ILC physics overview

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I will talk about the scientific significance of the ILC project, base on discussions made by Physics panel (subcommittee) of the academic expert committee of the project.

Big problem tackled by collider physics

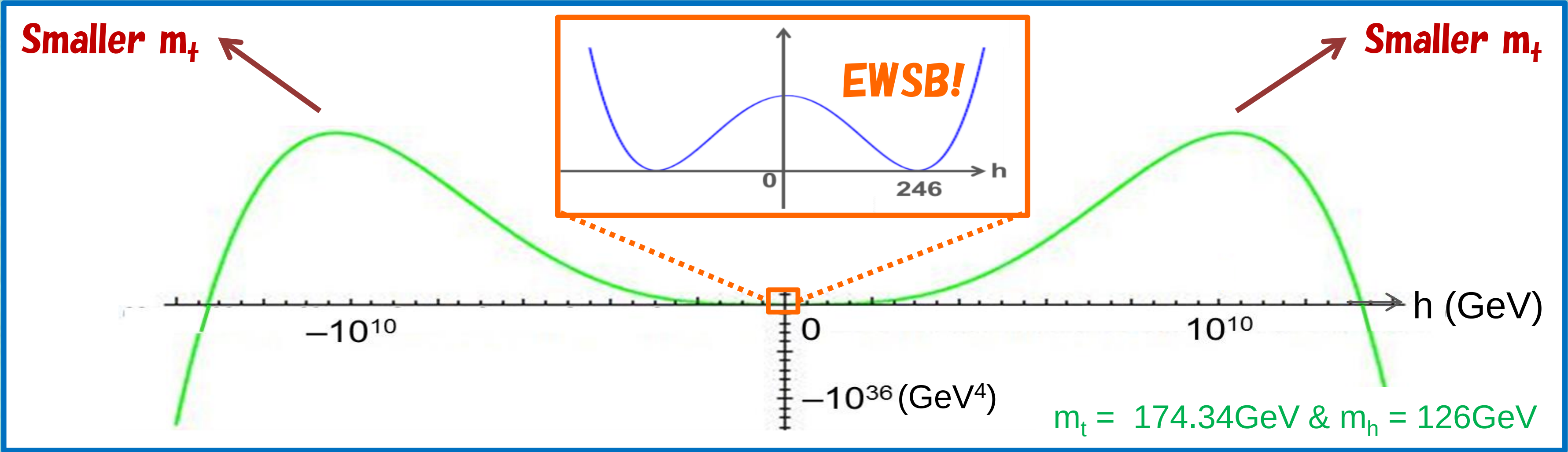
Why the EW symmetry is broken? Why at O(100)GeV?

The point: The SM can not answer the question, for it is assuming that the EW symmetry is just broken at the O(100)GeV.

A similar problem exists (& has been solved) in Condensed Mat. Phys.

Ginzburg-Landau theory → BCS theory (Higgs = :ee:)

What is the theory behind the EWSB corresponding to the BCS one?



Since quantum field theory of particle physics assumes Planck scale as a fundamental energy scale, EW symmetry seems to be unbroken at 0^{th} app. but broken due to some small breaking causing EW scale.

Big problem tackled by collider physics

Three possible physics behind the EWSB (Higgs physics)

TeV scale SUSY

Supersymmetry was broken at some high energy, and it causes the EW sym. breaking.

Higgs boson is merely one of many scalers.

Composite Higgs

Some dynamical sym. breaking occurred at high energy, causing the EW sym. breaking.

Higgs boson is a PNG associated with it.

Other possibilities

The EW symmetry is broken due to some other reasons / some other mechanisms.

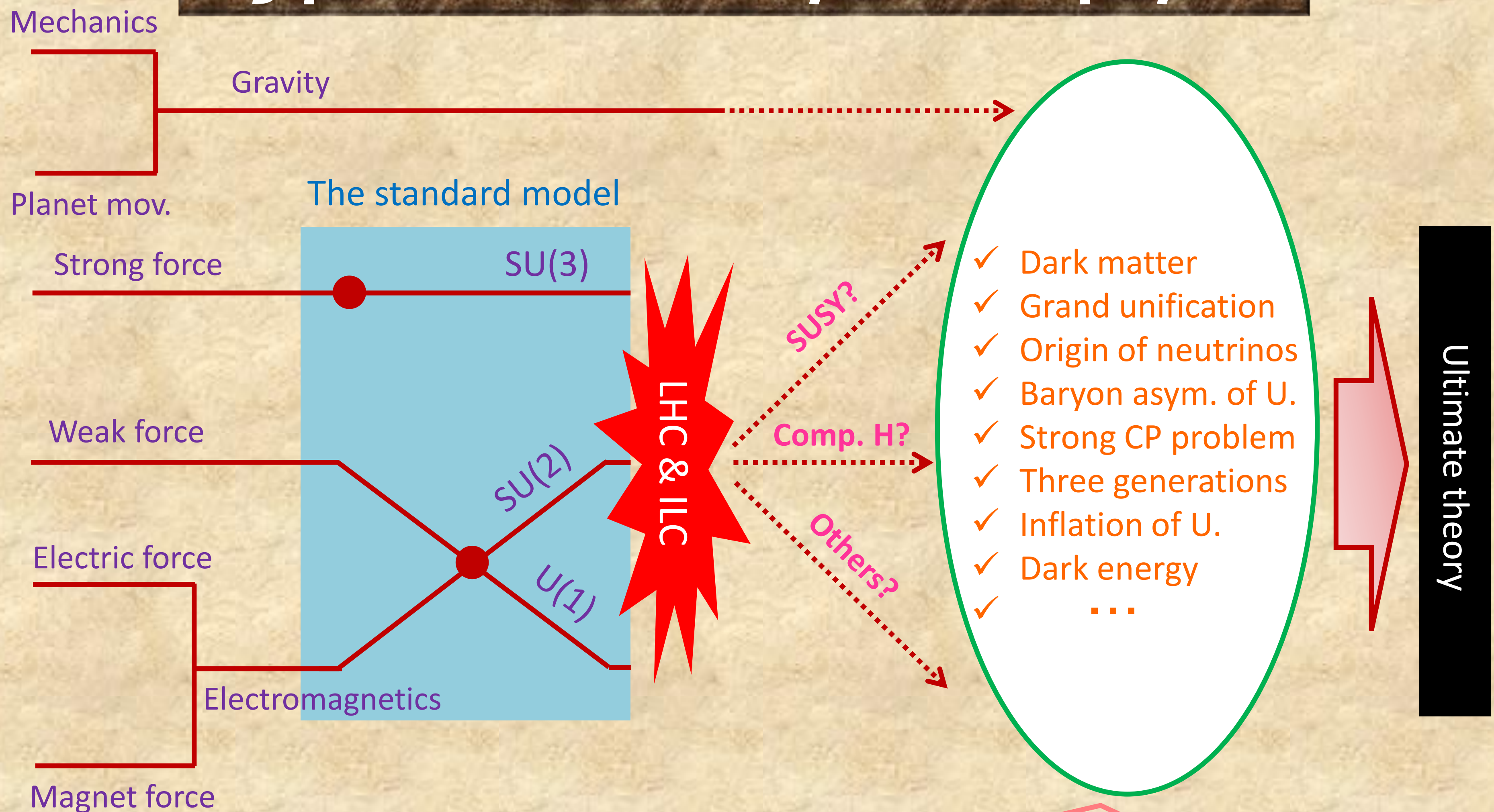
Higgs boson is often regarded as special.

One of the most important role of high energy physics is to clarify physics behind the EWSB or at least to get some clue to clarify it.
(Collider physics was historically (& still be) playing such a role!)

Colliders allow us to measure a huge amount of physics observables simultaneously, and are nice experiments for unknown unknowns!
If no signals are detected, very severe limits are put on new physics.

Both LHC and ILC have the same physics significance, and it is thus important to discuss their difference, complementarity and synergy.

Big problem tackled by collider physics



There are many other important problems which must be resolved. If new physics just above EW scale was clarified by energetic colliders, we will get a clue to solve the problems. This is nothing but synergy!

TeV scale Supersymmetry

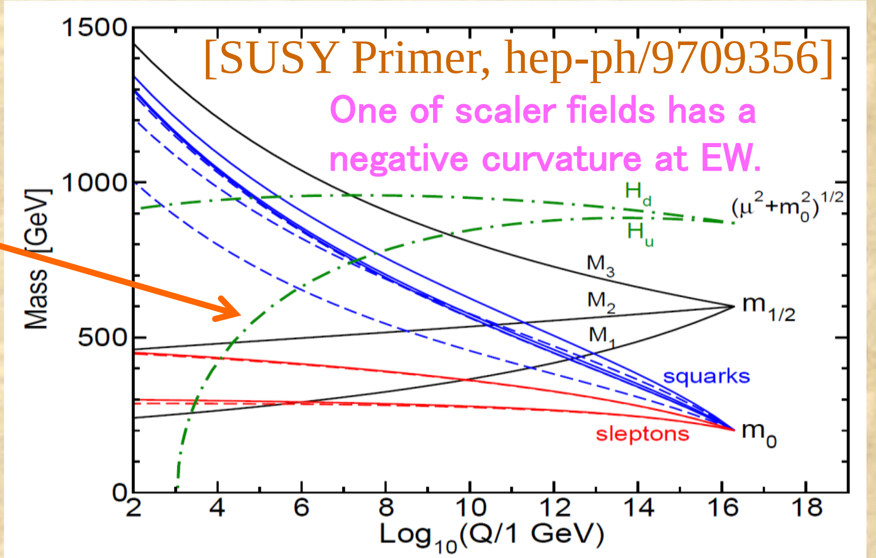
Why the coefficient is negative?

$$V = m^2|H|^2 + \lambda|H|^4$$

SUSY breaking →→→ EWSB

(Radiative corrections)

[K. Inoue, et. al, PTP,1982]



Why m^2 is O(100)GeV?

$$\boxed{m^2 = |\mu|^2 + m_{H_u}^2 + \delta m_{H_u}^2|_{\rm stop} + \delta m_{H_u}^2|_{\rm gluino} + \cdots}$$

- ✓ Higgsino mass
- ✓ Heavy Higgs mass
- ✓ Squark (Stop) mass
- ✓ Gluino mass
- …

$$\delta m_{H_u}^2|_{\rm stop} = -\frac{3}{8\pi^2}y_t^2\left(m_{Q_3}^2 + m_{U_3}^2 + |A_t|^2\right)\log\left(\frac{\Lambda}{\rm TeV}\right)$$

$$\delta m_{H_u}^2|_{\rm gluino} \simeq -\frac{2}{\pi^2}y_t^2\left(\frac{\alpha_s}{\pi}\right)|M_3|^2\log^2\left(\frac{\Lambda}{\rm TeV}\right)$$

TeV scale Supersymmetry

$$m^2 = |\mu|^2 + m_{H_u}^2 + \delta m_{H_u}^2|_{\rm stop} + \delta m_{H_u}^2|_{\rm gluino} + \cdots$$

↑ $(100\mathrm{GeV})^2$

No fine-tuning

$M_{SUSY} < O(0.1)$ TeV?

Small fine-tuning

$M_{SUSY} < O(1)$ TeV?

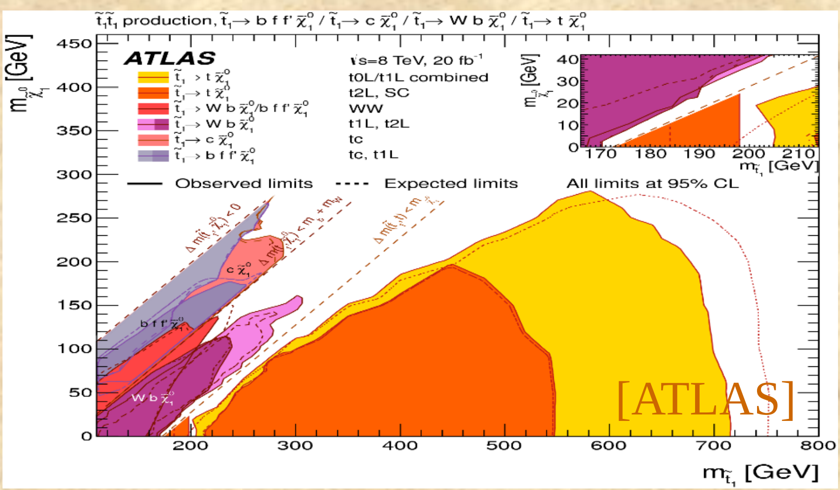
Fine-tunings in nature
- ✓ 3 Helium → Carbon
- ✓ Quadrupole in CMB

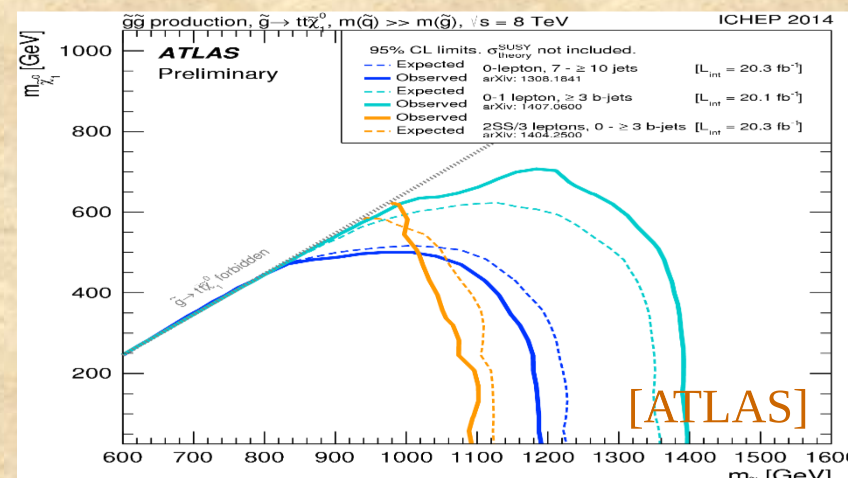
Coupling unification, DM

Time

LEP ⟵ LHC ⟵

Strategy @ LHC → Direct productions of colored new particles + ⋯





TeV scale Supersymmetry

Strategy @ ILC → Indirect probe via precise Higgs measurements + …

Indirect detections: Detecting BSM contributions to SM processes.

→ R-even new particles give larger contributions than odd ones.

→ R-even new particles = Heavy Higgs bosons in MSSM, and they give significant corrections to the lightest Higgs interactions.

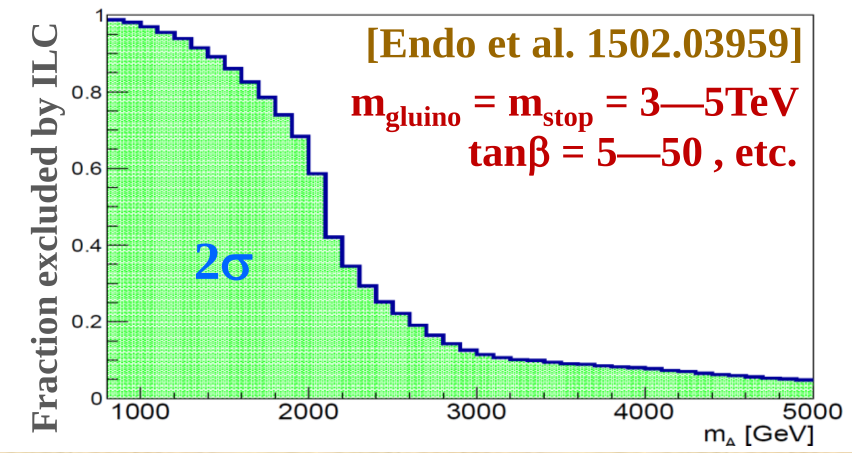
$\mathrm{I} = 1.15\mathrm{ab}^{-1}$ @ 250GeV $\oplus$ $1.6\mathrm{ab}^{-1}$ @ 500(550)GeV & $\mathrm{II} = \oplus\ 2.5\mathrm{ab}^{-1}$ @ 1TeV

	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%

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

↑ Couplings can be determined in a model-independent way!

Original parameter space were obtained by taking into account of all experimental constraints. (Collider, Flavor, Higgs, etc.) →



Composite Higgs

Why $|H|^2$ has a negative coefficient?

$G \to H$

A confining gauge theory
+
elementary SM fermions
+
SM gauge bosons

- ✓ Higgs is a pNGB associate with $G \to H$.
- ✓ SM fermions $\subset$ Incomplete multiplets.
- ✓ $G \supset SU(2) \times U(1)$ is partially gauged.
- ✓ Top Yukawa from partially compositeness.
- ✓ $V(h)$ ($= 0$ @ LO) is radioactively generated.

Explicit breaking of G

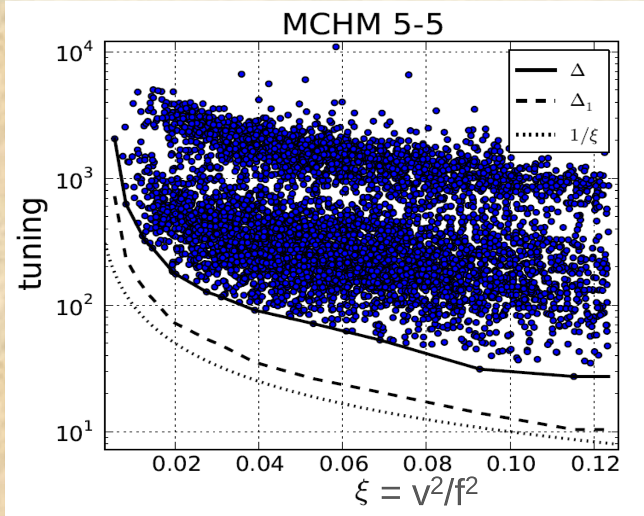
$$V(h) = \gamma \sin^2(h/f) + \beta \sin^4(h/f)$$

f = decay constant associated with $G \to H$

Why m^2 is $O(100)$GeV?

$O(v) \sim O(f)$ from $V(h)$, tuning $\sim O(v^2/f^2)$

When γ is from LO while β is from NLO, it becomes more severe, say double tuning. →



[J. Barnard et al. 1507.02332]

When both γ and β are from LO, it is still $O(v^2/f^2)$. Typical example is MCHM14-14.

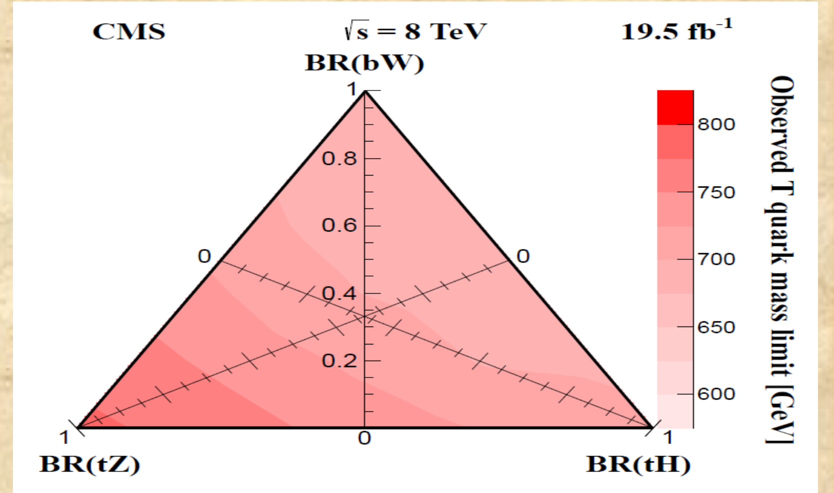
↓

Smaller f & lighter top partner favored!

Composite Higgs

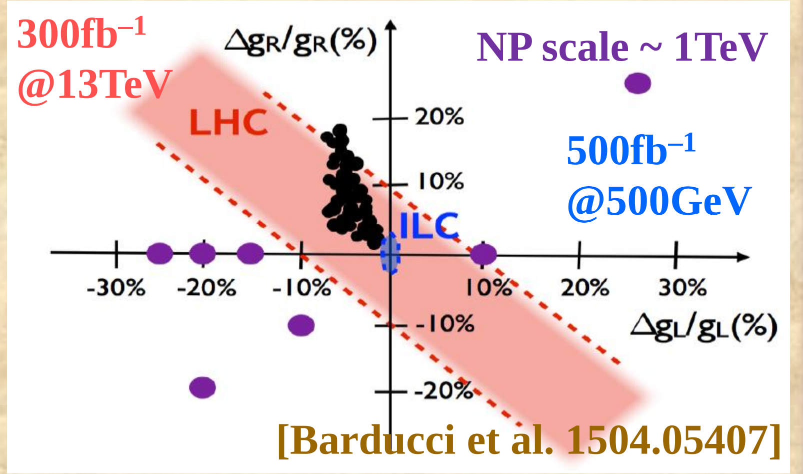
Strategy @ LHC → Productions of top partners, vector bosons + ⋯

- ✓ Top partner: m_T > 700—800GeV
  E.g. $1_{3/2}$ top partner:
  T → bW
  T → tZ →→→→→
  T → hZ
- ✓ G(H → WW/ZZ): f > 700GeV
- ✓ Vector boson production, etc.



Strategy @ ILC → Precise Higgs and top measurements + ⋯

- ✓ H to WW/ZZ coupling measurements.
- ✓ Yukawa coupling measurements.
- ✓ Precise top prop. measurements →
  [ttZ, Δm_t = 100MeV & $\Delta\Gamma_t$ = 32MeV]
- ✓ Higgs self-coupling measurement.
- ✓ Detecting vector boson resonances.



Other possibilities (EW Naturalness)

[In SUSY framework, J. Feng, K. Matchev, T. Moroi, 2000; H. Baer, et. al. as recent studies]

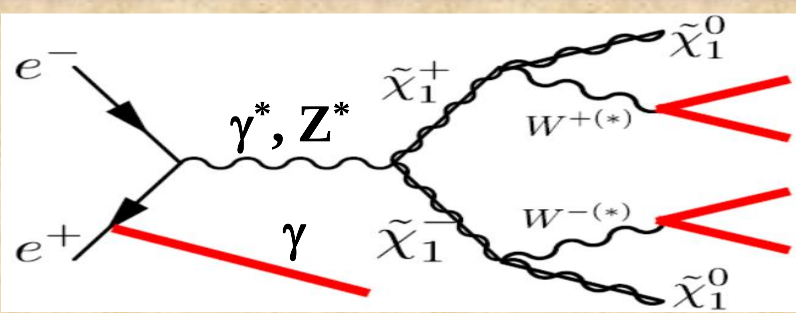
Radiative corrections to $|H|^2$ term are controlled by high energy physics.

$$\boxed{m^2 = |\mu|^2 + \underbrace{m_{H_u}^2 + \delta m_{H_u}^2|_{\rm stop} + \delta m_{H_u}^2|_{\rm gluino} + \cdots}_{= (\text{Small number}) \times (M_0)^2}}$$

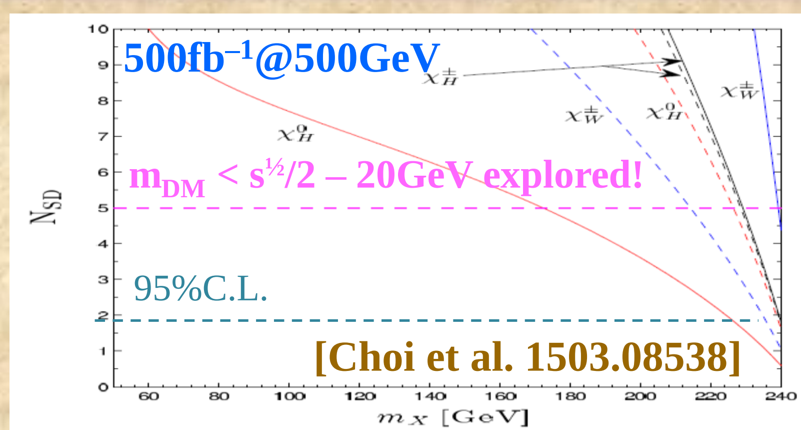
Corrections from ~~SUSY~~.

Prediction: ① The mass of sparticles >> 1TeV in general.
② Small μ term → Higgsino mass < 200GeV!
③ Small $(m_{Hd})^2$ term → Heavy Higgs lighter than $|\mu| \tan\beta$.

Hard to be tested at LHC but easy at ILC due to Higgsino production!



DM search: γ + $\not{E}$ + soft tracks, etc.
[Berggren et al. 1307.3566]



Other possibilities (Multiverse)

[Y. Nomura, 2011; Y. Nomura; S. Shirai, 2014 and M. Ibe, et. al, 2015 in SUSY framework]

Some physical observables are biased against observed values.

1. We are living universe in multiverse.
2. Each universe has different const.
3. We can live in the one with EW scale.

String theo. & Etern. Inflation support it.

Implication to SUSY

③ → $(M_{SUSY})^2 - |\mu|^2 \sim (100\text{GeV})^2$

- ✓ No scale dependence of M_{SUSY} (Dynamical SUSY breaking)
- ✓ Larger value of μ is favored.
- ✓ Smaller value of μ is favored to satisfy the equation ③.

Subset satisfying ③ considered, no favored μ scale is obtained.

↓ [PGM, Spread, Mini-split, …]

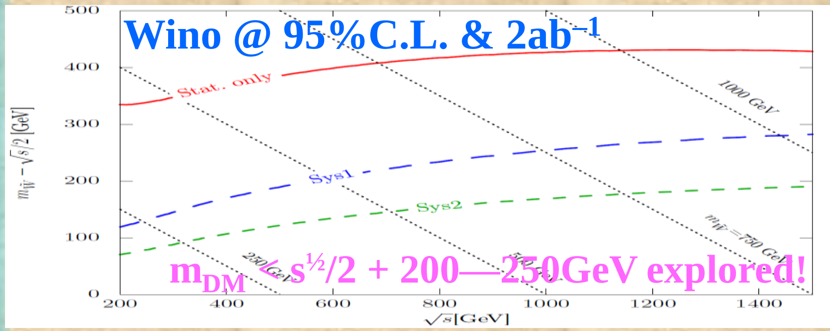
AMSB scenario [Giudice, et al, 1998]

Testing the scenario

All sparticles except gauginos become very heavy. LSP is Wino.

LHC: Disappearing track search.

ILC: Radiative correction to ee→ff



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%

Other possibilities (MPP)

[C. Froggatt, H. Nielsen, 1996; H. Kawai, et. al. for recent studies]

There may be a principle behind the action principle we usually use!

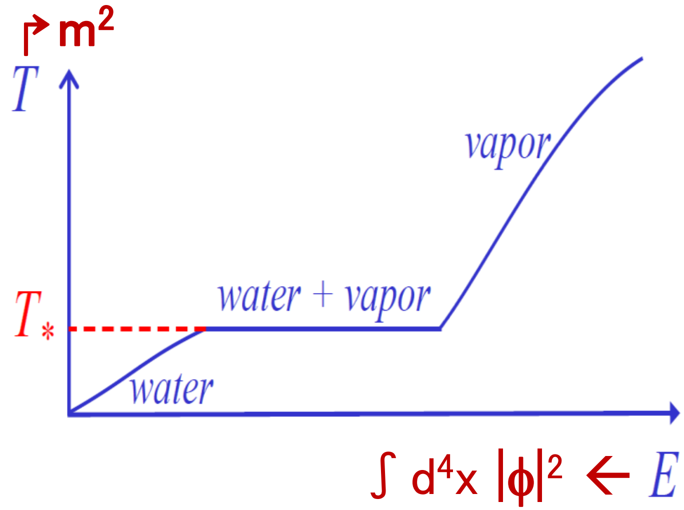
◎ **Canonical**

$$\int [d\varphi]\, e^{-\beta H[\varphi]}$$

↑

◎ **Micro-canonical**

$$\int [d\varphi]\, \delta(H[\varphi] - E)$$



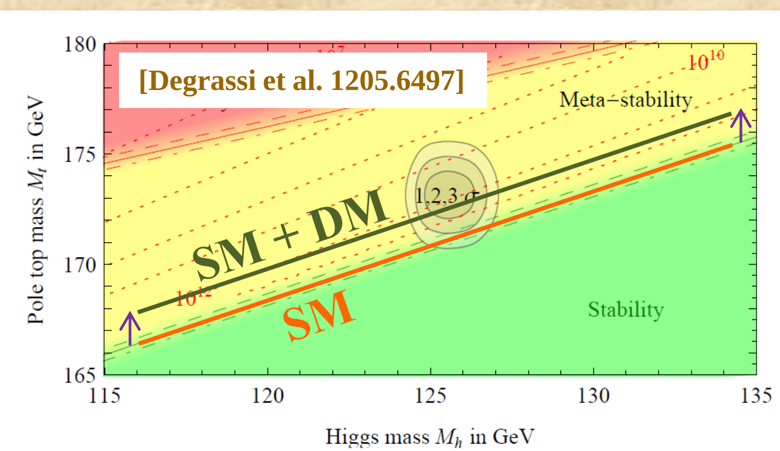
◎ **Standard model**

$$Z = \int [d\varphi]\, e^{iS[\varphi]}$$

↑

◎ **?????????**

Two phase coexistence

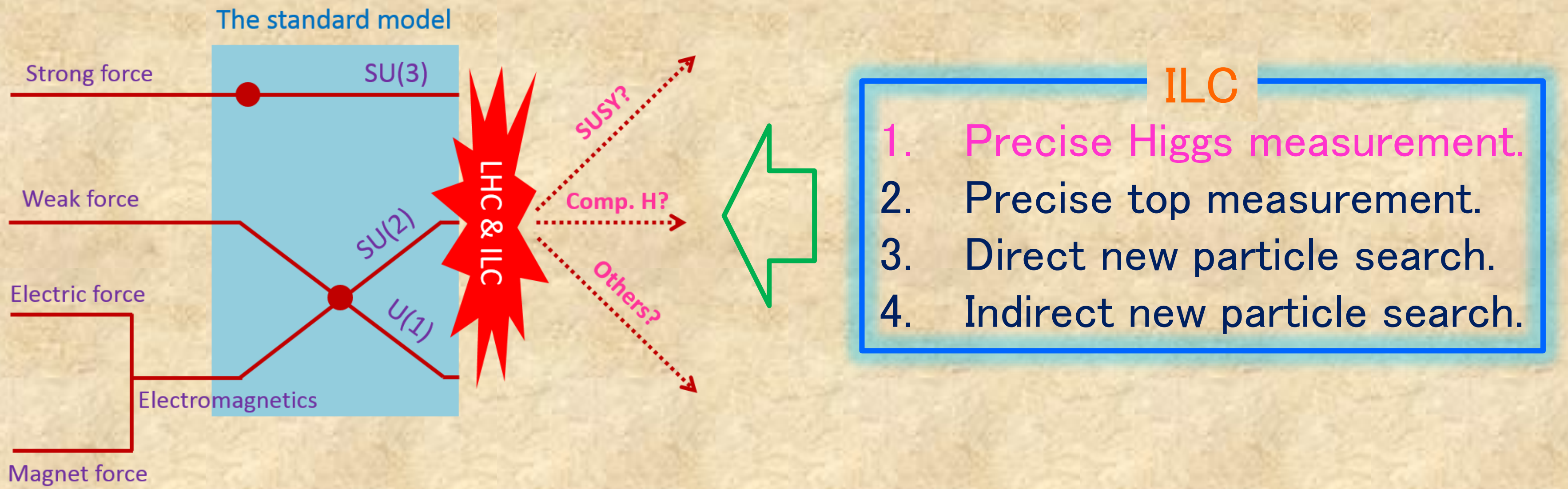


Testing the scenario

1. **Precise t & H measurements**
   → **As discussed before.**
2. **Detecting DM signals**
   [A consistent candidate is $SU(2)_L$-triplet fermion DM.]
   → **As discussed before.**

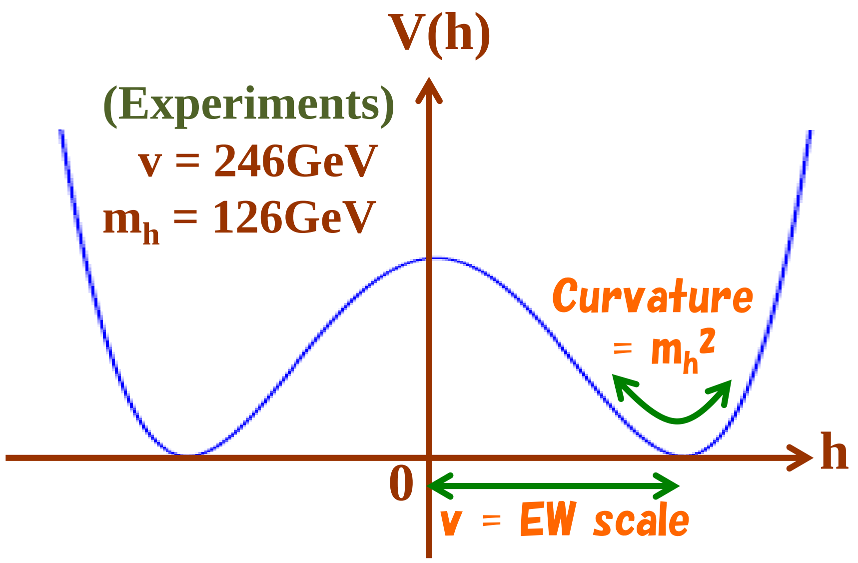
Summary

- The question **why the EW symmetry is broken at O(100)GeV** is one of the most important problems in particle physics. Solving the problem will eventually show us a definite direction toward finding the ultimate theory of nature. **ILC will play a crucial role** to answer the question via precise measurements of top quark and Higgs boson, and new particle (dark matter, etc.) searches.
- **ILC** will provide an ideal environment to tackle the problem.



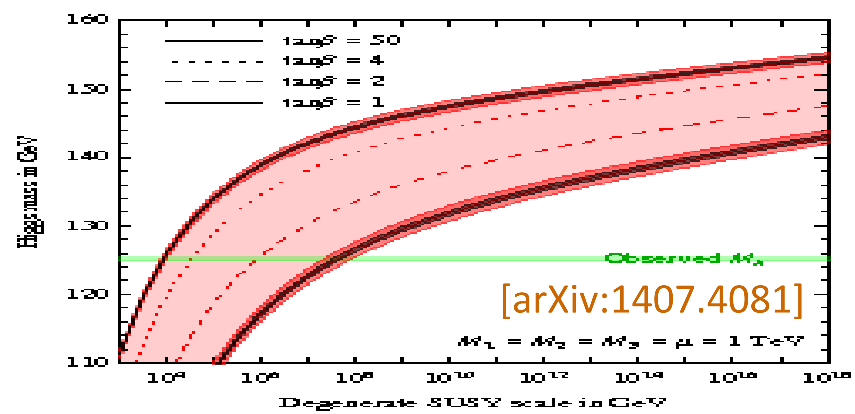
- To tackle physics behind EWSM, namely the Higgs mechanism, **the precise Higgs measurement** must be the most efficient way.

Higgs mass in SUSY



Relation between v and m_h in SUSY

[Okada, Yamaguchi, Yanagida (1990);
Ellis et al (1990); Haber et al (1990)]



ILC can determine couplings in a model independent way

- $\sigma \times BR$ 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.)

AMSBシナリオ

～ Pure Gravity Mediation Model ～

Scalar masses: [Gravitino mass is fixed to be O(100)TeV]

μ-term: [Inoue, Kawasaki, Yamaguchi, Yanagida, 1992]

Minimal (Simplest) Setup!

MSSM – SUGRA interactions – ~~SUSY~~

No singlets →

Anomaly Mediation: [H.Murayama, et. al., 1998; L.Randall, et. al., 1999]

Dark Matter: [Hisano, S.M., Nagai, Saito, Senami, 2007 (TH); T. Moroi, et. al., 1999 (NT),]

Higgs mass: [Okada, Yamaguchi, Yanagida, 1990; Ellis, et. al., 1990]

= **A conjecture on SUSY breaking mediation**

[Ibe, Moroi, Yanagida (2007), Ibe, Yanagida (2011), Ibe, Matsumoto, Yanagida (2012)]

Heavy WIno DM search

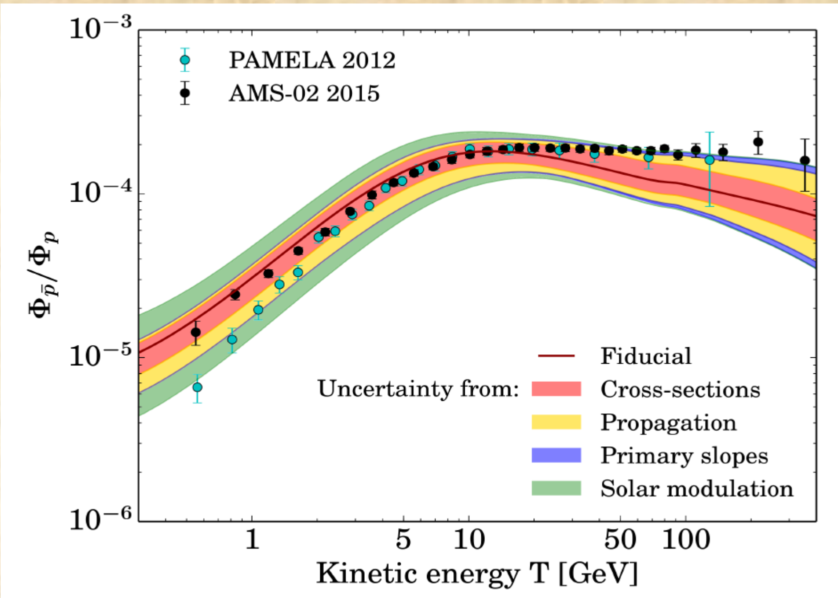
TeV scale thermal WIMP (DM relic abundance only from $\Omega_{TH}h^2$):

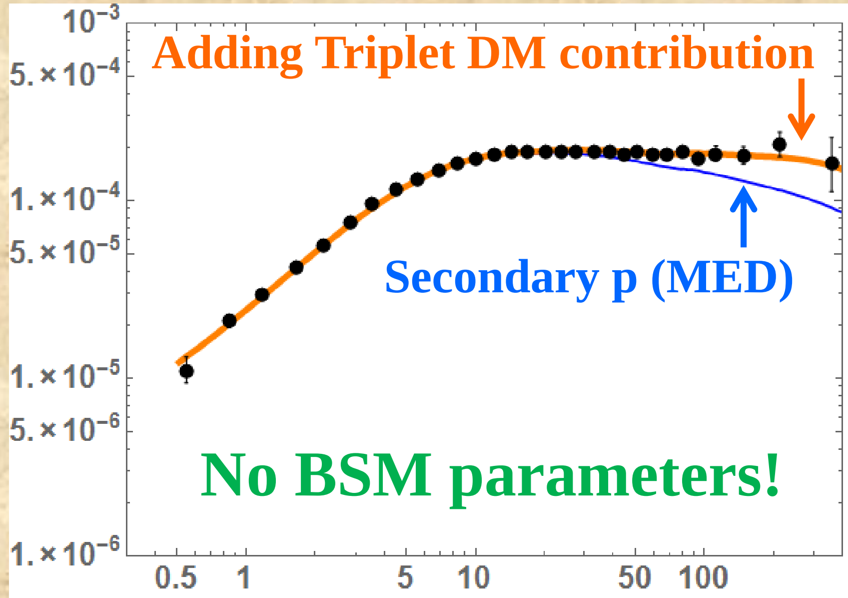
- When DM is from a $SU(2)_L$ doublet, its mass is predicted to be 1TeV.
- When DM is from a $SU(2)_L$ triplet, its mass is predicted to be 3TeV.

↓

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!

素粒子現象論の動向：LHC前から後へ

～ Personal thoughts on theoretical studies of new physics models ～

Before LHC (1st run)		After LHC (1st run)
Technicolor (TC/ETC)	→	Technicolor (TC/ETC)
Extra-dimension (GHU)	→	Extra-dimension (GHU)
	String people →	Flat land (Just SM)
Composite Higgs (CompH)	→	Composite Higgs (CompH)
Supersymmetry (SUSY)	EU →	Composite Higgs (CompH)
Supersymmetry (SUSY)	US & J →	Supersymmetry (SUSY)
Supersymmetry (SUSY)	A few →	Something new

SUSY becomes very attractive for those who study its cosmology seriously!