Electroweak corrections to Dark Matter Direct Detection

Rui Santos

ISEL & CFTC-UL

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Azevedo, Duch, Grzadkowski, Huang, Iglicki, Glaus, Mühlleitner, Müller, Patel, Römer, Biekötter, Gabriel, Olea-Romacho

JHEP 01 (2019) 138, 1810.06105 [hep-ph]; JHEP 10 (2019) 152, 1908.09249 [hep-ph], JHEP 12 (2020) 034, 2008.12985 [hep-ph], Phys.Lett.B 833 (2022) 137342, 2204.13145 [hep-ph], JHEP 10 (2022) 126, 2207.04973 [hep-ph].

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Peculiar Scalar extensions of the SM

Some models have negligible dark matter direct detection (DD) cross section at zero momentum transfer (at leading order). Barely affected by direct detection bounds.

True for models with a pNG dark matter candidate with origin in a potential of the form

$$\mathcal{V} = \sum_{ij} m_{ij}^2 \phi_i^\dagger \phi_j + \sum_{ijkl} \lambda_{ijkl}\, \phi_i^\dagger \phi_j \phi_k^\dagger \phi_l + \sum_{ij} \kappa_{ij} \left|\mathbb{S}\right|^2 \phi_i^\dagger \phi_j - \mu_S^2 \left|\mathbb{S}\right|^2 + \lambda_S \left|\mathbb{S}\right|^4 + \mu^2(\mathbb{S}^2 + \mathbb{S}^{*2})$$

with

$$\phi_i = \begin{pmatrix} c^\pm \\ \frac{1}{\sqrt{2}}(v_i + a_i + i b_i) \end{pmatrix} \qquad \mathbb{S} = \frac{1}{\sqrt{2}}(v_S + S + iA)$$

which is a model with N Higgs Doublet Model plus a complex singlet.

The potential is invariant under

$$\mathbb{S} \to \mathbb{S}^* \qquad \text{Stabilises } A$$

and without the red term it is also invariant under

$$\mathbb{S} \to e^{i\alpha}\mathbb{S}$$

The soft breaking term gives mass to the pNG dark matter.

Let us start with just one doublet and one complex singlet (CxSM)

The SM is extended by an extra complex scalar singlet $\mathbb{S}$ which has a global U(1) symmetry

$$\mathbb{S} \to e^{i\alpha}\mathbb{S}$$

Softly break dark U(1) symmetry to the residual Z_2 symmetry in one of the singlet components

$$\mathcal{L} = \mathcal{L}_{SM} + (D_\mu \mathbb{S})^\dagger (D^\mu \mathbb{S}) + \mu_S^2 \left|\mathbb{S}\right|^2 - \lambda_S \left|\mathbb{S}\right|^4 - \kappa \left|\mathbb{S}\right|^2 H^\dagger H + \mu^2(\mathbb{S}^2 + \mathbb{S}^{*2}) \qquad \mathbb{S} \to \mathbb{S}^*$$

SM + dark matter candidate A + a new scalar that mixes with the CP-even field in the doublet such that

$$m_\pm = \lambda_H v_H^2 + \lambda_S v_S^2 \pm \sqrt{\lambda_H^2 v_H^4 + \lambda_S^2 v_S^4 + \kappa v_H^2 v_S^2 - 2\lambda_H \lambda_S v_H^2 v_S^2}$$

The mass eigenstates fields h_1 and h_2 are obtained from h and S via

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix}$$

The conditions for the potential to be bounded from below are the same for the two models

$$\lambda_H > 0, \qquad \lambda_S > 0, \qquad \kappa > -2\sqrt{\lambda_H \lambda_S}.$$

The scalar mass matrix is

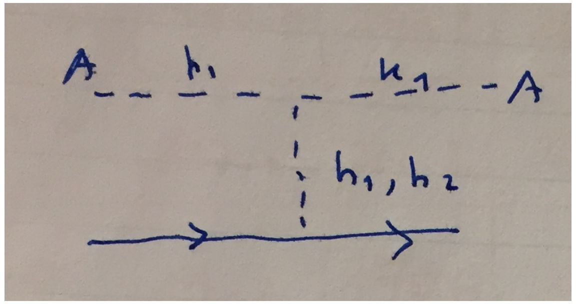
$$\mathcal{M}^2 = \begin{pmatrix} 2\lambda_H v^2 & \kappa v v_S & 0 \\ \kappa v v_S & 2\lambda_S v_S^2 & 0 \\ 0 & 0 & -4\mu^2 \end{pmatrix}$$

$$m_{DM} = -4\mu^2$$

The amplitude for the DM direct detection cross section

Gross, Lebedev, Toma, PRL119 (2017) no.19, 191801

$$i\mathcal{M} \sim \sin\alpha\cos\alpha\left(\frac{im_{h_2}^2}{t-m_{h_2}^2}-\frac{im_{h_1}^2}{t-m_{h_1}^2}\right)\left(\frac{-im_f}{v}\right)\bar{u}_f(k_2)u_f(p_2) \sim 0 \qquad (t\to 0)$$



And it vanishes for zero momentum transfer. Why? Going back to the Lagrangian,

$$\mathcal{L} = \mathcal{L}_{SM} + (D_\mu\mathbb{S})^\dagger(D^\mu\mathbb{S}) + \mu_S^2\left|\mathbb{S}\right|^2 - \lambda_S\left|\mathbb{S}\right|^4 - \kappa\left|\mathbb{S}\right|^2 H^\dagger H + \mu^2(\mathbb{S}^2+\mathbb{S}^{*2}) \qquad \mathbb{S}\to\mathbb{S}^*$$

Writing

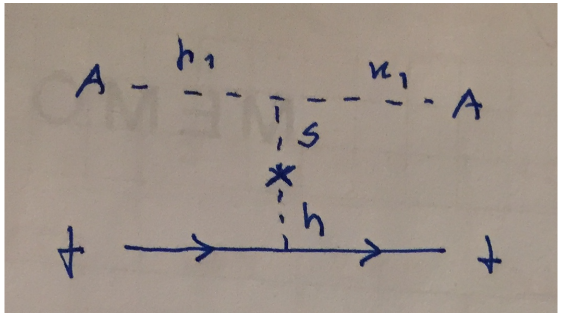
$$\mathbb{S} = \frac{v_S+S}{\sqrt{2}}e^{i\frac{A}{v_S}} \quad \Rightarrow \quad V_{soft} = -\mu^2(v_S+S)^2\cos\left(\frac{2A}{v_S}\right) = -\mu^2(v_S+S)^2\left(1-\frac{2A^2}{v_S^2}\right)+\ldots$$

Including the kinetic term leads to the following Lagrangian interaction

$$\mathcal{L}_{SA^2} = = \frac{1}{2v_S}(\partial^2 S)A^2 - \frac{1}{v_S}SA(\partial^2+m_A^2)A$$

First term proportional to p^2 of S and the second term vanishes when the DM particle is on-shell.
Amplitude is proportional to p^2 with A on-shell.

Cancellation in the CxSM



$$i\mathcal{M} \sim \left(\frac{-it}{v_S}\right)\frac{i}{t-m_S^2}(-i2\lambda_{SH}vv_S)\frac{i}{t-m_h^2}\left(\frac{-im_f}{v}\right)\bar{u}_f(k_2)u_f(p_2)$$

Which vanishes when t = 0

Azevedo, Duch, Grzadkowski, Huang, Iglicki, RS, PRD99, 015017 (2019)

Cai, Zeng, Zhang, JHEP 01 117 (2022).

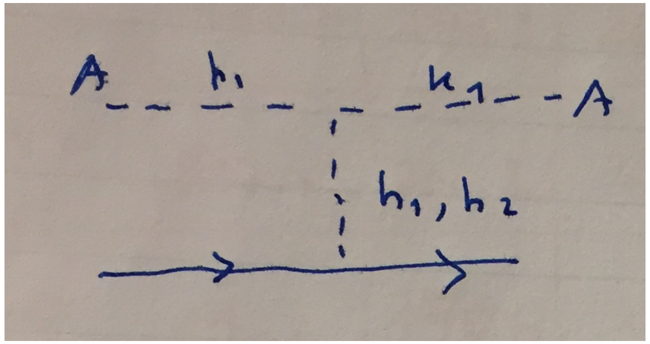
Note however if other soft breaking terms are added

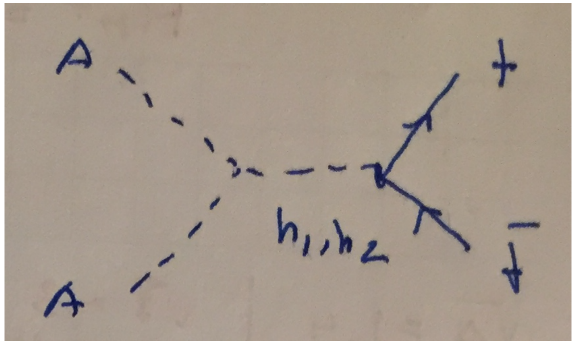
$$V'_{soft} = -\kappa_1^3(\mathbb{S}+\mathbb{S}^*) - \kappa_2|\mathbb{S}|^2(\mathbb{S}+\mathbb{S}^*) - \kappa_3(\mathbb{S}^3+\mathbb{S}^{*3})$$

the cancellation is lost except for fine-tuned values of the couplings

$$\kappa_1^3 = \frac{1}{2}(\kappa_2+9\kappa_3)v_S^2$$

Note that the cancellation does not happen in scattering





INDEPENDENT PARAMETERS

$$m_{DM};\ \sin\alpha;\ m_2;\ v_S$$

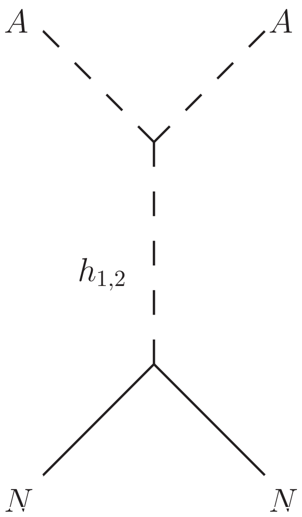
- m_{DM} → Mass of the DM particle
- $\sin\alpha$ → Mixing angle between doublet and singlet (real)
- m_2 → Mass of the second scalar
- v_S → Singlet VEV

There is obviously a 125 GeV Higgs (other scalar can be lighter or heavier).

Experimental and theoretical constraints included.

One-loop corrections in cXSM

The one-loop calculation in the CxSM



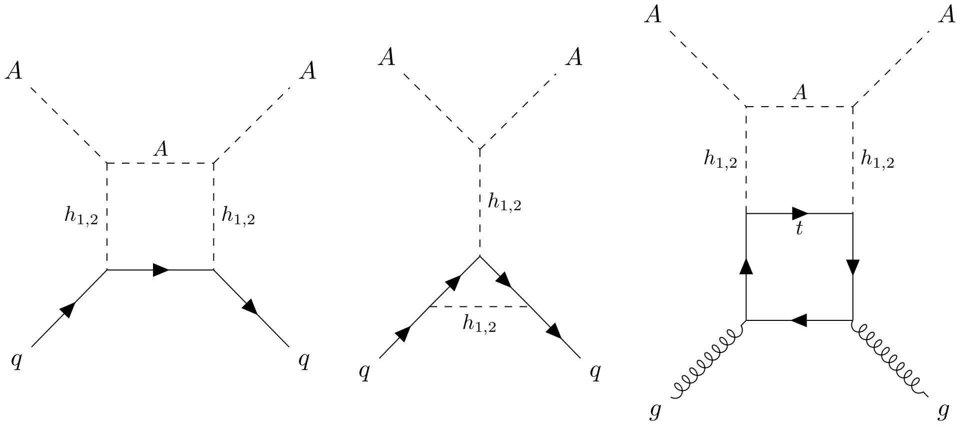
$$-i\mathcal{M}_{\text{tree}} \approx -i\frac{s_\alpha c_\alpha f_N m_N}{v_H v_S}\left(\frac{m_1^2 - m_2^2}{m_1^2 m_2^2}\right) q^2 \bar{u}_N(p_4) u_N(p_2)$$

The tree-level amplitude is proportional to q^2, this means more than 10 orders of magnitude below the recent experimental DD bounds.

In the one-loop calculation we will still work at the nucleon level, combining the Higgs-quark and Higgs-gluon couplings to a nucleon into a single Higgs-nucleon-nucleon form factor $f_N\, m_N\, / v_H$.

We work in the limit of zero momentum transfer $q^2 \to 0$ in order to simplify our calculation - the terms proportional to q^2 are suppressed by powers of the relative DM velocities.

Negligible contributions and counterterms



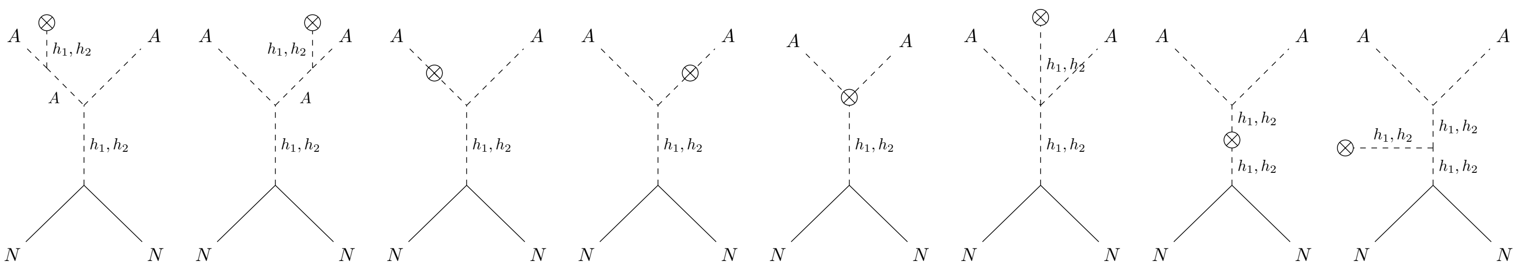
(a) (b) (c)

At the fundamental level, the DM-nucleon scattering can be understood as the scattering of the DM particle A with light quarks and gluons.

Light quark Yukawa couplings are extremely small, the diagrams (a) and (b) with multiple insertions of light quark Yukawa couplings, are expected to be negligibly small. Diagram (c) although small could contribute but we checked that it did not.

The counterterm potential is

$$V_c = -\delta\mu_H^2|H|^2 - \delta\mu_S^2|S|^2 + \delta\mu_H|H|^4 + \delta\mu_S|S|^4 + \delta\kappa|H|^2|S|^2 + (\delta\mu^2 S^2 + h.c.)$$

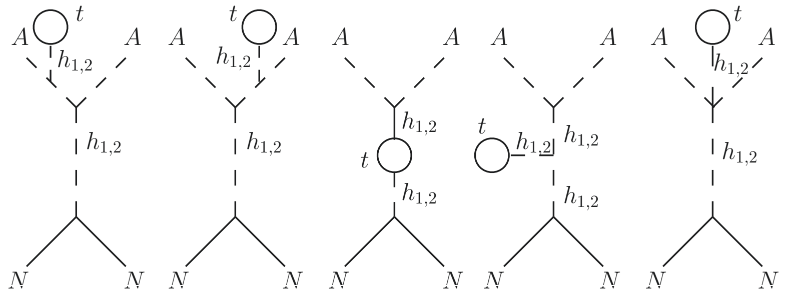


model has 6 independent parameters, we need 6 counterterms to cancel the UV divergences at one-loop.

Sum of all diagrams is zero. No need for renormalisation prescription - sum of all diagrams in the amplitude without counterterms has to be finite. Expected in the limit of zero momentum transfer.

Contribution proportional to the tree-level cross section

Many contributions are proportional to the tree-level amplitude and therefore vanish in the same limit

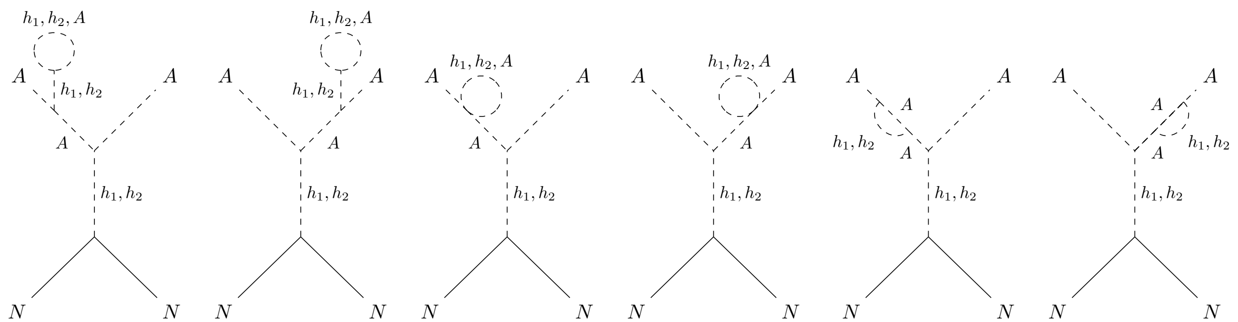


SM particles: quarks, leptons, and electroweak gauge bosons, couple to the Higgs bosons $h_{1,2}$ only through the rotation of the doublet neutral components h. The coupling modifiers are cosα, for h_1 and -sinα for h_2.

For the external lines $$\mathcal{F}_e = (-i)\frac{2L_1}{p^2 - m_A^2}\left(\frac{V_{AA1}c_\alpha}{m_1^2} + \frac{V_{AA2}s_\alpha}{m_2^2}\right)\mathcal{F}_0 = 0$$

$$\mathcal{F}_0 = \frac{V_{AA1}c_\alpha}{m_1^2} - \frac{V_{AA2}s_\alpha}{m_2^2}$$

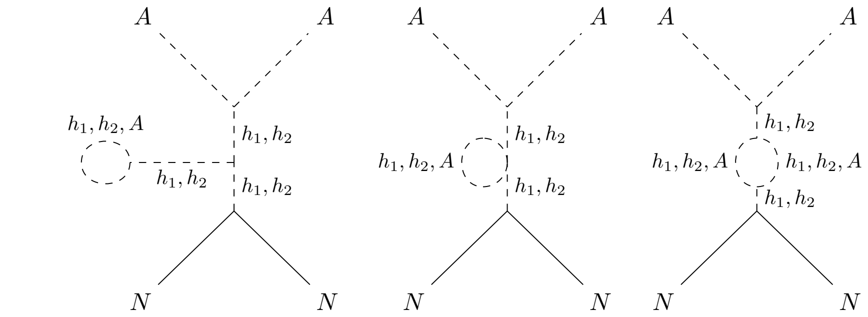
For the internal lines $$\mathcal{F}_{i+v} = \frac{(V^{(1)}_{AA1\,i} + V^{(1)}_{AA1\,v})c_\alpha}{m_1^2} - \frac{(V^{(1)}_{AA2\,i} + V^{(1)}_{AA2\,v})s_\alpha}{m_2^2} = 0$$



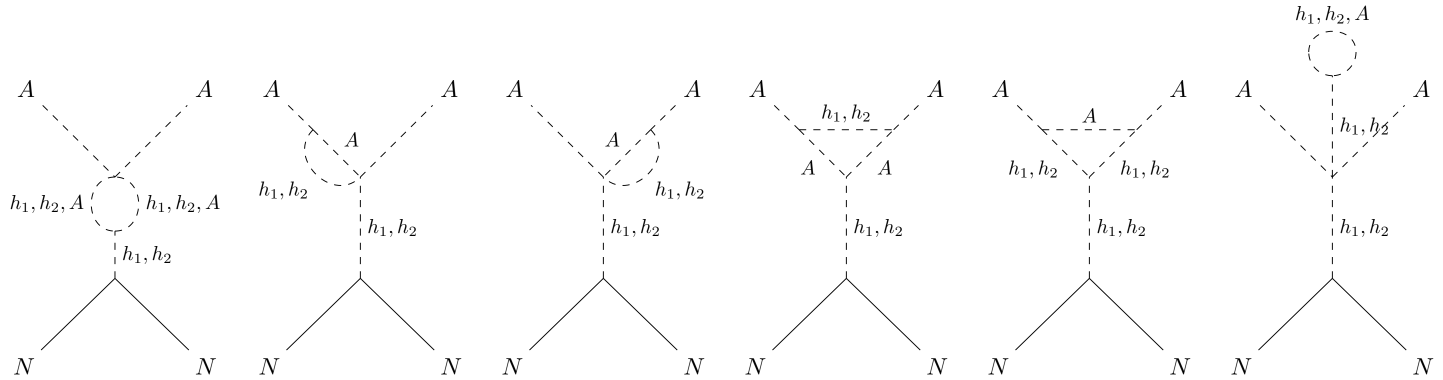
Scalar contributions to the external legs.

For the external lines $$\mathcal{F}_e = \frac{2i}{p^2 - m_A^2}\left[-i\Delta m_A^2 + \frac{2iV_{AA1}\Delta t_1}{m_1^2} + \frac{2iV_{AA2}\Delta t_2}{m_2^2}\right]\mathcal{F}_0 = 0$$

Corrections that survive



Internal scalars



Vertex corrections

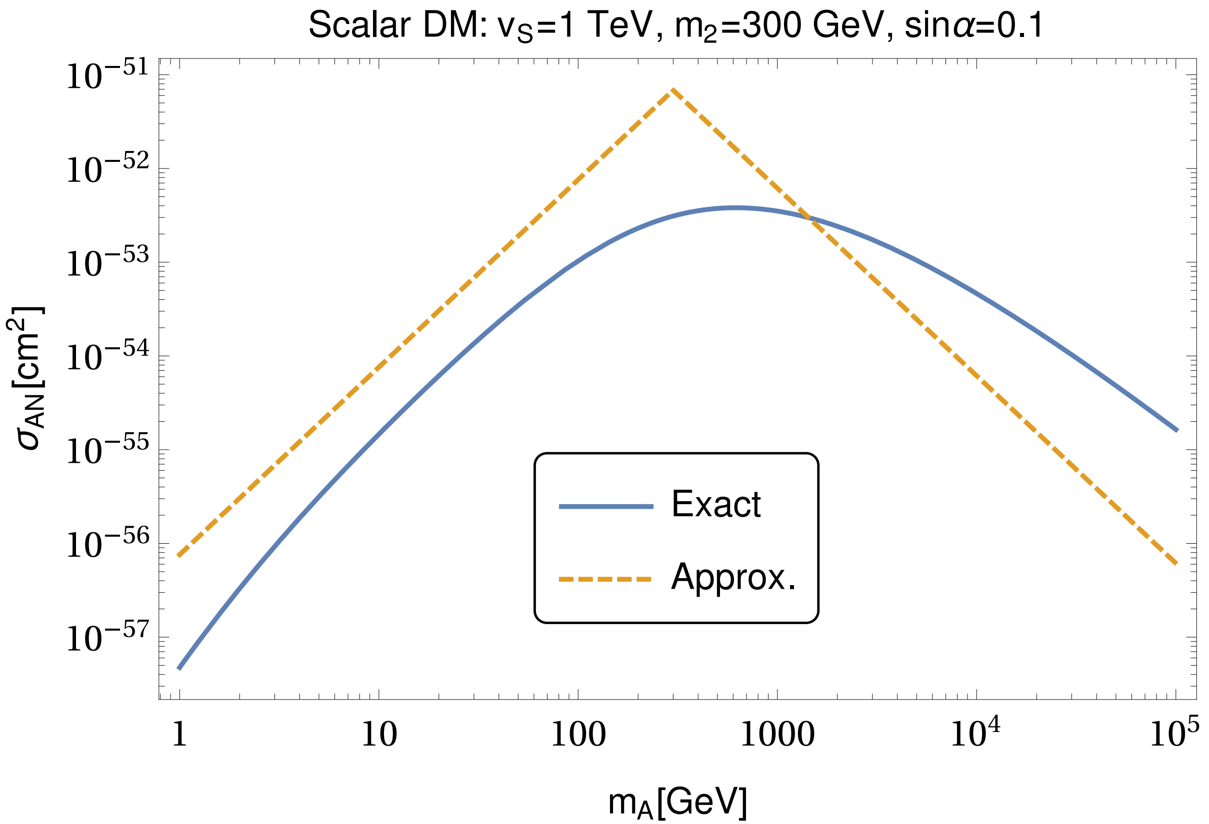
$$\mathcal{F} = -\frac{s_{2\alpha}(m_1^2 - m_2^2)m_A^2}{128\pi^2 v_H v_S^3 m_1^2 m_2^2}\left[\mathcal{A}_1 C_2(0, m_A^2, m_A^2, m_1^2, m_2^2, m_A^2)\right.$$
$$+\mathcal{A}_2 D_3(0, 0, m_A^2, m_A^2, 0, m_A^2, m_1^2, m_1^2, m_2^2, m_A^2)$$
$$\left.+\mathcal{A}_3 D_3(0, 0, m_A^2, m_A^2, 0, m_A^2, m_1^2, m_2^2, m_2^2, m_A^2)\right]$$

Very simple expression that you can insert in your code!

$$\mathcal{A}_1 \equiv 4(m_1^2 s_\alpha^2 + m_2^2 c_\alpha^2)(2m_1^2 v_H s_\alpha^2 + 2m_2^2 v_H c_\alpha^2 - m_1^2 v_S s_{2\alpha} + m_2^2 v_S s_{2\alpha}),$$
$$\mathcal{A}_2 \equiv -2m_1^4 s_\alpha[(m_1^2 + 5m_2^2)v_S c_\alpha - (m_1^2 - m_2^2)(v_S c_{3\alpha} + 4v_H s_\alpha^3)],$$
$$\mathcal{A}_3 \equiv 2m_2^4 c_\alpha[(5m_1^2 + m_2^2)v_S s_\alpha - (m_1^2 - m_2^2)(v_S s_{3\alpha} + 4v_H c_\alpha^3)].$$

$$\sigma_{\mathrm{AN}}^{(1)} = \frac{f_N^2}{\pi v_H^2}\frac{m_N^2 \mu_{\mathrm{AN}}^2}{m_A^2}\mathcal{F}^2$$

One-loop squared - because tree-level is zero



Results for the point presented as a function of the DM mass.

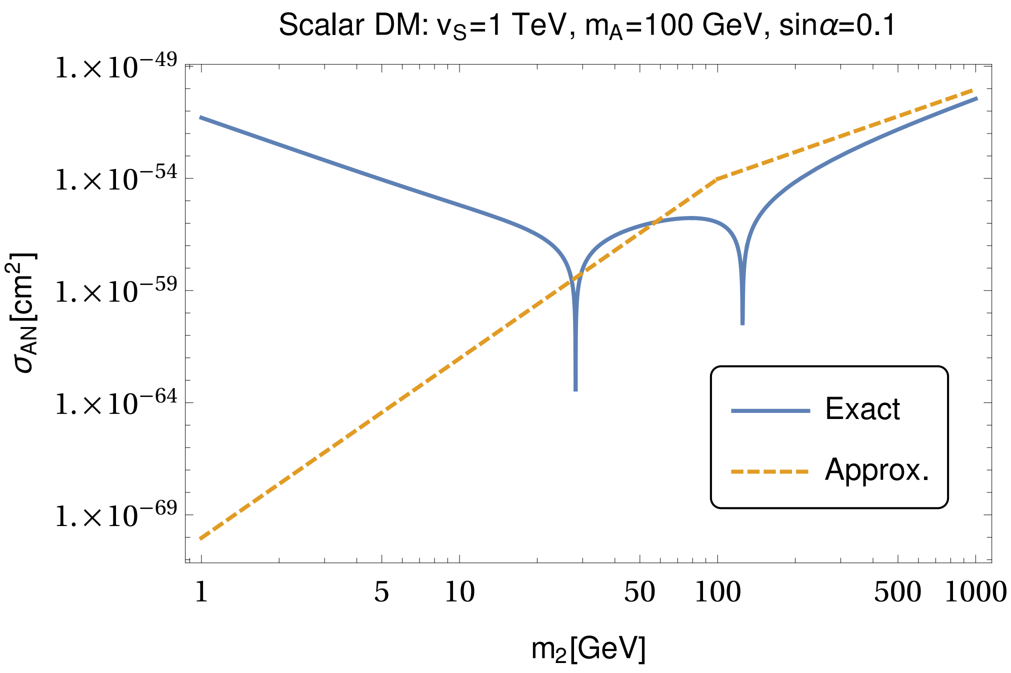
The approximation is quite good in reproducing the shape.

$$\sigma_{\rm AN}^{(1)} \approx \begin{cases} \dfrac{s_\alpha^2}{64\pi^5}\dfrac{m_N^4 f_N^2}{m_1^4 v_H^2}\dfrac{m_2^8}{m_A^2 v_S^6}\,, & m_A \geq m_2 \\[2ex] \dfrac{s_\alpha^2}{64\pi^5}\dfrac{m_N^4 f_N^2}{m_1^4 v_H^2}\dfrac{m_2^4 m_A^2}{v_S^6}\,, & m_A \leq m_2 \end{cases} .$$

Gross, Lebedev, Toma, PRL119 (2017) no.19, 191801

- For this set of parameters, the DM-nucleon scattering cross section varies between 10^{-58} cm^2 and 10^{-52} cm^2 when the DM mass m_A is in the range of 1-10^5 GeV.

- For the same set of the parameters the curve has a maximum value of $\sigma^{(1)} \sim 3 \times 10^{-53}$ cm^2 for $m_A \sim 630$ GeV. The tree-level contribution is $\sigma^{tree} \sim 10^{-69}$-$10^{-65}$ cm^2 for the same set of parameters.

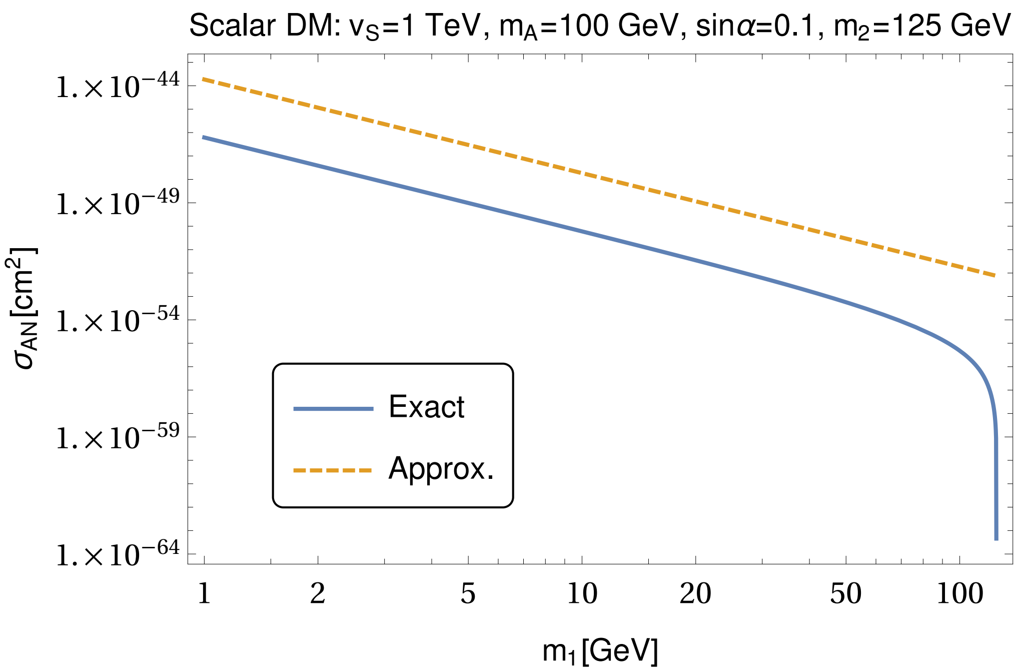


Behaviour with m_2 - approximation substantially deviates from the exact formula.

Two dips appear in the exact calculation:

a) one for $m_2 = m_1$ corresponding to the vanishing of the factor $(m_1^2 - m_2^2)$;

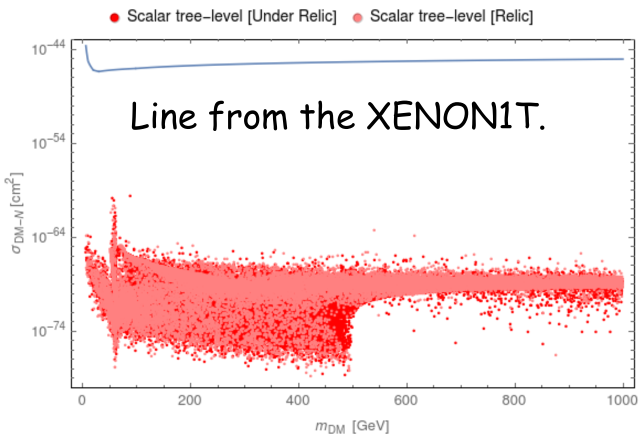
b) another one at around $m_2 \sim 30$ GeV which is caused by accidental cancellation between loop integrals. The location of this dip varies with the set of parameters chosen and is a combination of all input parameters.



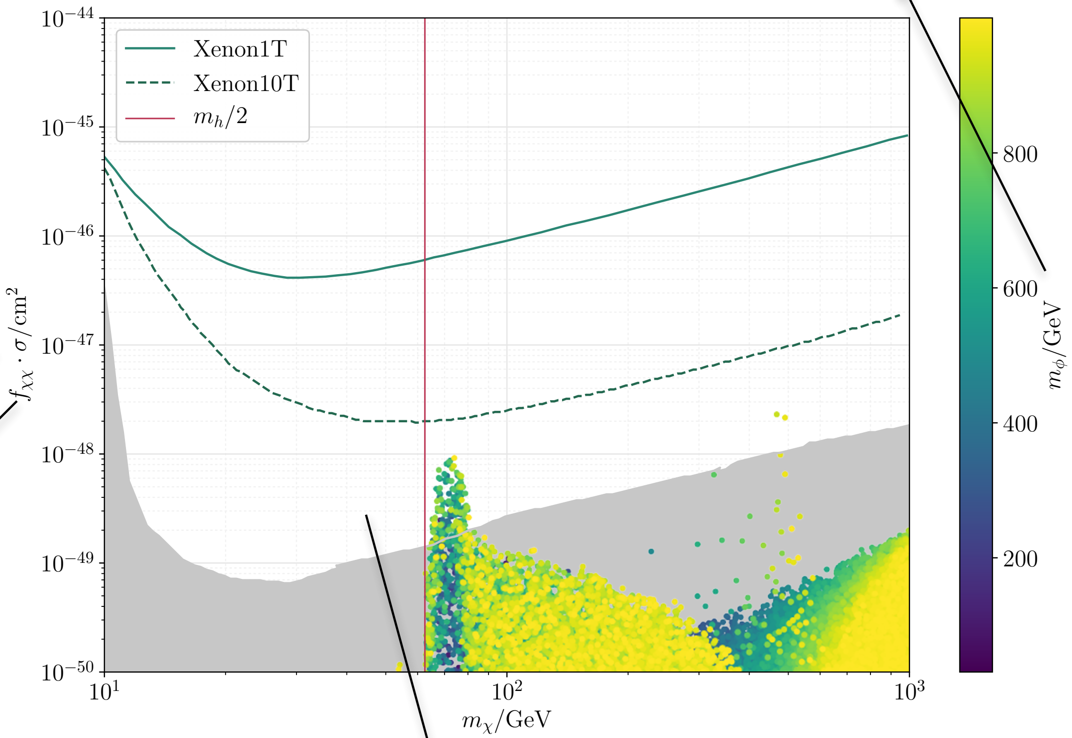
Finally we checked the behaviour with m_1 when m_2 is the 125 GeV Higgs.

Main difference here is just in the vanishing cross section related to the factor $(m_1^2 - m_2^2)$

Scan takes into account the most relevant theoretical and experimental constraints



Mass of the non-SM Higgs



Cross section

DM fraction

LHC Higgs to invisible bound (no points).

Combination of several constraints lead to a few scattered points above the neutrino floor. There are probably much more allowed points (220000 points that passed all constraints).

One-loop corrections in the S2HDM

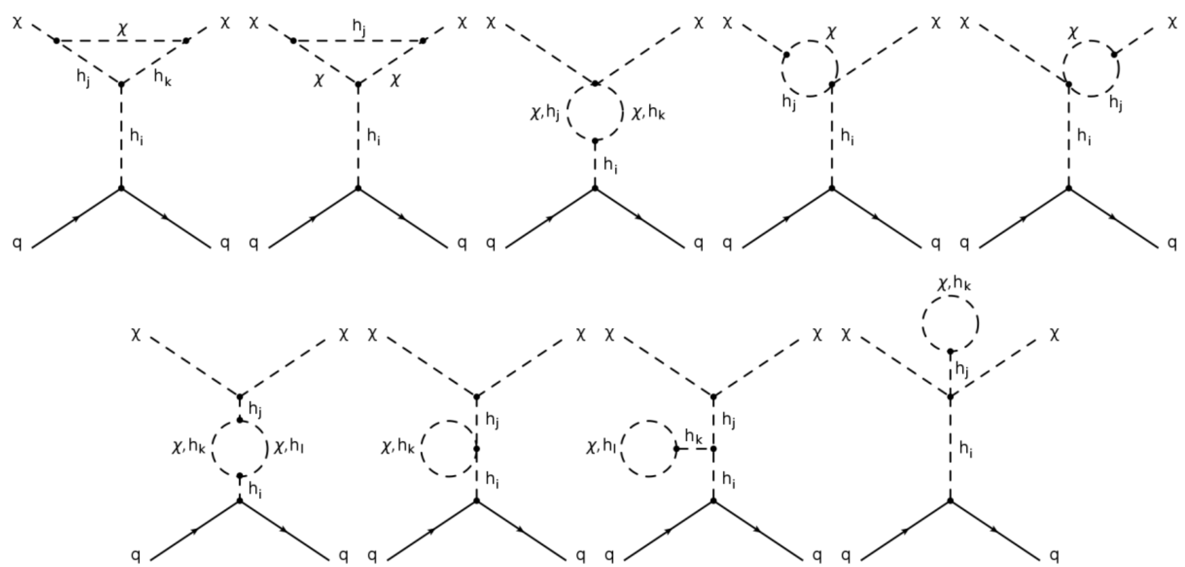
S2HDM - Now the SM is extended by one doublet and a complex singlet. There is an extra doublet compared to the previous model.

$$\mathscr{V} = \sum_{ij} m_{ij}^2 \phi_i^\dagger \phi_j + \sum_{ijkl} \lambda_{ijkl}\, \phi_i^\dagger \phi_j \phi_k^\dagger \phi_l + \sum_{ij} \kappa_{ij} \left|\mathbb{S}\right|^2 \phi_i^\dagger \phi_j - \mu_S^2 \left|\mathbb{S}\right|^2 + \lambda_S \left|\mathbb{S}\right|^4 + \mu^2(\mathbb{S}^2 + \mathbb{S}^{*2})$$

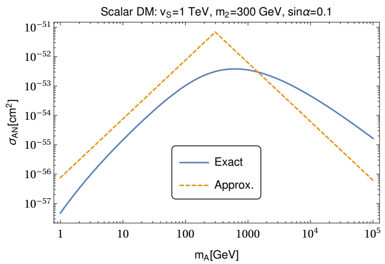
<u>Extra particles</u>: 2 CP-even scalars, 2 charged scalars and 1 CP-odd scalar and a DM particle. Free parameters $m_{h_{1,2,3}}, m_A, m_\chi, \alpha_{1,2,3}, \tan\beta, m_{12}^2, v_S$.

These models can lead to tree-level flavour changing neutral currents. These are very constrained by experiment. To solve this problem one usually forces the Yukawa Lagrangian to be invariant under a Z_2 symmetry. This leads to 4 possible Yukawa Lagrangians (the way scalars are combined with fermions).

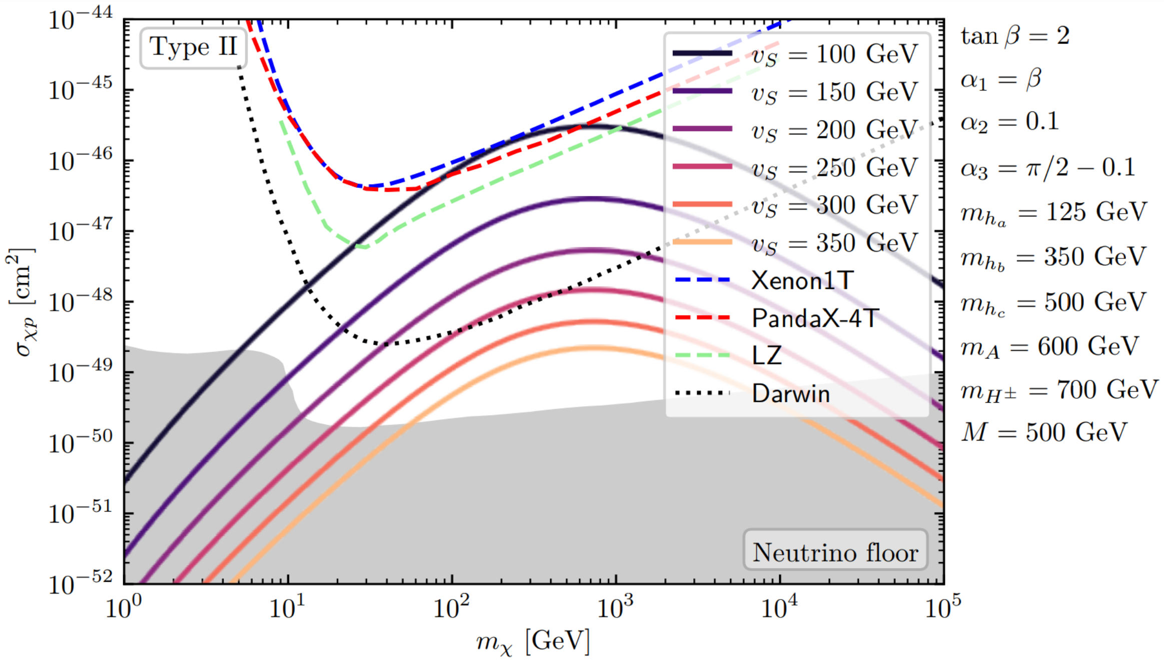
We just consider Type I and Type II. Besides that we just have more particles in the loop.

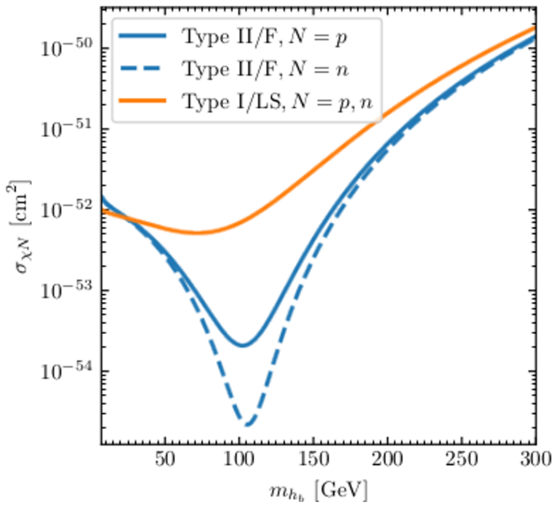


Diagrams that survive. Same type of diagrams as for the CxSM but with more particles in the loop.



Generic behaviour of the loop corrected cross section Type II



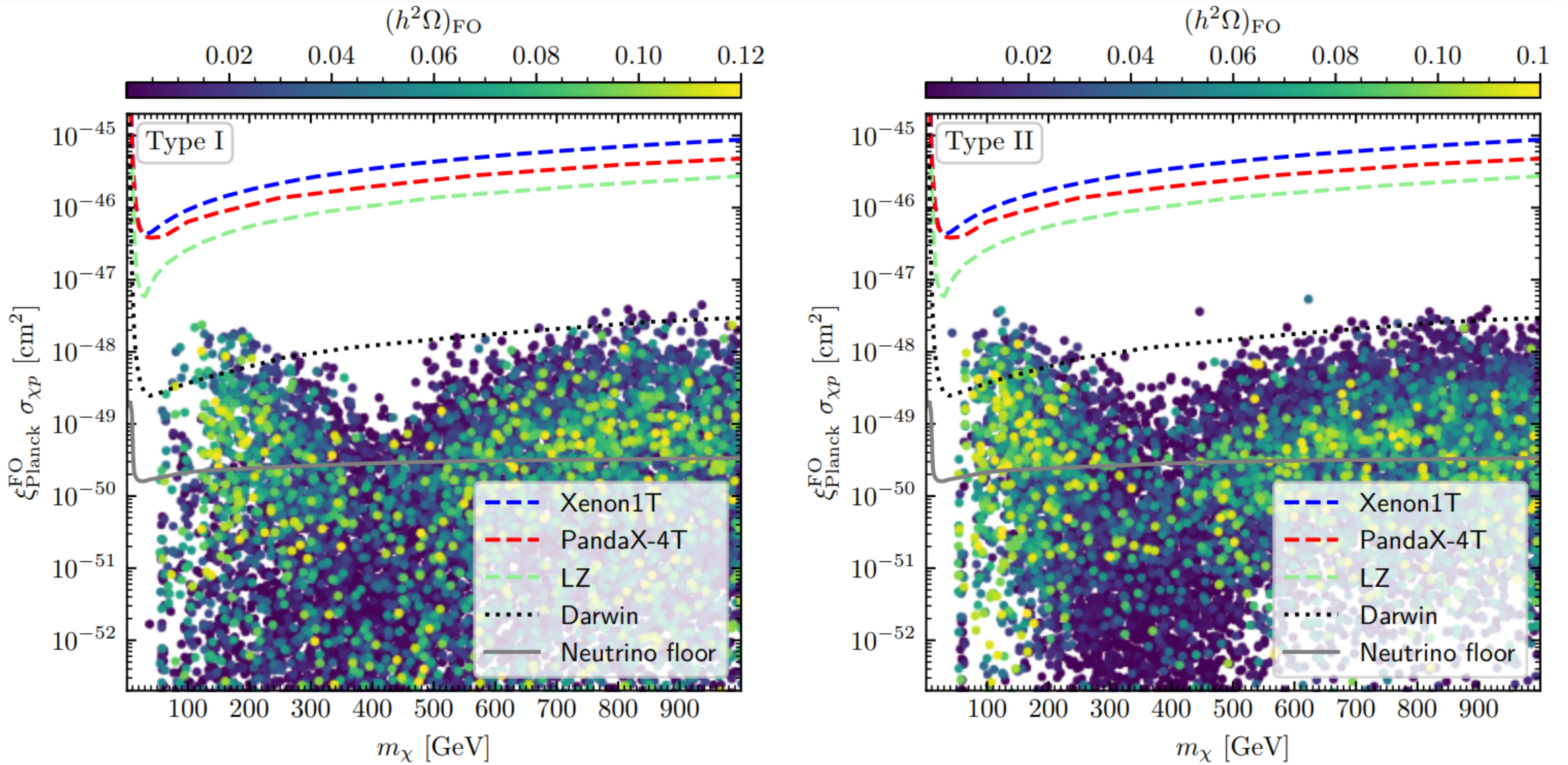


Type dependent blind-spots

Here we just fixed all input parameters except for the VEV of the singlet. The behaviour is similar for all values of the singlet VEV but as the VEV gets smaller a larger mass region in the WIMP region is excluded.

We also show Darwin as an example of some future projection. This is the total cross section.

Experimental prospect for direct detection in Types I and II



Type	m_{h_a}	$m_{h_b}, m_{h_c}, m_A, m_\chi$	$m_{H^\pm}$	$\alpha_{1,2,3}$	$\tan\beta$	M	v_S
I	125.09	[30,1000]	[150,1000]	$[-\pi/2, \pi 2]$	[1.5,10]	[20, 1000]	[30,1000]

Type	m_{h_a}	m_{h_b, m_A}	$m_{H^\pm}$	$m_{h_c,\chi}$	$\alpha_{1,2,3}$	$\tan\beta$	M	v_S
II	125.09	[200,1000]	[650,1000]	[30,1000]	$[-\pi/2, \pi 2]$	[1.5,10]	[450, 1000]	[30,1000]

One-loop corrections in a VDM model

A simple Vector Dark Matter (VDM) model

Dark $U(1)_X$ gauge symmetry: all SM particles are $U(1)_X$ neutral.
New complex scalar field - scalar under the SM gauge group but has unit charge under $U(1)_X$.
Lagrangian invariant under

$$X_\mu \to -X_\mu, \quad \mathbb{S} \to \mathbb{S}^*$$

Forbids kinetic mixing between the SM gauge boson from $U(1)_Y$ and the dark one from $U(1)_X$. The Lagrangian is

$$\mathscr{L} = \mathscr{L}_{SM} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} + (D_\mu \mathbb{S})^\dagger (D^\mu \mathbb{S}) + \mu_S^2 \left|\mathbb{S}\right|^2 - \lambda_S \left|\mathbb{S}\right|^4 - \kappa \left|\mathbb{S}\right|^2 H^\dagger H \qquad D_\mu = \partial_\mu + i g_X X_\mu$$

with

$$H = \begin{pmatrix} G^\pm \\ \frac{1}{\sqrt{2}}(v_H + h + i G_0) \end{pmatrix} \qquad \mathbb{S} = \frac{1}{\sqrt{2}}(v_S + S + i A)$$

h is the real doublet component, S is the new real scalar component and A is the Goldstone boson related with $U(1)_X$.

Hambye, JHEP 0901 (2009) 028. Lebedev, Lee, Mambrini, PLB707 (2012) 570. Farzan, Akbarieh; JCAP 1210 (2012) 026. Baek, Ko, Park, Senaha; JHEP 1305 (2013) 036, ...

With the previous definitions, the masses of the gauge bosons are

$$m_W = \frac{1}{2} g v_H; \; m_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\, v_H; \; m_{DM} = g_X v_S$$

and the masses of the two scalars are

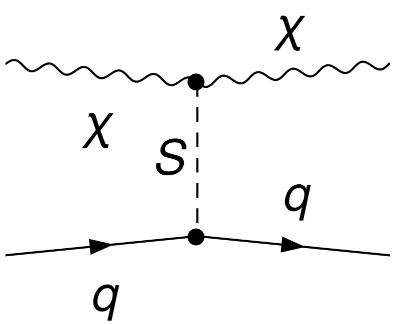
$$m_{\pm} = \lambda_H v_H^2 + \lambda_S v_S^2 \pm \sqrt{\lambda_H^2 v_H^4 + \lambda_S^2 v_S^4 + \kappa v_H^2 v_S^2 - 2\lambda_H \lambda_S v_H^2 v_S^2}$$

The mass eigenstates fields h_1 and h_2 are obtained from h and S via

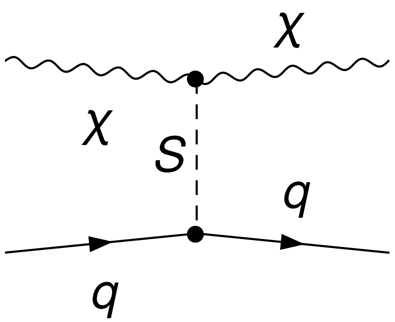
$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix}$$

Originally we studied this model because it is equal to the CxSM in the number of particles and number of parameters.

There is no tree-level cancelation in this case. Are electroweak one-loop corrections relevant?

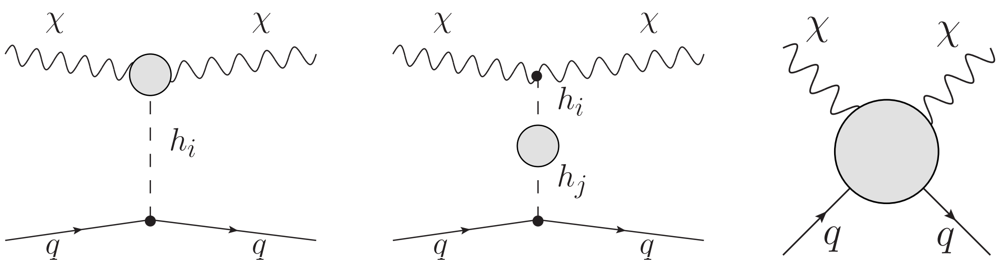


One-loop corrections in the VDM model



$$\mathcal{L}^{eff} = \sum_{q=u,d,s} \mathcal{L}_q^{eff} + \mathcal{L}_G^{eff}$$

We have used an effective Lagrangian starting with the interaction of dark matter with quarks and gluons.



(a) Vertex Corrections (b) Mediator Corrections (c) Box Corrections

Loops are calculated - including also CT diagrams. The result can be written in terms of the form factors of the effective Lagrangian.

Goodman, Witten, PRD31 3059 (1985); Ellis, Flores, NPB3017 883 (1988). K. Griest, PRL62 666 (1988); PRD38 2357 (1988); Srednicki, Watkins, PLB225 140 (1989); Giudice, Roulet, NPB316 429 (1989); Drees, Nojiri, PRD48 3483 (1993)

Hill, Solon, PRD91 043505 (2015)

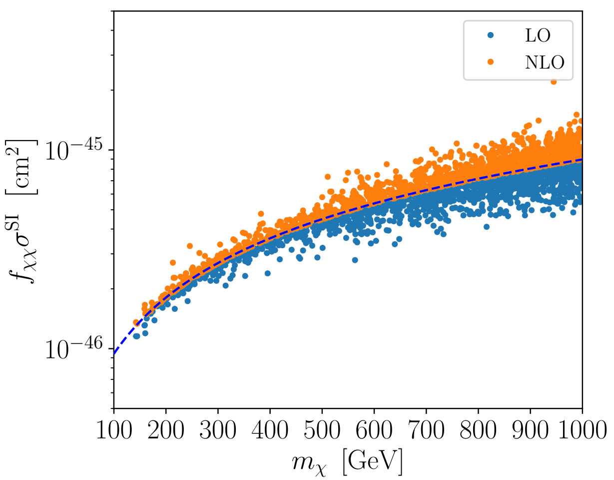
Hisano, Ishiwata, Nagaya, Yamanaka, PTP126 435 (2011)

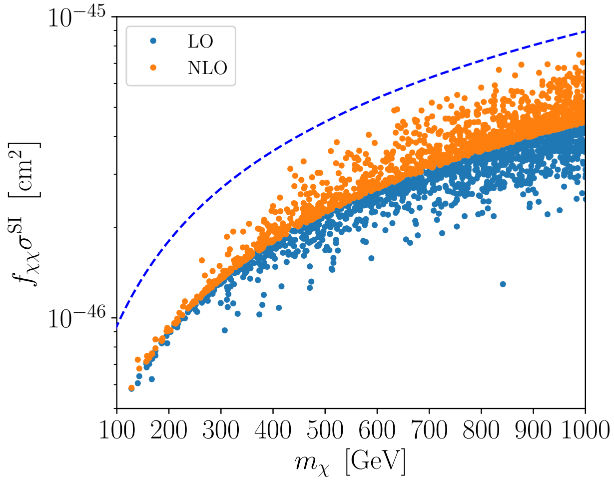
Abe, Fujiwara, and Hisano, JHEP 02 028 (2019)

Ertas, Kahlhoefer, JHEP06 052 (2019)

Results are translated into interactions with nucleons using the matrix elements of the quark and gluon operators in a nucleon state.

NLO vs. LO results for the VDM model





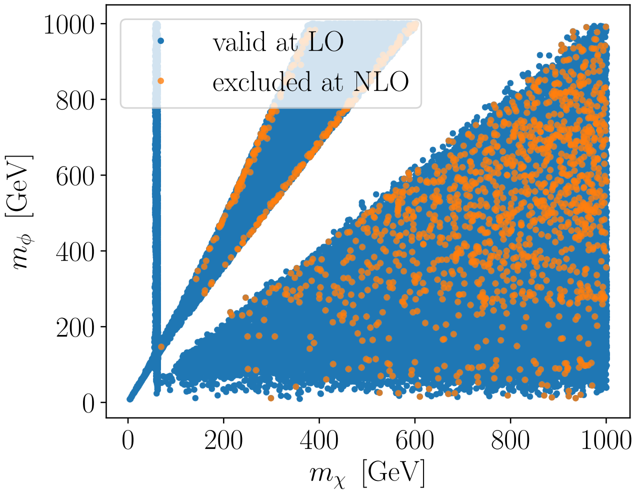
The K-factor (NLO/LO) is mostly positive and the bulk of K-factor values ranges between 1 and about 2.3.

Largest contribution comes from the triangle diagrams which are proportional to g_χ^3 at one-loop. If the coupling is below 1 corrections are smaller than 10%.

Left: points that are not excluded at LO but are excluded at NLO.

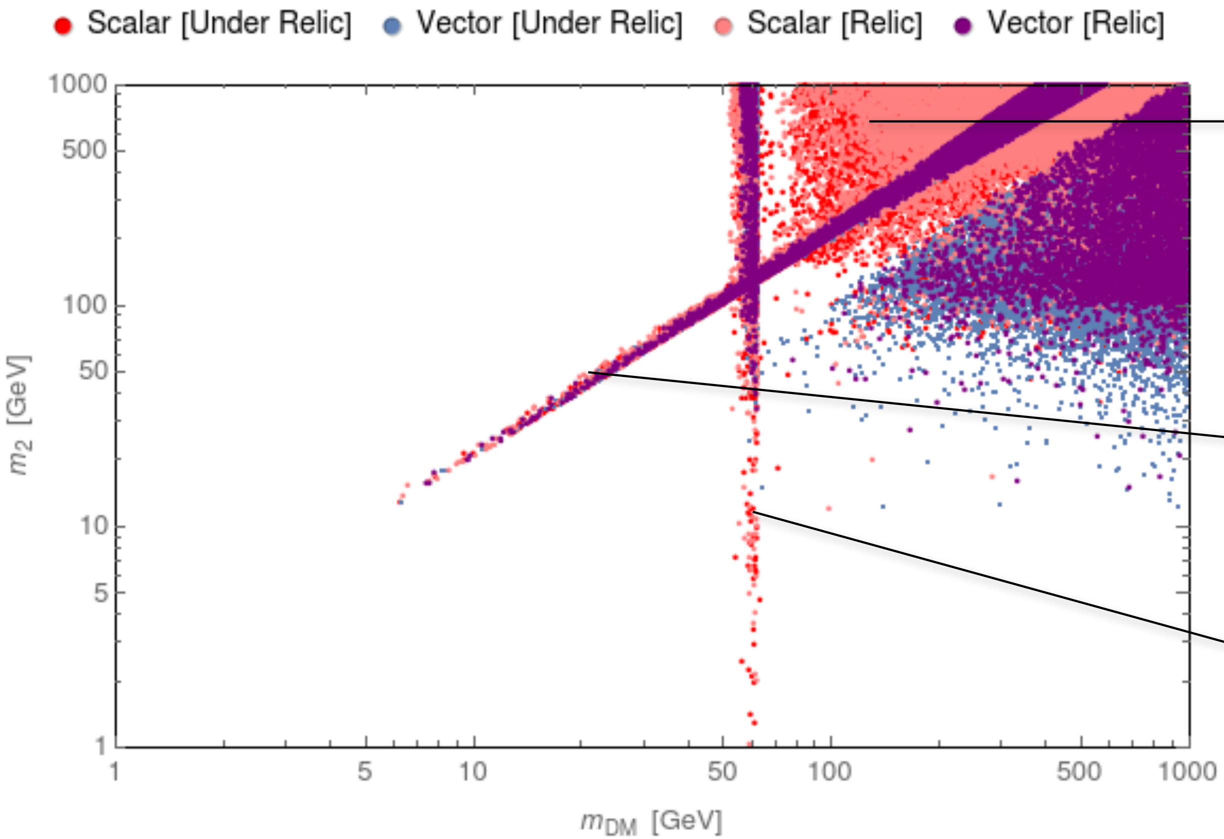
Right: points that are far way from exclusion but are pushed closed to the bound at NLO.

In a scan



In a scan one cannot distinguish between LO and NLO exclusion.

Comparing the two simplest models with vector or scalar DM



Region where only scalar DM survives. In this region, if we could measure the DM mass and m_2, Vector DM would be excluded.

Region where m_2 is close to $2m_{DM}$.

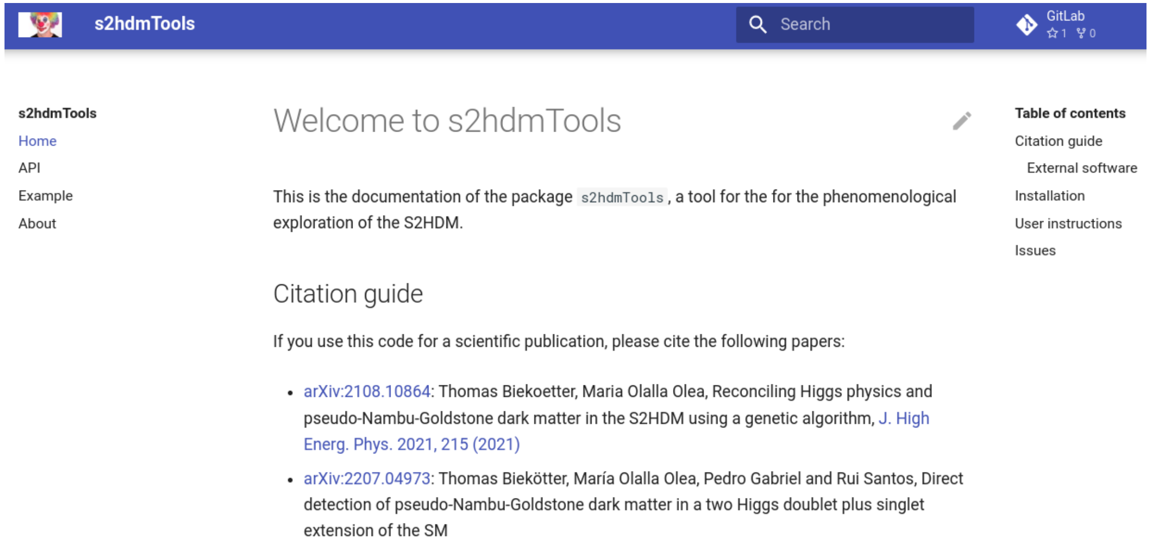
Region where m_1 is close to $2m_{DM}$.

Enhancement by the resonance must be compensated by suppressed couplings.

$m_2 \approx 2m_{DM}$ DM annihilation through the non-SM-like resonance h_2

$m_1 \approx 2m_{DM}$ DM annihilation through the non-SM-like resonance h_1

Thank you.



s2hdmTools

Search

GitLab

s2hdmTools

Home

API

Example

About

Welcome to s2hdmTools

This is the documentation of the package `s2hdmTools`, a tool for the for the phenomenological exploration of the S2HDM.

Citation guide

If you use this code for a scientific publication, please cite the following papers:

- arXiv:2108.10864: Thomas Biekoetter, Maria Olalla Olea, Reconciling Higgs physics and pseudo-Nambu-Goldstone dark matter in the S2HDM using a genetic algorithm, J. High Energ. Phys. 2021, 215 (2021)
- arXiv:2207.04973: Thomas Biekötter, María Olalla Olea, Pedro Gabriel and Rui Santos, Direct detection of pseudo-Nambu-Goldstone dark matter in a two Higgs doublet plus singlet extension of the SM

Table of contents

Citation guide

External software

Installation

User instructions

Issues

https://gitlab.com/thomas.biekoetter/s2hdmtools

Nuclear form factors

We here present the numerical values for the nuclear form factors defined in Eq. (4.59). The values of the form factors for light quarks are taken from `micrOmegas` [75]

$$f^p_{T_u} = 0.01513\,, \quad f^p_{T_d} = 0.0.0191\,, \quad f^p_{T_s} = 0.0447\,, \tag{A.99a}$$

$$f^n_{T_u} = 0.0110\,, \quad f^n_{T_d} = 0.0273\,, \quad f^n_{T_s} = 0.0447\,, \tag{A.99b}$$

which can be related to the gluon form factors as

$$f^p_{T_G} = 1 - \sum_{q=u,d,s} f^p_{T_q}\,, \qquad f^n_{T_G} = 1 - \sum_{q=u,d,s} f^n_{T_q}\,. \tag{A.100}$$

The needed second momenta in Eq. (4.59) are defined at the scale $\mu = m_Z$ by using the `CTEQ` parton distribution functions [76],

$$u^p(2) = 0.22\,, \qquad \bar{u}^p(2) = 0.034\,, \tag{A.101a}$$

$$d^p(2) = 0.11\,, \qquad \bar{d}^p(2) = 0.036\,, \tag{A.101b}$$

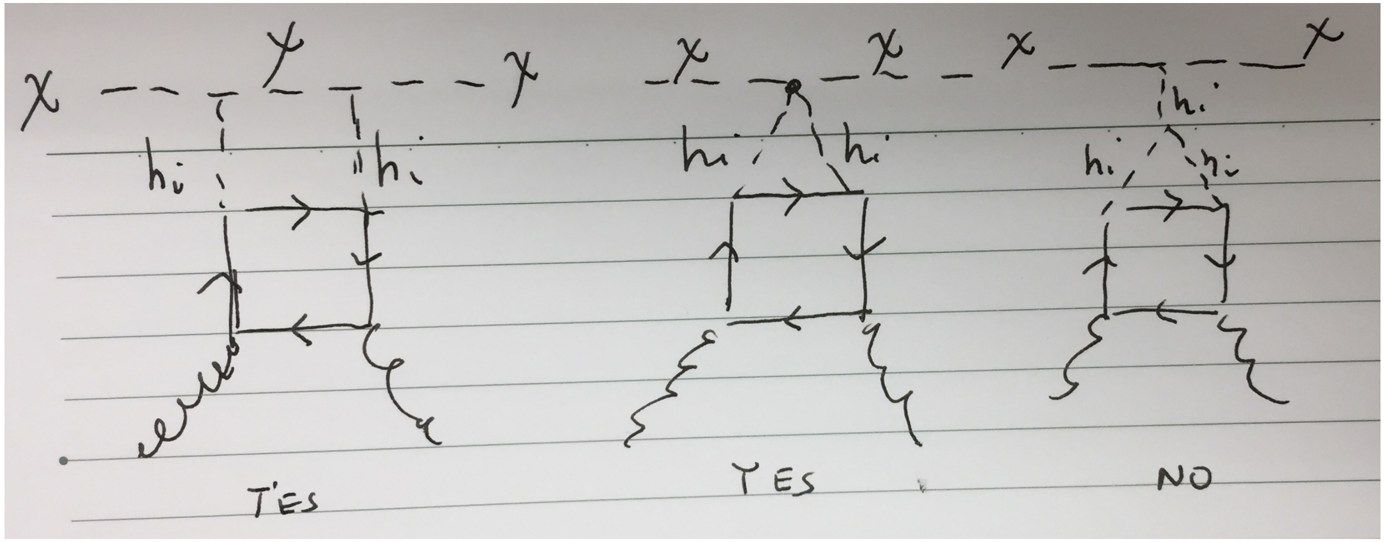
$$s^p(2) = 0.026\,, \qquad \bar{s}^p(2) = 0.026\,, \tag{A.101c}$$

$$c^p(2) = 0.019\,, \qquad \bar{c}^p(2) = 0.019\,, \tag{A.101d}$$

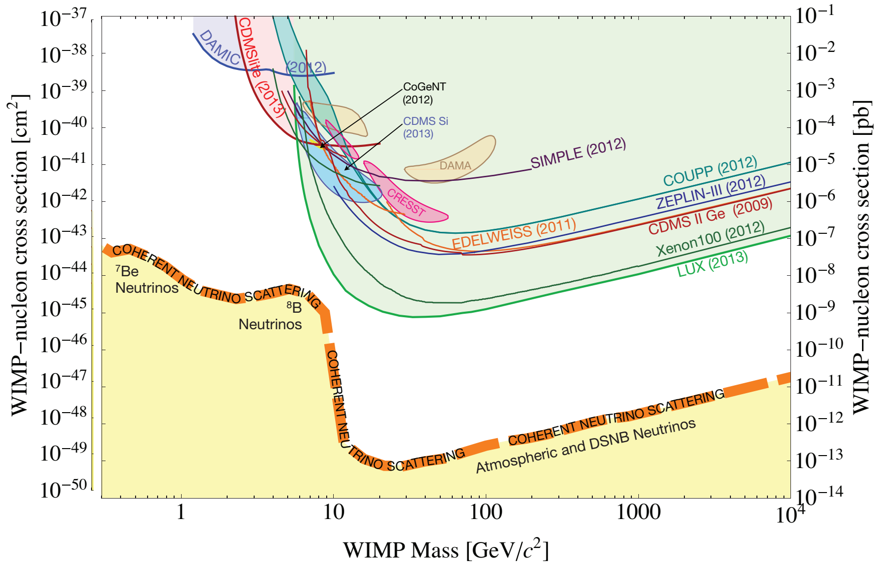
$$b^p(2) = 0.012\,, \qquad \bar{b}^p(2) = 0.012\,, \tag{A.101e}$$

where the respective second momenta for the neutron can be obtained by interchanging up- and down-quark values.

New calculation by Ishiwata and Toma, JHEP 1812 089 (2018)



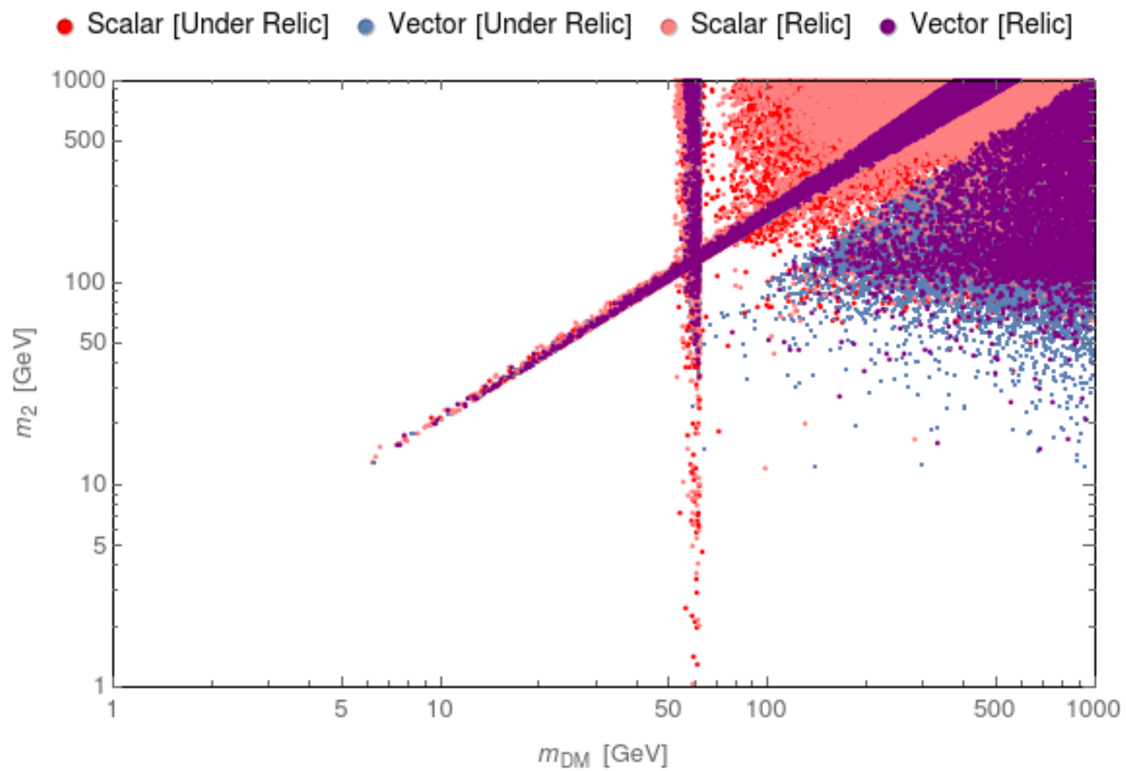
Third type of diagrams were not considered. We believe that is why the limit of $m^2{}_A = -4\mu^2 \rightarrow 0$, where the dark matter particle A is again a Goldstone boson.



Billard, Strigari, Figueroa-Feliciano, PRD89 (2014) 023524

Not so relevant in the very low mass region due to the neutrino floor.

Going back to the scan - no major changes after the exact one-loop calculation



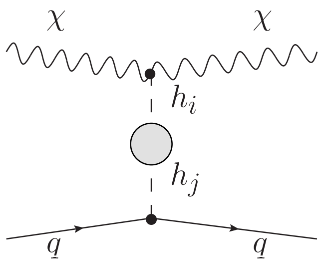
There were two consistency conditions that were checked:

- the tree-level AN recoiling amplitude vanishes in the limit of zero momentum transfer, the one-loop amplitude and F should be finite in the same limit. In other words, we do not need to renormalise the model (the set of diagrams with counterterms only is zero). Consequently, the sum of all diagrams has to be finite. .

- in the limit of $m^2_A = -4\mu^2 \to 0$, the dark matter particle A would return to its Goldstone boson nature due to the spontaneous breaking of the global U(1) symmetry. In this limit, the scattering amplitude should be only proportional to q^2 and thus it should vanish when $q^2 \to 0$, that is, F should approach zero in the limit $m^2_A \to 0$.

Since the exact one-loop results lead to cross sections that are below the Xenon1T limit, the plot looks exactly the same.

Mediator corrections



Again because we are working in the approximation of zero momentum exchange the contribution from the mediators can be written as

$$\Delta_{h_i h_j} = -\frac{\hat{\Sigma}_{h_i h_j}(p^2=0)}{m_{h_i}^2 m_{h_j}^2}$$

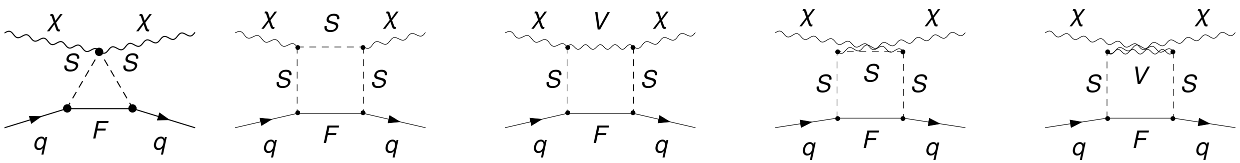
with

$$\begin{pmatrix} \hat{\Sigma}_{h_1 h_1} & \hat{\Sigma}_{h_1 h_2} \\ \hat{\Sigma}_{h_2 h_1} & \hat{\Sigma}_{h_2 h_2} \end{pmatrix} \equiv \hat{\Sigma}(p^2) = \Sigma(p^2) - \delta m^2 - \delta T + \frac{\delta Z}{2}\left(p^2 - \mathcal{M}^2\right) + \left(p^2 - \mathcal{M}^2\right)\frac{\delta Z}{2}$$

Projecting the one-loop correction on the corresponding tensor structure we obtain the one-loop correction to the Wilson coefficient of the operator $m_q \chi\chi\bar{q}q$ induced by the mediator corrections as

$$f_q^{\rm med} = \frac{g g_\chi m_\chi}{2 m_W} \sum_{i,j} R_{\alpha,i2} R_{\alpha,j1} \Delta_{h_i h_j} \qquad \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R_\alpha \begin{pmatrix} \Phi_H \\ \Phi_S \end{pmatrix} \equiv \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \Phi_H \\ \Phi_S \end{pmatrix}$$

Box corrections



$F, S = \{q\}, \{h_i\}$ $\quad$ $F, S = \{q\}, \{h_i, G_\chi\}$ $\quad$ $F, S, V = \{q\}, \{h_i, G_\chi\}, \{X\}$ $\quad$ $F, S = \{q\}, \{h_i\}$ $\quad$ $F, S, V = \{q\}, \{h_i, G_\chi\}, \{X\}$

The NLO EW SI cross section can be obtained using the one-loop form factor

$$\frac{f_N^{\rm NLO}}{m_N} = \sum_{q=u,d,s} f_q^{\rm NLO} f_{T_q}^N + \sum_{q=u,d,s,c,b} \frac{3}{4}\left(q(2)+\bar q(2)\right) g_q^{\rm NLO} - \frac{8\pi}{9\alpha_S} f_{T_G}^N f_G^{\rm NLO}$$

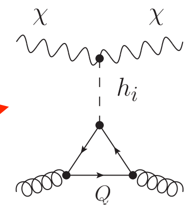
Box diagrams contribute to the two different quark operators.

with the Wilson coefficients at one-loop given by

$$f_q^{\rm NLO} = f_q^{\rm vertex} + f_q^{\rm med} + f_q^{\rm box}$$

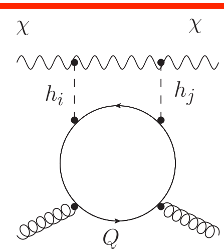
$$g_q^{\rm NLO} = g_q^{box}$$

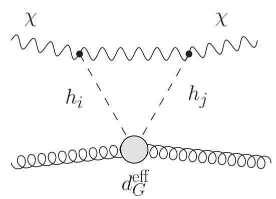
$$f_G^{\rm NLO} = -\frac{\alpha_S}{12\pi}\sum_{q=c,b,t}\left(f_q^{\rm vertex} + f_q^{\rm med}\right) + f_G^{\rm top}$$



The LO form factor is given by

$$\frac{f_N^{\rm LO}}{m_N} = f_q^{\rm LO}\left[\sum_{q=u,d,s} f_{T_q}^N + \sum_{q=c,b,t}\frac{2}{27} f_{T_G}^N\right]$$





Ertas, Kahlhoefer, JHEP06 052 (2019)

Abe, Fujiwara, Hisano, JHEP 02, 028 (2019)

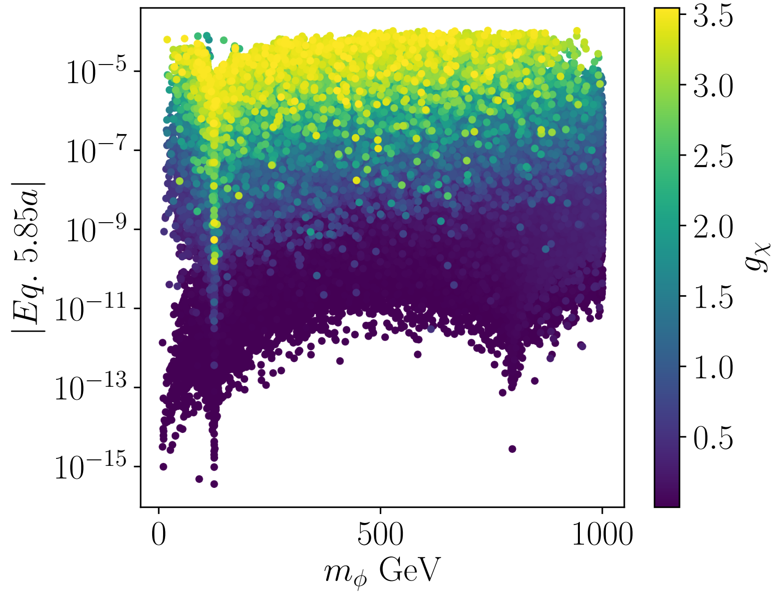
$$\mathcal{L}^{hhGG} = \frac{1}{2} d_G^{\rm eff} h_i h_j \frac{\alpha_S}{12\pi} G^a_{\mu\nu} G^{a\,\mu\nu}$$

$$f_G^{\rm top} = \left(d_G^{\rm eff}\right)_{ij} C_\triangle^{ij} \frac{-\alpha_S}{12\pi}\,.$$

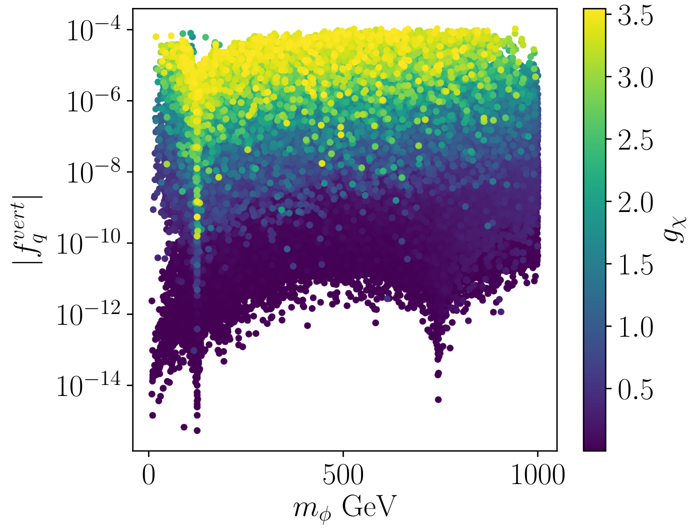
And the cross section at one-loop is

$$\sigma_N = \frac{1}{\pi}\left(\frac{m_N}{m_\chi + m_N}\right)^2 \left[|f_N^{\rm LO}|^2 + 2{\rm Re}\left(f_N^{\rm LO} f_N^{\rm NLO*}\right)\right]$$

$$f_q = \frac{1}{2}\frac{g g_\chi}{m_W}\frac{\sin(2\alpha)}{2}\frac{m_{h_1}^2 - m_{h_2}^2}{m_{h_1}^2 m_{h_2}^2} m_\chi\,, \quad q = u,d,s,c,b,t$$

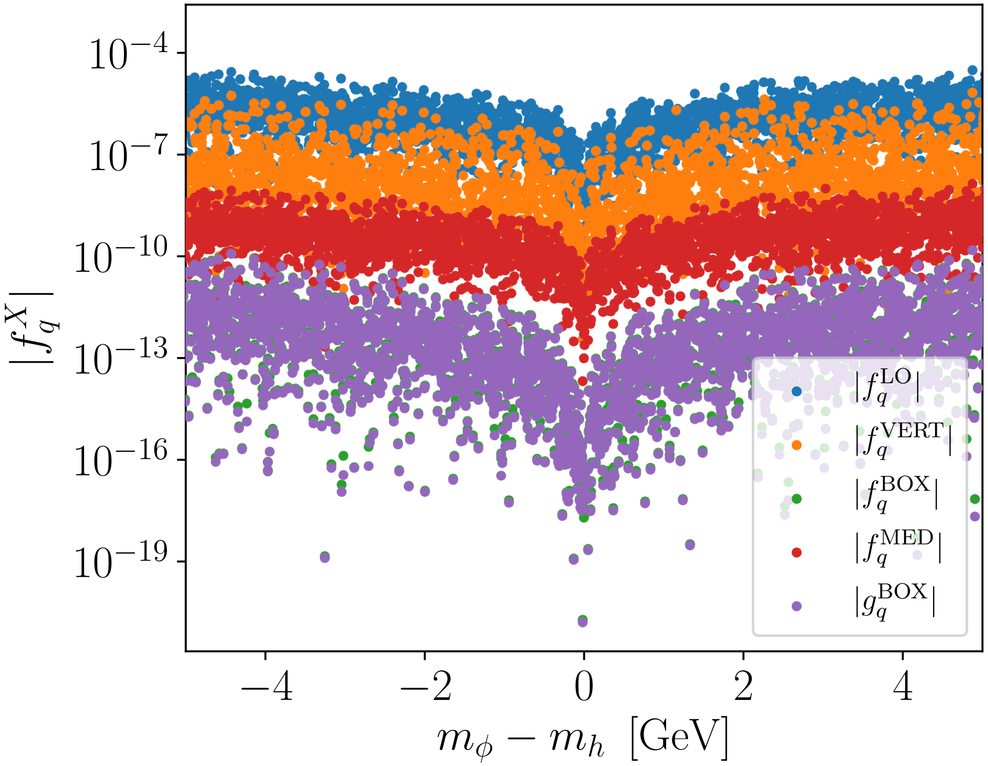


Wilson coefficient at one-loop as a function of the non-125 scalar (in units of GeV^{-2}) with the dark gauge coupling in the colour bar.



$$f_q^{\rm NLO} = f_q^{\rm vertex} + f_q^{\rm med} + f_q^{\rm box}$$

Largest contribution to f_q^{NLO} comes from f_q^{vert} but are smaller than the total.



Different contributions to the cross section with LO being the largest followed by the vertex contribution.

Even for small g_χ the vertex contribution dominates except for a few points where mediator take the lead - in those cases the LO is larger by several orders of magnitude.

Constraints

Theoretical and collider:

Points generated with ScannerS requiring

- absolute minimum
- boundedness from below
- that perturbative unitarity holds
- S,T and U

Signal strength: 125 GeV coupling measurements give a constraint on the mixing angle α

Searches: BR of Higgs to invisible below 24%

Searches: for the new scalar imposed via HiggsBounds which gives a bound that is a function of the new scalar mass and $\cos\alpha$

Constraints

DM abundance: we require

$$(\Omega h^2)_{DM} < 0.1186$$ [Calculated with MicroOmegas]

or to be in the 5σ allowed interval from the Planck collaboration measurement

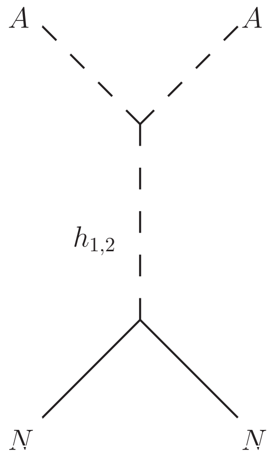
$$(\Omega h^2)_{DM}^{obs} = 0.1186 \pm 0.0020$$

Direct detection: we apply the latest XENON1T bounds

$$\sigma_{DM,N}^{eff} = f_{DM}\,\sigma_{DM,N} \quad \text{with} \quad f_{DM} = \frac{(\Omega h^2)_{DM}}{(\Omega h^2)_{DM}^{obs}}$$ [Fraction contributing to the scattering]

Indirect detection: for the DM range of interest, the Fermi-LAT upper bound on the dark matter annihilation from dwarfs is the most stringent. We use the Fermi-LAT bound on bb.

Where does this difference comes from? - Dark matter nucleon scattering at tree-level



$$-i\mathcal{M}_{\text{tree}} = -\frac{i2f_N m_N}{v_H}\left(\frac{V_{AA1}c_\alpha}{q^2-m_1^2} - \frac{V_{AA2}s_\alpha}{q^2-m_2^2}\right)\bar{u}_N(p_4)u_N(p_2)$$

$$-i\mathcal{M}_{\text{tree}} = -\frac{i\sin 2\alpha f_N m_N}{v_H}\left(\frac{m_1^2}{q^2-m_1^2} - \frac{m_2^2}{q^2-m_2^2}\right)\bar{u}_N(p_4)u_N(p_2)$$

$$-i\mathcal{M}_{\text{tree}} \approx -i\frac{s_\alpha c_\alpha f_N m_N}{v_H v_S}\left(\frac{m_1^2-m_2^2}{m_1^2 m_2^2}\right)q^2\bar{u}_N(p_4)u_N(p_2)$$

Gross, Lebedev, Toma, PRL119 (2017) no.19, 191801

The total cross section for DM-nucleon scattering is

$$\sigma^{\text{tree}}_{DM,N} \approx \frac{\sin^2 2\alpha f_N^2}{3\pi}\frac{m_N^2\mu^6_{DM,N}}{m^2_{DM}v_H^2v_S^2}\frac{(m_1^2-m_2^2)^2}{m_1^4m_2^4}v^4_{DM} \quad \text{where} \quad \mu_{DM,N} = \frac{m_{DM}m_N}{m_{DM}+m_N}$$

Because $\quad v_{DM} \sim 200\ \text{Km/s} \ \Rightarrow \ v^4_{DM} \sim 10^{-13}$

that is,

- Write the effective Lagrangian

$$\mathcal{L}^{\rm eff} = \sum_{q=u,d,s} \mathcal{L}_q^{\rm eff} + \mathcal{L}_G^{\rm eff}$$

$$\mathcal{L}_q^{\rm eff} = f_q \chi_\mu \chi^\mu m_q \bar{q} q + \frac{g_q}{m_\chi^2} \chi^\rho i\partial^\mu i\partial^\nu \chi_\rho \mathcal{O}^q_{\mu\nu} \,,$$
$$\mathcal{L}_G^{\rm eff} = f_G \chi_\rho \chi^\rho G^a_{\mu\nu} G^{a\,\mu\nu} \,,$$

$$\mathcal{O}^q_{\mu\nu} = \frac{1}{2} \bar{q} i \left(\partial_\mu \gamma_\nu + \partial_\nu \gamma_\mu - \frac{1}{2} \partial\!\!\!/ \right) q \,.$$

- Define the nucleon matrix elements

$$\langle N | \, m_q \bar{q} q \, | N \rangle = m_N f^N_{T_q}$$

$$-\frac{9\alpha_S}{8\pi} \langle N | \, G^a_{\mu\nu} G^{a,\mu\nu} \, | N \rangle = \left(1 - \sum_{q=u,d,s} f^N_{T_q} \right) m_N = m_N f^N_{TG}$$

$$\langle N(p) | \, \mathcal{O}^q_{\mu\nu} \, | N(p) \rangle = \frac{1}{m_N} \left(p_\mu p_\nu - \frac{1}{4} m_N^2 g_{\mu\nu} \right) \left(q^N(2) + \bar{q}^N(2) \right) \,,$$

f_{T_q} denotes the fraction of the nucleon mass that is due to light quark q (lattice)

SHIFMAN, VAINSHTEIN, ZAKHAROV, PLB78 443 (1978)

fraction of the nucleon momentum carried by the quarks (PDFs)

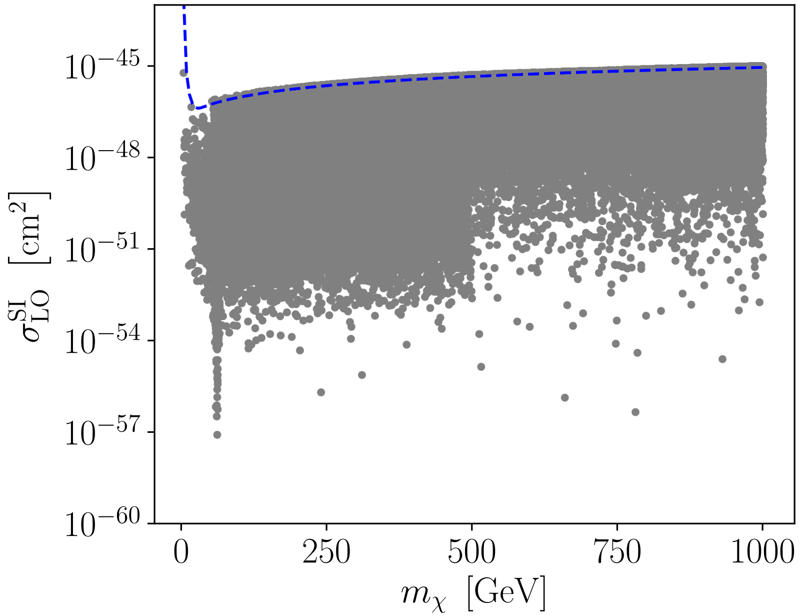
- And calculate the cross section

$$\sigma_N = \frac{1}{\pi} \left(\frac{m_N}{m_\chi + m_N} \right)^2 |f_N|^2 \,.$$

$$f_N / m_N = \sum_{q=u,d,s} f_q f^N_{T_q} + \sum_{q=u,d,s,c,b} \frac{3}{4} \left(q^N(2) + \bar{q}^N(2) \right) g_q - \frac{8\pi}{9\alpha_S} f^N_{TG} f_G \,.$$

And now we need to get all the Wilson coefficients f_q, g_q, f_G at NLO, but before that,

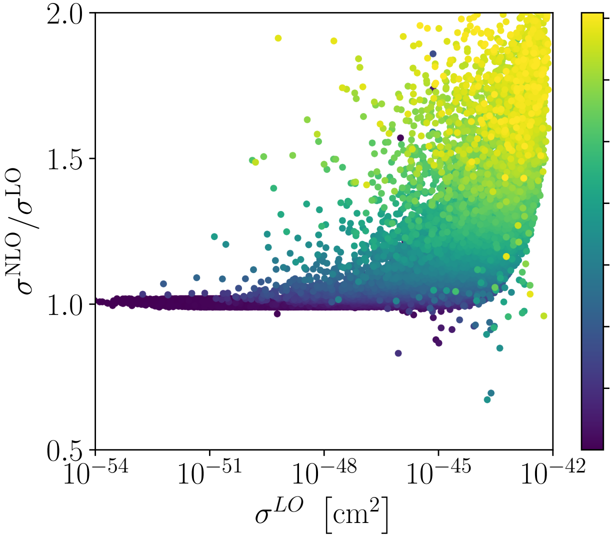
NLO vs. LO results for the VDM model

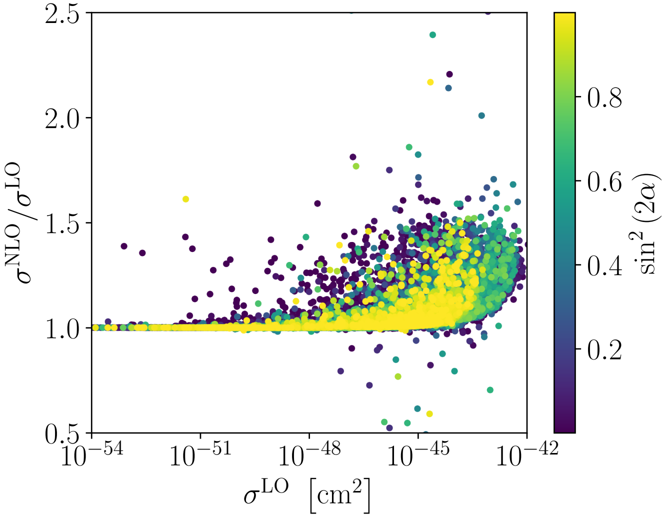


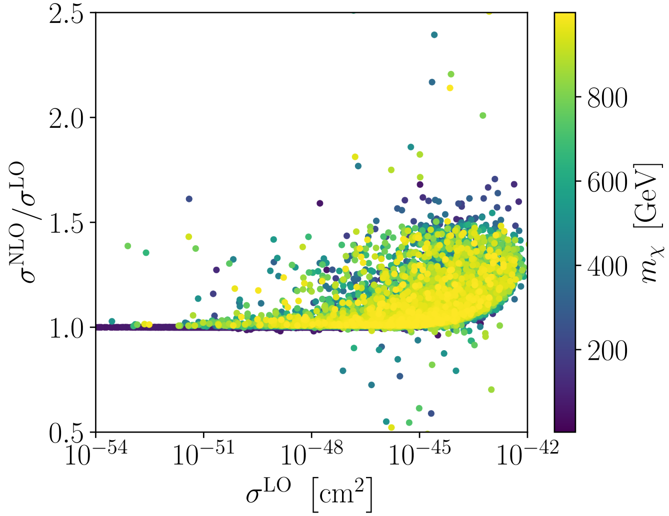
We start with points that at LO have passed all the theoretical and experimental constraints.

Both the LO and the NLO contribution to the SI direct detection cross section are proportional to f^{LO} and therefore proportional to g_χ, $\sin 2\alpha$ and $m_h^2 - m_\chi^2$.

Biggest contribution comes from the triangle diagrams which are proportional to g_χ^3 at one-loop.

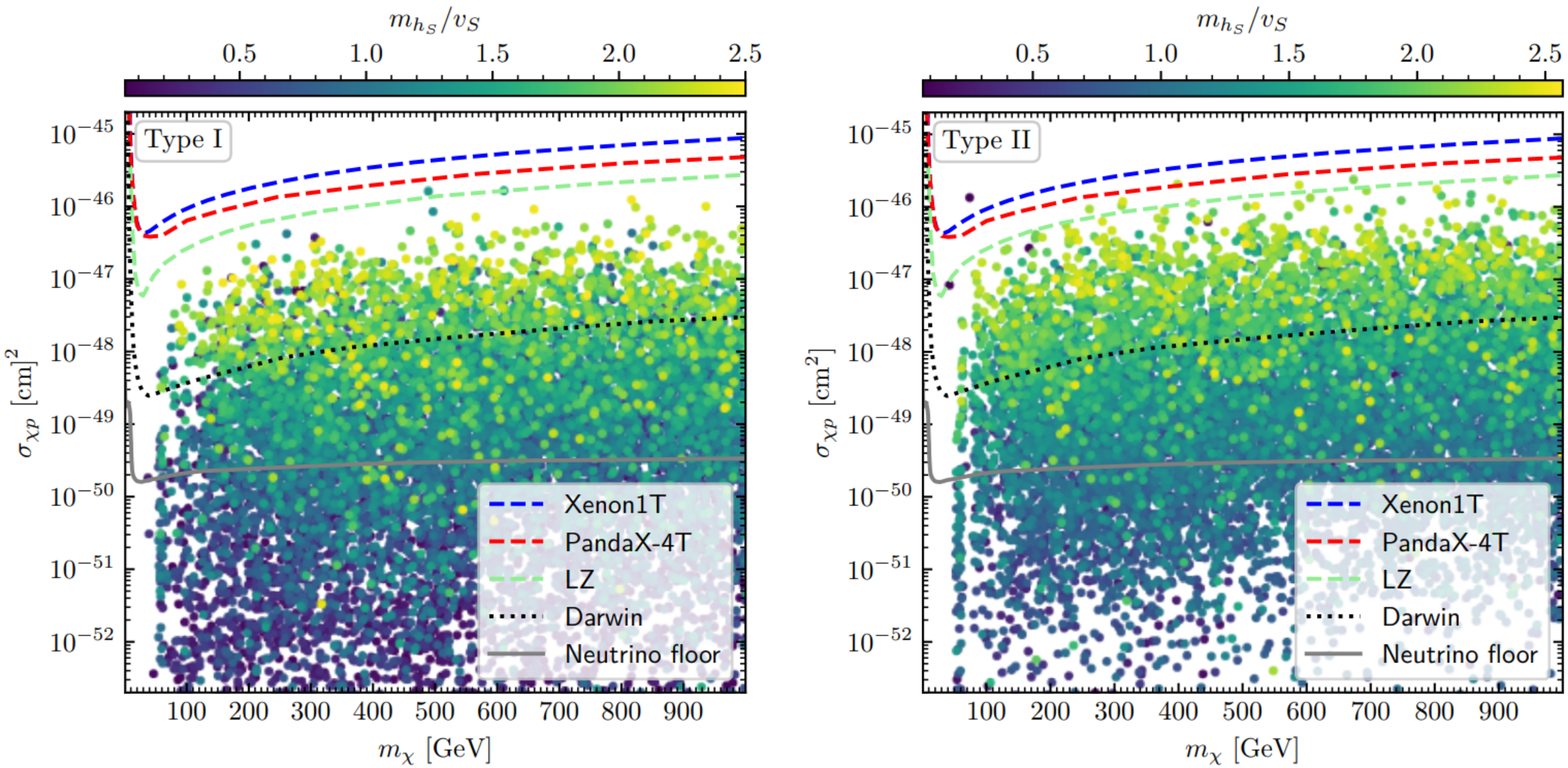






In the plots below we see the enhancement (only) with the dark coupling constant. The ratio between NLO and LO increases like g_χ.

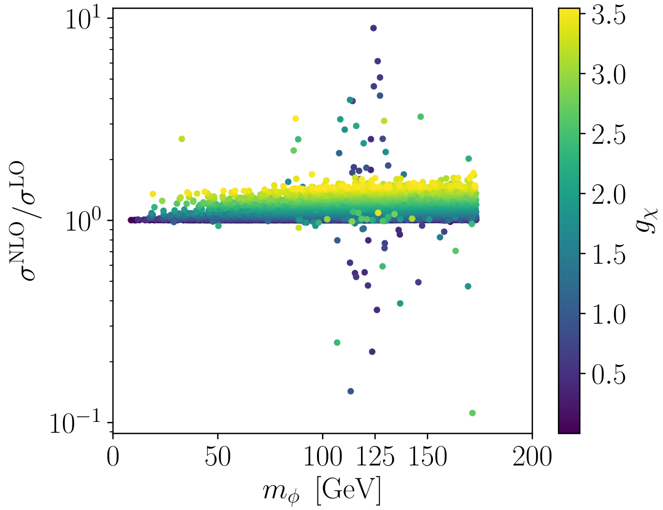
Experimental prospect for direct detection in Types I and II

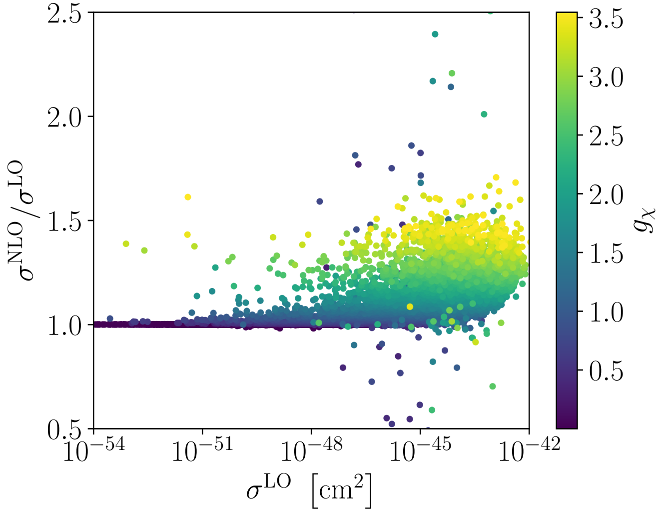


Type	m_{h_a}	$m_{h_b}, m_{h_c}, m_A, m_\chi$	$m_{H^\pm}$	$\alpha_{1,2,3}$	$\tan\beta$	M	v_S
I	125.09	[30,1000]	[150,1000]	$[-\pi/2, \pi 2]$	[1.5,10]	[20, 1000]	[30,1000]

Type	m_{h_a}	m_{h_b, m_A}	$m_{H^\pm}$	$m_{h_c, \chi}$	$\alpha_{1,2,3}$	$\tan\beta$	M	v_S
II	125.09	[200,1000]	[650,1000]	[30,1000]	$[-\pi/2, \pi 2]$	[1.5,10]	[450, 1000]	[30,1000]

NLO vs. LO results for the VDM model





The K-factor is mostly positive and the bulk of K-factor values ranges between 1 and about 2.3.

Biggest contribution comes from the triangle diagrams which are proportional to g_χ^3 at one-loop.

Points with $m_\Phi \approx m_h$ and K-factors where |K| > 2.5 are excluded. For $m_\Phi \approx m_h$ the interference effects between the h and Φ contributions, largely increase or suppress the (dominant) vertex contribution. NLO results are no longer reliable. Two-loop contributions might lead to a better perturbative convergence.

The blind spots at LO and at NLO are the same.

In our scan we did not find any other points where a specific parameter combination would lead to an accidental suppression at LO that is removed at NLO.

There is a further blind spot when α = 0 (SM-like Higgs boson with exactly SM-like couplings; new scalar only couples to the Higgs and to dark matter). The SM-like Higgs decouples from DM and we may end up with two dark matter candidates with the second scalar being metastable.