Physics Overview

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ILC Kick-Off Meeting, Tohoku University 12 Sep 2011

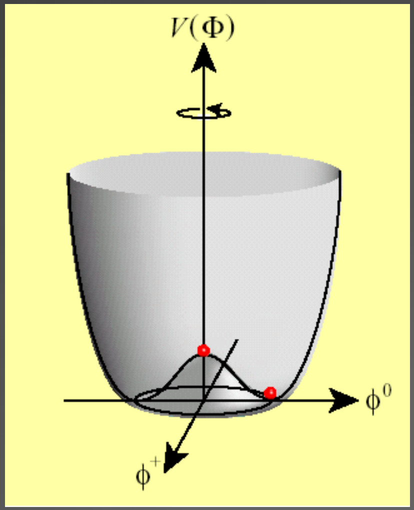
Where we are now?

- Standard Model
  - Gauge Symmetry
  - Electroweak Symmetry Breaking
- Higgs remains unknown
  - Origin of Mass yet to be confirmed
- LHC was designed to find Higgs
  - Experiment looks going very well
  - Discovery not yet, but under survey
  - We expect something will be found near future

SU(3) X SU(2) X U(1)

↓

$U(1)_{em}$



$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$

Where we are now?

In spite of success of the SM

We know that the SM cannot be fundamental

- Gravity is not included
- Empirically, we know phenomena which the SM cannot explain

Neutrino Mass,   Dark Matter, Baryon Asymmetry

Beyond SM?

Apart from the BSM penomena, we have many complains on the Standard Model in itself

- Gauge Symmetries SU(3)XSU(2)XU(1)

  Maybe unified into a larger but simple group?
- Why 3 generation?

  Sequential 4th generation strongly constrained
- No prediction on mass matrices, coupling constants
- Strong CP Problem
- ….

The SM should be only a low energy effective theory of a more fundamental theory

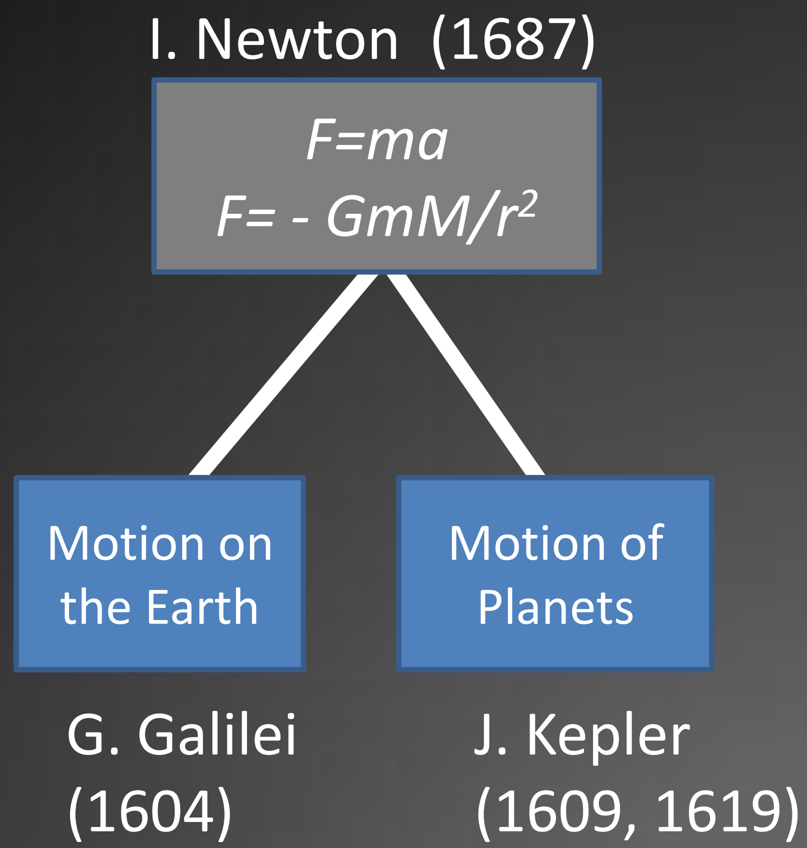
Beyond SM?

History of physics is that of unification of low in the nature

Unification is Goal

We are still on the way

It must be…



Beyond SM?

History tells us unification of low in the nature

Unification is Goal

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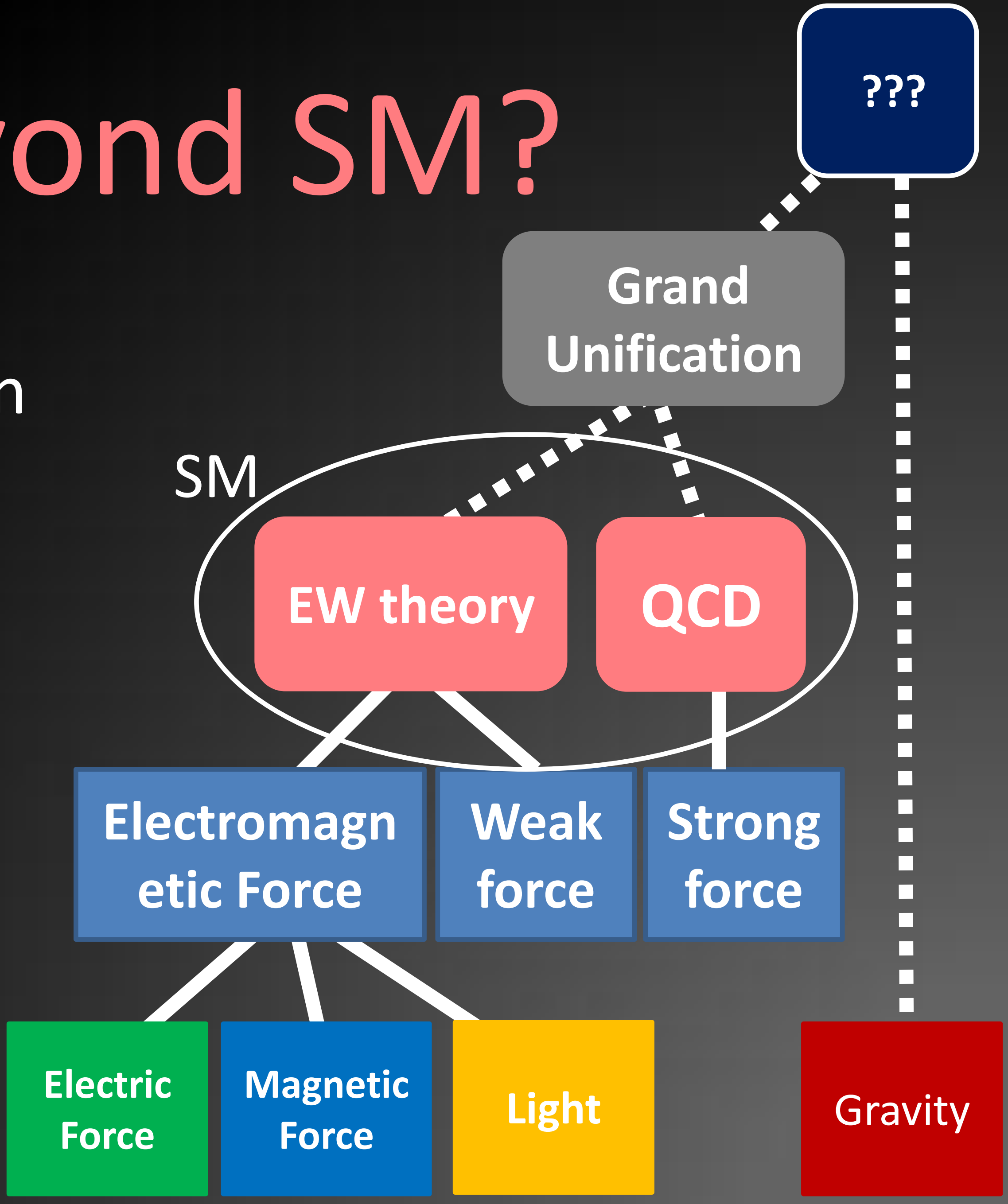
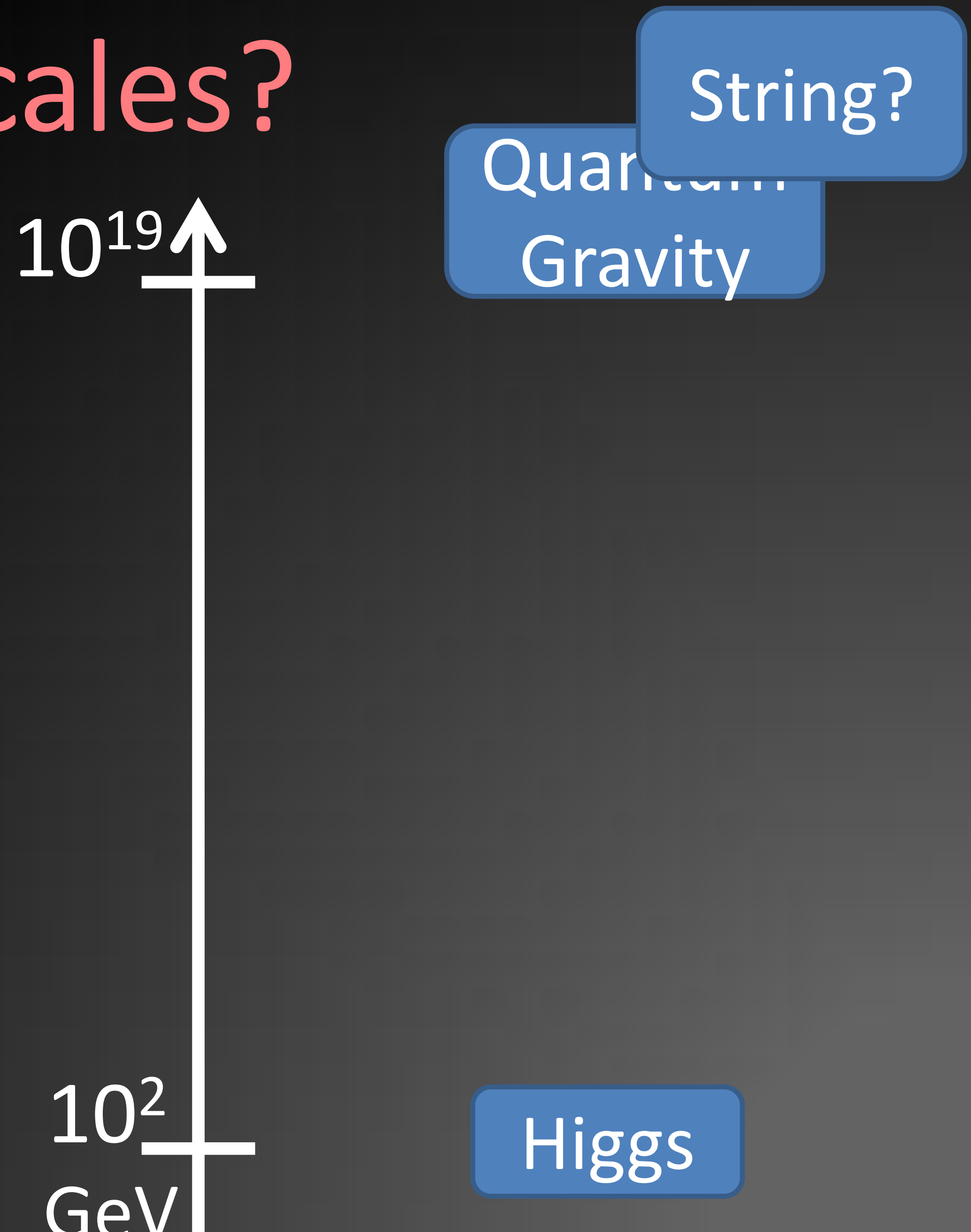


Scales?

- Planck Scale
- Grand Unification Scale
- ???
-
- Electroweak scale



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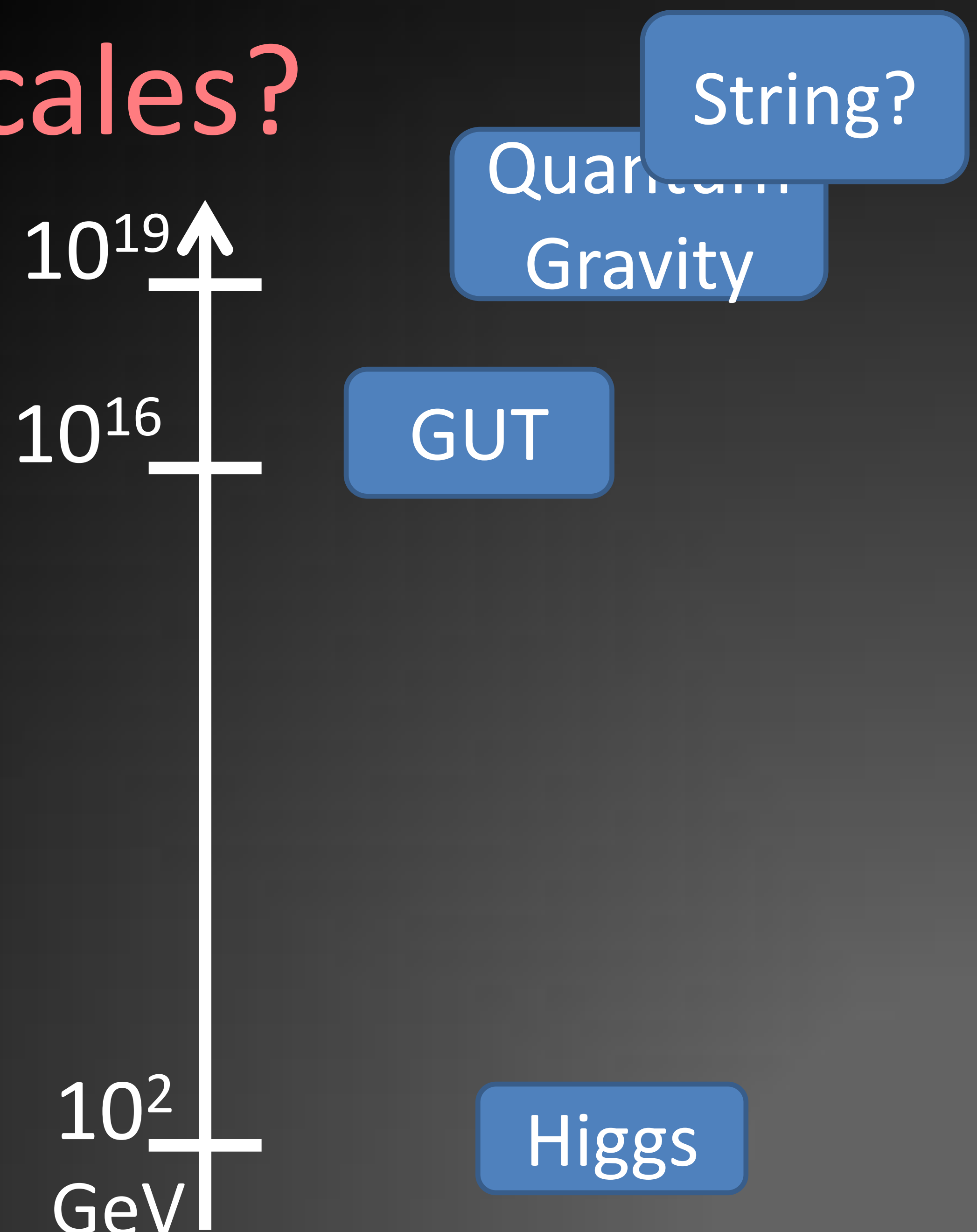
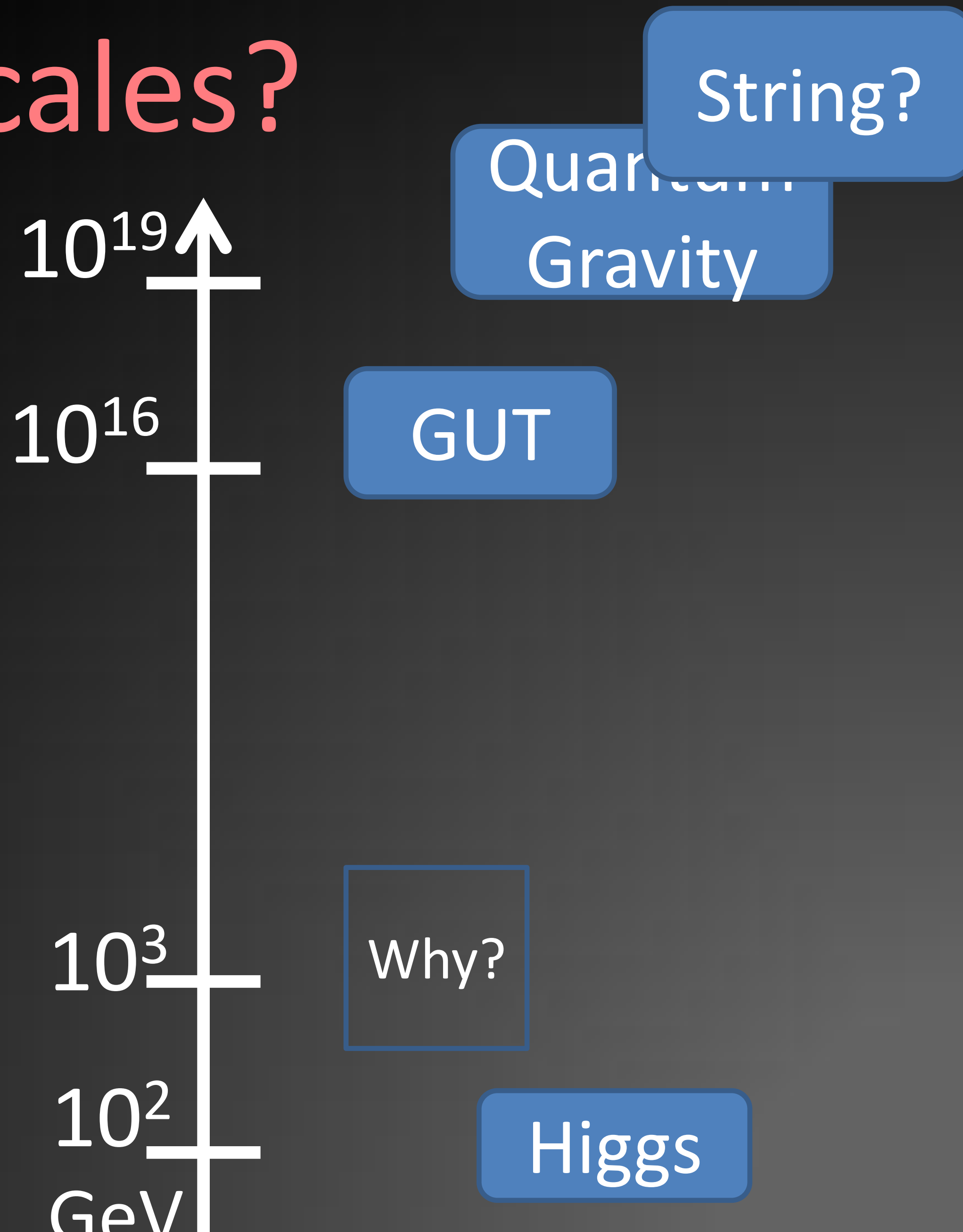


Scales?

- Planck Scale
- Grand Unification Scale
- ???
- TeV scale
- Electroweak scale



TeV scale

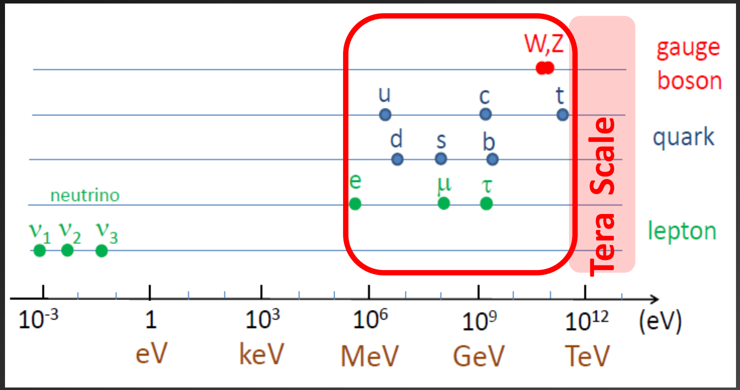
Physics of EWSB

Hierarchy Problem

WIMP Dark Matter

We therefore expect BSM at TeV scale

A step for physics at much higher scales



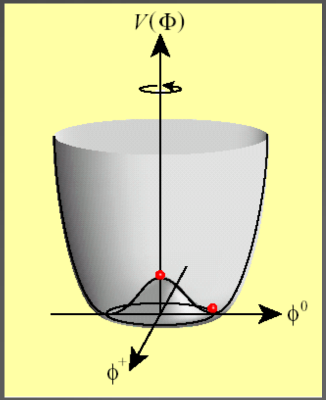
Origin of Mass?

Spontaneous EW Symmetry Breaking

$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$

VEV=0.3 TeV

Perturbative Unitairty
$m_h <$ 1 TeV



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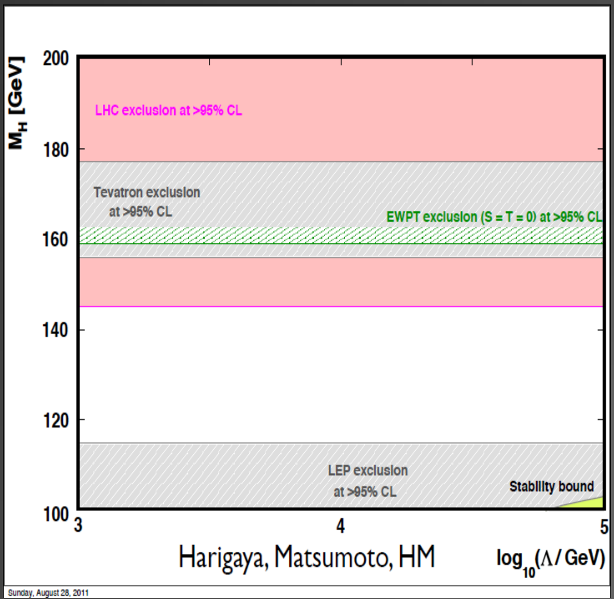
Quadratic Divergence

$$\delta m_H^2 = \frac{\Lambda_{cutoff}^2}{16\pi^2}$$

Huge fine tuning if $m_H << \Lambda$ ~ GUT scale

If at most 10%-1% fine tuning, Λ turns out to be **1 TeV -10 TeV**



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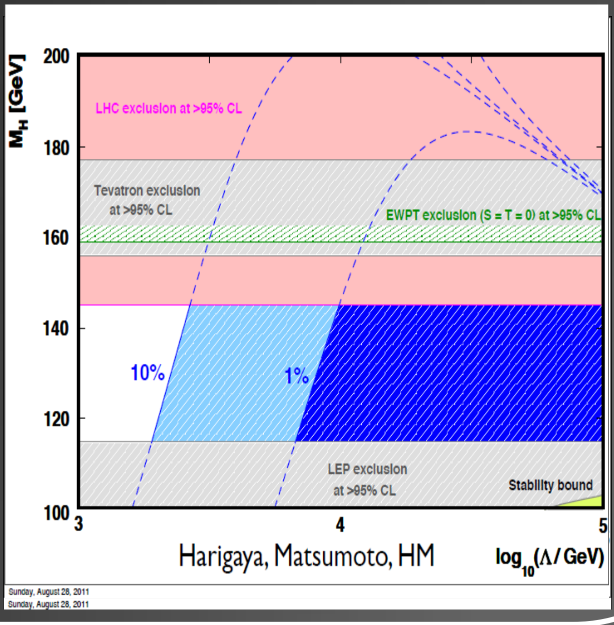

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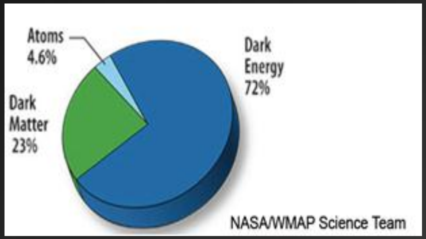
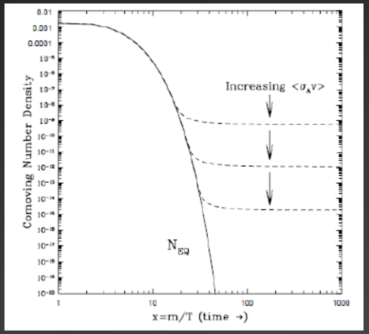




WIMP hypothesis

$$\Omega_{\rm DM} h^2 \simeq \frac{0.1 {\rm pb} \cdot c}{\langle \sigma v \rangle}$$

$$\langle \sigma v \rangle \sim (g^2/4\pi)^2/m^2$$

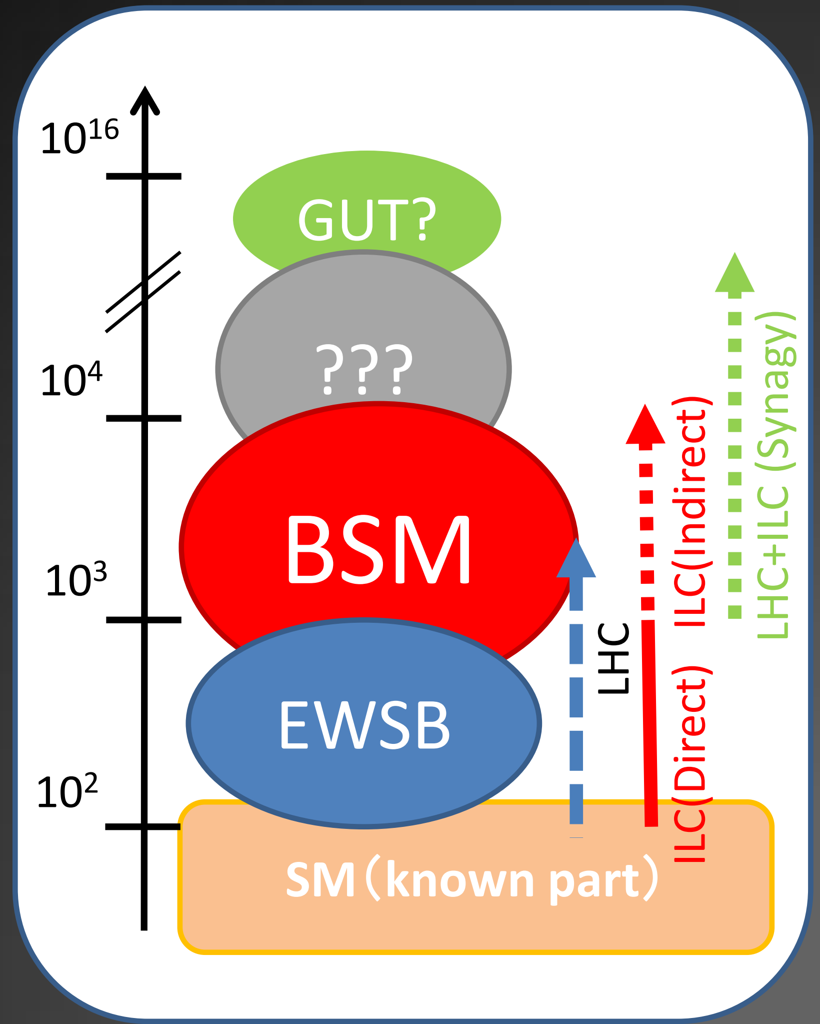
$$\Omega_{\rm DM} h^2 = 0.1 ({\rm WMAP})$$

$$m \sim g^2 \times (1 {\rm TeV})$$

Mass of WIMP DM is at TeV scale!

TeV scale

- Physics of EWSB
- Hierarchy Problem
- WIMP Dark Matter
- We therefore expect BSM at TeV scale
- A step for physics at much higher scales



TeV scale

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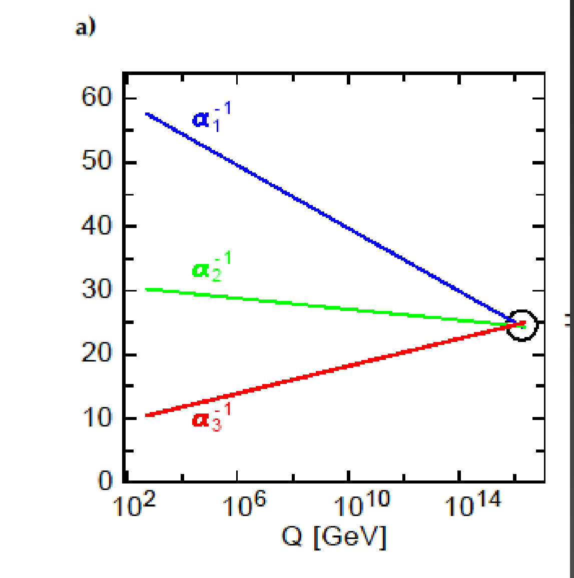
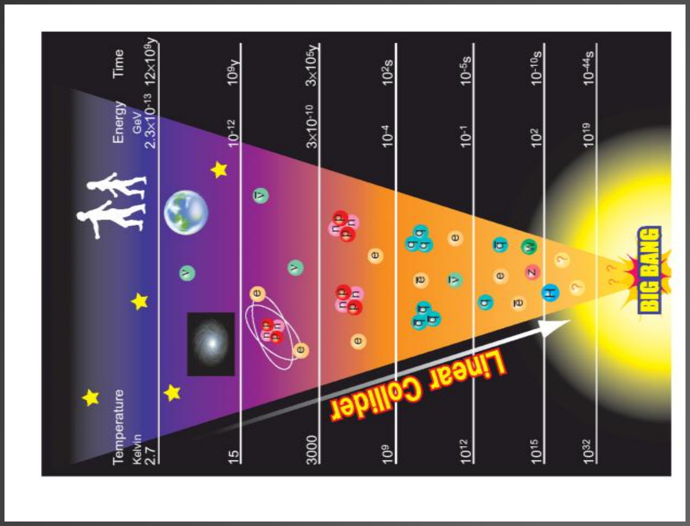




Higgs and New Physics

What is the essence of the Higgs field?

Higgs nature	⇔	New Physics scenario
– Elementary Scalar?		**Supersymmetry**
– Composite?		**Dynamical Symetry Breaking**
– Pseudo NG Boson?		**Little Higgs**
– A gauge field in Extra D?		**Gauge-Higgs unification**
– ……		**……**

Higgs sector can be considered as a probe of new physics

Higgs

Higgs

SM Higgs

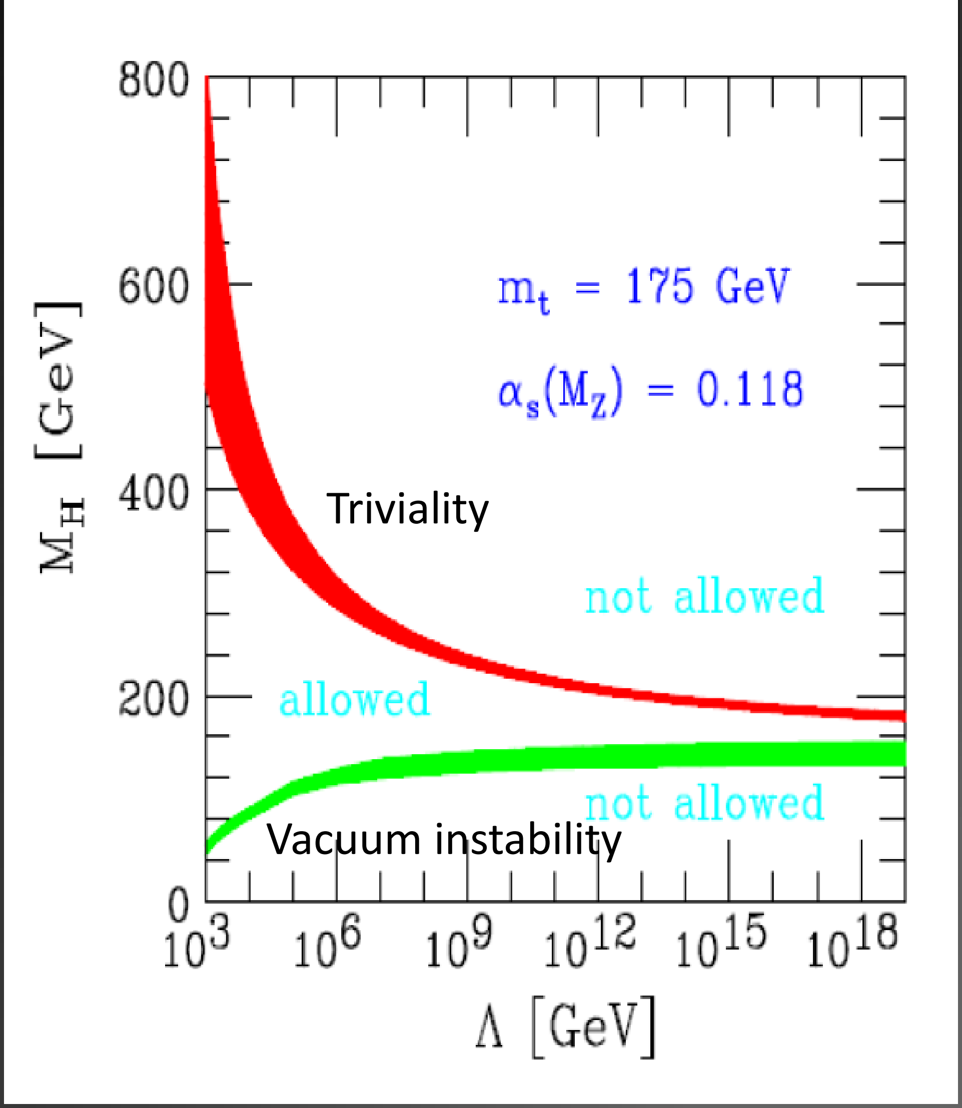
$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$$

mh: free parameter

$$m_h^2 = 2\,\lambda\, v^2$$

Hint for the cutoff Λ

- Light Higgs
  Weakly coupled: High Λ
- Heavy Higgs
  Strongly coupled: Low Λ



Higgs

Data tells us!

LEP Direct search

Tevatron (Aug. 2011)

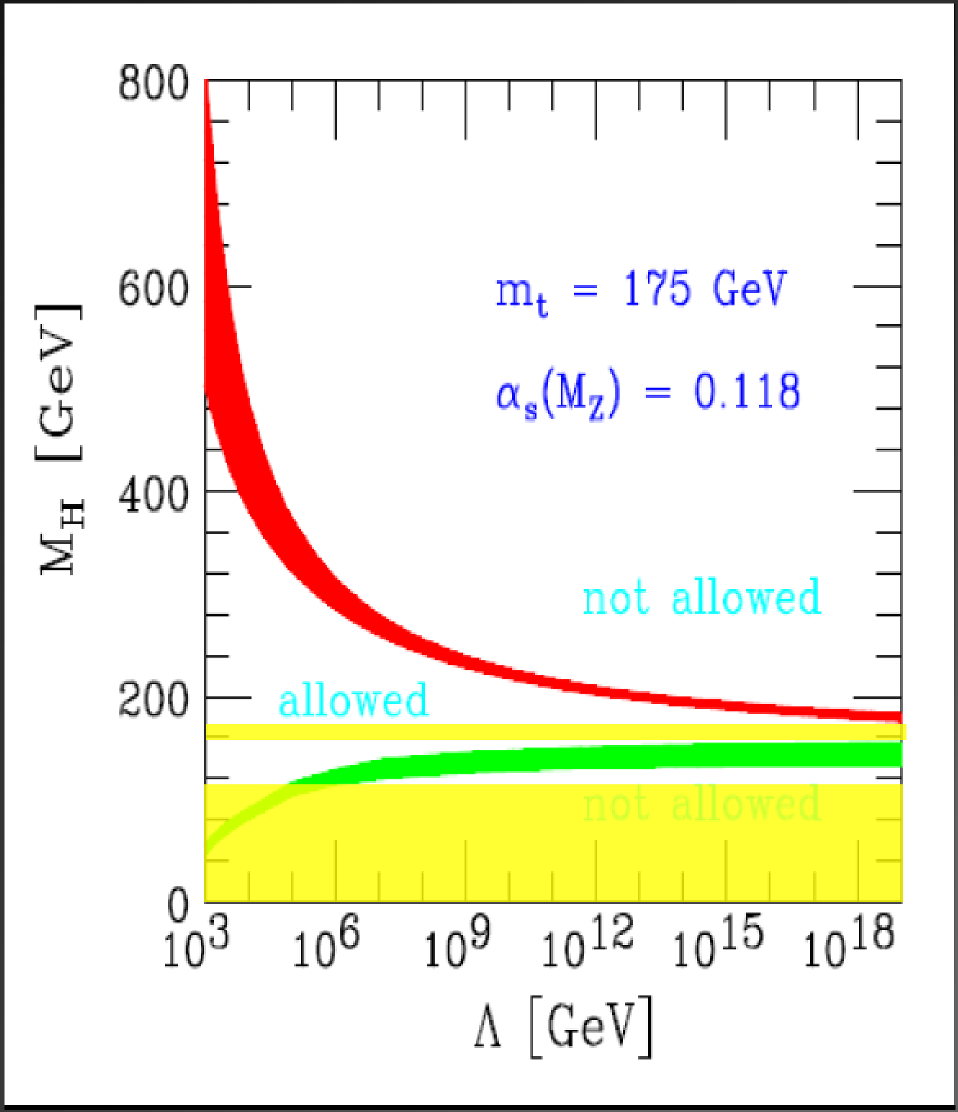
LHC (Aug. 2011)

LHC already exluded quite a few regions of mh!

Great achievement!

Only Possibilities

- 445- GeV
- 288-296 GeV (vanishing…)
- 114-145 GeV



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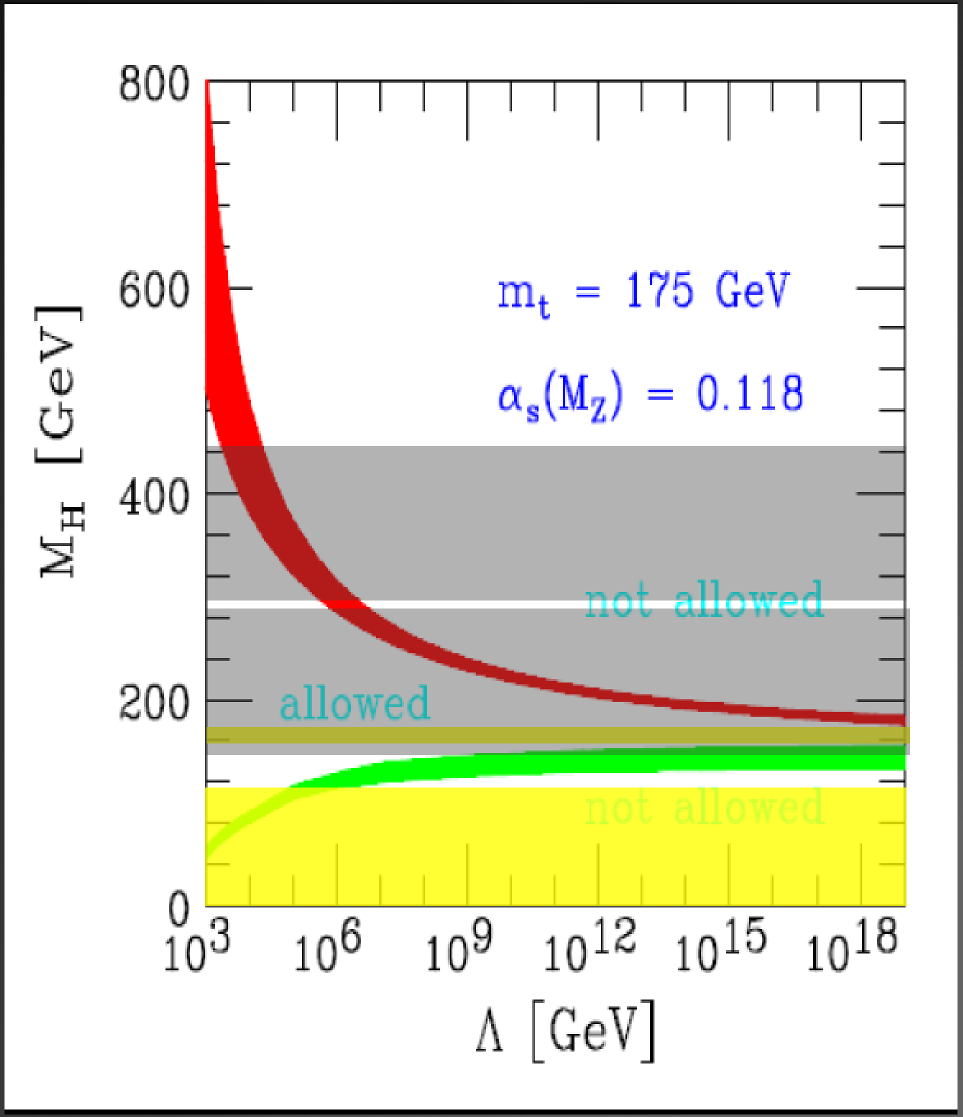

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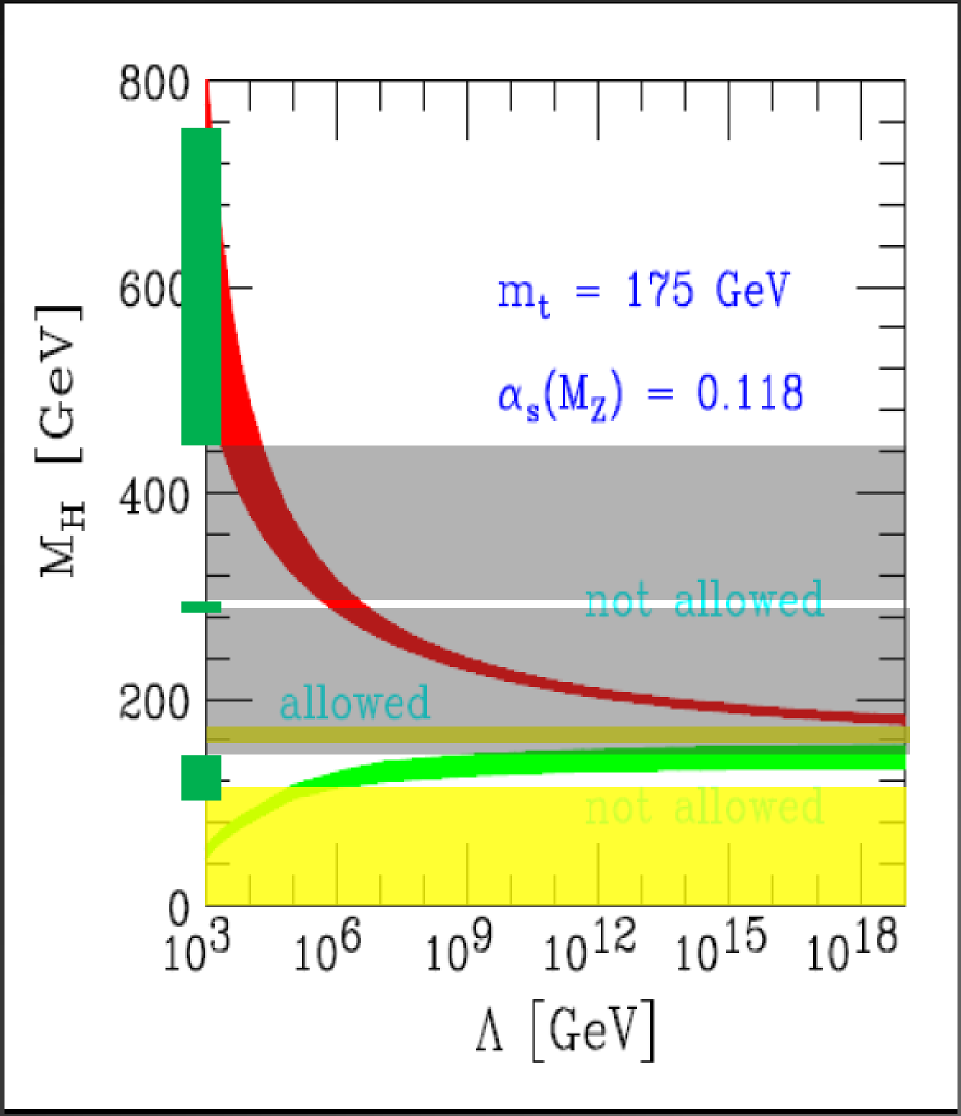


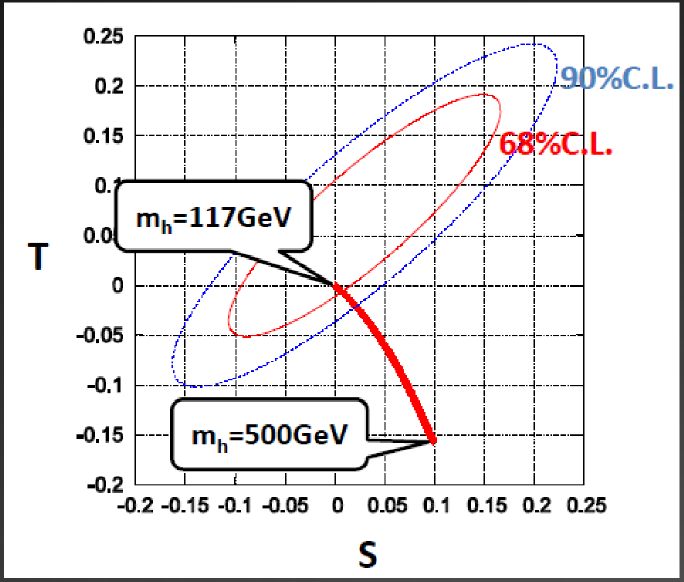
Higgs

LEP precision data tells us

Lighter Higgs boson

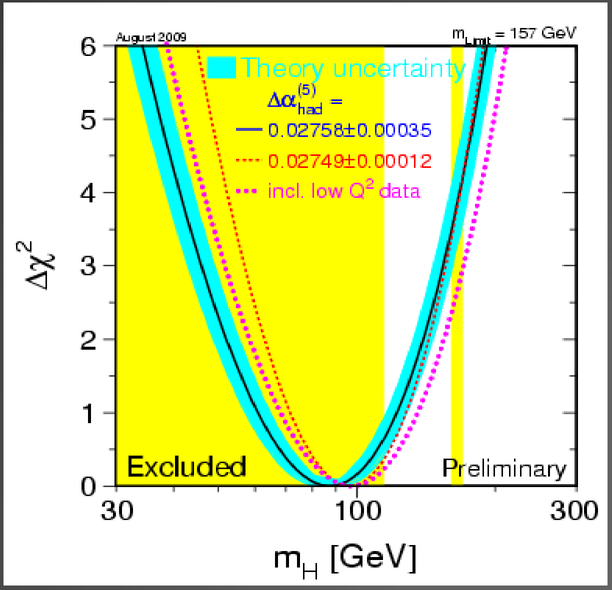
Preferable !

(mh< 149 GeV at 95 % CL)



All combined data

- 445- GeV
- 288-296 GeV (vanishing…)
- 114-145 GeV



Data suggest a light Higgs boson

Mh= 114 - 145 GeV

Possibility

	light H	heavy H	no H	NewParticle
Scenario 1	x			x
Scenario 2		x		x
Scenario 3			x	x
Scenario 4	x			
Scenario 5		x		
Scenario 6			x	

light H : 114GeV < m_h < 150 -200 GeV (Region consistent with LEP)

heavy H: 150-200 GeV < m_h (Region inconsistent with LEP)

Possibility

	light H	heavy H	no H	NewParticle
Scenario 1	x			x
Scenario 2		x		x
Scenario 3			x	x
Scenario 4	x			
Scenario 5		x		
Scenario 6			x	

light H : 114GeV < m_h < 150 -200 GeV (Region consistent with LEP)

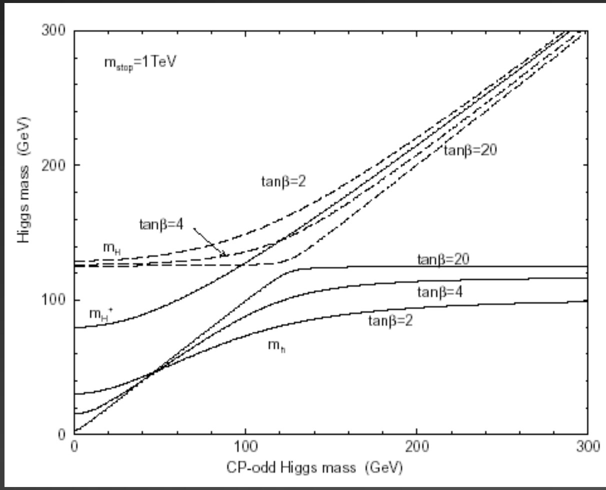
heavy H: 150-200 GeV < m_h (Region inconsistent with LEP)

Scenario1: Light Higgs with new physics

- The best scenario for us
- A lot of discovery
- Many NP scenarios predict a light Higgs

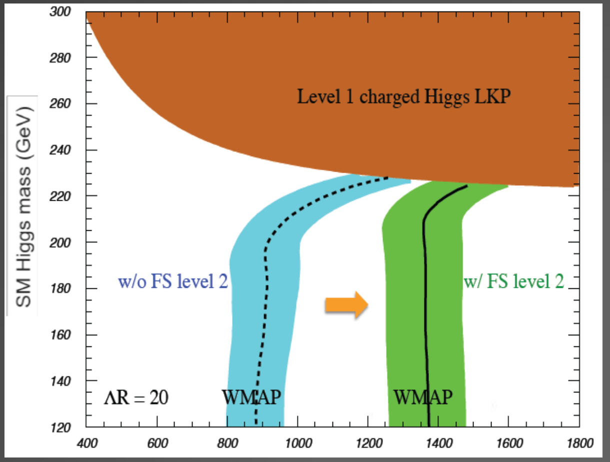
  SUSY, Little Higgs, UED, Gauge-Higgs, ….
  - Masses
  - Spins
  - couplings
  - ……..

MSSM
Predicts
A light Higgs



M. Kakizaki (2011))

UED Model
Also prefers
a light Higgs
under DM data



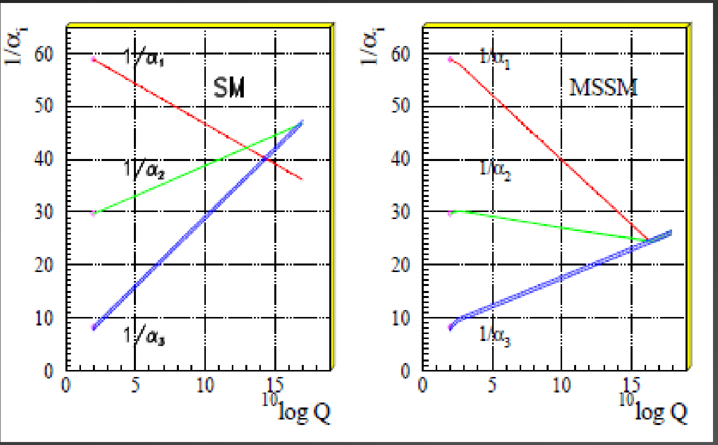
1/R

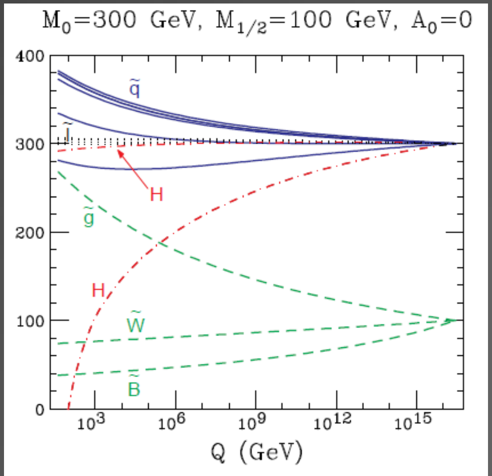
Determination of the new paradigm

New Lagrangian reconstruction

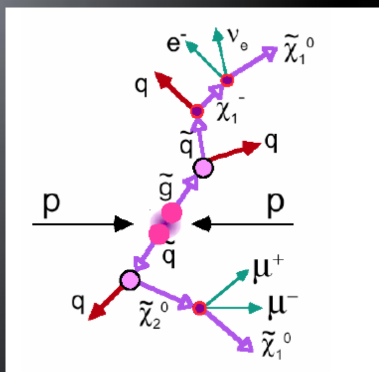
Supersymmetry

- Symmetry: Boson ⇔ Fermion
  - # of particles doubled
- MSSM
  - Minimal content with 2 Higgs doublets
  - R-parity
- Motivation
  - No quadratic divergence
  - Cold Dark Matter
  - Gauge coupling unification (SUSY GUT)
  - EWSB automatic in SUSY GUT
- A benchmark: CMSSM (MSUGRA) (m_0, $m_{1/2}$, A_0, $\tan\beta$, sign μ)





LHC tells us about SUSY



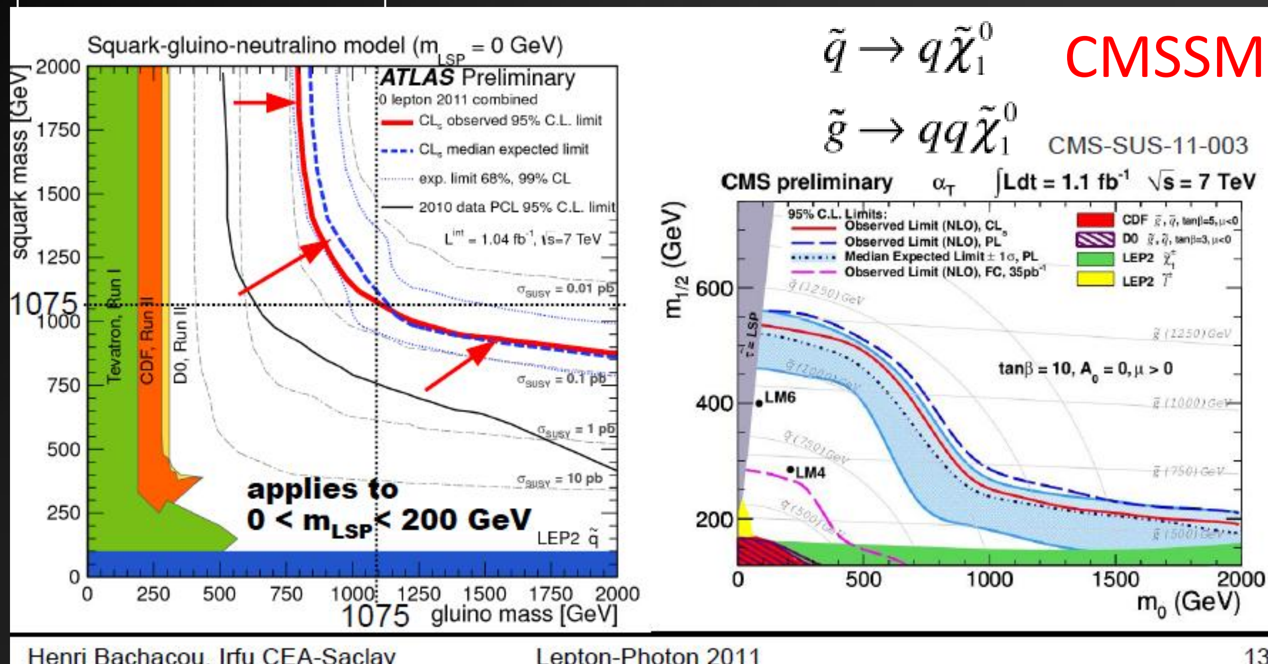
Produce via QCD process:

gluinos, squarks

Signal:

JETs+MET(+leptons)

Jets + Missing ET



No signal found up to now

Exclude up to ~ 1 TeV for m(squark) = m(gluino)

CMSSM (MSUGRA) is starting to be in trouble

It is time to give up on the cMSSM. But what should replace it ?

Here are two options:

1. Find a type of SUSY model in which the mass scale is least constrained by the condition of naturalness.

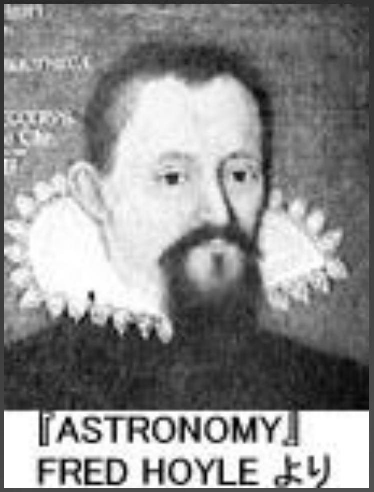
2. Accept that the theory of electroweak symmetry breaking might involve strong interactions.

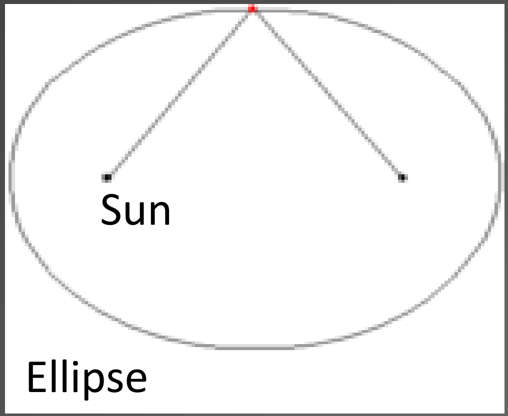
Where do these ideas lead ?

Michael Peskin, Summary Talk at LP11, Aug 2011

Minimality may not be true

- Would cause being wrong (History tells us....)
  - Ex) Kepler's low
  - People for many years thought that the orbit of planets might be circle because circle was perfect
  - Kepler showed with the data that it was not circle, but ellipse!
  - This lead to new era for physics
- Our simplest SUSY benchmark may be discarded, but we can consider many possibilities...





New Physics Paradigm

H. Murayama

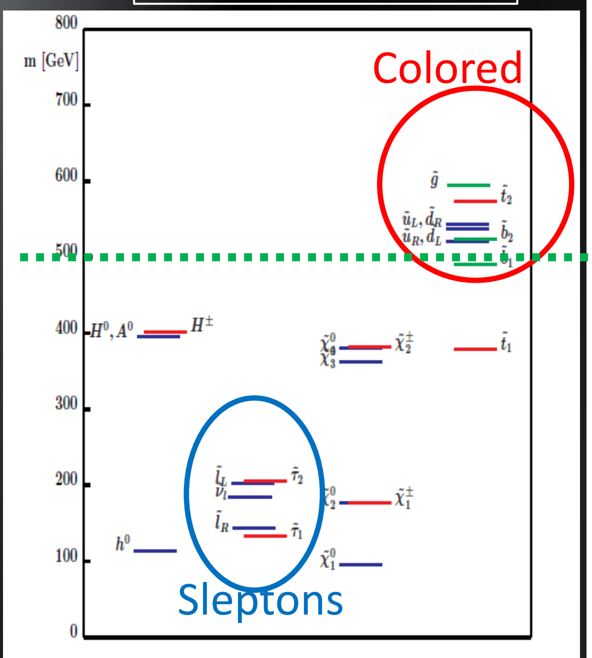
Colored sparticles are constrained from below by LHC

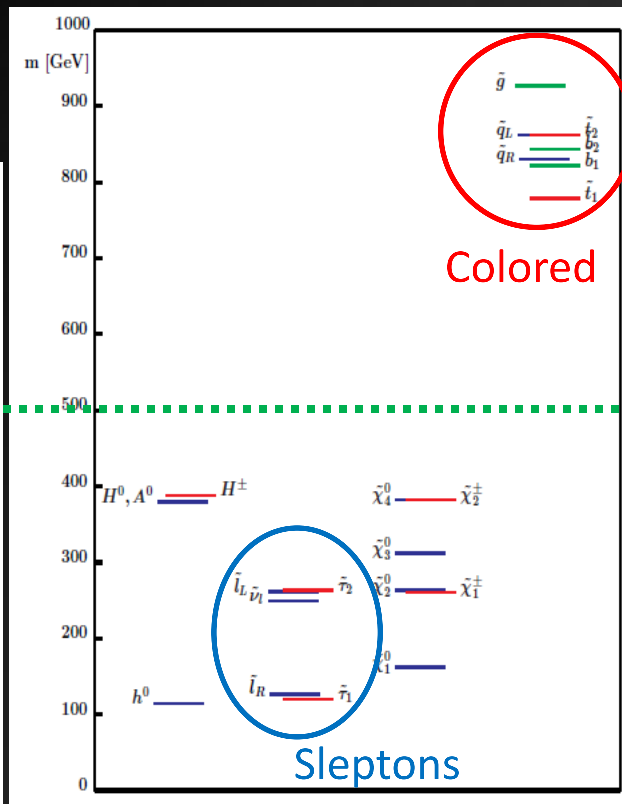
We need mass splitting between the colored sector and the uncolored sector

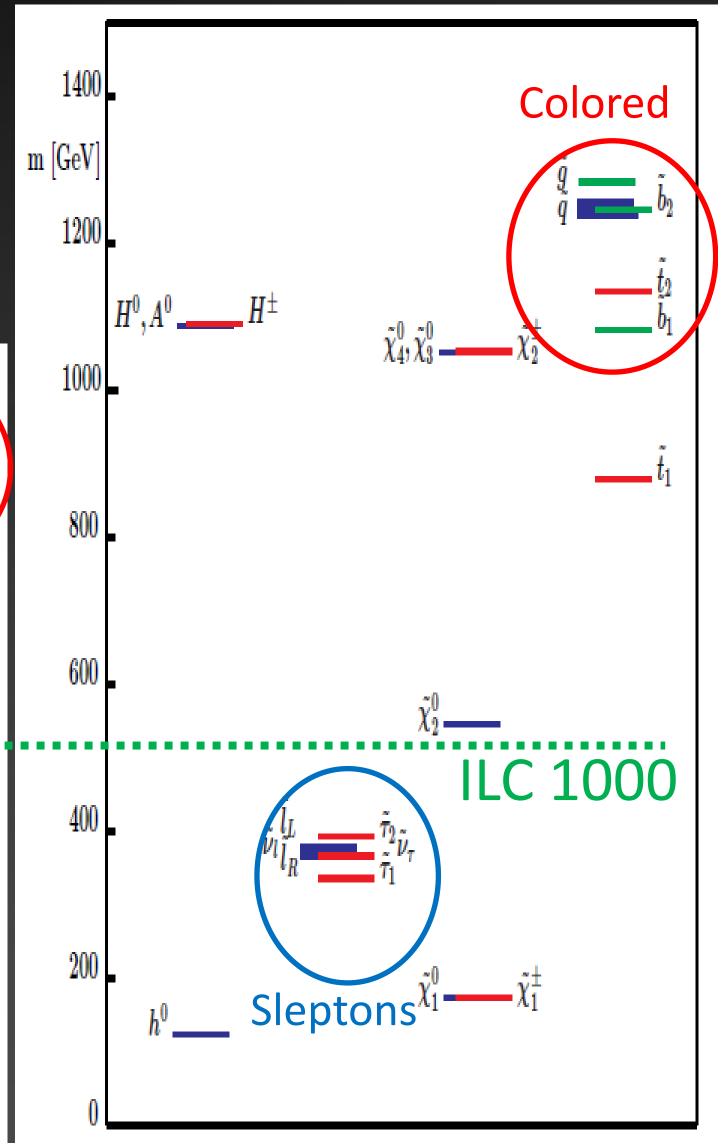
Typical AMSB scenario

Typical GMSB scenario

Typical CMSSM scenario







S. Heinemeyer

SUSY Particles

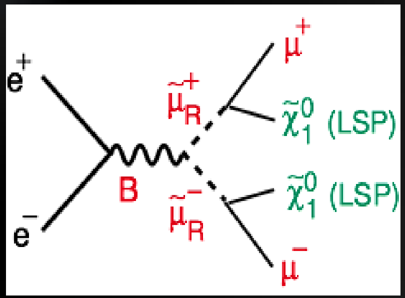
(S)LHC

Via QCD Process: gluinos, squarks

JET+MET(+leptons)

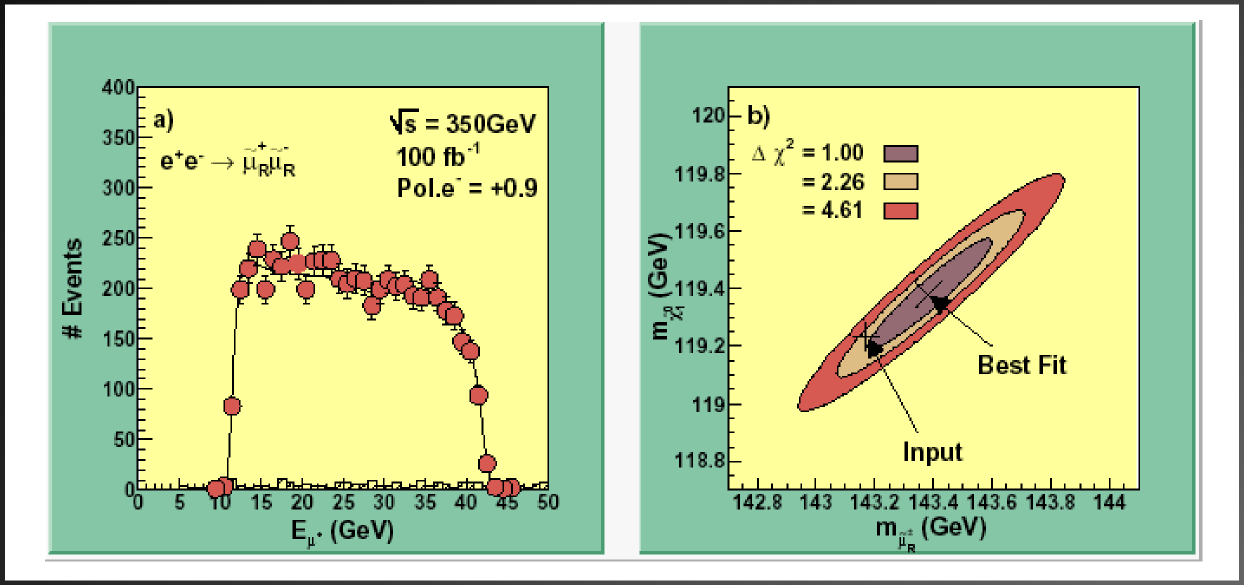
At the ILC

Pair production of sleptons, charginos, …



Mass determination

$\Delta m/m = O(0.1)\%$



Mass reconstraction of slepton and neutralino

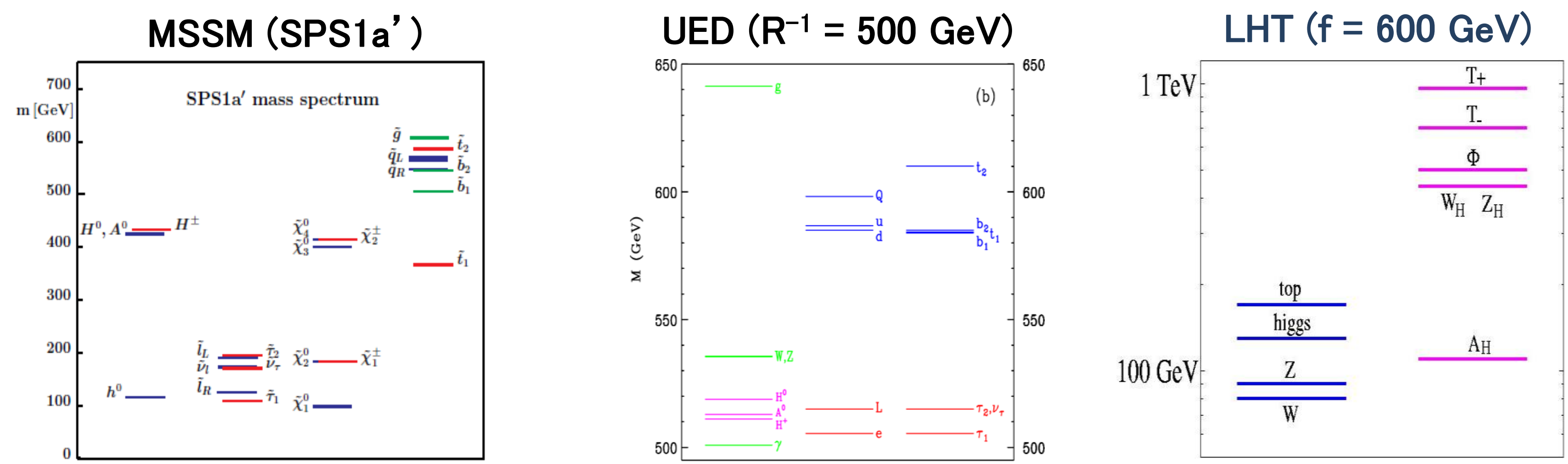
Super spectroscopy if we are lucky.

Mass Spectroscopy at ILC

We can distinguish various new physics models by measuring masses

- Measure 0.1 % accuracy@ILC

New particle mass spectra in various NP models

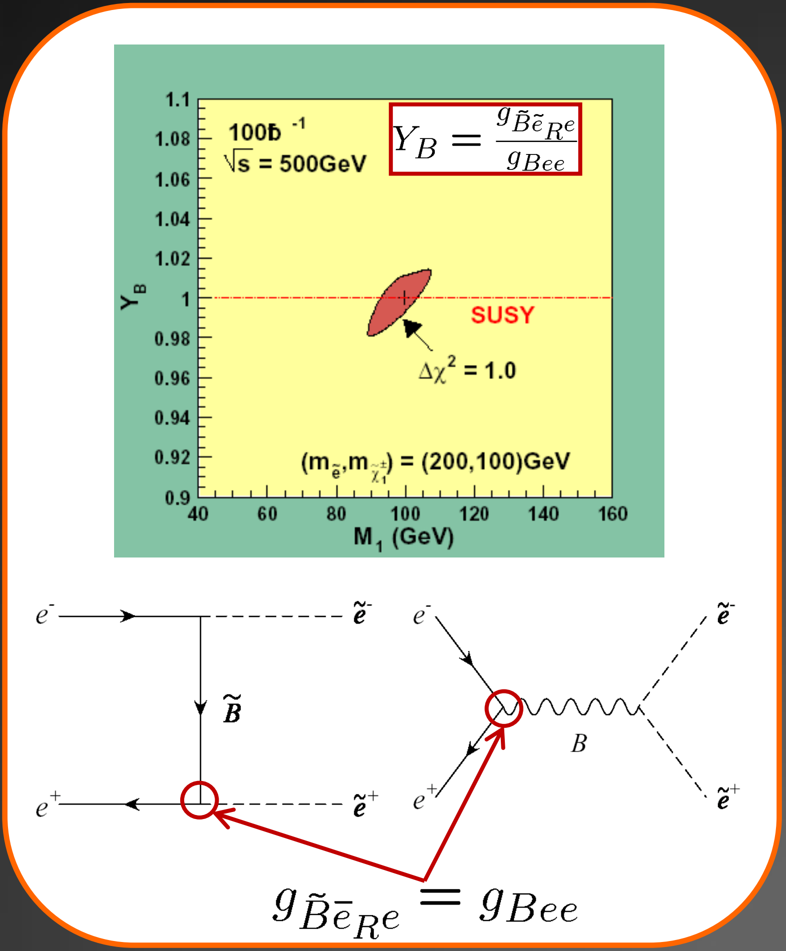


Direct measurement of SUSY

There is the SUSY relation between couplings

SUSY can be directly tested by precisely measuring the coupling constant

Precision measurement at ILC makes it possible to explore such new symmetries



Nojiri, Fujii, Tsukamoto, 1996

Connection with cosmology: Dark Matter

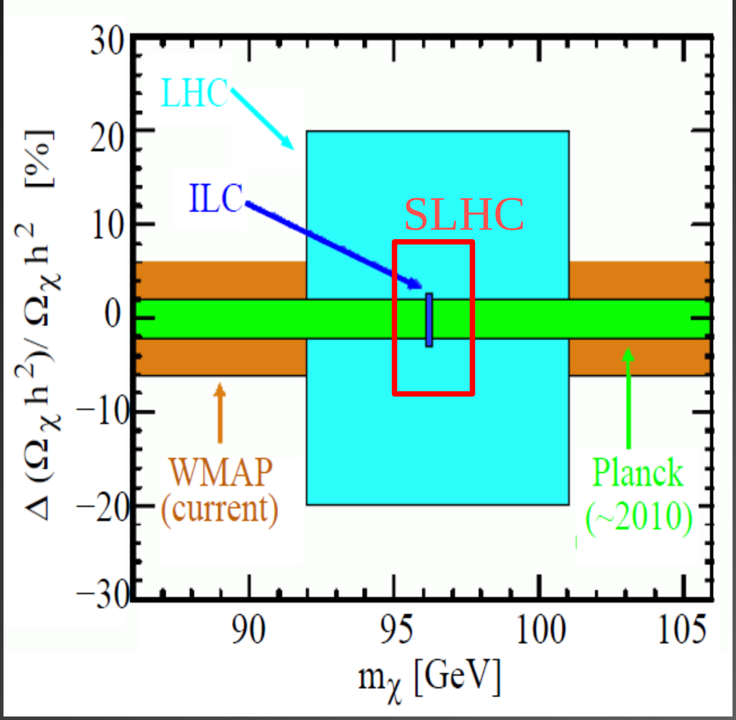
$$\Omega_{\rm DM} h^2 \simeq \frac{0.1\text{pb}\cdot c}{\langle \sigma v \rangle}$$

$$\langle \sigma v \rangle \sim (g^2/4\pi)^2/m^2$$

Nature of dark matter may be determined by precise measurement of masses and couplings for the SUSY particles

Many NP models contain DM candidate (Discrete Symmetry)

- SUSY
- UED
- Littlest Higgs with T parity
- Dark Higgs
- Radiative Seesaw



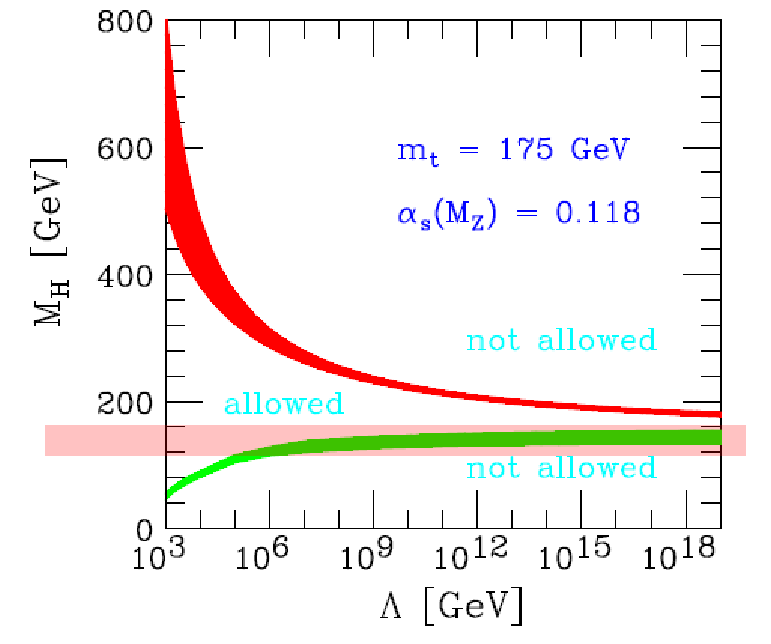
Measurement accuracy of neutralino's mass and thermal abundance in cMSSM scenario (SPS1a')

Scenario 4: Only a light Higgs found

Consistent with data!

High cutoff Λ

- $\Lambda=10^{19}$ GeV Possible for mh=140 GeV
- Perfect SM!
- Nothing is explained….



New Physics with relatively high masses for direct reach

Prediction on Higgs masses

- mh < 130 GeV (MSSM)
- mh < 140 GeV (NMSSM)
- mh < 180 GeV (SUSY with triplet)

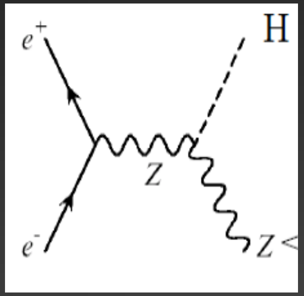
Precise determination of mh can distinguish the models

If only a light Higgs is found

Is it really the SM Higgs? Or a SM-like Higgs?

Precision measure of the property = ILC's task

Spin, mass, Decay width, Branching ratios, ….



ILC Low energy (E_{cm} = 0.24 - 0.36 GeV)

- Energy just above the threshold
- Precise mH determination
- Couplings Y_b, Y_c, Y_τ, g_{VVH} [a few %]
- Top pair threshold

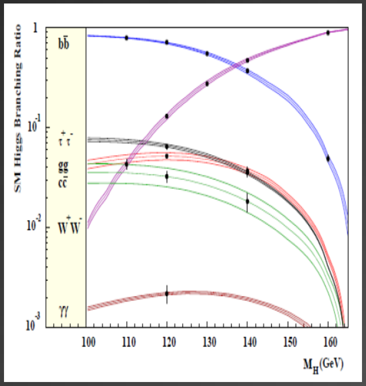
ILC High energy (0.4 < E_{cm} < 1 TeV)

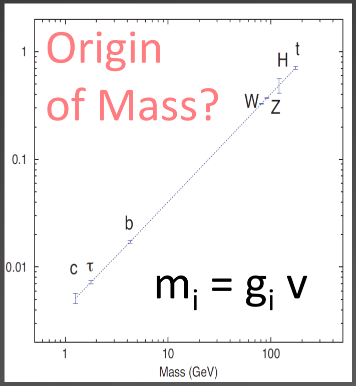
- Top Yukawa coupling O(10)%
- Self coupling O(10)%

First, confirm it's really the SM Higgs or not.

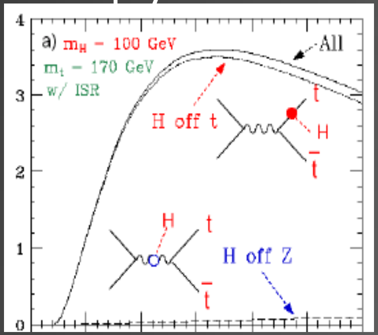
Second, go to higher energies

Branching ratio

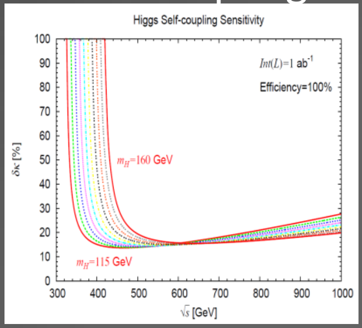




Top yukawa

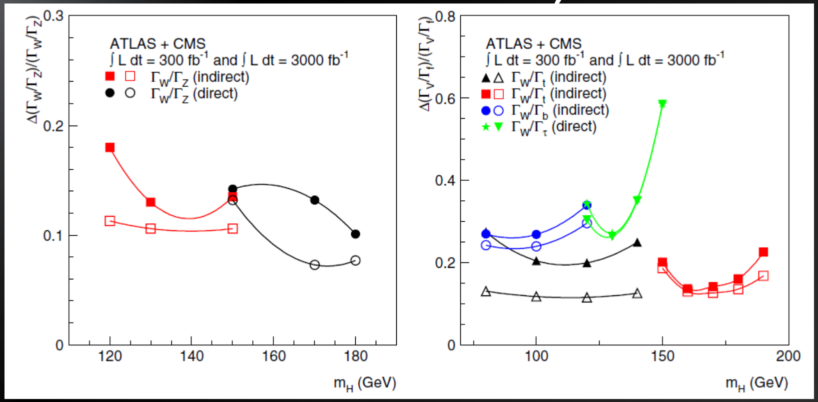


Self coupling

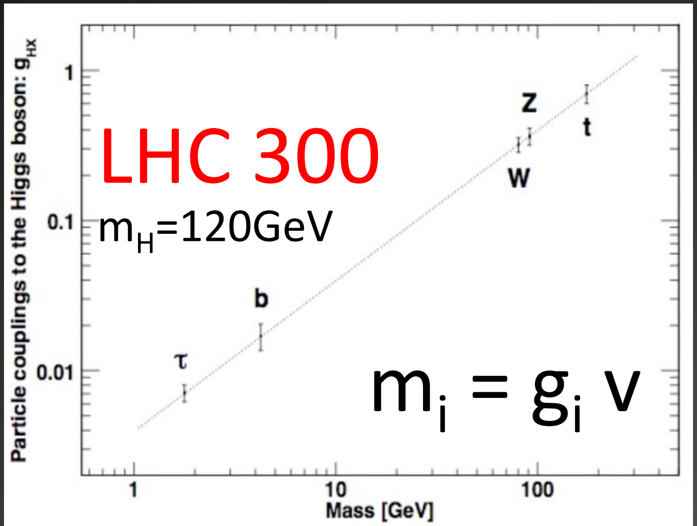


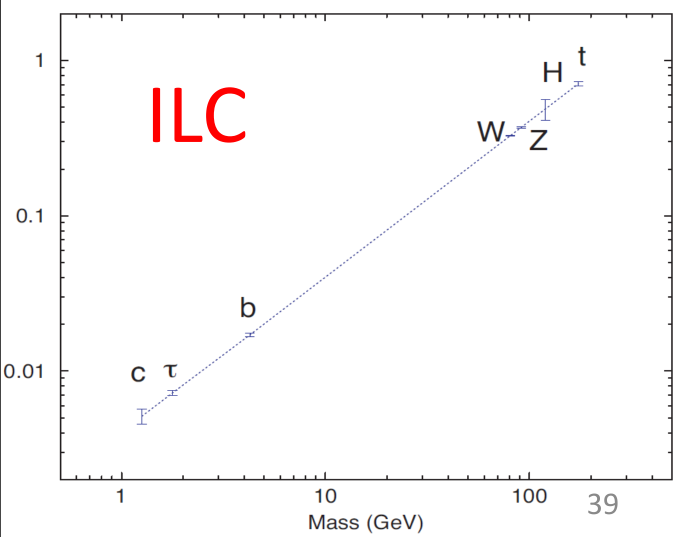
Origin of Mass?

Measurement at LHC, HL-LHC

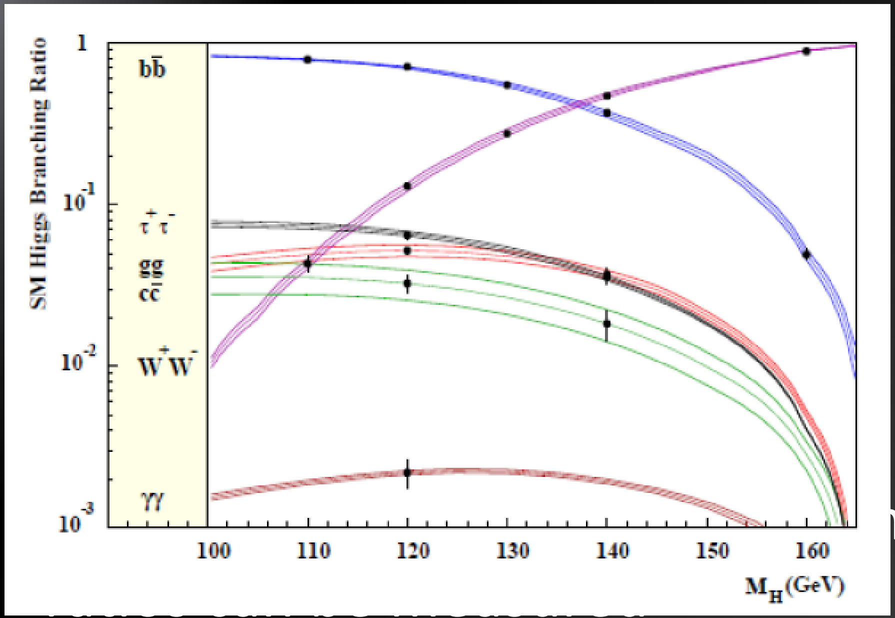


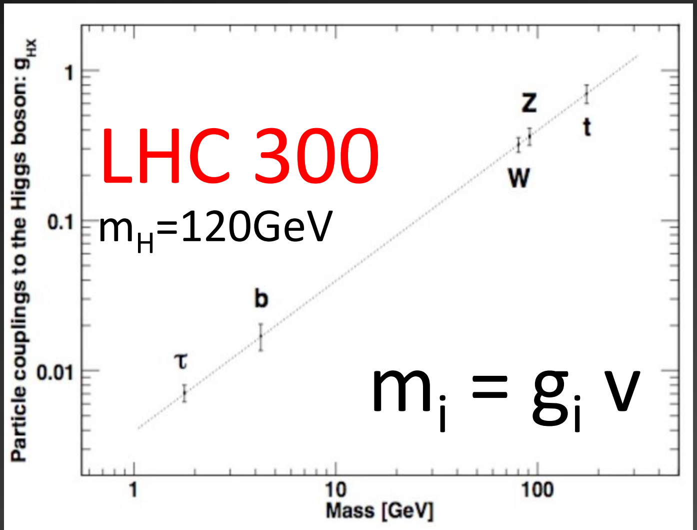
- At LHC, only the ratio of branching ratios can be measured
- At ILC, the absolute values can be measured
- Hbb can be precisely measured (M_H < 140GeV) [about 2%]
  HL-LHC > 30%

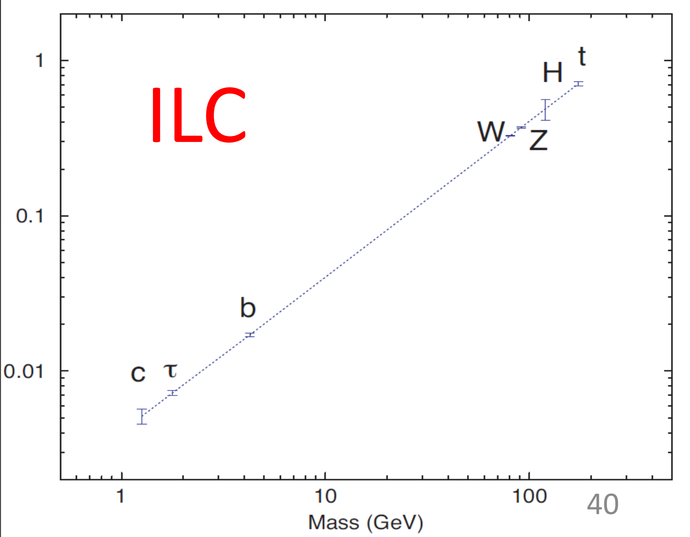




Origin of Mass?







- ng
- At ILC, the absolute values can be measured
- Hbb can be precisely measured (M_H < 140GeV) [about 2%]
  HL-LHC > 30%

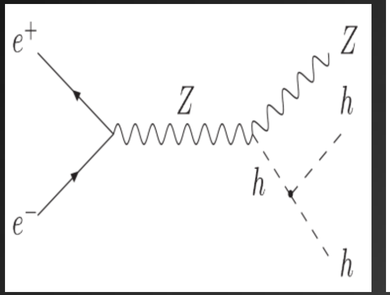
Higgs self-coupling at ILC

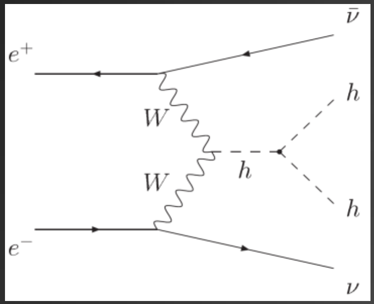
The nature of EWSB $V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$

LHC: Difficult for a light Higgs (< 140 GeV)

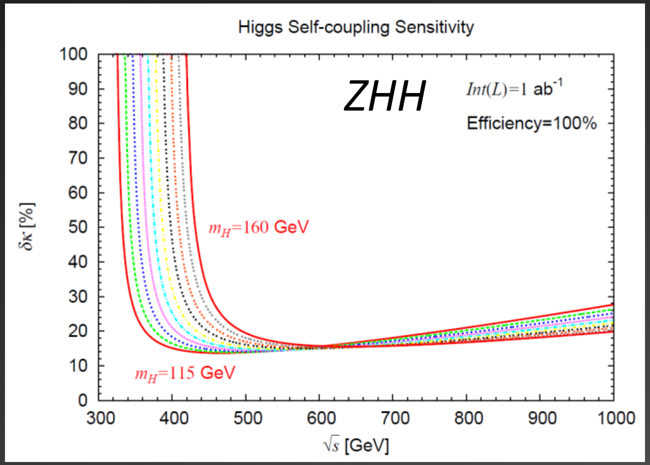
ILC: We can have hope
- Simulation study underway

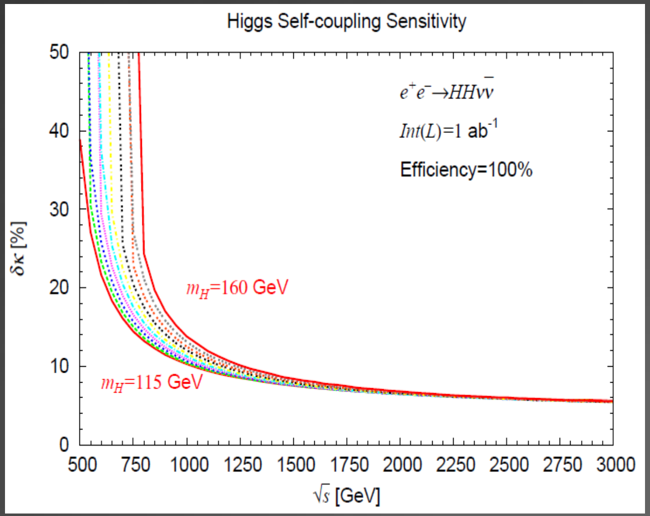
It is important to determine by O(10) %
- Reconstruction of the Higgs potential
- Electroweak Baryogenesis
- Distinguish models via the self-coupling





Higs self-coupling sensitivity





ILC Physics!

D. Harada 2010

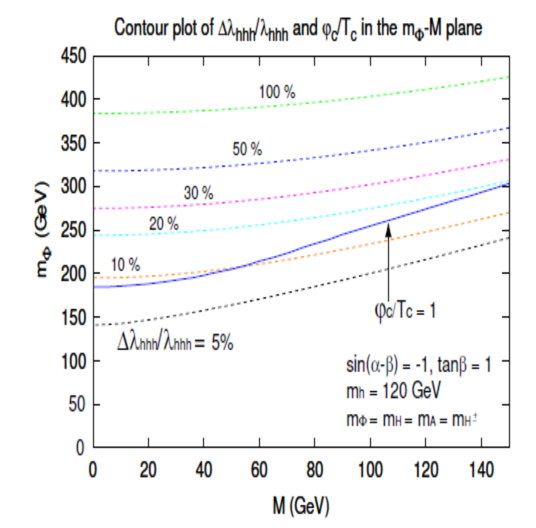
Mass and Self-coupling

- Connection with EW Baryogenesis

Deviation from the SM in the HHH coupling
＝ Strongly first order phase tarnsition

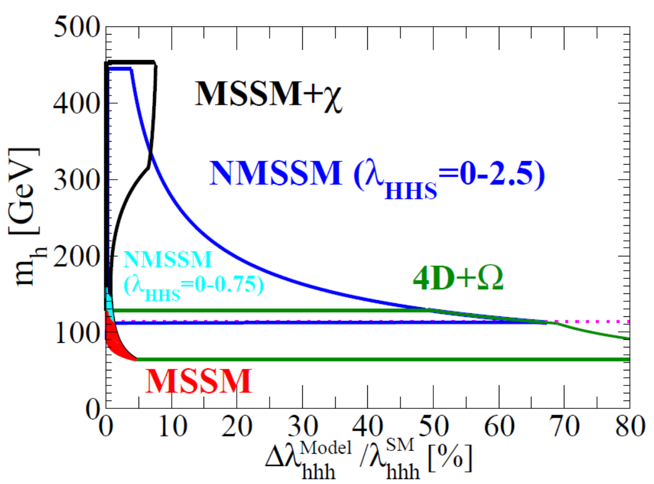
$$V(\phi,T) \Longleftrightarrow V(\phi)$$

EW Baryogenesis is testable via the HHH coupling



SK, Y. Okada, E. Senaha (2006))

- Various SUSY extended Higgs sectors
  - ・MSSM（2 Higgs doublets）
  - ・MSSM ＋singlet （μ problem）
  - ・MSSM ＋triplets
  - ・4DSSM＋charged singlets

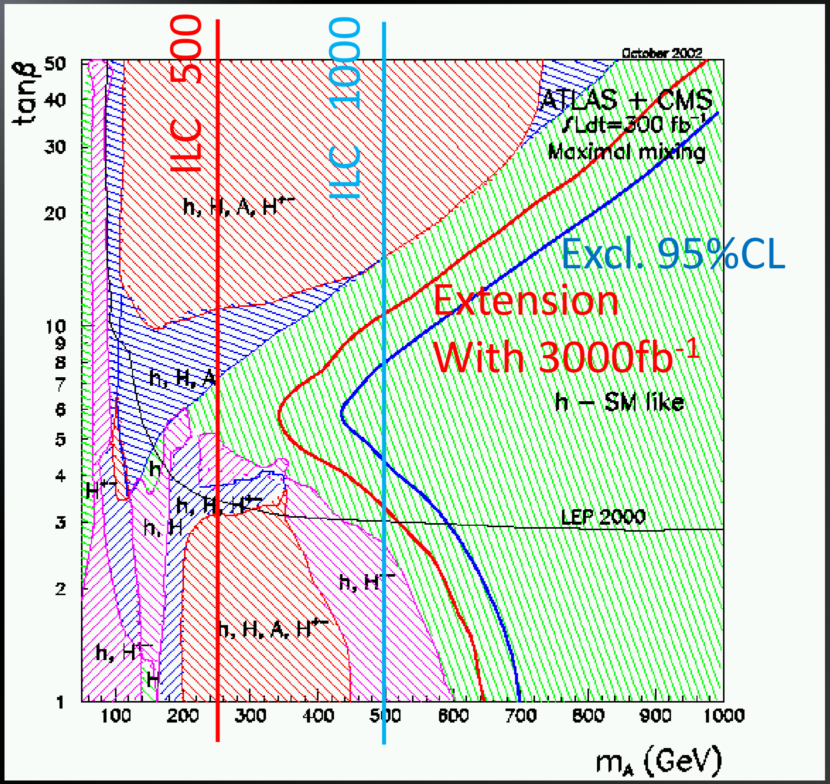


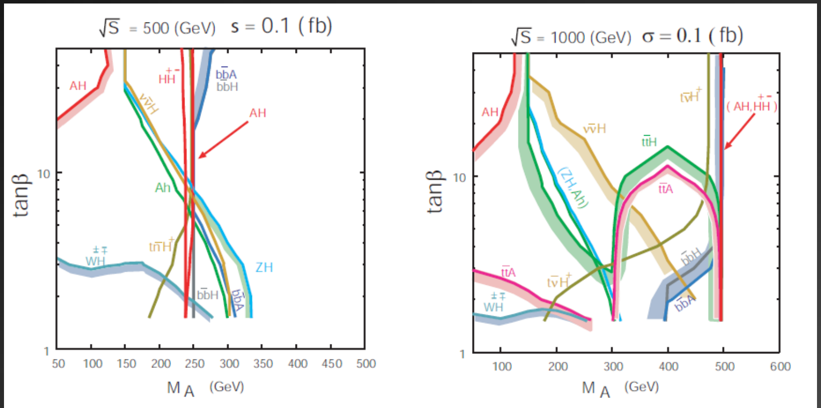
Even if new physics is rather heavy, we may be able to distinguish models by measuring the mass and the HHH coupling

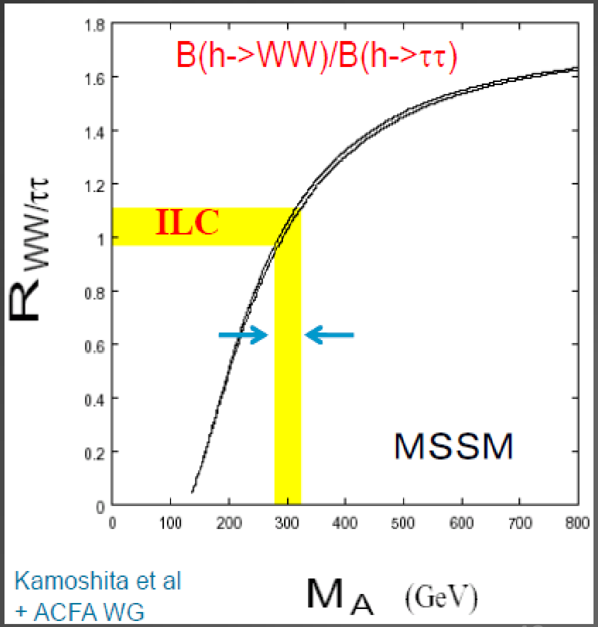
SK, T. Shindou, K. Yagyu, (2011)

HHH determination by O(10）% is requred

SUSY Higgs at LHC vs ILC







Direct search

- LHC, LH-LHC
- ILC (if kinematically reachable)

Indirect test [by measuring the SM-like Higgs]

Possibility

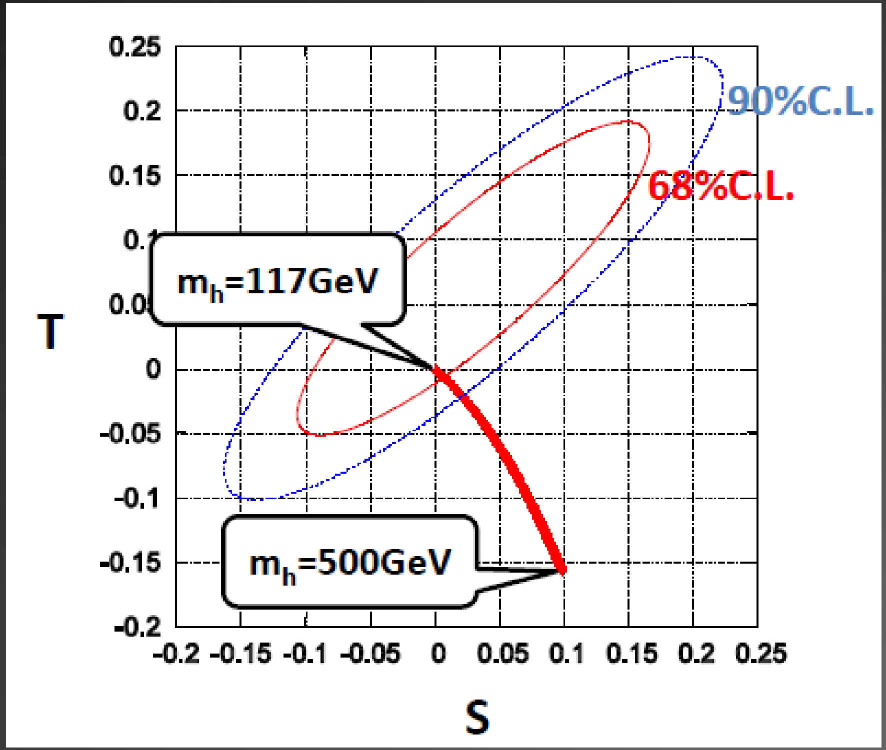
	light H	heavy H	no H	NewParticle
Scenario 1	x			x
Scenario 2		x		x
Scenario 3			x	x
Scenario 4	x			
Scenario 5		x		
Scenario 6			x	

light H : 114GeV < m_h < 150 -200 GeV (Region consistent with LEP)

heavy H: 150-200 GeV < m_h (Region inconsistent with LEP)

Heavy Higgs

- Heavy Higgs dead by LEP precision data?
- Not yet, if there is a new effect which contribute to the EW data
- Ex) Two Higgs doublets
  - h, H, A, H+
  - A Mass difference between A and H+ recovers the T-parameter



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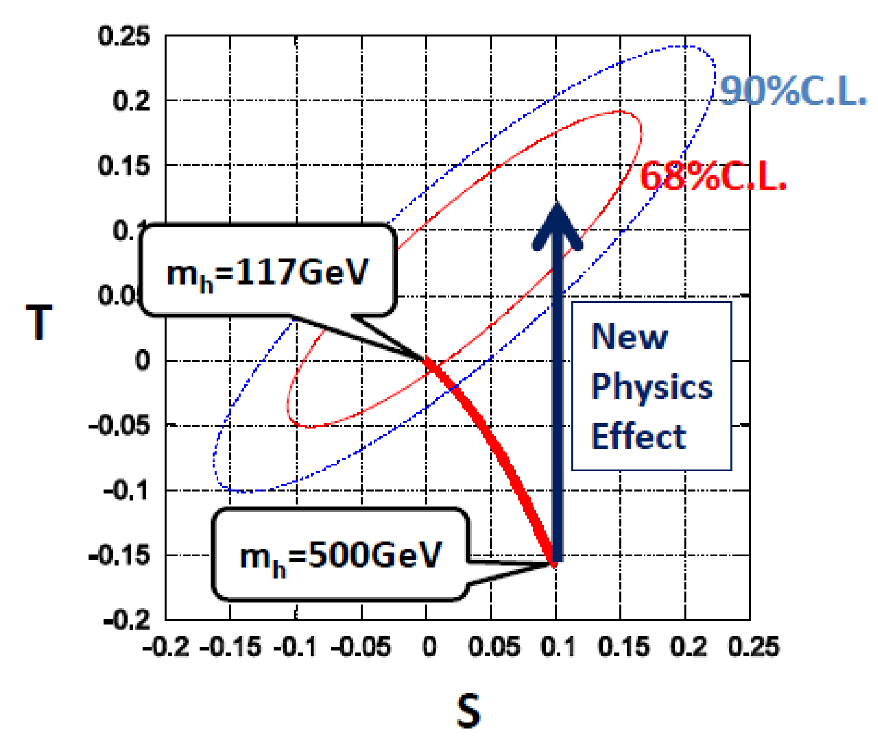

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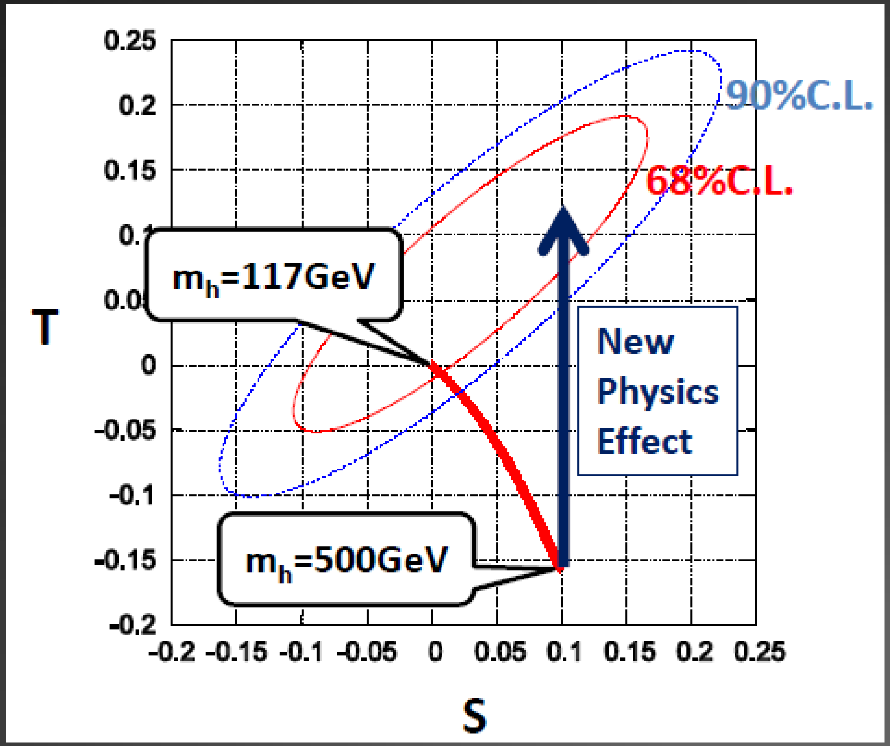
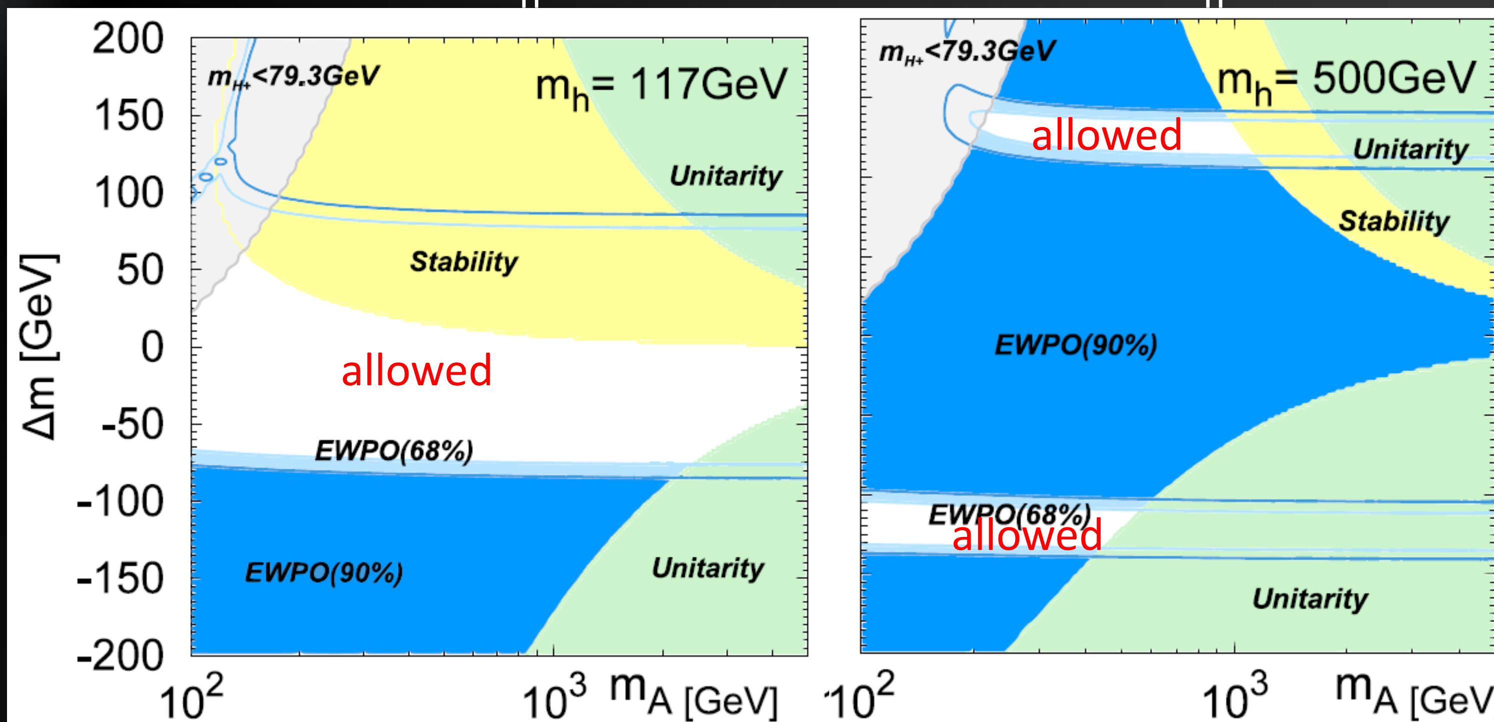


Heavy Higgs

Two Higgs doublet model

m_h = 117 GeV m_h = 500 GeV



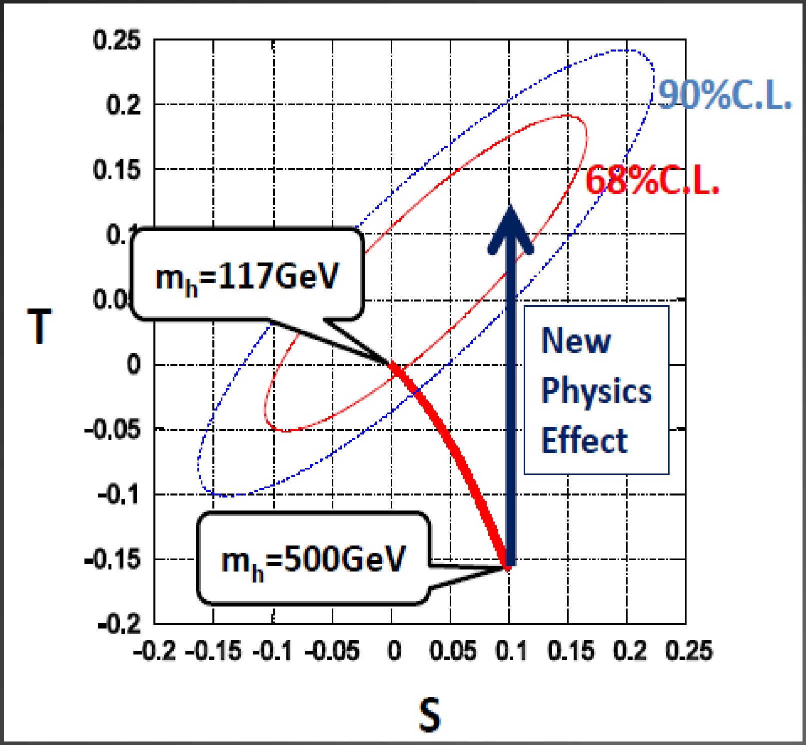
500 GeV SM-like Higgs is still allowed against all constraints including LEP. mA is bounded < 1 TeV, |Δ m| ~ 120 GeV

$\Delta m = m_{H+} - m_A$

S.K., Okada, Taniguchi, Tsumura (2011)

A heavy Higgs

- $M_h > 500$ GeV
- Can be consistent with LEP, Tevatron, and LHC data
- Dynamical with strong coupling at TeV scales
  - Extended Higgs sectors
  - Technicolor
  - Fat Higgs
  - UED
- Discover additional heavy particles at LHC!
- Precision measurement at ILC



SUSY…. but "Fat" Higgs

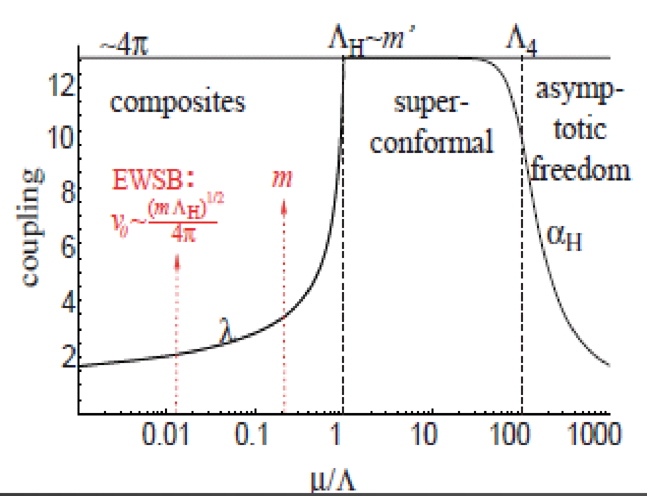
Harnik, Kribs, Larson, Murayama (2004)

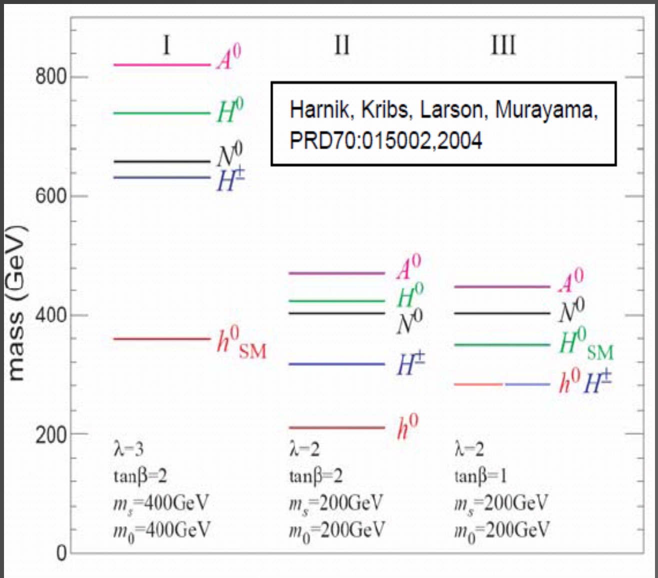
- SUSY with strong coupling
- Higgs field become composite at multi TeV
- NMSSM-like at low energy

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \underline{(\lambda_{HHS}^2 v^2/2) \sin^2 2\beta} + \delta m_{\rm loop}^2$$

- Extra Higgs mass spectrum different from MSSM

$$M_{H^\pm}^2 = M_A^2 - \lambda^2 v^2$$





No Higgs is found (Scenario 3 or 6)

- Higgs is there,
  but invisible....

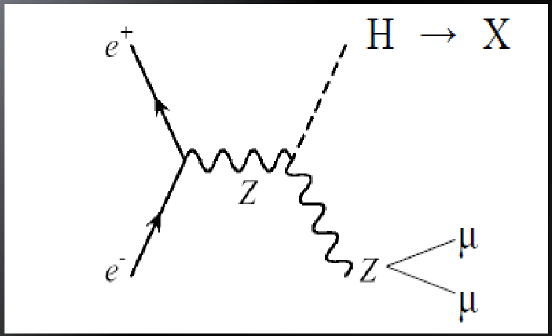
Higgs portal DM
Sneutrino DM
Radion mixing
……

- Really no Higgs produced

  Non-scalar paricle recovers unitarity: Higgsless model?

  Non-perturbative: Dynamical Symmetry breaking?

Invisible decays of Higgs



Dark matter :

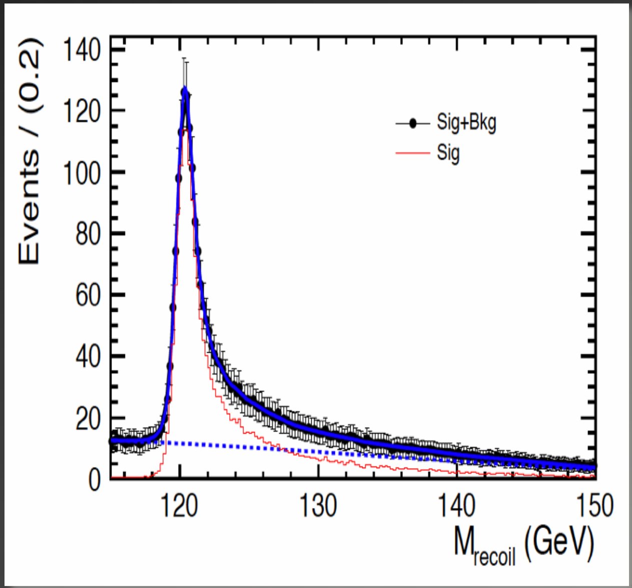
H → DM DM (invisible)

Extra Dimension

H → Radion (invisible)

ILC can measure the mass of the invisible decay of Higgs by using the recoil

Invisible decay



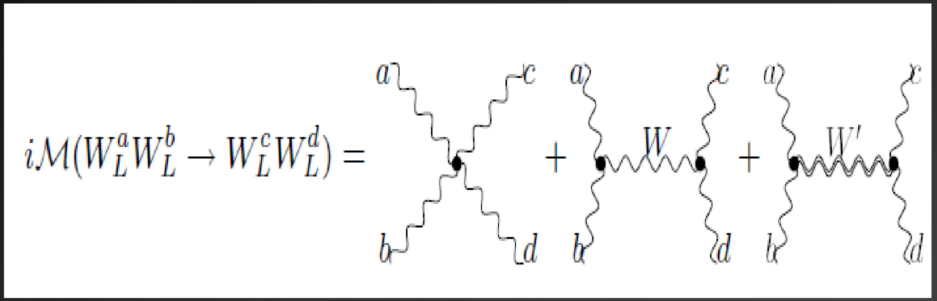
$$
\begin{aligned}
m_X^2 &= p_X^2 \\
&= s - 2\sqrt{s}E_Z + m_Z^2 \\
&= s - 2\sqrt{s}E_{\mu\mu} + m_{\mu\mu}^2
\end{aligned}
$$

Higgsless

Ex) Perturbative Unitarity for

WW → WW

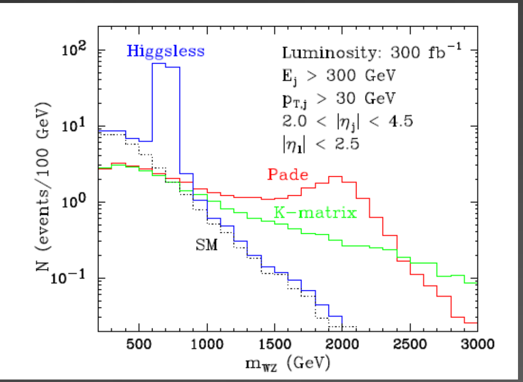
is guaranteed by a vector boson W’, not by Higgs



→ Then, for W’W’→W’W’, W’’ is needed ……

→ W’, W’’, W’’’, …..

→ KK Tower of the vector fields



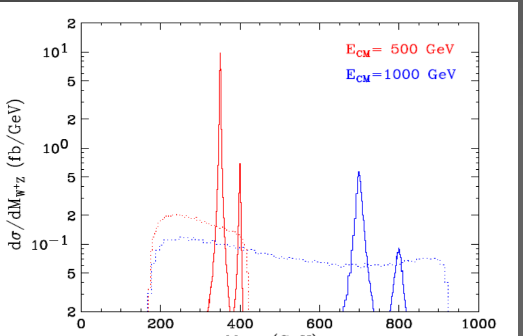
Chivukula, Dicus, He, Csaki, GrojeanMurayama, Pilo, Terning

5 dim Higgsless Model

Model	$WW \to WW$	$WZ \to WZ$	$WW \to ZZ$
SM	Yes	No	Yes
Higgsless	Yes	Yes	No

Find (W’), W’’, ….

Resonance structure in WZ

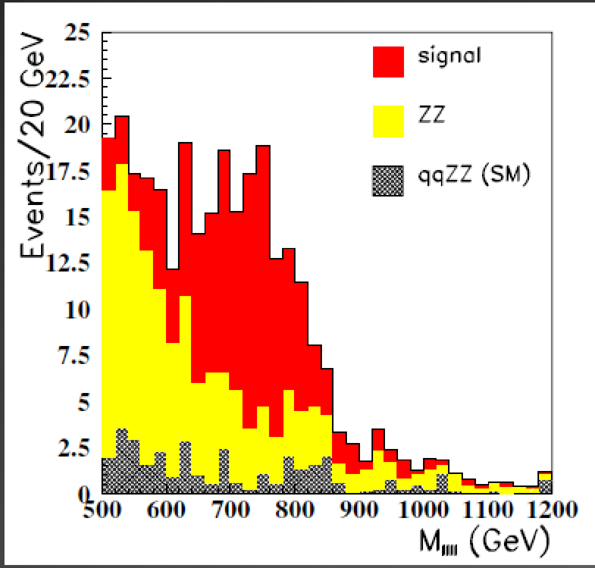


If nothing was found

- Dynamics of EWSB is strongly coupled one at TeV scale
- Otherwise, a new particle recover unitarity (like the Higgsless model)

Anything must be at TeV scales
Absolutely new!

Gianotti, et al., EPJC39, 293 (2005)



But scenario w/o discovery at LHC

- HL-LHC, HE-LHC may survey

WW scattering reveals the nature of EWSB

- ILC still can do something by precision like giga Z, mega W

Conclusions

LHC is opening the door
most possibly anything will
come out soon
Higgs and/or New particles

It must be!

Then ILC can determine new paradigm
for physics beyond the standard model

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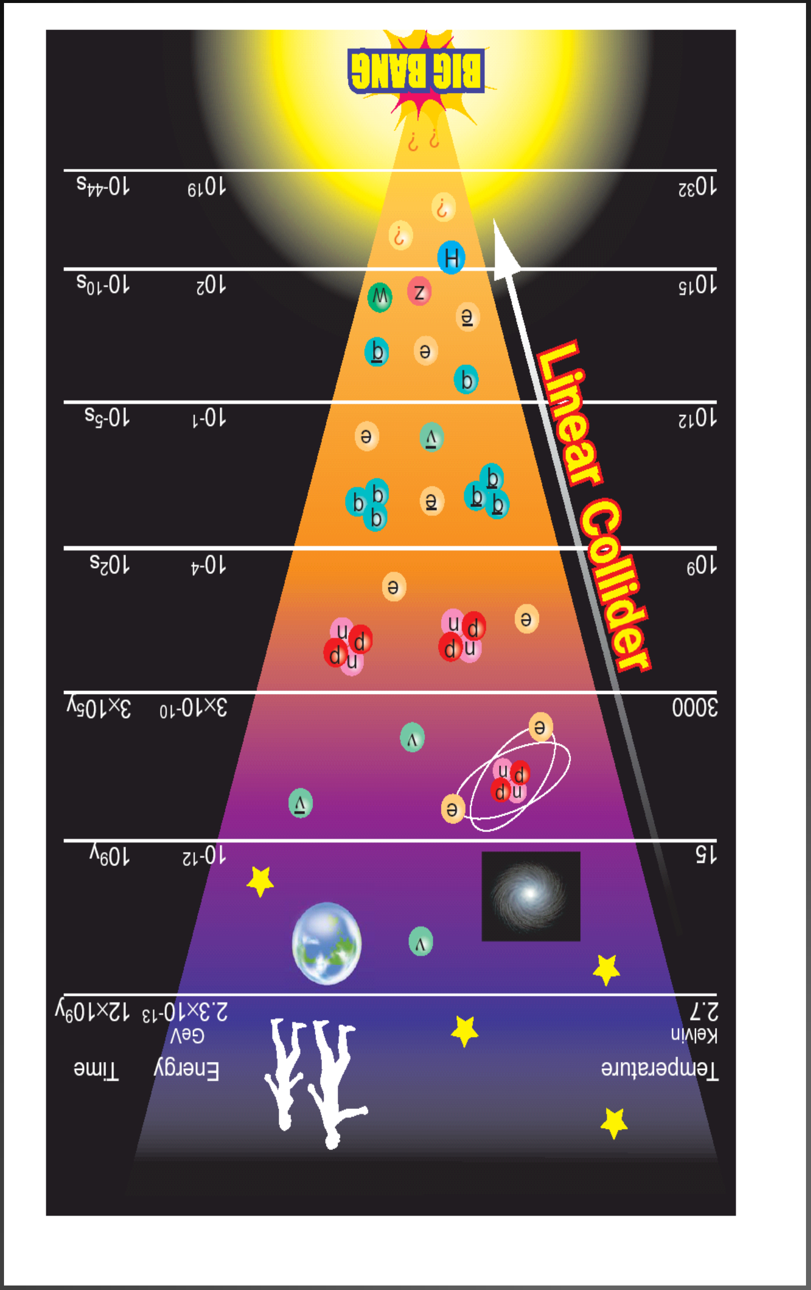
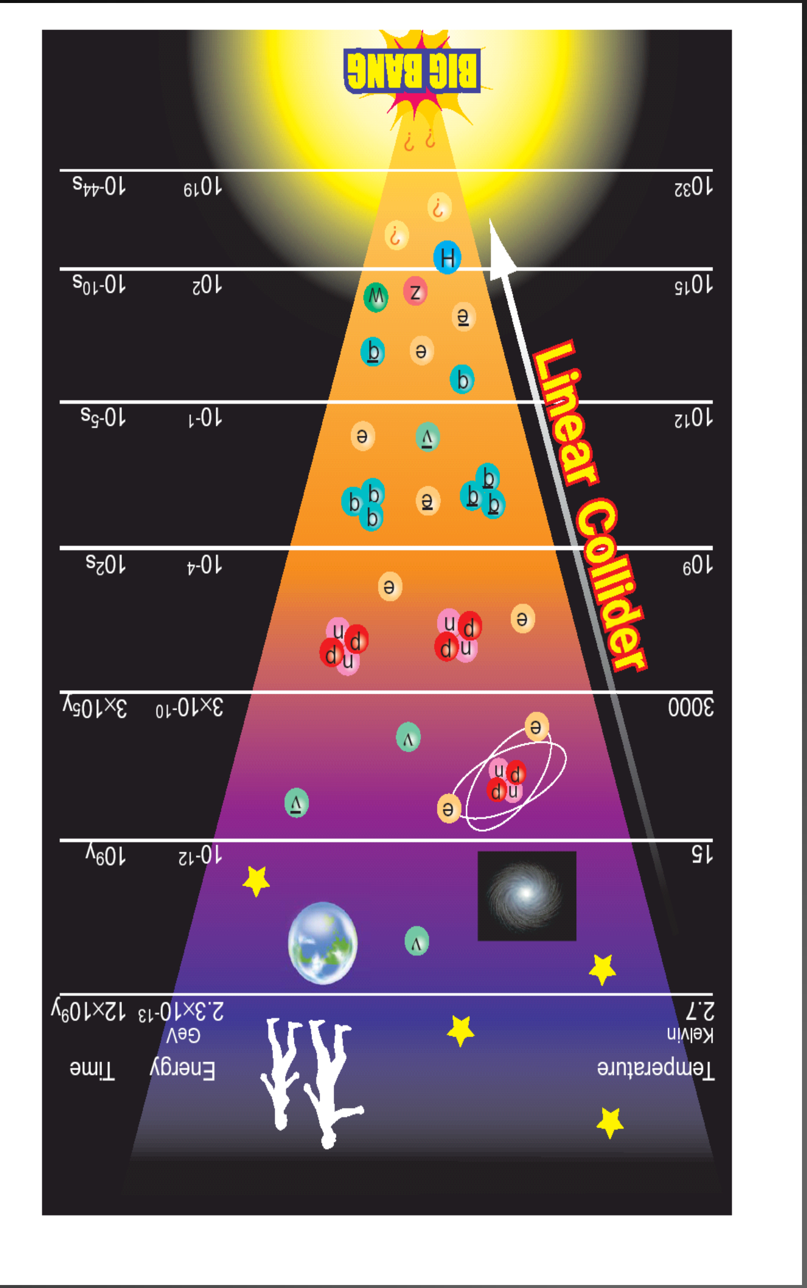
We need ILC



BIG BANG
Linear Collider
Temperature
Kelvin
Energy
GeV
Time
10^32 10^19 10^-44 s
10^15 10^2 10^-10 s
10^12 10^-1 10^-5 s
10^9 10^-4 10^2 s
3000 3x10^-10 3x10^5 y
15 10^-12 10^9 y
2.7 2.3x10^-13 12x10^9 y

We need ILC

Be prepared



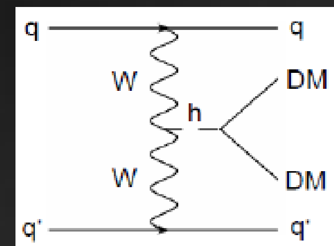
Higgs portal DM

DM interacts with SM via Higgs

$$L = c_{DM}\, DM^2 |\Phi|^2$$

Appear if other new physics particles are rather heavy. Z2 parity to stabilize DM.

LHC

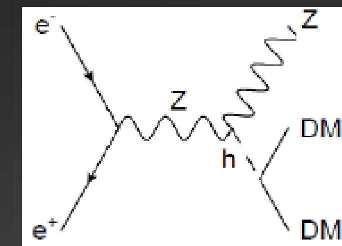


$30fb^{-1}$, E=14TeV

Br > 0.50 (95%CL)

Conf.@U. of Tokyo, 2009

ILC



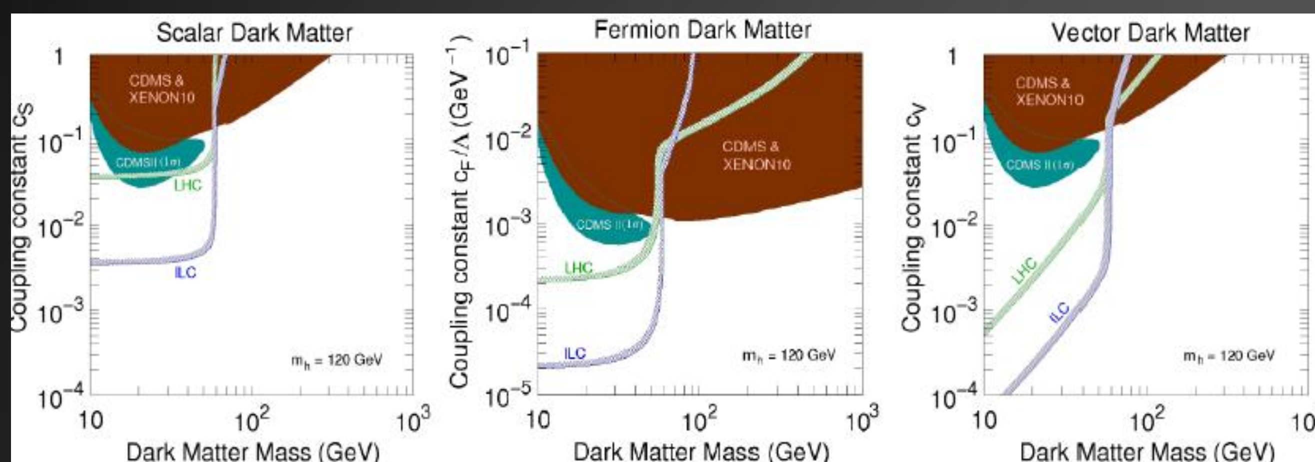
$500fb^{-1}$, E = 350 GeV

Br > 0.0095 (95%CL)

M. Schumacher, 2003

Invisible Decay

For $m_{DM} < m_H/2$

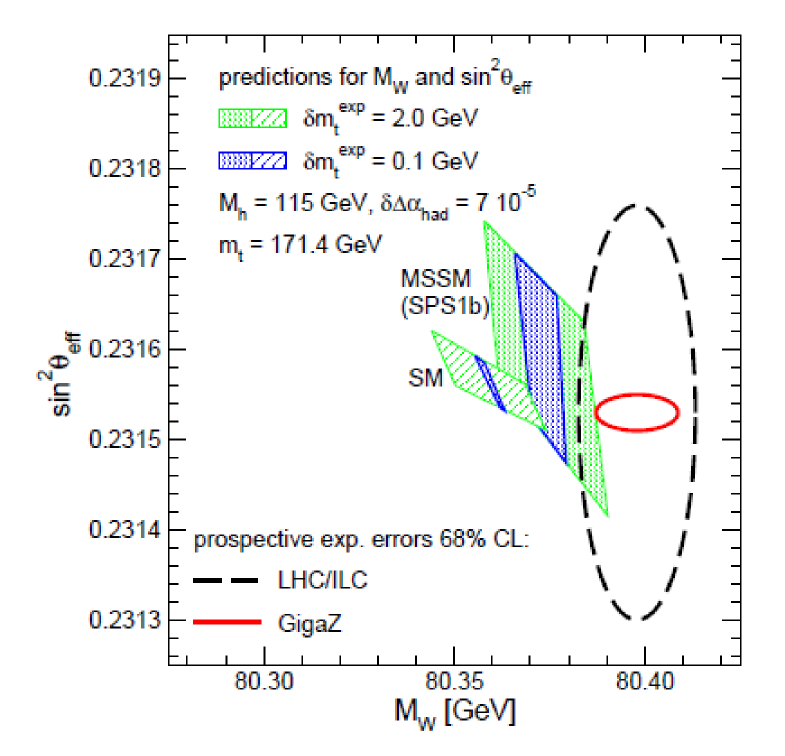


SK, S. Matsumoto, N. Okada, T. Nabeshima, 2010

Precision measurements

- Radiative correction
- Precise determination of the EW parameter
- Can study new physics

- Giga Z/Mega W?
- Repeat LEP experiment with large luminosity
- It can strongly constrain NP models

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