Effective Field Theory methods and direct detection of Dark Matter

Massimiliano Procura

University of Vienna

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Outline

- Introduction: Dark Matter and direct detection
- Effective field theories describing interactions between DM and SM fields: Novel constraints on Wilson coefficients from SM loops
- Improved evaluation of nucleon matrix elements of scalar quark currents in the framework of Chiral Perturbation Theory
- Conclusions and outlook

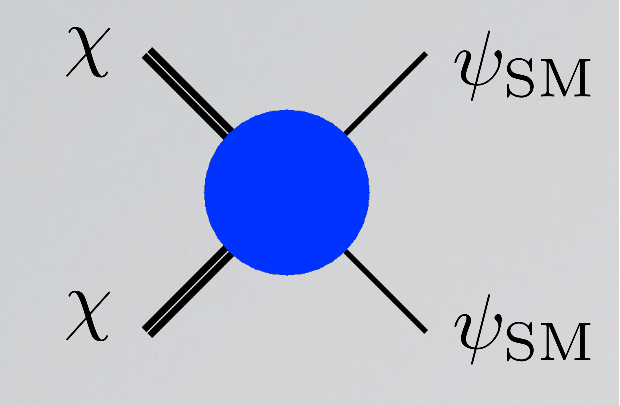
A. Crivellin, F. D'Eramo, M.P., arXiv: 1402.1173, Phys. Rev. Lett. 112 (2014) 191304

F. D'Eramo, M.P., arXiv: 1411.3342

A. Crivellin, M. Hoferichter, M.P., arXiv: 1312.4951, Phys. Rev. D 89 (2014) 054021

Dark Matter

- Astrophysical observations: most of our Universe is non-baryonic and dark
- Establishing the nature of DM is crucial for astrophysics and particle physics
- Widely discussed DM candidate: Weakly Interacting Massive Particle (WIMP), characterized by weak scale mass and weak-scale cross sections to SM fields



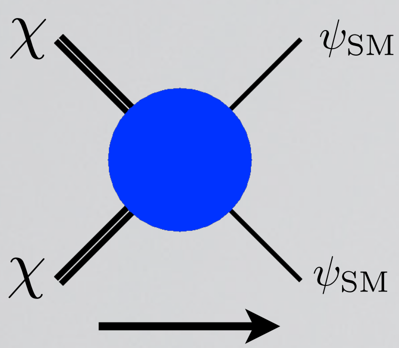
$$m_\chi \simeq m_{\rm weak}$$
$$\langle \sigma v_{\rm rel} \rangle_{\chi\chi \to \psi_{\rm SM}\psi_{\rm SM}} \simeq 1 \text{ pb}$$

- ubiquitous in New Physics models addressing the SM hierarchy problem
- a stable WIMP with mass ranging between about 10 GeV and 1 TeV has the right thermal relic abundance to account for DM energy density

- Interactions between WIMPs and SM fields: direct, indirect and collider searches

Dark Matter Searches

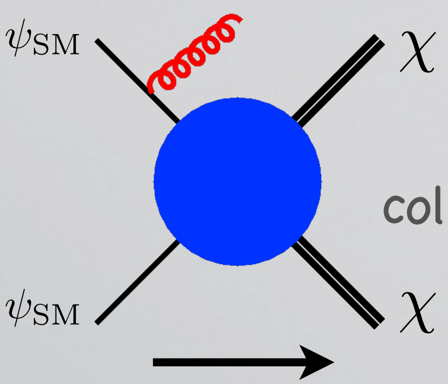
Indirect Searches



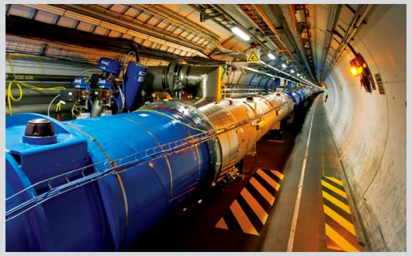
Milky Way WIMPs annihilations source of cosmic rays

FERMI GRT, Source: http://fermi.gsfc.nasa.gov

Collider Searches



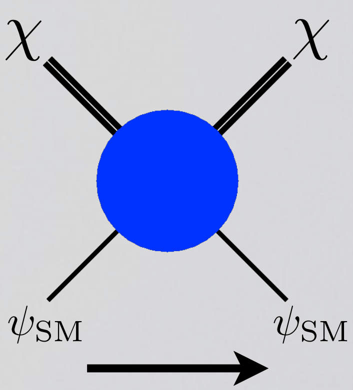
WIMPs may be pair-produced at colliders, accompanied by SM particles



LHC @ CERN, Source: http://home.web.cern.ch

Direct Searches

Milky Way WIMPs may scatter off target nuclei on the Earth



LUX detector, Source: http://lux.brown.edu

- In this talk focus on DIRECT SEARCHES: measure (or set limits on) nuclear recoil spectra for elastic scattering of WIMPs off target nuclei

$$E^{\max}_{\mathcal{N}\mathrm{Rec}} = \frac{\mu^2_{\chi\mathcal{N}}\, v^2_\chi}{m_\mathcal{N}} \simeq 200\,\mathrm{keV}$$

$$q^{\max} \simeq 200\,\mathrm{MeV}$$

for Xe detector and $m_\chi \simeq 1\,\mathrm{TeV}\,,\;\; v^{\rm gal}_\chi/c \simeq 10^{-3}$

much lower scales than m_{weak}

Spin-independent DD cross section

- Spin-independent (SI) and spin-dependent (SD) interactions (non-relativistic limit). The dependence of the WIMP-nucleus scattering rate on the momentum transfer is encoded in form factors. The zero-momentum SI WIMP-nucleus cross section for a Dirac WIMP :

$$\sigma^{\rm SI}_{\rm WIMP-nucleus} = \frac{\mu^2_{\chi\mathcal{N}}}{\pi}\Big[Z f_p + (A-Z) f_n\Big]^2$$

encode New Physics effects ~ $(1/\Lambda_{NP})^n$

- $\sigma^{\rm SI}_{\rm WIMP-nucleus}$ scales like A^2 if $f_p = f_n$ (no "isospin violation") : enhancement in the SI cross section compared to SD leads to stronger bounds from null searches on NP parameters for SI interactions

- In this talk we'll discuss bounds on Wilson coefficients for effective (fermion) WIMP-SM operators (systematic framework, representative of a class of models where all non-SM particles are above the weak scale, except possibly the WIMP)

DM and effective operators

- Integrate out heavy mediators (mediator mass scale $\Lambda \gtrsim 1\,\mathrm{TeV}$), match onto an EFT whose d.o.f. are DM field χ and SM fields: "SM_χ EFT"

- Supplement the SM Lagrangian with new operators allowed by symmetries

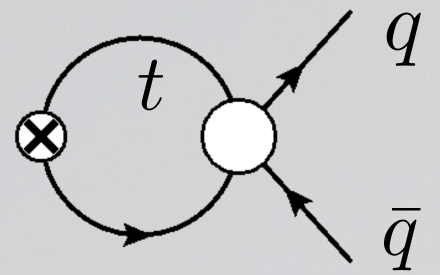
dimensionless Wilson coefficients

$$\mathcal{L}_{\mathrm{SM}_\chi} = \sum_{d>4} \mathcal{L}^{(d)}_{\mathrm{SM}_\chi} \qquad \mathcal{L}^{(d)}_{\mathrm{SM}_\chi} = \sum_\alpha \frac{c^{(d)}_\alpha}{\Lambda^{d-4}} O^{(d)}_\alpha$$

- Allows us to:
  - argue independently of details of specific UV completions
  - info on UV models via bounds on Wilson coefficients from direct detection: complementarity of searches, multiple tests of WIMP paradigm
  - properly connect operators at different scales, in terms of the effective d.o.f. at each scale: loop effects (matching, running, mixing)

DM and effective operators

- Example of from one-loop EW contribution to a Wilson coefficient :



$$\frac{\lambda_t^2}{4\pi^2} N^c \log\left(\frac{10\,\mathrm{TeV}}{1\,\mathrm{GeV}}\right) \simeq 1$$

usually neglected since it barely changes the order of magnitude of the rate ... BUT

- Effective d.o.f. for DD are DM particle, u-, d-, s-quark, gluons and photon : if the mediators couple DM with heavy SM particles or leptons, then the leading contribution to DD rates comes from LOOP EFFECTS

- If the mediators induce SUPPRESSED couplings to light quarks, then loop-induced couplings to NON-SUPPRESSED operators are important

D5	$\overline{\chi}\gamma^\mu\chi\,\overline{q}\gamma_\mu q$	SI
D6	$\overline{\chi}\gamma^\mu\gamma^5\chi\,\overline{q}\gamma_\mu q$	SI v^2 and SD q^2
D7	$\overline{\chi}\gamma^\mu\chi\,\overline{q}\gamma_\mu\gamma^5 q$	SD v^2 or q^2
D8	$\overline{\chi}\gamma^\mu\gamma^5\chi\,\overline{q}\gamma_\mu\gamma^5 q$	SD

Goodman et al., PRD82 (2010) (arXiv:1008.1783)

Connecting Λ and direct detection scale

$\Lambda \; (\gtrsim 1\,\mathrm{TeV})$ — Heavy messengers are integrated out: in our scenario, only DM and SM fields are effective d.o.f. for scales $\leq \Lambda$

↓ running and mixing in "SM_X EFT" (unbroken $SU(2)_L \times U(1)_Y$)

EWSB scale — Top, Higgs, W and Z get integrated out (matching)

↓ running and mixing in "$EMSM_X$ EFT"

Direct detection scale (hadronic scale) — u-, d-, s-quark and gluons appear in nucleon matrix elements (heavier quarks integrated out)

SI DM-nucleus scattering in EFT

- Unsuppressed operators of Dirac DM with light q and g at the DD scale to dim. 7:

$$O_{qq}^{VV} = \frac{1}{\Lambda^2}\,\bar\chi\gamma^\mu\chi\,\bar q\,\gamma_\mu\,q$$

$$O_{qq}^{SS} = \frac{m_q}{\Lambda^3}\,\bar\chi\chi\,\bar q q \qquad O_{gg}^{S} = \frac{\alpha_s}{\Lambda^3}\,\bar\chi\chi\,G_{\mu\nu}G^{\mu\nu}$$

- Correspondingly, the proton coupling in the DM-nucleus cross section, up to dim. 7 :

$$f_p = \frac{1}{\Lambda^2}\left[\sum_{q=u,d} C_{qq}^{VV}\,f_{V_q}^p + \frac{m_N}{\Lambda}\left(\sum_{q=u,d,s} C_{qq}^{SS}\,f_q^p - 12\pi\,C_{gg}^S\,f_Q^p\right)\right]$$

- vector couplings to quarks : $f_{V_u}^p = f_{V_d}^n = 2f_{V_d}^p = 2f_{V_u}^n = 2$
- scalar couplings : $\langle N|m_q\bar q q|N\rangle = f_q^N m_N$, for heavy quarks f_Q^N
- The Wilson coefficient C_{gg}^S encodes matching corrections from integrating out t-, b- and c-quarks

Plan of the talk

Two applications of EFTs for direct detection:

1) SM loop effects lead to novel bounds on Wilson coefficients at the scale Λ contributing via RGEs to C_{qq}^{VV} at the direct detection scale, extracted from experimental limits on $\sigma_{\chi\mathcal{N}}$.
Systematic one-loop analysis of running, matching, mixing for EFT operators giving rise to SI interactions at dimension 6. In our study we assume that DM is a Dirac fermion and a SM gauge singlet.

F. D'Eramo, M.P., arXiv: 1411.3342

A. Crivellin, F. D'Eramo, M.P., PRL (2014)

2) Improved determination of hadronic uncertainties in scalar nucleon matrix elements that define $f_q^{p,n}$ using Chiral Perturbation Theory.

A. Crivellin, M. Hoferichter, M.P., PRD (2014)

Operators at the scale Λ at dim. 5

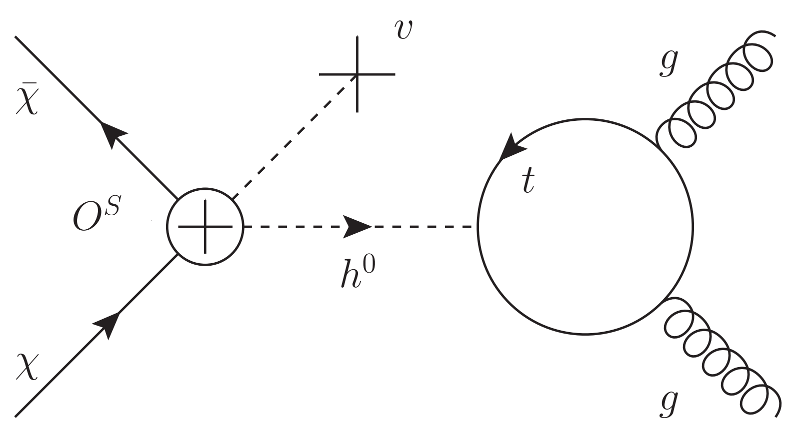
- Consider operators at the mediator mass scale Λ (> EWSB scale), i.e. in SM_χ EFT, giving unsuppressed contributions to SI WIMP-nucleus cross section. Operators at dimension 5 are well studied in the literature :

$\mathcal{O}_S$	$\bar\chi\chi\, H^\dagger H$
$\mathcal{O}_P$	$\bar\chi\gamma^5\chi\, H^\dagger H$
$\mathcal{O}_M$	$\bar\chi\sigma^{\mu\nu}\chi\, B_{\mu\nu}$
$\mathcal{O}_E$	$\bar\chi\sigma^{\mu\nu}\chi\, \epsilon_{\mu\nu\rho\sigma} B^{\rho\sigma}$

SM Higgs doublet

$U(1)_Y$ field strength tensor

► $\mathcal{O}_S$ contributes to the dim. 7 O^{SS}_{qq} after EWSB (tree-level Higgs exchange) and after integrating out heavy quarks also to O^S_{gg} ⟶ finite matching corrections



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SM Higgs doublet

$U(1)_Y$ field strength tensor

- $\mathcal{O}_S$ contributes to the dim. 7 O_{qq}^{SS} after EWSB (tree-level Higgs exchange) and after integrating out heavy quarks also to O_{gg}^{S} $\longrightarrow$ finite matching corrections

- Dipole DM strongly constrained by direct searches

Barger, Keung, Marfatia PLB (2011)

Banks, Fortin, Thomas, 1007.5515

Operators at the scale Λ at dim. 6

- At dim. 6 in SM$_\chi$ EFT ($SU(2)_L \times U(1)_Y$ is unbroken) :

LH and RH leptons

$\mathcal{O}^{(i)}_{\Gamma q}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{q^i_L}\gamma_\mu q^i_L$
$\mathcal{O}^{(i)}_{\Gamma u}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{u^i_R}\gamma_\mu u^i_R$
$\mathcal{O}^{(i)}_{\Gamma d}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{d^i_R}\gamma_\mu d^i_R$

$\mathcal{O}^{(i)}_{\Gamma l}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{l^i_L}\gamma_\mu l^i_L$
$\mathcal{O}^{(i)}_{\Gamma e}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{e^i_R}\gamma_\mu e^i_R$
$\mathcal{O}^{(i)}_{\Gamma H}$	$\overline{\chi}\,\Gamma^\mu\chi\,H^\dagger i\overleftrightarrow{D}_\mu H$

LH and RH quarks

$$\Gamma^\mu = \{\gamma^\mu, \gamma^\mu\gamma^5\}$$

- Since the DM bilinear is RG-invariant, we study the evolution from scale Λ down to the EWSB scale (= M$_Z$) of this 16-dimensional vector of Wilson coefficients

$$\mathcal{C}^T_{\text{SM}_\chi} \equiv \left(c^{(1)}_{\Gamma q}\; c^{(1)}_{\Gamma u}\; c^{(1)}_{\Gamma d} \,\vdots\, c^{(1)}_{\Gamma l}\; c^{(1)}_{\Gamma e} \,\Big|\, c^{(2)}_{\Gamma q}\; c^{(2)}_{\Gamma u}\; c^{(2)}_{\Gamma d} \,\vdots\, c^{(2)}_{\Gamma l}\; c^{(2)}_{\Gamma e} \,\Big|\, c^{(3)}_{\Gamma q}\; c^{(3)}_{\Gamma u}\; c^{(3)}_{\Gamma d} \,\vdots\, c^{(3)}_{\Gamma l}\; c^{(3)}_{\Gamma e} \,\Big\|\, c_{\Gamma H} \right)$$

One-loop RGE from Λ to EWSB scale

$$\mathcal{C}^T_{\mathrm{SM}_\chi} \equiv \left(c^{(1)}_{\Gamma q} \; c^{(1)}_{\Gamma u} \; c^{(1)}_{\Gamma d} \;\vdots\; c^{(1)}_{\Gamma l} \; c^{(1)}_{\Gamma e} \,\Big|\, c^{(2)}_{\Gamma q} \; c^{(2)}_{\Gamma u} \; c^{(2)}_{\Gamma d} \;\vdots\; c^{(2)}_{\Gamma l} \; c^{(2)}_{\Gamma e} \,\Big|\, c^{(3)}_{\Gamma q} \; c^{(3)}_{\Gamma u} \; c^{(3)}_{\Gamma d} \;\vdots\; c^{(3)}_{\Gamma l} \; c^{(3)}_{\Gamma e} \,\Big\|\, c_{\Gamma H} \right)$$

- The anomalous dimension is a 16x16 matrix :

$$\frac{d}{d\ln\mu}\mathcal{C}_{\mathrm{SM}_\chi} = \gamma_{\mathrm{SM}_\chi}\mathcal{C}_{\mathrm{SM}_\chi}$$

$$\frac{d}{d\ln\mu}\mathcal{C}_{\mathrm{SM}_\chi} = \left(\gamma_{\mathrm{SM}_\chi}\big|_\lambda + \gamma_{\mathrm{SM}_\chi}\big|_Y\right)\mathcal{C}_{\mathrm{SM}_\chi}$$

Yukawa contribution — hypercharge contribution

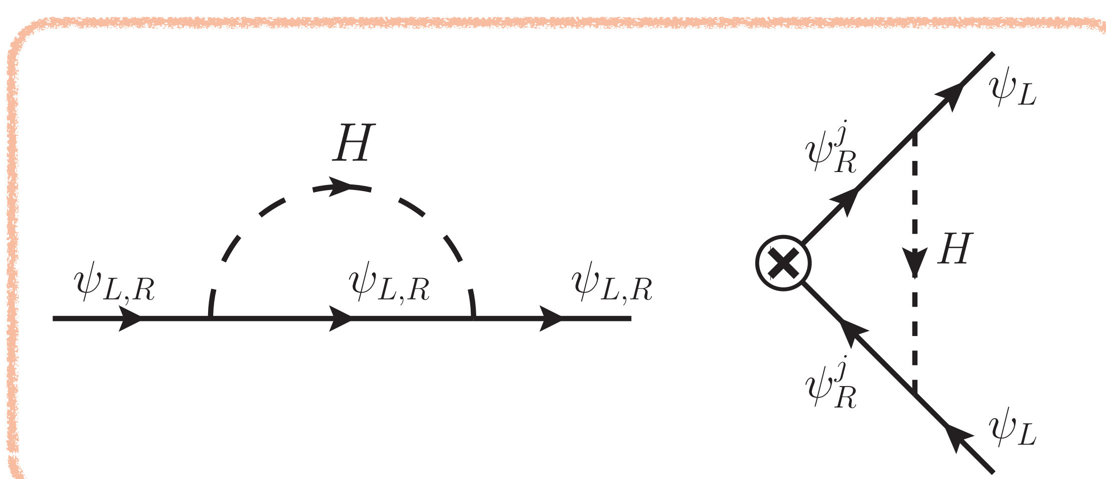
One-loop RGE from Λ to EWSB scale

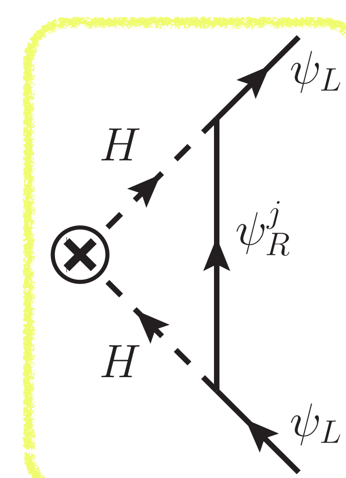
$$\mathcal{C}^T_{\mathrm{SM}_\chi} \equiv \left(c^{(1)}_{\Gamma q}\ c^{(1)}_{\Gamma u}\ c^{(1)}_{\Gamma d}\ \vdots\ c^{(1)}_{\Gamma l}\ c^{(1)}_{\Gamma e}\ \middle|\ c^{(2)}_{\Gamma q}\ c^{(2)}_{\Gamma u}\ c^{(2)}_{\Gamma d}\ \vdots\ c^{(2)}_{\Gamma l}\ c^{(2)}_{\Gamma e}\ \middle|\ c^{(3)}_{\Gamma q}\ c^{(3)}_{\Gamma u}\ c^{(3)}_{\Gamma d}\ \vdots\ c^{(3)}_{\Gamma l}\ c^{(3)}_{\Gamma e}\ \middle\|\ c_{\Gamma H} \right)$$

$$\gamma_{\mathrm{SM}_\chi}\Big|_\lambda = \frac{1}{8\pi^2}\times$$

$(\lambda_u^2+\lambda_d^2)/2$	$-\lambda_u^2/2$	$-\lambda_d^2/2$	0	0	0	0	0	0	0	0	0	0	0	0	$(\lambda_u^2+\lambda_d^2)/2$
$-\lambda_u^2$	λ_u^2	0	0	0	0	0	0	0	0	0	0	0	0	0	λ_u^2
$-\lambda_d^2$	0	λ_d^2	0	0	0	0	0	0	0	0	0	0	0	0	λ_d^2
0	0	0	$\lambda_e^2/2$	$-\lambda_e^2/2$	0	0	0	0	0	0	0	0	0	0	$\lambda_e^2/2$
0	0	0	$-\lambda_e^2$	λ_e^2	0	0	0	0	0	0	0	0	0	0	λ_e^2
0	0	0	0	0	$(\lambda_c^2+\lambda_s^2)/2$	$-\lambda_c^2/2$	$-\lambda_s^2/2$	0	0	0	0	0	0	0	$(\lambda_c^2+\lambda_s^2)/2$
0	0	0	0	0	$-\lambda_c^2$	λ_c^2	0	0	0	0	0	0	0	0	λ_c^2
0	0	0	0	0	$-\lambda_s^2$	0	λ_s^2	0	0	0	0	0	0	0	λ_s^2
0	0	0	0	0	0	0	0	$\lambda_\mu^2/2$	$-\lambda_\mu^2/2$	0	0	0	0	0	$\lambda_\mu^2/2$
0	0	0	0	0	0	0	0	$-\lambda_\mu^2$	λ_μ^2	0	0	0	0	0	λ_μ^2
0	0	0	0	0	0	0	0	0	0	$(\lambda_t^2+\lambda_b^2)/2$	$-\lambda_t^2/2$	$-\lambda_b^2/2$	0	0	$(\lambda_t^2+\lambda_b^2)/2$
0	0	0	0	0	0	0	0	0	0	$-\lambda_t^2$	λ_t^2	0	0	0	λ_t^2
0	0	0	0	0	0	0	0	0	0	$-\lambda_b^2$	0	λ_b^2	0	0	λ_b^2
0	0	0	0	0	0	0	0	0	0	0	0	0	$\lambda_\tau^2/2$	$-\lambda_\tau^2/2$	$\lambda_\tau^2/2$
0	0	0	0	0	0	0	0	0	0	0	0	0	$-\lambda_\tau^2$	λ_τ^2	λ_τ^2
$3(\lambda_u^2-\lambda_d^2)$	$-3\lambda_u^2$	$3\lambda_d^2$	$-\lambda_e^2$	λ_e^2	$3(\lambda_c^2-\lambda_s^2)$	$-3\lambda_c^2$	$3\lambda_s^2$	$-\lambda_\mu^2$	λ_μ^2	$3(\lambda_t^2-\lambda_b^2)$	$-3\lambda_t^2$	$3\lambda_b^2$	$-\lambda_\tau^2$	λ_τ^2	$3\sum_q \lambda_q^2+\sum_l \lambda_l^2$

- One-loop corrections to Wilson coefficients for LH fermions :



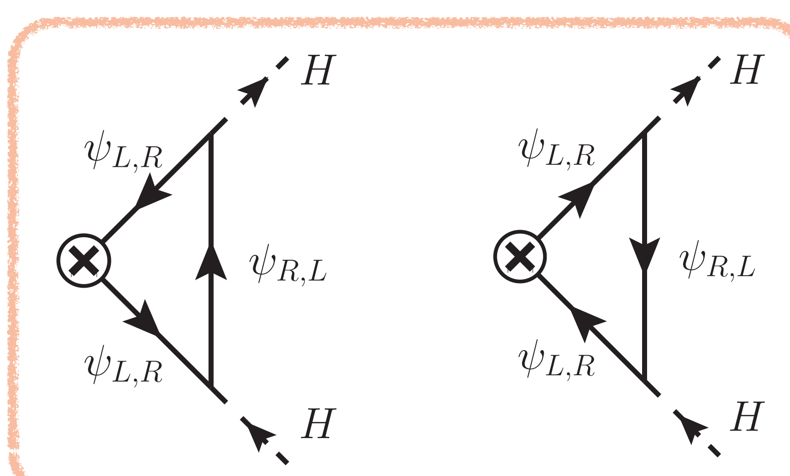


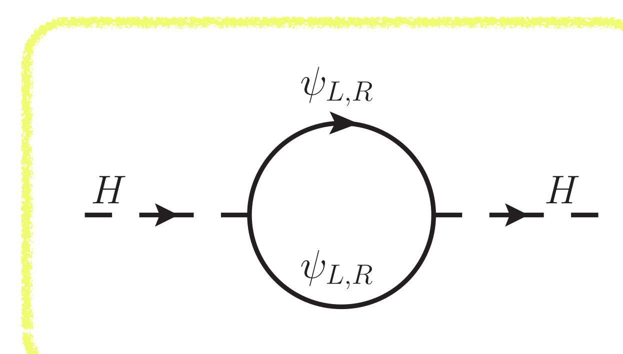
One-loop RGE from Λ to EWSB scale

$$\mathcal{C}^T_{\mathrm{SM}_\chi} \equiv \left(c^{(1)}_{\Gamma q}\ c^{(1)}_{\Gamma u}\ c^{(1)}_{\Gamma d} \;\vdots\; c^{(1)}_{\Gamma l}\ c^{(1)}_{\Gamma e} \;\Big|\; c^{(2)}_{\Gamma q}\ c^{(2)}_{\Gamma u}\ c^{(2)}_{\Gamma d} \;\vdots\; c^{(2)}_{\Gamma l}\ c^{(2)}_{\Gamma e} \;\Big|\; c^{(3)}_{\Gamma q}\ c^{(3)}_{\Gamma u}\ c^{(3)}_{\Gamma d} \;\vdots\; c^{(3)}_{\Gamma l}\ c^{(3)}_{\Gamma e} \;\Big\|\; c_{\Gamma H} \right)$$

$$\gamma_{\mathrm{SM}_\chi}\Big|_\lambda = \frac{1}{8\pi^2}\left(\begin{array}{ccc:cc|ccc:cc|ccc:cc||c}
(\lambda_u^2+\lambda_d^2)/2 & -\lambda_u^2/2 & -\lambda_d^2/2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & (\lambda_u^2+\lambda_d^2)/2 \\
-\lambda_u^2 & \lambda_u^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_u^2 \\
-\lambda_d^2 & 0 & \lambda_d^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_d^2 \\
\hdashline
0 & 0 & 0 & \lambda_e^2/2 & -\lambda_e^2/2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_e^2/2 \\
0 & 0 & 0 & -\lambda_e^2 & \lambda_e^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_e^2 \\
\hline
0 & 0 & 0 & 0 & 0 & (\lambda_c^2+\lambda_s^2)/2 & -\lambda_c^2/2 & -\lambda_s^2/2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & (\lambda_c^2+\lambda_s^2)/2 \\
0 & 0 & 0 & 0 & 0 & -\lambda_c^2 & \lambda_c^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_c^2 \\
0 & 0 & 0 & 0 & 0 & -\lambda_s^2 & 0 & \lambda_s^2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_s^2 \\
\hdashline
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_\mu^2/2 & -\lambda_\mu^2/2 & 0 & 0 & 0 & 0 & 0 & \lambda_\mu^2/2 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\lambda_\mu^2 & \lambda_\mu^2 & 0 & 0 & 0 & 0 & 0 & \lambda_\mu^2 \\
\hline
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & (\lambda_t^2+\lambda_b^2)/2 & -\lambda_t^2/2 & -\lambda_b^2/2 & 0 & 0 & (\lambda_t^2+\lambda_b^2)/2 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\lambda_t^2 & \lambda_t^2 & 0 & 0 & 0 & \lambda_t^2 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\lambda_b^2 & 0 & \lambda_b^2 & 0 & 0 & \lambda_b^2 \\
\hdashline
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_\tau^2/2 & -\lambda_\tau^2/2 & \lambda_\tau^2/2 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -\lambda_\tau^2 & \lambda_\tau^2 & \lambda_\tau^2 \\
\hline
3(\lambda_u^2-\lambda_d^2) & -3\lambda_u^2 & 3\lambda_d^2 & -\lambda_e^2 & \lambda_e^2 & 3(\lambda_c^2-\lambda_s^2) & -3\lambda_c^2 & 3\lambda_s^2 & -\lambda_\mu^2 & \lambda_\mu^2 & 3(\lambda_t^2-\lambda_b^2) & -3\lambda_t^2 & 3\lambda_b^2 & -\lambda_\tau^2 & \lambda_\tau^2 & 3\sum_q \lambda_q^2 + \sum_l \lambda_l^2
\end{array}\right)$$

- One-loop corrections to Wilson coefficient for Higgs doublet :





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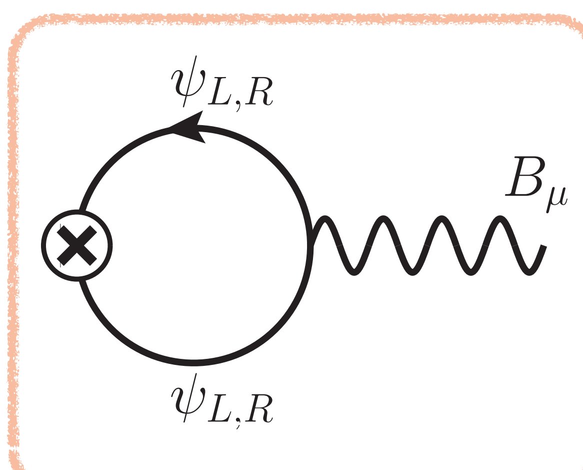
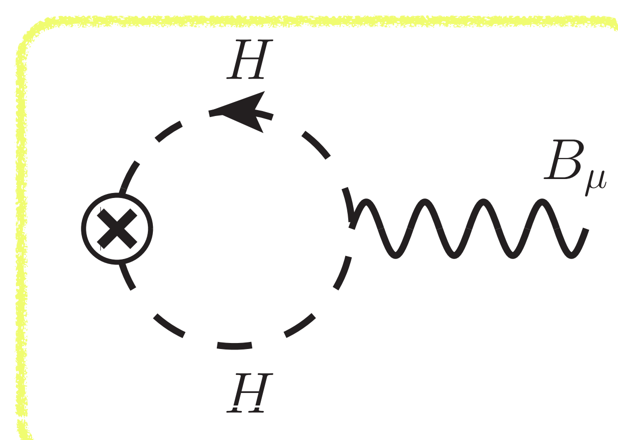
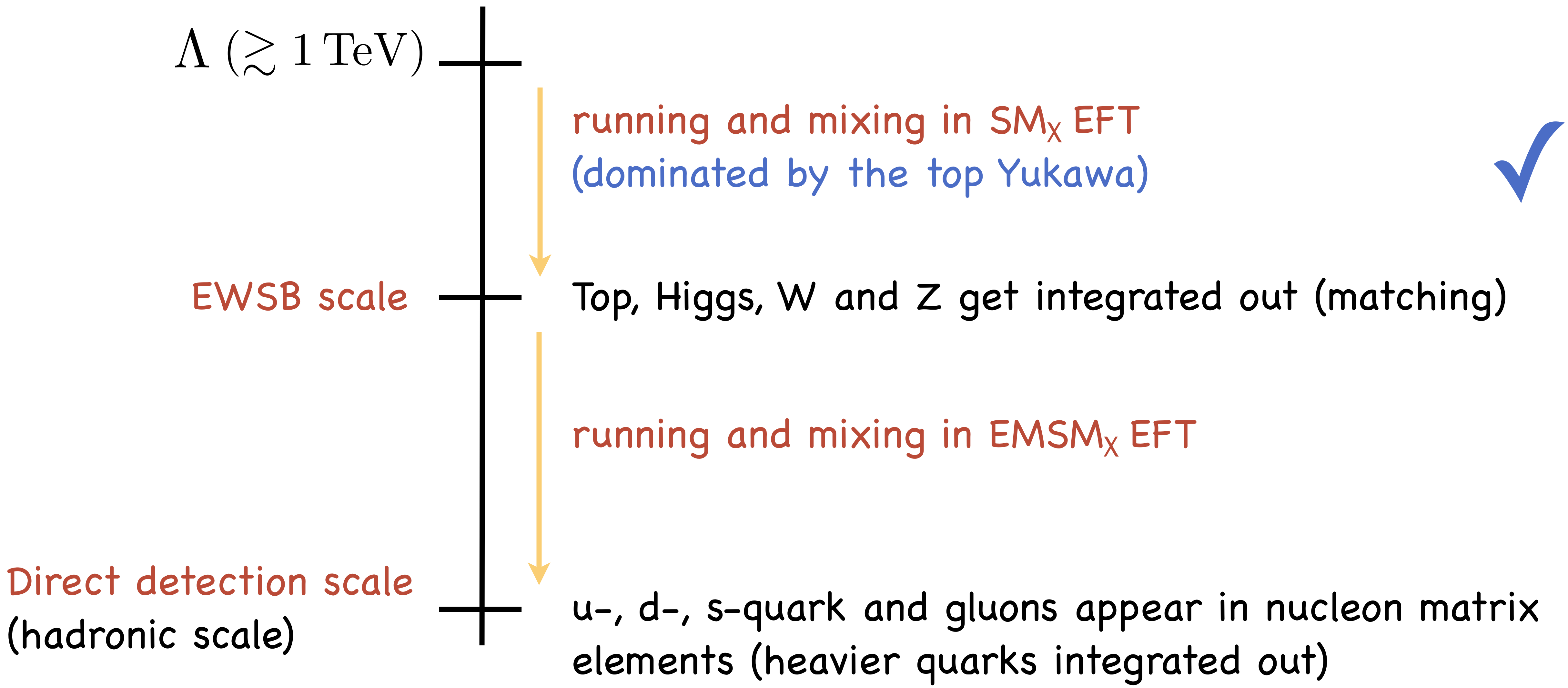
$$\gamma_{\mathrm{SM}_\chi}\Big|_Y = \frac{4}{3}\frac{g'^2}{16\pi^2} \left(\begin{array}{ccc:cc|ccc:cc|ccc:cc||c}
6y_q^2 & 3y_qy_u & 3y_qy_d & 2y_qy_l & y_qy_e & 6y_q^2 & 3y_qy_u & 3y_qy_d & 2y_qy_l & y_qy_e & 6y_q^2 & 3y_qy_u & 3y_qy_d & 2y_qy_l & y_qy_e & y_qy_H \\
6y_uy_q & 3y_u^2 & 3y_uy_d & 2y_uy_l & y_uy_e & 6y_uy_q & 3y_u^2 & 3y_uy_d & 2y_uy_l & y_uy_e & 6y_uy_q & 3y_u^2 & 3y_uy_d & 2y_uy_l & y_uy_e & y_uy_H \\
6y_dy_q & 3y_dy_u & 3y_d^2 & 2y_dy_l & y_dy_e & 6y_dy_q & 3y_dy_u & 3y_d^2 & 2y_dy_l & y_dy_e & 6y_dy_q & 3y_dy_u & 3y_d^2 & 2y_dy_l & y_dy_e & y_dy_H \\ \hdashline
6y_ly_q & 3y_ly_u & 3y_ly_d & 2y_l^2 & y_ly_e & 6y_ly_q & 3y_ly_u & 3y_ly_d & 2y_l^2 & y_ly_e & 6y_ly_q & 3y_ly_u & 3y_ly_d & 2y_l^2 & y_ly_e & y_ly_H \\
6y_ey_q & 3y_ey_u & 3y_ey_d & 2y_ey_l & y_e^2 & 6y_ey_q & 3y_ey_u & 3y_ey_d & 2y_ey_l & y_e^2 & 6y_ey_q & 3y_ey_u & 3y_ey_d & 2y_ey_l & y_e^2 & y_ey_H \\ \hline
6y_q^2 & 3y_qy_u & 3y_qy_d & 2y_qy_l & y_qy_e & 6y_q^2 & 3y_qy_u & 3y_qy_d & 2y_qy_l & y_qy_e & 6y_q^2 & 3y_qy_u & 3y_qy_d & 2y_qy_l & y_qy_e & y_qy_H \\
6y_uy_q & 3y_u^2 & 3y_uy_d & 2y_uy_l & y_uy_e & 6y_uy_q & 3y_u^2 & 3y_uy_d & 2y_uy_l & y_uy_e & 6y_uy_q & 3y_u^2 & 3y_uy_d & 2y_uy_l & y_uy_e & y_uy_H \\
6y_dy_q & 3y_dy_u & 3y_d^2 & 2y_dy_l & y_dy_e & 6y_dy_q & 3y_dy_u & 3y_d^2 & 2y_dy_l & y_dy_e & 6y_dy_q & 3y_dy_u & 3y_d^2 & 2y_dy_l & y_dy_e & y_dy_H \\ \hdashline
6y_ly_q & 3y_ly_u & 3y_ly_d & 2y_l^2 & y_ly_e & 6y_ly_q & 3y_ly_u & 3y_ly_d & 2y_l^2 & y_ly_e & 6y_ly_q & 3y_ly_u & 3y_ly_d & 2y_l^2 & y_ly_e & y_ly_H \\
6y_ey_q & 3y_ey_u & 3y_ey_d & 2y_ey_l & y_e^2 & 6y_ey_q & 3y_ey_u & 3y_ey_d & 2y_ey_l & y_e^2 & 6y_ey_q & 3y_ey_u & 3y_ey_d & 2y_ey_l & y_e^2 & y_ey_H \\ \hline
6y_q^2 & 3y_qy_u & 3y_qy_d & 2y_qy_l & y_qy_e & 6y_q^2 & 3y_qy_u & 3y_qy_d & 2y_qy_l & y_qy_e & 6y_q^2 & 3y_qy_u & 3y_qy_d & 2y_qy_l & y_qy_e & y_qy_H \\
6y_uy_q & 3y_u^2 & 3y_uy_d & 2y_uy_l & y_uy_e & 6y_uy_q & 3y_u^2 & 3y_uy_d & 2y_uy_l & y_uy_e & 6y_uy_q & 3y_u^2 & 3y_uy_d & 2y_uy_l & y_uy_e & y_uy_H \\
6y_dy_q & 3y_dy_u & 3y_d^2 & 2y_dy_l & y_dy_e & 6y_dy_q & 3y_dy_u & 3y_d^2 & 2y_dy_l & y_dy_e & 6y_dy_q & 3y_dy_u & 3y_d^2 & 2y_dy_l & y_dy_e & y_dy_H \\ \hdashline
6y_ly_q & 3y_ly_u & 3y_ly_d & 2y_l^2 & y_ly_e & 6y_ly_q & 3y_ly_u & 3y_ly_d & 2y_l^2 & y_ly_e & 6y_ly_q & 3y_ly_u & 3y_ly_d & 2y_l^2 & y_ly_e & y_ly_H \\
6y_ey_q & 3y_ey_u & 3y_ey_d & 2y_ey_l & y_e^2 & 6y_ey_q & 3y_ey_u & 3y_ey_d & 2y_ey_l & y_e^2 & 6y_ey_q & 3y_ey_u & 3y_ey_d & 2y_ey_l & y_e^2 & y_ey_H \\ \hline\hline
6y_Hy_q & 3y_Hy_u & 3y_Hy_d & 2y_Hy_l & y_Hy_e & 6y_Hy_q & 3y_Hy_u & 3y_Hy_d & 2y_Hy_l & y_Hy_e & 6y_Hy_q & 3y_Hy_u & 3y_Hy_d & 2y_Hy_l & y_Hy_e & y_H^2
\end{array} \right)$$

- The hypercharge contribution :





Matching at the EWSB scale



- Tree-level matching contributions from giving the Higgs a VEV and integrating out the Z boson (fermion pair is meant to be attached to the Z)

$$\mathcal{L}_{\chi\chi Z} = \frac{c_{\Gamma H}}{\Lambda^2}\,\overline{\chi}\,\Gamma^\mu \chi\,\langle H^\dagger\rangle\, i\overleftrightarrow{D}_\mu \langle H\rangle = -\frac{c_{\Gamma H}}{\Lambda^2}\, v^2 \sqrt{g^2+g'^2}\,\overline{\chi}\,\Gamma^\mu\chi\, Z_\mu$$

Running from EWSB scale to GeV scale

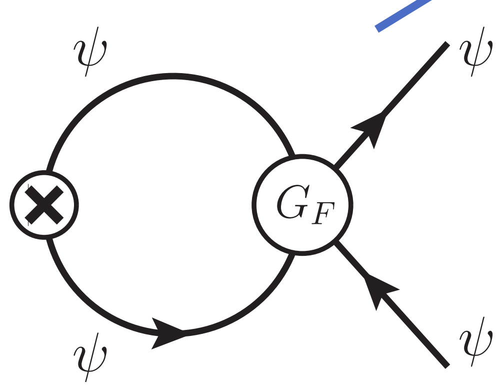
- In EMSM$_\chi$ EFT vector and axial currents instead of LH/RH currents

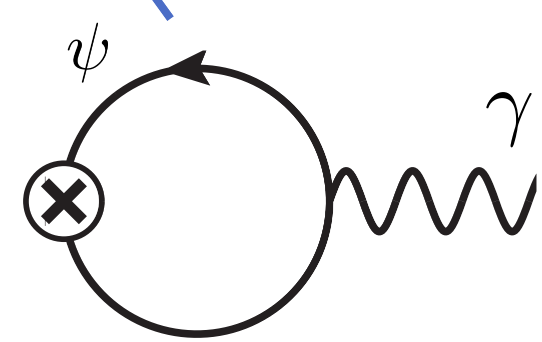
$\mathcal{O}^{(i)}_{\Gamma V u}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{u^i}\gamma_\mu u^i$	$\mathcal{O}^{(i)}_{\Gamma V d}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{d^i}\gamma_\mu d^i$	$\mathcal{O}^{(i)}_{\Gamma V e}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{e^i}\gamma_\mu e^i$
$\mathcal{O}^{(i)}_{\Gamma A u}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{u^i}\gamma_\mu\gamma_5 u^i$	$\mathcal{O}^{(i)}_{\Gamma A d}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{d^i}\gamma_\mu\gamma_5 d^i$	$\mathcal{O}^{(i)}_{\Gamma A e}$	$\overline{\chi}\,\Gamma^\mu\chi\,\overline{e^i}\gamma_\mu\gamma_5 e^i$

- We study the evolution for this 16-dimensional vector of Wilson coefficients

$$\mathcal{C}^T_{\mathrm{EMSM}_\chi} = \left(c^{(1)}_{\Gamma V u}\; c^{(1)}_{\Gamma V d}\; c^{(2)}_{\Gamma V u}\; c^{(2)}_{\Gamma V d}\; c^{(3)}_{\Gamma V d} \middle| c^{(1)}_{\Gamma V e}\; c^{(2)}_{\Gamma V e}\; c^{(3)}_{\Gamma V e} \middle\| c^{(1)}_{\Gamma A u}\; c^{(1)}_{\Gamma A d}\; c^{(2)}_{\Gamma A u}\; c^{(2)}_{\Gamma A d}\; c^{(3)}_{\Gamma A d} \middle| c^{(1)}_{\Gamma A e}\; c^{(2)}_{\Gamma A e}\; c^{(3)}_{\Gamma A e} \right)$$

$$\frac{d}{d\ln\mu}\mathcal{C}_{\mathrm{EMSM}_\chi} = \left(\gamma_{\mathrm{EMSM}_\chi}\big|_m + \gamma_{\mathrm{EMSM}_\chi}\big|_{\mathrm{em}} \right) \mathcal{C}_{\mathrm{EMSM}_\chi}$$



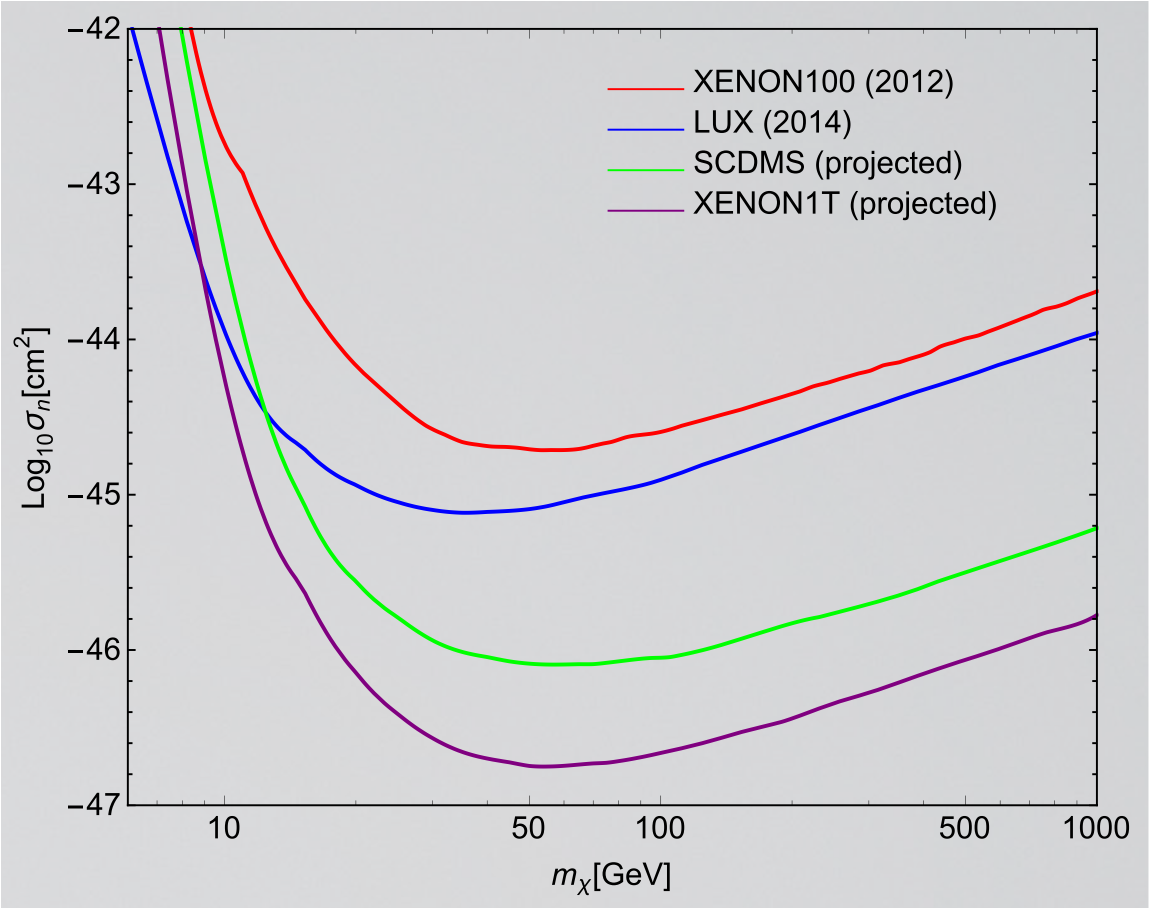


Evolution at dim. 6 and DD cross section

- RGEs allow us to connect Wilson coefficients at the high scale (UV complete models) with the ones in WIMP-nucleus cross section (low scale). At dimension 6,

$$\sigma^{\rm SI}_{\chi\mathcal{N}} = \frac{m_\chi^2\, m_\mathcal{N}^2}{(m_\chi + m_\mathcal{N})^2\, \pi\, \Lambda^4} \left| c^{(1)}_{VVu}(A+Z) + c^{(1)}_{VVd}(2A-Z) \right|^2$$

u- and d-quark vector-vector Wilson coefficients at a scale around 1 GeV



Constraints from experimental bounds

E. Aprile et al. (XENON100), PRL (2012)

D. Akerib et al. (LUX), PRL (2014)

T. Saab (SCDMS), talk at SSI (2012)

E. Aprile et al. (XENON1T), Proceedings DM 2012

Evolution at dim. 6 and DD cross section

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$$\sigma_{\chi\mathcal{N}}^{\mathrm{SI}} = \frac{m_\chi^2\, m_\mathcal{N}^2}{(m_\chi + m_\mathcal{N})^2\, \pi\, \Lambda^4} \left| c_{VVu}^{(1)}(A+Z) + c_{VVd}^{(1)}(2A-Z) \right|^2$$

Standard Model loops lead to novel constraints from DD:

- light quark vector currents from light quark axial-vector currents
- light quark vector currents from operators with heavy quarks
- light quark vector currents from operators with leptons

(Dark Matter bilinear here not affected: DM is SM gauge singlet)

The case of VV and VA operators

- Operators at the high scale Λ (mediator mass scale) :

$$\mathcal{L}_{\rm D5} = \frac{c_{\rm D5}}{\Lambda^2}\,\overline{\chi}\gamma^\mu\chi\,\left[\sum_i \overline{u^i}\gamma_\mu u^i + \sum_i \overline{d^i}\gamma_\mu d^i\right]\,, \qquad \mathcal{L}_{\rm D7} = \frac{c_{\rm D7}}{\Lambda^2}\,\overline{\chi}\gamma^\mu\chi\,\left[\sum_i \overline{u^i}\gamma_\mu\gamma_5 u^i + \sum_i \overline{d^i}\gamma_\mu\gamma_5 d^i\right]$$

For flavor-universal DM-quark coupling this corresponds to

$$c_\Lambda^T\big|_{\rm D5,D7} = \Big(c_L\ c_R\ c_R\,\vdots\,0\ 0\big|c_L\ c_R\ c_R\,\vdots\,0\ 0\big|c_L\ c_R\ c_R\,\vdots\,0\ 0\big\|0\Big)$$

with

$$c_{\rm D5} = \frac{c_L + c_R}{2} \qquad\qquad c_{\rm D7} = \frac{c_R - c_L}{2}$$

- Evolve down to 1 GeV, extract $c^{(1)}_{VVu}$, $c^{(1)}_{VVd}$ and determine bounds numerically

The case of VV and VA operators

- Operators at the high scale Λ (mediator mass scale) :

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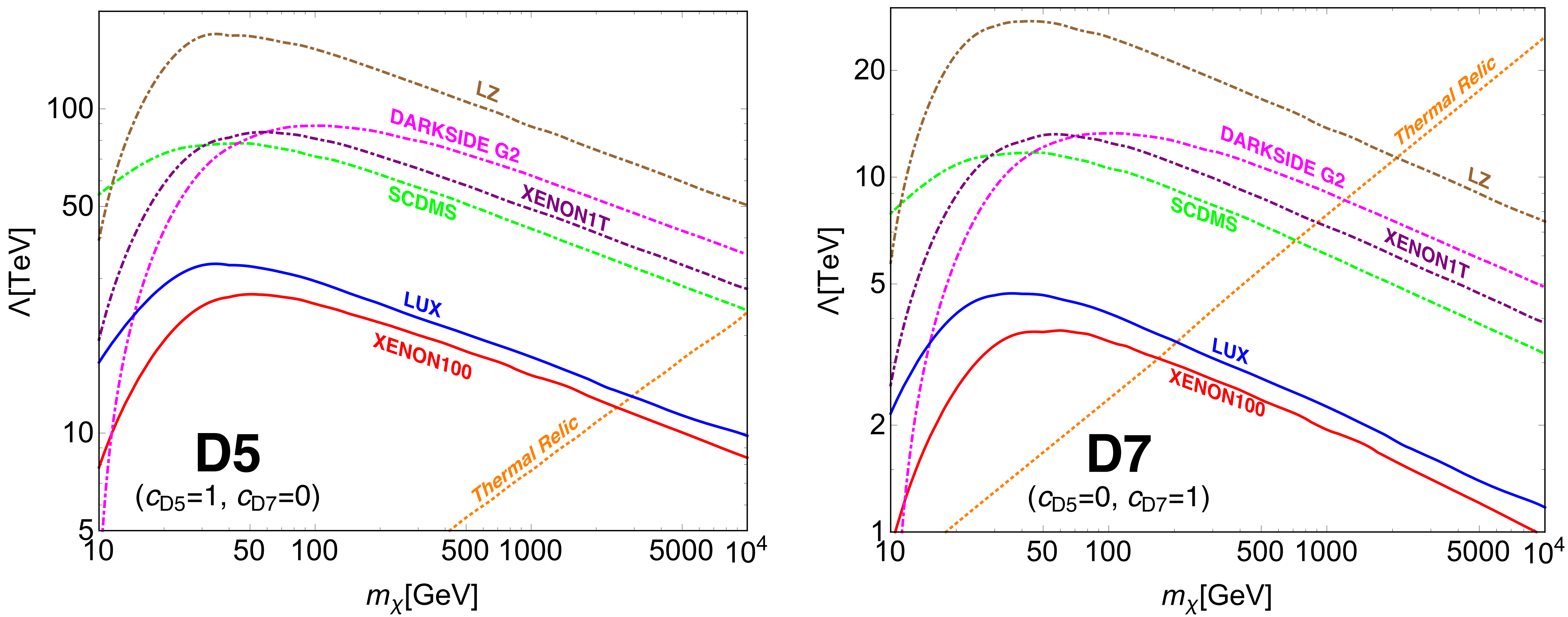
- First scenario: only one Wilson coefficient is non-vanishing (set = 1) at the scale Λ
- No constraint for VA case (D7) from SI cross section without RGE !

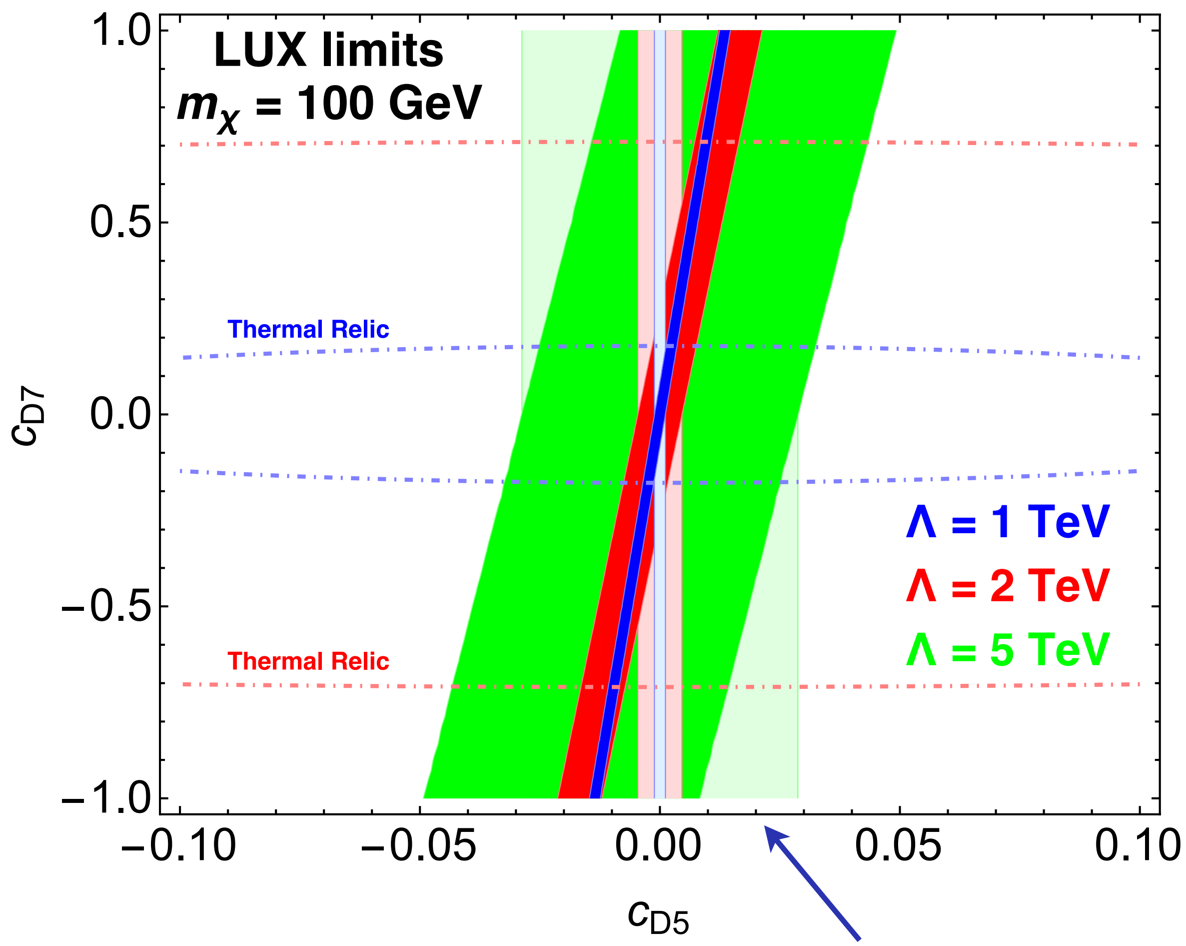


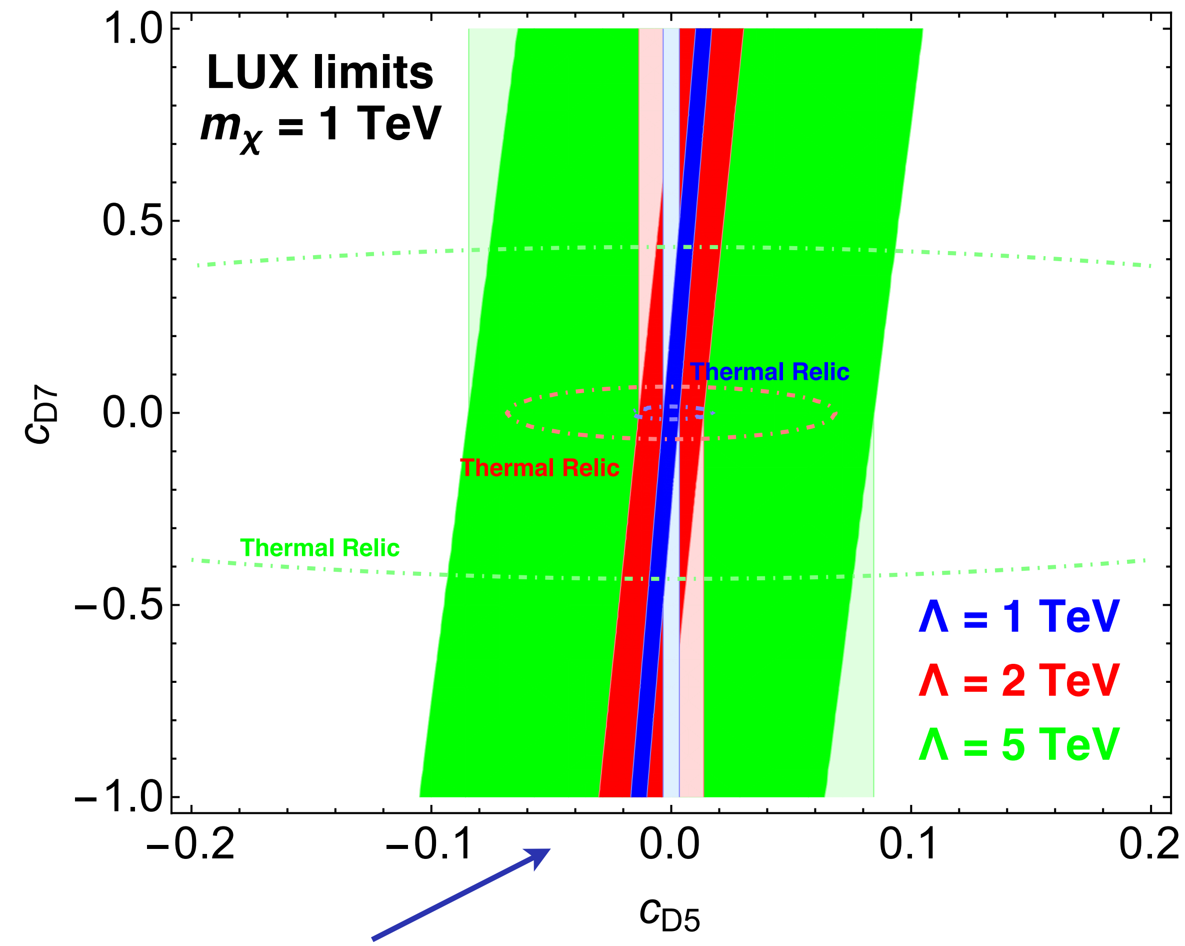
The case of VV and VA operators

- Operators at the high scale Lambda:

$$\mathcal{L}_{D5} = \frac{c_{D5}}{\Lambda^2}\,\overline{\chi}\gamma^\mu\chi\left[\sum_i \overline{u^i}\gamma_\mu u^i + \sum_i \overline{d^i}\gamma_\mu d^i\right], \qquad \mathcal{L}_{D7} = \frac{c_{D7}}{\Lambda^2}\,\overline{\chi}\gamma^\mu\chi\left[\sum_i \overline{u^i}\gamma_\mu\gamma_5 u^i + \sum_i \overline{d^i}\gamma_\mu\gamma_5 d^i\right]$$

- Second scenario: both Wilson coefficients are non-vanishing at the scale Λ. Fixing DM mass and mediator mass scale :





lighter bands if we neglect RGEs

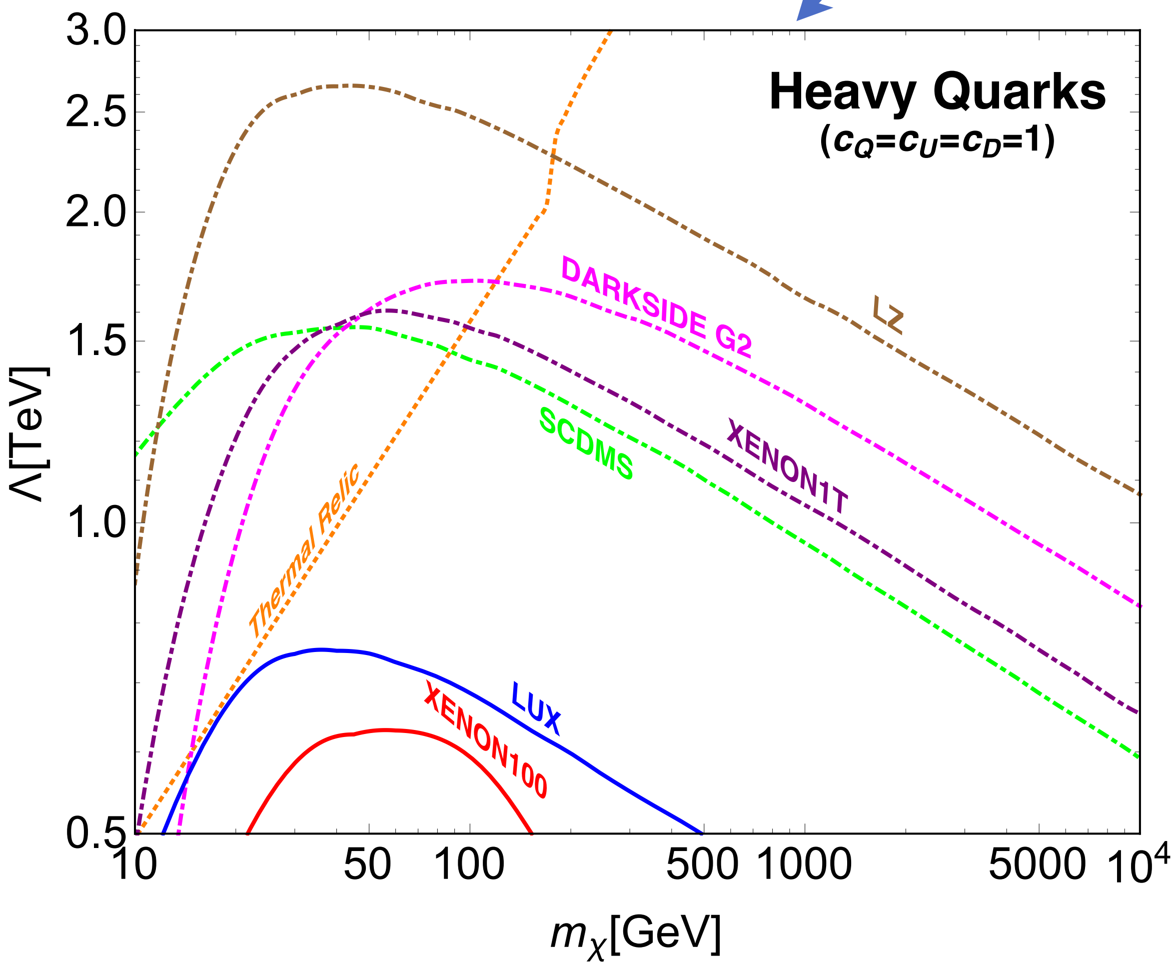
The case of operators with heavy quarks

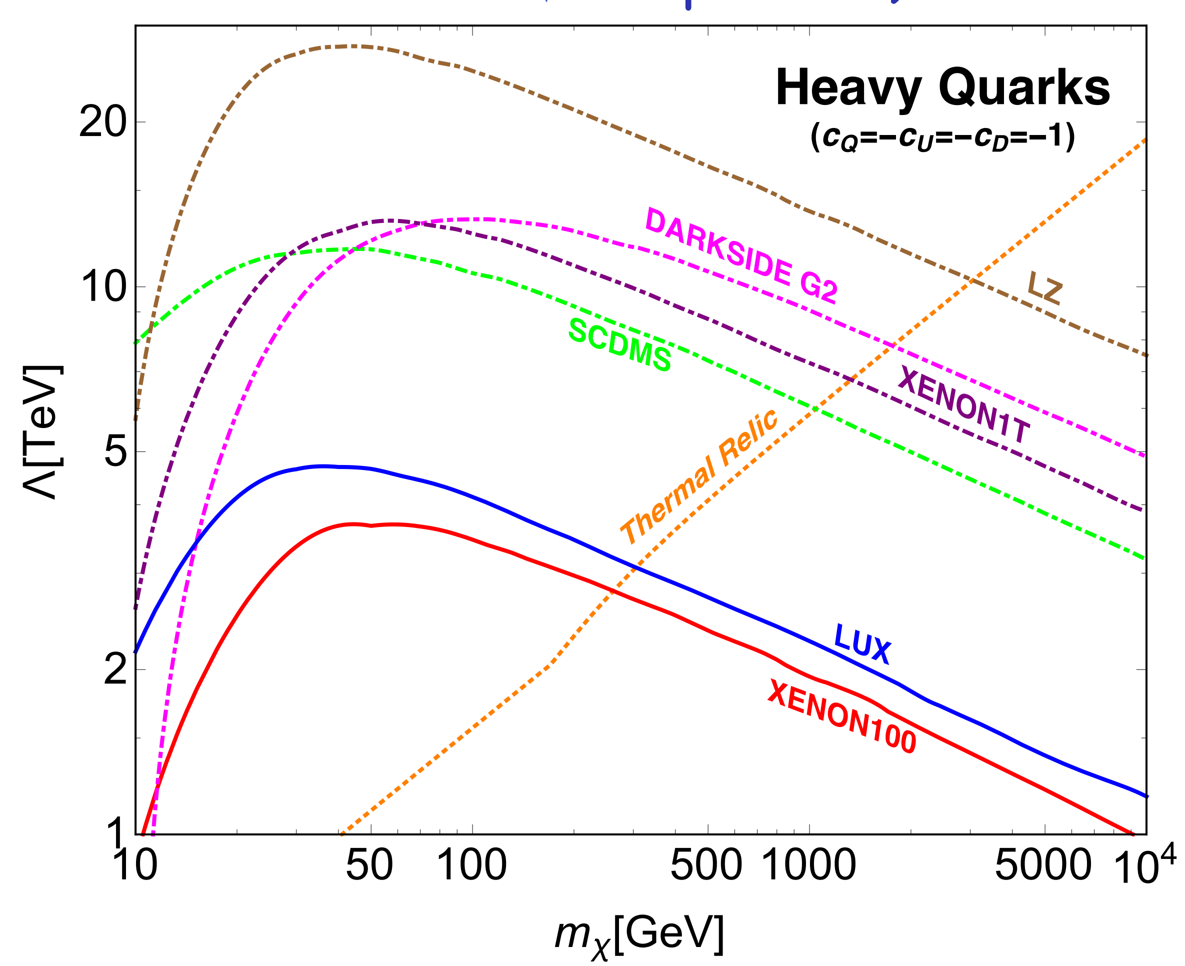
- If we have an UV complete model that couples DM only to heavy quarks

$$c_\Lambda^T\big|_{\mathrm{HQ}} = \left(0\ 0\ 0 \,\vdots\, 0\ 0 \,\big|\, 0\ 0\ 0 \,\vdots\, 0\ 0 \,\big|\, c_Q\ c_U\ c_D \,\vdots\, 0\ 0 \,\big\|\, 0\right)$$

- Less stringent bounds on HQ vector currents than HQ axial currents :

(due to top Yukawa and mixing with Higgs operator)





DM EFT constraints from SM loops

- Our study shows the importance of a systematic analysis which takes into account SM loop effects when connecting operators at mediator mass scale with those at direct detection scale: we can put novel constraints on Wilson coefficients that could not be bounded from direct detection before.
- Exploit complementarity of WIMP searches by describing UV complete models in terms of EFT operators after integrating out heavy mediators.
- We plan to study also the case of Majorana DM and spin-dependent cross section.
- Dim. 7: some mixing effect induced by EW interactions has already been pointed out by Haisch et al. (arXiv:1207.3971, 1302.4454, 1408.5046). Dim. 7 operators lead to interesting effects since EW field strength tensors are involved.
- Systematic and complete EFT analysis up to dim. 7 is desirable.

SI direct detection cross section

- Unsuppressed operators with SM d.o.f. (light q and g) at the DD scale :

$$O_{qq}^{VV} = \frac{1}{\Lambda^2}\,\bar\chi\gamma^\mu\chi\,\bar q\,\gamma_\mu\,q \qquad O_{qq}^{SS} = \frac{m_q}{\Lambda^3}\,\bar\chi\chi\,\bar q q \qquad O_{gg}^{S} = \frac{\alpha_s}{\Lambda^3}\,\bar\chi\chi\,G_{\mu\nu}G^{\mu\nu}$$

- Correspondingly, the proton coupling in the DM-nucleus cross section, up to dim. 7 :

$$f_p = \frac{1}{\Lambda^2}\left[\sum_{q=u,d} C_{qq}^{VV}\,f_{V_q}^p + \frac{m_N}{\Lambda}\left(\sum_{q=u,d,s} C_{qq}^{SS}\,f_q^p - 12\pi\,C_{gg}^{S}\,f_Q^p\right)\right]$$

▶ we now focus on the scalar couplings: $\langle N|m_q\bar q q|N\rangle = f_q^N m_N$

> f_q^N are sources of hadronic uncertainties: how to quantify them reliably?

Scalar couplings: traditional approach

- Usually two-flavor couplings $f_{u,d}^{p,n}$ are extracted from three-flavor quantities

Ellis et al. (2000, 2008); micrOMEGAs

$$y = \frac{2\langle N|\bar{s}s|N\rangle}{\langle N|\bar{u}u + \bar{d}d|N\rangle} \quad \text{and} \quad z = \frac{\langle N|\bar{u}u - \bar{s}s|N\rangle}{\langle N|\bar{d}d - \bar{s}s|N\rangle}$$

↓

$$f_d^p = \frac{2\,\sigma_{\pi N}}{(1 + m_u/m_d)\, m_p\, (1 + \alpha)}$$

with $\alpha = \frac{2z - (z-1)y}{2 + (z-1)y}$ and $\sigma_{\pi N} = 1/2\,\langle N|(m_u + m_d)(\bar{u}u + \bar{d}d)|N\rangle$

"pion-nucleon sigma term"

- y determined with large uncertainties from SU(3) Chiral Perturbation Theory

Borasoy, Meissner (1997)

z extracted from baryon octet mass relations derived in the SU(3) symmetric limit

Cheng (1989)

→ impossible within this approach to assign reliable theory uncertainties

Chiral Perturbation Theory

- Effective theory of QCD for energies below 1 GeV

- Effective d.o.f. are matter fields (nucleons, etc.) and Goldstone bosons associated with spontaneous chiral symmetry breaking (pions in two-flavor case, also kaons and eta in the three-flavor case)

- Explicit chiral symmetry breaking due to small u-, d- (and s-) quark masses

$$m_\pi^2 = B\,(m_u + m_d) + \mathcal{O}(m_{u,d}^2)$$

- Chiral expansion in small external momenta and quark (i.e. pion-, kaon-) masses

$$\left(\frac{p}{\Lambda_\chi}\right)^n, \quad \left(\frac{m_{\mathrm{GB}}}{\Lambda_\chi}\right)^n \quad \text{where} \quad \Lambda_\chi \simeq 1\,\mathrm{GeV}$$

- SU(2) ChPT better convergence in the quark mass expansion than SU(3) ChPT

Scalar couplings: our approach

- Unnecessary assumptions about soft SU(3) flavor symmetry breaking can be avoided by evaluating two-flavor matrix elements in SU(2) ChPT: better convergence properties and reliable uncertainty estimates

- From the quark mass expansion of m_N with strong isospin breaking $(m_u \neq m_d)$,

$$f_u^N = \frac{\sigma_{\pi N}}{2m_N}(1-\xi) + \Delta f_u^N, \qquad f_d^N = \frac{\sigma_{\pi N}}{2m_N}(1+\xi) + \Delta f_d^N$$

with $$\xi = \frac{m_d - m_u}{m_d + m_u} = 0.36 \pm 0.04$$

$$\Delta f_u^p = (1.0 \pm 0.2) \cdot 10^{-3}, \qquad \Delta f_u^n = (-1.0 \pm 0.2) \cdot 10^{-3},$$

$$\Delta f_d^p = (-2.1 \pm 0.4) \cdot 10^{-3}, \qquad \Delta f_d^n = (2.0 \pm 0.4) \cdot 10^{-3}$$

Crivellin, Hoferichter, M.P. (2014)

- Isospin violation effects $(f_u^p - f_u^n)$ and $(f_d^p - f_d^n)$ are overestimated by a factor of 2 in the traditional approach by Ellis et al. and micrOMEGAs

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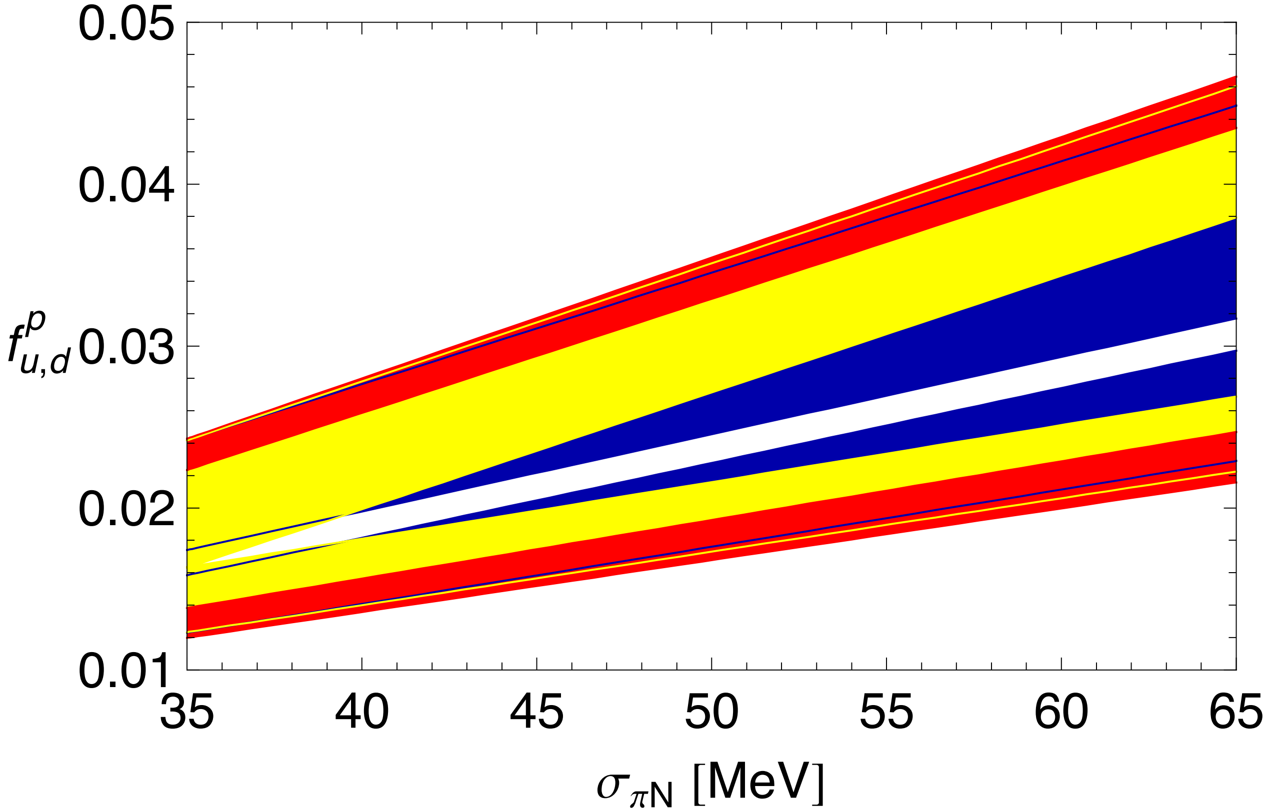
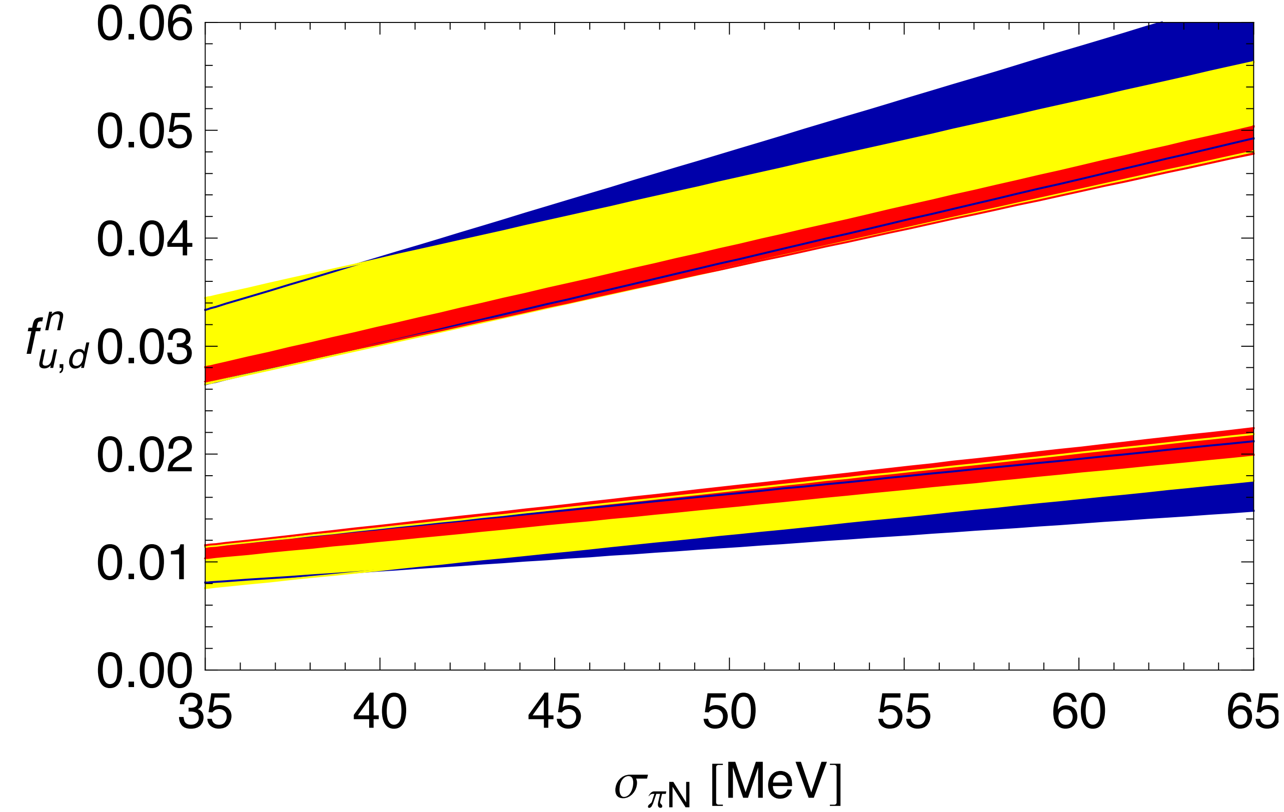
- Coupling with s-quark: average of lattice QCD results, $f_s^N = 0.043 \pm 0.011$

Junnarkar, Walker-Loud (2013)

- Heavy quark coupling : $f_Q^N = \frac{2}{27}(1 - f_u^N - f_d^N - f_s^N)$

Comparison between two approaches

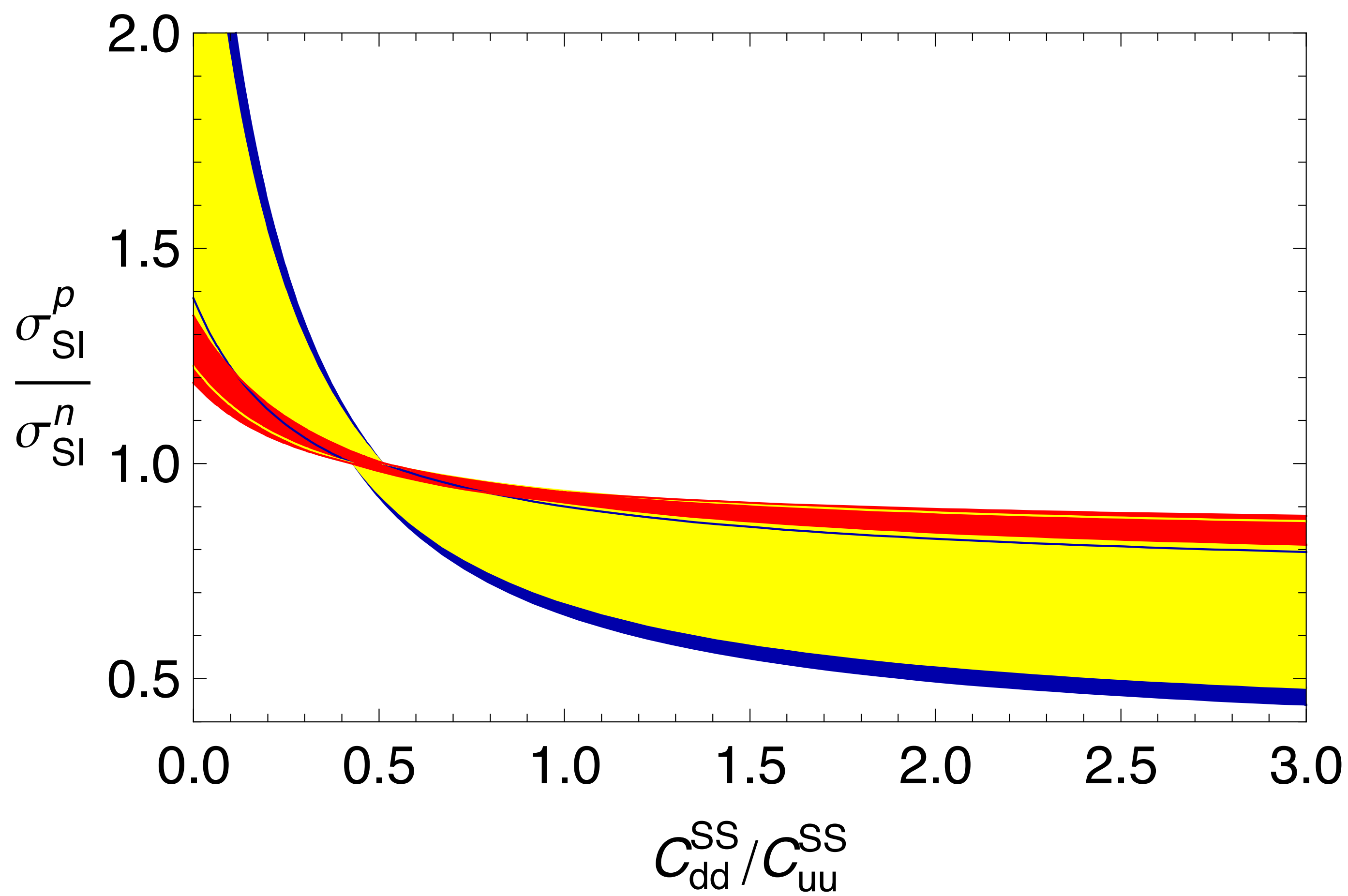




- Red bands: our approach
- Yellow bands: traditional approach with y estimated from SU(3) ChPT and z supplemented with a 30% error
- Blue bands: traditional approach with y estimated from lattice value for f_s^N and z supplemented with a 30% error

Isospin violation in the scalar sector

- Assume that C_{uu}^{SS} and C_{dd}^{SS} for the DM-quark scalar operators at dim. 7 are the only non-vanishing Wilson coefficients contributing to the SI cross section



here $\sigma_{\pi N} = 50\,\mathrm{MeV}$

Uncertainties get drastically reduced in our approach

Smaller isospin violating effects than previously thought

Conclusions and Outlook

- EFTs are useful tools in the context of direct detection of Dark Matter. They allow us to argue independently of details of specific UV completions and to properly connect operators at different scales, involving different d.o.f.

- A complete, systematic analysis for operators up to dimension 7 is motivated and desirable. Very stringent bounds are expected from forthcoming experiments.

- Chiral effective field theory allows us to estimate hadronic uncertainties in nucleon matrix elements contributing to direct detection. Ongoing efforts to pin down the crucial pion-nucleon sigma term (based on lattice QCD, dispersion relations and ChPT...) and to extend the chiral approach to incorporate nuclear effects (see for example Cirigliano, Graesser, Ovanesyan, 1205.2695).