Higgs Physics at LCs

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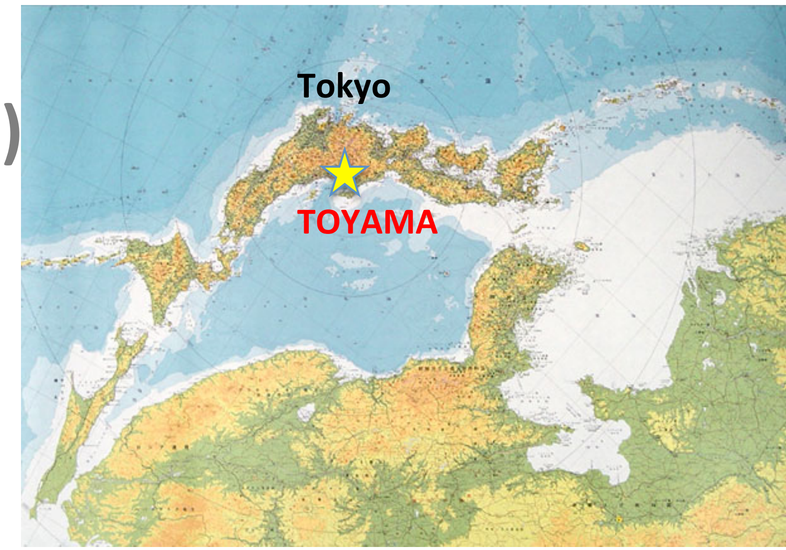
University of TOYAMA

5^{th} NExT PhD Workshop "Higgs and Beyond", Abington, 8 June, 2015

Toyama?

- **Toyama is at Centre of Japan!**
- Toyama (富山Rich Mountains)
- High Mountains (Japan Alps)
- Much Snow
- Nice Fresh Fishes
- Univ. of Toyama
  Closest to Kamioka



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Mt. Tsurugi in Toyama

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End of April, Toyama

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SUSHI

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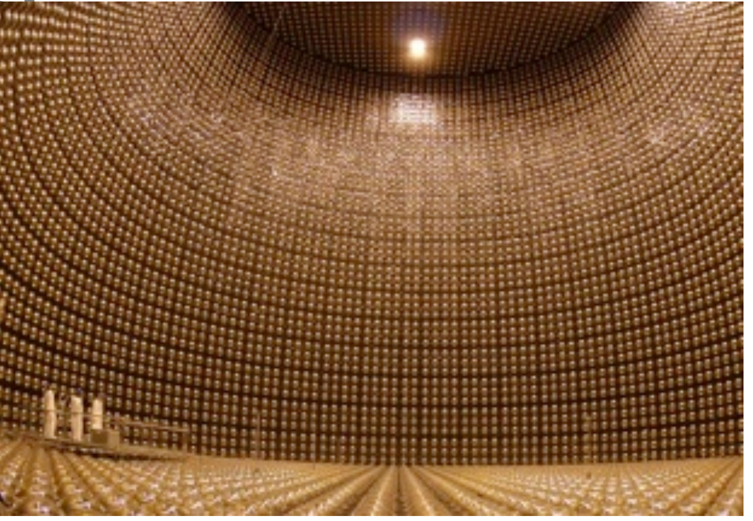


Super Kamiokande

Introduction

What is the Higgs?

It couples to all particles

It gets a VEV (v) by EWSB (scalar field)

Higgs mechanism $m_W = g\, v$

Yukawa interaction $m_{q,l} = Y_{q,l}\, v$

Dimension 5 operator (neutrino mass) $m_\nu = C_\nu v^2/M$

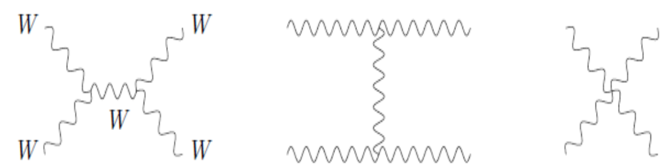
Higgs = Origin of Mass

Introduction

$W_L^+ W_L^-$ Elastic Scattering

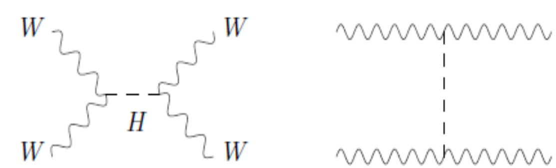
$a^0(W_L^+ W_L^- \rightarrow W_L^+ W_L^-) \approx A\, E^4 + B\, E^2 + C \quad (E \rightarrow \infty)$

Unitarity Violation if $A, B \neq 0$



A=0 because of gauge symmetry

To make B=0, diagrams mediated by a scalar field h must be added



Higgs field is required to save unitarity

Perturbative Unitarity

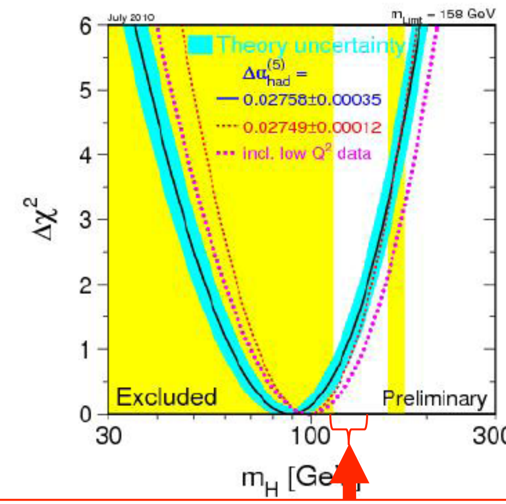
$|a^0(W_L^+ W_L^- \rightarrow W_L^+ W_L^-)| < 1 \quad \Rightarrow \quad m_h < 1\ \text{TeV}$

Higgs discovery in 2012

The mass is 125 GeV

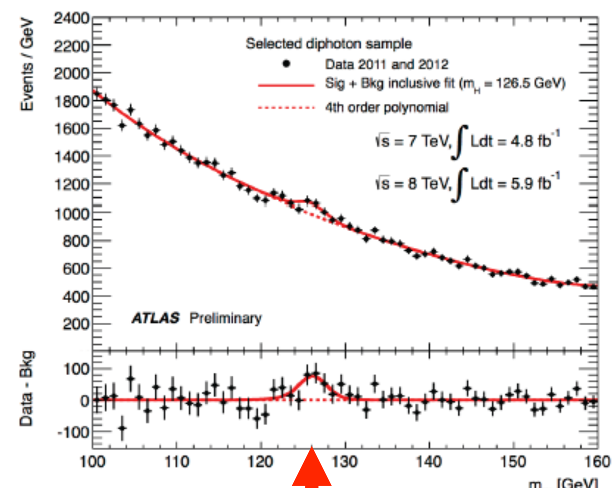
Spin/Parity 0^+

It couples to ***γγ, ZZ, WW, bb, ττ, …***



Higgs Mass indicated by LEP/SLC

This is really a Higgs!

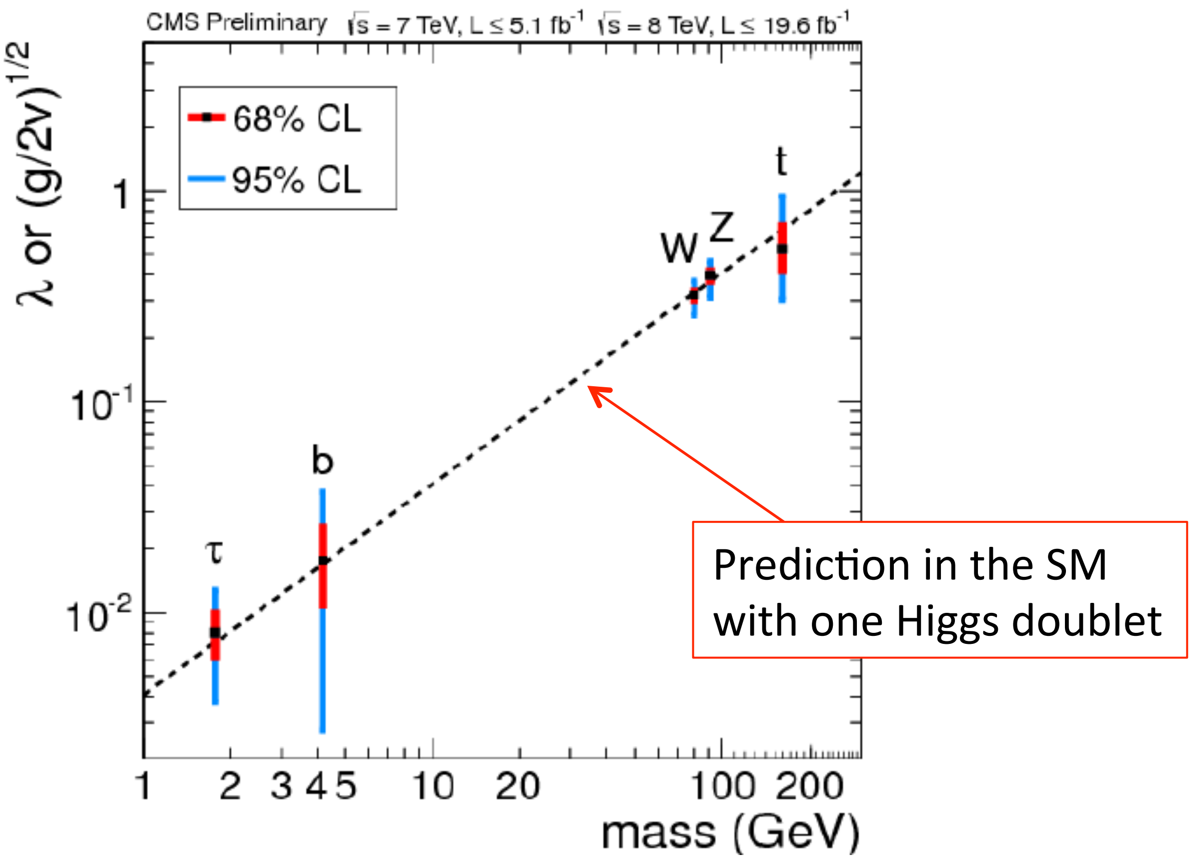


Measured couplings look consistent with the SM Higgs within the current errors

ATLAS/CMS July 2012

New Particle !

What a coincidence!

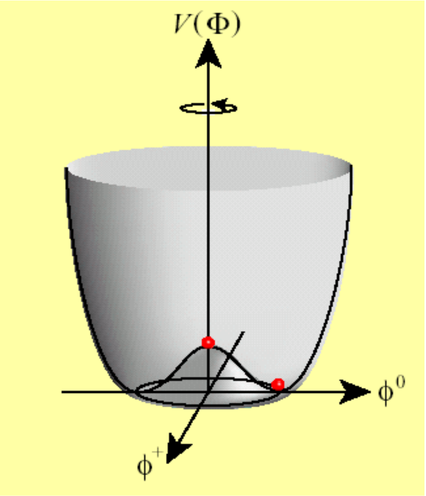


Introduction

Higgs Sector in the Standard Model :

One SU(2) doublet Φ

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



Assumption of $\mu^2 < 0$ $\Rightarrow$ EWSB

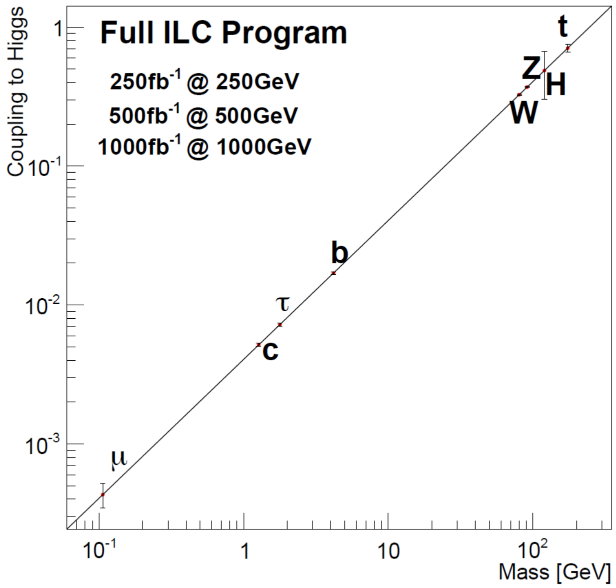
This is simple but …

Questions:

Why minimal? (no reason)

Why $\mu^2 < 0$

What is Origin of the Higgs force λ?



Beyond the Standard Model

However, many reasons to consider New Physics beyond SM

Unification of Law
- Paradigm of Grand Unification
- Yukawa structure (flavor physics)

Problem in the SM Higgs
- Hierarchy Problem, Shape of Higgs sector, Essence, …

BSM Phenomena
- Dark Matter
- Neutrino mass and mixing
- Baryon Asymmetry of Universe
- Inflation, Dark Energy, Gravity,…

New Physics is necessary　　At which scale?

If TeV scale, they should have connection with Higgs physics

Introduction

Second Higgs boson?

SM Higgs sector = just a guess!

No principle for the minimal Higgs sector of the SM

Many possibilities for non-minimal Higgs sectors

These extended Higgs sectors can provide sources for

- **Baryogenesis**
- **Dark Matter**
- **Neutrino Mass**
- **…**

Higgs sector = Window for new physics

Introduction

Scalar field causes quadratic divergences

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

Hierarchy problem

Ideas of new physics to solve the problem

- Supersymmetry
- Dynamical Symmetry Breaking (Technicolor)
- Extra Dimensions (such as gauge-Higgs unification)
- Higgs as a Pseudo-Nambu-Goldstone boson
- …

These ideas give different pictures for the essence of the Higgs boson

Higgs sector = Window for new physics

Introduction

Higgs is important not only for EWSB but also as a window to new physics beyond the SM

Discovery of a Higgs boson in 2012:

Great step to construct the Higgs sector
and to understand the essence of the Higgs field

From the detailed study of the Higgs sector, we can determine direction of new physics beyond the SM

New era has started !

Contents of Talk

1. Introduction (done)
2. Essence of the Higgs boson
3. Extended Higgs sectors
4. Radiative Corrections
5. Fingerprinting New Physics via Higgs couplings by future precision measurements at LCs
6. Summary

Essence of Higgs

What is the essence of the Higgs field?

Higgs Nature	⇔	BSM Paradigm
– Elementary Scalar		Supersymmetry
– Composite of fermions		Dynamical Symetry Breaking
– A vector field in extra D		Gauge-Higgs Unification
– Pseudo NG Boson		Minimal Composite Higgs
– ……		……

Each model has a specific Higgs sector at EW scale

Higgs sector in new paradigm

- **SUSY**
  - **2 Higgs doublets** are required (**type II** 2HDM)
  - Quartic couplings are given by weak gauge couplings
  - Prediction on the mass of h ($< m_Z$) (MSSM)
  - Some extensions with a singlet (NMSSM etc)

- **Higgs as a pseudo NG boson (pNGB)**

  # of pNGB is determined by the group structure of dynamics at high energy

  - SO(5)/SO(4) # = 4 → 1 doublet (MCHM)
  - SU(4)/Sp(4) # = 5 → 1 doublet + 1 singlet
  - SO(9)/SO(8) # = 8 → 2 doublets

Multiplet structure of the Higgs sector is related to new physics

Phenomena beyond the SM

We already know **BSM** phenomena:

- Neutrino oscillation

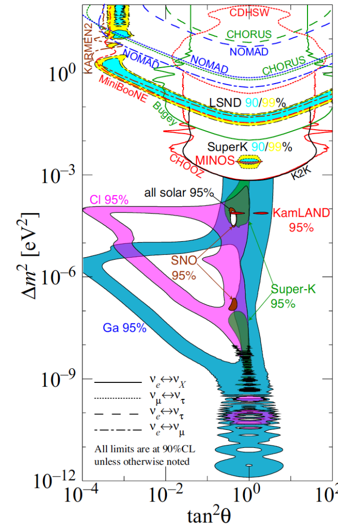
  $\Delta m^2 \sim 8\times10^{-5}\,\mathrm{eV}^2,\ \Delta m^2 \sim 2\times10^{-3}\ \mathrm{eV}^2$

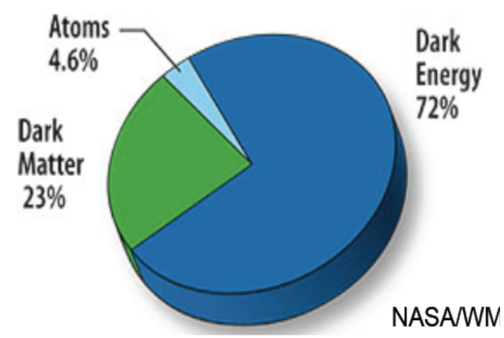
- Dark Matter

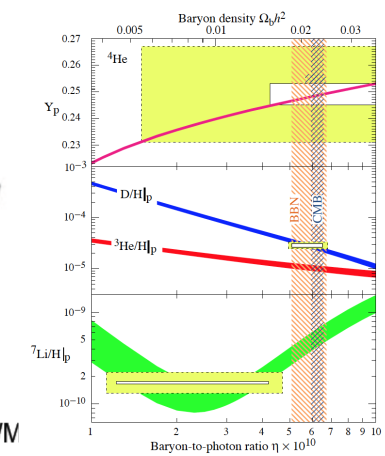
  $\Omega_{DM}h^2 \sim 0.12$

- Baryon Asymmetry of the Universe

  $n_B/n_\gamma \sim 6\times10^{-10}$







New physics is necessary!

Which scale?

$$\eta_B = \frac{n_B}{n_\gamma} = \frac{n_b - n_{\bar{b}}}{n_\gamma}$$

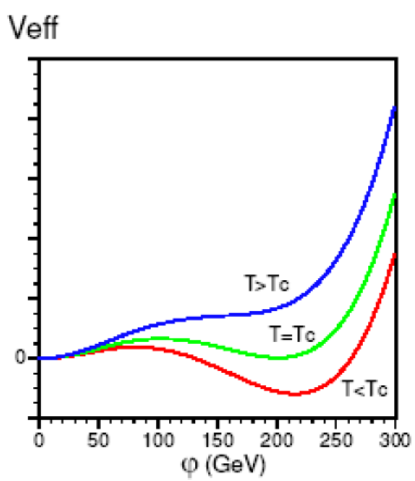
If NP appears at the **TeV scale**, it should have a strong connection with the physics behind the **Higgs sector**

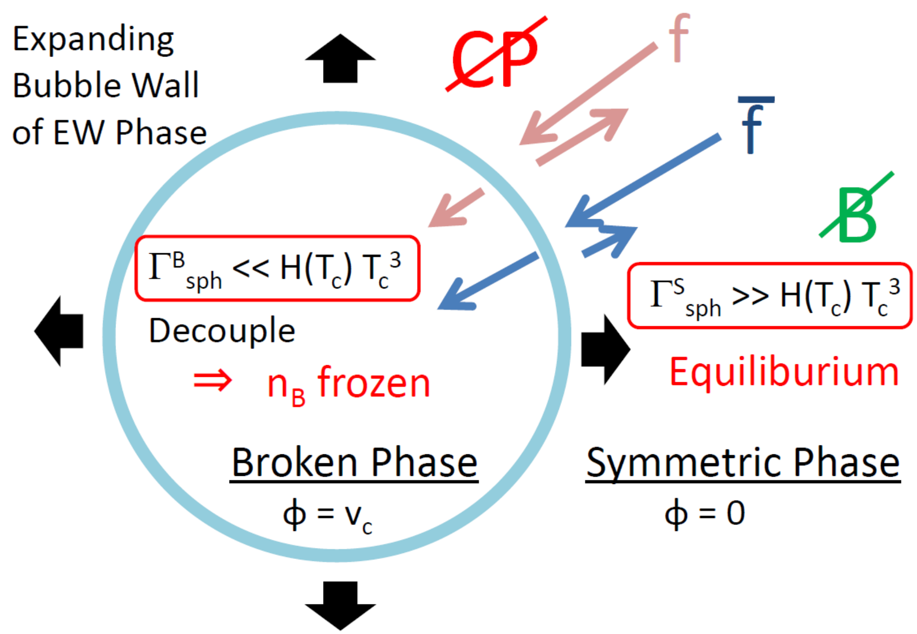
Electroweak Baryogenesis

$$\Gamma \sim e^{-E_{\rm sph}/T} \quad (T < T_c)$$
$$\Gamma \sim \kappa(\alpha_W T)^4 \quad (T_c < T)$$

Sakharov's conditions:

- B Violation → Sphaleron transition at high T
- C and CP Violation → CP Phases in extended scalar sector
- Departure from Equilibrium → 1^{st} Order EW Phase Transition





Quick sphaleron decoupling is required to retain sufficient baryon number in Broken Phase

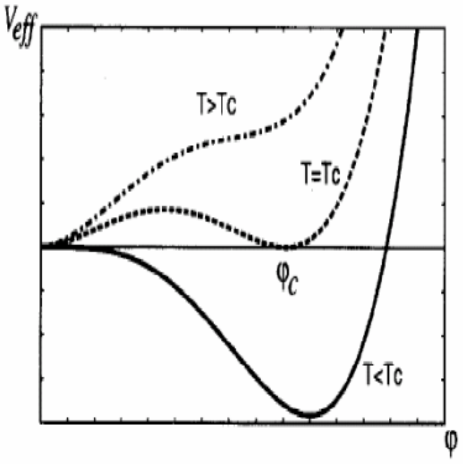
(Sphaleron Rate) < (Expansion Rate) ⇒ $$\frac{\varphi_c}{T_c} \gtrsim 1$$

Condition of Strong 1st OPT ($\varphi_c/T_c > 1$)

Finite Temperature Potential

$$V_T(\phi, T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda_T}{4}\phi^4 + \ldots..$$

$$\phi_c/T_c > 1 \Rightarrow 2E/\lambda_{T_c} > 1$$



EWBG was ruled out in the SM

$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3) \quad \Rightarrow \quad m_h \ll 125 \text{ GeV}$$

Contradiction with LHC results

Muti-Higgs models can satisfy the condition

$$E = \frac{1}{12\pi v^3}(2m_W^3 + m_Z^2 + m_H^3 + m_A^3 + 2m_{H^\pm}^3).$$

Thermal loop effect by additional Higgs boson

In order to satisfy $\phi_c/T_c > 1$ with m_h=125GeV, Extension of the Higgs sector is necessary

Neutrino Mass

Neutirno Mass Term (= Effective dim-5 operator)

$$L^{eff} = (c_{ij}/M)\, \nu^i{}_L \nu^j{}_L\, \phi\, \phi$$

$\langle\phi\rangle = v = 246\text{GeV}$

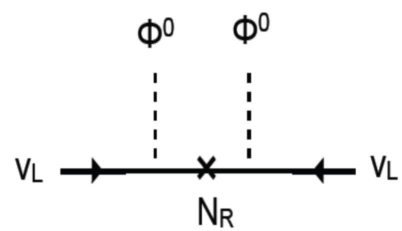
Mechanism for tiny masses:

$$m^\nu{}_{ij} = (c_{ij}/M)\, v^2 \;\; < 0.1\ \text{eV}$$

<u>Seesaw (tree level)</u>

$$m^\nu{}_{ij} = y_i y_j\, v^2/M$$

Minkowski
Yanagida
Gell-Mann et al



(M>> 1TeV)

<u>Quantum Effects (Radiative seesaw)</u>

N-th order of perturbation

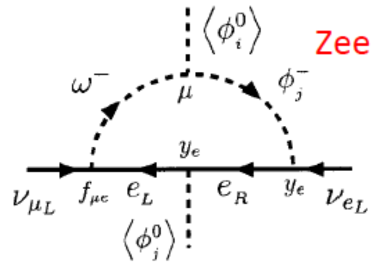
$$m^\nu{}_{ij} = [g^2/(16\pi^2)]^N\, C_{ij}\, v^2/M$$

(M can be 1 TeV)

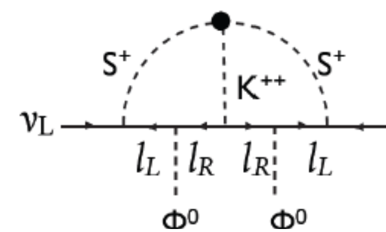
Explanations by the TeV scale physics

Radiative Seesaw Scenario

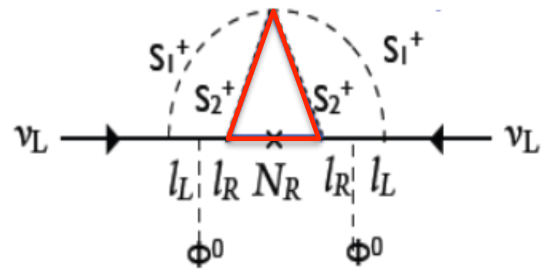
- Extended Higgs sector
- Z_2 parity
  - Neutrino mass generated at loop levels
  - WIMP Dark Matter
    - Lightest Z_2-odd particle
    - LSP (in SUSY extension)



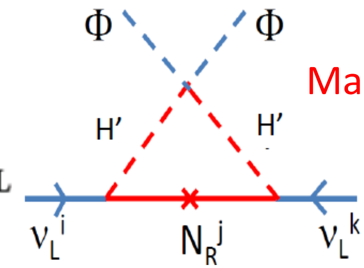
Zee



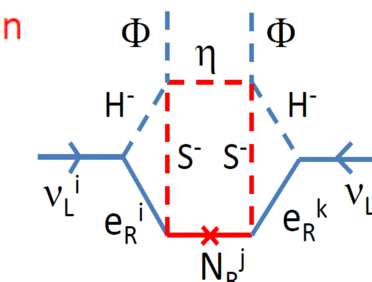
Babu



Krauss, Nasri, Trodden



Ma



Aoki, SK, Seto

Electroweak Baryogenesis

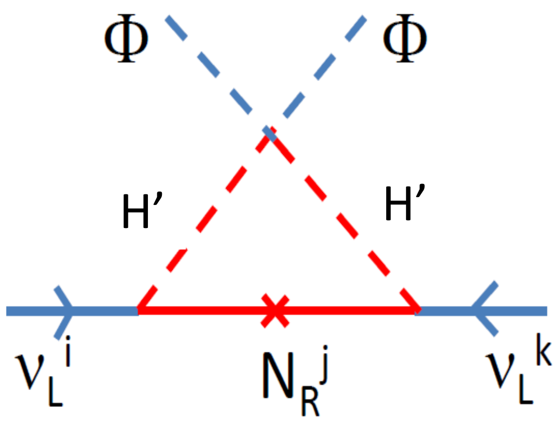
- Sphaleron
- Additional CP Phases
- Strong 1st Order Phase Transition

These scenarios are strongly related to the Higgs physics!

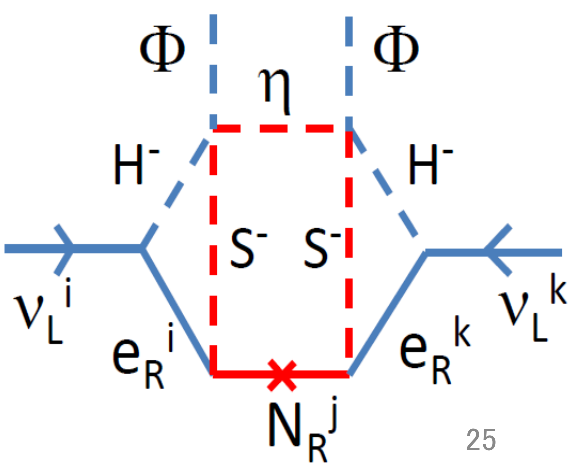
Radiative seesaw with Z_2

Z_2-parity plays roles:
1. No tree-level Yukawa (Radiative neutrino mass)
2. Stability of the lightest Z_2-odd particle (WIMP)

Ex1) 1-loop *Ma (2006)*
- Simplest model
- SM + Inert scalar doublet (H') + N_R
- DM candidate [H' or N_R]



Ex2) 3-loop *Aoki-Kanemura-Seto (2008)*
- Neutrino mass from O(1) coupling
- 2 Higgs doublets + η^0 + S^+ + N_R
- DM candidate [η^0 (or N_R)]
- Electroweak Baryogenesis



All 3 problems may be solved by TeV physics

Strategy

- Although the 125 GeV Higgs boson was found , we do not know the structure of the Higgs sector yet
- Many new physics scenarios predict special non-minimal Higgs sectors
- Comprehensive study of various extended Higgs sectors is very important
- Reconstruction of the Higgs sector by future experiments at LHC, HL-LHC and future lepton colliders
- From the Higgs sector to new physics BSM!

Extended Higgs Sector

The “SM-like” does not necessarily mean the SM.
Every extended Higgs sector can contain the SM-like Higgs boson *h* in its decoupling regime.

General Extended Higgs models

Multiplet Structure

Φ_{SM}+Singlet, Φ_{SM}+Doublet (2HDM),

Φ_{SM}+Triplet, …

Additional Symmetry

Discrete or Continuous?

Exact or Softly broken?

Interaction

Weakly coupled or Strongly Coupled ?

Decoupling or Non-decoupling?

Multiplet Structure

If the Higgs sector contains more than one scalar bosons, possibility would be

- SM + extra Singlets (NMSSM, B-L Higgs, ...)
- SM + extra Doublets (MSSM, CPV, EW Baryogenesis, Neutrino mass, …)
- SM + extra Triplets (Type II seesaw, LR models….)
- ….

Basic experimental quantities:

- Electroweak rho parameter
- Flavor Changing Neutral Current (FCNC)

Electroweak rho parameter

$\rho_{exp} = 1.0008^{+0.0017}_{-0.0007}$

$Q = I_3 + Y/2$

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{\sum_i \left[4T_i(T_i+1) - Y_i^2\right] |v_i|^2 c_i}{\sum_i 2Y_i^2 |v_i|^2}$$

T_i : $SU(2)_L$ isospin
Y_i : hypercharge
v_i : v.e.v.
c_i : 1 for complex representation
1/2 for real representation

Possibility

1. $\rho=1$ SM + doublets (ϕ) + singlets (S), (Septet, ...)

2. $\rho\approx1$ SM + Triplets (Δ)

$$\rho_{\text{tree}} = \frac{1 + \frac{2v_\Delta^2}{v_\Phi^2}}{1 + \frac{4v_\Delta^2}{v_\Phi^2}} \simeq 1 - \frac{2v_\Delta^2}{v_\Phi^2}$$

a) $v_\Delta \ll v_\varphi$

b) Combination of several representations

[(ex) Georgi-Machasek model] $v_\Delta \approx v_\varphi$

Multi-doublets (+singlets) seem the most natural choice?

2 Higgs Doublet Model

$$V_{\text{THDM}} = +m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2\left(\Phi_1^\dagger\Phi_2 + \Phi_2^\dagger\Phi_1\right)$$
$$+\frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2$$
$$+\lambda_4\left|\Phi_1^\dagger\Phi_2\right|^2 + \frac{\lambda_5}{2}\left[\left(\Phi_1^\dagger\Phi_2\right)^2 + (\text{h.c.})\right]$$

$$\Phi_i = \begin{bmatrix} w_i^+ \\ \frac{1}{\sqrt{2}}(h_i + v_i + ia_i) \end{bmatrix} \quad (i = 1, 2)$$

Diagonalization

$$\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix}\begin{bmatrix} H \\ h \end{bmatrix} \qquad \begin{bmatrix} z_1^0 \\ z_2^0 \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix}\begin{bmatrix} z^0 \\ A^0 \end{bmatrix}$$

$$\begin{bmatrix} w_1^\pm \\ w_2^\pm \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix}\begin{bmatrix} w^\pm \\ H^\pm \end{bmatrix}$$

$$\frac{v_2}{v_1} \equiv \tan\beta$$

Φ_1 and $\Phi_2 \Rightarrow h,\ H,\ A^0,\ H^\pm \oplus$ Goldstone bosons

↑ ↑ ↑charged

CPeven CPodd

$$m_h^2 = v^2\left(\lambda_1\cos^4\beta + \lambda_2\sin^4\beta + \frac{\lambda}{2}\sin^2 2\beta\right) + \mathcal{O}\left(\frac{v^2}{M_{\text{soft}}^2}\right),$$

$$m_H^2 = M_{\text{soft}}^2 + v^2(\lambda_1 + \lambda_2 - 2\lambda)\sin^2\beta\cos^2\beta + \mathcal{O}\left(\frac{v^2}{M_{\text{soft}}^2}\right),$$

$$m_{H^\pm}^2 = M_{\text{soft}}^2 - \frac{\lambda_4 + \lambda_5}{2}v^2,$$

$$m_A^2 = M_{\text{soft}}^2 - \lambda_5 v^2.$$

M_{soft}: soft breaking scale

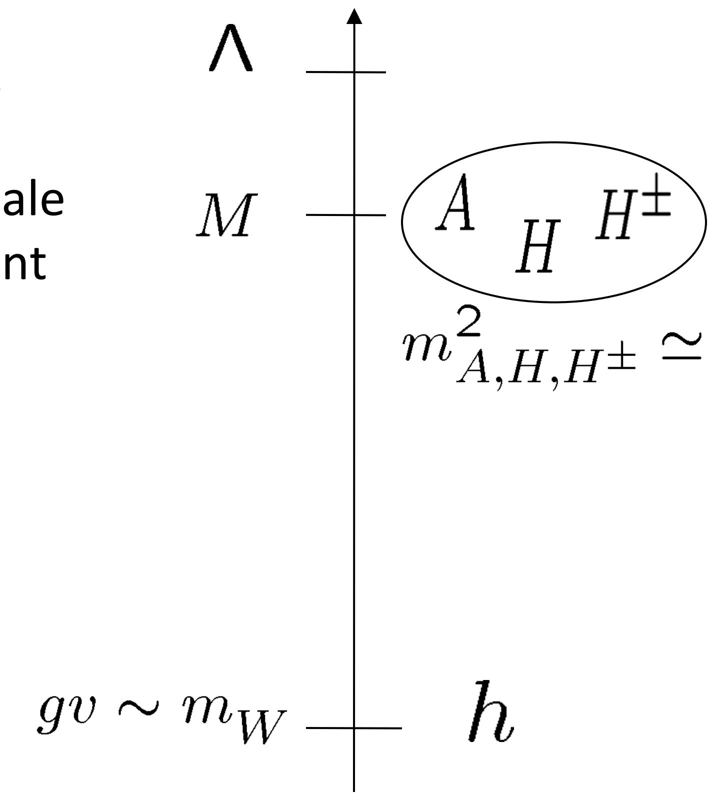
$M_{\text{soft}}\ \left(= \frac{m_3}{\sqrt{\cos\beta\sin\beta}}\right)$:

soft-breaking scale
of the discrete symm.

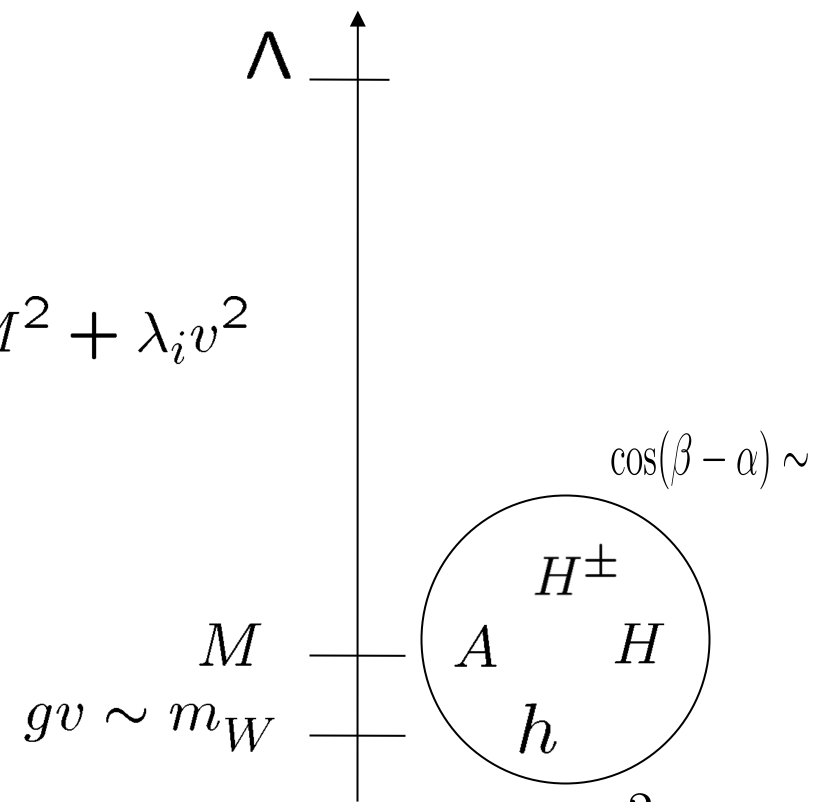
Two Possibilities

Λ: Cutoff

M: Mass scale irrelevant to VEV



$$m^2_{A,H,H^\pm} \simeq M^2 + \lambda_i v^2$$



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{v^2}{M^2}\mathcal{O}^{(6)}$$

Effective Theory is the SM

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{nonSM}} + \frac{v^2}{\Lambda^2}\mathcal{O}^{(6)}$$

Effective Theory is an extended Higgs sector

Non-decoupling effect

FCNC Suppression

Multi-Higgs model: FCNC appears via Higgs mediation

2 Higgs doublet models:

to avoid FCNC, give different charges to Φ_1 and Φ_2

Discrete sym. $\Phi_1 \rightarrow +\Phi_1, \quad \Phi_2 = -\Phi_2$

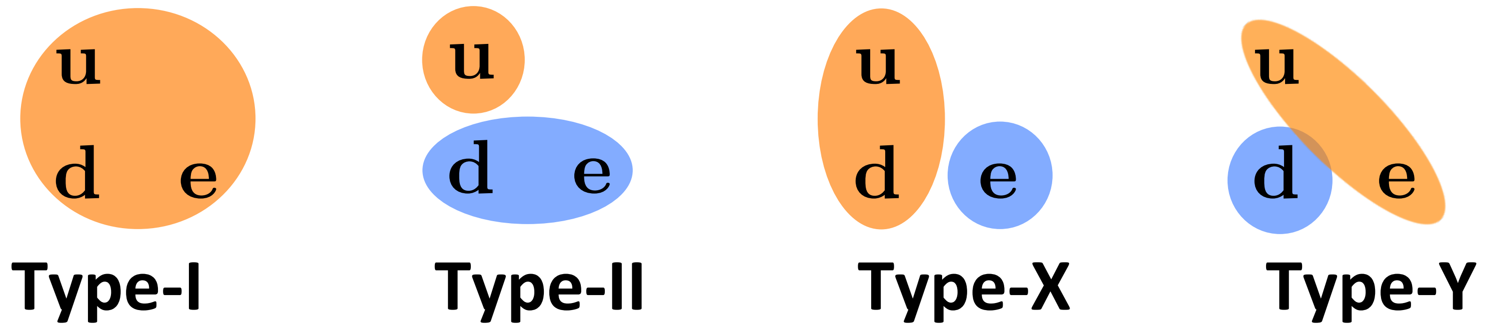
Each quark or lepton couples only one Higgs doublet

No FCNC at tree level

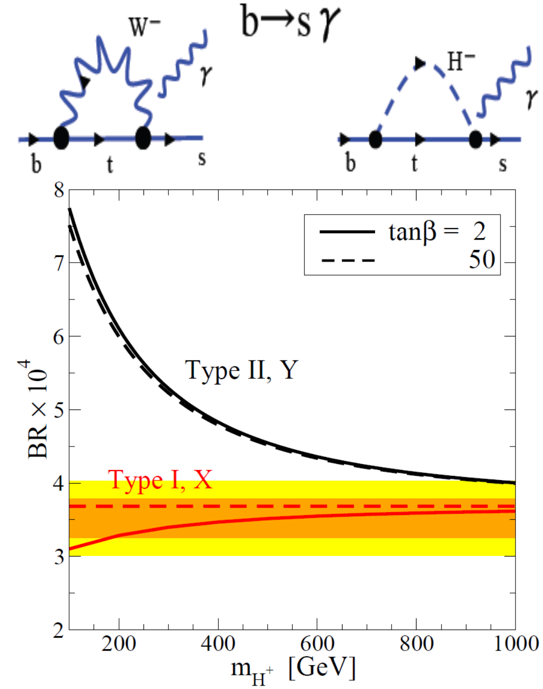
Barger, Hewett, Phillips

Classified by Z_2 charge assignment

Four Types of Yukawa coupling



Type of 2HDM

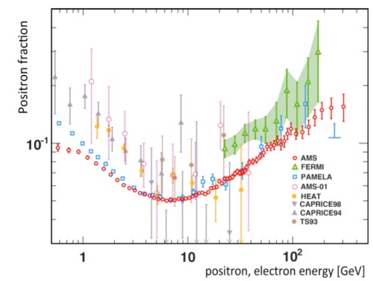


Aoki, SK, Tsumura, Yagyu (09)

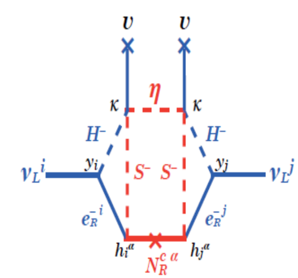
Type-I Fermiofobic 2HDM
Neutrinophillic 2HDM

Type-II MSSM, NMSSM, other
Extended SUSY Higgs models

Type-X Lepton-specific 2HDM
Radiative Neutrino mass
Positron Excess
H portal DM (tau spesific)

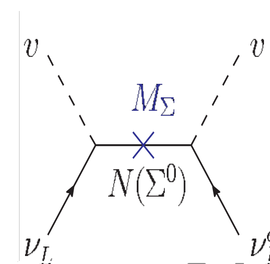


Goh, Hall, Kumar (09)



Aoki, SK, Seto (09)

Type-Y Flipped 2HDM



Ma (02)

Search for Extended Higgs sectors

Many new physics models predict non-minimal Higgs sectors

Experimental determination of the Higgs sector is the Key to clarify the EWSB and also to explore new physics!

- **Direct Search**
  - **Discovery of the “second” Higgs boson at LHC**
- **Indirect Search (find deviation in Higgs couplings)**
  - **How we can extract the shape of the Higgs sector from detailed measurement of the 126GeV SM-like Higgs boson *h*?**
  - **It is a solid target!**

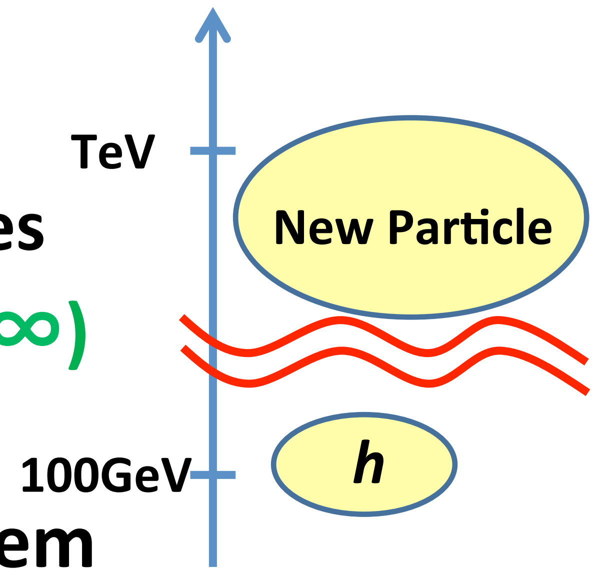
Decoupling/Non-decoupling

- **Decoupling Theorem**

  Appelquist-Carazzone 1975

  New phys. loop effect in observables

  $1/M^n \rightarrow 0$ **(decouple for $M \rightarrow \infty$)**



- **Violation of the decoupling theorem**
  - **Chiral fermion loop (ex. Top, 4th gen.)**

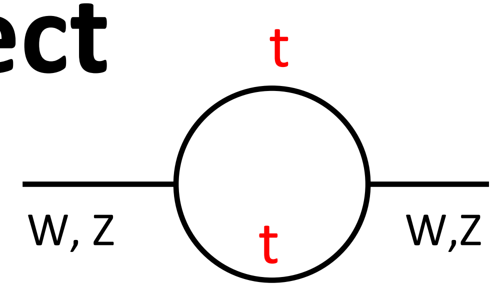
    $$m_f = y_f v$$

  - **Boson loop (ex. H^+ in non-SUSY 2HDM)**

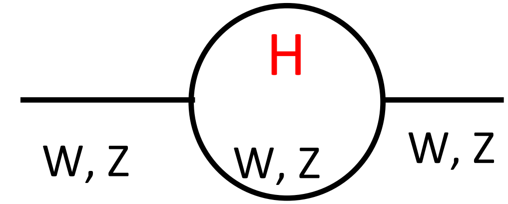
    $$m_\Phi^2 = \lambda_i v^2 + M^2 \quad (\text{when } \lambda v^2 > M^2)$$

Non-decoupling effect

Non-decoupling effect



Example (Electroweak *T* parameter)



$$\rho = \frac{m_W}{m_Z \cos\theta_W}, \quad \Delta\rho = \rho - 1 = \alpha T$$

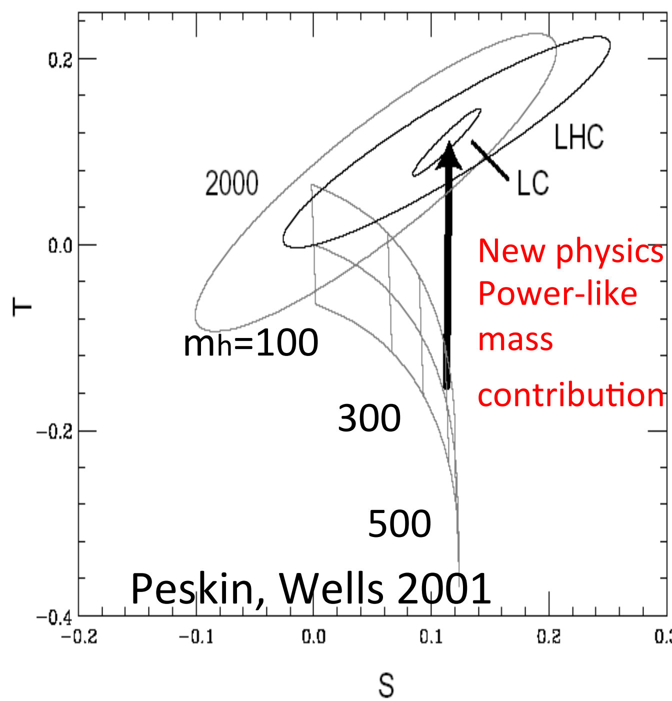
Data $|T| < 0.1$

$$\Delta T_{\text{top}} \propto \frac{m_t^2}{M_W^2}$$

$$\Delta T_{\text{Higgs}} \simeq - \ln \frac{m_H^2}{M_W^2}$$ (SM)

$$\Delta T_{\text{Higgs}} \sim - \ln \frac{m_h^2}{M_W^2} + \frac{(m_A^2 - m_{H\pm}^2)^2}{M_W^2 m_A^2}$$

(2HDM)

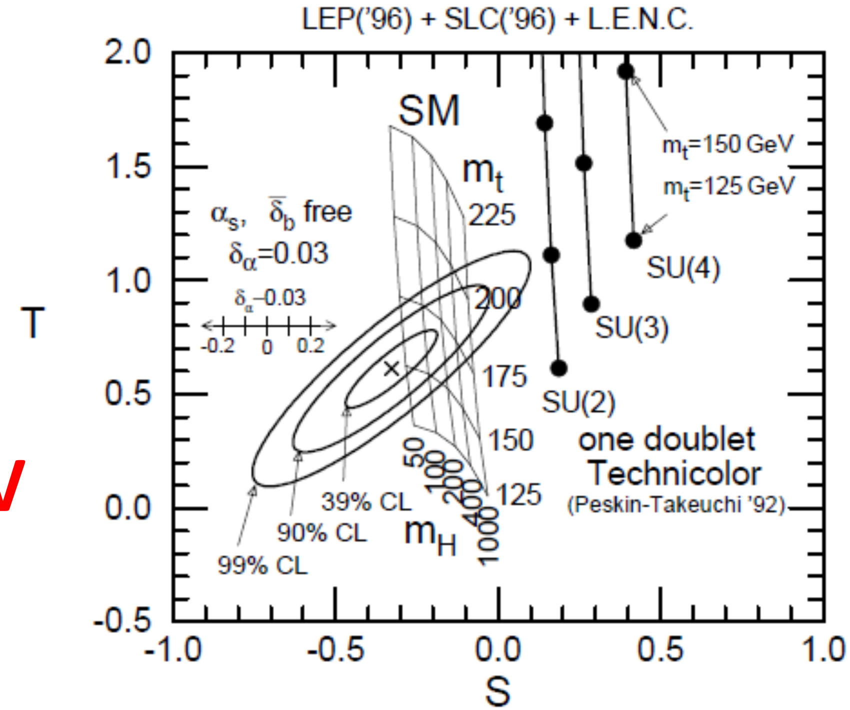


Quadratic mass contribution
(non-decoupling effect)

We knew the mass before discovery!

Case of the top quark

- Quadratic mass dep. in ρ parameter (T parameter)
- Forget about m_H because it is only logarithmic
- LEP1 says m_t=150-200GeV
- Discovery at Tevatron （about 175GeV）



Hagiwara、et al

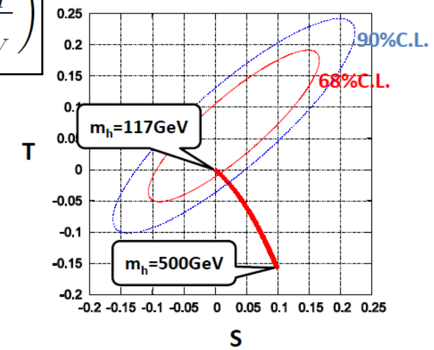
$$\Delta\rho \simeq \frac{3G_F}{8\sqrt{2}\pi^2}\left(m_t^2 - M_Z^2 \sin^2\theta_W \ln\frac{m_H^2}{m_W^2}\right)$$

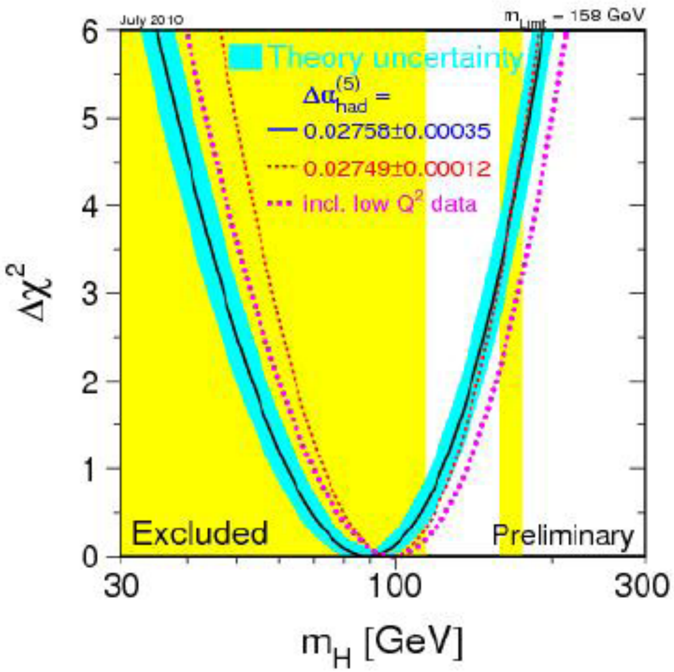
It was repeated for Higgs at LEP2

$$\Delta\rho \simeq \frac{3G_F}{8\sqrt{2}\pi^2}\left(m_t^2 - M_Z^2 \sin^2\theta_W \ln\frac{m_H^2}{m_W^2}\right)$$

Case of Higgs boson

- Now we know top mass
- Rho is a funcution of only m_H
- Precision measurement at LEP2
- 114GeV< mH <150 GeV!
- LHC found new boson at 126 GeV（Higgs boson!）





LEP Electroweak Working Group 2010

Victory of precision measurements and theory calculations

（VIVA! SM）

All SM parameters are found

Next target is new physics!

- **Importance of Radiative Correction calculation**
- **Future precision measurements**
  - ***S, T, U*** **(Giga Z, Mega W)**
  - **Top (e.g. ttZ) couplings**
  - **Couplings of the discovered Higgs**

hgg, hγγ, hWW, hZZ, htt, hbb, hττ, hμμ, hcc, …, hhh

At ILC, we may be able to distinguish models by detecting a pattern of deviations in the *h* couplings from the SM values!

Fingerprinting new physics models

Snowmass White Paper (Aug. 2013)

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%	$-/5.5/<5.5\%$	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.13%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.44%	0.22%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%	$3.5/1.4/<1.3\%$	0.51%
κ_d	$10-13\%$	$4-7\%$	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
κ_u	$14-15\%$	$7-10\%$	2.5%	1.3%	1.3%	0.76%	3.1/1.0/0.7%	0.69%

$g(hxx)=\kappa_x\, g(hxx)_{SM}$

ILC Higgs White Paper

Asner, Barklow, Fujii, Haber, Kanemura, Miyamoto, Weiglein, et al.

	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250	250+500	250+500+1000	250+500+1000
L (fb^{-1})	250	250+500	250+500+1000	1150+1600+2500
$\gamma\gamma$	17 %	8.3 %	3.8 %	2.3 %
gg	6.1 %	2.0 %	1.1 %	0.7 %
WW	4.7 %	0.4 %	0.3 %	0.2 %
ZZ	0.7 %	0.5 %	0.5 %	0.3 %
$t\bar{t}$	6.4 %	2.5 %	1.3 %	0.9 %
$b\bar{b}$	4.7 %	1.0 %	0.6 %	0.4 %
$\tau^+\tau^-$	5.2 %	1.9 %	1.3 %	0.7 %
$\Gamma_T(h)$	9.0 %	1.7 %	1.1 %	0.8 %
$\mu^+\mu^-$	91 %	91 %	16 %	10 %
hhh	–	83 %	21 %	13 %
BR(invis.)	< 0.7 %	< 0.7 %	< 0.7 %	< 0.3 %
$c\bar{c}$	6.8 %	2.9 %	2.0 %	1.1 %

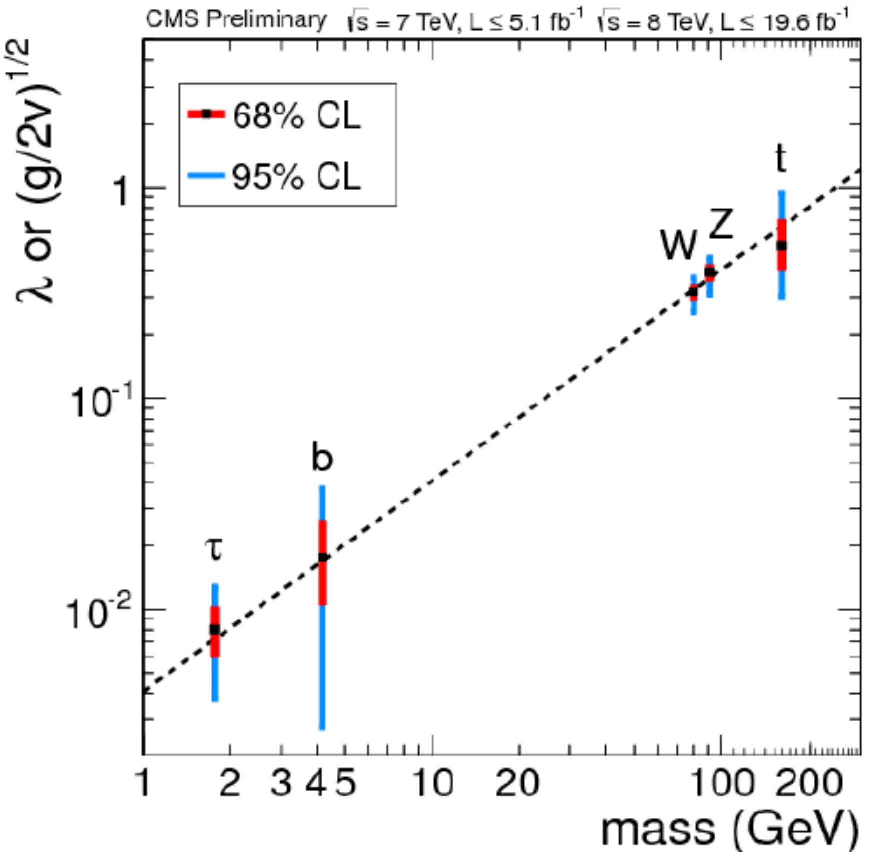
Future measurement of Higgs Couplings

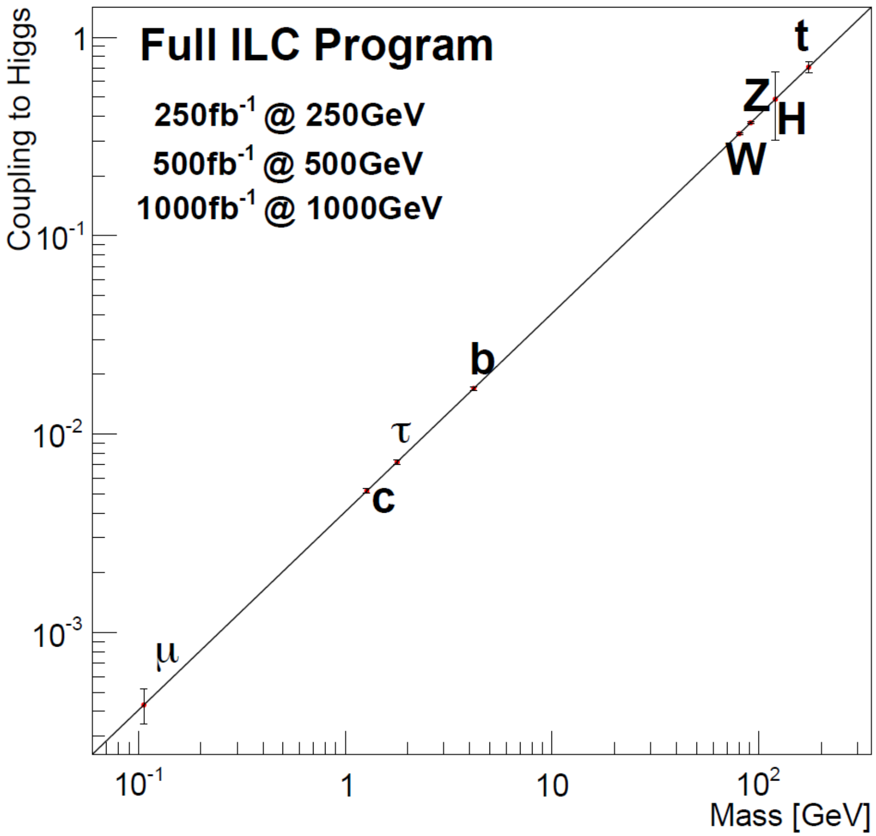
Facility	LHC	HL-LHC	ILC500	ILC500-up
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500
$\int \mathcal{L} dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$	0.93%	0.60%
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$	2.5%	1.3%

Snowmass Report
1310.8361

Coupling constants can be typically
Measured with better than 1 % at ILC

Current LHC data v.s. Full ILC





The precision must be improved in future at LHC 13-14 TeV and at the LC

The ILC is really needed!

Type2-2HDM (MSSM) Higgs couplings

VEV's: $v_1^2 + v_2^2 = v^2 \simeq (246\ \mathrm{GeV})^2$

Higgs mixing

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

$$\tan\beta = \frac{v_2}{v_1}$$

SM		2HDM Type2	
		hVV	HVV
Gauge coupling: $\phi VV \quad (V = Z, W)$	$\Rightarrow$	$\sin(\beta-\alpha)$,	$\cos(\beta-\alpha)$
		$hb\bar{b}$	$Hb\bar{b}$
Yukawa coupling: $\phi b\bar{b}$	$\Rightarrow$	$\frac{\sin\alpha}{\cos\beta}$,	$\frac{\cos\alpha}{\cos\beta}$
		$ht\bar{t}$	$Ht\bar{t}$
$\phi t\bar{t}$	$\Rightarrow$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\sin\alpha}{\sin\beta}$,

SM-like regime

hVV	HVV
$\sin(\beta-\alpha)$	$\cos(\beta-\alpha)$

$$\sin(\beta-\alpha) \simeq 1$$

Only the lightest Higgs *h* couples to weak gauge bosons

h **behaves like the SM Higgs**

$$g_{hVV} \rightarrow g^{\mathrm{SM}}_{\phi VV} \qquad g_{HVV} \rightarrow 0$$

$$y_{ht\bar{t}} \rightarrow y^{\mathrm{SM}}_{\phi t\bar{t}} \qquad y_{Ht\bar{t}} \rightarrow y^{\mathrm{SM}}_{\phi t\bar{t}} \cot\beta$$

$$y_{hb\bar{b}} \rightarrow y^{\mathrm{SM}}_{\phi b\bar{b}} \qquad y_{Hb\bar{b}} \rightarrow y^{\mathrm{SM}}_{\phi b\bar{b}} \tan\beta$$

$$y_{h\tau\tau} \rightarrow y^{\mathrm{SM}}_{\phi\tau\tau} \qquad y_{H\tau\tau} \rightarrow y^{\mathrm{SM}}_{\phi\tau\tau} \tan\beta$$

Type-II 2HDM (applies to the H Yukawa couplings above)

Gauge Couplings *hVV*

$L = g_{hVV} \sin(\beta-\alpha)\, hVV + g_{HVV} \cos(\beta-\alpha)\, HVV$

- Changed by mixing with the other scalars

$$\frac{g_{hVV}^{\rm THDM}}{g_{hVV}^{\rm SM}} = \sin(\beta-\alpha)$$

- Sum-rule for a multi-doublet structure
  $g_{hVV}^2 + g_{HVV}^2 = g_V^2$

SM-like case
$\sin^2(\beta-\alpha) \approx 1$

$\sin^2(\beta-\alpha) < 1 \Leftrightarrow \kappa_V^2 = (g_{hVV}/g_{hVV}^{SM})^2 < 1$

- Higgs sector with an exotic representation
  $\kappa_V^2 > 1$ is also possible!

Higgs triplet model
Georgi-Machasek model
Models with a septet field, …

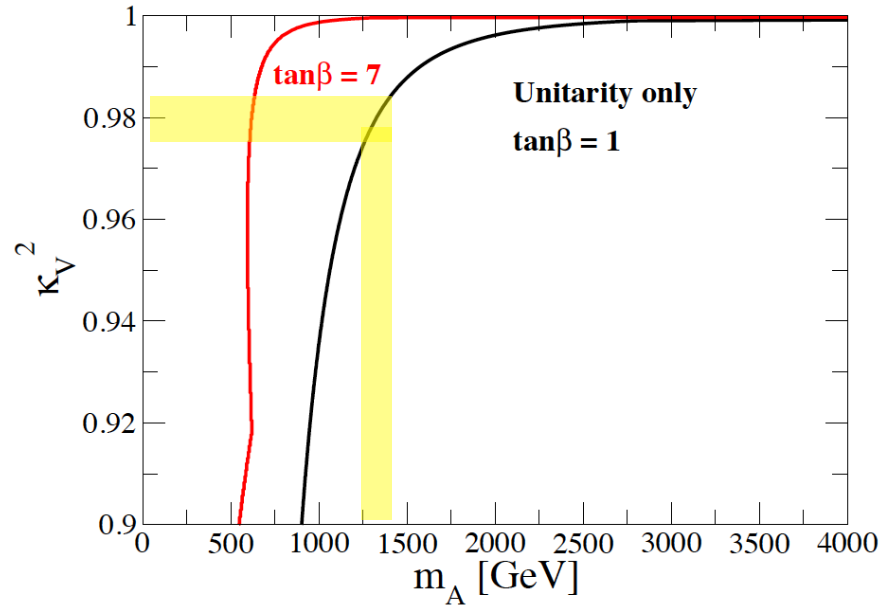
Unitarity in Non-SUSY 2HDM

$\kappa_V^2 = \sin^2(\beta-\alpha)$

If κ_V^2 is found to be less than 1, the upper bound on the mass of the second Higgs is obtained

Φ_1 *and* Φ_2 share v=246 GeV

$v_1^2 + v_2^2 = v^2$

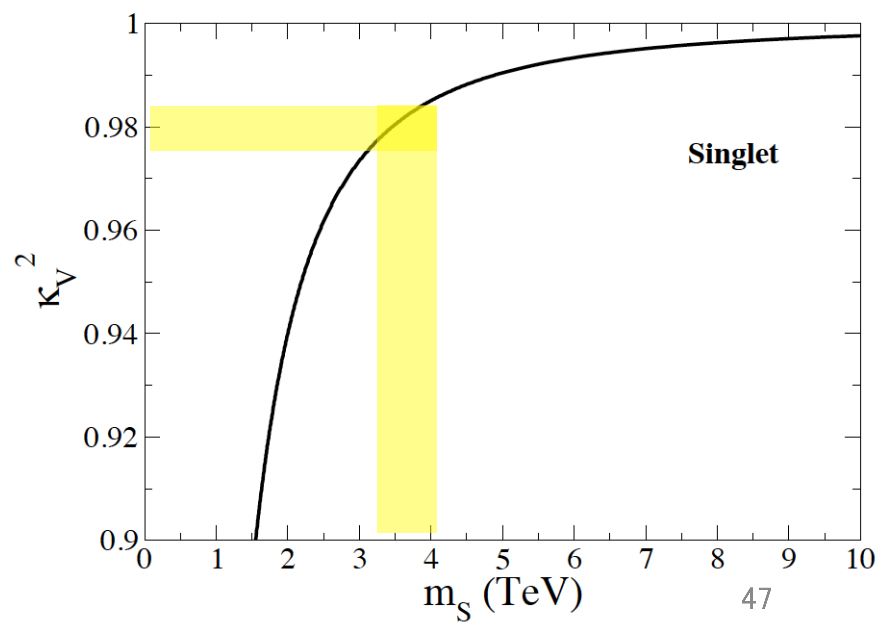


In Higgs Singlet model (Φ+S)

$\kappa_V^2 = \cos^2\theta$

Situation is similar, but the bound is much relaxed

S has the VEV but it does not share v (= 246 GeV)

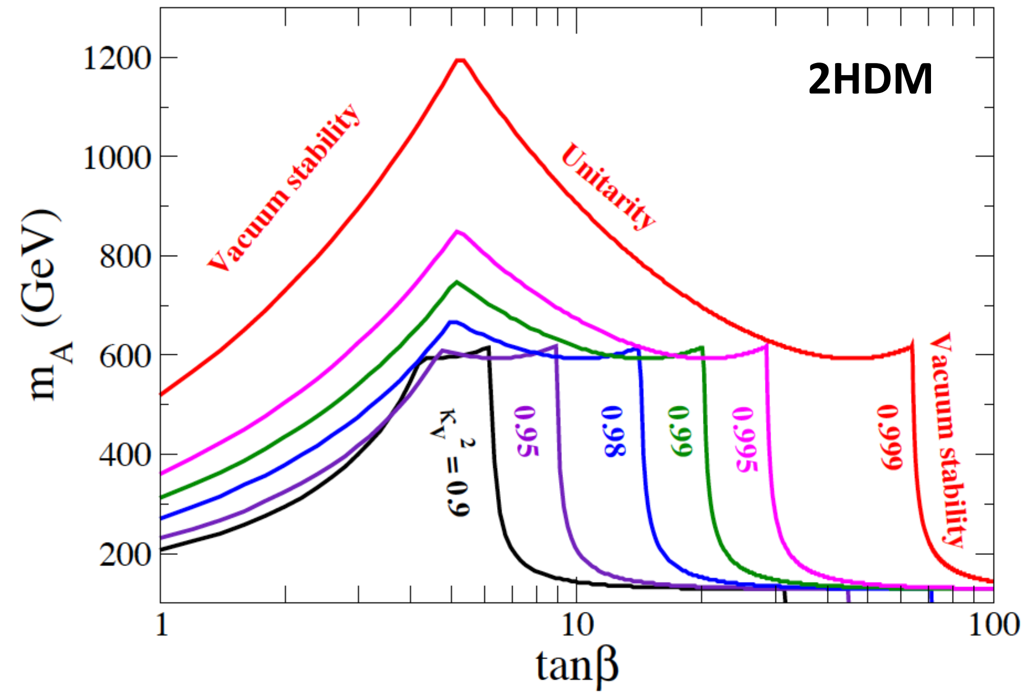


Theoretical upper bounds on the second Higgs mass, when $\kappa_V^2 < 1$

If measured κ_V^2 is slightly smaller than 1 (say, 0.99), the second Higgs must be lighter than 700 GeV.

Then, if no second Higgs is found below 700 GeV, the 2HDM is excluded

The rest possibility may be the Higgs singlet model, or other exotics



Precision determination of *hVV* coupling is very important

Pattern in deviations of g_{hVV} and Y_{hff}

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

cos(β-α) < 0

Singlet can be distinguished from the Type-I 2HDM

Y_{hff}/g_V=1 in the singlet model but $Y_{hff}/g_V \neq 1$ in the 2HDM-I

In the triplet model, quark-Yukawa couplings are universally smaller, Lepton-Yukawa deviate universal. **κ_V can be greater than 1**

$\kappa_V > 1$ is a signature of exotic Higgs (with higher representations)

Extended Higgs models are distinguishable by precisely measuring *hVV* and *hff*

Fingerprinting the 2HDM (tree level)

$$\kappa_V \equiv \frac{g_{hVV(2HDM)}}{g_{hVV(SM)}} = \sin(\beta - \alpha)$$

$x = \cos(\beta - \alpha)$ **SM-like: $x \ll 1$**

$$\kappa_V = 1 - (1/2)\, x^2 + \ldots$$

When a Fermion couples to Φ_1

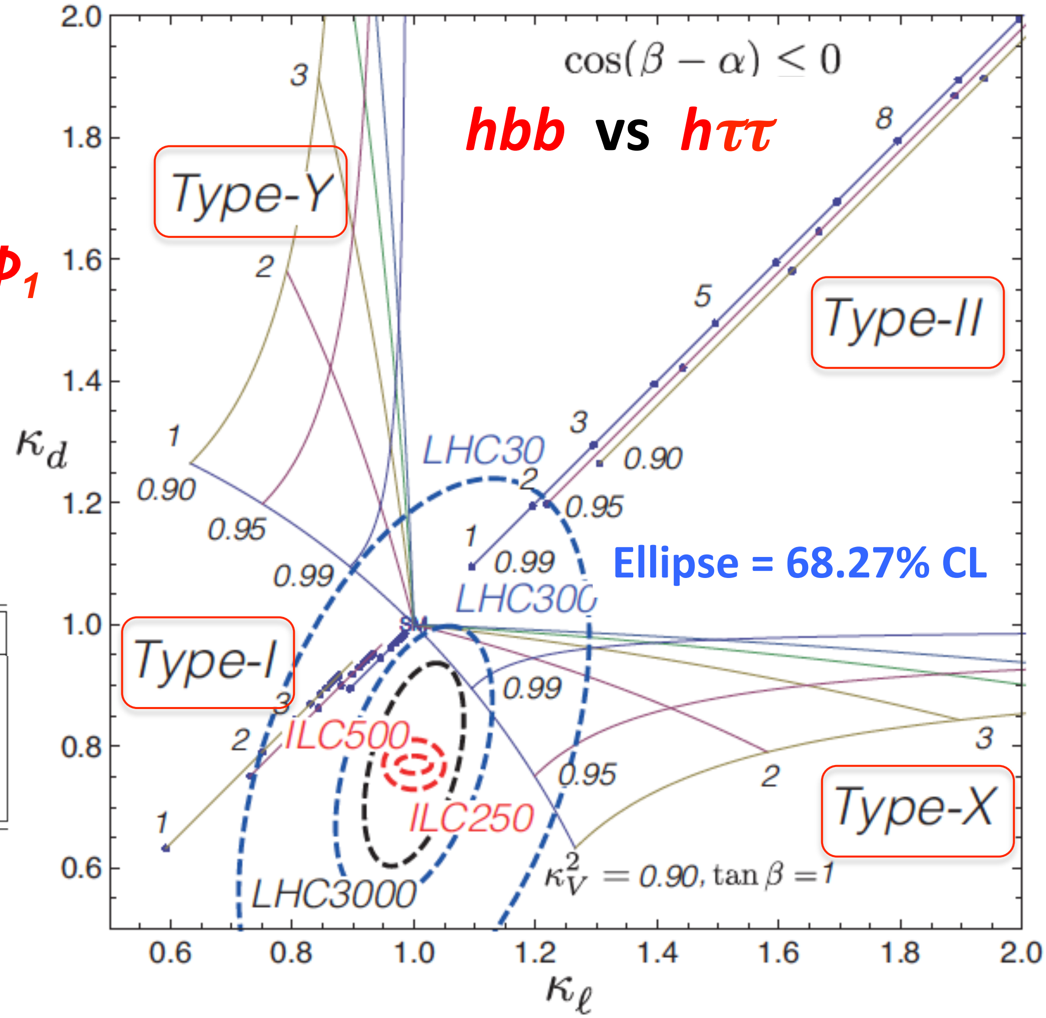
$$\kappa_f = 1 + \cot\beta\; x + \ldots$$

and if it couples to Φ_2

$$\kappa_f = 1 - \tan\beta\; x + \ldots$$

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

SK, K. Tsumura, K. Yagyu, H. Yokoya 2014
ILC Higgs White Paper 2013



How do this result change with radiative corrections?

Fingerptinting the model (Exotics)

SK, K. Tsumura, K. Yagyu, H. Yokoya 2013

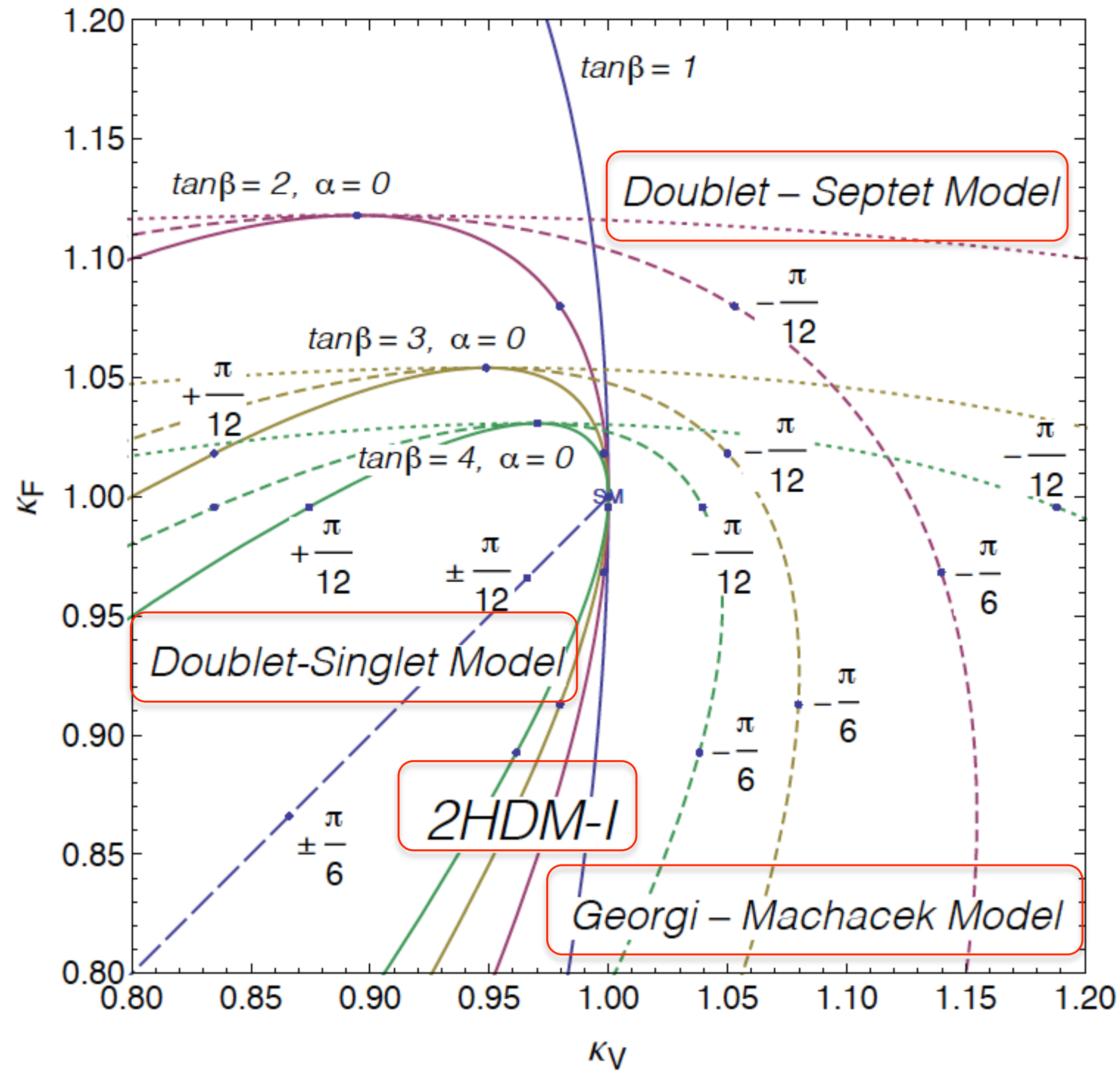
Universal Fermion Coupling (κ_F)

VS

***hVV* coupling (κ_V)**

Exotic models predict $\kappa_V > 1$

We can discriminate Exotic models



Fingerptinting the model (Exotics)

SK, K. Tsumura, K. Yagyu, H. Yokoya 2013

Universal Fermion Coupling (κ_F)

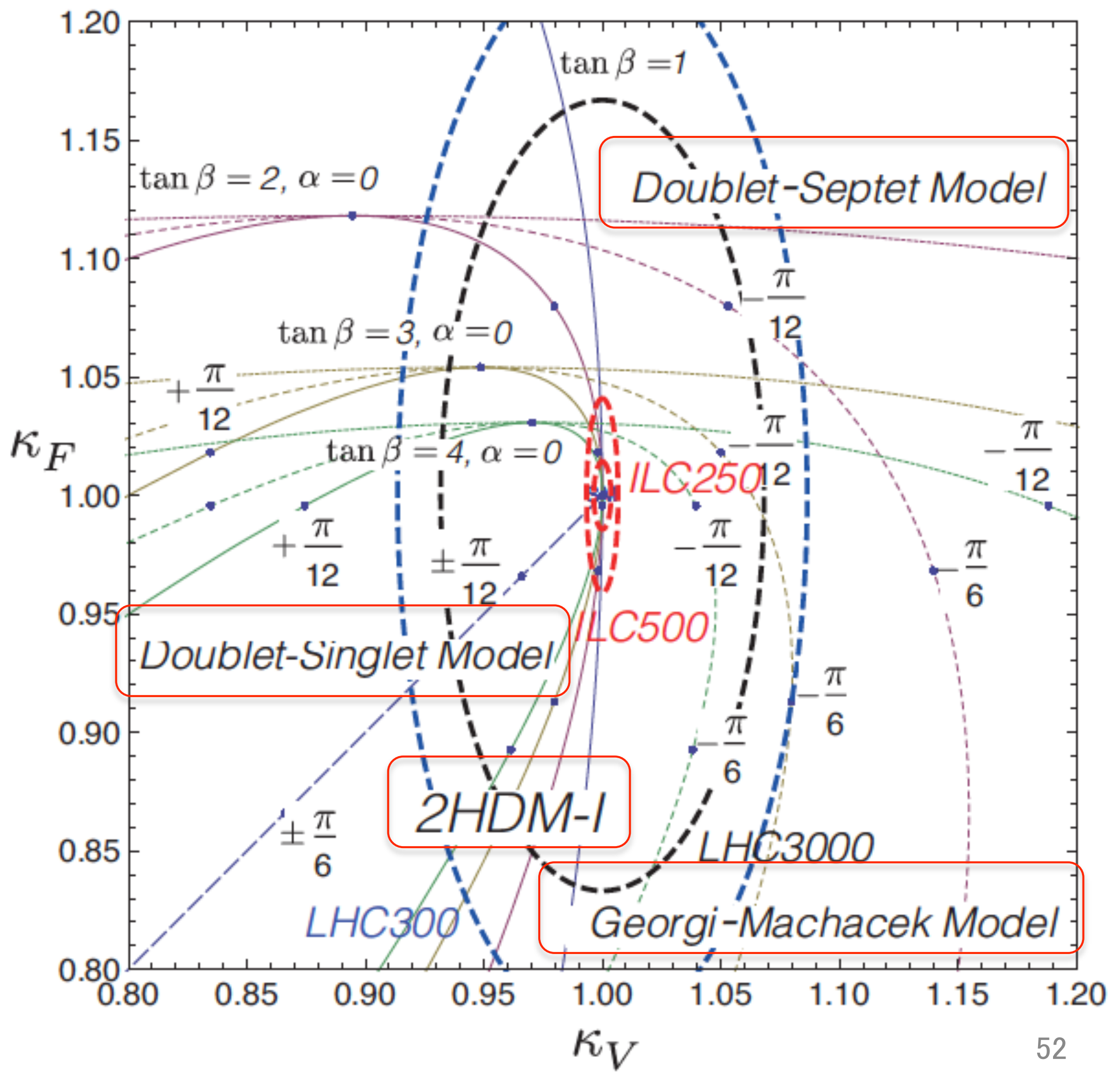
VS

***hVV* coupling (κ_V)**

Exotic models predict $\kappa_V > 1$

We can discriminate Exotic models

Ellipse = 68.27% CL



Higgs as a Pseudo NG boson

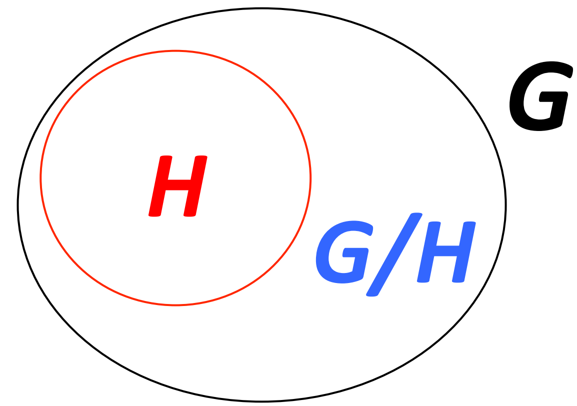
Agashe, Contino, Pamarol, Nucl.Phys.B719

Contino, arXiv.1005.4269

Minimal Higgs Composite Models

G/H = SO(5)/SO(4): # of pNGB = 10-6=4

Decay constant *f*



pNGB:
Higgs field

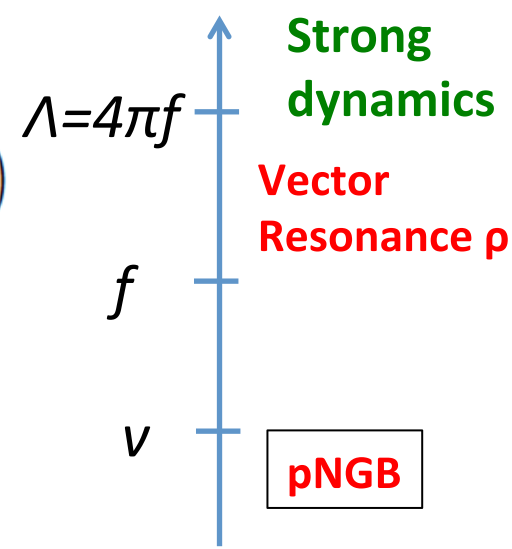
$$\Sigma = \frac{\sin(h/f)}{h}(h^1, h^2, h^3, h^4, h\cot(h/f))$$

$U(1)x \times SO(4) = U(1)_X \times SU(2)_L \times SU(2)_R$

↓ EWSB by CW potential

$U(1)_{em}$ $\langle\Sigma\rangle = \left(0,\ 0,\ \sqrt{\xi},\ 0,\ \sqrt{1-\xi}\right)$

$\xi = v^2/f^2$



Non-linear structure gives

$$f_\pi^2 \sin^2\frac{h}{f_\pi} = v^2 + 2v\sqrt{1-\xi}\hat{h} + (1-2\xi)\hat{h}^2 + \cdots$$

This deviates the Higgs boson couplings

Deviation in *hff*

If $\Delta\kappa_V = 1\,\%$

Singlet, Exotics,

$\Delta\kappa_u = -(1/2)\,x^2$, $\Delta\kappa_d = -(1/2)\,x^2$, $\Delta\kappa_\tau = -(1/2)\,x^2$ O(1) %

Type I 2HDM

$\Delta\kappa_u = +\cot\beta\, x$, $\Delta\kappa_d = +\cot\beta\, x$, $\Delta\kappa_\tau = +\cot\beta\, x$ O(10) %

Type X (Lepton Specific) 2HDM

$\Delta\kappa_u = +\cot\beta\, x$, $\Delta\kappa_d = +\cot\beta\, x$, $\Delta\kappa_\tau = -\tan\beta\, x$ O(10) %

MSSM (Type II 2HDM)

$\Delta\kappa_u = +\cot\beta\, x$, $\Delta\kappa_d = -\tan\beta\, x$, $\Delta\kappa_\tau = -\tan\beta\, x$ O(10) %

MCHM4

$\Delta\kappa_u = -(1/2)\,x^2$, $\Delta\kappa_d = -(1/2)\,x^2$, $\Delta\kappa_\tau = -(1/2)\,x^2$ O(1) %

MCHM5

$\Delta\kappa_u = -(3/2)\,x^2$, $\Delta\kappa_d = -(3/2)\,x^2$, $\Delta\kappa_\tau = -(3/2)\,x^2$ O(1) %

Radiative Corrections

In future, the Higgs couplings will be measured with much better accuracies

Clearly, tree level analyses are not enough

Analysis with Radiative Corrections (including quantum effect of the 2nd Higgs/BSM particles) is necessary

Theoretical predictions at loop levels × **Precision measurements at future colliders**

⬇

New Physics !

Scale Factors (1-loop level) in 2HDM

Mixing parameter x = cos(β−α) $\left[\sin(\beta-\alpha) = 1 - \frac{x^2}{2}\right]$ **SM-like x << 1**

Scale Factor of the *hVV* Couplings

$\Delta\kappa_X = \kappa_X - 1$

$$\Delta\hat{\kappa}_V \simeq -\frac{1}{2}x^2 - \underline{A(m_\Phi^2, M^2)}$$

mixing loop

Loop Effect

$$A(m_\Phi, M) = \frac{1}{16\pi^2}\frac{1}{6}\sum_\Phi c_\Phi \frac{m_\Phi^2}{v^2}\left(1 - \frac{M^2}{m_\Phi^2}\right)^2$$

$m_\Phi^2 = M^2 + \lambda_i v^2$
$(\Phi = H^\pm, A, H)$

where

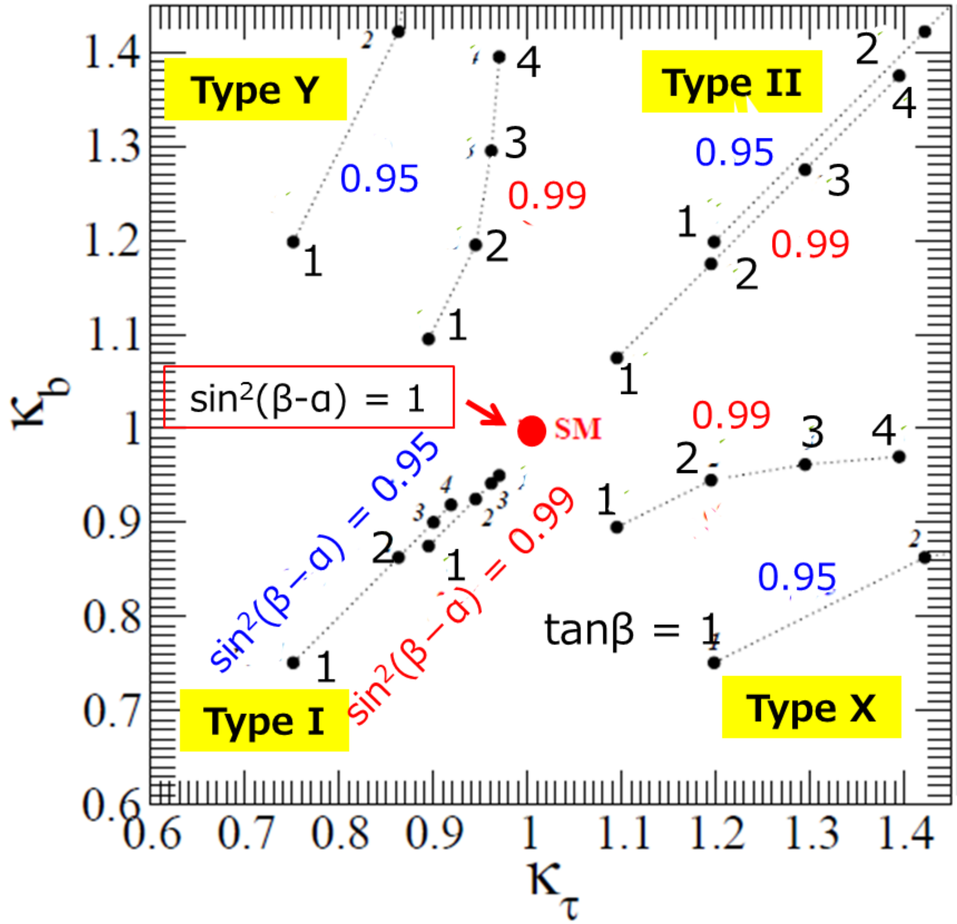
$$m_\Phi^2\left(1 - \frac{M^2}{m_\Phi^2}\right)^2 \begin{cases} \propto \dfrac{1}{m_\Phi^2} & (M \gg v) \\ \propto m_\Phi^2 & (M \sim v) \end{cases}$$

Decoupling! ($M >> v$)

Non-decoupling! ($M \sim v$)

Which Yukawa Type ? (tree)

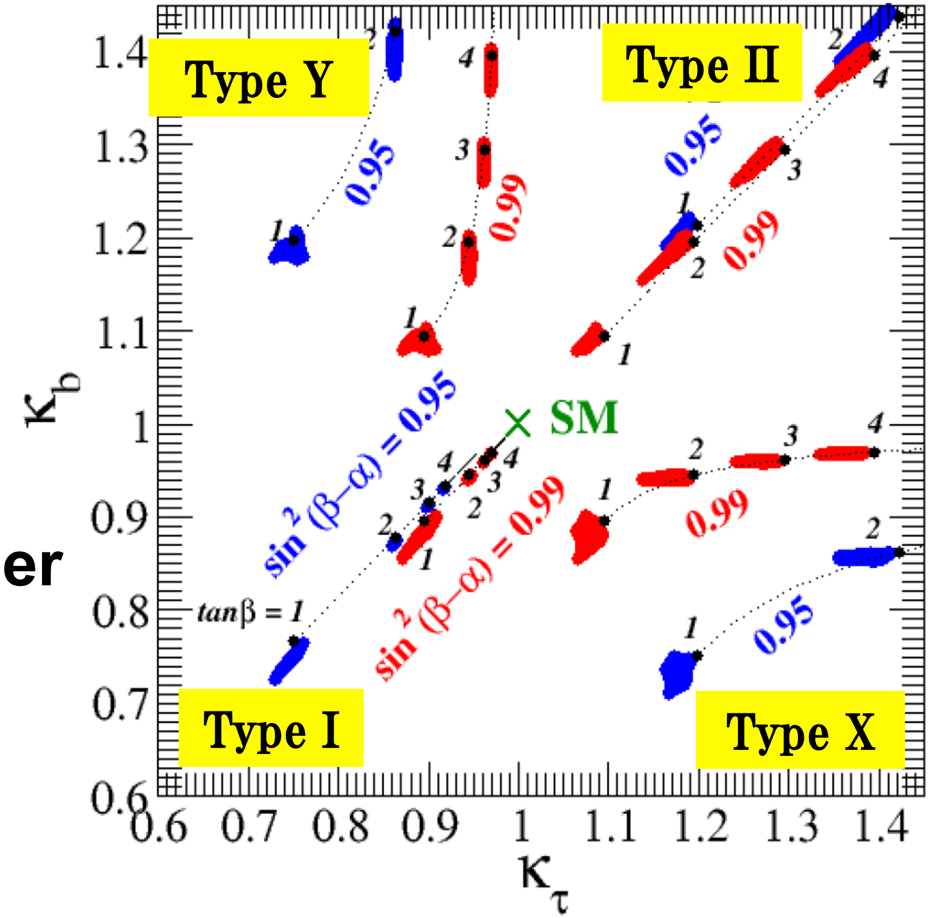
Model	μ	τ	b	c	t	g_V
Singlet mixing	↓	↓	↓	↓	↓	↓
2HDM-I	↓	↓	↓	↓	↓	↓
2HDM-II (SUSY)	↑	↑	↑	↓	↓	↓
2HDM-X (Lepton-specific)	↑	↑	↓	↓	↓	↓
2HDM-Y (Flipped)	↓	↓	↑	↓	↓	↓



What is going on with radiative correction?

Which Yukawa Type ? (loop)

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



Evaluation at one-loop

Scan of inner parameters under theoretical and experimental constraints (for each tanβ)

The separation of type can also be done at loop level !

S.K., M. Kikuchi, K. Yagyu, PLB731 (2014) 27

Slide by
Mariko Kikuchi

Extraction of parameters

In the future,
how much precise can we extract values of inner parameters by using LHC3000 and ILC500 data ?

Case A

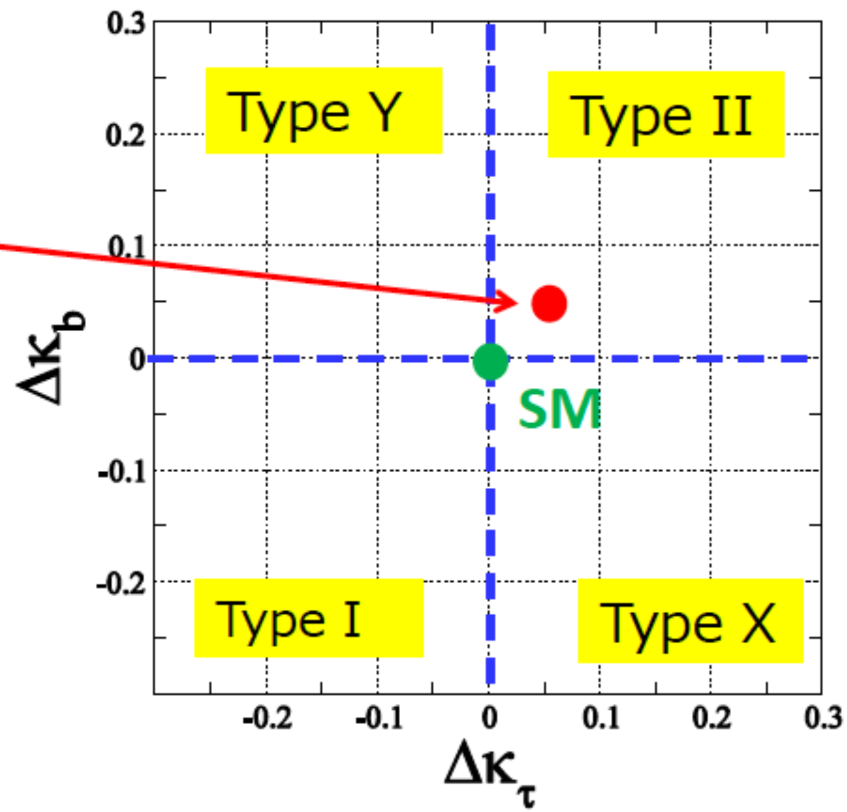
	LHC3000	ILC500	1σ
$\Delta\hat{\kappa}_V = -2.0$	±2.0	±0.4%	
$\Delta\hat{\kappa}_\tau = +5$	±2.0	±1.9%	
$\Delta\hat{\kappa}_b = +5$	±4.0	±0.9%	

Errors are from ILC(500) *in Snowmass 2014 Rep.*

Type-II

We survey parameter regions by scanning inner parameters

x, $\tan\beta$, m_Φ, M



Φ = H^+, H, A

Extraction of parameters

$$x = \cos(\beta - \alpha)$$

$$\Delta\hat{\kappa}_\tau - \Delta\hat{\kappa}_V \simeq -\tan\beta\, x$$

Input

Errors are from ILC(500)
in Snowmass 2014 Rep.

$$\eta = 1 - \frac{M^2}{m_\Phi^2}$$

Case A

		LHC3000	ILC500
$\Delta\hat{\kappa}_V$	= -2.0	±2.0	±0.4%
$\Delta\hat{\kappa}_\tau$	= +5	±2.0	±1.9%
$\Delta\hat{\kappa}_b$	= +5	±4.0	±0.9%

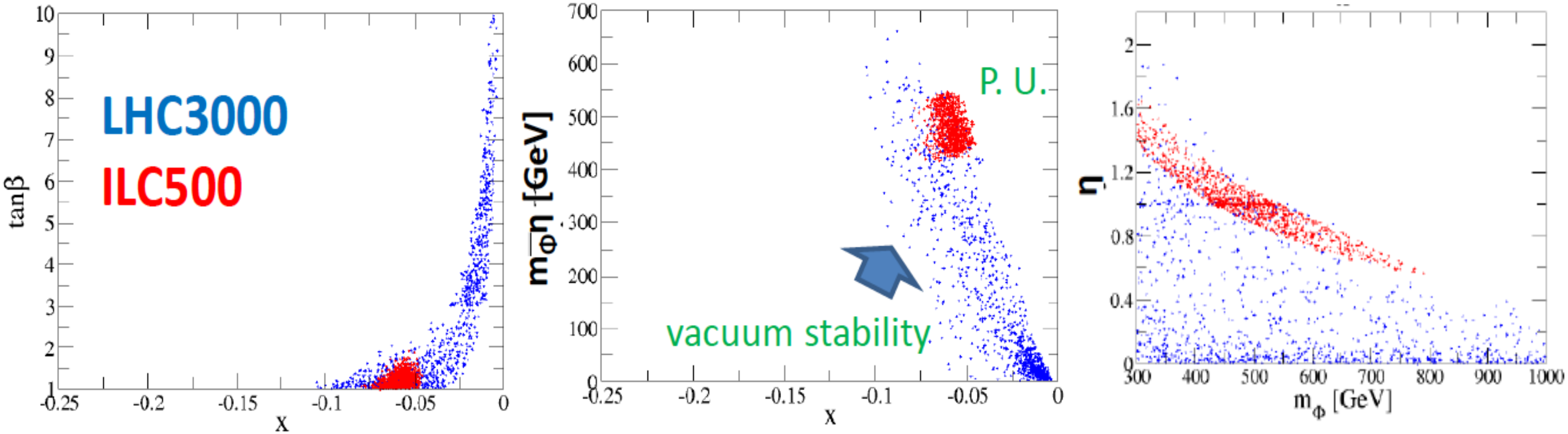
$$\Delta\hat{\kappa}_V \simeq -\frac{1}{2}x^2 - A(m_\Phi^2, M^2)$$

$$A(m_\Phi, M) = \frac{1}{16\pi^2}\frac{1}{6}\sum_\Phi c_\Phi \frac{1}{v^2}\left\{m_\Phi\left(1 - \frac{M^2}{m_\Phi^2}\right)\right\}^2$$

$$(\Phi = H^\pm, A, H)$$

Errors are from ILC(500)
in Snowmass 2014 Rep.

Type-II



New mass scale can be extracted! m_Φ < 800 GeV

In addition to the type, parameters x and tanβ can be extracted !!

Self-Coupling Constant

It is very important to know *hhh* coupling to reconstruct the Higgs potential

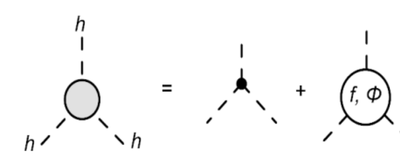
$$V_{\text{Higgs}} = \frac{1}{2}\underline{m_h^2} h^2 + \frac{1}{3!}\underline{\lambda_{hhh}} h^3 + \frac{1}{4!}\lambda_{hhhh} h^4 + \cdots$$

Effective Potential

$$V_{\text{eff}}(\varphi) = -\frac{\mu_0^2}{2}\varphi^2 + \frac{\lambda_0}{4}\varphi^4 + \sum_f \frac{(-1)^{2s_f} N_{C_f} N_{S_f}}{64\pi^2} m_f(\varphi)^4 \left[\ln\frac{m_f(\varphi)^2}{Q^2} - \frac{3}{2}\right]$$

Renoramalization

$$\left.\frac{\partial V_{\text{eff}}}{\partial\varphi}\right|_{\varphi=v} = 0, \quad \left.\frac{\partial^2 V_{\text{eff}}}{\partial\varphi^2}\right|_{\varphi=v} = m_h^2, \quad \left.\frac{\partial^3 V_{\text{eff}}}{\partial\varphi^3}\right|_{\varphi=v} = \lambda_{hhh}$$



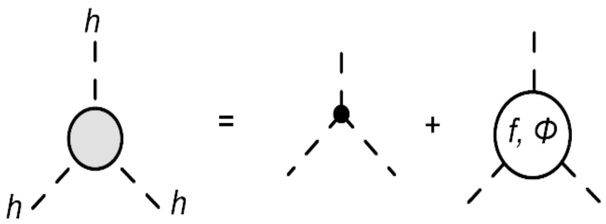
Top loop Effect in the SM

$$\lambda_{hhh}^{\text{SMloop}} \sim \frac{3m_h^2}{v}\left(1 - \frac{N_c m_t^4}{3\pi^2 v^2 m_h^2} + \cdots\right)$$

Non-decoupling effect

Case of Non-SUSY 2HDM

- Consider when the lightest *h* is SM-like [sin(β−α)=1]
- At tree, the *hhh* coupling takes the same form as in the SM
- At 1-loop, non-decoupling effect $m_\Phi{}^4$ (If *M* < *v*)



Φ = *H*, *A*, *H*±

SK, Kiyoura, Okada, Senaha, Yuan, PLB558 (2003)

$$\lambda_{hhh}^{\rm 2HDM} \simeq \frac{3m_h^2}{v}\left[1+\frac{m_\Phi^4}{12\pi^2 m_h^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3-\frac{m_t^4}{\pi^2 v^2 m_h^2}\right]$$

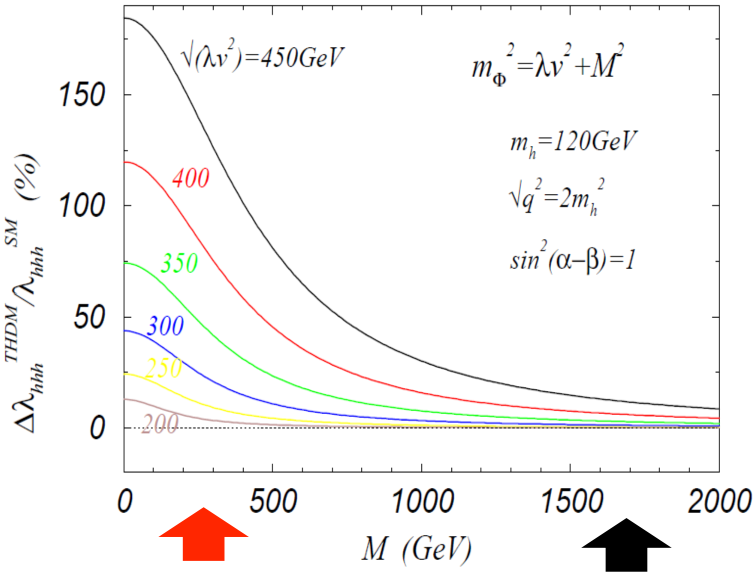
Extra scalar loop

Top loop

$$m_\Phi^2 = M^2 + \lambda_i v^2$$

(Φ = *H*, *A*, *H*±)

Correction can be huge 〜 100%



Non-decoupling effect

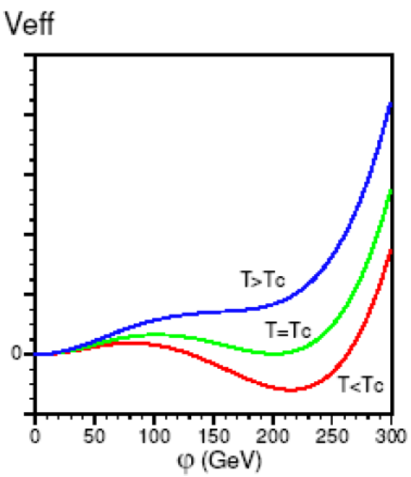
Decoupling

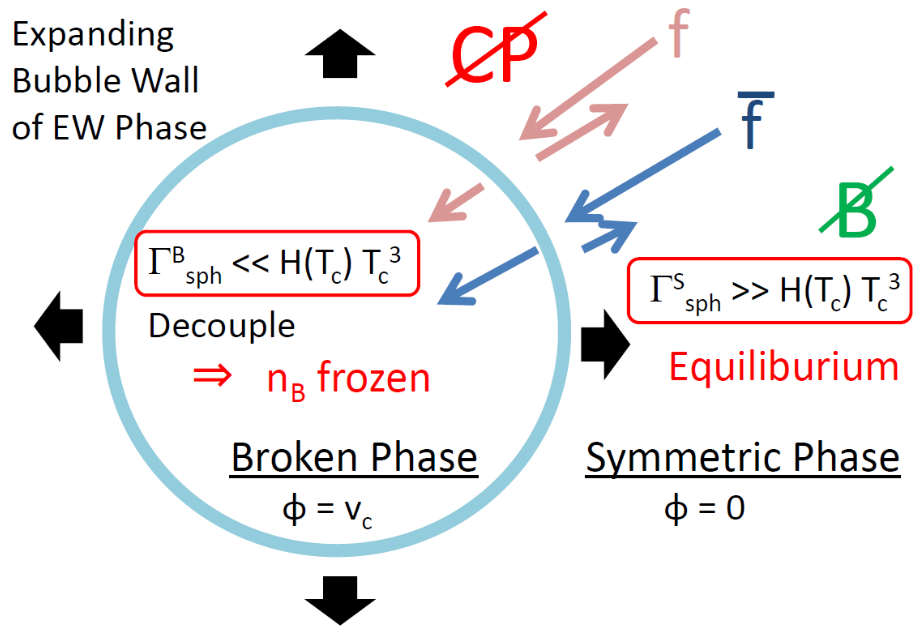
Electroweak Baryogenesis

$$\Gamma \sim e^{-E_{\text{sph}}/T} \quad (T < T_c)$$
$$\Gamma \sim \kappa(\alpha_W T)^4 \quad (T_c < T)$$

Sakharov's conditions:

- B Violation → Sphaleron transition at high *T*
- C and CP Violation → CP Phases in extended scalar sector
- Departure from Equilibrium → 1st Order EW Phase Transition





Quick sphaleron decoupling is required to retain sufficient baryon number in Broken Phase

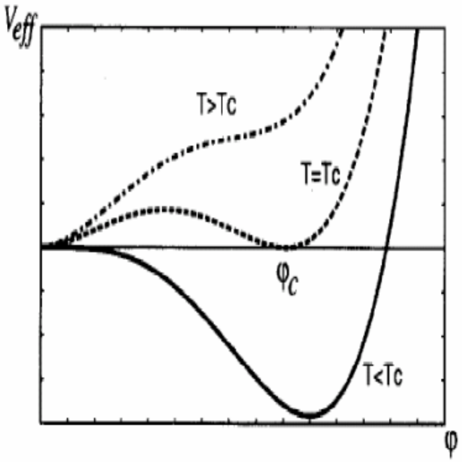
(Sphaleron Rate) < (Expansion Rate) ⇒ $\boldsymbol{\varphi_c / T_c > 1\text{-}1.4}$

Condition of Strong 1st OPT ($\varphi_c/T_c > 1$)

Finite Temperature Potential

$$V_T(\phi,T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda_T}{4}\phi^4 + \ldots$$

$$\phi_c/T_c > 1 \Rightarrow 2E/\lambda_{T_c} > 1$$



EWBG was ruled out in the SM

$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3) \quad \Rightarrow \quad m_h \ll 125 \text{ GeV}$$

Contradiction with LHC results

Muti-Higgs models can satisfy the condition

$$E = \frac{1}{12\pi v^3}(2m_W^3 + m_Z^2 + m_H^3 + m_A^3 + 2m_{H^\pm}^3).$$

Thermal loop effect by additional Higgs boson

In order to satisfy $\phi_c/T_c > 1$ with m_h=125GeV, Extension of the Higgs sector is necessary

EW Baryogenesis and the *hhh* coupling

SK, Okada, Senaha (2005)

Higgs Potential at Finite Temperatures

$$V_T(\phi,T) = D(T^2 - T_0^2)\phi^2 - ET\phi^3 + \frac{\lambda_T}{4}\phi^4 + \ldots..$$

$$\phi_c/T_c = 2E/\lambda_{T_c}$$

$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3)$$ + **Non-decoupling effect of new particles**

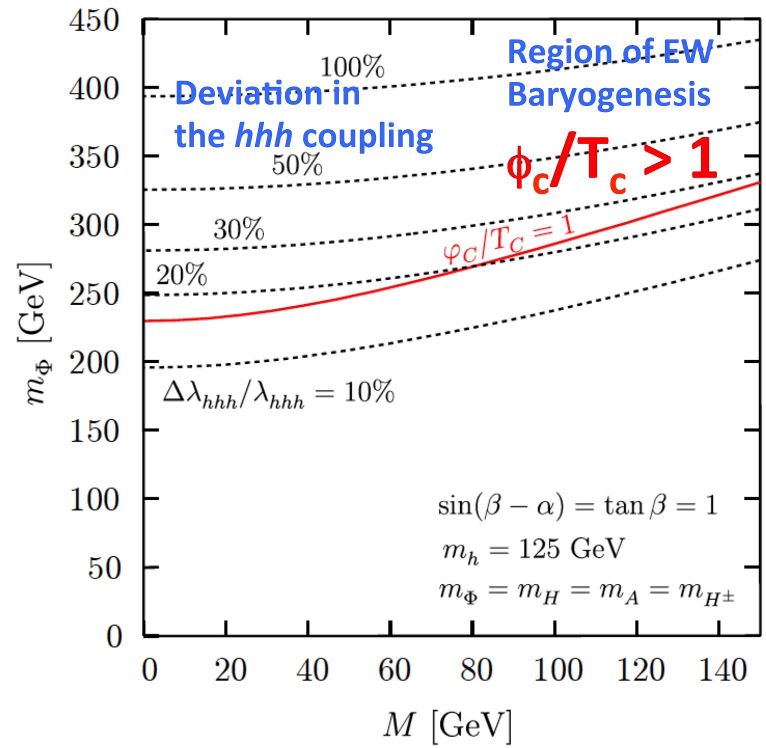
$$\lambda_T = m_h^2/2v^2 + \text{log corrections}$$

Condition of strongly 1st OPT

$$\phi_c/T_c > 1 \Rightarrow 2E/\lambda_{T_c} > 1$$

SM: m_h < 48 GeV: Excuded !

2HDM: m_h = 125GeV: Possible



EW Baryogenesis ⇔ Nondecoupling effect ⇔ large deviation in *hhh*

If *hhh* can be measured by O(10) %, the scenario of EW Baryogenesis can be tested

Connection between cosmology and collider physics!

Snowmass White Paper (Aug. 2013)

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	5 − 7%	2 − 5%	8.3%	4.4%	3.8%	2.3%	−/5.5/<5.5%	1.45%
κ_g	6 − 8%	3 − 5%	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	4 − 6%	2 − 5%	0.39%	0.21%	0.21%	0.13%	1.5/0.15/0.11%	0.10%
κ_Z	4 − 6%	2 − 4%	0.49%	0.24%	0.44%	0.22%	0.49/0.33/0.24%	0.05%
κ_ℓ	6 − 8%	2 − 5%	1.9%	0.98%	1.3%	0.72%	3.5/1.4/<1.3%	0.51%
κ_d	10 − 13%	4 − 7%	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
κ_u	14 − 15%	7 − 10%	2.5%	1.3%	1.3%	0.76%	3.1/1.0/0.7%	0.69%

$$g(hxx) = \kappa_x \, g(hxx)_{SM}$$

ILC Higgs White Paper

Asner, Barklow, Fujii, Haber, Kanemura, Miyamoto, Weiglein, et al.

	ILC(250)	ILC(500)	ILC(1000)	ILC(LumUp)
$\sqrt{s}$ (GeV)	250	250+500	250+500+1000	250+500+1000
L (fb^{-1})	250	250+500	250+500+1000	1150+1600+2500
$\gamma\gamma$	17 %	8.3 %	3.8 %	2.3 %
gg	6.1 %	2.0 %	1.1 %	0.7 %
WW	4.7 %	0.4 %	0.3 %	0.2 %
ZZ	0.7 %	0.5 %	0.5 %	0.3 %
$t\bar{t}$	6.4 %	2.5 %	1.3 %	0.9 %
$b\bar{b}$	4.7 %	1.0 %	0.6 %	0.4 %
$\tau^+\tau^-$	5.2 %	1.9 %	1.3 %	0.7 %
$\Gamma_T(h)$	9.0 %	1.7 %	1.1 %	0.8 %
$\mu^+\mu^-$	91 %	91 %	16 %	10 %
hhh	–	83 %	21 %	13 %
BR(invis.)	< 0.7 %	< 0.7 %	< 0.7 %	< 0.3 %
$c\bar{c}$	6.8 %	2.9 %	2.0 %	1.1 %

Summary

- **The SM currently looks a good low energy theory, but some deviations might be observed in future precision measurements**
- **In fact, there are many new physics models, which slightly deviatie Higgs couplings**

  hVV, hff, hγγ, hhh, …
- **Prediction on the pattern of the deviations is different among new physics models**
- **We can fingerprint new physics models by using the future precision measurement at LCs**
- **Direct searches at LHC and indirect searches at LCs are complementary to explore BSM!**

We need ILC