Precise calculations of the Higgs decay rates in multi-Higgs models

Based on Phys. Lett. B783 (2018) 140;

Comput. Phys. Commun. 233 (2018) 134.

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September. 4th Multi-Higgs Models 2018

Introduction

- Properties of the Higgs bosons have been measured at the LHC:

  Masses, hVV couplings, hff couplings,⋯

  Current exp. data are consistent with predictions of the SM.

- Deviations from the SM may be found in the future collider exp.

  HL-LHC, ILC, CLIC, FCC-ee, CPEC, HE-LHC,FCC-hh,⋯

  The Higgs couplings will be measured with a few % accuracy.

⇒ Can we clarify the shape the Higgs sector with the precise measurement of the Higgs observables?

In this talk, we discuss whether we can discriminate various extended Higgs modes via 1-loop corrected Higgs decay rates.

Extended Higgs models

We focus on 4 types of THDMs and the Higgs singlet model (HSM).

THDMs	Φ_1	Φ_2	u_R	d_R	e_R
Type-I	+	−	−	−	−
Type-II	+	−	−	+	+
Type-X	+	−	−	−	+
Type-Y	+	−	−	+	−

[V. D. Barger, J. L. Hewett and R. J. N. Phillips, PRD41 (1990) 3421]
[Y. Grossman, NPB426(1994)355]; [A. G. Akeroyd and W. J. Stirling, Nucl. Phys. B447 (1995)3]
[M. Aoki, S. Kanemura, K. Tsumura and K. Yagyu, PRD80 (2009) 015017]

	THDMs Type I, II, X, Y (Softly broken Z_2 sym., CP conserved)	HSM (No global sym.)
Higgs sector	$\Phi_1 + \Phi_2$ $\Phi_i = \begin{pmatrix} w_i \\ 1/\sqrt{2}(v + h_i + i z_i) \end{pmatrix}$ (i = 1,2)	$\Phi + S$ (Real singlet) $S = v_s + s$
Physical states (h : 125 GeV Higgs)	$h, H, A, H^\pm$	h, H
Free parameters	$m_H, m_A, m_{H^\pm}, \alpha, \beta, M^2$	$m_H, \alpha, m_S^2, \lambda_S\ \mu_S$
Higgs coup. ($s_\theta \equiv \sin\theta$, $c_\theta \equiv \cos\theta$)	$\Gamma^{1,\text{tree}}_{hVV} = -\frac{2m_V^2}{v} s_{\beta-\alpha}$, $\Gamma^{S,\text{tree}}_{hff} = -\frac{m_f}{v}(s_{\beta-\alpha} + \xi_f c_{\beta-\alpha})$	$\Gamma^{1,\text{tree}}_{hff} = -\frac{2m_V^2}{v} c_\alpha$, $\Gamma^{S,\text{tree}}_{hff} = -\frac{m_f}{v} c_\alpha$

H-COUP

[Kanemura, Kikuchi KS, Yagyu, CPC 233 (2018) 134]

H-COUP is a program to evaluate Higgs boson couplings at the 1-loop level.

- Renormalization scheme: improved on-shell scheme
  [S. Kanemura, M. Kikuchi, KS, K. Yagyu, PRD96 (2017),035014]

  Gauge dependence coming from the renormalization for mixing angles are removed by the pinch technique. [F. Bojarski, G. Chalons, D. Lopez-Val, T. Robens, JHEP02 (2016) 147.]; [M. Krause, R. Lorenz, M. Muhlleitner, R. Santos, H. Ziesche, JHEP 09 (2016) 143.]

- Model:

  Higgs singlet model (HSM)

  Two Higgs Doublet Models (THDMs) Type I, II, X, Y

  Inert Doublet Model

- Outputs : Renormalized Higgs 3-point vertex functions Γ_{hXX}

  $\Gamma^{\rm i}_{\rm hVV}(2)$, $\Gamma^{\rm j}_{\rm hff}(8)$, $\Gamma_{hhh,}$ $\Gamma(h\to\gamma\gamma), \Gamma(h\to Z\gamma), \Gamma(h\to gg)$

Higgs decay rates are evaluated at the 1-loop level by using H-COUP:

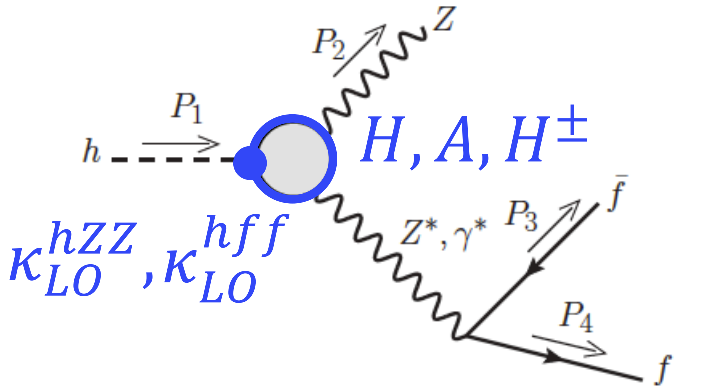
$\Gamma(h\to f\bar{f}),\ \Gamma(h\to ZZ^*\to Zf\bar{f}),\ \Gamma(h\to\gamma\gamma),\ \Gamma(h\to Z\gamma),\ \Gamma(h\to gg)$

Diagrams for $\mathrm{h} \to ZZ^* \to Zf\bar{f}$

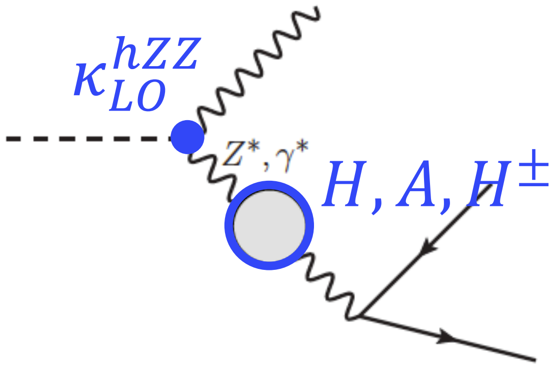
(THDM): $\kappa_{LO}^{hZZ} = \sin(\beta - \alpha)$

$\kappa_{LO}^{hff} = \sin(\beta - \alpha) + \xi_f \cos(\beta - \alpha)$

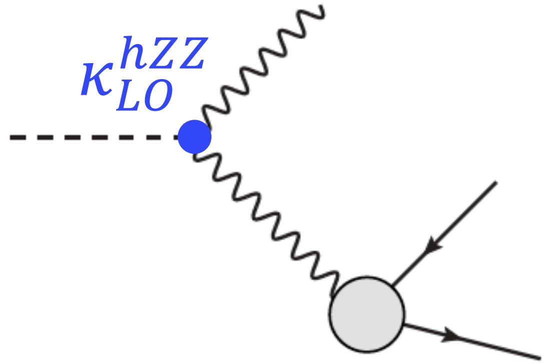
(HSM): $\kappa_{LO}^{hZZ} = \kappa_{LO}^{hff} = \cos(\alpha)$



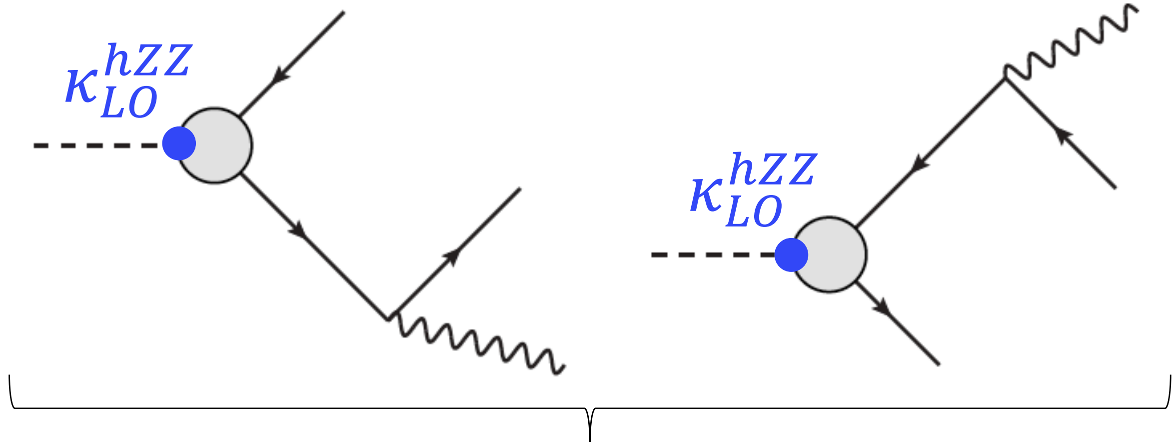
hZZ vertex correction



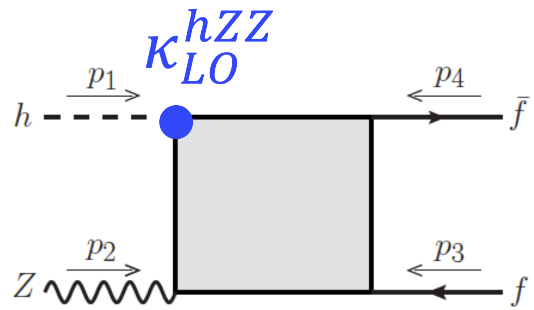
Self-energy correction



Zff vertex correction



hff vertex correction

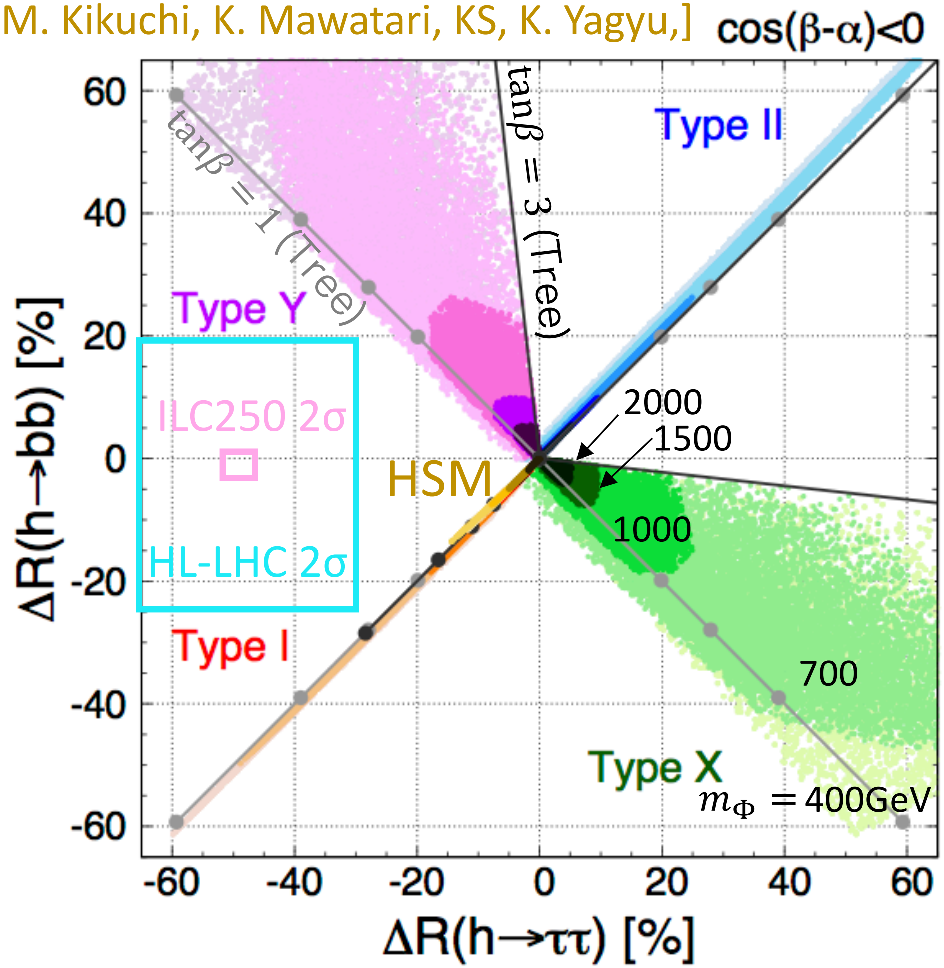


Box diagram correction

$\Delta R(h \to b\bar{b})$ vs $\Delta R(h \to \tau\bar{\tau})$

$$\Delta R(h \to XX) = \frac{\Gamma(h \to XX)_{EX}}{\Gamma(h \to XX)_{SM}} - 1$$

[S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu,]



- Color plots : predictions at the 1-loop level for each model
- A contrast of color : values of mass of extra Higgs bosons
- Black line : predictions at the tree level ($tan\beta = 1{,}3$).

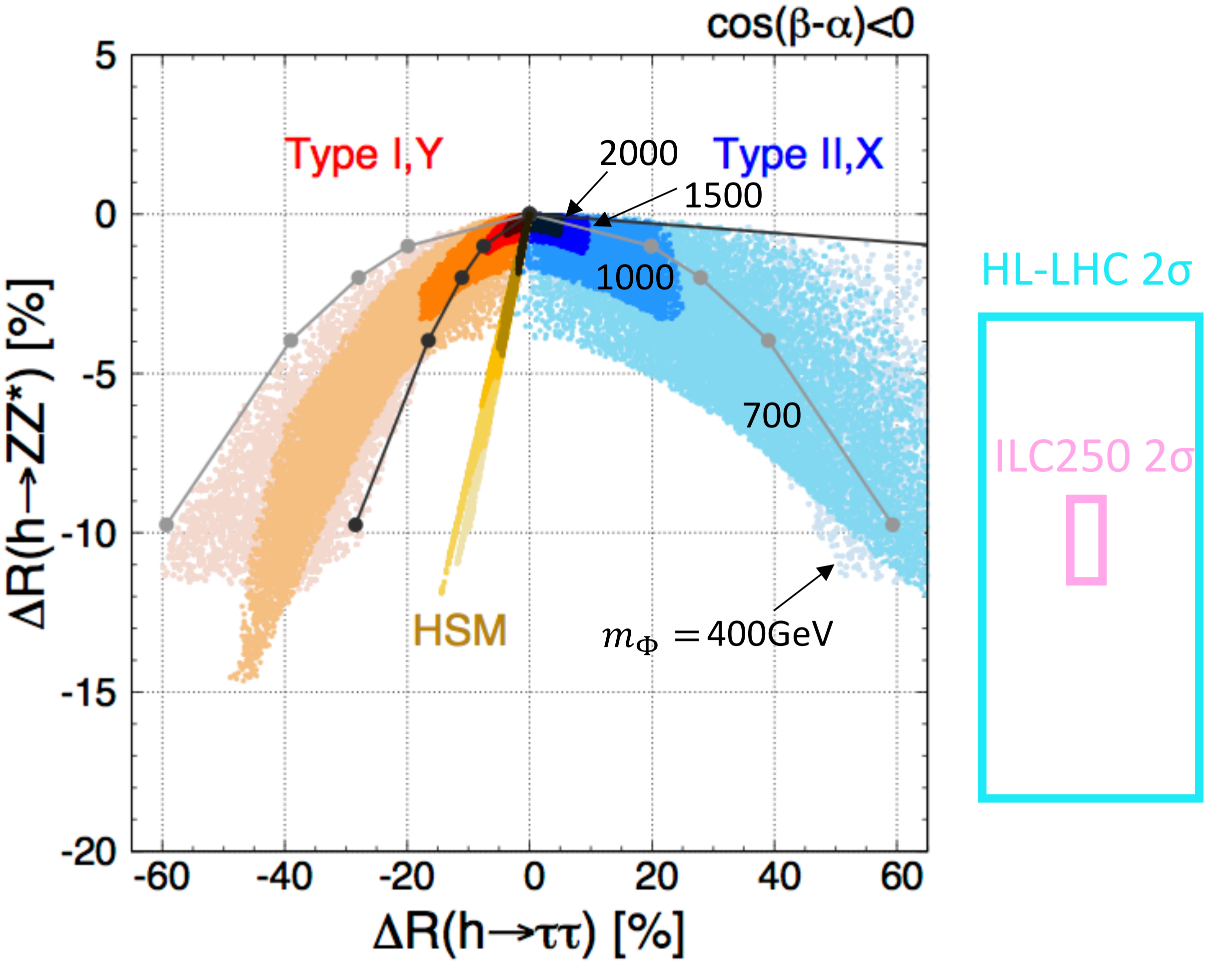
→ 4 types of THDMs are discriminated by pattern of deviations.

→ The upper bounds of mass of extra Higgs can be obtained from magnitude of deviations due to theoretical constraints.

$\Delta R(h \to ZZ^*)$ vs $\Delta R(h \to \tau\bar{\tau})$

$$\Delta R(h \to XX) = \frac{\Gamma(h \to XX)_{EX}}{\Gamma(h \to XX)_{SM}} - 1$$

[S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu]



→ HSM can be separated from the THDMs.

→ Type I and Type II can be discriminated in this plane.

Summary

- We discussed a possibility of discrimination among the HSM and 4 types of THDMs with precise measurement of Higgs decay rates.

- We evaluated the Higgs decay rates at the 1-loop level by utilizing H-COUP.

→ Pattern of deviations : HSM and 4 types of THDMs can be discriminated.

→ Magnitude of deviations : Information of the mass of extra Higgs bosons can be obtained.

We need the ILC!

Back up slides

Accuracy of the Higgs couplings measurements

Current data (LHC Run I)

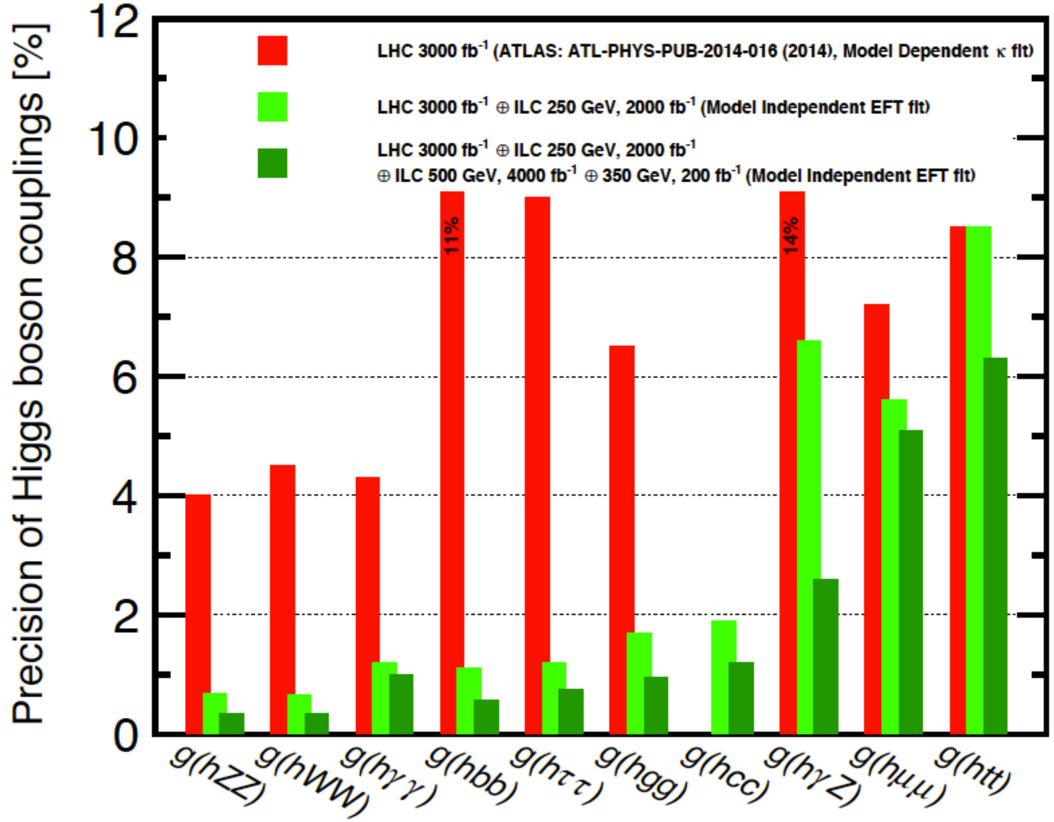
scaling factor: $\kappa_X = g_{hXX}^{exp.} / g_{hXX}^{SM}$

[ATLAS and CMS, JHEP08(2016)045]

κ_Z	-0.98 $[-1.08, -0.88] \cup$ $[0.94, 1.13]$
κ_W	0.87 $[0.78, 1.00]$
κ_t	$1.40^{+0.24}_{-0.21}$
$\lvert\kappa_\tau\rvert$	$0.84^{+0.15}_{-0.11}$
$\lvert\kappa_b\rvert$	$0.49^{+0.27}_{-0.15}$
$\lvert\kappa_g\rvert$	$0.78^{+0.13}_{-0.10}$
$\lvert\kappa_\gamma\rvert$	$0.87^{+0.14}_{-0.09}$

Future prospect (HL-LHC, ILC)

[K. Fujii, et al., arXiv:1710.07621]



→ We should evaluate the theoretical predictions including radiative corrections.

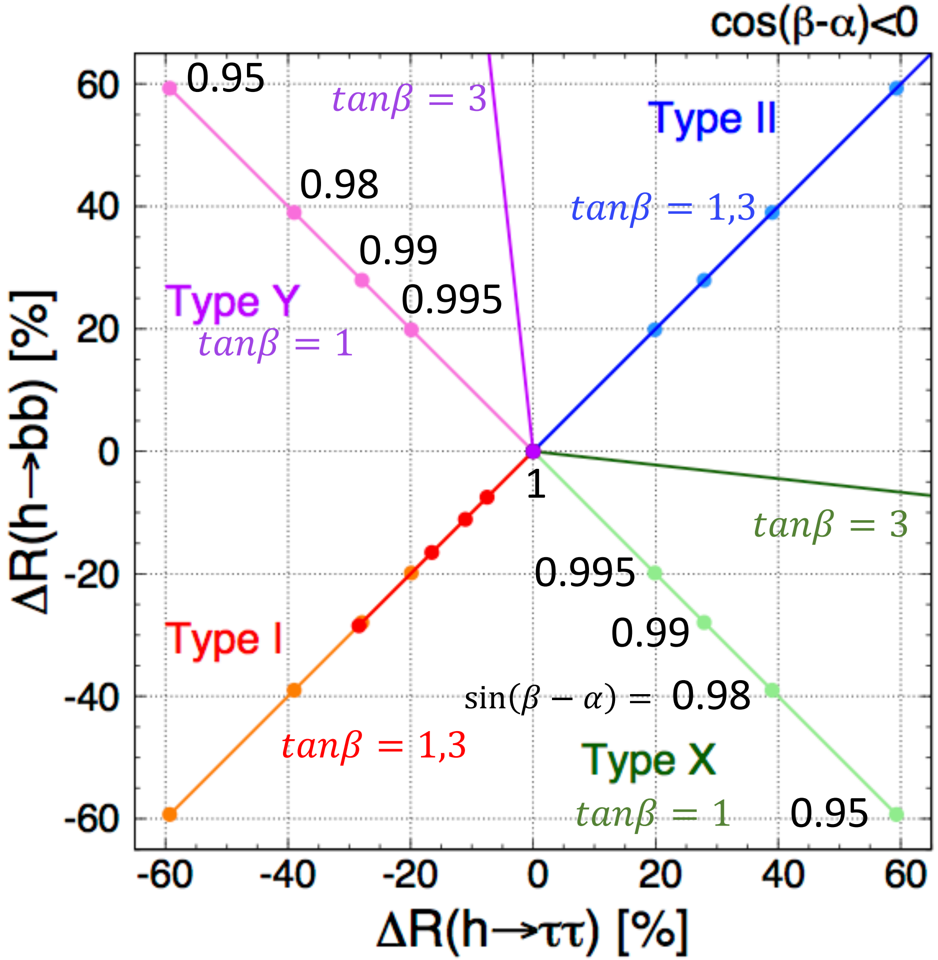
$\Delta R(h \to b\bar{b})$ vs $\Delta R(h \to \tau\bar{\tau})$ [Tree]

$$\Delta R(h \to XX) = \frac{\Gamma(h \to XX)_{EX}}{\Gamma(h \to XX)_{SM}} - 1$$

For THDMs :

$$\Delta R(h \to f\bar{f})^{LO} = (\sin(\beta - \alpha) - \xi_f \cos(\beta - \alpha))^2 - 1$$

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



[S. Kanemura, K. Tsumura, K. Yagyu, H. Yokoya, PRD90 (2014) 075001.]

In this plane, 4 types of THDMs can be distinguished.

Numerical calculations (1-loop)

We discuss whether or not THDMs and the HSM can be distinguished by deviations from the SM in the decay widths.

- Scan region of input parameters in the THDMs :

$$0.95 < \sin(\beta - \alpha) < 1, \quad 1 < tan\beta < 3,$$
$$m_\Phi = m_H = m_A = m_{H^\pm},$$
$$m_\Phi = 400, 700, 1000, 1500, 2000 \text{ GeV},$$
$$0 < M < m_\Phi$$

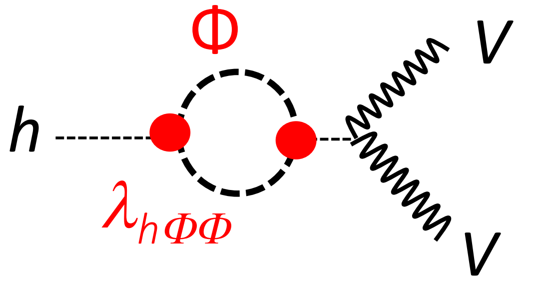
- Scan region for the HSM :

$$0.95 < \cos\alpha < 1,$$
$$m_\Phi = 500, 1000, 2000, 3000, 5000 \text{ GeV},$$
$$0 < m_s < m_\Phi, \ \lambda_s = \mu_s = 0$$

- Constraints :

Perturbative unitarity, Vacuum stability, Wrong vacuum condition (for HSM), S, T parameters

Impact of Loop correction of extra Higgs in *hZZ* vertex



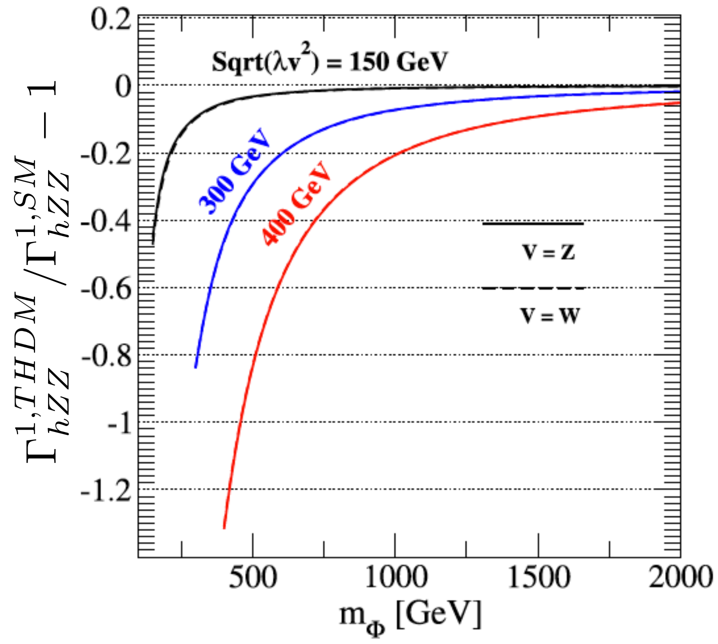
Approximate formula （ $m_A, m_{H^\pm}, m_H$ >> m_h, ）
$\sin(\beta-\alpha)=1, \tan\beta=1$

$$\Gamma^1_{hZZ}=\frac{2m_Z^2}{v}\left\{1-\sum_{\Phi=A,H,H^\pm}c_\Phi\frac{1}{6}\frac{m_\Phi^2}{v^2}\left(1-\frac{M^2}{m_{\Phi^2}}\right)^2\right\}$$

1) $M^2 \gg v^2$ Decoupling case

$$m_\Phi^2\simeq M^2+\lambda_i v^2\sim M^2$$

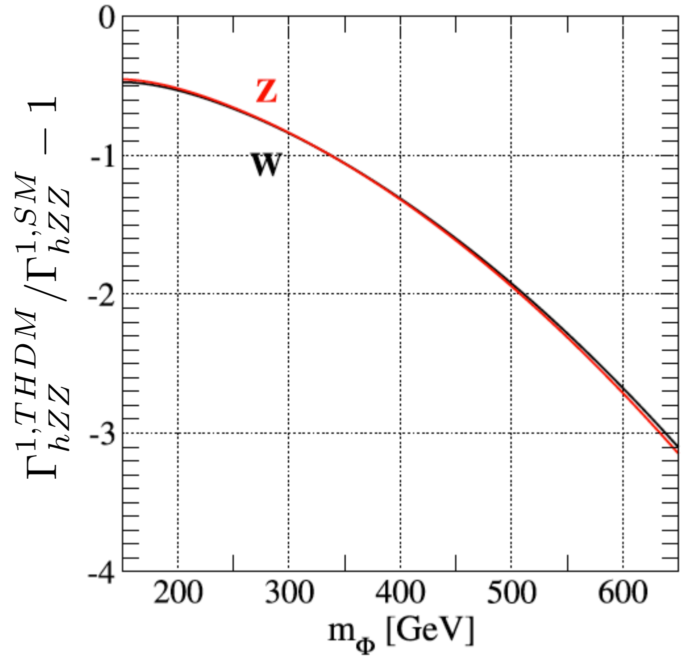
[S. Kanemura, M. Kikuchi, K. Yagyu Nucl.Phys. B896,80.]



2) $M^2 \lesssim v^2$ Non-decoupling case

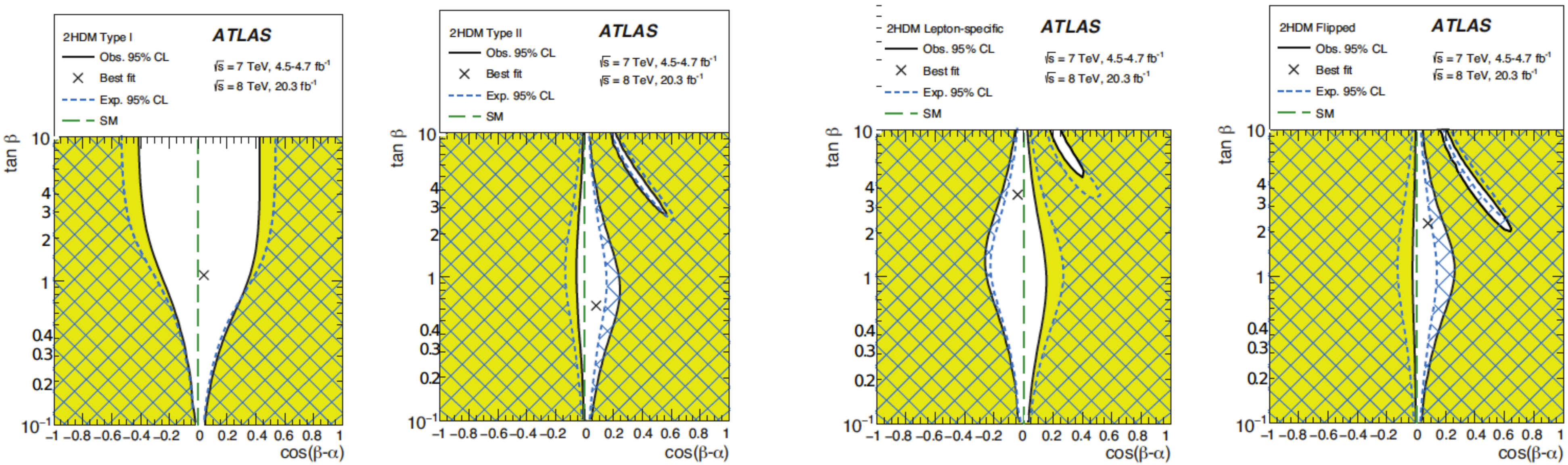
$$m_\Phi^2\simeq M^2+\lambda_i v^2\sim \lambda_i v^2$$

[S. Kanemura, M. Kikuchi, K. Yagyu Nucl.Phys. B896,80.]



constraint for THDMs (Higgs signal strength)

[ATLAS, JHEP1511(2015)206]



(a) Type I (b) Type II (c) Lepton-specific (d) Flipped

$$c_{\beta-\alpha} = 0.1 \rightarrow s_{\beta-\alpha} = 0.99$$

$$c_{\beta-\alpha} = 0.2 \rightarrow s_{\beta-\alpha} = 0.98$$

$$c_{\beta-\alpha} = 0.3 \rightarrow s_{\beta-\alpha} = 0.95$$

Constraint of direct search (HSM)

[T. Robens, T. Stefaniak, Eur. Phys. J. C (2016) 76,268]

LHC Run II

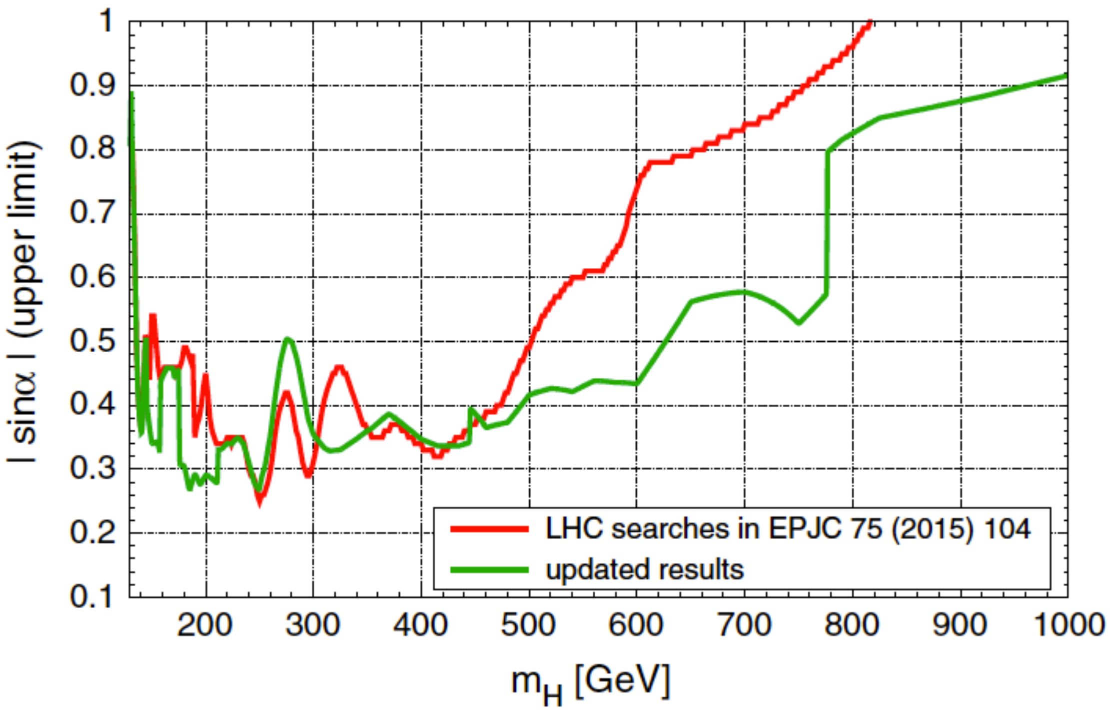
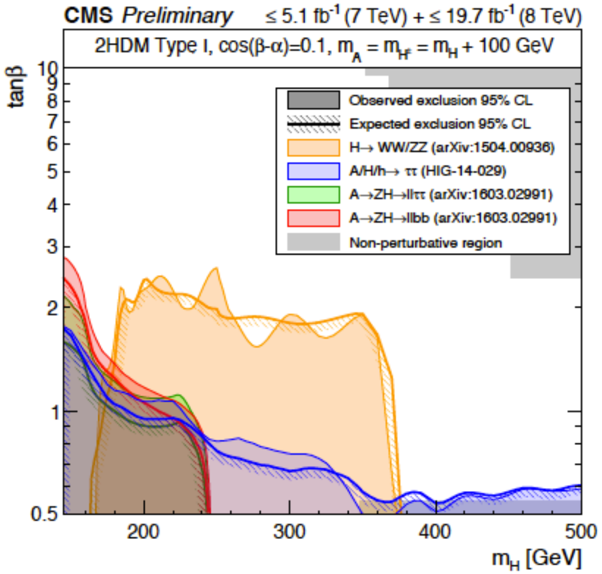


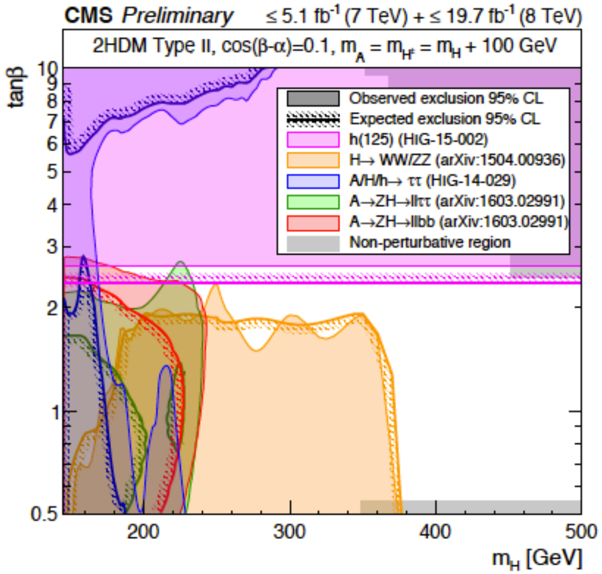
Table 1 List of LHC Higgs search channels that are applied by HiggsBounds in the high-mass region, yielding the upper limit on $|\sin\alpha|$ shown in Figs. 1 and 2

Range of m_H [GeV]	Search channel	Reference
130–145	$H \to ZZ \to 4l$	[94] (CMS)
145–158	$H \to VV$ (V=W,Z)	[66] (CMS)
158–163	SM comb.	[95] (CMS)
163–170	$H \to WW$	[96] (CMS)
170–176	SM comb.	[95] (CMS)
176–211	$H \to VV$ (V=W,Z)	[66] (CMS)
211–225	$H \to ZZ \to 4l$	[94] (CMS)
225–445	$H \to VV$ (V=W,Z)	[66] (CMS)
445–776	$H \to ZZ$	[70] (ATLAS)
776–1000	$H \to VV$ (V=W,Z)	[66] (CMS)

Status of direct search of extra Higgs

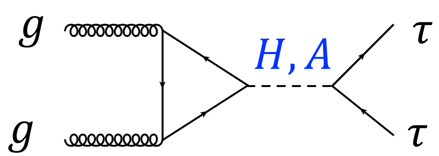
- constraint for THDMs (LHC Run I, Summary plots by CMS) [CMS PAS HIG-16-007]

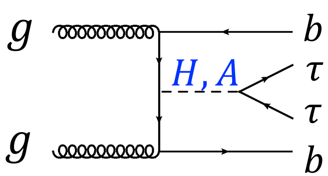


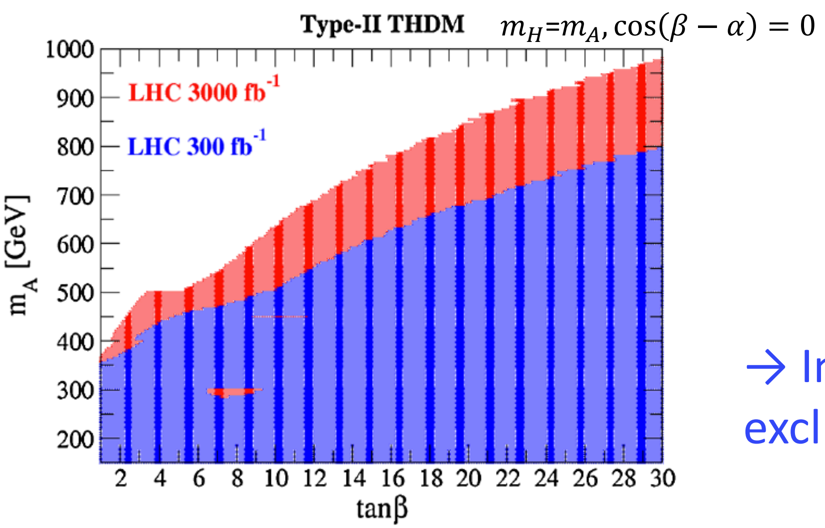


→ Basically, for Type II $tan\beta < 2$, $m_H < 380$ GeV are excluded.

- Future prospect of excluded regions [Kanemura, Tsumura, Yagyu, Yokoya, PRD90(2014)075001]







→ In the future exp. excluded regions are spread.

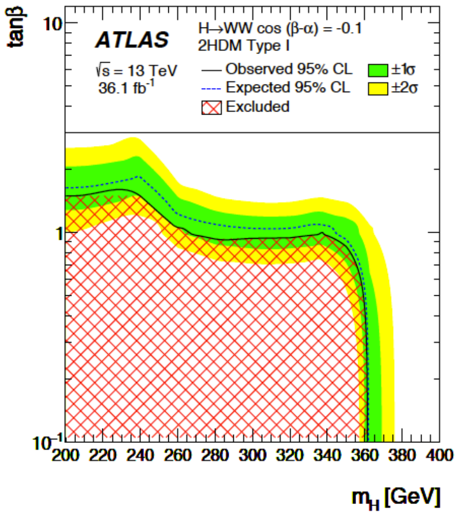
Constraint of direct search (THDM)

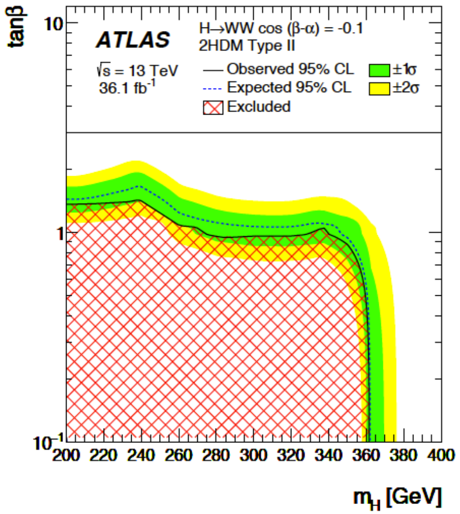
At LHC Run II

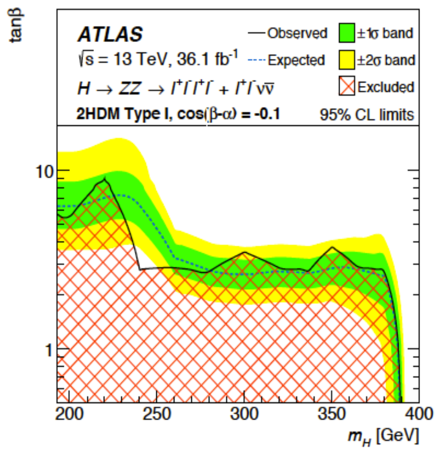
[ATLAS ,Eur.Phys.J. C78 (2018) 24]

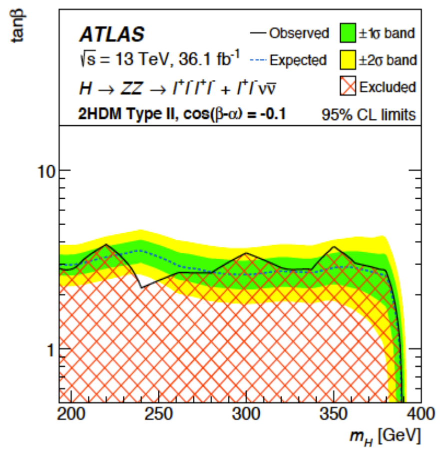
[ATLAS, arXiv:1712.06386]

ℓ: e, μ









final state: eνμν

Signal strength(current data)

JHEP08,045

Decay channel	ATLAS+CMS	ATLAS	CMS
$\mu^{\gamma\gamma}$	$1.14^{+0.19}_{-0.18}$ $\left(^{+0.18}_{-0.17}\right)$	$1.14^{+0.27}_{-0.25}$ $\left(^{+0.26}_{-0.24}\right)$	$1.11^{+0.25}_{-0.23}$ $\left(^{+0.23}_{-0.21}\right)$
μ^{ZZ}	$1.29^{+0.26}_{-0.23}$ $\left(^{+0.23}_{-0.20}\right)$	$1.52^{+0.40}_{-0.34}$ $\left(^{+0.32}_{-0.27}\right)$	$1.04^{+0.32}_{-0.26}$ $\left(^{+0.30}_{-0.25}\right)$
μ^{WW}	$1.09^{+0.18}_{-0.16}$ $\left(^{+0.16}_{-0.15}\right)$	$1.22^{+0.23}_{-0.21}$ $\left(^{+0.21}_{-0.20}\right)$	$0.90^{+0.23}_{-0.21}$ $\left(^{+0.23}_{-0.20}\right)$
$\mu^{\tau\tau}$	$1.11^{+0.24}_{-0.22}$ $\left(^{+0.24}_{-0.22}\right)$	$1.41^{+0.40}_{-0.36}$ $\left(^{+0.37}_{-0.33}\right)$	$0.88^{+0.30}_{-0.28}$ $\left(^{+0.31}_{-0.29}\right)$
μ^{bb}	$0.70^{+0.29}_{-0.27}$ $\left(^{+0.29}_{-0.28}\right)$	$0.62^{+0.37}_{-0.37}$ $\left(^{+0.39}_{-0.37}\right)$	$0.81^{+0.45}_{-0.43}$ $\left(^{+0.45}_{-0.43}\right)$
$\mu^{\mu\mu}$	$0.1^{+2.5}_{-2.5}$ $\left(^{+2.4}_{-2.3}\right)$	$-0.6^{+3.6}_{-3.6}$ $\left(^{+3.6}_{-3.6}\right)$	$0.9^{+3.6}_{-3.5}$ $\left(^{+3.3}_{-3.2}\right)$

Definition of μ^f

$$\mu^f = \frac{\mathrm{BR}_{EX}}{\mathrm{BR}_{SM}}$$

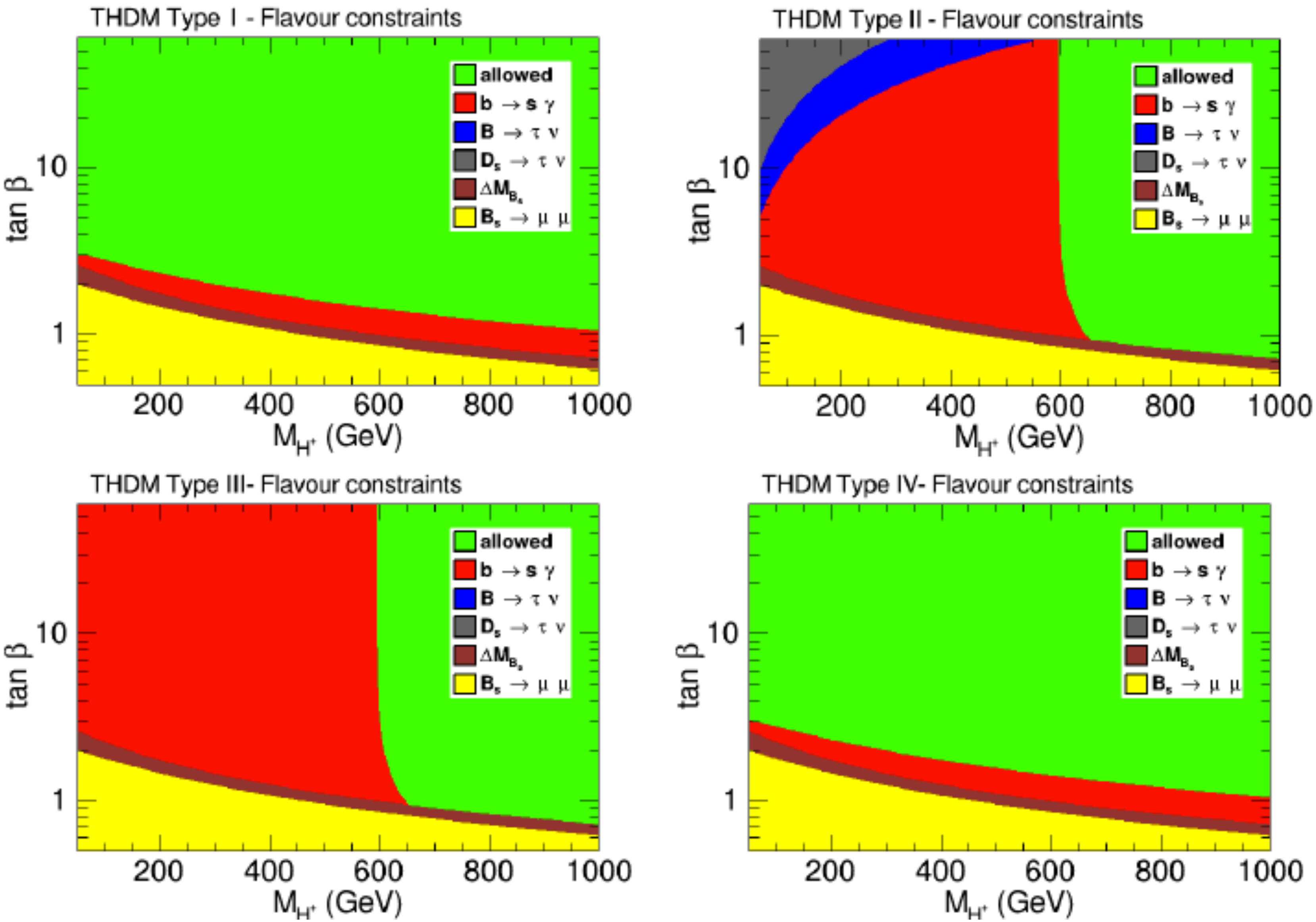
Signal strength by ILC (prospect)

ArXiv: 1310.8361

	ILC 250/500/1000 GeV		ILC LumiUp[‡] 250/500/1000 GeV	
	ZH	$\nu\bar{\nu}H$	ZH	$\nu\bar{\nu}H$
Inclusive	2.6/3.0/–%	–	1.2/1.7/–%	–
$H \to \gamma\gamma$	29-38%	–/20-26/7-10%	16/19/–%	–/13/5.4%
$H \to gg$	7/11/–%	–/4.1/2.3%	3.3/6.0/–%	–/2.3/1.4%
$H \to ZZ^*$	19/25/–%	–/8.2/4.1%	8.8/14/–%	–/4.6/2.6%
$H \to WW^*$	6.4/9.2/–%	–/2.4/1.6%	3.0/5.1/–%	–/1.3/1.0%
$H \to \tau\tau$	4.2/5.4/–%	–/9.0/3.1%	2.0/3.0/–%	–/5.0/2.0%
$H \to b\bar{b}$	1.2/1.8/–%	11/0.66/0.30%	0.56/1.0/–%	4.9/0.37/0.30%
$H \to c\bar{c}$	8.3/13/–%	–/6.2/3.1%	3.9/7.2/–%	–/3.5/2.0%
$H \to \mu\mu$	–	–/–/31%	–	–/–/20%
	$t\bar{t}H$		$t\bar{t}H$	
$H \to b\bar{b}$	–/28/6.0%		–/16/3.8%	

Constraint from flavor experiments

A. Arbey, F. Mahmoudi, O. Stal T. Stefaniak arXiv:1706.07414v1



Higgs singlet model(HSM)

- Higgs potential

$$\Phi = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + \phi + iG^0) \end{pmatrix}, \quad S = v_S + s,$$

$$V(\Phi, S) = m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \mu_{\Phi S}|\Phi|^2 S + \lambda_{\Phi S}|\Phi|^2 S^2 + t_S S + m_S^2 S^2 + \mu_S S^3 + \lambda_S S^4$$

- Mass eigenstates

$$\begin{pmatrix} s \\ \phi \end{pmatrix} = R(\alpha) \begin{pmatrix} H \\ h \end{pmatrix} \quad \text{with} \quad R(\alpha) = \begin{pmatrix} c_\alpha & -s_\alpha \\ s_\alpha & c_\alpha \end{pmatrix}$$

Physical state :*h, H*

- Physical parameters

$$\mathrm{v}, \mathrm{m_h}, \mathrm{m_H}, , \alpha, m_S^2, \lambda_S, \mu_{\Phi S}$$

Two Higgs doublet model(THDM)

- Higgs potential

$$\Phi_i = \begin{pmatrix} w_i^+ \\ \frac{1}{\sqrt{2}}(v_i + h_i + iz_i) \end{pmatrix} \quad \text{with} \quad i = 1, 2$$

$$\begin{aligned} V =& m_1^2|\Phi_1|^2 + m_2^2|\Phi_2|^2 - m_3^2(\Phi_1^\dagger\Phi_2 + \text{h.c.}) \\ &+ \frac{1}{2}\lambda_1|\Phi_1|^4 + \frac{1}{2}\lambda_2|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{1}{2}\lambda_5[(\Phi_1^\dagger\Phi_2)^2 + \text{h.c.}] \end{aligned}$$

- Mass eigenstates

$$\begin{pmatrix} h_1 \\ h_2 \end{pmatrix} = R(\alpha) \begin{pmatrix} H \\ h \end{pmatrix}, \quad \begin{pmatrix} z_1 \\ z_2 \end{pmatrix} = R(\beta) \begin{pmatrix} z \\ A \end{pmatrix}, \quad \begin{pmatrix} w_1^+ \\ w_2^+ \end{pmatrix} = R(\beta) \begin{pmatrix} w^+ \\ H^+ \end{pmatrix}$$

Physical state :*h, H, A,* $H^{\pm}$

- Physical parameters

$$\mathrm{v}, \mathrm{m_h}, \mathrm{m_H}, \mathrm{m_A}, \mathrm{m_{H^\pm}}, \alpha, \beta, M^2$$

Scaling factor

$$\kappa_X = \Gamma_{hXX}^{EX} / \Gamma_{hXX}^{SM}$$

THDM :

$$\Gamma(h \to \gamma\gamma) \simeq \frac{G_F \alpha_{\rm em}^2 m_h^3}{128\sqrt{2}\pi^3} \left| -\frac{1}{3}\left(1 - \frac{M^2}{m_{H^\pm}^2}\right) + \sum_f Q_f N_c^f (1 + \xi_f\, x - \frac{x^2}{2}) I_F + (1 - \frac{x^2}{2}) I_W \right|^2$$

HSM :

$$\kappa_\gamma = \cos\alpha^2$$

Definition of form factors for *hVV* and hff

$$\hat{\Gamma}^{\mu\nu}_{hVV} = \underline{\hat{\Gamma}^{1}_{hVV}} g^{\mu\nu} + \underline{\hat{\Gamma}^{2}_{hVV}} \frac{p_1^{\mu} p_2^{\nu}}{m_V^2} + i \underline{\hat{\Gamma}^{3}_{hVV}} \epsilon^{\mu\nu\rho\sigma} \frac{p_{1\rho} p_{2\sigma}}{m_V^2} ,$$

$$\begin{aligned} \hat{\Gamma}_{hff} = {} & \underline{\hat{\Gamma}^{S}_{hff}} + \gamma_5 \underline{\hat{\Gamma}^{P}_{hff}} + \not{p}_1 \underline{\hat{\Gamma}^{V1}_{hff}} + \not{p}_2 \underline{\hat{\Gamma}^{V2}_{hff}} \\ & + \not{p}_1 \gamma_5 \underline{\hat{\Gamma}^{A1}_{hff}} + \not{p}_2 \gamma_5 \underline{\hat{\Gamma}^{A2}_{hff}} + \not{p}_1 \not{p}_2 \underline{\hat{\Gamma}^{T}_{hff}} + \not{p}_1 \not{p}_2 \gamma_5 \underline{\hat{\Gamma}^{PT}_{hff}} , \end{aligned}$$

hVV: 7 form factors

hff: 3 form factors

Another tools

Prophecy4f :

arXiv:1710.07598

- Model: THDMs, HSM
- h → WW/ZZ → 4 fermions

RECOLA2 :

arXiv:1711.07388

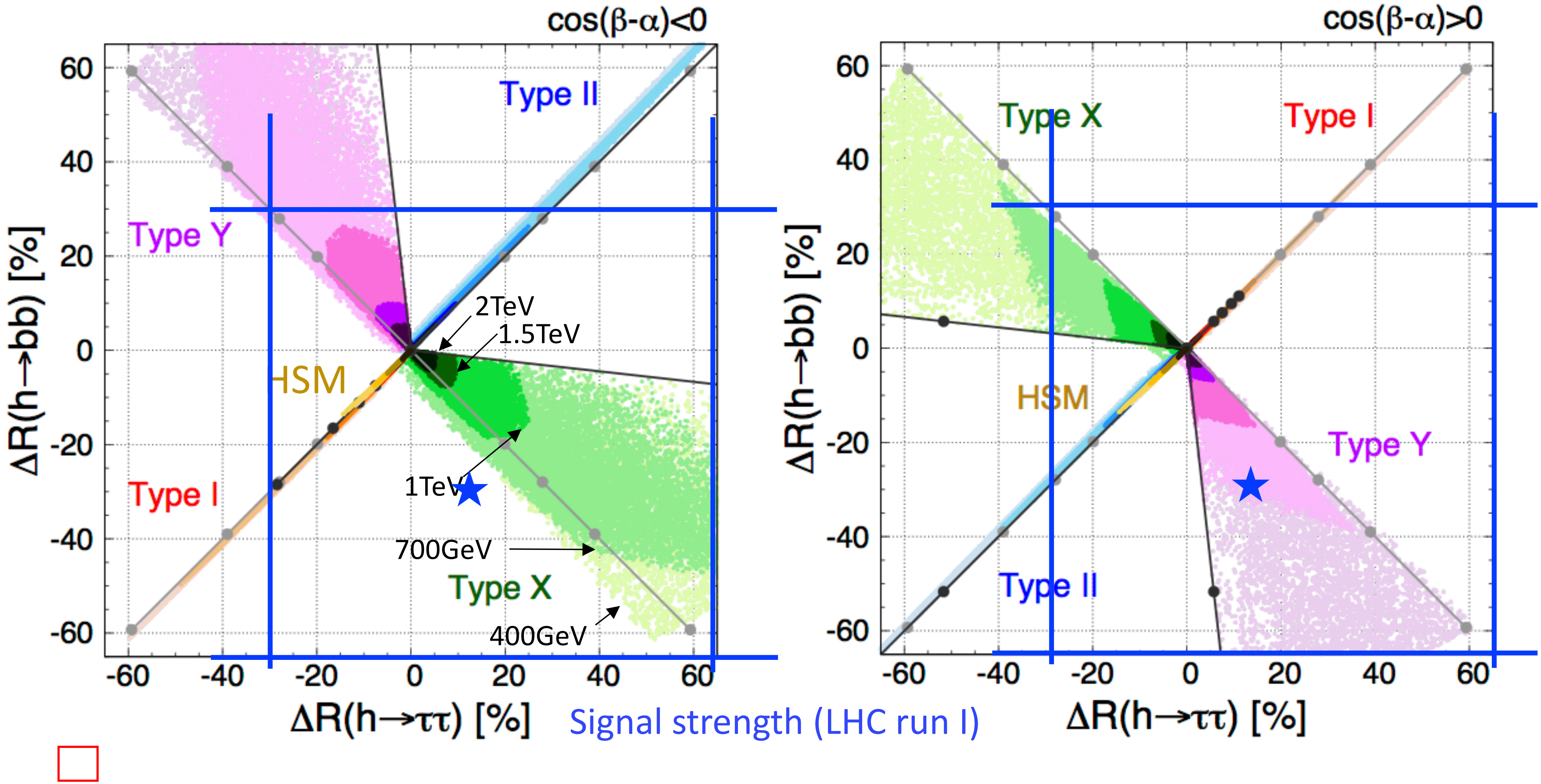
- Model: THDMs, HSM
- Calculation to NLO amplitude

Other plot

$\Delta R(h \to b\bar{b})$ vs $\Delta R(h \to \tau\bar{\tau})$

[S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu]

$$\Delta R(h \to XX) = \frac{\Gamma(h \to XX)_{EX}}{\Gamma(h \to XX)_{SM}} - 1$$



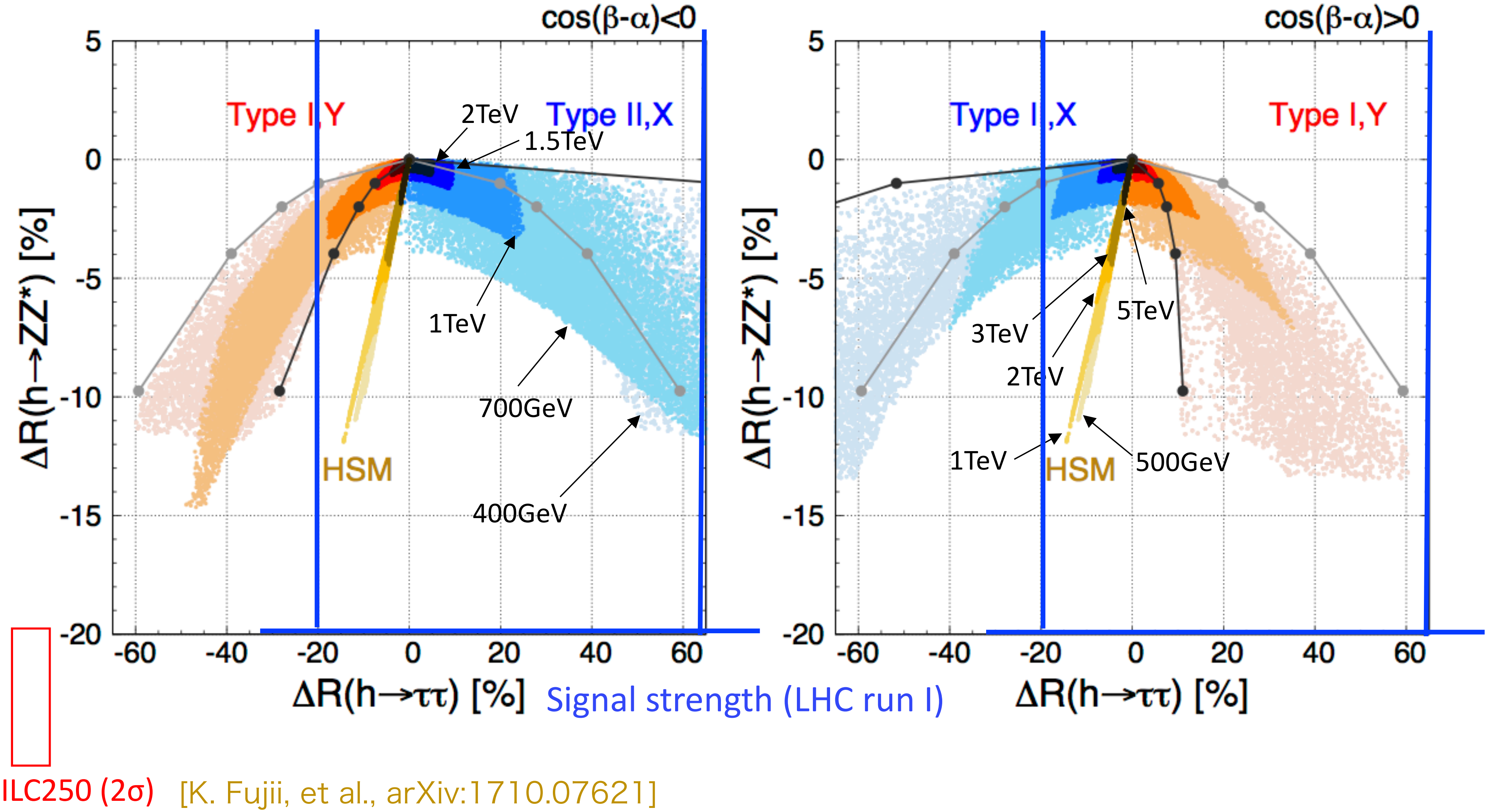
ILC250 (2σ) [K. Fujii, et al., arXiv:1710.07621]

→ Type X and Y can be discriminated from other models.

$\Delta R(h \to ZZ^*)$ vs $\Delta R(h \to \tau\bar{\tau})$

[S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu]

$$\Delta R(h \to XX) = \frac{\Gamma(h \to XX)_{EX}}{\Gamma(h \to XX)_{SM}} - 1$$



[K. Fujii, et al., arXiv:1710.07621]

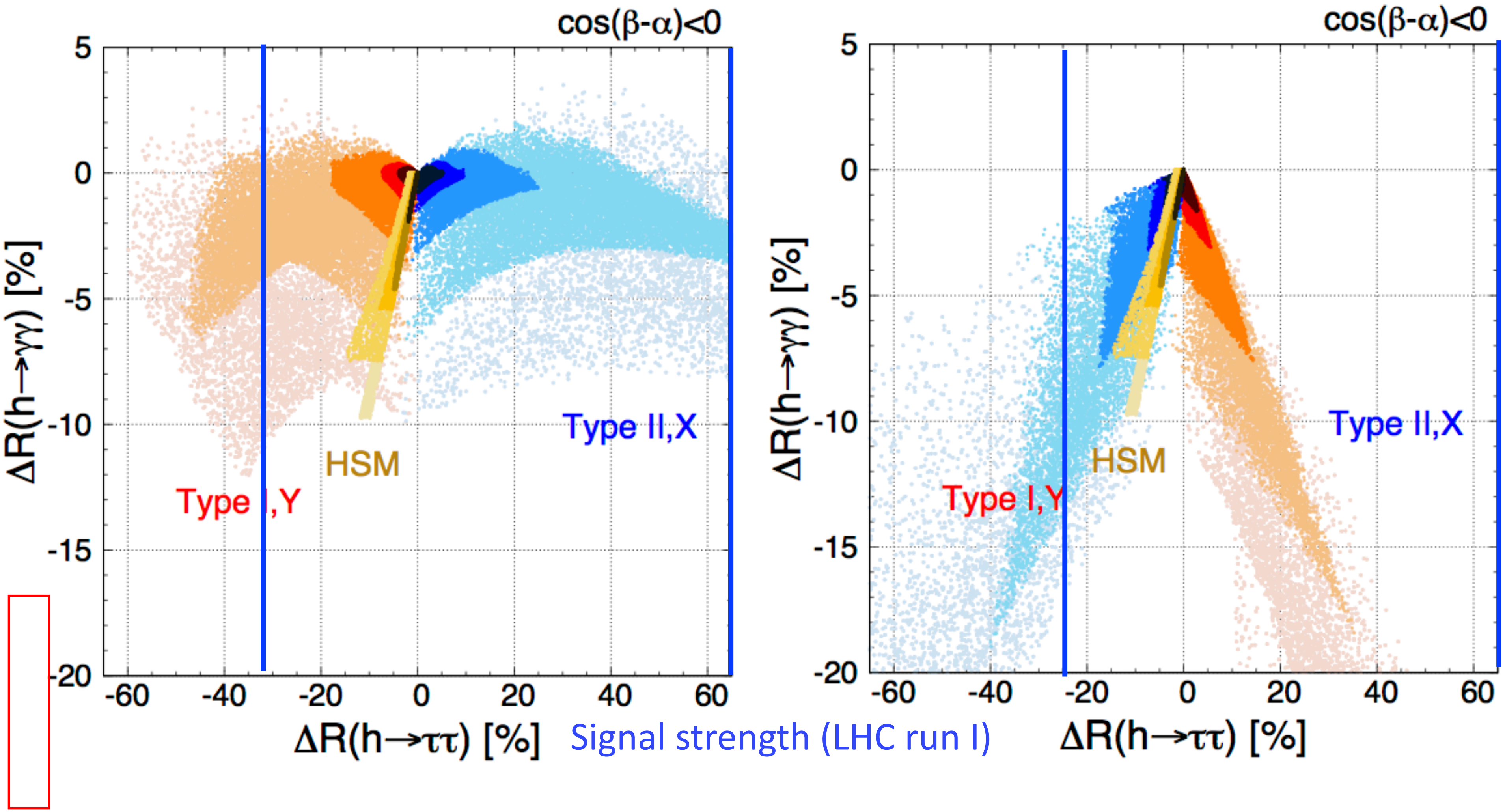
→ HSM can be separated from the THDMs.

→ Type I and Type II can be discriminated in this plane.

$\Delta R(h \to \gamma\gamma)$ vs $\Delta R(h \to \tau\bar{\tau})$

[S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu]

$$\Delta R(h \to XX) = \frac{\Gamma(h \to XX)_{EX}}{\Gamma(h \to XX)_{SM}} - 1$$



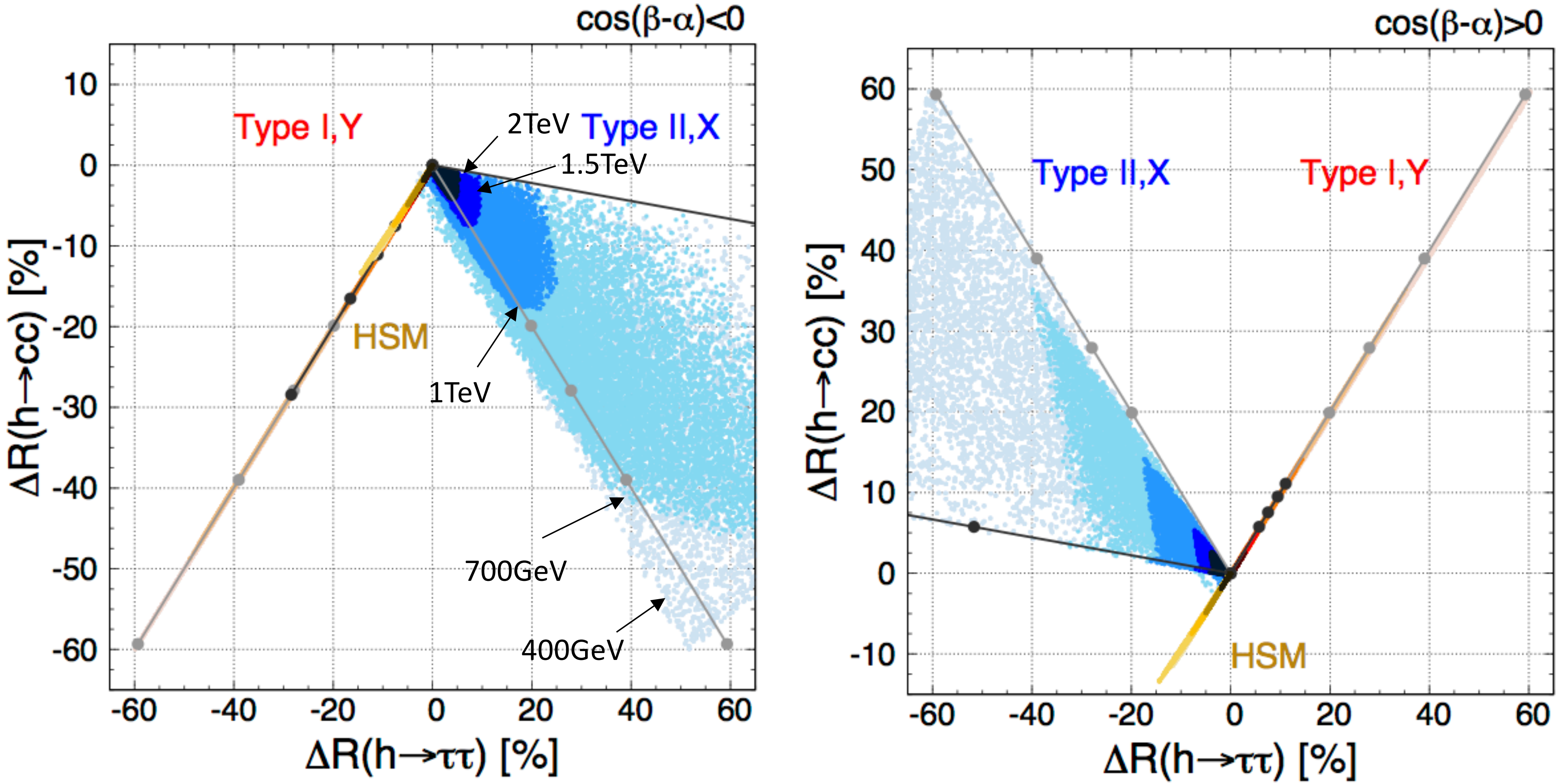
ILC250 (2σ) [K. Fujii, et al., arXiv:1710.07621]

→ Type X and Y can be discriminated from other models.

$\Delta R(h \to c\bar{c})$ vs $\Delta R(h \to \tau\bar{\tau})$

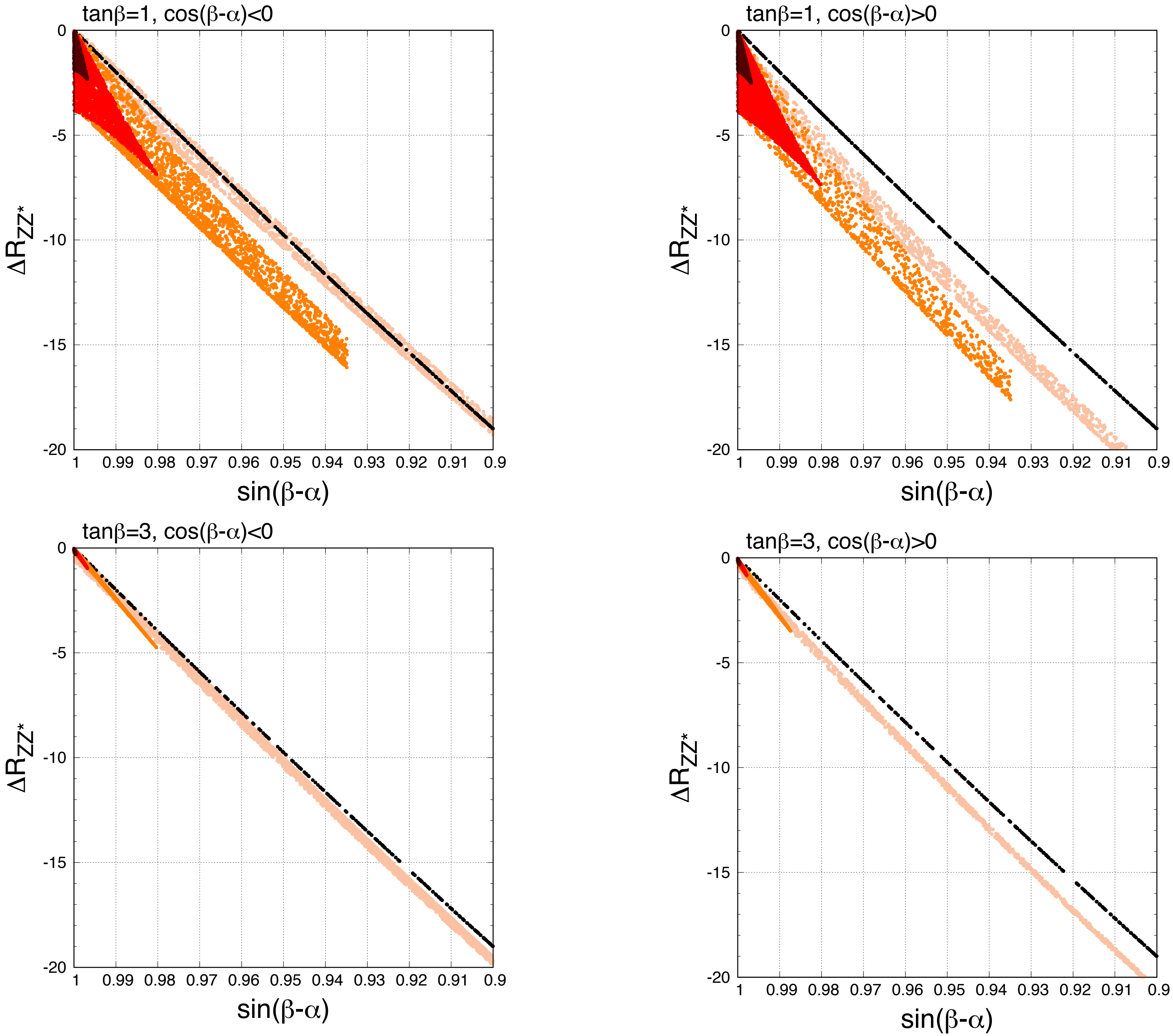
$$\Delta R(h \to XX) = \frac{\Gamma(h \to XX)_{EX}}{\Gamma(h \to XX)_{SM}} - 1$$

[S. Kanemura, M. Kikuchi, K. Mawatari, KS, K. Yagyu]



→ Type I and Type II can be discriminated in this plane.

$\Delta R(h \to ZZ^*)$ vs $Sin(\beta - \alpha)$

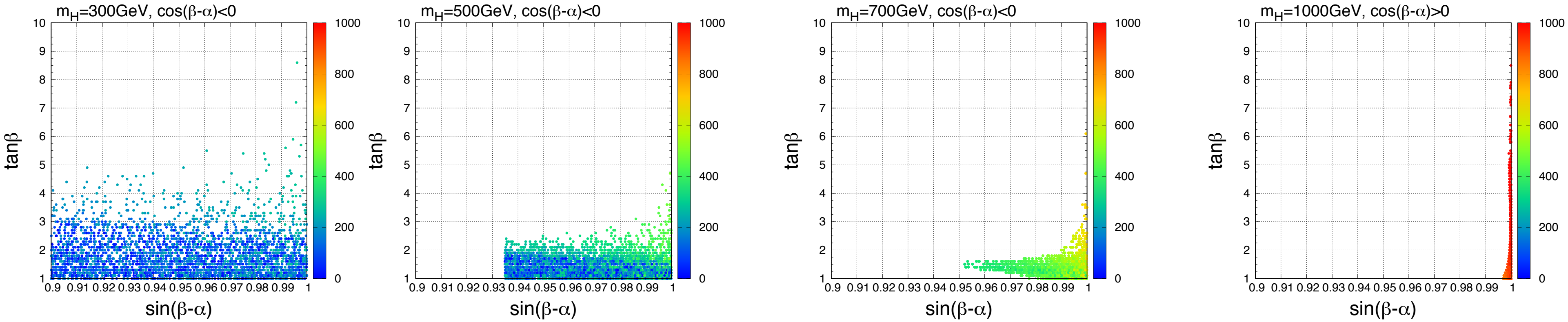


300GeV,
500GeV,
700GeV,
1TeV

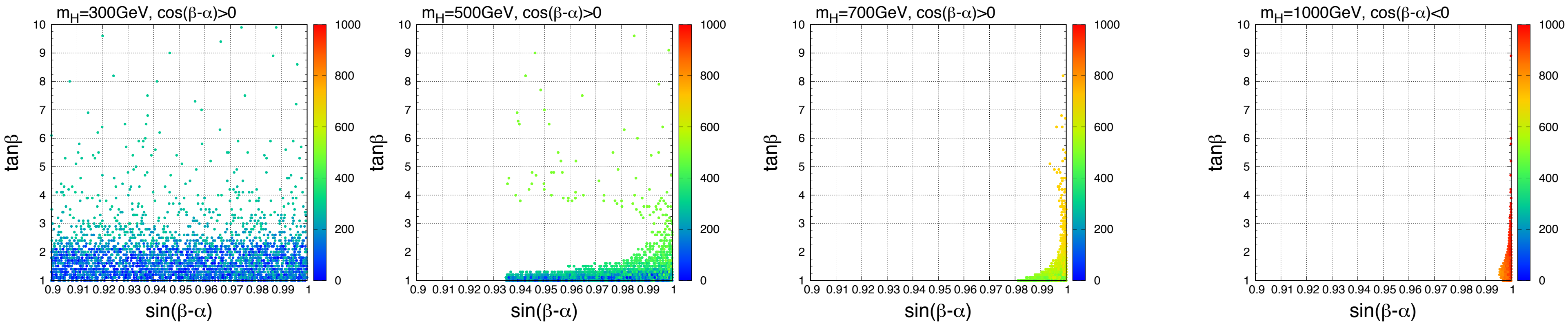
$\tan\beta$ vs $Sin(\beta - \alpha)$

constraint:
Perturbative unitarity
vacuum stability
S, T parameters

M



M



Renormalization of scalar sector

Renormalization of Higgs sector

We have used improved on-shell scheme renormalization in calculations for Higgs boson couplings at the 1loop level. [S. Kanemura, M. Kikuchi, KS, K. Yagyu, PRD96,035014]

- We introduce counter terms
  - Parameters in Higgs potential ： 8

    $v,\ m_h,\ m_H,\ m_A,\ m_{H^\pm},\ M^2,\ \alpha,\ \beta$
  - Fields of Higgs sector ： 6

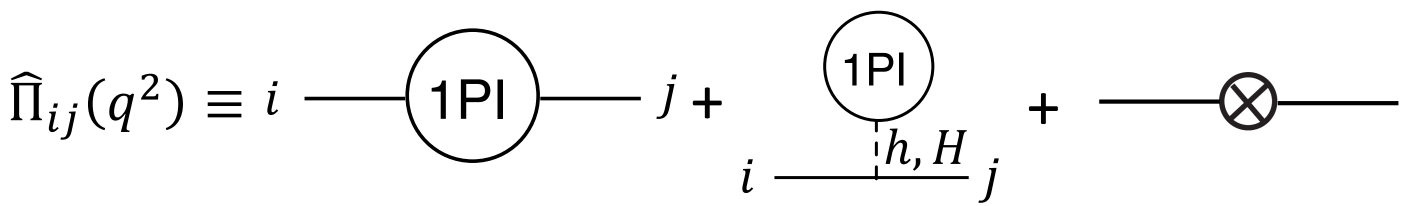
    $h,\ H^\pm,\ H,\ A,\ G^0,\ G^\pm$
  - Shift of parameters : (Φ= $h, H^\pm, H, A$)

$$m_\Phi \to m_\Phi + \delta m_\Phi,\ M \to M + \delta M,\ \alpha \to \alpha + \delta\alpha,\ \beta \to \beta + \delta\beta,$$

$$\begin{pmatrix} H \\ h \end{pmatrix} \to \begin{pmatrix} 1+\frac{1}{2}\delta Z_H & \delta C_{Hh}+\delta\alpha \\ \delta C_{hH}-\delta\alpha & 1+\frac{1}{2}\delta Z_h \end{pmatrix} \begin{pmatrix} H \\ h \end{pmatrix}$$

→ We obtain 20 counter terms :

$$\mathrm{v}, \delta m_\Phi^2, \delta M^2, \delta\alpha, \delta\beta, \delta Z_\Phi, \delta C_{\Phi_1\Phi_2}\ (\Phi = h, H, A, H^+, G^0, G^\pm)$$



- We set following on shell conditions :

δm_Φ : $\hat{\Pi}_{\varphi\varphi}(m_\varphi^2) = 0$ (Φ =h, H , A , $H^\pm$)

δZ_Φ : $\frac{d}{dp^2}\hat{\Pi}_{\varphi\varphi}(p^2)\big|_{p^2=m_\varphi^2} = 0$ (Φ =h, H , A , $H^\pm$,$G^\pm$,G^0)

$\delta\alpha$, $\delta\beta$, $\delta C_{\Phi1\Phi2}$: $\hat{\Pi}_{\phi_1\phi_2}(m_{\phi_1}^2) = \hat{\Pi}_{Hh}(m_{\phi_2}^2) = 0$ (Φ_1, Φ_2 =h, H , A , $H^\pm$,$G^\pm$,G^0)

δv : This counter term is determined in gauge sector.

δM : This counter term is determined by minimal subtraction

In this way, with above 20 renormalization conditions, all counter terms are determined.

Gauge dependence on mixing parameters

- for renormalization of scalar mixing parameters $\delta\alpha, \delta\beta$
  originally, We had used ordinary on-shell scheme.

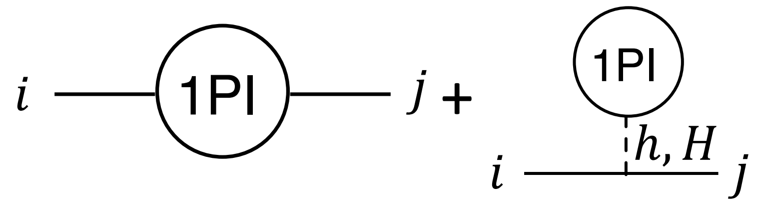
- Renormalized Higgs observables in ordinal on-shell scheme possess a gauge dependence through $\delta\alpha, \delta\beta$.

  [M. Krause, R. Lorenz, M. Muhlleitner, R. Santos, H. Ziesche, JHEP 09 (2016) 143]

- We have removed this gauge dependence by using the pinch technique.

  [J. Papavassiliou, PRD50, 5958]

Gauge dependence on the counter terms

$\Pi_{ij}(q^2) \equiv$ 

Nielsen identity : [N. K. Nielsen, NPB101 (1975) 173, Y. Yamada, PRD64(2001)036008]

$$\partial_\xi \Pi_{ij}(q^2) = \left(q^2 - m_i^2\right)\Lambda_i(q^2) + \left(q^2 - m_j^2\right)\Lambda_j(q^2)$$

$\Lambda_i(q^2), \Lambda_j(q^2)$: sum of loop function

ex.1) δm_h^2 (the counter term of the Higgs boson mass m_h^2)

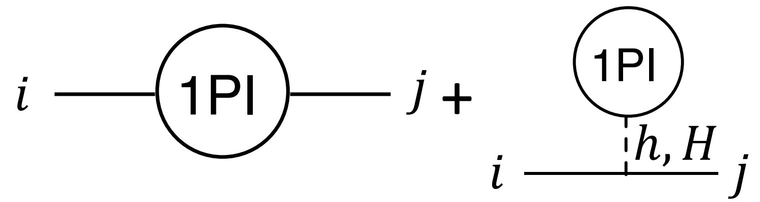
$$\delta m_h^2 = \Pi_{hh}(m_h^2)$$

From the Nielsen identity $q^2 = m_h^2,\ \mathrm{m_i^2} = \mathrm{m_j^2} = \mathrm{m_h^2}$

➡ $\partial_\xi(\delta m_h^2) = 0$

Gauge dependence on the counter terms

$\Pi_{ij}(q^2) \equiv$



Nielsen identity : [N. K. Nielsen, NPB101 (1975) 173, Y. Yamada, PRD64(2001)036008]

$$\partial_\xi \Pi_{ij}(q^2) = \left(q^2 - m_i^2\right)\Lambda_i(q^2) + \left(q^2 - m_j^2\right)\Lambda_j(q^2)$$

$\Lambda_i(q^2), \Lambda_j(q^2)$: sum of loop function

ex.2) $\delta\beta$ (the counter term of the mixing angle β)

$$\delta\beta = -\frac{1}{2m_A^2}\left[\Pi_{AG^0}\left(m_{\mathrm{A}}^2\right) + \Pi_{AG^0}(0)\right]$$

Appling to the Nielsen identity

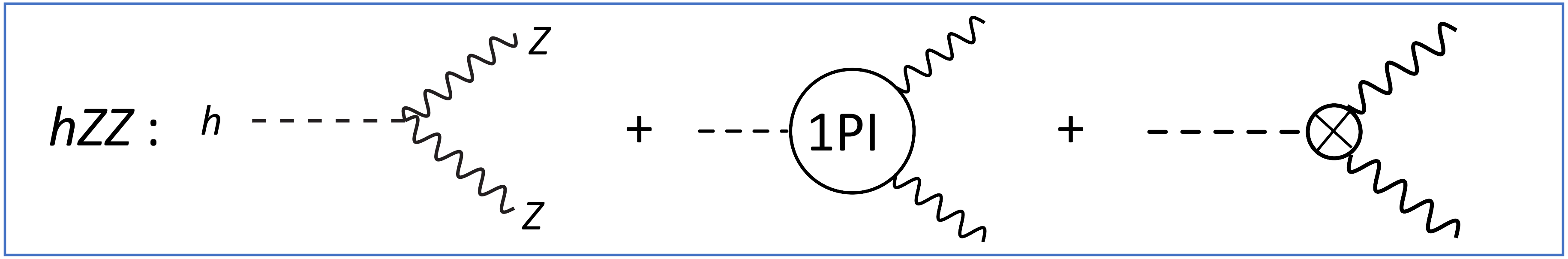
$$\partial_\xi(\delta\beta) = -\frac{1}{2m_A^2}\left[\left(m_{\mathrm{A}}^2 - 0\right)\Lambda_G(0) + \ (0 - m_A^2)\Lambda_A(0)\right]$$

➡ $\partial_\xi(\delta\beta) \neq 0$

With the same argument, we can also find $\partial_\xi(\delta\alpha) \neq 0$

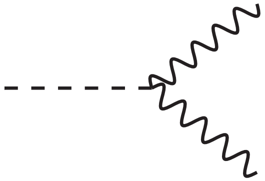
Gauge dep. for Higgs 3point vertex

EX.) renormalized hZZ vertex



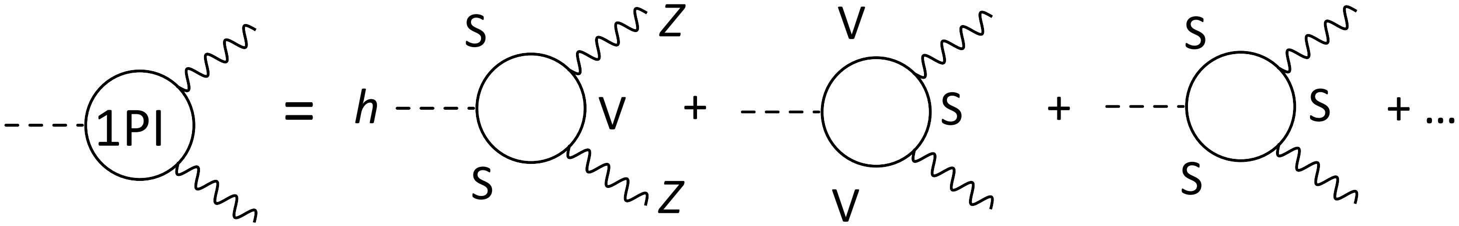
Tree level　　　1-loop level　　　Counter term

tree level

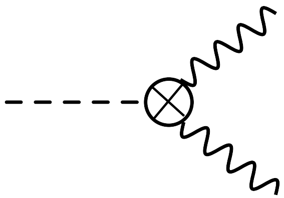


$$= -2\frac{m_Z^2}{v}\sin(\beta-\alpha)$$

1-loop level



counter term

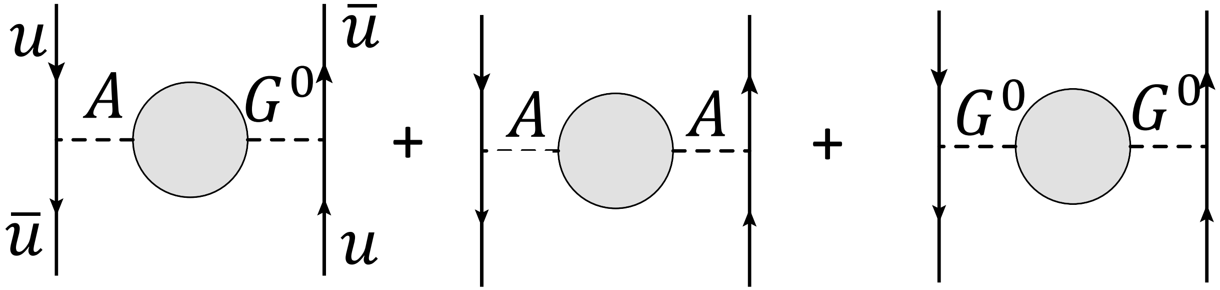


$$= -2\frac{m_Z^2}{v}\left[s_{\beta-\alpha}\left(\frac{\delta m_Z^2}{m_Z^2}+\delta Z_Z+\frac{1}{2}\delta Z_h-\frac{\delta v}{v}\right)+c_{\beta-\alpha}(\delta\beta+\delta C_h)\right]$$

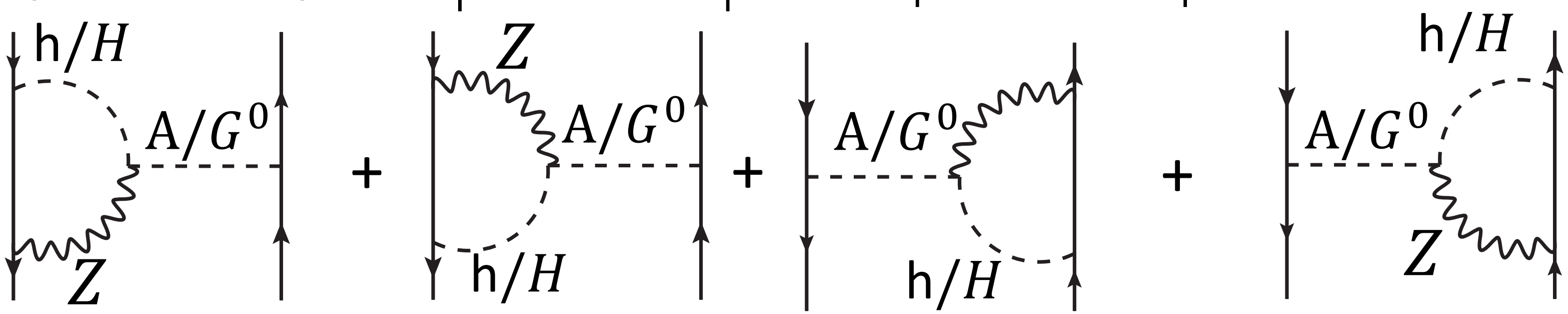
Pinch technique

I demonstrate that ξ_Z dependence for $\Pi_{AG}(q^2)$ are removed.

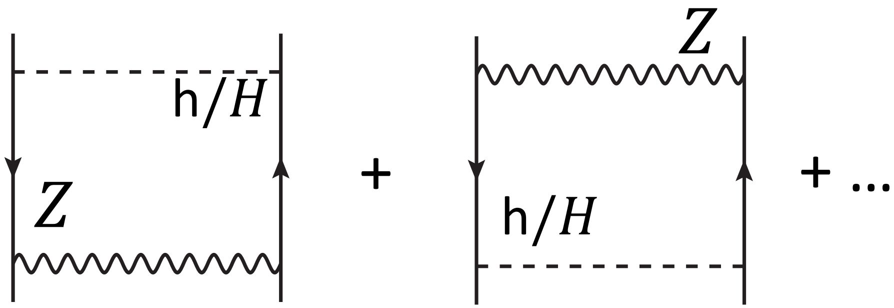
$\mathcal{M}_{self}$ =



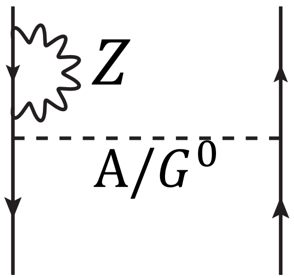
$\mathcal{M}_{vert}^{pinch} \ni$



$\mathcal{M}_{box}^{pinch} \ni$



$\mathcal{M}_{wave}^{pinch} \ni$



Pinch technique

Toy process : $u\bar{u} \to u\bar{u}$

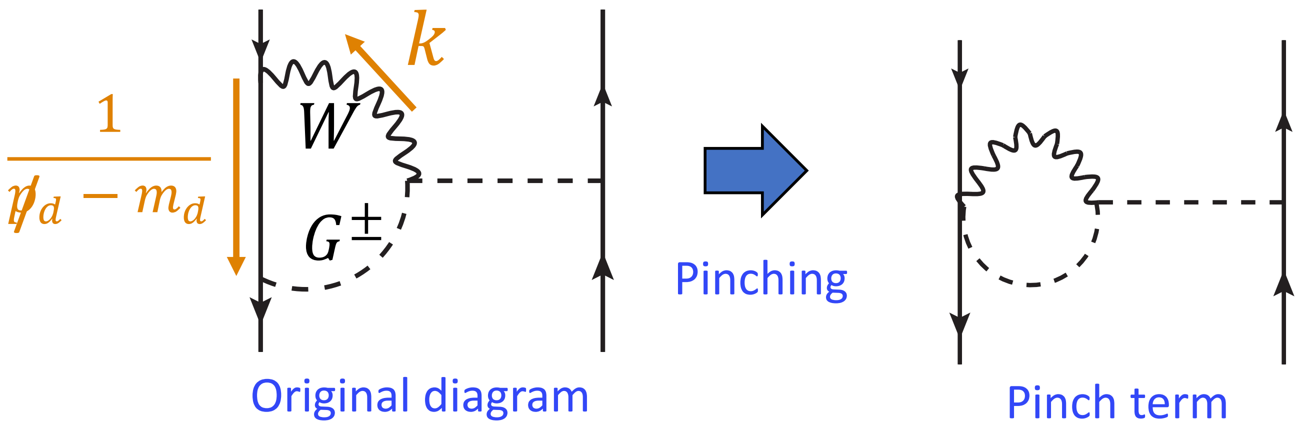
$\mathcal{M}^{PT}_{vert}, \mathcal{M}^{PT}_{box}, \mathcal{M}^{PT}_{wave}$: Pinch term

$\mathcal{M}_{sel}$

$\mathcal{M}^{PT}_{ver}$

$\mathcal{M}^{PT}_{bo}$

$\mathcal{M}^{PT}_{wa}$



Wff coupling

$$\gamma^{\mu} k_{\mu} = (\not{p}_d - m_d) - (\not{p}_d - \not{k} - m_d)$$

Derivative coupling or W boson propagator

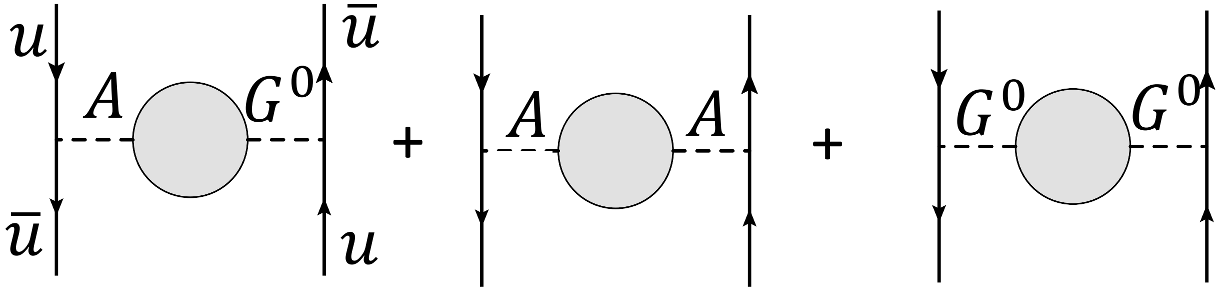
$^{T}_{ave}$) =0

We obtained the gauge invariant Π_{hH} ,
adding the pinch terms

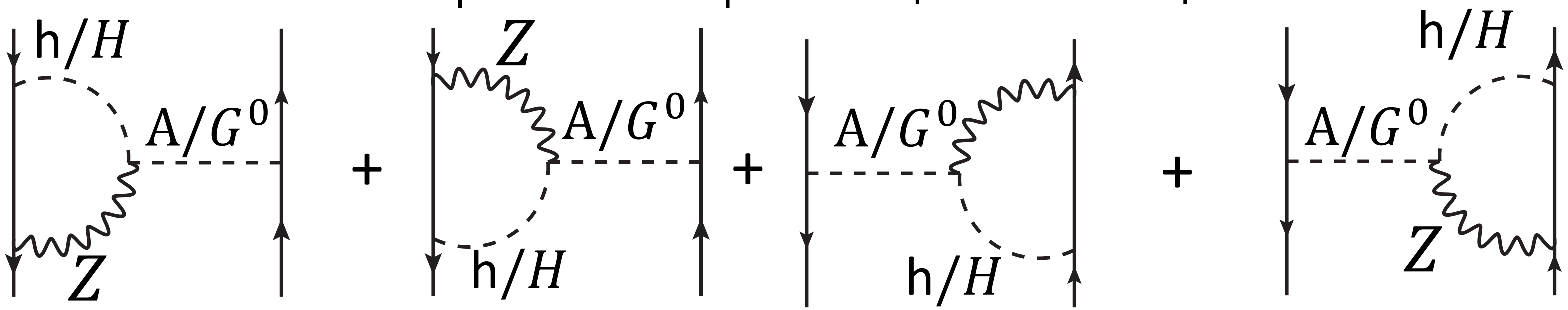
Pinch technique

I demonstrate that ξ_Z dependence for $\Pi_{AG}(q^2)$ are removed.

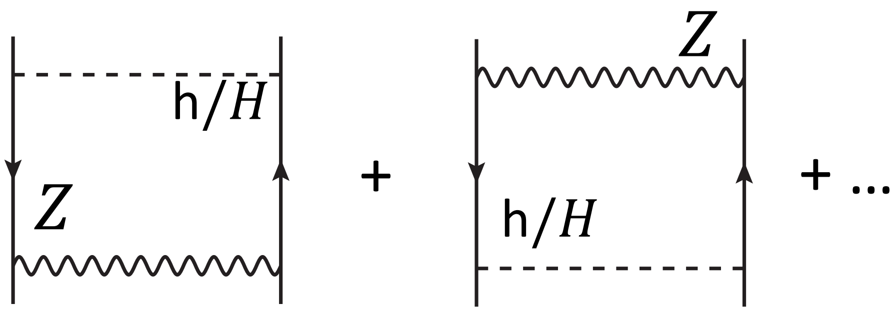
$\mathcal{M}_{self}$ =



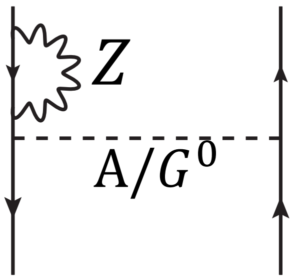
$\mathcal{M}_{vert}^{pinch} \ni$



$\mathcal{M}_{box}^{pinch} \ni$

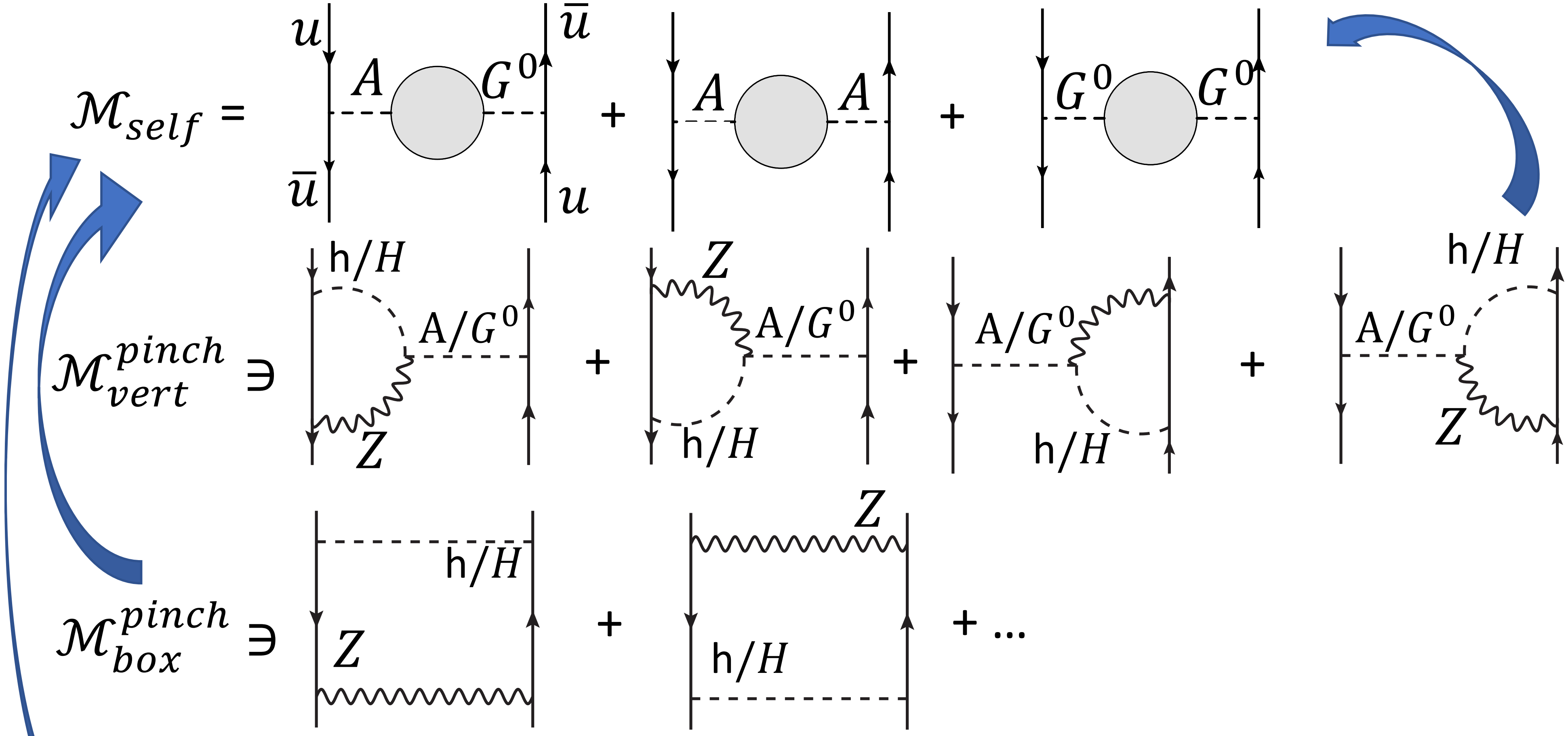


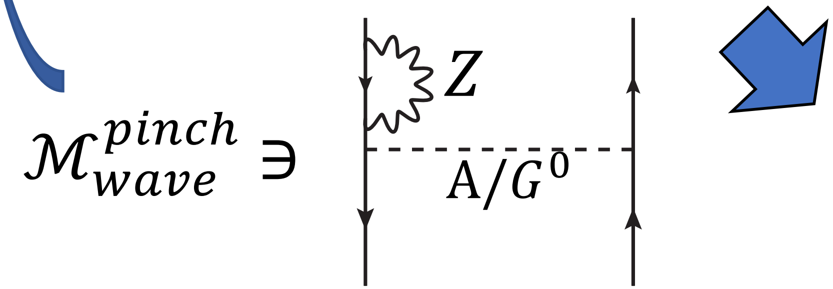
$\mathcal{M}_{wave}^{pinch} \ni$



Pinch technique

I demonstrate that ξ_Z dependence for $\Pi_{AG}(q^2)$ are removed.





$$\frac{\partial}{\partial \xi_Z}(\mathcal{M}_{self} + \mathcal{M}_{vert}^{PT} + \mathcal{M}_{box}^{PT} + \mathcal{M}_{wave}^{PT}) = 0$$

We obtained the gauge invariant Π_{AG} ,
by adding the pinch terms