Towards testing the WIMP paradigm

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S. Mukhopadhyay, Y. L. Sming Tsai, [JHEP 1410 (2014) 155]
S. Banerjee, K. Mukaida, Y. L. Sming Tsai, [Arxiv:1511.xxxxx]

Is it possible to test the WIMP paradigm itself without any prejudices (independent of any specific BSMs)?

1. Building a model-independent framework for WIMP.
2. Showing present status of WIMP via global fitting.
3. Discussing future prospects in upcoming searches.

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Appling this study to investigate the ILC capability to search for WIMP at International Liner Collider (ILC).

WIMP paradigm

- ✓ **Property:** Stable and neutral under electromagnetic and strong interactions. The mass of WIMP should be around 10GeV – 1TeV.
- ✓ **Thermal history:** WIMP is in thermal & chemical equilibrium with SM particles when $T > m_{WIMP}$. Its thermal relic gives $\Omega_{TH}h^2 = 0.1$.
- ✓ **Picture behind:** WIMP could be one of new particles predicted by theory of EWSB. Origin of EW scale and m_{WIMP} could be the same.

Second item above is particularly important, for it guarantees the existence of some interactions between WIMP and SM particles.

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∃Couplings w/ enough strength.

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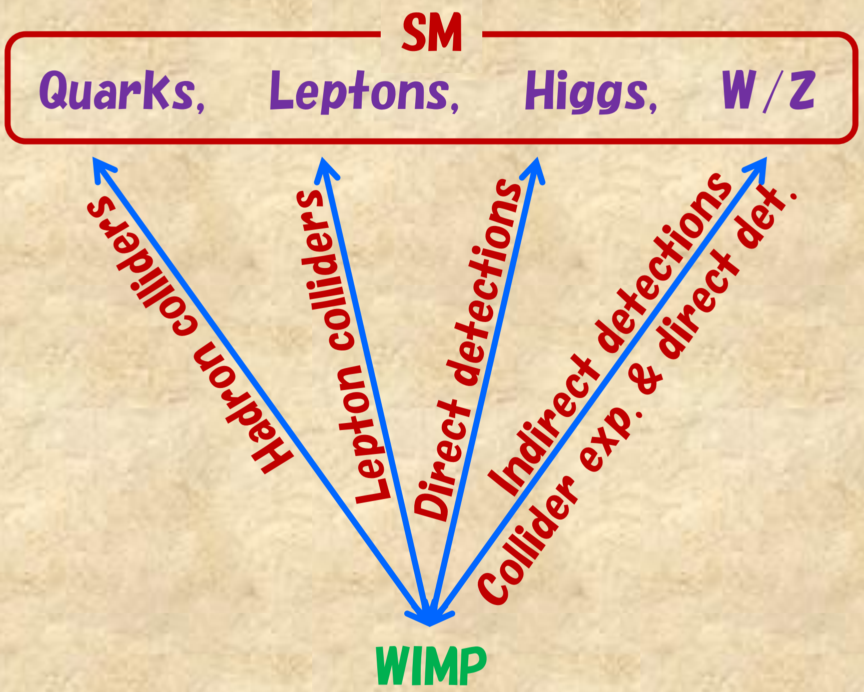
Testability of the WIMP paradigm.

The purpose of the study here is to quantify these naive thoughts!



Basic strategy

Classifying WIMP based on its quantum number (spin, weak isospin)

$$\text{WIMP} = \Sigma_i\, z_i\, [\chi_i(x)]_{\text{Neutral component}}$$

1. Spin of WIMP is fixed. 2. $\Sigma_i |z_i|^2 = 1$ w/ $\chi_i(x) = 1_0, 2_{\pm 1/2}, 3_0, 3_{\pm 1}$, etc.

E.g. when WIMP is fermionic

- ✓ $|z_i| \sim 1$ for $\chi_i(x) = 1_0$, Singlet-like WIMP (e.g. Bino).
- ✓ $|z_i| \sim 1$ for $\chi_i(x) = 2_{\pm 1/2}$, Doublet-like WIMP (e.g. Higgsino).
- ✓ $|z_i| \sim 1$ for $\chi_i(x) = 3_0$, Triplet-like WIMP (e.g. Wino).
- ✓ $|z_i| \sim 1$ for $\chi_i(x) = 3_{\pm 1}$, Triplet-like WIMP (Another type).
- ✓ …
- ✓ None of $|z_i| \sim 1$, Mixed (well-tempered) WIMP

WIMP field χ_i is close to an eigenstate of the weak int.

Assuming Z_2-symmetry for the WIMP stability, we can construct an WIMP effective field theory in each case (e.g. Singlet-like, Doublet-like one, etc.), which should involve all interactions responsible for the relic abundance.

Basic strategy

We take the following 2 assumptions on the theory parameter space.

Strength of coupling constants

Each effective field theory of WIMP involves several interactions, and their coupling constants form the theory parameter space. Assuming that physics behind the WIMP is described by weak interacting theory,

We consider the region of the space satisfying $|\text{any coupling}| \leq 1$.

Thermal relic abundance

WIMP scenario satisfies the condition $\Omega_{TH}h^2 = 0.1$ in a narrow sense. But, if there is some non-thermal contribution to the WIMP abundance (e.g. the late time decay of the gravitino into the WIMP), the condition becomes $\Omega_{TH}h^2 + \Omega_{NT}h^2 = 0.1$ w/ $\Omega_{NT}h^2 \geq 0$. Assuming such a potential contribution from a non-thermal production process,

We consider the region of the space satisfying $\Omega_{TH}h^2 \leq 0.1$.

This assumption gives a lower limit on the strength of some couplings.

Singlet-like fermion WIMP is considered below as a concrete example!

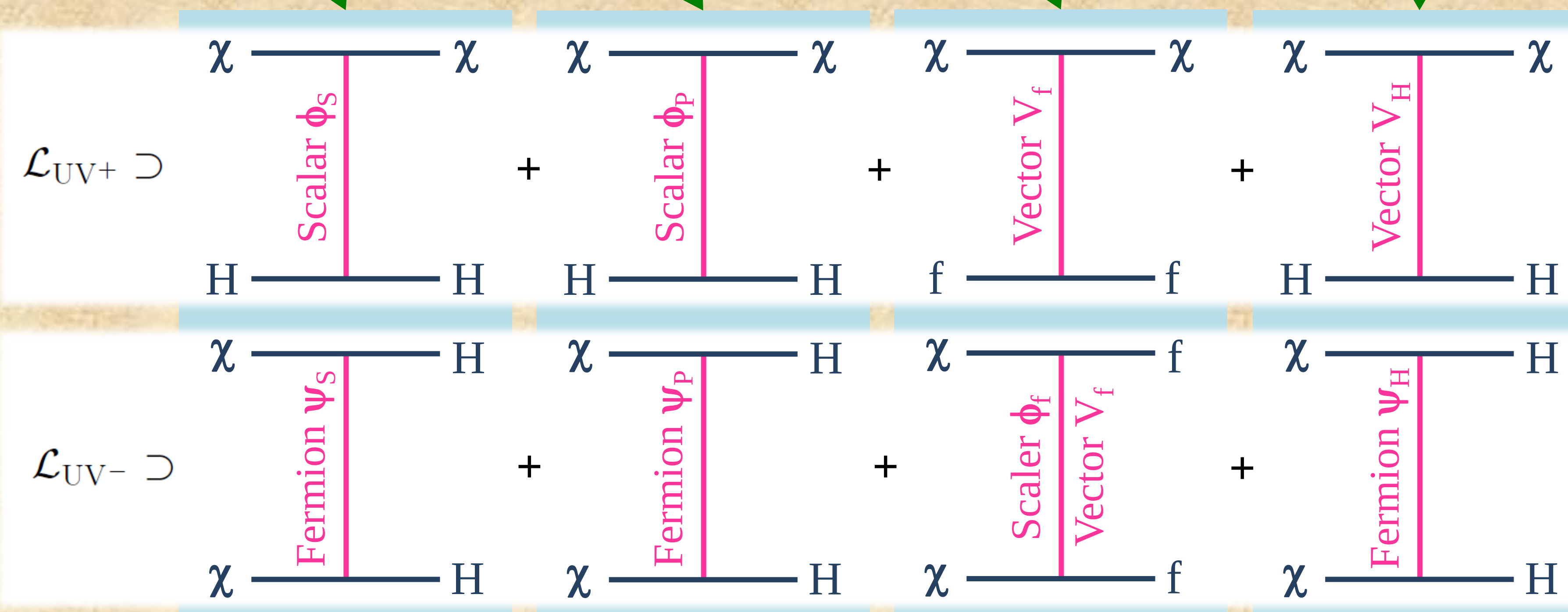
Singlet-like (Majorana) fermion WIMP

Since there is no renormalizable interaction between WIMP and SM particles, some other new particles must be introduced. Assuming that these new ones are heavier enough than m_{WIMP} and electroweak scale, however, we will have

Mixing effects are automatically involved.

$$\mathcal{L}_{\rm EFT} \supset \frac{c_S}{2\Lambda_S}(\bar\chi\chi)|H|^2 + \frac{c_P}{2\Lambda_P}(\bar\chi i\gamma_5\chi)|H|^2 + \sum_f \frac{c_f}{2\Lambda_f^2}(\bar\chi\gamma^\mu\gamma_5\chi)(\bar f\gamma_\mu f) + \frac{c_H}{2\Lambda_H^2}(\bar\chi\gamma^\mu\gamma_5\chi)(H^\dagger i\overleftrightarrow{D}_\mu H)$$

When we calculate collider signals at LEP, LHC and ILC, we consider



Current status on the singlet-like WIMP

The dimension of the model parameter space (#parameters) is large.
Following assumptions are imposed to see the trend of the status:

- ✔ Flavor blindness of 4-Fermi interactions.
- ✔ CP-conserving WIMP interactions (c_P=0). → #parameters = 9
- ✔ Common cutoff mass scale ($\Lambda \equiv \Lambda_S = \Lambda_f = \Lambda_H$).

Then we perform a global fit analysis via the multi sampling method!

Relic abundance

- ◆ Focusing on the case Λ is enough larger than m_χ & the EW scale,
  We consider the region where it satisfies $\Lambda >$ Max[$3m_\chi$, 300GeV].

Direct detections

- ◆ SI scattering @ LUX
  Sensitive to the scalar-type coupling between WIMP & H.
- ◆ SD_n scattering @ XENON100
  SD_p scattering @ PICO-60
  Sensitive to current-current couplings between WIMP & f.

Indirect detections

- ◆ CP conserving interactions
  Annihilation cross sections are helicity suppressed, and no sizable limits obtained.
- ◆ CP violating interaction
  Indirect detection limits will be the most important ones.

Current status on the singlet-like WIMP

We use L_{UV+} & L_{UV-} instead of L_{EFT} to evaluate constraints from colliers.

✔ Invisible Higgs decay @ LHC: Sensitive to the scalar type coupling.
✔ Invisible Z decay @ LEP: Sensitive to WIMP-Higgs current coupling.
✔ Mono-γ search @ LEP: Sensitive to WIMP-Lepton & Higgs couplings.
✔ Mono-jet search @ LHC: Sensitive to WIMP-Quark couplings.

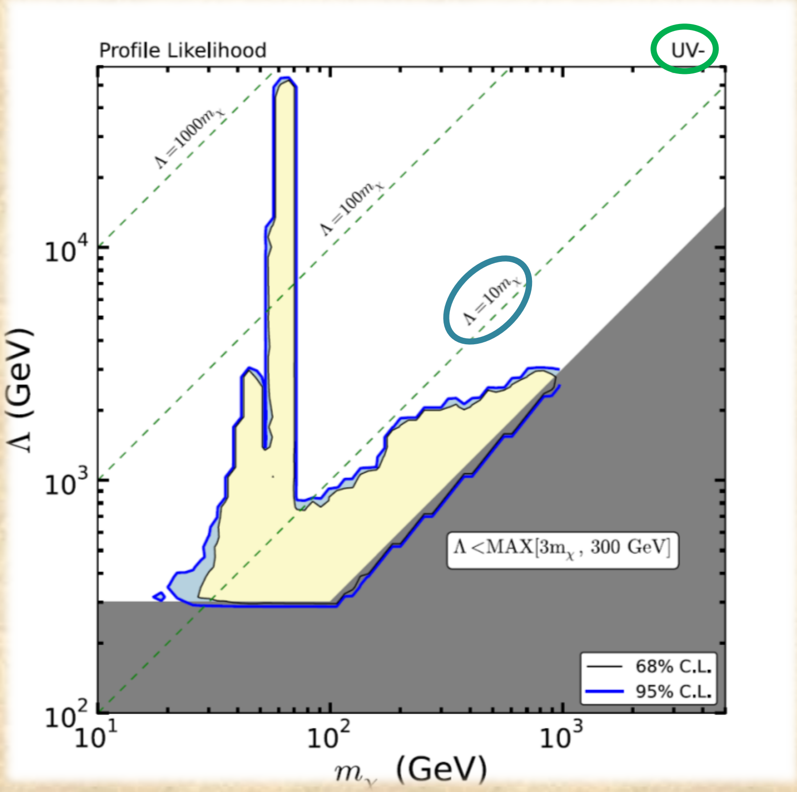
Decay widths of mediator particles are fixed as $\Gamma=\Lambda/2$ in the analysis.

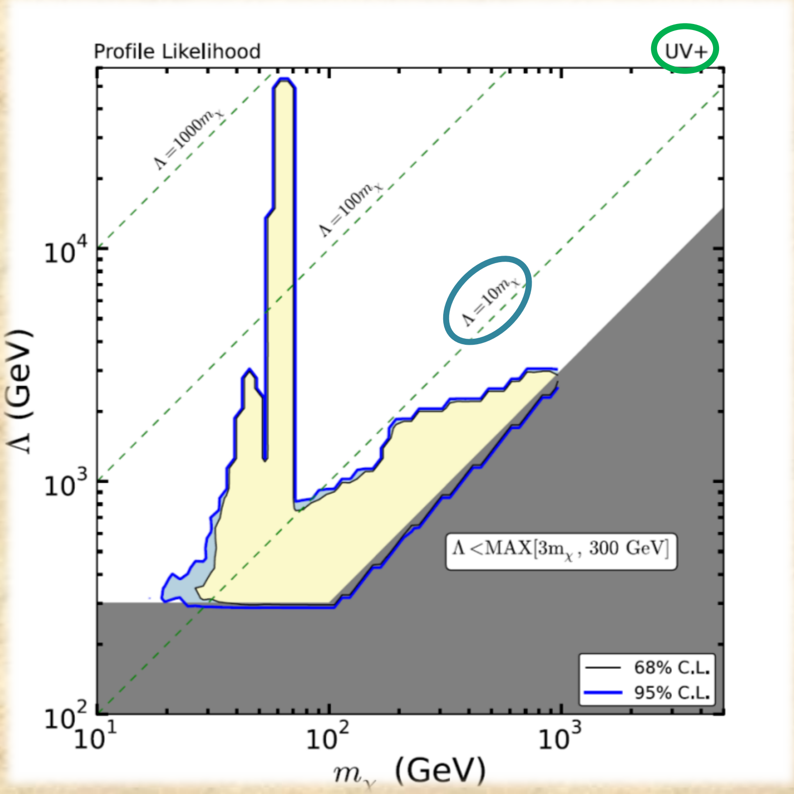
Are there some other channels?

- Radiative corrections (off-shell contributions) from the mediators.
  Mediator particles may contribute to some SM processes (e.g. SM 4-Fermi couplings). The contribution could be, however, alleviated by introducing other new particles coupled only to SM particles.

- On-shell productions of the mediator particles at the LHC.
  Some single productions (and decays into WIMP) are included.
  For Z_2-even mediators, single productions into 2jets are weaker.
  For Z_2-odd mediators, pair productions give weaker signals.

Current status on the singlet-like WIMP



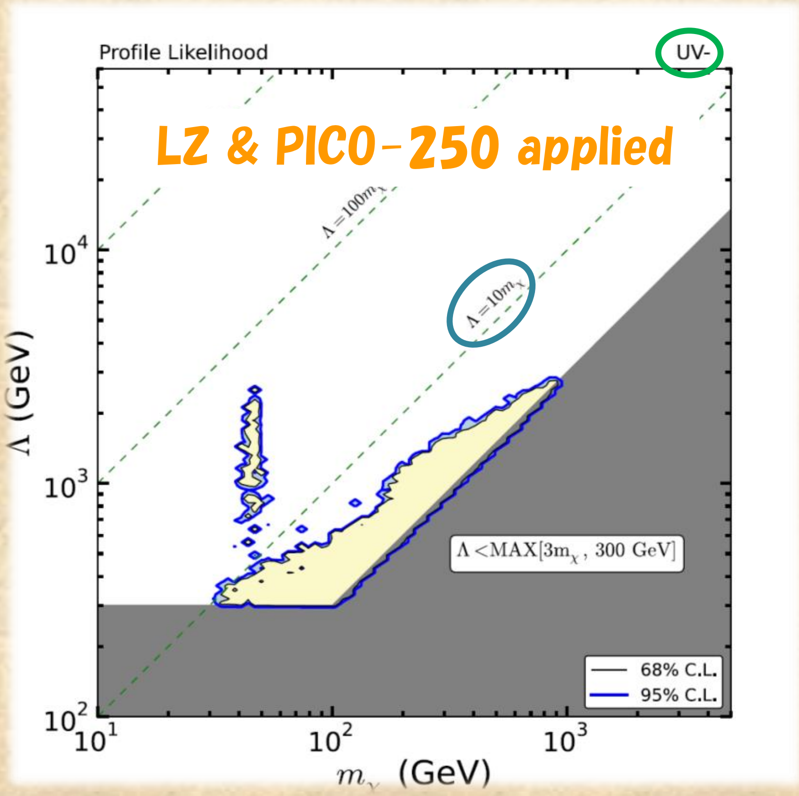


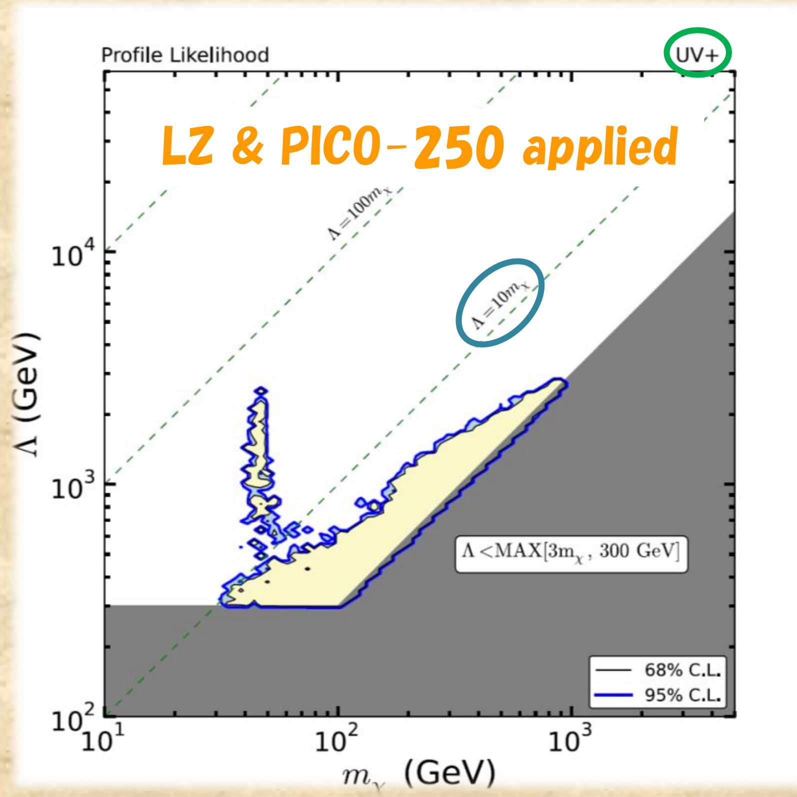
Both UV+ & UV- models give almost the same result on this plane.

- ☐ Resonant region @ $m_\chi \sim m_Z/2$: $\chi\chi \to Z \to$ SM fermions dominates.
- ☐ Resonant region @ $m_\chi \sim m_h/2$: $\chi\chi \to h \to$ bottom pair dominates.
- ☐ Other regions: Other regions are always below the $\Lambda = 10m_\chi$ line.

[$\chi\chi \to h \to$ top pair dominates when $m_\chi > m_t$]

Future prospects on the singlet-like WIMP

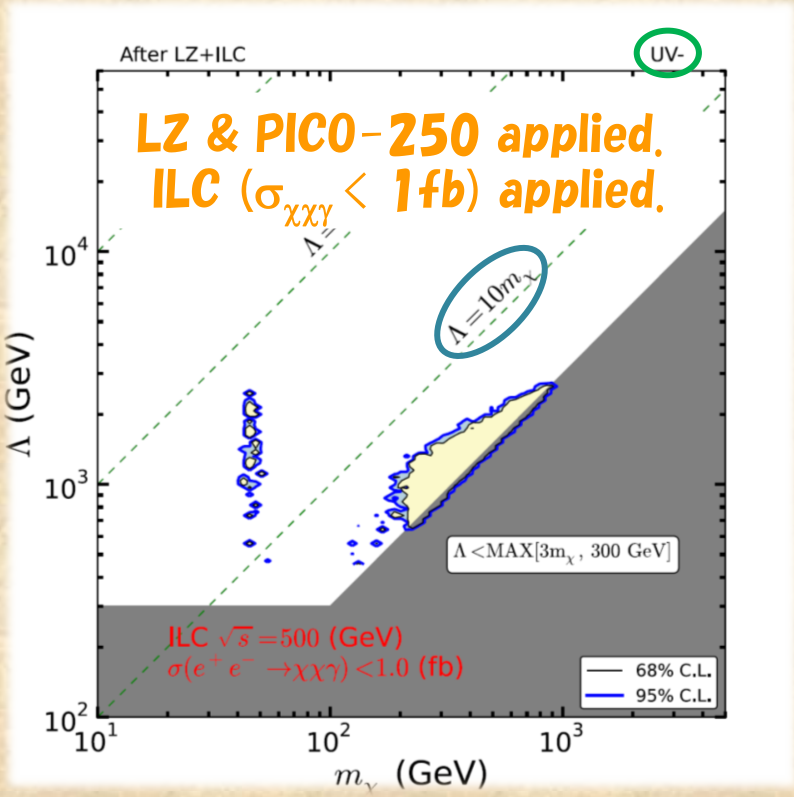


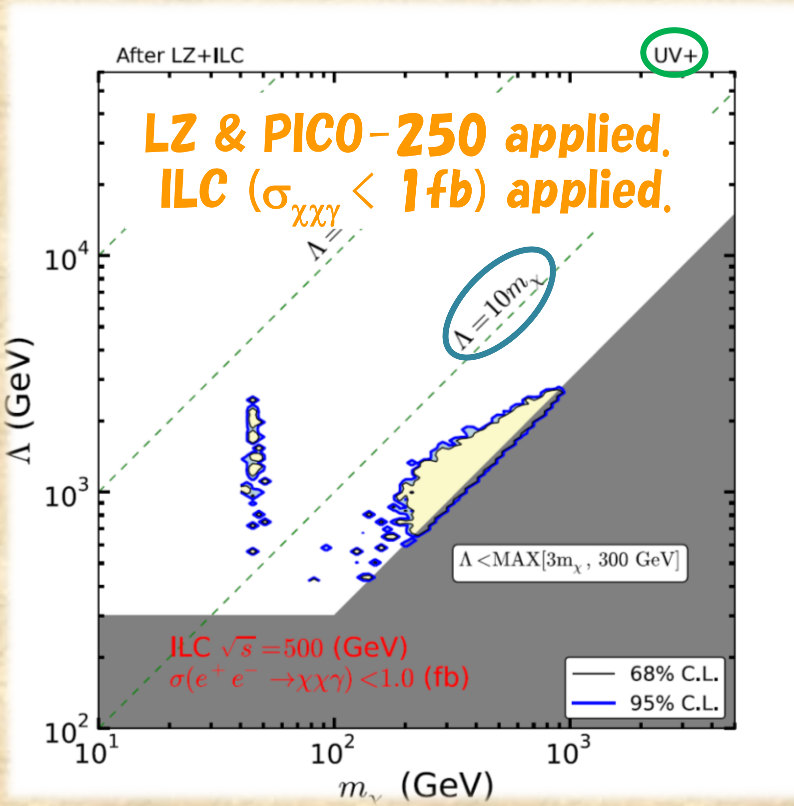


H-resonant region is governed by WIMP-H int. with a small coupling.

- ✓ It is hard to probe WIMP in this region at collider experiments.
  [Invisible H decay measurement (for $m_\chi < m_h/2$) is not enough.]
- ✓ Indirect detections does not work due to p-wave annihilations.
- ✓ 10ton level direct detection can fully cover the resonant region.

Future prospects on the singlet-like WIMP



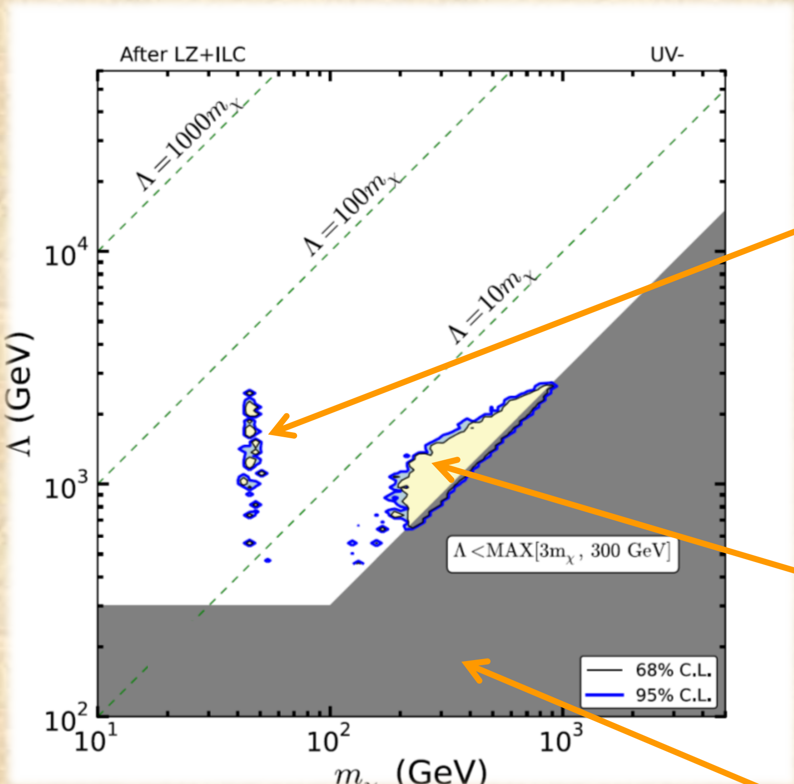


Low dark DM region is governed mainly by WIMP-lepton interaction.

- ✓ Indirect detections does **not work** for suppressed annihilations.
- ✓ It does **not contribute** to scatterings off a nucleus at direct det.
- ✓ Lepton colliders can cover the most of the low mass DM region!

[CEPC is also hopeful to search for dark matter in this region.]

Future prospects on the singlet-like WIMP



The remaining Z-pole region is governs by WIMP-Z interaction.

Since the coupling is very small, the Giga-Z option at the ILC or CEPC seems to be working well.

WIMP-quarks (in particular top) interaction governs the region.

13 TeV run at the LHC and the HL-LHC in the near future may be possible to cover the region.

Discussions based on the EFT are no longer valid in the grey region.

- ✓ Coannihilation region by a Z_2-odd new mediator with $\Lambda \sim m_\chi$.
- ✓ Funnel region by a Z_2-even new mediator with $\Lambda \sim 2m_\chi$.
- ✓ Light mediator region by a Z_2-even new mediator with $\Lambda << m_\chi$.

Best strategy: Searching for a mediator particle instead of WIMP.

Summary

- ✓ We have considered a model-independent framework to test the WIMP paradigm, which was built based on WIMP quantum numbers.
- ✓ Focusing on a singlet-like fermion WIMP we derived an effective theory involving all interactions which can be responsible for its thermal relics abundance. Moreover, we have also developed the method to apply the theory to physics at high energy colliders.
- ✓ Current and future expected limits on the WIMP are as follows:
  1. Higgs funnel region where WIMP mass is half of Higgs mass, which will be fully explored by 10 ton level direct detections.
  2. Z boson funnel region where WIMP mass is half of Z mass, which will be almost fully explored by future e^+e^- colliders.
  3. Region where a mediator particle lives in the WIMP mass scale, which is expected to be covered by the current & future LHC and future e^+e^- colliders in the region of $\Lambda > 3\, m_{WIMP}$.
- ✓ This method can be applied for WIMPs having different quantum numbers. For WIMPs in the $SU(2)_L$ singlet-doublet mixed case, see the talk by Yue-Lin Sming Tsai in this session (the last talk).