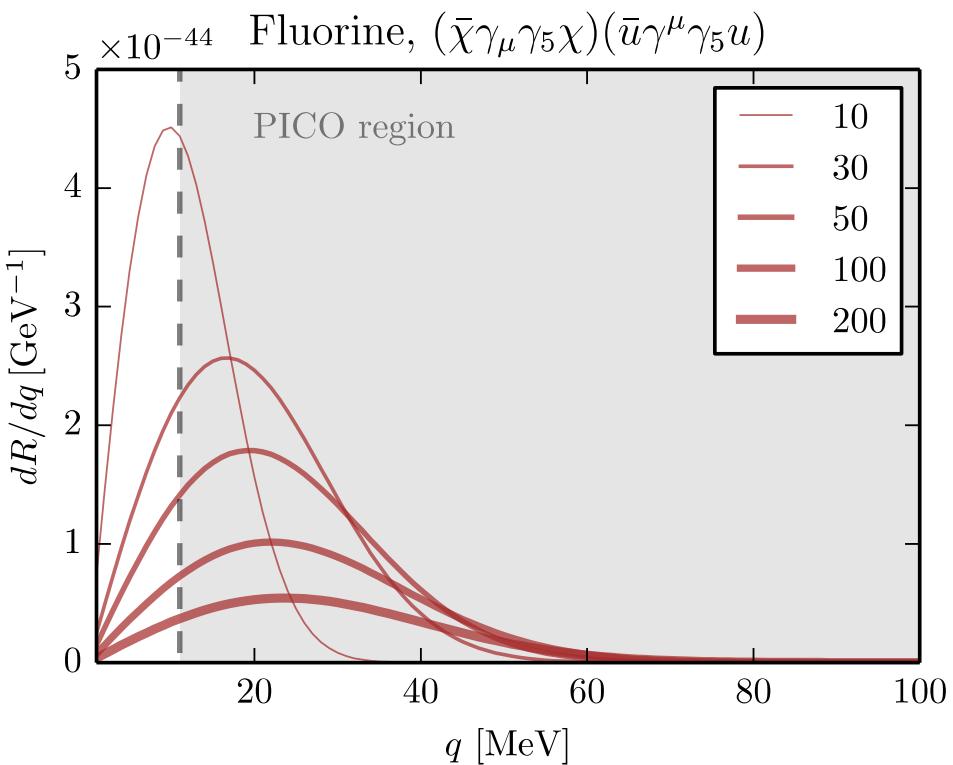
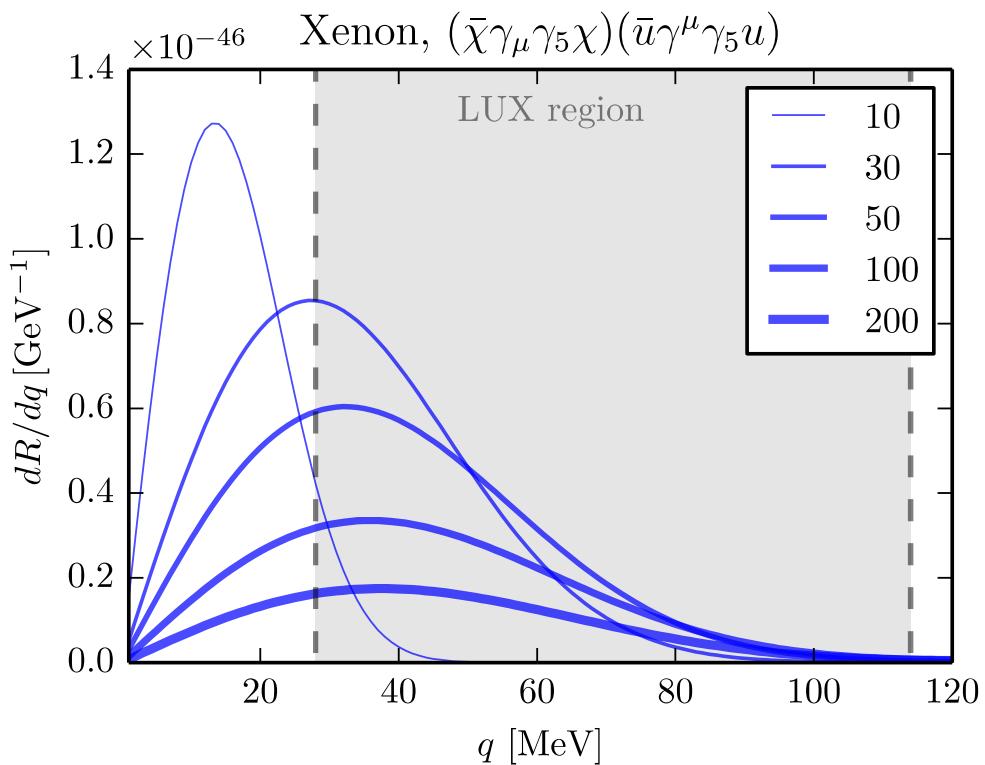
$$\nu = 4 - A - 2C + 2L + \sum_i V_i (d_i + n_i/2 - 2) + \epsilon_\chi$$

effective chiral dim.

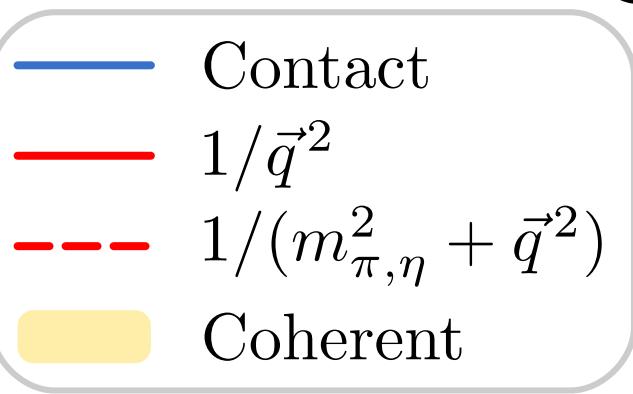
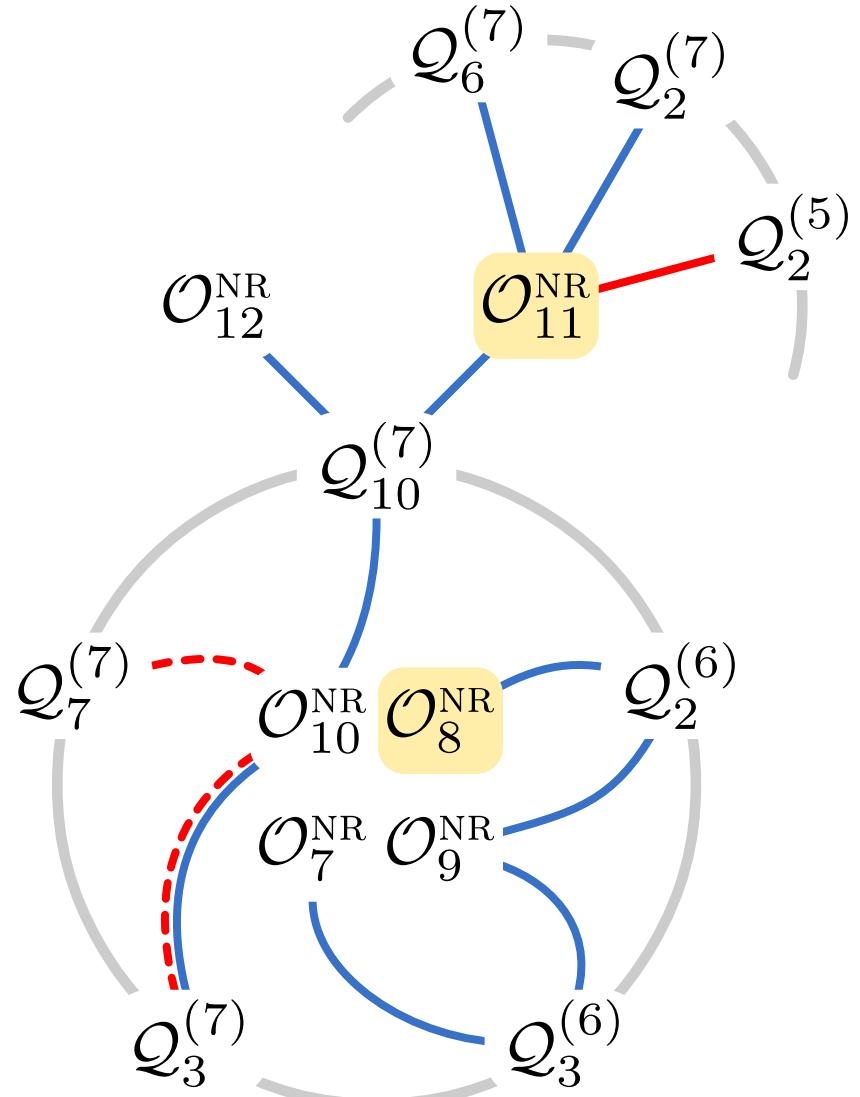
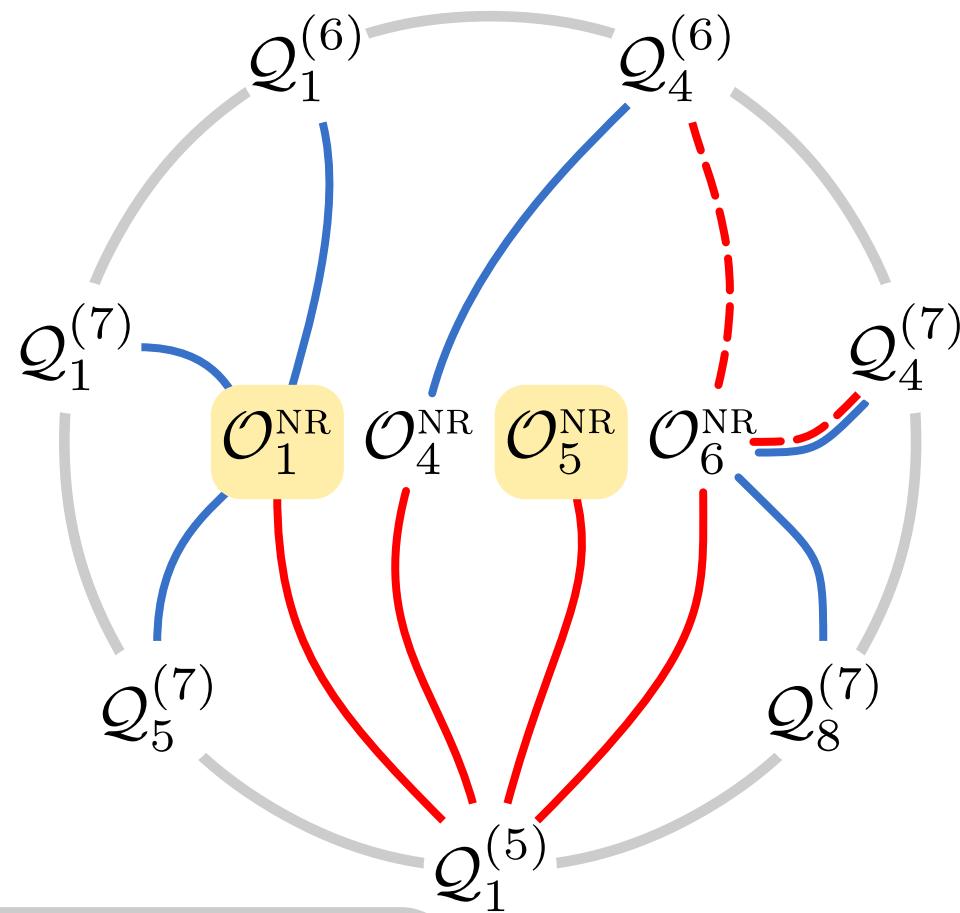
no. of connected diag's no. of loops $\sum_i V_i$ (chiral dim. \sim no. of deriv's no. of nuc. legs

- Gives scaling for LO and NLO potentials
more nucleons legs in vertex \rightarrow more suppressed

Differential event rate



Matching at a glance



Example of NLO in q^2

$$c_1^p = -\frac{\alpha}{2\pi m_\chi} Q_p \hat{\mathcal{C}}_1^{(5)} + \sum_q \left(F_1^{q/p} \hat{\mathcal{C}}_{1,q}^{(6)} + F_S^{q/p} \hat{\mathcal{C}}_{5,q}^{(7)} \right) + F_G^p \hat{\mathcal{C}}_1^{(7)},$$

$$c_5^p = \frac{2\alpha Q_p m_N}{\pi \vec{q}^2} \hat{\mathcal{C}}_1^{(5)},$$

$$c_1^{p,\text{NLO}} \supset -\frac{\vec{q}^2}{2m_\chi m_N} \sum_q \left(F_{T,0}^{q/p} - F_{T,1}^{q/p} \right) \hat{\mathcal{C}}_{9,q}^{(7)},$$

$$c_5^{p,\text{NLO}} \supset 2 \left(F_{T,0}^{q/p} - F_{T,1}^{q/p} \right) \hat{\mathcal{C}}_{9,q}^{(7)}.$$