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Higgs Physics as a probe of new physics

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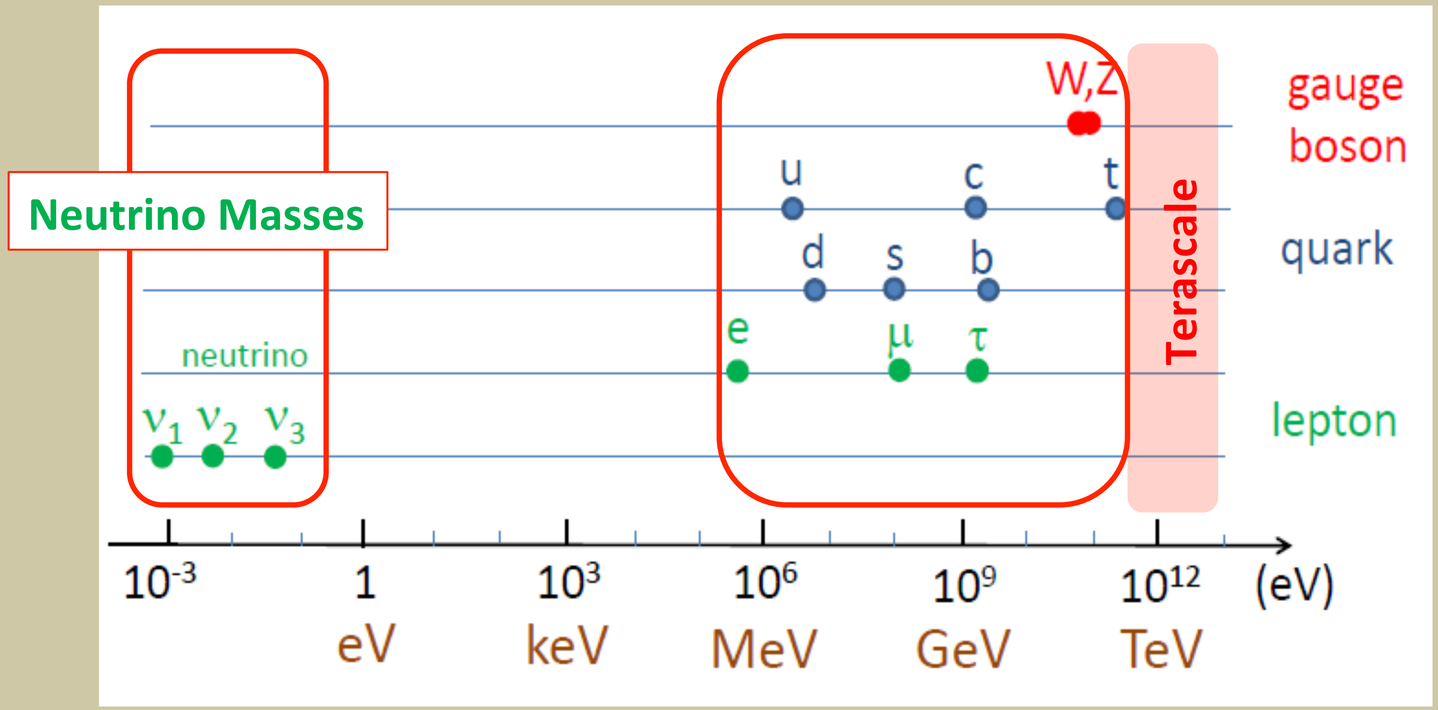
Introduction

Why Higgs is important?

Mass spectrum of particles



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

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

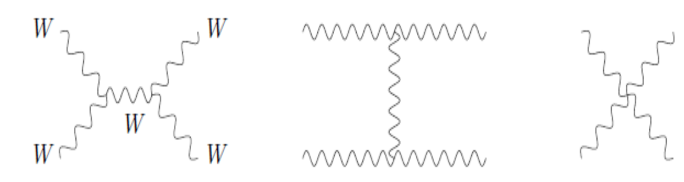
Introduction

$W_L^+W_L^-$ Elastic Scattering

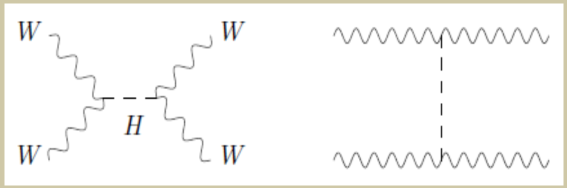
$$a^0(W_L^+W_L^- \to W_L^+W_L^-) \approx A\,E^4 + B\,E^2 + C \quad (E \to \infty)$$

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

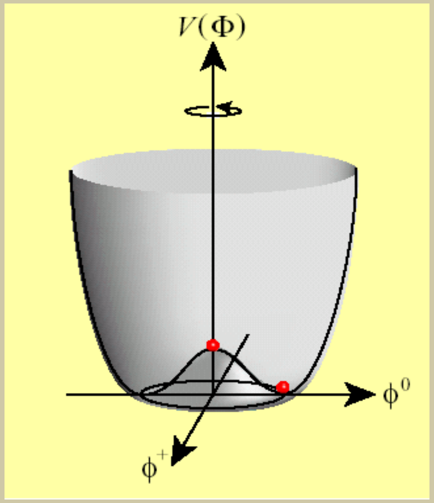
Minimal Form

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?

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**
- **Radiative 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
- …

Higgs sector = Window for new physics

In 2012 July, a boson *h* was found

The mass is 126 GeV

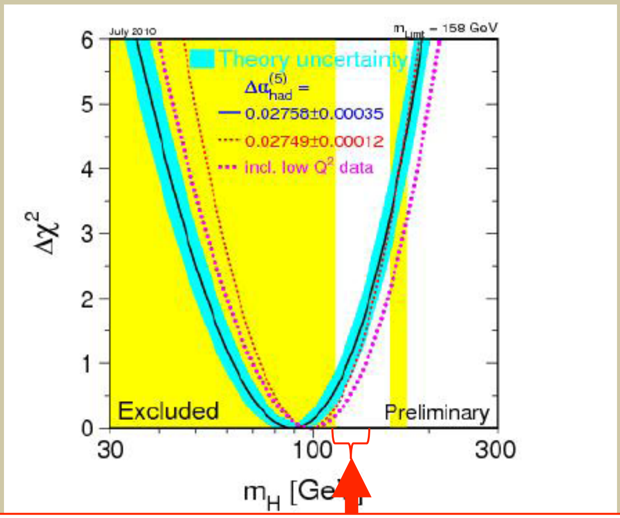
Spin/Parity 0^+

It couples to

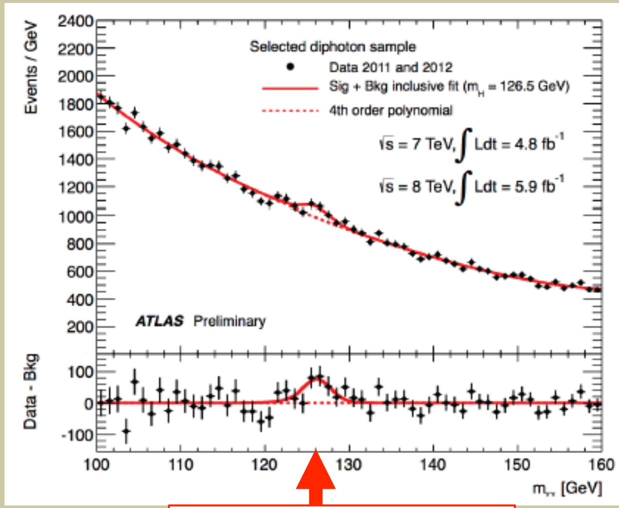
γγ, WW, ZZ, bb, ττ

This is really a SM-like Higgs!

Why SM-like?



Higgs Mass indicated by LEP/SLC



ATLAS/CMS July 2012

New Particle !

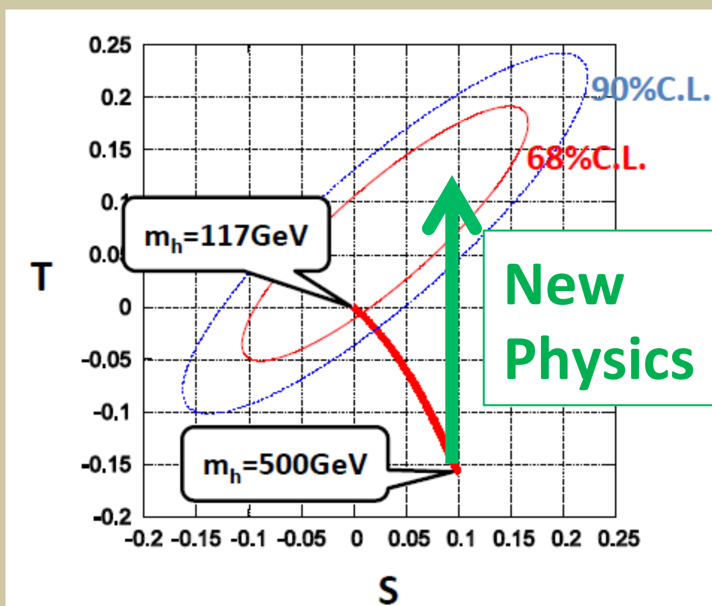
LEP/SLC did not require SM-like Higgs

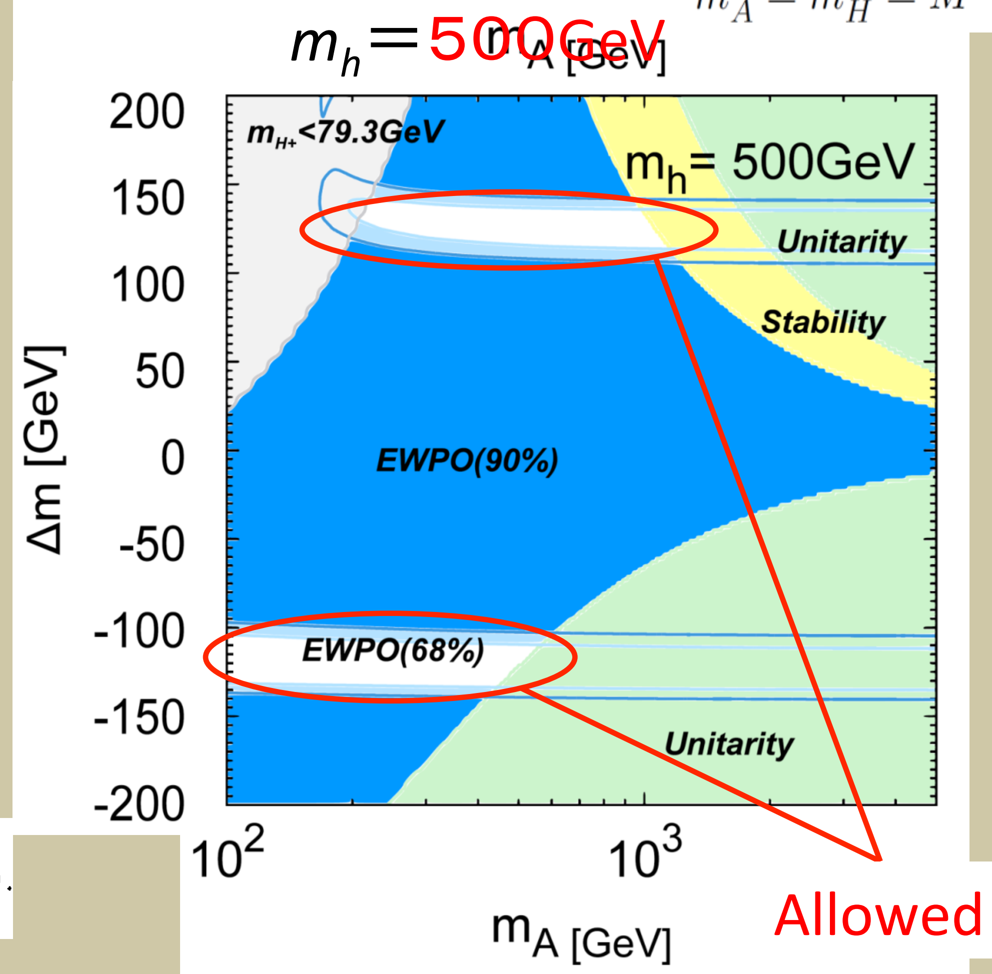
$\Delta m = m_A - m_{H^\pm}$

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

$m_A^2 = m_H^2 = M^2$

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





Case of the 2 Higgs doublet model

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

SK, Okada, Taniguchi, Tsumura, 2011

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
- Higgs boson in the SM
- 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

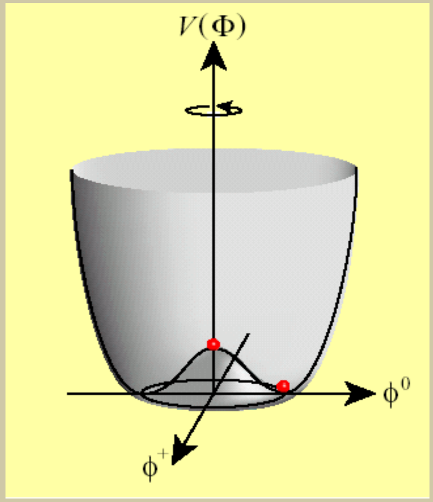
Higgs boson in the SM

SM Higgs

Minimal: an iso-spin doublet *Φ* ***I=1/2, Y=1***

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

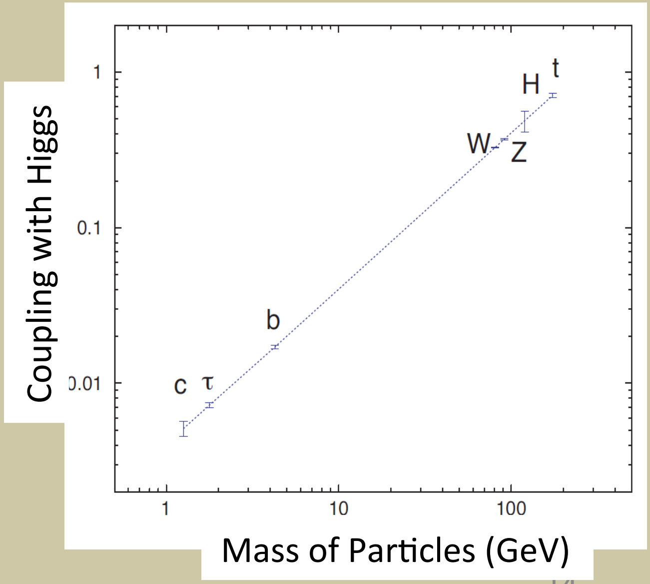
$$\Phi = \begin{bmatrix} w^+ \\ \frac{1}{\sqrt{2}}(H + v + iz^0) \end{bmatrix}$$



$\mu^2 < 0$ ⇒ $\langle \phi \rangle = v \simeq 246\text{GeV}$

Origin of mass

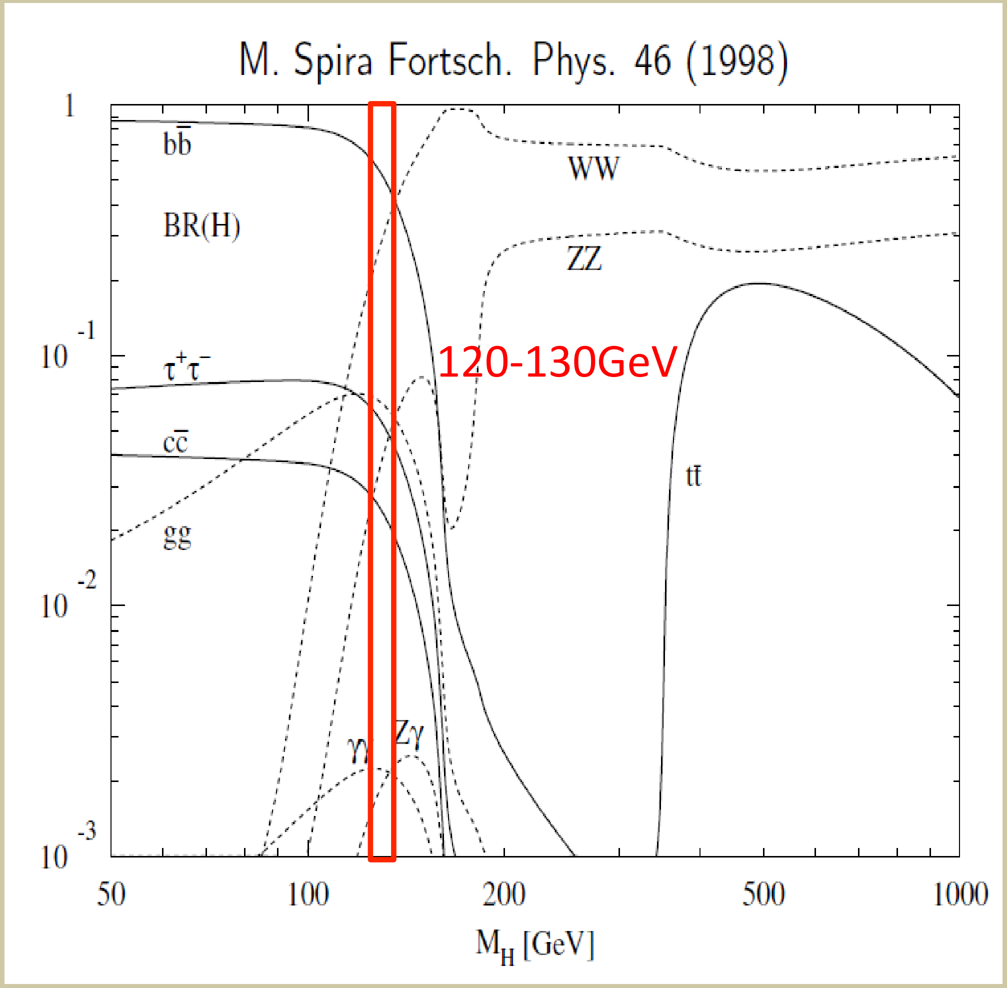
- **Higgs mechanism** → $m_W \propto g^2 v$
- **Yukawa coupling** → $m_f \propto Y_f v$
- **Self-coupling** → $m_h^2 \propto \lambda v^2$



Mass-Coupling Universality

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**



The mass was the last unknown parameter

- **Minimal Higgs model**
- **2 parameters in V(ϕ)**

  μ and λ

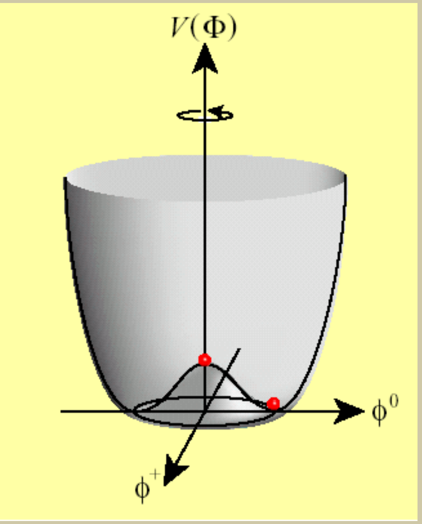
$$V(\Phi) = -\mu^2|\Phi|^2 + \lambda|\Phi|^4$$

- **They are replaced by**

  v (=246GeV)* and *m_h

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

- **The mass is directly related to the dynamics**
  - **Light Higgs ⇔ weakly coupled**
  - **Heavy Higgs ⇔ strongly coupled**

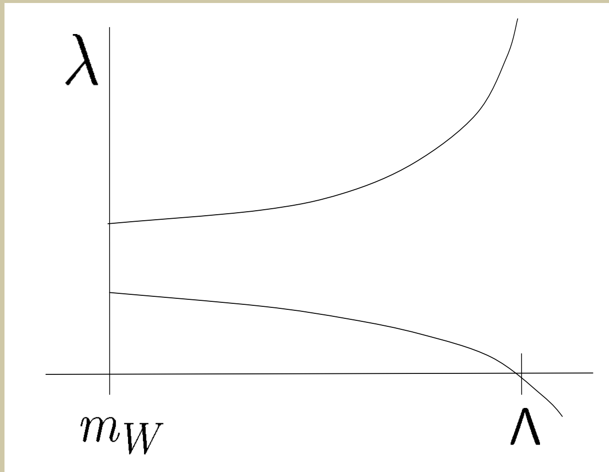


Triviality and vacuum stability

Require that the theory is stable below a scale Λ

- No Landau pole below Λ
- Vacuum is stabilized below Λ

  (V(ϕ)>0 ⇔ λ＞0)



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

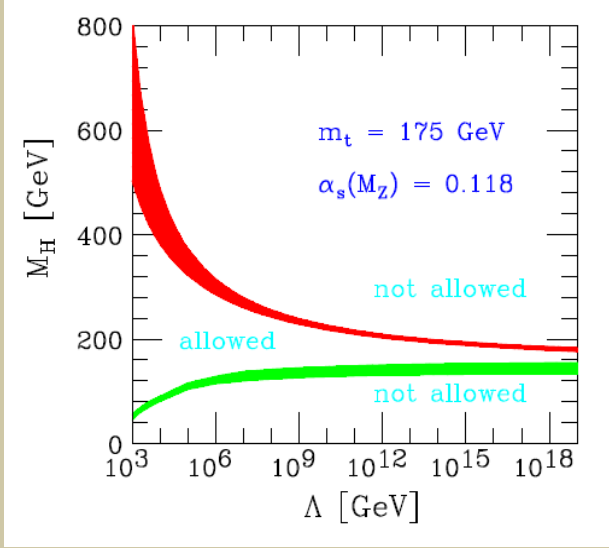
RGE

m_t=175GeV
⇔ y_t=O(1)

$$16\pi^2\mu\frac{d}{d\mu}\lambda = 24\lambda^2 - 6y_t^4 + \ldots$$

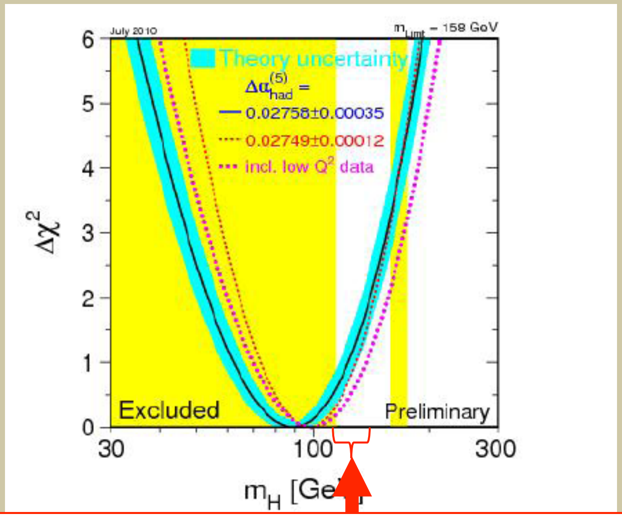
Beta function is positive if λ is not small
Landau pole may appear

λ becomes negative and Fall down if y_t is large
Vacuum is not stabilized

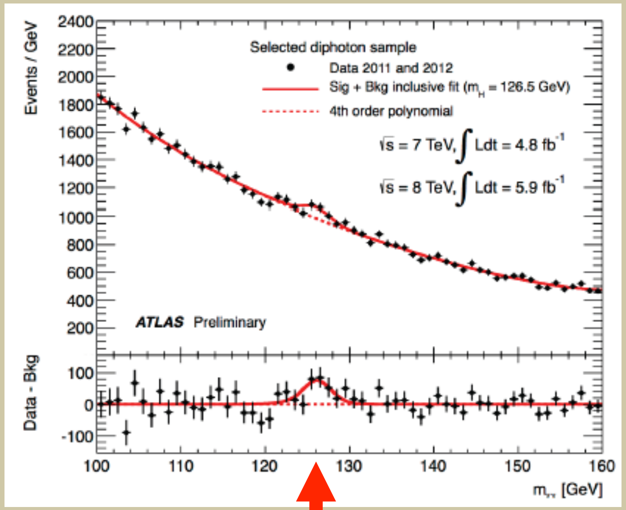


2012-2013

- A new boson was found at LHC
  - 126 GeV: It's a very region that LEP/SLC experiments indicate
  - Spin/parity O+
  - Decays are being measured
    hγγ, hZZ, hWW*, hττ, hbb, ….*
  - The boson looks like the SM Higgs boson
- No other particle is found
- Not only the gauge sector but also the Higgs sector of the SM have been confirmed



Higgs Mass indicated by LEP/SLC



New Particle !

ATLAS/CMS July 2012

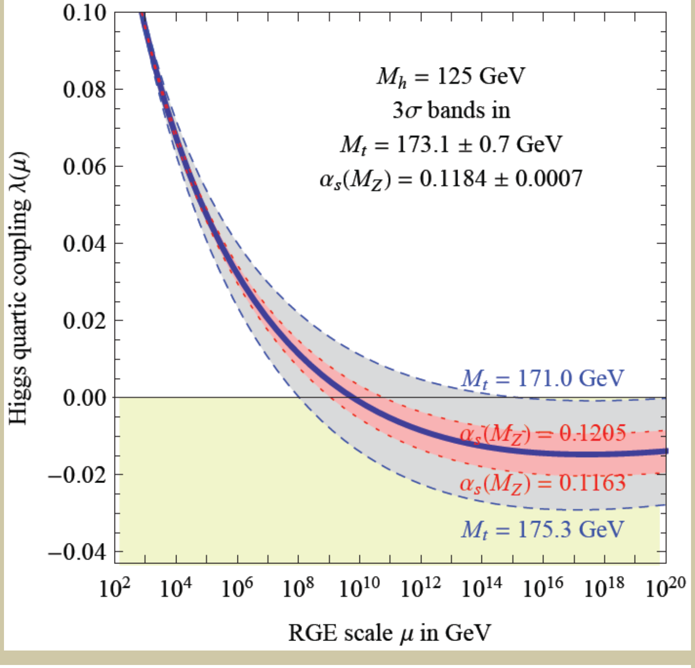
Vacuum Stability of the SM

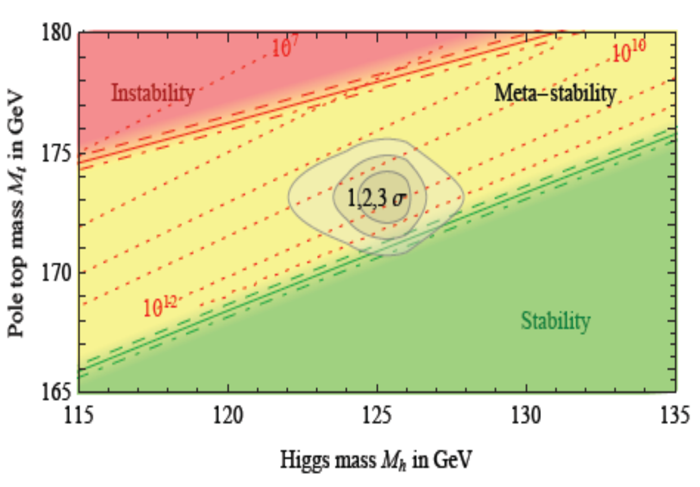
With the discovered 126 GeV Higgs boson, λ becomes negative below Planck Scale

Cut off $\Lambda = 10^7 - 10^{15}$ GeV
large uncertainty comes from large Δm_t

At ILC, $\Delta m_t \approx 30$ MeV is expected
Cutoff Λ can be better determined

At Planck Scale, $\lambda(M_{pl}) < 0$, but the theory satisfies the condition of the meta-stable vacuum





arXiv:1205.6497, Degrassi et al

Beyond the Standard Model

There are many reasons to consider New Physics of BSM

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

Problem in the SM Higgs
- Hierarchy Problem

BSM Phenomena
- Dark Matter, Neutrino Mass,
- Baryon Asymmetry of Universe
- Inflation
- Dark Energy

New Physics is necessary

At which scale?

If TeV scale, they should have connection with Higgs physics

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 contain the SM-like Higgs boson**

The shape of the Higgs sector must be determined by experiments

Extended Higgs

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

- Extra singlets (NMSSM, B-L Higgs, ...)
- Extra doublets (SUSY, CPV, EW Baryogenesis, …)
- 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 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) $v_\Delta << v_\varphi$

b) Combination of several representations

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

Muliti-doublets (+ singlets) seem natural choice?

2 Higgs Doublet Model (2HDM)

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

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

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

↑ CPeven ↑ CPodd ↑charged

Diagonalization

$$\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix} \begin{bmatrix} H \\ h \end{bmatrix}$$

$$\begin{bmatrix} z_1^0 \\ z_2^0 \end{bmatrix} = \begin{bmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{bmatrix} \begin{bmatrix} z^0 \\ A^0 \end{bmatrix}$$

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

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

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

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

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

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

M_{soft}: soft breaking scale

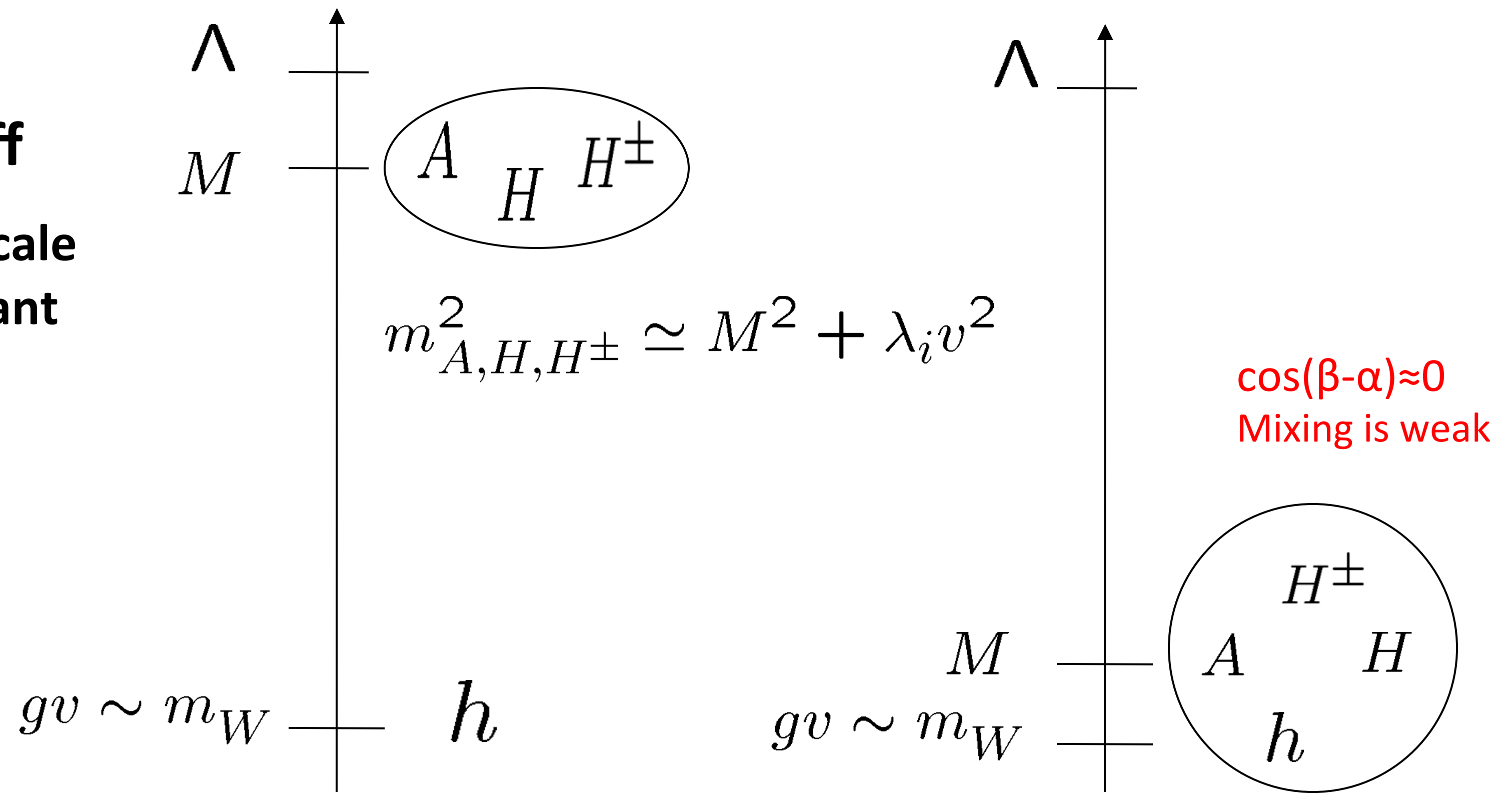
$M_{\mathrm{soft}} \quad \left(= \frac{m_3}{\sqrt{\cos\beta \sin\beta}}\right)$:

soft-breaking scale of the discrete symm.

Extended Higgs（2 cases）

Λ: Cutoff

M: Mass scale irrelevant to VEV



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

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

Non-decoupling effect

FCNC Suppression

Multi-Higgs models: **FCNC appear via Higgs med.**

ex) 2 Higgs doublet models:

to avoid FCNC, impose a discrete symmetry

$$\Phi_1 \rightarrow +\Phi_1, \qquad \Phi_2 = -\Phi_2$$

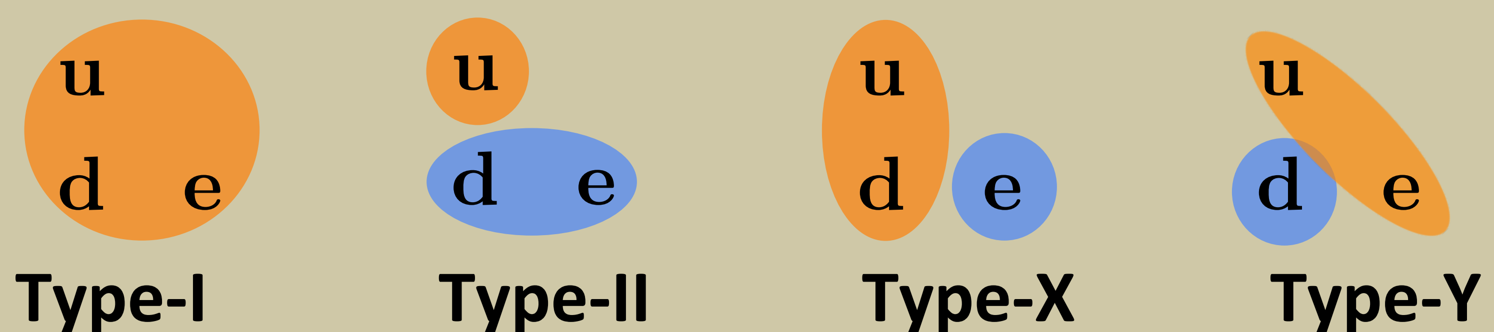
Each quark or lepton couples only one Higgs doublet

No FCNC at tree level

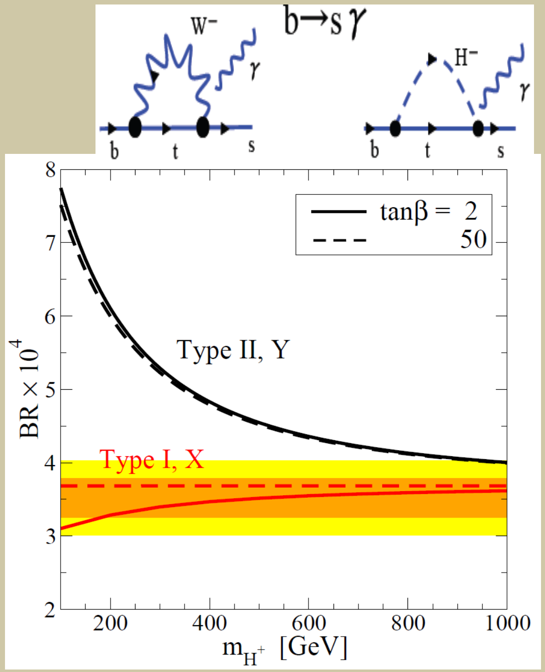
Barger, Hewett, Phillip

Four Types of Yukawa coupling

Classified by Z_2 charge assignment



Type of 2HDM

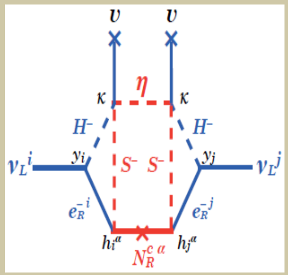


Aoki, SK, Tsumura, Yagyu (09)

Type-I Fermio-phobic 2HDM
Neutrino-phillic 2HDM

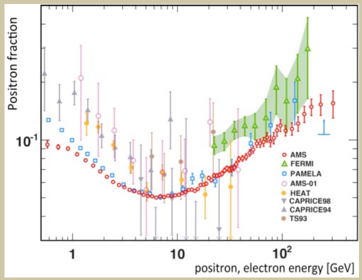
Type-II **MSSM, NMSSM**

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

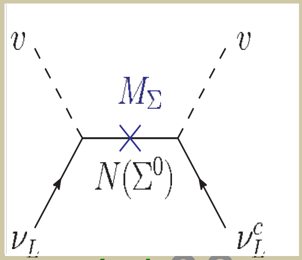


Aoki, SK, Seto (09)

Type-Y Flipped 2HDM



Goh, Hall, Kumar (09)



Ma (02)

SUSY and m_h=126GeV

Higgs potential

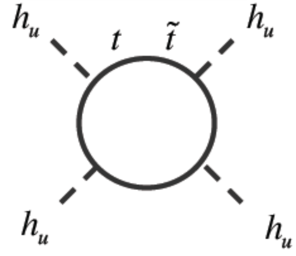
$$V = |D|^2 + |F|^2 + (\text{soft-breaking})$$

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



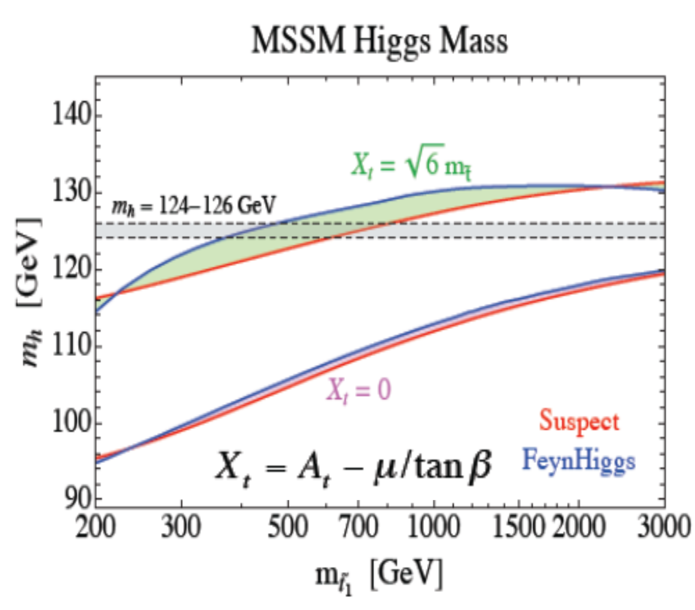
126 GeV can be realized by

Large Stop Masses OR Large Stop LR-mixing

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

Consistent with the data?

But tension with Hierarchy Problem

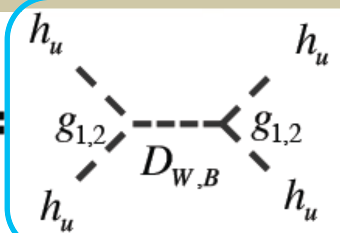


Hall, Pinner, Ruderman (2011)

Exteded SUSY models

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

$m_h^2 =$



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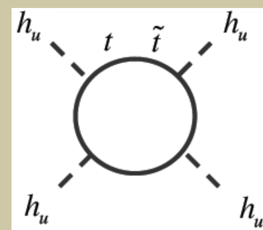
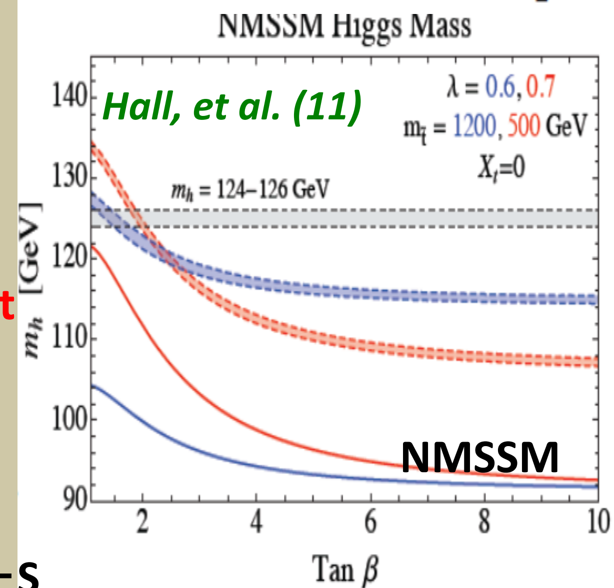
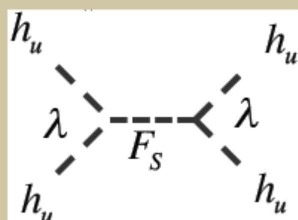


MSSM

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



F-term +

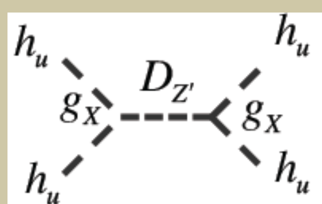


Addition of new Singlet, Triplet

Ex) NMSSM

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

D-term +



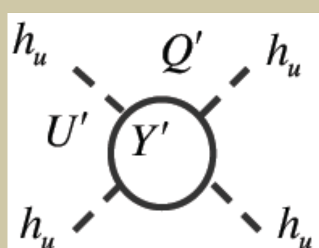
New gauge symmetry $U(1)_X$

Ex) MSSM + RH-Neutrino＋S＋S

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

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)

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**
  - **They cannot be directly found at LHC because of a large mass, non-color interaction, huge BG, …**

- **Indirect Search**
  - **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* ⇔ *φ*)

Gauge couplings (*hVV*):
Yukawa couplings (*hff*):
The pattern of deviation strongly depend on the model

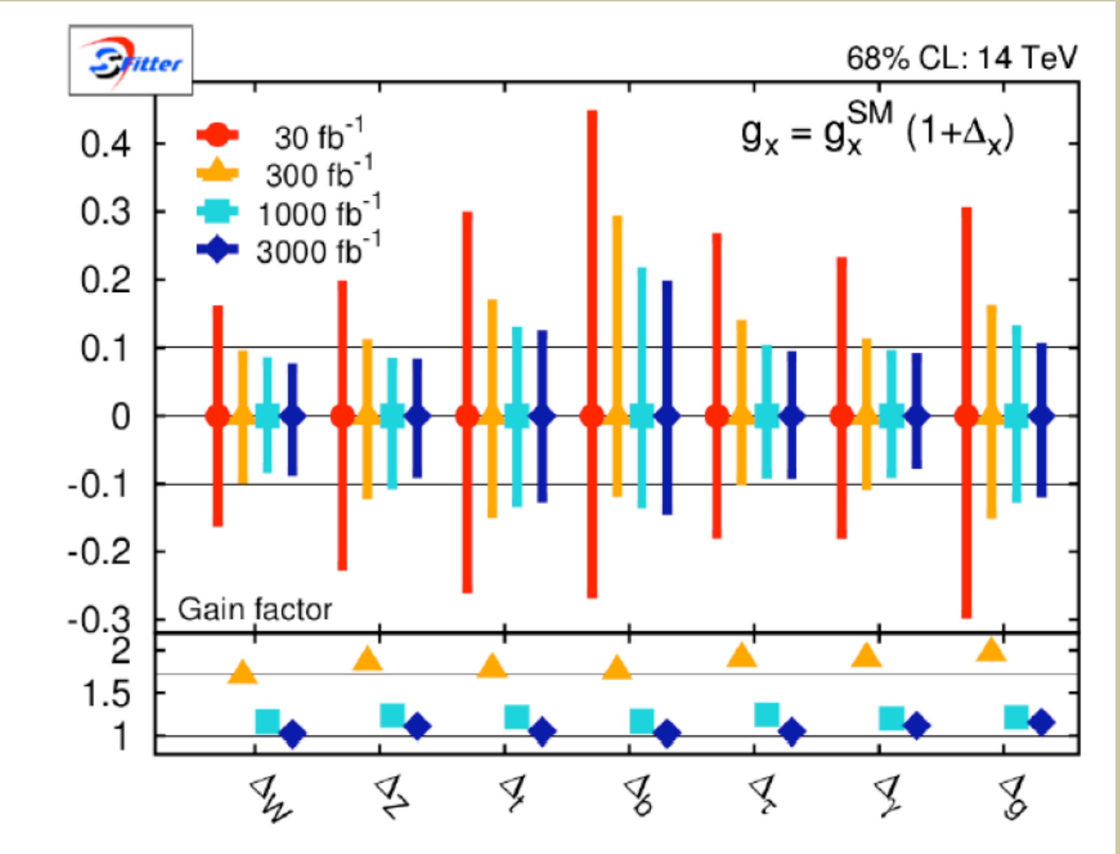
Quantum effects

Large deviation in loop-induced processes (*h→γγ* and *h→gg*)
Large quantum correction can also appear in the *hhh* coupling

Higgs coupling measurement at the LHC

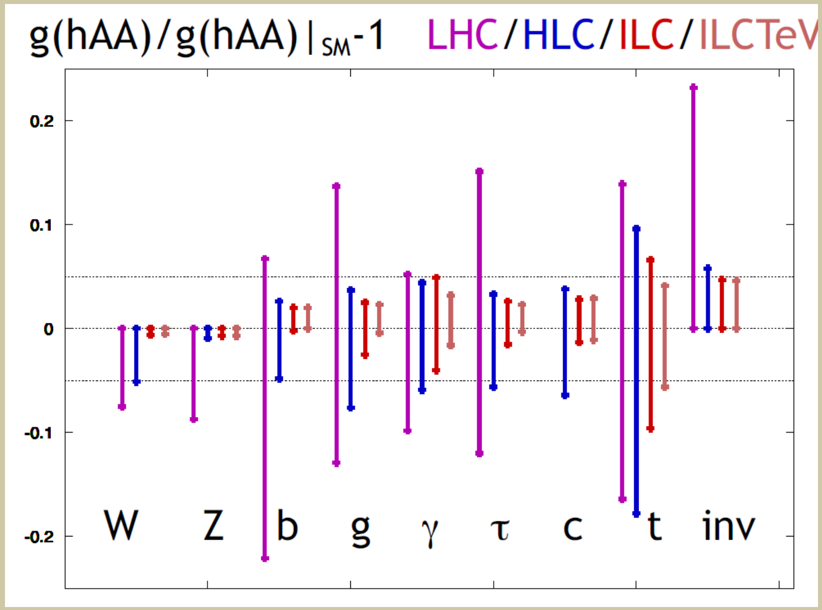
Accuracy is typically O(10) %

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

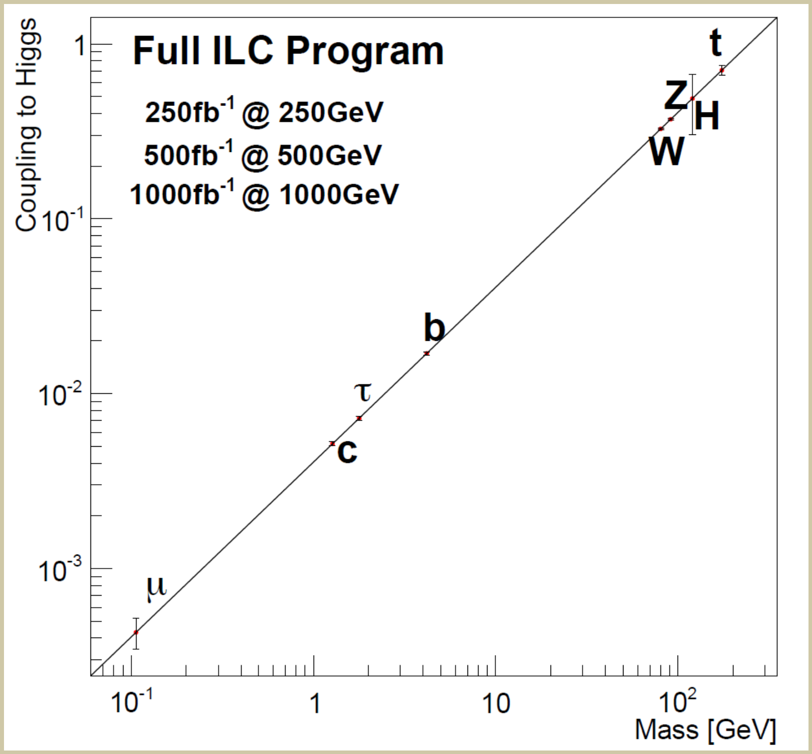


Sfitter - Zerwas

International Linear Collider



M. Peskin, 2012



Coupling measureable by a few%, and *hhh* can also be measured by around 20 % (Fujii)

We may be able to distinguish models by detecting the pattern of deviations in the *h* couplings from the SM values!

Model-independent Global Fit for Couplings

Canonical ILC program

250 GeV: 250 fb^{-1}
500 GeV: 500 fb^{-1}
1 TeV: 1000 fb^{-1}

(M_H = 125 GeV)

P(e-,e+)=(-0.8,+0.3) @ 250, 500 GeV

P(e-,e+)=(-0.8,+0.2) @ 1 TeV

coupling	250 GeV	250 GeV + 500 GeV	250 GeV + 500 GeV + 1 TeV
HZZ	1.3%	1.3%	1.3%
HWW	4.8%	1.4%	1.4%
Hbb	5.3%	1.8%	1.5%
Hcc	6.5%	2.9%	2.0%
Hgg	7.0%	2.5%	1.8%
Hττ	5.7%	2.5%	2.0%
Hγγ	25%	12%	5.2%
Hμμ	-	-	16%
Γ_0	11%	5.9%	5.6%
Htt	-	16%	3.8%
HHH	-	104%	26%

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)

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*

	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*

Type-II

hbb ∝ sin(β−α) − tanβ cos(β−α)

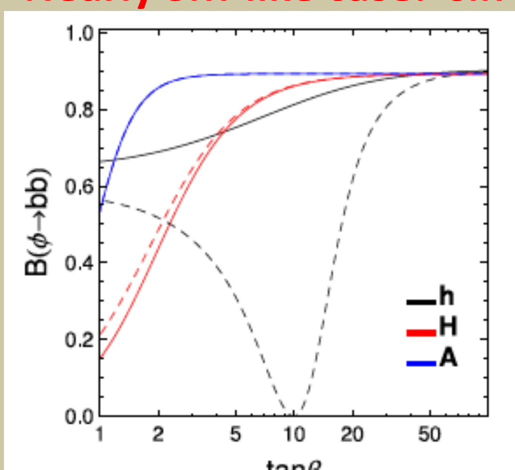
hττ ∝ sin(β-α) − tanβ cos(β−α)

Type-X

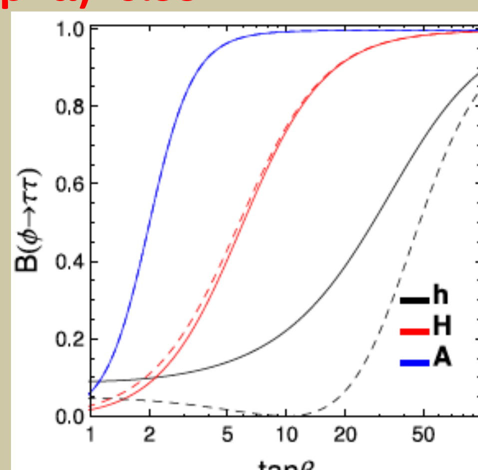
hbb ∝ sin(β−α) + cotβ cos(β−α)

hττ ∝ sin(β-α) − tanβ cos(β−α)

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



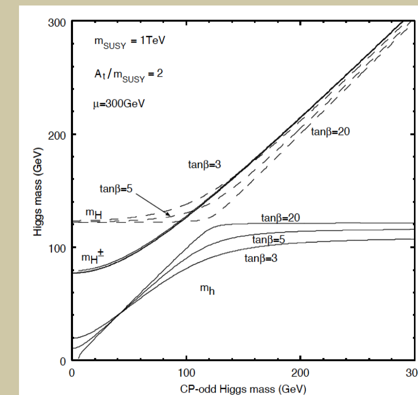
Type II



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

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

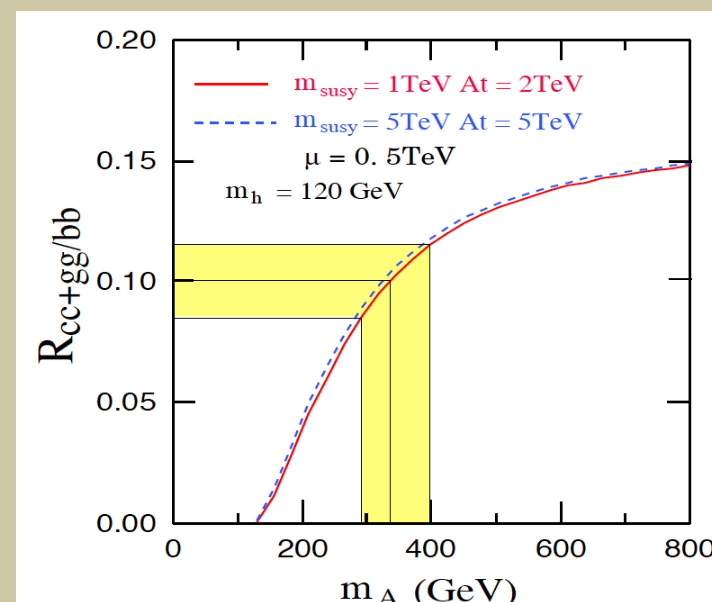
tanβ=5

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

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

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

Peskin et al (2012)



Y. Okada (01)

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*

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

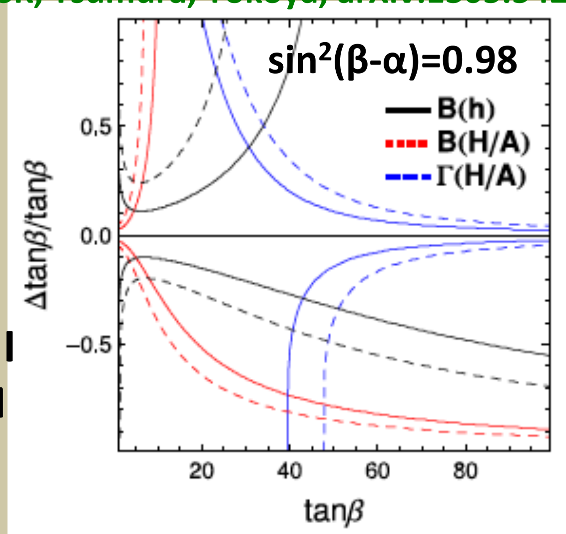
2. Total width of *H, A* — Berger, Han, jiang (01); Gunion, Han, Jiang, Sopczak (03)

useful for large tanβ

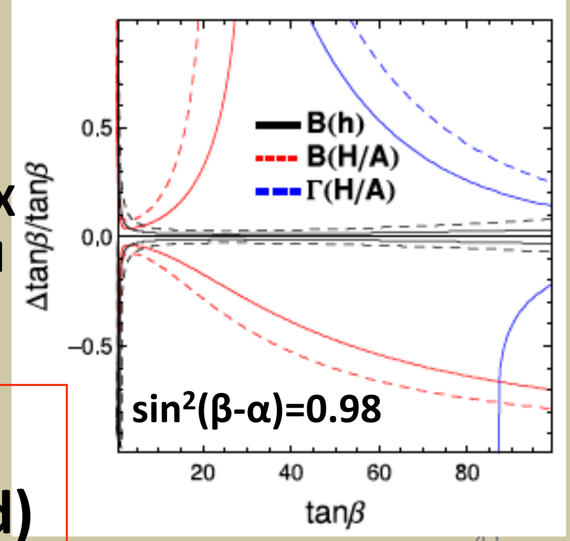
3. Decay of SM-like Higgs *h* when sin(β-α) is slightly smaller than 1

SK, Tsumura, Yokoya, arXiv:1305.5424

Type-II 2HDM



Type-X 2HDM

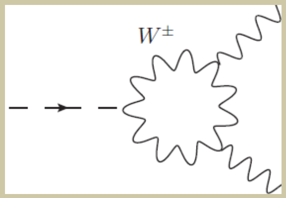


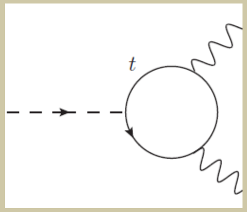
Precision measurement of the *h* decay at ILC is very useful (information of H,A not required)

Di-photon Decay Width

Loop induced process in the SM

New physics effect enters at the same order of perturbation





SM loop destructive

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

In the Higgs Triplet model

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

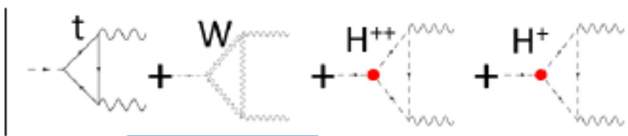
➤ イベント率 $h \to \gamma\gamma$

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

$R_{\gamma\gamma}$ は λ_4 に依存する

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

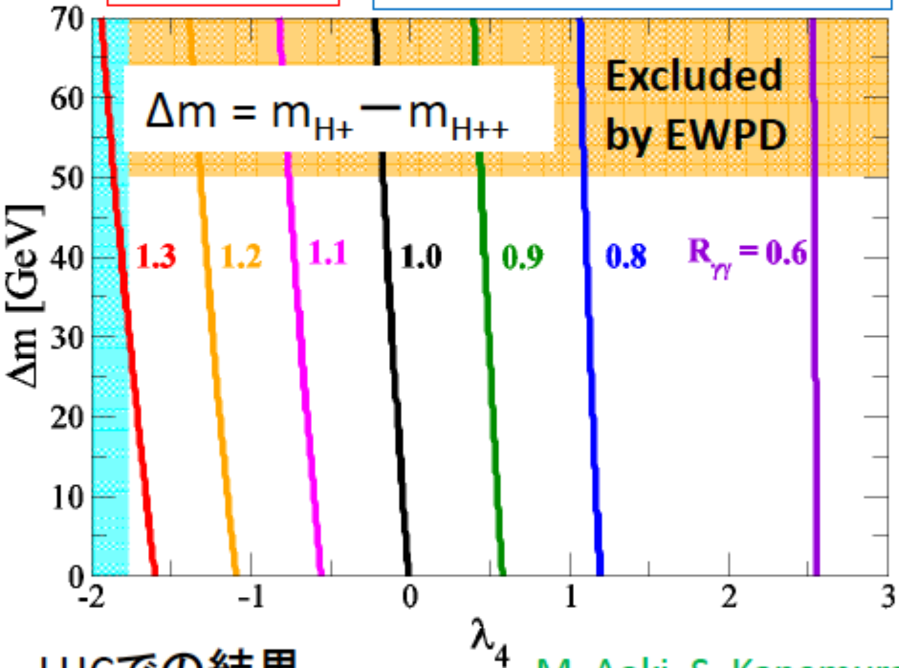
$\Gamma(h \to \gamma\gamma)_{HTM} = \Big|$



$\Big|^2$

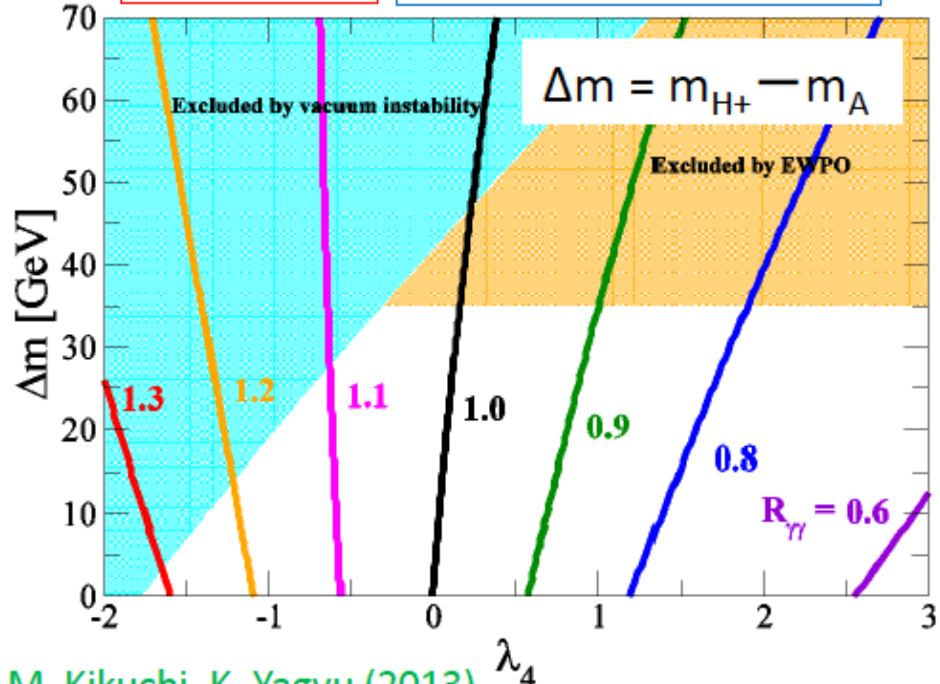
CaseI $\lambda_5 \geq 0$

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

Self-coupling *hhh*

It is important to determine the structure of Higgs potential

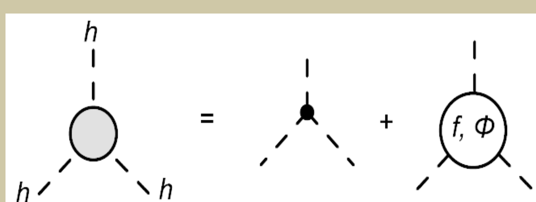
$$V_{\rm Higgs} = \frac{1}{2}m_h^2 h^2 + \frac{1}{3!}\lambda_{hhh}h^3 + \frac{1}{4!}\lambda_{hhhh}h^4 + \cdots$$

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

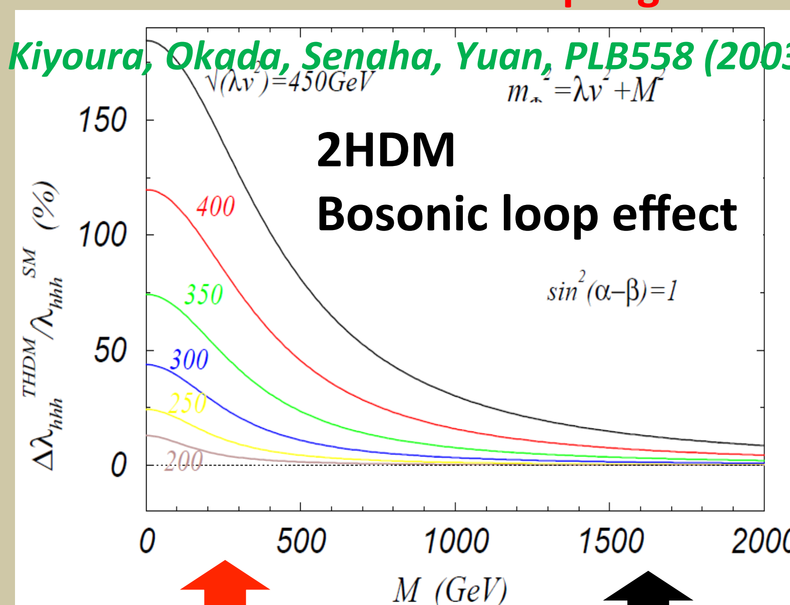


Φ = H, A, H±

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

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

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

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

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

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

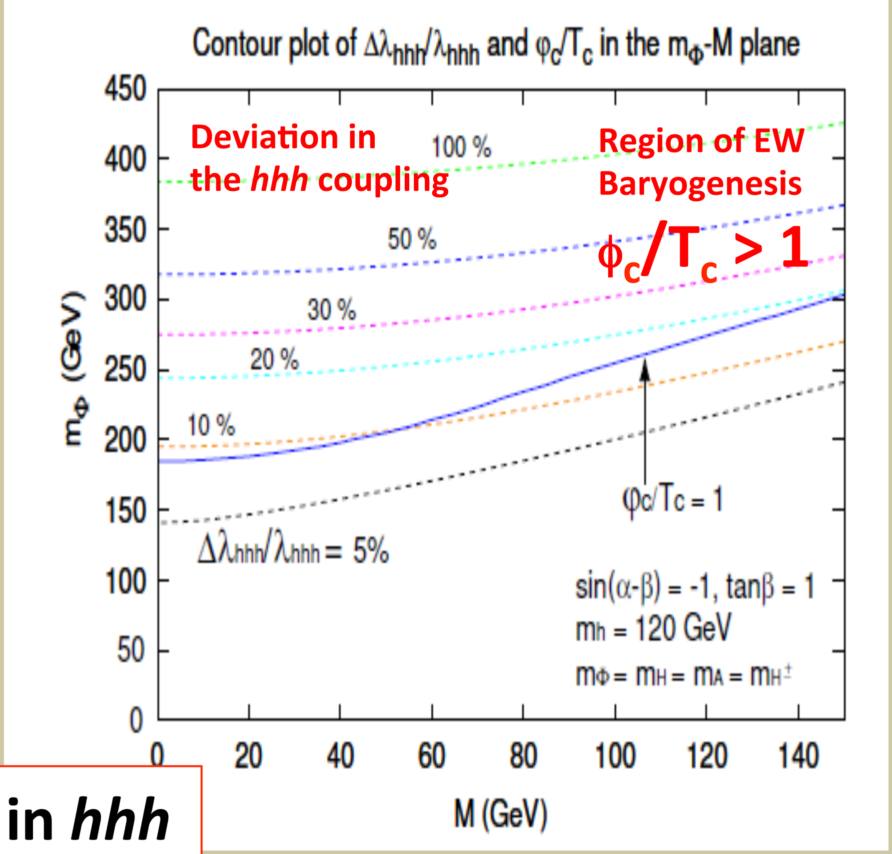
Condition of strongly 1st OPT

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

SM: $m_h < 60$GeV: **Excuded！**

2HDM: $m_h = 125$GeV: **Possible**

SK, Okada, Senaha (2005)



EW Baryogenesis ⇔ 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

DBD full simulation

Higgs self-coupling @ 1 TeV

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

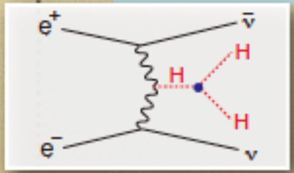
	Expected	After Cut
ννhh (WW F)	272	35.7
ννhh (ZHH)	74.0	3.88
BG (tt/ννZH)	7.86×10^{5}	33.7
significance	0.30	4.29

- 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)

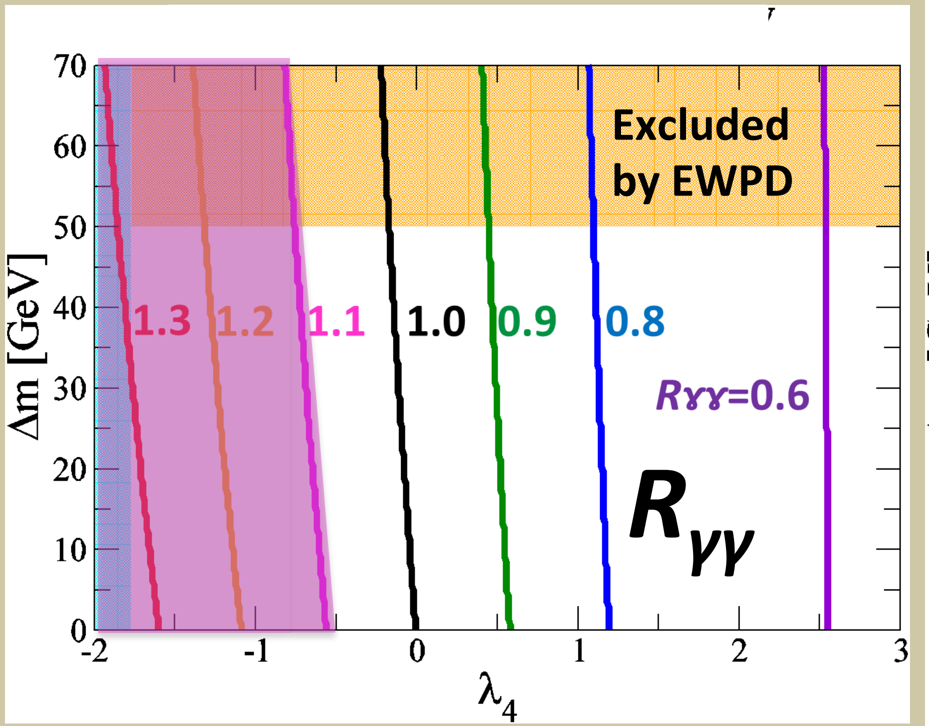
Correlation between *hγγ* and *hhh*

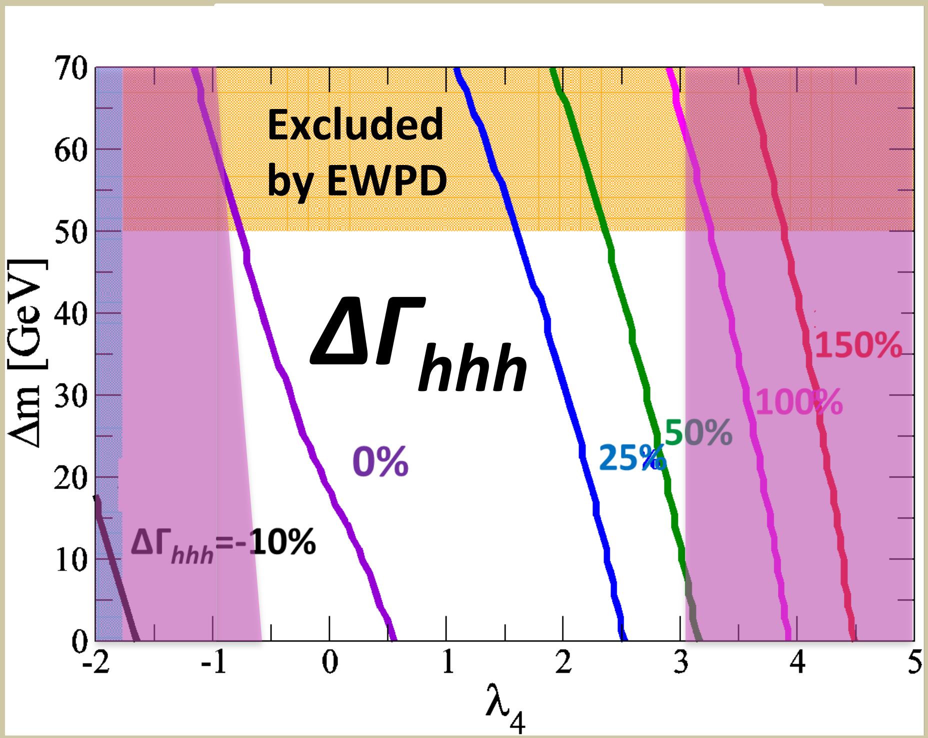
Ex) Higgs Triplet Model (SM-like *h* + Triplet)

$m_{H^{++}}$=300GeV, v_Δ=1MeV

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

$R_{\gamma\gamma}$ = 0.8 ± 0.3 (CMS)





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

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

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**

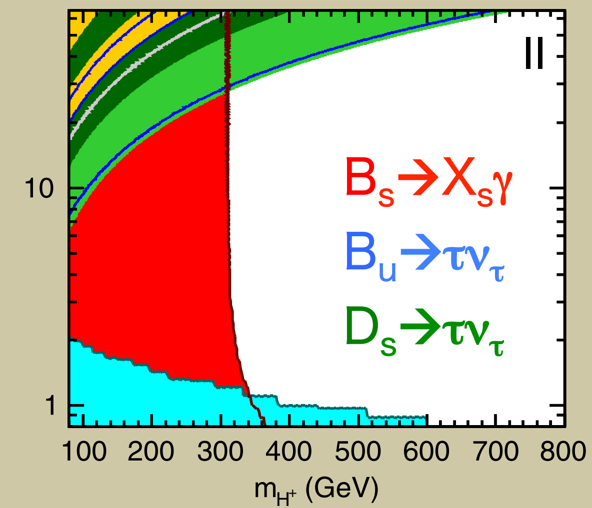
$$\sin(\beta-\alpha) \simeq 1 - \frac{2m_Z^4}{m_A^4 \tan^2\beta}$$

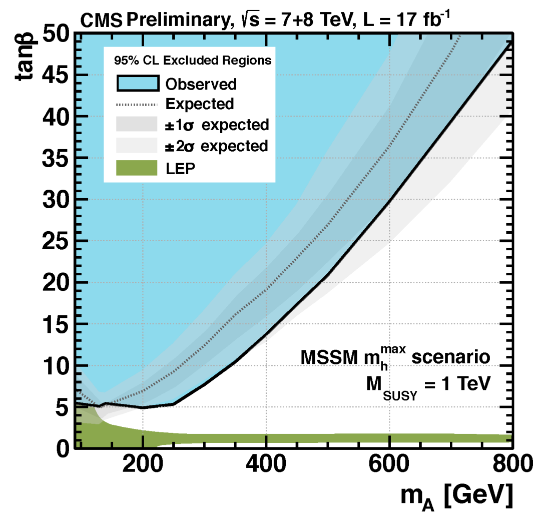
Extra Higgs bosons

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

***HVV*:**	**cos(β-α)**	**<<1**
***HAZ*:**	**sin(β-α)**	**≈ 1**
H^{+}***H***$^{-}$***γ*:**	***1***	

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

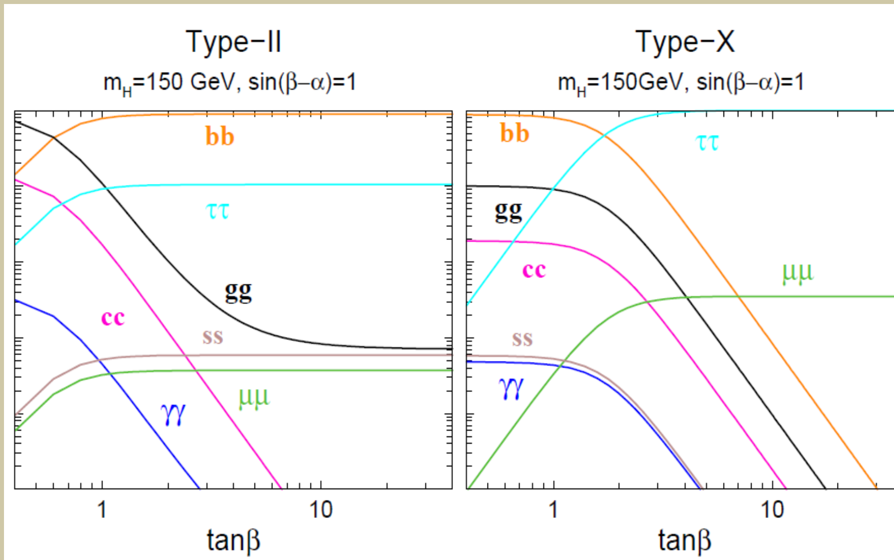




Flavor experiments and LHC give strong constraints on MSSM (Type-II 2HDM)

MSSM vs Type X 2HDM

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

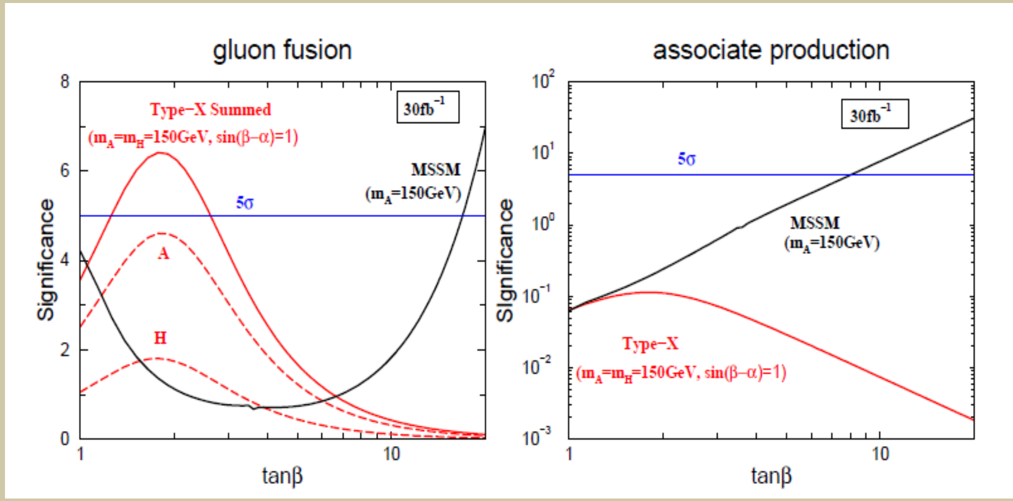


At LHC, Type X 2HDM can be discriminated from MSSM (Type-II) by the combination of $\tau\tau$ gluon fusion

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

and bb associate (H)A production

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



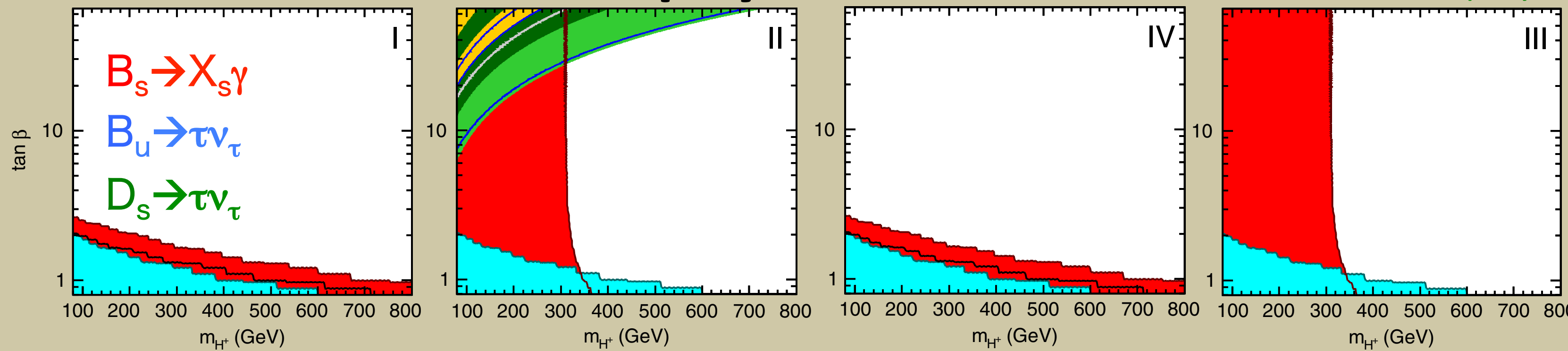
	ξ^u	ξ^d	ξ^ℓ
Type-I	$1/\tan\beta$	$-1/\tan\beta$	$-1/\tan\beta$
Type-II	$1/\tan\beta$	$\tan\beta$	$\tan\beta$
Type-X	$1/\tan\beta$	$-1/\tan\beta$	$\tan\beta$
Type-Y	$1/\tan\beta$	$\tan\beta$	$-1/\tan\beta$

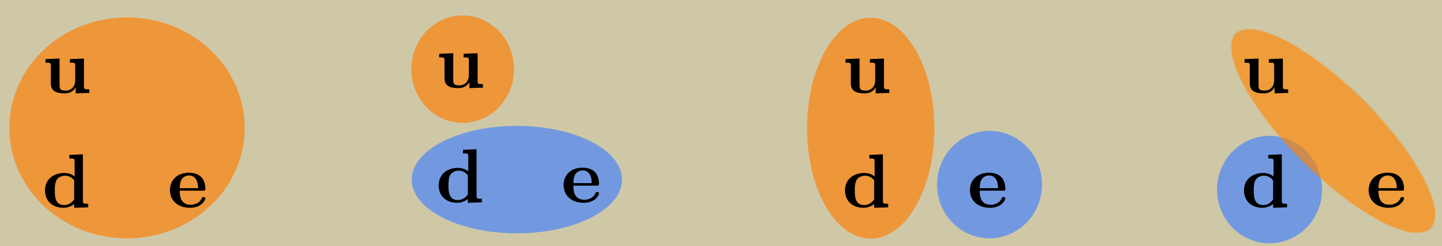
Aoki, SK, Tsumura, Yagyu (10)

Non-SUSY 2HDM

Constraint from flavor physics

Mahmoudi, Stal (09)





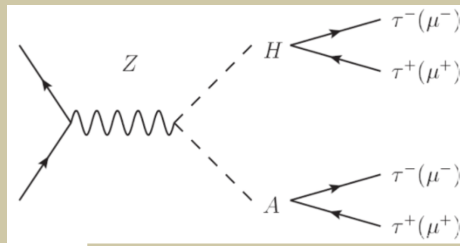
Type-I Type-II Type-X Type-Y

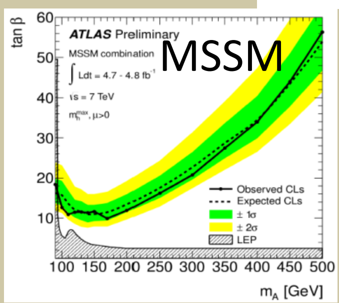
In Type-I and Type-X, light *H, A, H^+* can be allowed

⇒Pair Production

HA Production (Type X 2HDM)

LHC

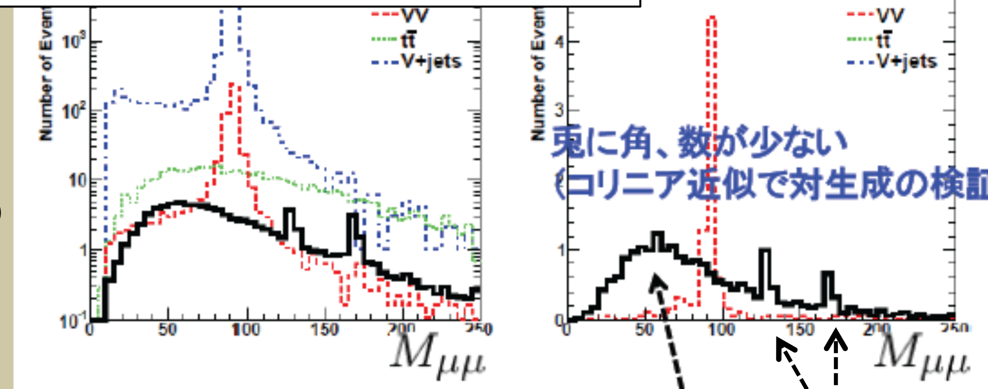




σ(pp→HA) = O(10-100) fb

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})



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

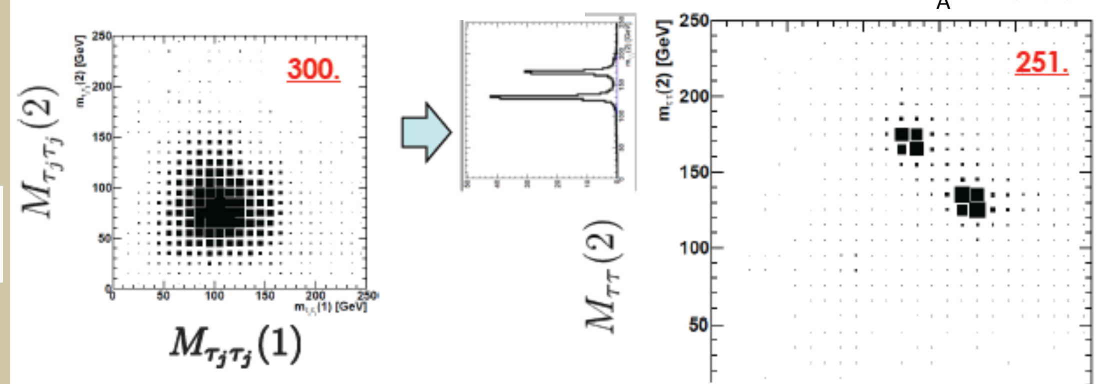
m_H=130GeV
m_A=170 GeV

ILC

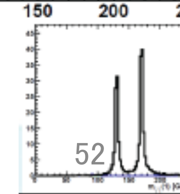
HA can be reconstructed by collinear approximation

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

$4\tau_h$ event analysis	HA	VV	$t\bar{t}$	S (100 fb^{-1})
Pre-selection	300.	10.6	1.2	38.
$0 \le z_{1-4} \le 1$	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

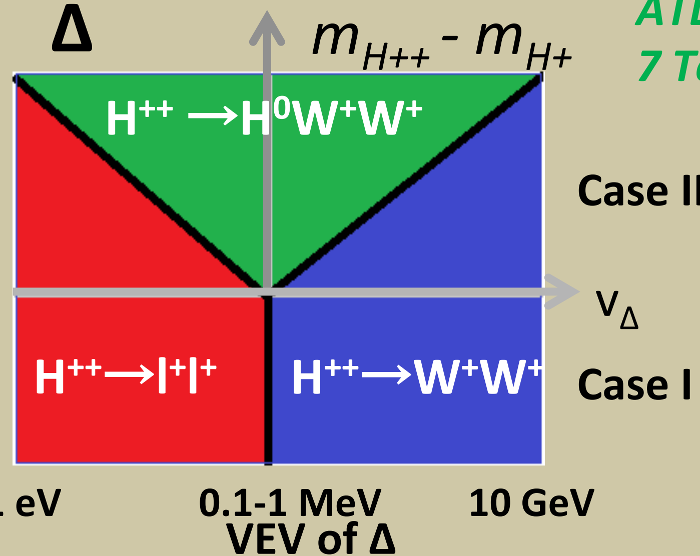


SK, Tsumura, Yokoya (11)

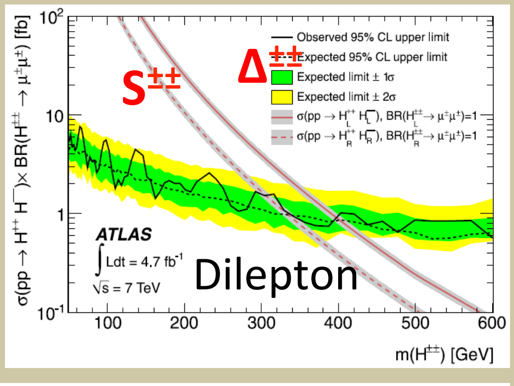
Doubly charged Higgs Δ^{++}

Higgs Triplet Model Δ

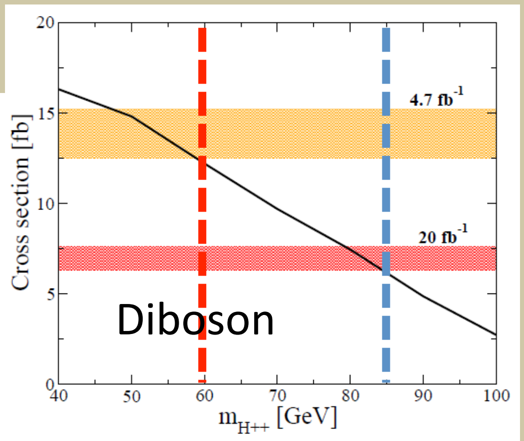
$$\Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \Delta^0 & -\frac{\Delta^+}{\sqrt{2}} \end{pmatrix}$$



ATLAS, Eur. Phys. J.C. 72 (2012), 7 TeV, 4.7 fb^{-1}



Main decay mode of H^{++} depends on VEV of Δ



SK, Yokoya, Yagyu (13)

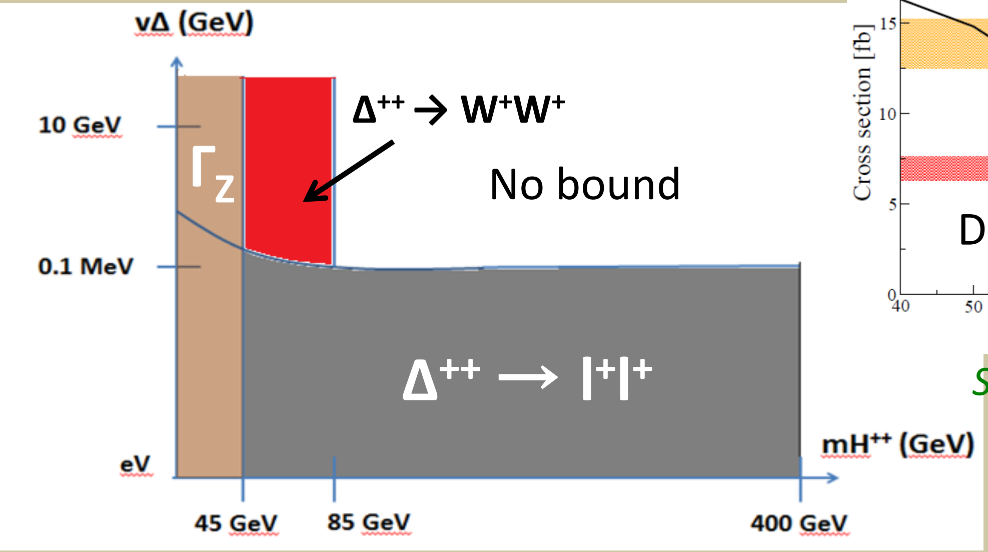
Current bound

If l^+l^+ is dominant,

$m_H^{++} > 400$ GeV

If W^+W^+ is dominat

$m_H^{++} > 60$ GeV



Summary

- A SM-like Higgs boson *h* was discovered

- The Higgs sector remains unknown

  SM-like ≠ SM

  Extended Higgs ⇔ New Physics

- Direct Searches of *H, A,* H^+, H^{++} at LHC (and ILC)

- Detailed study of *h* makes it clear the shape and dynamics of Higgs sector (Finger printing models)

- **Higgs is a good probe of new physics BSM!**

We need ILC

Be prepared