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Extended Higgs Sectors

30 May 2016, Rencontres de Blois 2016

Introduction

Discovery of *h*(125) at LHC in 2012

- Existence of a scalar particle,
- Mass and measured couplings are consistent with the SM

Higgs sector remains unknown

- SM Higgs sector does not have a strong motivation/problematic …
- Most of extended Higgs sectors can also satisfy current data as well

Requirement of BSM

- Hierarchy Problem *SUSY, Dynamical Symmetry Breaking, Shift-Symmetry*
- BSM Phenomena *Baryon Asymmetry, Neutrino Masses, Dark Matter, …*

Higgs sector is a probe of new physics

- Shape of Higgs sector (multiplet structure, symmetry, scales, …) is related to BSM scenarios
- Essence of the Higgs particle is directly connected to a BSM paradigm

Essence of Higgs

Higgs Nature ⇔ BSM Paradigm

- Elementary Scalar — SUSY, Scale invariance
- Composite of fermions — Dynamical Symmetry Breaking
- A vector field in extra D — Gauge Higgs Unification
- Pseudo NG Boson — Minimal Composite Models
- …… — ……

Each new paradigm predicts a specific Higgs sector

Higgs sector and New Phenomena

DM（WIMP） ・Inert doublet, singlet, triplet models

Odd under a new unbroken symmetry

Baryogenesis ・EW Baryogenesis (Extended Higgs)

First Order Phase Transition
CP Violation

Neutrino mass ・Type-II Seesaw (Exotic Higgs (triplet))

Exotic representations

・Radiative neutrino mass models

New charged Higgs bosons

Multiplet structures, new symmetries, and the strength of couplings in the Higgs sector are closely related to new physics

Higgs sector is a window to the new physics beyond the SM

Higgs portal new physics

SUSY
Dynamical symmetry breaking
pNGB
CW mechanism
Higgs portal dark matter
Inert scalar models
Radiative neutrino mass models
Electroweak baryogenesis
…

This talk

- Introduction (done)
- Extended Higgs sectors
- Fingerprinting by using future precision measurements of the Higgs boson couplings
- Higgs potential and new physics
- Summary

Extended Higgs Sectors

The "SM-like" does not necessarily mean the SM.
Every extended Higgs sector can contain the SM-like Higgs boson *h*(125) in its decoupling regime.

Properties of extended Higgs sectors

Multiplet Structure (2nd simplest Higgs models)

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

Additional Symmetry

Discrete or Continuous?
Exact or Softly broken?

Interaction

Weakly coupled or Strongly Coupled ?
Decoupling or Non-decoupling?

Note: 2nd simplest Higgs models (HSM, 2HDMs, …) can be effective theories of more complicated Higgs sectors

Electroweak rho parameter

$$\rho_{\mathrm{exp}} = 1.0004^{+0.0003}_{-0.0004}$$

$Q = I_3 + Y/2$

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

T_i : $\mathrm{SU(2)_L}$ isospin

Y_i : hypercharge

v_i : v.e.v.

c_i : 1 for complex representation

1/2 for real representation

N=1 SM Higgs doublet Φ (T=1/2, Y=1) $\rho = 1$!

N=2 What kind of (2 field) extended Higgs sector $\Phi + X(T_X, Y_X)$ can satisfy $\rho = 1$?

We solve the equation

$$4\, T_X(T_X+1) = 3Y_X{}^2$$

$(T_X,$	$Y_X)$	X
(0,	0)	Singlet
(1/2,	1)	Doublet
(3,	4)	Septet
(25/2,	15)	26-plet
….		….

Larger T_x disfavored by unitarity (Logan et al,2014)

2 Higgs Doublet Model (soft-broken Z_2)

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

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

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

↑ ↑ ↑charged

CPeven CPodd

Diagonalization

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

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

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

Masses

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

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

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

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

M_{soft}: soft breaking scale

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

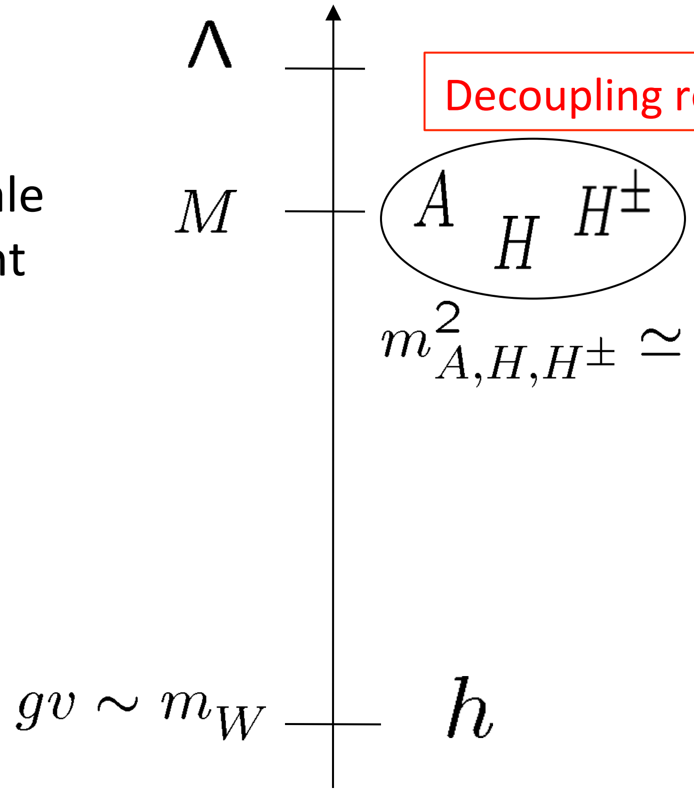
soft-breaking scale

of the discrete symm.

Two Possibilities

Λ: Cutoff

M: Mass scale irrelevant to VEV

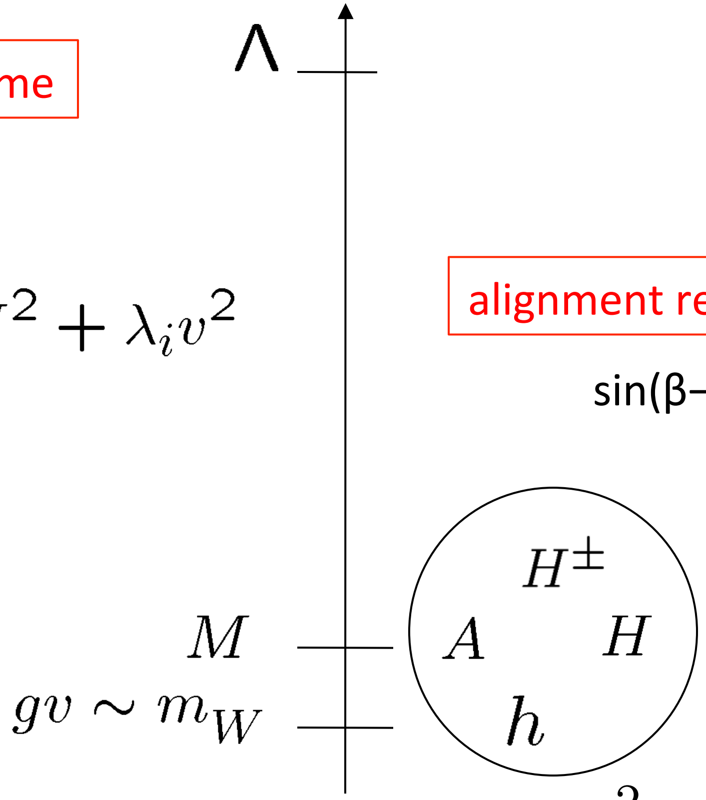


Decoupling regime

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

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

Effective Theory is the SM



alignment regime

sin(β−α) ~ 1

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

Effective Theory is an extended Higgs sector

Non-decoupling effects

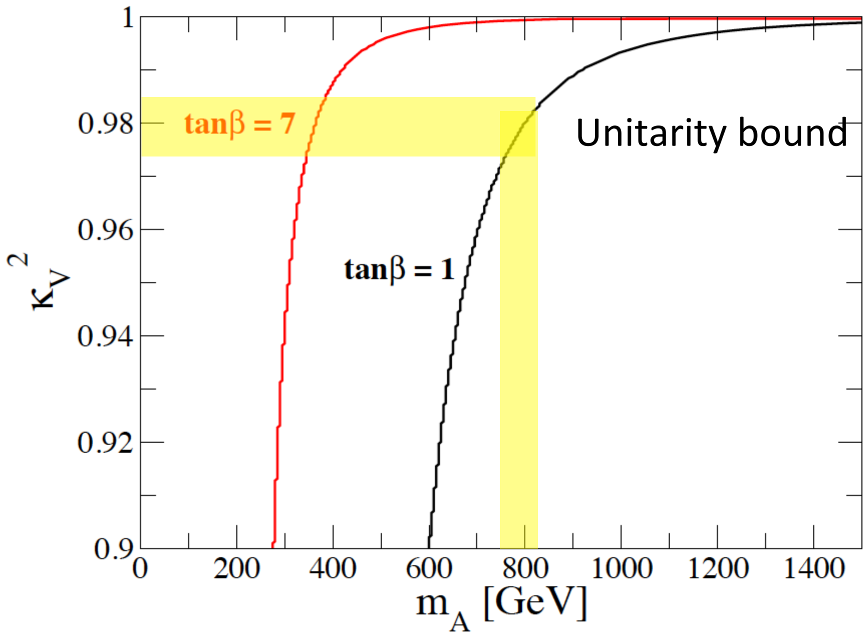
Unitarity in Non-SUSY 2HDM

Φ_1 *and* Φ_2 share v=246 GeV

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

m_h=125 GeV

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



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

$$\boxed{\tan 2(\beta-\alpha) = \frac{2M_{12}^2}{M_{11}^2 - M_{22}^2} \sim -\frac{\lambda' v^2}{M^2}}$$

$$M_{11}^2 = v^2(\lambda_1\cos^4\beta + \lambda_2\sin^4\beta) + \frac{v^2}{2}\bar{\lambda}\sin^2 2\beta,$$

$$M_{22}^2 = \underline{M^2} + v^2\sin^2\beta\cos^2\beta(\lambda_1+\lambda_2-2\bar{\lambda}),$$

$$M_{12}^2 = \frac{v^2}{2}\sin 2\beta(-\lambda_1\cos^2\beta + \lambda_2\sin^2\beta) + \frac{v^2}{2}\sin 2\beta\cos 2\beta\bar{\lambda}.$$

FCNC Suppression

Multi-Higgs model: FCNC appears via Higgs mediation

2 Higgs doublet models:

to avoid FCNC, give different charges to Φ_1 and Φ_2

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

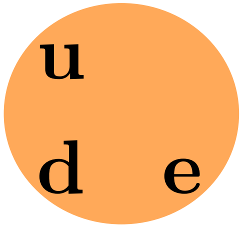
Each quark or lepton couples only one Higgs doublet

No FCNC at tree level

Barger, Hewett, Phillips

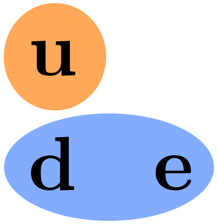
Classified by Z_2 charge assignment

Four Types of Yukawa coupling



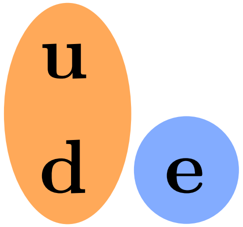
Type-I

Fermiofobic
Neutrinophilic



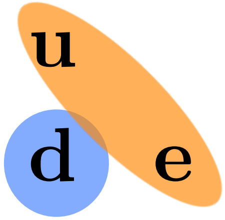
Type-II

MSSM
NMSSM



Type-X

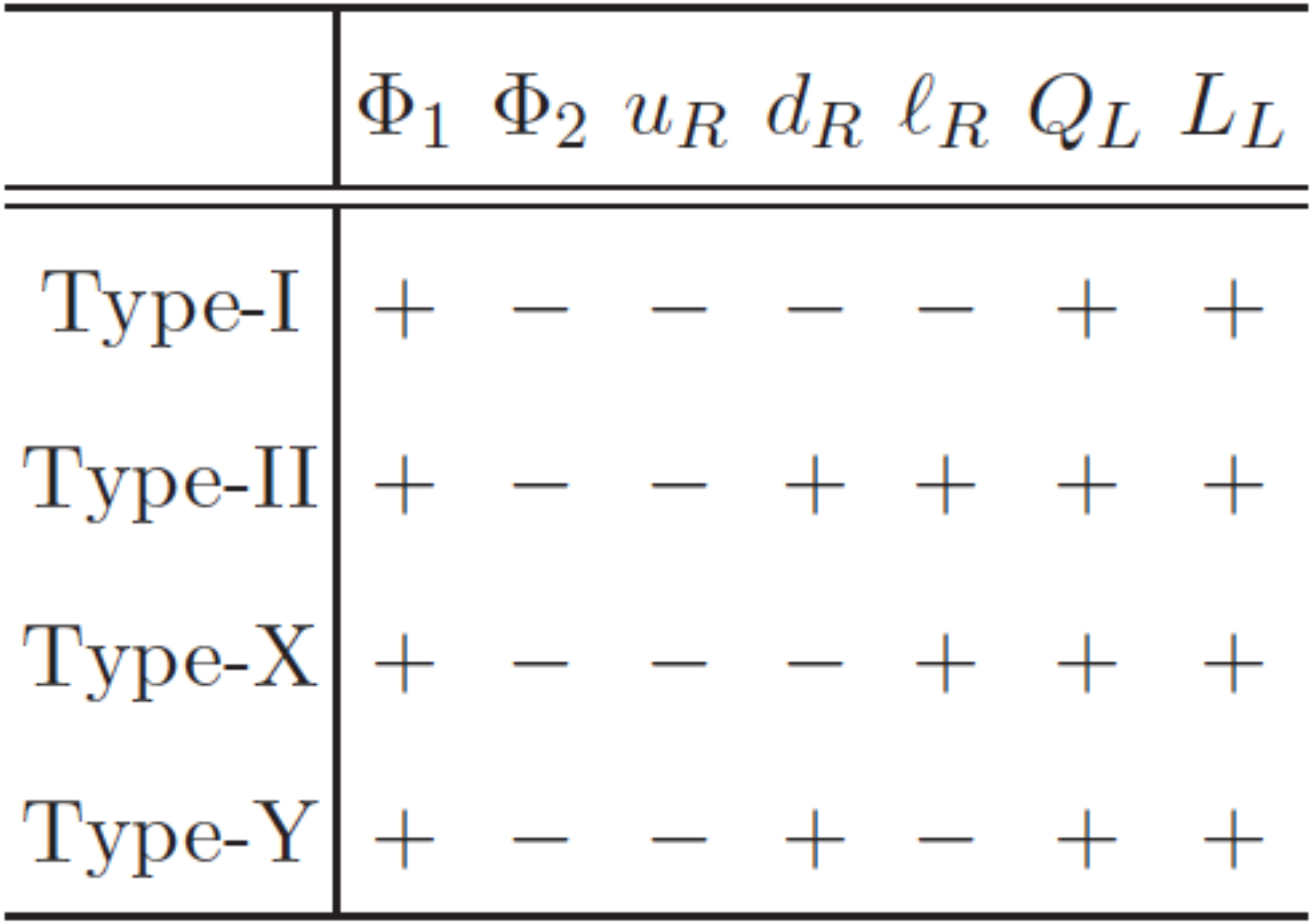
Lepton specific
Neutrino mass model
Muon g-2



Type-Y

Flipped
???

Z_2 assignment



	Φ_1	Φ_2	u_R	d_R	ℓ_R	Q_L	L_L
Type-I	+	−	−	−	−	+	+
Type-II	+	−	−	+	+	+	+
Type-X	+	−	−	−	+	+	+
Type-Y	+	−	−	+	−	+	+

Type2-2HDM (MSSM) Higgs couplings

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

Higgs mixing

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

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

SM

2HDM Type2

Gauge coupling:

$$\phi VV \quad (V = Z, W) \Rightarrow \begin{matrix} hVV & HVV \\ \sin(\beta-\alpha), & \cos(\beta-\alpha) \end{matrix}$$

Yukawa coupling:

$$\phi b\bar{b} \Rightarrow \begin{matrix} hb\bar{b} & Hb\bar{b} \\ \frac{\sin\alpha}{\cos\beta}, & \frac{\cos\alpha}{\cos\beta} \end{matrix}$$

$$\phi t\bar{t} \Rightarrow \begin{matrix} ht\bar{t} & Ht\bar{t} \\ \frac{\cos\alpha}{\sin\beta} & \frac{\sin\alpha}{\sin\beta}, \end{matrix}$$

SM-like (alignment) regime

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

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

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

_h_ behaves like the SM Higgs

$$g_{hVV}\longrightarrow g^{\text{SM}}_{\phi VV} \qquad g_{HVV}\longrightarrow 0$$

$$y_{ht\bar{t}}\longrightarrow y^{\text{SM}}_{\phi t\bar{t}}$$

$$y_{hb\bar{b}}\longrightarrow y^{\text{SM}}_{\phi b\bar{b}}$$

$$y_{h\tau\tau}\longrightarrow y^{\text{SM}}_{\phi\tau\tau}$$

$$\left.\begin{aligned} y_{Ht\bar{t}}&\longrightarrow y^{\text{SM}}_{\phi t\bar{t}}\cot\beta \\ y_{Hb\bar{b}}&\longrightarrow y^{\text{SM}}_{\phi b\bar{b}}\tan\beta \\ y_{H\tau\tau}&\longrightarrow y^{\text{SM}}_{\phi\tau\tau}\tan\beta \end{aligned}\right\}\ \text{Type-II 2HDM}$$

In difference type, the pattern is different

Fingerprinting Higgs sectors

by using future precision data for the couplings of *h*(125)

How we test the Higgs sector

Direct searches of the 2nd Higgs boson

Clear evidence of non-minimal Higgs sectors

Indirect searches

- By detailed measurements of ***hVV*** and ***hff***, we can indirectly test extended Higgs sectors by detecting the deviation from the SM

ATLAS-CONF-2015-044

Run 1

Best fit values for combination of ATLAS and CMS

Assumption,
absense of BSM particles in the loops
and $BR_{BSM} = 0$

$$\kappa_Z = 1.00^{+0.10}_{-0.11}$$

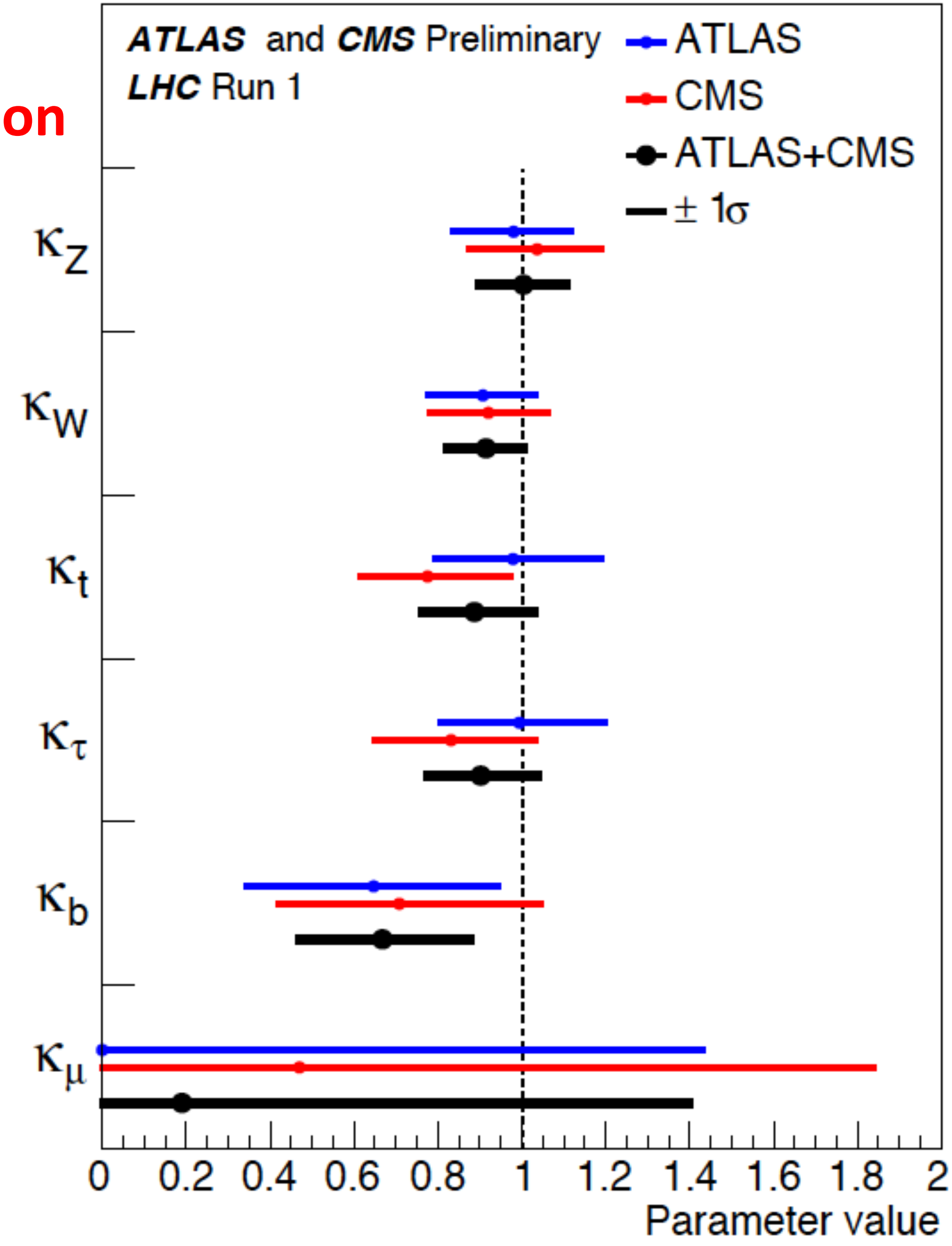
$$\kappa_W = 0.91^{+0.09}_{-0.09}$$

$$\kappa_t = 0.89^{+0.15}_{-0.13}$$

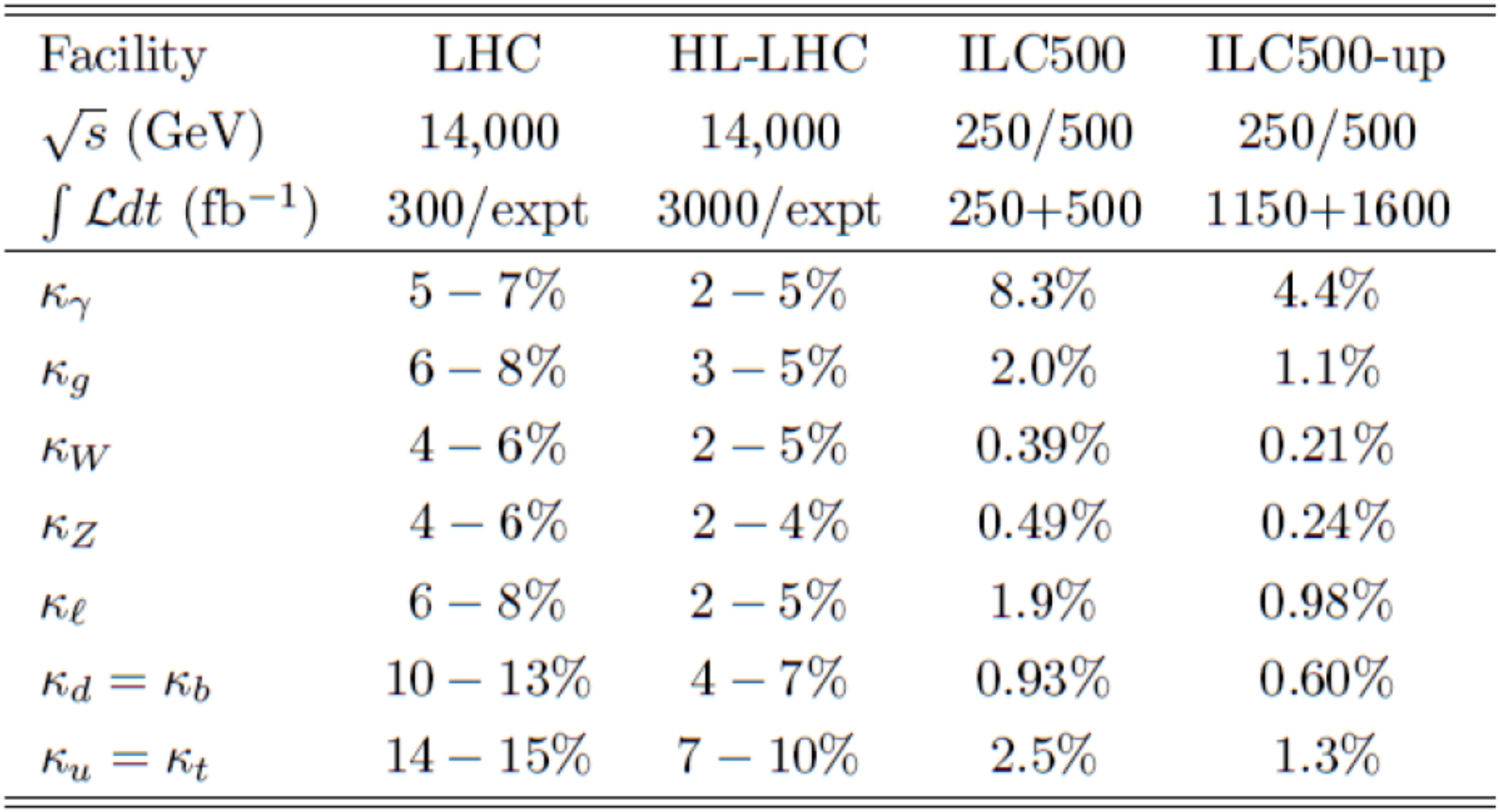
$$\kappa_\tau = 0.90^{+0.14}_{-0.13}$$

$$\kappa_b = 0.67^{+0.22}_{-0.20}$$

$5\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 7$ TeV and $20\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 8$ TeV



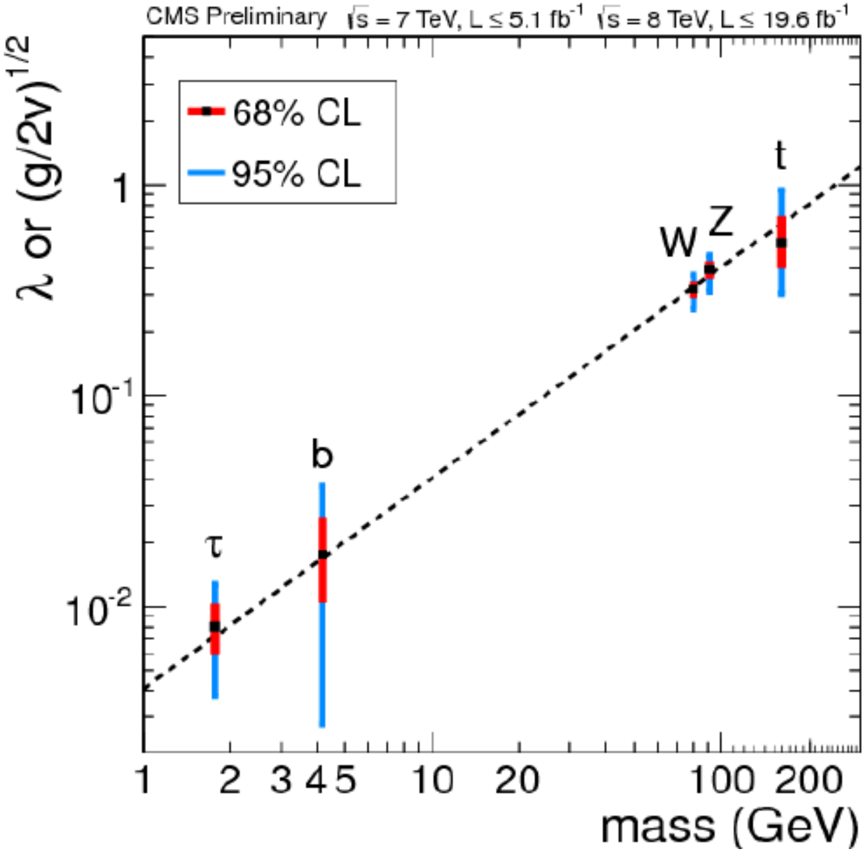
Future *h*(125)-coupling measurements

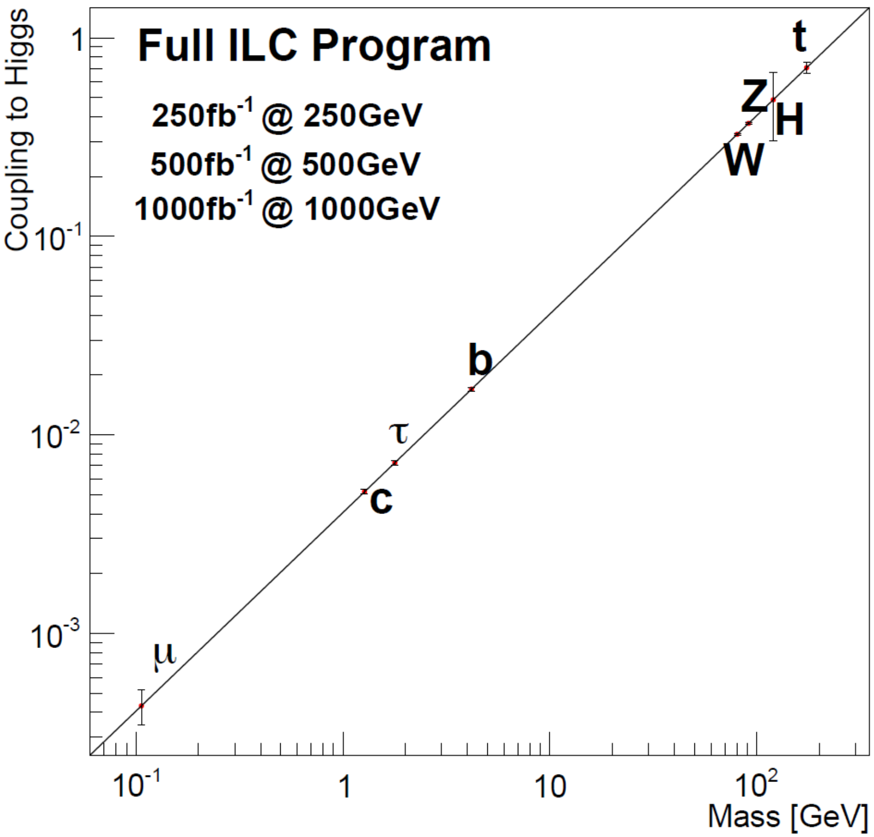


Facility	LHC	HL-LHC	ILC500	ILC500-up
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%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

Snowmass Higgs Working Group Report 1310.8361

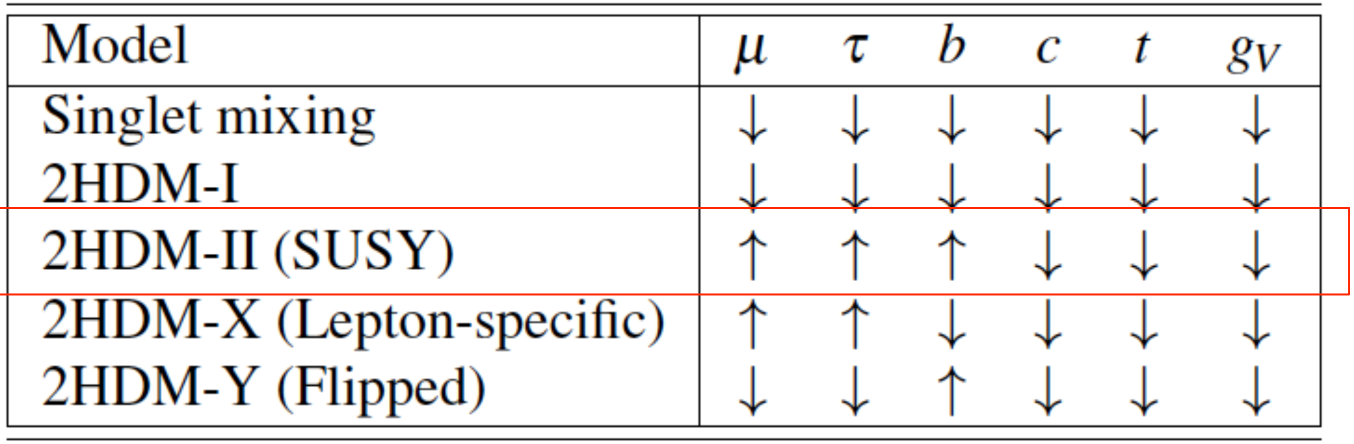
Current LHC data v.s. Full ILC





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

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 2HDM (tree level)

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

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

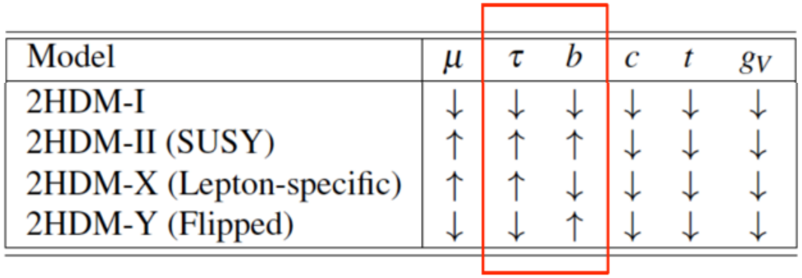
$$\kappa_V = 1 - (1/2)\,x^2 + \ldots$$

When a Fermion couples to Φ_1

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

and if it couples to Φ_2

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



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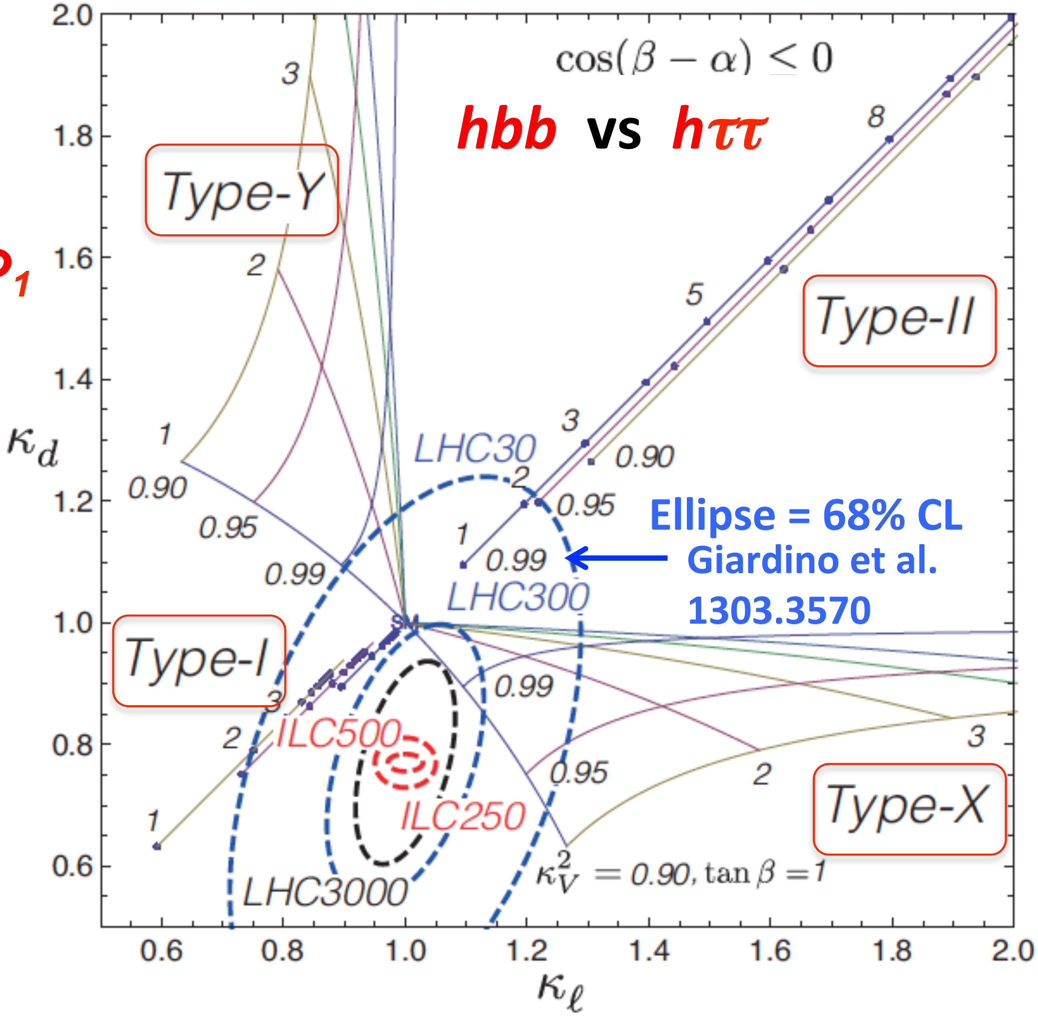
2HDM-X (Lepton-specific)	↑	↑	↓	↓	↓	↓
2HDM-Y (Flipped)	↓	↓	↑	↓	↓	↓

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



Ellipse = 68% CL
Giardino et al. 1303.3570

How do this result change with radiative corrections?

Scaling factors at one-loop level

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

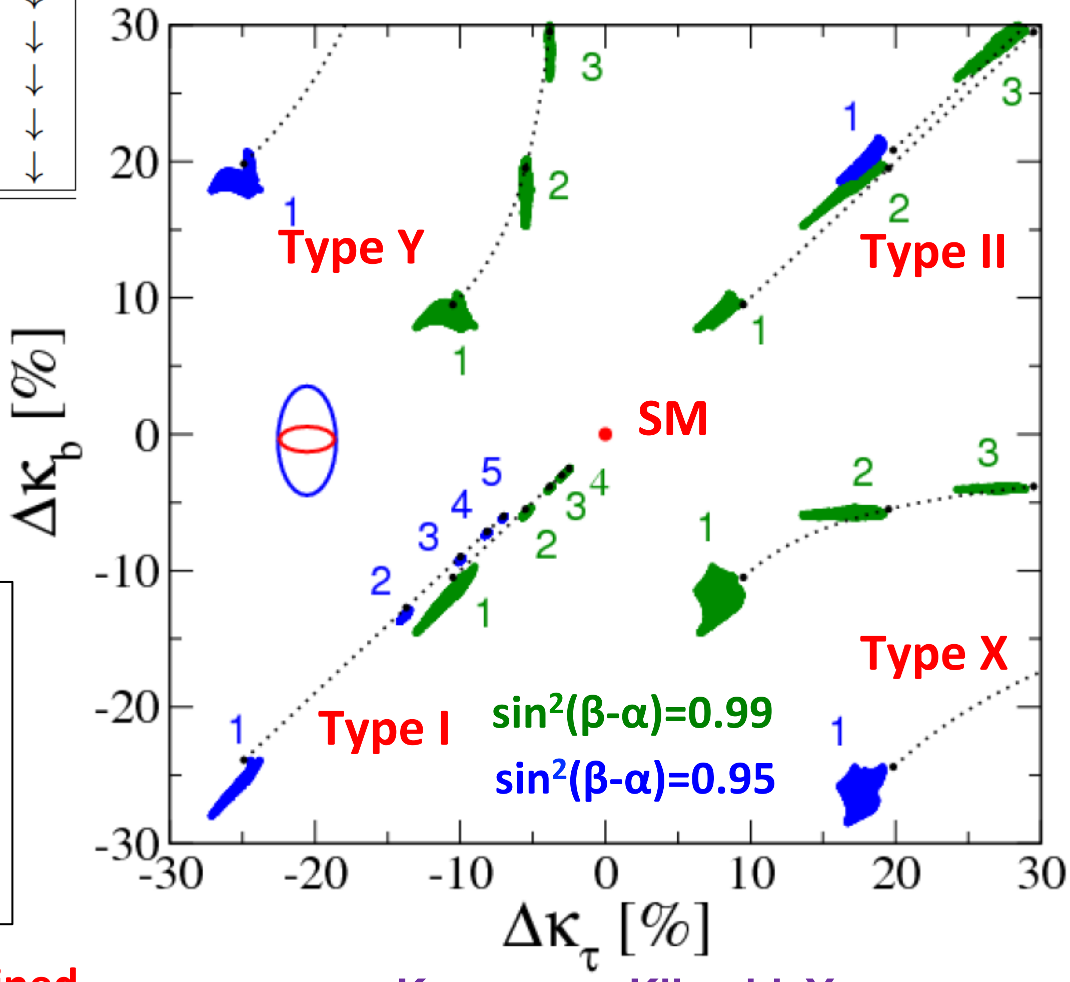
Evaluation at one-loop

Scan of inner parameters (for each sin(β-α) and tanβ) under theoretical constraints

Even if only κ_V slightly differ from 1, the type of Yukawa interactions can be separated by precision measurements at the LHC3000 and LCs.

tanβ, sin(β-α) can also be determined

Ellipse, ±1σ at LHC3000 and ILC500



Kanemura, Kikuchi, Yagyu, PLB731 (2014) 27.

hVV coupling in the ϕ-X model (X: second scalar)

- Mixing angle α (ϕ and X)
- tanβ: Ratio of VEV between ϕ and X

Doublet-Singlet Model (1/2,1) + (0,0)

$$\kappa_V = \cos\alpha$$

$\kappa_V < 1$

2HDM (1/2,1) + (1/2,1)

$$\kappa_V = \sin\beta\cos\alpha - \cos\beta\sin\alpha = \sin(\beta-\alpha)$$

Doublet-Triplet Model (Georgi-Machasek Model) (1/2,1) + (1,2) + (1,0)

$$\kappa_V = \sin\beta\cos\alpha - 2\sqrt{2}\cos\beta\sin\alpha$$

Doublet-Septet Model (1/2,1) + (3, 4)

$$\kappa_V = \sin\beta\cos\alpha - 4\cos\beta\sin\alpha$$

$\kappa_V > 1$ is possible

Fingerptinting the model (Exotics)

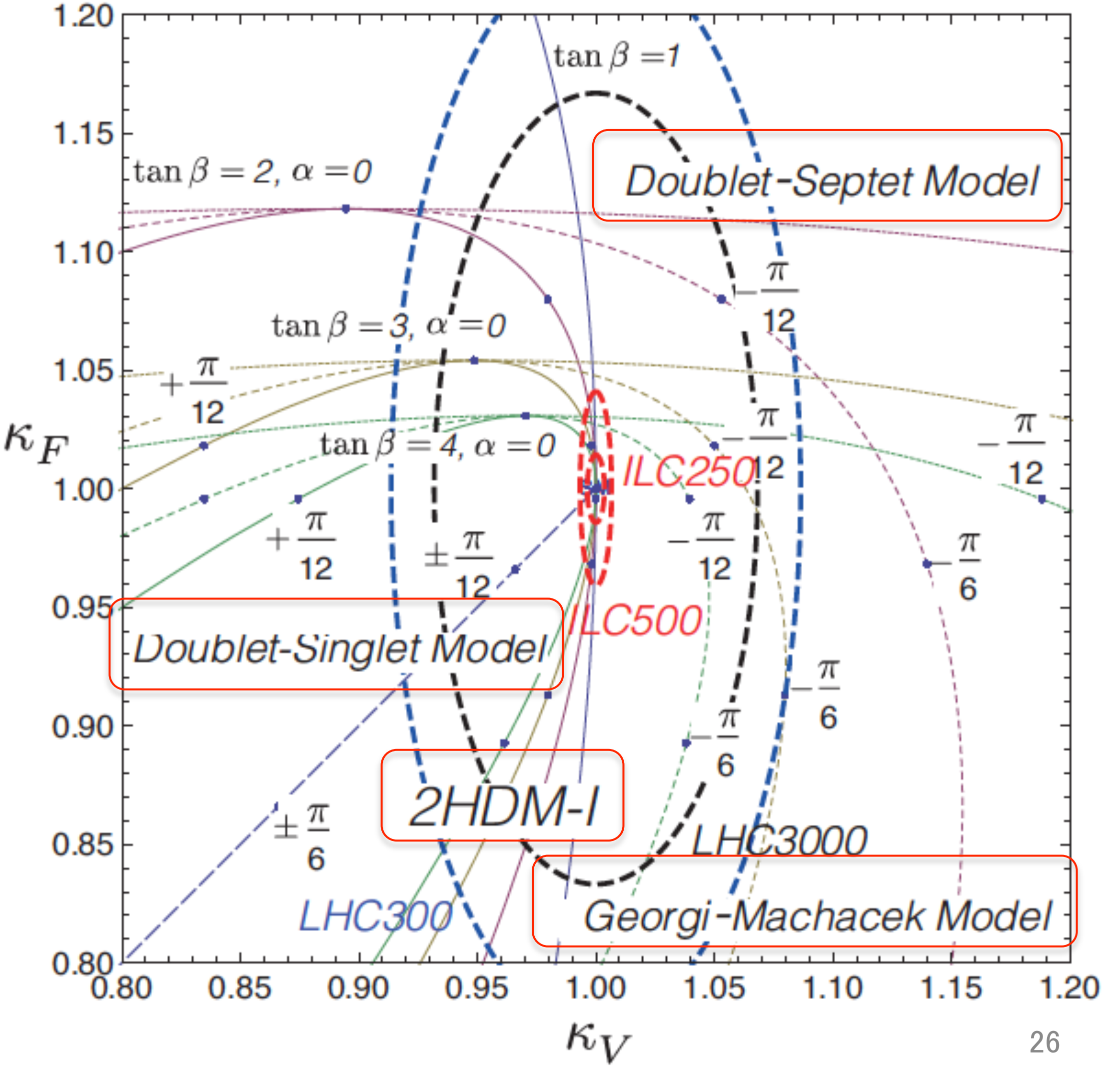
SK, K. Tsumura, K. Yagyu, H. Yokoya 2013

Universal Fermion Coupling (κ_F)
VS
***hVV* coupling (κ_V)**

Exotic models predict $\kappa_V > 1$

We can discriminate Exotic models

Ellipse = 68% CL



Comparison of

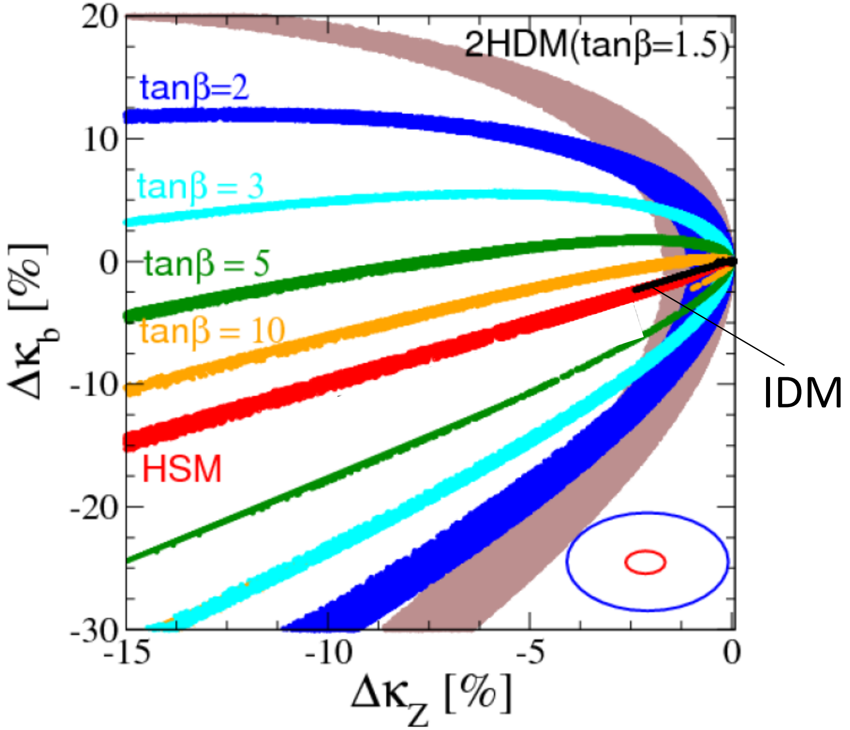
1. 2HDM-I
2. Doublet-Singlet Model (HSM)
3. Inert Doublet Model (IDM)

Scan of inner parameters (mass, mixing angles) under the theoretical conditions of

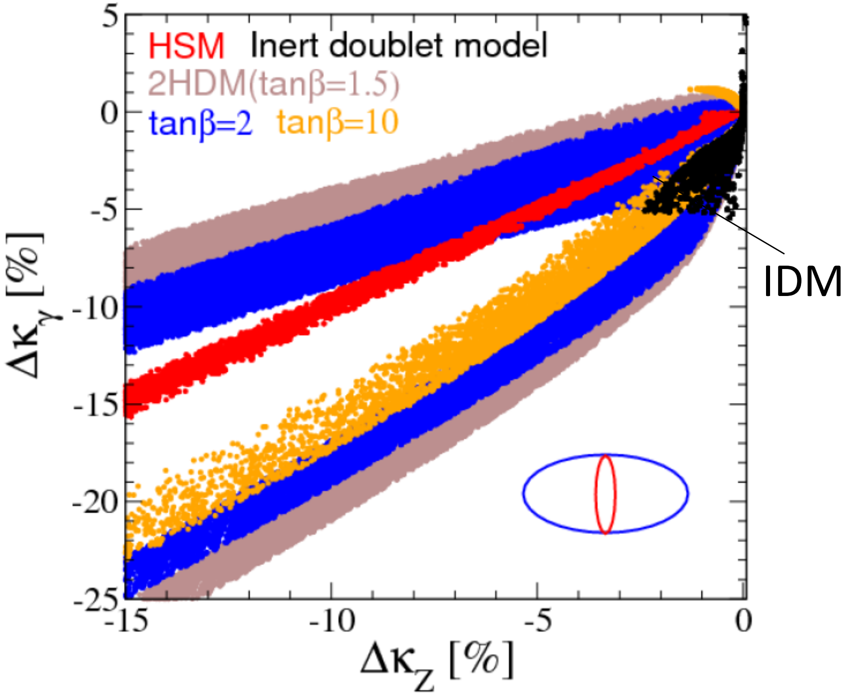
Perturbative unitarity

Vacuum stability

Condition for avoiding wrong vacuum (HSM)



These models may be distinguished, as long as a deviation in κ_Z is detected



Ellipse, ±1σ at LHC3000 and ILC500

Higgs potential and new physics

Although *h*(125) was found, we know nothing about the structure of the Higgs potential yet

Higgs potential

To understand the essence of EWSB, we must know the self-coupling in addition to the mass independently

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

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

Renormalization Conditions

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

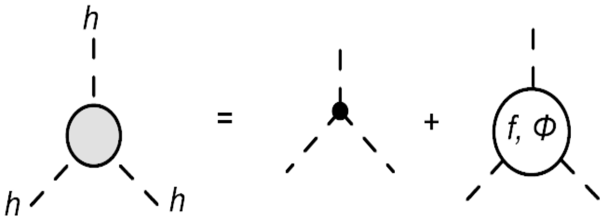
SM Case

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

Non-decoupling effect

Case of Non-SUSY 2HDM

- Consider when the lightest *h* is SM-like [$\sin(\beta-\alpha)=1$]
- At tree, the *hhh* coupling takes the same form as in the SM
- At 1-loop, non-decoupling effect m_Φ^4 (If $M < v$)



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

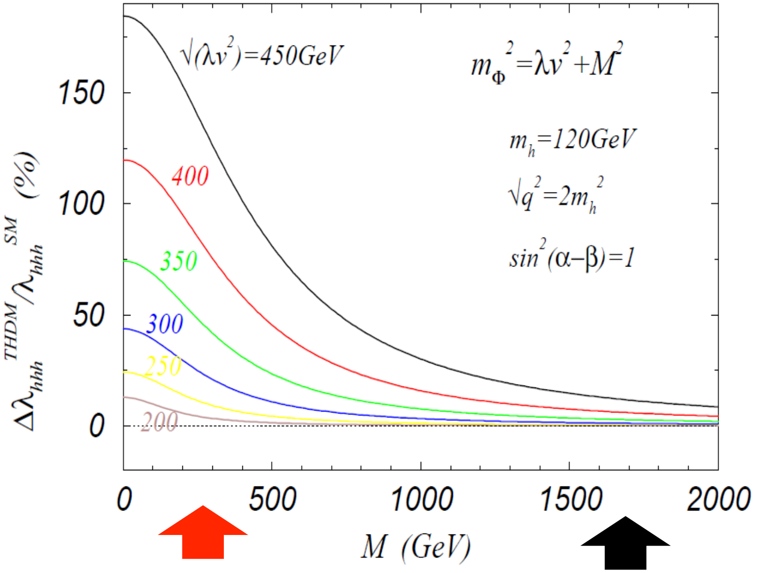
SK, Kiyoura, Okada, Senaha, Yuan, PLB558 (2003)

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

Extra scalar loop **Top loop**

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

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



Non-decoupling effect

Decoupling

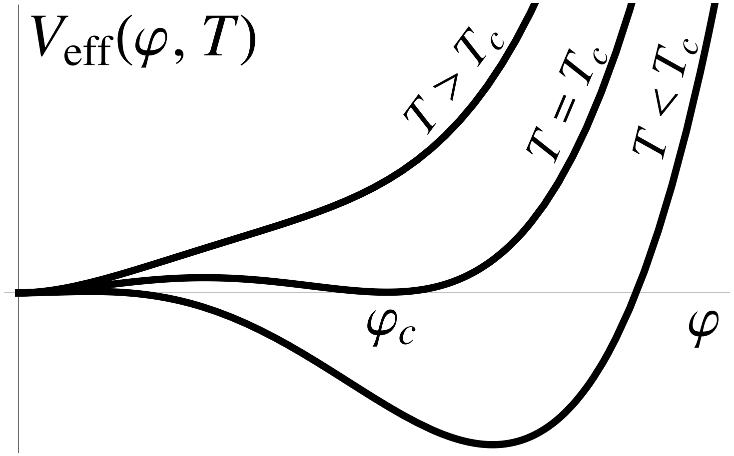
Correction can be huge ～ 100%

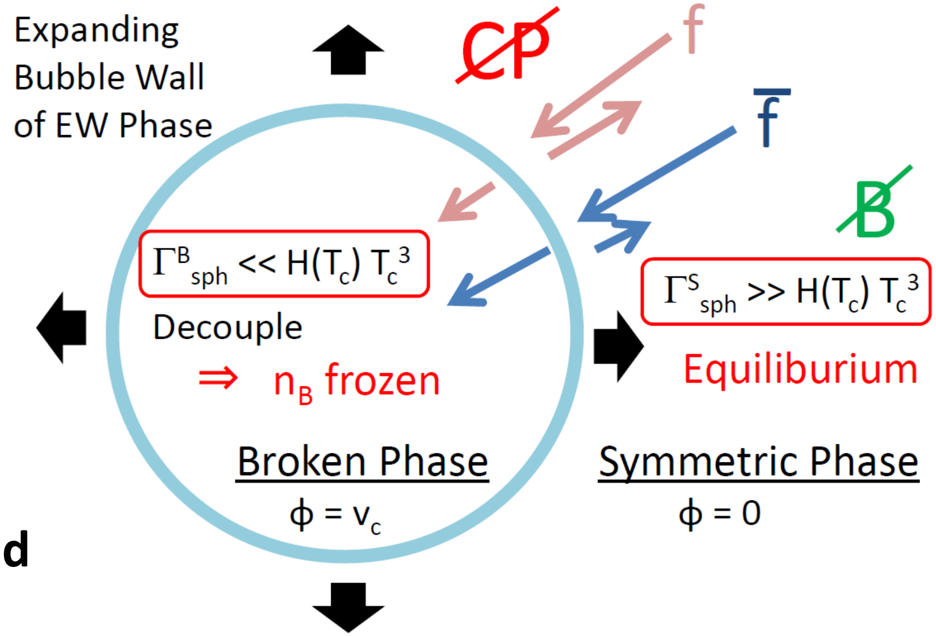
An example: EW Baryogenesis

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

Sakharov 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





Expanding Bubble Wall of EW Phase

$\cancel{CP}$

f

$\bar{f}$

$\cancel{B}$

$\Gamma^B_{\text{sph}} \ll H(T_c)\, T_c^3$

Decouple

⇒ n_B frozen

$\Gamma^S_{\text{sph}} \gg H(T_c)\, T_c^3$

Equiliburium

Broken Phase

$\phi = v_c$

Symmetric Phase

$\phi = 0$

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

(Sphaleron Rate) < (Expansion Rate) → $\boldsymbol{\varphi_c / T_c > 1}$

The SM cannot satisfy the condition

High Temperature Expansion (just for sketch)

$$V_{\text{eff}}(\varphi, T) \simeq D(T^2 - T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots$$

Condition of Strongly 1st OPT

$$\boxed{\frac{\varphi_C}{T_C} \simeq \frac{2E}{\lambda_{T_C}} > 1}$$

However, the SM cannot realize the strongly 1st OPT

$$E \simeq \frac{1}{12\pi v^3}\left(6m_W^3 + 3m_Z^3 + \cdots\right) \quad \lambda_{T_C} \sim \frac{m_h^2}{2v^2} + \cdots$$

$$\boxed{\frac{\varphi_C}{T_C} \simeq \frac{6m_W^3 + 3m_Z^3 + \cdots}{3\pi v m_h^2} \ll 1}$$

For m_h = 125 GeV

We need a mechanism to enlarge φ_c/T_c to realize strongly 1st OPT

1st OPT in extended Higgs sectors

High Temperature Expansion (just for sketch)

$$V_{\rm eff}(\varphi,T) \simeq D(T^2-T_0^2)\varphi^2 - ET\varphi^3 + \frac{\lambda_T}{4}\varphi^4 + \cdots$$

Condition of
Strongly 1st OPT

$$\boxed{\frac{\varphi_C}{T_C} \simeq \frac{2E}{\lambda_{T_C}} > 1}$$

The condition can be satisfied by thermal loop effects of additional scalar bosons Φ (Φ = *H*, *A*, *H*+, …) $m_\Phi^2 \simeq M^2 + \lambda_i v^2$

$$\frac{\varphi_C}{T_C} \simeq \frac{1}{3\pi v m_h^2}\left\{6m_W^3 + 3m_Z^3 + \underline{\sum_\Phi m_\Phi^3\left(1-\frac{M^2}{m_\Phi^2}\right)^3\left(1+\frac{3M^2}{2m_\Phi^2}\right)}\right\} > 1$$

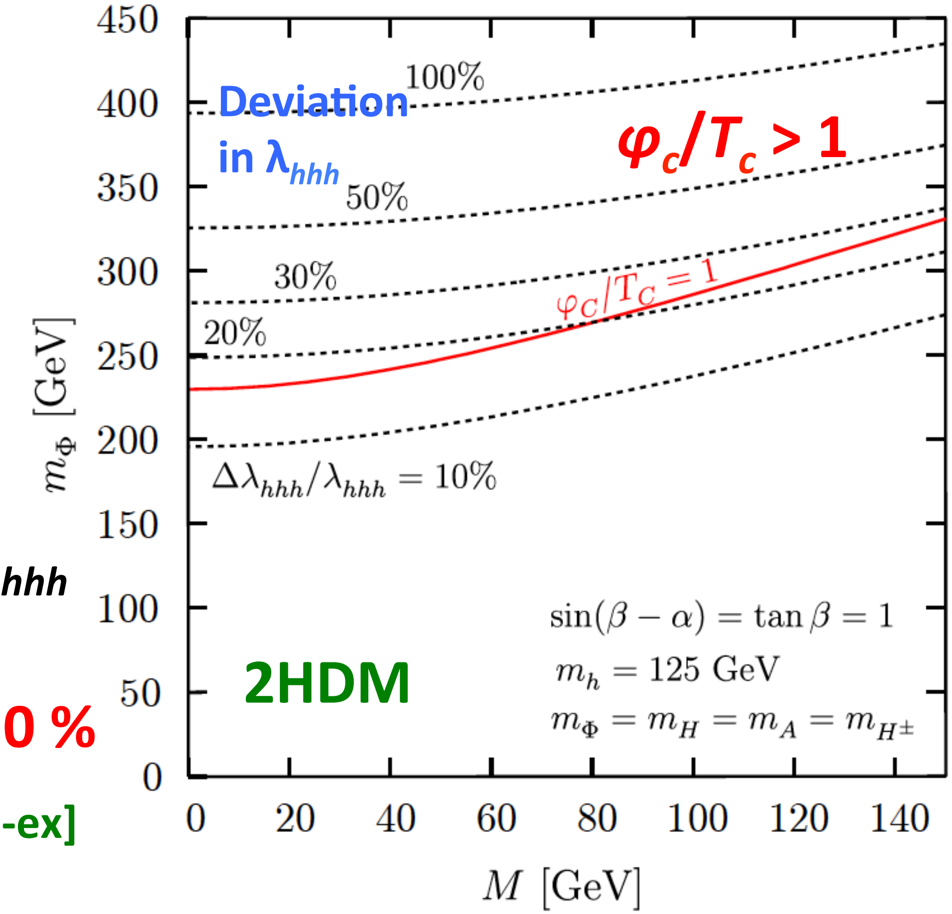
In this case, large quantum effects also appear in the *hhh* coupling

$$\lambda_{hhh} \simeq \frac{3m_h^2}{v^2}\left\{1 - \frac{m_t^4}{\pi^2 v^2 m_h^2} + \underline{\sum_\Phi \frac{m_\Phi^4}{12\pi^2 v^2 m_h^2}\left(1-\frac{M^2}{m_\Phi^2}\right)^3}\right\} > \lambda_{hhh}^{SM}$$

Strong 1^{st} OPT and the *hhh* coupling

SK, Y Okada, E Senaha (2005)

Strongly 1^{st} OPT
⇔ Non-decoupling effect
⇔ large deviation in *hhh*



At LHC, challenging to measure λ_{hhh}

ILC (1 TeV) can measure λ_{hhh} by 10 %

K.Fujii et al., arXiv:1506.05992 [hep-ex]

EW Baryogenesis can be tested at ILC!

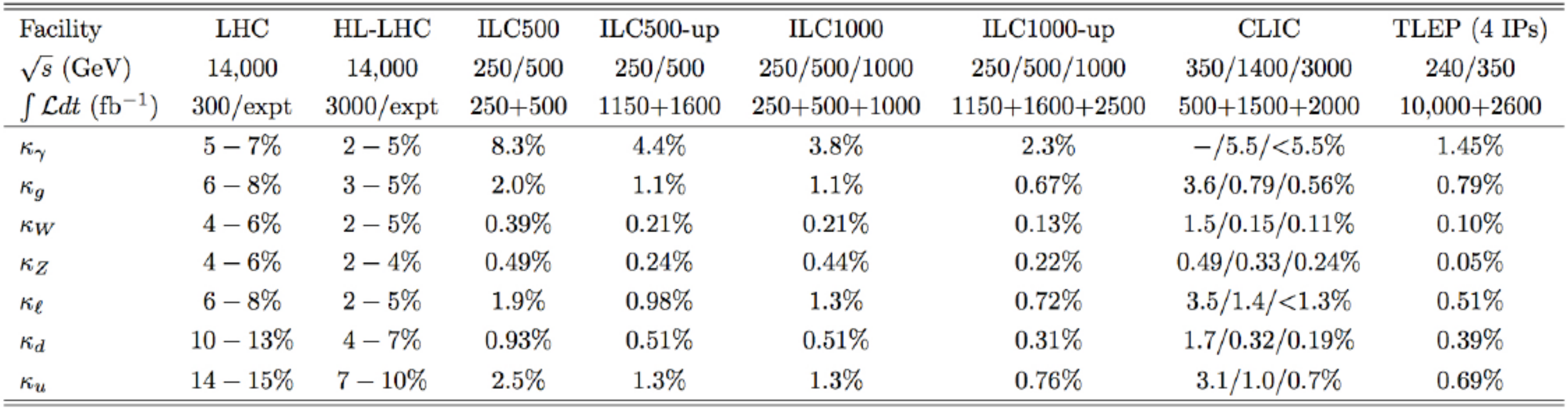
Summary

- Structure of the Higgs sector is directly connected to new physics
- Extended Higgs sectors can be tested directly by discovering the 2nd Higgs bosons, or indirectly by measuring the couplings of *h*(125).
- Detecting a pattern of deviations in the *h*(125) couplings, we can fingerprint the Higgs sector and further direction of new physics
- The *hhh* coupling is a window for Higgs potential

  Precision measurement of the *hhh* coupling can test 1st OPT, which is required for electroweak baryogenesis

Higgs sector is a good probe of new physics

Snowmass White Paper (Aug. 2013)

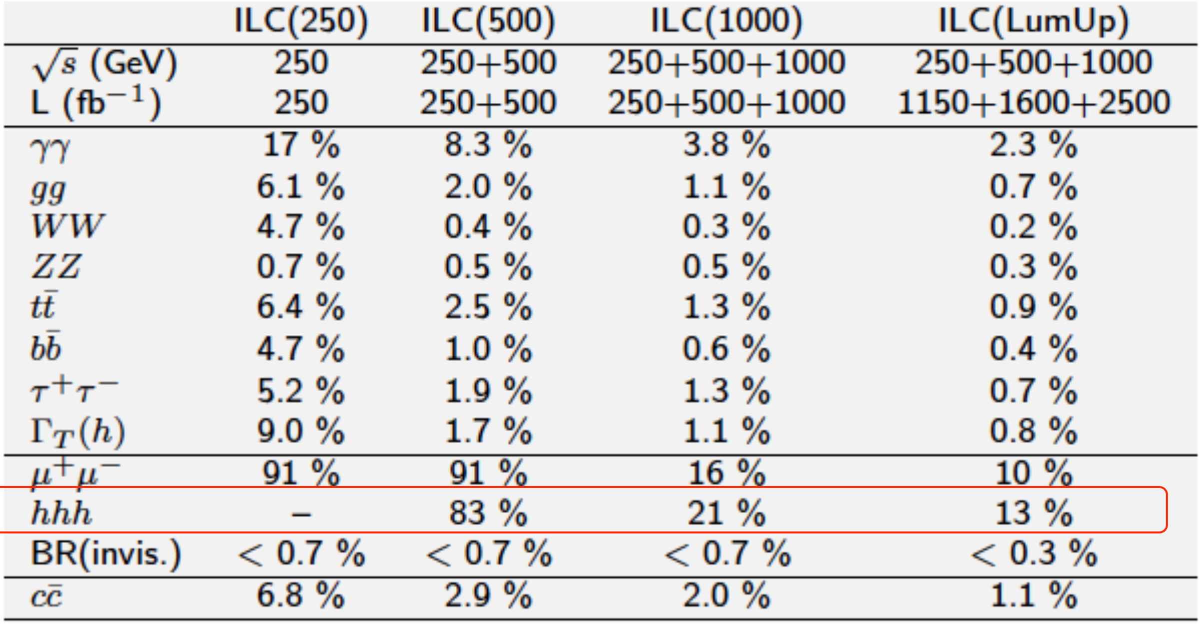


Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$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

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

ILC Higgs White Paper

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



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

$$
\begin{aligned}
-\mathcal{L}_Y^{\text{int}} = &\sum_{f=u,d,e} \frac{m_f}{v}\left[\xi_h^f \overline{f} f h + \xi_H^f \overline{f} f H - 2 i I_f \xi_f \overline{f} \gamma_5 f A\right] \\
&+ \frac{\sqrt{2}}{v}\left[V_{ud}\overline{u}\,(m_d \xi_d P_R - m_u \xi_u P_L)\, d\, H^+ + m_e \xi_e \overline{\nu} P_R e H^+ + \text{h.c.}\right]
\end{aligned}
$$

	ξ_h^u	ξ_h^d	ξ_h^ℓ	ξ_H^u	ξ_H^d	ξ_H^ℓ	ξ_A^u	ξ_A^d	ξ_A^ℓ
Type-I	c_α/s_β	c_α/s_β	c_α/s_β	s_α/s_β	s_α/s_β	s_α/s_β	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	c_α/s_β	$-s_\alpha/c_\beta$	$-s_\alpha/c_\beta$	s_α/s_β	c_α/c_β	c_α/c_β	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-X	c_α/s_β	c_α/s_β	$-s_\alpha/c_\beta$	s_α/s_β	s_α/s_β	c_α/c_β	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-Y	c_α/s_β	$-s_\alpha/c_\beta$	c_α/s_β	s_α/s_β	c_α/c_β	s_α/s_β	$\cot\beta$	$\tan\beta$	$-\cot\beta$

SM limit

$$
\left.\begin{aligned}
\cos\alpha/\sin\beta &= \sin(\beta-\alpha) + \cos(\beta-\alpha)\cot\beta \\
-\sin\alpha/\cos\beta &= \sin(\beta-\alpha) - \cos(\beta-\alpha)\tan\beta
\end{aligned}\right\} \quad 1
$$

$$
\begin{aligned}
\sin\alpha/\sin\beta &= \cos(\beta-\alpha) - \sin(\beta-\alpha)\cot\beta \longrightarrow -\cot\beta \\
\cos\alpha/\cos\beta &= \cos(\beta-\alpha) + \sin(\beta-\alpha)\tan\beta \longrightarrow +\tan\beta
\end{aligned}
$$

Higgs Sector

Mass Generation mechanisms

Higgs Mechanism

hWW

hZZ

Yukawa Interaction

$h\tau\tau$, hbb

htt, …

Dim 6 Operators

hgg

$H\gamma\gamma$, $hZ\gamma$

$$L_{eff} = |D_\mu \Phi|^2 - y\, L\Phi R - 1/v^2\, |\Phi|^2 GG$$

Flavor Structure

New particle effect
in the loop

$$- V_{eff}(\Phi)$$

EW Symmetry Breaking

hhh, $hhhh$

Multiplet structure
Physics behind EWSB
Essence of Higgs boson

Higgs Sector

Mass Generation mechanisms

Higgs Mechanism

hWW

hZZ

Yukawa Interaction

$h\tau\tau$, hbb

htt, …

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Flavor Structure

New particle effect in the loop

$$-\, V_{eff}(\Phi)$$

EW Symmetry Breaking

hhh, $hhhh$

Multiplet structure
Physics behind EWSB
Essence of Higgs boson

Being measured at LHC, Deviation pattern corresponds to each model

Higgs Sector

Mass Generation mechanisms

Higgs Mechanism

hWW
hZZ

Yukawa Interaction

$h\tau\tau$, hbb
htt, …

Dim 6 Operators

hgg
$H\gamma\gamma$, $hZ\gamma$

$$L_{eff} = |D_\mu \Phi|^2 - y\, L\Phi R \;-\; 1/v^2\, |\Phi|^2 GG$$

Flavor Structure

New particle effect
in the loop

$$-\, V_{eff}(\Phi)$$

EW Symmetry Breaking

hhh, $hhhh$

Multiplet structure
Physics behind EWSB
Essence of Higgs boson

Little is known about the Higgs potential

GW : another probe of 1st OPT?

Gravitational Wave Experiments

aLIGO (USA), KAGRA (JPN), aVIRGO (ITA), …

- Trial for first discovery of GWs (Recently LIGO did make it!)
- GWs from astronomical phenomena (binary of NSs, BHs, …)

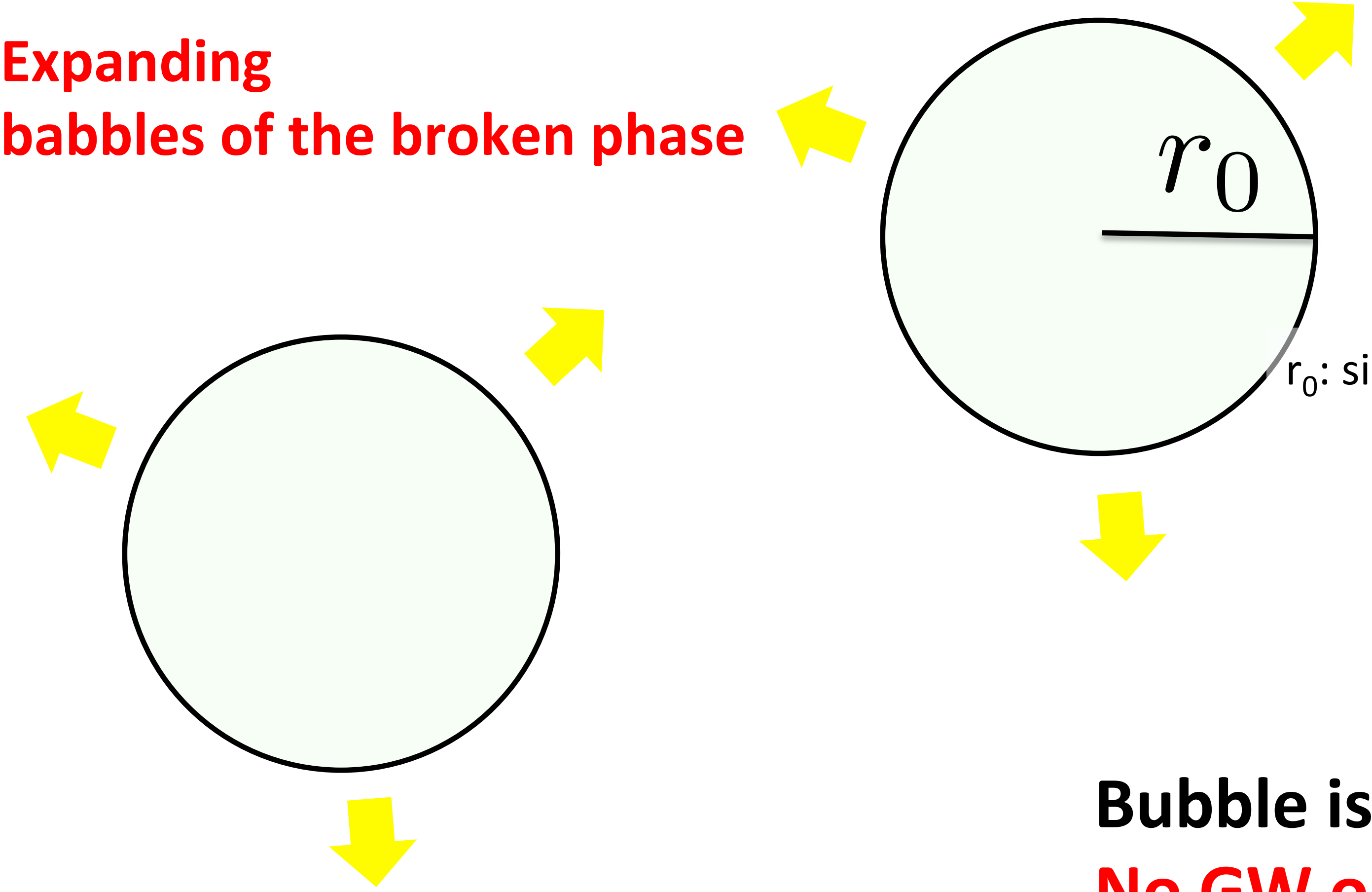
New era of GW astronomy has come ture!

Future exp: eLISA [EUR], DECIGO [JPN], …

- GWs from early Universe (Inflation, 1st OPT, …)

GWs may be used for exploration of the Higgs potential, as a complementary mean with collider experiments.

Origin of GWs from 1st OPT



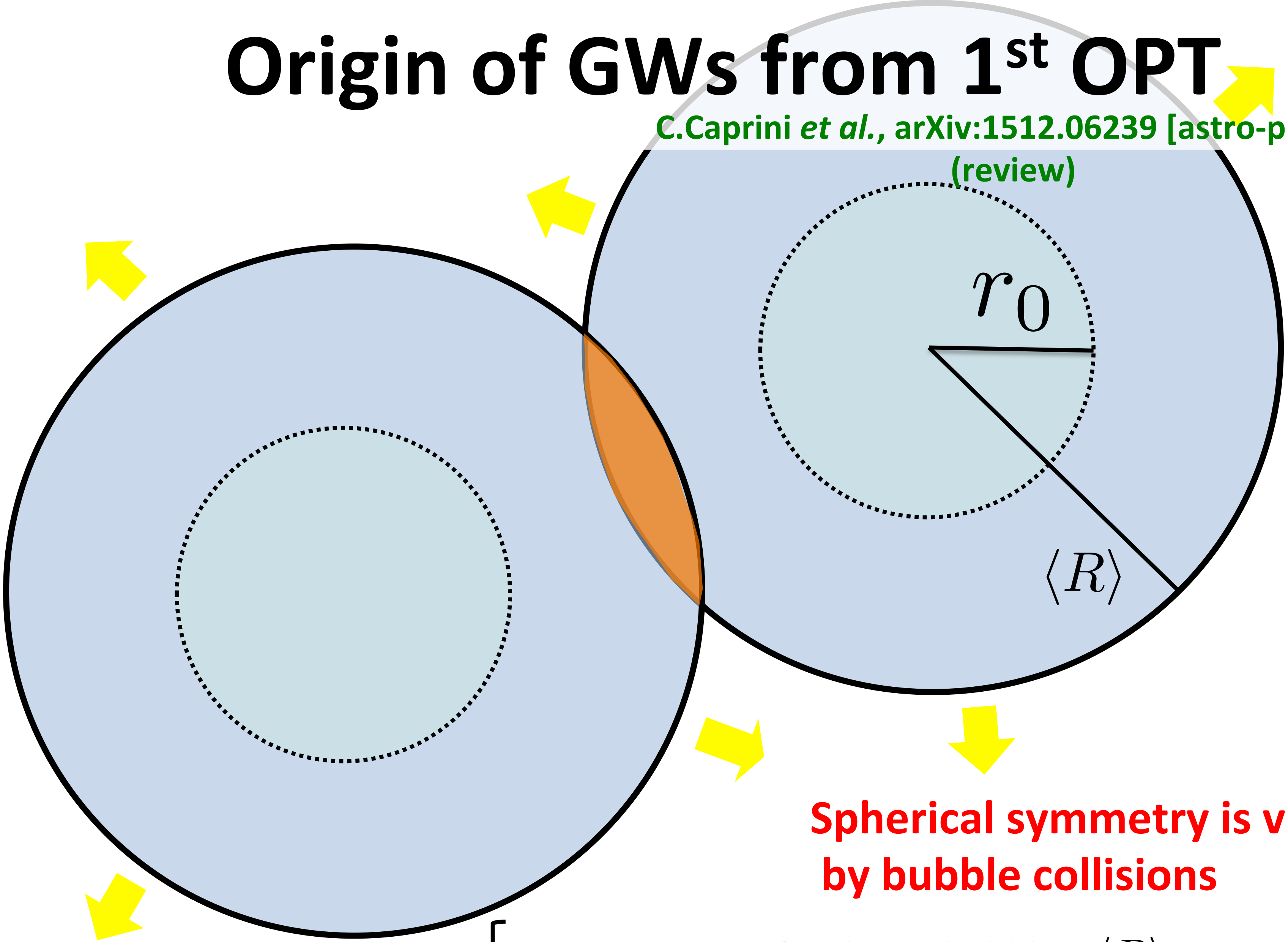
Expanding
babbles of the broken phase

r_0: size of critical bubble

Bubble is spherical
No GW occurs

Origin of GWs from 1st OPT

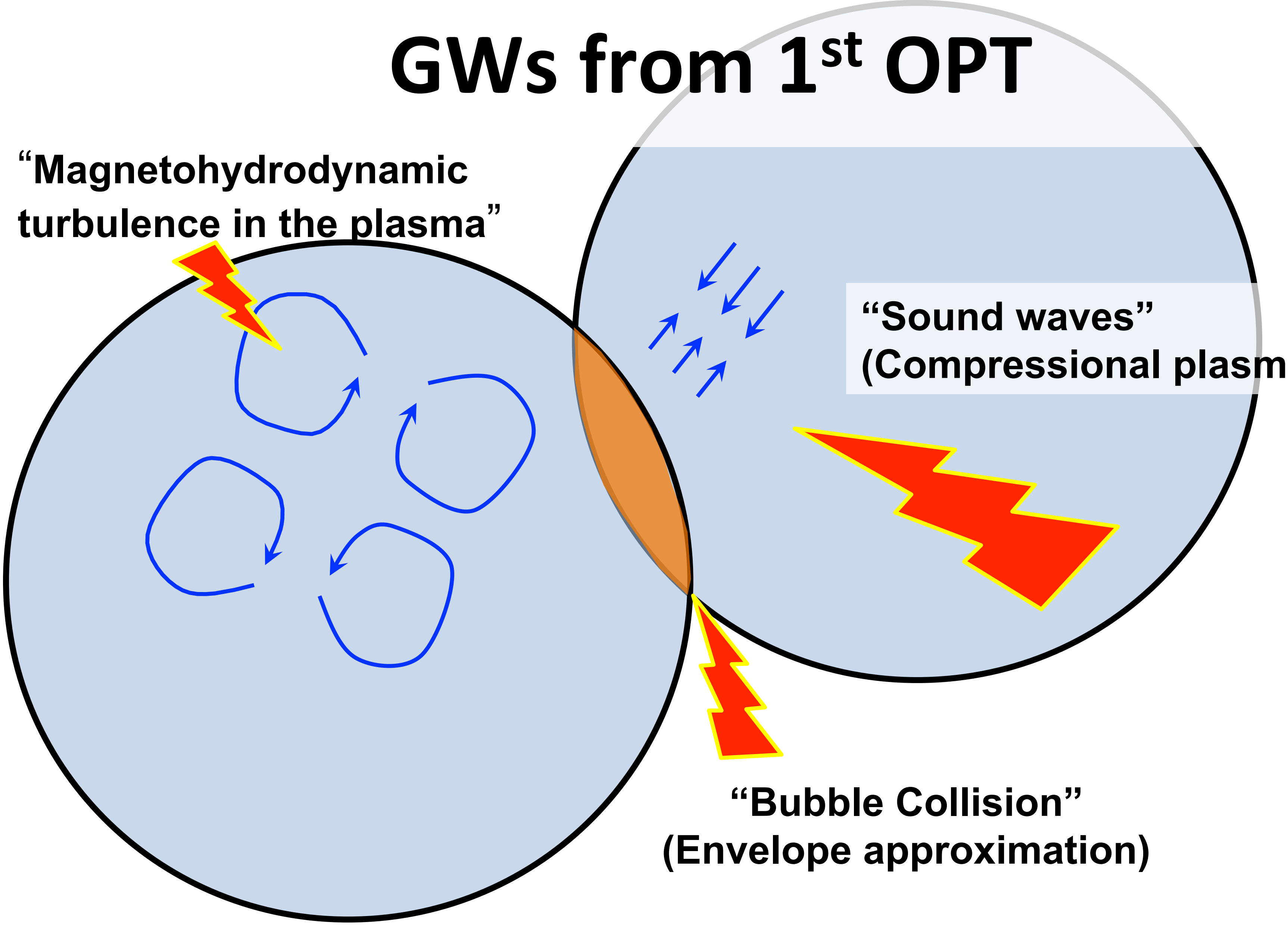
C.Caprini *et al.*, arXiv:1512.06239 [astro-ph.CO] (review)



Spherical symmetry is violated by bubble collisions

- Typical radius of colliding bubbles: $\langle R \rangle \propto v_b \tau$
- Transition time: $\tau \simeq \beta^{-1}$

GWs from 1^{st} OPT



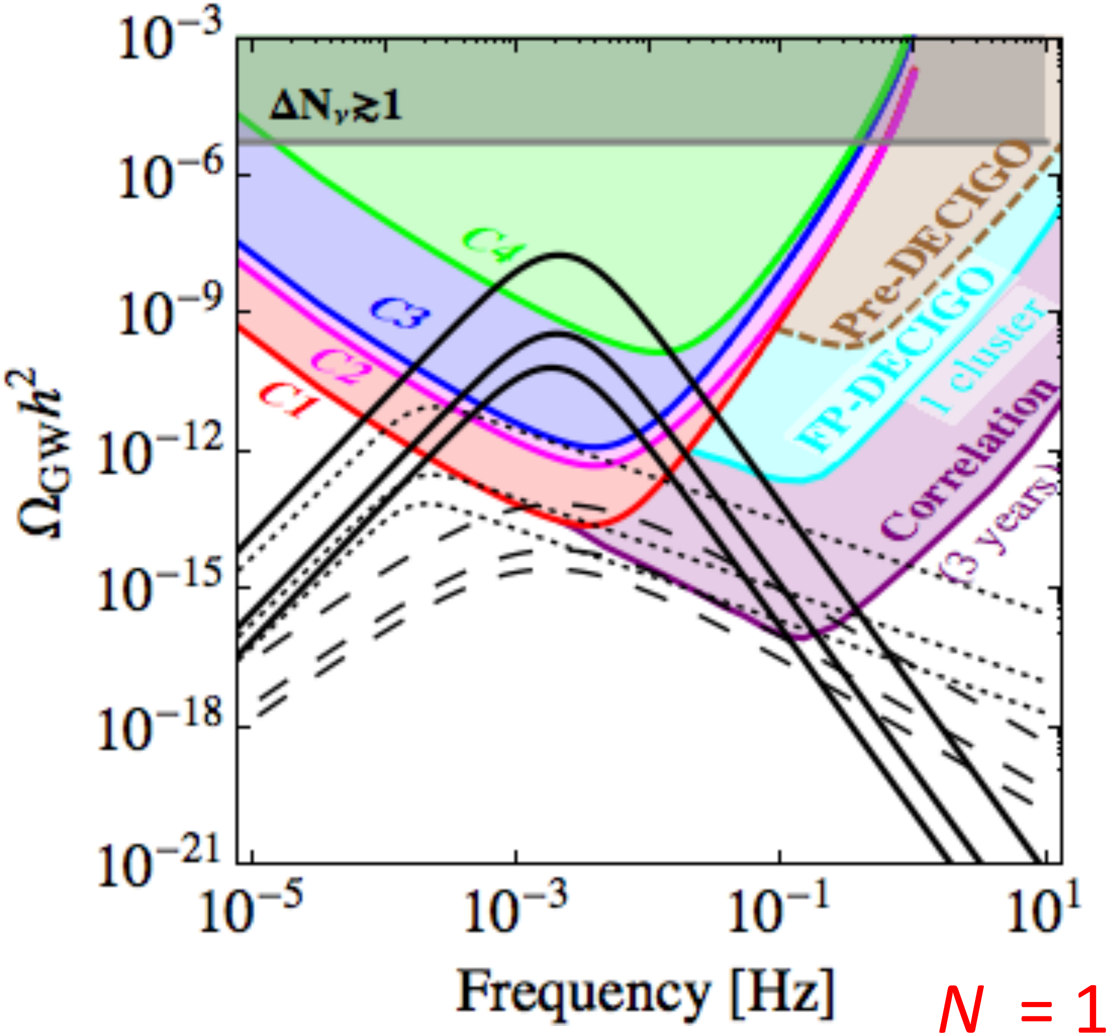
“Magnetohydrodynamic turbulence in the plasma”

“Sound waves”
(Compressional plasma)

“Bubble Collision”
(Envelope approximation)

C.Caprini *et al.*, arXiv:1512.06239

GW spectrum from 1^{st} OPT



Sensitivities

eLISA
arXiv:1512.06239

DECIGO,
Class. Quant. Grav.
28, 094011 (2011)

$N = 1, 4, 60$

M.Kakizaki, S.Kanemura, T.Matsui, arXiv:1509.08394 [hep-ph]

LHC current data of *h*(125) couplings

Data at LHC ($\sqrt{s}$ = 7 and 8 TeV)

ATLAS-CONF-2014-009, 1412.8662

$$\kappa_V = 1.15 \pm 0.08, \quad \kappa_F = 0.99^{+0.08}_{-0.15}, \quad \text{ATLAS}$$

$$\kappa_V = 1.01 \pm 0.07, \quad \kappa_F = 0.87^{+0.14}_{-0.13}, \quad \text{CMS}$$

(Assumption; $\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$, $\kappa_V = \kappa_Z = \kappa_W$)

$$\kappa_g = 1.08^{+0.15}_{-0.13}, \quad \kappa_\gamma = 1.19^{+0.15}_{-0.12}, \quad \text{ATLAS}$$

$$\kappa_g = 0.89^{+0.11}_{-0.10}, \quad \kappa_\gamma = 1.14^{+0.12}_{-0.13}, \quad \text{CMS}$$

(Assumption; $\kappa_F = \kappa_V$)

Scaling factors are in agreement with those of the SM within the 2-sigma uncertainties of the current data.

Fingerprinting the 2HDM (tree level)

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

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

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

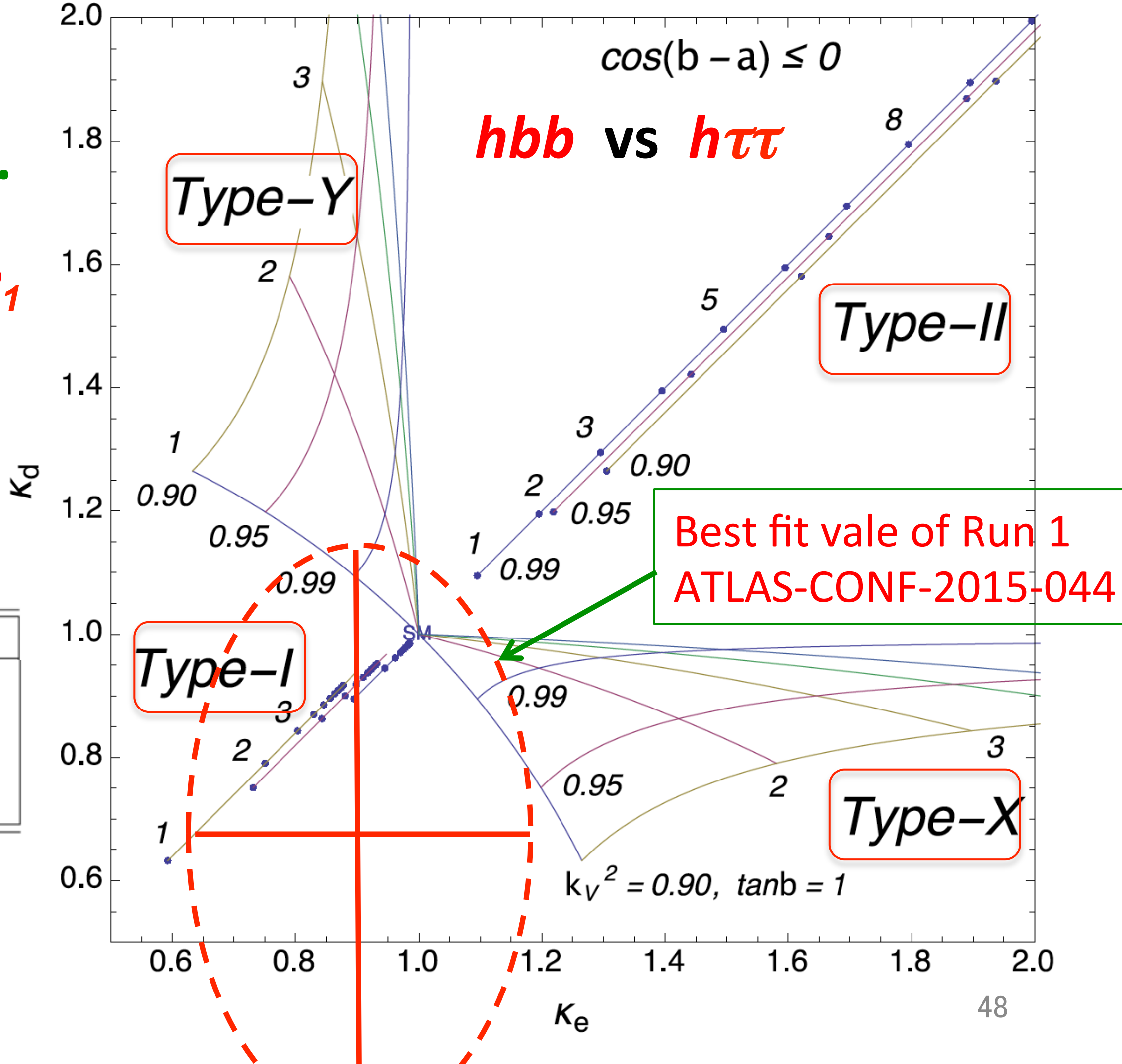
When a fermion couples to Φ_1

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

and if it couples to Φ_2

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

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



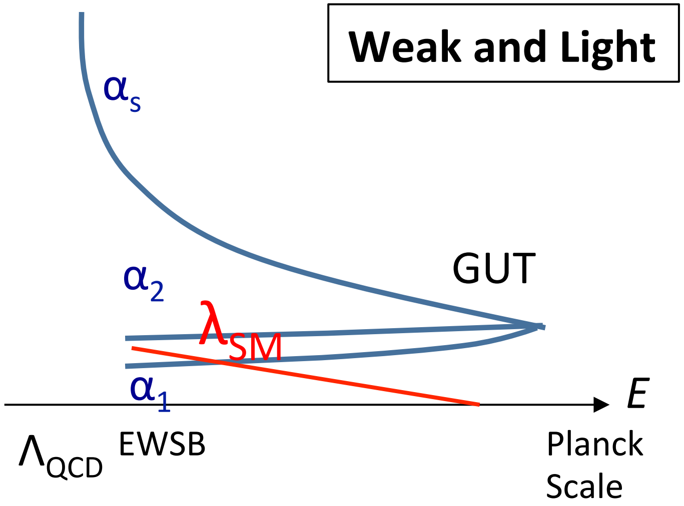
Best fit vale of Run 1 ATLAS-CONF-2015-044

How do this result change with radiative corrections?

Dynamics behind the 125 GeV Higgs

- **Weak and Light Scenario**
  - Perturbative
  - Grand Desert
  - Traditional Grand Unification

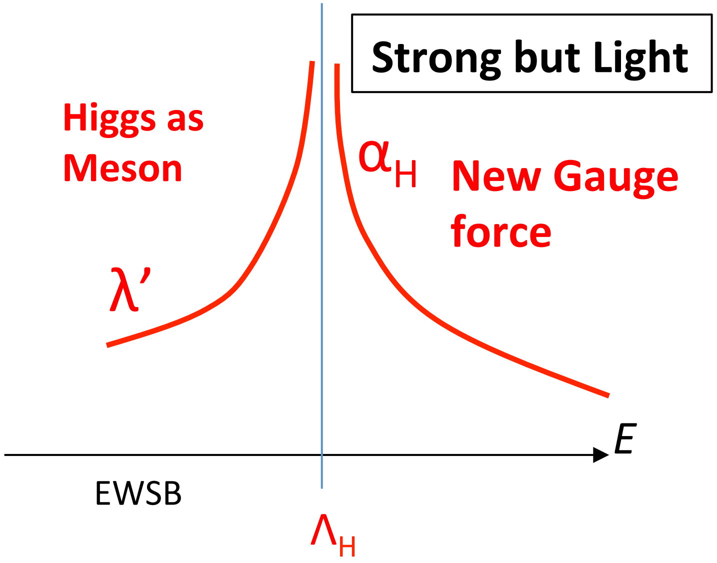
$$m_h^2 \propto \lambda v^2$$



- **Strong but Light Scenario**

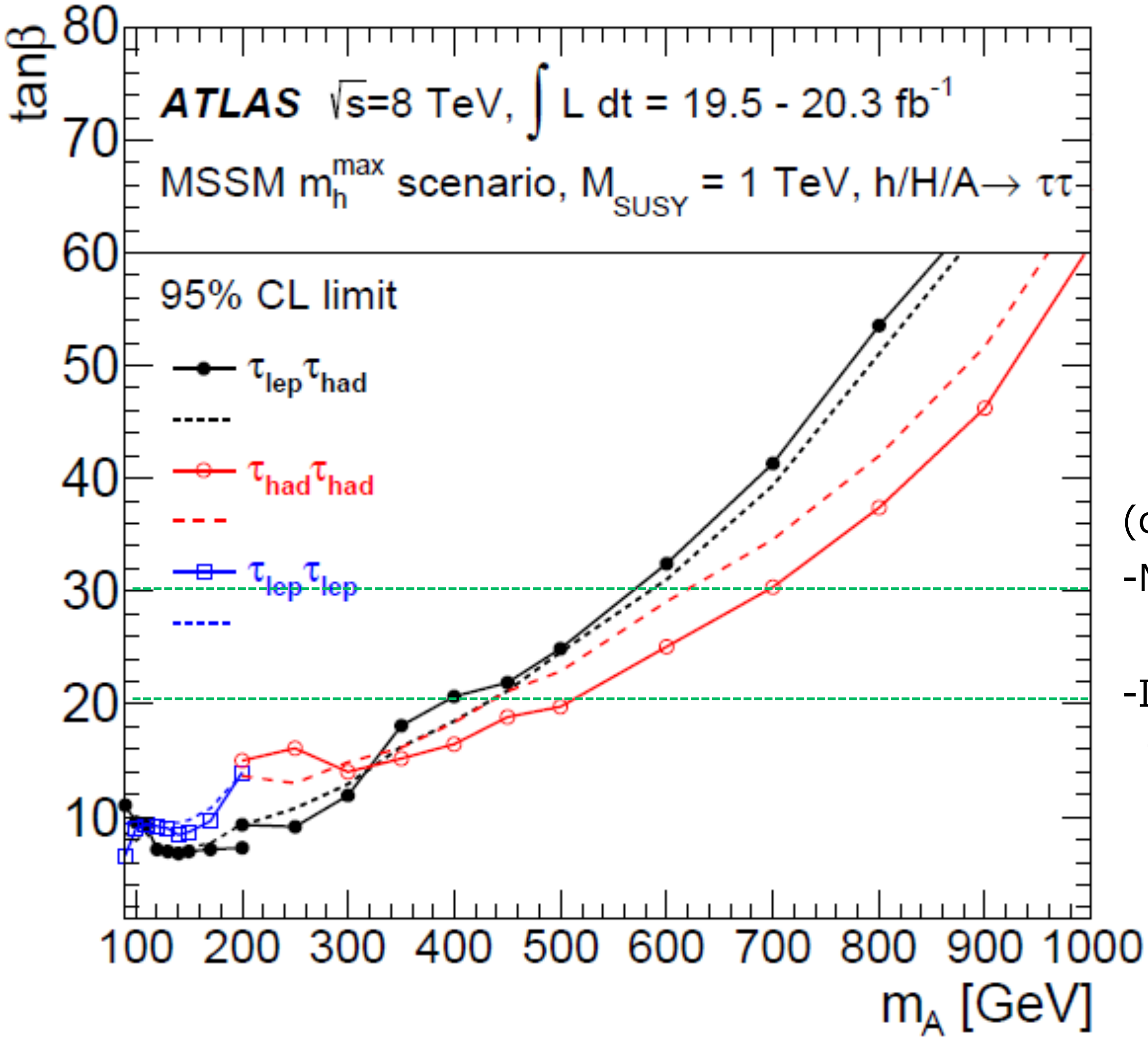
$$m_h^2 \propto \frac{\lambda'^2}{(4\pi)^2} v^2$$

  - IR theory:
    Higgs as a composite field
    Landau pole at Λ_H
  - UV theory:
    A new gauge symmetry with confinement at Λ_H



Excluded parameter region (Current)

ATLAS, 1409.6064



(c.f.) H^+ search (1412.6663)

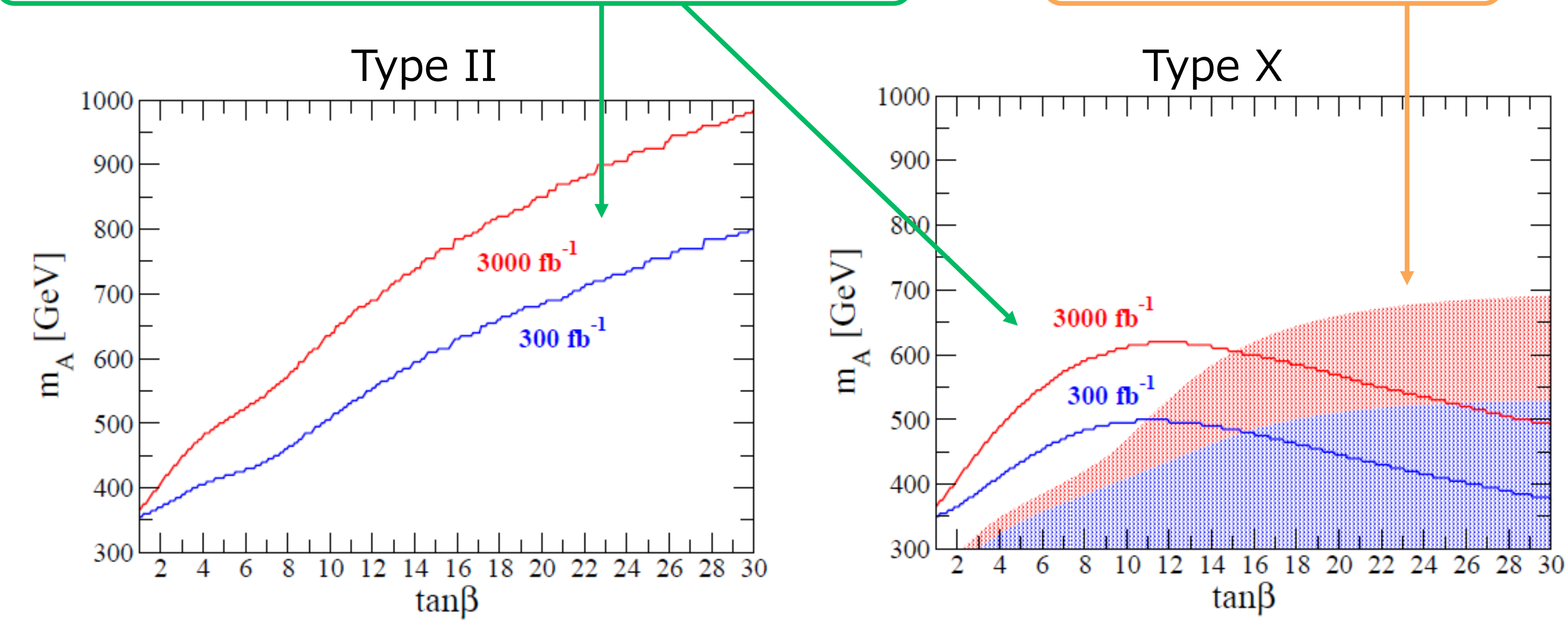
-Most of the parameter space is excluded in the case of mH+ < mt.

-In mH+ = 200 GeV , tanβ > 50 is excluded at 95% CL.

重いヒッグスの直接探索

$gg \to H/A \to \tau^+\tau^-$ + $gg \to b\bar{b}H/A \to b\bar{b}\tau^+\tau^-$

$q\bar{q} \to HA \to 4\tau$

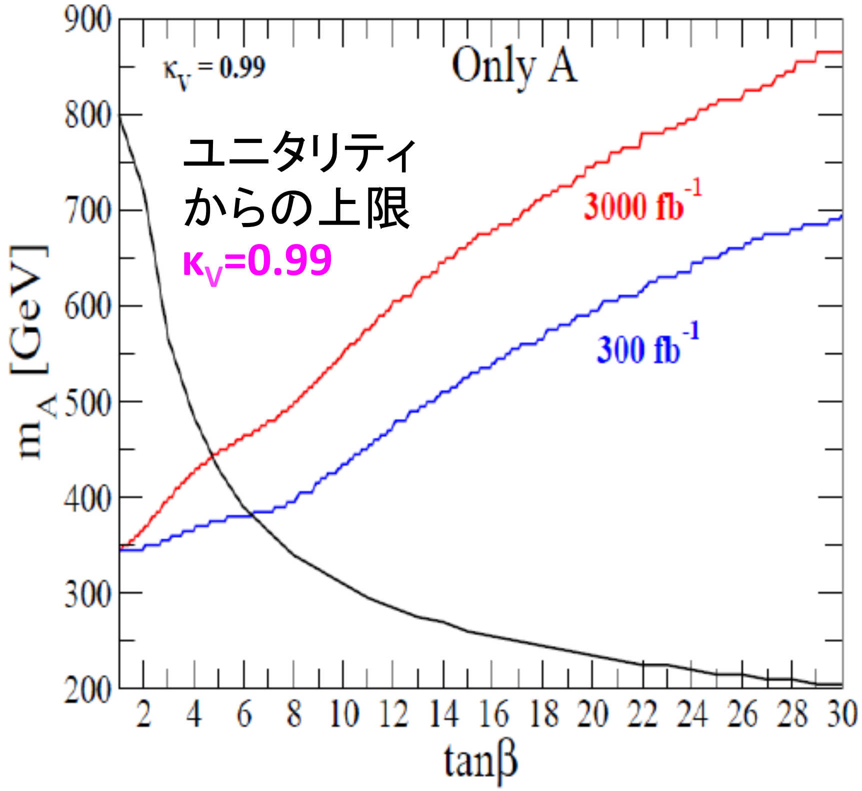


SK, Tsumura, Yagyu, Yokoya, PRD90 (2014)

- ・グルオン融合生成からのタウ対とボトム随伴生成からのタウ対による探索領域
- ・Type−X では, 対生成 HA からの 4タウの過程が大きなtan β でより強く探索できる .

第2ヒッグスの直接/間接探索領域

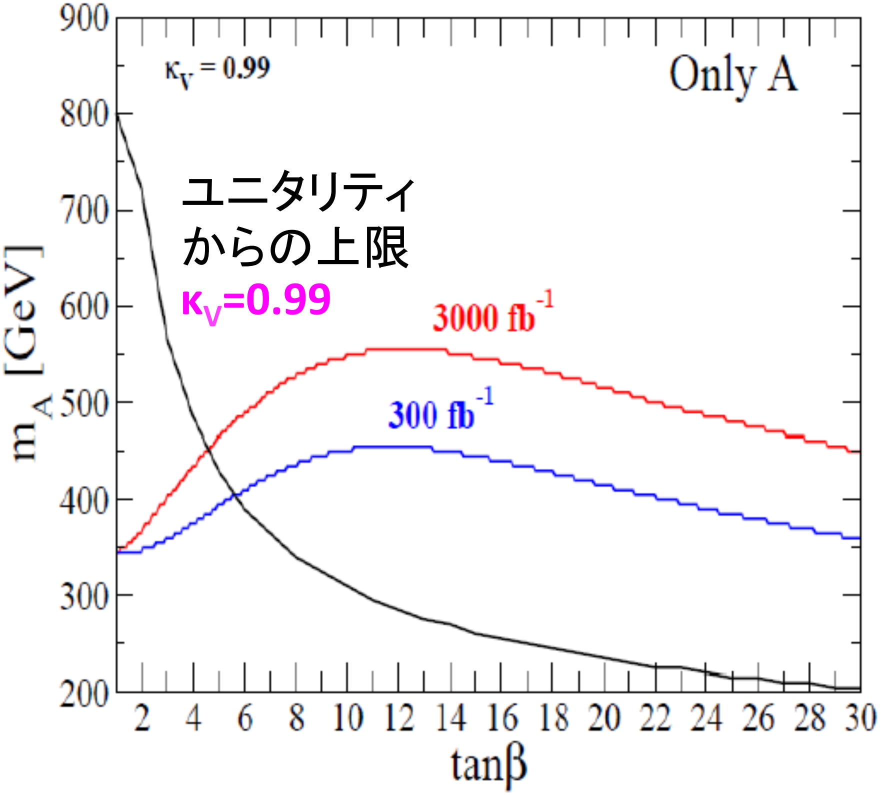
Type II



ユニタリティからの上限

κ_V=0.99

Type X



ユニタリティからの上限

κ_V=0.99

直接探索で見つけられない場合でも、*h*(125)の湯川結合の測定でκ_Vのずれを検出することで第2のヒッグス粒子を間接的に発見できる