Effective Higgs Couplings in models with extended Higgs sectors

Junping Tian (U' of Tokyo)

ongoing work in collaboration with
K.Fujii (KEK), S.Kanemura (Osaka U'),
K.Mawatari (Osaka U'), K.Yagyu (Seikei U')

Asian Linear Collider Workshop (ALCW) 2018,
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outline

(i) SMEFT for Higgs couplings at e+e-

some personal recaps (see details in Sunghong's talk)

(ii) Effective Higgs Couplings in BSM

focus on today SM+extended Higgs sector

(iii) Numerical Results

(i) effective field theory analysis at e+e-

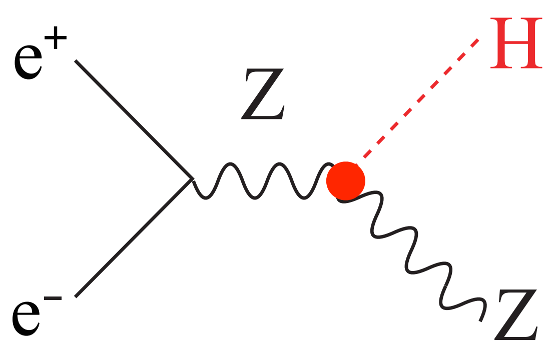
arXiv:1708.09079
arXiv:1708.08912

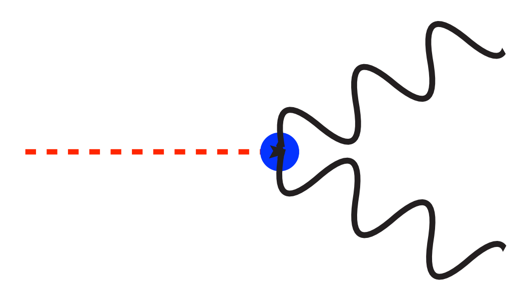
- we didn't want to base on EFT from the very beginning
- it camp up as the BEST approach in terms of model independent determination of Higgs (self-)couplings

recap 1: model dependence in kappa framework

- σ(e+e- ->Zh) ∝ κ^2_Z ∝ Γ(h->ZZ*) not any more: EFT is more general than kappa-framework

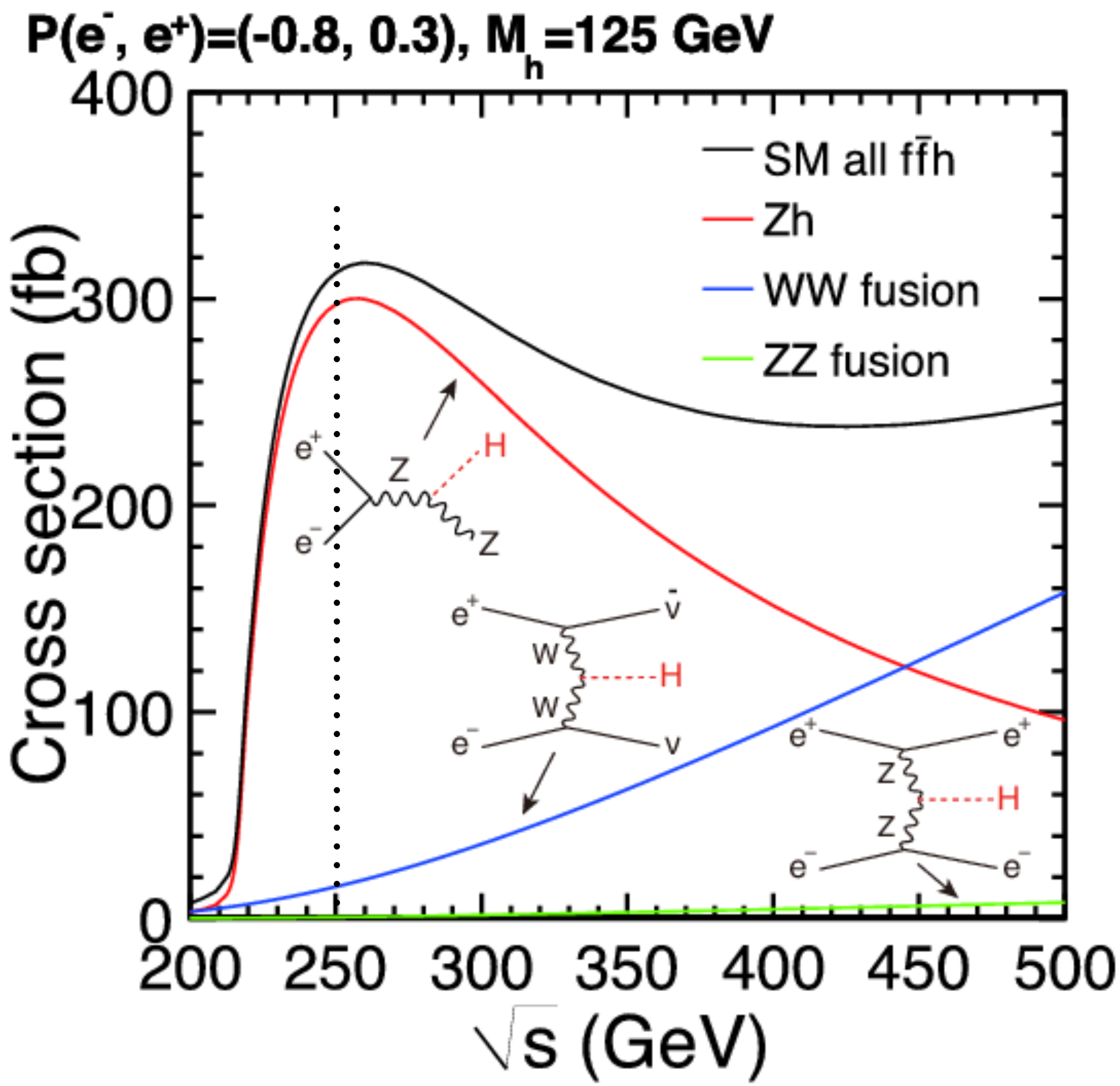
$$\delta\mathcal{L} = (1+\eta_Z)\frac{m_Z^2}{v} h Z_\mu Z^\mu + \zeta_Z \frac{h}{2v} Z_{\mu\nu} Z^{\mu\nu}$$





$$\sigma(e^+e^- \to Zh) = (SM) \cdot (1 + 2\eta_Z + (5.5)\zeta_Z) \neq \Gamma(h \to ZZ^*) = (SM) \cdot (1 + 2\eta_Z - (0.50)\zeta_Z)$$

recap 2: can we do precision Higgs physics at $\sqrt{s}$ = 250 GeV?



WW-fusion is smaller by x10 than 500 GeV recap 2: hWW is determined as precisely as hZZ @ $\sqrt{s}$ = 250 GeV

- hWW/hZZ ratio can be determined to <0.1%: feature of a general SU(2) x U(1) gauge theory

$$\Gamma(h \to ZZ^*) = (SM) \cdot (1 + 2\eta_Z - (0.50)\zeta_Z) \ ,$$

$$\Gamma(h \to WW^*) = (SM) \cdot (1 + 2\eta_W - (0.78)\zeta_W)$$

SM-like hVV

$$\eta_W = -\frac{1}{2} c_H$$

$$\eta_Z = -\frac{1}{2} c_H - c_T$$

custodial symmetry

$c_i \sim O(10^{-4}\text{-}10^{-3})$

anomalous hVV

$$\zeta_W = (8c_{WW})$$

$$\zeta_Z = c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + (s_w^4/c_w^2)(8c_{BB})$$

recap 3: σ_{ZH}, σ_{ZHH} & beam polarizations

$$\boxed{\frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi)}$$

$$\boxed{\frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3}$$

- c_H has to be determined by inclusive σ_{Zh} measurement

  unique role of recoil mass analysis remains same

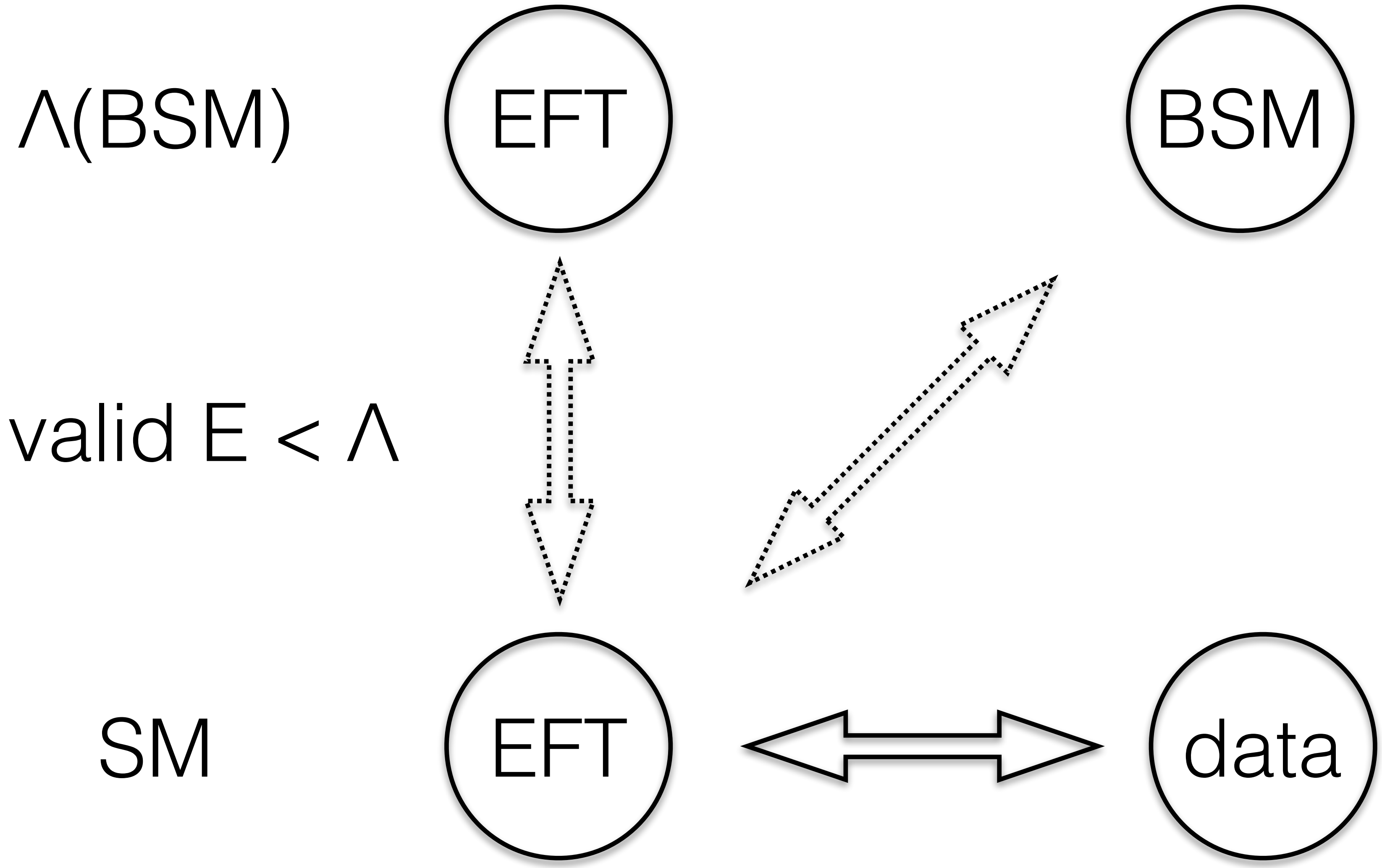
- c_6 has to be determined by double Higgs measurement

  c6 is decoupled with single Higgs process (tree level), large deviation is allowed

- beam polarizations very powerful in EFT, in particular the 80% polarization for electron beam: improved precisions and provide means to test EFT validity

(ii) what's next?

- EFT provides a precise/model independent formalism to describe/combine the experimental data
- But in the end of day, we would like to know what the BSM physics is, or what the BSM scale is



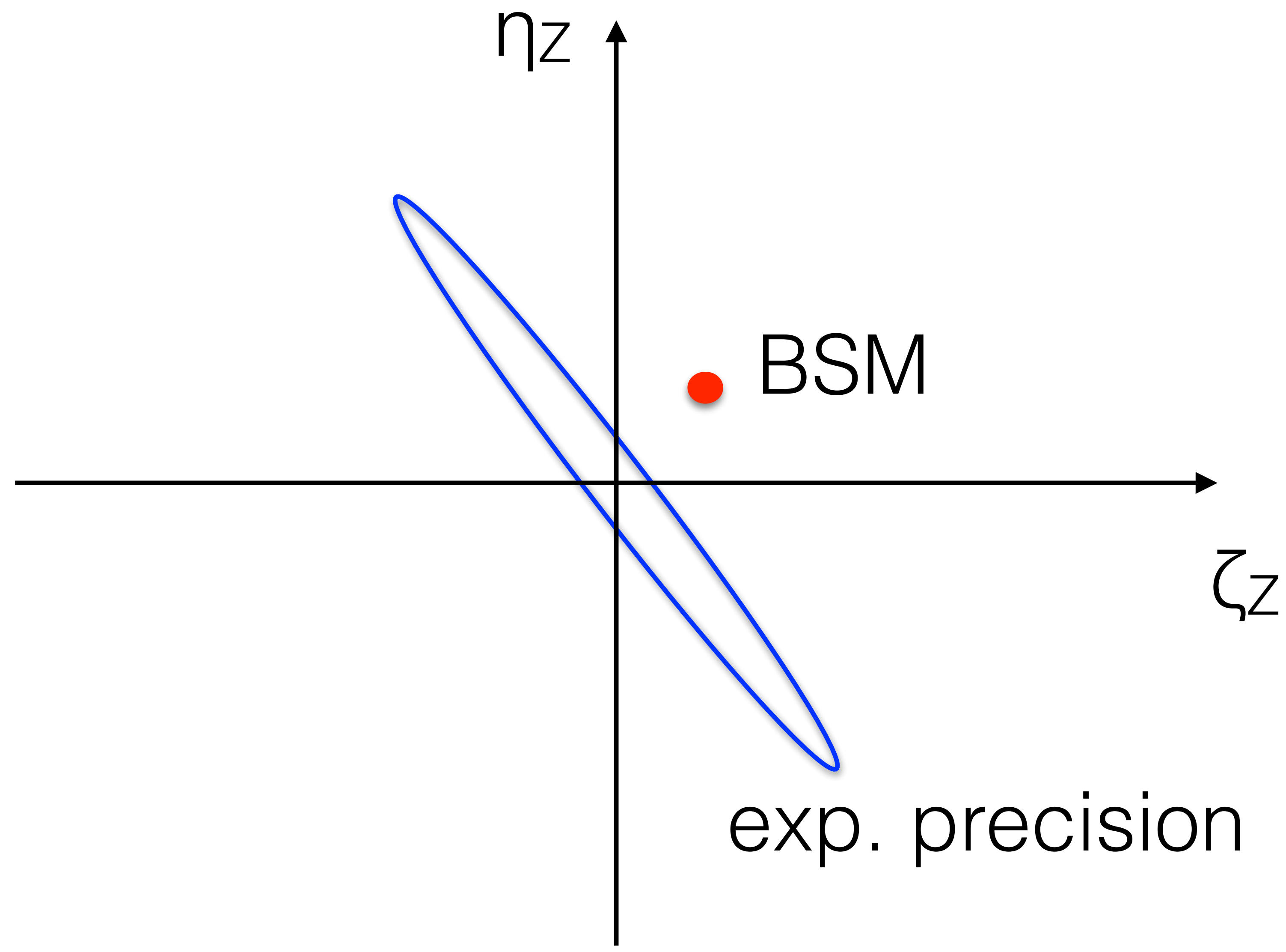
a strategy: find the maps between EFT and BSM

- may help identify the BSM (one example next slide)
- more importantly, can help understand the origin of each D-6 operator in each BSM model,
- or quantitatively how important each D-6 operator is in each BSM model
- which in turn would tell us the dependence on new particle mass scale / validity of EFT formalism

one example for helping identify BSM

$$\delta\mathcal{L} = (1+\eta_Z)\frac{m_Z^2}{v}hZ_\mu Z^\mu + \zeta_Z\frac{h}{2v}Z_{\mu\nu}Z^{\mu\nu}$$

- if we look at only decay width Γ(h->ZZ*), we may find difficult to discriminate BSM from SM
- but BSM can be identified if we look at η_Z, ζ_Z plane (high correlation, see talk by Ogawa)



maps between EFT and BSM

- we need some tools which can calculate loops

arXiv:1710.04603

H-COUP:

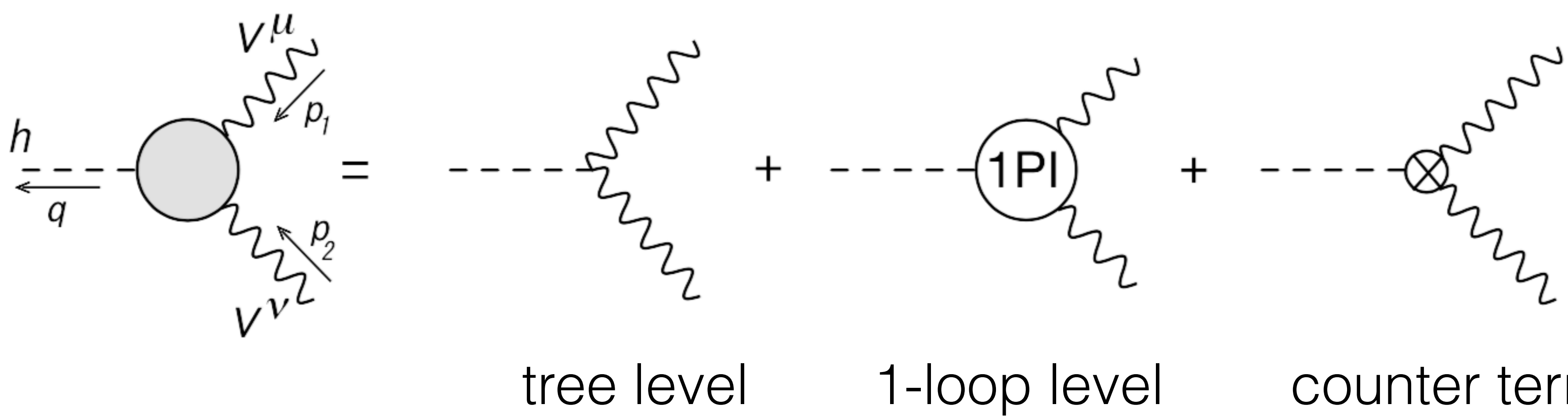
a program for one-loop corrected Higgs boson couplings in non-minimal Higgs sectors

Shinya Kanemura,[1,*] Mariko Kikuchi,[2,†] Kodai Sakurai,[3,‡] and Kei Yagyu[4,§]

(see talks by Mawatari today, Sakurai on Thursday)

a first step

look at effective hZZ coupling in models: SM, SM+Singlet (HSM), THDM



renormalized hZZ vertex can be decomposed into 3 form factors

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

the three form factors are calculated numerically by H-COUP

a first step

if we start from EFT Lagrangian for hZZ coupling (arXiv:1708.09079)

$$\delta\mathcal{L} = (1 + \eta_Z)\frac{m_Z^2}{v} h Z_\mu Z^\mu + \zeta_Z \frac{h}{2v} Z_{\mu\nu} Z^{\mu\nu}$$

let's focus on CP-even terms for now

vertex from η-term: $$g^{\mu\nu}\frac{2m_Z^2}{v}(1 + \eta_Z)$$

vertex from ζ-term: $$(g^{\mu\nu} p_1 \cdot p_2 - p_1^\mu p_2^\nu)\frac{2\zeta_Z}{v}$$

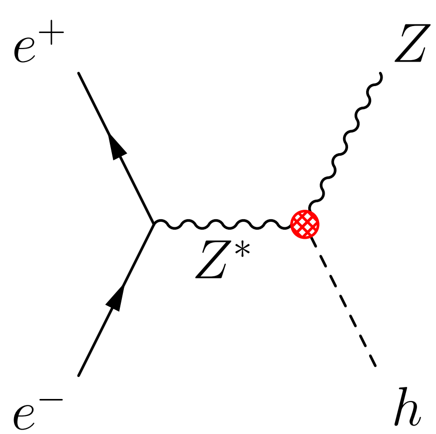
a first step

by comparing the vertex Lorentz structures in EFT and BSM:

$$\hat{\Gamma}^{1}_{hZZ} = \frac{2m_Z^2}{v}(1+\eta_Z) + p_1 \cdot p_2 \frac{2\zeta_Z}{v}$$

$$\hat{\Gamma}^{2}_{hZZ} = -\frac{2m_Z^2}{v}\zeta_Z$$

in case of



$$p_1 = (\sqrt{s}, \mathbf{0})$$

$$p_2 = (E_Z, \mathbf{p}_Z)$$

$$\boxed{\begin{aligned} \eta_Z &= \frac{v}{2m_Z^2}\hat{\Gamma}^1 + \frac{\sqrt{s}E_Z v}{2m_Z^4}\hat{\Gamma}^2 - 1 \\ \zeta_Z &= -\frac{v}{2m_Z^2}\hat{\Gamma}^2 \end{aligned}}$$

(a map from BSM to EFT found?)

(iii) numerical results

following conventions in arXiv:1705.05399

HSM

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

input parameters: $m_H, \quad \alpha, \quad \lambda_S, \quad \lambda_{\Phi S}, \quad \mu_S.$

THDM

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

input parameters: $m_H, \ m_A, \ m_{H^\pm}, \ s_{\beta-\alpha}, \ \tan\beta, \ M^2, \ \text{Sign}(c_{\beta-\alpha}),$

numerical results: SM loops

$$\hat{\Gamma}^1 = 66.70 \text{ GeV}$$

$$\eta_Z = -2.4\%$$

$$\frac{\hat{\Gamma}^2}{\hat{\Gamma}^1} = -0.17\%$$

$$\zeta_Z = -0.17\%$$

recall “recap 1”: in kappa framework
model dependence due to ζ-term

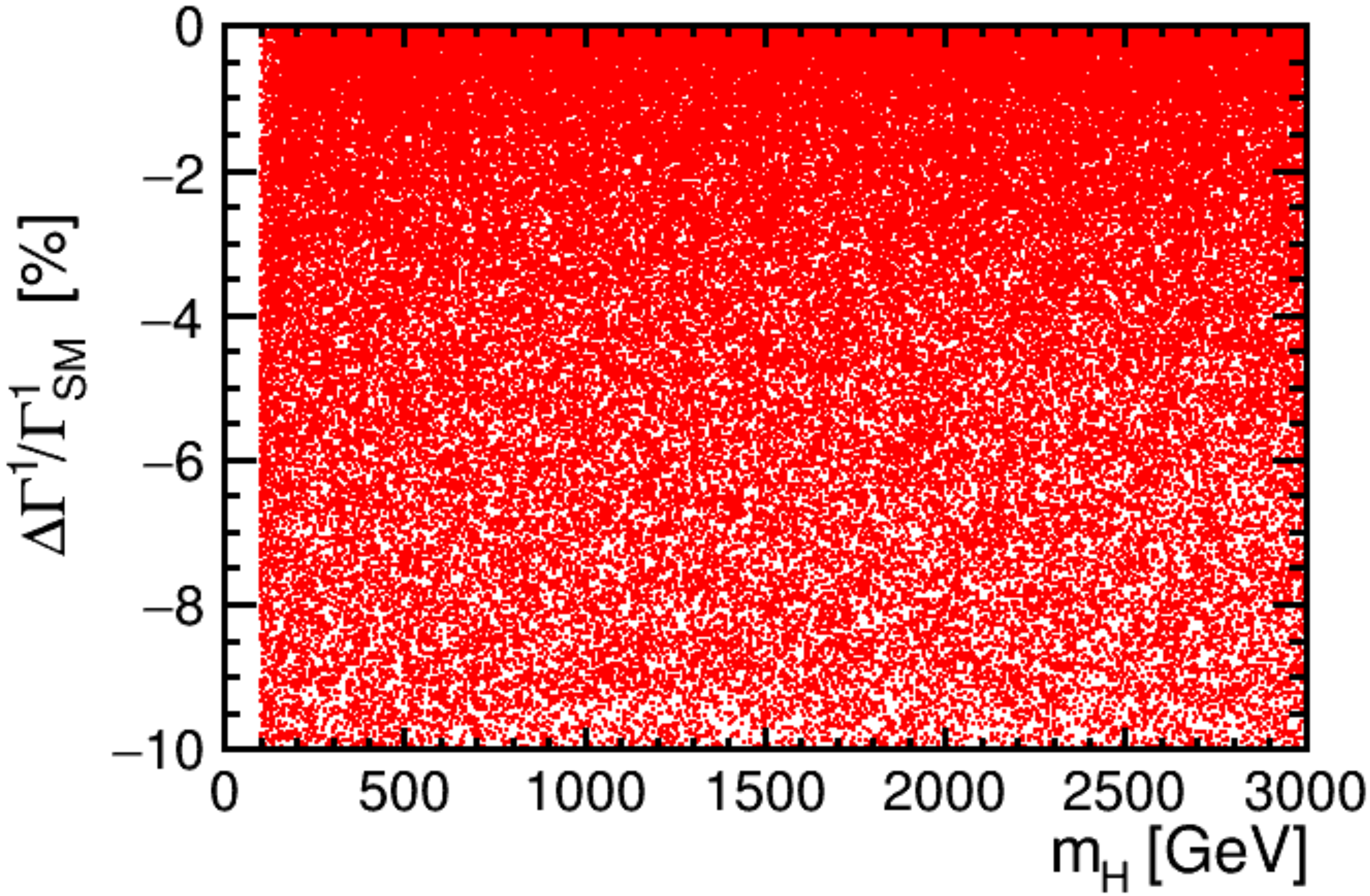
$\zeta_Z \sim 0.17\%$ would break by ~1%
the relation between $\delta\sigma_{ZH}$ and δΓ(h->ZZ*)

numerical results: HSM

$$\frac{\Delta\hat{\Gamma}^1}{\hat{\Gamma}^1_{\rm SM}} = \frac{\hat{\Gamma}^1 - \hat{\Gamma}^1_{\rm SM}}{\hat{\Gamma}^1_{\rm SM}}$$

scan:~100K points

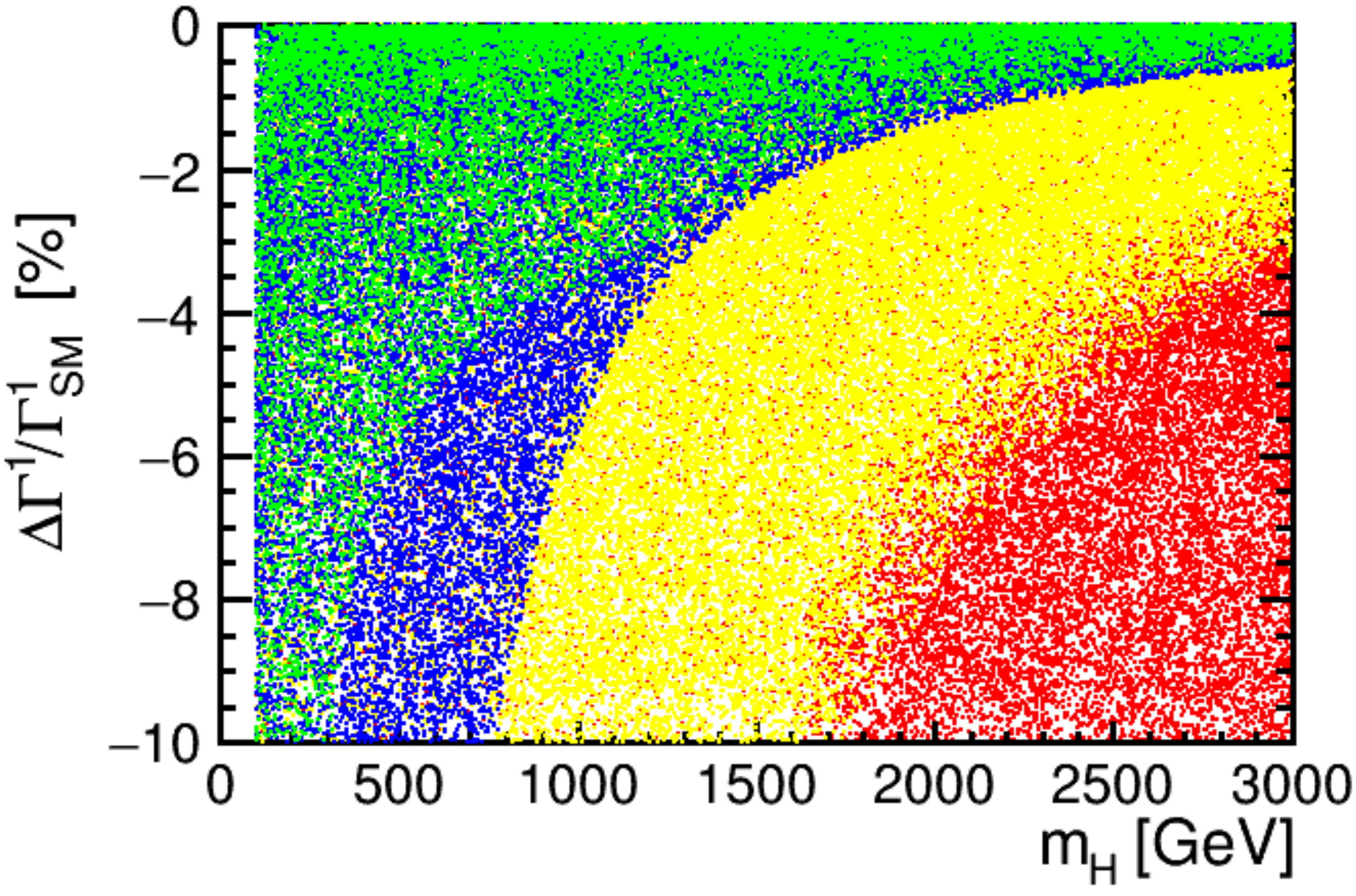
$$m_H \geq 300 \text{ GeV}, \quad -0.44 \leq \sin\alpha \leq 0.44, \quad |\lambda_{\Phi S}| \leq 3, \quad \text{with } \mu_S = \lambda_S = 0.$$



clearly something is going strange: no decoupling!

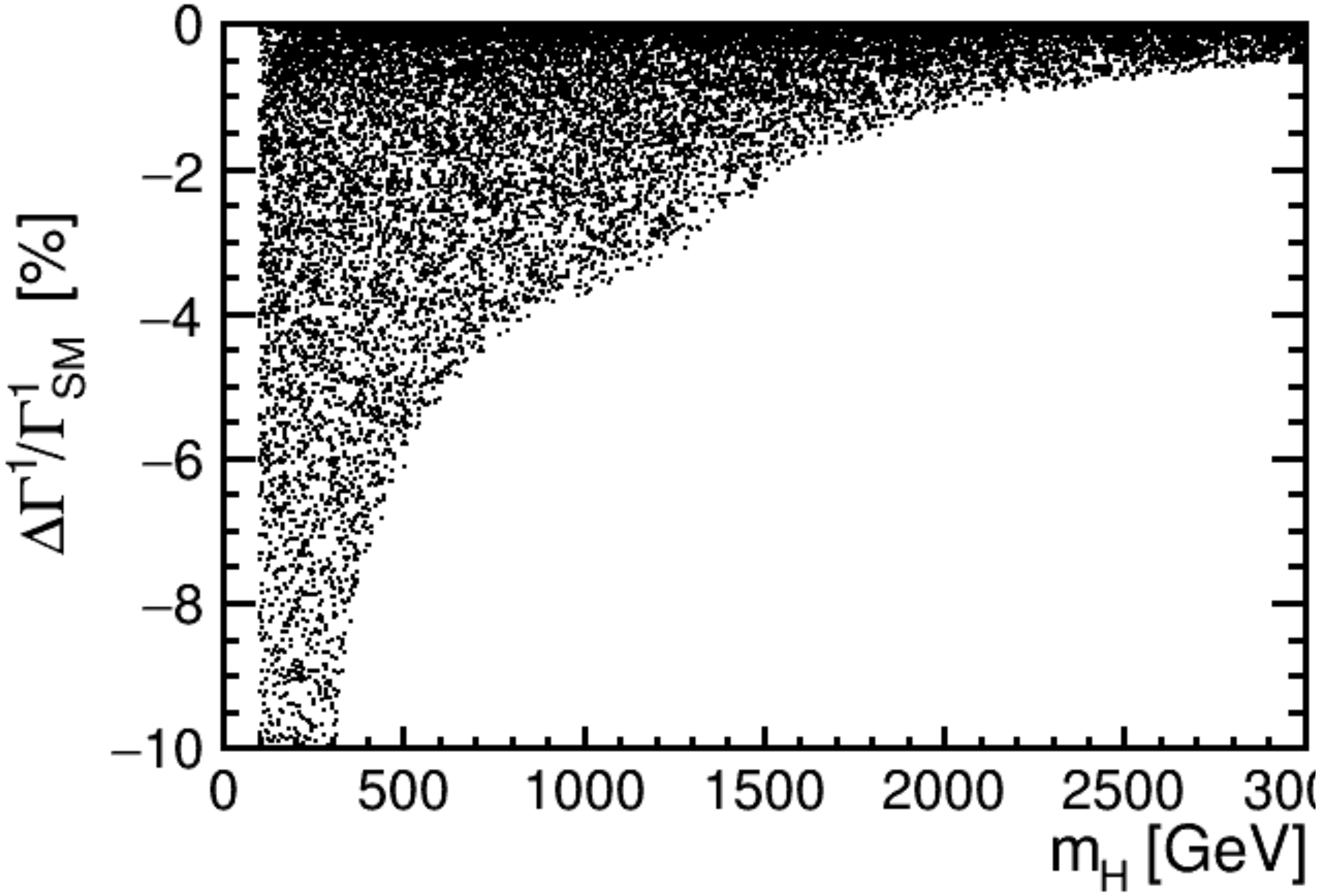
numerical results: HSM

constraints: Perturbative Unitarity (yellow), + Triviality (blue), Vacuum Stability + False Vacuum + ST Parameters (green)



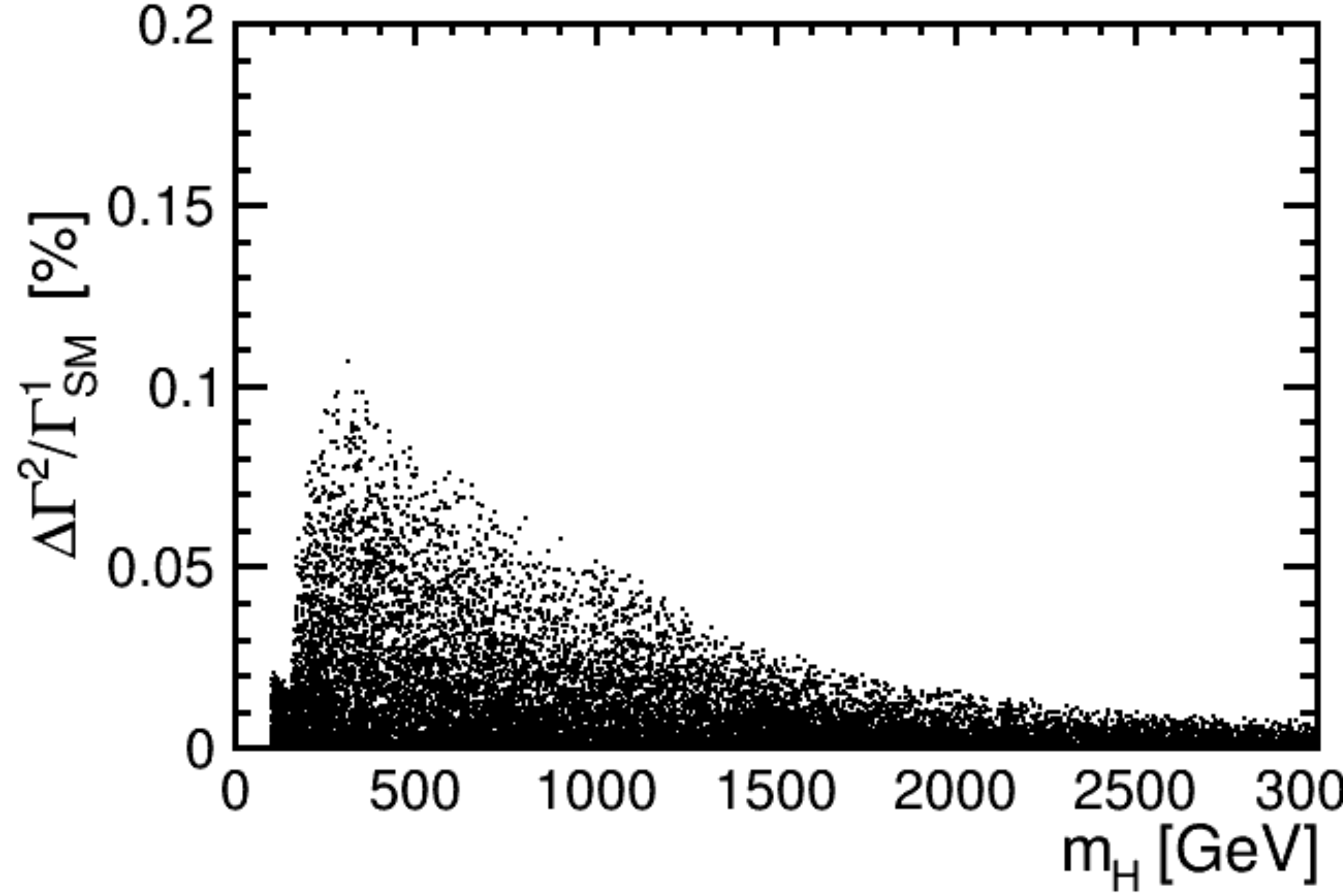
numerical results: HSM

$$\Delta\hat{\Gamma}^1 = \hat{\Gamma}^1 - \hat{\Gamma}^1_{\rm SM}$$



(reproduced results in arXiv:1705.05399)

$$\Delta\hat{\Gamma}^2 = \hat{\Gamma}^2 - \hat{\Gamma}^2_{\rm SM}$$



new results

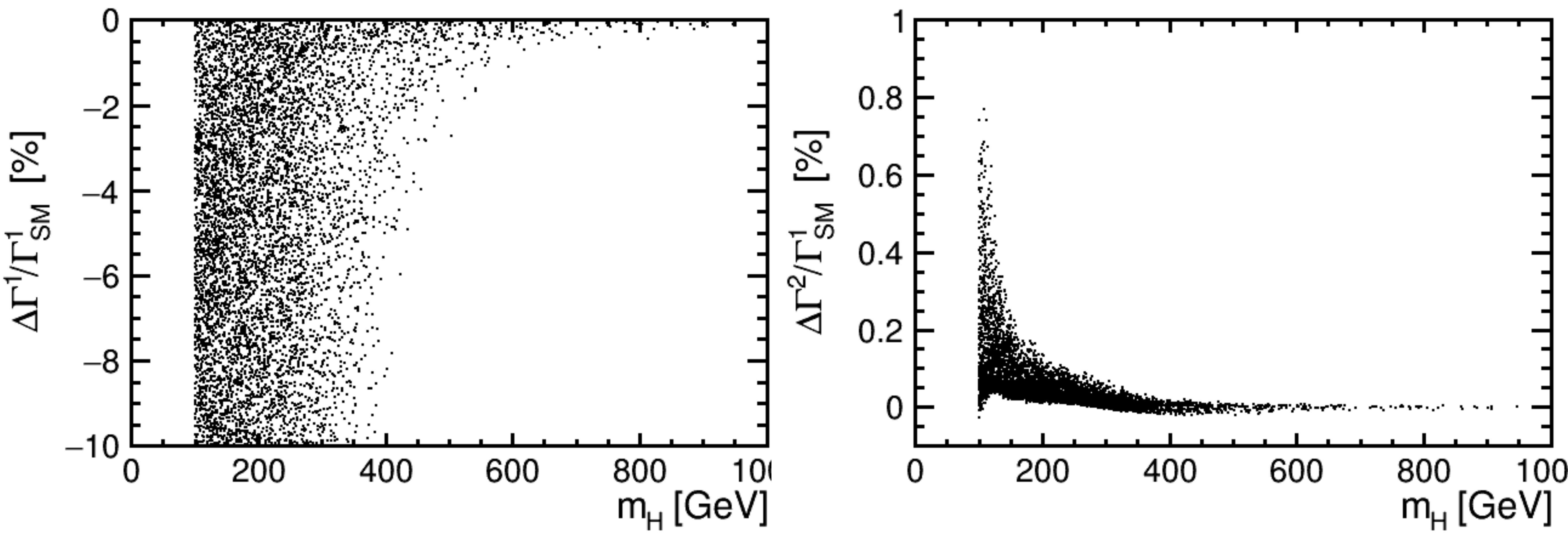
clear decoupling behavior in both

numerical results: THDM

scan: ~1M points

$$m_\Phi \geq 300 \text{ GeV}, \quad 0.90 \leq s_{\beta-\alpha} \leq 1, \quad |\lambda_{\Phi\Phi h}| \leq 3, \quad 1 \leq \tan\beta \leq 10,$$

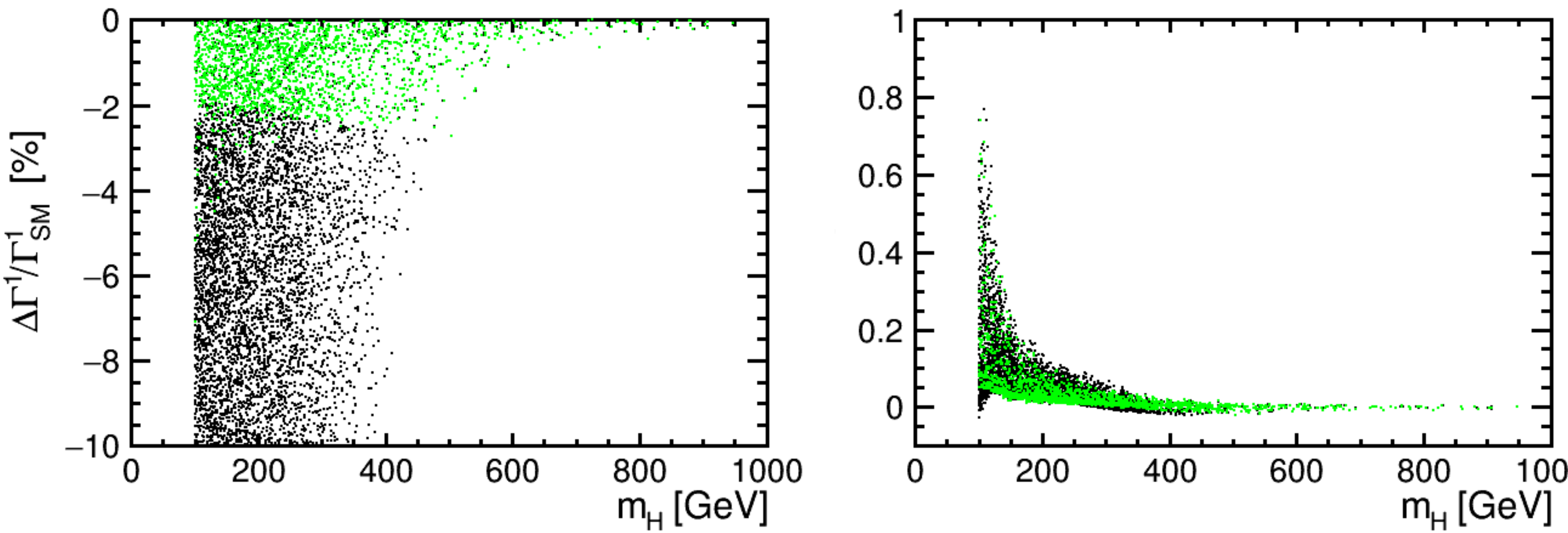
where $\lambda_{\Phi\Phi h} \equiv (m_\Phi^2 - M^2)/v^2$ and $m_\Phi = m_{H^\pm}(= m_A = m_H)$



approaching decoupling limit much
more quickly in THDM than in HSM

numerical results: THDM

green: sin(β-α)>0.98



$\Delta\Gamma^1$ mainly from tree level effect sin(β-α)

$\Delta\Gamma^1$ loop effects very small,
even when m_H~150 GeV

Γ^2 mainly from loop level effect
not much changed even sin(β-α)=1

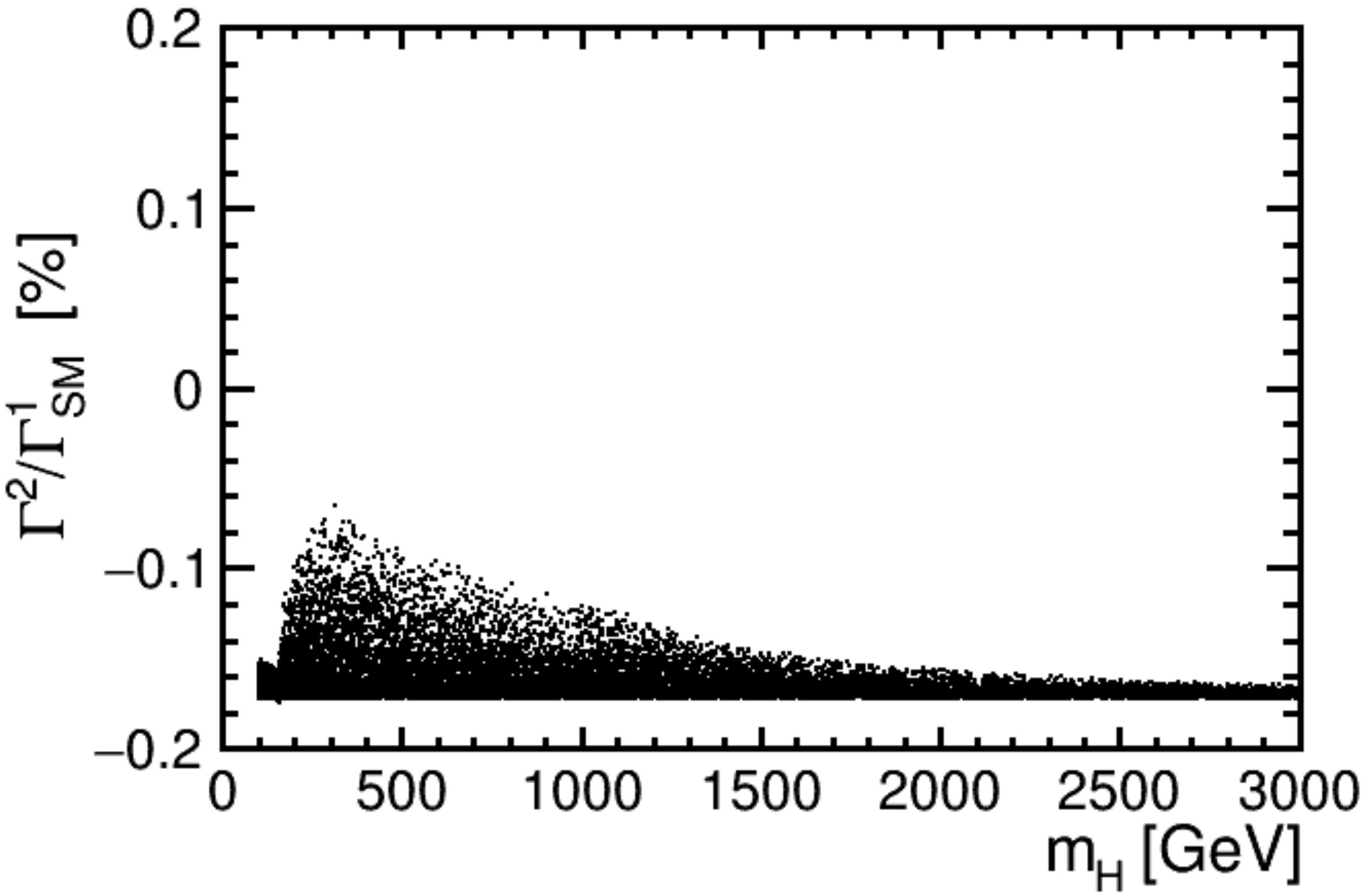
summary & next

- EFT provides a precise/model-independent formalism for Higgs couplings determination at e+e-
- a first step is tried to find the effective Higgs couplings, both η_Z and ζ_Z, in BSM models based on full one-loop calculation
- no "strong" dependence on new particle mass found for the loop level contribution in HSM and THDM: deviation is ~ a few% as long as mH > 150 GeV (large as radiative correction, but still make D-6 linear expansion valid)
- next step: try to go further from η, ζ to D-6 operators, c_H, c_{WB}, c_{BB}, c_{WW}, etc.; include other effective Higgs couplings, in particular Yukawa couplings

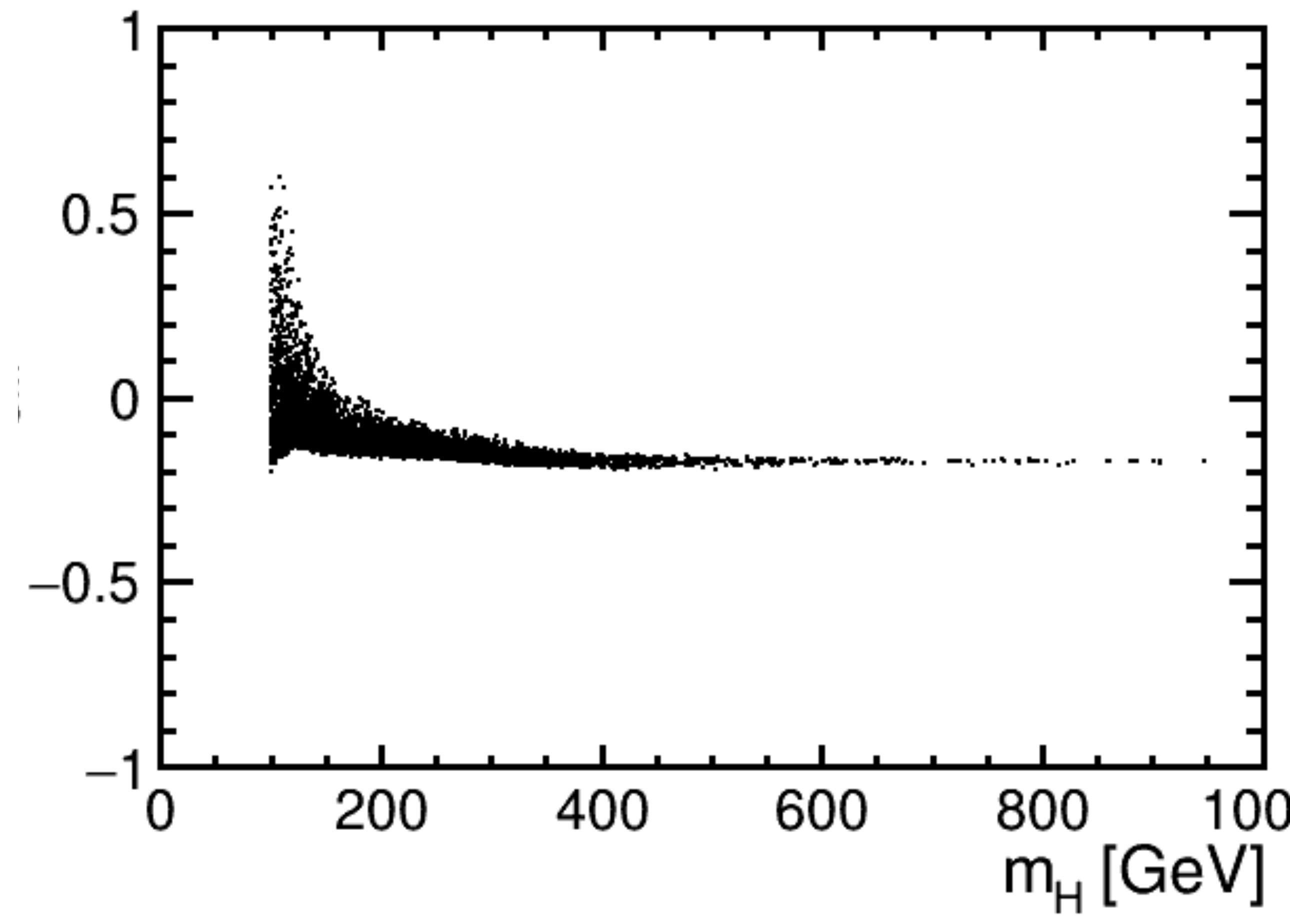
backup

numerical results: Γ^2 instead of $\Delta\Gamma^2 = \Gamma^2 - \Gamma^2_{SM}$

HSM



THDM



arXiv:1705.05399

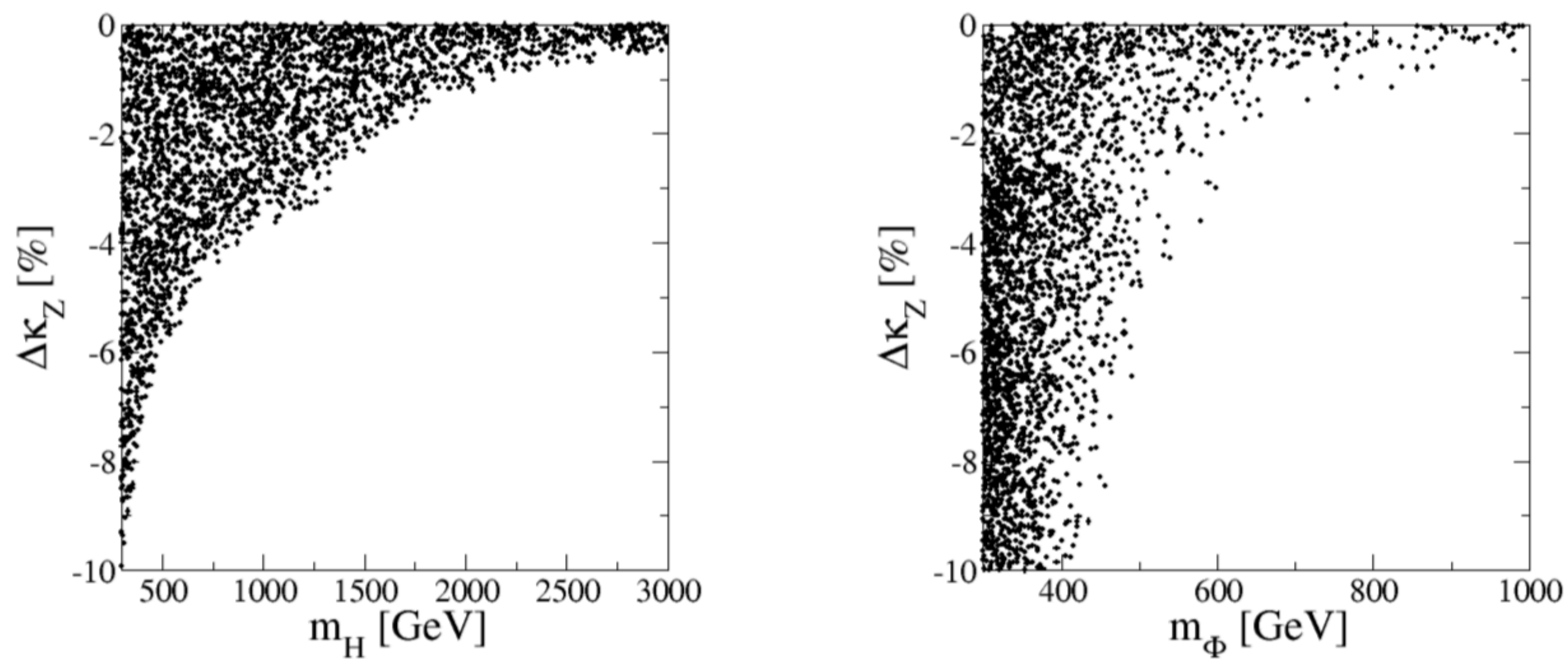


FIG. 14: Allowed parameter region under the constraints from the perturbative unitarity, the vacuum stability, the triviality and the S, T parameters on the $\Delta\kappa_Z$–m_H plane and the $\Delta\kappa_Z$–m_Φ plane in the HSM (left) and in the THDM (right), respectively.

arXiv:1708.09079
arXiv:1708.08912

SM Effective Field Theory

("Warsaw" basis, JHEP 1010 (2010) 085)

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$
$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a \Phi W^a_{\mu\nu}B^{\mu\nu}$$
$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$
$$+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\overline{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu \Phi)(\overline{L}\gamma_\mu t^a L)$$
$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\overline{e}\gamma_\mu e)\ .$$

Φ: Higgs field; $D\mu$: gauge-covariant derivative
$W^a_{\mu\nu}$, $B_{\mu\nu}$: Yang-Mills field strength tensor for SU(2) and U(1)
L: left-handed lepton field; e: right-handed lepton field
g, g': gauge couplings for SU(2) and U(1); $t^a=\sigma^\alpha/2$
v: vacuum expectation value; λ: quartic Higgs self-coupling

$$\Phi^\dagger \overleftrightarrow{D}_\mu \Phi = \Phi^\dagger D_\mu \Phi - D_\mu \Phi^\dagger \Phi$$

one example for illustrating the physics effect

$$\boxed{\frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi)}$$

after EWSB:

(1) $\frac{c_H}{2}\partial^\mu h\partial_\mu h$ $\longrightarrow$ renormalize kinetic term of SM Higgs field $\frac{1}{2}\partial^\mu h\partial_\mu h$

h $\longrightarrow$ $(1-c_H/2)h$

$\longrightarrow$ shift all SM Higgs couplings by $-c_H/2$

(2) $\frac{c_H}{v}h\partial^\mu h\partial_\mu h$ $\longrightarrow$ anomalous triple Higgs coupling

(3) $\frac{c_H}{2v^2}hh\partial^\mu h\partial_\mu h$ $\longrightarrow$ anomalous quartic Higgs coupling

full formalism
23 parameters

SM Effective Field Theory

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$
$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}$$
$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$
$$+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L)$$
$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .$$

10 operators (h,W,Z,γ): c_H, c_T, c_6, c_{WW}, c_{WB}, c_{BB}, c_{3W}, c_{HL}, c'_{HL}, c_{HE}

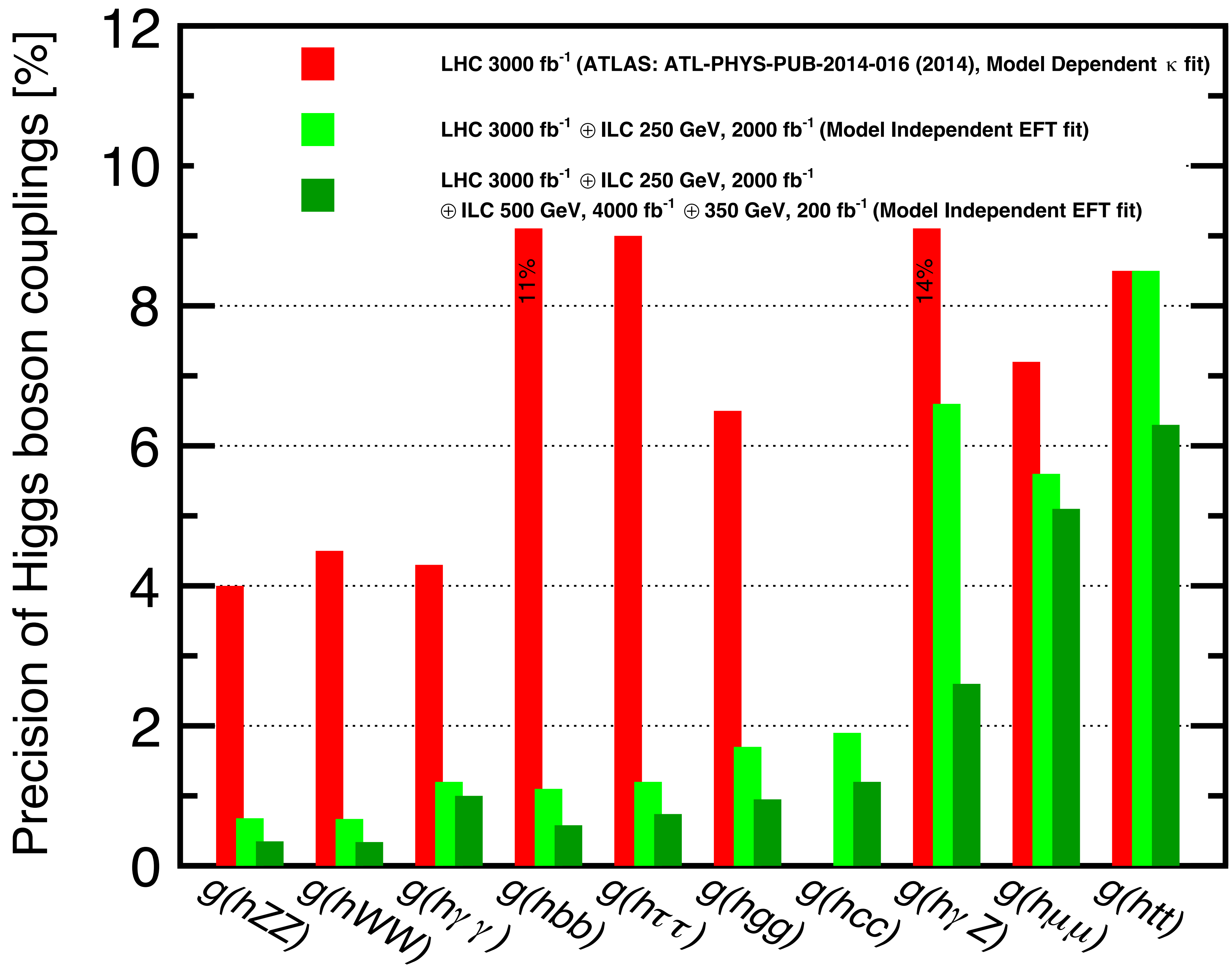
+ 4 SM parameters: g, g’, v, λ

+ 5 operators modifying h couplings to b, c, τ, μ, g

+ 2 parameters for h->invisible and exotic

+ 2 operators for contact interaction with quarks

what a 250 GeV ILC would deliver



note the synergy: HL-LHC input is always included

summary

- advantage of e+e- (e.g. ILC): model-independent determination of all Higgs couplings (and precisely)
  - ➡ kappa formalism turns out not general enough to accommodate all BSM effects
  - ➡ EFT formalism (combined EWPOs+TGCs+Higgs) is more suitable, and a realistic fit based on this formalism is proved to work very well

- one important conclusion based on the EFT formalism: hWW coupling can be determined precisely at $\sqrt{s}$ = 250 GeV without relying on WW-fusion process —> go ahead ILC250 (or any other affordable Higgs factory)

- beam polarization shows additional importance in EFT formalism

- EFT opens up new (better) way for BSM model discrimination

Large Scale
$\phi_j,\ \chi$

$\mathcal{L}_H(\chi, \phi) + \mathcal{L}(\phi)$ $\Bigg\downarrow$ renormalization group

$\mu = M$
particle mass

MATCHING

$\mathcal{L}(\phi) + \delta\mathcal{L}(\phi)$ $\Bigg\downarrow$ renormalization group

Low Energy
ϕ_j

Figure 4: The general form of a matching calculation.

reminder: model independence in kappa framework

- recoil mass technique —> inclusive σ_{Zh}
- σ_{Zh} —> κ_Z —> Γ(h->ZZ*)
- WW-fusion $\nu_e\nu_e$h —> κ_W —> Γ(h->WW*)
- total width Γ_h = Γ(h—>ZZ*)/BR(h->ZZ*)
- or Γ_h = Γ(h—>WW*)/BR(h->WW*)
- then all other couplings

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on-shell renormalization

- D-6 operators modify the SM expressions for precision electroweak observables, thus shift the appropriate values for the SM couplings —> g, g', v, λ free parameters
- D-6 operators also renormalize the kinetic terms of the SM fields —> rescale the boson fields

$$\mathcal{L} = -\frac{1}{2}W^+_{\mu\nu}W^{-\mu\nu}\cdot(1-\delta Z_W) - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu}\cdot(1-\delta Z_Z)$$
$$-\frac{1}{4}A_{\mu\nu}A^{\mu\nu}\cdot(1-\delta Z_A) + \frac{1}{2}(\partial_\mu h)(\partial^\mu h)\cdot(1-\delta Z_h) \ ,$$

with

$$\delta Z_W = (8c_{WW})$$
$$\delta Z_Z = c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + s_w^4/c_w^2(8c_{BB})$$
$$\delta Z_A = s_w^2\Big((8c_{WW}) - 2(8c_{WB}) + (8c_{BB})\Big)$$
$$\delta Z_h = -c_H \ .$$

$$\Delta\mathcal{L} = \frac{1}{2}\,\delta Z_{AZ}\,A_{\mu\nu}Z^{\mu\nu} \ , \qquad \delta Z_{AZ} = s_w c_w\Big((8c_{WW}) - (1-\frac{s_w^2}{c_w^2})(8c_{WB}) - \frac{s_w^2}{c_w^2}(8c_{BB})\Big)$$

Higgs couplings in EFT

$$\Delta\mathcal{L}_h = \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}m_h^2 h^2 - (1+\eta_h)\overline{\lambda} v h^3 + \frac{\theta_h}{v} h \partial_\mu h \partial^\mu h$$
$$+(1+\eta_W)\frac{2m_W^2}{v}W_\mu^+ W^{-\mu} h + (1+\eta_{WW})\frac{m_W^2}{v^2}W_\mu^+ W^{-\mu} h^2$$
$$+(1+\eta_Z)\frac{m_Z^2}{v}Z_\mu Z^\mu h + \frac{1}{2}(1+\eta_{ZZ})\frac{m_Z^2}{v^2}Z_\mu Z^\mu h^2$$
$$+\zeta_W \hat{W}_{\mu\nu}^+ \hat{W}^{-\mu\nu}\left(\frac{h}{v} + \frac{1}{2}\frac{h^2}{v^2}\right) + \frac{1}{2}\zeta_Z \hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}\left(\frac{h}{v} + \frac{1}{2}\frac{h^2}{v^2}\right)$$
$$+\frac{1}{2}\zeta_A \hat{A}_{\mu\nu}\hat{A}^{\mu\nu}\left(\frac{h}{v} + \frac{1}{2}\frac{h^2}{v^2}\right) + \zeta_{AZ}\hat{A}_{\mu\nu}\hat{Z}^{\mu\nu}\left(\frac{h}{v} + \frac{1}{2}\frac{h^2}{v^2}\right) .$$

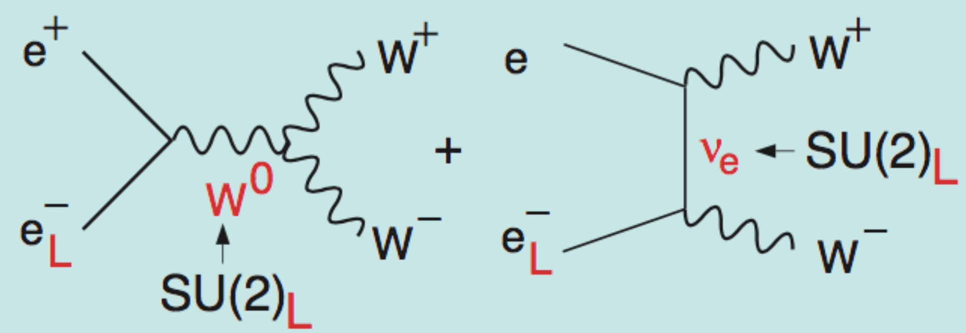
$$\eta_h = \delta\overline{\lambda} + \delta v - \frac{3}{2}c_H + c_6$$
$$\eta_W = 2\delta m_W - \delta v - \frac{1}{2}c_H$$
$$\eta_{WW} = 2\delta m_W - 2\delta v - c_H$$
$$\eta_Z = 2\delta m_Z - \delta v - \frac{1}{2}c_H - c_T$$
$$\eta_{ZZ} = 2\delta m_Z - 2\delta v - c_H - 5c_T$$

$$\theta_h = c_H$$
$$\zeta_W = \delta Z_W$$
$$\zeta_Z = \delta Z_Z$$
$$\zeta_A = \delta Z_A$$
$$\zeta_{AZ} = \delta Z_{AZ}$$

Power of Beam Polarization

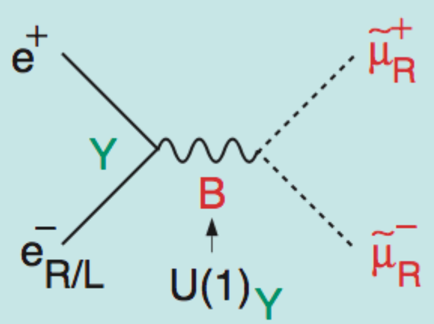
W^+W^- *(Largest SM BG in SUSY searches)*

BG Suppression



In the symmetry limit, $\sigma_{WW} \to 0$ for e^-_R !

Slepton Pair

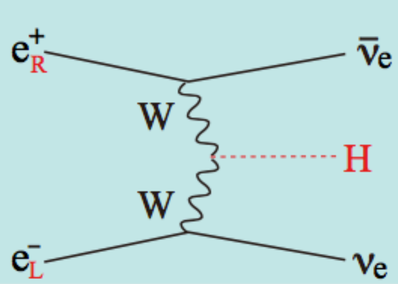


$Y_L = -1/2 : e^-_L$

$Y_R = -1 \quad : e^-_R$

In the symmetry limit, $\sigma_R = 4\,\sigma_L$!

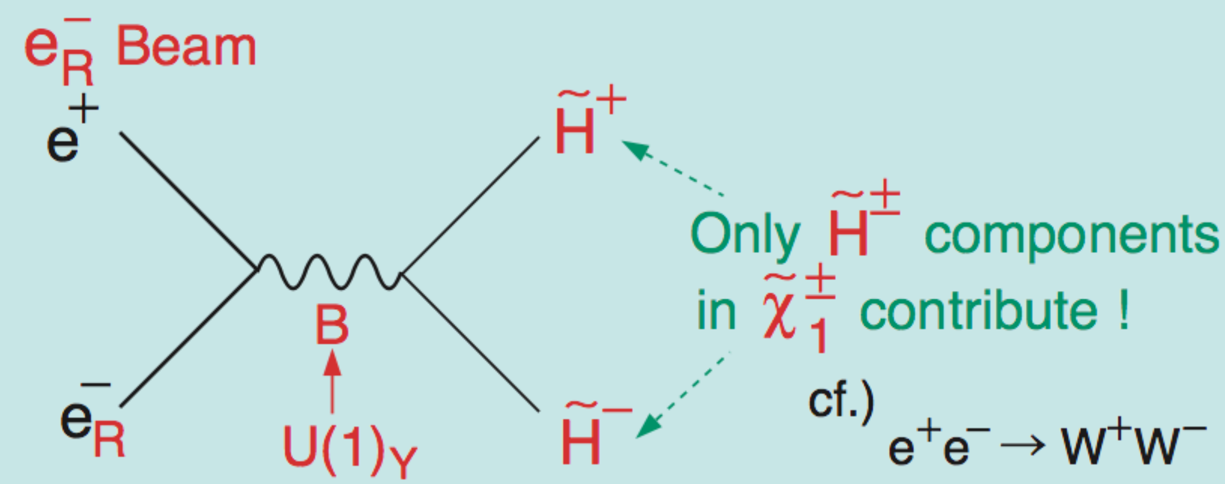
WW-fusion Higgs Prod.



	ILC
Pol (e^-)	-0.8
Pol (e^+)	+0.3
$(\sigma/\sigma_0)_{\nu H}$	1.8x1.3=2.34

Signal Enhancement

Chargino Pair



$$\tilde{\chi}^{\pm}_1 = \bigcirc \cdot \tilde{W}^{\pm} + \bullet \cdot \tilde{H}^{\pm}$$

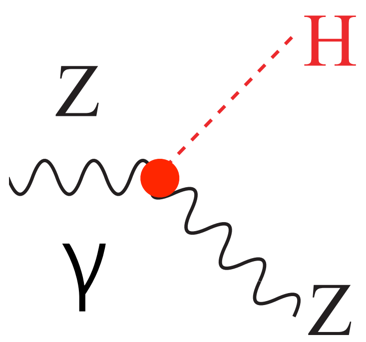
$$\bullet = \langle \tilde{H}^{\pm} | \tilde{\chi}^{\pm}_1 \rangle$$

Decomposition

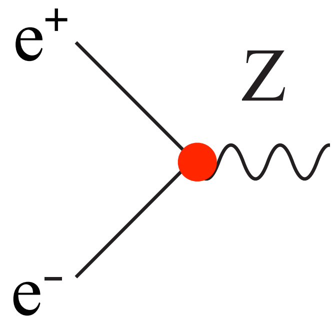
comments on beam polarizations

- not changed: important for systematics control, nature of new particle (once found), e.g. Higgsino, WIMPs
- new roles in EFT

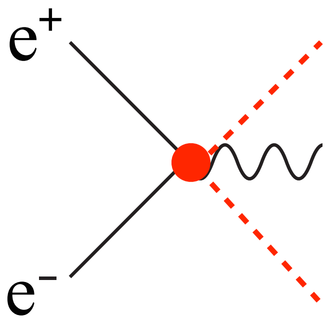
-> separate hZZ and hγZ couplings



-> improve A_{LR} in Z-e-e coupling



important to constrain contact interaction



comments on validity of our EFT analysis

- though most of the coefficients are assumed to be small, it is not necessary for c6, which modifies triple higgs coupling only, would not affect the formalism of other part (tree level)
- thus it can be applied to the case where λ_{hhh} is significantly enhanced (e.g. EWBG, CSI)
- in general we assume the mass scales of new particles which contribute to the D-6 operators are heavy, but it is fine with light WIMP, if it is only relevant in h->invisible decay (decoupled with other observable)