

Electroweak corrections to Dark Matter direct detection

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AZEVEDO, DUCH, GRZADKOWSKI, HUANG, IGLICKI, GLAUS, MÜHLLEITNER,
MÜLLER, PATEL, RÖMER, BIEKÖTTER, GABRIEL, OLEA-ROMACHO

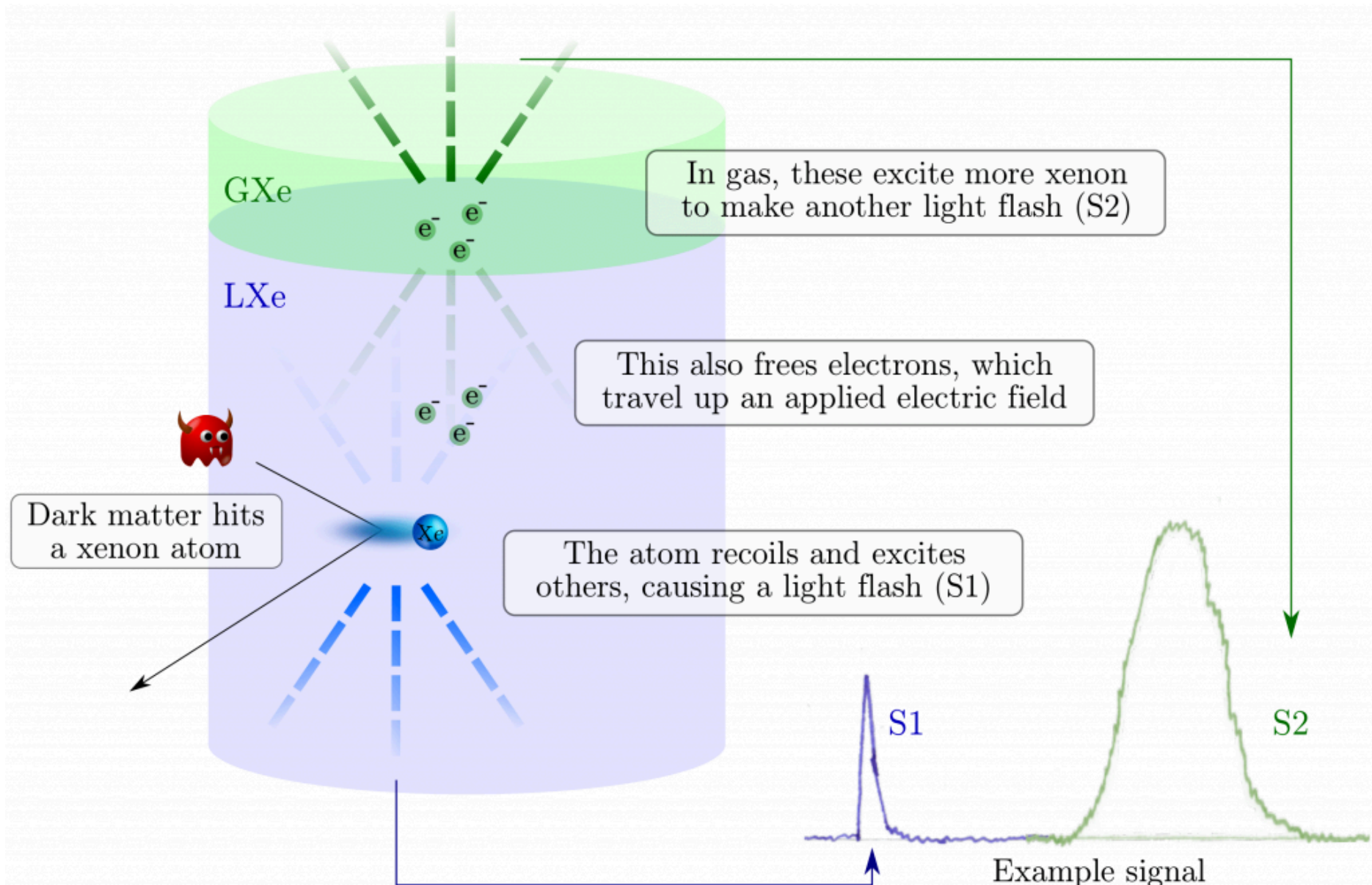
JHEP 01 (2019) 138, [1810.06105](#) [HEP-PH]; JHEP 10 (2019) 152, [1908.09249](#) [HEP-PH], JHEP 12 (2020) 034, [2008.12985](#) [HEP-PH],
PHYS.LETT.B 833 (2022) 137342, [2204.13145](#) [HEP-PH], JHEP 10 (2022) 126, [2207.04973](#) [HEP-PH].

HPNP2023, Osaka University

Outline

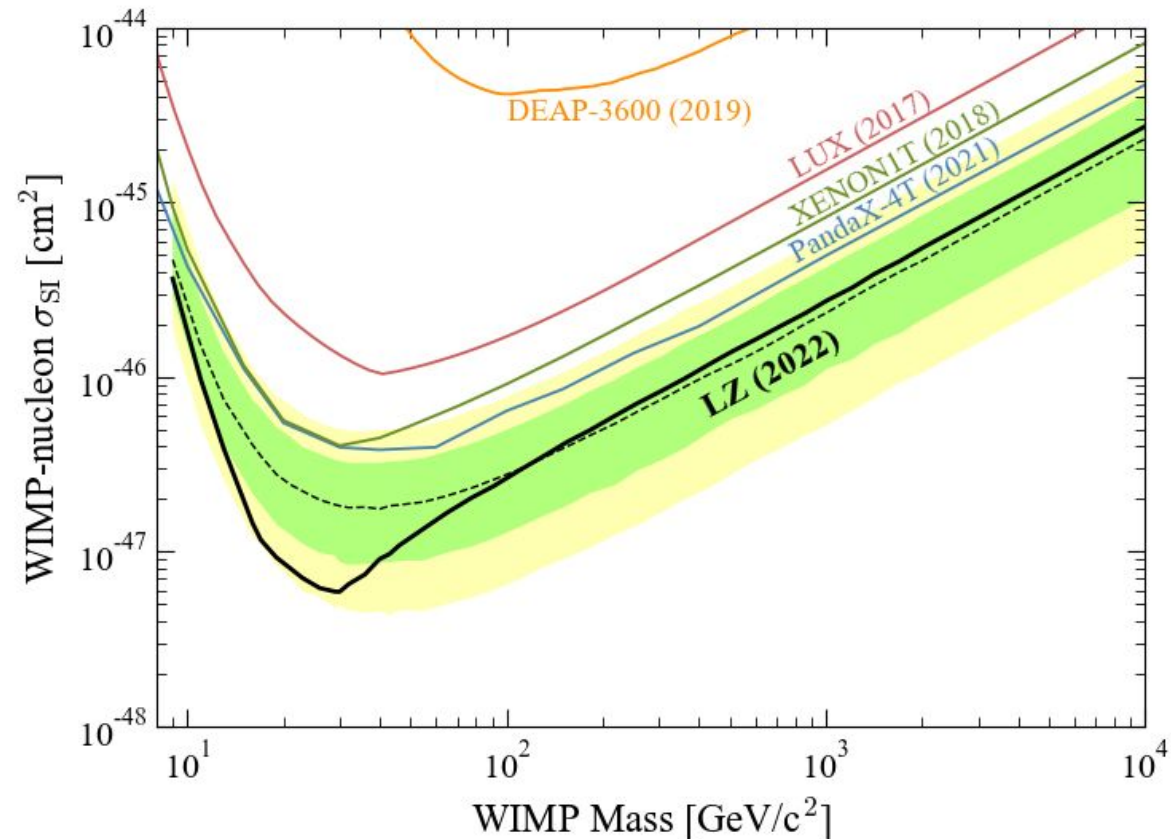
- 📌 Several ongoing experiments to directly probe the existence of Dark Matter in the WIMP region;
- 📌 Uncertainties not related to particle physics;
- 📌 Electroweak corrections not relevant most of the times ;
- 📌 In some models the leading order cross section is negligible;
- 📌 Higher order corrections are needed;
- 📌 Cross sections can be probed in future experiments.

Direct detection experiments



Direct detection experiments

- Curves:
 - Solid black: observed limit
 - Dashed-black: median expected sensitivity
- No evidence of WIMPs at any mass
- Minimum exclusion on WIMP-nucleon cross section (SI) of $6 \times 10^{-48} \text{ cm}^2$ at 30 GeV
- Comparing to existing strongest upper limit:
 - x6.7 improvement at 30 GeV
 - x1.7 improvement above 1 TeV



So far no event was recorded and bounds were set on cross-section/coupling vs. mass.

Direct detection

Assume Standard Halo Model with a density profile of $\rho(r) \sim r^{-2}$. The velocities obey a Boltzmann-Maxwell distribution. The local circular speed of DM is (218-246) Km/s.

The DM stream may interact with a nucleus and transfer a small amount of energy (recoil energy). The differential scattering can be written as

$$\frac{dR(E_R, t)}{dE_R} = N_T \frac{\rho}{m_\chi} \int_{v > v_{min}} v f(\vec{v} + \vec{v}_E(t)) \frac{d\sigma(E_R, v)}{dE_R} d^3v \quad v_{min} = \sqrt{\frac{m_N E_R}{2\mu^2}}, \quad \mu = \frac{m_N m_\chi}{m_N + m_\chi}$$

where E_R is the recoil energy, N_T is the number of nuclei, v is the velocity in the rest frame of the experiment, f is the velocity distribution function and v_{min} is the minimum velocity of DM causing a recoil energy and m_N is the nucleon mass. The differential rate can further be divided in a spin-dependent (SD) and a spin-independent (SI) part. The time integrated differential cross section is then written as

$$\frac{d\sigma(E_R, v)}{dE_R} = \frac{m_N}{2\mu^2 v^2} (\sigma^{SI} F_{SI}^2(E_R) + \sigma^{SD} F_{SD}^2(E_R))$$

where F are nuclear form factors.

Peculiar extensions of the SM

Some models have negligible dark matter direct detection (DD) cross section at zero momentum transfer (at tree-level). **Barely affected by direct detection bounds.**

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

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

with

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

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

The potential is invariant under

$$\mathbb{S} \rightarrow \mathbb{S}^* \quad \text{Stabilises } A$$

and without the red term it is also invariant under

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

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

One extra complex singlet (CxSM) - the simplest scenario

The SM is extended by adding a complex scalar singlet S ,

$$\mathcal{L} = \mathcal{L}_{SM} + (D_\mu S)^\dagger (D^\mu S) + \mu_S^2 |S|^2 - \lambda_S |S|^4 - \kappa |S|^2 H^\dagger H + \mu^2 (S^2 + S^{*2}) \quad S \rightarrow S^*$$

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

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

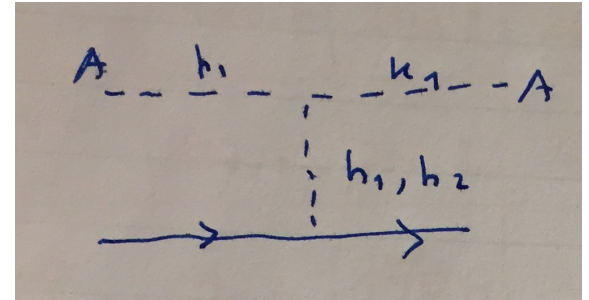
The scalar mass matrix is

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

One extra complex singlet (CxSM) - the simplest scenario

The amplitude for the DM direct detection cross section

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



GROSS, LEBEDEV, TOMA, PRL 119 (2017) NO.19, 191801

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

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

Writing

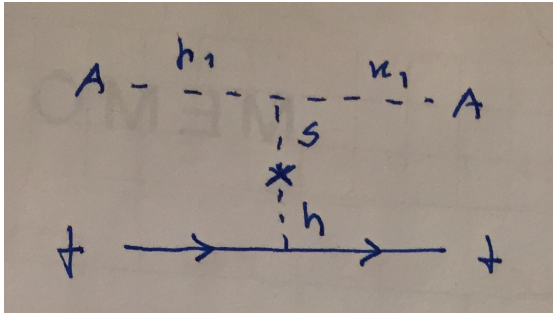
$$\mathbb{S} = \frac{v_S + S}{\sqrt{2}} e^{i\frac{A}{v_S}} \Rightarrow V_{soft} = -\mu^2 (v_S + S)^2 \cos\left(\frac{2A}{v_S}\right) = -\mu^2 (v_S + S)^2 \left(1 - \frac{2A^2}{v_S^2}\right) + \dots$$

Including the kinetic term leads to the following Lagrangian interaction

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

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 (transferred momentum) and A is on-shell. Therefore the amplitude vanishes.

One extra complex singlet (CxSM) - the simplest scenario



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

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 terms of the same type are added

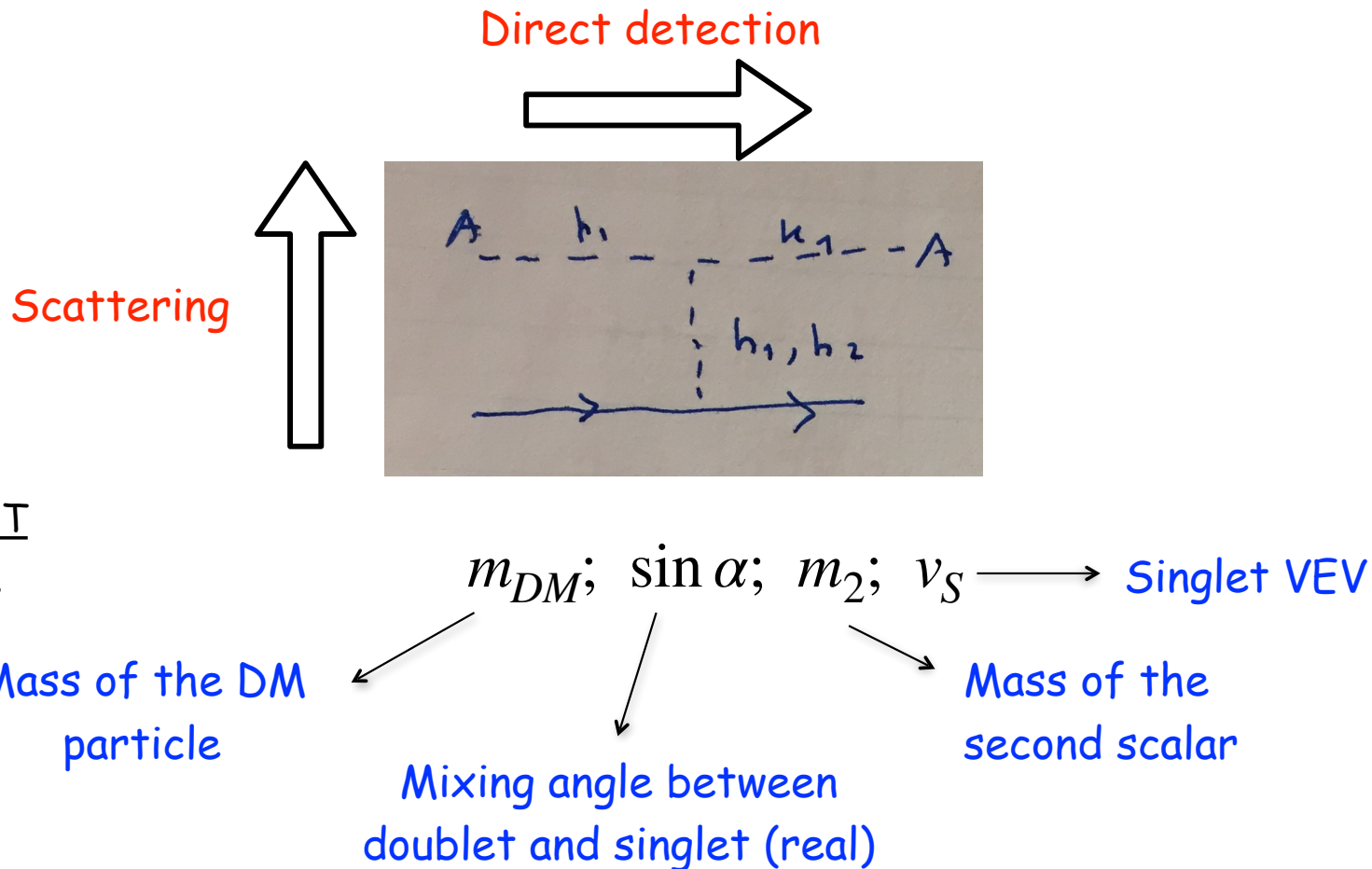
$$V' = -\kappa_1^3 (S + S^*) - \kappa_2 |S|^2 (S + S^*) - \kappa_3 (S^3 + S^{*3})$$

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

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

One extra complex singlet (CxSM) - the simplest scenario

Also - the cancellation does not happen in scattering

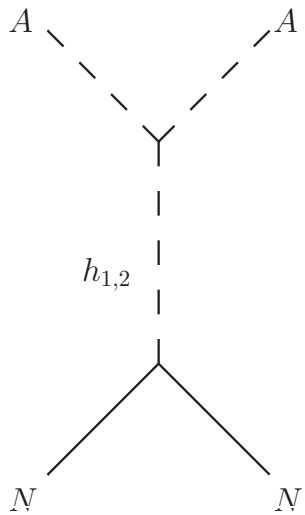


There is obviously a 125 GeV Higgs (other scalar can be lighter or heavier).
Experimental and theoretical constraints included.

One-loop corrections in cXSM - version 1

AZEVEDO, DUCH, GRZADKOWSKI, HUANG, IGLICKI, RS,
JHEP 01 (2019) 138, [1810.06105](#) [HEP-PH];

One-loop corrections in cXSM - version 1

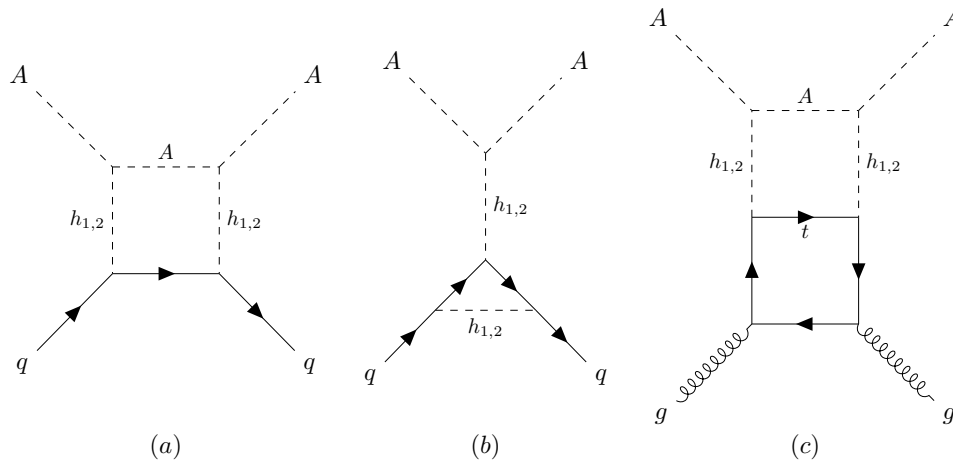


$$-i\mathcal{M}_{\text{tree}} \approx -i \frac{s_\alpha c_\alpha f_N m_N}{v_H v_S} \left(\frac{m_1^2 - m_2^2}{m_1^2 m_2^2} \right) q^2 \bar{u}_N(p_4) u_N(p_2)$$

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 $f_N m_N / v_H$

Negligible contributions and counterterms

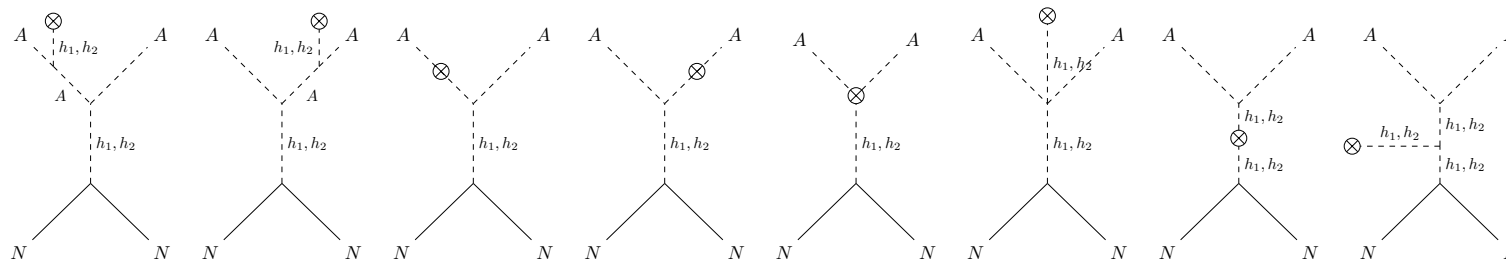


At the fundamental level, the DM-nucleon scattering can be understood as the scattering of the DM particle A with light quarks and gluons.

Light quark Yukawa couplings are very small, the diagrams (a) and (b) with multiple insertions of light quark Yukawa couplings, are expected to be negligibly small. Diagram (c) although (in principle) small could contribute.

The counterterm potential is

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

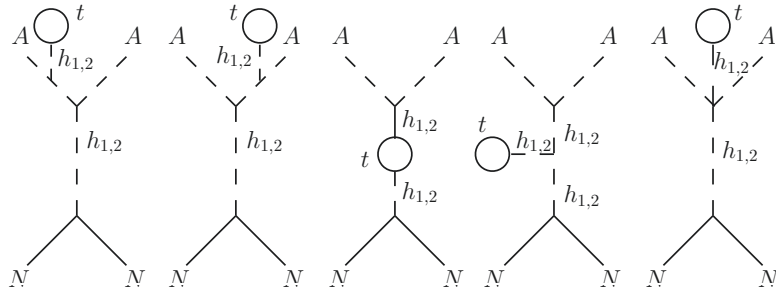


model has 6 independent parameters, we need 6 counterterms to cancel the UV divergences at one-loop.

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 $\cos\alpha$, for h_1 and $-\sin\alpha$ for h_2 .

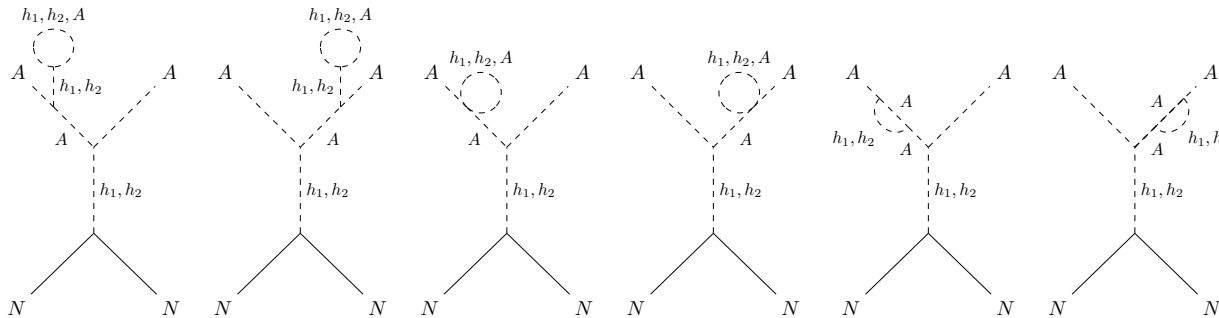
For the external lines

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

For the internal lines

$$\mathcal{F}_{i+v} = \frac{(V_{AA1}^{(1)}i + V_{AA1}^{(1)}v)c_\alpha}{m_1^2} - \frac{(V_{AA2}^{(1)}i + V_{AA2}^{(1)}v)s_\alpha}{m_2^2} = 0$$

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

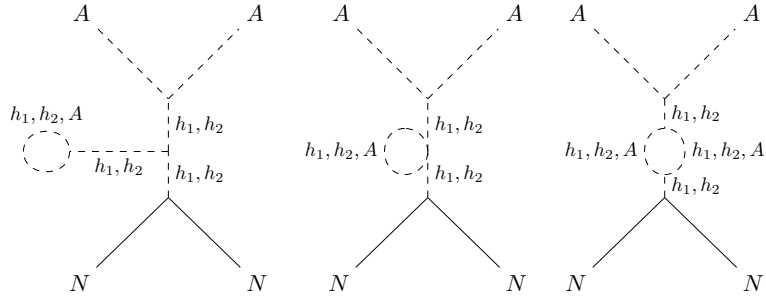


Scalar contributions to the external legs.

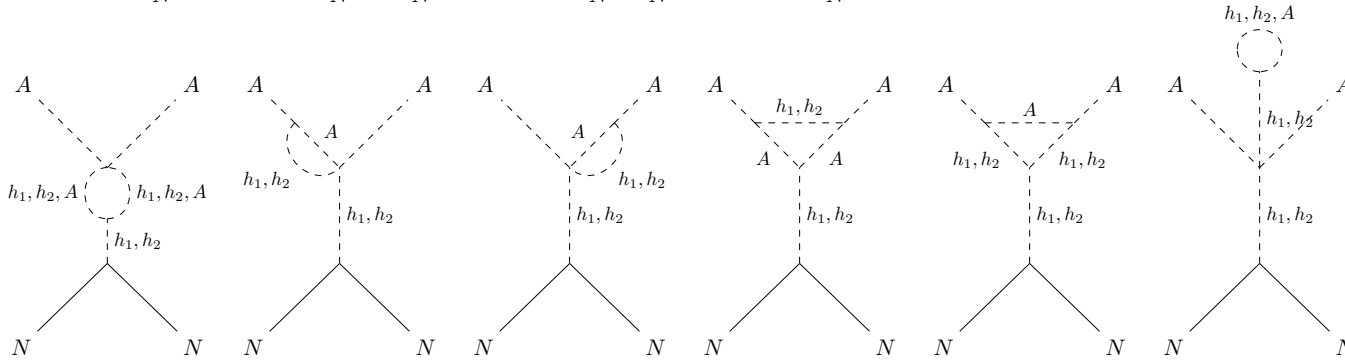
For the external lines

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

Corrections that survive



Internal scalars



Vertex corrections

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

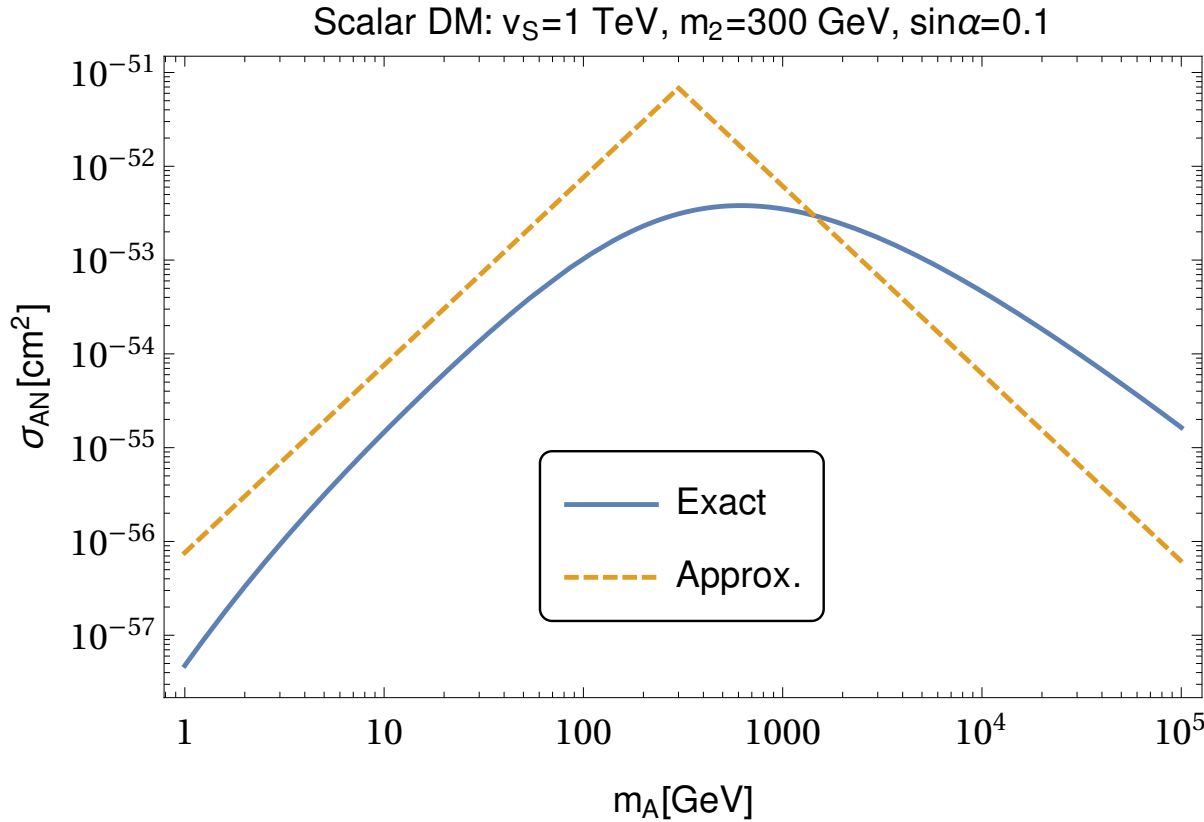
Very simple expression that you can insert in your code!

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

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

One-loop squared - because tree-level is zero

Results



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

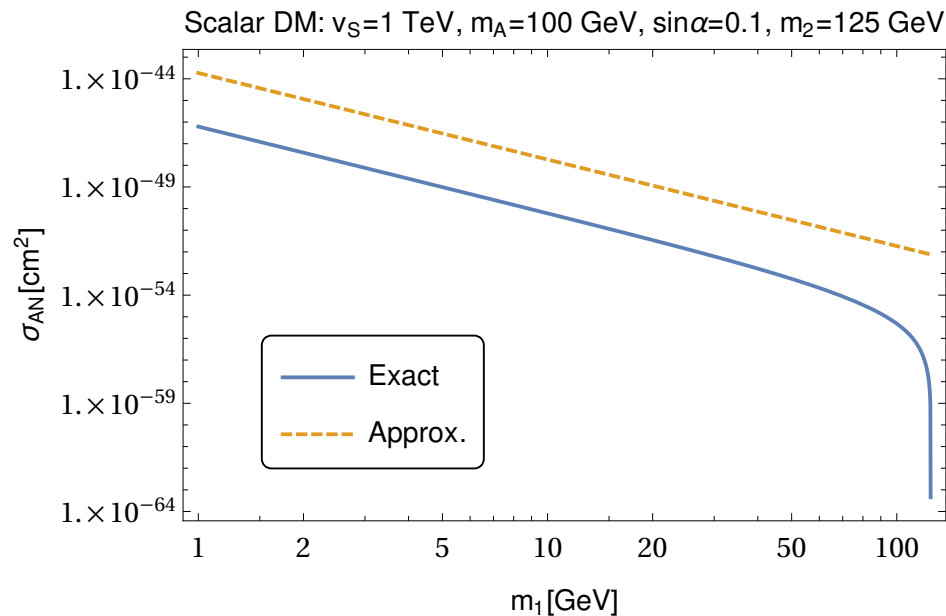
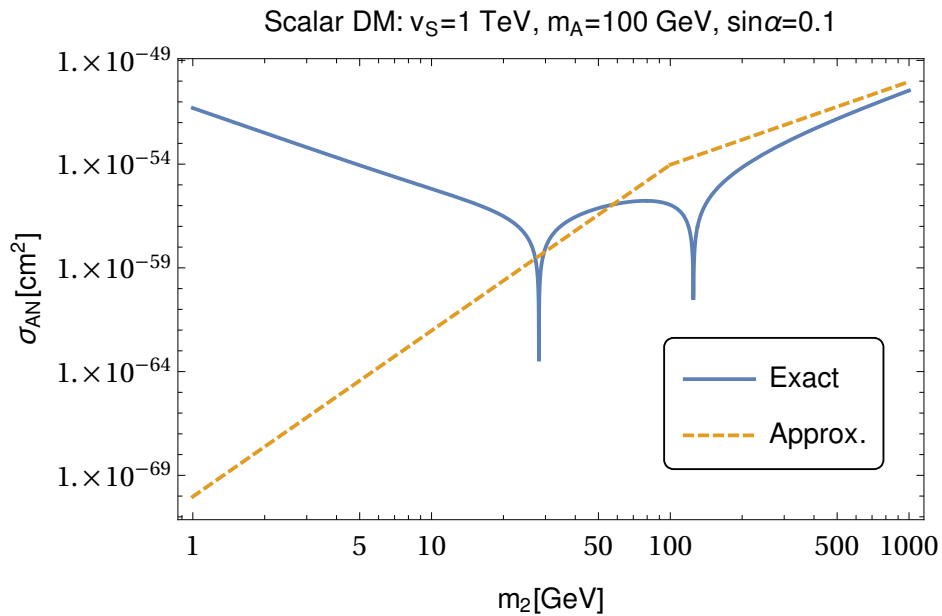
The approximation is quite good in reproducing the shape.

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

GROSS, LEBEDEV, TOMA, PRL119 (2017) NO.19, 191801

- The Goldstone nature of DM is recovered - the cross section vanishes in the zero DM mass limit.
- For this set of parameters the curve has a maximum value of $\sigma^{(1)} \sim 3 \times 10^{-53} \text{ cm}^2$ for $m_A \sim 630 \text{ GeV}$. The tree-level contribution is $\sigma^{\text{tree}} \sim 10^{-69} - 10^{-65} \text{ cm}^2$ for the same set of parameters.

Results



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 $(m_1^2 - m_2^2)$

One-loop corrections in cXSM - version 2

GLAUS, MÜHLEITNER, MÜLLER, PATEL, RÖMER, RS, JHEP 12 (2020) 034,
2008.12985 [HEP-PH].

Direct detection at LO for scalars

Write the effective Lagrangian

$$\mathcal{L}_{\text{eff}} = \sum_q C_S^q \mathcal{O}_S^q + C_S^g \mathcal{O}_S^g + \sum_q C_T^q \mathcal{O}_T^q$$

$$\begin{aligned} \mathcal{O}_S^q &= m_q \chi^2 \bar{q} q, \\ \mathcal{O}_S^g &= \frac{\alpha_s}{\pi} \chi^2 G_{\mu\nu}^a G^{a\mu\nu}, \\ \mathcal{O}_T^q &= \frac{1}{m_\chi^2} \chi i \partial^\mu i \partial^\nu \chi \mathcal{O}_{\mu\nu}^q. \end{aligned}$$

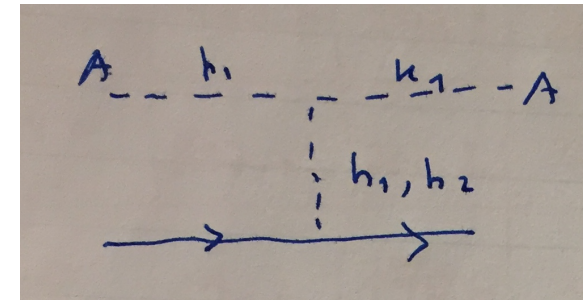
Quark contributions

$$\mathcal{A}_{\text{gen}} = \sum_i C_{\chi\chi h_i} C_{qq h_i} \frac{1}{q^2 - m_{h_i}^2} \bar{u}(\mathbf{p}) u(\mathbf{p} + \mathbf{q}) \xrightarrow{q^2 \rightarrow 0} - \sum_i C_{\chi\chi h_i} C_{qq h_i} \frac{1}{m_{h_i}^2} \bar{u}(\mathbf{p}) u(\mathbf{p})$$

Assuming scalar-like couplings we can write

$$\mathcal{L}_{\text{eff}} \supset - \sum_i \frac{C_{\chi\chi h_i} C_{qq h_i}}{2m_{h_i}^2} \chi \chi \bar{q} q \quad \text{Term in the effective Lagrangian}$$

Exchanged momentum very small



And so the Wilson coefficient is

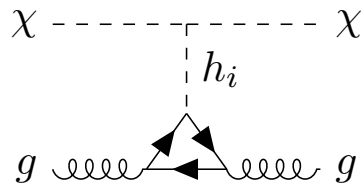
$$C_S^q \supset - \sum_i \frac{C_{\chi\chi h_i} C_{qq h_i}}{2m_q m_{h_i}^2}$$

There can be additional contributions to the quark operators generated through other diagrams, even though at tree level the t-channel exchange is the only topology contributing to this operator in the models under investigation.

Direct detection at LO for scalars

Gluon contributions

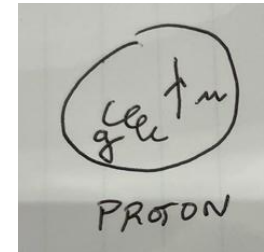
$$m_Q \bar{Q}Q \rightarrow -\frac{\alpha_s}{12\pi} G_{\mu\nu}^a G^{a\mu\nu}$$



SHIFMAN, VAINSHTEIN, ZAKHAROV, PLB78 443 (1978)

This transformation can be used to write

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



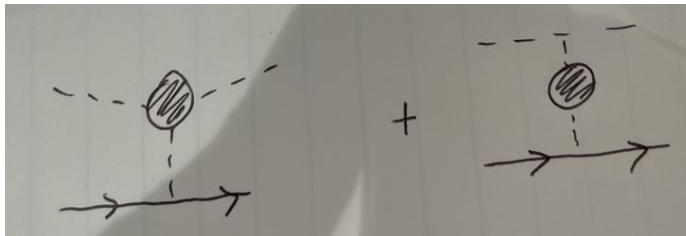
Fraction of proton mass due to gluons

Fraction of proton mass due to light quarks

And so the final cross section is

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

In our first calculation we considered the same "PDF" for the proton and corrected the upper vertex and the mediator

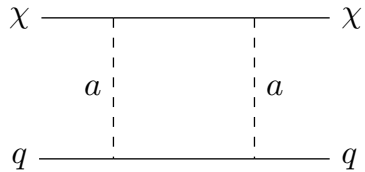


LO "PDF" -> NLO "PDF"

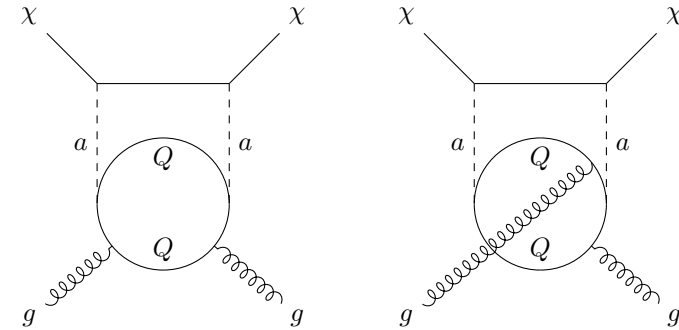
Direct detection at NLO for scalars

Missing: "lower vertex" corrections. Box type diagrams

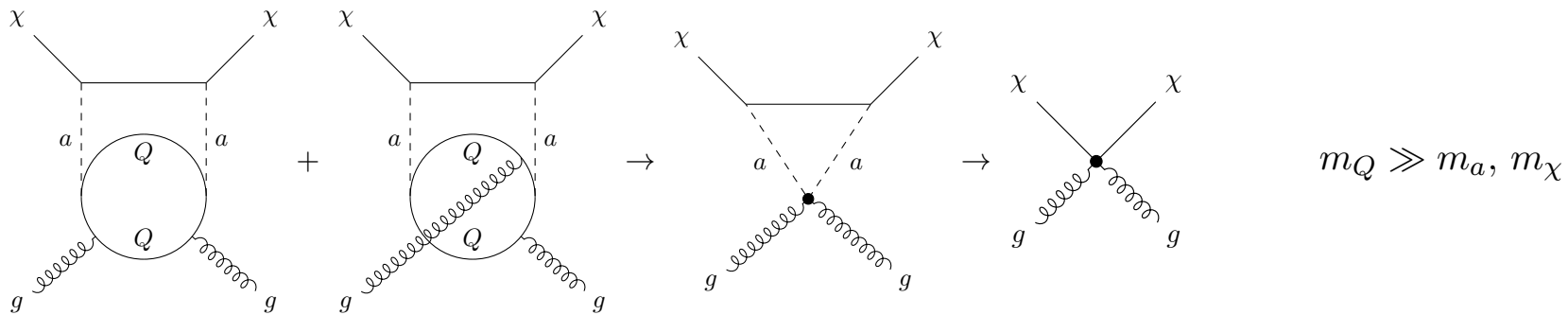
$$m_Q \bar{Q}Q \rightarrow -\frac{\alpha_s}{12\pi} G_{\mu\nu}^a G^{a\mu\nu}$$



The gluon PDF now originates from the diagrams on the right. Factorisation is no longer possible.



An effective vertex was calculated in the limit of heavy quark.



ABE, FUJIWARA, AND HISANO, JHEP 02 028 (2019)

ERTAS, KAHLHOEFER, JHEP06 052 (2019)

Direct detection at NLO for scalars

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

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

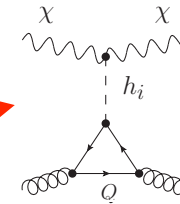
with the Wilson coefficients at one-loop given by

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

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

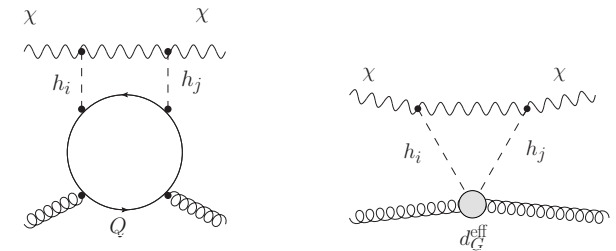
$$f_G^{\text{NLO}} = -\frac{\alpha_S}{12\pi} \sum_{q=c,b,t} (f_q^{\text{vertex}} + f_q^{\text{med}}) + f_G^{\text{top}}$$

Box diagrams contribute to the two different quark operators.



The NLO cross section is

$$\sigma_n = \frac{1}{\pi} \left(\frac{m_n}{m_\chi + m_n} \right)^2 |f_n|^2$$



ERTAS, KAHLHOEFER, JHEP06 052 (2019)

ABE, FUJIWARA, HISANO, JHEP 02, 028 (2019)

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

$$f_G^{\text{top}} = \left(d_G^{\text{eff}} \right)_{ij} C_{\Delta}^{ij} \frac{-\alpha_S}{12\pi}$$

Constraints

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 11%

Searches: for the new scalar - bound that is a function of the new scalar mass and $\cos\alpha$

DM abundance: we require

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

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

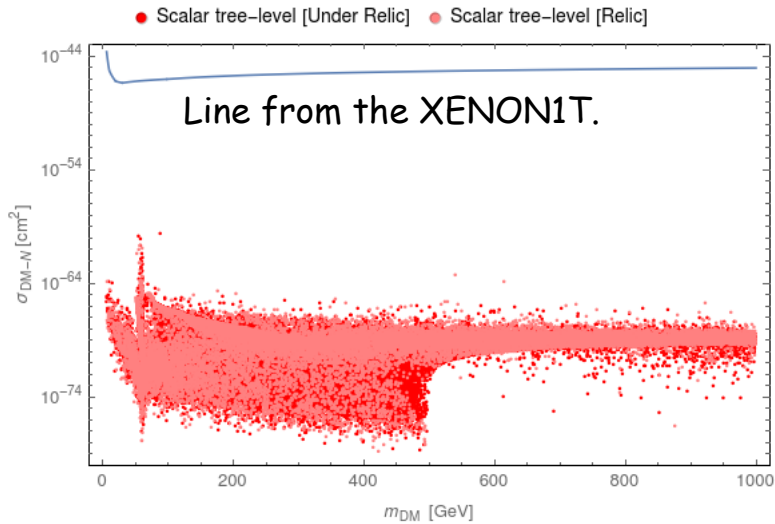
Direct detection: we apply the latest XENON1T bounds

$$(\Omega h^2)_{DM}^{obs} = 0.1186 \pm 0.0020 \quad \sigma_{DM,N}^{eff} = f_{DM} \sigma_{DM,N} \quad \text{with} \quad f_{DM} = \frac{(\Omega h^2)_{DM}}{(\Omega h^2)_{DM}^{obs}}$$

[Fraction contributing to the scattering]

Results

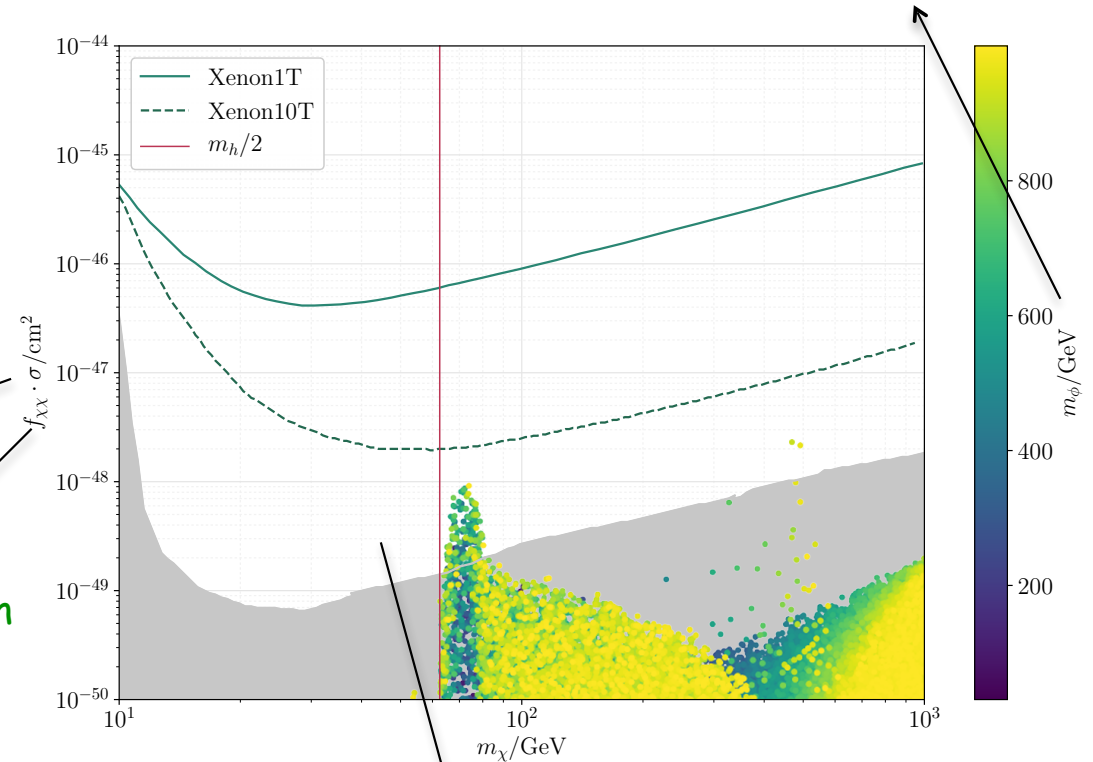
Tree-level cross section



Cross section

DM fraction

Mass of the non-SM Higgs



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).

LHC Higgs to invisible bound (no points).

Differences between the two calculations below 5%.

One-loop corrections in the S2HDM

**BIEKÖTTER, GABRIEL, OLEA-ROMACHO, RS, JHEP 10 (2022) 126,
2207.04973 [HEP-PH].**

S2HDM - two doublets plus one real singlet

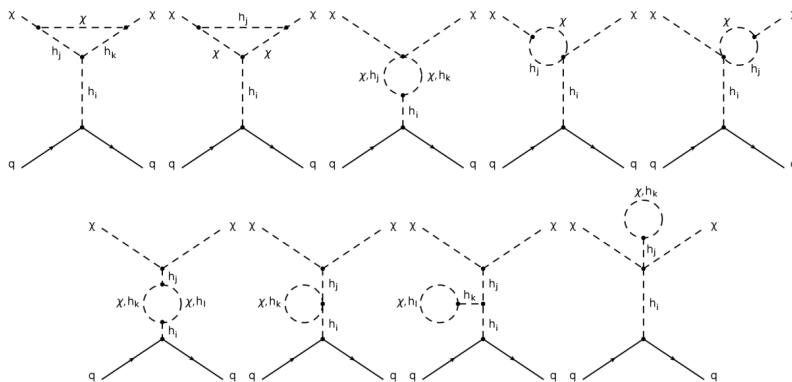
S2HDM - Now the SM is extended by one doublet and a complex singlet. There is an extra doublet compared to the previous model.

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

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

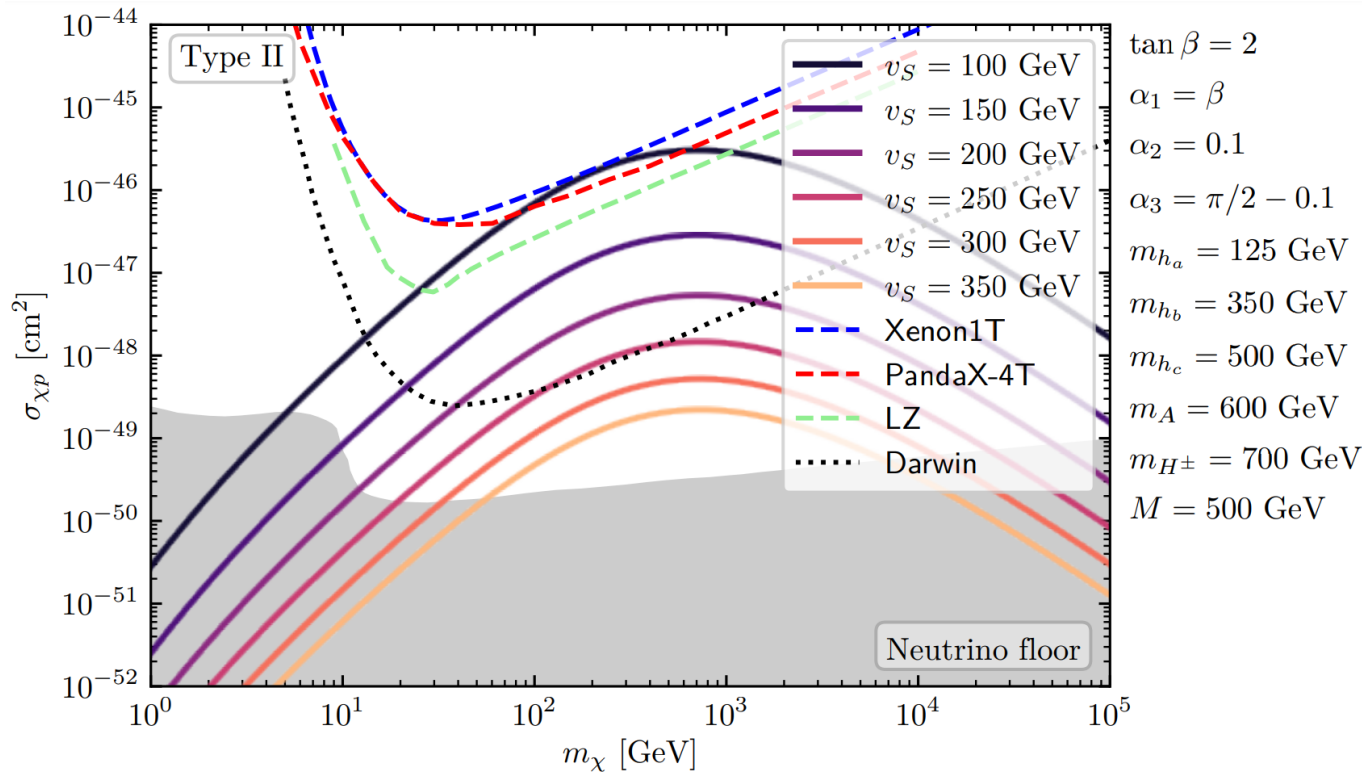
These models can lead to tree-level flavour changing neutral currents. These are very constrained by experiment. To solve this problem one usually forces the Yukawa Lagrangian to be invariant under a Z_2 symmetry. This leads to 4 possible Yukawa Lagrangians (the way scalars are combined with fermions).

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.

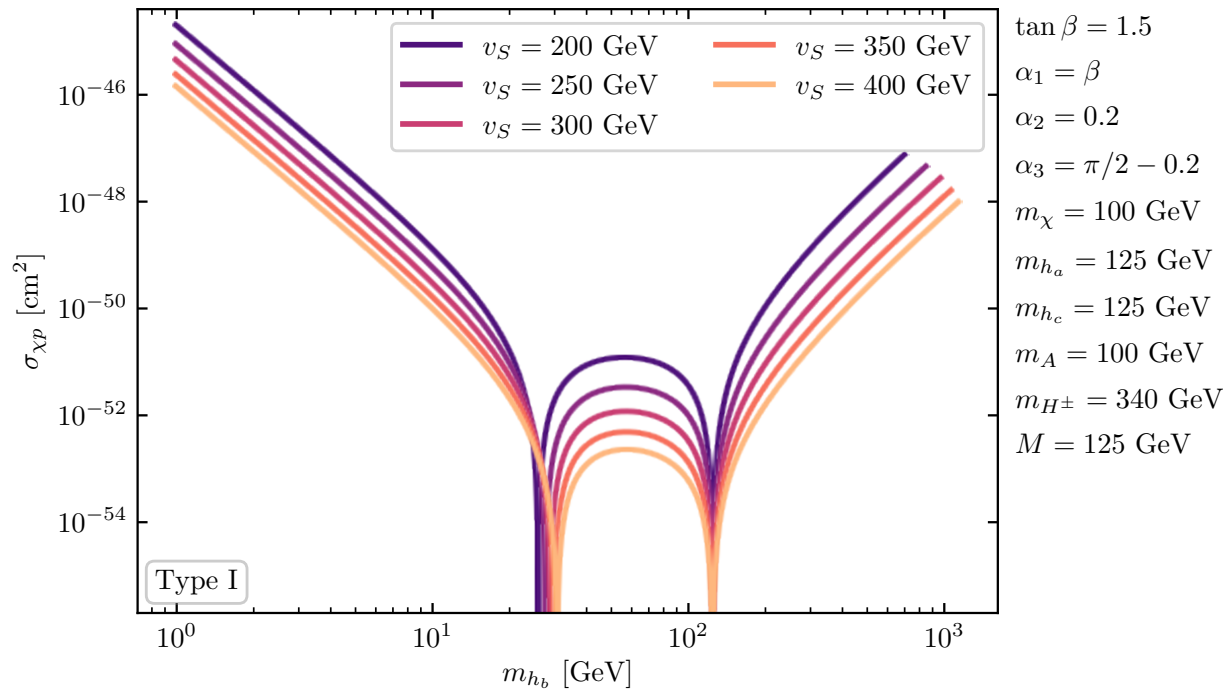
Generic behaviour of the loop corrected cross section Type II



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.

Blind spots in Type I



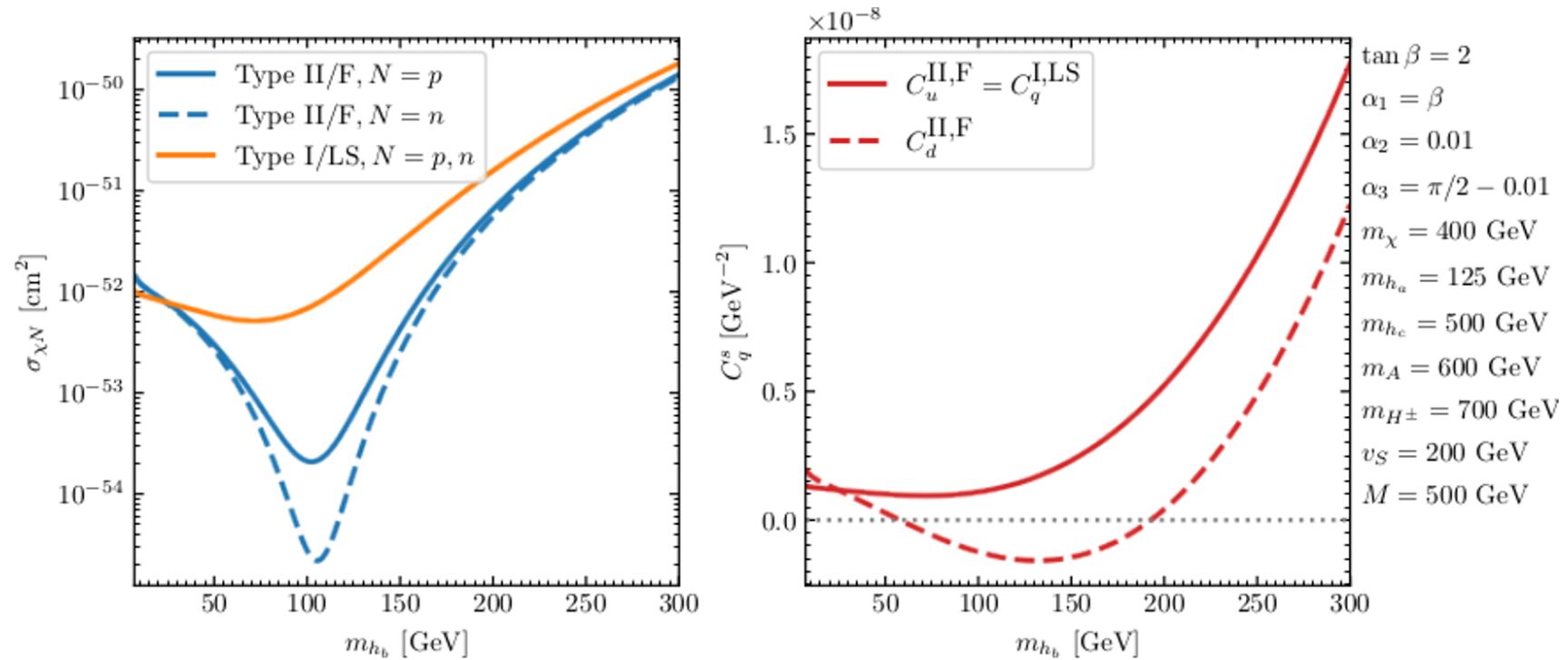
Behaviour with the non-SM Higgs is again very similar to the one doublet case.

Two blind spots appear

a) one for the case when all neutral masses are equal (in the CxSM the blind spot appeared at $m_2 = m_1$);

b) another one at around $m_{h_b} \sim 30$ 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.

2HDM Type-dependent blind spot

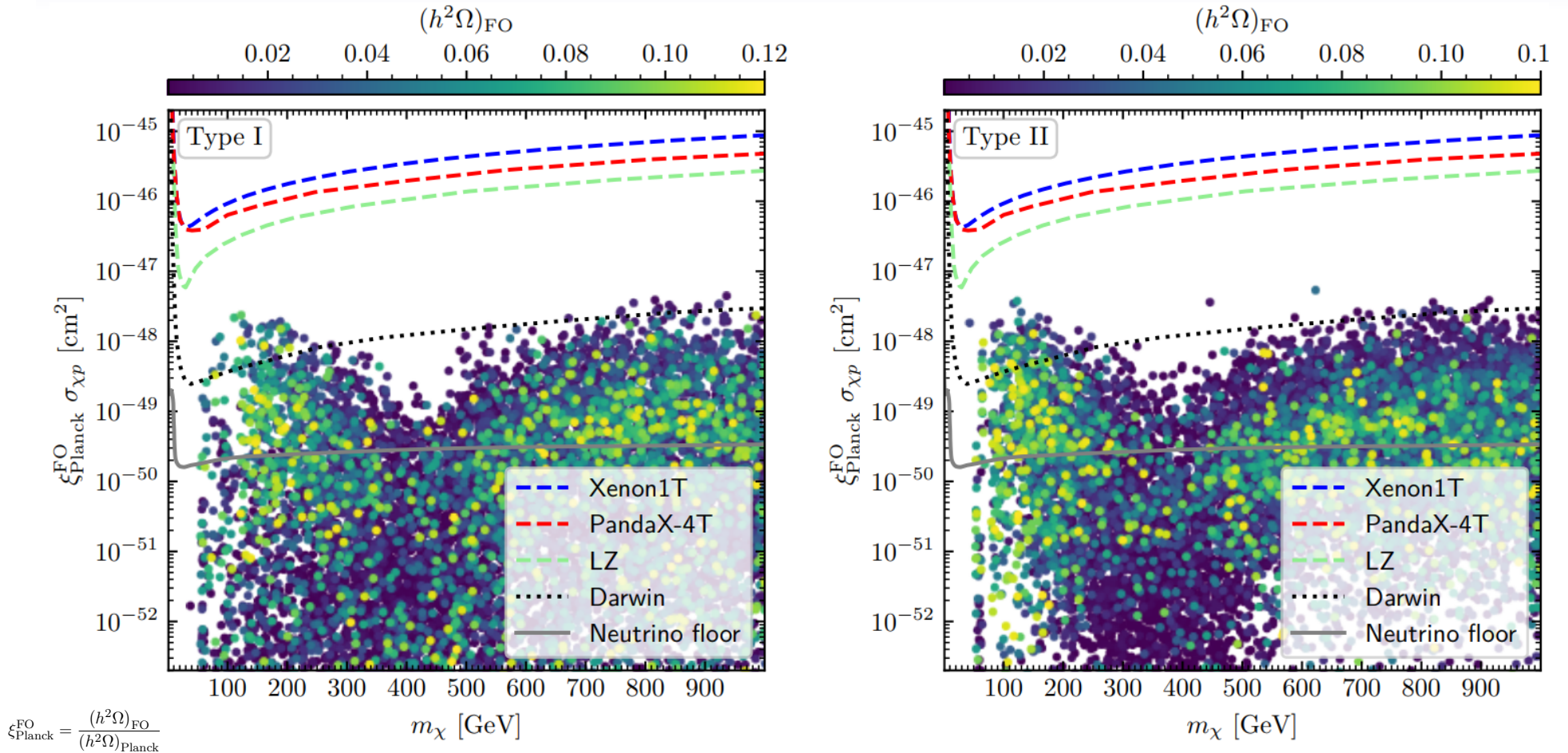


What is new for this model is that we have scenarios where:

a) Blind spots appear in one type but not in other. In this case in Type II but not in Type I.

b) Blind spots may depend on whether the collision is with a proton or with a neutron.

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

GLAUS, MÜHLEITNER, MÜLLER, PATEL, RS, JHEP 10 (2019) 152,
1908.09249 [HEP-PH]

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

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

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

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} + (D_\mu \mathbb{S})^\dagger (D^\mu \mathbb{S}) + \mu_S^2 |\mathbb{S}|^2 - \lambda_S |\mathbb{S}|^4 - \kappa |\mathbb{S}|^2 H^\dagger H \quad D_\mu = \partial_\mu + ig_X X_\mu$$

with

$$H = \begin{pmatrix} G^\pm \\ \frac{1}{\sqrt{2}}(v_H + h + iG_0) \end{pmatrix} \quad \mathbb{S} = \frac{1}{\sqrt{2}}(v_S + S + iA)$$

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, ...

A simple Vector Dark Matter (VDM) model

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

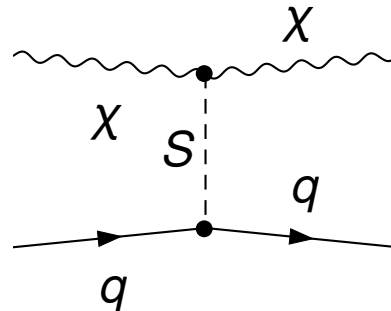
$$m_{\pm} = \lambda_H v_H^2 + \lambda_S v_S^2 \pm \sqrt{\lambda_H^2 v_H^4 + \lambda_S^2 v_S^4 + \kappa v_H^2 v_S^2 - 2\lambda_H \lambda_S v_H^2 v_S^2}$$

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

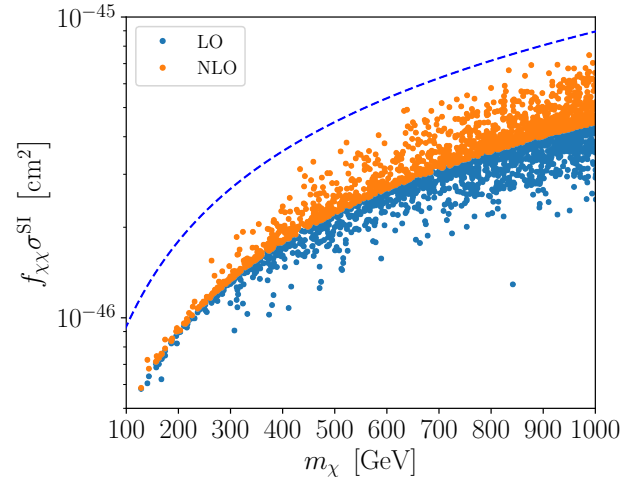
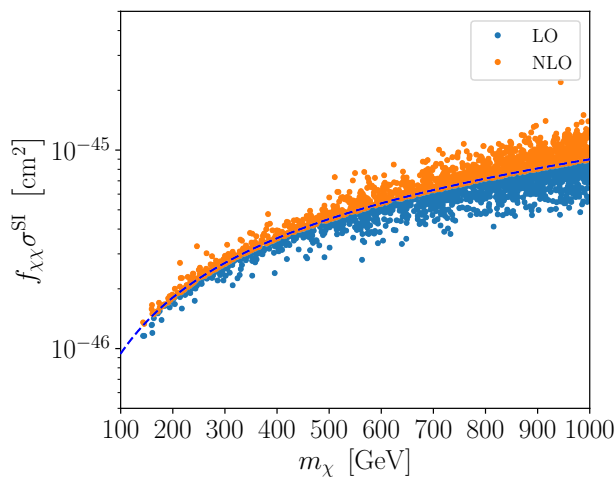
$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = \begin{pmatrix} \cos \alpha & \sin \alpha \\ -\sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h \\ S \end{pmatrix}$$

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?



NLO vs. LO results for the VDM model

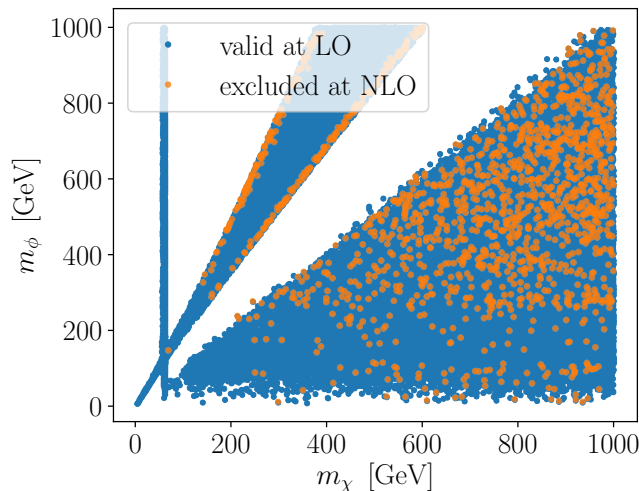


The K-factor (NLO/LO) is mostly positive and the bulk of K-factor values ranges between 1 and about 2.3.

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%.

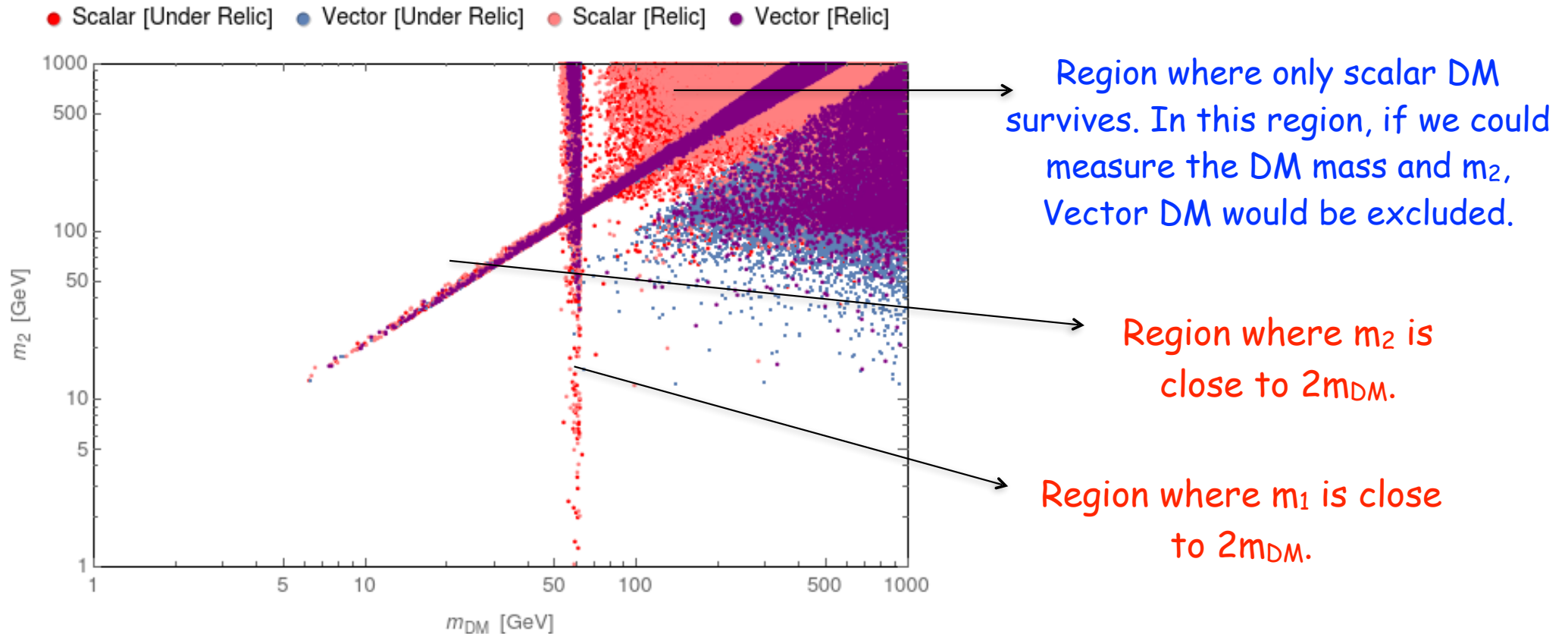
Left: points that are not excluded at LO but are excluded at NLO.

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



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

Comparing two simple models with vector or scalar 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

AZEVEDO, DUCH, GRZADKOWSKI, HUANG, IGLICKI, RS, PRD 99 (2019) 1, 015017, 1808.01598 [HEP-PH].

The Naoshima pumpkin is back!



My picture of the Naoshima pumpkin in 2019.



Photo: Tadasu Yamamoto | © Yayoi Kusama 'Pumpkin' (2022)

The iconic Yayoi Kusama yellow pumpkin on Naoshima is back

The art island's trademark yellow pumpkin by Yayoi Kusama is back on display after it was damaged in a typhoon last summer

Summary

- ▶ Direct detection experiments impose important constraints on WIMP models.
- ▶ When the tree-level cross section is not negligible electroweak corrections have K-factor (NLO/LO) and mostly positive and the bulk of K-factor values ranges between 1 and about 2.3.
- ▶ In the VDM, 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%.
- ▶ For pNGB with negligible cross sections at tree-level electroweak corrections are needed.
- ▶ There are no big differences if the number of doublets is increased.
- ▶ These models can be probed in future direct detection experiments

Thank you!

s2hdmTools

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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

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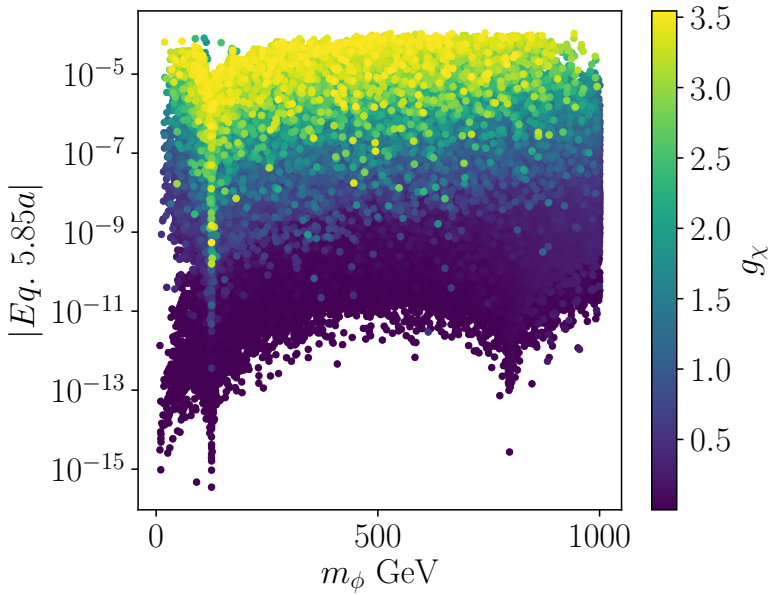
[External software](#)

[Installation](#)

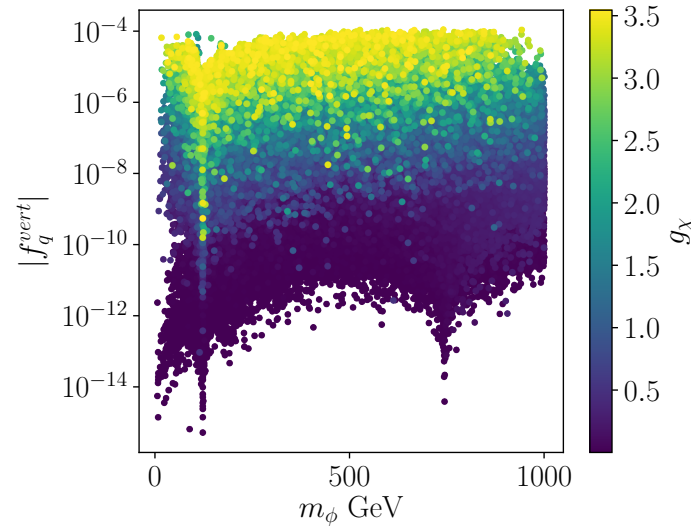
[User instructions](#)

[Issues](#)

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

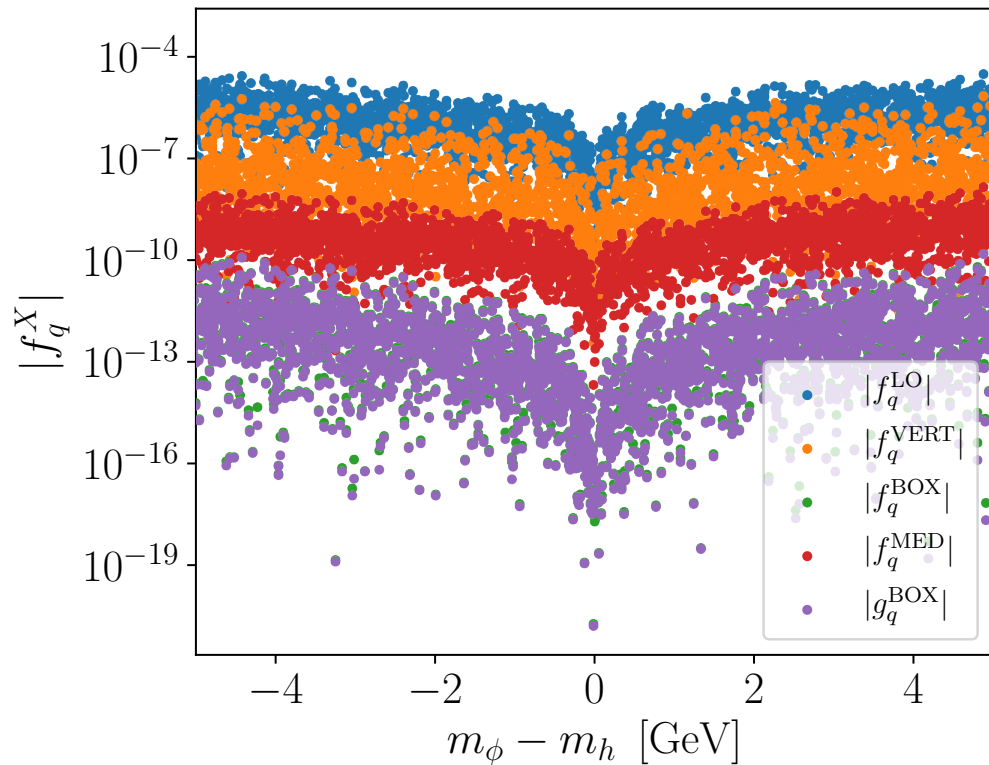


Wilson coefficient at one-loop as a function of the non-125 scalar (in units of GeV^{-2}) with the dark gauge coupling in the colour bar.



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

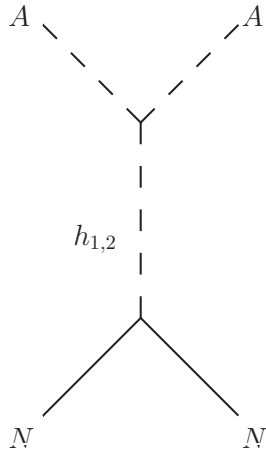
Largest contribution to f_q^{NLO} comes from f_q^{vert} but are smaller than the total.



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.

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

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

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

NEW CALCULATION BY ISHIWATA AND TOMA, JHEP 1812 089 (2018)

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]

$$f_{T_u}^p = 0.01513, \quad f_{T_d}^p = 0.0191, \quad f_{T_s}^p = 0.0447, \quad (\text{A.99a})$$

$$f_{T_u}^n = 0.0110, \quad f_{T_d}^n = 0.0273, \quad f_{T_s}^n = 0.0447, \quad (\text{A.99b})$$

which can be related to the gluon form factors as

$$f_{T_G}^p = 1 - \sum_{q=u,d,s} f_{T_q}^p, \quad f_{T_G}^n = 1 - \sum_{q=u,d,s} f_{T_q}^n. \quad (\text{A.100})$$

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

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

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

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

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

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

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

Nuclear form factors

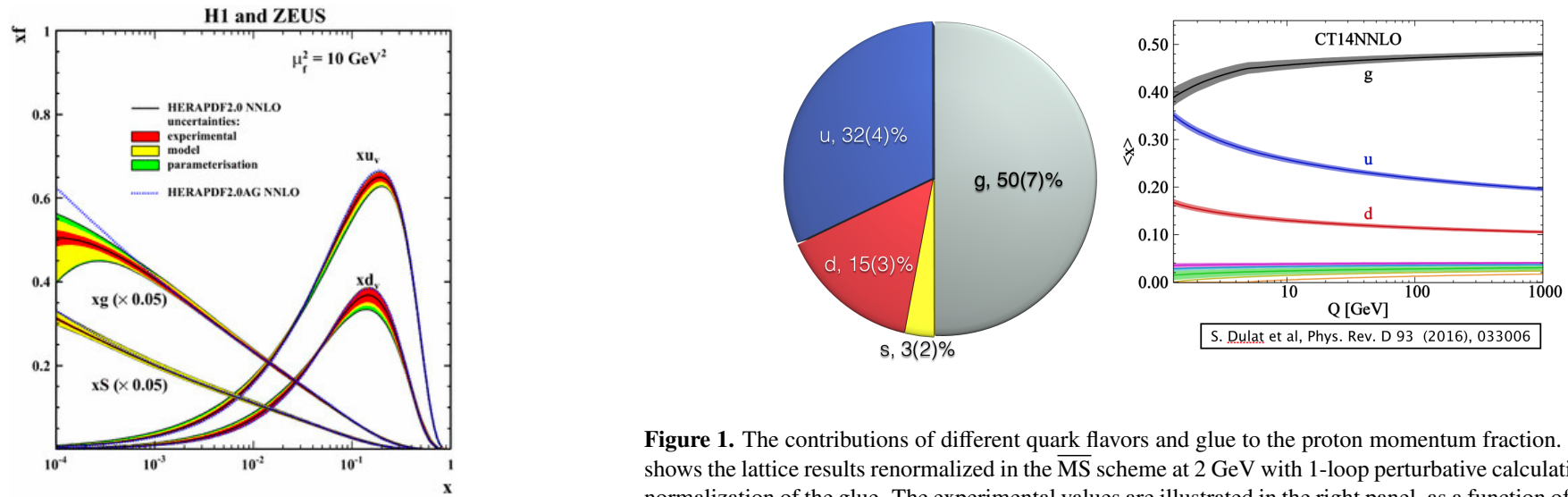
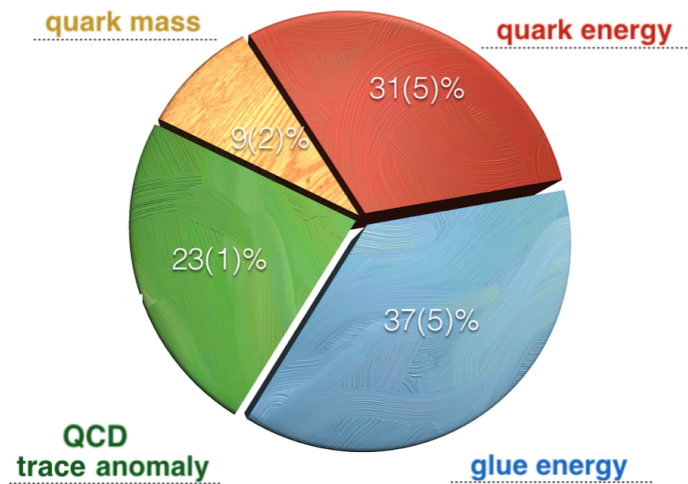


Figure 1. The contributions of different quark flavors and glue to the proton momentum fraction. The left panel shows the lattice results renormalized in the $\overline{\text{MS}}$ scheme at 2 GeV with 1-loop perturbative calculation and proper normalization of the glue. The experimental values are illustrated in the right panel, as a function of the $\overline{\text{MS}}$ scale. Our results agree with the experimental values at 2 GeV.



YANG ET AL., ARXIV:1710.09011V1 (2018)

Figure 2. The pie chart of the proton mass decomposition, in terms of the quark mass, quark energy, glue field energy and trace anomaly.