Higgs/EWSB Summary

LCWS 2012

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University of TOYAMA

LCWS12, Univ. of Texas, Arlington, October 26, 2012

23 speakers

Higgs/EWSB Sesssion and Joint Sessions:

F. Bezrukov, C. Calancha Paredes, S. Kawada
T. Lastovicka, H. Ono, T. Price, P. Roloff
M. Thomson, J. Tian, J. Yu, D. Zerwas
J. Hewett, A. Juste Rosas, T. Kakizaki, Y. Kikuta
J. List, T. Nabeshima, M. Peskin, J. Reuter,
T. Shindou, K. Tsumura, K. Yagyu, T. Yamada

11 Experimentalists

12 Theorists

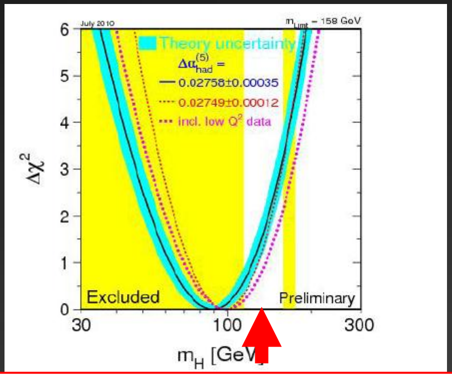
Thank you for the contribution!

I am sorry to skip some of them because of the time

Current Status

July 2012: 5σ discovery of “a new particle” at 126 GeV

126 GeV Higgs is consistent with the SM prediction at the quantum level with LEP/SLC precision data

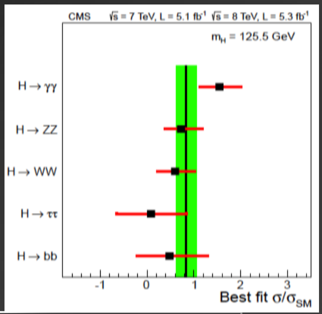


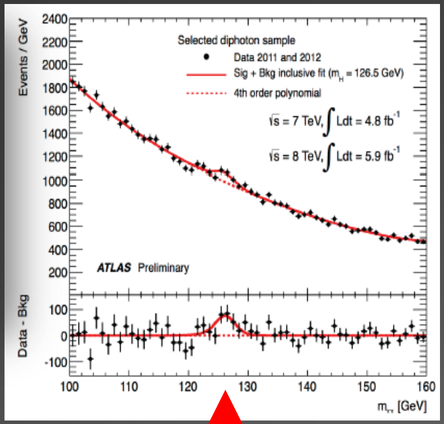
Allowed region by LEP/SLC

Existence of *h* couplings to

γγ, gg, ZZ, WW, ττ, bb, tt

is being confirmed at LHC





New discovery

The particle seems consistent with the SM Higgs

No other new particle has been found yet

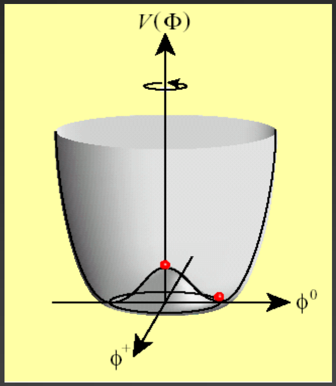
It is a great victory of the standard model!

Yes. But this is not the end of the story

Why new physics BSM?

Problem in the SM

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

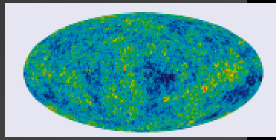


Higgs Sector:

- Minimal/Non-minimal? (No principle)
- Quadratic divergences (Hierarchy Problem)
- Why $\mu^2 < 0$? (EWSB)
- What is λ coupling? (Dynamics behind)

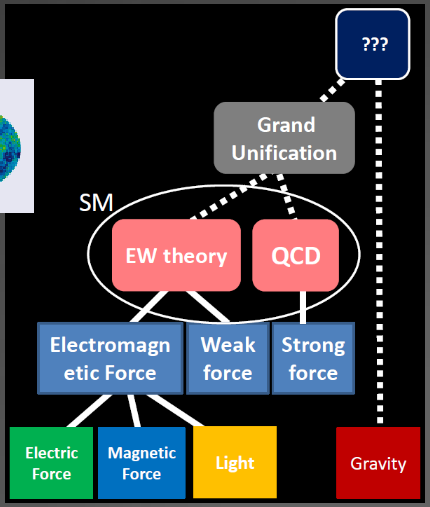
BSM Phenomena (What SM cannot explain):

Dark Matter, Neutrino Mass, Baryogenesis, Inflation …



Unification (we are still on the way):

Charge discretization, Coupling Unification, Flavor, Gravity , ….



SM must be replaced by new physics

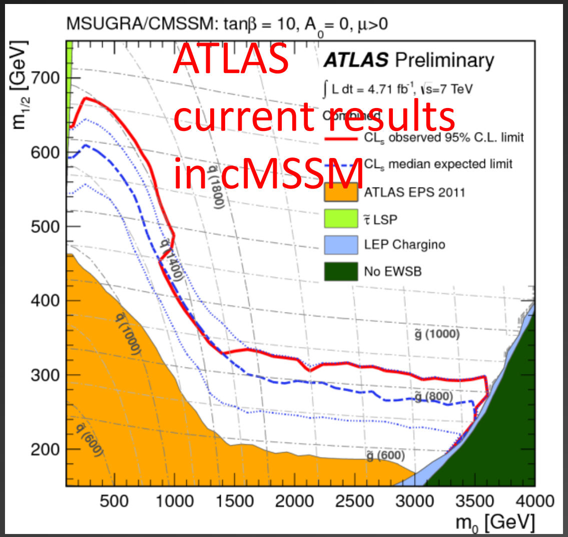
At which scale?

Terascale

This is expected to solve Hierarchy Problem
WIMP Hypothesis predicts DM candidate at TeV scale

LHC has not yet found new physics at TeV scale

Mass of Gluino, Squarks > O(1) TeV (cMSSM)



Where is the new physics?
It would possibly be at TeV scales, but the mass of new particles strongly depends on new physics

There are many new physics models

Murayama

Let us wait for new result from 14 TeV Run at LHC

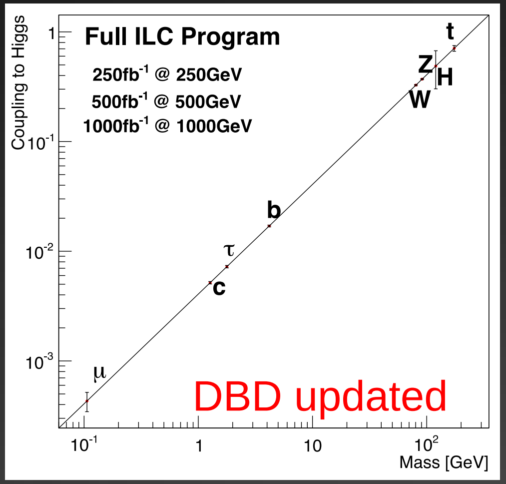
Surely we need luck!

Solid target is the Higgs sector

Notice that SM-like ≠ SM !

- Does it play a role of the origin of mass?
- Minimal/Non-Minimal?
  - Minimal Higgs sector Just a guess [Peskin]
  - Various possibility for (extended) Higgs sectors
    Extra singlets, doublets, triplets…
  - Elementary? or Composite?

M_h=125GeV ⇒ We can calculate SM predictions exactly.
Deviation ⇒ Non-standard model physics



Mass-Coupling Relation

Precision measurement of Higgs couplings

Coupling with weak bosons: *hZZ, hWW*
Yukawa couplings : *hbb, htt, hττ, hcc, hμμ*

Sensitive to mixing with extra Higgses
Type of extended Higgs sector can be separated by looking at the pattern of deviations

Finger printing of the model

Model	μ	τ	b	c	t	g_V
Singlet mixing	↓	↓	↓	↓	↓	↓
2HDM-I	↓	↓	↓	↓	↓	↓
2HDM-II (SUSY)	↑	↑	↑	↓	↓	↓
2HDM-X (Lepton-specific)	↑	↑	↓	↓	↓	↓
2HDM-Y (Flipped)	↓	↓	↑	↓	↓	↓

[K. Fujii]

Loop induced couplings: *hγγ, hgg, (hhh)*

Sensitive to loop effect of new particels

Mass scale and dynamics of new physics particles may be better extracted

Deviation of $O(v^2/M^2)$
by the decoupling theorem

Higgs as a probe of new physics

To this end, how accurately we have to measure the couplings?

Decoupling Theorem

When new physics scale *M* is large, low energy theory is the SM
Up to m_h^2/M^2 [O(1-10)% for *M*=TeV]

Supersymmetry:	$g(\tau)/SM = 1 + 10\% \left(\frac{400\ \text{GeV}}{m_A}\right)^2$
	$g(b)/SM = g(\tau)/SM + (1-3)\%$
Little Higgs:	$g(g)/SM = 1 + (5-9)\%$
	$g(\gamma)/SM = 1 + (5-6)\%$
Composite Higgs:	$g(f)/SM = 1 + (3-9)\% \cdot \left(\frac{1\ \text{TeV}}{f}\right)^2$

1. New physics can potentially tweak any Higgs coupling independently of the others.
2. If we cannot reach 5% accuracy, we likely are not in the game.
3. If we are able to reach 1% accuracy, we can be sensitive to new particles at 3 TeV or higher.

The ILC gives new capabilities both for qualitative and quantitative improvement in our understanding of the Higgs boson.

[M.Peskin]

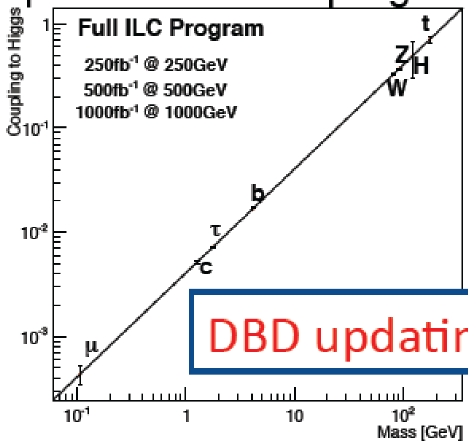
Higgs BRs in DBD physics chapter [Ono]

ILC Higgs physics performances are summarized in DBD physics chapter

Higgs BRs summary (E_{cm}=250 GeV, L=250fb^{-1}, (e^-, e^+)=(0.8,0.3))

Mode	BR	σBR	ΔσBR/σBR	ΔBR/BR
h→bb	65.7%	232.8	1.0%	2.7%
h→cc	3.6%	12.7	6.9%	7.3%
h→gg	5.5%	19.5	8.5%	8.9%
h→WW*	15.0%	53.1	8.2%	8.6%
h→ττ	8.0%	28.2	4-6%	5-7%
h→ZZ	1.7%	6.1	28(?)%	28(?)%
h→γγ	0.29%	1.02	23-30%	23-30%

Updated mass coupling relation



DBD updating

E_{cm}=250, 500 GeV study is still progressing with full simulation

- h→WW/ZZ, invisible and bb, cc, gg @500 GeV (H. Ono working in progress)
- h→ττ (S. Kawada Oct. 24 Higgs&EWSB)
- h→γγ, μμ (C. Calancha)

Ref. DBD physics chapter
http://lcsim.org/papers/DBDPhysics.pdf

These results used M_h=120 GeV → Update with 125 GeV

Higgs branching study for ILC 1TeV has also underway [Ono et al.]

h→bb, cc, gg (two jets)
h→WW* (four jets via hadronic decay)
h→μμ (dilepton)

Total Width and Coupling Extraction

One of the major advantages of the LC

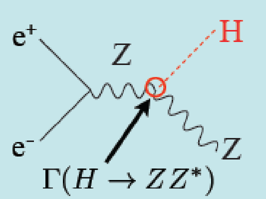
To extract couplings from BRs, we need the total width:

$$g^2_{HAA} \propto \Gamma(H \to AA) = \Gamma_H \cdot BR(H \to AA)$$

To determine the total width, we need at least one partial width and corresponding BR:

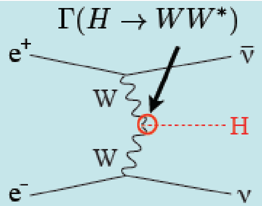
$$\Gamma_H = \Gamma(H \to AA)/BR(H \to AA)$$

In principle, we can use the A=Z, or W for which we can measure both the BRs and the couplings:



$BR(H \to ZZ^*)$

BR=O(1%): precision limited by low stat. for H->ZZ* events



$BR(H \to WW^*)$

More advantageous but not easy at low E

$250\,\mathrm{fb}^{-1}$@$250\,\mathrm{GeV}$

$\Delta\Gamma_H/\Gamma_H \simeq 10\%$

Jenny List's talk

9

[Fujii]

[J. List]

Measurement accuracy of Γ_H^{tot}

$$\frac{\Delta\sigma(\text{WW-fusion})}{\sigma(\text{WW-fusion})} \;\&\; \frac{\Delta BR(H \to WW)}{BR(H \to WW)}^{**} \longrightarrow \frac{\Delta\Gamma_H^{tot}}{\Gamma_H^{tot}}$$

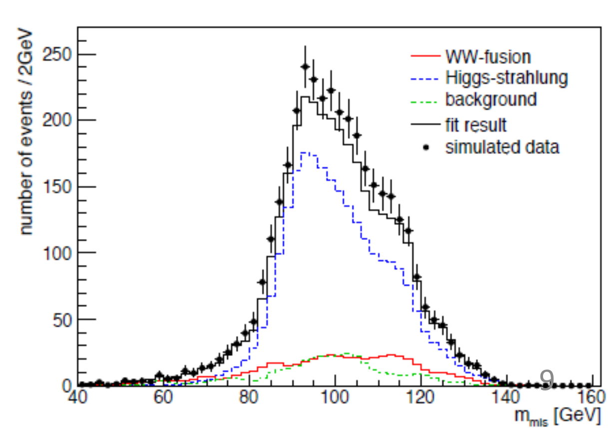
$$\frac{\Delta BR(H \to b\bar{b})}{BR(H \to b\bar{b})} = 3.0\,\%$$

$$\frac{\Delta BR(H \to WW)}{BR(H \to WW)} = 4.6\,\%$$

$$\Delta\Gamma_H^{tot}/\Gamma_H^{tot} = 11.88\,\%$$

E=250GeV

~ 5-6 % (500GeV)



Observable	Expected Error
ILC at 250 GeV with 250 fb^{-1}	
$\sigma(Zh)$	0.025
$\sigma(Zh)\cdot BR(b\bar{b})$	0.010
$\sigma(Zh)\cdot BR(c\bar{c})$	0.069
$\sigma(Zh)\cdot BR(gg)$	0.085
$\sigma(Zh)\cdot BR(WW)$	0.08
$\sigma(Zh)\cdot BR(ZZ)$	0.28
$\sigma(Zh)\cdot BR(\tau^+\tau^-)$	0.05
$\sigma(Zh)\cdot BR(\gamma\gamma)$	0.27
$\sigma(Zh)\cdot BR(\mathrm{invisible})$	0.005

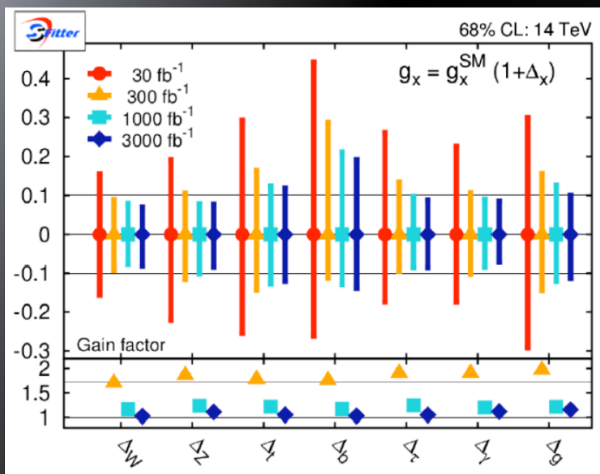
ILC at 500 GeV with 500 fb^{-1}	
$\sigma(Zh)\cdot BR(b\bar{b})$	0.016
$\sigma(Zh)\cdot BR(c\bar{c})$	0.11
$\sigma(Zh)\cdot BR(gg)$	0.13
$\sigma(Zh)\cdot BR(\tau^+\tau^-)$	0.07
$\sigma(Zh)\cdot BR(\gamma\gamma)$	0.36
$\sigma(WW)\cdot BR(b\bar{b})$	0.006
$\sigma(WW)\cdot BR(c\bar{c})$	0.04
$\sigma(WW)\cdot BR(gg)$	0.049
$\sigma(WW)\cdot BR(WW)$	0.03
$\sigma(WW)\cdot BR(\tau^+\tau^-)$	0.05
$\sigma(WW)\cdot BR(\gamma\gamma)$	0.28
$\sigma(t\bar{t}h)\cdot BR(b\bar{b})$	0.2
ILC at 1 TeV with 1000 fb^{-1}	
$\sigma(WW)\cdot BR(WW)$	0.01
$\sigma(WW)\cdot BR(gg)$	0.018
$\sigma(WW)\cdot BR(\tau+\tau-)$	0.02
$\sigma(WW)\cdot BR(\gamma\gamma)$	0.05
$\sigma(t\bar{t}h)\cdot BR(b\bar{b})$	0.12

Fujii, Miyamoto, Ono, Tian

We can test the Mass-Coupling Relation accurately at ILC

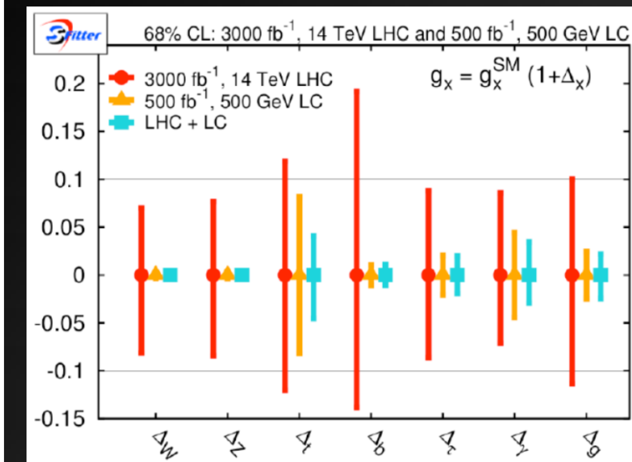
visualize the improvement of ILC over LHC

LHC (30/300/1000/3000 fb^{-1})



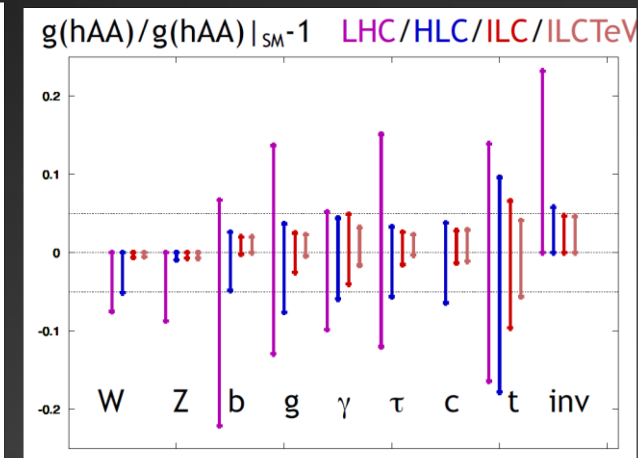
[D. Zerwas]

LHC (3000 fb^{-1}) and LC(500GeV/500fb^{-1})



[D. Zerwas]

LHC (3000 fb^{-1}) and LC(HLC/ILC/ILCTeV)



[M. Peskin]

At LHC, coupling determination starts limited by systematics for 300 fb^{-1}

⇒

No drastic improvement at 3000fb^{-1} ?

LC can measure independently

X-sections $\sigma(e^+e^- \to Zh)$ (250GeV)

$\sigma(e^+e^- \to \nu\nu h)$ (350-500GeV)

$\sigma(e^+e^- \to \nu\nu h)$ (700GeV-TeV)

Branching ratios

Invisible and unexpected *h* decays

hcc, hττ, hhh, htt, hγγ

ILC can measure the Higgs couplings acculately! ⇒ Use to test new physics

A variety of new physics models

In the Higgs/EWSB related Sessions, many new models with extended Higgs sectors have been discussed

- SM up to Planck scale (Berzukov)
- MSSM (pMSSM) (Hewett)
- Two Higgs doublet model (Tsumura)
- SUSYGUT with Hosotani mechanism (Kakizaki)
- Higgs Inflation in Inert doublet model (Nabeshima)
- Higgs as a pseudo Nambu-Goldstone boson (Kikuta)
- Extended SUSY Higgs for EW Baryogenesis (Shindou)
- and its UV complete theory (Yamada)
- Higgs triplet model for neutrino mass (Yagyu)

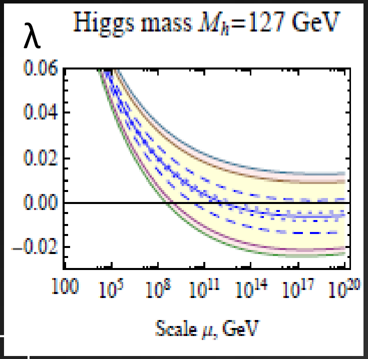
0. They compatible with m_h=126 GeV
1. Indirect test of models by fingerprinting via precisely measured h couplings
2. Possibility of direct detection

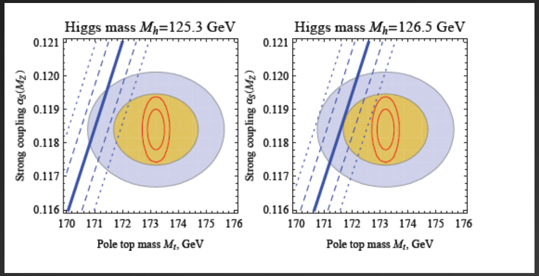
Interpretation of 126 GeV

Standard Model [Bezrukov]

The running coupling λ may be vanishing with its derivative at Planck Scale!

$$M_{\min} = \left[129.5 + \frac{M_t - 173.2\,\mathrm{GeV}}{0.9\,\mathrm{GeV}} \times 1.8 - \frac{\alpha_s - 0.1184}{0.0007} \times 0.6 \pm 2\right] \mathrm{GeV}$$





We may be learning about physics at M_P

Physics above M_P
Multiple point principle (Nielsen et al)
Higgs Inflation (Shaposhnikov et al)

Is this coincidence really there?

To know it, we need
- **Lepton collider** at > 350GeV (mH, mt)
- **Calculate higher order relations** between MSbar parameters and masses

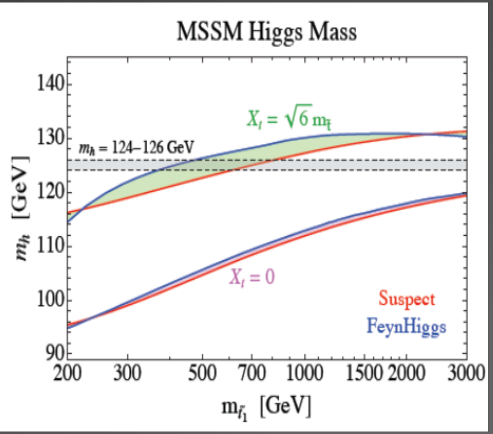
Supersymmetry V = |D|² + |F|² + (soft-breaking)

MSSM (only D term (with loop) contributes to the Higgs mass)

$$m_h^2 < m_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2}\left[\ln\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{A_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{A_t^2}{12 m_{\tilde{t}}^2}\right)\right]$$

Large stop mass, or large soft-breaking A parameter

Tension with the hierarchy problem?



Relaxing constraint among parameters (pMSSM) [J. Hewett]
Extension with an extra gauge
Extension with additional matter fields
Extension of Higgs sector (NMSSM, 4HDMΩ, …) [Kakizaki, Shindou, Yamada]

Phenomenological MSSM (pMSSM)

cMSSM is in trouble ⇒ Relaxing parameters

[J. Hewett]

The phenomenological MSSM (pMSSM)

- Most general CP-conserving MSSM
- Minimal Flavor Violation, First 2 sfermion generations are degenerate w/ negligible Yukawas
- No GUT, SUSY-breaking assumptions!
- 19 real, weak-scale parameters

  scalars: $m_{Q_1}, m_{Q_3}, m_{u_1}, m_{d_1}, m_{u_3}, m_{d_3}, m_{L_1}, m_{L_3}, m_{e_1}, m_{e_3}$

  gauginos: M_1, M_2, M_3

  tri-linear couplings: A_b, A_t, A_τ

  Higgs/Higgsino: $\mu, M_A, \tan\beta$

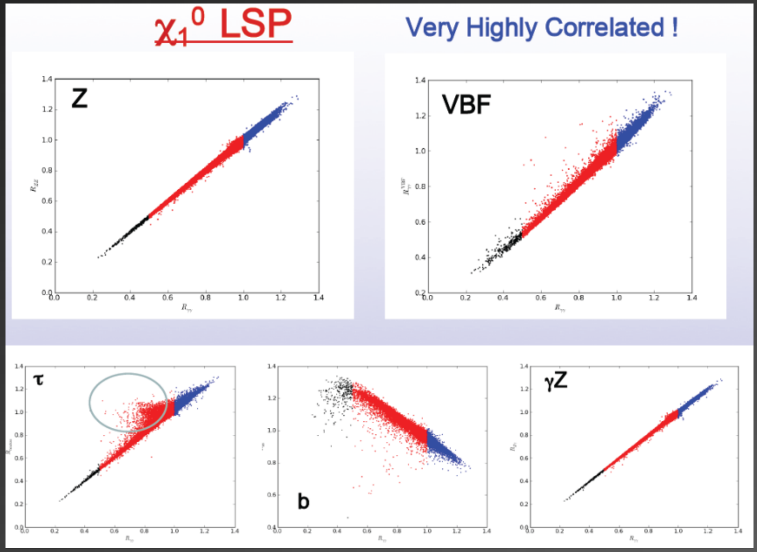
Higgs branching fractions are correlated

- Lower bb predicted
- Lower ττ difficult

Reasonable fine-tuning ~1% is possible

- Selects region of parameter space
- Light stop/sbottom
- Very light and compressed EW-ino sector: Tailor-made for the ILC!

$R_{XX} = \sigma(gg\to h)\, B(h\to XX)|_{pMSSM/SM}$

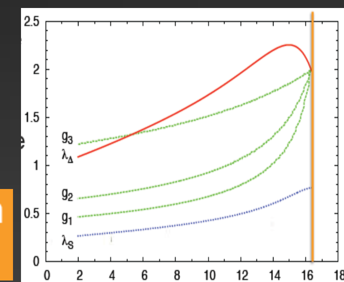


Fingerprinting the model

Direct searches of EW-ino sector

Test of High Scale Physics at ILC

Effect of Physics at very high scale (eg, GUT scale) vanishes at low energy due to the decoupling theorem !
However, if they predict a specific Higgs sector, they can be tested via Higgs physics.



High predictability on the Higgs properties

[Kakizaki]

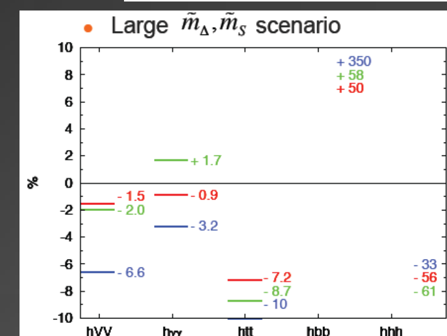
A model of SUSY GUT where Hosotani Mechasism breaks the GUT symmetry (for doublet–triplet Splitting)

New light chiral adjoints are predicted

Color octet superfield:	$O(8,1,0)$
SU(2) triplet superfileld:	$\Delta(1,3,0)$
SU(2) singlet superfield:	$S(1,1,0)$

Extended Higgs!

Deviation in h couplings by % levels predicted



The model can be tested by Fingerprinting

[Nabeshima]

Viable Higgs inflation model (Inert doublet model + N_R)

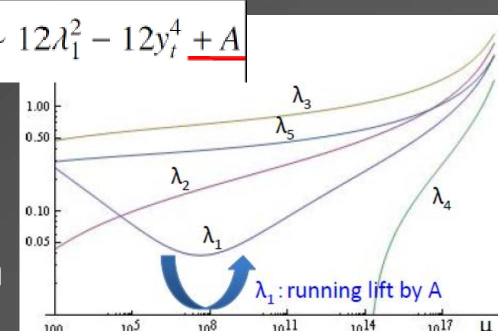
$$16\pi^2\mu\frac{d\lambda_1}{d\mu} \sim 12\lambda_1^2 - 12y_t^4 + A$$

Inflaton = Higgs

- **Higgs boson mass (m_h=126GeV)**
- **Slow-roll condition(ε, η)**
- **CMB temperature fluctuations (P_R)**

$$\varepsilon \equiv \tfrac{1}{2}M_P^{\,2}(V'/V)^2 \ll 1 \quad \eta \equiv M_P^{\,2}V''/V \ll 1$$

Effect of the inert doublet
Stabilize vaccuum up to M_{planck}



Inflation, Neutrino data, DM data

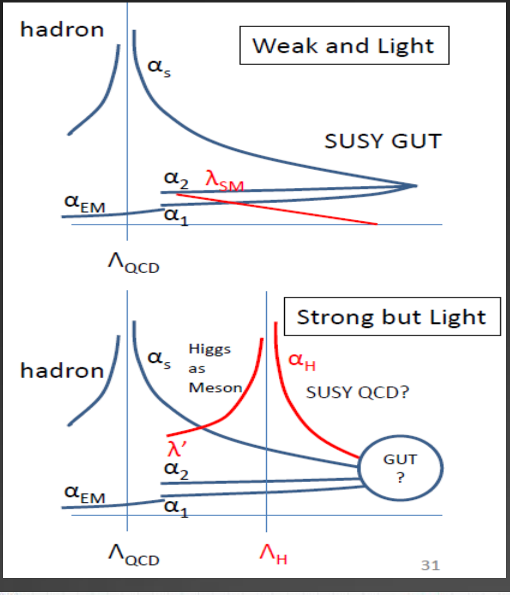
$m_A < m_H$ ($\approx$90GeV) $< m_h < m_{H\pm}$ ($\approx$140GeV)

Specific mass spectrum for inert slacars = Only testable at ILC

Higgs Self-Coupling

Importance of Higgs potential (essence of EWSB)

- Higgs Dynamics
  - Weakly coupled with a light Higgs
    GUT above Grand Desert (SUSY GUTs)
  - Strongly coupled but a light Higgs [Shindou]
    Landau pole at 10-100TeV EW Baryogenesis, PNGB [Kikuta]
  - Test by looking at $W_L W_L$ elastic scatterings
  - Test by *hhh* coupling



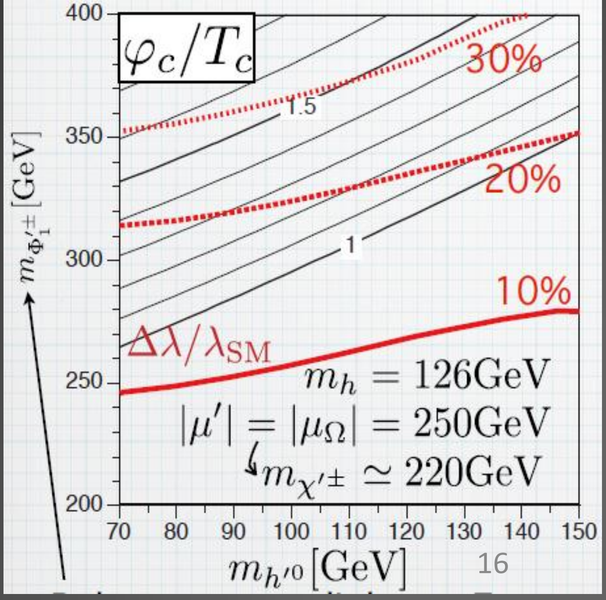
[Shindou]

SUSY extended Higgs sector with 4HDM and singlets

Electroweak Baryogenesis possible
Large *hhh* deviation for sufficient strong 1st OPT (>10-20%)
Higgs mass 125 GeV easily satisfied
Landau pole Λ at O(10) TeV (Strong-but-Light!)

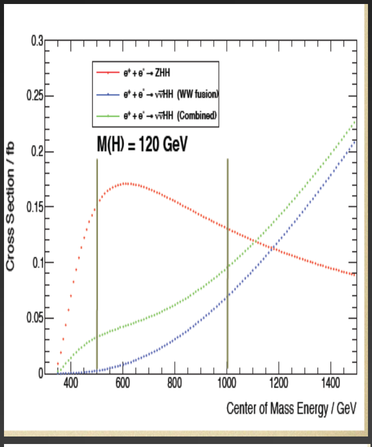
[Yamada]

UV complete theory above Λ can be construced
SU(2)H with $N_f = N_c + 1$ (asymptotic free)
Higgs as a meson of more fundamental matter field



Higgs Self-Coupling

- For the hhh coupling, 10-20 % accuracy may be required to test some scenario of new physics
  - Test the Strong-but-Light Scenario
  - EW baryogenesis [Shindou, Yamada]
  - Neutrino Masses [Yagyu]

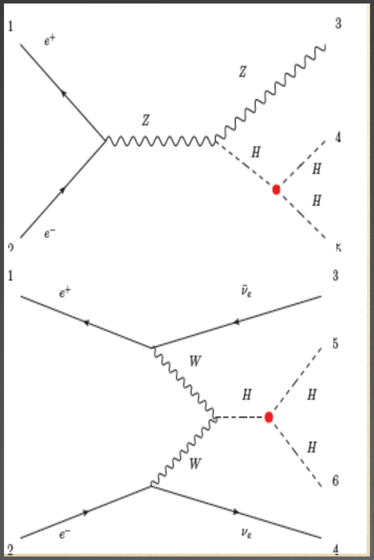


- At LHC [J. Yu]
  - 3σ observation at $3000 fb^{-1}$

- ILC [0.5 TeV, 1 TeV] [J. Tian]
  - M(H)=120GeV, $\delta\sigma/\sigma \sim 24\%$, $\delta\lambda/\lambda \sim 40\%$ ($500GeV/2fb^{-1}$)
  - $\delta\sigma/\sigma \sim 22\%$, $\delta\lambda/\lambda \sim 17\%$ ($1TeV/2fb^{-1}$)

Expecting 20% or better for m_h=125GeV [K. Fujii]

Zhh production



hhνν production

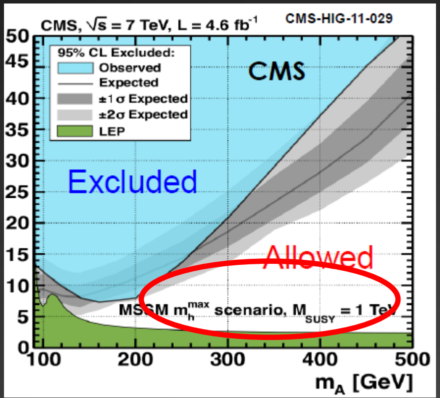
- CLIC [1.4TeV-3TeV] [Lastvicka]
  - 30 – 35% λ_{HHH} uncertainty @ 1.4 TeV
  - 15 – 20% uncertainty @ 3 TeV

ILC/CLIC is required!

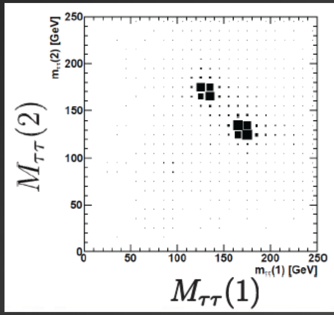
Direct Searches of extra Higgs bosons

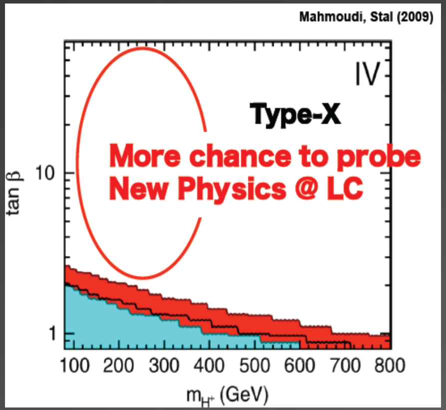
[K. Tsumura]

In the MSSM (2HDM-II) , LHC will discover H, A, H^+ as long as m_A is relatively small except for tanβ~5-7. via pair $H^+H^- \to l\nu l\nu$, $HA \to bb\tau\tau$ etc



In other type of 2HDM (such as leptophilic or Type X), LHC may be difficult to discover *H, A, H^+* even if m_A is relatively low. ILC can discover them if kinematically allowed, via $e^+e^- \to HA \to 4\tau$. By the collinear approximation, masses of H and A can be reconstructed

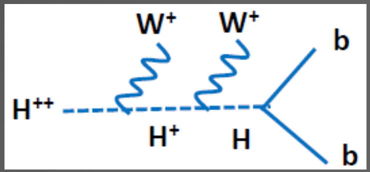




[K. Yagyu]

H^{++} in the Higgs triplet model (type-II Seesaw scenario).

For v_Δ small, m_Δ small	$H^{++} \to l^+l^+$	Constrained at LHC
For v_Δ large m_Δ small	W^+W^+	To be constrained at LHC
For m_Δ large	W^+H^+	Only testable at ILC



Using LHC and ILC all possibilities in the model can be examined

Summary

- After July 2012, the world has changed
  - Higgs discovery is not the end of the story
  - The new stage just started
- Higgs Sector (Still being mystery)
  - Origin of Mass?   Essence of EWSB?
  - Its shape, dynamics, couplings are related with each scenario of New Physics models beyond the SM
- New Physics
  - Direct searches (strongly model dependent)
  - Indirect test by fingerprinting from details of *h* couplings (guaranteed physics)

Higgs as a probe of new physics!

To this end we need precise measurement and accurate theoretical predictions with m_t, α_s

This is going to be done at ILC/CLIC!

Who cares?

We care!

Higds
= Window toBSM

We need LC

Thank you very much