How important is the Higgs invisible decay search for dark matter?

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The Higgs invisible decay is often addressed as one of the best processes to search for dark matter at collider exps, Is it really true? This search is really better than those at underground experiments? I would like to introduce a few candidates that the invisible Higgs decay search is indeed essential within the framework of the WIMP dark matter.

Dark matter candidates

What is DM?

10^{-22}eV < m < 10^{35}g

Wave-like (Eg. Axion)

10^{-22}eV < m < 0.1GeV

Particle-like

0.1 eV < m < 10^{19}GeV

Macroscopic (Eg. PBH)

10^{19}GeV < m < 10^{35}g

Thermal

10^{2}keV < m < 10^{5}GeV

Non-thermal (Eg. Sterile ν)

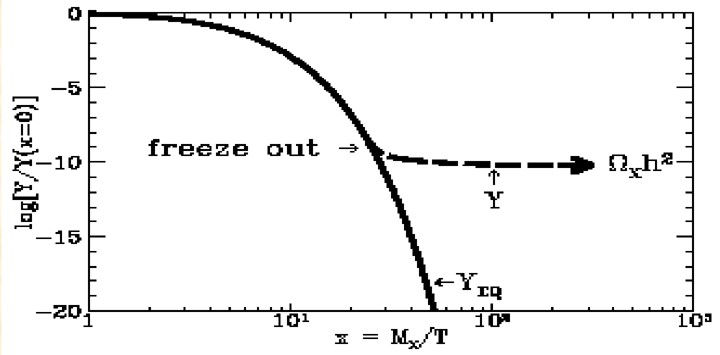
DM candidates in this category are free from the initial condition problem, and relatively easy to be detected at detection experiments.

Eg. WIMP, SIMP, ADM, Semi-ann. DM, etc.

WIMP dark matter Hypothesis

We consider WIMP DM candidates, where its abundance observed today is mainly generated by Freeze-out mechanism!!

The mechanism is known to describe the BBN & the recombination phenomena successfully.



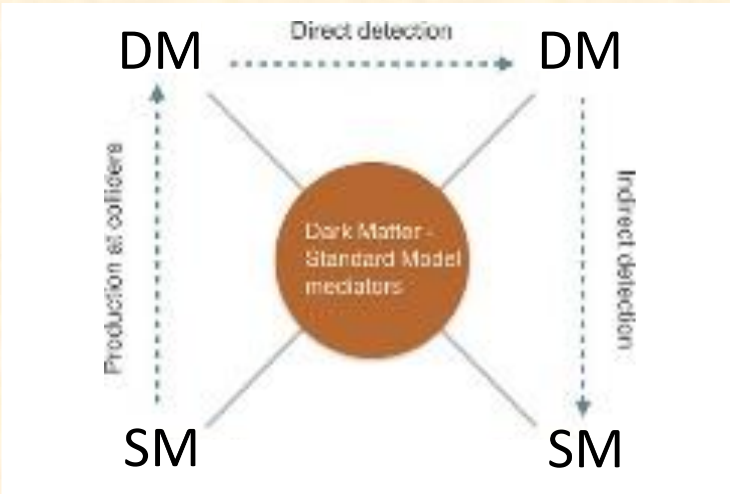
A way to systematically study WIMP DM cadidates:

New physics models beyond SM. ⇔ Effective theories of the WIMP DMs. ⇒ Signals at various DM experiments.

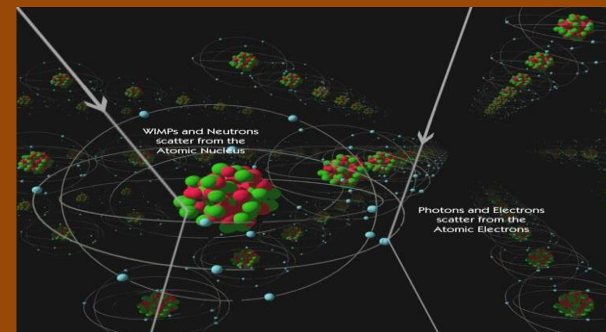
1. Phenomenology of WIMP dark matter candidates is essentially determined by their quantum numbers (spin and weak isospin).
2. Effective theories of WIMP dark matter candidates can be (almost uniquely) determined by minimality & renormalizablility viewpoint.
3. The role of new physics models is to explain why DM has such a quantum number, to give non-trivial relations among interactions.

WIMP dark matter detections

Once the effective theories of WIMPs are given,

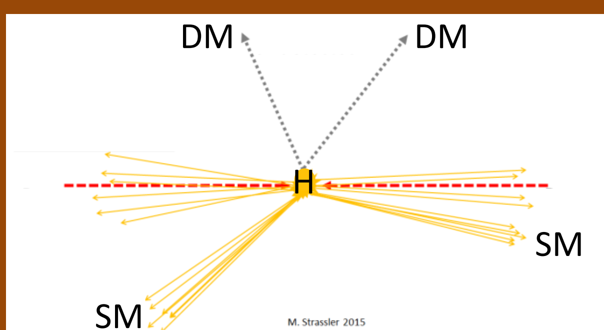


Detection @ Underground



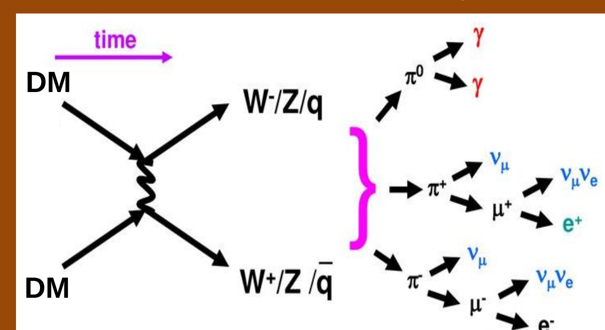
Scattering via Higgs exchange?

Detection @ Colliders



Produced via Higgs decay?

Detection @ Telescopes

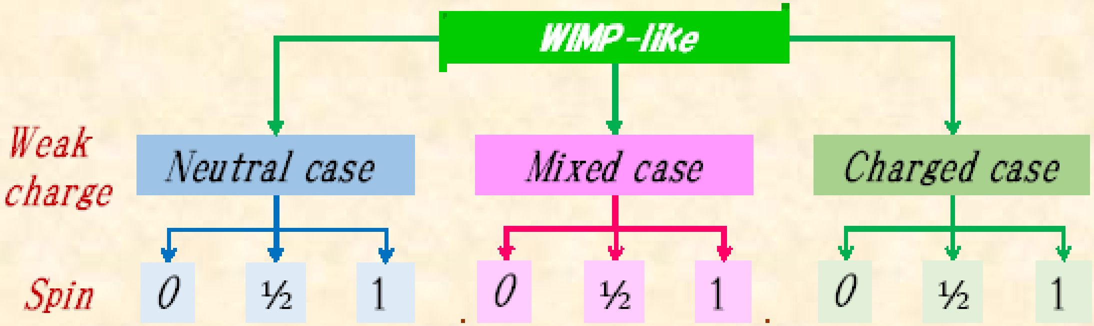


Annihilating via/into Higgs?

WIMP dark matter Hypothesis

How can we construct the effective theoris of WIMPs?

1. Classifying the dark matter in terms of its quantum numbers and constructing the minimal & renormalizable lagrangian in each case.



Z_2 symmetry imposed.

2. Putting the thermal relic abundance condition and imposing all the (expected) limits from DM searches at present (in near future).
3. Discussing the role of the colliders in allowed parameter regions.

- ✓ Singlet scalar WIMP as an example of the one inducing h → DM DM.
- ✓ Singlet fermion WIMPs are those the invisible H decay is important.

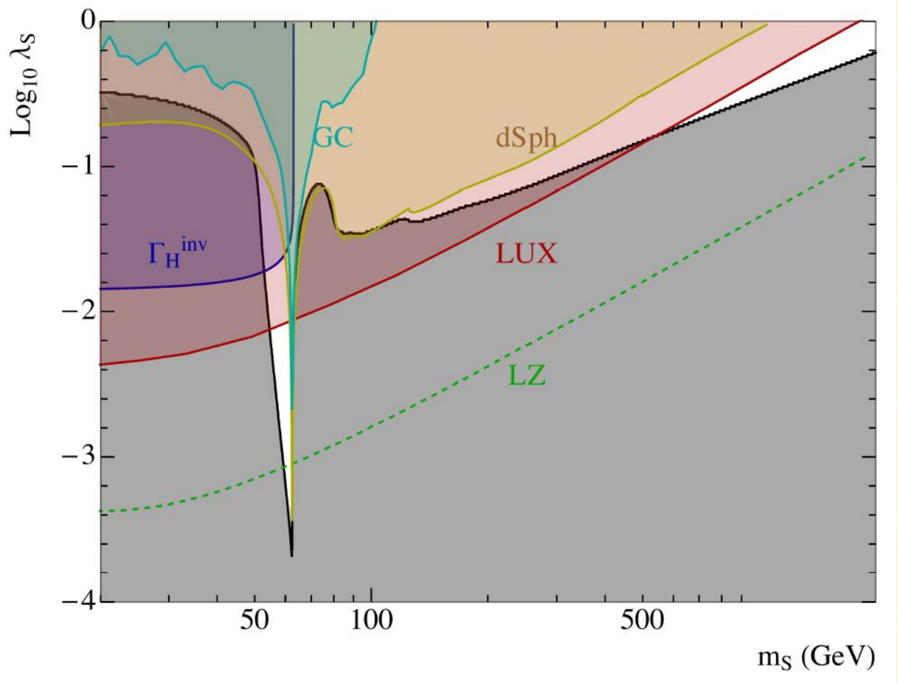
- Mixed WIMPs have already been severely limited by the direct DM detection.
  [S. Banerjee, S. M., K. Mukaida, Y. Tsai, JHEP (2016); T. Abe, R. Sato, PRD (2019)]
- Weak charged WIMPs are predicted to be as heavy as those with a O(1)TeV mass.
  [J. Hisano, S. M., M. Nagai, O. Saito, M. Senami, PLB (2007)]
- Singlet vector WIMP tend to be severely constrained by the direct DM detection.
  [T. Abe, M. Kakizaki, S. M., O. Seto, PLB (2012)]

Scenarios inducing invisible Higgs decay 1

Singlet (real) scalar WIMP

$$\mathcal{L}_{\rm HP} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_0^2 S^2 - \frac{1}{2}\lambda_S |H|^2 S^2 - \frac{1}{4}\lambda_4 S^4$$

gives
- the invisible Higgs decay width
- the SI scattering with a nucleus
- the correct relic abundance $\Omega_{DM}h^2$



[J. A. Casas, et. al, JHEP (2017)]

Direct dark matter detection is more sensitive than the invisible H decay search for this WIMP!

The parameter region that satisfies thermal relic abundance condition has already been excluded by direct dark matter detection and invisible H decay search at the present LHC.

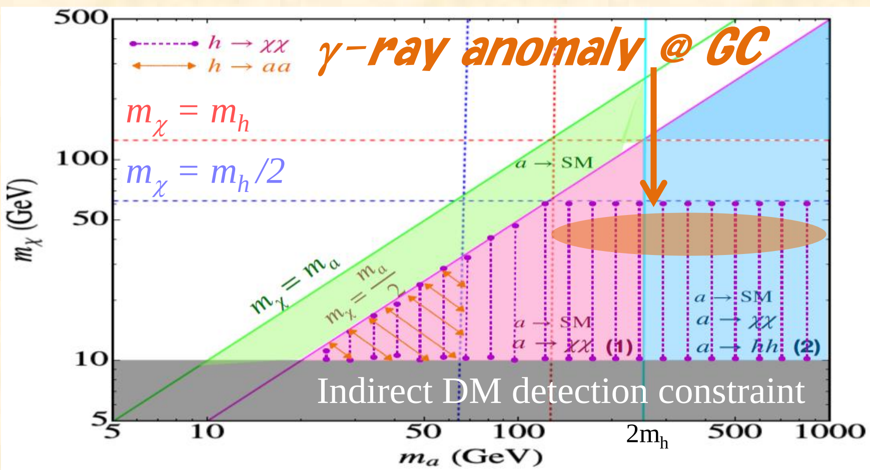
Scenarios inducing invisible Higgs decay 2

Singlet (Majorana) fermion WIMP with PS mediator

No renormalizable interaction in the DM + SM system!

- ✓ Mediator is introduced for a renormalizable interaction of DM & SM.
- ✓ Many scenarios depending on the choice of the mediator particle.
  The mediator can be Z_2-even scalar/vector, Z_2-even pseudo scalar, Z_2-odd scalar/vector having a lepton or baryon number, etc.

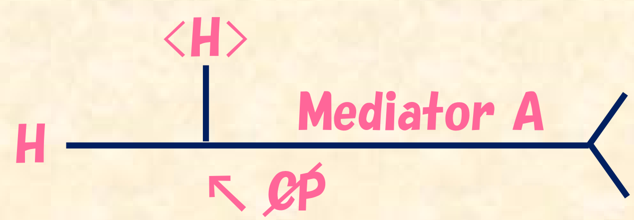
$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial A)^2 - \frac{\mu_A^2}{2}A^2 - \frac{y_P}{2}A(\bar{\chi}\, i\gamma_5\chi) - V(A,H)$$



[S. Horigome, T. Katayose, S. M., I. Saha, M. Takeuchi (2021)]

∪ Terms breaking CP softly.

Direct DM detection does not give a severe constraint on the WIMP due to the PS coupling, while it induces the invisible H decay via

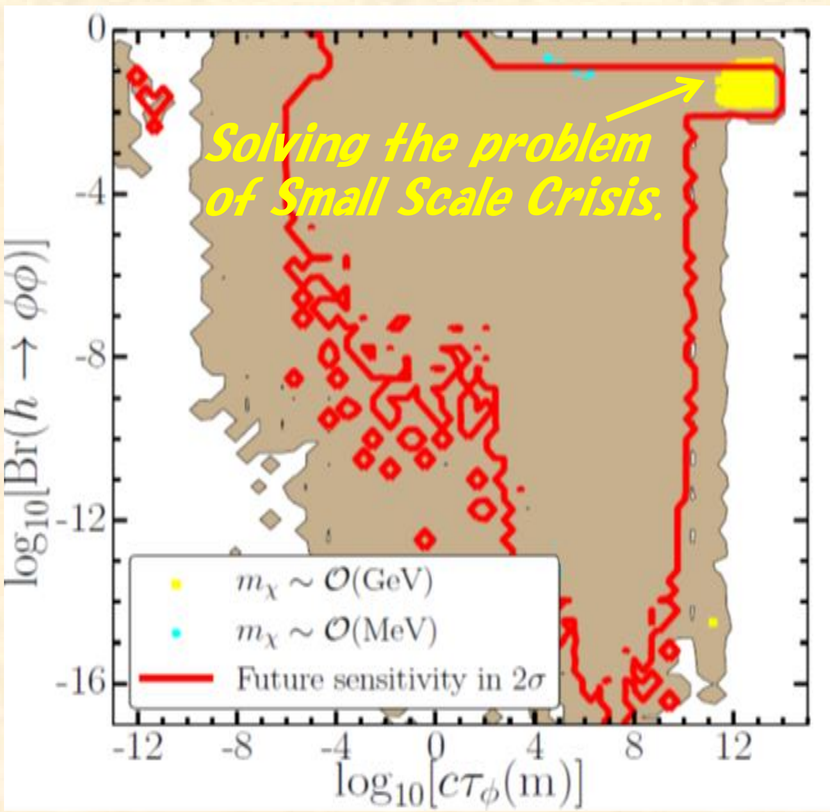


Scenarios inducing invisible Higgs decay 4

The light WIMP with a light scalar mediator

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{2}\bar{\chi}(i\partial\!\!\!/ - m_\chi)\chi + \frac{1}{2}(\partial\Phi)^2 - \frac{c_s}{2}\Phi\bar{\chi}\chi - V(\Phi,H)$$

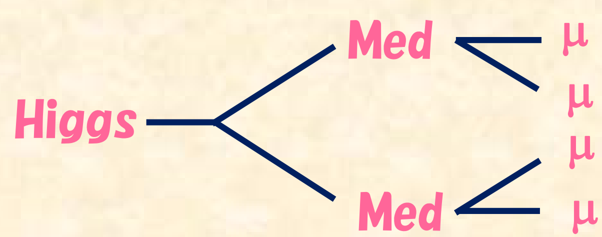
CP conservation imposed.



[S.M., Y. S. Tsai, P. Y. Tsng, JHEP07, 2019]

Light WIMP region, i.e. its mass is less than O(1)GeV, can be realized when the mediator is a Z_2-even singlet scalar. The WIMP avoids a severe constraint from the direct DM detection due to its small mass.

The invisible H decay is induced by the light scalar mediator (rather than WIMP) having a long lifetime.



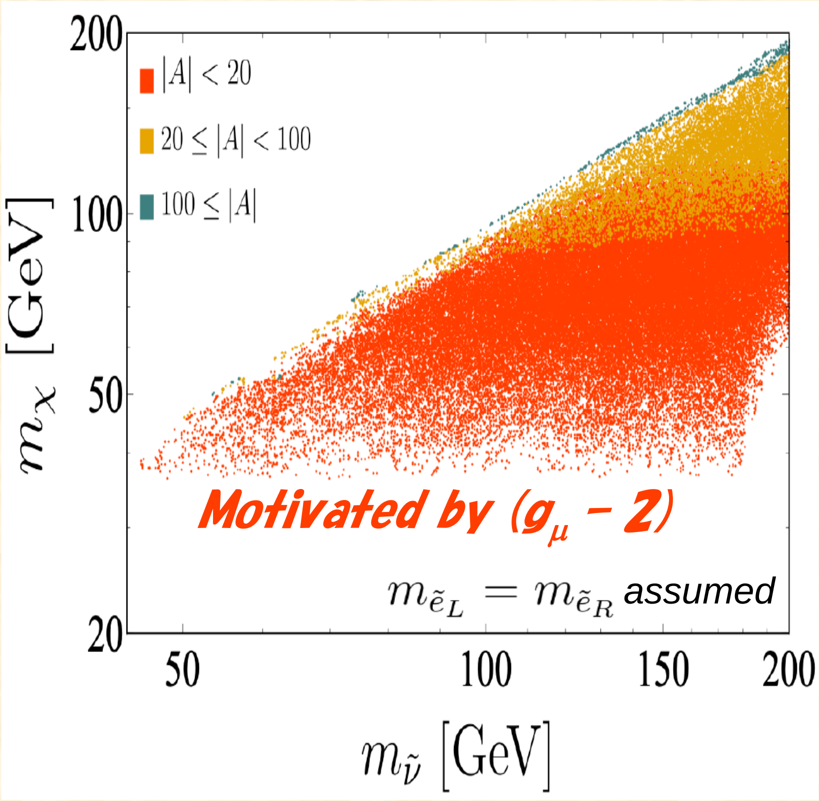
Scenarios inducing invisible Higgs decay 3

The same WIMP with leptophilic scalar mediator(s)

$$\mathscr{L}_{LR} = \mathscr{L}_{SM} + \frac{1}{2}\bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + (D_L^\mu \tilde{L}_i)^\dagger (D_{L\mu}\tilde{L}_i) + (D_R^\mu \tilde{R}_i)^\dagger (D_{R\mu}\tilde{R}_i)$$
$$-(y_L \bar{L}_i \tilde{L}_i \chi + y_R \bar{E}_i \tilde{R}_i \chi + h.c) - V_{LR}(H, \tilde{L}_i, \tilde{R}_i)$$

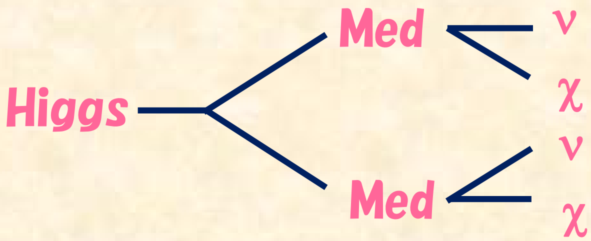
$\cup$

$A m_i \tilde{L}_i^\dagger H \tilde{R}_i + h.c.$



[S. Horigome, T. Katayose, S. M., I. Saha (2021)]

Direct DM detection does not give a severe constraint on the WIMP due to its leptophilic nature, while the invisible H decay is induced by the leptophilic mediator @tree Lv.:

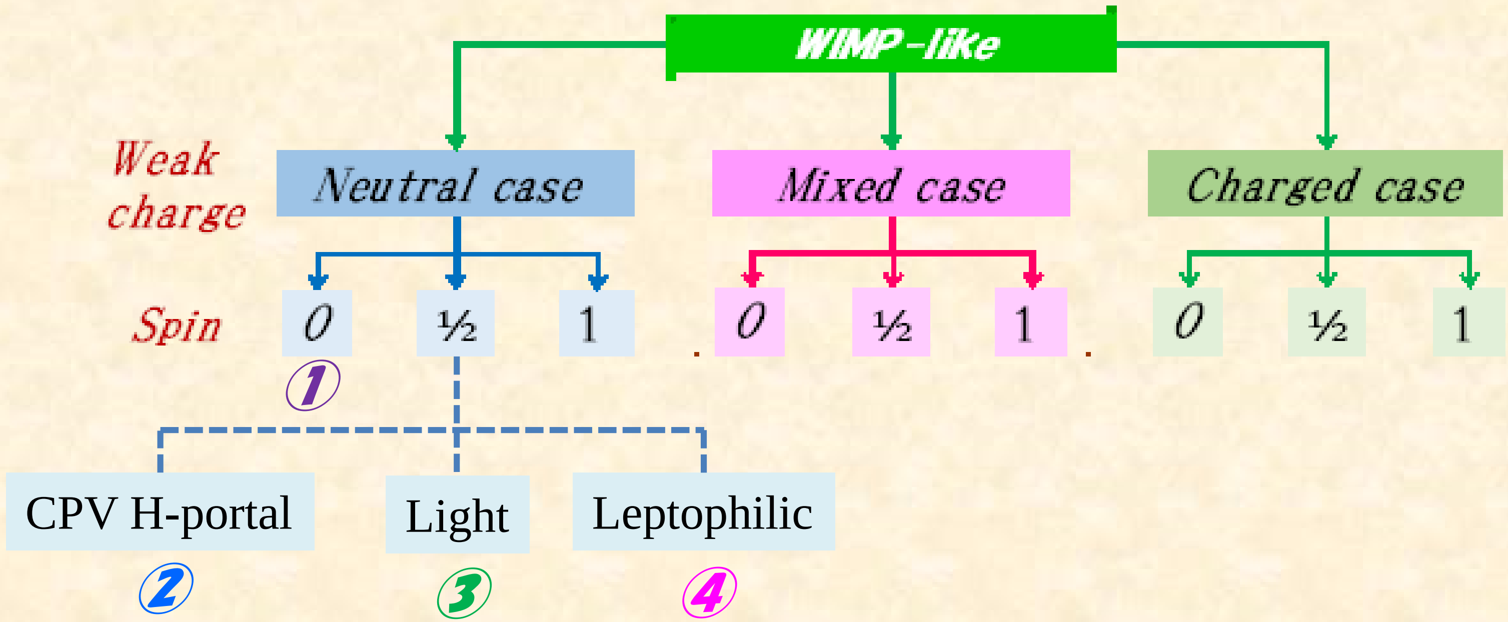


Other processes (pair productions of mediators & mono-photon) at future colliders (i.e. ILC) are also important.

Summary

We have introduced several WIMP candidates that the invisible H decay plays an important role to search for the candidates with evading the severe constraint from the direct DM detection @ underground exps.

The candidates which (inherently) predict the invisible H decay are



① Direct detection is more sensitive than Invisible H → 2DM search.

② Invisible H → 2DM search is more sensitive than Direct detection.

③ Invisible H decay is from a very long-lived neutral mediator, H → $\phi\phi$.

④ Invisible H decay is from invisible mediator decays, H → $\tilde{\nu}\tilde{\nu}$ → $\nu\nu\chi\chi$.