UNIVERSITY OF TOYAMA 富山大学

Higgs in BSM models

Shinya KANEMURA

University of TOYAMA

富山大学理学部

Tohoku Forum for Creativity
– Particle Physics and Cosmology after the discovery of a Higgs boson –
21-25 Octber 2013, Tohoku University

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

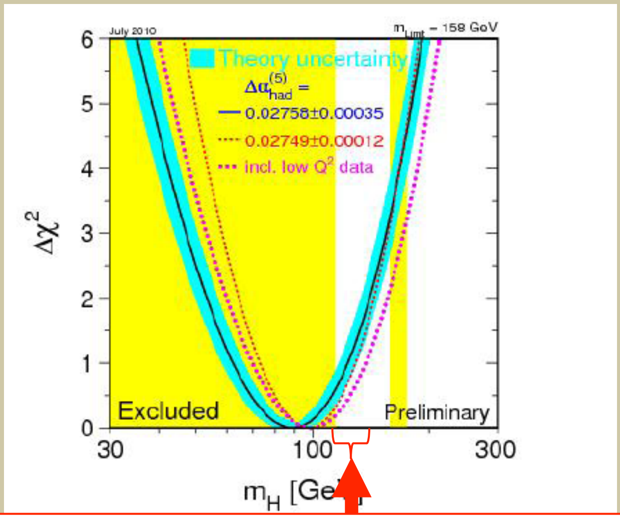
In 2012 July, a boson was found

The mass is 126 GeV

Spin/Parity   0⁺

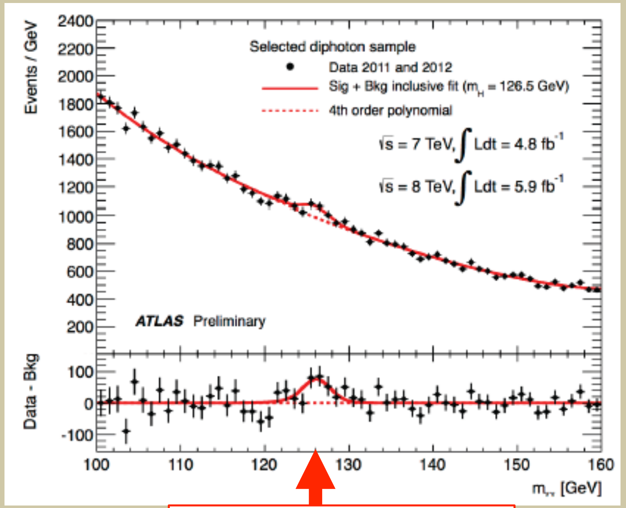
It couples to *γγ, WW, ZZ, bb, ττ, …*

This is really a Higgs!



Higgs Mass indicated by LEP/SLC

Measured Couplings look consistent with the SM Higgs



Why SM-like???

ATLAS/CMS July 2012

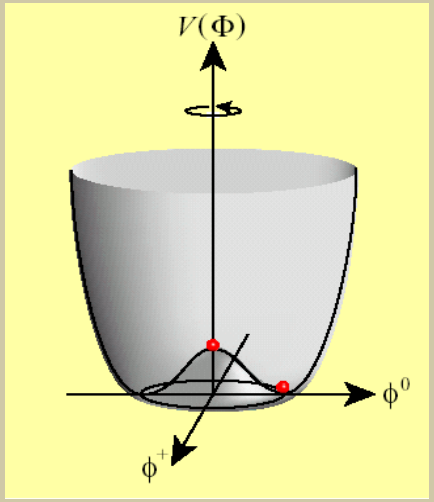
New Particle！

Introduction

Minimal Form

Standard Model Higgs Sector :
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 …

Question:
Why minimal? (no principle)
Why $\mu^2 < 0$
What is Origin of the Higgs force λ?

Higgs sector = Window for new 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 source for

- Baryogenesis (CP violation/1st Order Phase Transition)
- Dark Matter
- Neutrino Mass

Higgs sector = Window for new physics

Introduction

Scalar field is problematic

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

Problem of quadratic divergences

Hierarchy problem

Ideas of new physics to solve the problem

- Supersymmetry
- Dynamical Symmetry Breaking (Technicolor)
- Little Higgs mechanism
- Extra Dimensions
- …

Many of these NP models predict specific extended Higgs sectors

Higgs sector = Window for new physics

Introduction

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

Discovery of a Higgs boson:
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 models of new physics

New era has started !

Beyond the Standard Model

There are many reasons to consider New Physics of BSM

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

Problem in the SM Higgs
- Hierarchy Problem

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

Contents

- Introduction
- BSM models and extended Higgs sectors
- Deviation in couplings of the SM-like Higgs h in non-minimal models
- Direct search of the second Higgs bosons
- Summary

Higgs and New Physics

What is the essence of the Higgs field?

Higgs Nature	⇔	BSM Paradigm
– Elementary Scalar		Supersymmetry
– Composite		Dynamical Symetry Breaking
– Pseudo NG Boson		Little Higgs
– A gauge field in Extra D		Gauge-Higgs unification
– ……		……

Each model has a specific (extended) Higgs sector

SUSY and m_h=126GeV

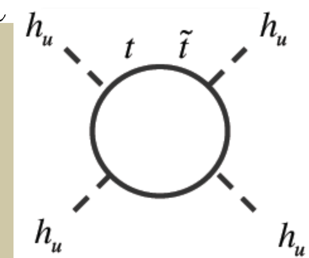
Higgs potential $V = |D|^2 + |F|^2 + \text{(soft-breaking)}$

MSSM: Type-II 2HDM (H_u, H_d)

Self-coupling comes from gauge couplings g,g' ⇒ $m_h < m_Z$ at tree level

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

Loop effect



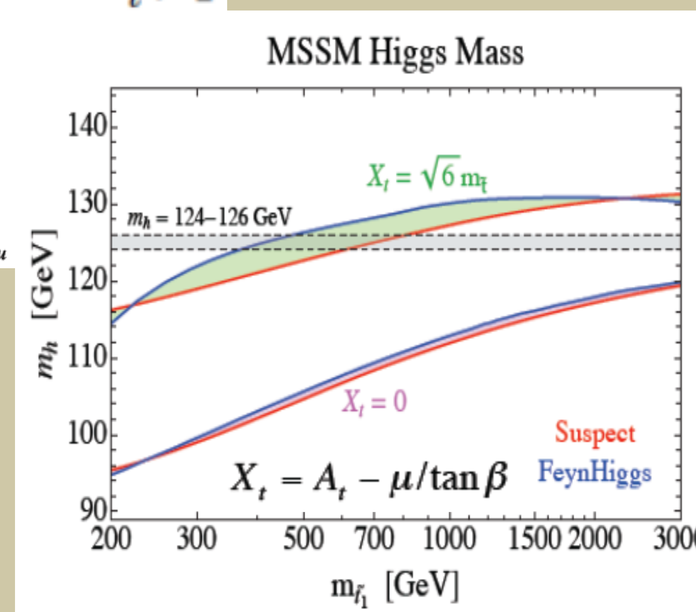
126 GeV can be realized by

Large Stop Masses OR Large Stop LR-mixing

$M_{SUSY} \sim$ 10TeV (X_t=0)

Consistent with the data

But tension with Hierarchy Problem



Hall, Pinner, Ruderman (2011)

Phenomena beyond the SM

We already know BSM phenomena:

– **Neutrino oscillation**

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

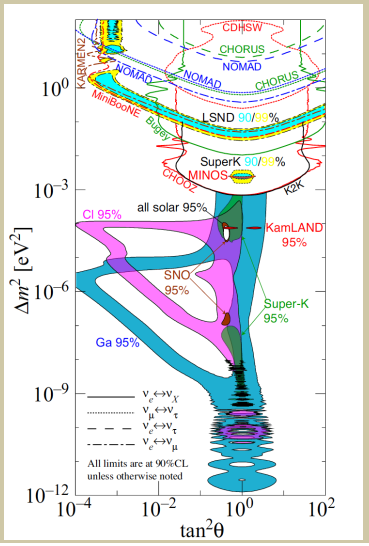
– **Dark Matter**

$\Omega_{DM}h^2 \sim 0.11$

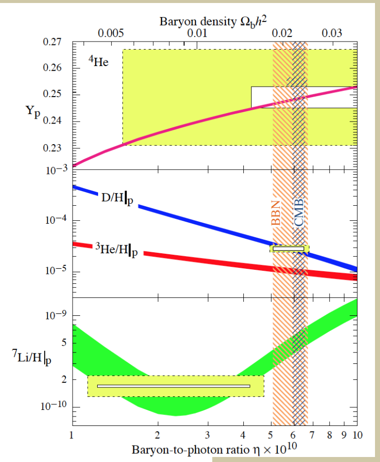
– **Baryon Asymmetry of the Universe**

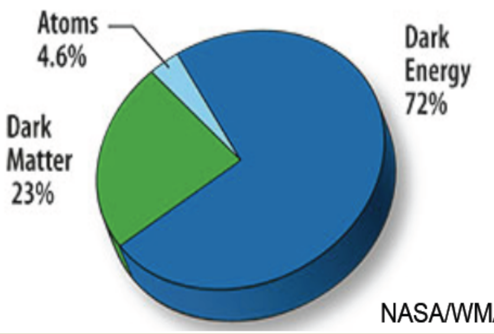
$n_B/n_\gamma \sim 6\times10^{-10}$

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



PDG2012





NASA/WMAP Science Team

To understand these phenomena, we need to go beyond-SM

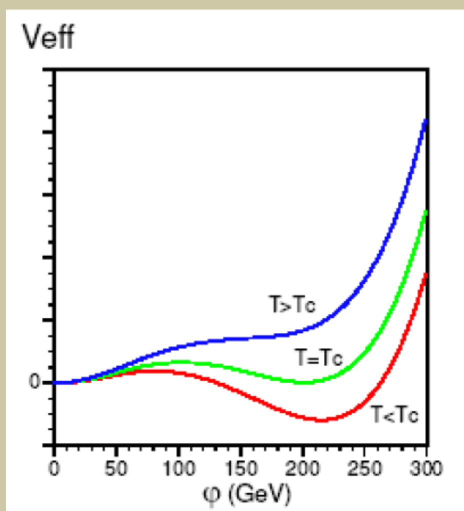
At which scale?

Electroweak Baryogenesis

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

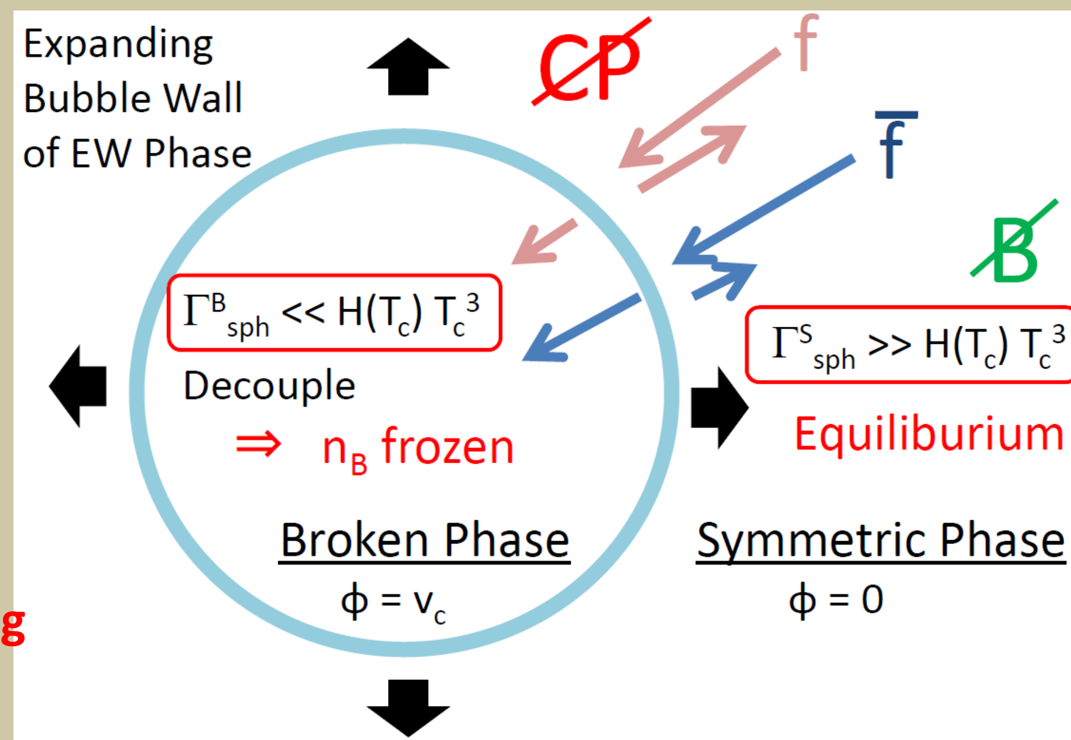
Sakharov's conditions:

- 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



$$\frac{\varphi_c}{T_c} \gtrsim 1$$

Condition of **quick sphaleron decoupling** to keep sufficient baryon number in Broken Phase



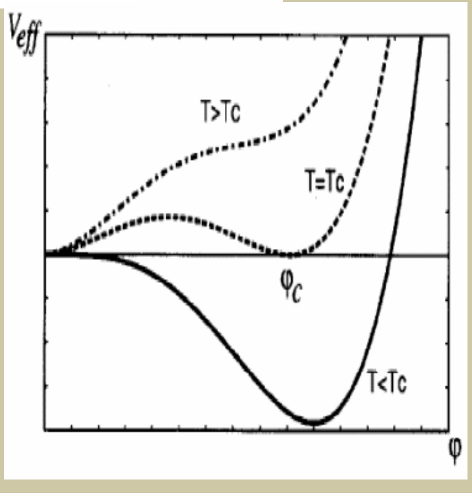
Physics of Higgs potential !

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

Finite Temperature Potential

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

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



Excluded in the SM

$$E = \frac{1}{12\pi v^3}(6m_W^3 + 3m_Z^3) \quad \Rightarrow \quad m_h = 60 \text{ GeV!}$$

Muti-Higgs models can satisfy the condition

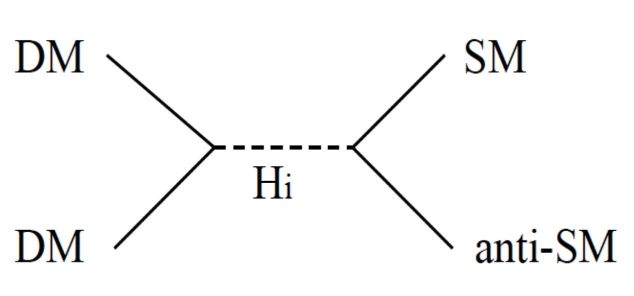
$V(\phi_{SM}, \Phi) = .. + \lambda_{SM}\, \phi_{SM}^4 + \lambda'\, \phi_{SM}^2\, \Phi^2 + \ldots$ **2HDM, MSSM, …**

$$E \propto \frac{m_\Phi^3}{\lambda_T} = \frac{(\lambda')^{3/2}}{\lambda_T} \quad \Rightarrow \quad \lambda' > \lambda_{SM} = 0.3 \ \ (\text{for } m_h = 126 \text{ GeV})$$

$\phi_c/T_c > 1$ when $\lambda' > O(1)$

WIMP Dark Matter

Higgs Portal Dark Matter



SM gauge singlet field (*S, ψ, or V*) with odd under Z_2

SM+DM DMs annihilate into bottom pairs

2HDM (Type-X)+DM, ... DMs annihilate into tau pairs

Strong correlation with direct/indirect searches,
theirmal relic abundance and invisible decay of Higgs boson(s)

Inert Doublet Model SM+ H'

Z_2-odd iso-doublet field H' (neutral component is DM)

A class of 2HDM, but one of the doublets has no VEV

BSM: Neutrino Masses

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>

$m^\nu{}_{ij} = y_i y_j\, v^2/M$ (M>> 1TeV or y_i <<1)

<u>Quantum Effects</u> N-th order of perturbation theory

$m^\nu{}_{ij} = [g^2/(16\pi^2)]^N\, C_{ij}\, v^2/M$ (M can be 1 TeV)

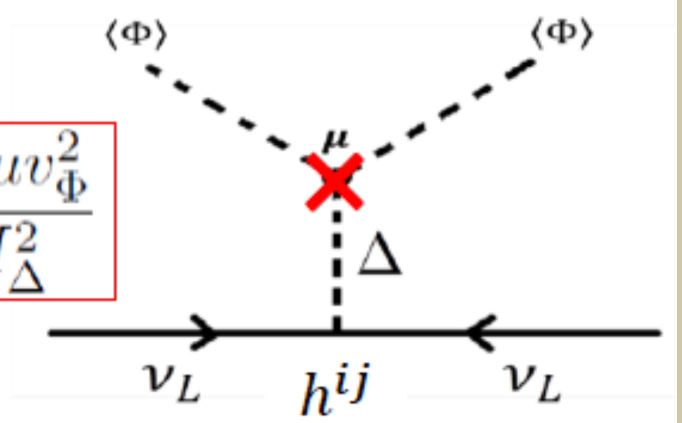
Type-II Seesaw (Higgs triplet model)

Cheng, Li (1980)

Mohapatra, Senjanovic (1981)

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} + \Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & \frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$$

$$M_\nu^{ij} = \frac{h^{ij} \mu v_\Phi^2}{M_\Delta^2}$$



Appearance of Doubly (H^{++}) and singly (H^{+}) charged Higgs bosons

Seesaw Mechanism

$$h^{ij}\,\mu\,v_\Delta \ll M_\Delta^2$$

Unique Phenomenology

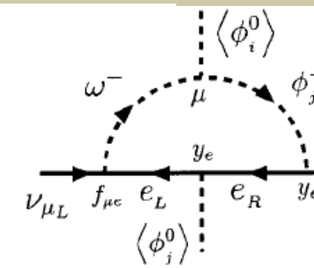
Loop induced mass at TeV scale

Radiative Seesaw Scenario

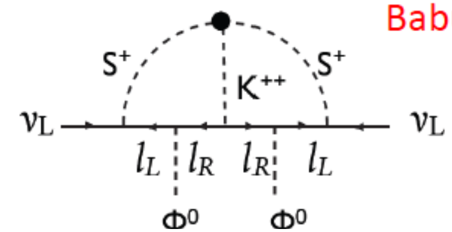
- Extended Higgs sector
- Z_2 parity
  - Neutrino mass generated at the loop level
  - WIMP Dark Matter
    - Lightest Z_2-odd particle
    - LSP (in SUSY extension)

Electroweak Baryogenesis

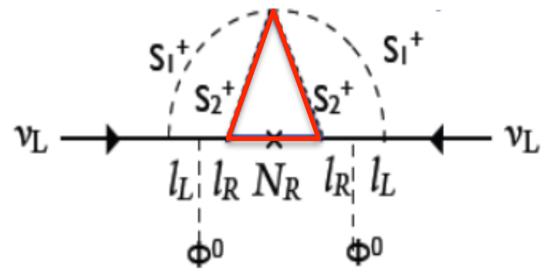
- Sphaleron
- Additional CP Phases
- Strong 1st Order Phase Transition



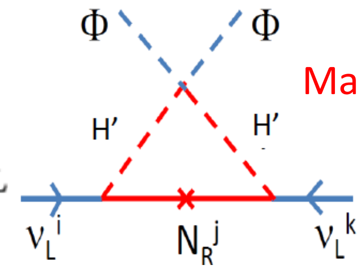
Zee



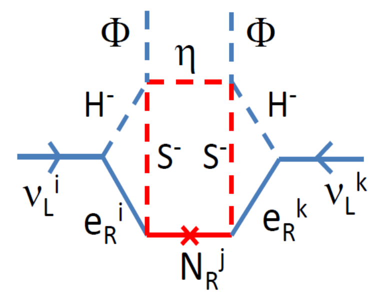
Babu



Krauss, Nasri, Trodden



Ma



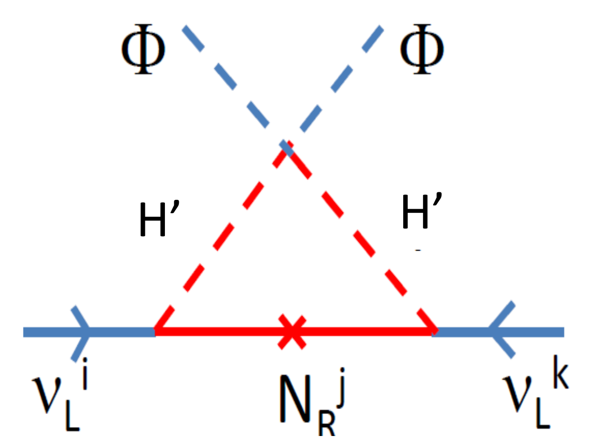
Aoki, SK, Seto

These scenarios are strongly related to the Higgs physics!

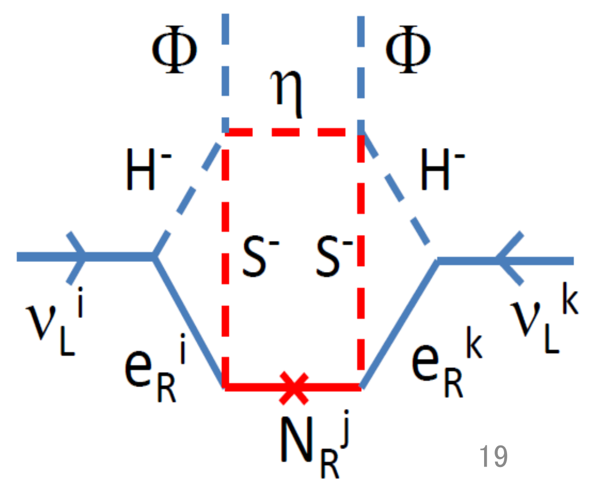
Radiative seesaw with Z_2

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

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



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



Extended Higgs Sector
bottom up approach

The "SM-like" does not necessarily mean the SM.
All extended Higgs sector can contain the SM-like Higgs boson.

Extended Higgs

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. $\rho \approx 1$ 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) $v_\Delta << v_\varphi$

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

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

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

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

↑ ↑ ↑charged

CPeven CPodd

Diagonalization

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

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

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

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

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

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

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

M_{soft}: soft breaking scale

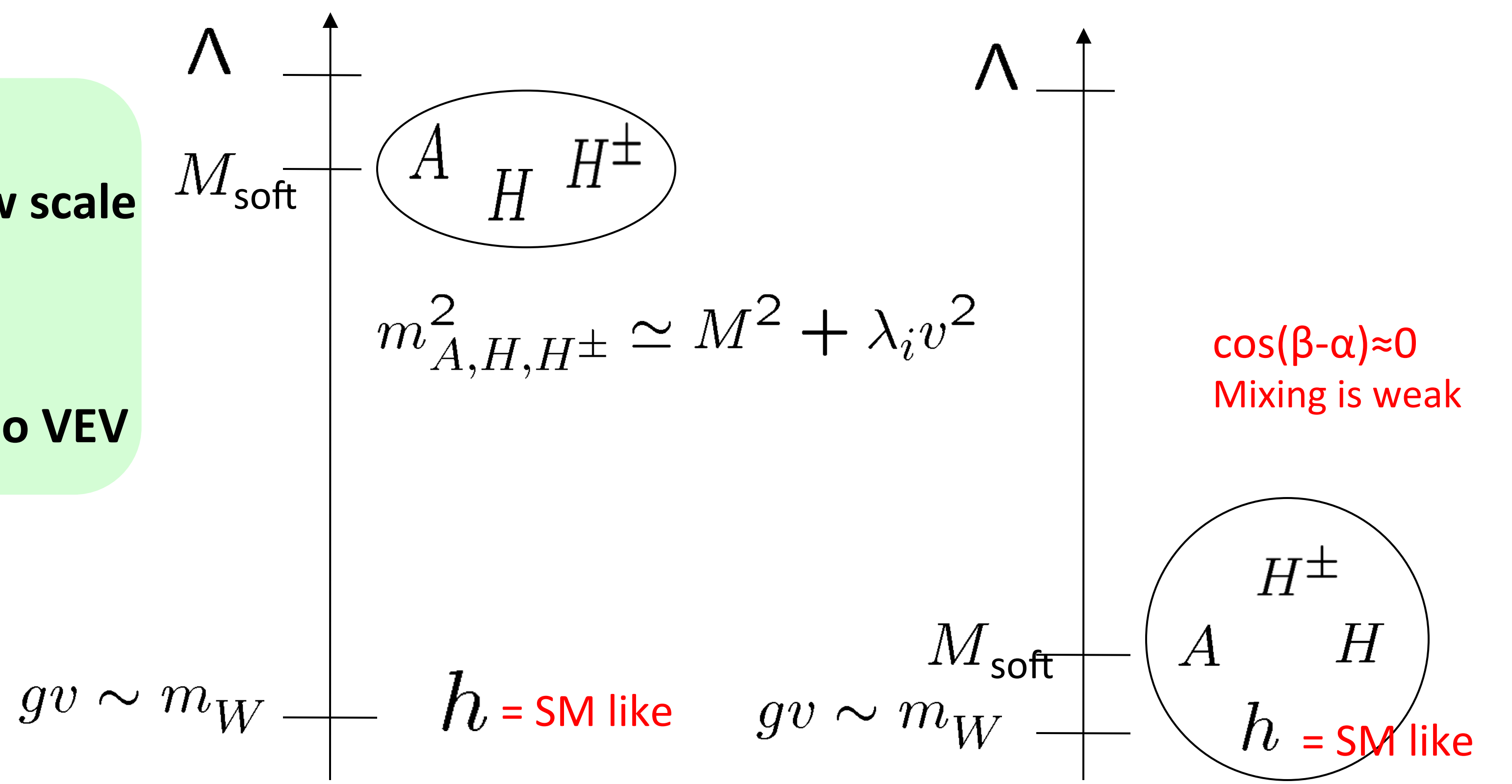
$M_{\text{soft}} \quad \left(= \frac{m_3}{\sqrt{\cos\beta \sin\beta}}\right)$:

soft-breaking scale
of the discrete symm.

The SM-like *h* (two possibilities)

Λ :
Cutoff, New scale

M M_{soft}**:**
Mass scale irrelevant to VEV



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

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

Non-decoupling effect

FCNC Suppression

Multi-Higgs model: FCNC appears via Higgs mediation

ex) 2 Higgs doublet models:

to avoid FCNC, impose a discrete symmetry

$$\Phi_1 \rightarrow +\Phi_{1,} \qquad \Phi_2 = -\Phi_2$$

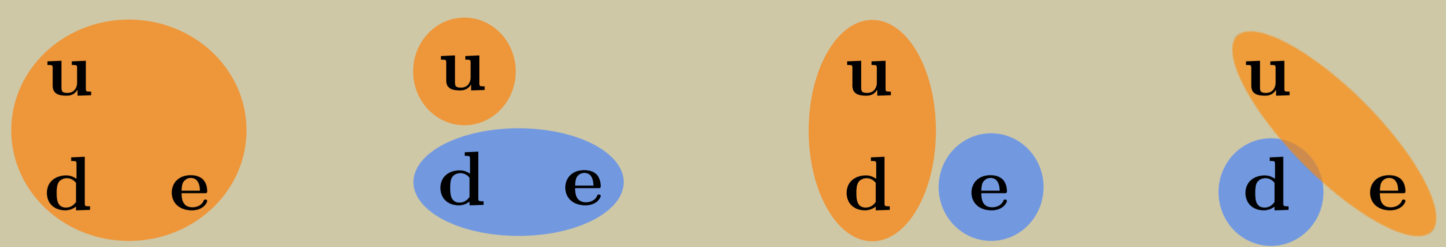
Each quark or lepton couples only one Higgs doublet

No FCNC at tree level

Barger, Hewett, Phillips

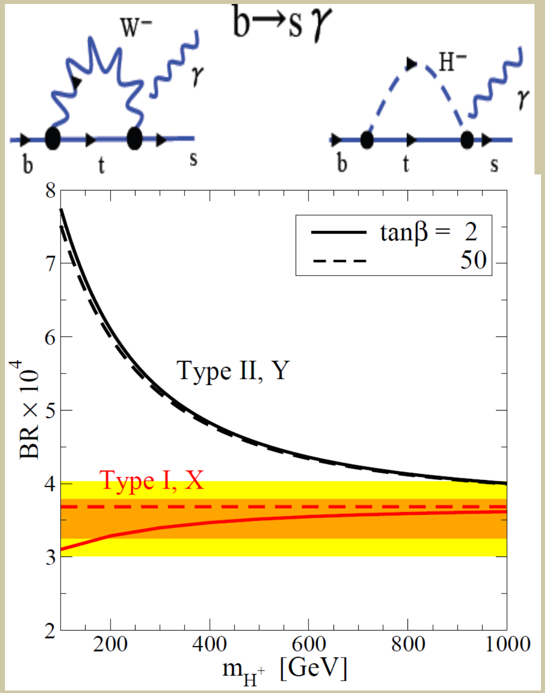
Four Types of Yukawa coupling

Classified by Z_2 charge assignment



Type-I Type-II Type-X Type-Y

Type of 2HDM

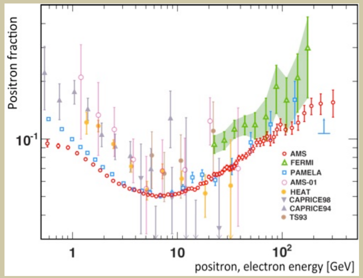


Aoki, SK, Tsumura, Yagyu (09)

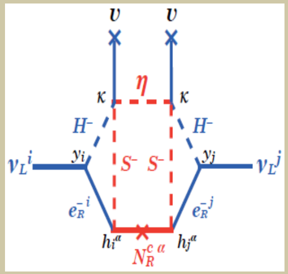
Type-I Fermiophobic 2HDM
Neutrinophillic 2HDM

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

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

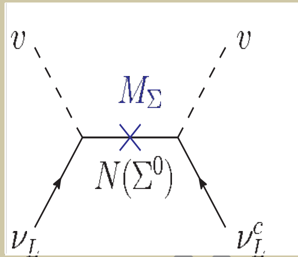


Goh, Hall, Kumar (09)



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*?**
  - **Solid target!**

Search for Extended Higgs sectors

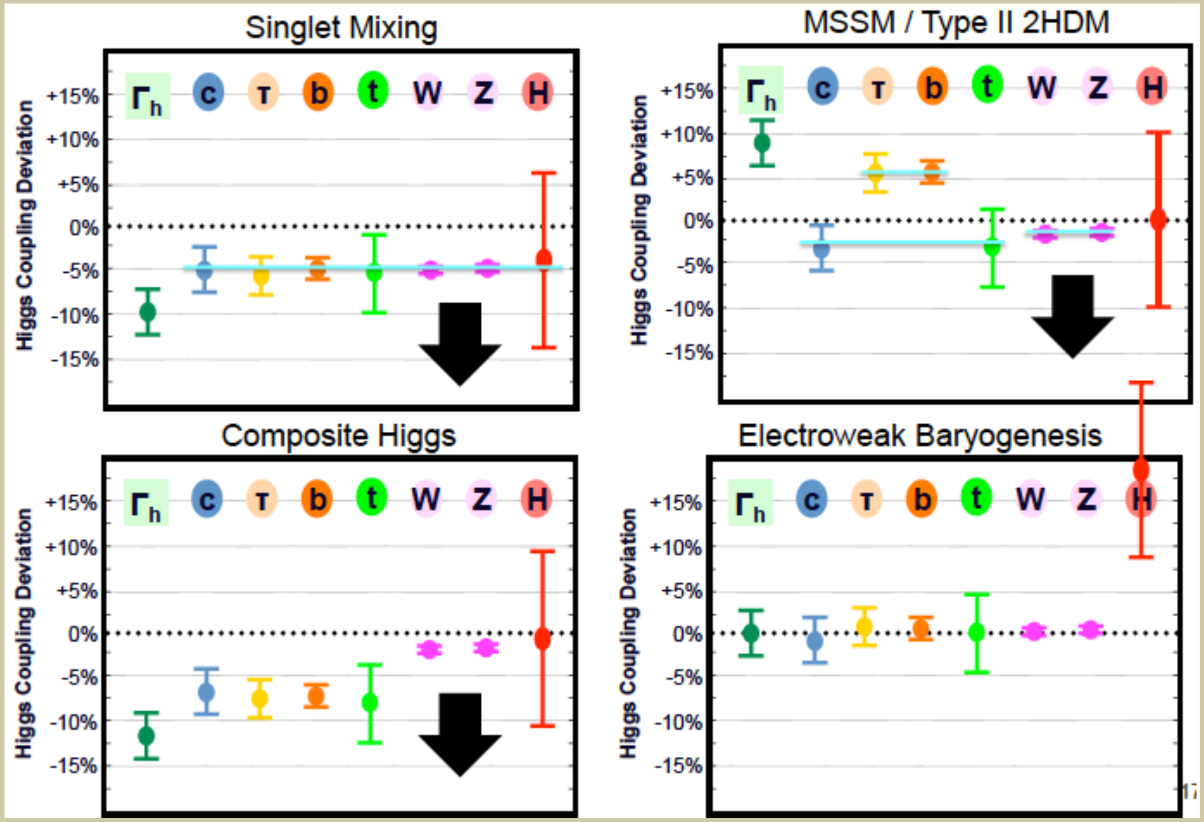
Many new physics models predict non-minimal Higgs sectors

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*?**
  - **Solid target!**

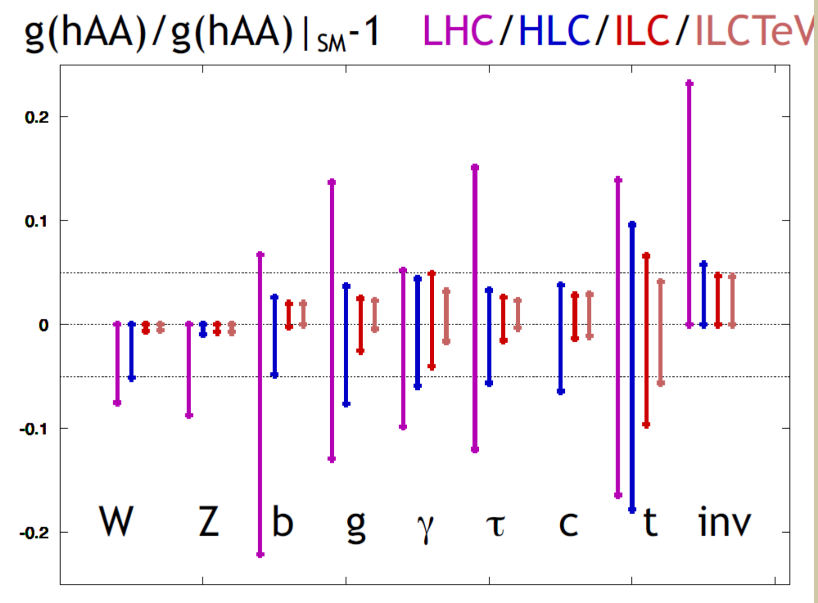
Precision measurement of the SM-like Higgs boson *h*

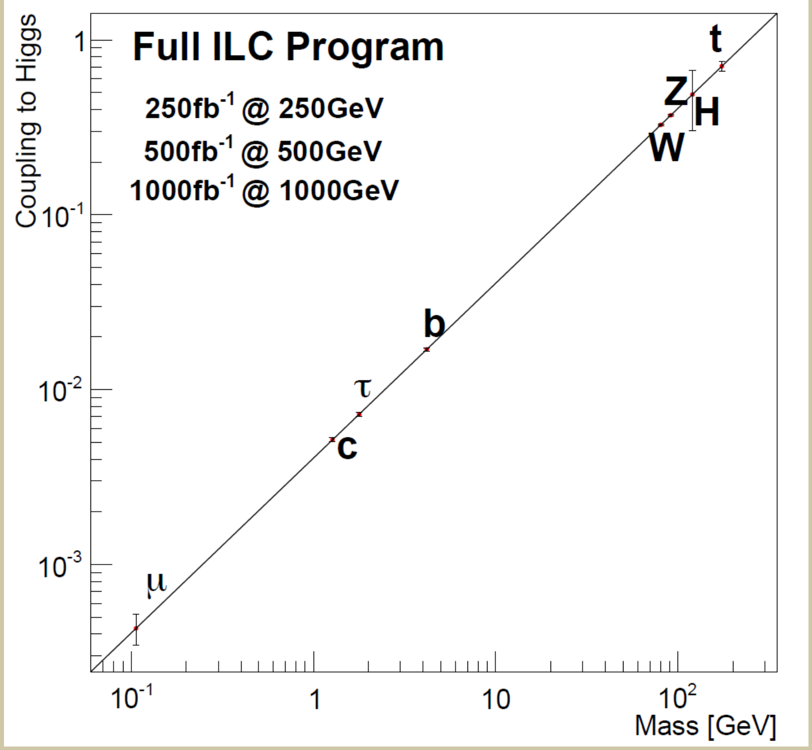
Fingerprinting the models via Higgs couplings



S. Yamashita 2005

International Linear Collider





M. Peskin, 2012

Coupling measureable by a few%, and *hhh* can also be measured by around O(10) %

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

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 %

See Tian's Talk

Discrimination of models via coupling of the 125GeV Higgs boson *h*

BSM models can be distinguished by the pattern in deviations of the SM-like Higgs couplings

hγγ, hgg, hWW, hZZ, htt, hff, hhh

Scalar Mixing (*h* ⇔ *φ*)

Gauge couplings (*hVV*):

Yukawa couplings (*hff*):

The pattern of deviation strongly depend on the model

Quantum effects (Non-decoupling effect)

Large deviation in loop-induced processes (*h*→*γγ* and *h*→*gg*)

Large quantum correction can also appear in the *hhh* coupling

We need to measure the Higgs coupling constants as accurately as possible

Deviation in κ_i^2 and the scale of BSM

- **Mass of the second Higgs boson is a free parameter**

- **Correlation with the SM-like *h* couplings**
  - **Structure of BSM (MSSM)**
  - **Unitarity and Vacuum Stability in general**

- **If $\kappa_V^2 < 1$ is observed by experiment, the scale of the second Higgs boson is obtained**

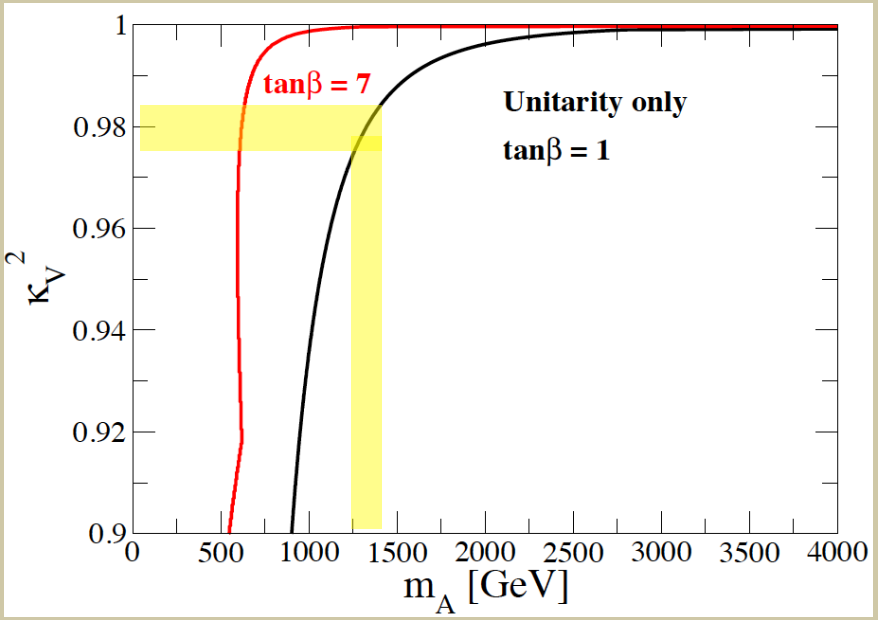
Unitarity bound in the 2HDM

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

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

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

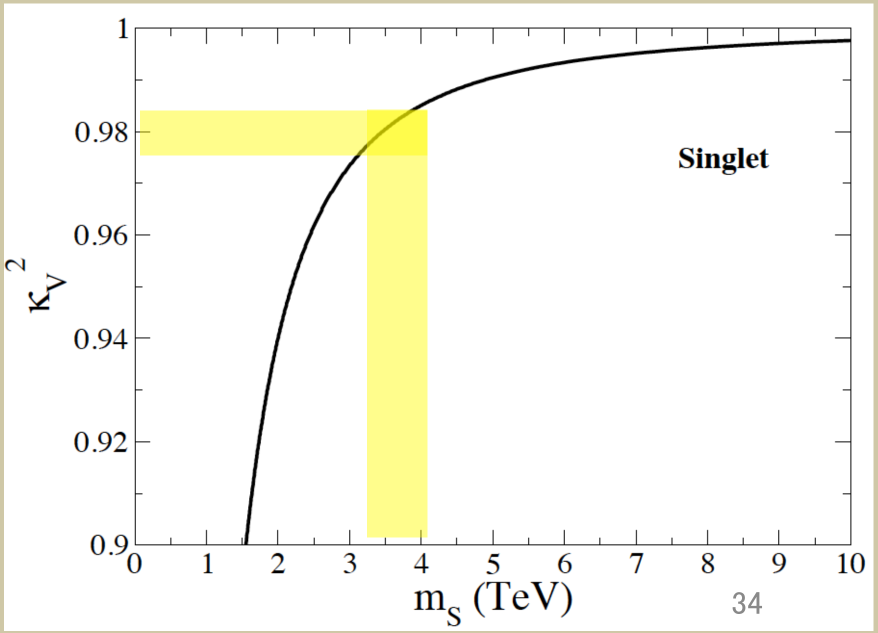


In Higgs Singlet model (Φ+S)

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

Situation is similar, but the bound is much relaxed

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

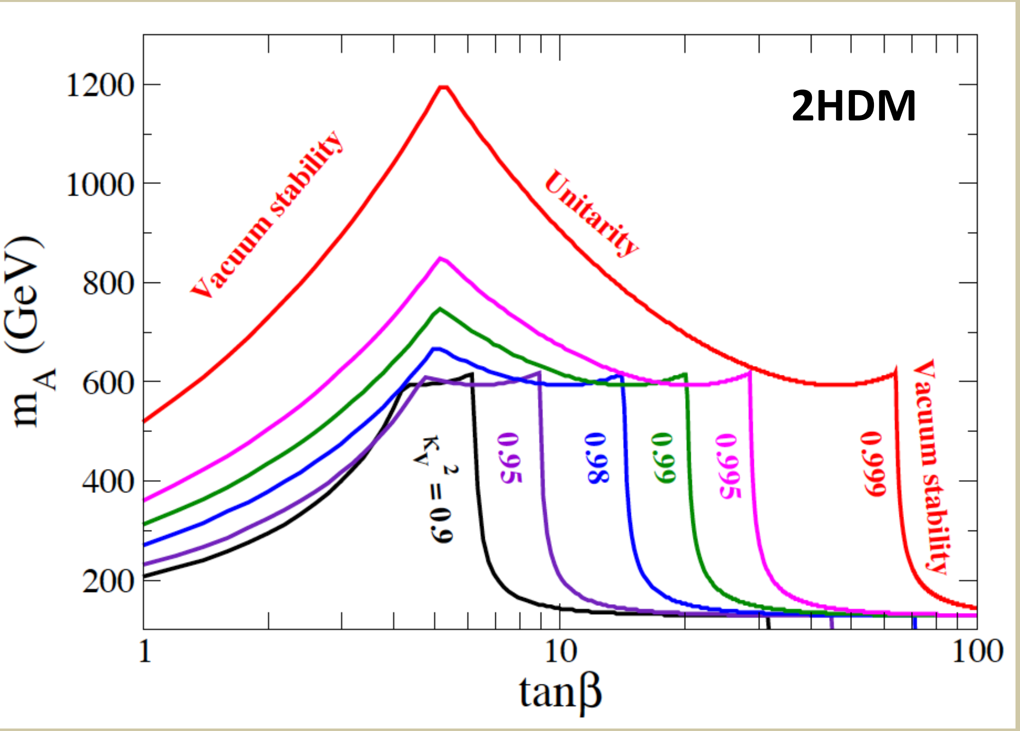


Theoretical upper bounds on the second Higgs mass, when $\kappa_V^2 < 1$

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

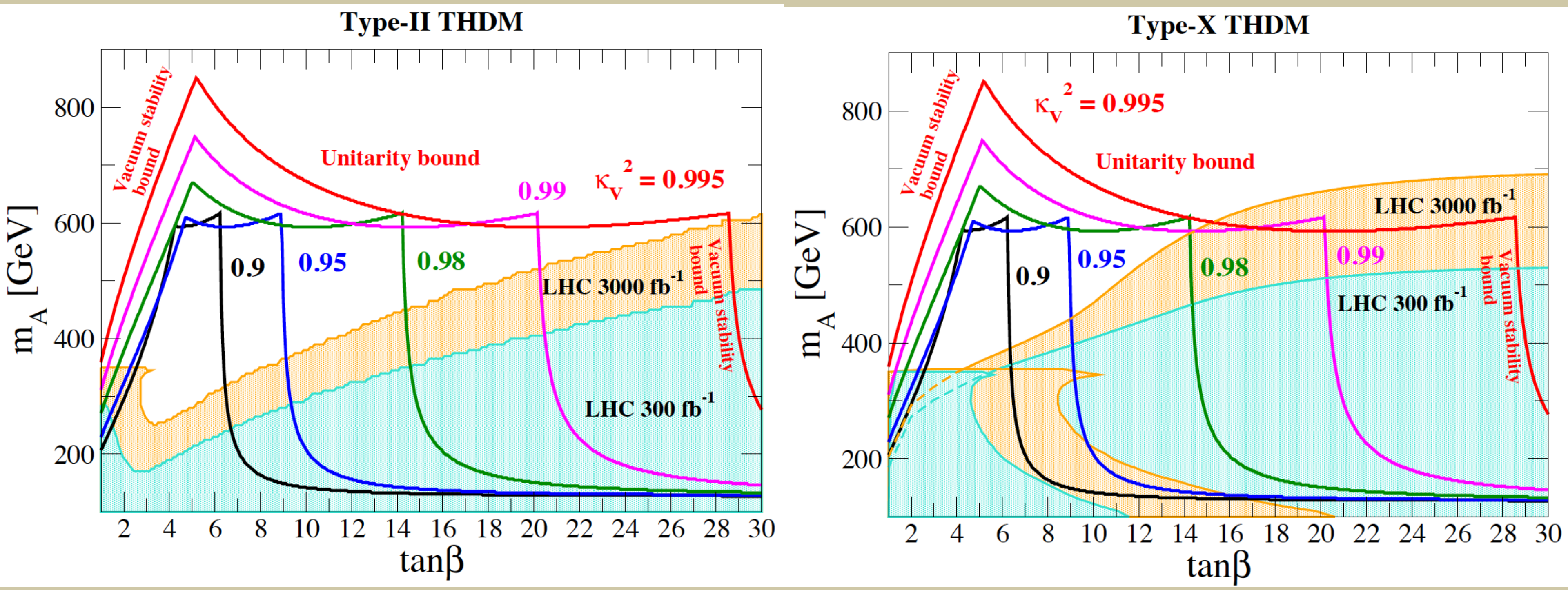
Then, if no second Higgs is found below 700 GeV, the 2HDM is excluded

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



Precision determination of *hVV* coupling is very important

LHC can search relatively large tanβ regions



Yukawa couplings *hff*

Effects of the mixing (α, tanβ) change Yukawa couplings of *h*

	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L, L_L
Type I	+	−	−	−	−	+
Type II (SUSY)	+	−	−	+	+	+
Type X (Lepton-specific)	+	−	−	−	+	+
Type Y (Flipped)	+	−	−	+	−	+

Type-II

$hbb \propto \sin(\beta-\alpha) - \tan\beta \cos(\beta-\alpha)$

$h\tau\tau \propto \sin(\beta-\alpha) - \tan\beta \cos(\beta-\alpha)$

Type-X

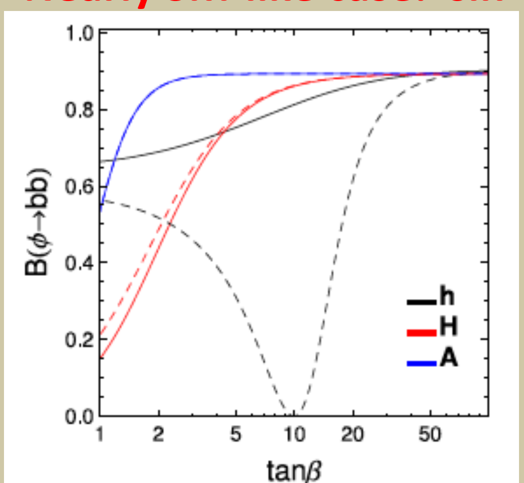
$hbb \propto \sin(\beta-\alpha) + \cot\beta \cos(\beta-\alpha)$

$h\tau\tau \propto \sin(\beta-\alpha) - \tan\beta \cos(\beta-\alpha)$

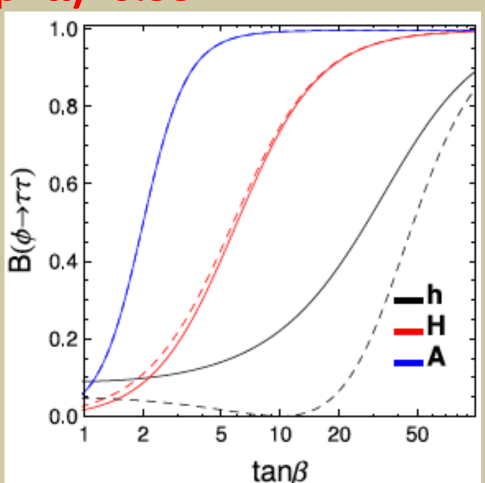
	ξ_h^u	ξ_h^d	ξ_h^ℓ
Type-I	c_α/s_β	c_α/s_β	c_α/s_β
Type-II	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$
Type-X	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$
Type-Y	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β

Coefficient of *hff*

Nearly SM-like case: $\sin^2(\beta-\alpha)=0.99$



Type II



Type X

S.K., K. Tsumura, H. Yokoya 2013

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)	↓	↓	↑	↓	↓	↓

$\cos(\beta-\alpha) < 0$

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)

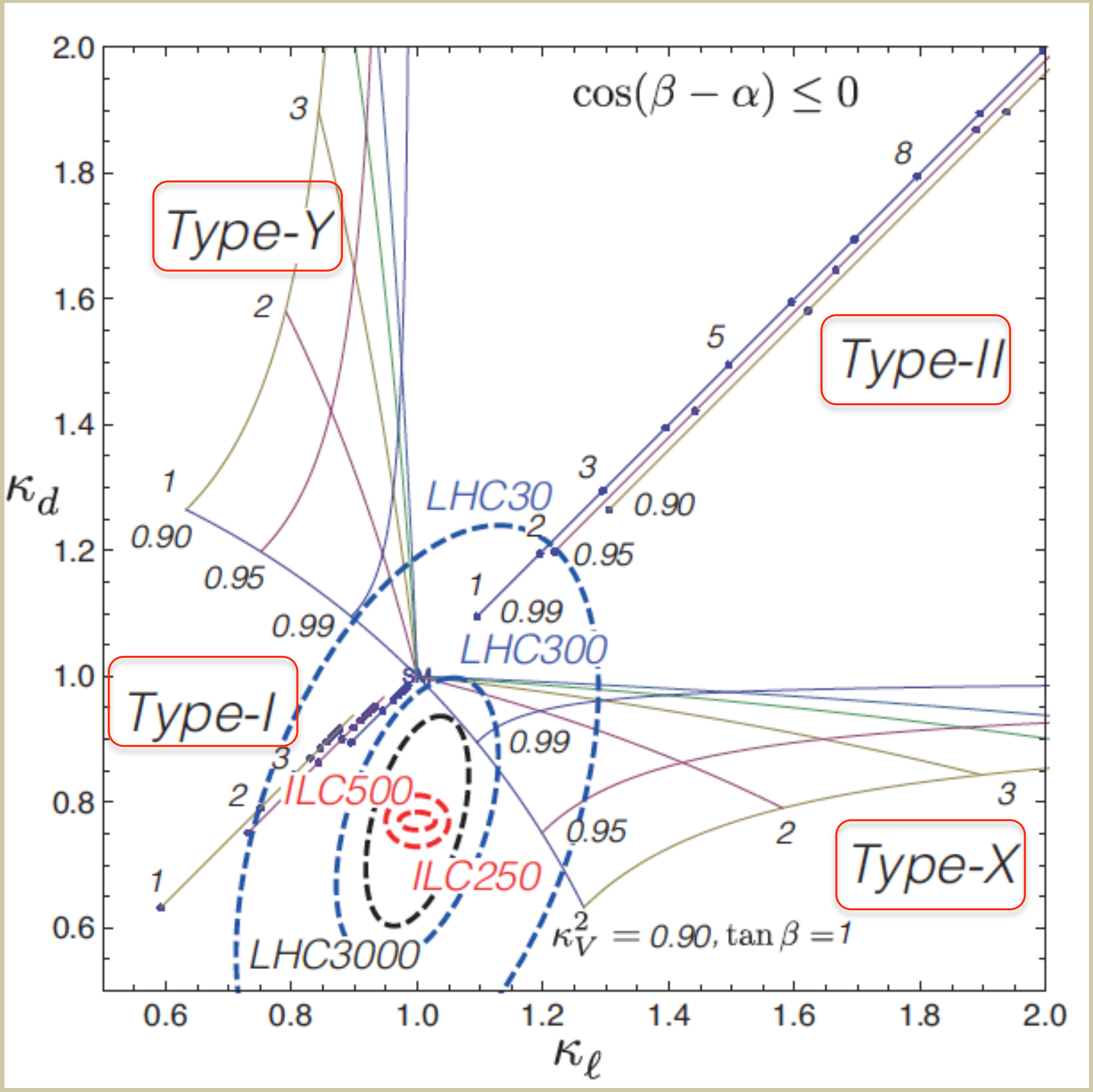
Extended Higgs models are distinguishable by precisely measuring *hVV* and *hff*

Fingerprinting the model (2HDM)

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

hbb vs hττ

We can determine the type of Yukawa interacion in the 2HDM



Ellipse = 68.27% CL

Fingerptinting the model (Exotics)

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

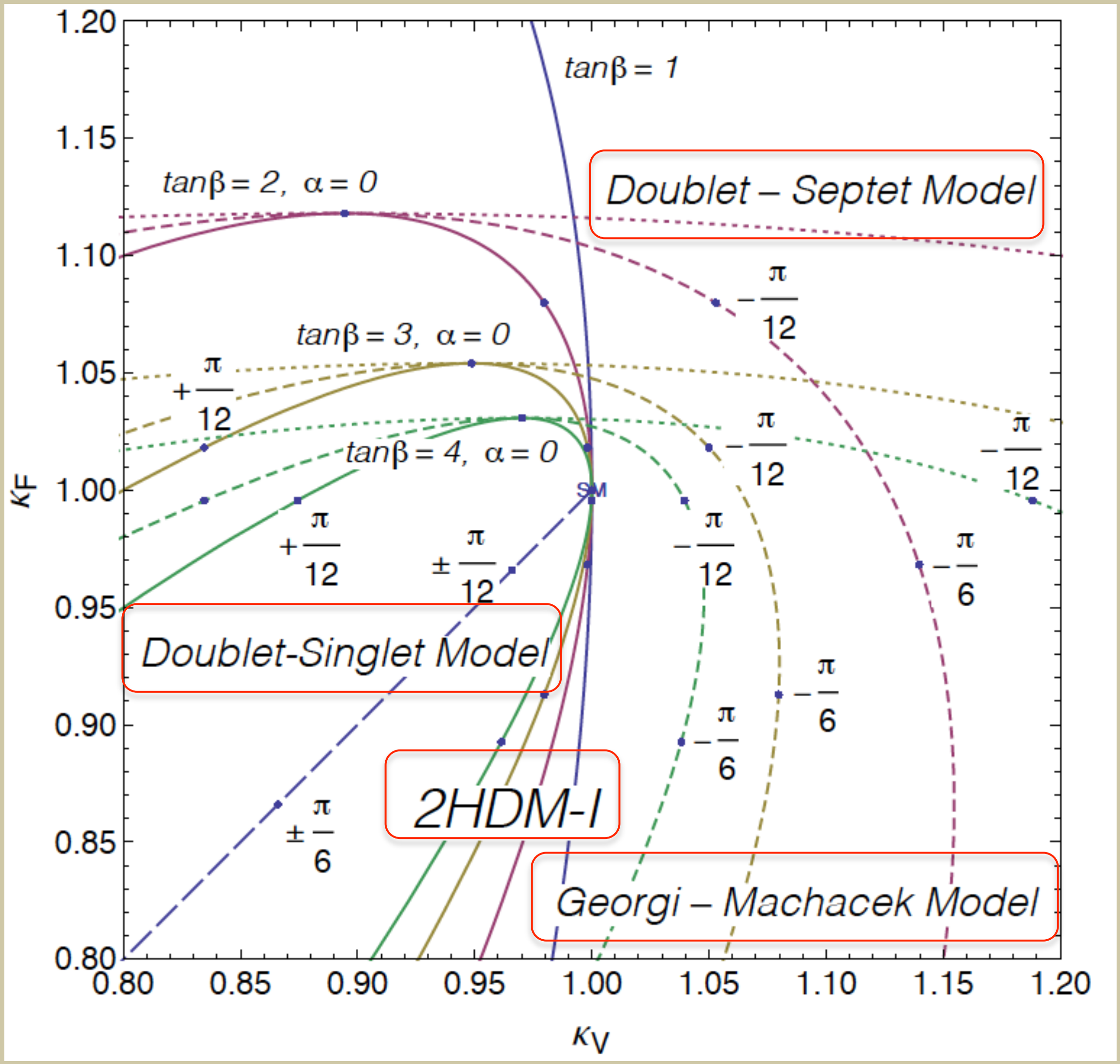
Universal Fermion Coupling (κ_F)

VS

***hVV* coupling (κ_V)**

Exotic models predict $\kappa_V > 1$

We can discriminate Exotic models



Measurement of tanβ at ILC

SK, Tsumura, Yokoya, arXiv:1305.5424

sin(β-α) and tanβ are important

hVV → sin(β-α)

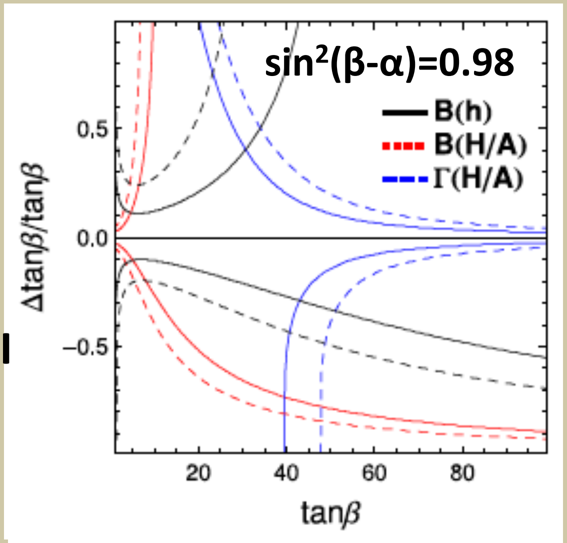
How about tanβ?

tanβ determination

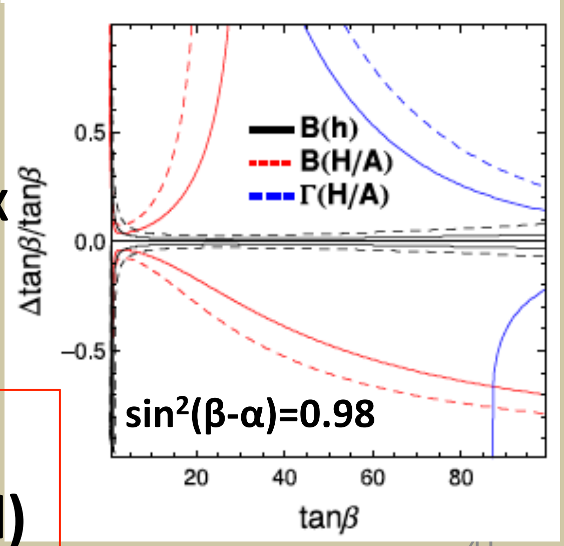
1. Branching ratio of *H, A*
   useful for small tanβ
2. Total width of *H, A* — Berger, Han, jiang (01); Gunion, Han, Jiang, Sopczak (03)
   useful for large tanβ
3. Decay of SM-like Higgs *h* when sin(β-α) is slightly smaller than 1

SK, Tsumura, Yokoya, arXiv:1305.5424

Type-II 2HDM



Type-X 2HDM

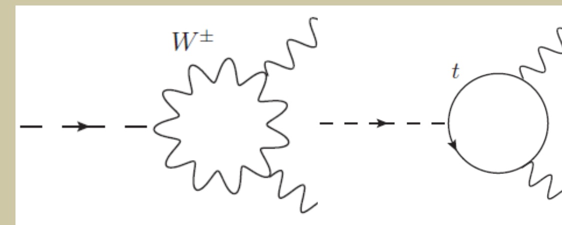


Precision measurement of the *h* decay at ILC is very useful (information of H,A not required)

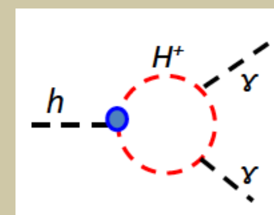
Di-photon Decay Width

Loop induced process in the SM

New physics effect enters at the same order of perturbation



SM loop destructive

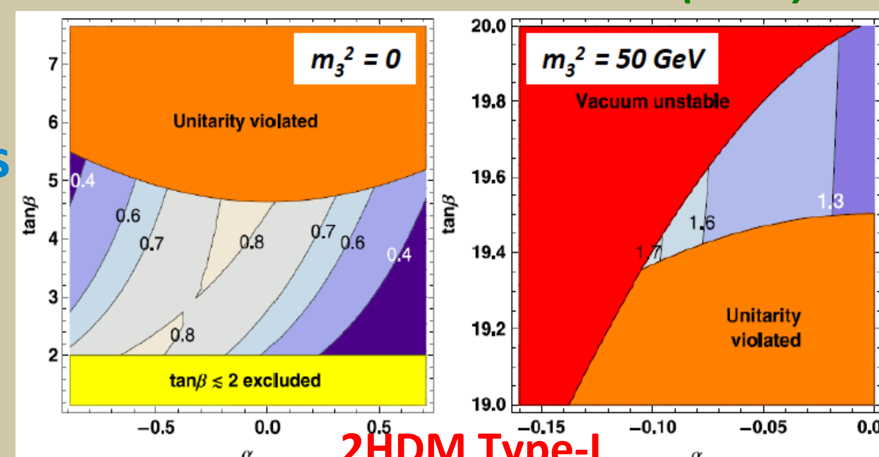


H^{+} loop in 2HDM

New physics particles which realize a large deviation in hγγ

- W' boson
- Singly/Doubly Charged Scalars
- New Charged Leptons
- SUSY
- …..

P. Posch (2011)



2HDM Type-I

Parameters can be constrained

⇒ Test a model by correlation to the other observable

Self-coupling *hhh*

It is important to determine the structure of Higgs potential

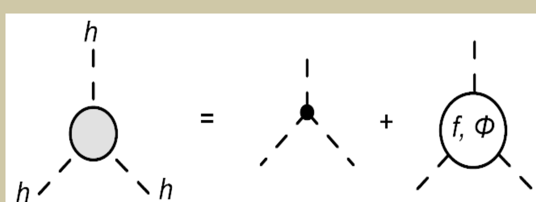
$$V_{\rm Higgs} = \frac{1}{2}m_h^2 h^2 + \frac{1}{3!}\lambda_{hhh}h^3 + \frac{1}{4!}\lambda_{hhhh}h^4 + \cdots$$

Even if *h* is SM-like (sin(α-β)=1), a large deviation can appear due to non-decoupling loop effects

SM

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

Non-decoupling effect

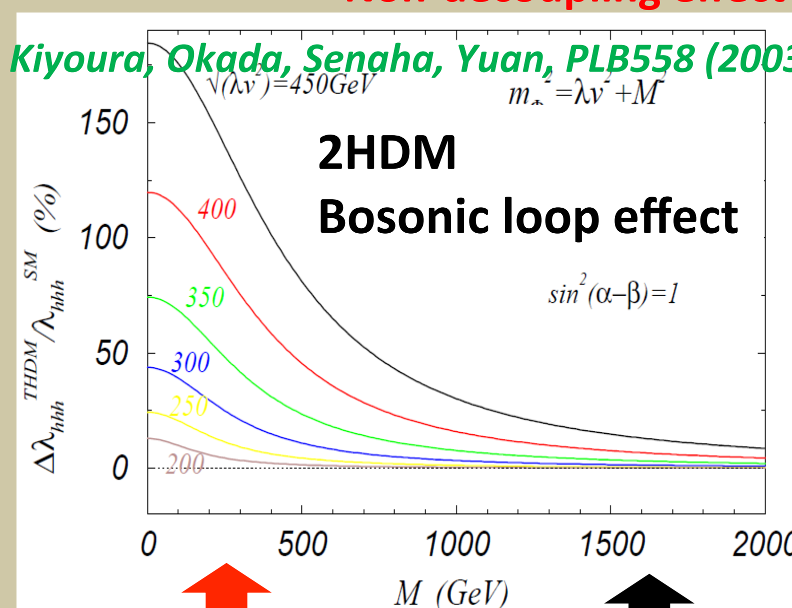


Φ = H, A, H±

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

In extended Higgs models the deviation can be ～ 100% by bosonic loop effect

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



Non-decoupling effect **Decoupling**

EW Baryogenesis and the *hhh* coupling

Higgs Potential at Finite Temperatures

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

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

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

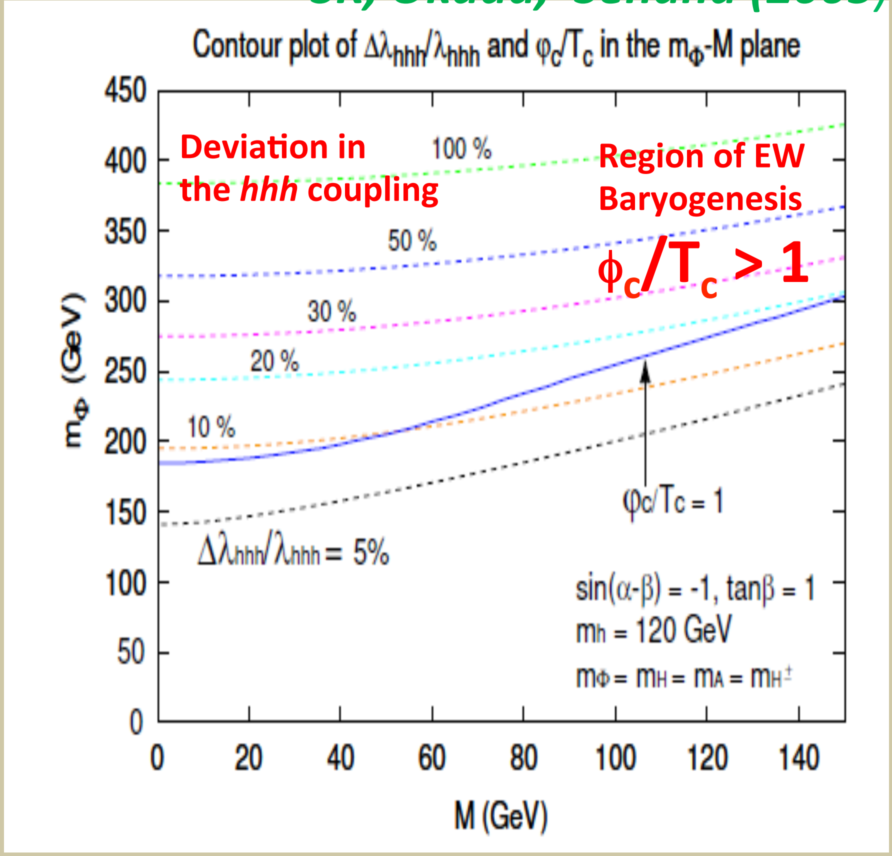
$$\lambda_T = m_h^2/2v^2 + \text{log corrections}$$

Condition of strongly 1st OPT

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

EW Baryogenesis
⇔ Non-decoupling effect
⇔ large deviation in *hhh*

SK, Okada, Senaha (2005)



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

Connection between cosmology and collider physics

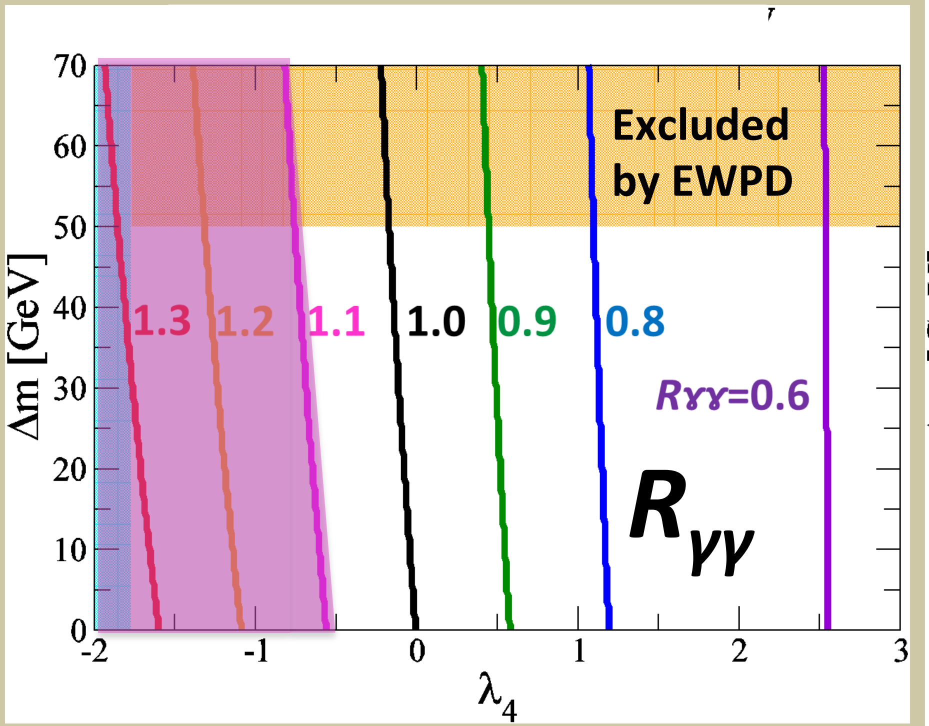
Correlation between *hγγ* and *hhh*

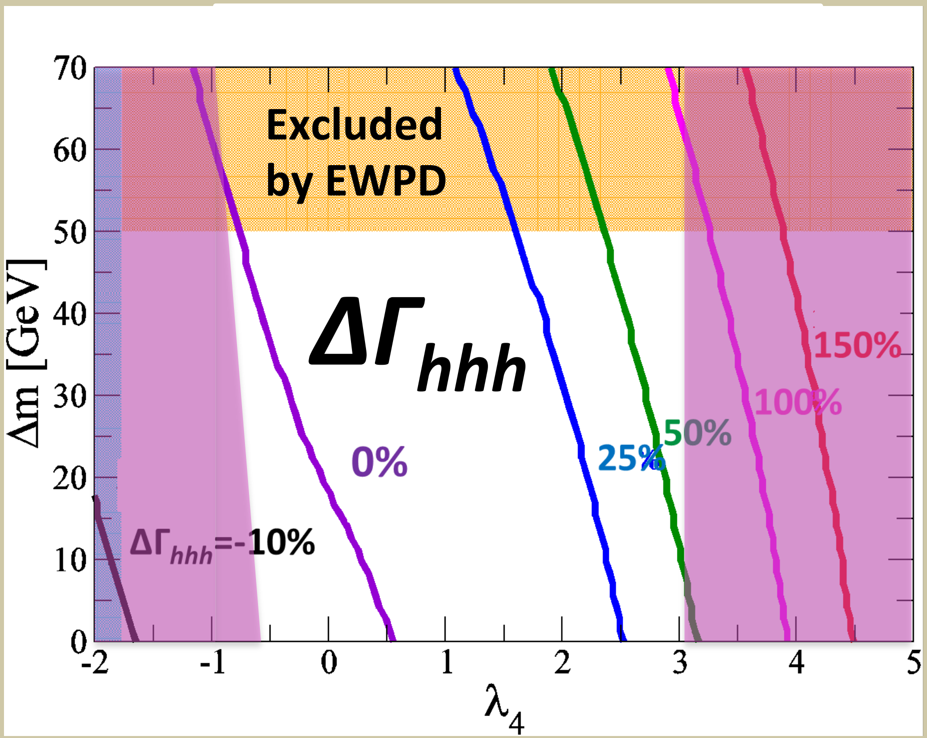
Ex) Higgs Triplet Model (SM-like *h* + Triplet)

m_{H++}=300GeV, v_Δ=1MeV

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

$R_{\gamma\gamma}$ = 0.8 ± 0.3 (CMS)



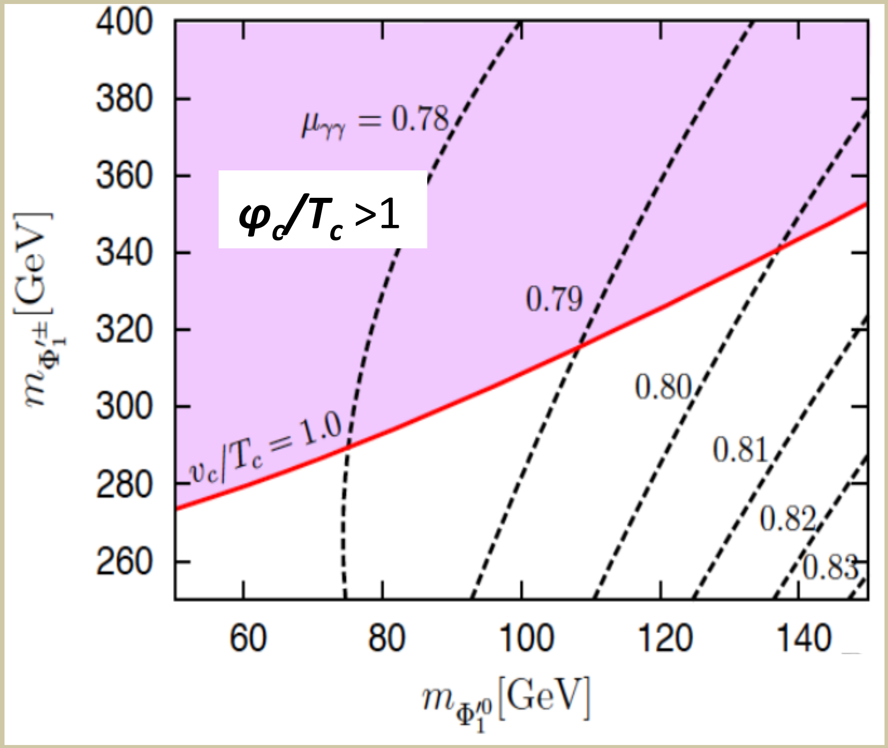


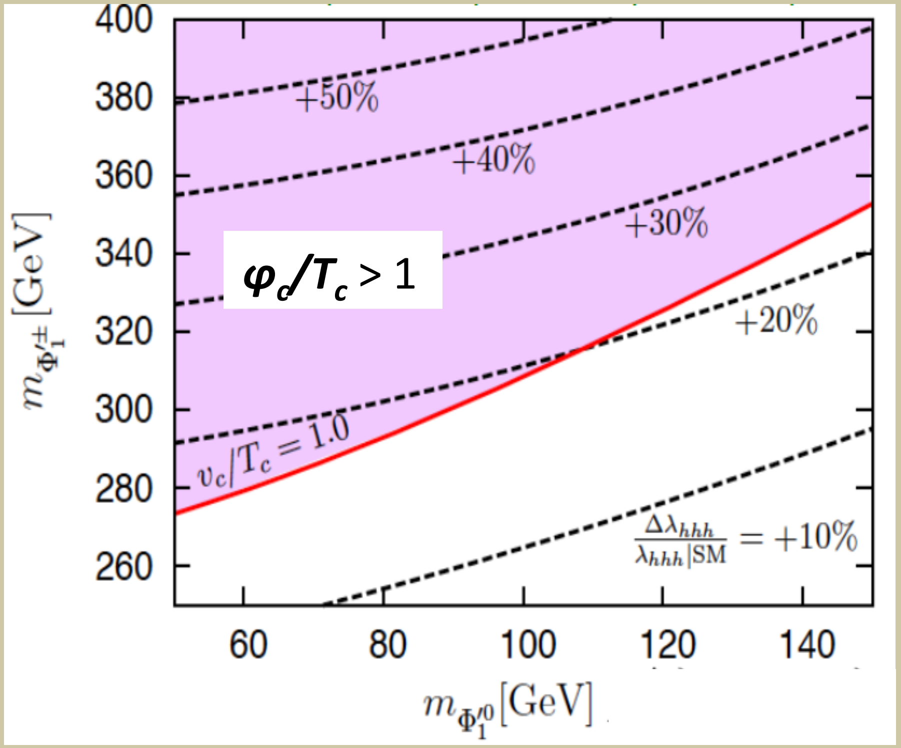
$$R_{\gamma\gamma} \equiv \frac{\sigma(gg \to h)_{\rm HTM} \times {\rm BR}(h \to \gamma\gamma)_{\rm HTM}}{\sigma(gg \to h)_{\rm SM} \times {\rm BR}(h \to \gamma\gamma)_{\rm SM}}$$

$$\Delta\Gamma_{hhh} \equiv \frac{{\rm Re}\Gamma_{hhh} - {\rm Re}\Gamma_{hhh}^{\rm SM}}{{\rm Re}\Gamma_{hhh}^{\rm SM}}$$

Correlation between *hγγ* and *hhh*

Ex) Strong-but-light scenario in the SUSY $SU(2)_H$ Model for EWBG





Deviation in the *hγγ* coupling is −20%
Deviation in the *hhh* coupling is +20%

Properties of extra Higgs bosons

H, A, H^{+}, H^{++}

MSSM (Type-II 2HDM)

SM-like Higgs
m_h=126 GeV

h

***hVV*: sin(β-α)≈1**

$$\sin(\beta-\alpha) \simeq 1 - \frac{2m_Z^4}{m_A^4 \tan^2\beta}$$

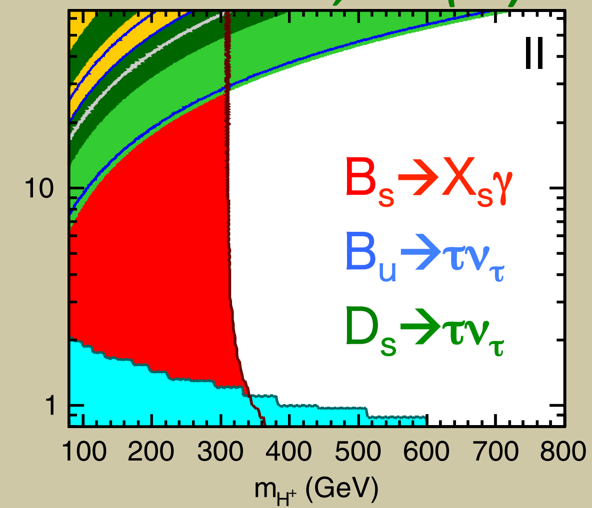
Extra Higgs bosons

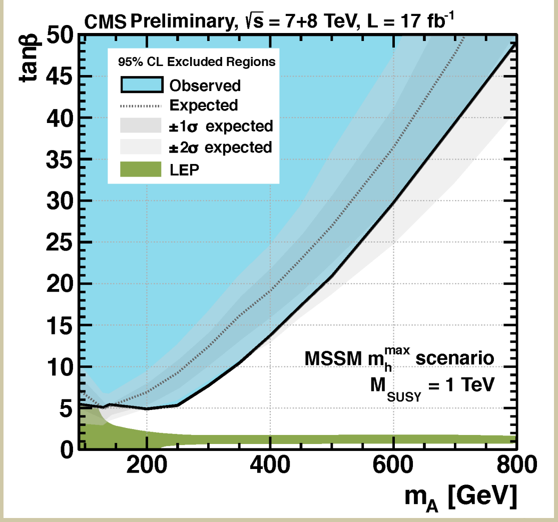
H, A, H±

***HVV*: cos(β-α) <<1**
***HAZ*: sin(β-α) ≈ 1**
H⁺H⁻γ*: *1

***Htt* (*Att*): m_t cotβ**
***Hbb* (*Abb*): m_b tanβ**
***Hττ* (*Aττ*): m_τ tanβ**

Mahmoudi, Stal (09)

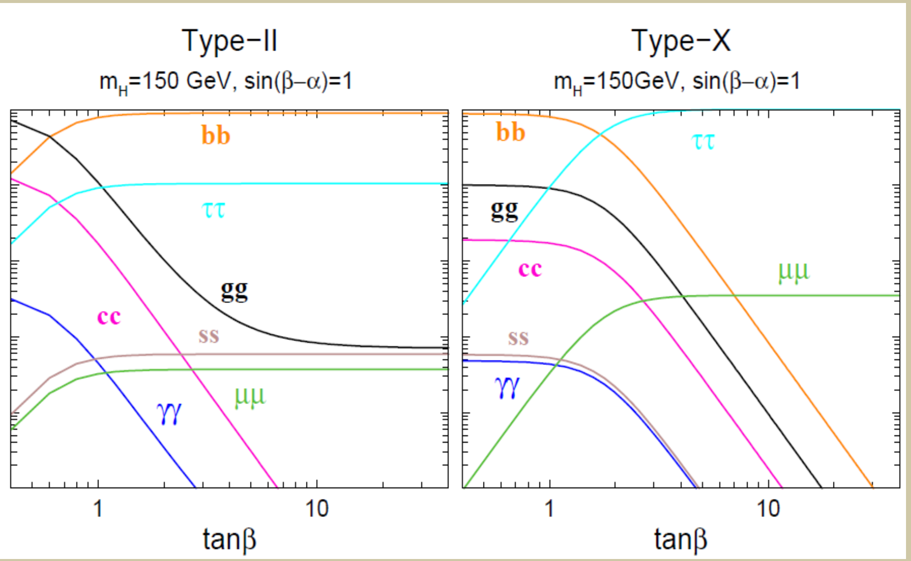




Flavor experiments and LHC give strong constraints on MSSM (Type-II 2HDM)

MSSM vs Type X 2HDM

Type II: *H, A* decay into *bb*
Type X: *H, A* decay into $\tau\tau$

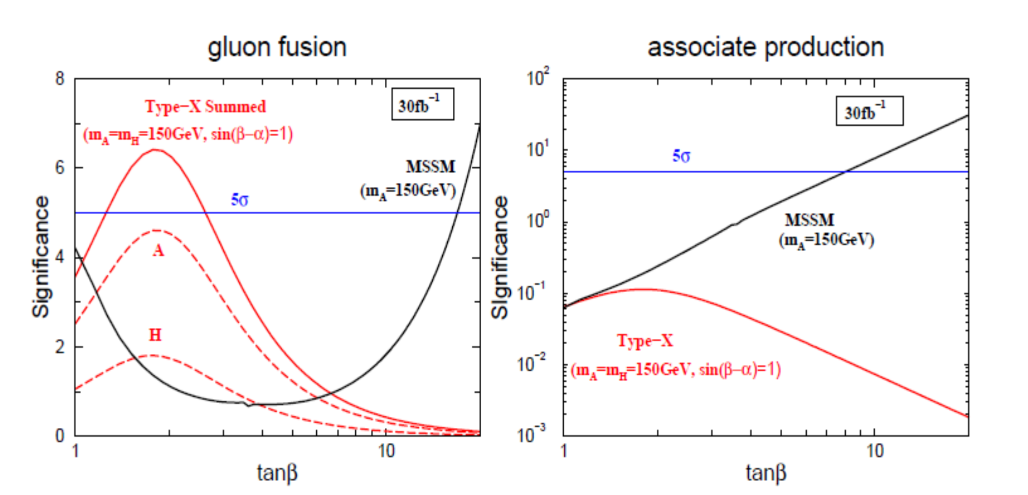


At LHC, Type X 2HDM can be discriminated from MSSM (Type-II) by the combination of ττ gluon fusion

$$pp \to A\ (H) \to \tau\tau$$

and bb associate (H)A production

$$pp \to bbA\ (bbH)$$



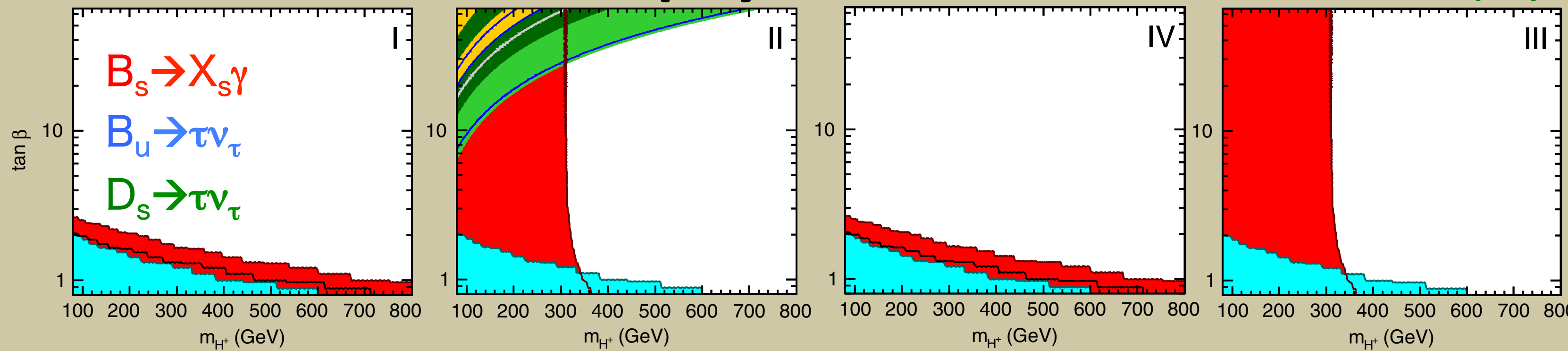
	ξ^u	ξ^d	ξ^ℓ
Type-I	$1/\tan\beta$	$-1/\tan\beta$	$-1/\tan\beta$
Type-II	$1/\tan\beta$	$\tan\beta$	$\tan\beta$
Type-X	$1/\tan\beta$	$-1/\tan\beta$	$\tan\beta$
Type-Y	$1/\tan\beta$	$\tan\beta$	$-1/\tan\beta$

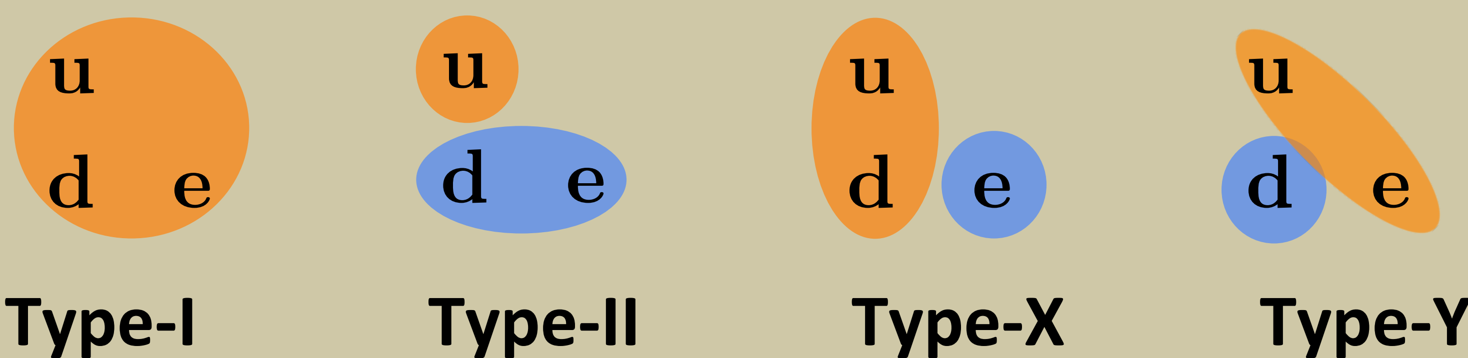
Aoki, SK, Tsumura, Yagyu (10)

Non-SUSY 2HDM

Constraint from flavor physics

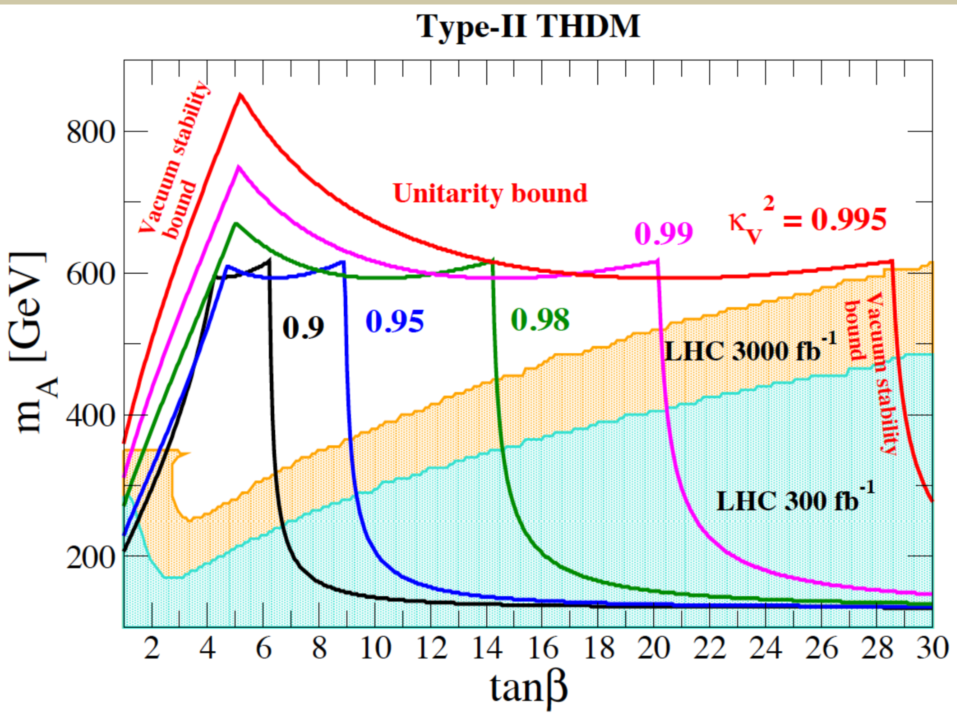
Mahmoudi, Stal (09)

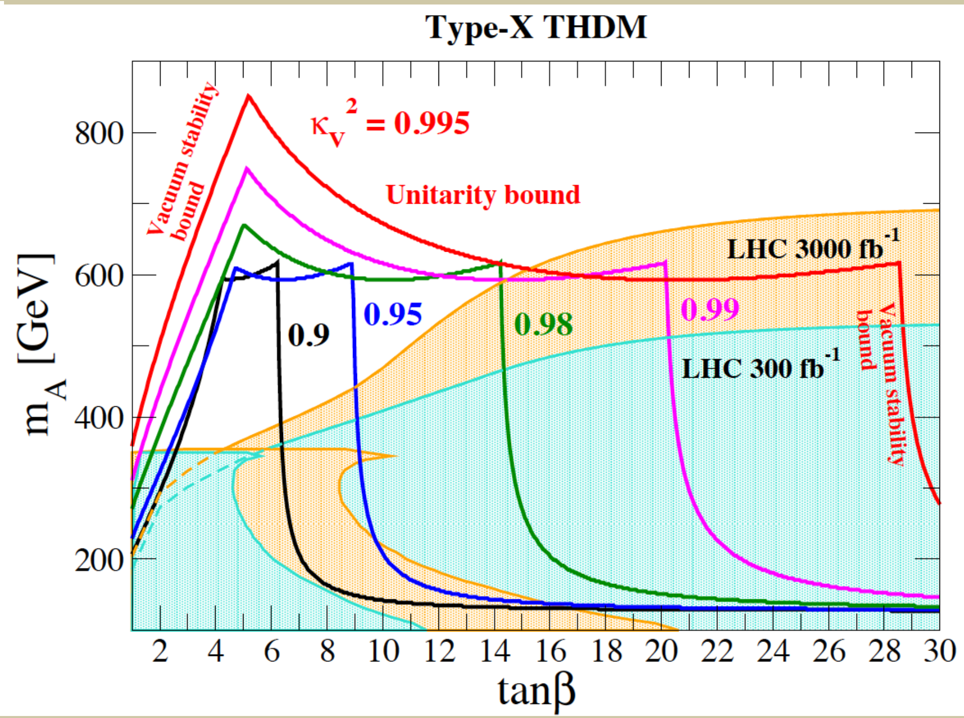




In Type-I and Type-X, light *H, A, H⁺* can be allowed

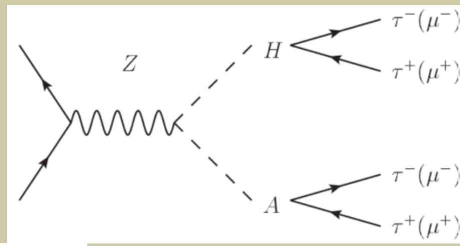
⇒Pair Production

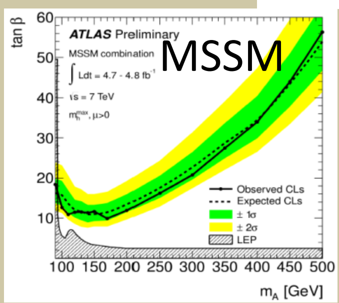

Type-II THDM
Vacuum stability bound
Unitarity bound
$\kappa_V^2 = 0.995$
0.99
0.9
0.95
0.98
LHC 3000 fb^{-1}
Vacuum stability bound
LHC 300 fb^{-1}
m_A [GeV]
tanβ


Type-X THDM
Vacuum stability bound
$\kappa_V^2 = 0.995$
Unitarity bound
LHC 3000 fb^{-1}
0.95
0.98
0.99
0.9
LHC 300 fb^{-1}
Vacuum stability bound
m_A [GeV]
tanβ

HA Production (Type X 2HDM)

LHC

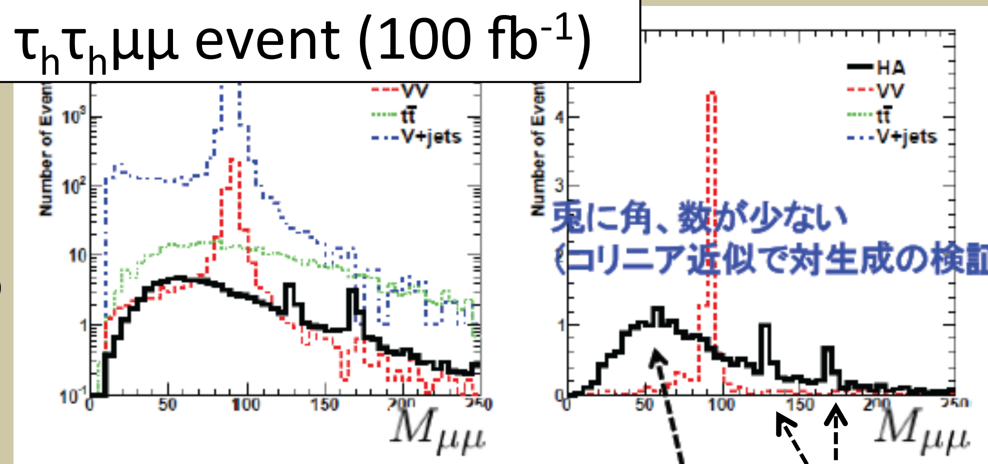




$\sigma(pp \rightarrow HA) = O(10\text{-}100)$ fb

Diferently from MSSM
（*bbH, H→μμ,ττ*）
Rather hard to see Type-X at LHC

$\tau_h\tau_h\mu\mu$ event (100 fb^{-1})



$4\tau \rightarrow 2\mu 2\tau_j$

m_H=130GeV
m_A=170 GeV

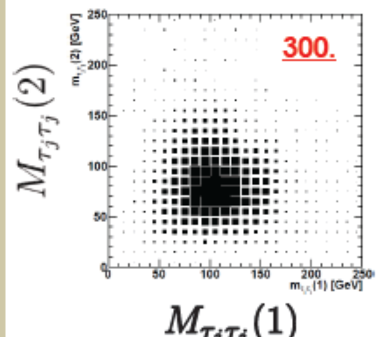
ILC

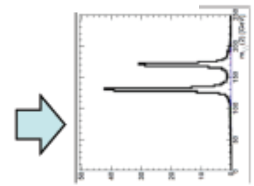
HA can be reconstructed by collinear approximation

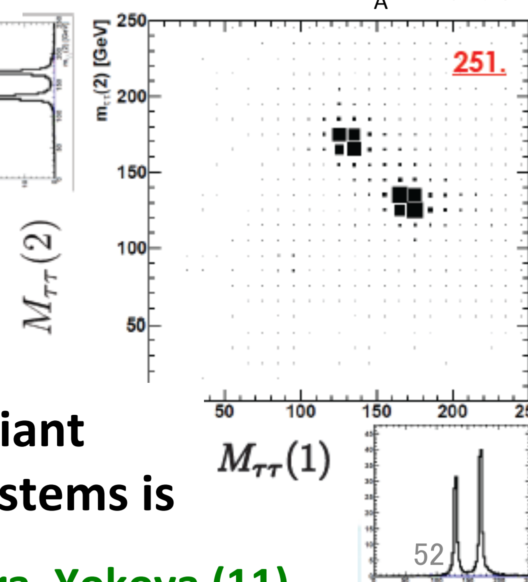
$$\vec{p}_\nu \simeq c\,\vec{p}_{\tau_j}$$

$$\vec{p}_{\tau_j} \simeq z\vec{p}_\tau = \frac{1}{1+c}\vec{p}_\tau$$

$4\tau_h$ event analysis	HA	VV	$t\bar{t}$	S (100 fb^{-1})
Pre-selection	300.	10.6	1.2	38.
$0 \leq z_{1-4} \leq 1$	251.	6.2	0.1	38.
$(m_Z)_{\tau\tau} \pm 20$ GeV	238.	1.8	0.	43.







Reconstruction of invariant masses of the two ττ systems is possible

SK, Tsumura, Yokoya (11)

Summary

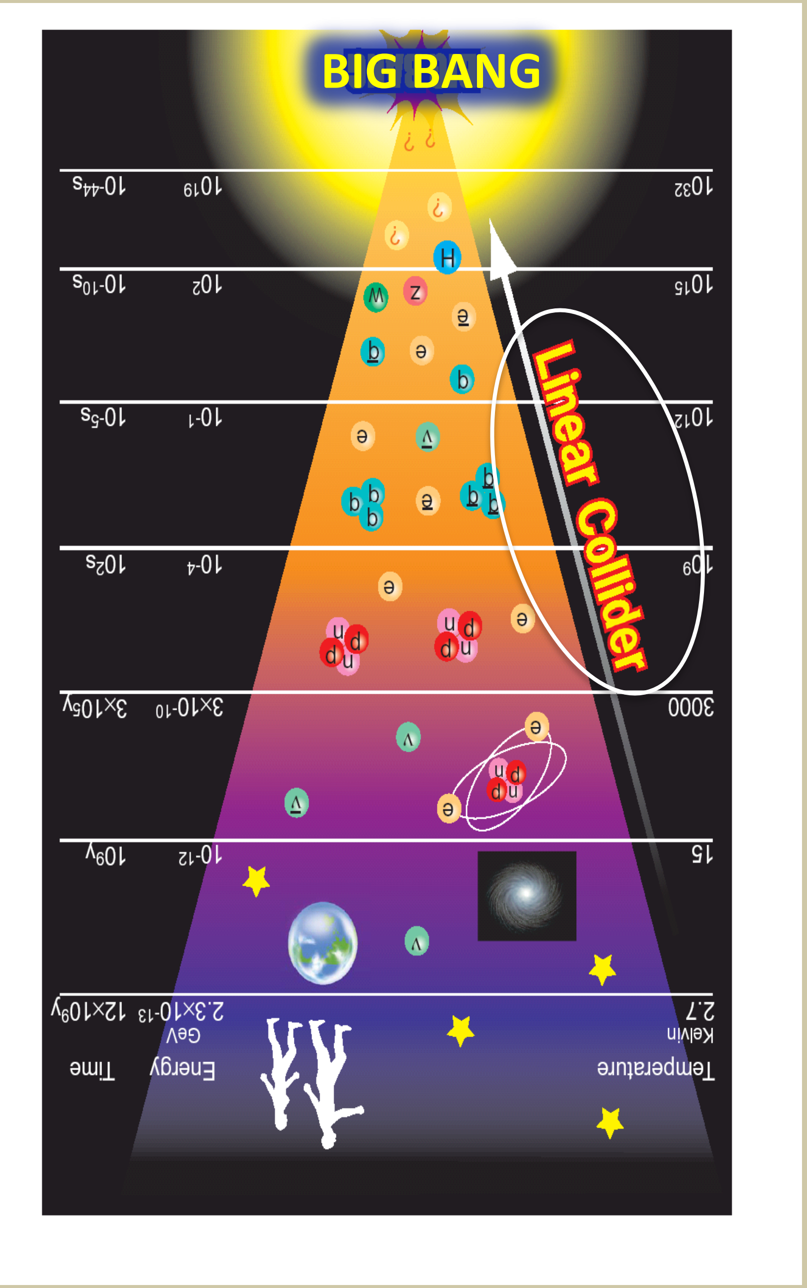
- A SM-like Higgs boson *h* was discovered
- The Higgs sector remains unknown

  SM-like ≠ SM

  Extended Higgs (⇔ New Physics)

- Detailed study of *h* makes it clear the shape and dynamics of Higgs sector (Finger printing models)
- Direct Searches of *H, A,* H^+*,* H^{++} at LHC (and ILC)
- Higgs is a good probe of new physics BSM!

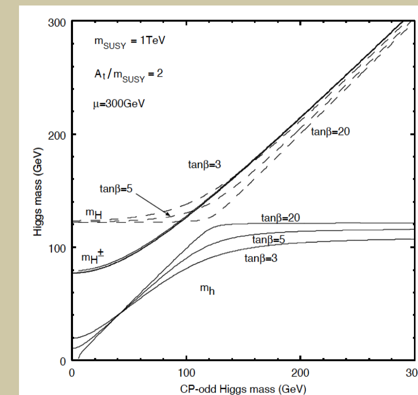
We need LC



Back Up Slides

Decoupling and heavy Higgs mass

Mass scales of *H, A, H^+* can be determined by precision measurements of the *h* couplings



MSSM（**α is a function of tanβ and m_A**）

Ratio of branching ratios

$$R_{cc+gg/bb} \simeq \left(\frac{m_A^2 - m_h^2}{m_A^2 + m_Z^2}\right)^2 R_{cc+gg/bb}(SM)$$

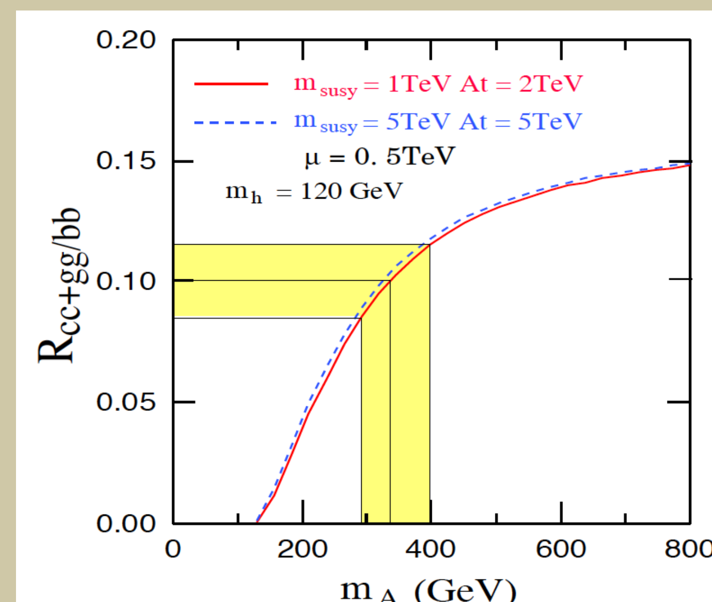
tanβ=5

$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 0.3\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^4$$

$$\frac{g_{htt}}{g_{h_{SM}tt}} = \frac{g_{hcc}}{g_{h_{SM}cc}} \simeq 1 - 1.7\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^2$$

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 40\% \left(\frac{200\ \mathrm{GeV}}{m_A}\right)^2 .$$

Peskin et. al (2012)



Y. Okada (01)

SUSY and m_h=126GeV

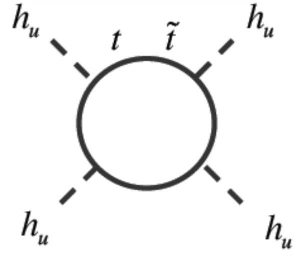
Higgs potential $V = |D|^2 + |F|^2 + \text{(soft-breaking)}$

MSSM is type-II 2HDM（H_u, H_d）

Self-coupling comes from gauge couplings g,g' ⇒ **$m_h < m_Z$ at tree level**

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

Loop effect

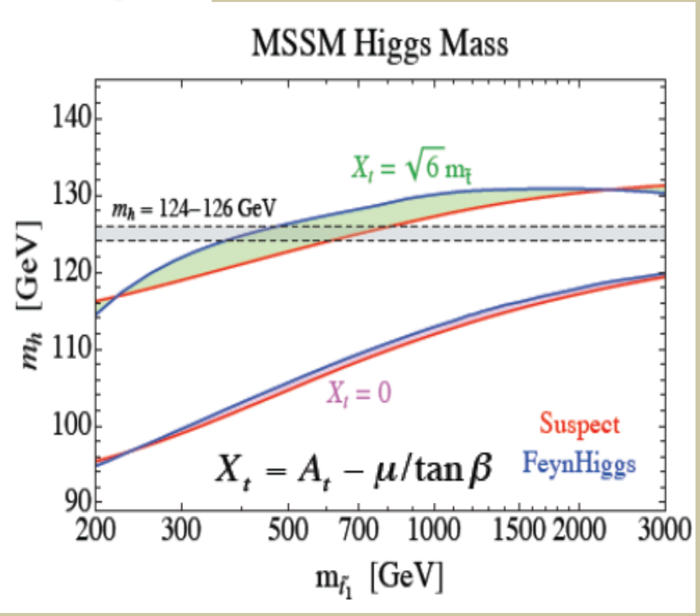


126 GeV can be realized by

Large Stop Masses OR Large Stop LR-mixing

M_{SUSY} ∼ 10TeV (X_t=0)

Consistent with the data
But tension with Hierarchy Problem

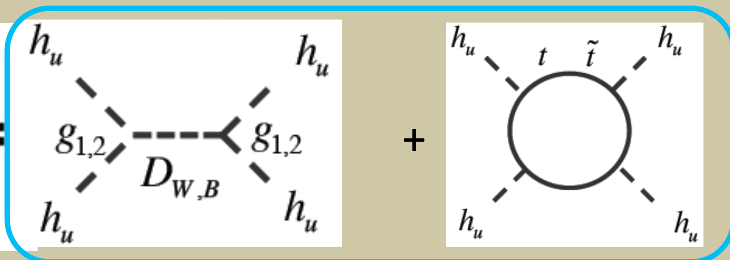


Hall, Pinner, Ruderman (2011)

Exteded SUSY models

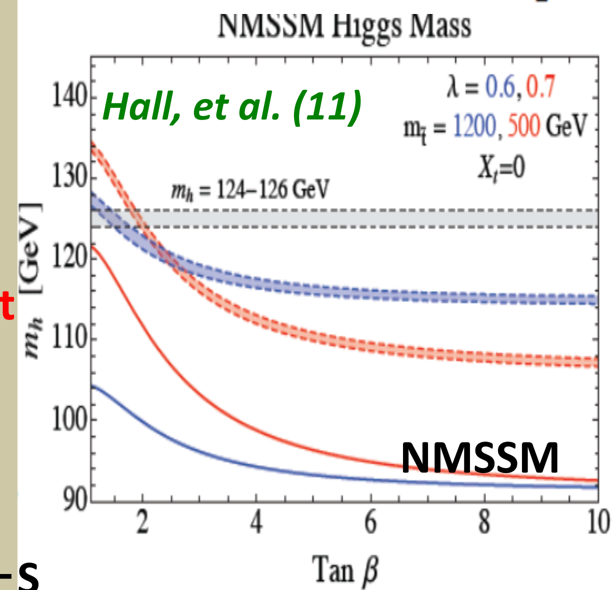
It is possible to gain m_h by NEW F-term, D-term or loop effects

$m_h^2 =$

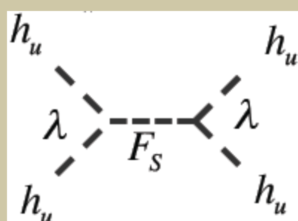


MSSM

$$W = W_{\rm MSSM} + \lambda_S S H_u H_d + \mu H_u H_d + \frac{M_s^2}{2} S^2$$



F-term +

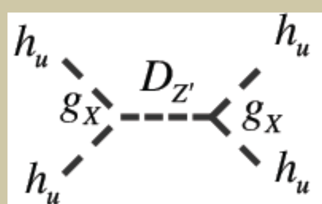


Addition of new Singlet, Triplet

Ex) NMSSM

$$\Delta m_h^2 = \frac{\lambda_S^2 v^2}{2} \sin^2 2\beta$$

D-term +



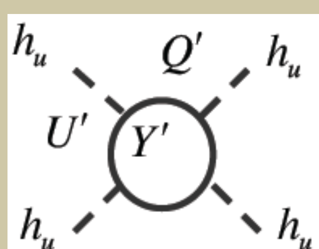
New gauge symmetry $U(1)_X$

Ex) MSSM + RH-Neutrino + S + S

$$\Delta m_h^2 \simeq 2 g_X^2 x^2 (v_{H_u}^2 + v_{H_d}^2) \cos^2(2\beta) \frac{2m_S^2}{2m_S^2 + m_{Z'}^2}$$

Endo, Hamaguchi, Iwamoto, Yokozaki (11)

Loop-effect +



Loop effect by new matter particles

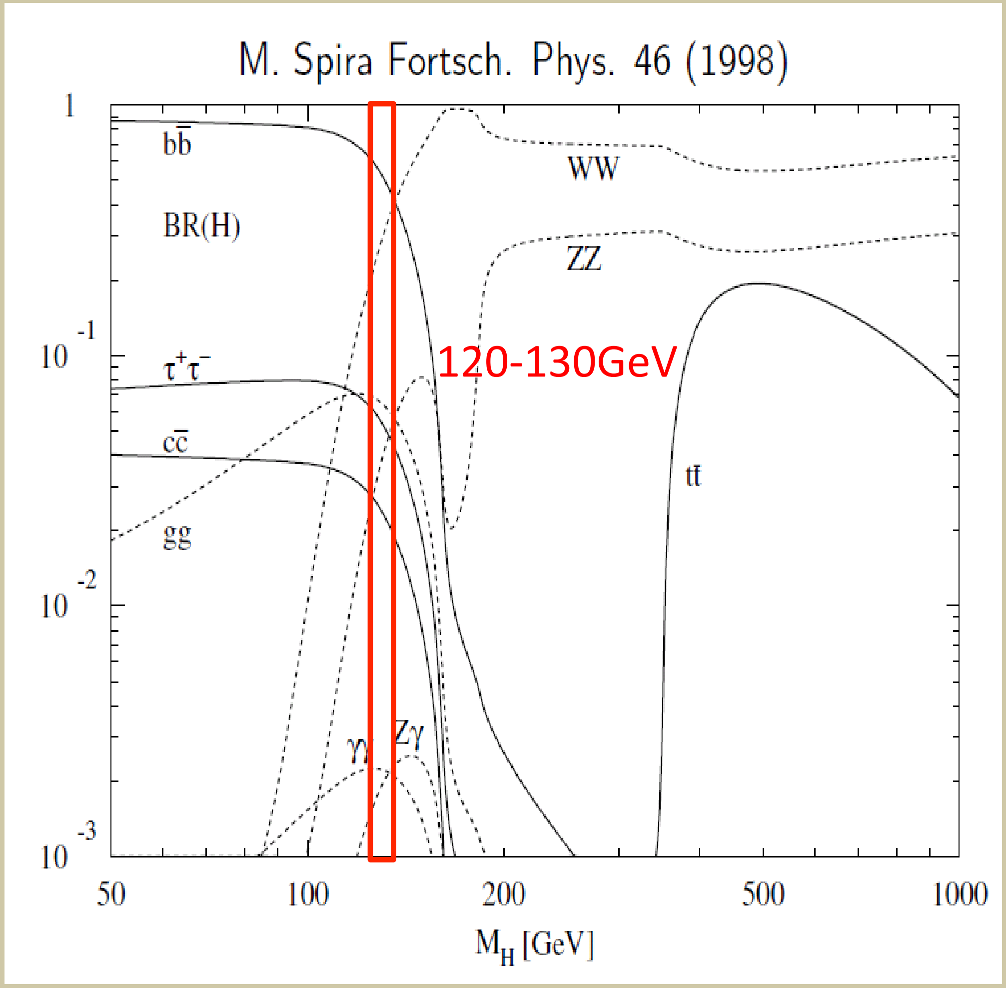
Ex) Strong-but-Light Scenario (for EWBG)

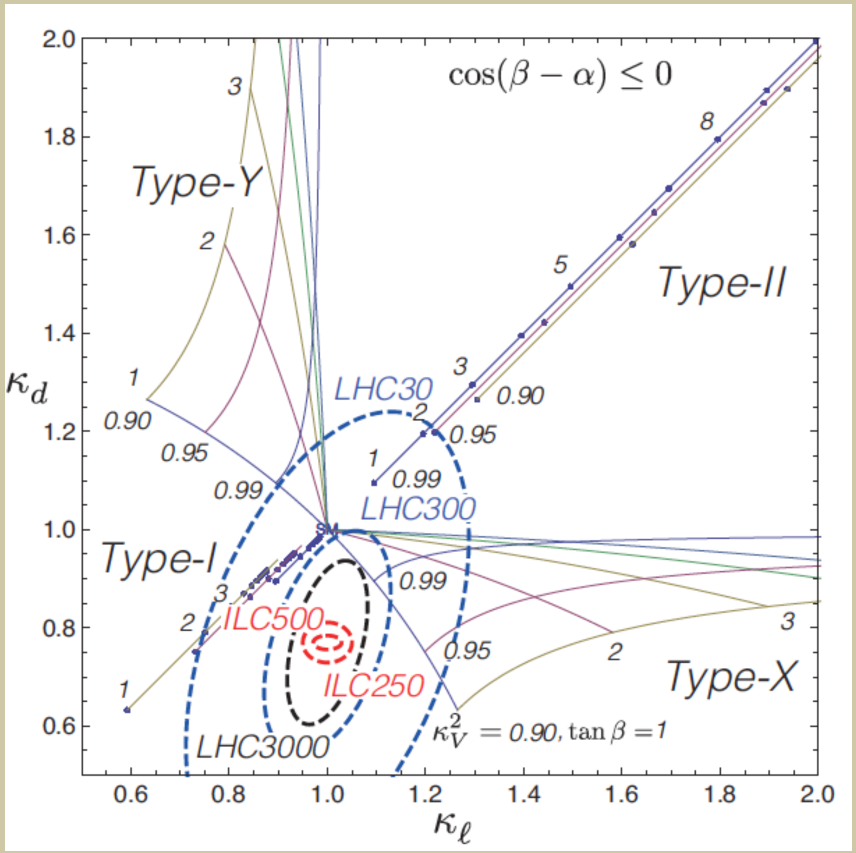
$$\Delta m_h^2 = \frac{3 Y'^4 v^2}{4\pi^2} \ln \frac{m_S^2}{m_F^2}$$

SK, Shindo, Yamada (12)

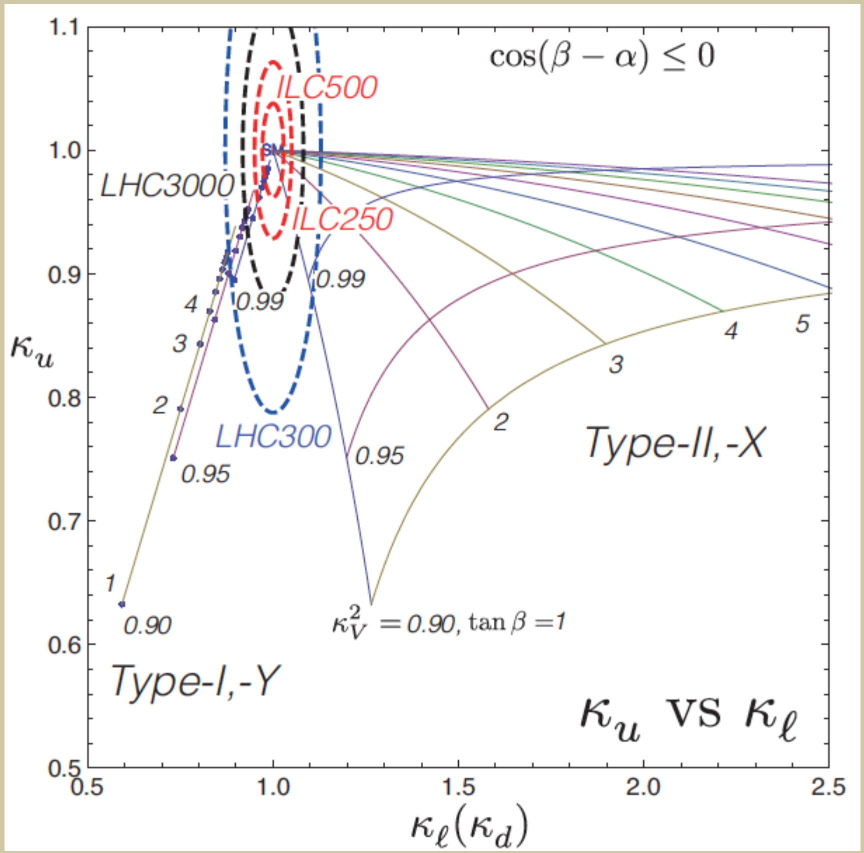
Decay branching ratios of SM Higgs

- SM Higgs couples to all the particles
  [**hγγ, hgg**（via loop）
  hhνν (dim-5)]
- For m_h=126 GeV, various decay modes can be available



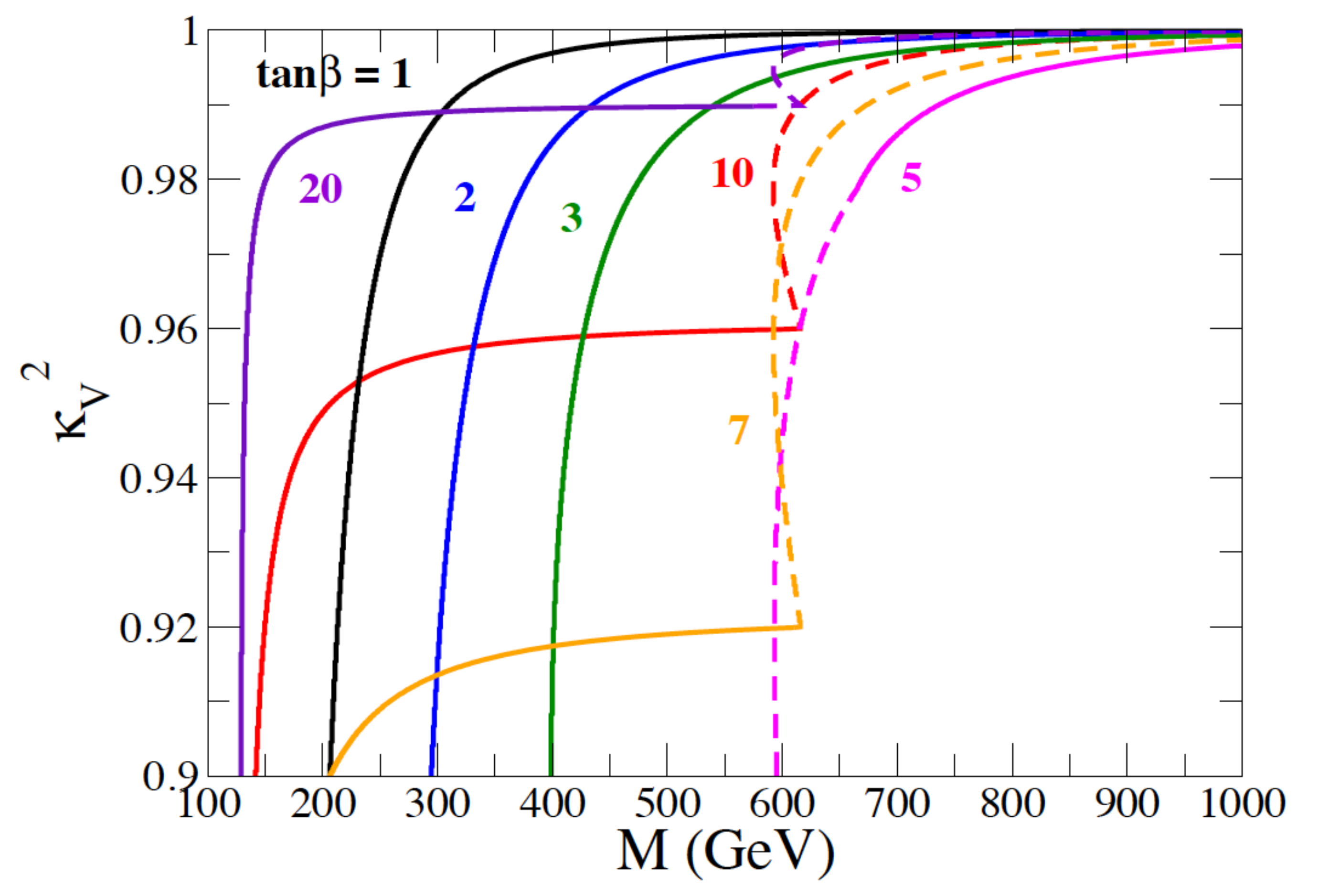


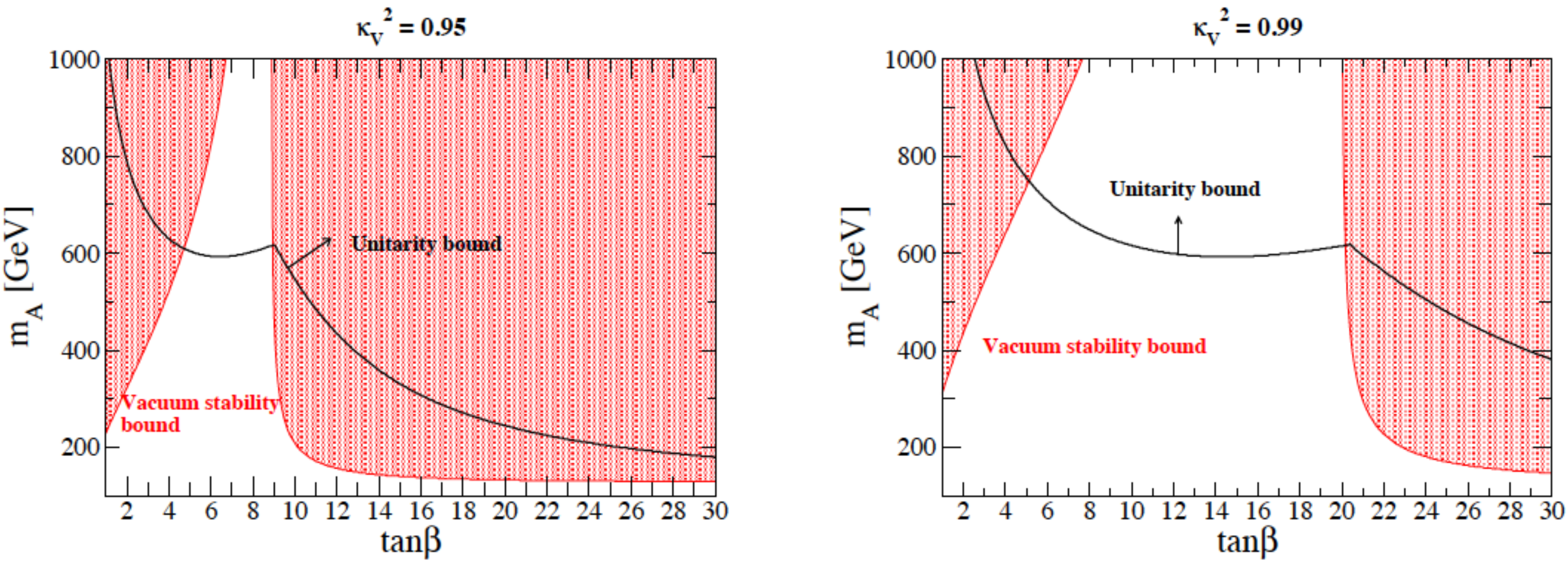
$\cos(\beta-\alpha)\leq 0$
Type-Y
Type-II
Type-I
Type-X
LHC30
LHC300
LHC3000
ILC500
ILC250
SM
κ_V^2 = 0.90, $\tan\beta$ =1
κ_d
κ_ℓ



$\cos(\beta-\alpha)\leq 0$
ILC500
ILC250
LHC3000
LHC300
Type-II,-X
Type-I,-Y
κ_V^2 = 0.90, $\tan\beta$ =1
κ_u vs κ_ℓ
κ_u
$\kappa_\ell(\kappa_d)$

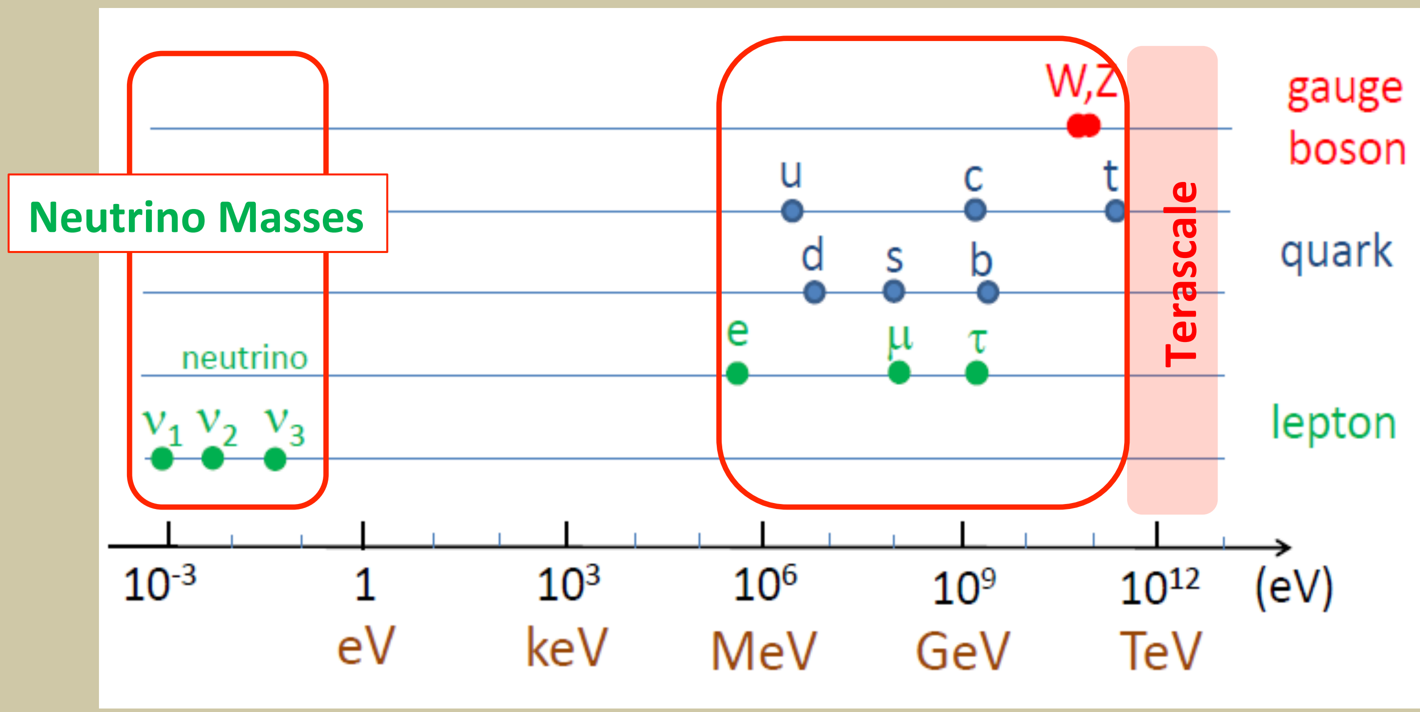
Vacuum stability bound also important





$\kappa_V^2 = 0.95$
m_A [GeV]
$\tan\beta$
Unitarity bound
Vacuum stability bound
$\kappa_V^2 = 0.99$
m_A [GeV]
$\tan\beta$
Unitarity bound
Vacuum stability bound

Mass spectrum of particles



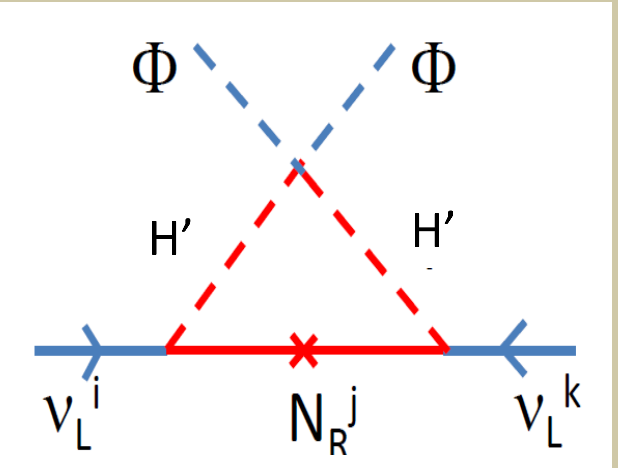
Masses of particles are zero in the Lagrangian
Vacuum gives masses to them by EWSB

Radiative seesaw with Z_2

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

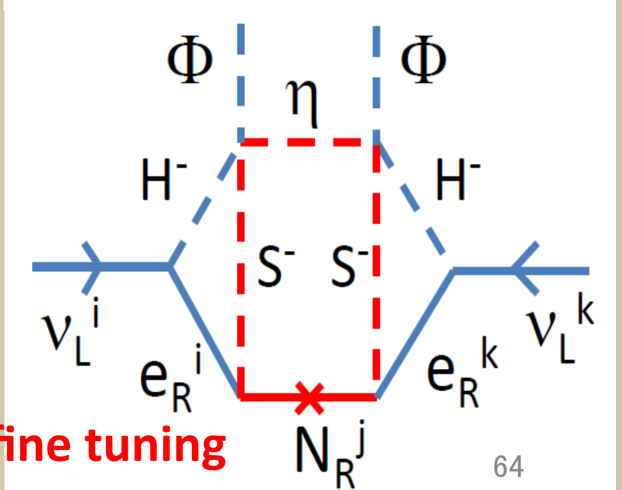
Ex1) 1-loop Ma (2006)

- Simplest model
- SM + N_R + Inert doublet (H')
- DM candidate [H' or NR]



Ex2) 3-loop Aoki-SK-Seto (2008)

- Neutrino mass from O(1) coupling
- 2HDM + η^0 + S^+ + N_R
- DM candidate [η^0 (or NR)]
- Electroweak Baryogenesis



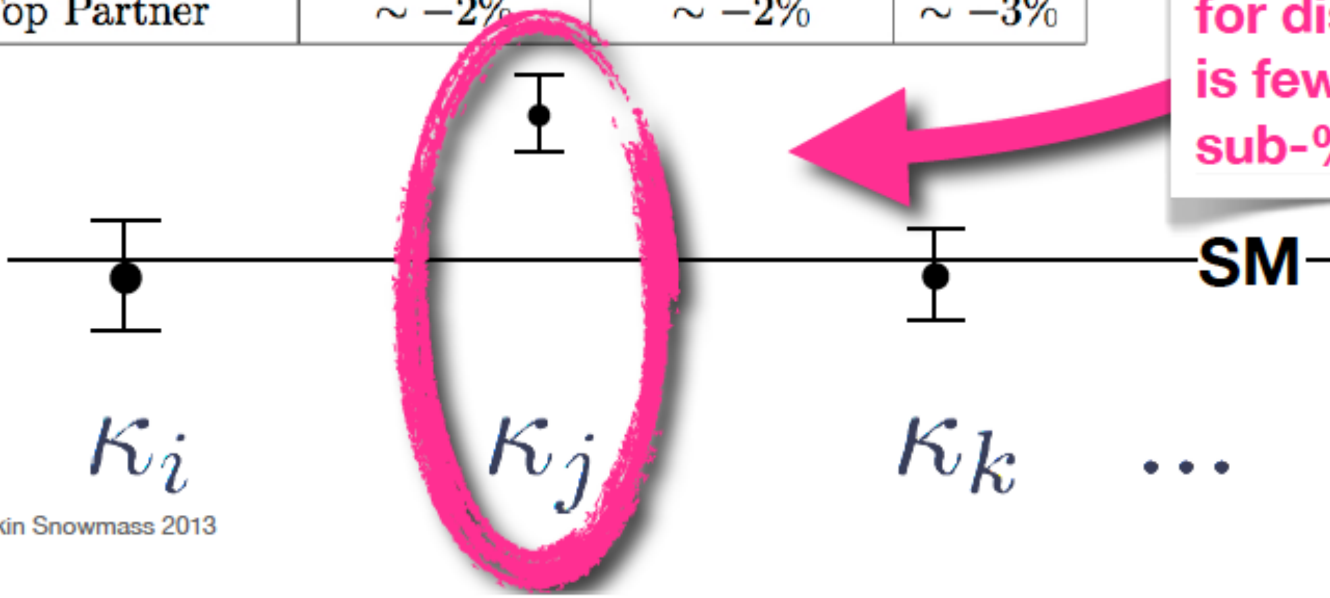
All 3 problems may be solved by TeV physics w/o fine tuning

precision for precision's sake?

No - this is a discovery search

	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

Benchmark for discovery is few % to sub-%



Gauge Couplings *hVV*

$L = g\sin(\beta-\alpha)\, hVV + g\cos(\beta-\alpha)\, HVV$

- **Changed by mixing with the other scalars**
- **Sum-rule for a multi-doublet structure** $g_{hVV}^2 + g_{HVV}^2 = g_V^2$

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

- **Higgs sector with an exotic representation**

$(g_{hVV}/g_{hVV}^{SM})^2 > 1$ **is also possible!**

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

SM-like case

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

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

Hisano, Tsumura (13)
SK, Kikuchi, Yagyu (13)

In the Higgs Triplet model

A. Arhrib, R. Benbrik, M. Chabab, G. Moultaka (2012); A. G. Akeroyd, S. Moretti (2012);

- イベント率 $h \to \gamma\gamma$

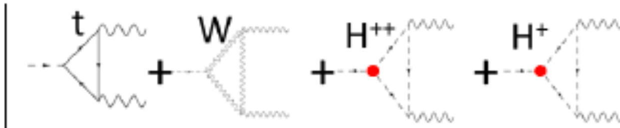
$$R_{\gamma\gamma} \equiv \frac{\sigma(gg \to h)_{\rm HTM} \times {\rm BR}(h \to \gamma\gamma)_{\rm HTM}}{\sigma(gg \to h)_{\rm SM} \times {\rm BR}(h \to \gamma\gamma)_{\rm SM}}$$

$R_{\gamma\gamma}$ は λ_4 に依存する

$$\lambda_{hH^{++}H^{--}} \approx -\lambda_4 v$$

$$\lambda_{hH^{+}H^{-}} \approx -(\lambda_4 + \frac{\lambda_5}{2})v$$

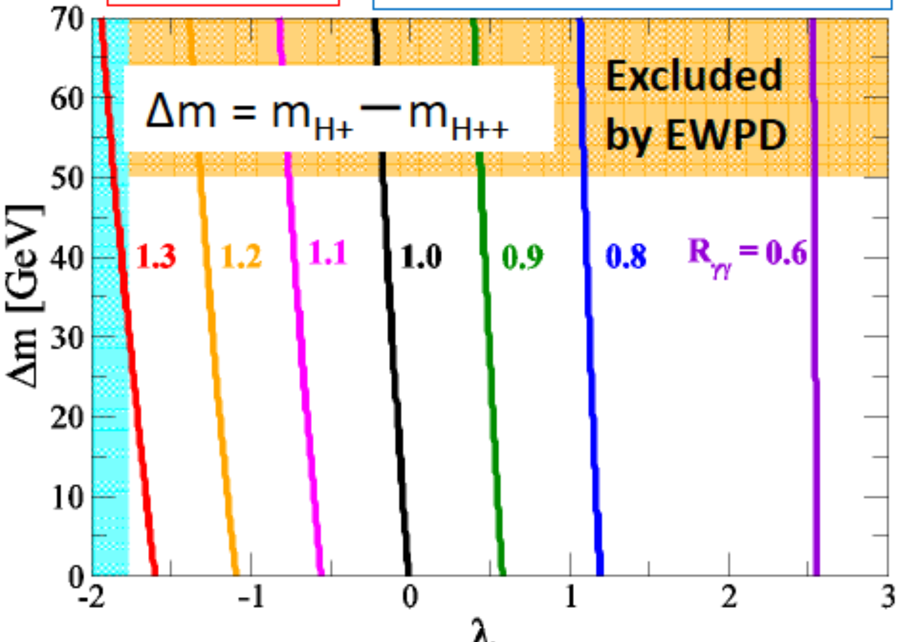
$\Gamma(h \to \gamma\gamma)_{HTM} = \Big|$



$\Big|^2$

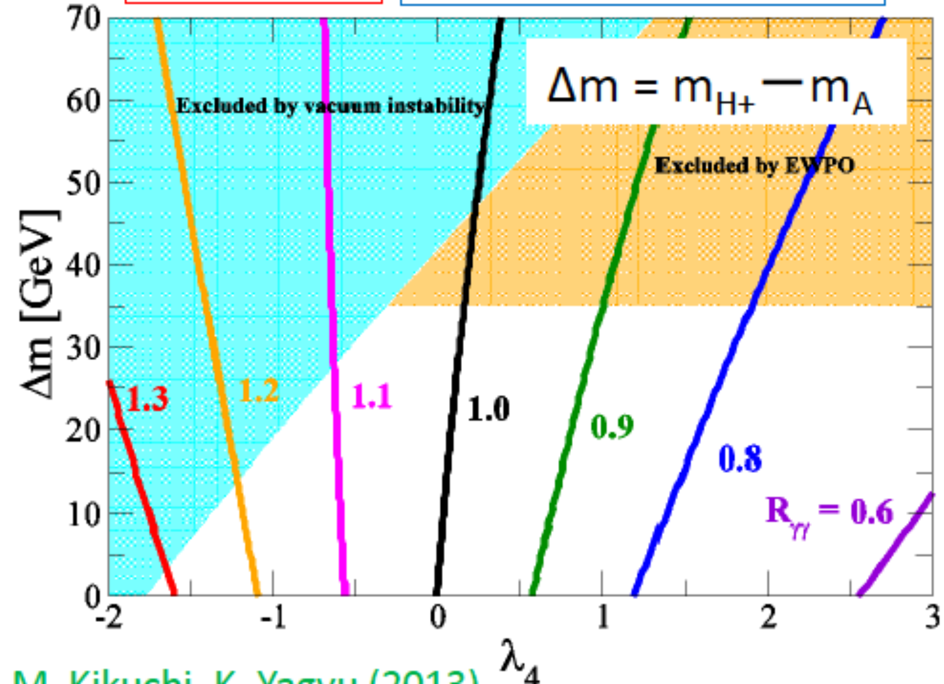
CaseI $\lambda_5 \geq 0$

$m_{H^{++}}$=300GeV, v_Δ=1MeV



CaseII $\lambda_5 \leq 0$

m_A=300GeV, v_Δ=1MeV



M. Aoki, S. Kanemura, M. Kikuchi, K. Yagyu (2013)

LHCでの結果

$R_{\gamma\gamma}^{\rm exp} = 0.5 - 1.1$

(CMS)

菊地真吏子さん
のスライドより

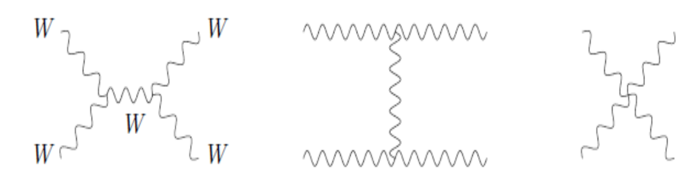
Introduction

$W_L^+ W_L^-$ Elastic Scattering

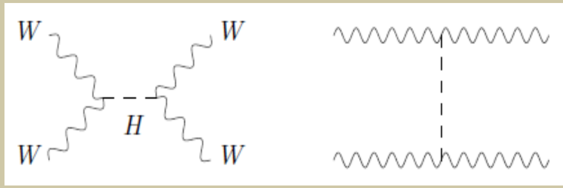
$$a^0(W_L^+W_L^- \rightarrow W_L^+W_L^-) \approx A\,E^4 + B\,E^2 + C \qquad (E \rightarrow \infty)$$

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

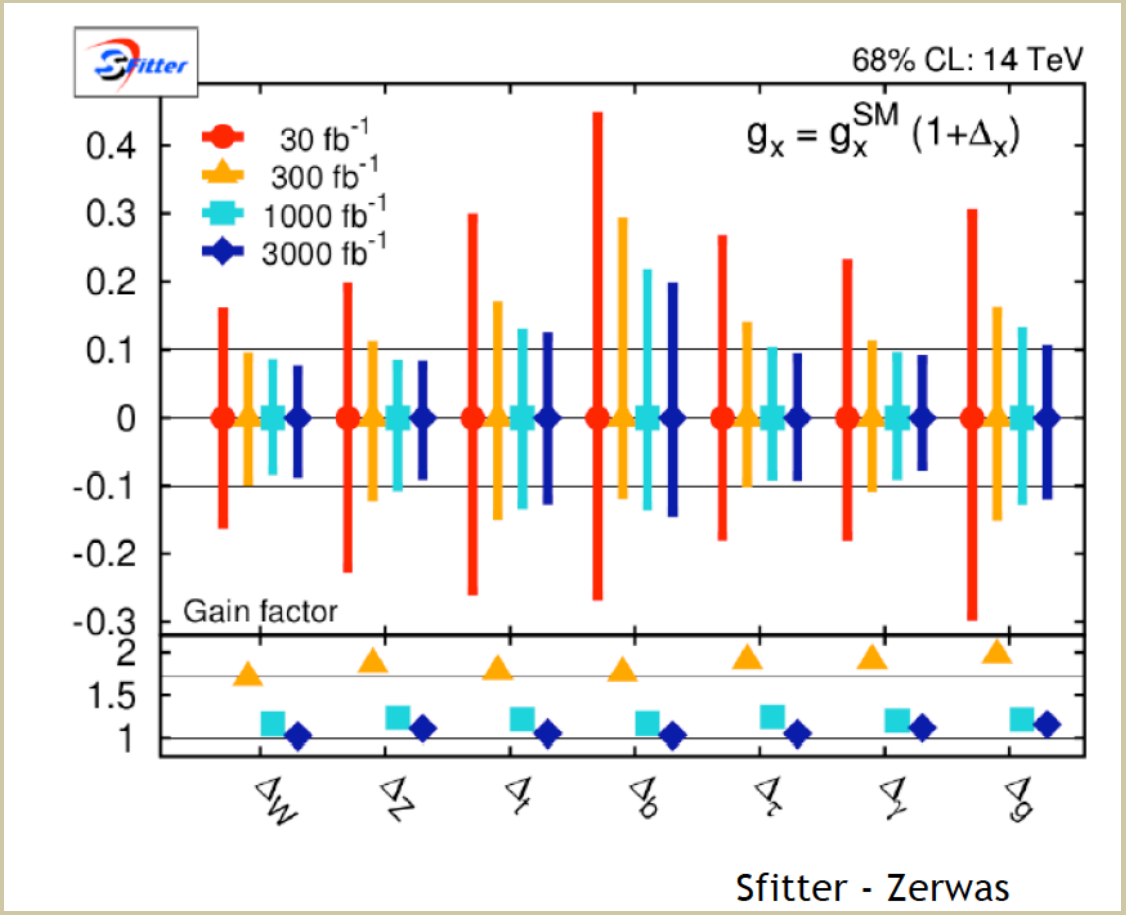
Perturbative Unitarity

$$|a^0(W_L^+W_L^- \rightarrow W_L^+W_L^-)| < 1 \quad \Rightarrow \quad m_h < 1.2\ \text{TeV}$$

Higgs coupling measurement at the LHC

Accuracy is typically O(10) %

Not very well improved for 300→3000 fb^{-1} due to systematic errors



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