UNIVERSITY OF TOYAMA 富山大学

Higgs Physics as a probe of new physics

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LC13 Workshop
exploring QCD from the infrared regime to heavy flavour scales at B-factories, the LHC and a Linear Collider 16-20 September 2013, ECT, Villa Tambosi, Italy*

Introduction

Why Higgs is important?

Introduction

Higgs field couples to all particles
Higgs field gets a VEV (v) by EWSB

Higgs mechanism
Yukawa interaction

$$m_W = g\, v$$
$$m_{q,l} = Y_{q,l}\, v$$

Dimension 5 operator
(neutrino mass)

$$m_\nu = C_\nu\, v^2/M$$

Higgs filed = Origin of Mass

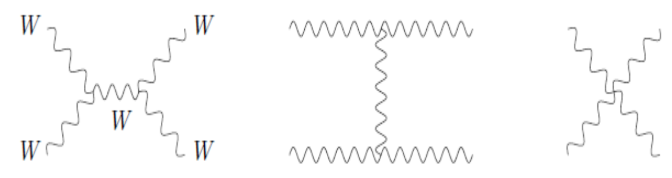
Introduction

$W_L^+W_L^-$ Elastic Scattering

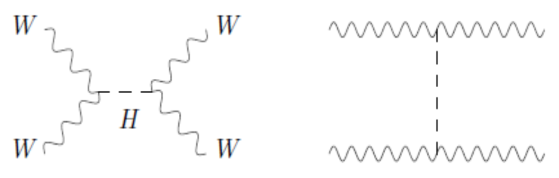
$$a^0(W_L^+W_L^- \to W_L^+W_L^-) \approx A\,E^4 + B\,E^2 + C \qquad (E \to \infty)$$

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

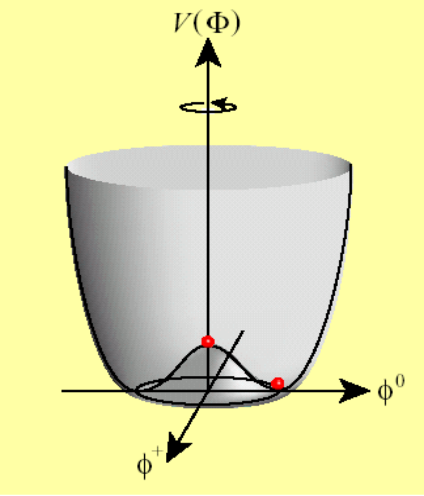
$$|a^0(W_L^+W_L^- \to W_L^+W_L^-)| < 1 \quad \Rightarrow \quad m_h < 1\ \text{TeV}$$

Introduction

Higgs Sector in the SM :

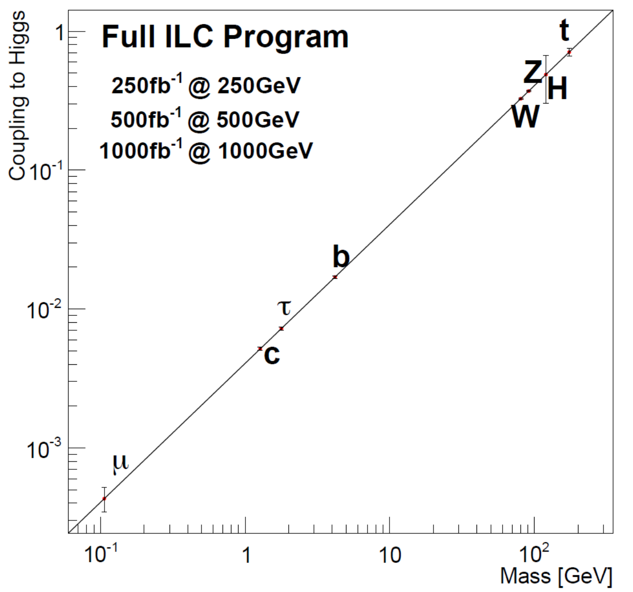
One SU(2) doublet Φ

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



Assumption of $\mu^2 < 0$ ⇒ EWSB

This is simple but …



Question:

Why minimal? (no principle)

Why $\mu^2 < 0$

What is Origin of the Higgs force λ?

In 2012 July, a boson *h* was found

The mass is 126 GeV

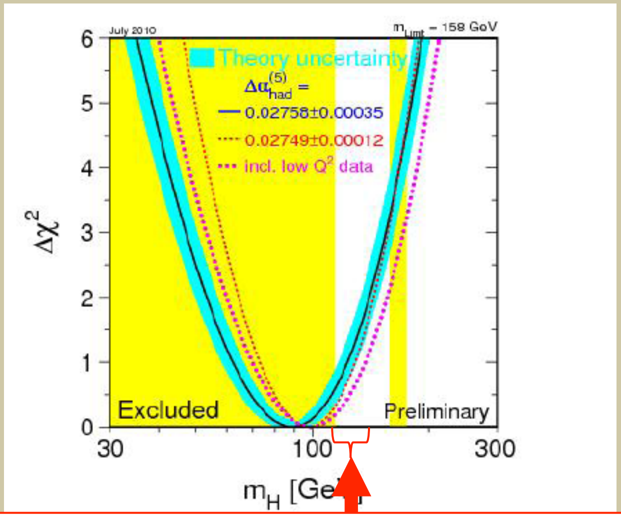
Spin/Parity 0^+

It couples to

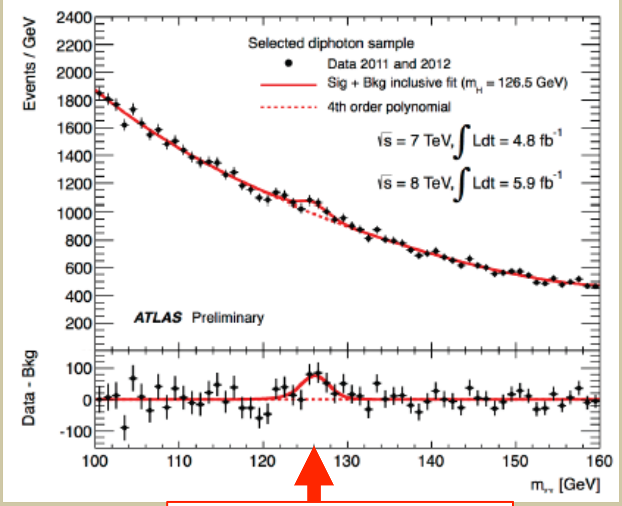
γγ, WW, ZZ, bb, ττ

This is really a SM-like Higgs!

Why SM-like?



Higgs Mass indicated by LEP/SLC



ATLAS/CMS July 2012

New Particle !

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 provide source for

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

Higgs sector = Window for new physics

Introduction

Scalar field in the SM 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 Window to new physics beyond SM

Discovery of the 126GeV SM-like Higgs *h* at LHC is a great step to determine the shape and to understand the essence of the Higgs sector

From the detailed study of the Higgs sector, we can determine models of new physics

New era has just started !

Contents

- Introduction
- Extended Higgs Sectors and New Physics
- Higgs as a probe of new physics
  - Precision measurement of the SM-like Higgs boson ***h***
  - Properties of extra Higgs bosons $H, A, H^+, H^{++}, \ldots$
- Summary

Extended Higgs Sector and New Physics

Higgs Sector

- **LHC found the SM-like Higgs boson *h* !**
- **But, the "SM-like" does not necessarily mean the SM**
- **Non-minimal Higgs models necessarily can contain the SM-like Higgs boson, and this can satisfy the current LHC data.**

The shape of the Higgs sector must be determined by future experiments

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 (SUSY, 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

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

$Q = I_3 + Y/2$

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

T_i : SU(2)$_{\text{L}}$ isospin

Y_i : hypercharge

v_i : v.e.v.

c_i : 1 for complex representation

1/2 for real representation

Possibility of ρ≈1

1. **SM + doublets (ϕ) + singlets（S）**

2. **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] $v_\Delta \approx v_\varphi$

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

2 Higgs Doublet Model

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

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

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

↑ ↑ ↑charged

CPeven CPodd

Diagonalization

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

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

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

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

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

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

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

M_{soft}: soft breaking scale

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

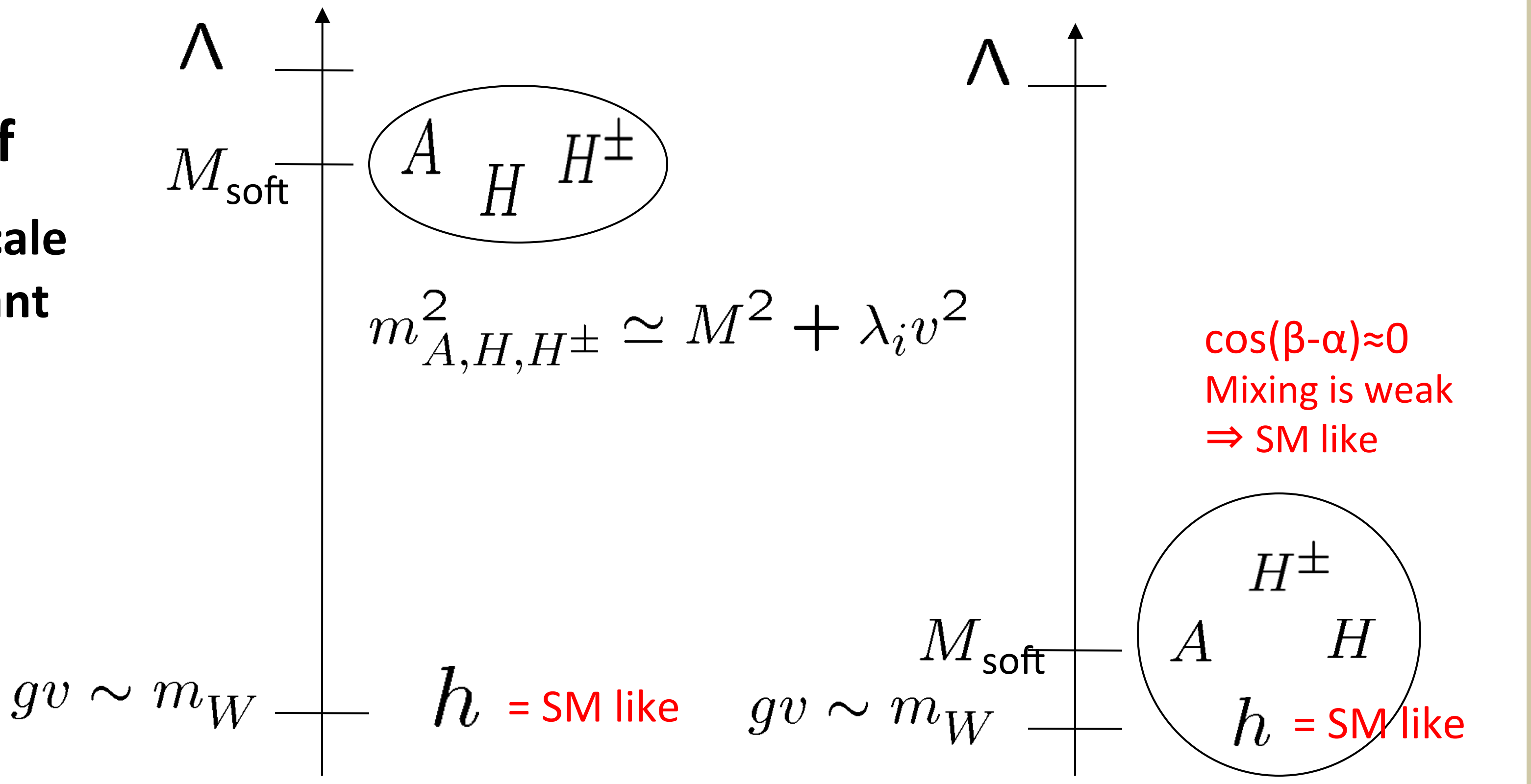
soft-breaking scale

of the discrete symm.

Extended Higgs（2 cases of SM-like *h*）

Λ: Cutoff

M: Mass scale irrelevant to VEV



Λ

M_{soft}

$A \quad H \quad H^{\pm}$

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

$gv \sim m_W$

h = SM like

Λ

cos(β-α)≈0
Mixing is weak
⇒ SM like

M_{soft}

$H^{\pm}$

$A \quad H$

$gv \sim m_W$

h = SM like

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

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

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

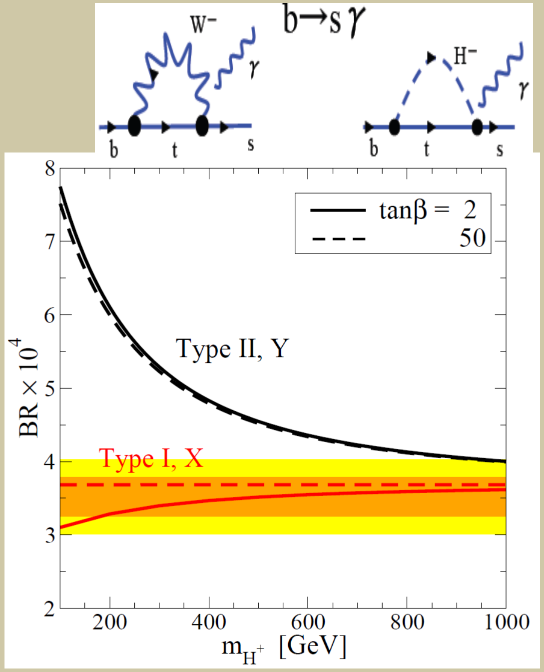
Barger, Hewett, Phillip

Four Types of Yukawa coupling

Classified by Z_2 charge assignment

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

Type of 2HDM

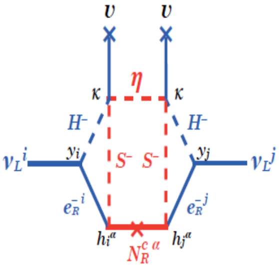


Aoki, SK, Tsumura, Yagyu (09)

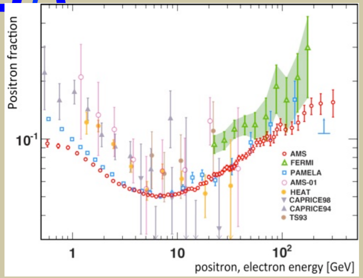
Type-I Fermiophobic 2HDM
Neutrinophillic 2HDM

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

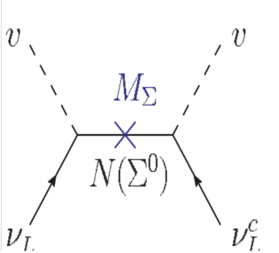
Type-X Lepton-specific 2HDM
Models of Neutrino Masses
Positron Excess
(models with light *H, A, H*±)



Aoki, SK, Seto (09)



Goh, Hall, Kumar (09)



Ma (02)

Type-Y Flipped 2HDM

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!**

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

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

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

hγγ, hgg, hWW, hZZ, htt, hff, hhh

Mixing ($h \Leftrightarrow \varphi$)

Gauge couplings (*hVV*):

Yukawa couplings (*hff*):

The pattern of deviation strongly depend on the model

Quantum effects

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

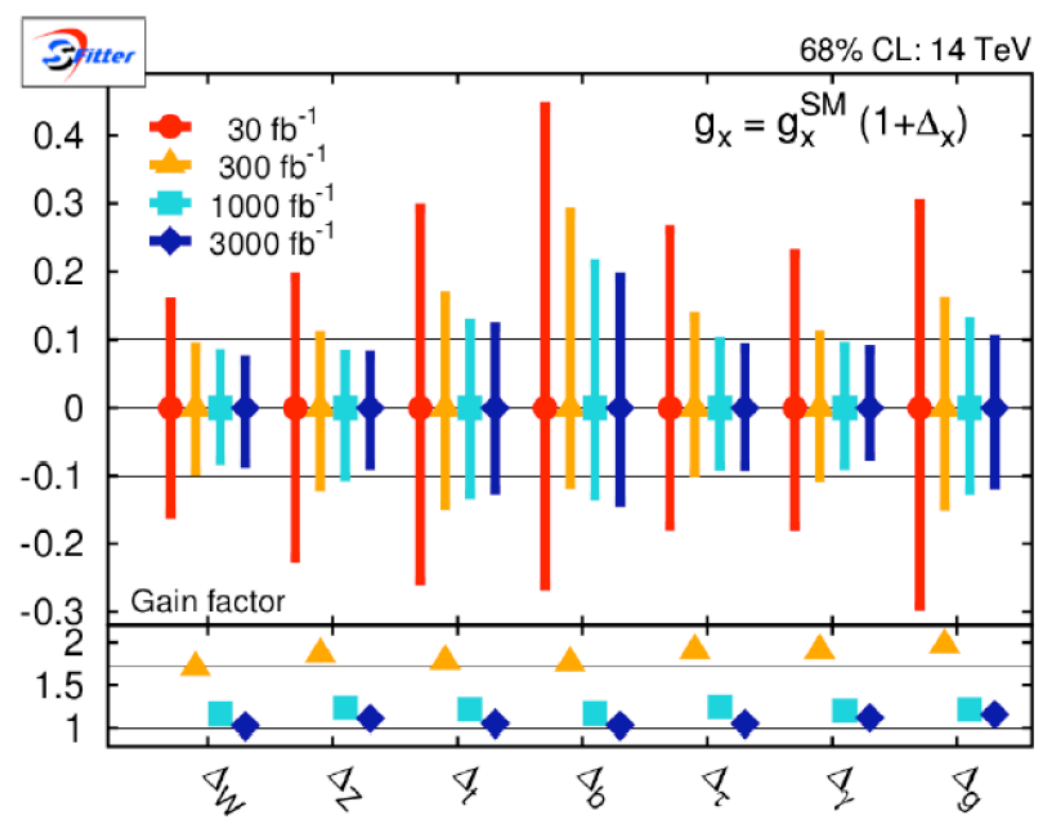
Large quantum correction can also appear in the *hhh* coupling

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

Higgs coupling measurement at the LHC

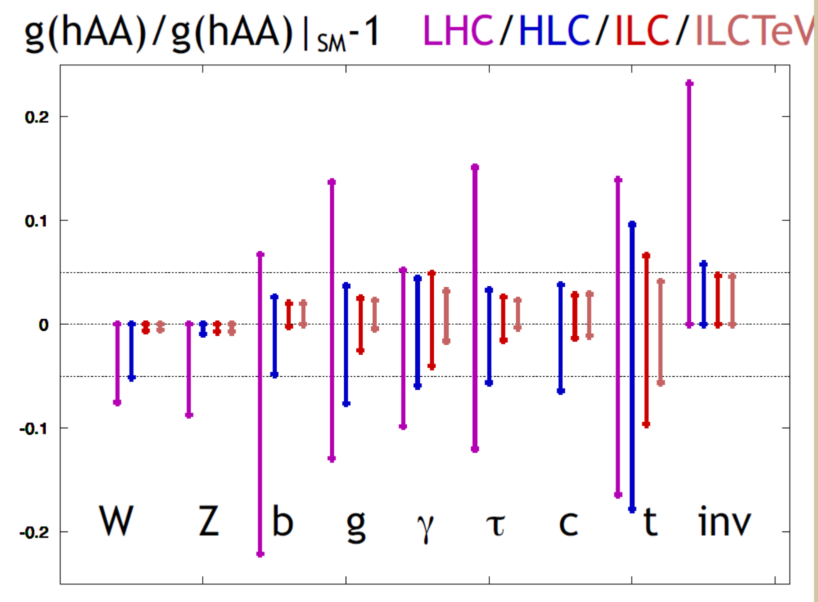
Accuracy is typically O(10) %

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

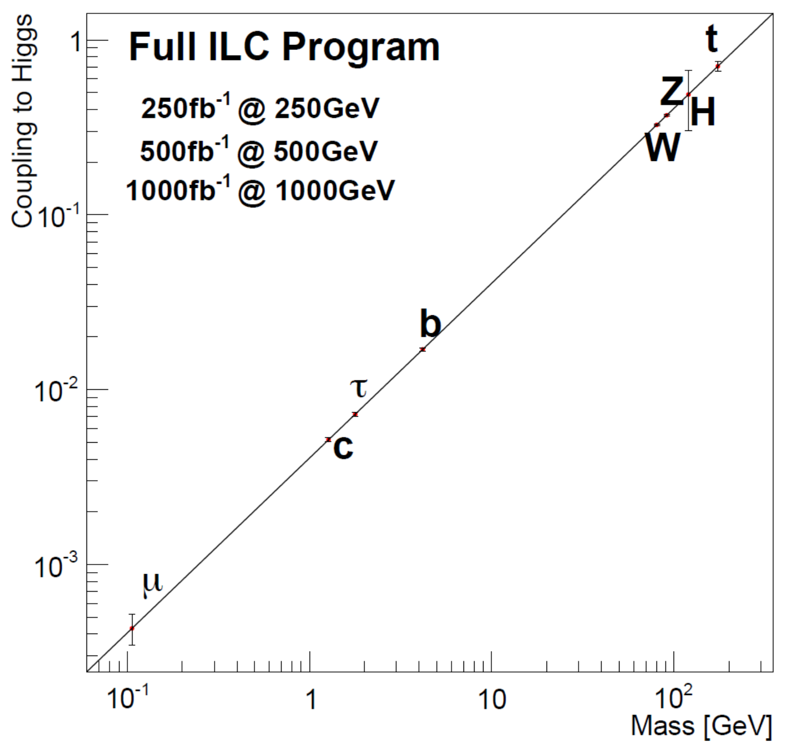


Sfitter - Zerwas

International Linear Collider



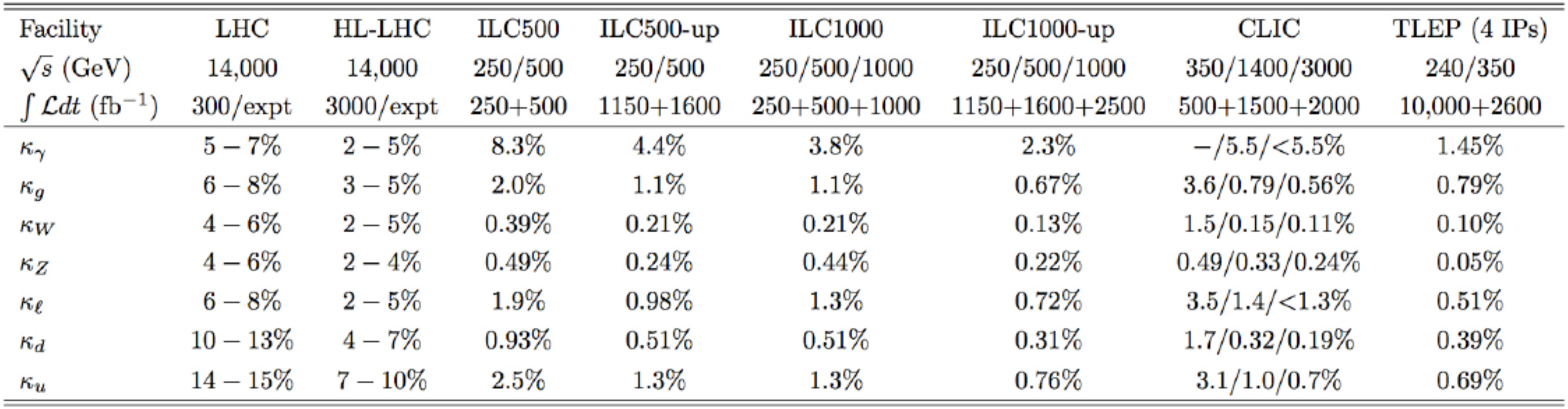
M. Peskin, 2012



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

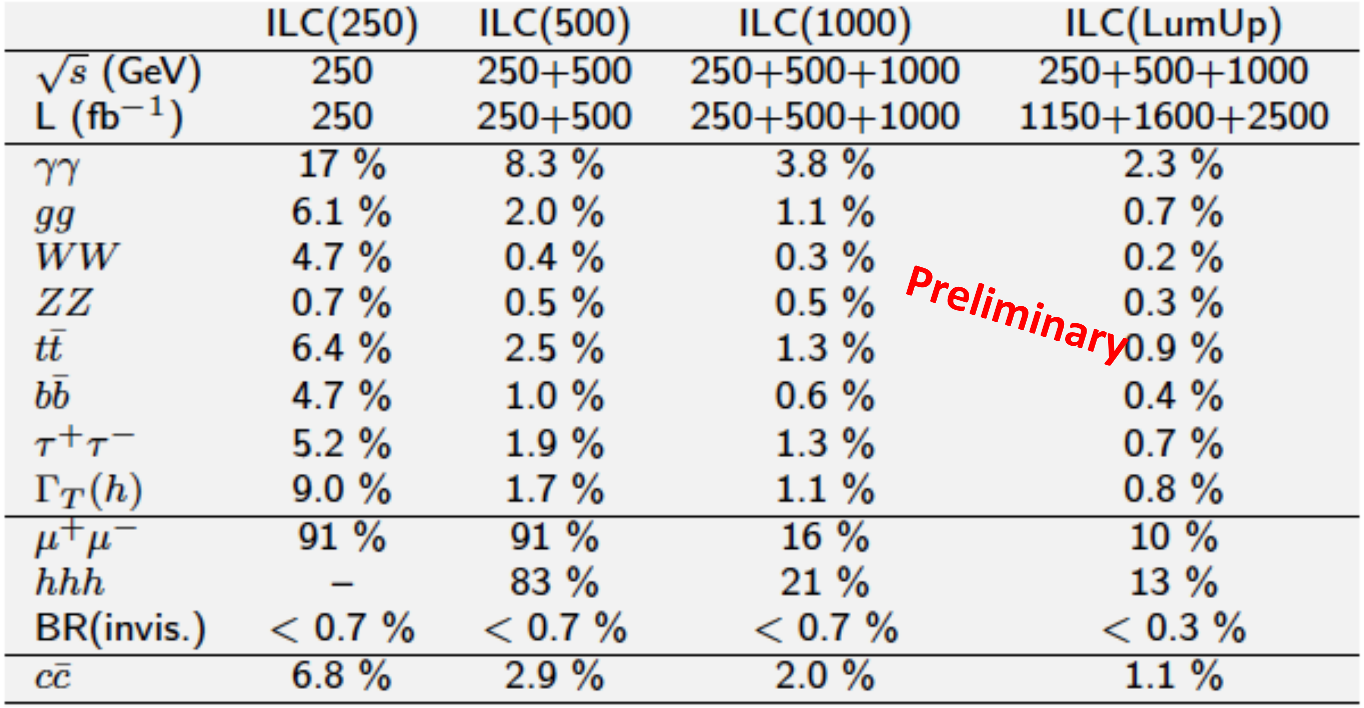
At ILC, we may be able to distinguish models by detecting a pattern of deviations in the *h* couplings from the SM values!

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(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 %

Preliminary

ILC Higgs White Paper

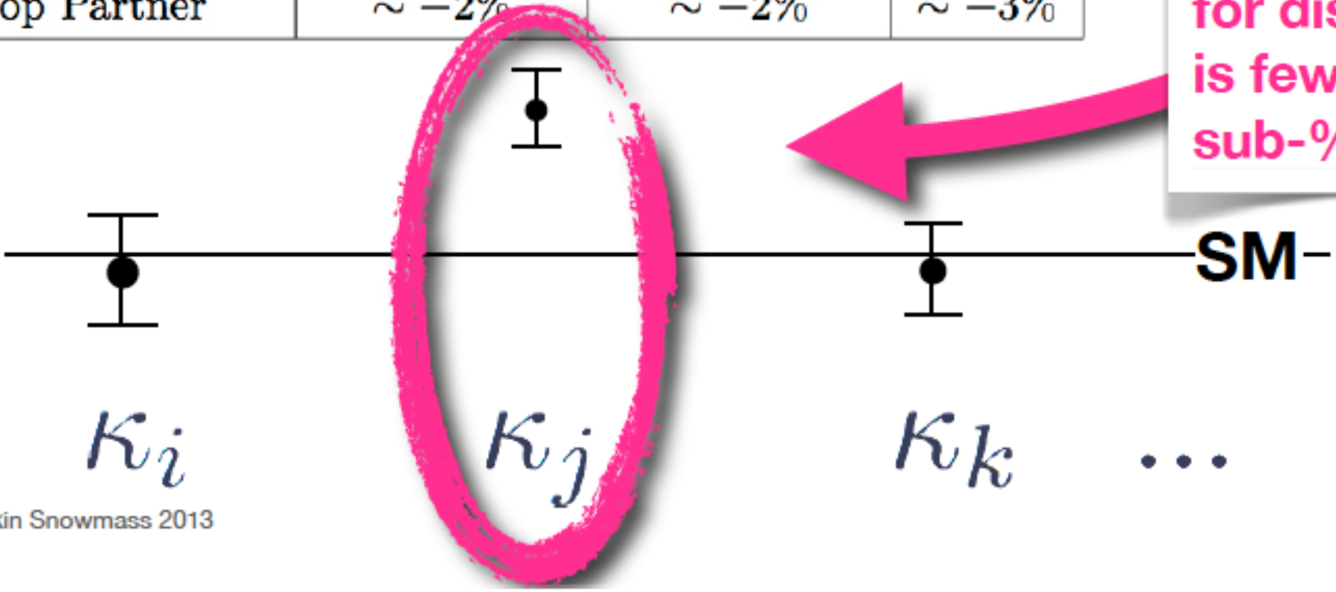
To appear at the end of this month.

Asner, Barklow, Fujii, Haber, Kanemura, Miyamoto,Weiglein

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-%

Brock/Peskin Snowmass 2013

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!

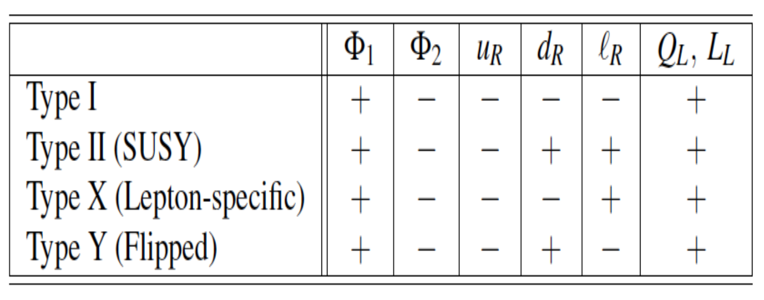
$$\frac{g_{hVV}^{\rm THDM}}{g_{hVV}^{\rm SM}} = \sin(\beta-\alpha)$$

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)

Yukawa couplings *hff*



	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)	$+$	$-$	$-$	$+$	$-$	$+$

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

Type-II

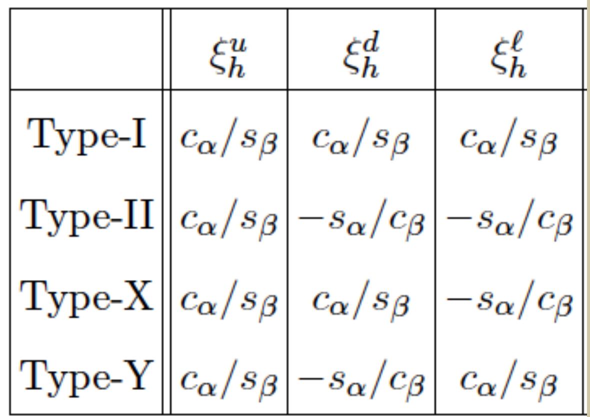
hbb $\propto$ $\sin(\beta-\alpha) - \tan\beta \cos(\beta-\alpha)$

hττ $\propto$ $\sin(\beta\text{-}\alpha) - \tan\beta \cos(\beta-\alpha)$

Type-X

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

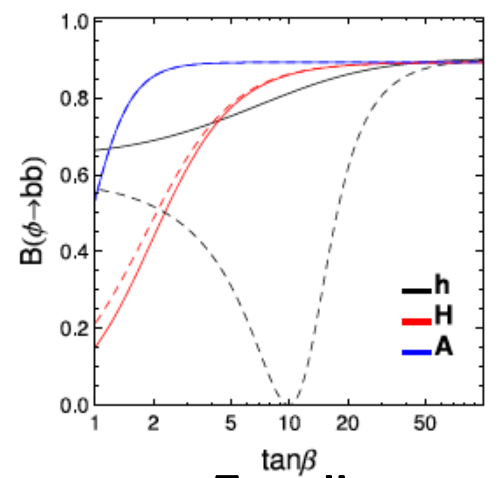
hττ $\propto$ $\sin(\beta\text{-}\alpha) - \tan\beta \cos(\beta-\alpha)$



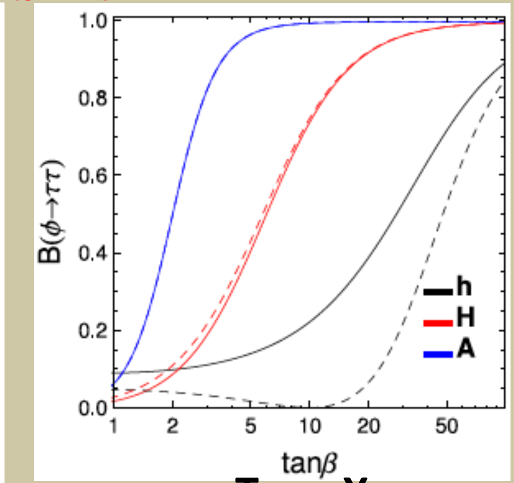
	ξ_h^u	ξ_h^d	ξ_h^ℓ
Type-I	c_α/s_β	c_α/s_β	c_α/s_β
Type-II	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$
Type-X	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$
Type-Y	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β

Coefficient of *hff*

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



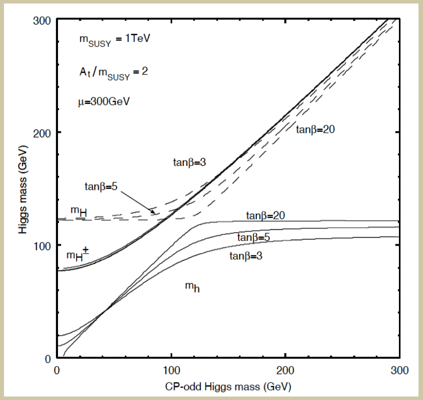
Type II



Type X

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

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

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

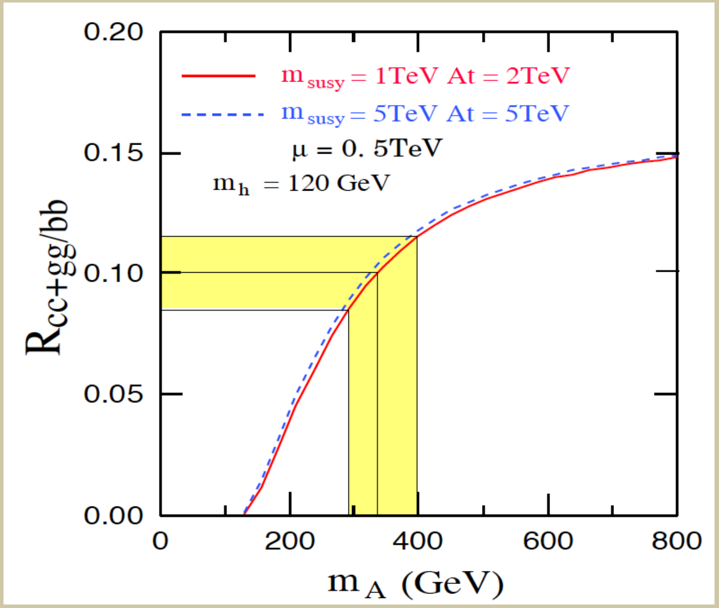
tanβ=5

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

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

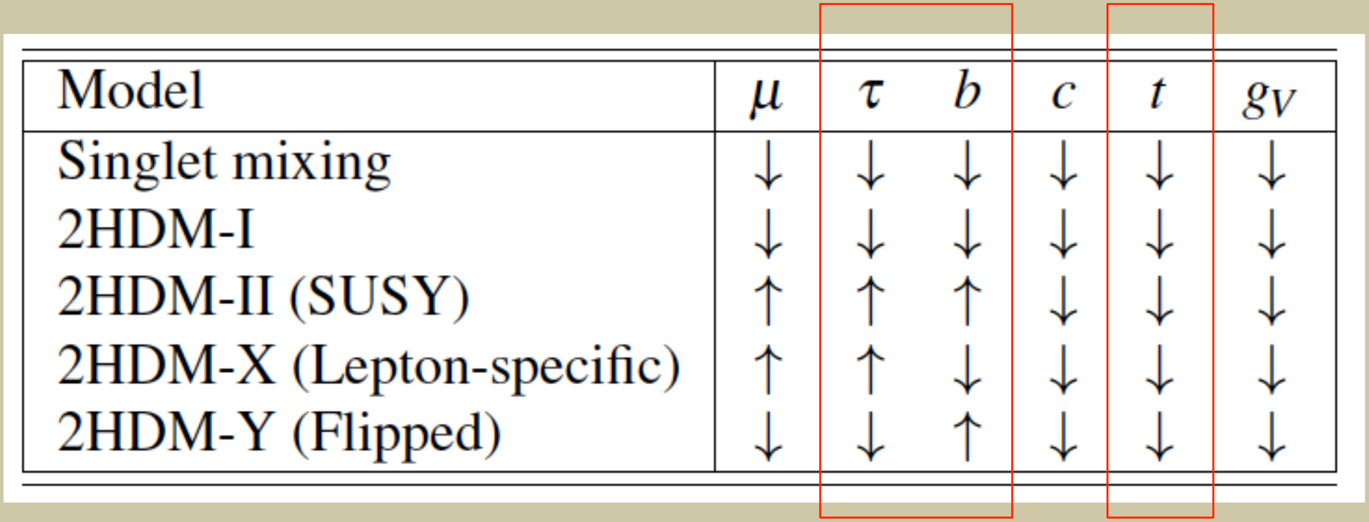
$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 40\% \left(\frac{200\ {\rm GeV}}{m_A}\right)^2 .$$

Peskin et. al (2012)



Y. Okada (01)

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 univarsal. g_V can be greater than 1

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

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

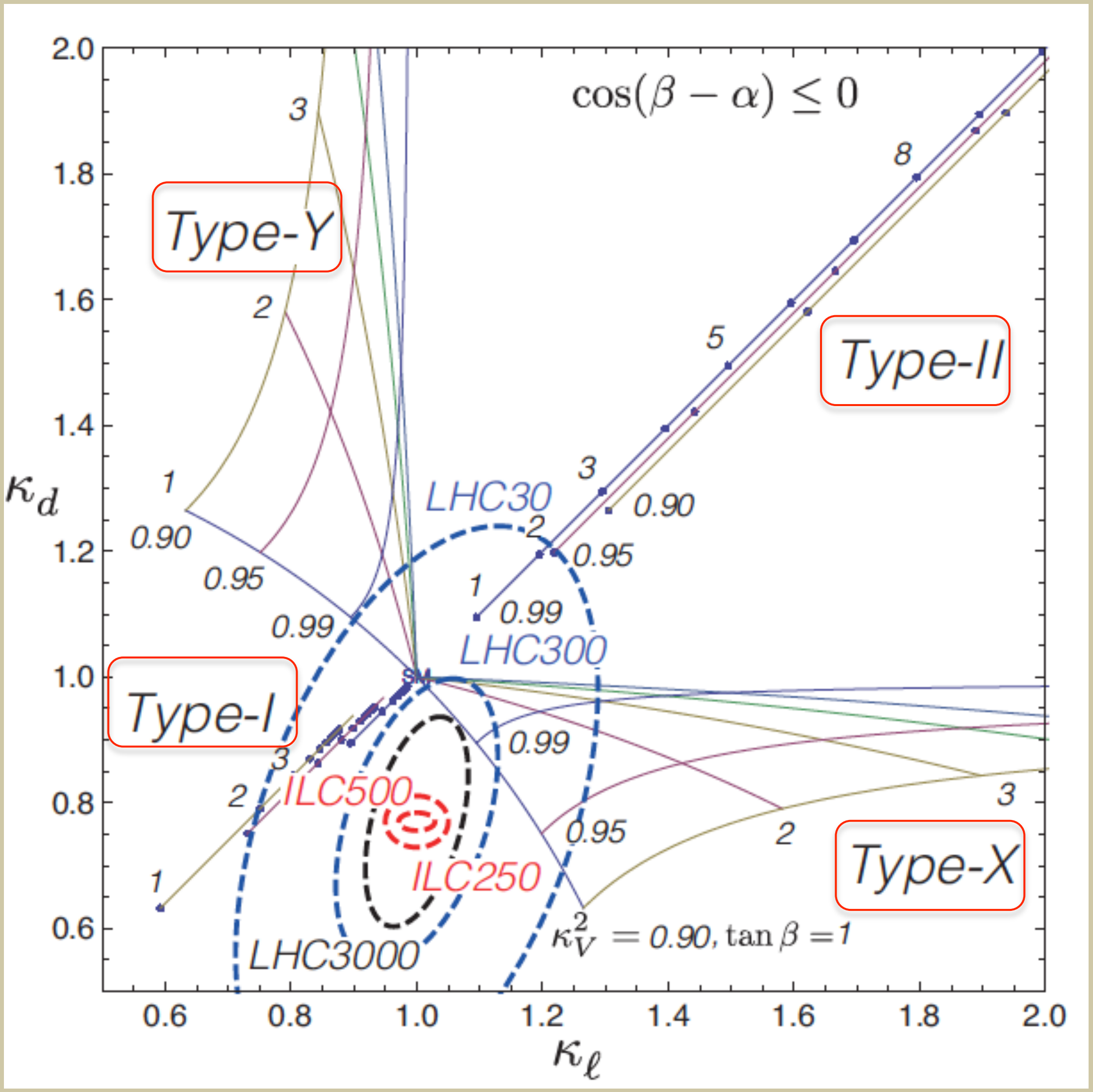
Fingerptinting the model (2HDM)

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

hbb vs h$\tau\tau$

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

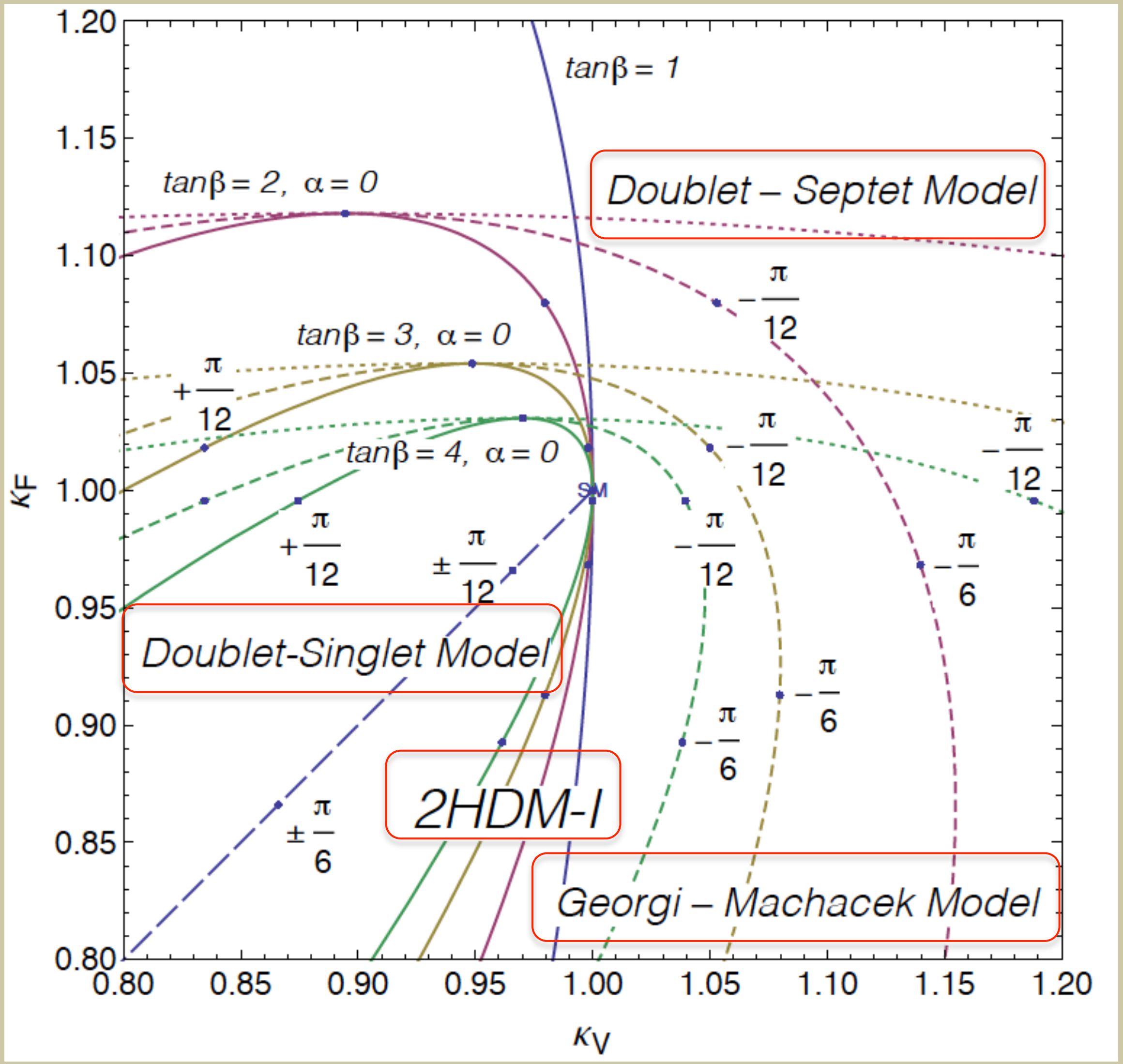
Universal Fermion Coupling (κ_F)

VS

***hVV* coupling (κ_V)**

Exotic models predict $\kappa_V > 1$

We can discriminate Exotic models



Fingerptinting the model (Exotics)

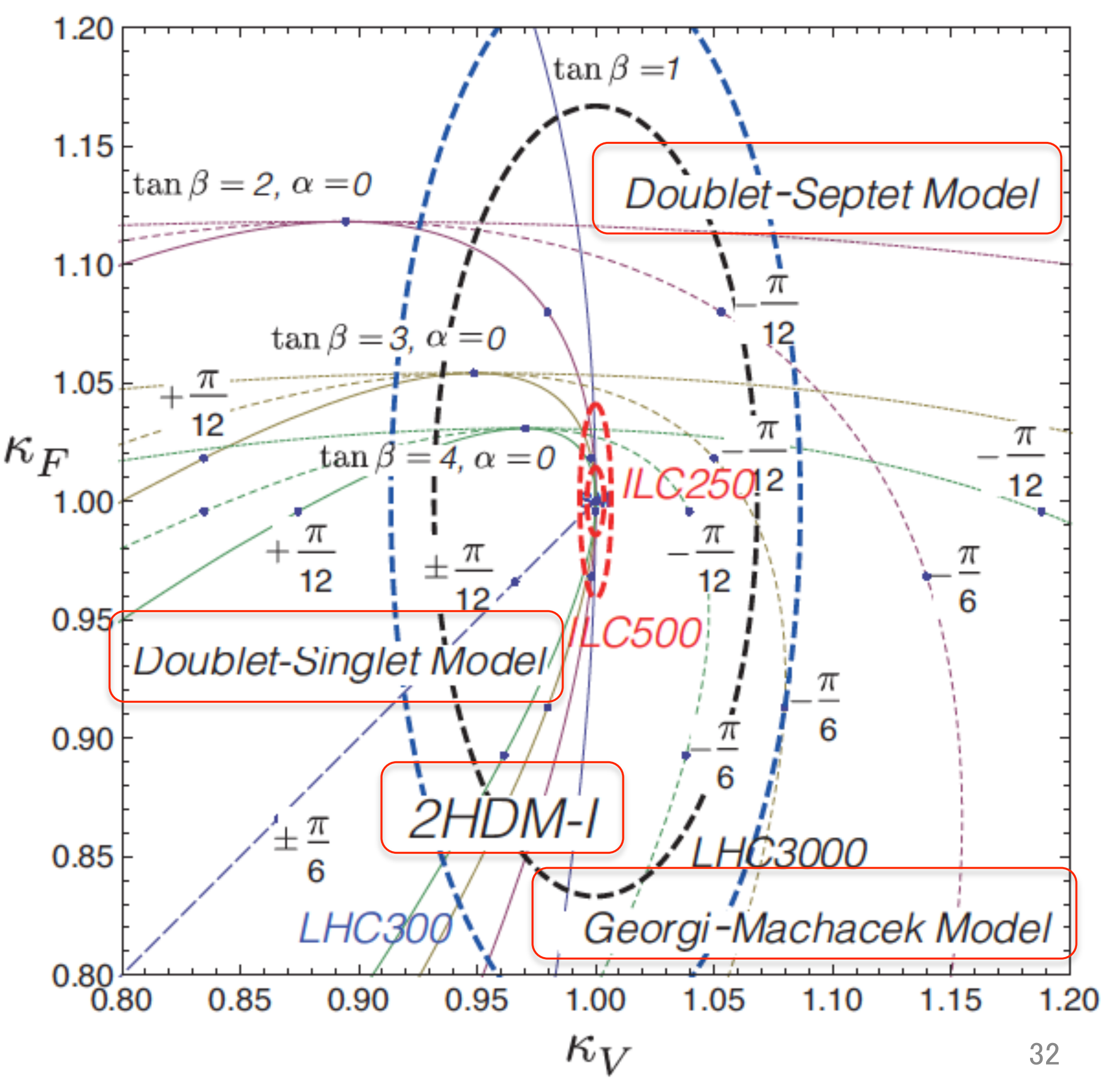
SK, K. Tsumura, K. Yagyu, H. Yokoya

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



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)

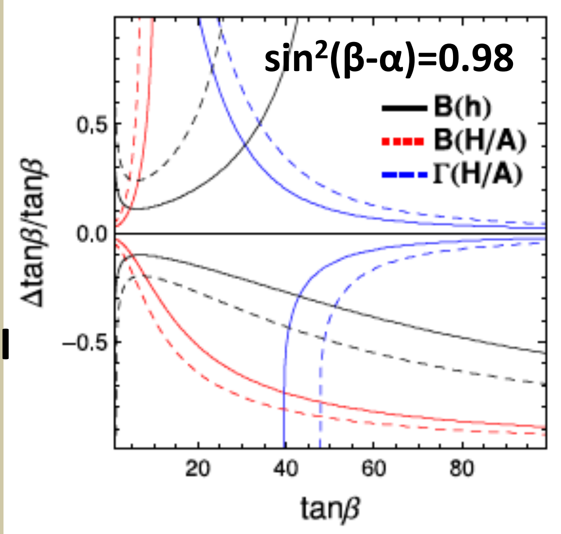
   useful for large tanβ

3. Decay of SM-like Higgs *h* when sin(β-α) is slightly smaller than 1

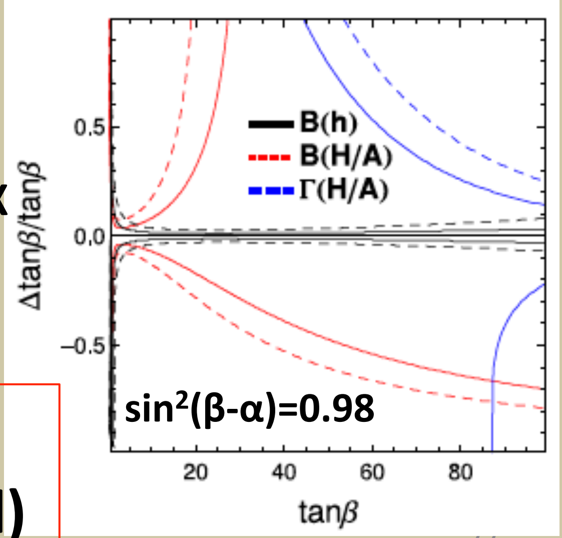
SK, Tsumura, Yokoya, arXiv:1305.5424

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

Type-II 2HDM



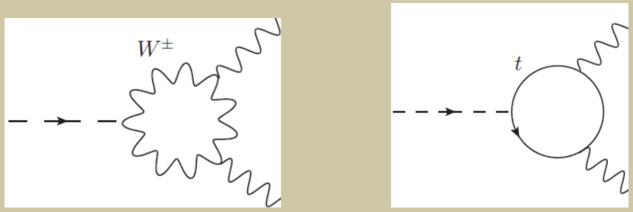
Type-X 2HDM



Di-photon Decay Width

Loop induced process in the SM

New physics effect enters at the same order of perturbation



SM loop destructive

New physics particles which realized a large deviation in h→γγ

- W' boson
- Singly/Doubly charged scalars
- New charged leptons
- SUSY
- .....

In MSSM, stop effect

$$\frac{g_{h\gamma\gamma}}{g_{h_{SM}\gamma\gamma}} \simeq 1 - 0.4\% \left(\frac{1\ \mathrm{TeV}}{m_T}\right)^2$$

Inner parameters (BSM mass, coupling) can be constrained

⇒ Test a model by seeing correlation to the other observable

Self-coupling *hhh*

It is important to determine the structure of Higgs potential

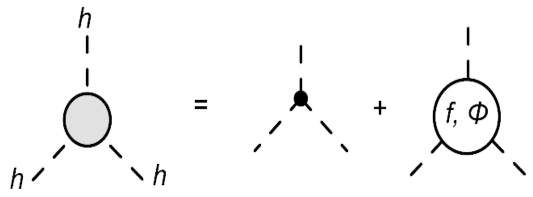
$$V_{\rm Higgs} = \frac{1}{2}\underline{m_h^2}h^2 + \frac{1}{3!}\underline{\lambda_{hhh}}h^3 + \frac{1}{4!}\lambda_{hhhh}h^4 + \cdots$$

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

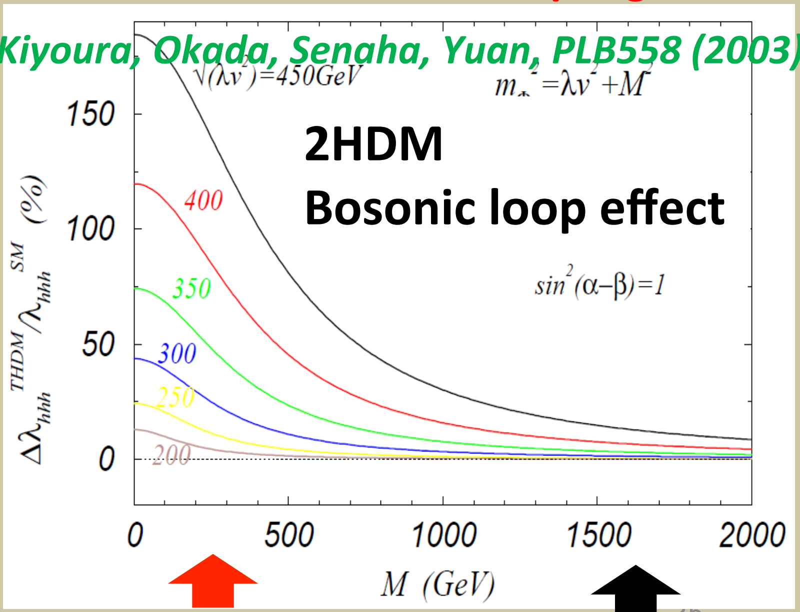


Φ = *H, A, H*±

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

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

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



2HDM

Bosonic loop effect

Non-decoupling effect **Decoupling**

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**

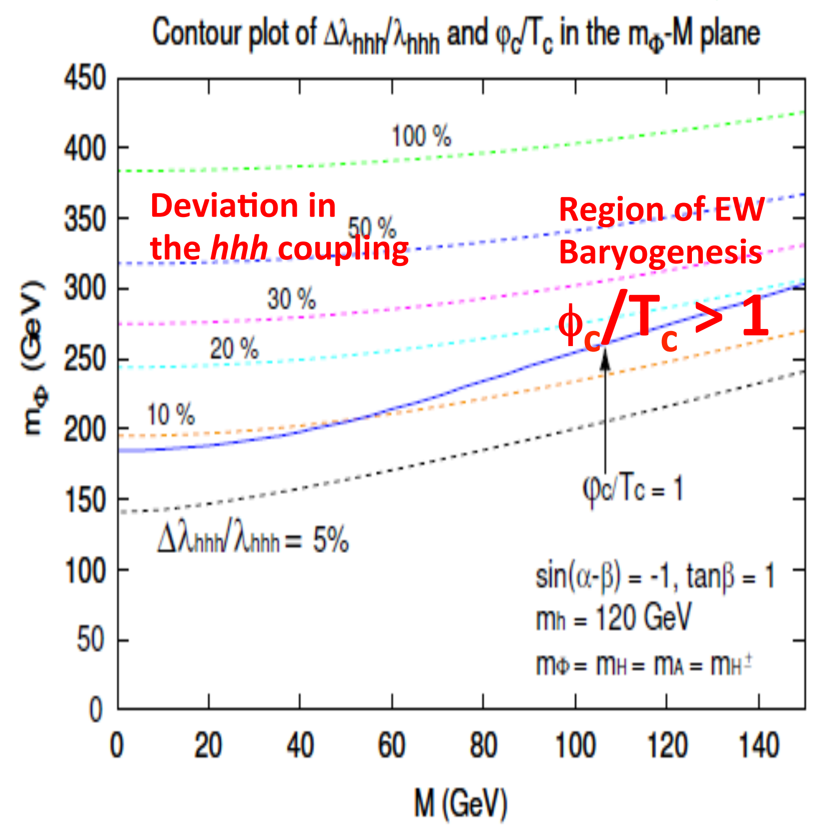
$$\lambda_T = m_h^2/2v^2 + \text{log corrections}$$

Condition of strongly 1st OPT

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

SM: m_h < 60GeV: Excuded！

2HDM: m_h = 125GeV: Possible



Deviation in the *hhh* coupling

Region of EW Baryogenesis

$\phi_c/T_c > 1$

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

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**

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

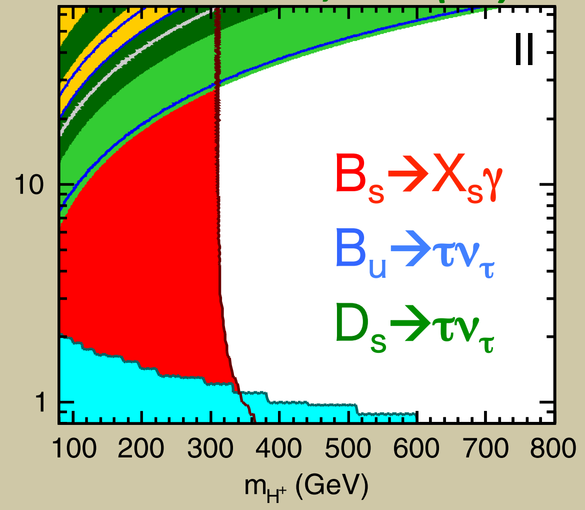
Extra Higgs bosons

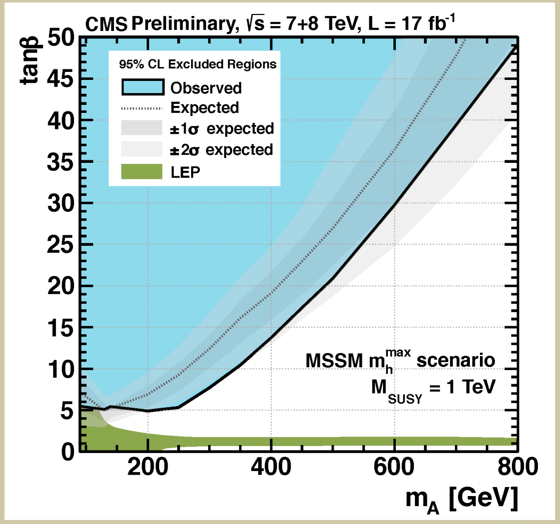
H, A, $H^{\pm}$

***HVV*: cos(β-α) <<1**
***HAZ*: sin(β-α) ≈ 1**
$H^+H^-\gamma$*: *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

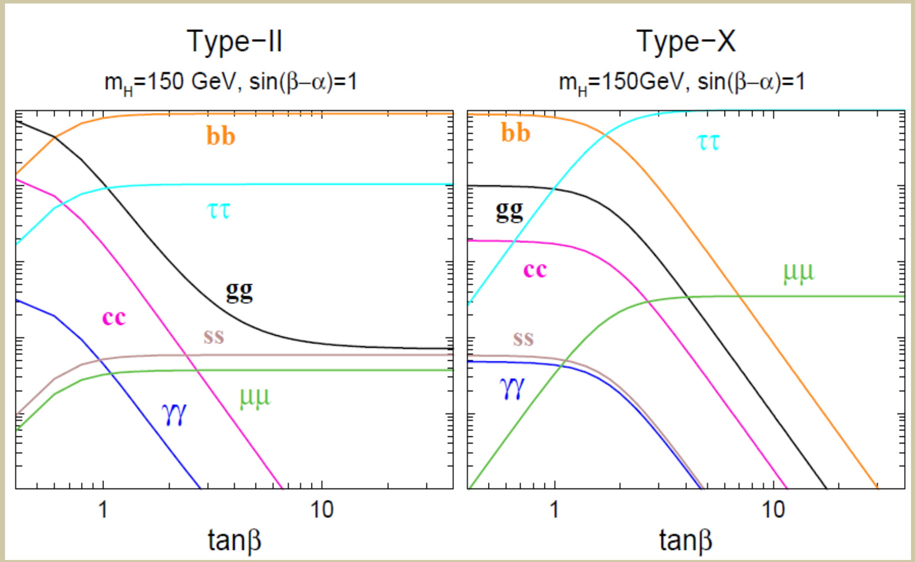
Type II: ***H, A*** **decay into** ***bb***
Type X: ***H, A*** **decay into** $\tau\tau$

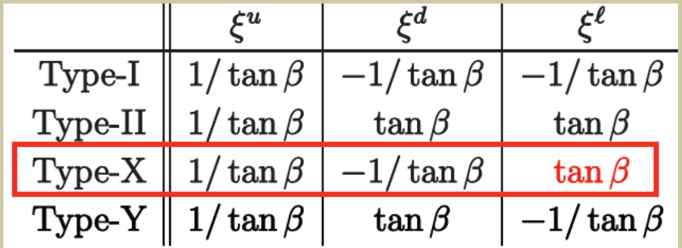
At LHC, Type X 2HDM can be discriminated from MSSM (Type-II) by the combination of ττ gluon fusion

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

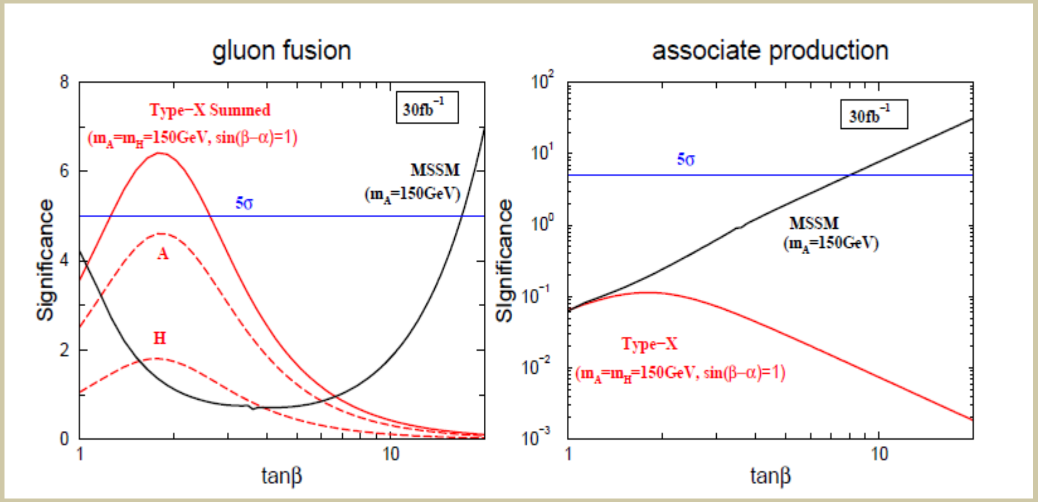
and bb associate (H)A production

$$pp \rightarrow bbA\ (bbH)$$





	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	$1/\tan\beta$	$\tan\beta$	$-1/\tan\beta$

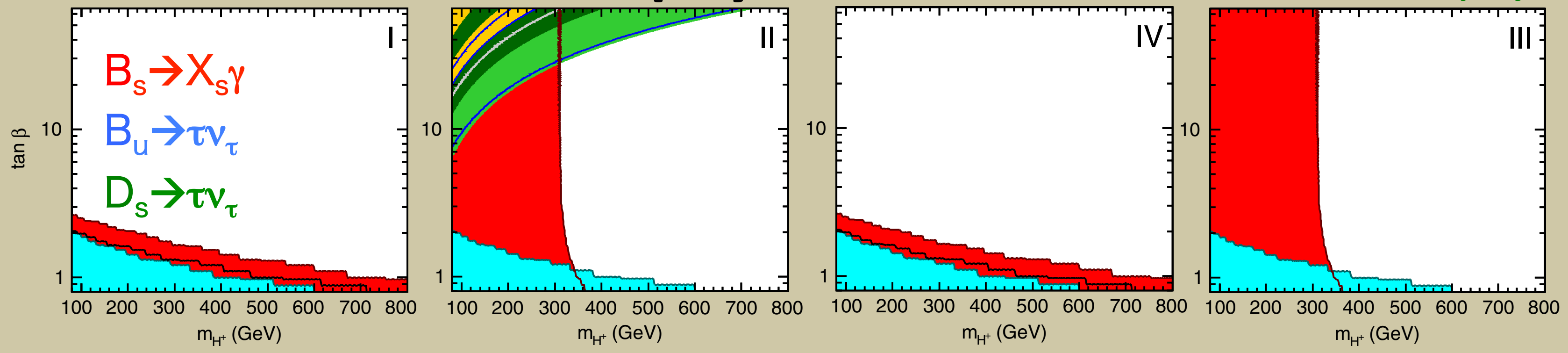


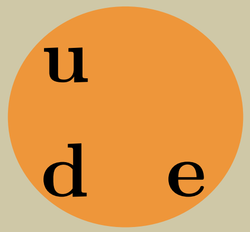
Aoki, SK, Tsumura, Yagyu (10)

Non-SUSY 2HDM

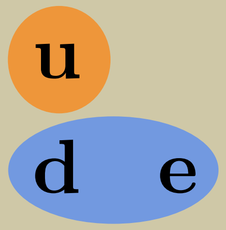
Constraint from flavor physics

Mahmoudi, Stal (09)

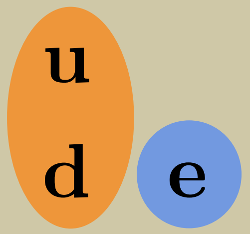




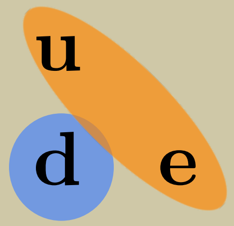
Type-I



Type-II



Type-X

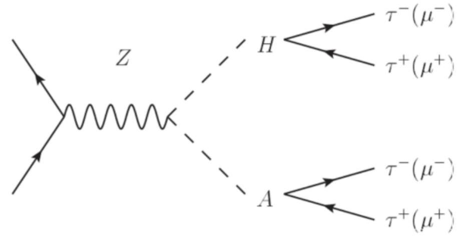


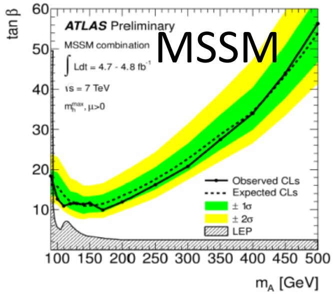
Type-Y

In Type-I and Type-X, light *H, A, H^+* can be allowed
⇒Pair Production

HA Production (Type X 2HDM)

LHC

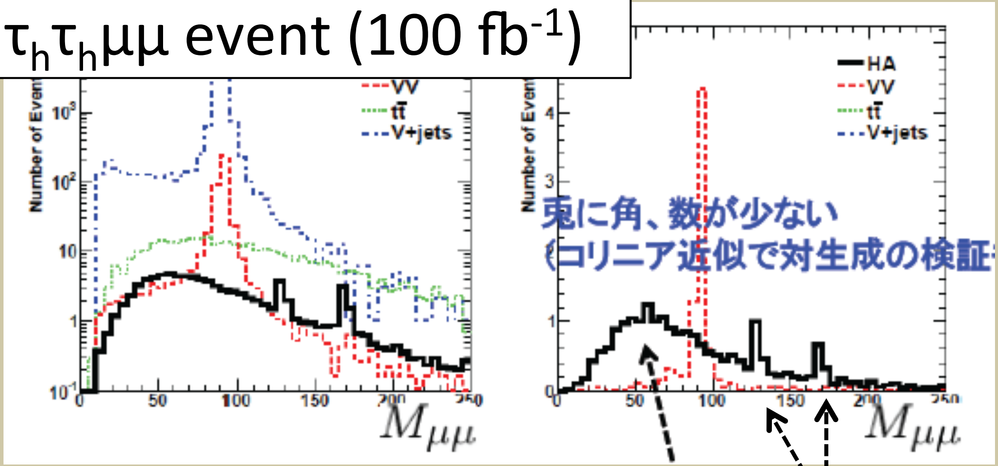




σ(pp→HA) = O(10-100) fb

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})



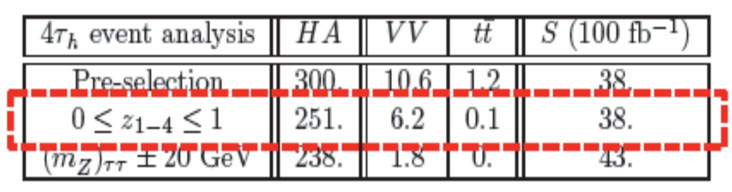
$4\tau \rightarrow 2\mu 2\tau_j$

m_H=130GeV
m_A=170 GeV

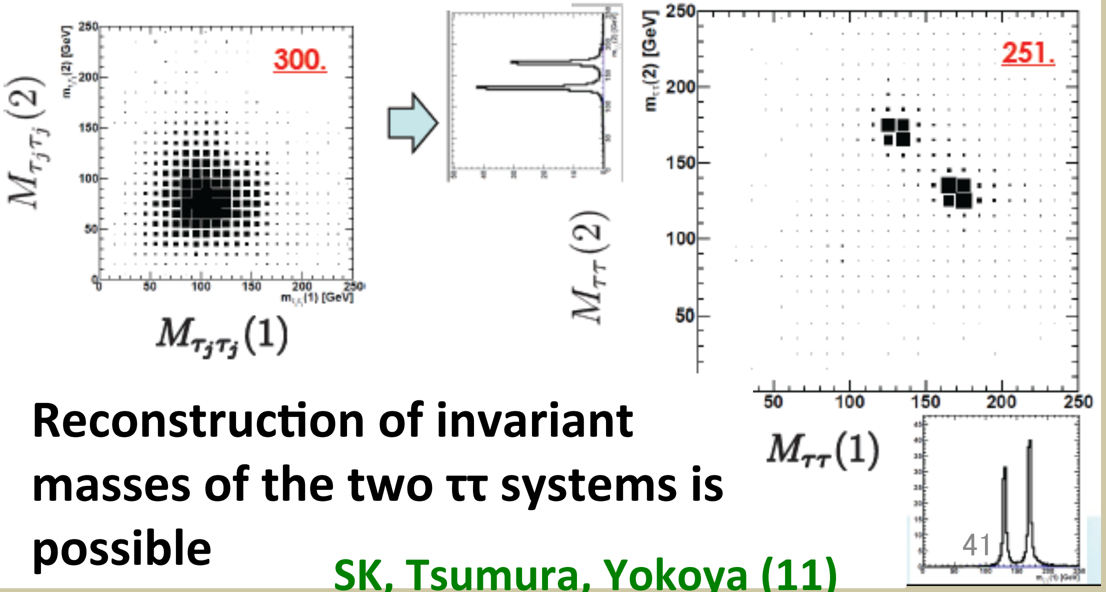
ILC

HA can be reconstructed by collinear approximation

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



$4\tau_h$ 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

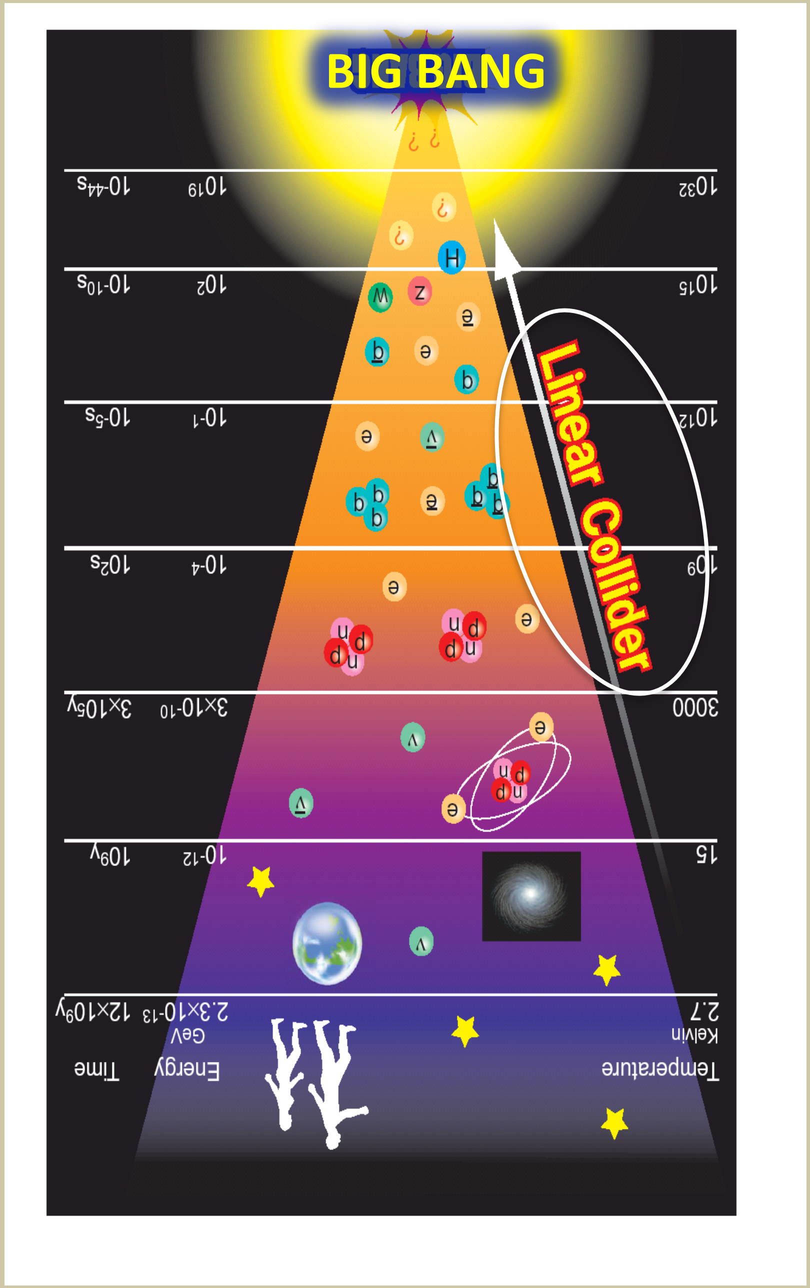
Extended Higgs ⇔ New Physics

- 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


BIG BANG
Linear Collider
Time
Energy
GeV
Temperature
Kelvin
10-44s
10^19
10^32
10-10s
10^2
10^15
10-5s
10-1
10^12
10^2s
10-4
10^9
3×10^5y
3×10-10
3000
10^9y
10-12
15
12×10^9y
2.3×10-13
2.7
H
W
Z
e
q
u
d
ν

Back Up Slides

DBD full simulation

Higgs self-coupling @ 1 TeV

P(e-,e+)=(-0.8,+0.2) $e^{+} + e^{-} \to \nu\bar{\nu}HH$ $M(H) = 120\text{GeV}$ $\int Ldt = 2\text{ab}^{-1}$

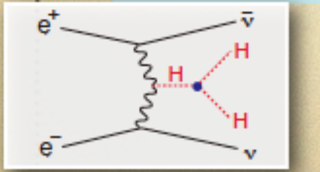
	Expected	After Cut
ννhh (WW F)	272	35.7
ννhh (ZHH)	74.0	3.88
BG (tt / ννZH)	7.86×10^{5}	33.7
significance	0.30	4.29

- better sensitive factor
- benefit more from beam polarization
- BG tt x-section smaller
- more boosted b-jets

$$\frac{\Delta\sigma}{\sigma} \approx 23\% \qquad \frac{\Delta\lambda}{\lambda} \approx 18\%$$

Double Higgs excess significance: $> 7\sigma$

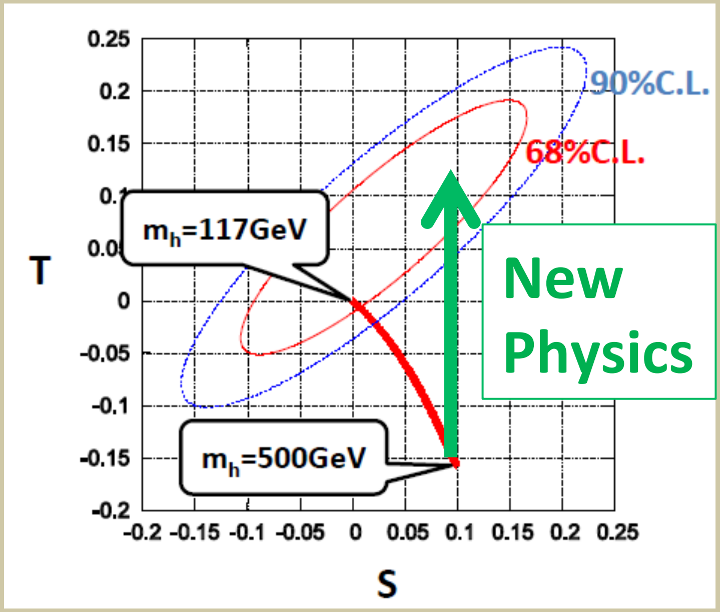
Higgs self-coupling significance: $> 5\sigma$



ILD DBD Study (Junping Tian)

LEP/SLC did not require SM-like Higgs

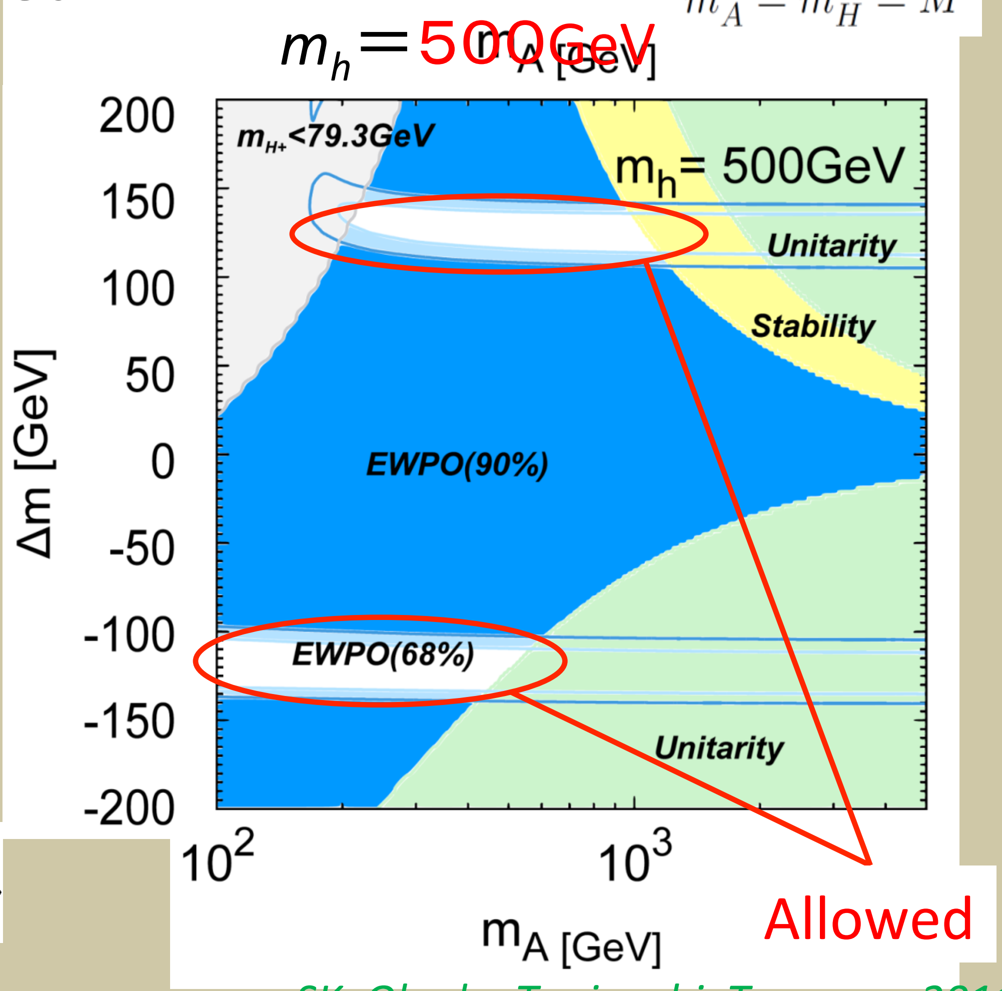
A heavy ***h*** was also allowed
by non-standard effects



Case of the 2 Higgs doublet model

$$\Delta T_{\text{Higgs}} \sim -\ln\frac{m_h^2}{M_W^2} + \frac{(m_A^2 - m_{H^\pm}^2)^2}{M_W^2 m_A^2} \quad (\sim 0).$$

$$\Delta m = m_A - m_{H^\pm}$$
$$\sin(\beta - \alpha) = 1$$
$$m_A^2 = m_H^2 = M^2$$



SK, Okada, Taniguchi, Tsumura, 2011

SUSY and m_h=126GeV

Higgs potential

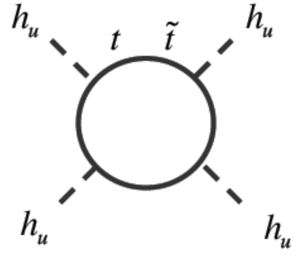
V = |D|^2 + |F|^2 + (soft-breaking)

MSSM is type-II 2HDM（H_u, H_d）

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

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

Loop effect

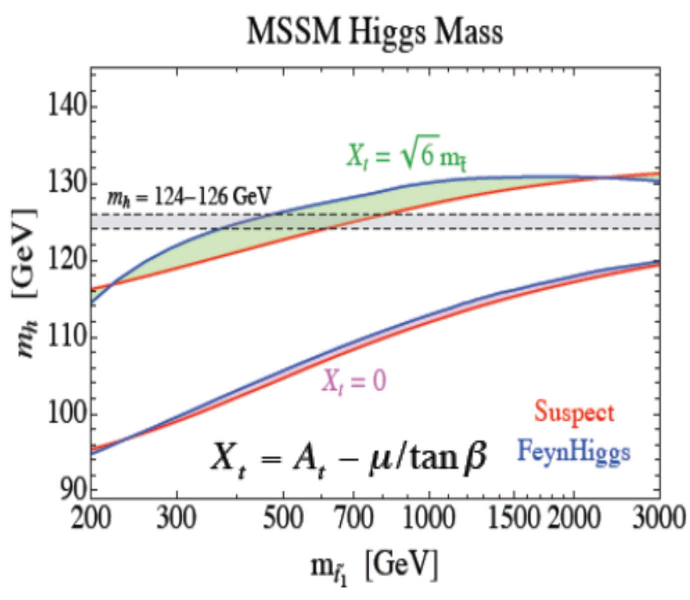


126 GeV can be realized by

Large Stop Masses OR Large Stop LR-mixing

M_{SUSY} ∼ 10TeV (X_t=0)

Consistent with the data
But tension with Hierarchy Problem

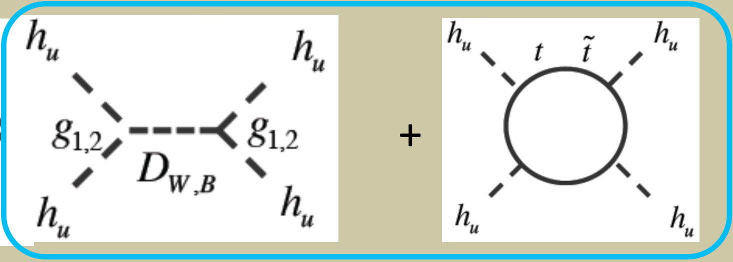


Hall, Pinner, Ruderman (2011)

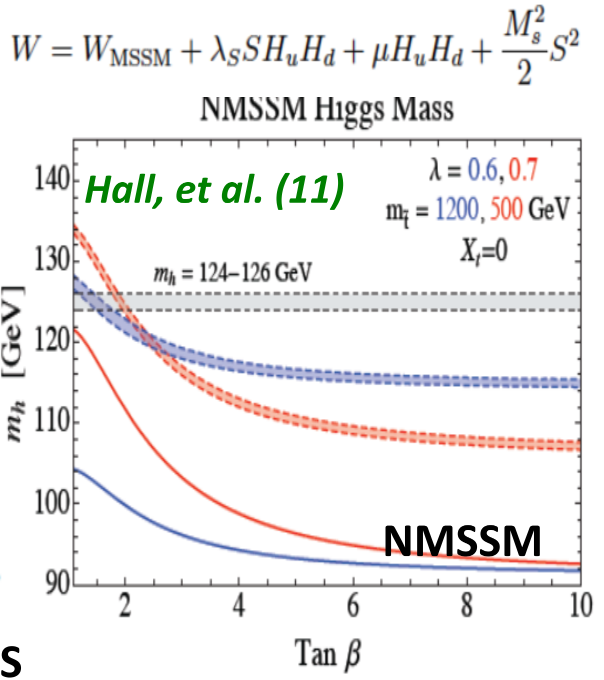
Exteded SUSY models

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

$$m_h^2 =$$

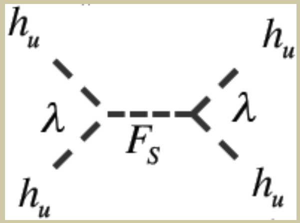


MSSM



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

F-term +

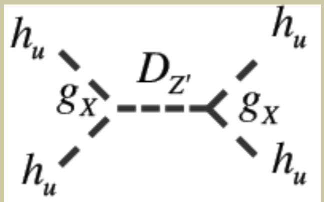


Addition of new Singlet, Triplet

Ex) NMSSM

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

D-term +



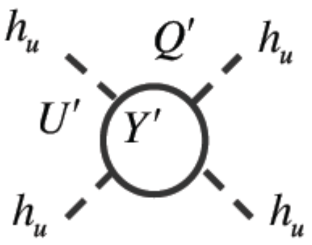
New gauge symmetry $U(1)_X$

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 +



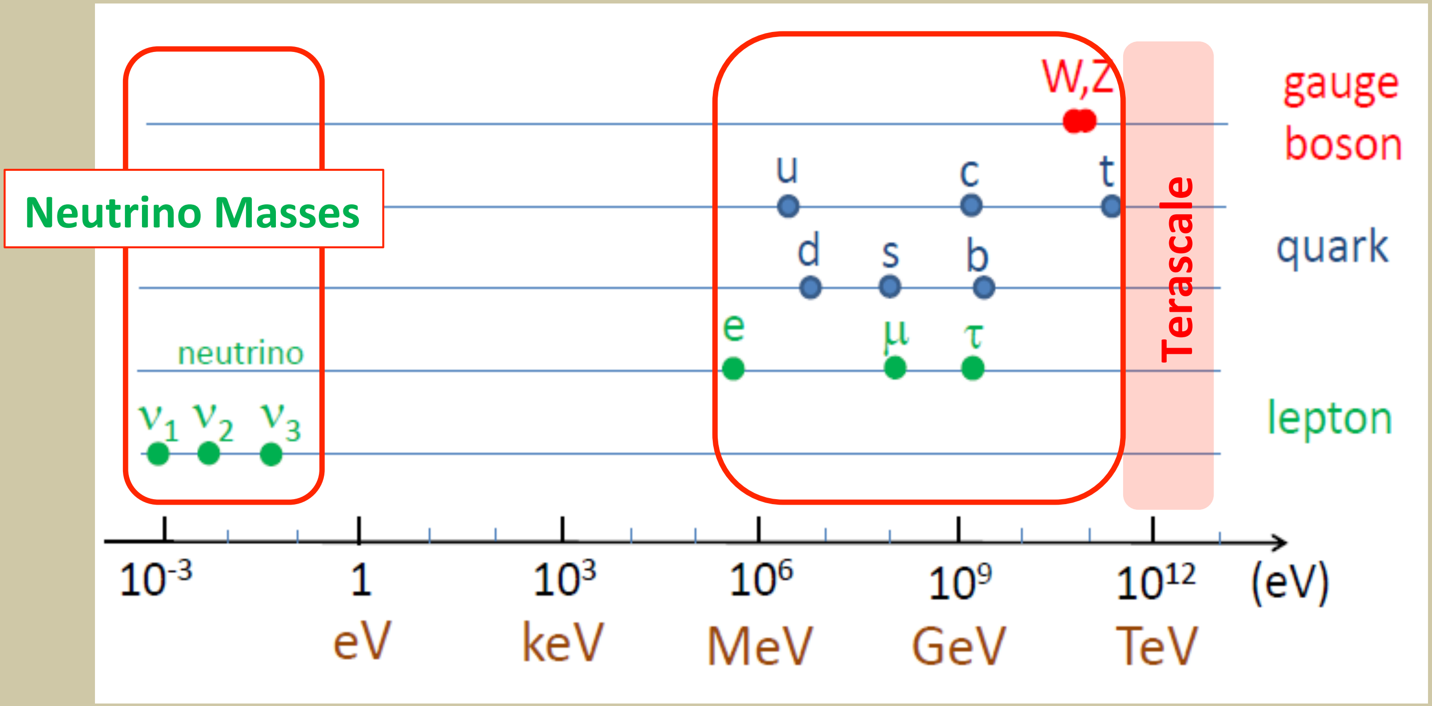
Loop effect by new matter particles

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

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

SK, Shindo, Yamada (12)

Mass spectrum of particles

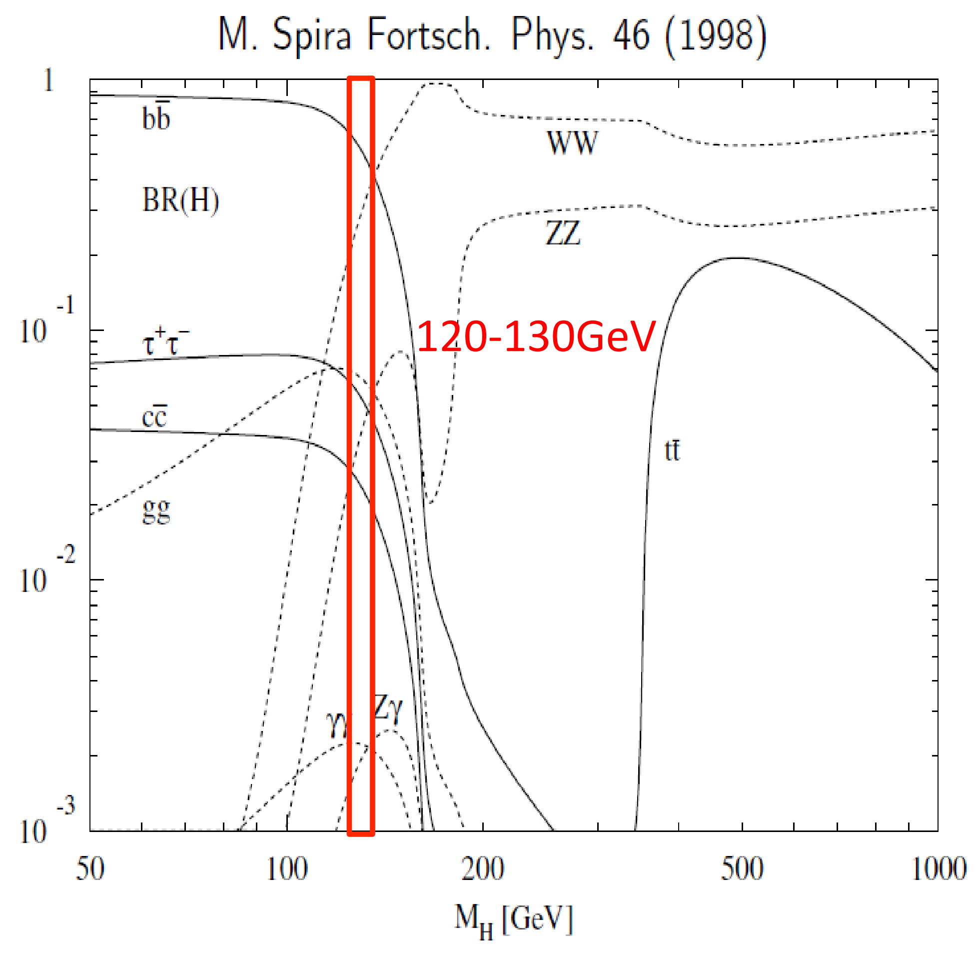


Masses of particles are zero in the Lagrangian
Vacuum gives masses to them by EWSB

Decay branching ratios of SM Higgs

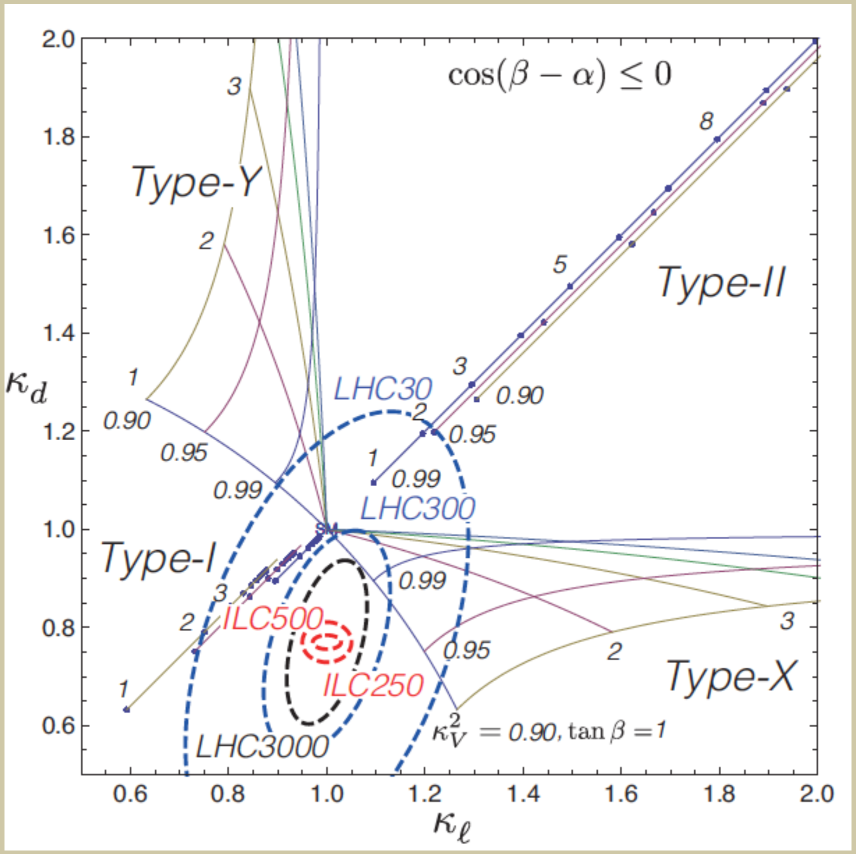
- **SM Higgs couples to all the particles**
  [hγγ, hgg (via loop)
  hhνν (dim-5)]

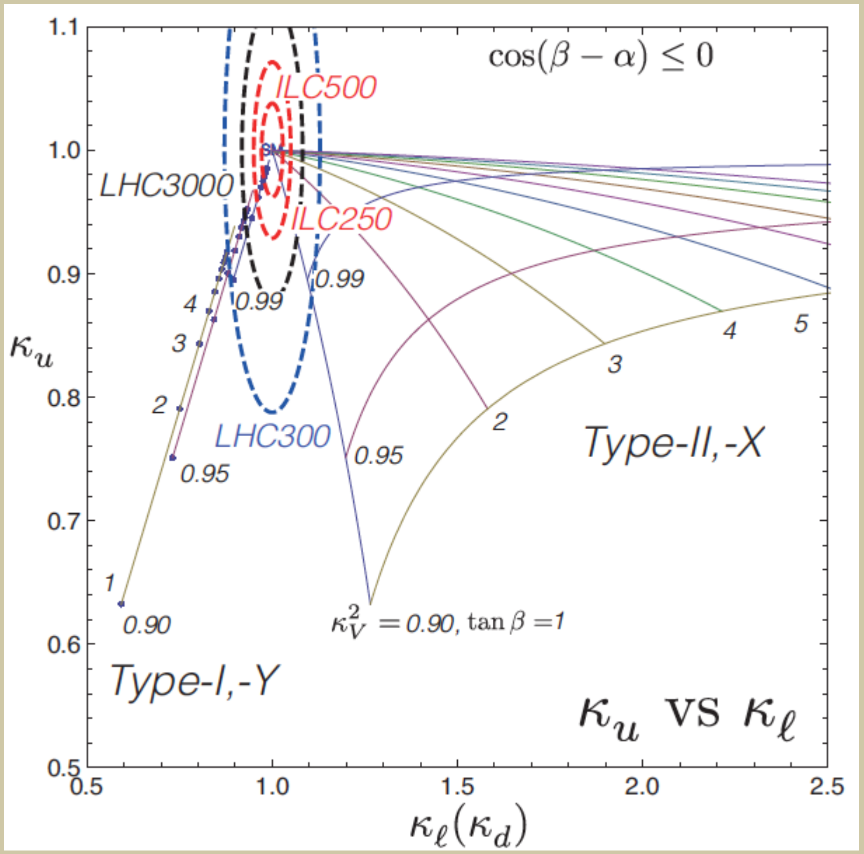
- **For m_h=126 GeV, various decay modes can be available**

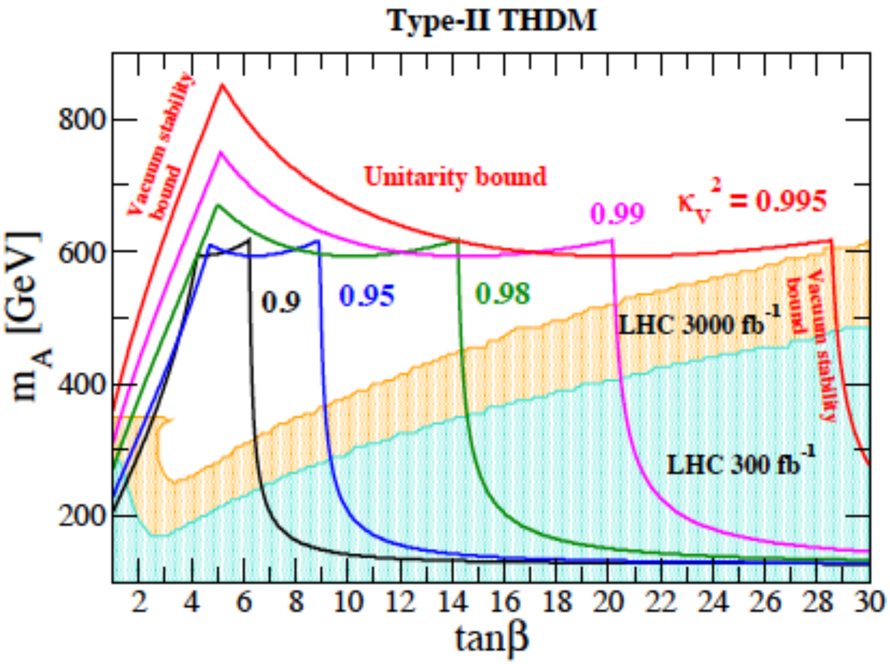


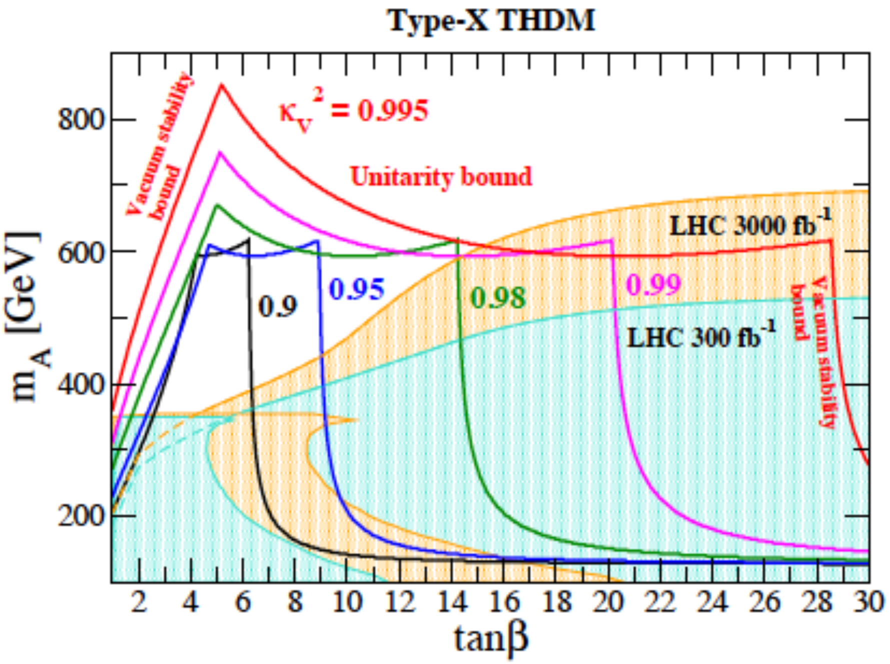
M. Spira Fortsch. Phys. 46 (1998)

120-130GeV


$\cos(\beta-\alpha)\le 0$
Type-Y
Type-II
Type-I
Type-X
LHC30
LHC300
LHC3000
ILC500
ILC250
SM
κ_V^2 = 0.90, $\tan\beta$ = 1
0.90
0.95
0.99
1
2
3
5
8
κ_d
κ_ℓ
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0


$\cos(\beta-\alpha)\le 0$
ILC500
ILC250
LHC3000
LHC300
SM
Type-II,-X
Type-I,-Y
κ_V^2 = 0.90, $\tan\beta$ = 1
0.90
0.95
0.99
1
2
3
4
5
κ_u VS κ_ℓ
κ_u
$\kappa_\ell(\kappa_d)$
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.5
1.0
1.5
2.0
2.5


Type-II THDM
Vacuum stability bound
Unitarity bound
$\kappa_V^2 = 0.995$
0.99
0.98
0.95
0.9
LHC 3000 fb^{-1}
LHC 300 fb^{-1}
Vacuum stability bound
m_A [GeV]
800
600
400
200
tanβ
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30


Type-X THDM
Vacuum stability bound
$\kappa_V^2 = 0.995$
Unitarity bound
LHC 3000 fb^{-1}
0.9
0.95
0.98
0.99
LHC 300 fb^{-1}
Vacuum stability bound
m_A [GeV]
800
600
400
200
tanβ
2 4 6 8 10 12 14 16 18 20 22 24 26 28 30