

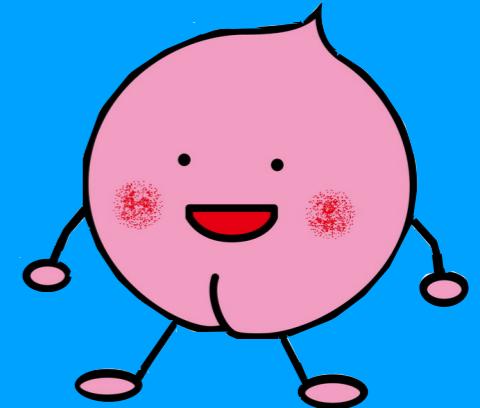
Double Higgs boson production at future linear colliders in the two-Higgs doublet model : non-alignment case

based on Phys. Rev. D 99, 095027 (2019)

arXiv: hep-ph/1812.09843



Takuto Nagura
(Seikei Univ.)



collaboration with

Tadashi Kon, Takahiro Ueda (Seikei Univ.), Kei Yagyu (Osaka Univ.)

Outline

- Introduction
- Model: 2HDM
- Non-alignment case
- Constraints
- Numerical results: $e^+e^- \rightarrow hh\bar{f}\bar{f}$
- Summary

Introduction

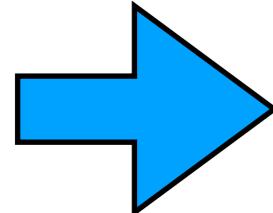
■ In the LHC, we have observed

1. Higgs-gauge couplings (hZZ^* and hWW^*)
2. Yukawa couplings ($ht\bar{t}$, $hb\bar{b}$, $h\tau\bar{\tau}$)

Introduction

■ In the LHC, we have observed

1. Higgs-gauge couplings (hZZ^* and hWW^*)
2. Yukawa couplings ($ht\bar{t}$, $hb\bar{b}$, $h\tau\bar{\tau}$)

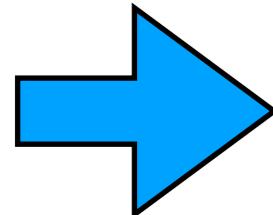


no doubt for existence of **at least** an isospin scalar doublet.

Introduction

■ In the LHC, we have observed

1. Higgs-gauge couplings (hZZ^* and hWW^*)
2. Yukawa couplings ($ht\bar{t}$, $hb\bar{b}$, $h\tau\bar{\tau}$)



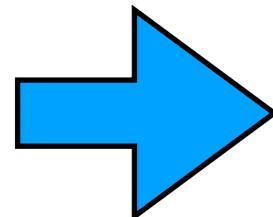
no doubt for existence of **at least** an isospin scalar doublet.

Question : How many doublets are there in the Higgs sector?

Introduction

■ In the LHC, we have observed

1. Higgs-gauge couplings (hZZ^* and hWW^*)
2. Yukawa couplings ($ht\bar{t}$, $hb\bar{b}$, $h\tau\bar{\tau}$)



no doubt for existence of **at least** an isospin scalar doublet.

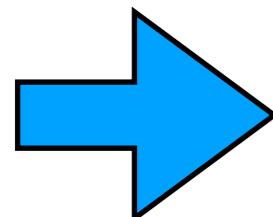
Question : How many doublets are there in the Higgs sector?

- Multi-doublet structure (n HDMs) is favored by
 - Electroweak Baryogenesis
 - $\rho = 1$ at tree level

Introduction

■ In the LHC, we have observed

1. Higgs-gauge couplings (hZZ^* and hWW^*)
2. Yukawa couplings ($ht\bar{t}$, $hb\bar{b}$, $h\tau\bar{\tau}$)



no doubt for existence of **at least** an isospin scalar doublet.

Question : How many doublets are there in the Higgs sector?

- Multi-doublet structure (n HDMs) is favored by
 - Electroweak Baryogenesis
 - $\rho = 1$ at tree level

We consider a simple extension of the SM: 2HDMs

New Physics and 2HDMs

New Physics and 2HDMs

Unsolved phenomena in the SM

- The gauge hierarchy problem
- Neutrino masses
- Dark matter
- Baryon asymmetry (EW baryogenesis)

New Physics and 2HDMs

New Physics

- **Supersymmetry (MSSM)**
Haber and Kane, Phys. Rep. 117, 75 (1985).
- **Compositeness (Higgs as pNGB)**
Curtis, Delle Rose, Moretti and Yagyu, High Energy Phys. (2018)
- **Zee model**
Zee, Phys. Lett. B93, 38 (1980)
- **Inert doublet model**
Barbieri, Hall and Rychkov (2006)

Unsolved phenomena in the SM

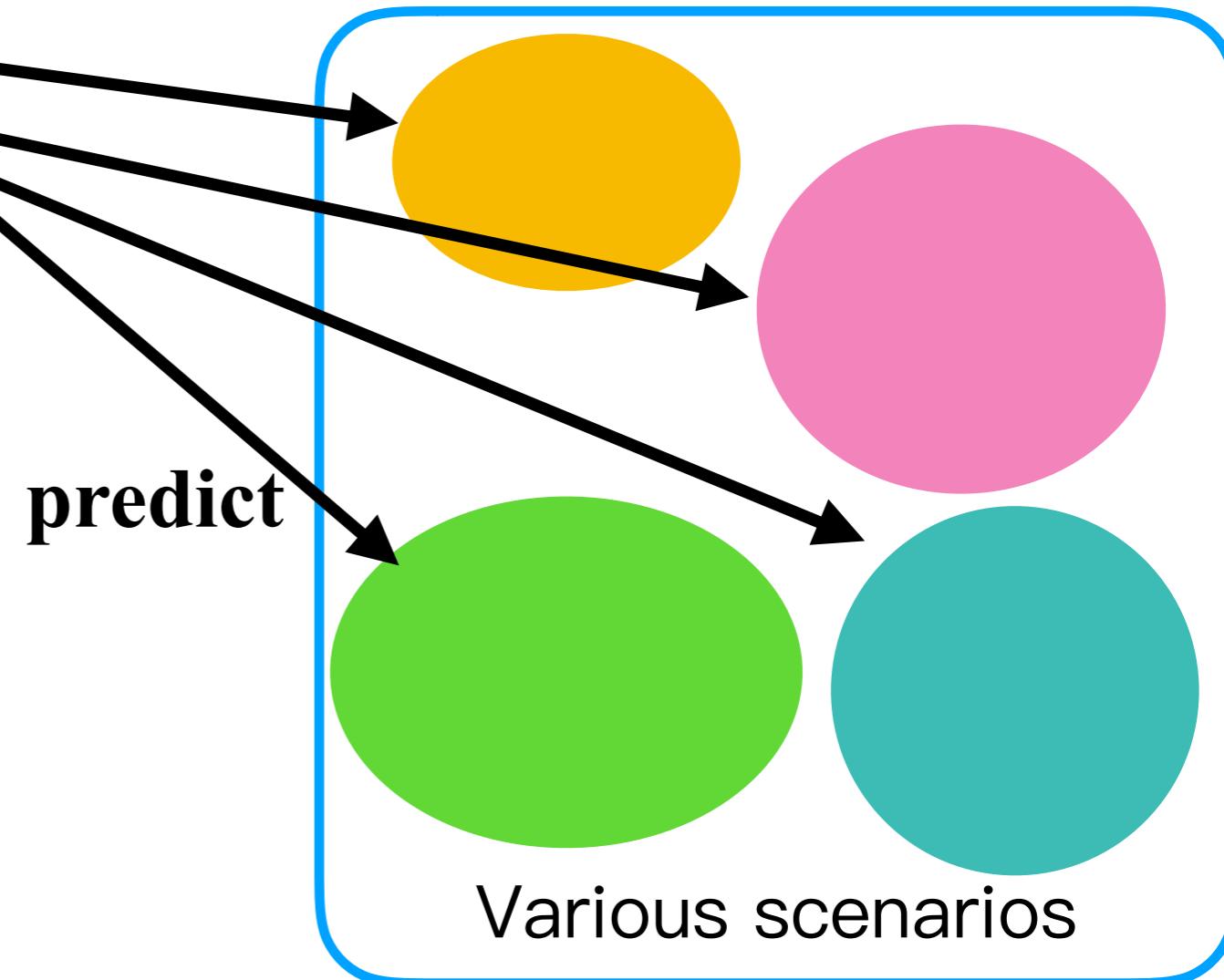
- The gauge hierarchy problem
- Neutrino masses
- Dark matter
- Baryon asymmetry (EW baryogenesis)

New Physics and 2HDMs

New Physics

- Supersymmetry (MSSM)
Haber and Kane, Phys. Rep. 117, 75 (1985).
- Compositeness (Higgs as pNGB)
Curtis, Delle Rose, Moretti and Yagyu, High Energy Phys. (2018)
- Zee model
Zee, Phys. Lett. B93, 38 (1980)
- Inert doublet model
Barbieri, Hall and Rychkov (2006)

2HDMs



Unsolved phenomena in the SM

- The gauge hierarchy problem
- Neutrino masses
- Dark matter
- Baryon asymmetry (EW baryogenesis)

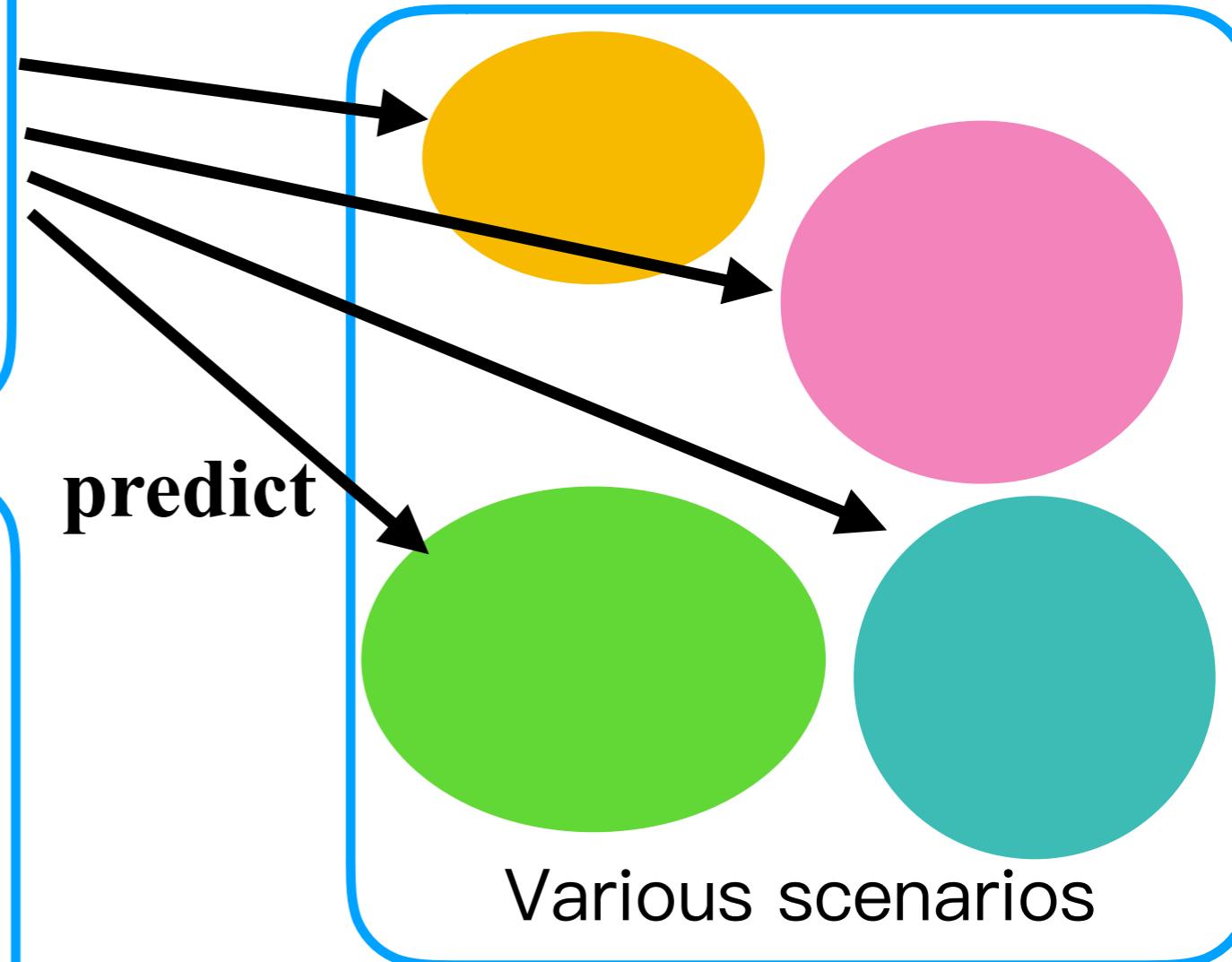
New Physics and 2HDMs

New Physics

- Supersymmetry (MSSM)
Haber and Kane, Phys. Rep. 117, 75 (1985).
- Compositeness (Higgs as pNGB)
Curtis, Delle Rose, Moretti and Yagyu, High Energy Phys. (2018)
- Zee model
Zee, Phys. Lett. B93, 38 (1980)
- Inert doublet model
Barbieri, Hall and Rychkov (2006)

determine

2HDMs



Unsolved phenomena in the SM

- The gauge hierarchy problem
- Neutrino masses
- Dark matter
- Baryon asymmetry (EW baryogenesis)

The way to test the 2HDMs

1. the direct searches (additional Higgs boson)

The way to test the 2HDMs

1. the direct searches (additional Higgs boson)
2. the indirect searches (precisely measured h couplings)
 - Higgs–gauge couplings: hVV ($V = W^\pm$ and Z)
 - Yukawa couplings: hff (e.g., $h\tau\tau$, $hb\bar{b}$)

The way to test the 2HDMs

1. the direct searches (additional Higgs boson)
2. the indirect searches (precisely measured h couplings)
 - Higgs–gauge couplings: hVV ($V = W^\pm$ and Z)
 - Yukawa couplings: hff (e.g., $h\tau\tau$, $hb\bar{b}$)

HL-LHC : a few percent level

arXiv : 1903.01629

The way to test the 2HDMs

1. the direct searches (additional Higgs boson)
2. the indirect searches (precisely measured h couplings)
 - Higgs–gauge couplings: hVV ($V = W^\pm$ and Z)
 - Yukawa couplings: hff (e.g., $h\tau\tau$, $hb\bar{b}$)

HL-LHC : a few percent level

arXiv : 1903.01629

+ ILC250 : $hVV \sim$ **sub-percent level**
 $hff \sim$ **one percent level**

K. Fujii *et al.*, arXiv : 1710.07621

The way to test the 2HDMs

1. the direct searches (additional Higgs boson)
2. the indirect searches (precisely measured h couplings)
 - Higgs–gauge couplings: hVV ($V = W^\pm$ and Z)
 - Yukawa couplings: hff (e.g., $h\tau\tau$, $hb\bar{b}$)

HL-LHC : a few percent level

arXiv : 1903.01629

+ ILC250 : $hVV \sim$ **sub-percent level**
 $hff \sim$ **one percent level**

K. Fujii *et al.*, arXiv : 1710.07621

In the 2HDMs, these h couplings can deviate from the SM prediction

The way to test the 2HDMs

1. the direct searches (additional Higgs boson)
2. the indirect searches (precisely measured h couplings)
 - Higgs–gauge couplings: hVV ($V = W^\pm$ and Z)
 - Yukawa couplings: hff (e.g., $h\tau\tau$, $hb\bar{b}$)
 - Higgs self–couplings

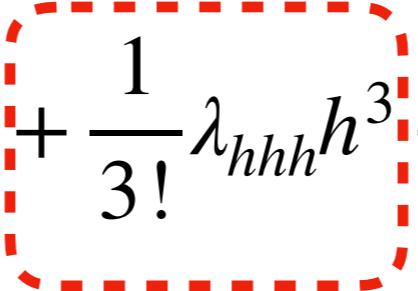
The way to test the 2HDMs

1. the direct searches (additional Higgs boson)
2. the indirect searches (precisely measured h couplings)
 - Higgs–gauge couplings: hVV ($V = W^\pm$ and Z)
 - Yukawa couplings: hff (e.g., $h\tau\tau$, $hb\bar{b}$)
 - Higgs self–couplings

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

The way to test the 2HDMs

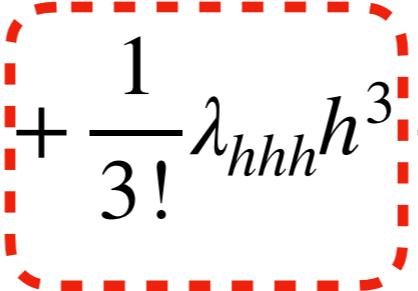
1. the direct searches (additional Higgs boson)
2. the indirect searches (precisely measured h couplings)
 - Higgs–gauge couplings: hVV ($V = W^\pm$ and Z)
 - Yukawa couplings: hff (e.g., $h\tau\tau$, $hb\bar{b}$)
 - Higgs self–couplings

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


ILC can measure the h trilinear coupling

The way to test the 2HDMs

1. the direct searches (additional Higgs boson)
2. the indirect searches (precisely measured h couplings)
 - Higgs–gauge couplings: hVV ($V = W^\pm$ and Z)
 - Yukawa couplings: hff (e.g., $h\tau\tau$, $hb\bar{b}$)
 - Higgs self–couplings

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


ILC can measure the h trilinear coupling

We focus on the $e^+e^- \rightarrow hh\bar{f}\bar{f}$ process to test the 2HDMs.

The Higgs basis

SM + additional SU(2) doublet : ϕ_1, ϕ_2 .

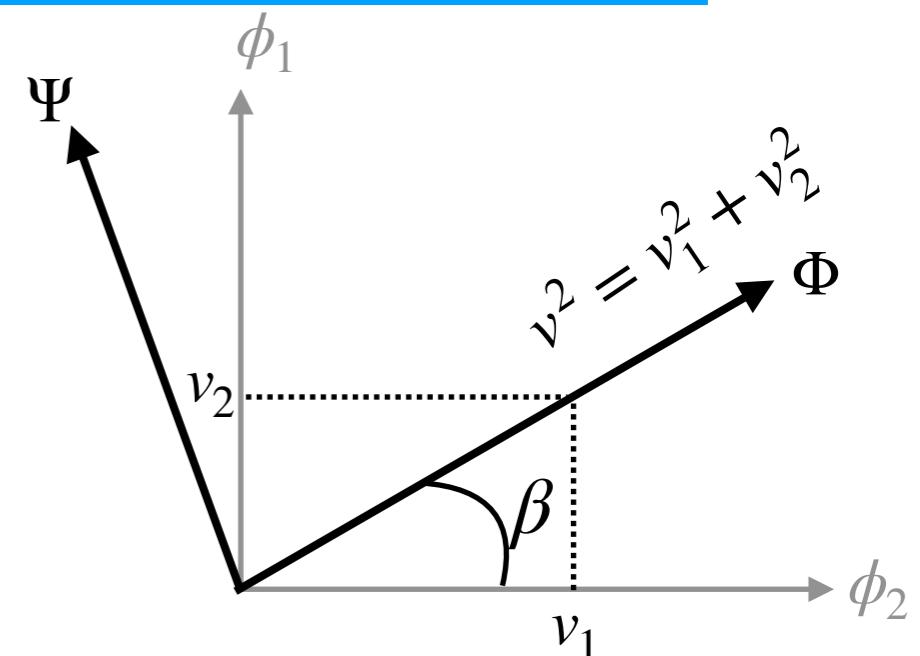
The Higgs basis

Davidson and Haber, PRD72 (2005) 035004

Georgi and Nanopoulos, Phys. Lett. 82B, 95 (1979).

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos \beta & -\sin \beta \\ \sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} \Phi \\ \Psi \end{pmatrix}$$

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



$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h'_1 + iG^0) \end{pmatrix} \quad \Psi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h'_2 + iA^0) \end{pmatrix}$$

The Higgs basis

SM + additional SU(2) doublet : ϕ_1, ϕ_2 .

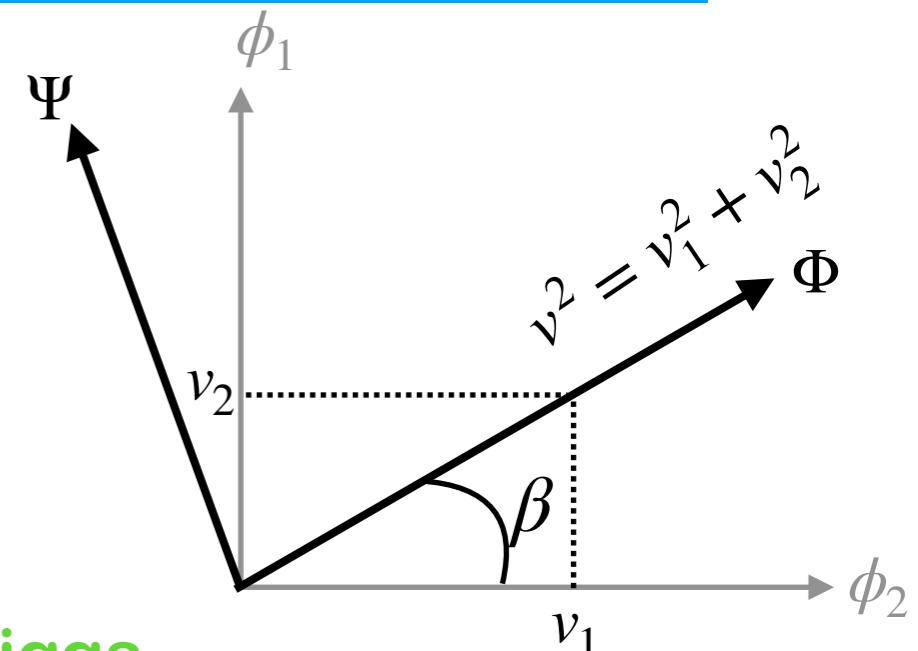
The Higgs basis

Davidson and Haber, PRD72 (2005) 035004

Georgi and Nanopoulos, Phys. Lett. 82B, 95 (1979).

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos \beta & -\sin \beta \\ \sin \beta & \cos \beta \end{pmatrix} \begin{pmatrix} \Phi \\ \Psi \end{pmatrix}$$

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



NG boson

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h'_1 + iG^0) \end{pmatrix} \quad \Psi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h'_2 + iA^0) \end{pmatrix}$$

CP even Higgs

CP odd Higgs

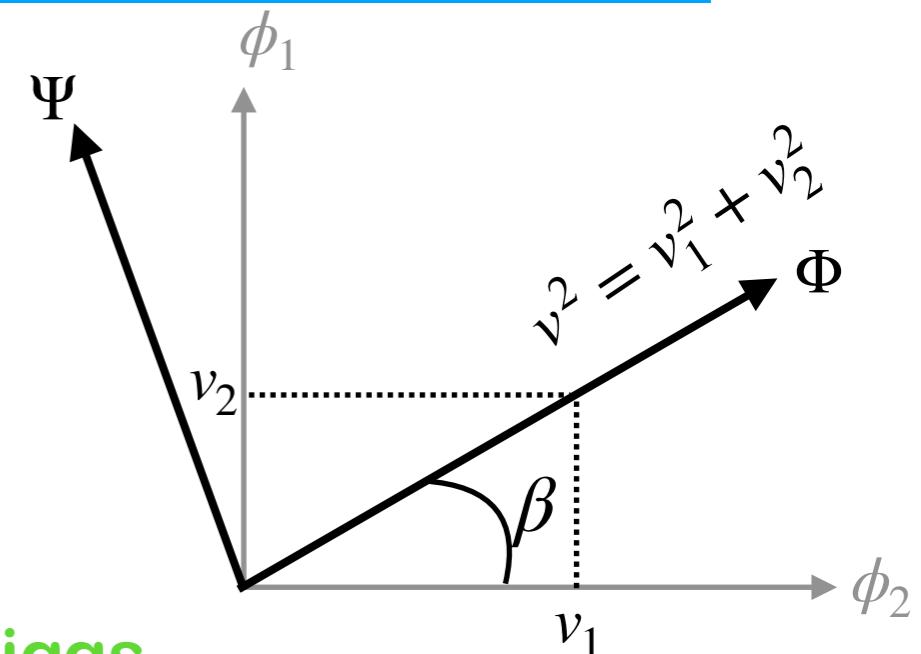
The Higgs basis

SM + additional SU(2) doublet : ϕ_1, ϕ_2 .

The Higgs basis Davidson and Haber, PRD72 (2005) 035004
Georgi and Nanopoulos, Phys. Lett. 82B, 95 (1979).

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi \\ \Psi \end{pmatrix}$$

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



NG boson

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h'_1 + iG^0) \end{pmatrix} \quad \Psi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h'_2 + iA^0) \end{pmatrix}$$

CP even Higgs **CP odd Higgs**

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

The Higgs basis

SM + additional SU(2) doublet : ϕ_1, ϕ_2 .

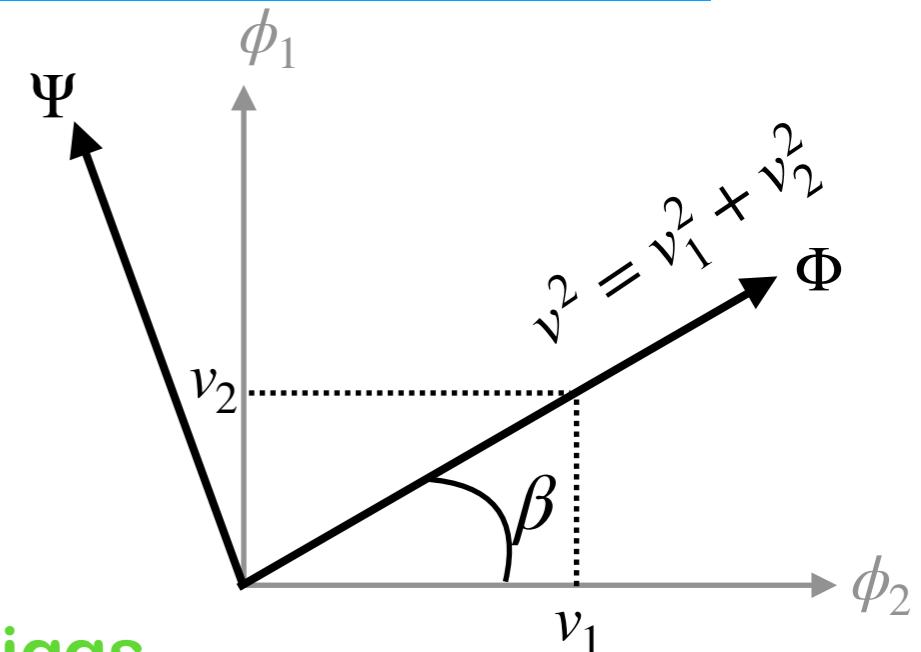
The Higgs basis

Davidson and Haber, PRD72 (2005) 035004

Georgi and Nanopoulos, Phys. Lett. 82B, 95 (1979).

$$\begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi \\ \Psi \end{pmatrix}$$

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



NG boson

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

CP even Higgs

charged Higgs

$$\Psi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h'_2 + iA^0) \end{pmatrix}$$

CP odd Higgs

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



SM-like Higgs boson



Heavier CP-even Higgs boson



CP odd Higgs



charged Higgs

The Higgs potential

The Higgs potential (softly-broken Z_2 symmetry and CP conservation)

$$\begin{aligned}
 V_{\text{2HDM}} = & \mu_1^2(\phi_1^\dagger \phi_1) + \mu_2^2(\phi_2^\dagger \phi_2) - \mu_3^2 [(\phi_1^\dagger \phi_2) + h.c.] \\
 & + \frac{1}{2} \lambda_1 (\phi_1^\dagger \phi_1)^2 + \frac{1}{2} \lambda_2 (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) \\
 & + \lambda_4 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) + \frac{1}{2} \lambda_5 [(\phi_1^\dagger \phi_2)^2 + h.c.]
 \end{aligned}$$

$$\phi_i = \begin{pmatrix} \omega_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + iz_i) \end{pmatrix} \quad (i = 1, 2)$$

$$v^2 = v_1^2 + v_2^2 = (246 \text{ GeV})^2$$

$$Z_2 \text{ sym. } \phi_1 \rightarrow \phi_1, \phi_2 \rightarrow -\phi_2$$

8 parameters

$v (= 246 \text{ GeV}), m_h (= 125 \text{ GeV})$
 $\sin(\beta - \alpha), \tan \beta, m_H, m_A, m_H^\pm$ and M^2

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

$$M^2 = \frac{\mu_3^2}{s_\beta c_\beta}$$

The Higgs potential

The Higgs potential (softly-broken Z_2 symmetry and CP conservation)

$$\begin{aligned}
 V_{\text{2HDM}} = & \mu_1^2(\phi_1^\dagger \phi_1) + \mu_2^2(\phi_2^\dagger \phi_2) - \mu_3^2 [(\phi_1^\dagger \phi_2) + h.c.] \\
 & + \frac{1}{2} \lambda_1 (\phi_1^\dagger \phi_1)^2 + \frac{1}{2} \lambda_2 (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) \\
 & + \lambda_4 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) + \frac{1}{2} \lambda_5 [(\phi_1^\dagger \phi_2)^2 + h.c.]
 \end{aligned}$$

$$\phi_i = \begin{pmatrix} \omega_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + iz_i) \end{pmatrix} \quad (i = 1, 2)$$

$$v^2 = v_1^2 + v_2^2 = (246 \text{ GeV})^2$$

$$Z_2 \text{ sym. } \phi_1 \rightarrow \phi_1, \phi_2 \rightarrow -\phi_2$$

8 parameters

$v (= 246 \text{ GeV}), m_h (= 125 \text{ GeV})$
 $\sin(\beta - \alpha), \tan \beta, m_H, m_A, m_H^\pm$ and M^2

When $\sin(\beta - \alpha) \rightarrow 1$ (alignment limit)

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

$$M^2 = \frac{\mu_3^2}{s_\beta c_\beta}$$

h couplings become the SM prediction

The Higgs potential

The Higgs potential (**softly-broken Z_2 symmetry** and **CP conservation**)

$$\begin{aligned}
 V_{\text{2HDM}} = & \mu_1^2(\phi_1^\dagger \phi_1) + \mu_2^2(\phi_2^\dagger \phi_2) - \mu_3^2 [(\phi_1^\dagger \phi_2) + h.c.] \\
 & + \frac{1}{2} \lambda_1 (\phi_1^\dagger \phi_1)^2 + \frac{1}{2} \lambda_2 (\phi_2^\dagger \phi_2)^2 + \lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) \\
 & + \lambda_4 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) + \frac{1}{2} \lambda_5 [(\phi_1^\dagger \phi_2)^2 + h.c.]
 \end{aligned}$$

$$\phi_i = \begin{pmatrix} \omega_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + iz_i) \end{pmatrix} \quad (i = 1, 2)$$

$$v^2 = v_1^2 + v_2^2 = (246 \text{ GeV})^2$$

$$Z_2 \text{ sym. } \phi_1 \rightarrow \phi_1, \phi_2 \rightarrow -\phi_2$$

8 parameters

$v (= 246 \text{ GeV}), m_h (= 125 \text{ GeV})$
 $\sin(\beta - \alpha), \tan \beta, m_H, m_A, m_H^\pm$ and M^2

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

$$M^2 = \frac{\mu_3^2}{s_\beta c_\beta}$$

We consider $\sin(\beta - \alpha) \neq 1$ (**non-alignment case**).

h couplings deviate from SM prediction !

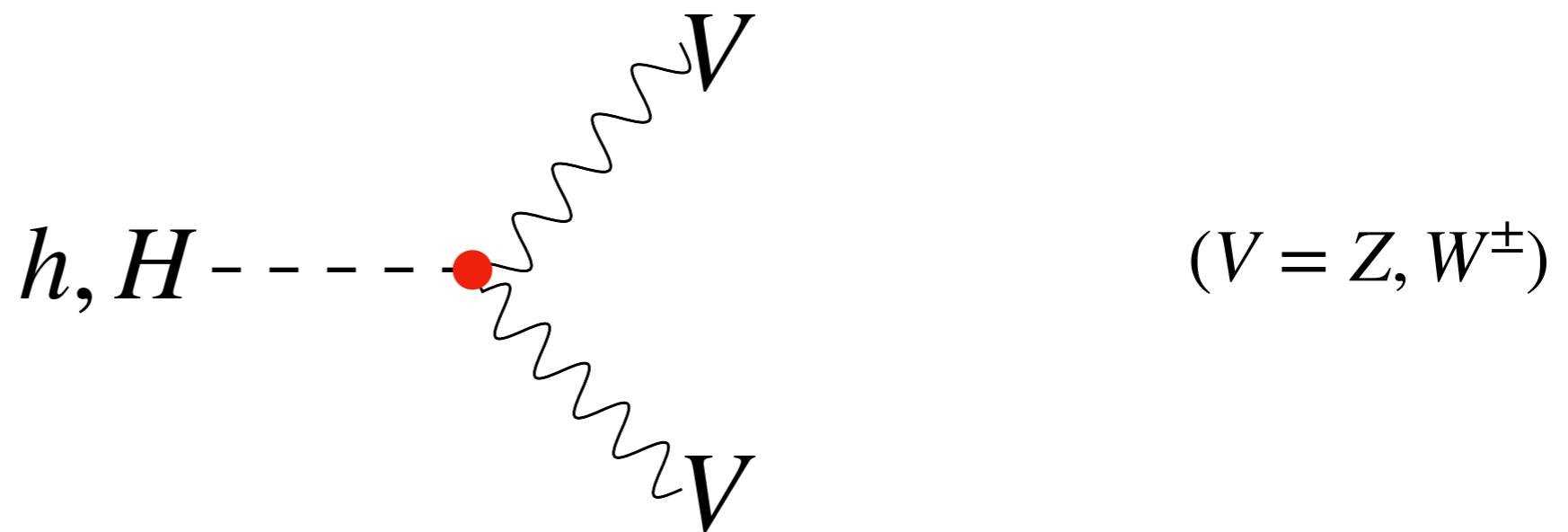
Higgs-gauge couplings

$$\mathcal{L}_{kin} = \sum_{i=1,2} |D_\mu \phi_i|^2 = |D_\mu \Phi|^2 + |D_\mu \Psi|^2$$

Higgs-gauge-gauge Higgs-Higgs-gauge

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

$$\Psi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h'_2 + iA^0) \end{pmatrix}$$



$$= (s_{\beta-\alpha}, c_{\beta-\alpha}) \times g_{\text{SM}}^{hVV}$$

$$c_\theta \equiv \cos \theta$$

Higgs-gauge couplings

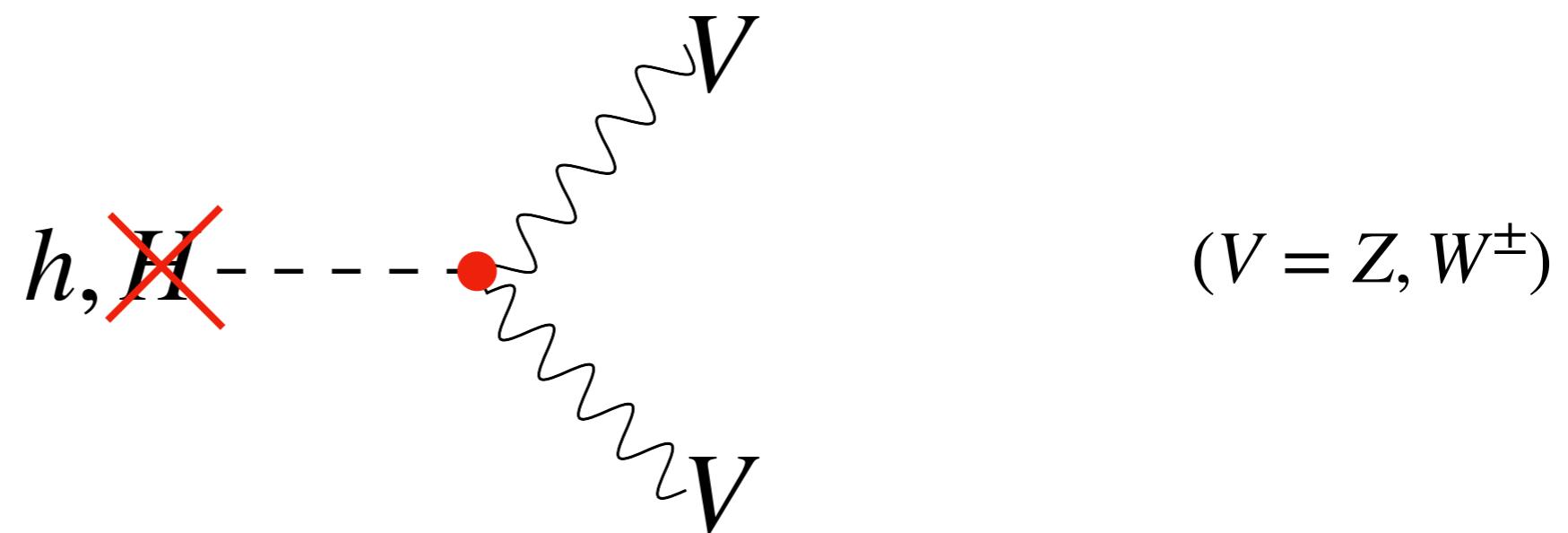
$$\mathcal{L}_{kin} = \sum_{i=1,2} |D_\mu \phi_i|^2 = |D_\mu \Phi|^2 + |D_\mu \Psi|^2$$

Higgs-gauge-gauge Higgs-Higgs-gauge

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

$$\Psi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h'_2 + iA^0) \end{pmatrix}$$

alignment limit: $\sin(\beta - \alpha) \rightarrow 1$



$$= (s_{\beta-\alpha}, c_{\beta-\alpha}) \times g_{\text{SM}}^{hVV}$$

$$c_\theta \equiv \cos \theta$$

hVV coupling becomes the SM value, and H dose not couple to V .

Higgs-gauge couplings

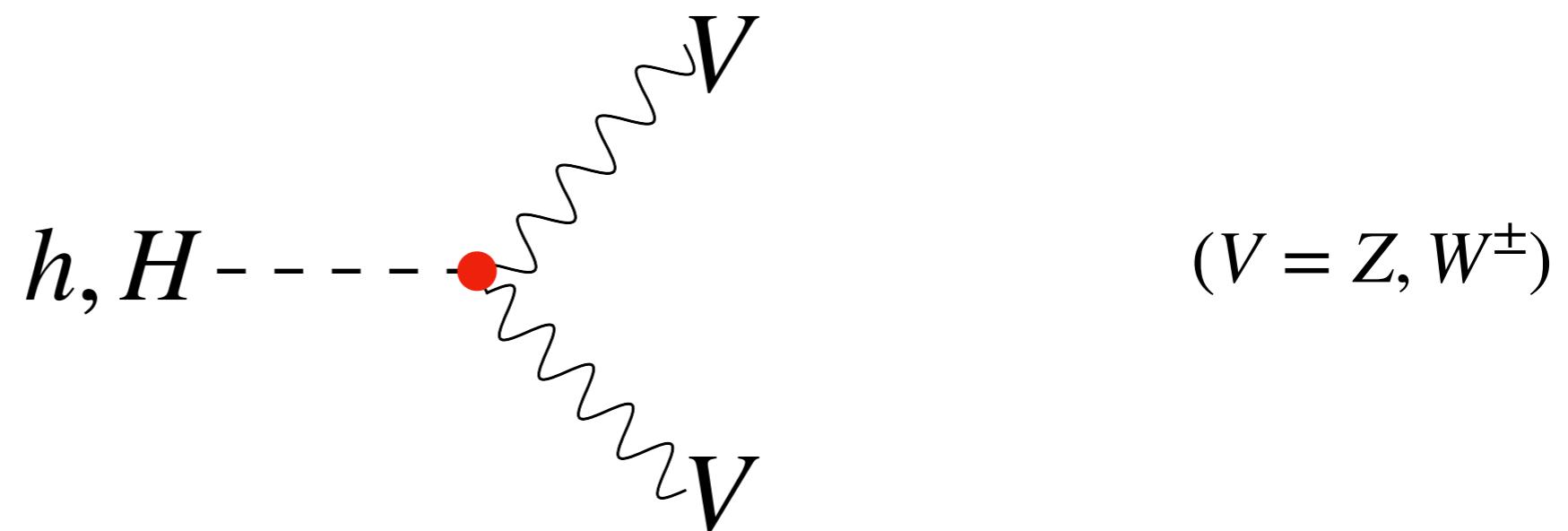
$$\mathcal{L}_{kin} = \sum_{i=1,2} |D_\mu \phi_i|^2 = |D_\mu \Phi|^2 + |D_\mu \Psi|^2$$

Higgs–gauge–gauge Higgs–Higgs–gauge

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

$$\Psi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h'_2 + iA^0) \end{pmatrix}$$

non-alignment case: $\sin(\beta - \alpha) \neq 1$



$$= (s_{\beta-\alpha}, c_{\beta-\alpha}) \times g_{\text{SM}}^{hVV}$$

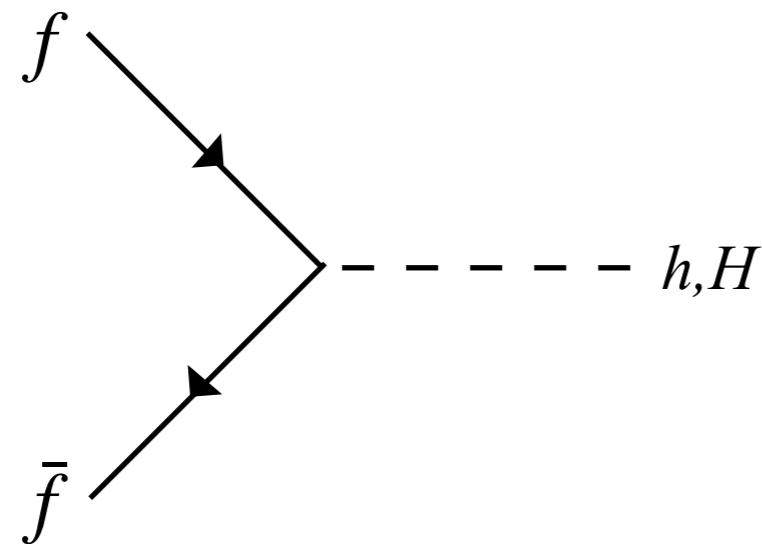
$$c_\theta \equiv \cos \theta$$

hVV couplings can deviate from SM prediction and HVV couplings appear.

Yukawa Interaction

Example. bottom quark

$$y_b Q_L \Phi_b b_R = \frac{\sqrt{2} m_b}{v} Q_L (\Phi + \xi_b \Psi) b_R$$



	ξ_u	ξ_d	ξ_e
I	$\cot\beta$	$\cot\beta$	$\cot\beta$
II	$\cot\beta$	$-\tan\beta$	$-\tan\beta$
X	$\cot\beta$	$\cot\beta$	$-\tan\beta$
Y	$\cot\beta$	$-\tan\beta$	$\cot\beta$

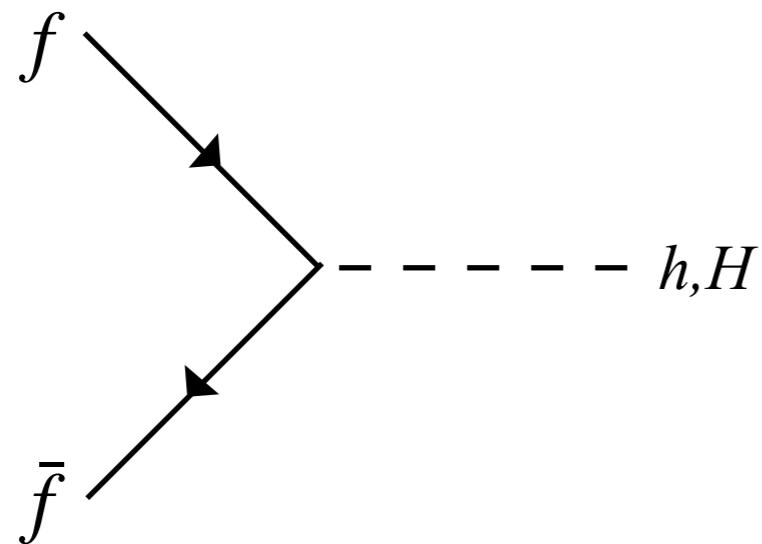
Barger, Hewett and Phillips, PRD41(1991),
 Grossman, NPB426 (1994),
 Aoki, Kanemura, Tsumura, Yagyu, PRD80 (2009)

$$= \begin{cases} (\sin(\beta - \alpha) + \xi_f \cos(\beta - \alpha)) \times g_{hff}^{\text{SM}} & \text{for } h \\ (\cos(\beta - \alpha) - \xi_f \sin(\beta - \alpha)) \times g_{Hff}^{\text{SM}} & \text{for } H \end{cases}$$

Yukawa Interaction

Example. bottom quark

$$y_b Q_L \Phi_b b_R = \frac{\sqrt{2} m_b}{v} Q_L (\Phi + \xi_b \Psi) b_R$$



	ξ_u	ξ_d	ξ_e
I	$\cot \beta$	$\cot \beta$	$\cot \beta$
II	$\cot \beta$	$-\tan \beta$	$-\tan \beta$
X	$\cot \beta$	$\cot \beta$	$-\tan \beta$
Y	$\cot \beta$	$-\tan \beta$	$\cot \beta$

Barger, Hewett and Phillips, PRD41(1991),
Grossman, NPB426 (1994),
Aoki, Kanemura, Tsumura, Yagyu, PRD80 (2009)

alignment limit ($\sin(\beta - \alpha) \rightarrow 1$)

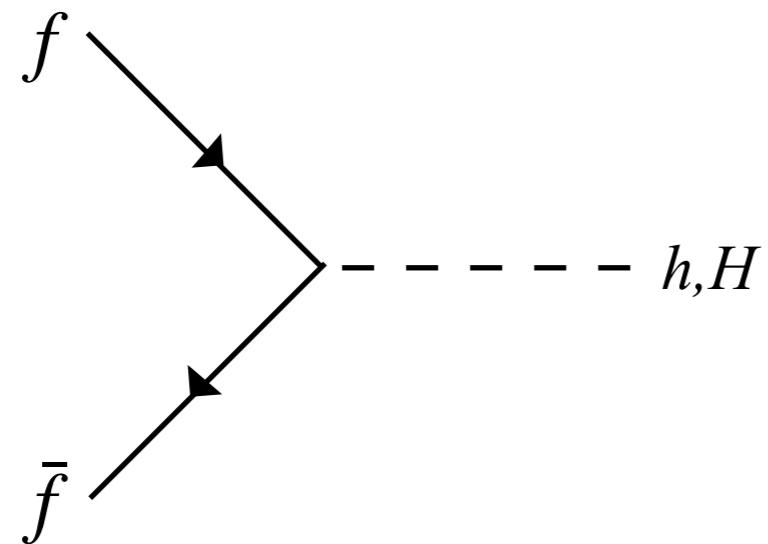
$$= \begin{cases} (\sin(\beta - \alpha) + \cancel{\xi_f \cos(\beta - \alpha)}) \times g_{hff}^{\text{SM}} & \text{for } h \\ \cancel{(\cos(\beta - \alpha))} - \xi_f \sin(\beta - \alpha) \times g_{Hff}^{\text{SM}} & \text{for } H \end{cases}$$

hff couplings become the SM values.

Yukawa Interaction

Example. bottom quark

$$y_b Q_L \Phi_b b_R = \frac{\sqrt{2} m_b}{v} Q_L (\Phi + \xi_b \Psi) b_R$$



	ξ_u	ξ_d	ξ_e
I	$\cot \beta$	$\cot \beta$	$\cot \beta$
II	$\cot \beta$	$-\tan \beta$	$-\tan \beta$
X	$\cot \beta$	$\cot \beta$	$-\tan \beta$
Y	$\cot \beta$	$-\tan \beta$	$\cot \beta$

non-alignment case: $\sin(\beta - \alpha) \neq 1$

Barger, Hewett and Phillips, PRD41(1991),
Grossman, NPB426 (1994),
Aoki, Kanemura, Tsumura, Yagyu, PRD80 (2009)

$$= \begin{cases} (\sin(\beta - \alpha) + \xi_f \cos(\beta - \alpha)) \times g_{hff}^{\text{SM}} & \text{for } h \\ (\cos(\beta - \alpha) - \xi_f \sin(\beta - \alpha)) \times g_{Hff}^{\text{SM}} & \text{for } H \end{cases}$$

hVV couplings are deviate from SM prediction.

Higgs trilinear couplings

■ The Higgs potential

$$V_{\text{2HDM}} = \lambda_{hhh} hhh + \lambda_{Hhh} Hhh + \dots$$

$$\lambda_{hhh} = -\frac{m_h^2}{2\nu} s_{\beta-\alpha} + \mathcal{O}(c_{\beta-\alpha}^2) + \dots$$

$$\lambda_{Hhh} = -\frac{1}{2\nu} (4M^2 - 2m_h^2 - m_H^2) c_{\beta-\alpha} + \mathcal{O}(c_{\beta-\alpha}^2) + \dots$$

Higgs trilinear couplings

■ The Higgs potential

$$V_{\text{2HDM}} = \lambda_{hhh} hhh + \lambda_{Hhh} Hhh + \dots$$

alignment limit ($\sin(\beta - \alpha) \rightarrow 1$)

$$\lambda_{hhh} = -\frac{m_h^2}{2v} s_{\beta-\alpha} + \mathcal{O}(\cancel{c_{\beta-\alpha}^2}) + \dots$$

$$\lambda_{Hhh} = -\frac{1}{2v} (\cancel{4M^2 - 2m_h^2 - m_H^2}) c_{\beta-\alpha} + \mathcal{O}(\cancel{c_{\beta-\alpha}^2}) + \dots$$

hhh coupling becomes the SM value, and Hhh coupling vanishes.

Higgs trilinear couplings

■ The Higgs potential

$$V_{\text{2HDM}} = \lambda_{hhh} hhh + \lambda_{Hhh} Hhh + \dots$$

non-alignment case: $\sin(\beta - \alpha) \neq 1$

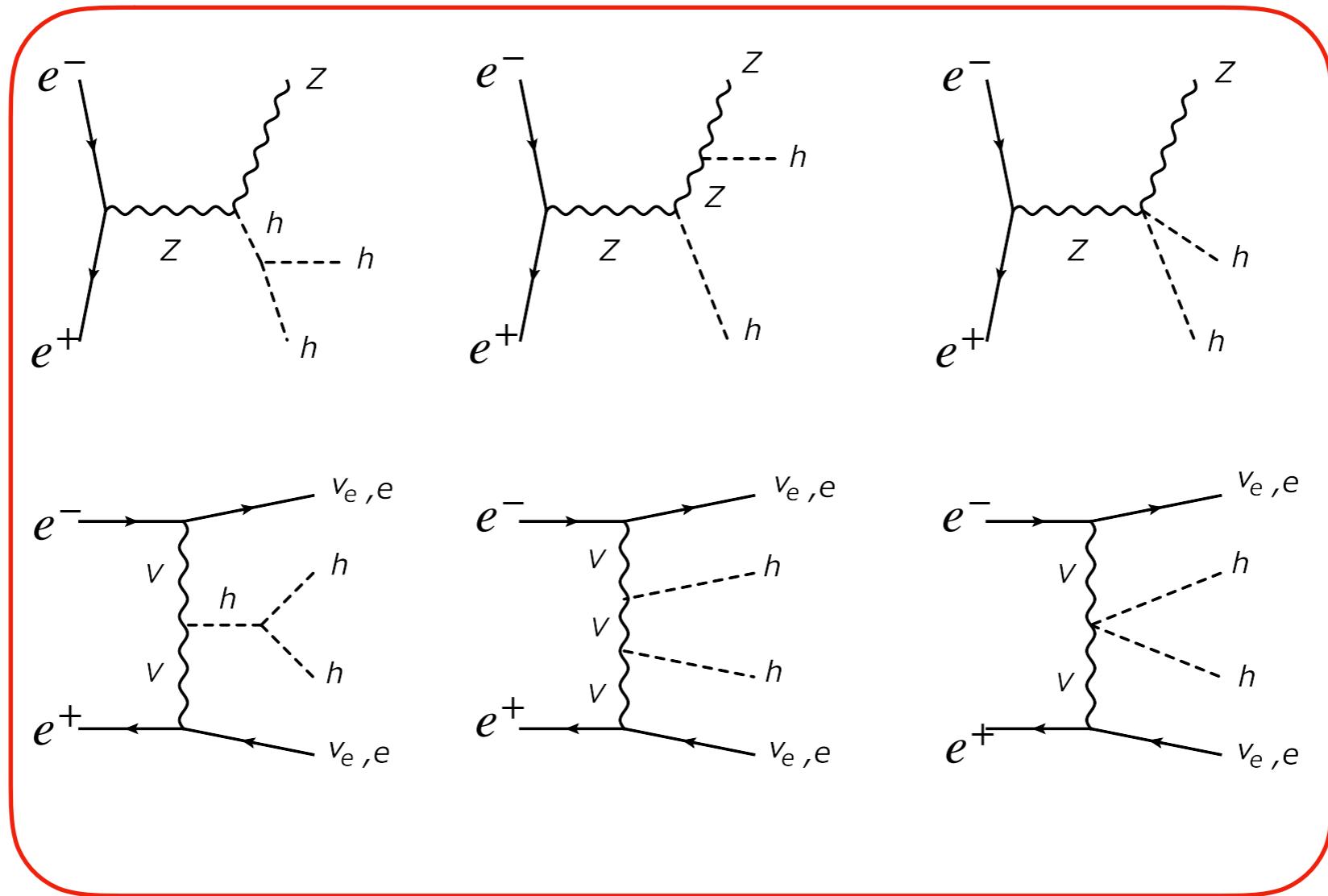
$$\lambda_{hhh} = -\frac{m_h^2}{2\nu} s_{\beta-\alpha} + \mathcal{O}(c_{\beta-\alpha}^2) + \dots$$

$$\lambda_{Hhh} = -\frac{1}{2\nu} (4M^2 - 2m_h^2 - m_H^2) c_{\beta-\alpha} + \mathcal{O}(c_{\beta-\alpha}^2) + \dots$$

hhh and Hhh couplings also deviate from the values of predictions in the SM

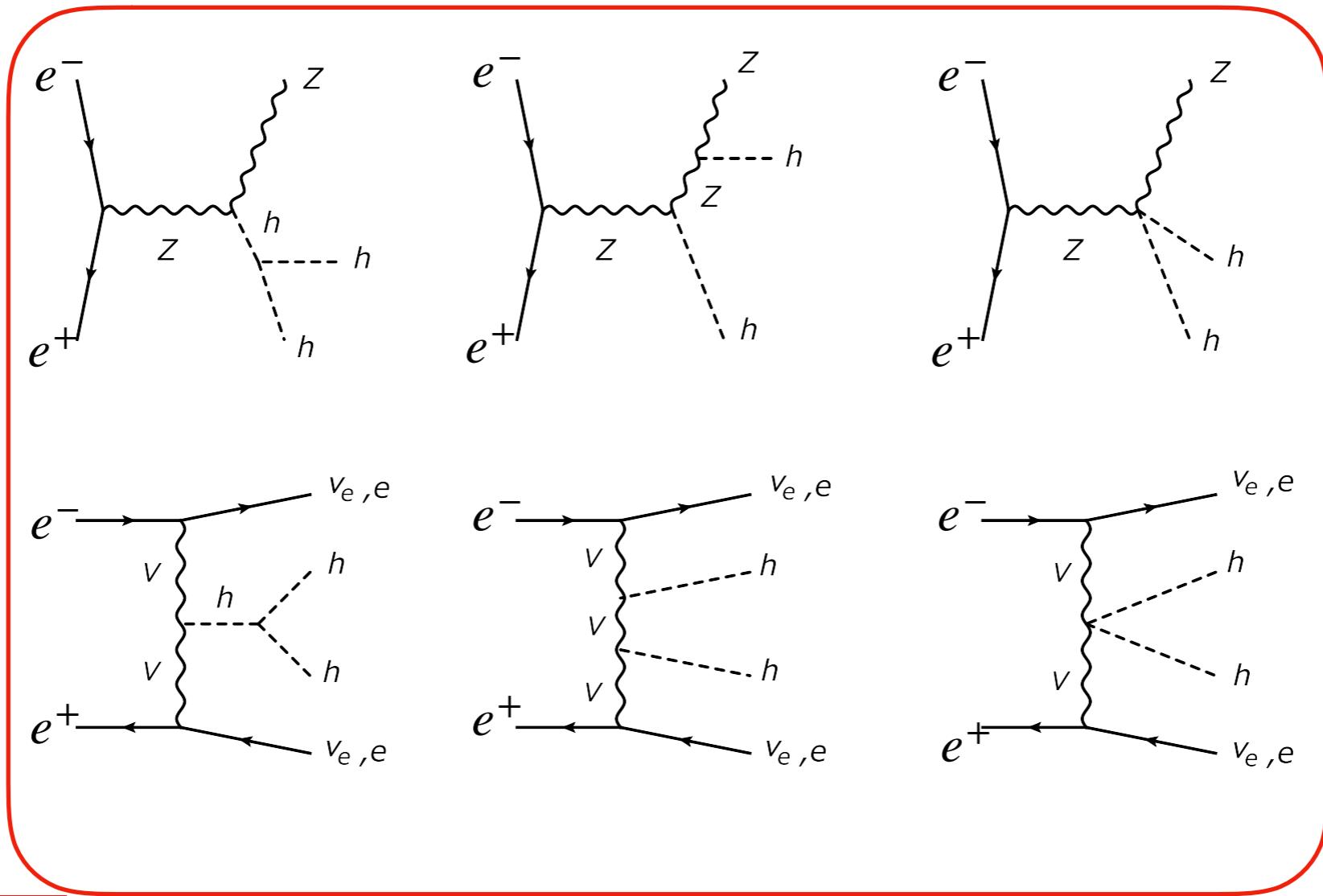
Double Higgs boson production

SM



Double Higgs boson production

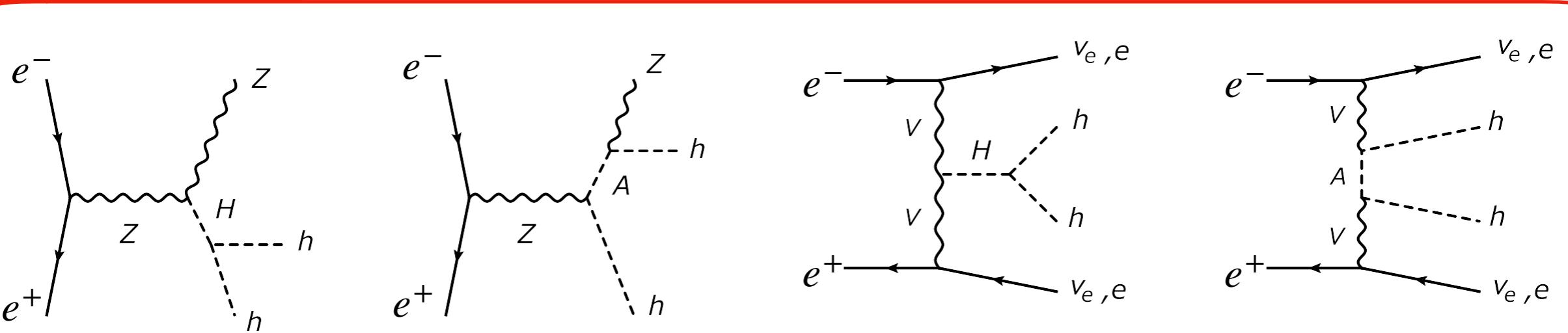
2HDM



alignment limit
Asakawa, Harada,
Kanemura, Okada,
Tsumura, Phys. Rev.
D82, 115002 (2010)

non-alignment case

+



Constraints

Kon, TN, Ueda, Yagyu PRD99 (2019) 095027

Type I 2HDM the other types are highly constrained by the experiment

$$\kappa_f = \sin(\beta - \alpha) + \frac{\cos(\beta - \alpha)}{\tan \beta} \quad \kappa_f \equiv \frac{g_{hff}^{THDM}}{g_{hff}^{SM}}$$

★ κ_f does not depend on the choice of the fermion f .

Constraints

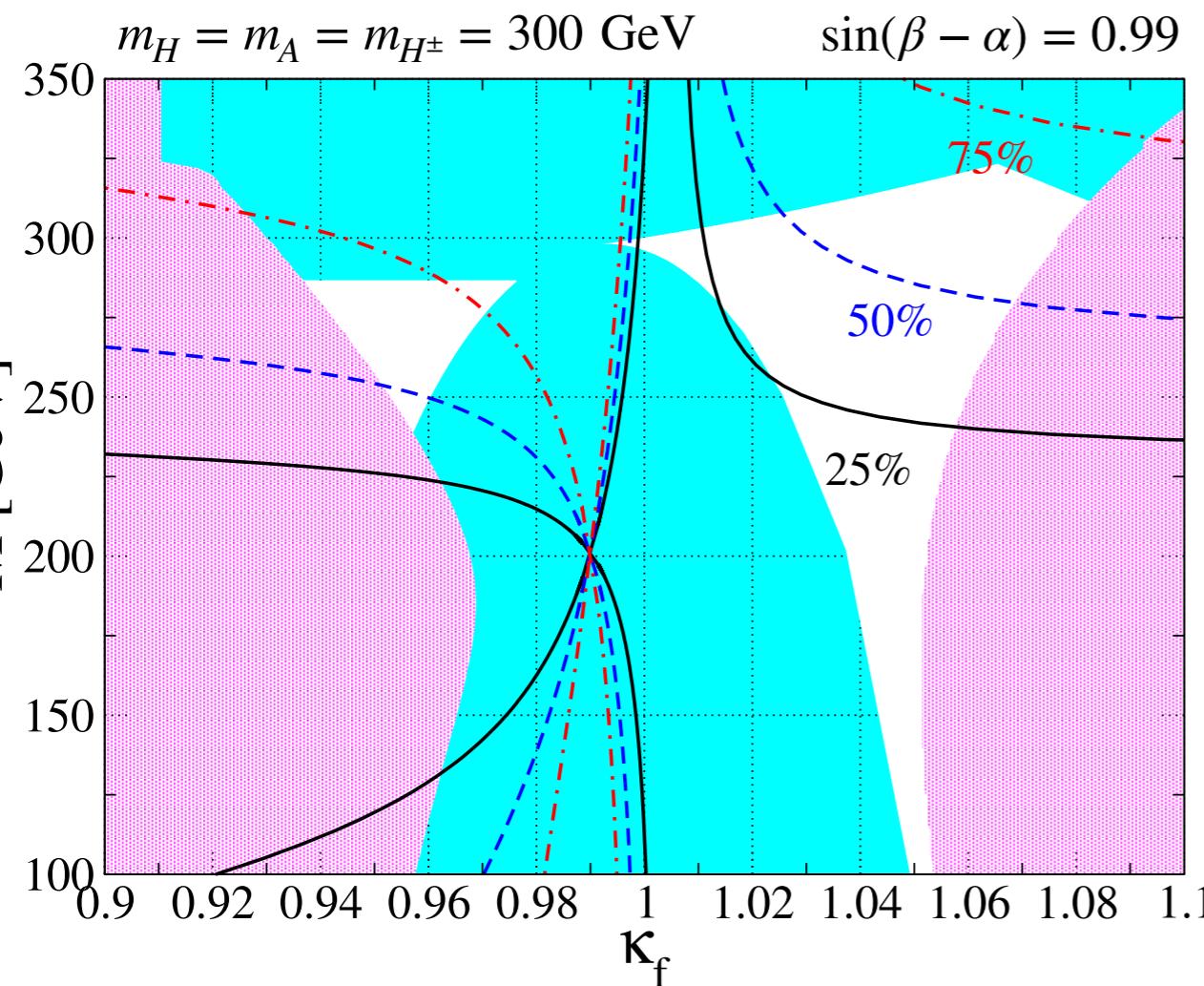
Kon, TN, Ueda, Yagyu PRD99 (2019) 095027

Type I 2HDM the other types are highly constrained by the experiment

$$\kappa_f = \sin(\beta - \alpha) + \frac{\cos(\beta - \alpha)}{\tan \beta}$$

$$\kappa_f \equiv \frac{g_{hff}^{THDM}}{g_{hff}^{SM}}$$

★ κ_f does not depend on the choice of the fermion f .



blue · · · The perturbative bound, the vacuum stability bound, and the electroweak oblique S, T parameters.

magenta · · · Direct searches at the LEP, Tevatron, and the LHC experiments

Constraints

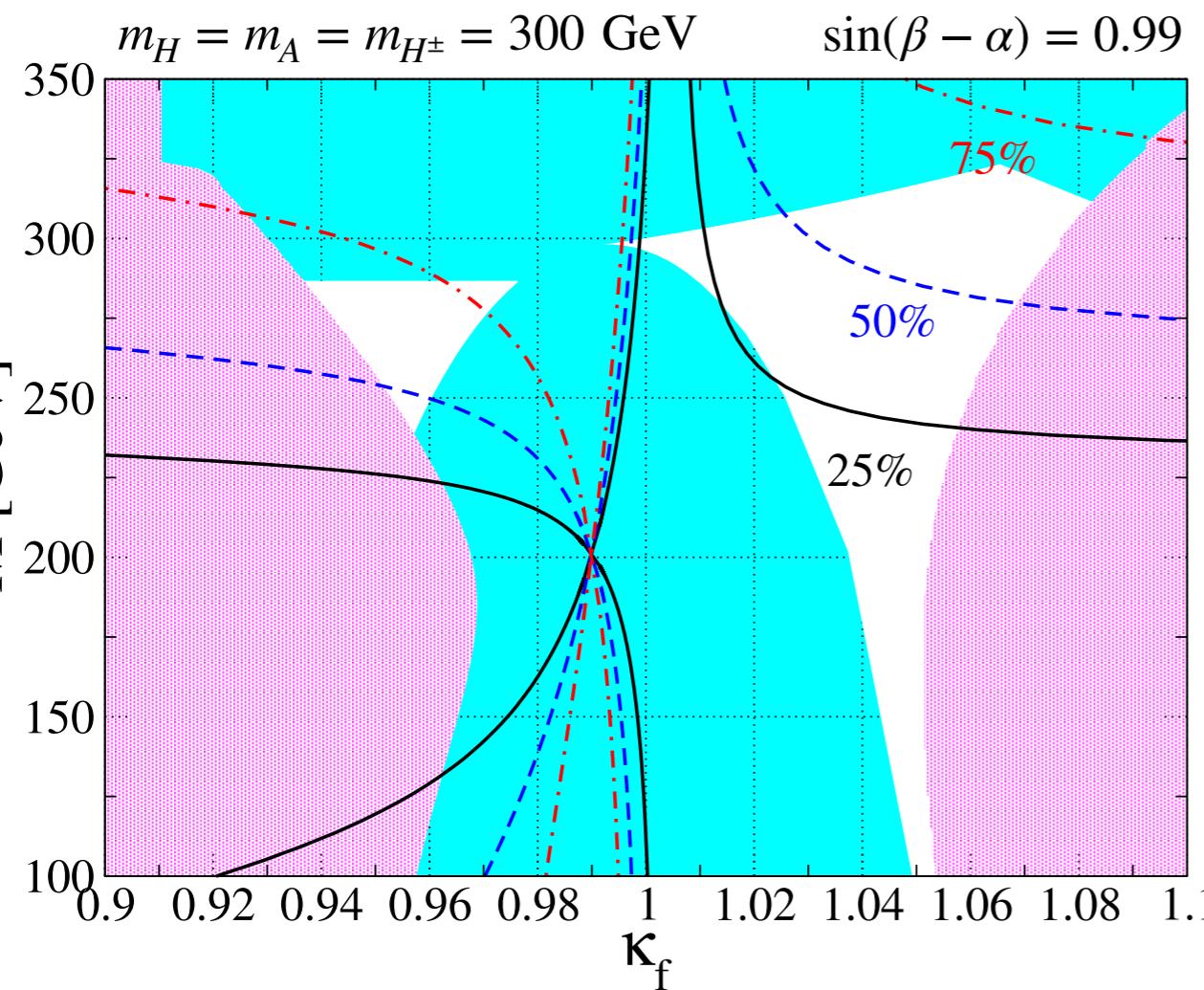
Kon, TN, Ueda, Yagyu PRD99 (2019) 095027

Type I 2HDM the other types are highly constrained by the experiment

$$\kappa_f = \sin(\beta - \alpha) + \frac{\cos(\beta - \alpha)}{\tan \beta}$$

$$\kappa_f \equiv \frac{g_{hff}^{THDM}}{g_{hff}^{SM}}$$

★ κ_f does not depend on the choice of the fermion f .



$\text{BR}(H \rightarrow hh)$

$$= \left\{ \begin{array}{ll} \text{—} & 25\% \\ \text{---} & 50\% \\ \text{---} & 75\% \end{array} \right.$$

blue · · · The perturbative bound, the vacuum stability bound, and the electroweak oblique S, T parameters.

magenta · · · Direct searches at the LEP, Tevatron, and the LHC experiments

Constraints

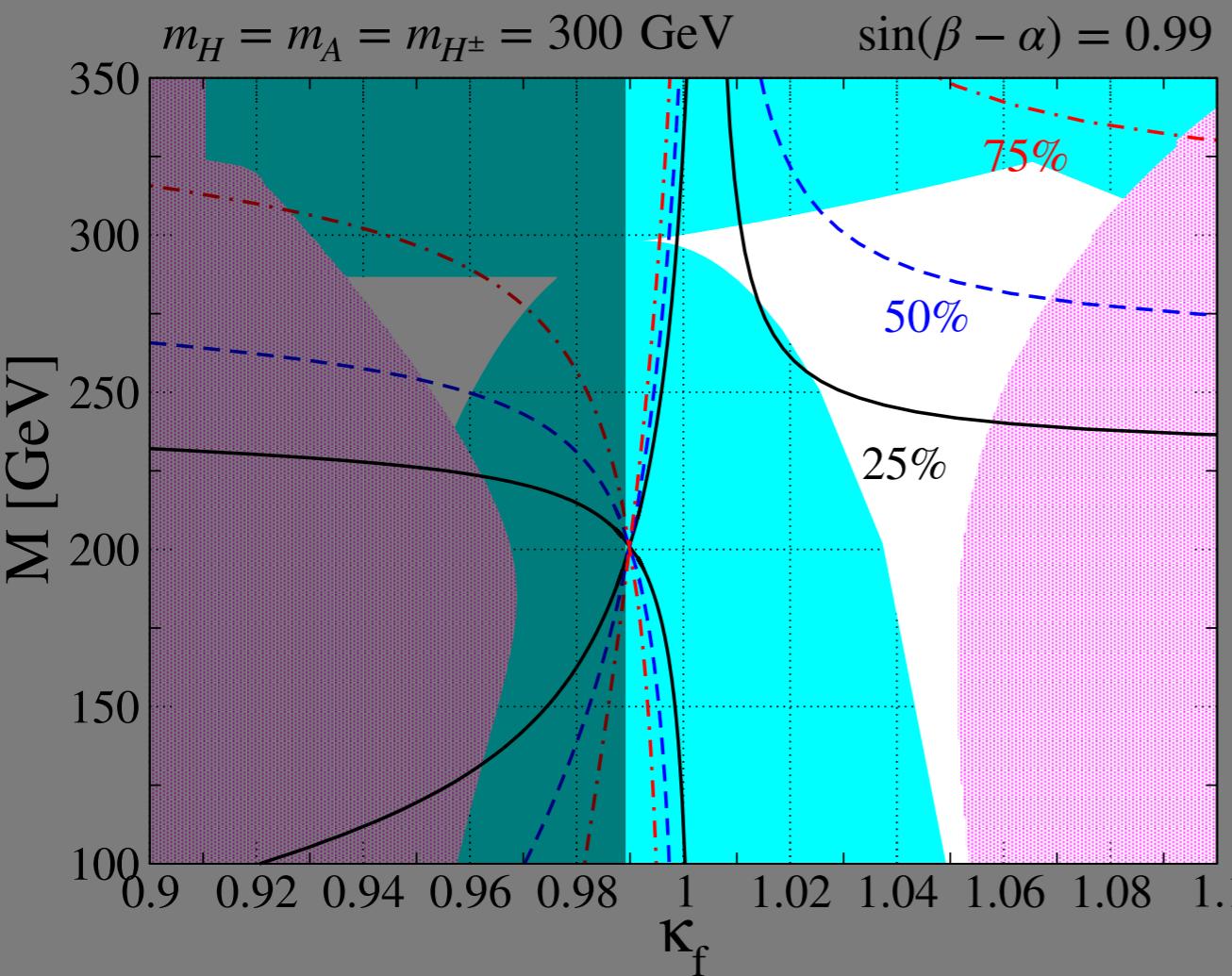
Kon, TN, Ueda, Yagyu PRD99 (2019) 095027

Type I 2HDM the other types are highly constrained by the experiment

$$\kappa_f = \sin(\beta - \alpha) + \frac{\cos(\beta - \alpha)}{\tan \beta}$$

$$\kappa_f \equiv \frac{g_{hff}^{THDM}}{g_{hff}^{SM}}$$

★ κ_f does not depend on the choice of the fermion f .



$$\cos(\beta - \alpha) > 0$$

$$\text{BR}(H \rightarrow hh)$$

$$= \left\{ \begin{array}{ll} \text{—} & 25\% \\ \text{---} & 50\% \\ \text{---} & 75\% \end{array} \right.$$

blue · · · The perturbative bound, the vacuum stability bound, and the electroweak oblique S, T parameters.

magenta · · · Direct searches at the LEP, Tevatron, and the LHC experiments

Constraints

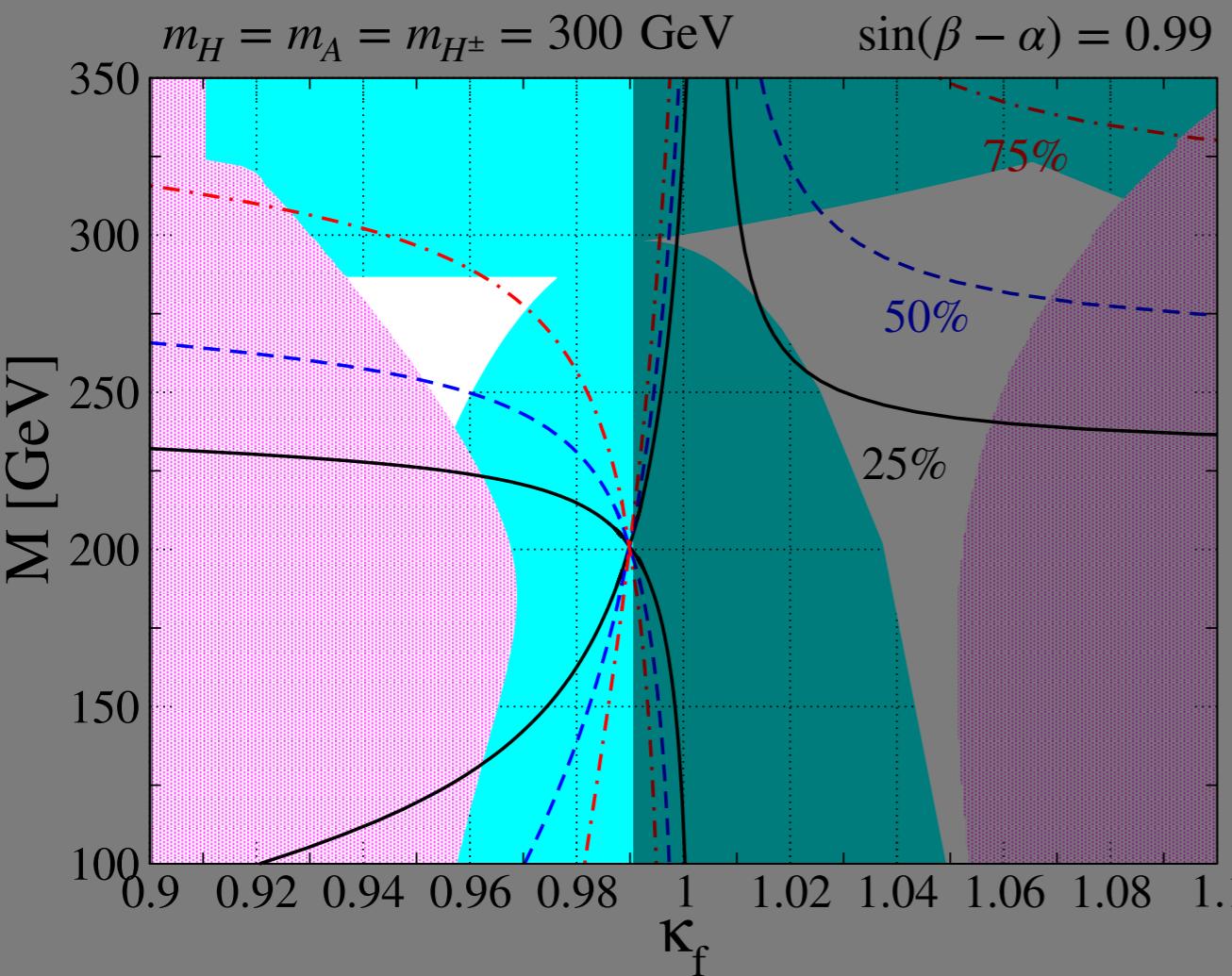
Kon, TN, Ueda, Yagyu PRD99 (2019) 095027

Type I 2HDM the other types are highly constrained by the experiment

$$\kappa_f = \sin(\beta - \alpha) + \frac{\cos(\beta - \alpha)}{\tan \beta}$$

$$\kappa_f \equiv \frac{g_{hff}^{THDM}}{g_{hff}^{SM}}$$

★ κ_f does not depend on the choice of the fermion f .



$$\cos(\beta - \alpha) < 0$$

$$\text{BR}(H \rightarrow hh)$$

$$= \left\{ \begin{array}{ll} \text{—} & 25\% \\ \text{---} & 50\% \\ \text{---} & 75\% \end{array} \right.$$

blue · · · The perturbative bound, the vacuum stability bound, and the electroweak oblique S, T parameters.

magenta · · · Direct searches at the LEP, Tevatron, and the LHC experiments

Constraints

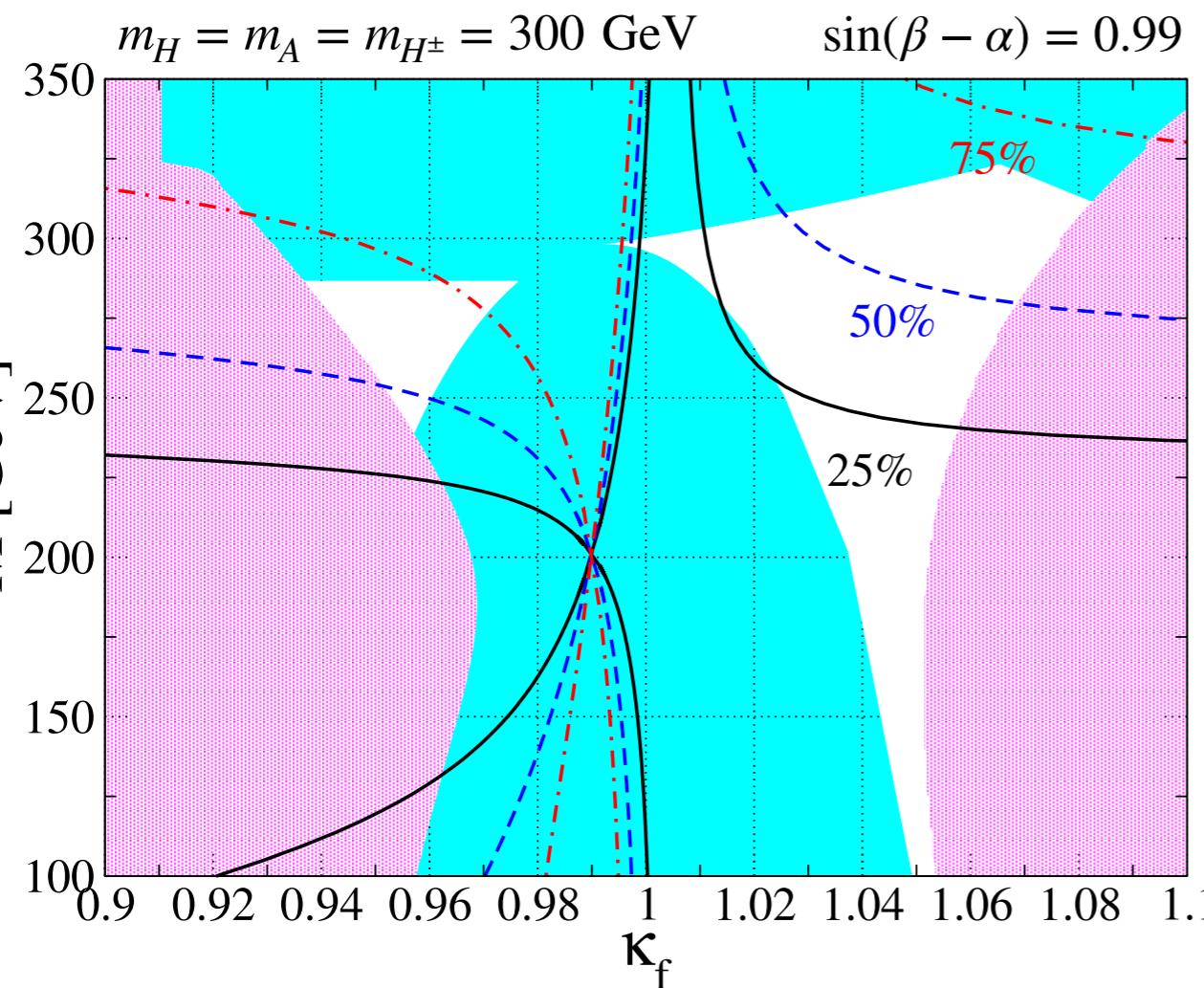
Kon, TN, Ueda, Yagyu PRD99 (2019) 095027

Type I 2HDM the other types are highly constrained by the experiment

$$\kappa_f = \sin(\beta - \alpha) + \frac{\cos(\beta - \alpha)}{\tan \beta}$$

$$\kappa_f \equiv \frac{g_{hff}^{THDM}}{g_{hff}^{SM}}$$

★ κ_f does not depend on the choice of the fermion f .



The LHC constraints only exclude the case with low $\tan \beta$

The theory constraints excluded in the large $\tan \beta$ region

blue · · · The perturbative bound, the vacuum stability bound, and the electroweak oblique S, T parameters.

magenta · · · Direct searches at the LEP, Tevatron, and the LHC experiments

Constraints

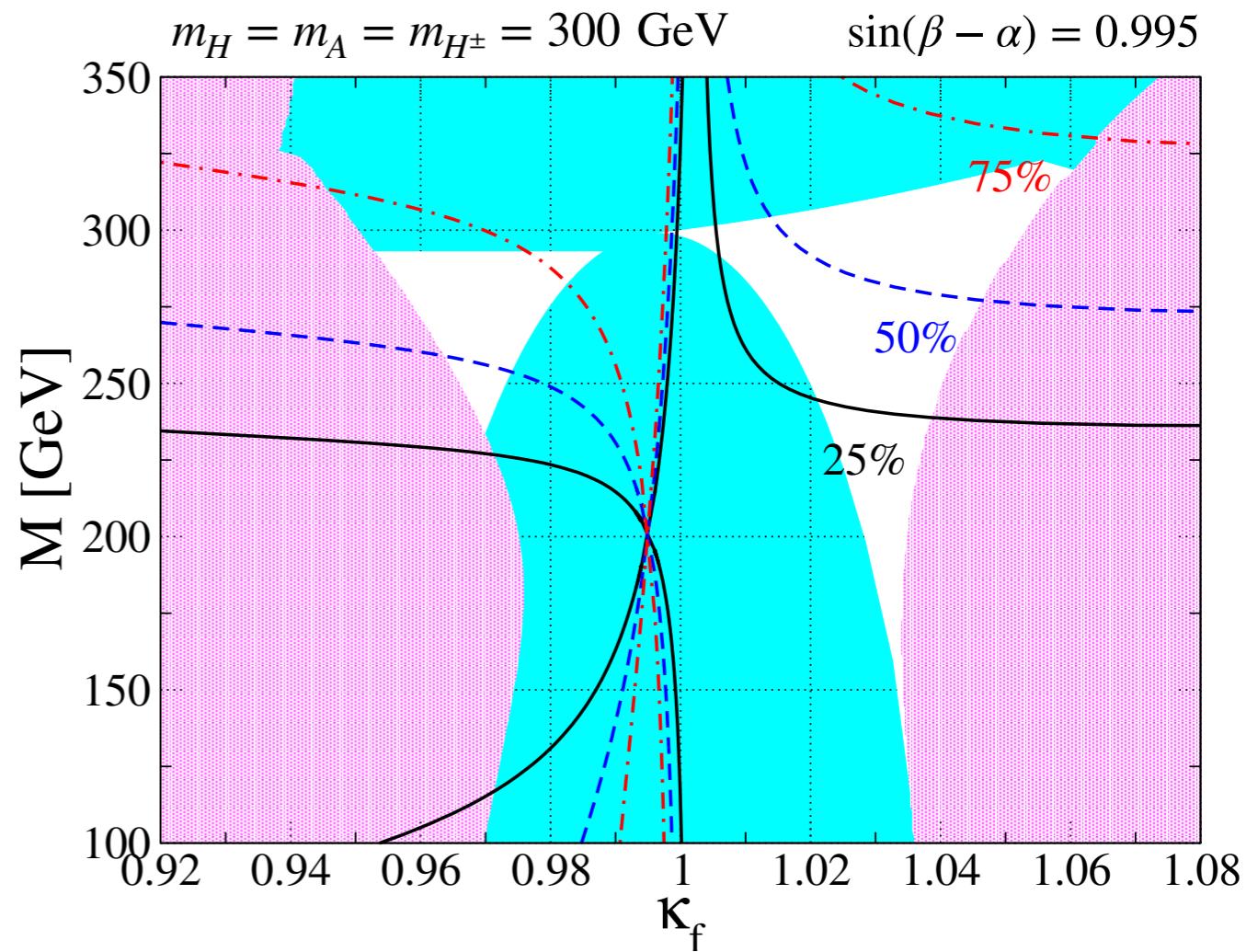
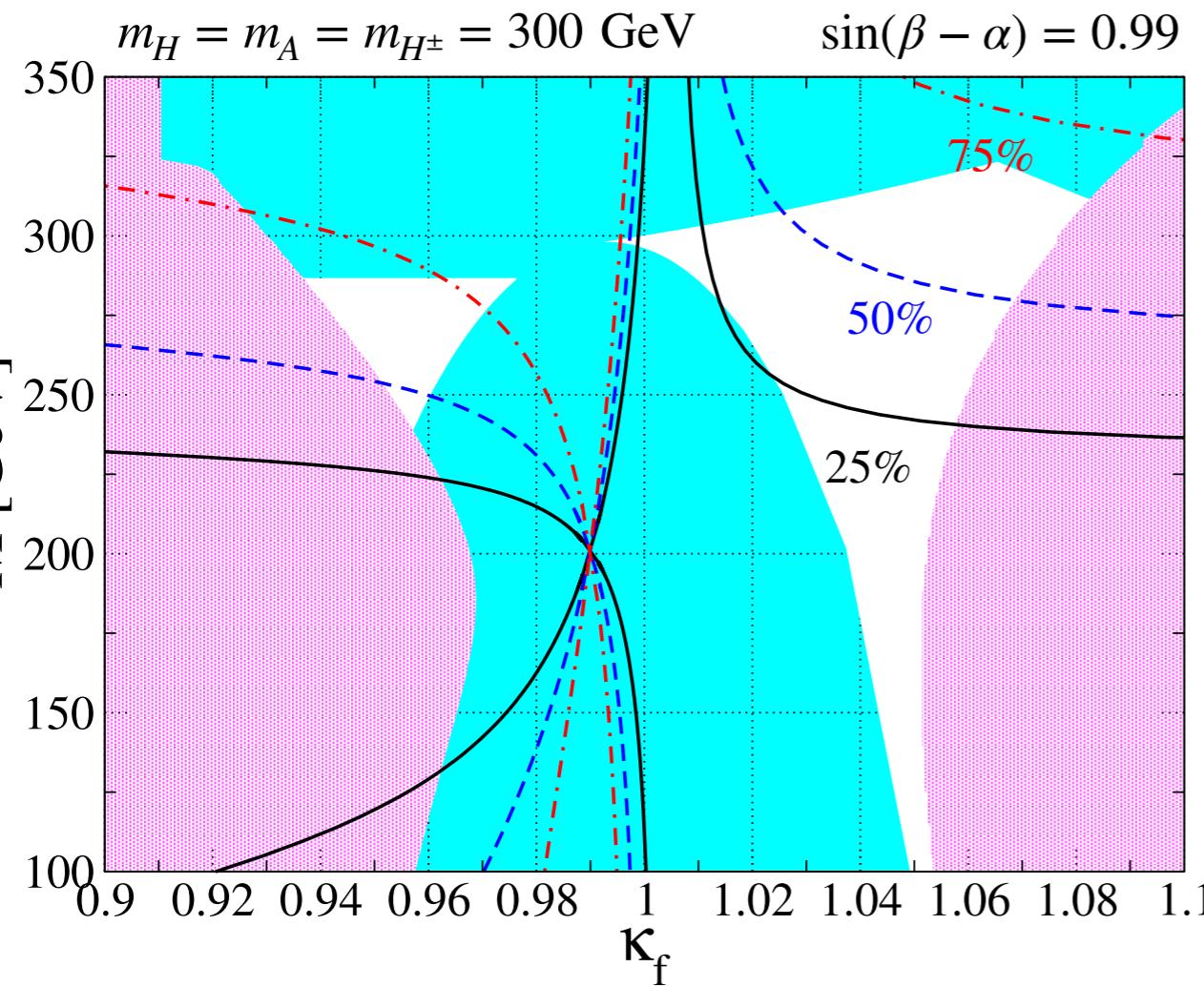
Kon, TN, Ueda, Yagyu PRD99 (2019) 095027

Type I 2HDM the other types are highly constrained by the experiment

$$\kappa_f = \sin(\beta - \alpha) + \frac{\cos(\beta - \alpha)}{\tan \beta}$$

$$\kappa_f \equiv \frac{g_{hff}^{THDM}}{g_{hff}^{SM}}$$

★ κ_f does not depend on the choice of the fermion f .



blue

- • • The perturbative bound, the vacuum stability bound, and the electroweak oblique S , T parameters.

magenta

- • • Direct searches at the LEP, Tevatron, and the LHC experiments

Numerical Results : κ_f VS R

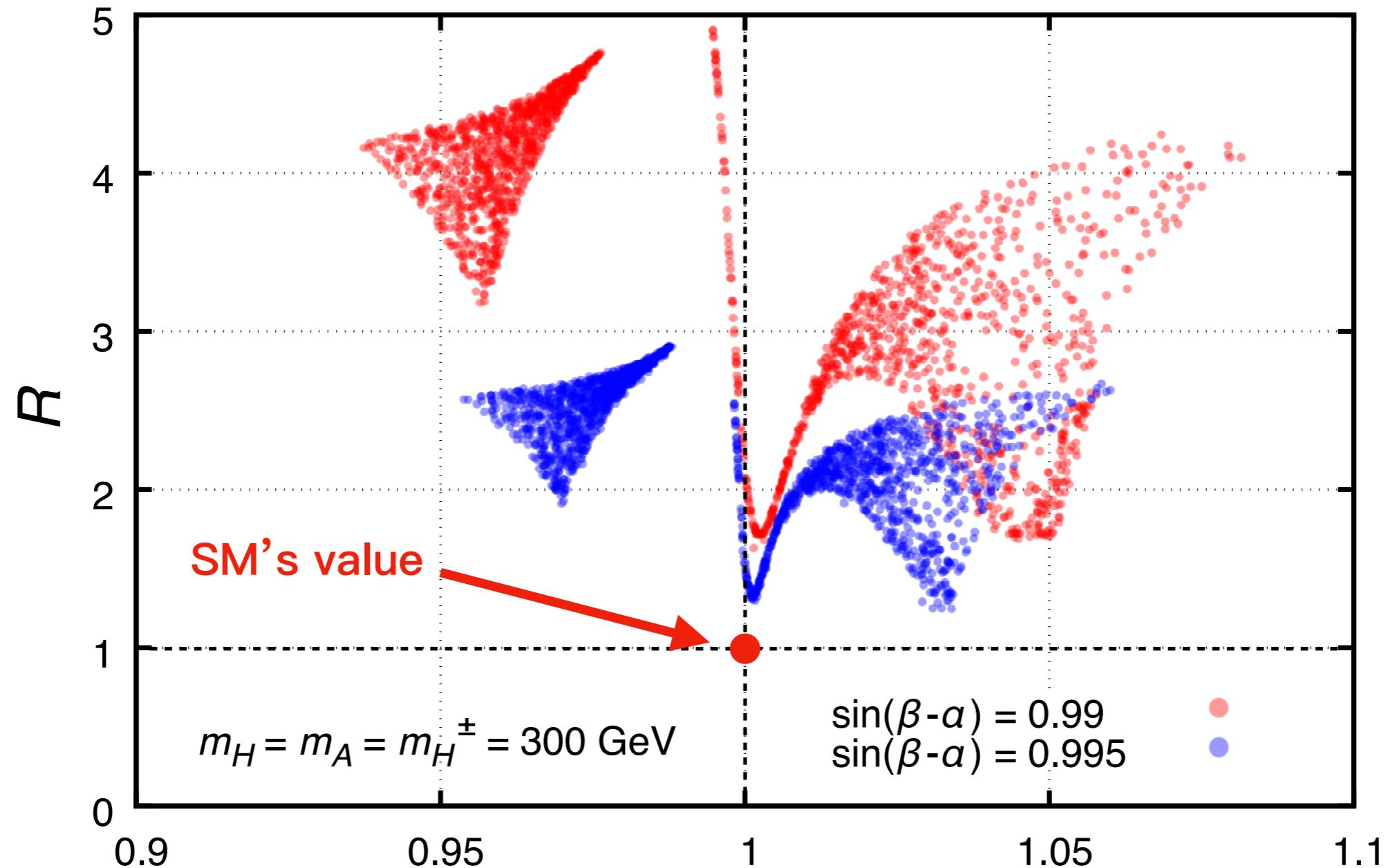
Kon, TN, Ueda, Yagyu
PRD99 (2019) 095027

11/14

$$R \equiv \frac{\sum_f \sigma^{\text{2HDM}}(e^+e^- \rightarrow f\bar{f}hh)}{\sum_f \sigma^{\text{SM}}(e^+e^- \rightarrow f\bar{f}hh)}$$

$\sqrt{s} = 500 \text{ GeV}$

$1 \leq \tan \beta \leq 30, 0 \leq M^2 \leq (300 \text{ GeV})^2$



Numerical Results : κ_f VS R

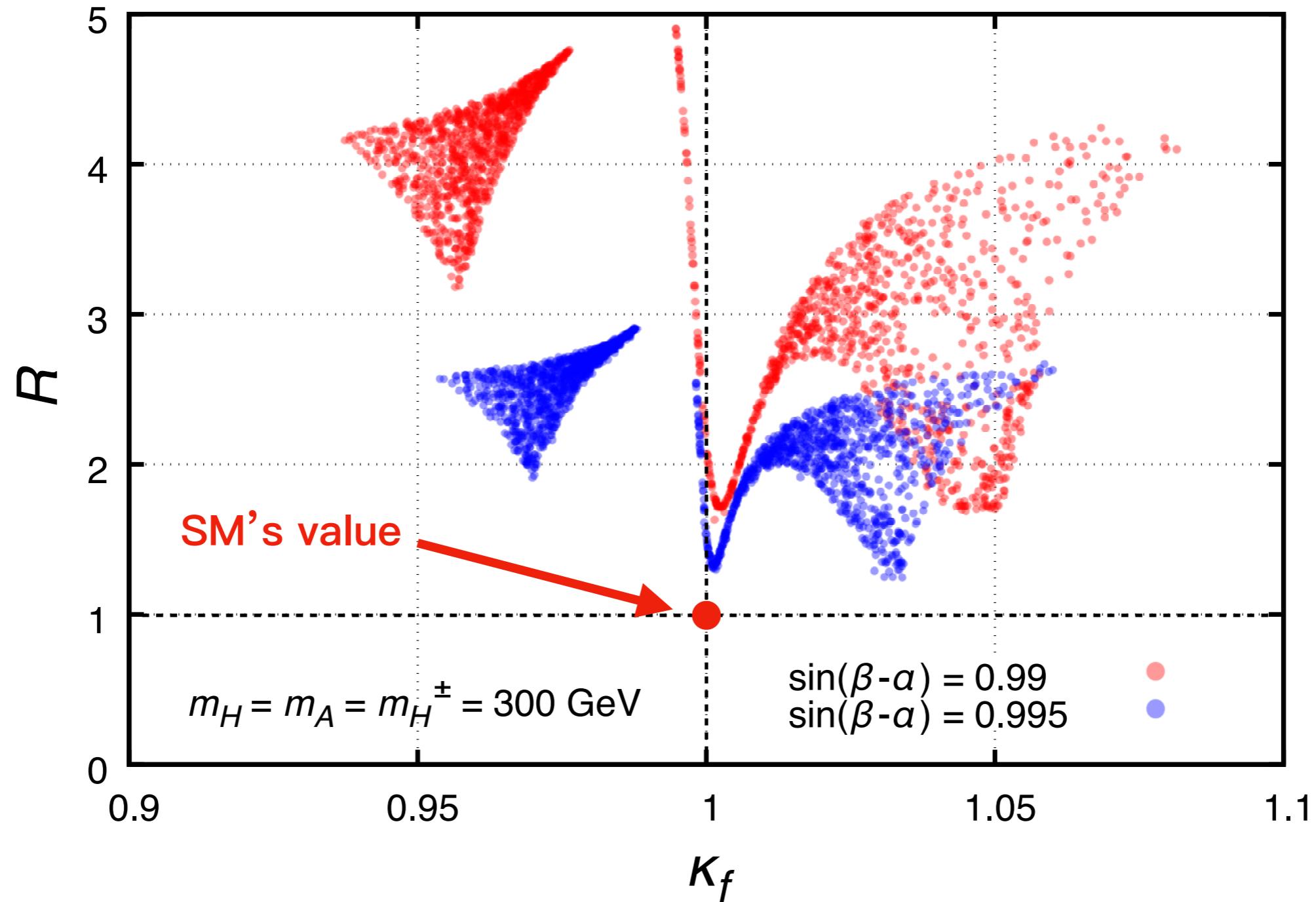
Kon, TN, Ueda, Yagyu
PRD99 (2019) 095027

11/14

$$R \equiv \frac{\sum_f \sigma^{\text{2HDM}}(e^+e^- \rightarrow f\bar{f}hh)}{\sum_f \sigma^{\text{SM}}(e^+e^- \rightarrow f\bar{f}hh)}$$

$\sqrt{s} = 500 \text{ GeV}$

$1 \leq \tan \beta \leq 30, 0 \leq M^2 \leq (300 \text{ GeV})^2$



- The value of R can be maximally around 5(3) for $s_{\beta-\alpha} = 0.99$ ($s_{\beta-\alpha} = 0.995$)

Numerical Results : κ_f VS R

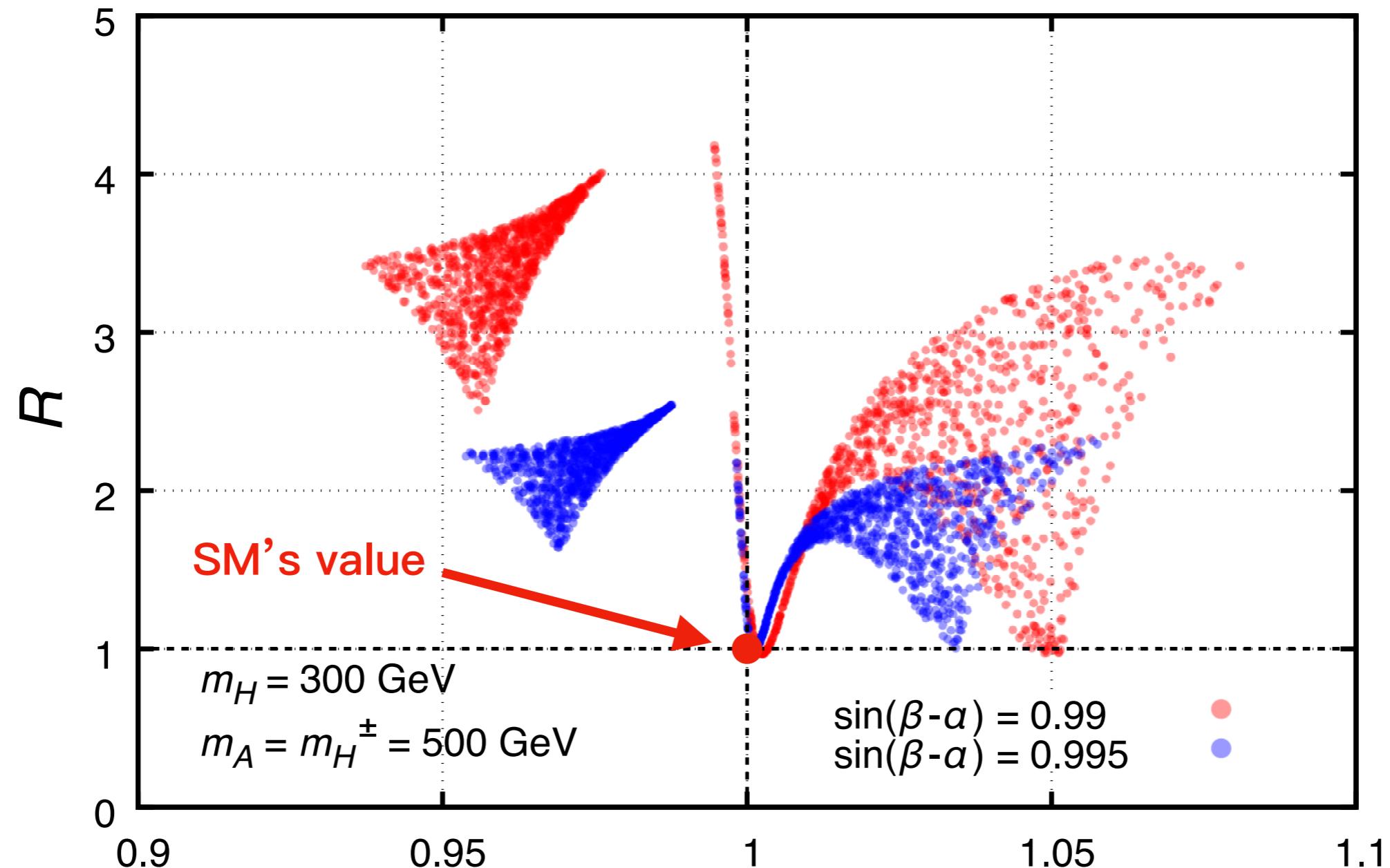
Kon, TN, Ueda, Yagyu
PRD99 (2019) 095027

12/14

$$R \equiv \frac{\sum_f \sigma^{\text{2HDM}}(e^+e^- \rightarrow f\bar{f}hh)}{\sum_f \sigma^{\text{SM}}(e^+e^- \rightarrow f\bar{f}hh)}$$

$\sqrt{s} = 500 \text{ GeV}$

$1 \leq \tan \beta \leq 30, 0 \leq M^2 \leq (300 \text{ GeV})^2$



Numerical Results : κ_f VS R

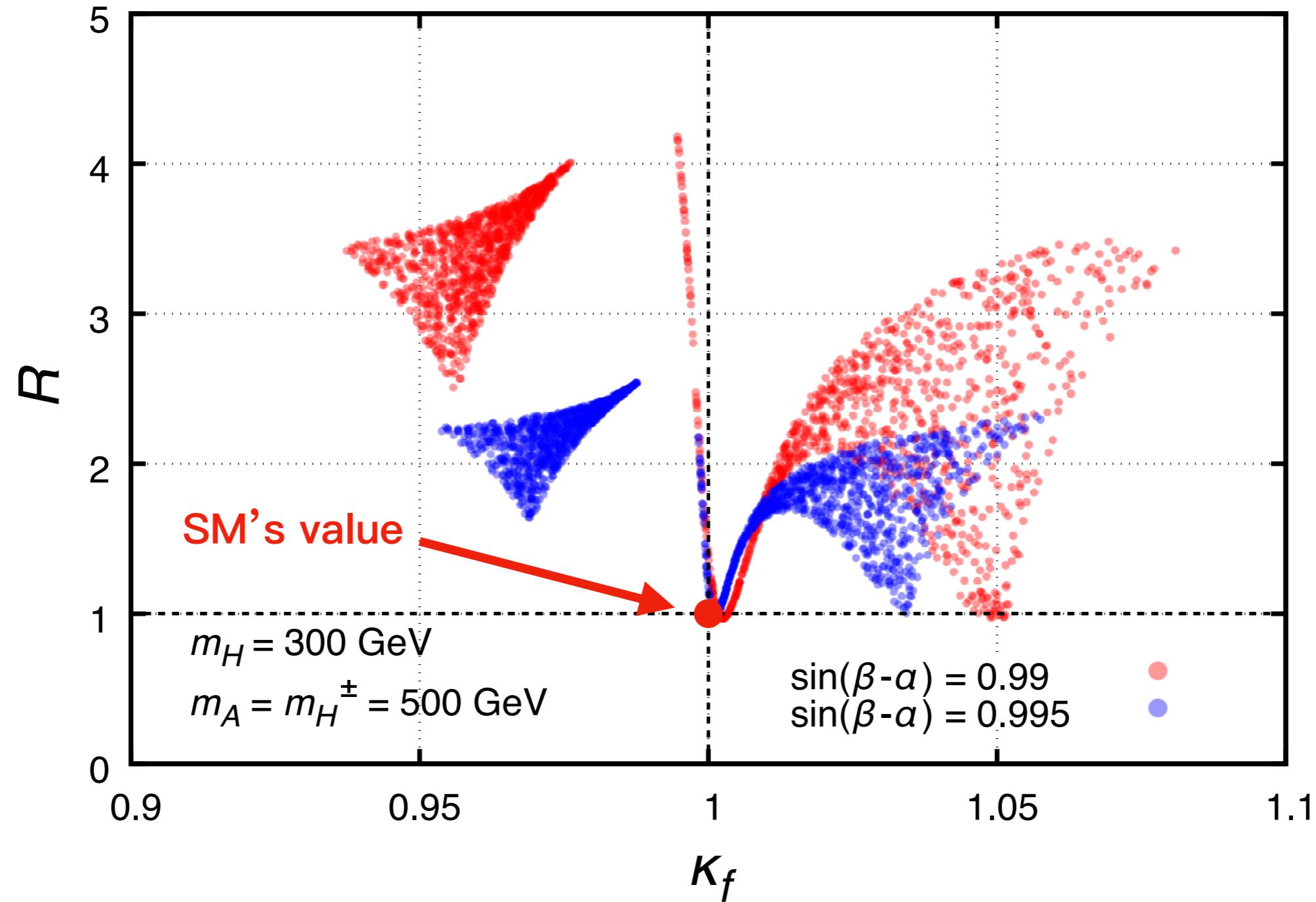
Kon, TN, Ueda, Yagyu
PRD99 (2019) 095027

12/14

$$R \equiv \frac{\sum_f \sigma^{\text{2HDM}}(e^+e^- \rightarrow f\bar{f}hh)}{\sum_f \sigma^{\text{SM}}(e^+e^- \rightarrow f\bar{f}hh)}$$

$\sqrt{s} = 500 \text{ GeV}$

$1 \leq \tan \beta \leq 30, 0 \leq M^2 \leq (300 \text{ GeV})^2$



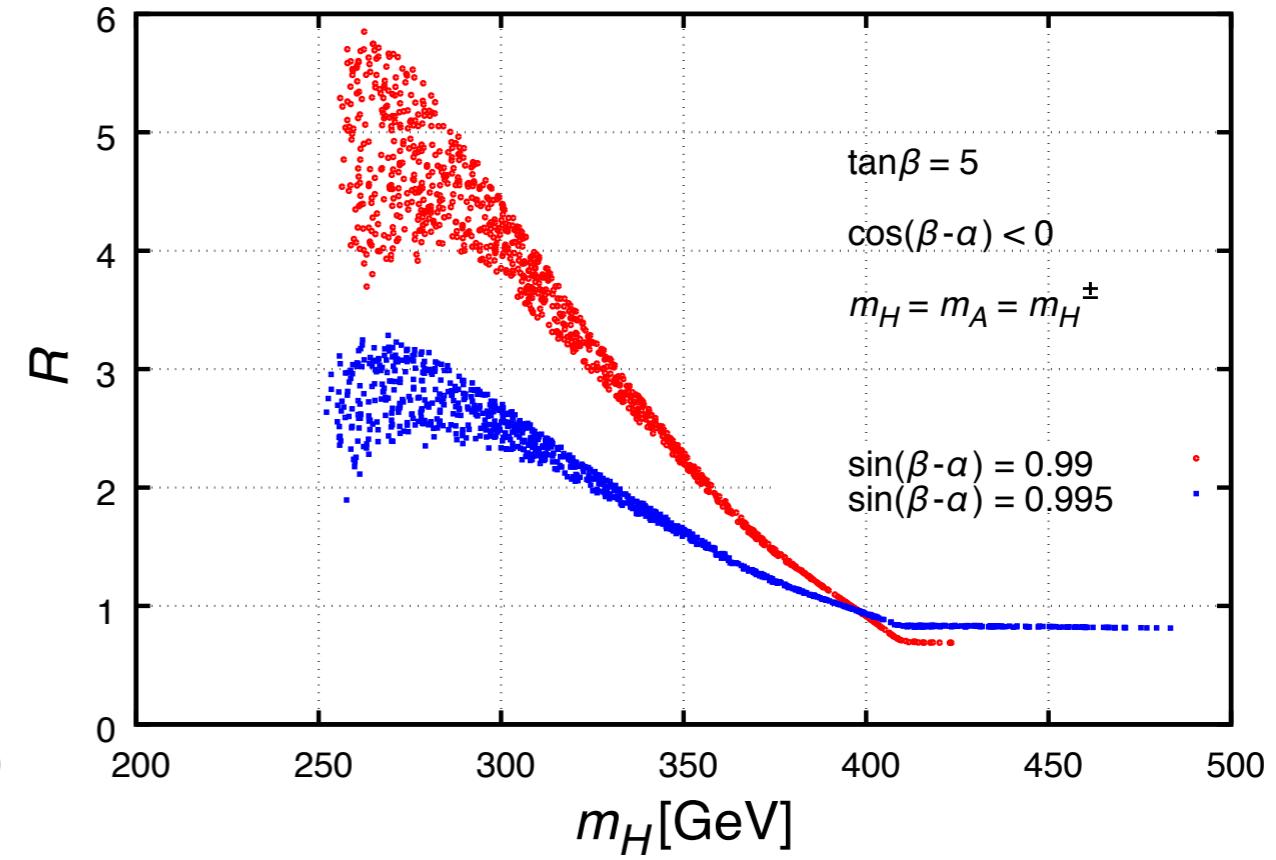
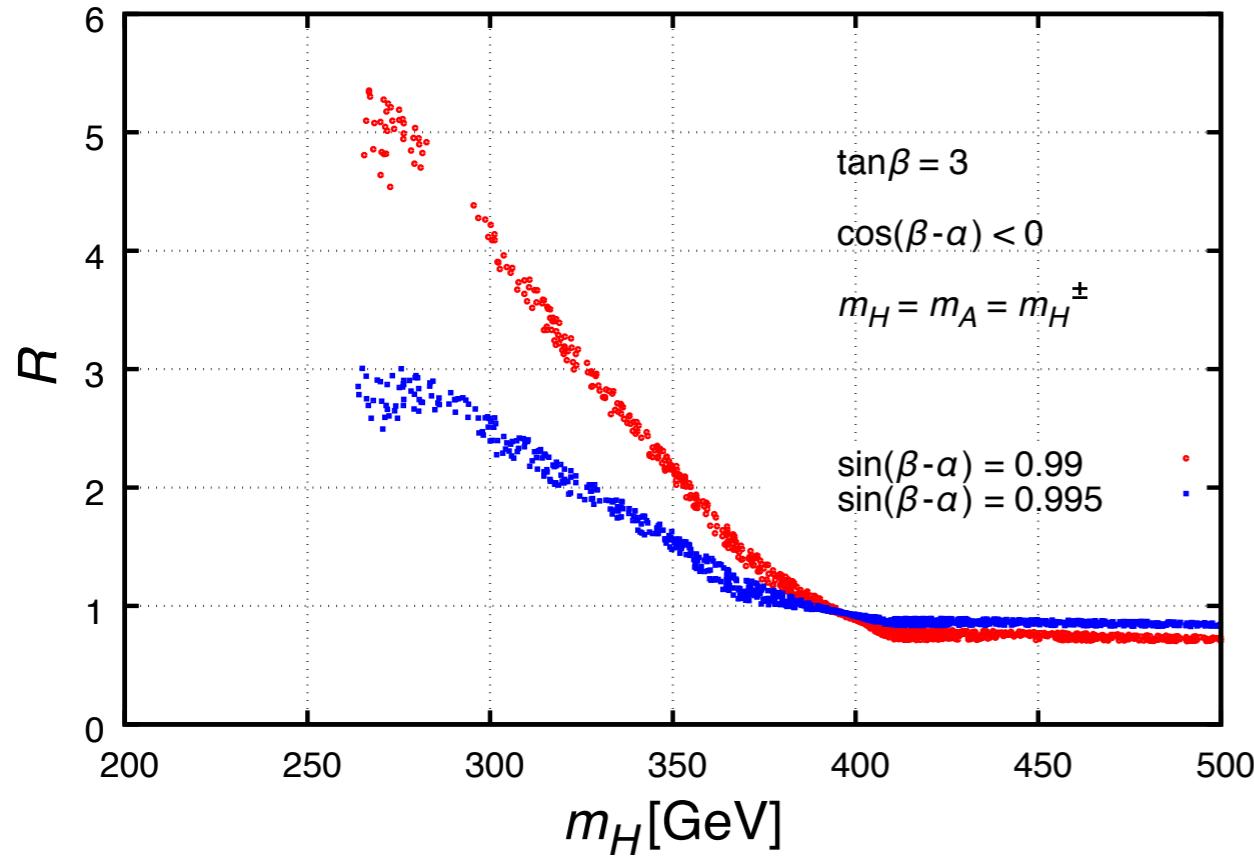
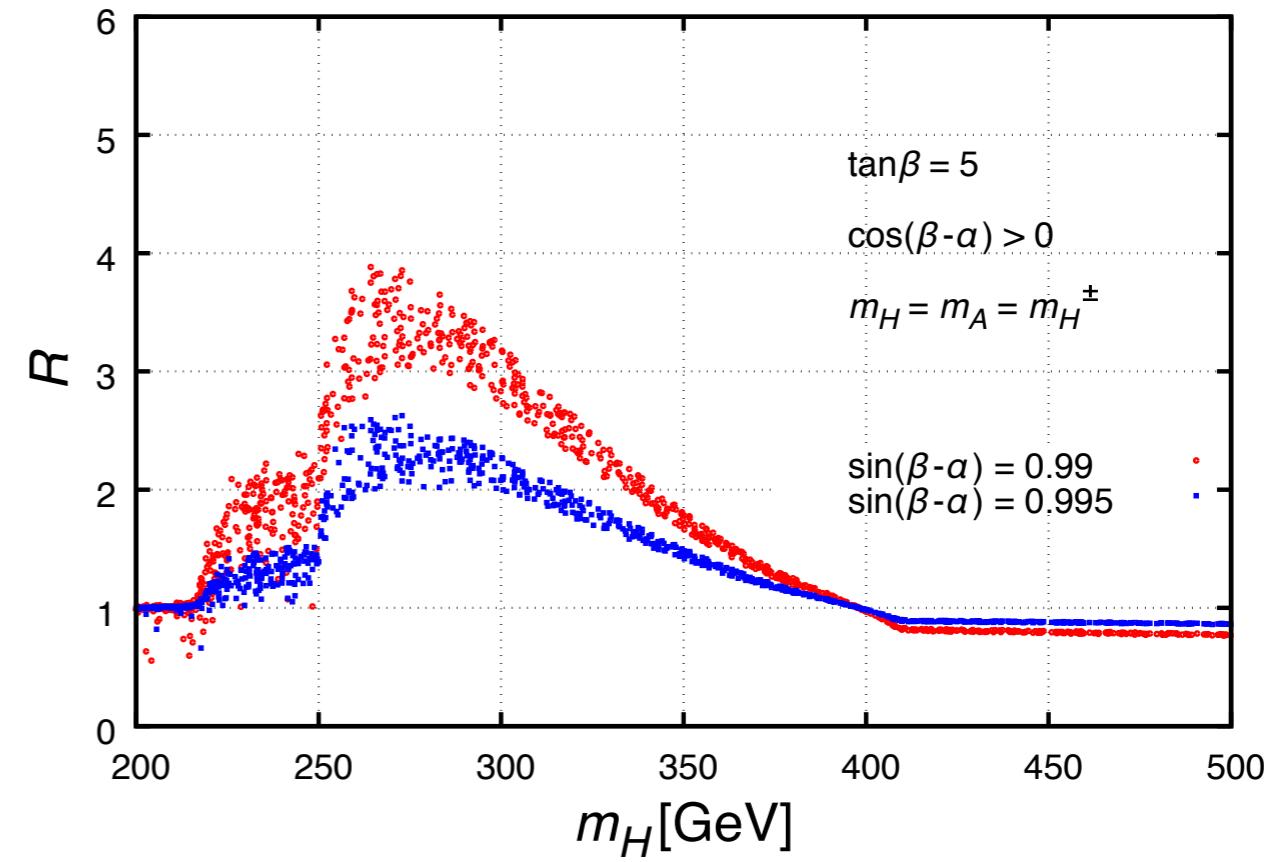
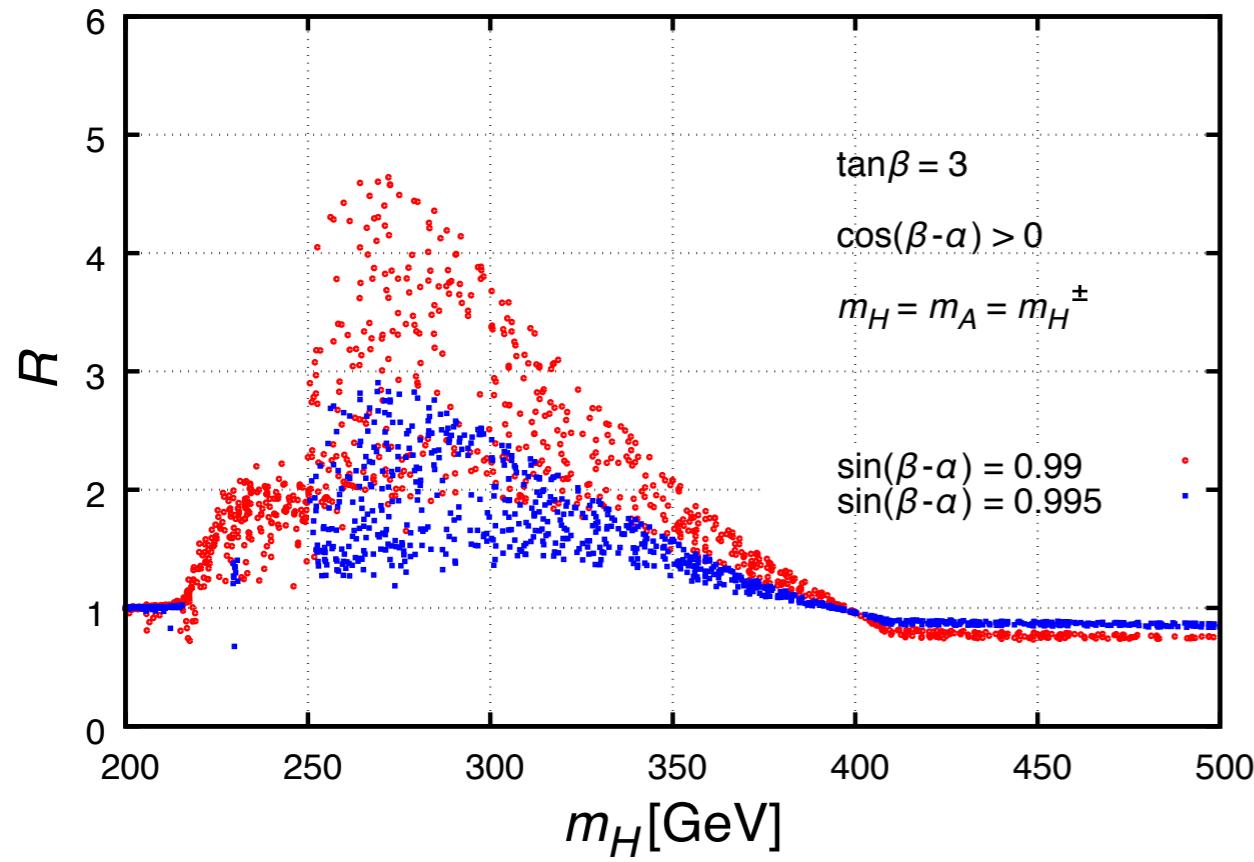
■ Because A becomes off-shell, scattering points is shifted to below.

Numerical Results : m_H vs R

Kon, TN, Ueda, Yagyu
PRD99 (2019) 095027

13/14

$$\sqrt{s} = 500 \text{ GeV}, m_H = m_A = m_{H^\pm}$$

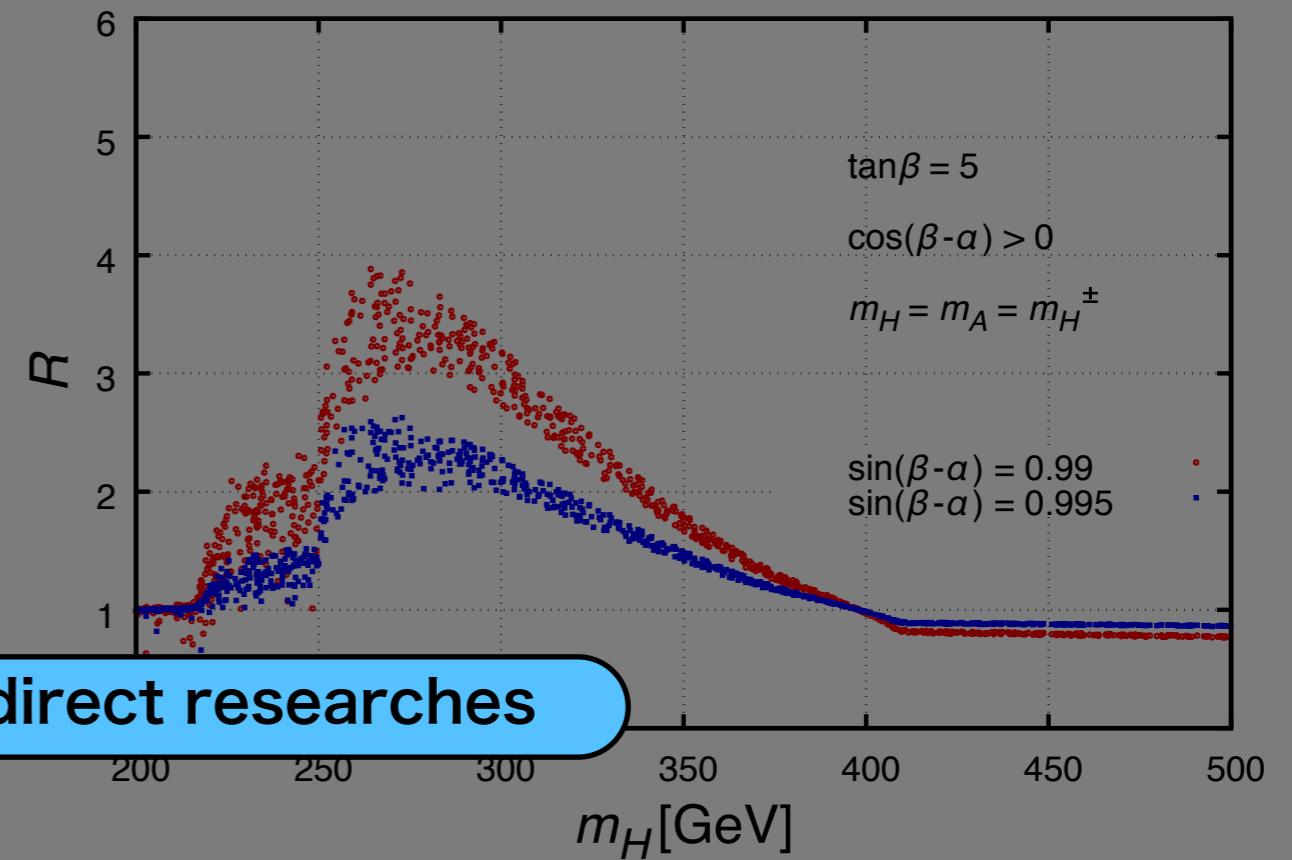
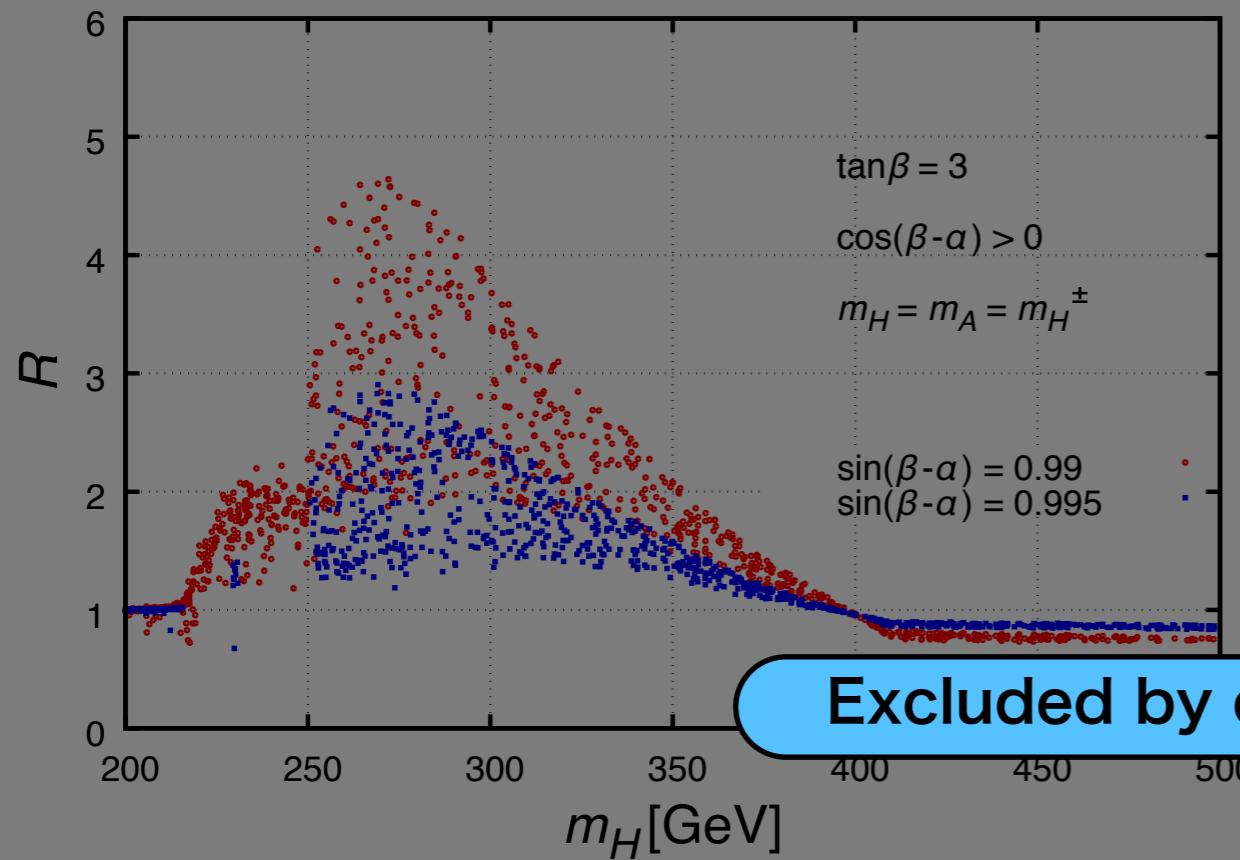


Numerical Results : m_H vs R

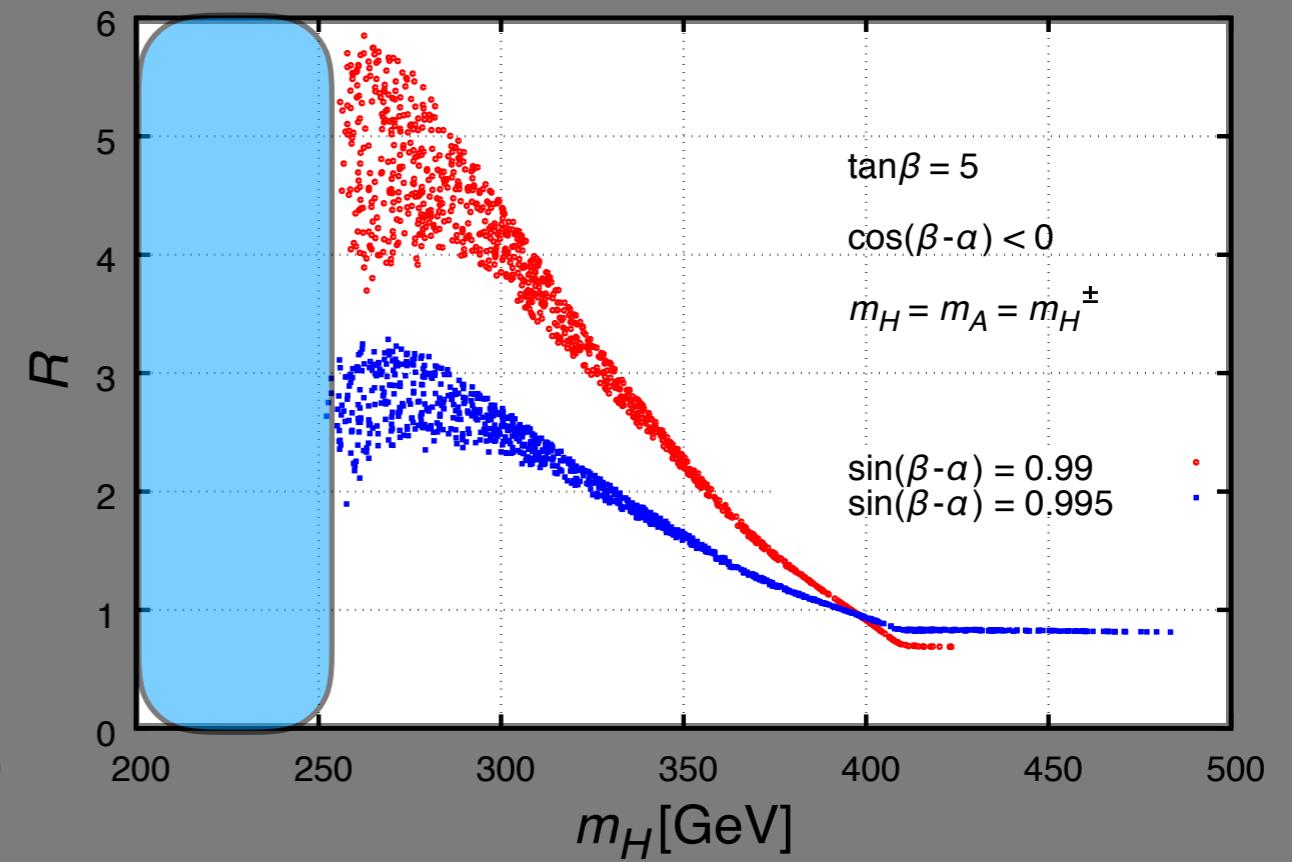
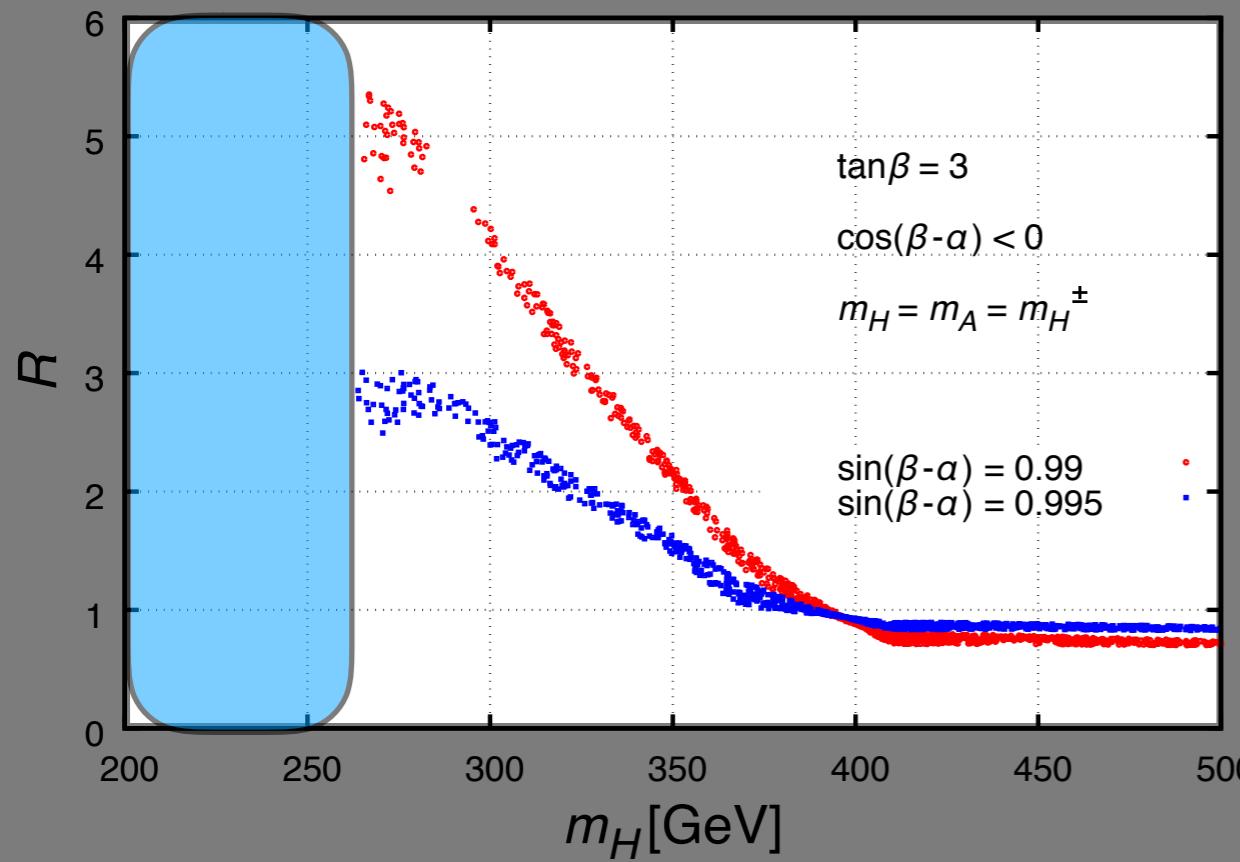
Kon, TN, Ueda, Yagyu
PRD99 (2019) 095027

13/14

$$\sqrt{s} = 500 \text{ GeV}, m_H = m_A = m_{H^\pm}$$



Excluded by direct researches

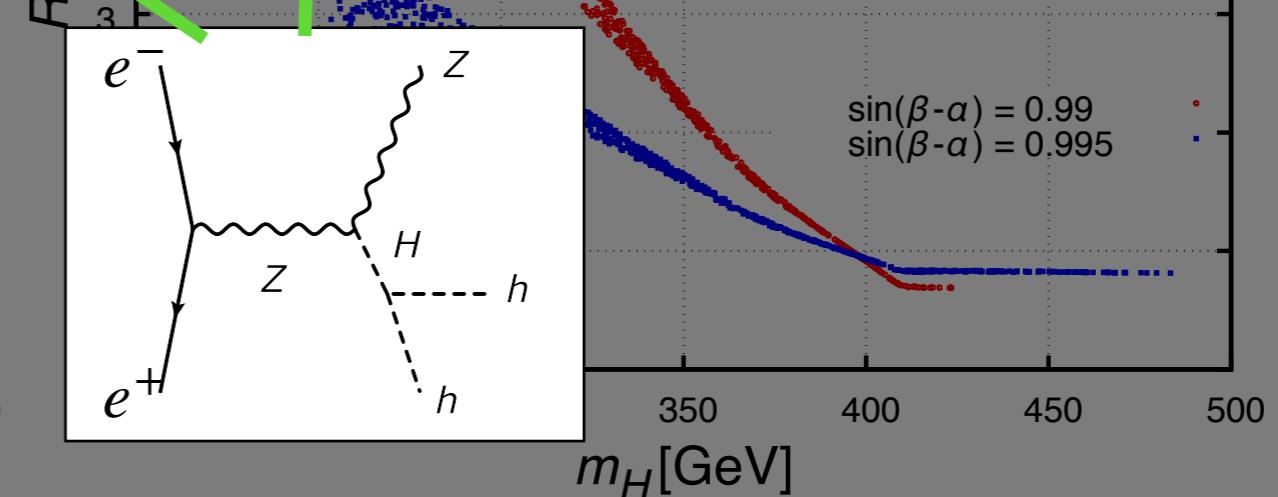
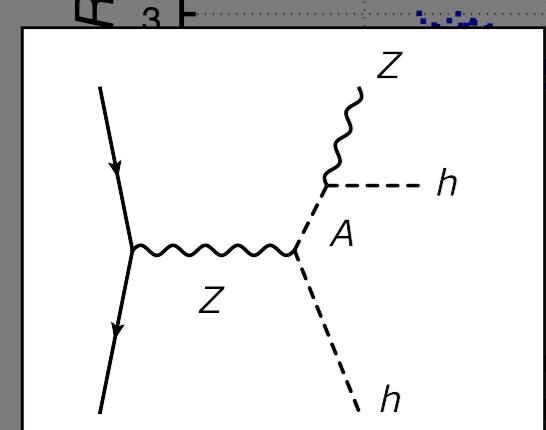
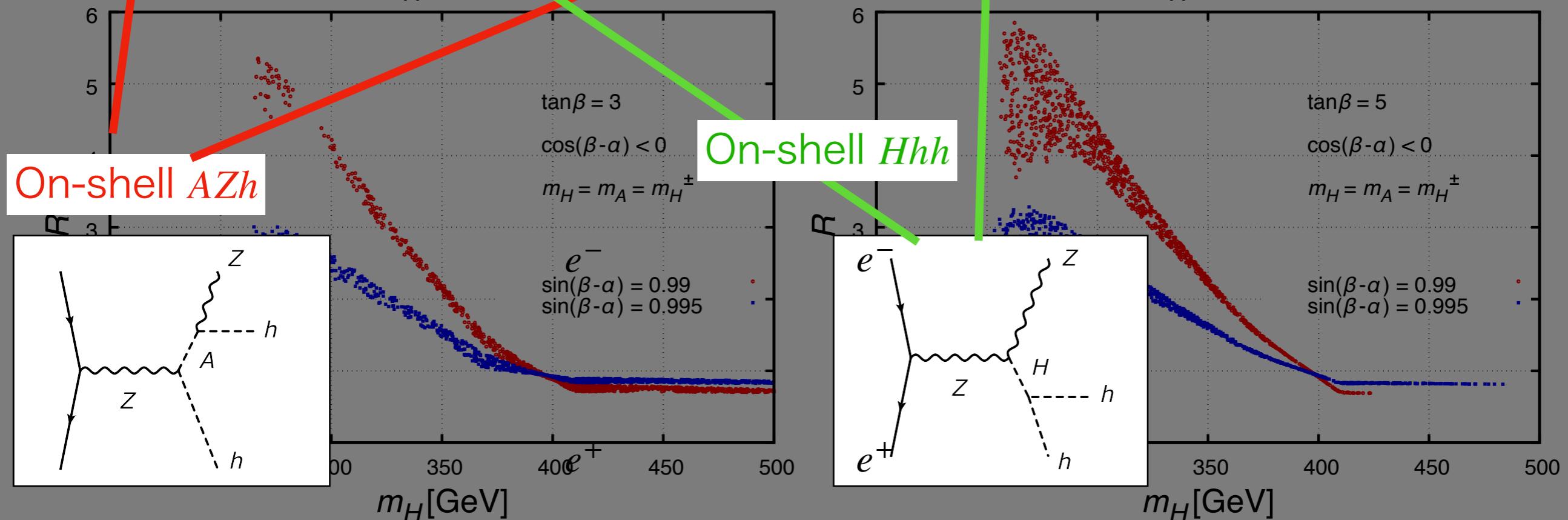
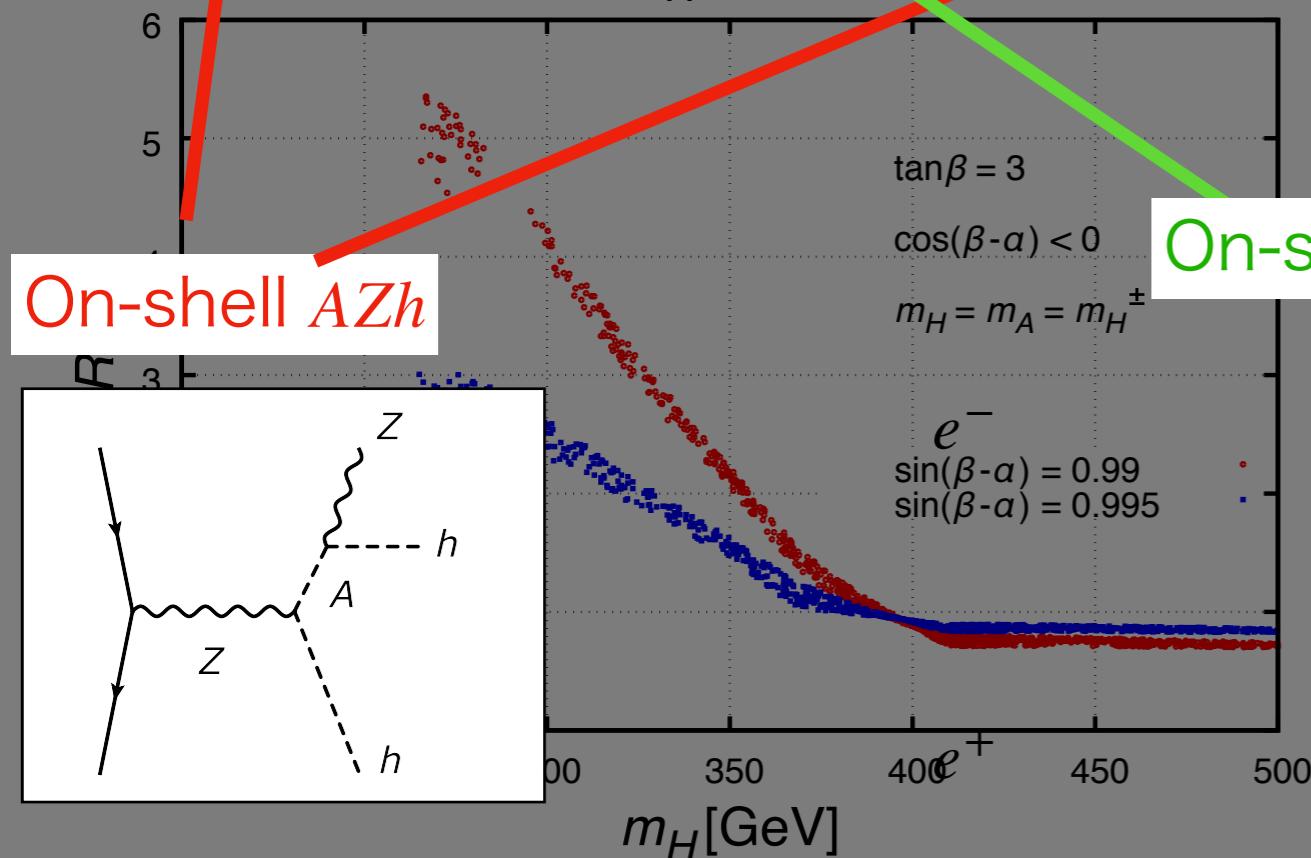
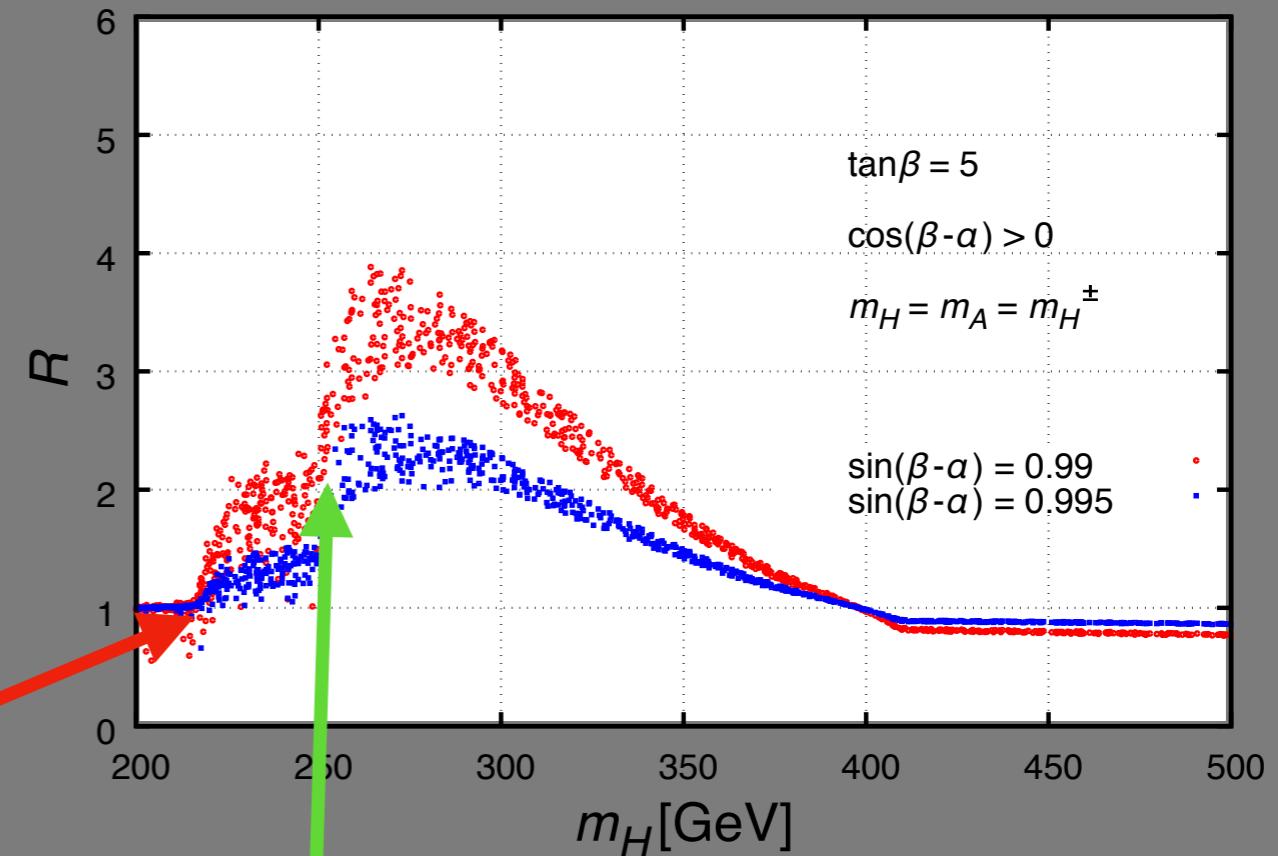
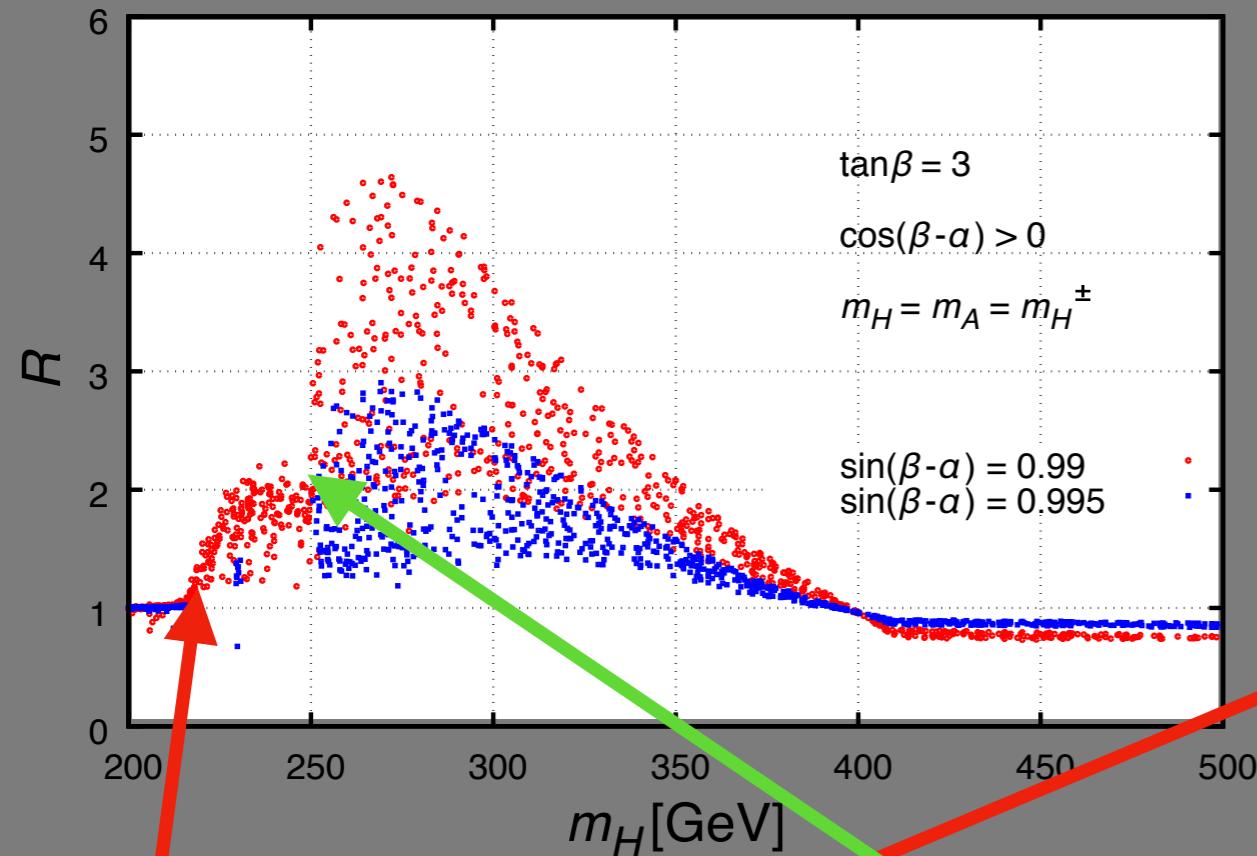


Numerical Results : m_H vs R

Kon, TN, Ueda, Yagyu
PRD99 (2019) 095027

13/14

$$\sqrt{s} = 500 \text{ GeV}, m_H = m_A = m_{H^\pm}$$



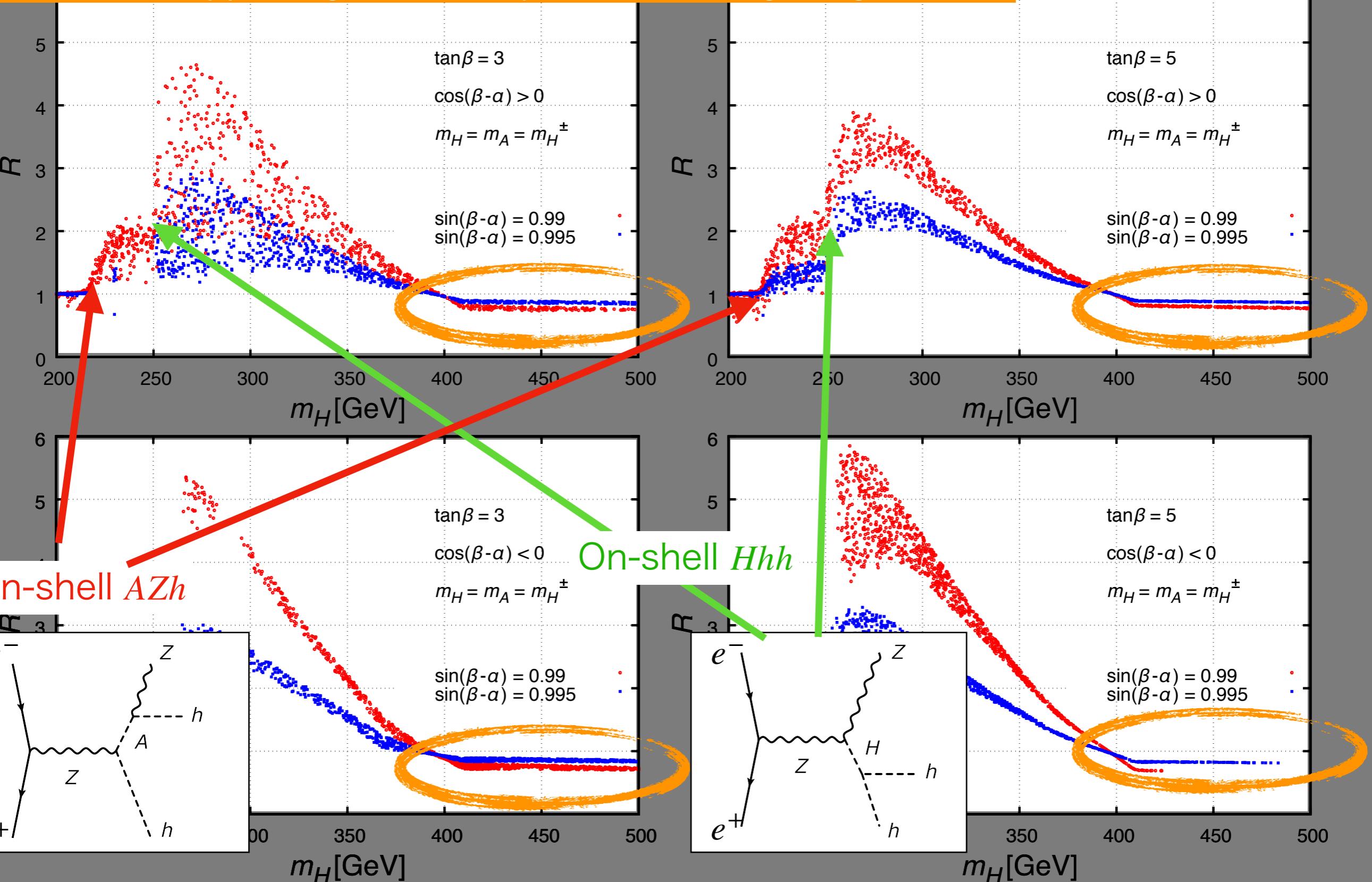
Numerical Results : m_H vs R

Kon, TN, Ueda, Yagyu
PRD99 (2019) 095027

13/14

$$\sqrt{s} = 500 \text{ GeV}, m_H = m_A = m_{H^\pm}$$

the H and A appearing in the Zhh production are getting off-shell.



Summary

- We focus on $e^+e^- \rightarrow hh + X$ processes in the **2HDM: non-alignment case**.
- We have found a considerable enhancement in the cross section, typically **several times** larger than the SM prediction.
- The correlation between κ_f and the cross section may give us a clue how the Higgs sector should be extended.
- If an enhancement in the cross section is observed as shown in this study, it suggests a possibility of the **non-alignment case**.

Thank you for your attention!

Back Up

EW ρ parameter

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

$$\rho_{\text{exp}} = 1.0005 \pm 0.0009$$

PDG(2018)

T: isospin, Y: hypercharge, v: VEV

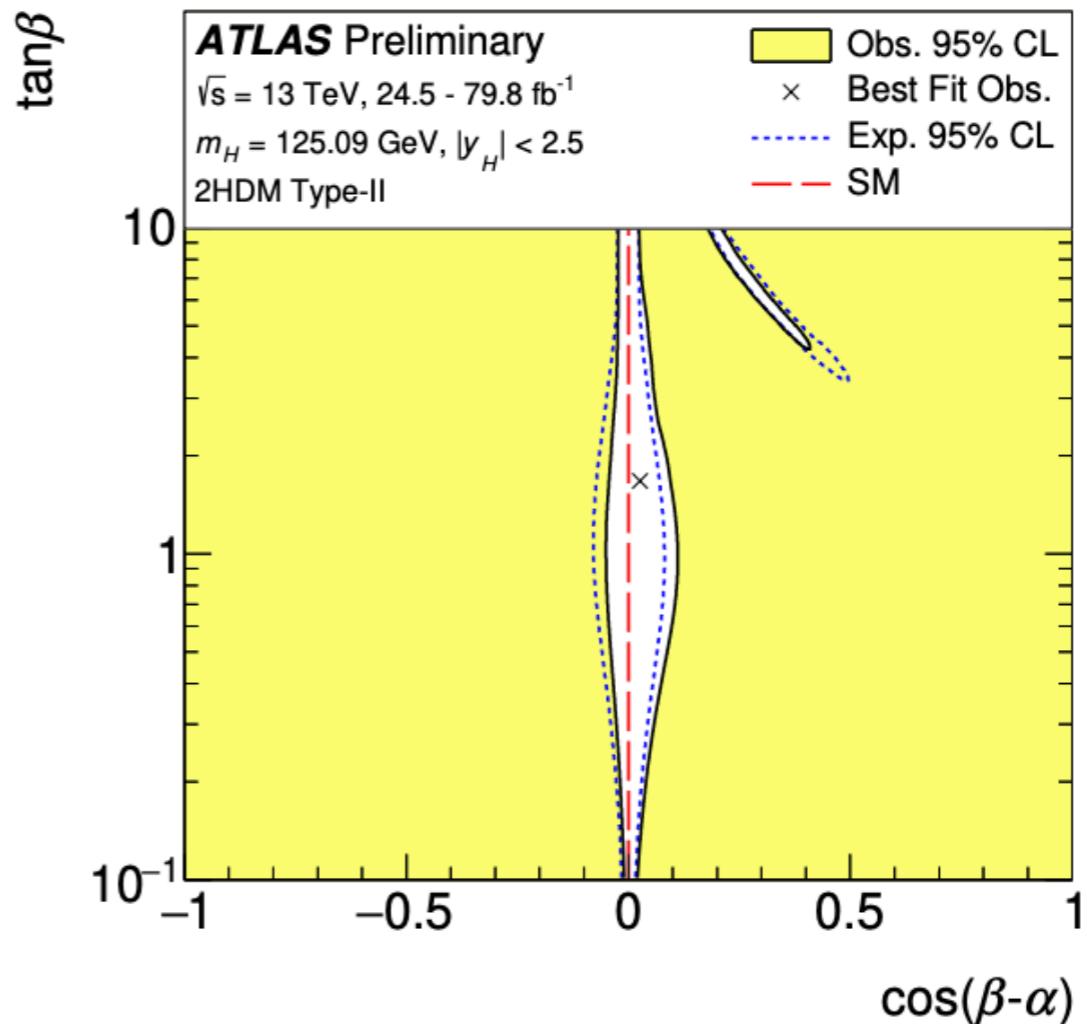
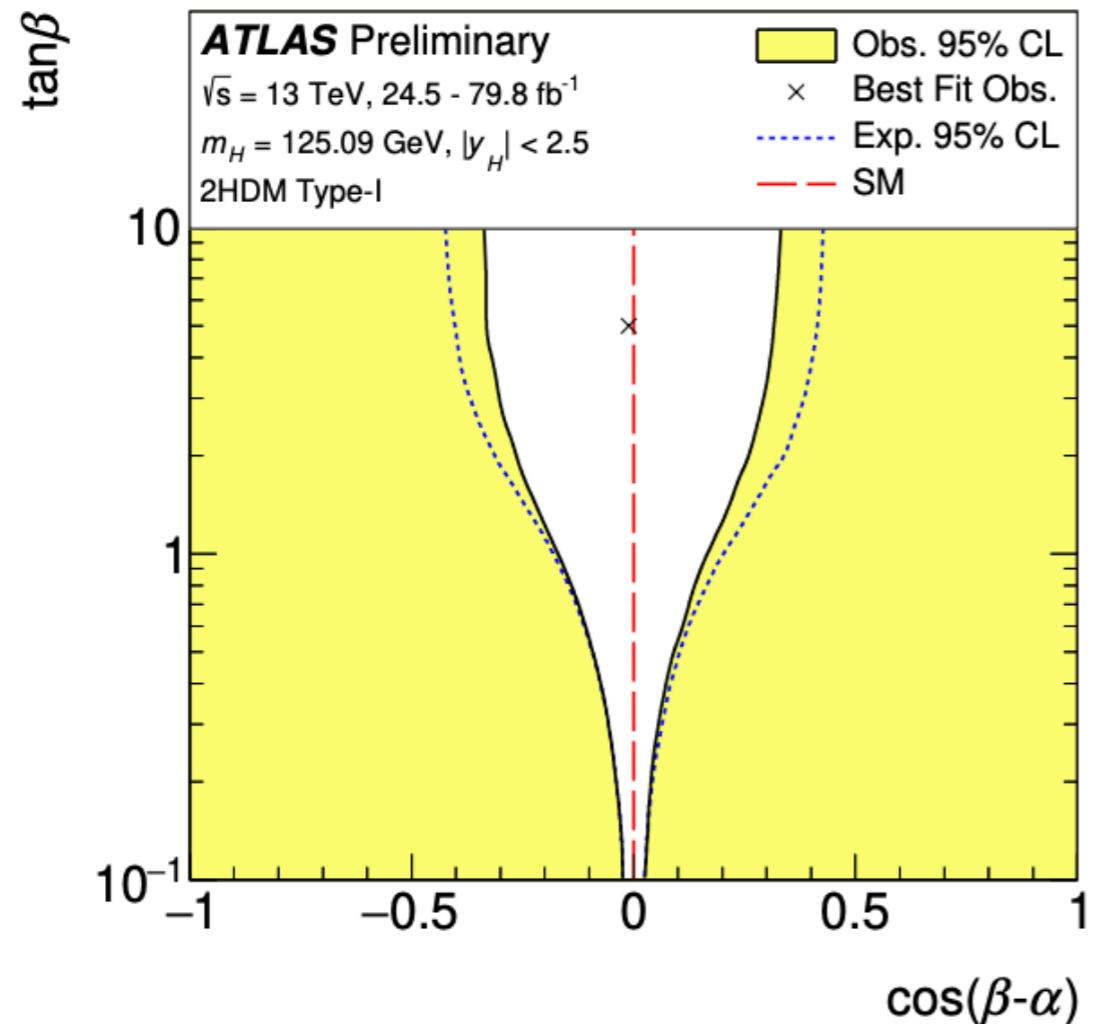
$$\rightarrow T(T + 1) = 3Y^2$$

T	Y
0	0
1/2	1/2
3	2

Fulfill the singlet, multi–doublet or septet

We consider the simplest but important expanded model of SM's Higgs sector i.e., **2HDMs**.

Constraints



In Type-II 2HDM, the constraints region of the parameter space on $\cos(\beta - \alpha)$ and $\tan\beta$ is very small.

Four types of charge assignment of the Z_2 symmetry

- (Softly-broken) Z_2 symmetry : $\Phi_1 \rightarrow \Phi_1, \Phi_2 \rightarrow -\Phi_2$

$$\mathcal{L}_{\text{THDM}}^Y = - Y_u \overline{Q}_L \tilde{\Phi}_u u_R - Y_d \overline{Q}_L \Phi_d d_R - Y_l \overline{L}_L \Phi_l l_R + \text{H.c.}$$

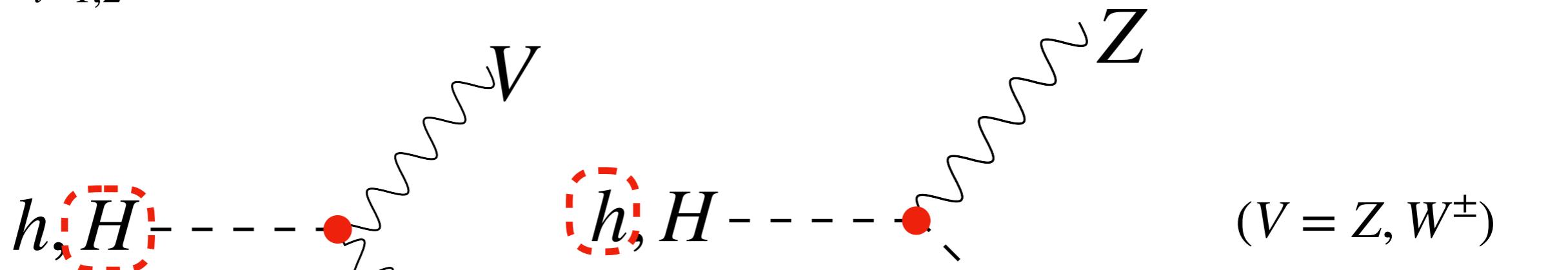
	Φ_1	Φ_2	u_R	d_R	l_R	Q_L, L_L
Type-I	+	-	-	-	-	+
Type-II	+	-	-	+	+	+
Type-X	+	-	-	-	+	+
Type-Y	+	-	-	+	-	+

Higgs-gauge couplings

$$\mathcal{L}_{kin} = \sum_{i=1,2} |D_\mu \phi_i|^2 = |D_\mu \Phi|^2 + |D_\mu \Psi|^2$$

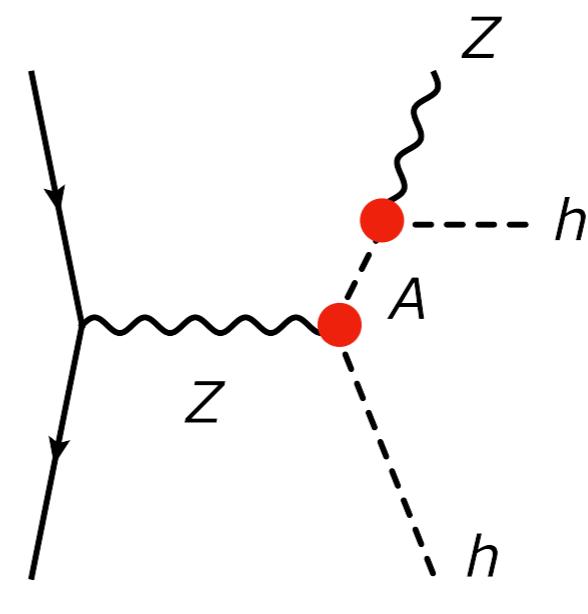
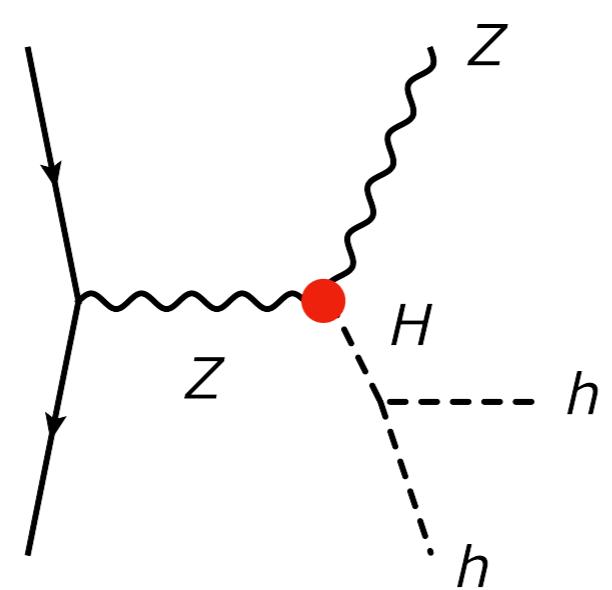
Higgs-gauge-gauge Higgs-Higgs-gauge

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h'_1 + iG^0) \end{pmatrix} \quad \Psi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h'_2 + iA^0) \end{pmatrix}$$



$$= (s_{\beta-\alpha}, c_{\beta-\alpha}) \times g_{SM}^{hVV}$$

$$= \frac{g}{2c_w} \times (c_{\beta-\alpha}, s_{\beta-\alpha}) \quad \cos \theta = c_\theta$$



Higgs-gauge couplings

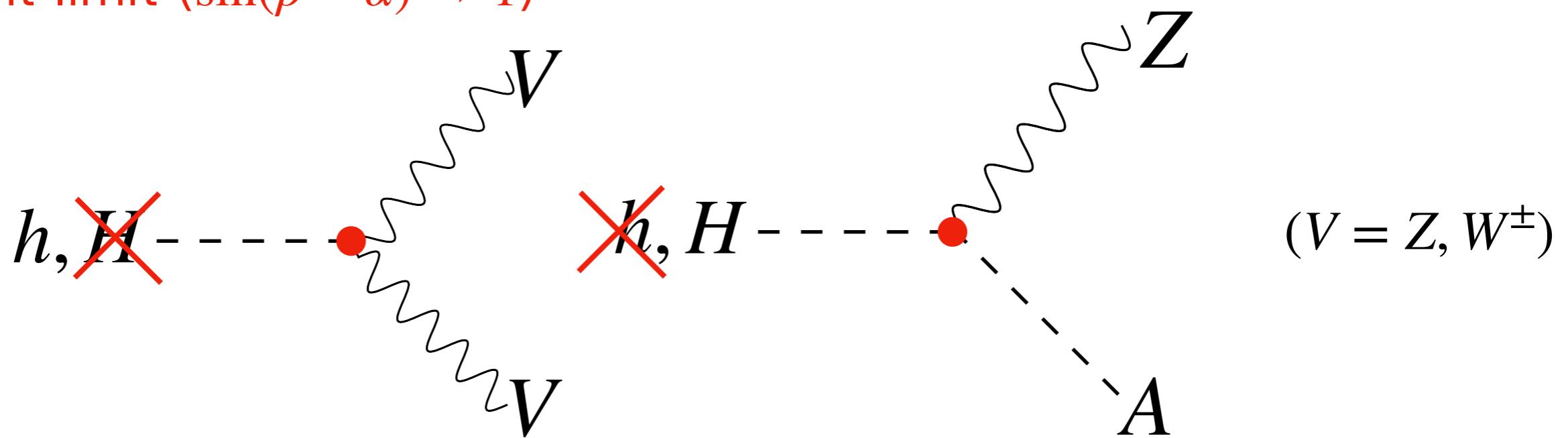
$$\mathcal{L}_{kin} = \sum_{i=1,2} |D_\mu \phi_i|^2 = |D_\mu \Phi|^2 + |D_\mu \Psi|^2$$

Higgs–gauge–gauge Higgs–Higgs–gauge

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

$$\Psi = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(h'_2 + iA^0) \end{pmatrix}$$

alignment limit ($\sin(\beta - \alpha) \rightarrow 1$)



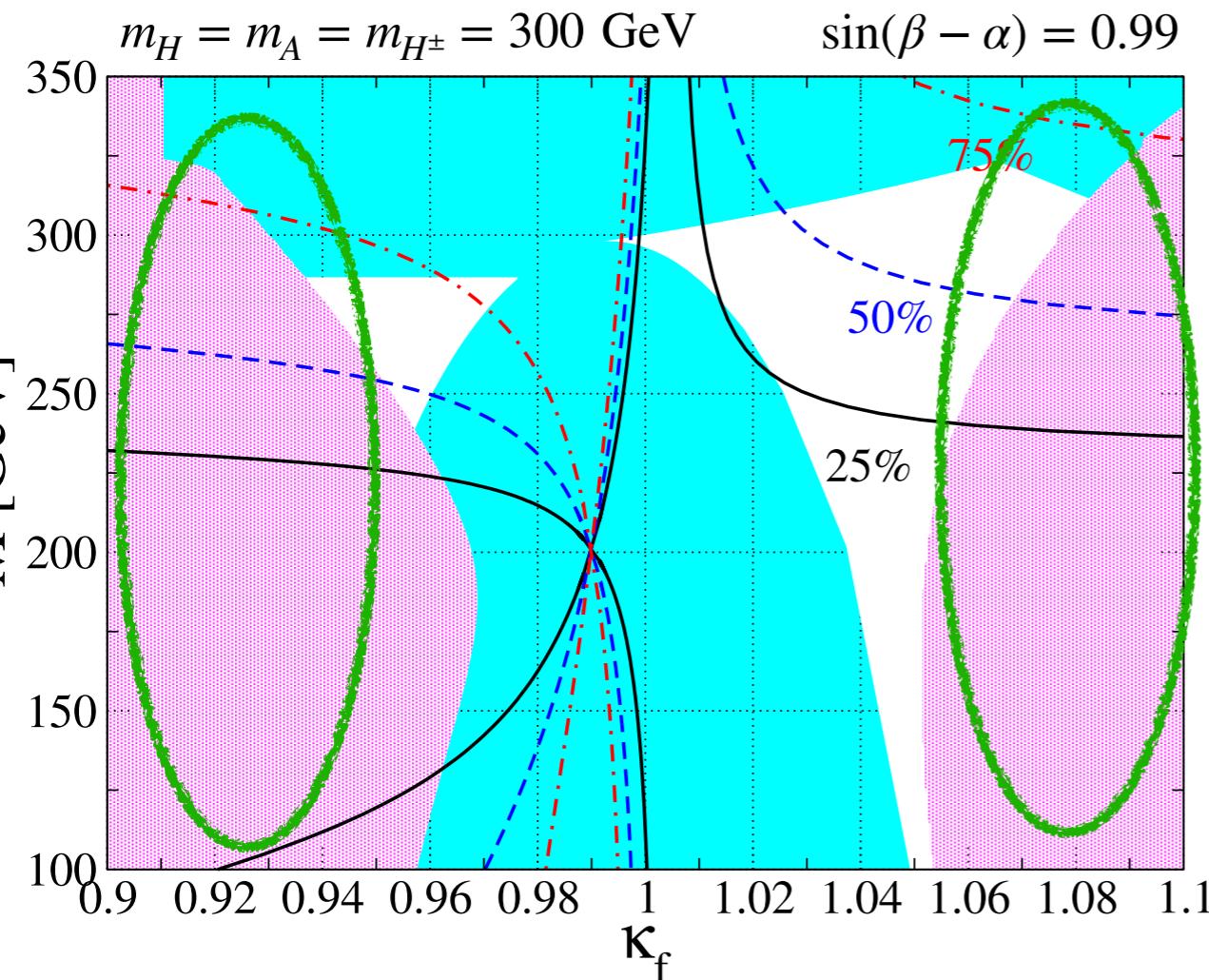
$$= (s_{\beta-\alpha}, c_{\beta-\alpha}) \times g_{\text{SM}}^{hVV}$$

$$= \frac{g}{2c_w} \times (c_{\beta-\alpha}, s_{\beta-\alpha}) \quad \cos \theta = c_\theta$$

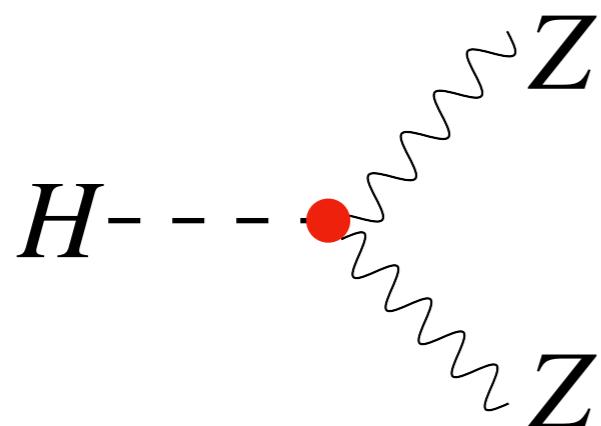
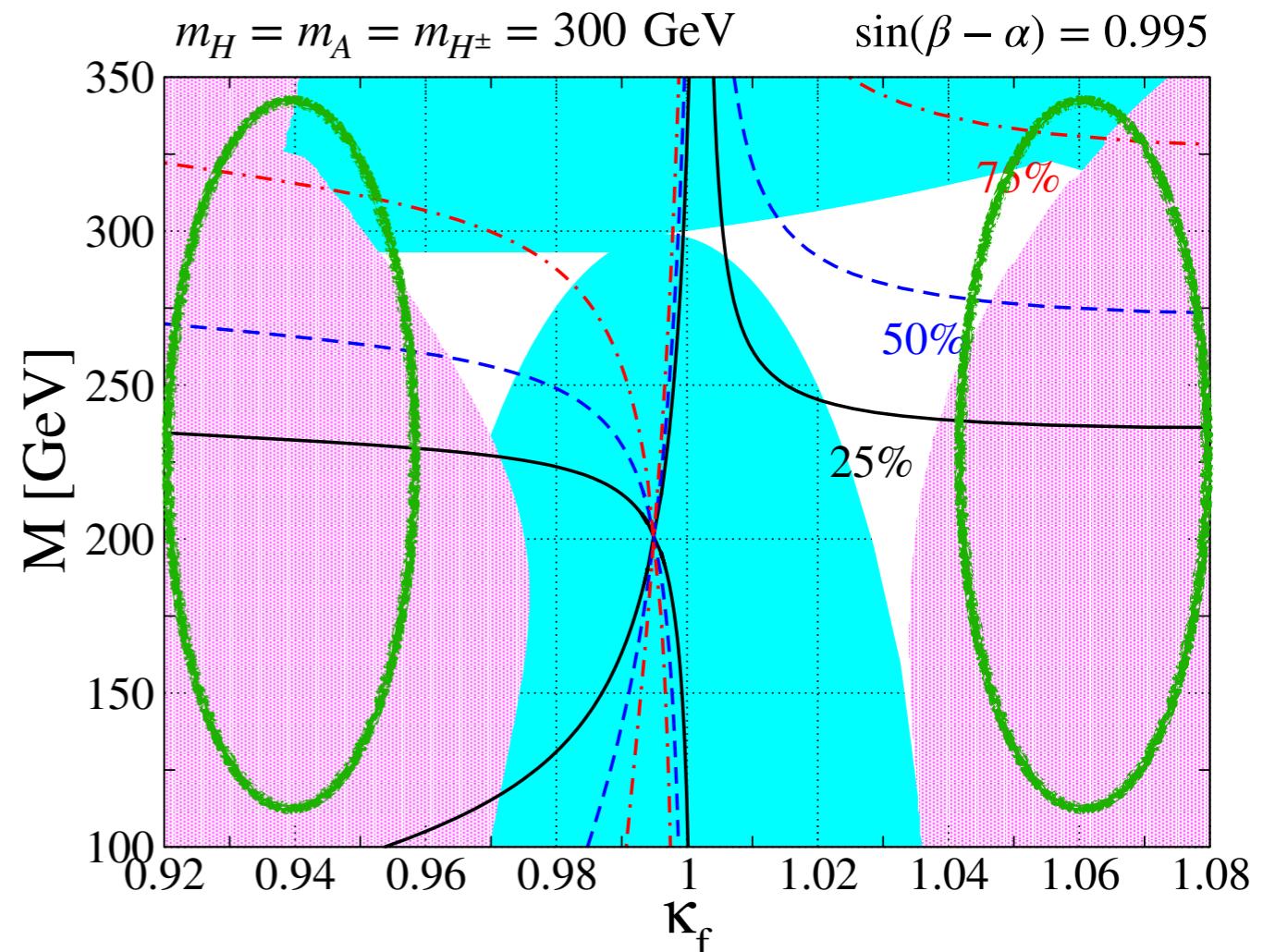
hVV coupling becomes the SM value, and H dose not couple to V .

Constraints

Kon, TN, Ueda, Yagyu PRD99 (2019) 095027



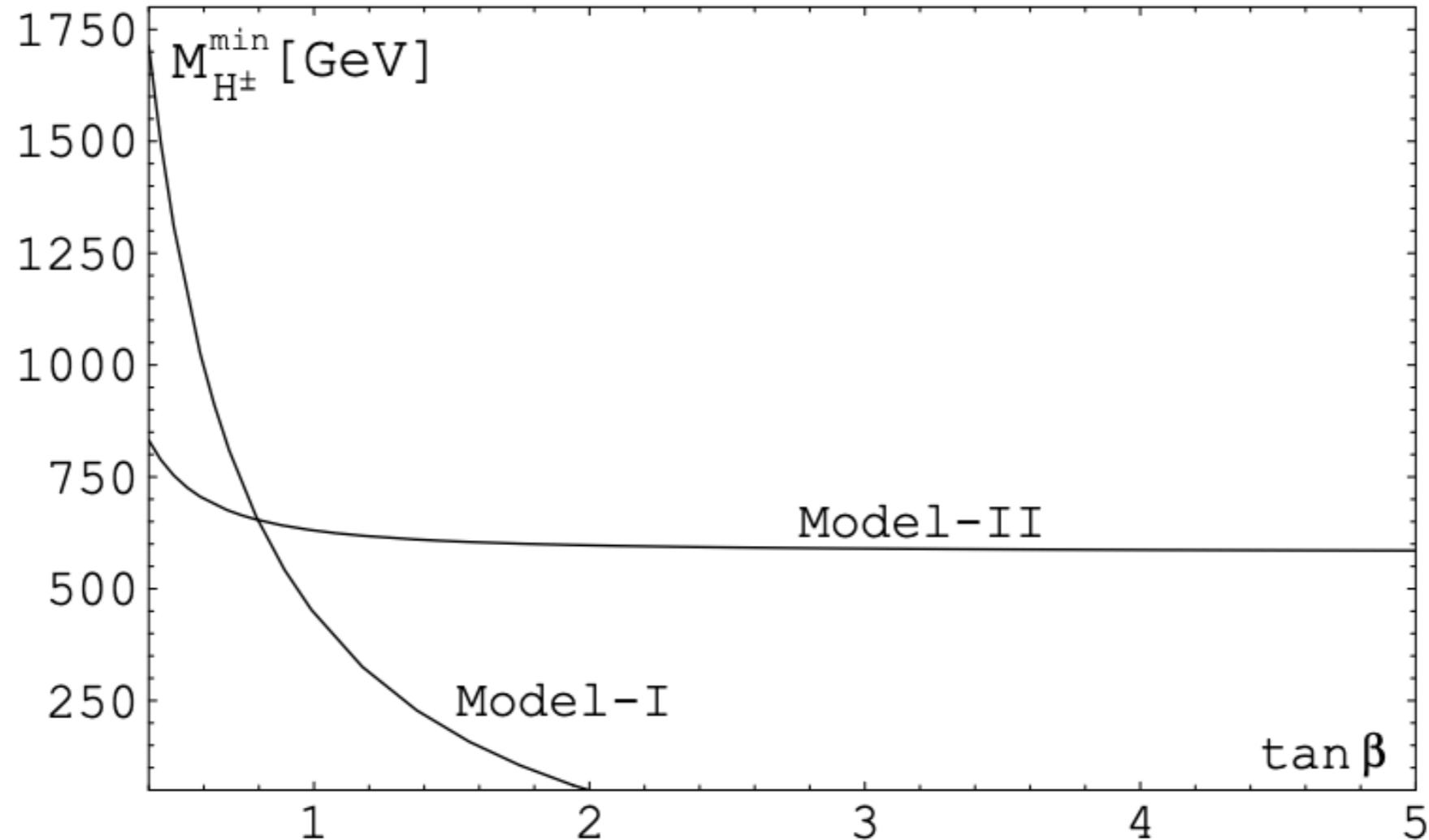
small $\tan \beta$ is Excluded by experiment



At the LHC

$$gg \rightarrow H \propto \cot^2 \beta$$

Constraints of charged Higgs boson mass from $B \rightarrow X_s \gamma$ data



In the Type-I THDM,

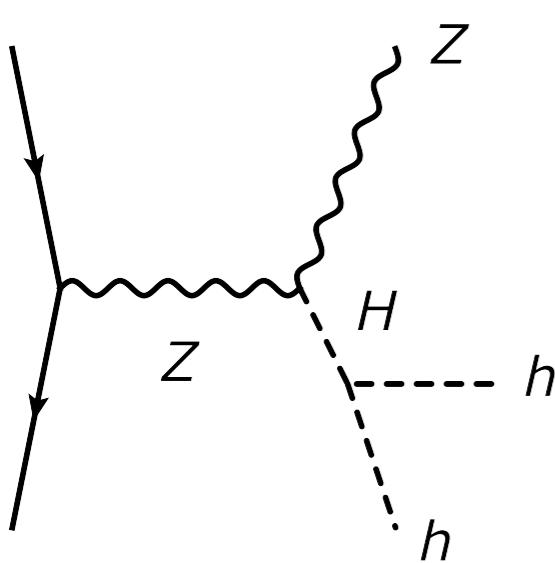
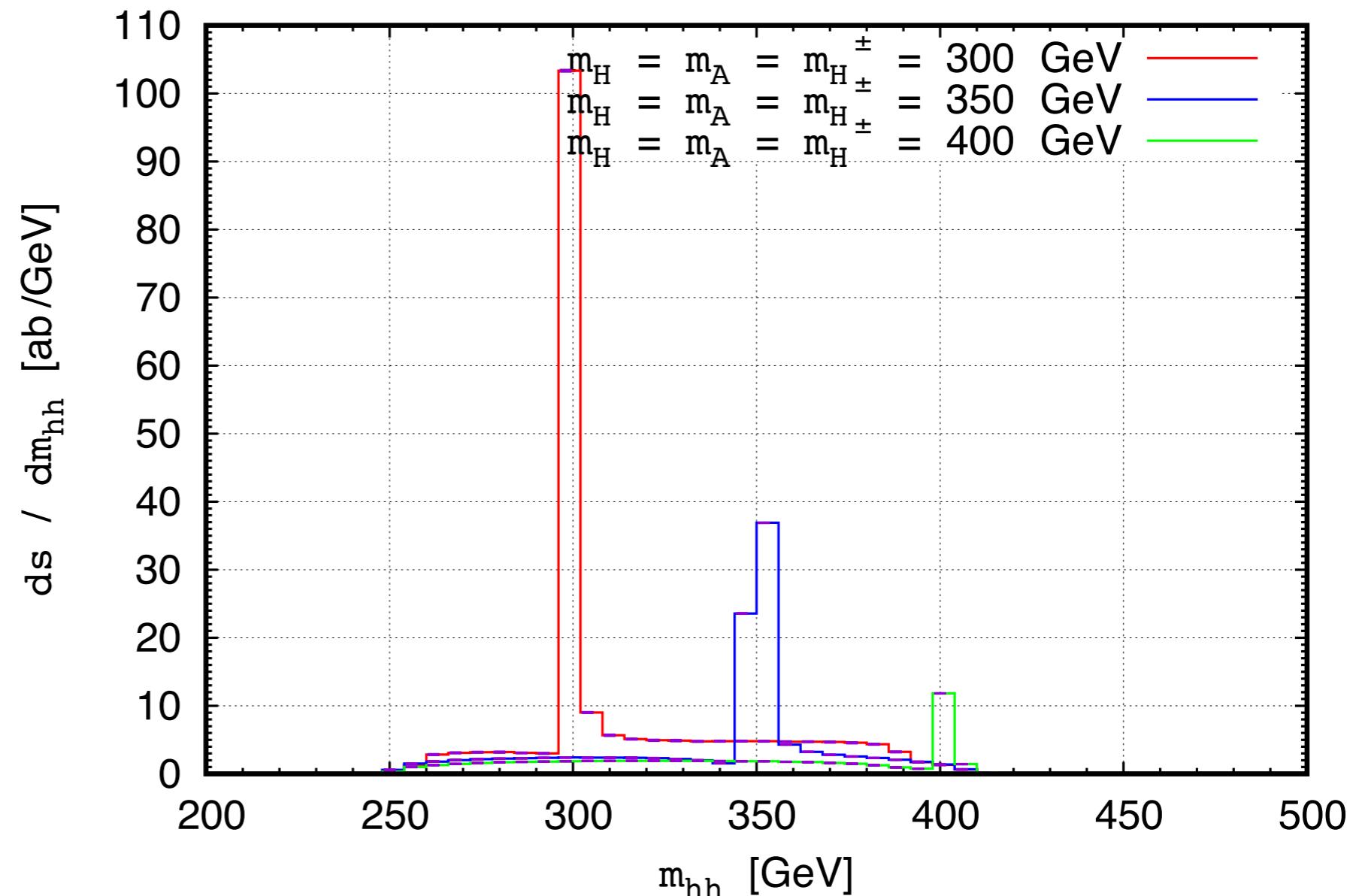
$O(100)$ GeV of the charged Higgs boson mass is allowed by the $B \rightarrow X_s \gamma$ data when $\tan \beta > \sim 2$.

While $m_{H^\pm} < 600$ GeV is excluded with 95% confidence level in the Type-II THDM.

Mikolaj Misiak and Matthias Steinhauser,
“Weak radiative decays of the B meson and bounds
on M_{H^\pm} in the Two-Higgs-Doublet Model,”
Eur. Phys. J. C77, 201 (2017)

Invariant mass

Kon, TN, Ueda, Yagyu PRD99 (2019) 095027



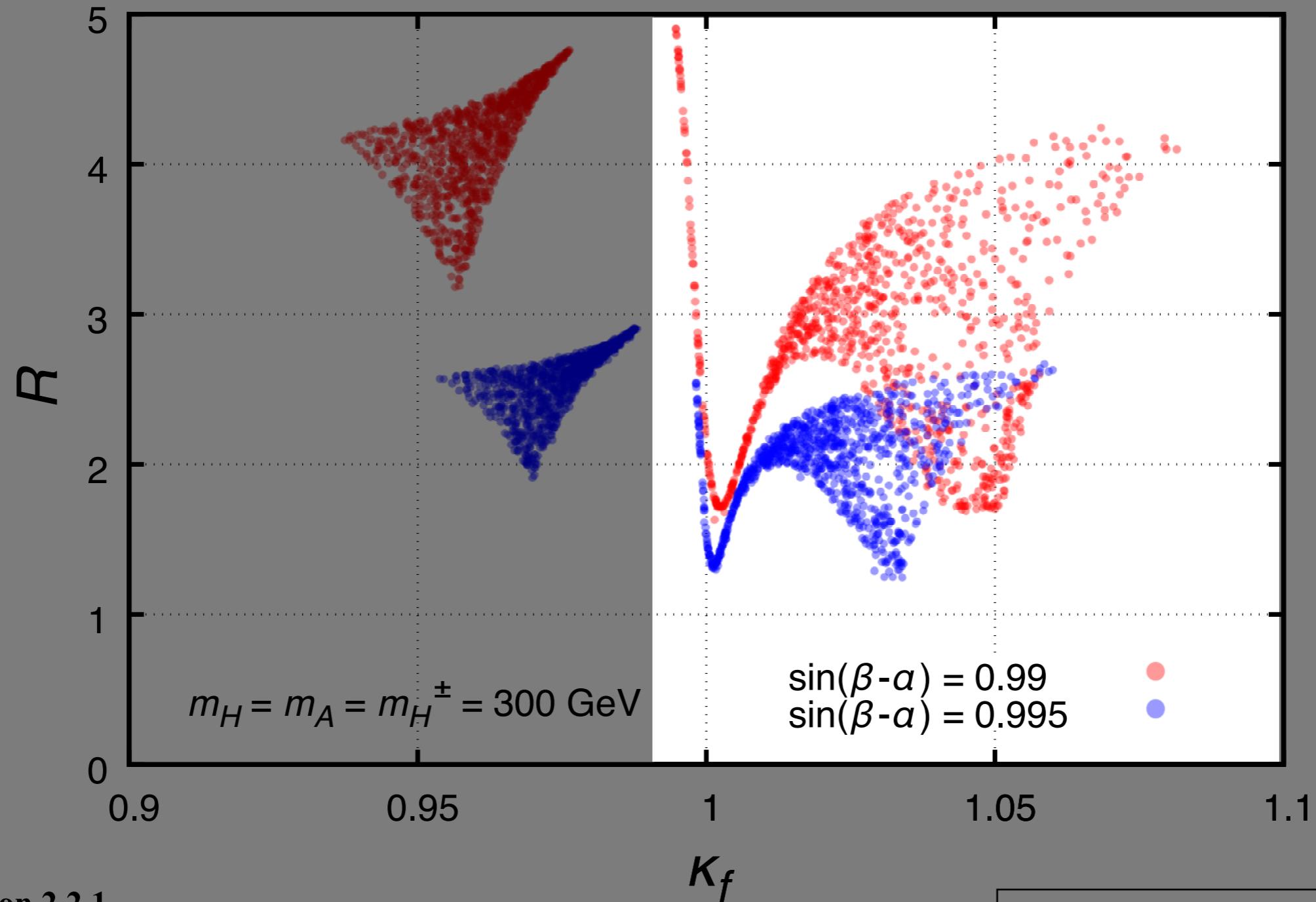
Numerical Results : κ_f vs R

$$R \equiv \frac{\sum_f \sigma^{\text{2HDM}}(e^+e^- \rightarrow f\bar{f}hh)}{\sum_f \sigma^{\text{SM}}(e^+e^- \rightarrow f\bar{f}hh)}$$

$$\cos(\beta - \alpha) > 0$$

$$1 \leq \tan \beta \leq 30, 0 \leq M^2 \leq (300 \text{ GeV})^2$$

$$\sqrt{s} = 500 \text{ GeV}$$



$$\boxed{\kappa_f = \sin(\beta - \alpha) + \frac{\cos(\beta - \alpha)}{\tan \beta}}$$

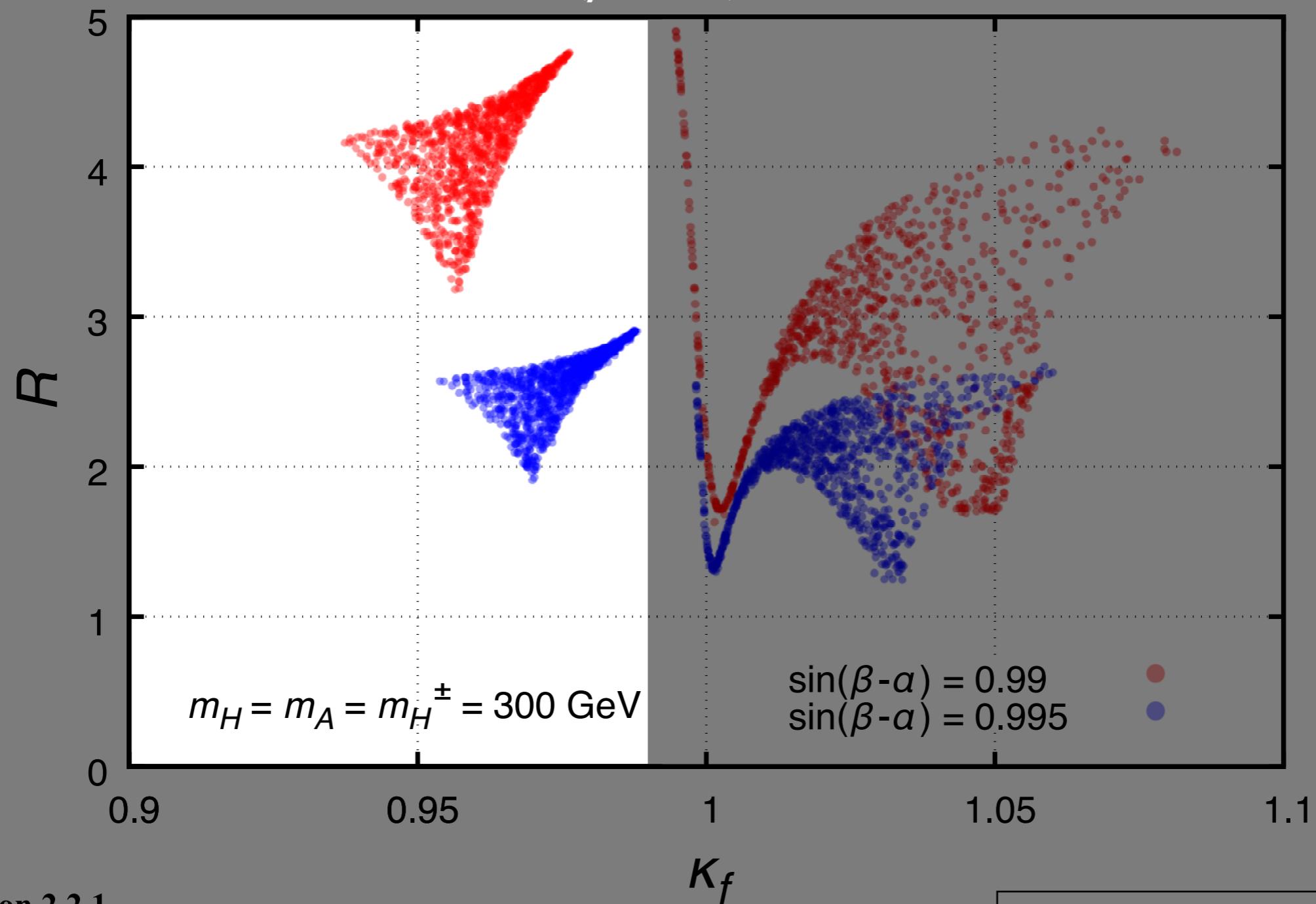
Numerical Results : κ_f vs R

$$R \equiv \frac{\sum_f \sigma^{\text{2HDM}}(e^+e^- \rightarrow f\bar{f}hh)}{\sum_f \sigma^{\text{SM}}(e^+e^- \rightarrow f\bar{f}hh)}$$

 $\sqrt{s} = 500 \text{ GeV}$

$\cos(\beta - \alpha) < 0$

$1 \leq \tan \beta \leq 30, 0 \leq M^2 \leq (300 \text{ GeV})^2$



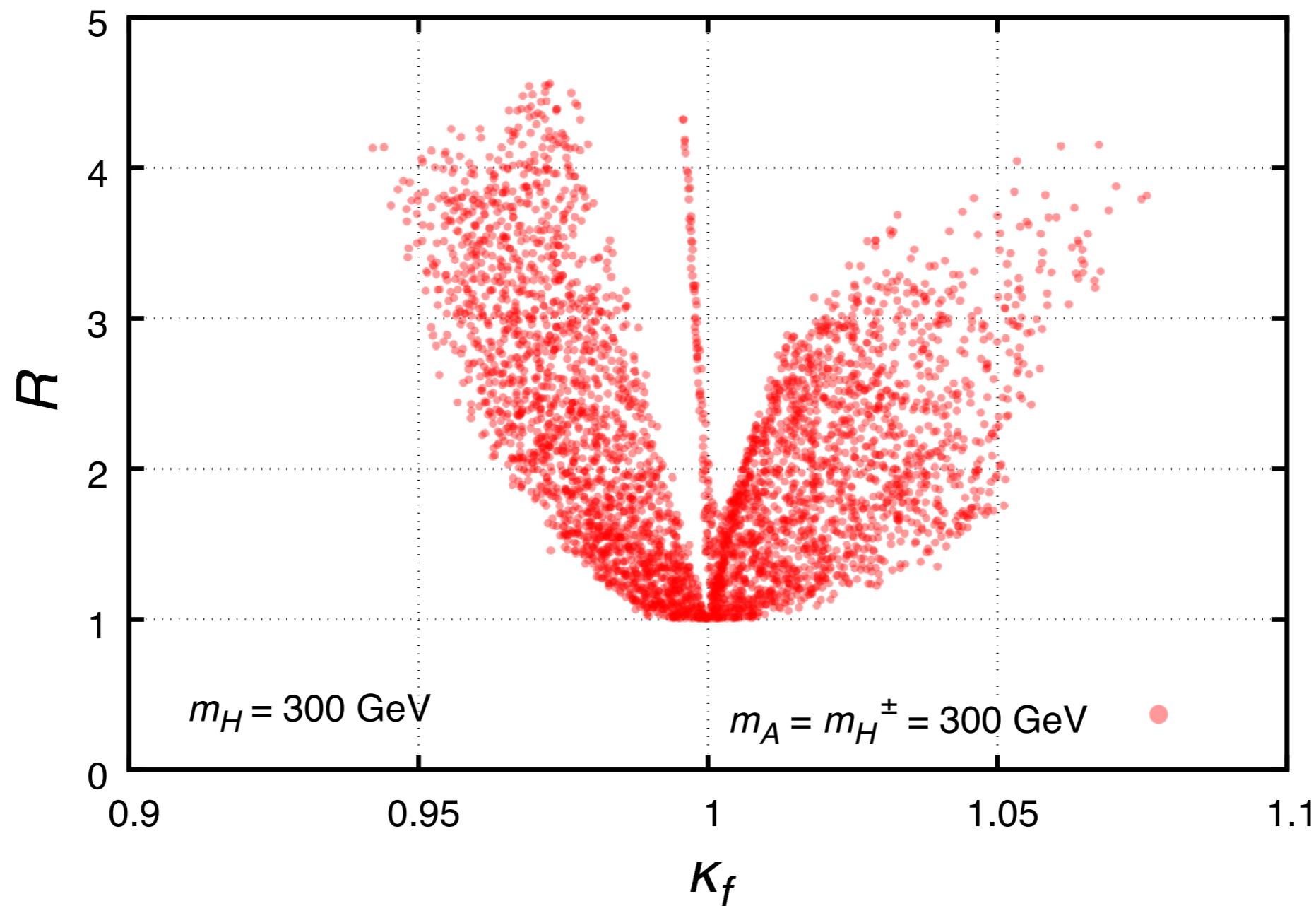
Numerical Results : κ_f VS R

Kon, TN, Ueda, Yagyu
PRD99 (2019) 095027

$$R \equiv \frac{\sum_f \sigma^{\text{2HDM}}(e^+e^- \rightarrow f\bar{f}hh)}{\sum_f \sigma^{\text{SM}}(e^+e^- \rightarrow f\bar{f}hh)}$$

$\sqrt{s} = 500 \text{ GeV}$

$1 \leq \tan \beta \leq 30, 0 \leq M^2 \leq (300 \text{ GeV})^2$



GRACE version 2.2.1
F. Yuasa et al., (2000)
J. Fujimoto et al., 2003

$$\kappa_f = \sin(\beta - \alpha) + \frac{\cos(\beta - \alpha)}{\tan \beta}$$

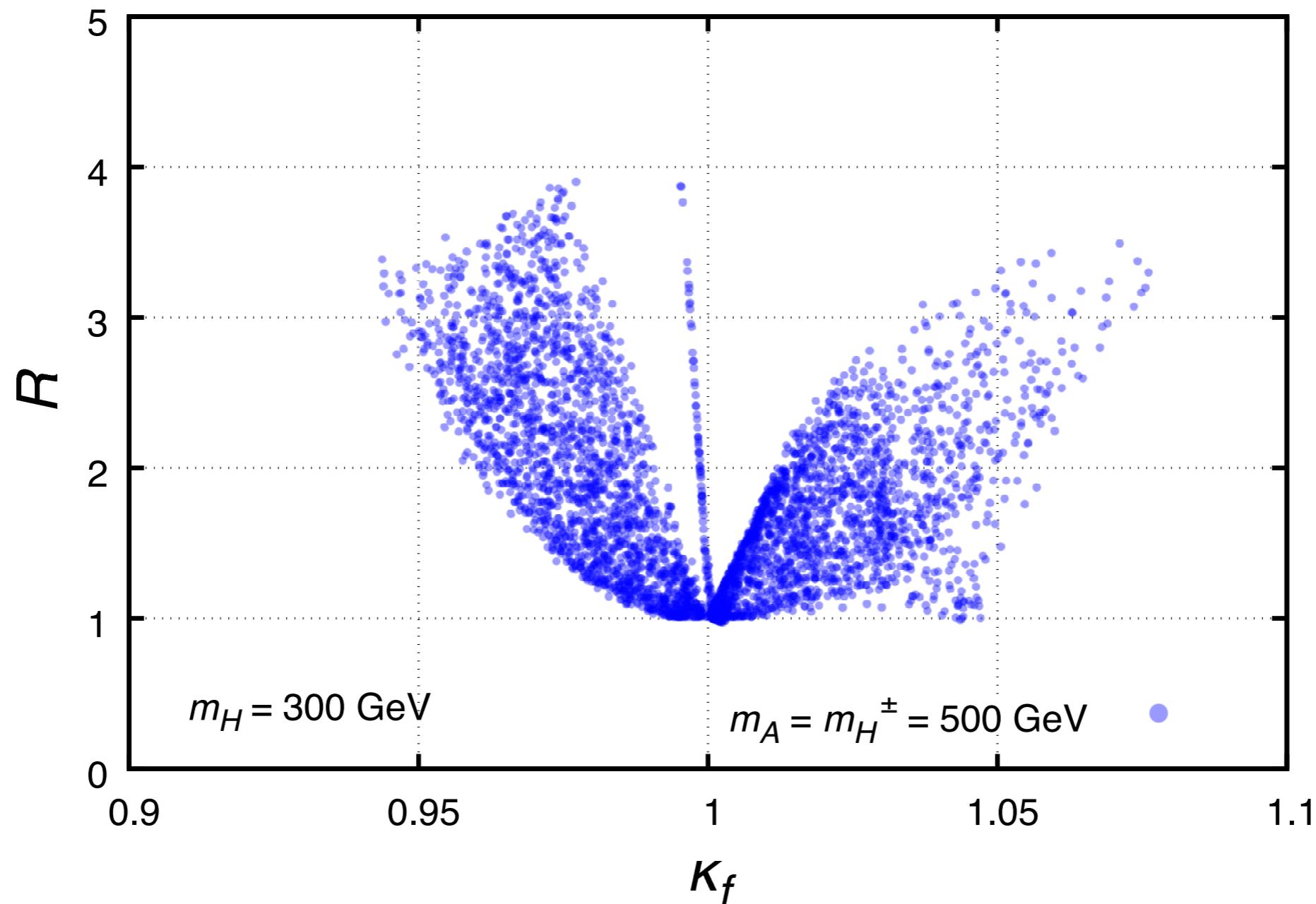
Numerical Results : κ_f VS R

Kon, TN, Ueda, Yagyu
PRD99 (2019) 095027

$$R \equiv \frac{\sum_f \sigma^{\text{2HDM}}(e^+e^- \rightarrow f\bar{f}hh)}{\sum_f \sigma^{\text{SM}}(e^+e^- \rightarrow f\bar{f}hh)}$$

$\sqrt{s} = 500 \text{ GeV}$

$1 \leq \tan \beta \leq 30, 0 \leq M^2 \leq (300 \text{ GeV})^2$



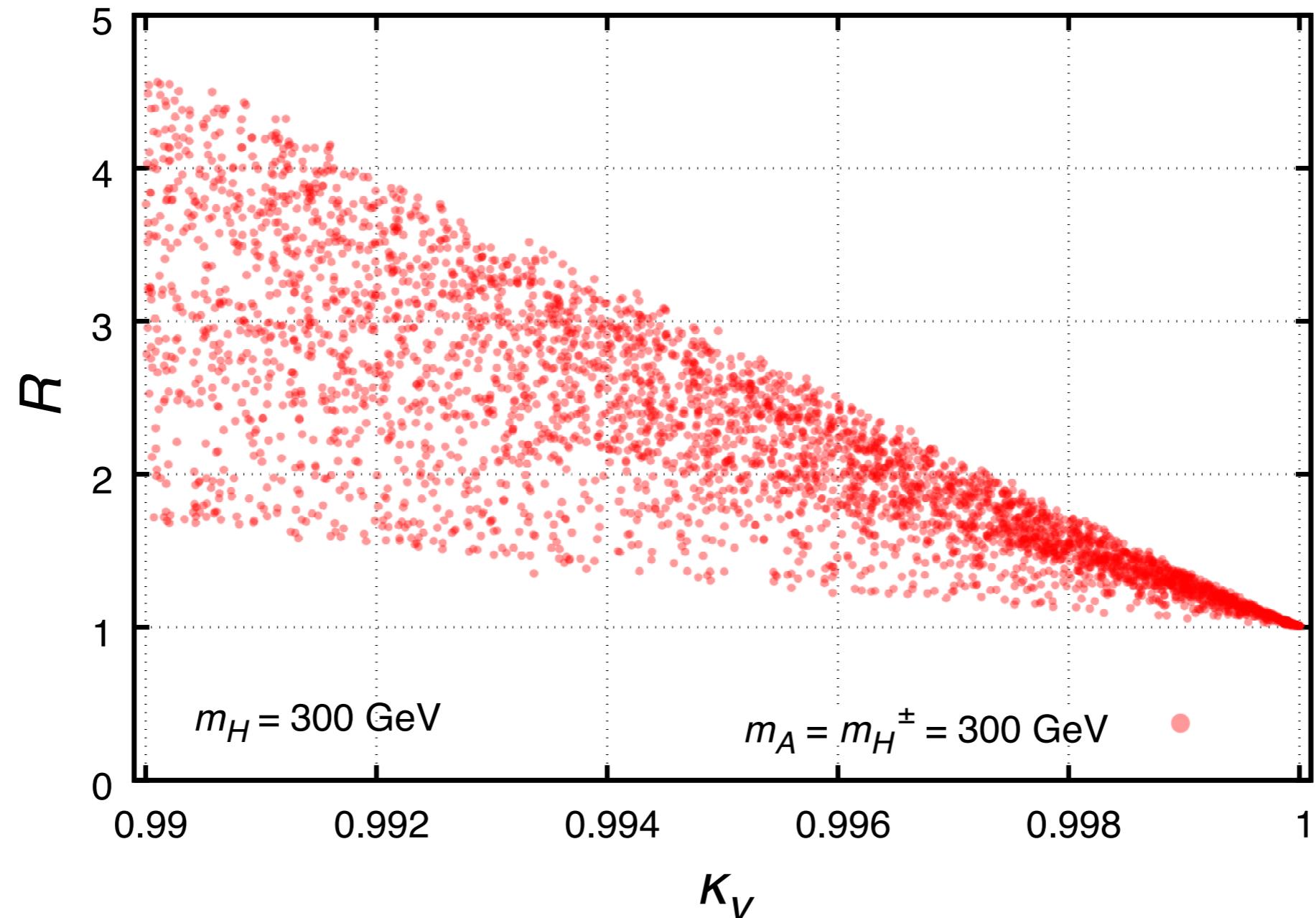
Numerical Results : κ_V VS R

Kon, TN, Ueda, Yagyu
PRD99 (2019) 095027

$$R \equiv \frac{\sum_f \sigma^{\text{2HDM}}(e^+e^- \rightarrow f\bar{f}hh)}{\sum_f \sigma^{\text{SM}}(e^+e^- \rightarrow f\bar{f}hh)}$$

$\sqrt{s} = 500 \text{ GeV}$

$1 \leq \tan \beta \leq 30, 0 \leq M^2 \leq (300 \text{ GeV})^2$



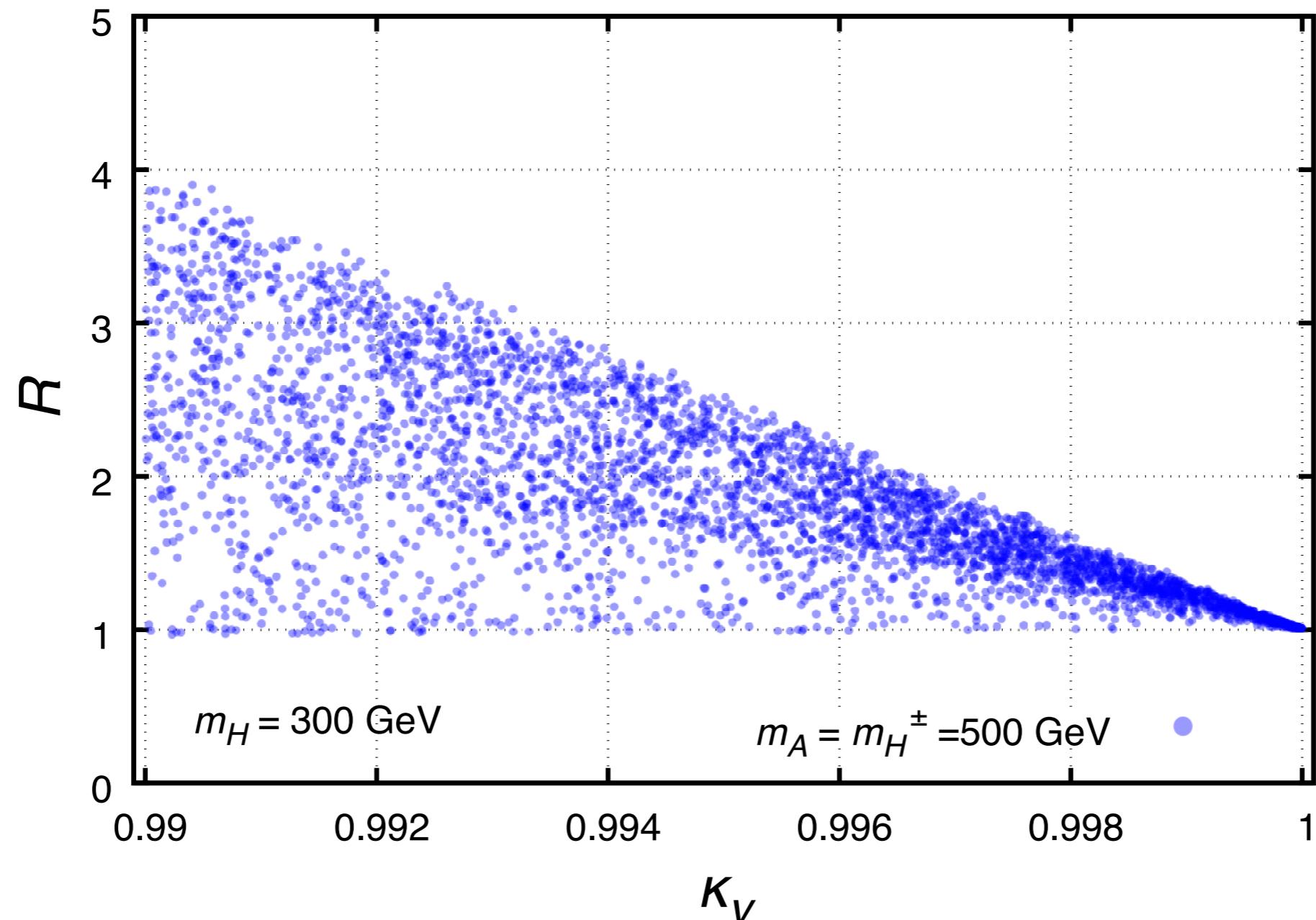
Numerical Results : κ_V VS R

Kon, TN, Ueda, Yagyu
PRD99 (2019) 095027

$$R \equiv \frac{\sum_f \sigma^{\text{2HDM}}(e^+e^- \rightarrow f\bar{f}hh)}{\sum_f \sigma^{\text{SM}}(e^+e^- \rightarrow f\bar{f}hh)}$$

$\sqrt{s} = 500 \text{ GeV}$

$1 \leq \tan \beta \leq 30, 0 \leq M^2 \leq (300 \text{ GeV})^2$



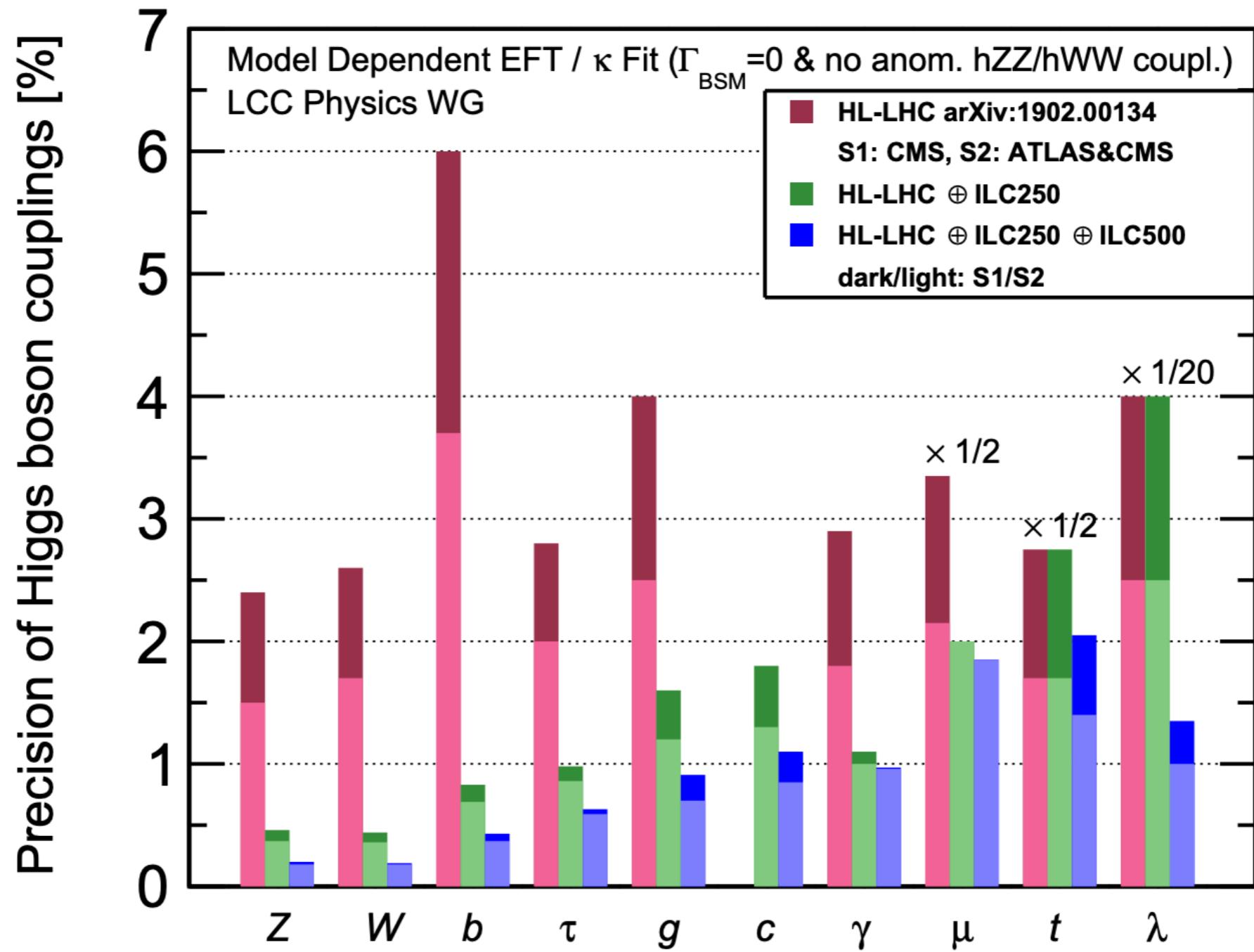
The Higgs boson couplings

K. Fujii *et al.*, arXiv : 1710.07621

	ILC250		+ILC500	
	κ fit	EFT fit	κ fit	EFT fit
$g(hbb)$	1.8	1.1	0.60	0.58
$g(hcc)$	2.4	1.9	1.2	1.2
$g(hgg)$	2.2	1.7	0.97	0.95
$g(hWW)$	1.8	0.67	0.40	0.34
$g(h\tau\tau)$	1.9	1.2	0.80	0.74
$g(hZZ)$	0.38	0.68	0.30	0.35
$g(h\gamma\gamma)$	1.1	1.2	1.0	1.0
$g(h\mu\mu)$	5.6	5.6	5.1	5.1
$g(h\gamma Z)$	16	6.6	16	2.6
$g(hbb)/g(hWW)$	0.88	0.86	0.47	0.46
$g(h\tau\tau)/g(hWW)$	1.0	1.0	0.65	0.65
$g(hWW)/g(hZZ)$	1.7	0.07	0.26	0.05
Γ_h	3.9	2.5	1.7	1.6
$BR(h \rightarrow inv)$	0.32	0.32	0.29	0.29
$BR(h \rightarrow other)$	1.6	1.6	1.3	1.2

Higgs boson couplings

arXiv : 1903.01629



ILC 250 can measure hVV couplings with one percent level.

Double Higgs boson production at the e^-e^+ colliders

