Exploring Wrong-Sign Scenarios in the Yukawa Aligned 2HDM

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In collaboration with

Shinya Kanemura (Osaka U.) and Tanmoy Mondal
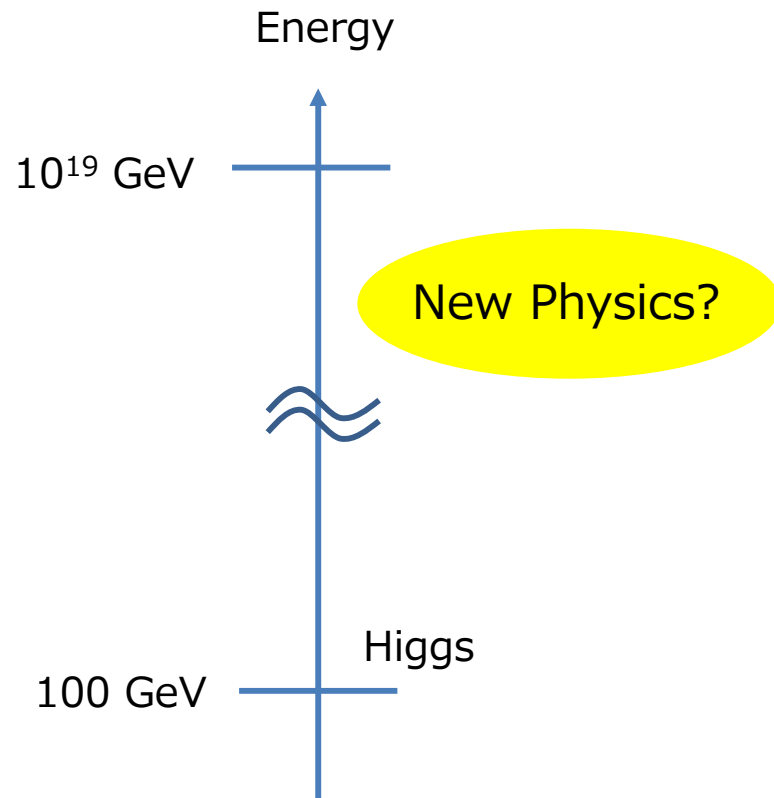
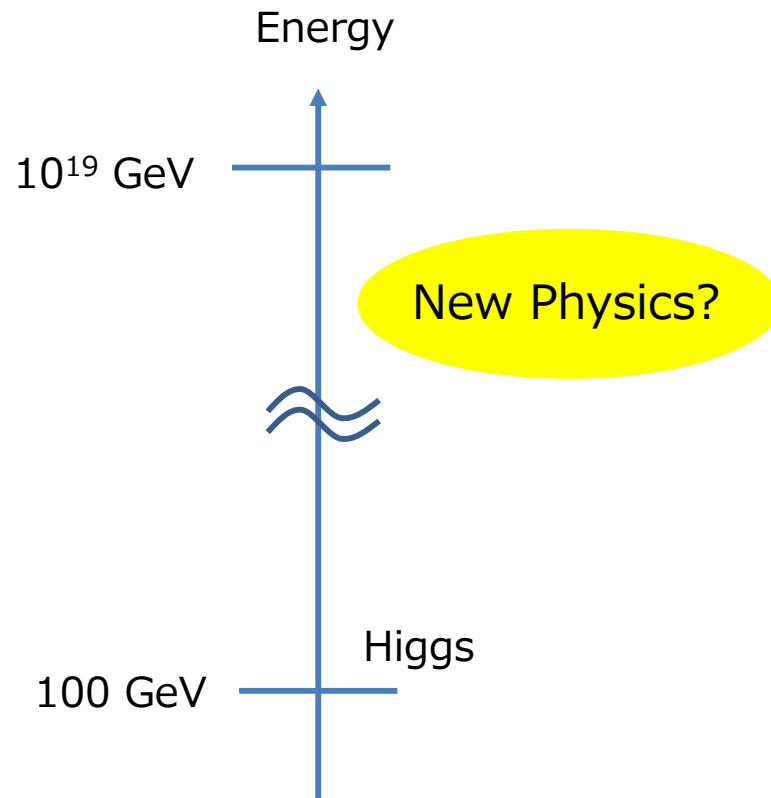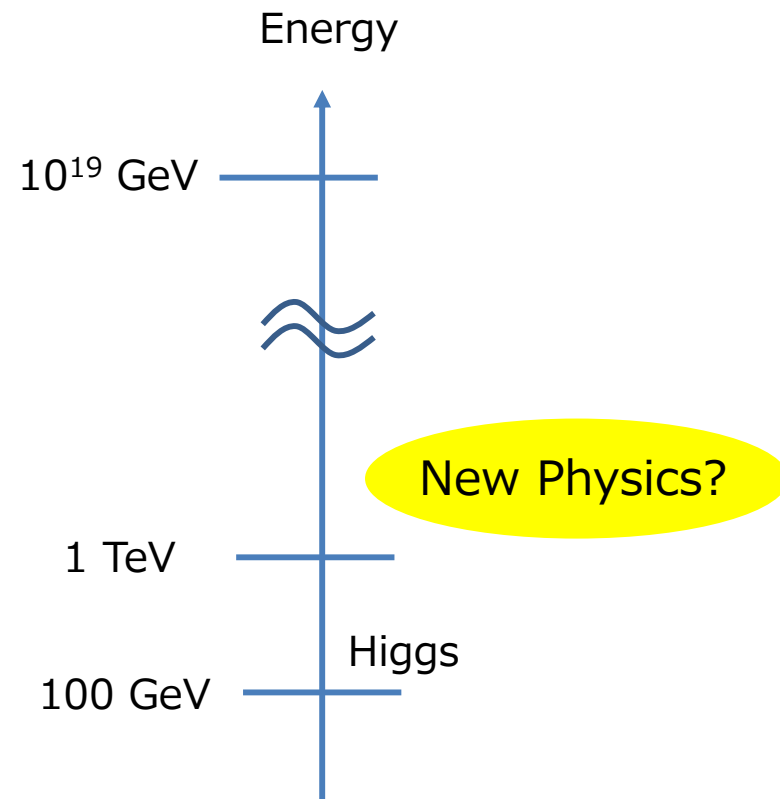(Osaka U. → Birla Institute of Tech. & Sci.)

HPNP2023

June 5th, Osaka U.

Higgs Physics: Current Status

Decoupling scenario

Higgs Physics: Current Status
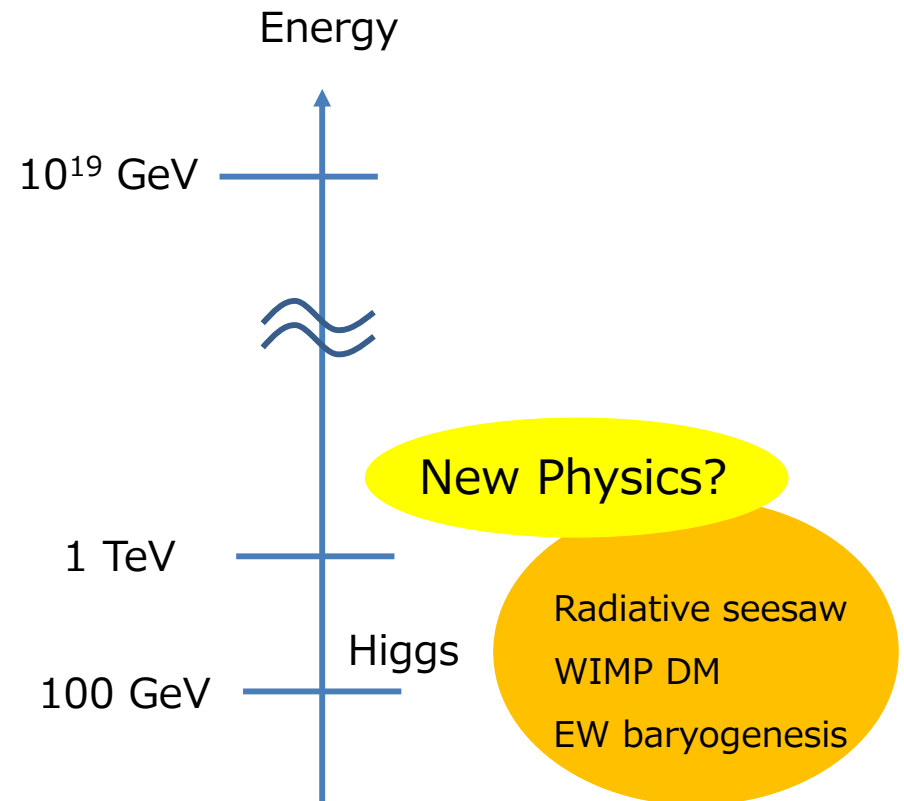
Decoupling scenario

Energy

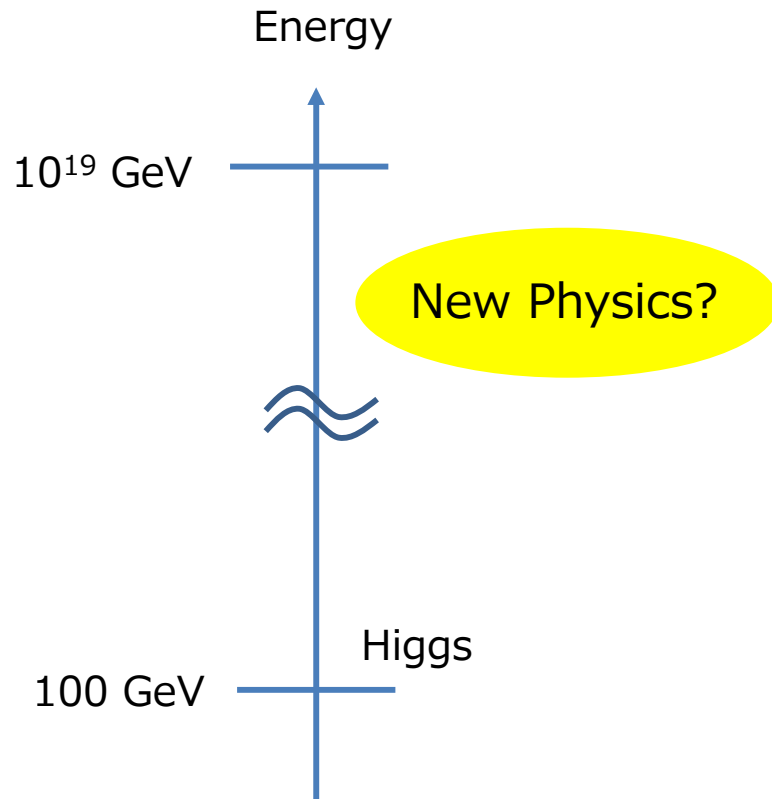10^{19} GeV

New Physics?

Higgs

100 GeV

"Alignment" scenario

Energy

10^{19} GeV

New Physics?

1 TeV

Higgs

100 GeV

Higgs Physics: Current Status

Decoupling scenario

Energy

10^{19} GeV

New Physics?

Higgs

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"Alignment" scenario

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10^{19} GeV

New Physics?

1 TeV

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100 GeV

Radiative seesaw

WIMP DM

EW baryogenesis

Higgs Physics: Current Status

Decoupling scenario

Energy

10^{19} GeV

New Physics?

Higgs

100 GeV

"Alignment" scenario

Energy

10^{19} GeV

New Physics?

Anomalies

$(g-2)_\mu$

B decays

M_W, ⋯

1 TeV

Higgs

100 GeV

Radiative seesaw

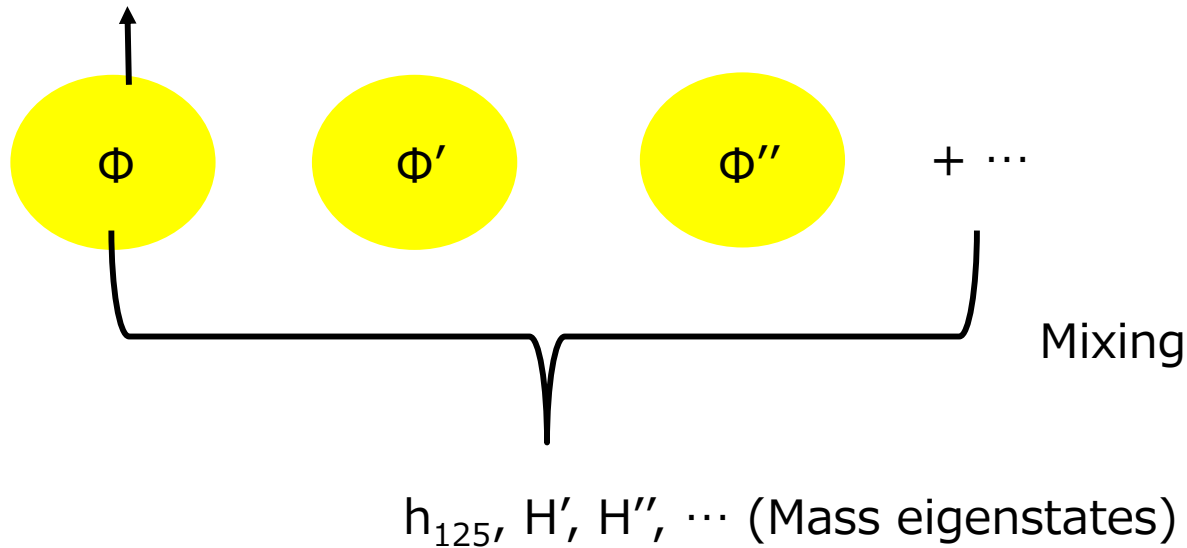WIMP DM

EW baryogenesis

Non-minimal Higgs sectors often appear.

"Alignment" has been the keyword for non-minimal Higgs sectors!

What is the Alignment?

Gauge boson & fermion masses

h_{125}, H′, H″, ⋯ (Mass eigenstates)

What is the Alignment?

Gauge boson & fermion masses

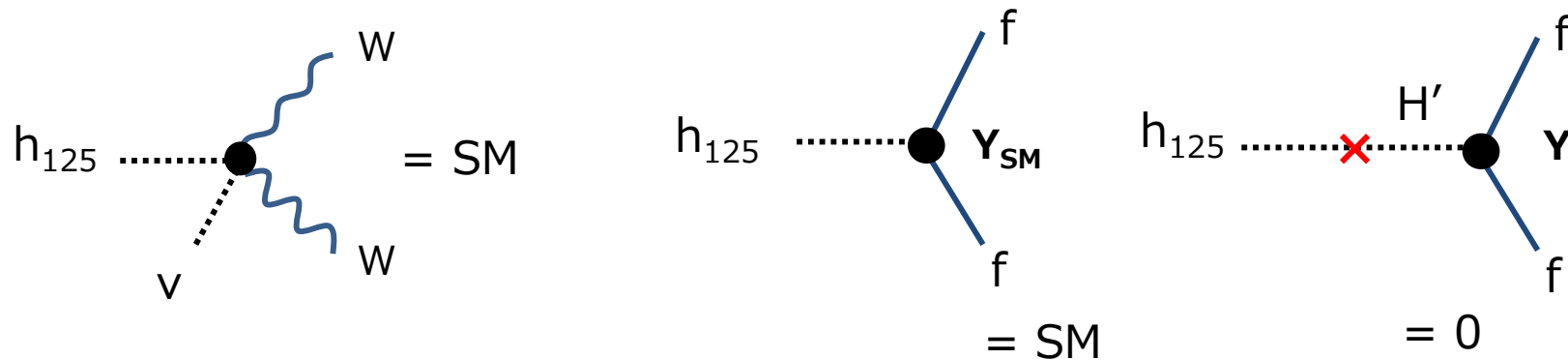Φ Φ' Φ'' $+ \cdots$

h_{125}

Alignment

$H', H'', \cdots$

Mixing

What is the Alignment?

What is the Alignment?

Gauge boson & fermion masses

Φ Φ' Φ'' $+ \cdots$

h_{125}

Alignment

H', H'', $\cdots$

Mixing
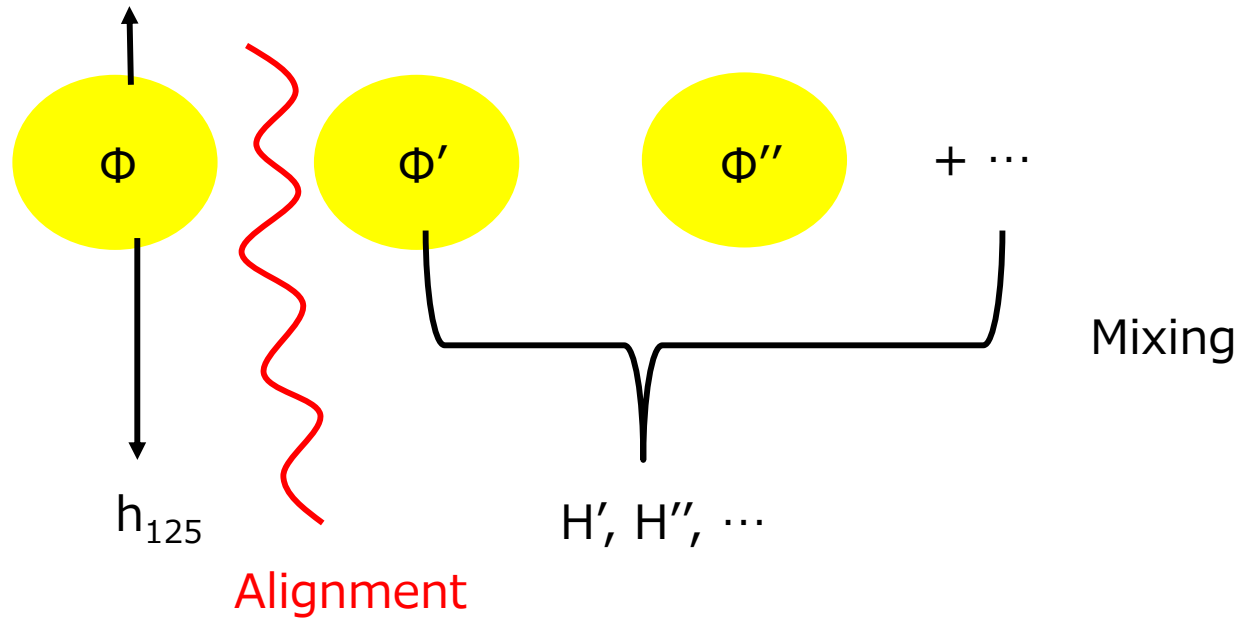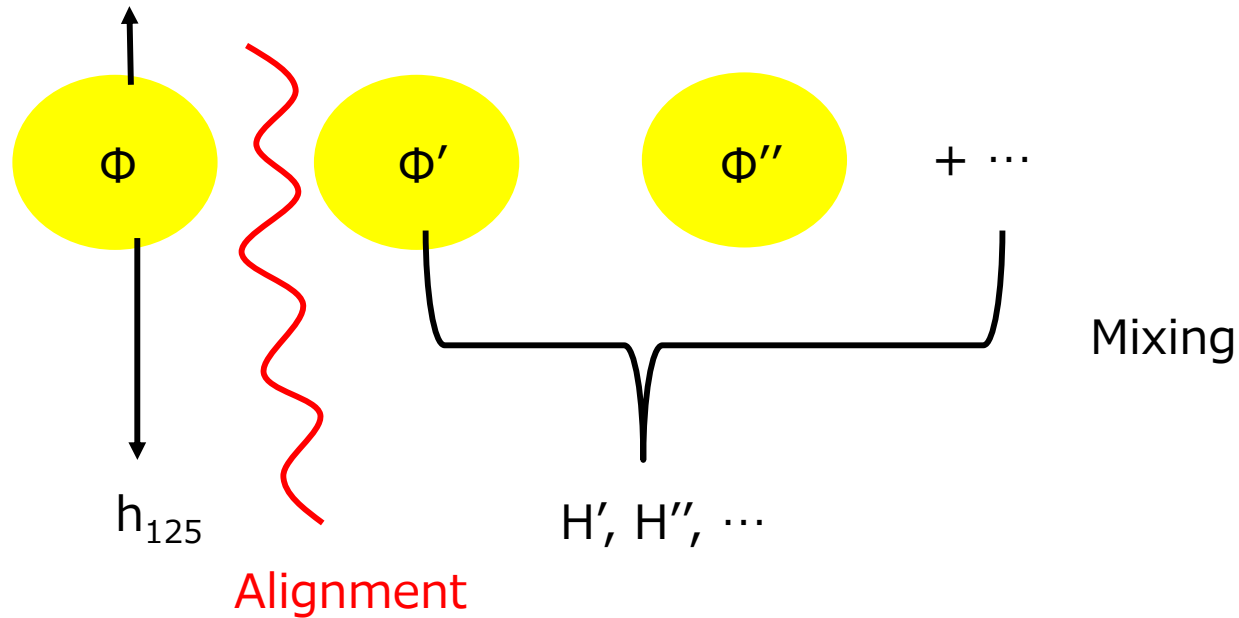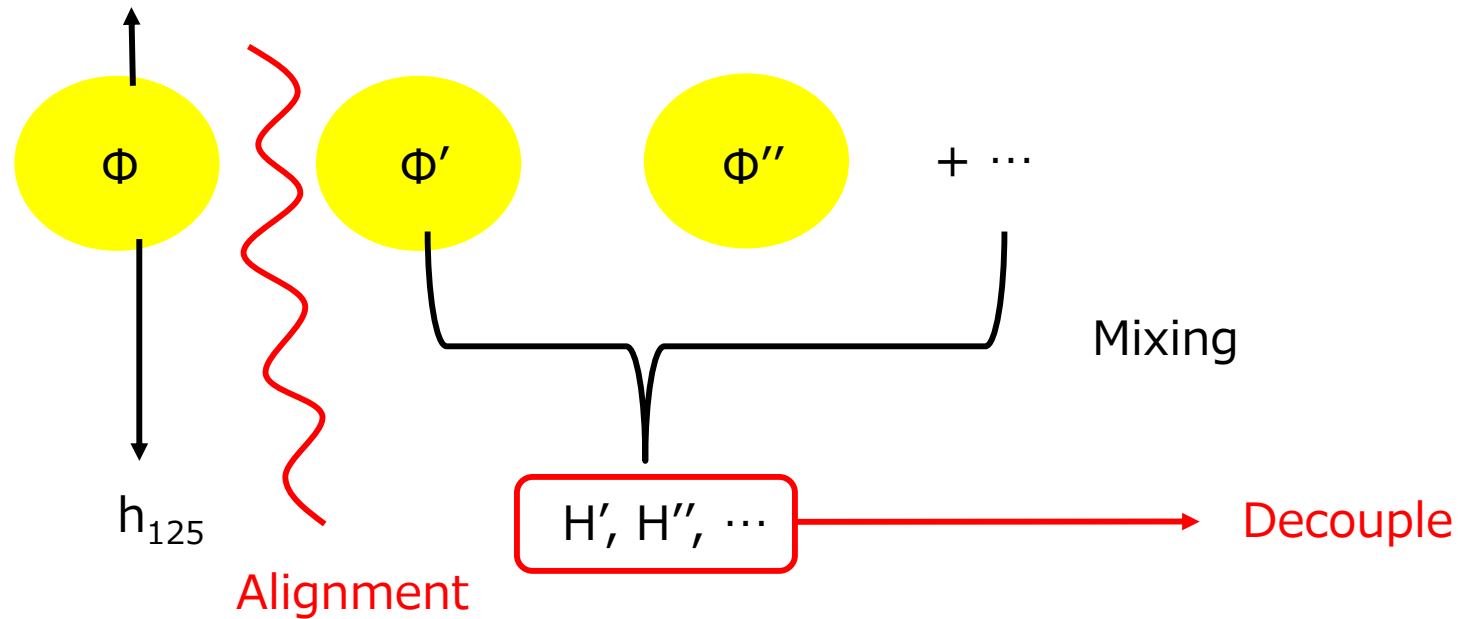
Decouple

The alignment is just a consequence of the decoupling.

Alignment without Decoupling

Gauge boson & fermion masses

Φ

Φ'

Φ''

$+ \cdots$

Mixing

h_{125}

Alignment

H', H'', $\cdots$

~ EW scale

Alignment without decoupling (Motivated by TeV scale NP, e.g., EWBG)

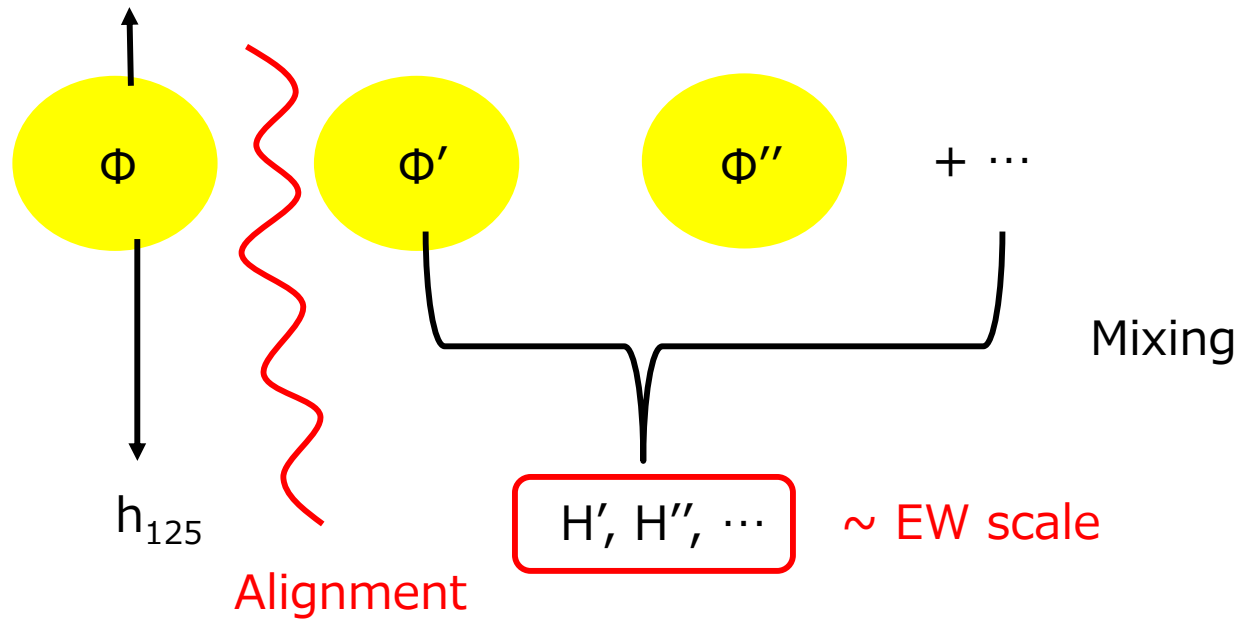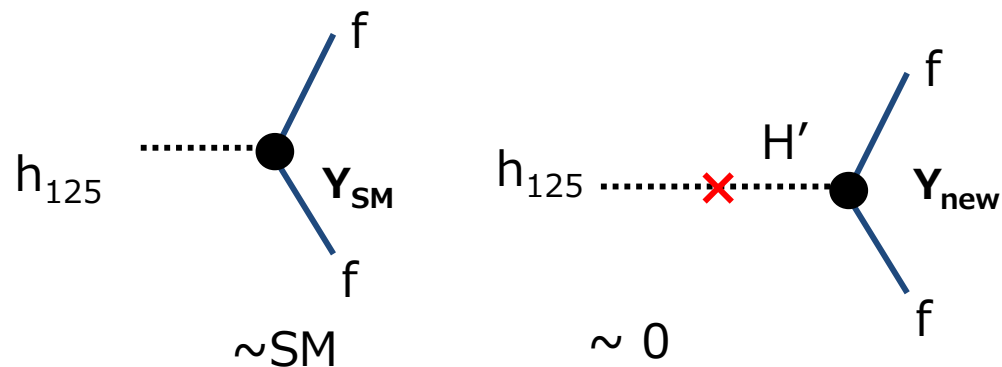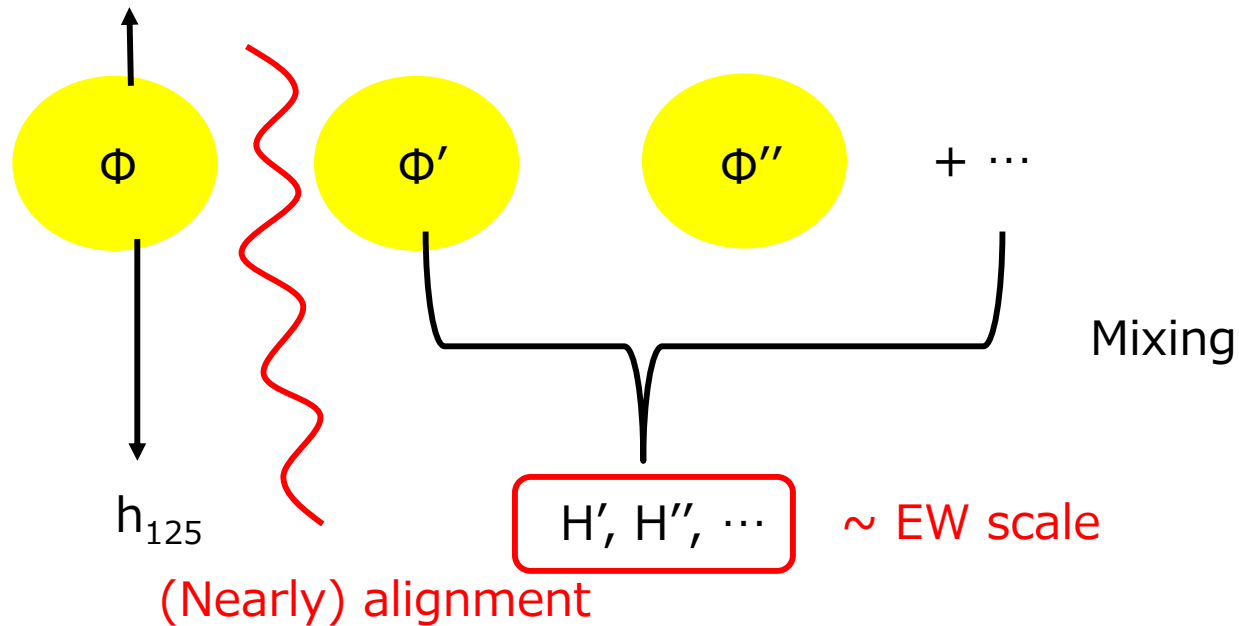See the talk by Mura (Wed., Morning)

Alignment without Decoupling

Gauge boson & fermion masses

Φ

Φ′

Φ″

+ ⋯

h_{125}

(Nearly) alignment

Mixing

$H', H'', \cdots$ ~ EW scale

h_{125} ⋯⋯● Y_{SM}

f

f

~SM

h_{125} ⋯⋯✕⋯⋯● Y_{new}

H′

f

f

~ 0

"Right-sign" (RS) Yukawa

Alignment without Decoupling

Gauge boson & fermion masses

Φ Φ' Φ'' $+ \cdots$

Mixing

h_{125}

H', H'', $\cdots$ ~ EW scale

(Nearly) alignment

h_{125} $\mathbf{Y_{SM}}$ h_{125} $\times$ H' $\mathbf{Y_{new} \sim -2Y_{SM}/\theta}$ ~ -SM
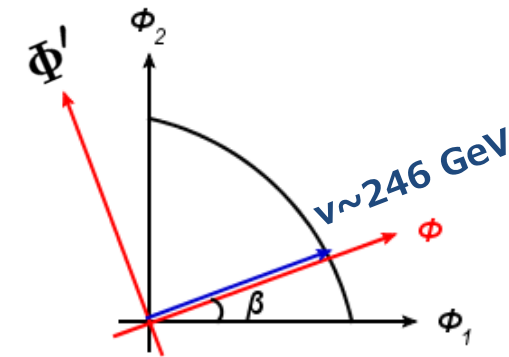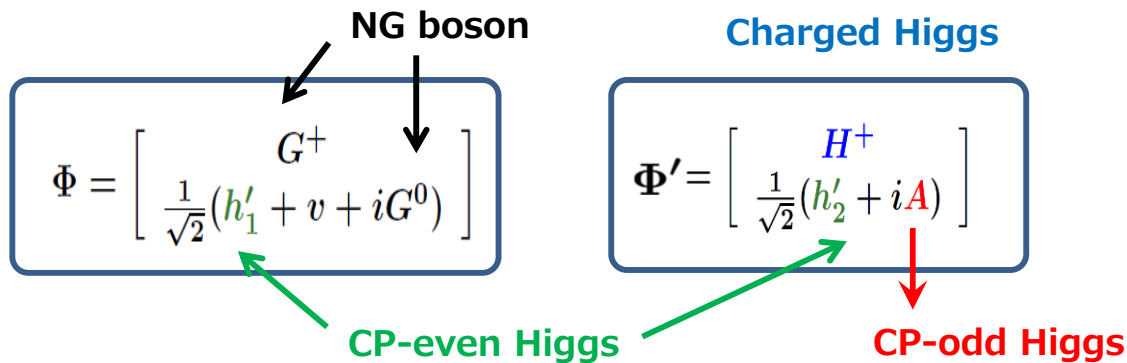
f   f

f   f

~SM   ~ -2×SM
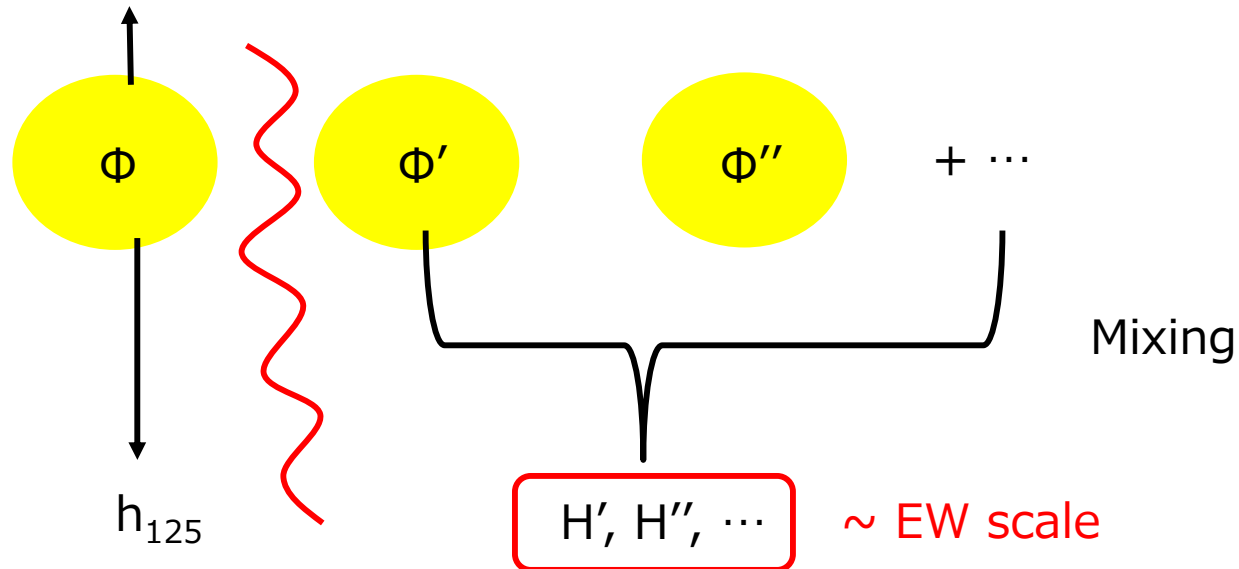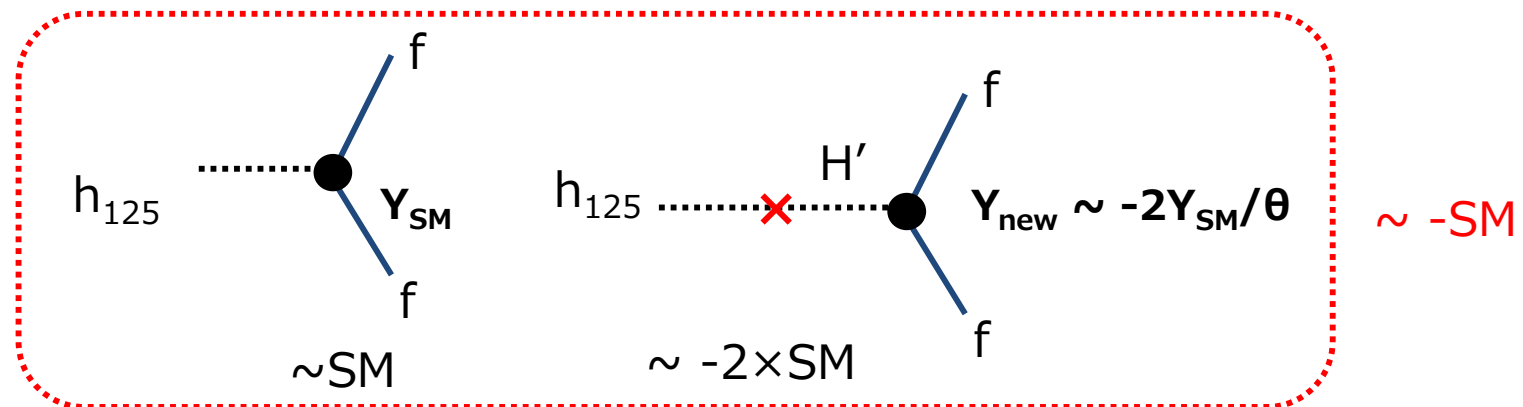
"Wrong-sign" (WS) Yukawa

2 Higgs Doublet Models (CP-Conserved)

- Higgs basis *Davidson, Haber PRD71 (2005)*

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi \\ \bar{\Phi}' \end{pmatrix}$$

$\tan\beta = v_2/v_1$

NG boson

Charged Higgs

$$\Phi = \begin{bmatrix} G^+ \\ \frac{1}{\sqrt{2}}(h'_1 + v + iG^0) \end{bmatrix}$$

$$\Phi' = \begin{bmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h'_2 + iA) \end{bmatrix}$$

CP-even Higgs

CP-odd Higgs

- Higgs mixing

$$\begin{pmatrix} h'_1 \\ h'_2 \end{pmatrix} = \begin{bmatrix} \cos(\beta-\alpha) & \sin(\beta-\alpha) \\ -\sin(\beta-\alpha) & \cos(\beta-\alpha) \end{bmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

125 GeV Higgs

- Decoupling limit: $M^2 \to \infty$

$m_h^2 \sim \lambda v^2, \quad m_\Phi^2 \sim M^2 + \lambda' v^2$

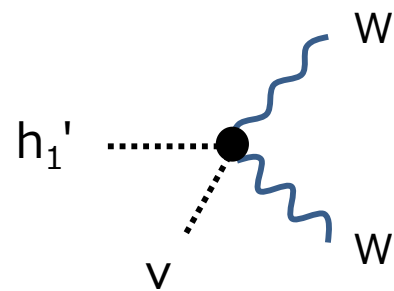$\Phi = H, A, H^{\pm}$

- Alignment limit: $\sin(\beta-\alpha) \to 1$

Higgs Boson Couplings

$$\mathcal{L}_{2\text{HDM}} \supset |D_\mu \Phi|^2 + |D_\mu \Phi'|^2 - Y_f^{\text{SM}} \bar{\Psi}_L \Phi \Psi_R - \boxed{Y_f'} \bar{\Psi}_L \Phi' \Psi_R$$
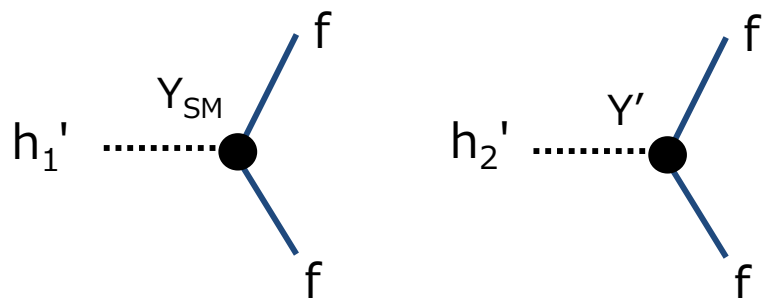
$$Y_f^{\text{SM}} \times \zeta_f$$

Pich, Tuzon (2009)

Yukawa alignment

Z_2

Yukawa alignment

(no FCNC at tree level)

1/tanβ or −tanβ

in the Z_2 case

h_1' W W v $\longrightarrow$ $(\text{SM}) \times \sin(\beta - \alpha)$

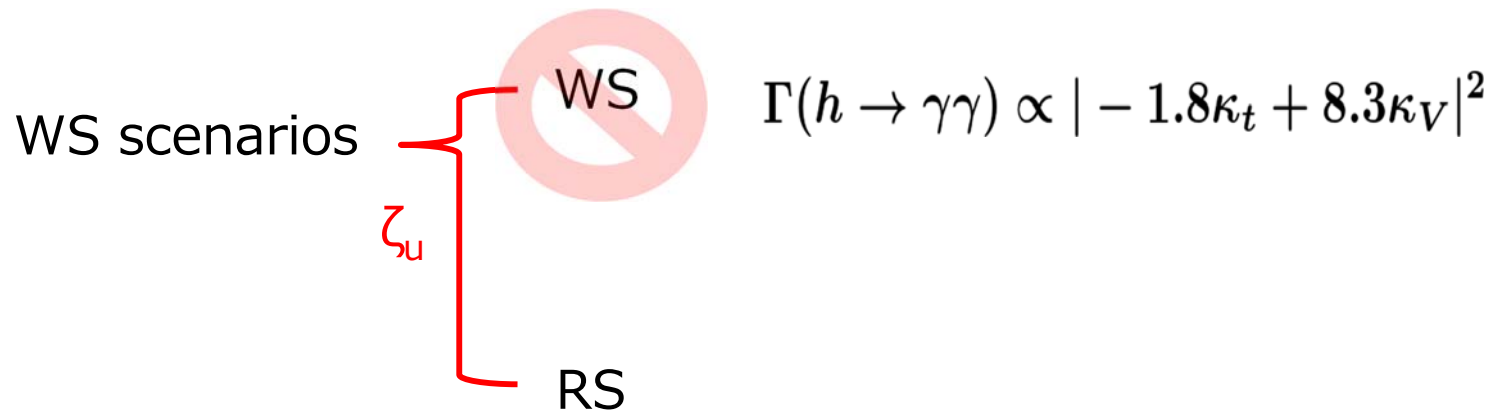h_1' Y_{SM} f f $\qquad$ h_2' Y' f f $\longrightarrow$ $(\text{SM}) \times [\sin(\beta - \alpha) + \zeta_f \cos(\beta - \alpha)]$
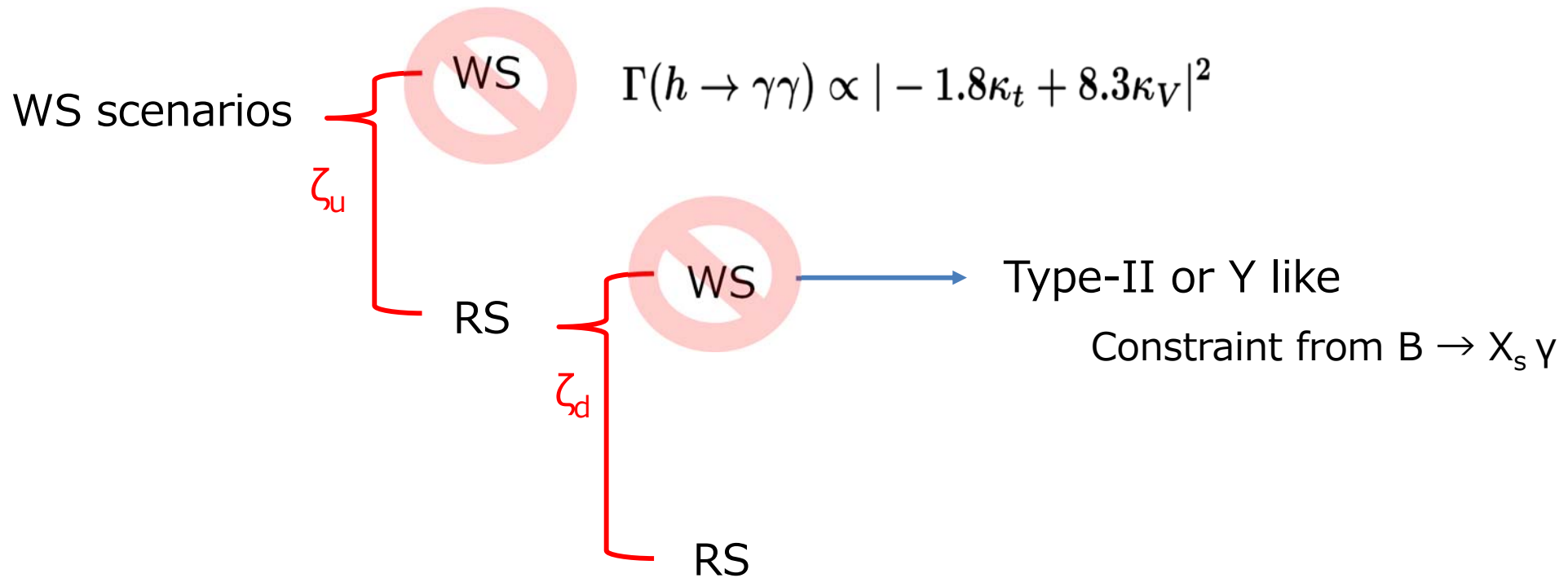
Ferreira, Gunion, Haber, Santos (2014)
For Type-II 2HDM

Wrong-sign Yukawa is obtained by $\zeta_f \simeq -2/\cos(\beta - \alpha)$

Classification of the WS Scenarios

WS scenarios

WS

ζ_u

RS

$$\Gamma(h \to \gamma\gamma) \propto |-1.8\kappa_t + 8.3\kappa_V|^2$$

Classification of the WS Scenarios

$$\Gamma(h \to \gamma\gamma) \propto |-1.8\kappa_t + 8.3\kappa_V|^2$$

WS scenarios

WS

ζ_u

RS

WS ⟶ Type-II or Y like

Constraint from B → X_s γ

ζ_d

RS

Classification of the WS Scenarios

WS scenarios

ζ_u

$\Gamma(h \to \gamma\gamma) \propto |-1.8\kappa_t + 8.3\kappa_V|^2$

WS

RS

WS → Type-II or Y like

Constraint from B → X_s γ

ζ_d

RS

WS → Type-X like

ζ_e

RS → Type-I like

Motivated by (g-2)$_\mu$

Broggio, Chun, Passera, Patel, Vempati (2014)

Abe, Sato, Yagyu (2015)
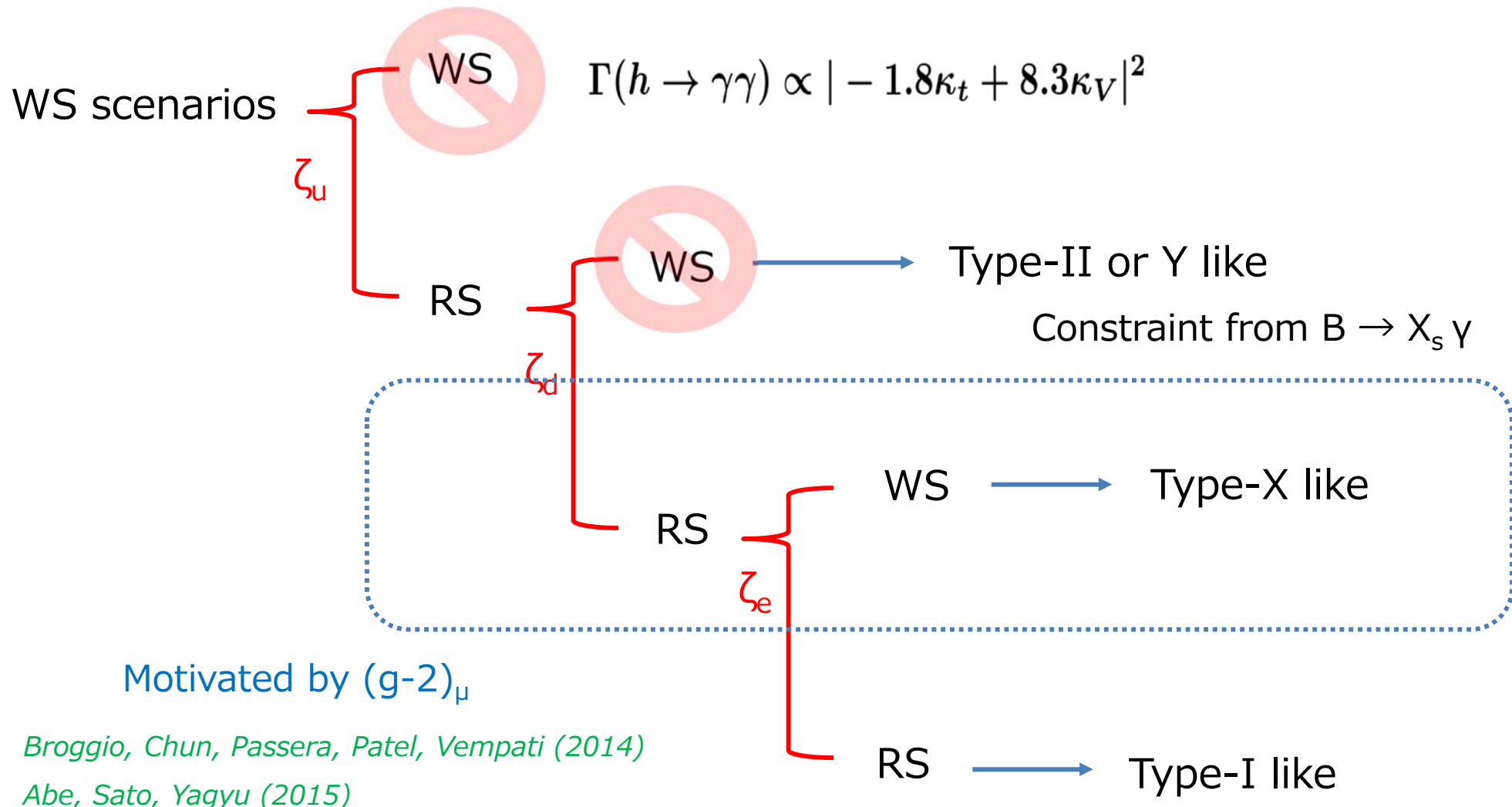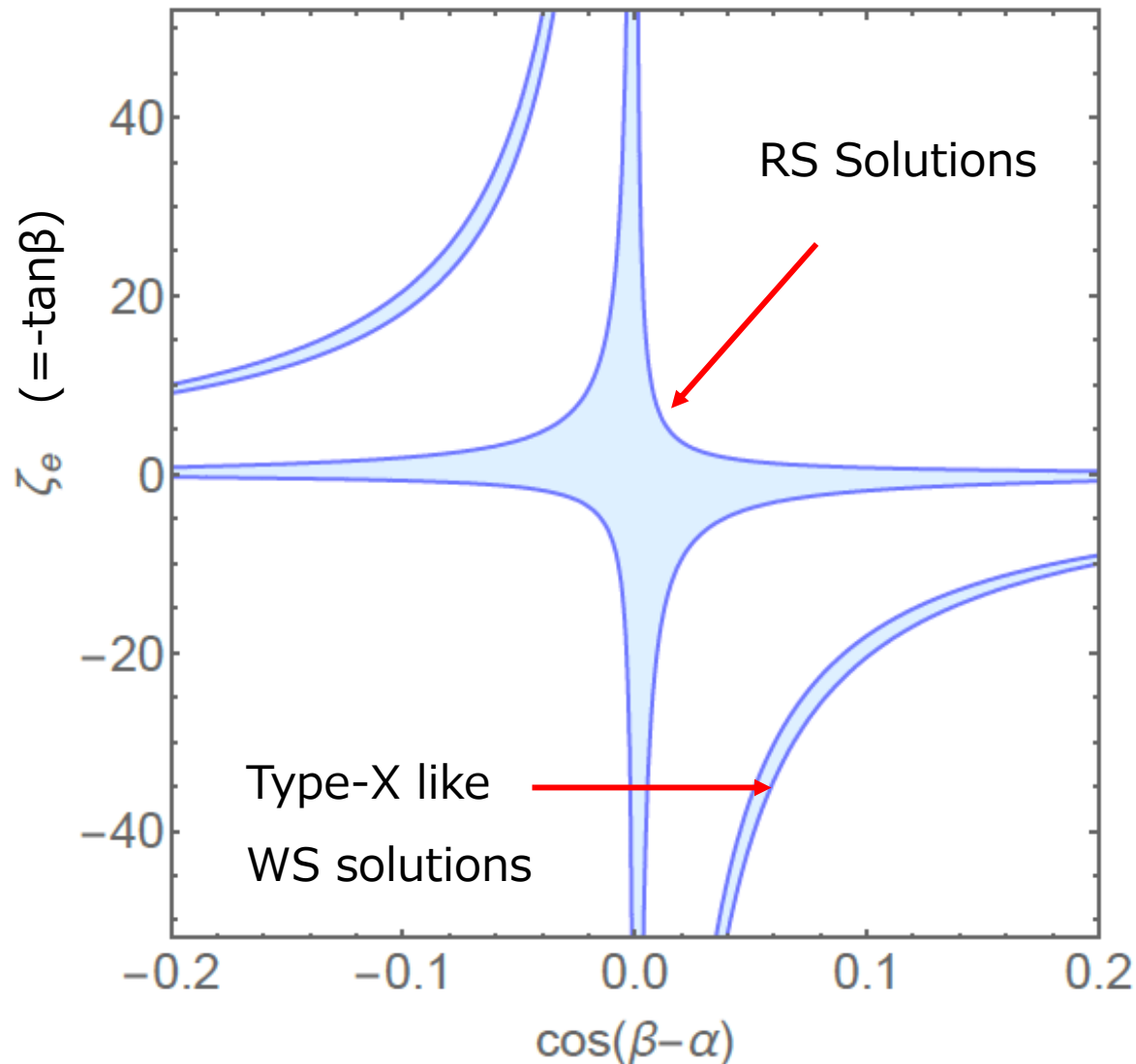
Can we distinguish the RS & WS scenarios?

Constraint from Higgs Signals at LHC

2σ allowed region by Higgs signals
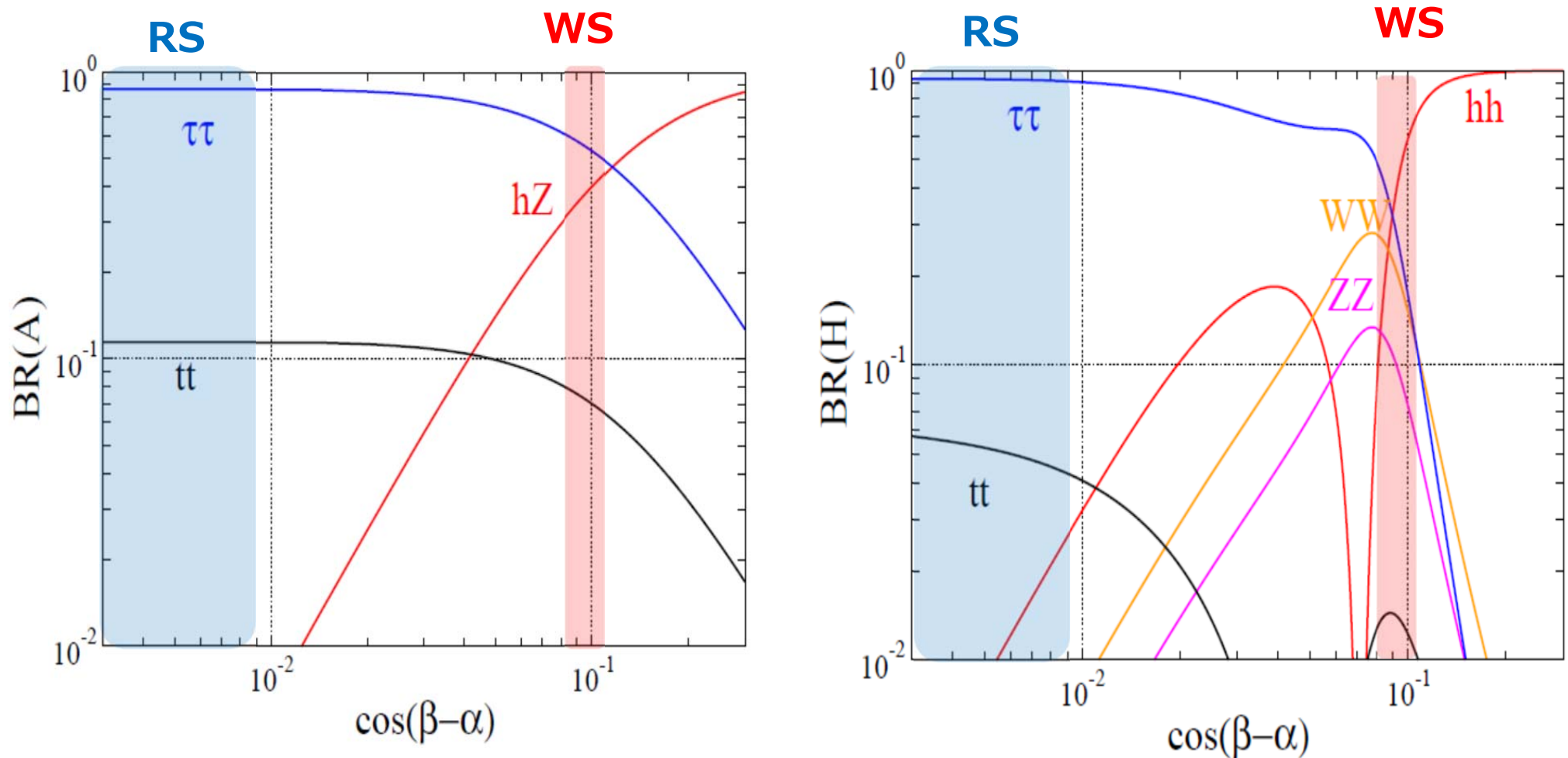

· Larger $\cos(\beta - \alpha)$ is required in WS.

→ Unitarity bound sets stronger upper limits on extra Higgs masses to be ~600 GeV in the softly-broken Z_2 case.
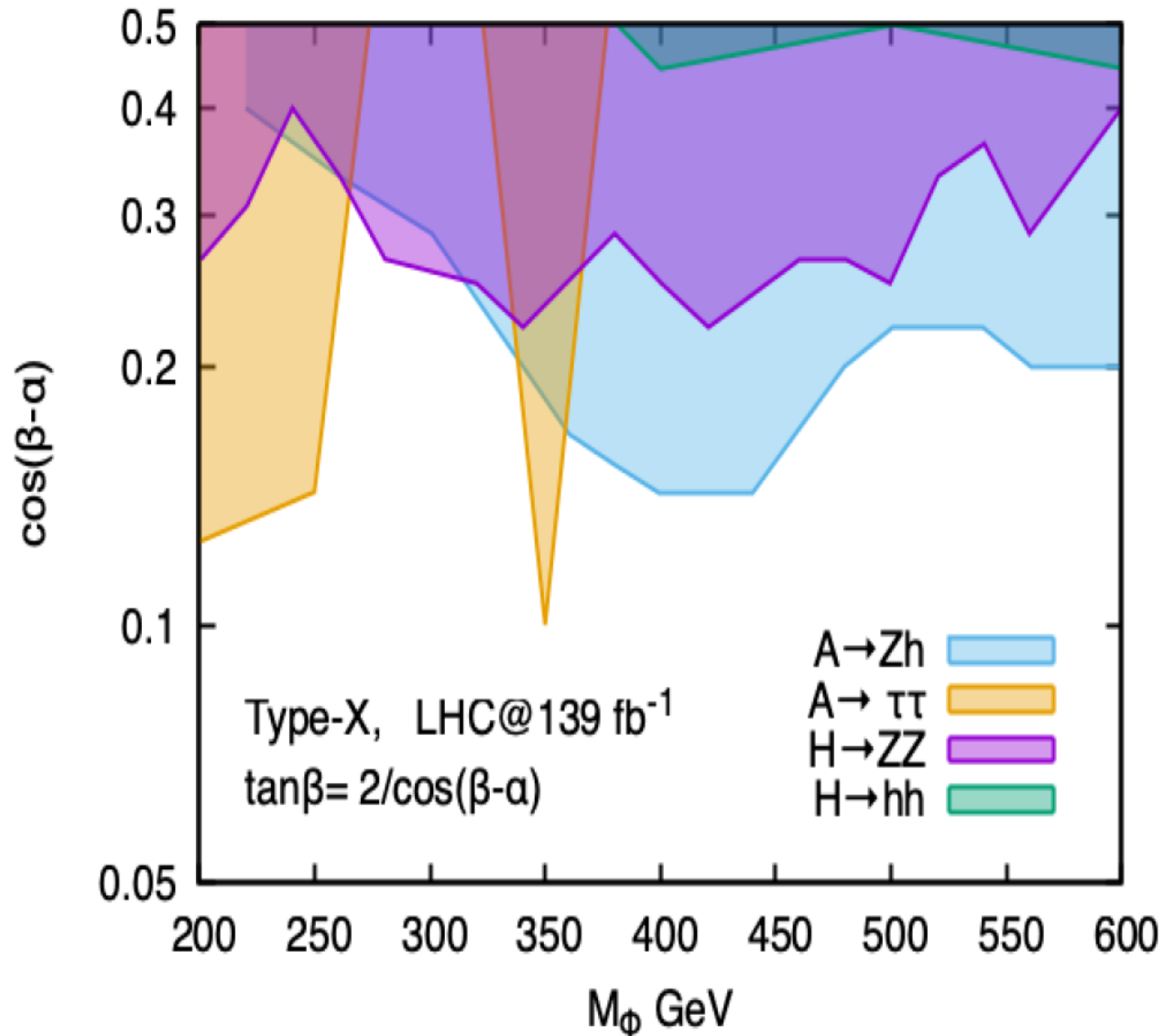
Branching Ratios (Type-X)

tanβ = 20, mH = mA = mH+ = 500 GeV

1-loop calculations: See the talk by Kikuchi (Wed., Morning)

Higgs to Higgs and di-tau decays become important.
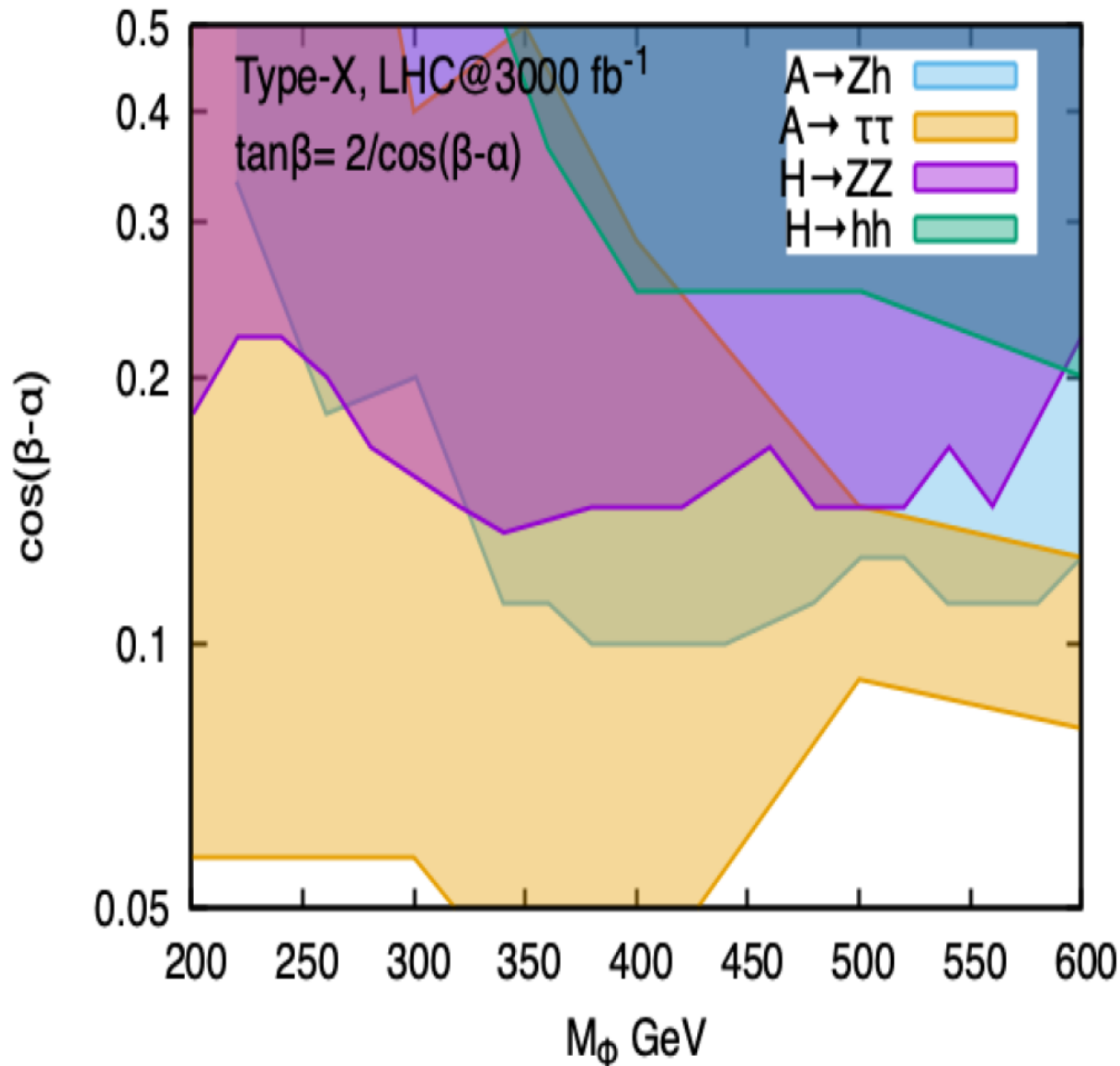
Exploring WS Type-X Scenario at Current LHC

A → Zh: 139 fb⁻¹ (2207.00230 [hep-ex])

A → ττ: 139 fb⁻¹ (2002.12223 [hep-ex])

H → hh: 139 fb⁻¹ (2207.00230 [hep-ex])

H → ZZ: 139 fb⁻¹ (2009.14791 [hep-ex])

Exploring WS Type-X Scenario at HL-LHC

$A \to Zh$: 139 fb^{-1} (2207.00230 [hep-ex])

$A \to \tau\tau$: 139 fb^{-1} (2002.12223 [hep-ex])

$H \to hh$: 139 fb^{-1} (2207.00230 [hep-ex])

$H \to ZZ$: 139 fb^{-1} (2009.14791 [hep-ex])

Summary

☐ Current LHC data could suggest WS Yukawa scenarios.

☐ WS charged lepton Yukawa provides phenomenologically interesting scenarios, e.g., muon g-2 and light Higgs bosons.

☐ WS scenario requires extra Higgs boson mass below ~ 600 GeV from the perturbative unitarity bound.

☐ RS or WS can be distinguished by searching for Higgs to Higgs decays and di-tau decays at LHC.