DM Search at the ILC

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Physics perspectives at the ILC experiment
on the systematical search for the WIMP DM.

Current status of the ILC project in Japan

May 27, 2013

Asking Science Council of Japan (SCJ) to deliberate the ILC project from an academic point of view.

LCC (LC collaboration) activities including ILC TDR completion, etc.

Sep 30, 2013 (SCJ)

A report was submitted to MEXT.

Dec 24, 2013

$0.5M for investigatory study was approved. The same amount was approved for the following year.

- Discussing scientific significance.
- Verifying TDR in details.
- Investigating economical ripple effect, technology transfer, etc.

May 01, 2014

An academic expert committee (ACE) was established under MEXT.

Academic expert committee

May 08, 2014: 1st Meeting of ACE

Nov 05, 2014: 2nd Meeting of ACE

Apr 10, 2015: 3rd Meeting of ACE [Interim report came out]

Jun XX, 2015: 4th Meeting of ACE

…

By Mar 31, 2016 (Extendable)

MEXT will receive a report from ACE.

Physics perspectives at the ILC

Why the electroweak symmetry is broken at O(100)GeV?

I. Precise measurements of the Higgs boson and the top quark

New physics@O(1)TeV predicts the deviation of Higgs couplings (and top couplings) from SM predictions at O(1)% level. Precise measurement of m_t is also important for BSMs behind the EWSB.

II. Direct and indirect searches for new particles (new phenomena)

BSM of EWSB often predicts new particles at around 1TeV. Among those, the most promising candidate is WIMP dark matter!

Model-dependent way

Merit: Well-defined framework/Connection to a big picture.

Demerit: Many possibilities of BSMs/No signals so far at the LHC.

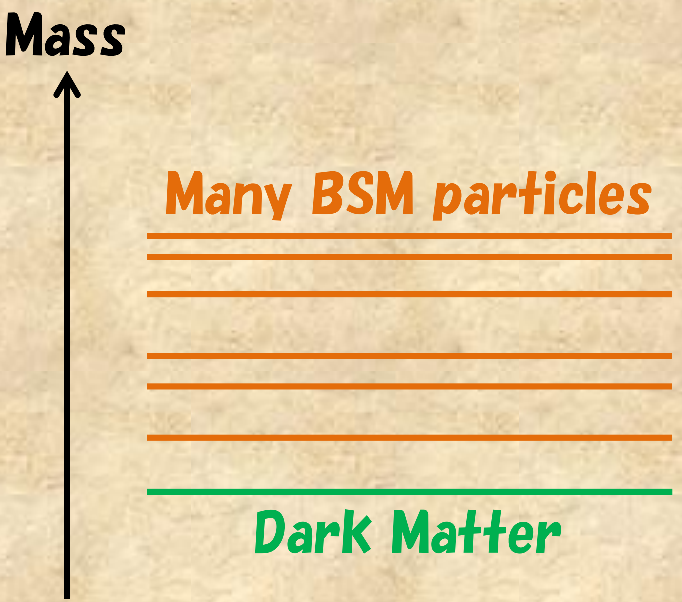
Model-independent way

Merit: Investigating the entire concept of the WIMP dark matter.

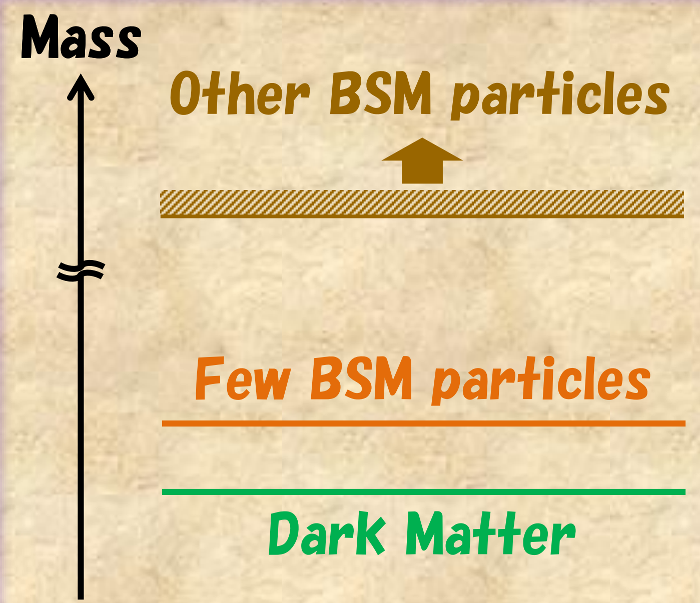
Demerit: Framework tends to be complicated.

Basic philosophy of our approach

What kind of BSM spectrum should we consider?



Optimistic case?



Pessimistic case?

We consider the most pessimistic case, where only SM fields and those composing the DM particle exist at O(1)TeV energy scale.

Effects of other heavy BSM particles are expressed as higher dimensional operators composed of SM and DM fields.

Searching for WIMP dark matter

It is convenient to categorize WIMP DM candidates according to their quantum numbers: Spin and Weak isospin. (EM and color charges = 0)

Weak isospin of the WIMP DM:

1. Singlet-like case:

   WIMP DM is an (almost) singlet under SM gauge interactions $SU(3)_c \times SU(2)_L \times U(1)_Y$. Typical examples are the bino, the singlino, etc.

2. Multiplet-like case:

   WIMP DM is an (almost) neutral component of a $SU(2)_L$ multiplet. Typical examples are the Higgsino, the wino, the minimal DM, etc.

3. Mixed case:

   WIIMP DM is a mixture of different $SU(2)_L$ representations due to the EWSB. Typical examples are Bino-Higgsino dark matter, etc.

We consider 3 three cases with the dark matter in reverse order, and assume that it is a fermion to make the discussion concrete.

Upper bound on the dark matter mass

Dark matter cosmology gives an upper bound on the WIMP DM mass as long as we consider non-exotic thermal history of the universe!

1. Some amount of DM particles are always survived until today because of the WIMP mechanism, which is estimated to be

$$\Omega_{TH}h^2 \sim 0.1[pb/c]/\langle\sigma_{ann}v\rangle \propto (m_{DM})^2$$

2. There may be some non-thermal production which does not alter the thermal history at all, e.g. late-time decay of a heavy particle.

$$\Omega_{NT}h^2 \ (\propto m_{DM} \text{ in many cases}) > 0$$

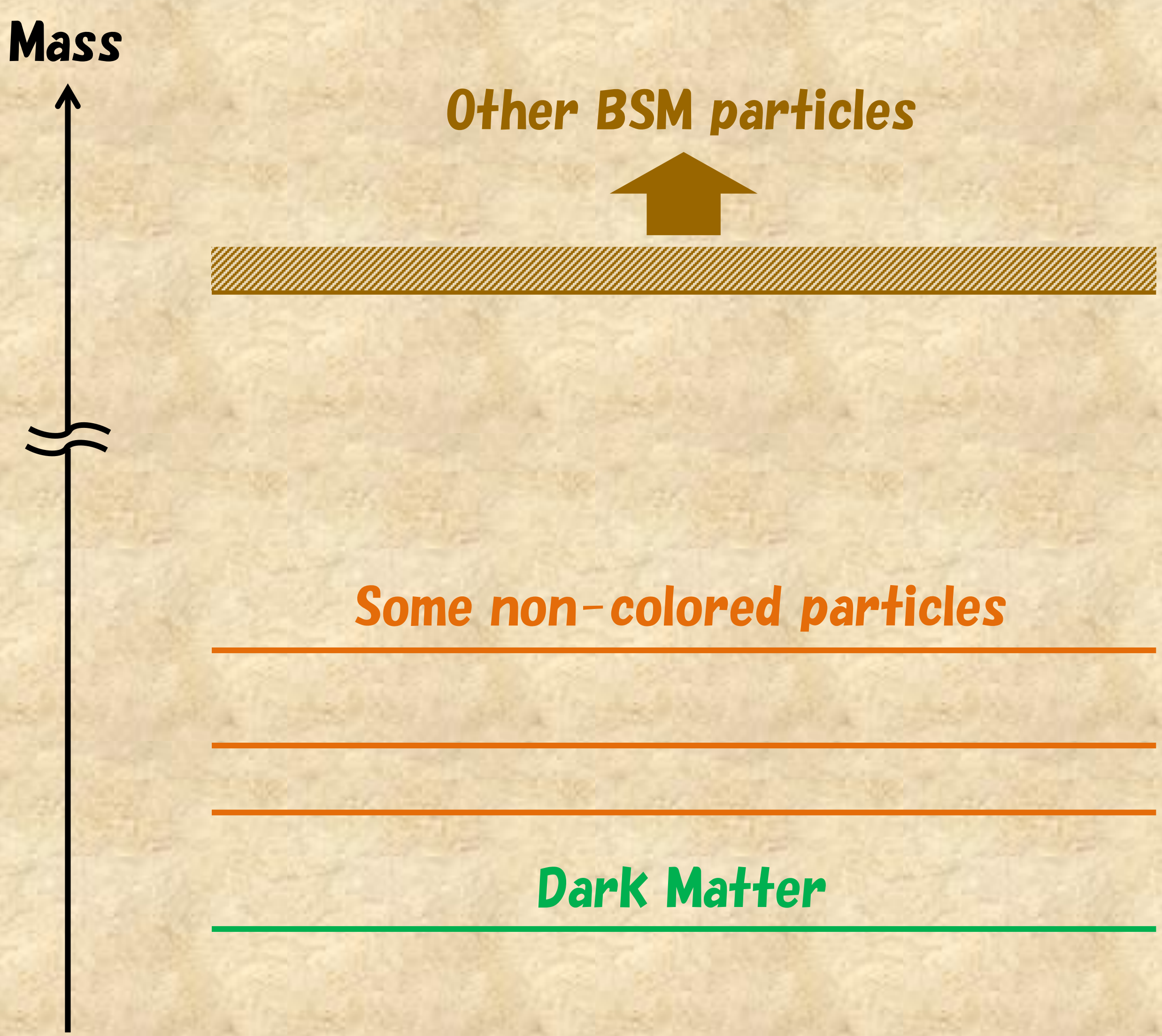
3. DM abundance has already been measured very accurately.

$$\Omega_{0B}h^2 = 0.02225 \pm 0.00016 \text{ (PLANCK)}$$

As a result, we have the following upper bound on the DM mass:

$$\Omega_{TH}h^2 + \Omega_{NT}h^2 = \Omega_{0B}h^2 \rightarrow \Omega_{TH}h^2 \propto (m_{DM})^2 < \Omega_{0B}h^2$$

WIMP DM search (Mixed case)



$SU(2)_L$ Singlet-Doublet mixing dark matter

WIMP DM search (Mixed case)

Characteristics:

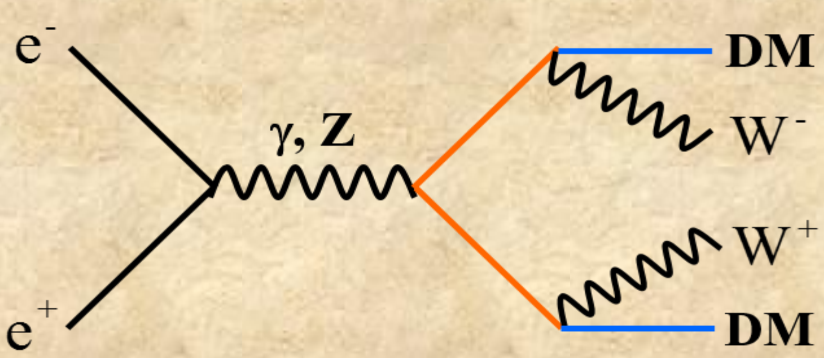
- Several non-colored particles exist in the same mass scale of DM.
- DM has a sizable coupling to the Higgs boson (DM-DM-Higgs).
- DM will be in between EW and TeV scales. (Singlet-Doublet case).

The WIMP DM will be discovered at DM direct detection experiments or the LHC at first. (This case is gradually being excluded by experiments so far, but there are still parameter regions evading these limits.)

↓

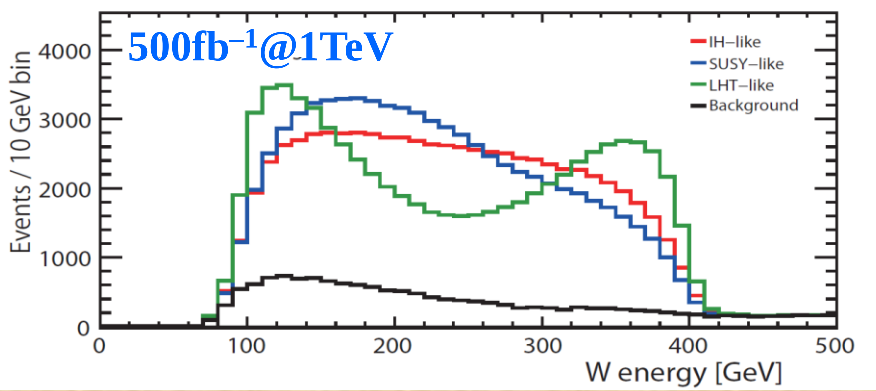
The role of the ILC is to study its property in details.

Production of EM charged (non-colored) particles decaying to DM



Signal: 4-jets (from WW) + Emiss

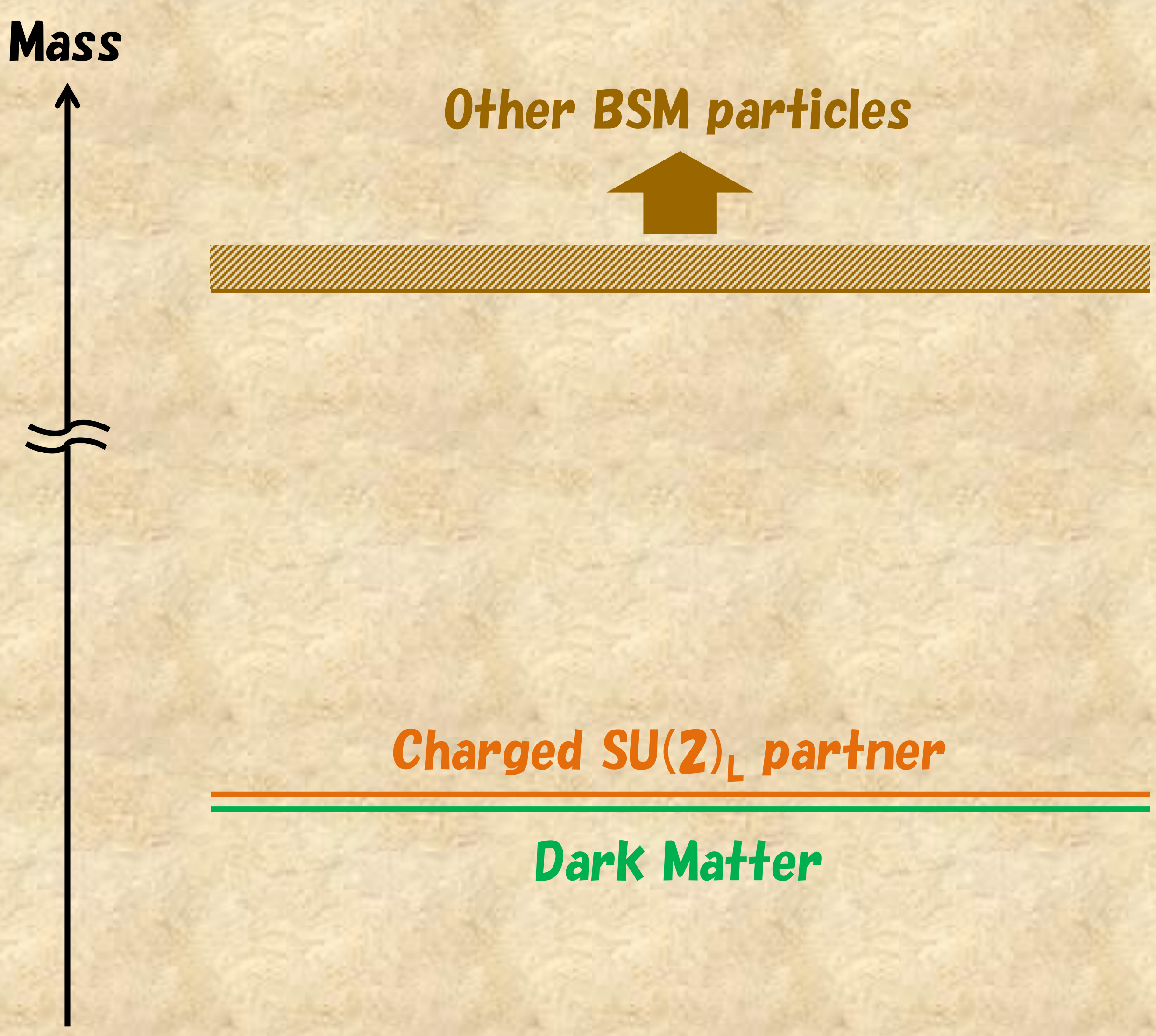
Energy of reconstructed W



[Asano, S.M., Okada et al. 1106.1932]

Property is determined in detail!

WIMP DM search (Mixed case)



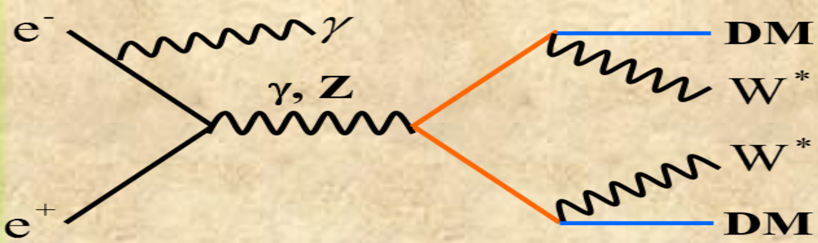
$SU(2)_L$ Triplet dark matter

WIMP DM search (Multiplet-like case)

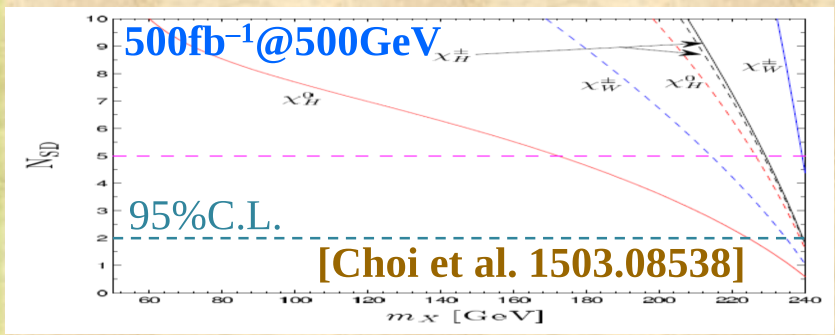
Characteristics: … A challenging case for the LHC

- DM is highly degenerate with EM charged $SU(2)_L$ partners.
- Physics of the DM is governed mainly by $SU(2)_L$ gauge interaction.
- The mass of the DM can be as high as O(1)TeV when $\Omega_{NT}\,h^2$ is small.

Production of $SU(2)_L$ partners



Signal: γ + Emiss + soft tracks

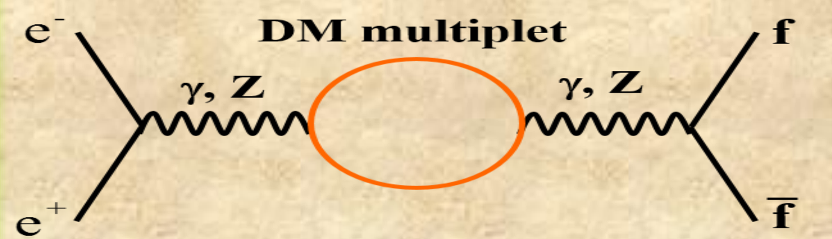


$m_{DM} < 0.5\ s^{1/2} - 20$GeV is explored.

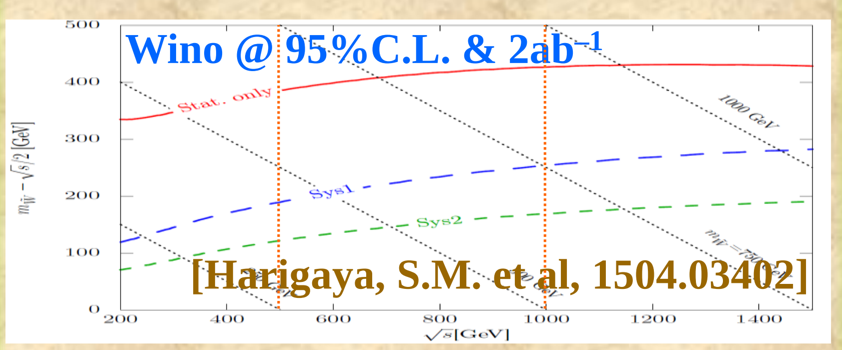
Property is determined in detail.

[Berggren et al. 1307.3566]

Corrections to SM processes



Signal: Interference with SM one



Sys1. e:0.2%, μ:0.15%, b:0.5%, c:1.0%

Sys2. e:0.4%, μ:0.30%, b:1.0%, c:2.0%

$m_{DM} < s^{1/2}/2 + 200$GeV explored.

WIMP DM search (Multiplet-like case)

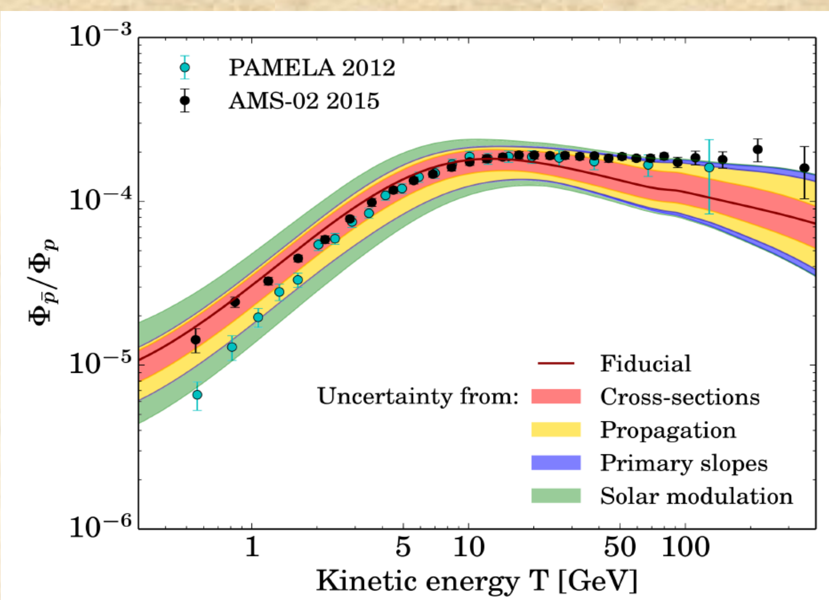
TeV scale thermal WIMP (DM relic abundance only from $\Omega_{TH} h^2$):

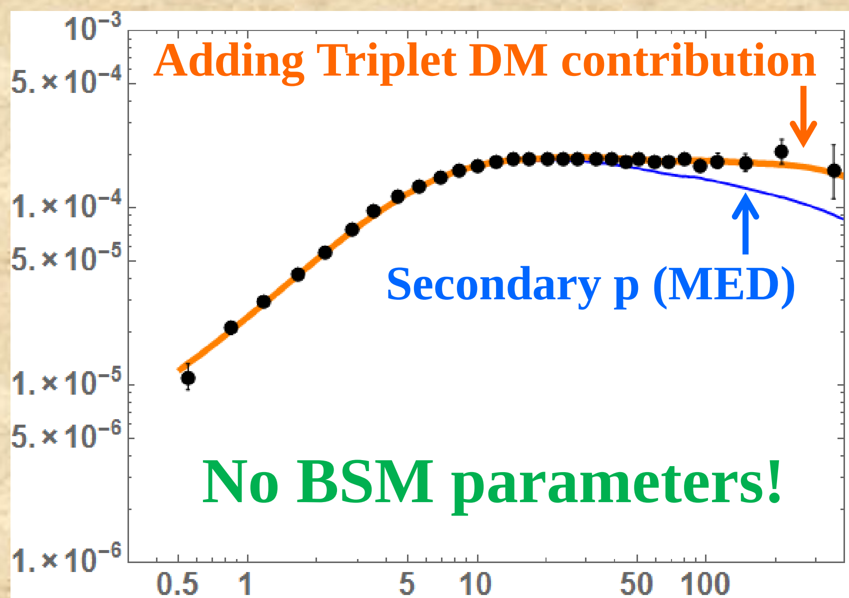
- When DM is from a $SU(2)_L$ doublet, its mass is predicted to be 1TeV.
- When DM is from a $SU(2)_L$ triplet, its mass is predicted to be 3TeV.

↓

None of current & near future collider experiments can access the DM.
Only DM indirect detection experiments have a possibility to detect it.

A hint of the TeV scale WIMP from the AMS-02 anti-p/p data?:





If this is true, we need the CLIC or the 100TeV collider!

WIMP DM search (Singlet-like case)

$SU(2)_L$ singlet, namely SM singlet, dark matter

WIMP DM search (Singlet-like case)

Characteristics:

- No renormalizable interactions with SM particles (DM-DM-SM).
- The mass of the DM is within a very natural region, say EW scale.

↓

We have to consider an EFT involving higher dimensional operators.

$$\mathcal{L}_{\mathrm{F}_0} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{2}\bar{\chi}\left(i\partial\!\!\!/ - M_\chi\right)\chi + \sum_{n,i}\frac{c_i^{(n)}}{\Lambda^{n-4}}\mathcal{O}_i^{(n)}$$

$$\begin{aligned}
\mathcal{O}_S^{(5)} &= (\bar{\chi}\chi)|H|^2, \\
\mathcal{O}_H^{(6)} &= (\bar{\chi}\gamma^\mu\gamma_5\chi)(H^\dagger i\overleftrightarrow{D_\mu}H), \\
\mathcal{O}_Q^{(6)} &= (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{Q}\gamma_\mu Q), \\
\mathcal{O}_U^{(6)} &= (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{U}\gamma_\mu U) \\
\mathcal{O}_D^{(6)} &= (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{D}\gamma_\mu D) \\
\mathcal{O}_L^{(6)} &= (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{L}\gamma_\mu L) \\
\mathcal{O}_E^{(6)} &= (\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{E}\gamma_\mu E)
\end{aligned}$$

With CP invariance and flavor blindness in the DM sector, we have 7 independent SM gauge invariant operators.

↓

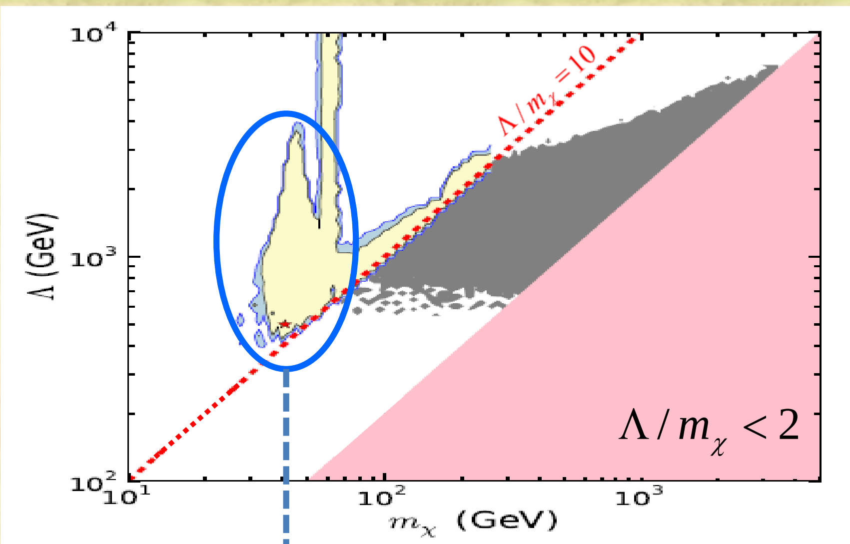
We have to consider the EFT with all 'c_i' being treated as independent couplings.

[S. M., Mukhopadhyay, Tsai, 1405.1859]

↓

Clarifying parameter regions consistent with current limits, and go to ILC issues.

WIMP DM search (Singlet-like case)



Limits considered:

Relics abundance: $\Omega_{DM} h^2 < 0.1$

Direct detection: SI, SD-p, SD-n

Collider (LEP): Mono-γ, Γ_Z

Collider (LHC): Mono-j, Γ_h

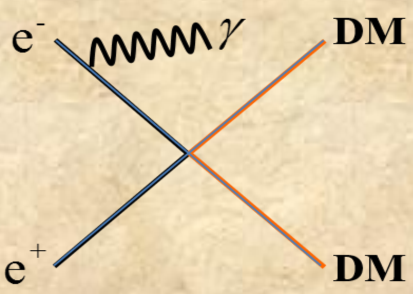
↓

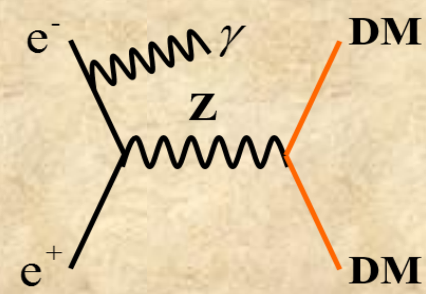
Shape of the region (twin peaks) is determined mainly by $\Omega_{DM} h^2$.

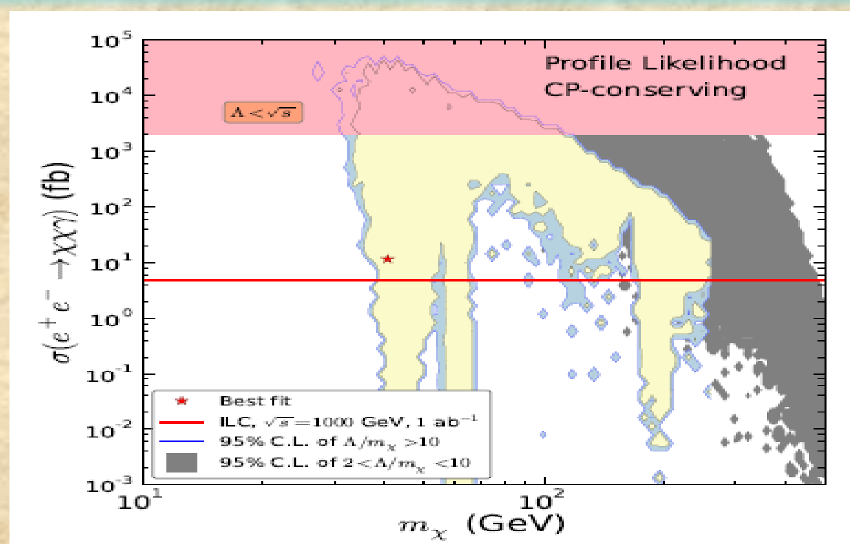
Hunting grounds of the ILC

$$(\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{L}\gamma_\mu L)$$
$$(\bar{\chi}\gamma^\mu\gamma_5\chi)(\bar{E}\gamma_\mu E)$$

$$(\bar{\chi}\gamma^\mu\gamma_5\chi)(H^\dagger i\overleftrightarrow{D_\mu} H)$$







Signal: mono-γ search (γ + Emiss)

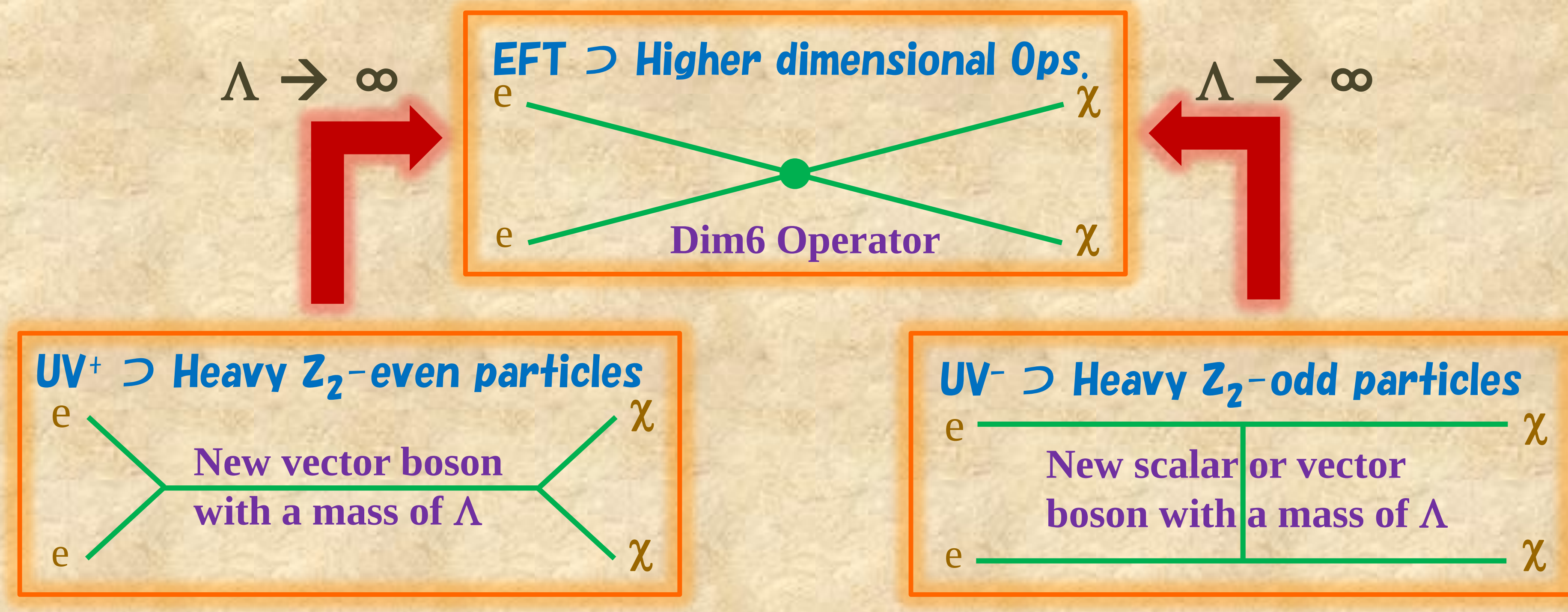
WIMP DM search (Singlet-like case)

The EFT does not work well for physics of high energy colliders when the energy of collision is close to or beyond the suppression scale Λ.

↓

Some simplified models can come to a assistance for this EFT.

Example: Let us consider a four-Fermi operator, $(c/\Lambda^2)(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{e}_R\gamma^\mu e_R)$.



EFT, UV$^+$, UV$^-$ interactions are first used to calculate collider signals (scattering cross sections) and we accept the most conservative one.

Summary

The ILC will offer a unique way to search for the WIMIP dark matter.

Mixed case:

WIIMP DM will be discovered at DM detect detection experiments or the LHC. The role of the ILC is to investigate its property in detail.

- When other BSM particles degenerate with DM, new idea is needed.

Multiplet-like case:

When WIMP DM is not heavy, it will be discovered by the production of EM charged $SU(2)_L$ partners or the deviation from SM prediction at $e^- e^+ \to ff$ processes. Property of DM can also be investigated.

- New idea to detect light multiplet-like DMs at the LHC is needed.
- Indirect DM detection will be a unique way when the DM is O(1)TeV.

Singlet-like case:

Wide parameter regions will be covered by the ILC via the mono-γ search. This case is now regarded as the most important one for the ILC, for it predicts the WIMP mass at the electroweak scale.

- Comprehensive framework for the singlet DM should be developed.
- The LHC plays a complementary role, and its synergy is important.

Back up: Precise Higgs measurements

Please refer also to K. Fujii's talk slides in PHENO 2014

I = 1.15ab^{-1} @ 250GeV ⊕ 1.6ab^{-1} @ 500(550)GeV & II = ⊕ 2.5ab^{-1} @ 1TeV

	Δm_h	Γ_h	κ_t	κ_b	κ_τ	κ_c	κ_Z	κ_W	κ_g	κ_γ	λ
I.	30MeV	2.5%	7.8(2.3)%	0.8%	1.2%	1.5%	0.5%	0.6%	1.2%	4.5(1.7)%	46%
II.	---	2.3%	1.9(1.7)%	0.7%	0.9%	1.0%	0.5%	0.6%	0.9%	2.4(0.8)%	13%

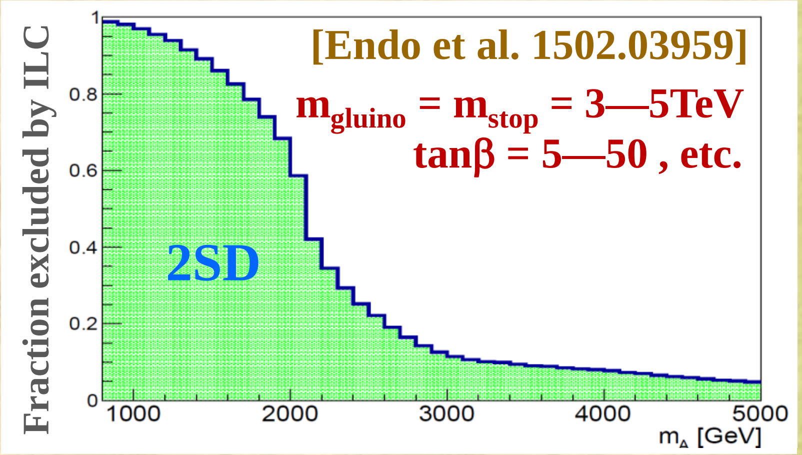
↳ [$s^{1/2}$ = 550GeV I/O 500GeV] [LHC-ILC synergy] ↲

ILC can determine couplings in a model independent way

- σ×BR measured in each mode
- σ measured from recoil mass, namely, $e^-e^+ \to H\, Z \to X\, \mu^-\mu^+$.
- Total width of H obtained by $e^-e^+ \to \nu\nu\, H \to \nu\nu\, W^-W^+$. ($s^{1/2}$ > 350GeV is crucial.)

Coupling determinations!

An implication to SUSY scenario



m_h = 126GeV &several constraints are already included in the analysis.

m_A = a few TeV can be covered.

Back up: Precise top measurements

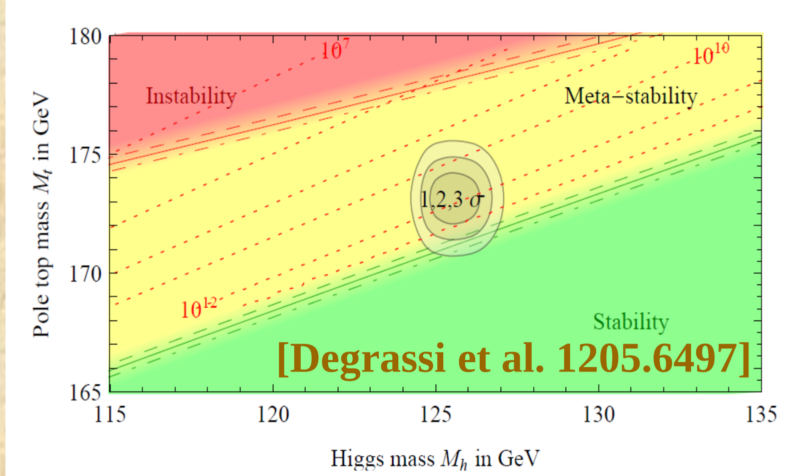
Please refer also to K. Fujii's talk slides in PHENO 2014

10fb^{-1} each (11bins) @ 340-350GeV ⊕ 500fb^{-1} @ 500GeV

$$\Gamma_{\mu}^{ttX}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\widetilde{F}_{1V}^X(k^2) + \gamma_5\widetilde{F}_{1A}^X(k^2)\right) + \frac{(q-\bar{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^X(k^2) + \gamma_5\widetilde{F}_{2A}^X(k^2)\right)\right\}$$

Δm_t	$\Delta\Gamma_t$	$\widetilde{F}^{\gamma}_{1V}$	$\widetilde{F}^{Z}_{1V}$	$\widetilde{F}^{Z}_{1A}$	$\widetilde{F}^{\gamma}_{2V}$	$\widetilde{F}^{Z}_{2V}$
100MeV	32MeV	±0.002	±0.002	±0.006	±0.001	±0.002

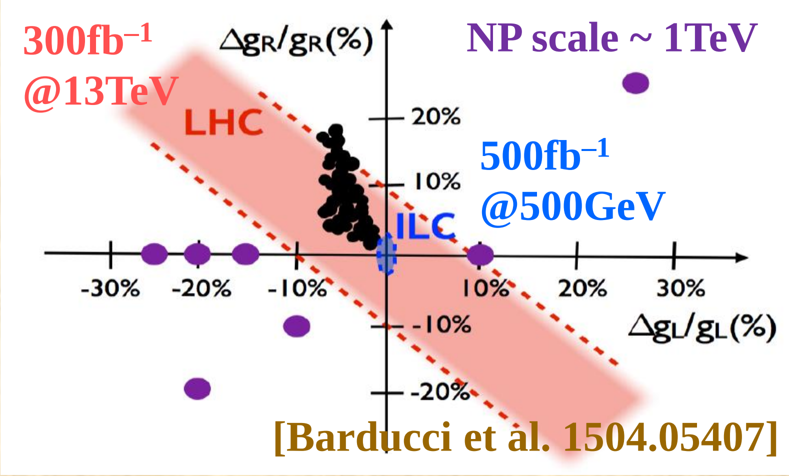
Stability of the Higgs potential



Boundary condition $\lambda(m_{pl}) = 0$?

Precise measurements of m_t!

An implication to CHMs, etc.



Precise top measurements can be used to discriminate NPMs!