Higgs Precision (Multi-Higgs Sector) at the ILC

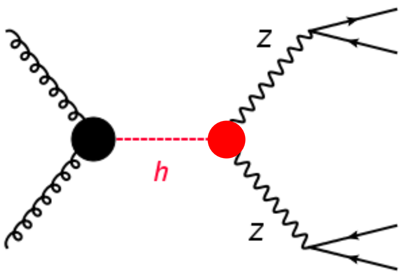
Kei Yagyu（Osaka U）

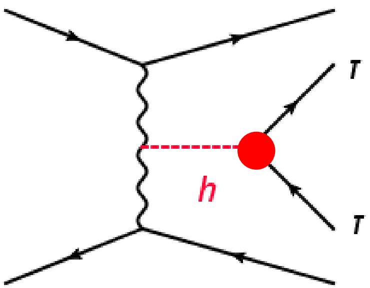
HPNP2019 (ILC Symposium)

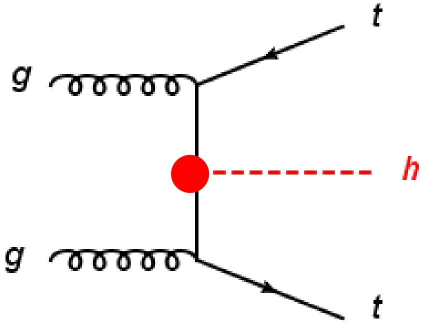
2019, Feb. 18th, Osaka U

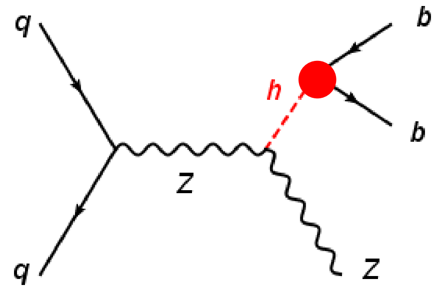
Introduction

- After LHC Run-II: we have measured







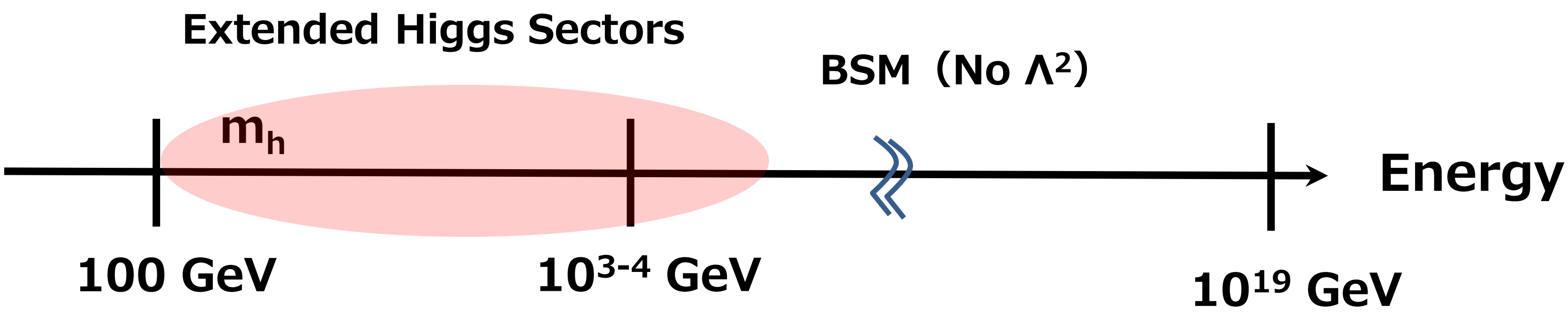


$$\left|(\partial_\mu - ig\frac{\sigma^a}{2}W^a_\mu)\Phi\right|^2 \qquad y_t\bar{Q}_L\tilde{\Phi}t_R + y_b\bar{Q}_L\Phi b_R + y_\tau\bar{L}_L\Phi\tau_R$$

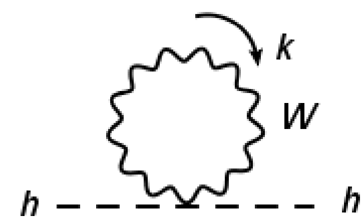
- No new particle has been observed yet.

Is the SM enough? **Definitely No!**

Nature of the Higgs



$$(125\ \mathrm{GeV})^2 \sim (m_h^0)^2 + \frac{\Lambda^2}{16\pi^2} - \delta m_h^2$$



- ☐ Nature of the Higgs boson → New physics beyond the SM

Higgs is a

- Scalar boson (Supersymmetry) : Chiral Symmetry
- Fermion (Compositeness) : Chiral Symmetry
- Gauge boson (Gauge-Higgs Unification): Gauge Symmetry

BSM Phenomena

- BSM phenomena → New physics beyond the SM

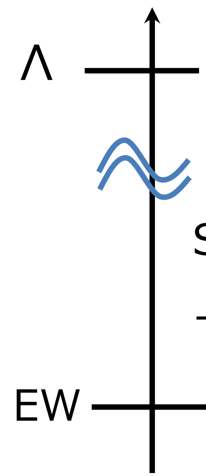
Neutrino masses	Radiative seesaw models (Loop level ν mass gen.)
Dark matter	Inert models (Higgs sector with an unbroken parity)
Baryon asymmetry	EWBG (CPV and strong 1^{st} order phase transition)

Studying the **H**iggs sector is a **P**robe of **N**ew **P**hysics

Bottom-Up Approach

Effective Field Theory

(Tian’s talk)



SM particles

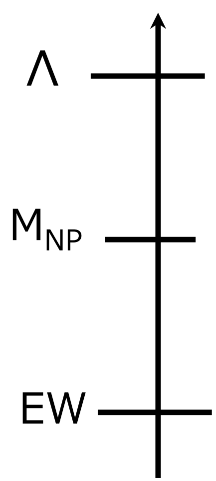
+ High order OP.

☺ Generic

☹ No relation to M_{NP}

Renormalizable Models

(Multi-Higgs fields)



SM particles

+ $H^{\pm}$, A, H, ⋯

☺ Connection to M_{NP}

☹ Model dependent

Basic Constraints

1. Electroweak ρ parameter: $\rho_{exp} = 1.00039 \pm 0.000019$ *PDG*

Introduction of **higher isospin Higgs fields** is constrained.

$$\rho_{\text{tree}} = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{\sum_j v_j^2 [T_j(T_j+1) - Y_j^2]}{\sum_i 2Y_i^2 v_i^2}$$

T: Isospin, Y: Hypercharge,

v: VEV

→ Φ + singlets + doublets (+ inert fields)

There are models with $\rho_{\text{tree}} = 1$ containing higher isospin Higgs fields.

2. Flavor Changing Neutral Currents (FCNC)

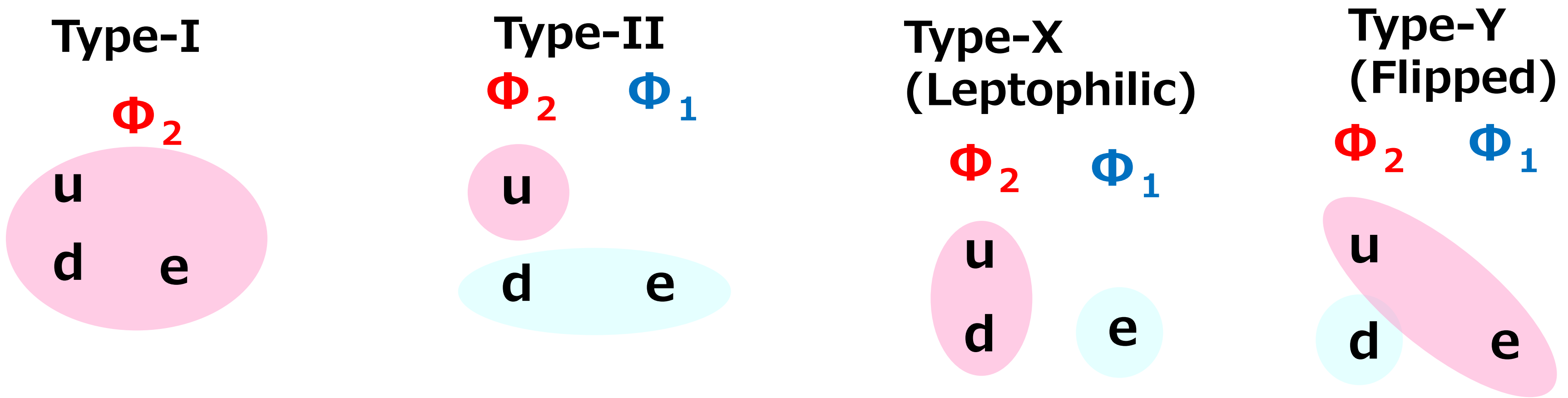
Introduction of **multi-doublet structure** is constrained.

→ Multi-doublet with Natural Flavor Conservation (NFC)

2 Higgs doublet models with NFC

- Four possibilities (types) of the 2HDM with NFC

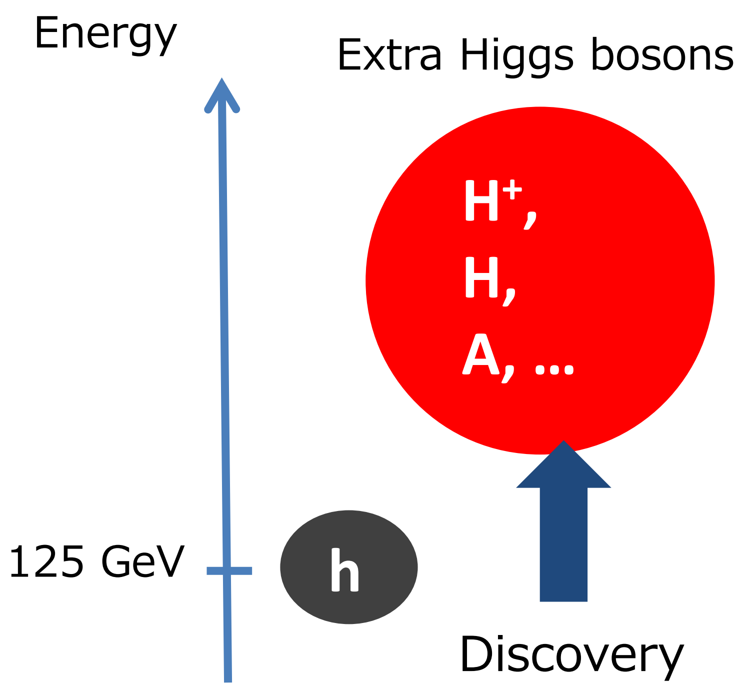
Barger, Hewett, Phillips, PRD41 (1990);
Grossman, NPB426 (1994);
Aoki, Kanemura, Tsumura, Yagyu, PRD80 (2009)



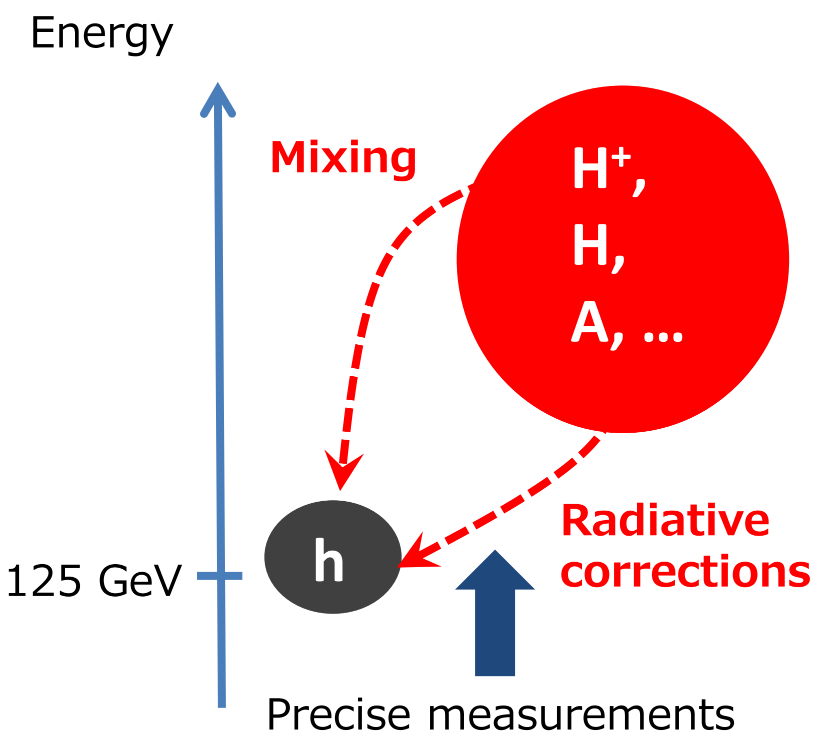
In my talk, I mainly focus on the 2HDMs (4 types) as the representative multi-Higgs model.

How to test the multi Higgs models

1．Direct search



2．Indirect search

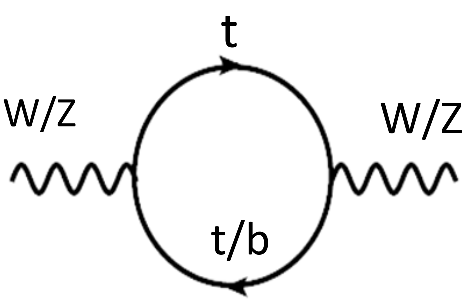


Synergy of two searches is important.

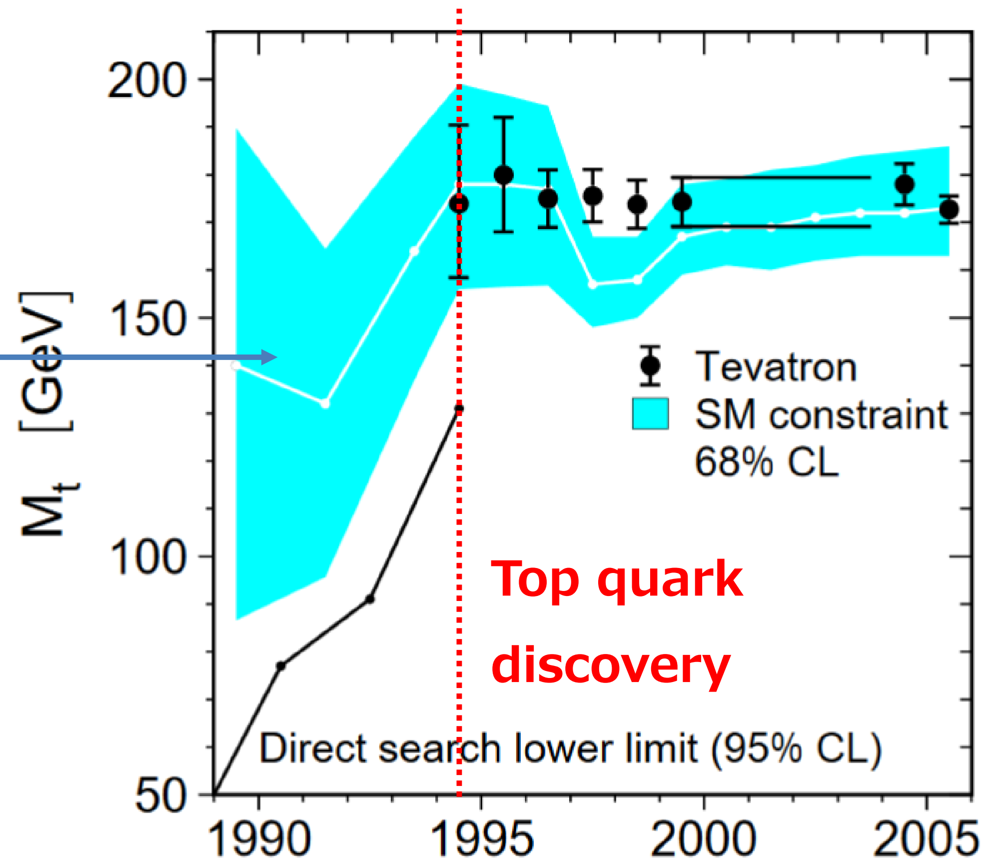
Backing to 90's

LEP Working Group, Phys. Rept. 427, 257 (2006)

Indirect search by LEP



$$\rho - 1 \sim \frac{3g^2}{32\pi^2}\frac{m_t^2}{m_W^2}$$



Precision physics has already **"known"** the top mass before the discovery!!

We can do it for the Higgs physics.

Indirect Search = Higgs Precision Physics

HL-LHC, ILC, ···

Loop level calculation

Precise measurements/calculations of h(125) properties
(couplings, width, BRs, cross sections, ···)

When deviations are found

We can extract

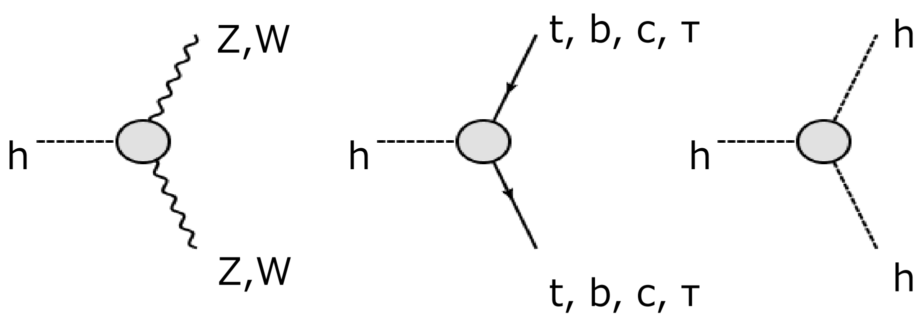
2nd Higgs mass scale and Higgs structure!!

"No-Loose Theorem" of the Higgs Physics

Higgs Couplings at 1-loop Level

Kanemura, Kikuchi, Sakurai, KY, Comp. Phys. Comm. 233, 134-144 (2018)

- H-COUP: A fortran90 code to calculate 1-loop corrected h(125) couplings based on the on-shell renormalization scheme



✓ UV finiteness

✓ IR finiteness

✓ Gauge invariance

Aoki, Kanemura, Kikuchi , KY, PRD87 (2013)

Chiang, Kuo, KY, PRD98 (2018)

H-COUP_v1

- Models

SM: Φ

Higgs Singlet Model: Φ S

2 Higgs Doublet Models: Φ Φ′

Triplet Models: Φ Δ

Fleischer, Jegerlehner, PRD23 (1981)

Kniehl, Phys. Rept. 240 (1994)

Kanemura, Kikuchi, KY, NPB907 (2016)

Kanemura, Kikuchi, KY, NPB917 (2017)

Kanemura, Okada, Senaha, Yuan, PRD70 (2004)

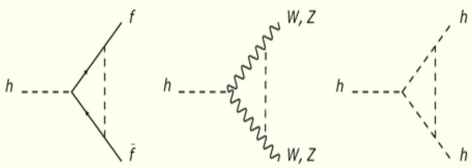
Kanemura, Kikuchi, KY, NPB896 (2015)

Krause, Lorenz, Santos, Muhlleitner, Ziesche, JHEP1609 (2016)

H-COUP

Kanemura, Kikuchi, Sakurai, KY, Comp. Phys. Comm. 233, 134-144 (2018)

H-COUP



H-COUP is a calculation tool composed of a set of Fortran codes to compute the renormalized Higgs boson couplings with radiative corrections in various non-minimal Higgs models, such as the Higgs singlet model, four types of two Higgs doublet models and the inert doublet model. The impolved on-shell renormalization scheme is adopted, where the gauge depdence is eliminated.

Authors: Shinya Kanemura, Mariko Kikuchi, Kodai Sakurai and Kei Yagyu

The manual for H-COUP version 1.0 can be taken on arXiv:1710.04603 [hep-ph].

Downloads

- H-COUP version 1.0 : [HCOUP-1.0.zip] [The manual is here]

For details, please see Sakurai's poster on Thursday.

Synergy b/w Direct & Indirect Searches

$m_\Phi = m_{H+} = m_A = m_H$

Type-I 2HDM

Expected exclusion by LHC 14TeV, 3000/fb

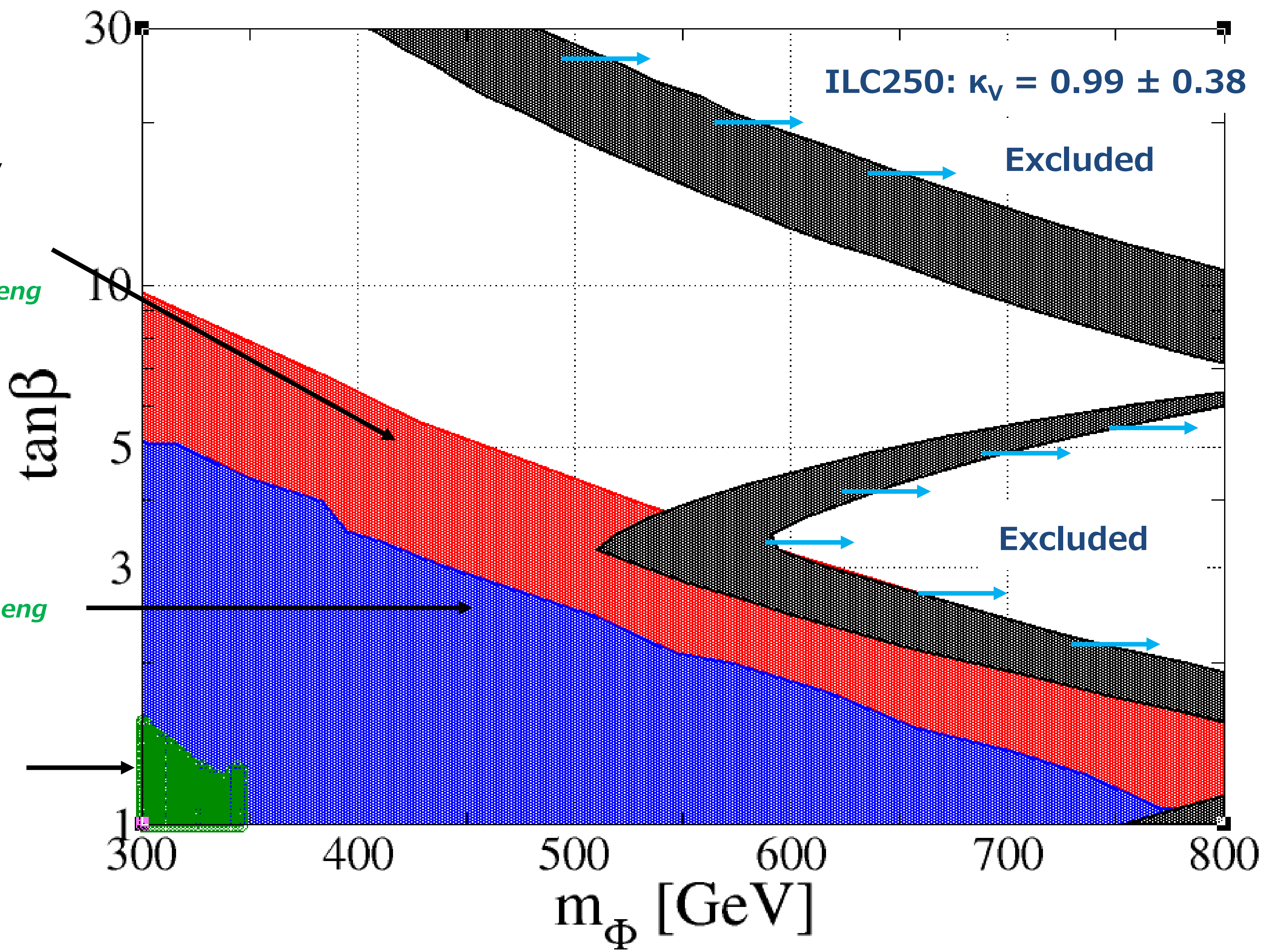
Kanemura, Yokoya, Zheng NPB886, 524 (2014)

Expected exclusion by LHC 14TeV, 300/fb

Kanemura, Yokoya, Zheng NPB886, 524 (2014)

Excluded by current LHC data

Higgs-Bounds 5



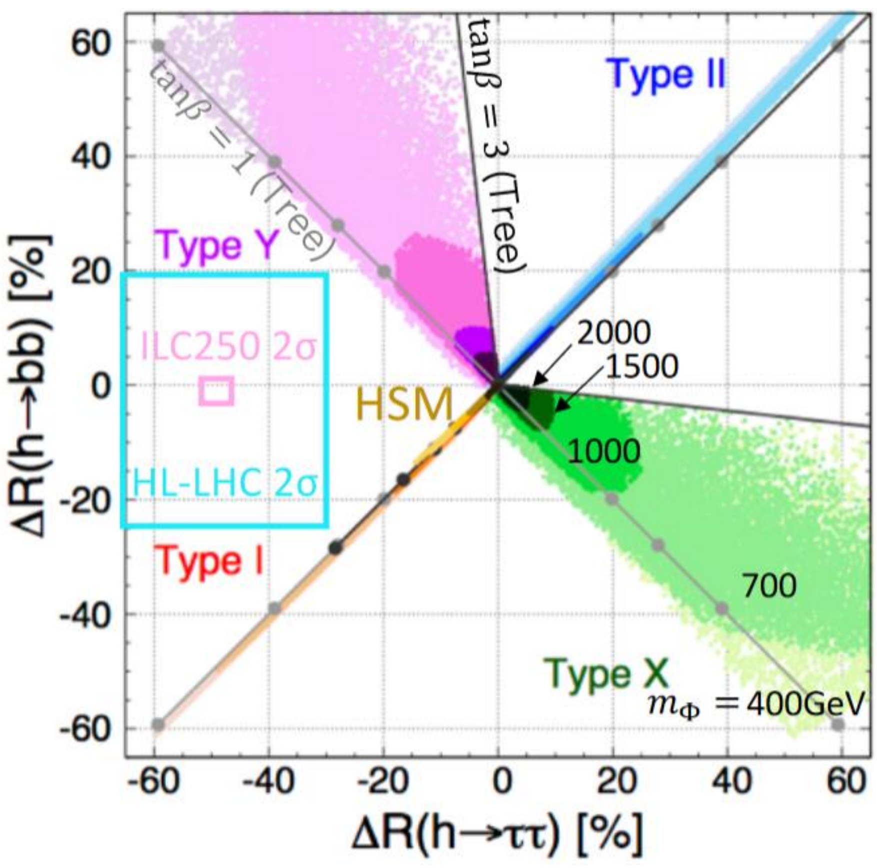
Fingerprinting the Higgs Sector at NLO

Kanemura, Kikuchi, Sakurai, Mawatari, KY, PLB783, 140 (2018)

$$\Delta R(h \to XX) = \frac{\Gamma(h \to XX)_{\mathrm{NP}}}{\Gamma(h \to XX)_{\mathrm{SM}}}$$

Accuracies at the HL-LHC and ILC250 :
Fujii et al, 1710.07621 [hep-ph]

cos(β-α) < 0



HL-LHC: **O(10)%** deviation is needed for discrimination.

ILC250: **O(1)%** deviation could be enough for discrimination!!

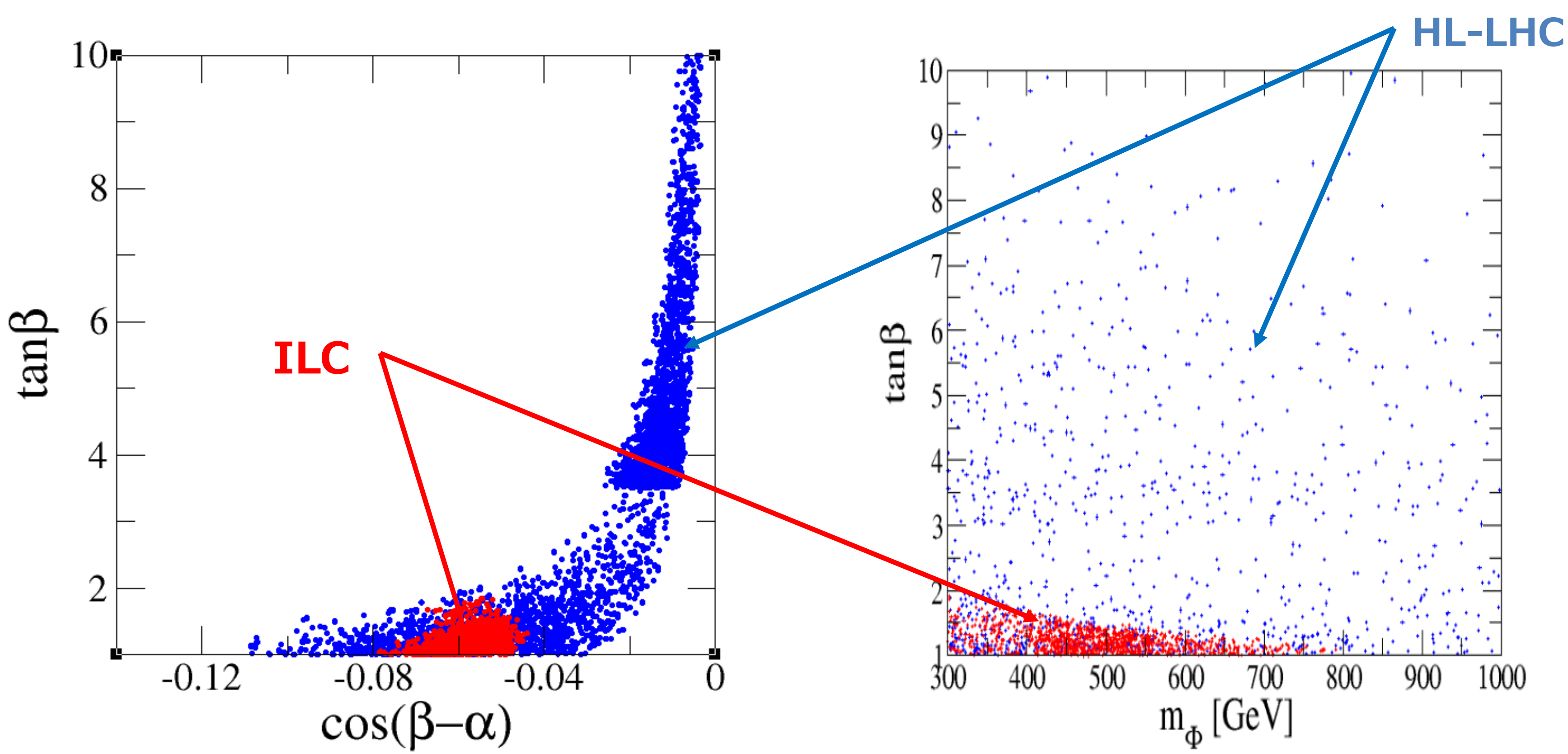
Power of the ILC Precision

Kanemura, Kikuchi, KY, NPB896, 80 (2015)

- Once we determine the type, we can further extract model parameters.

Ex. Type-II 2HDM like scenario: $(\Delta\kappa_V, \Delta\kappa_\tau, \Delta\kappa_b)$ = (-2±2%, 5±2%, 5±4%) at HL-LHC

(-2±0.4%, 5±1.9%, 5±0.9%) at ILC



Summary

- Higgs physics is the window of New Physics.

- Synergy between (HL-)LHC direct searches and ILC indirect precision physics is important to narrow down model parameters.

- Deviations in the h(125) property tell us the structure of the Higgs sector and the scale of the 2^{nd} Higgs boson.

- O(1)% level accuracy of the h coupling measurements is required for the realistic fingerprinting of the Higgs sector.

We need the ILC to find “next step” to reach New Physics!

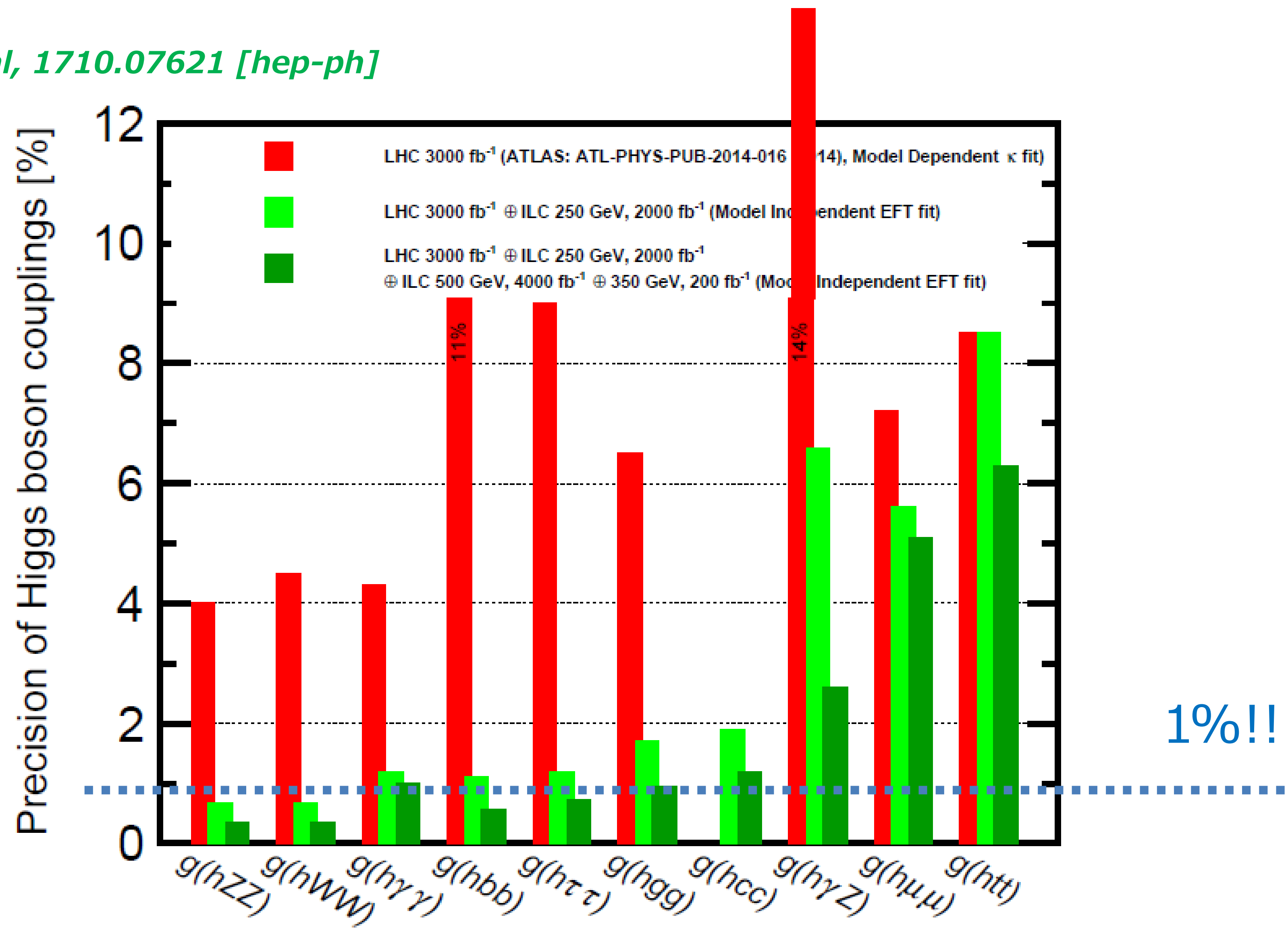
I hope Japanese new era (Heisei → ???) will be with ILC!!

ATLAS-CONF-2018-31 (13 TeV, 80/fb)

Parameter	(a) no BSM
κ_Z	1.07 ± 0.10
κ_W	1.07 ± 0.11
κ_b	$0.97^{+0.24}_{-0.22}$
κ_t	$1.09^{+0.15}_{-0.14}$
κ_τ	$1.02^{+0.17}_{-0.16}$
κ_γ	$1.02^{+0.09}_{-0.12}$
κ_g	$1.00^{+0.12}_{-0.11}$
B_{BSM}	-

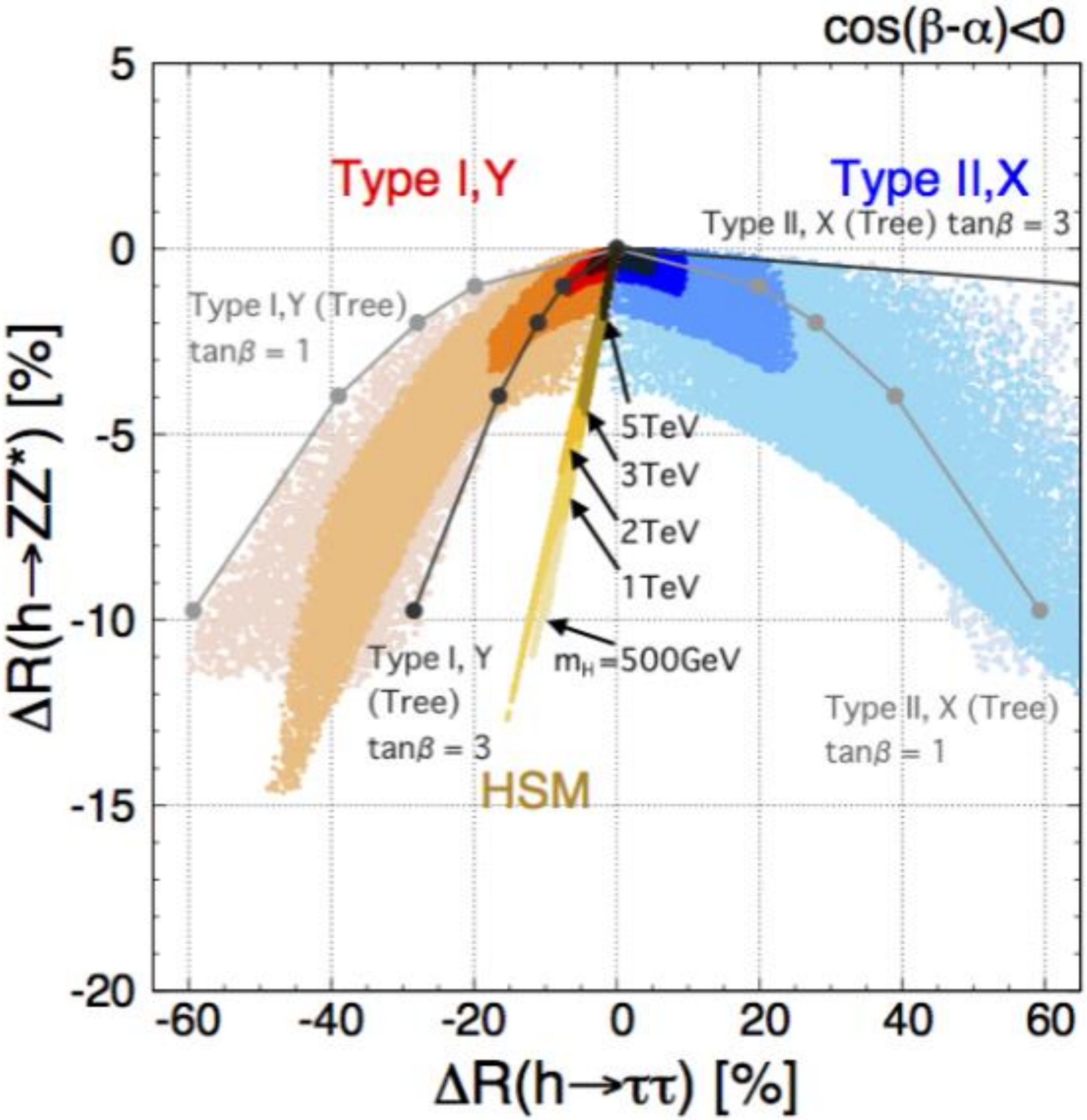
$$\kappa_X = \frac{{g_{hXX}}^{\mathrm{Exp}}}{{g_{hXX}}^{\mathrm{SM}}}$$

Fujii et al, 1710.07621 [hep-ph]

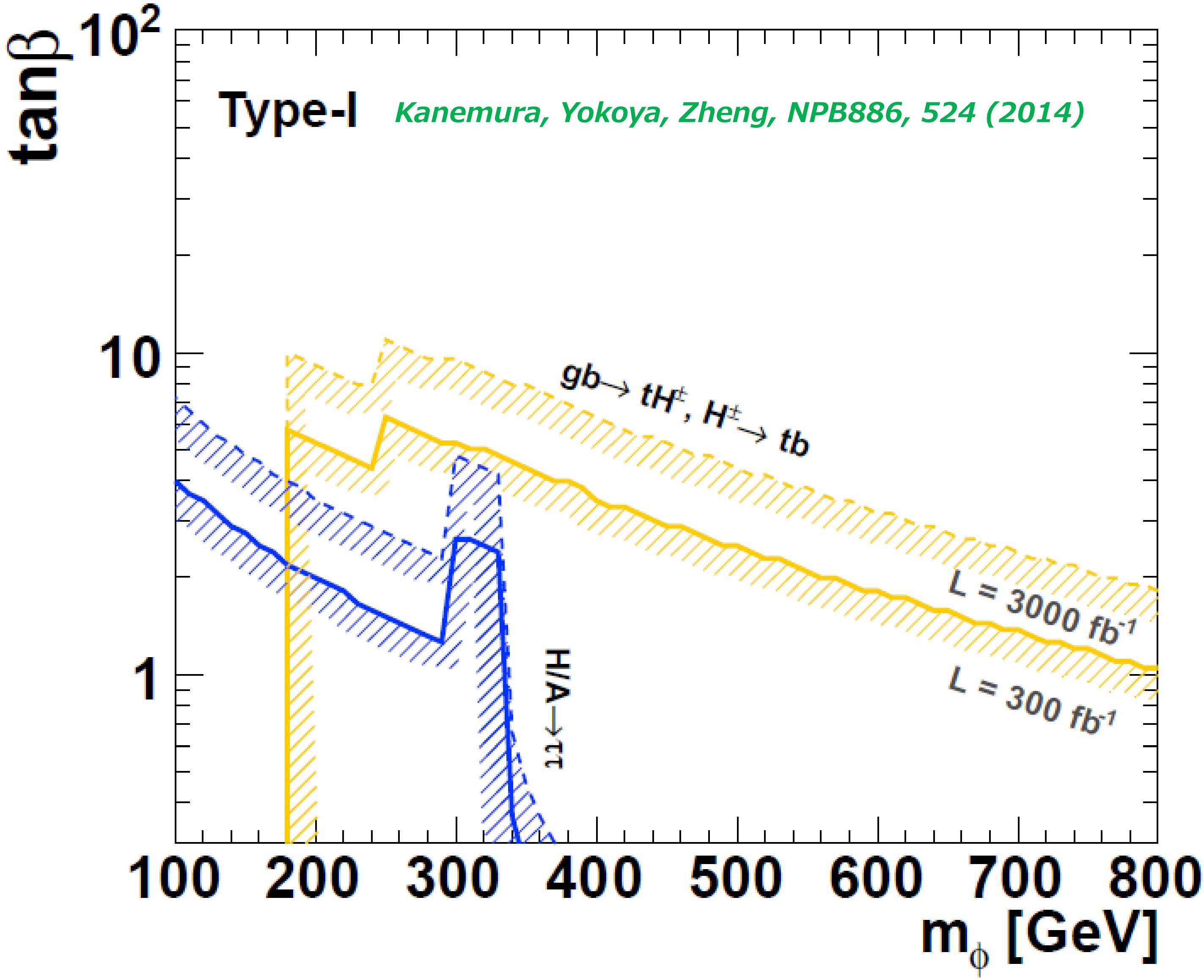


Higgs Working Group Report, 1310.8361 [hep-ph]

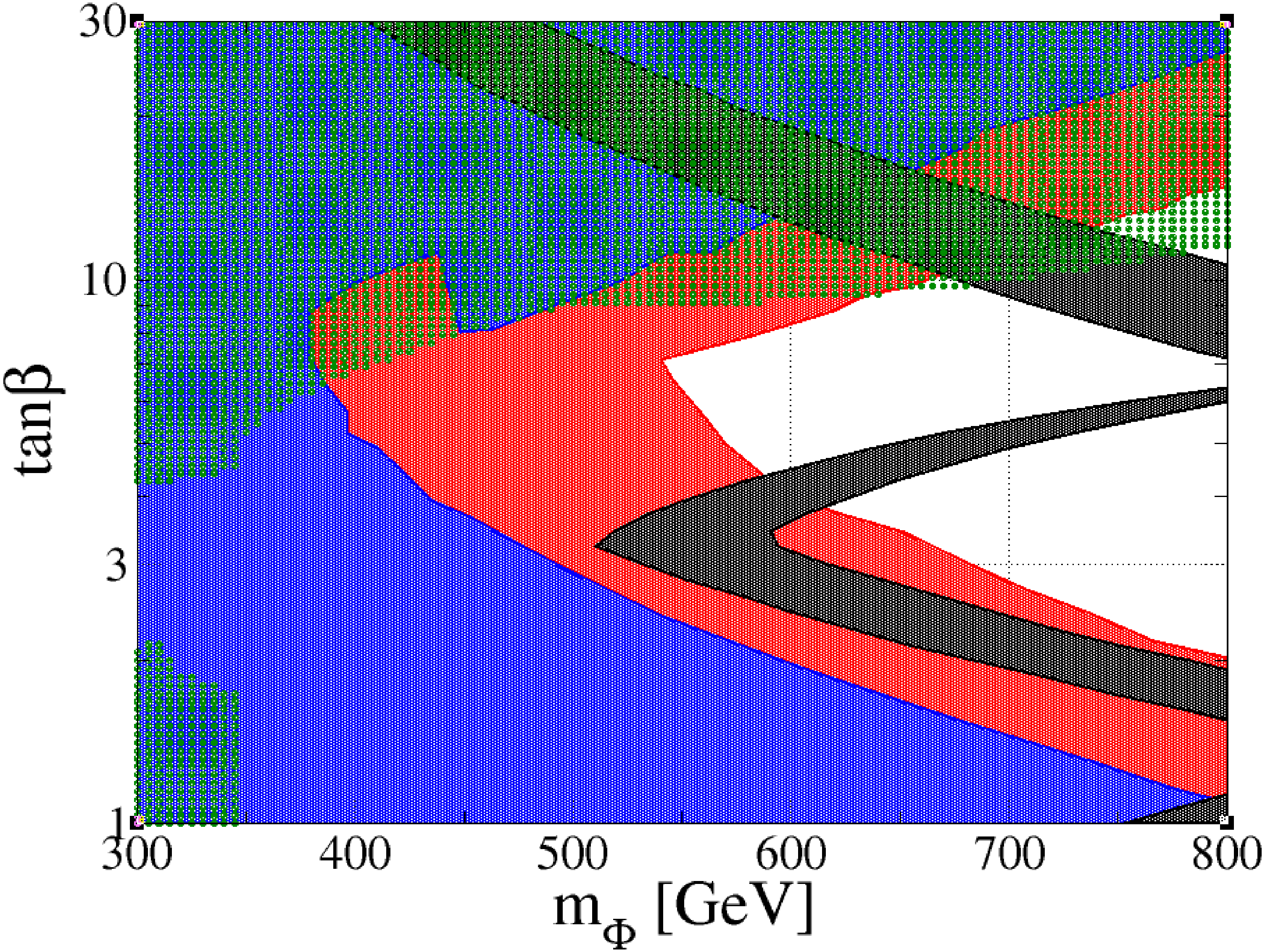
Facility	LHC	HL-LHC
$\sqrt{s}$ (GeV)	14,000	14,000
$\int \mathcal{L} dt$ (fb^{-1})	300/expt	3000/expt
κ_γ	$5-7\%$	$2-5\%$
κ_g	$6-8\%$	$3-5\%$
κ_W	$4-6\%$	$2-5\%$
κ_Z	$4-6\%$	$2-4\%$
κ_ℓ	$6-8\%$	$2-5\%$
$\kappa_d = \kappa_b$	$10-13\%$	$4-7\%$
$\kappa_u = \kappa_t$	$14-15\%$	$7-10\%$



cos(β-α)<0
Type I,Y
Type II,X
Type II, X (Tree) tanβ = 3
Type I,Y (Tree)
tanβ = 1
5TeV
3TeV
2TeV
1TeV
m_H =500GeV
Type I, Y
(Tree)
tanβ = 3
HSM
Type II, X (Tree)
tanβ = 1
ΔR(h→ZZ*) [%]
ΔR(h→ττ) [%]
5
0
-5
-10
-15
-20
-60
-40
-20
0
20
40
60



tanβ
10^2
10
1
Type-I
Kanemura, Yokoya, Zheng, NPB886, 524 (2014)
$gb \to tH^{\pm}$, $H^{\pm} \to tb$
$L = 3000\ fb^{-1}$
$L = 300\ fb^{-1}$
$H/A \to \tau\tau$
100
200
300
400
500
600
700
800
m_ϕ [GeV]



30
10
3
1
tanβ
300
400
500
600
700
800
m_Φ [GeV]

2 Higgs doublet models with NFC

- Natural Flavor Conservation (NFC) Scenario

$\Phi_{u,d,e}$: Either Φ_1 or Φ_2

$$-\mathcal{L}_Y = Y_u \bar{Q}_L (i\sigma_2) \Phi_u^* u_R + Y_d \bar{Q}_L \Phi_d d_R + Y_e \bar{L}_L \Phi_e e_R + \mathrm{h.c.}$$

- This can be realized by imposing a (softly-broken) Z_2 symmetry.

Barger, Hewett, Phillips, PRD41 (1990);Grossman, NPB426 (1994)