

Well-tempered n-plet dark matter

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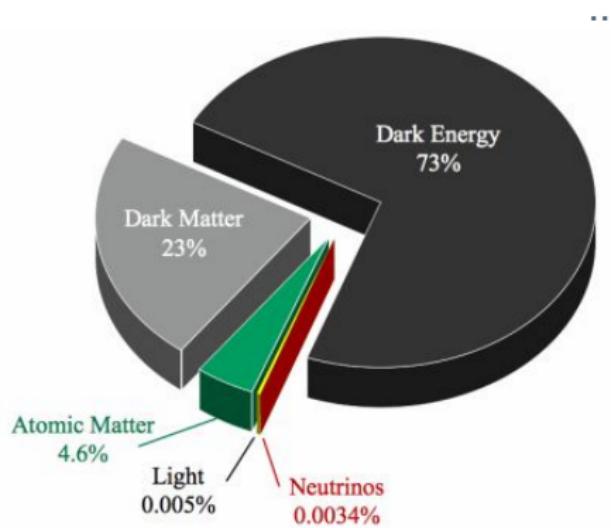
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Context

Standard Model (SM) of particle physic
Well-tested, very good agreement with the observations

But this is not the end of the story !

asymmetry matter-antimatter ? dark matter (DM) ? neutrino masses ?



Relic density

Measure the amount
of DM in the universe.

Planck data :

$$\Omega h^2 = 0.1199 \pm 0.0022$$

arXiv :1502.01589

Model building

What we want :

- To have a good fermionic dark matter candidate.
- To pass through DD limits.
- To be testable at the LHC \Rightarrow new masses around the EW scale.

WIMP paradigm \Rightarrow DM with a mass of 1-10 TeV.

DM candidate with a mass $\mathcal{O}(100 \text{ GeV})$ must necessarily originate mostly from an $SU(2) \times U(1)$ singlet, and feel the electroweak gauge interactions at most through a small coupling to a non-singlet.

What we do :

- Add a singlet χ and a n-plet ψ under $SU(2)_L \otimes U(1)_Y$.
- Induce a mixing of the neutral components through an effective operator.
- Impose $\Lambda_{UV} \geq 1 \text{ TeV}$

The Model

The Lagrangian for n odd

$$\mathcal{L}_{\text{DM}} = i \psi^\dagger \bar{\sigma}^\mu D_\mu \psi + i \chi^\dagger \bar{\sigma}^\mu \partial_\mu \chi - \left(\frac{1}{2} M \psi \psi + \frac{1}{2} m \chi \chi + \text{h.c.} \right)$$

$$+ \frac{1}{2} \frac{\kappa}{\Lambda} \phi^\dagger \phi \chi \chi + \text{h.c.} \quad (\mathcal{L}_{\text{quartic}})$$

$$+ \frac{\lambda}{\Lambda^{n-2}} (\phi^\dagger \phi)^{\frac{n-1}{2}} \psi \chi + \text{h.c.} \quad (\mathcal{L}_{\text{mix}}, \text{schematical})$$

Comments

- \mathbb{Z}_2 symmetry to ensure the stability of the DM.
- ψ is a Majorana fermion in $SU(2)_L \otimes U(1)_Y$ (\mathbf{n}_0).
- χ is a Majorana singlet.
- ϕ is a SM Higgs doublet.

The Model

The Lagrangian for n even

$$\mathcal{L}_{\text{DM}} = i \psi^\dagger \bar{\sigma}^\mu D_\mu \psi + i \bar{\psi}^\dagger \bar{\sigma}^\mu D_\mu \bar{\psi} + i \chi^\dagger \bar{\sigma}^\mu \partial_\mu \chi - \left(M \psi \bar{\psi} + \frac{1}{2} m \chi \chi + \text{h.c.} \right)$$

$$+ \frac{1}{2} \frac{\kappa}{\Lambda} \phi^\dagger \phi \chi \chi + \text{h.c.} \quad (\mathcal{L}_{\text{quartic}})$$

$$+ \frac{1}{\Lambda^{n-2}} (\phi^\dagger \phi)^{\frac{n-2}{2}} \left(\lambda \phi \chi \psi - \lambda' \phi^\dagger \chi \bar{\psi} + \text{h.c.} \right) \quad (\mathcal{L}_{\text{mix}}, \text{schematical})$$

Comments

- \mathbb{Z}_2 symmetry to ensure the stability of the DM.
- $(\psi, \bar{\psi}^\dagger)$ form a Dirac spinor transforming in the $\mathbf{n}_{\frac{1}{2}}$.
- χ is a Majorana singlet.
- ϕ is a SM Higgs doublet.

Mixing and dark sector

Hypothesis

- The dark matter is mostly a singlet-like (χ -like).
- $\Rightarrow m < M$. ($(M - m) \sim \text{few} 10 \cdot \text{GeV}$ for the case of interest).
- Our effective description valid up to $\Lambda \geq 1 \text{TeV}$.

What happened ?

- EWSB $\Rightarrow \mathcal{L}_{\text{mix}}$ induce a mixing between the neutral states.
- The lightest neutralino is the dark matter.

$n = 3$

Dark sector :

$$\chi_{1,2}^0, \chi^\pm$$

Mixing :

$$\theta \simeq \frac{\sqrt{2}\lambda v^2}{\Lambda(M-m)}$$

$n = 4$

Dark sector :

$$\chi_{1,2,3}^0, \chi_{1,2}^\pm, \chi^{\pm\pm}$$

Mixing :

$$\theta_\pm \simeq \frac{(\lambda \pm \lambda')v^3}{\sqrt{6} \Lambda^2 (M \mp m)}$$

$n = 5$

Dark sector :

$$\chi_{1,2}^0, \chi^\pm, \chi^{\pm\pm}$$

Mixing :

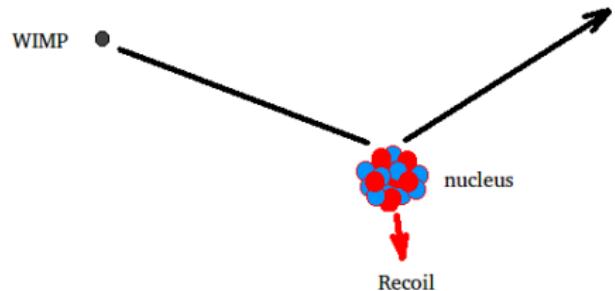
$$\theta \simeq \sqrt{\frac{2}{3}} \frac{\lambda v^4}{\Lambda^3 (M-m)}$$

DM properties

If \mathcal{L}_{mix} dominates ...

- Tiny θ : θ too small for χ_1^0 to be in equilibrium \Rightarrow relic density predicted if initial conditions are assumed.
- Small θ : Equilibrium \Rightarrow **freeze-out mechanism**.
 $\psi_i \rightarrow \chi_1^0 + \text{SM}$ and $\chi_1^0 + \text{SM} \rightarrow \psi_i + \text{SM}$ occur.
 χ_1^0 abundance is determined by ψ_i annihilation.
- Not so small θ : Processes directly involving χ_1^0 become important.
The relic density is now a function of both the masses and θ .
- $\theta \sim \mathcal{O}(1)$: Our effective theory is approaching the limits of its validity.

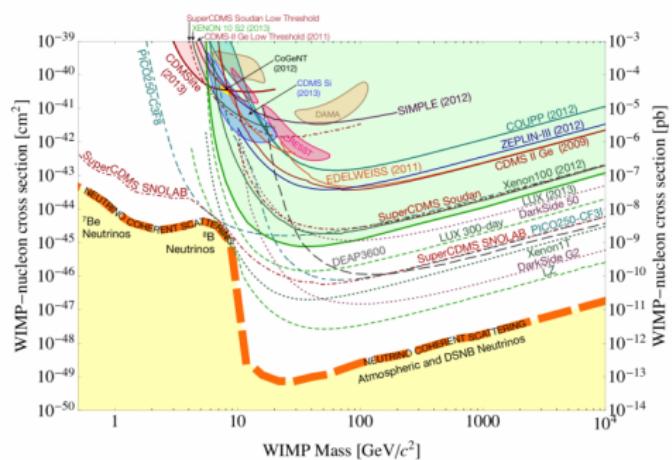
Direct detection



Principle

Detect a collision of a nucleus
with a dark matter particle
by measuring the recoil energy.

Experiments : LUX, Xenon1T, ...



Constraints

Upper limits on the
cross-section
WIMP-nucleon

Observables : σ_{SI} , σ_{SD}

Parametrization

For n odd (3 or 5) :

- Input : Physical masses $m_{\chi_1^0}$, $\Delta m = m_{\chi_2^0} - m_{\chi_1^0}$
 - Couplings : $\lambda = 1$ (we work in λ unit).
 - Running of the cut-off Λ_{UV} .
-

For n even (4) :

- Input : Physical masses $m_{\chi_1^0}$, $\Delta m = m_{\chi_2^0} - m_{\chi_1^0}$
- Couplings : $\lambda = 1$. Then we choose $\theta_- = 0$.
- Running of the cut-off Λ_{UV} .

Note that θ_- is suppressed compare to θ_+ . Therefore this choice corresponds to a generic case.

$$\theta_{\pm} \propto \frac{(\lambda \pm \lambda')}{(M \mp m)}$$

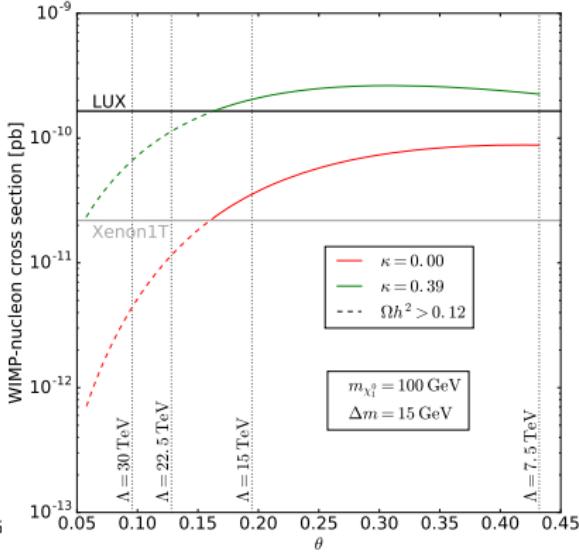
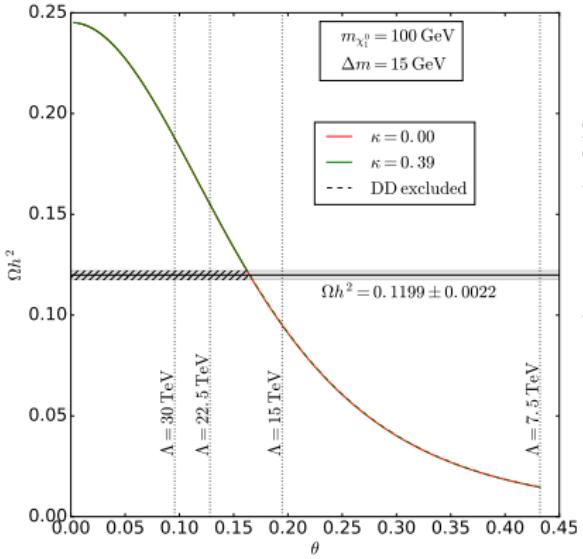
Analysis

- The models are implemented with *FeynRules 2.0*. [[1310.1921](#)]
- The relic density and the DD cross-sections are computed with *micrOMEGAs 4.3*. [[1305.0237](#)]
- All the theoretical cross-sections are rescaled by a factor $\frac{\Omega h^2|_\chi}{\Omega h^2|_{exp}}$ in order to be compared with **LUX** results [[1608.07648](#)] and **Xenon1T** prospects [[1512.07501](#)]
- At one loop the masses received corrections from electroweak gauge bosons. In the absence of mixing : [[arXiv :hep-ph/0512090](#)]

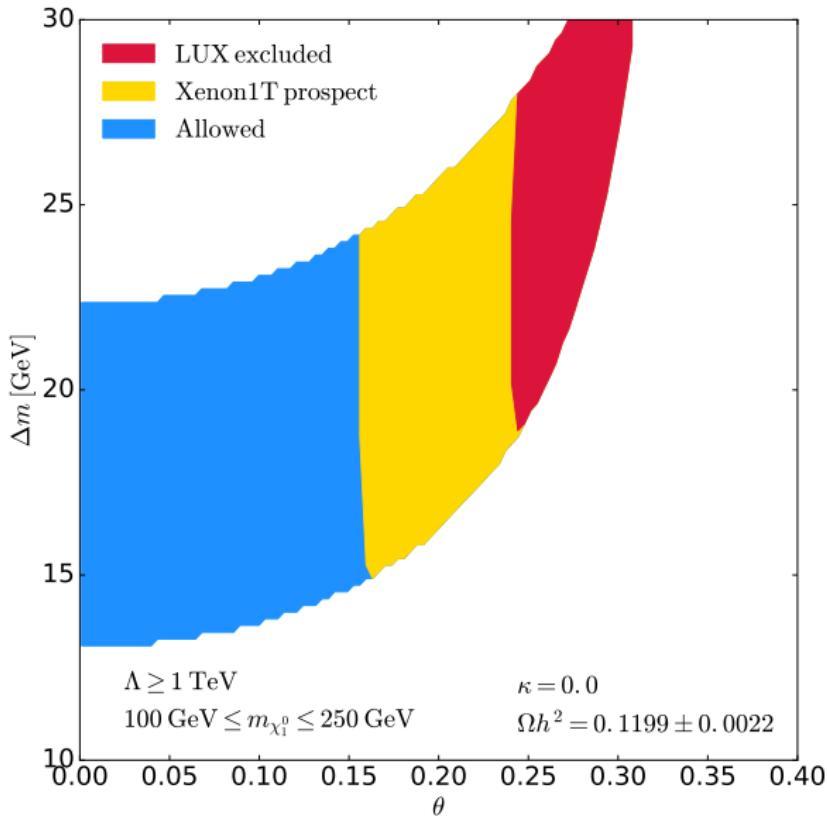
$$\Delta_{m_Q - m_{\chi_2^0}}^{\text{one loop}} = \frac{g^2}{16\pi^2} M \left(Q^2 s_W^2 f\left(\frac{m_Z}{M}\right) + Q(Q - 2Y) f\left(\frac{m_W}{M} - \frac{m_Z}{M}\right) \right)$$

$$f(x) = \frac{x}{2} \left(2x^3 \log x - 2x + \sqrt{x^2 - 4}(x^2 + 2) \log \frac{x^2 - x\sqrt{x^2 - 4} - 2}{2} \right)$$

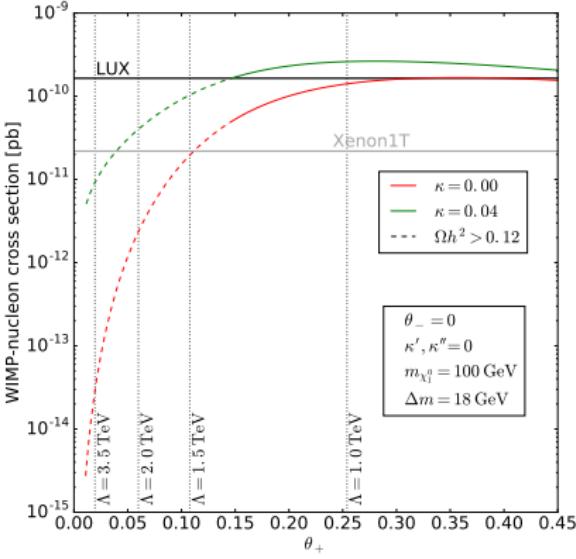
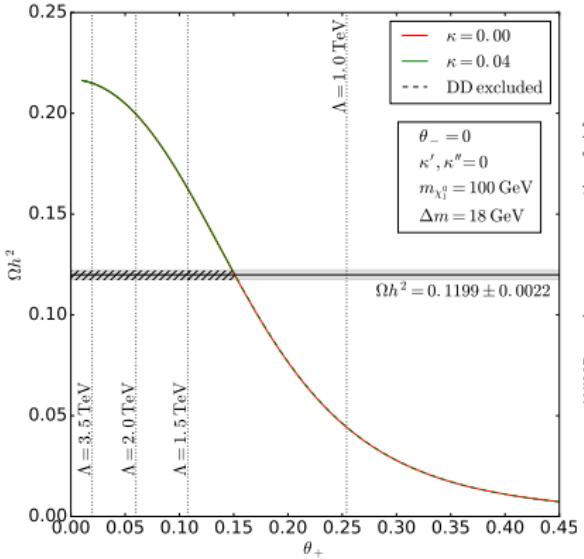
Results : n=3



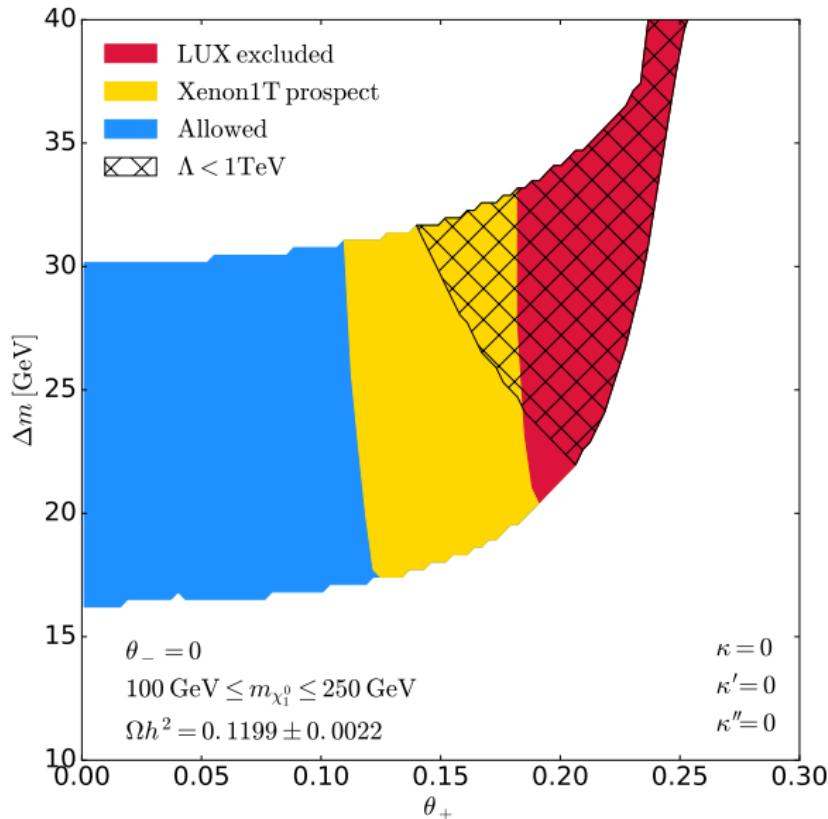
Results : n=3



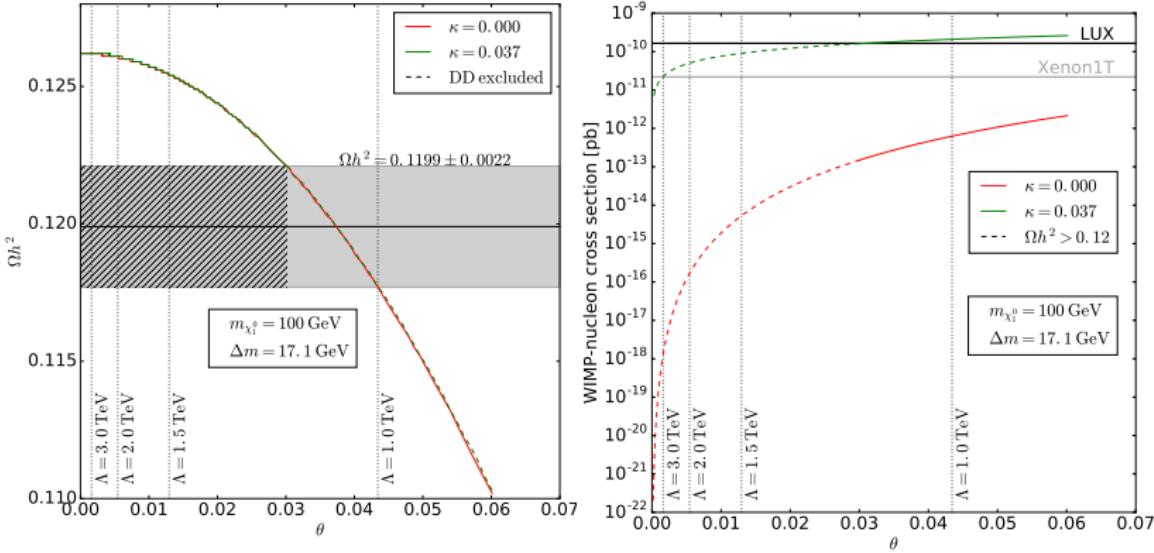
Results : n=4



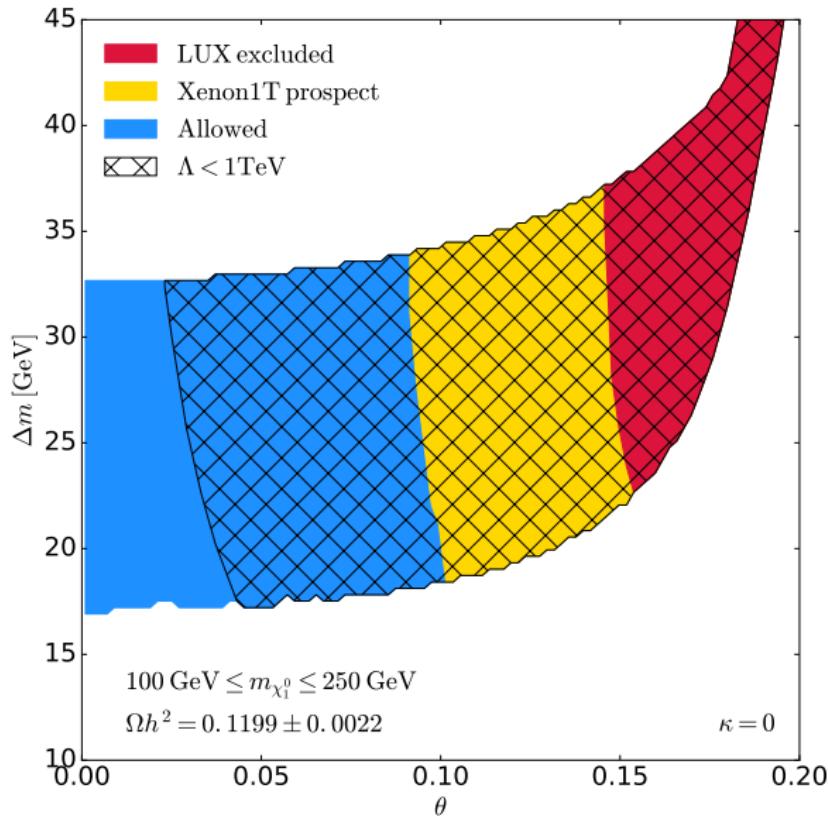
Results : n=4



Results : n=5



Results : n=5



Conclusion

Summarize :

- Simple effective models for fermionic WIMP DM at EW scale.
- DM is the mixture of a singlet and a n-plet of $SU(2)_L \otimes U(1)_Y$.
- κ is strongly constraints by DD.
- Relic density must be dominated by \mathcal{L}_{mix} rather than $\mathcal{L}_{quartic}$, i.e. $\kappa \ll \lambda$.
- Impact of κ (dim-5 operator) is more and more important when n increases. (\mathcal{L}_{mix} is a dim- $(n+2)$ operator).
- Suitable choice for the parameters can always be found.
- Potentially ruled out with the future DD experiment results.
- Testable at the LHC.

Perspectives : To study the phenomenology at the LHC.
(ISR + missing energy, Disappearing track, Displaced vertex, ...)

The end !

Thank you for your attention !

Back-up

About effective operators

Other effective operators than \mathcal{L}_{mix} and $\mathcal{L}_{quartic} \dots$

dimension 5 (n even) :

- **ψ -quartic** : $\phi^\dagger \phi \psi \bar{\psi}$
- **Dipole operators** : $g' Y \psi (\sigma^{\mu\nu}) \bar{\psi} B_{\mu\nu} + g \psi (\sigma^{\mu\nu}) t^a \bar{\psi} W_{\mu\nu}^a$
- **With generators** : $(\phi^\dagger \tau^a \phi)(\psi t^a \bar{\psi})$, $(\phi^\dagger \tau^a \phi^\dagger)(\psi t^a \psi)$, $(\phi \tau^a \phi)(\bar{\psi} t^a \bar{\psi})$

χ -like DM \Rightarrow mixing suppressed.

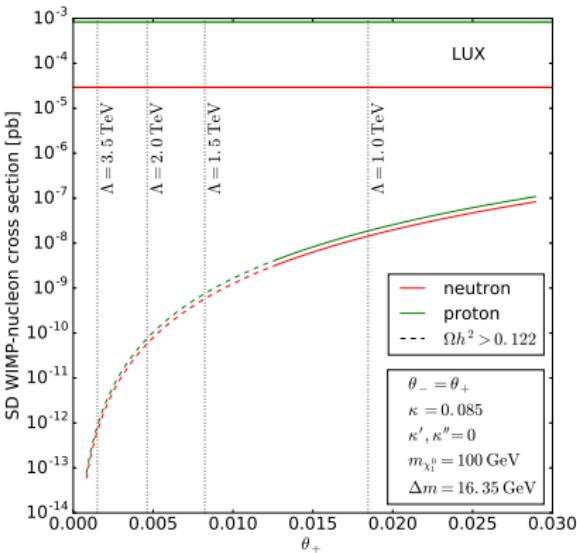
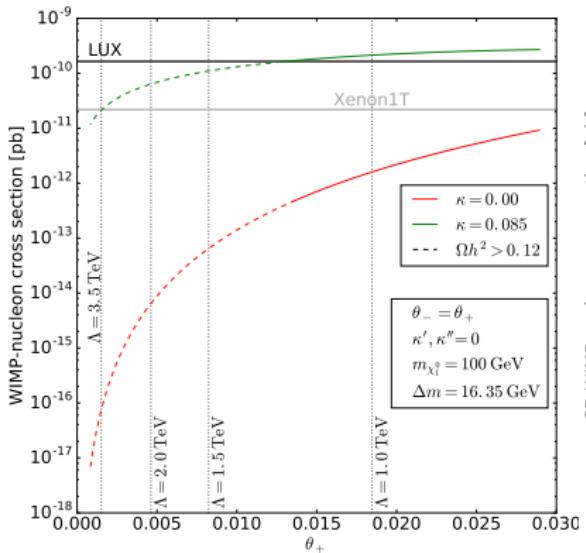
Operators with τ^a have an impact on the mass spectrum after EWSB.

dimension 6 :

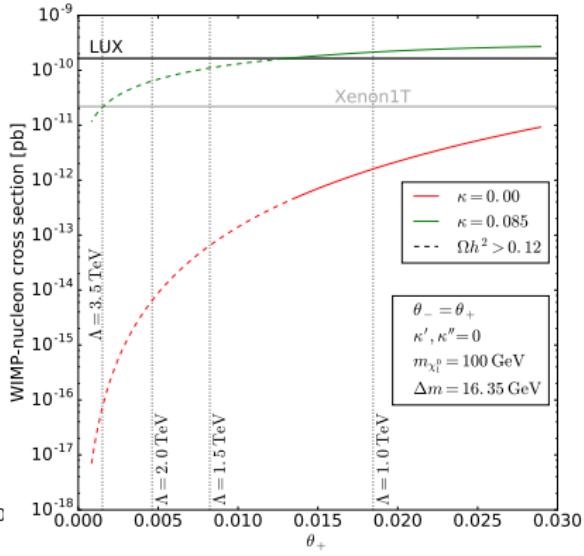
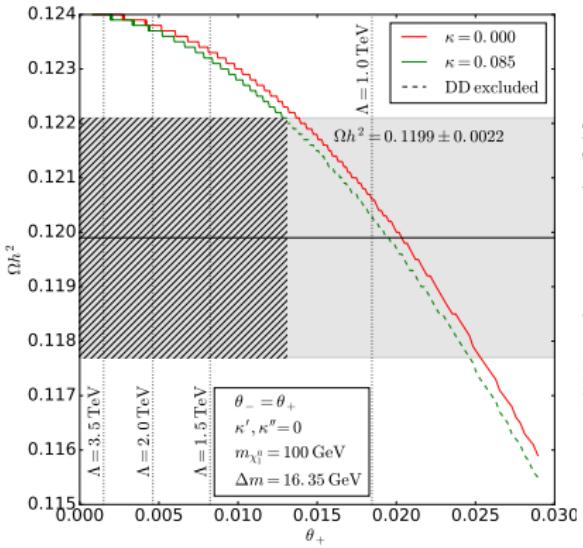
- **4 fermions** : $(c_{ij}^l l_i^\dagger \bar{\sigma}_\mu l_j)(\chi^\dagger \bar{\sigma}^\mu \chi) + (c_{ij}^q q_i^\dagger \bar{\sigma}_\mu q_l l_j)(\chi^\dagger \bar{\sigma}^\mu \chi)$

Suppressed since these lead to FCNC.

SD limits ?

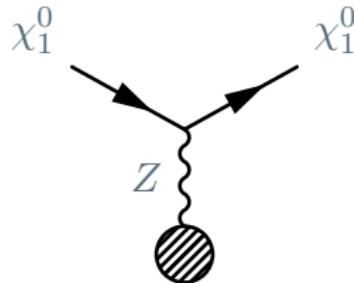


Results : $n=4$ with $\theta_- = \theta_+$

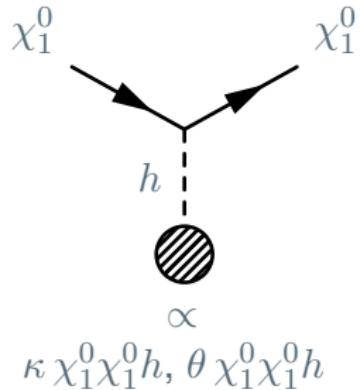


σ contributions

SI contributions :

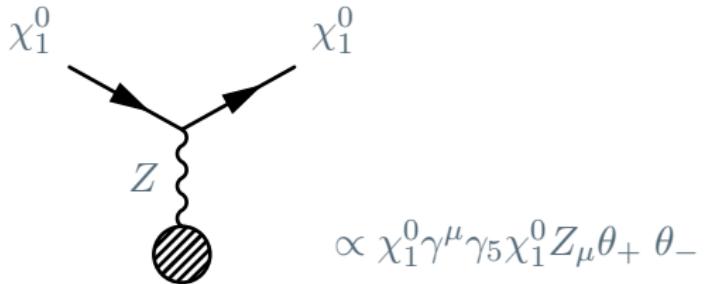


$$\propto \chi_1^0 \gamma^\mu \chi_1^0 Z_\mu = 0 \\ (\text{Majorana})$$



$$\propto \kappa \chi_1^0 \chi_1^0 h, \theta \chi_1^0 \chi_1^0 h$$

SD contributions :



$$\propto \chi_1^0 \gamma^\mu \gamma_5 \chi_1^0 Z_\mu \theta_+ \theta_-$$