Theory and Phenomenology of Composite 2-Higgs Doublet Models

Stefania De Curtis

INFN and Dept. of Physics and Astronomy, Florence University, Italy

Based on: SDC, S. Moretti, K. Yagyu and E. Yildirim, Phys.Rev.D94 (2016);
arXiv:1610.02687[hep-ph]; in preparation.

637. Wilhelm und Else Heraeus-Seminar
UNDERSTANDING THE LHC
Physikzentrum Bad Honnef, Germany, Feb. 12-15, 2017

Motivations and Outline

- The search for additional Higgses is one of the most important tasks of the LHC. Moreover, extra spineless states can induce sizeable effects in the couplings of the discovered one
- From a theoretical point of view, extra Higgses do not give an explanation for naturalness. Their pNGB nature can link them to natural theories at the weak scale
- Focus on Composite Two Higgs Doublet Models (C2HDMs) emerging from specific symmetry breaking patterns. Results for SO(6)→SO(4)xSO(2)
- Perturbative unitarity and vacuum stability properties of the C2HDM
- Phenomenology at the LHC of the different Yukawa Type C2HDMs and comparison with the Elementary 2HDM predictions
- Phenomenology at future e^+e^- colliders (preliminary)

Generalities on Extended Composite Higgs Models

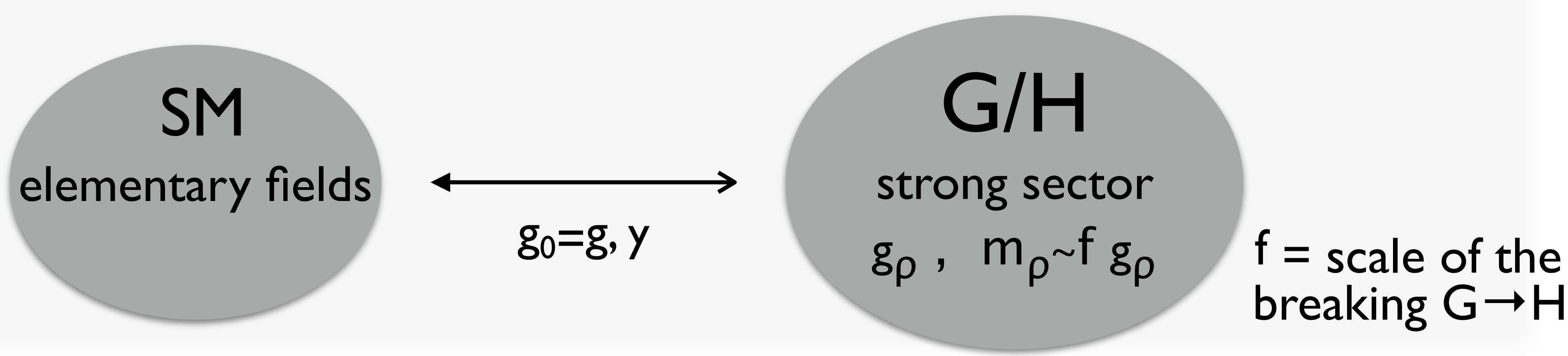
Models with a larger Higgs structure with respect to the SM have been proposed —> 2HDMs offer a rich phenomenology in EW and flavour physics

In 2HDMs, as in the SM, the Higgs sector is very sensitive to UV physics —> Hierarchy problem

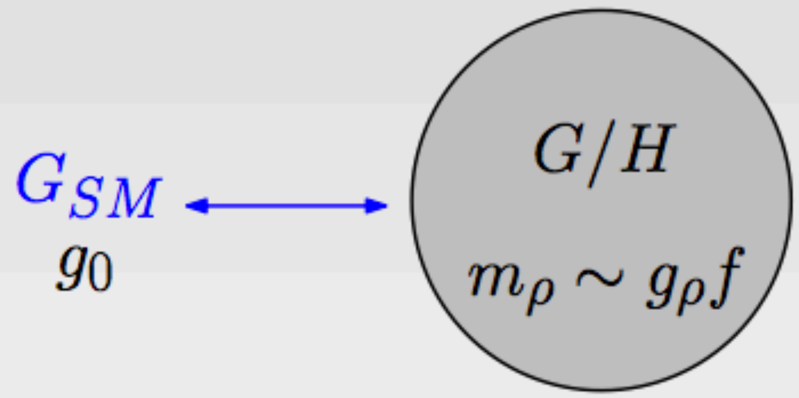
Is it Naturalness a good guideline?

The most popular solution, Supersymmetry, requires two Higgs doublets with specific Yukawa and potential terms

A natural alternative is to consider the Higgs bosons as composite states from a strong sector. They can be lighter than the strong scale if they are pNGBs of G/H



Higgs as a Composite Pseudo Goldstone Boson



Kaplan, Georgi '80s

The basic idea

- Higgs as Goldstone Boson of G/H in a **strong** sector
- An idea already realized for pions in QCD

How to get an Higgs mass?

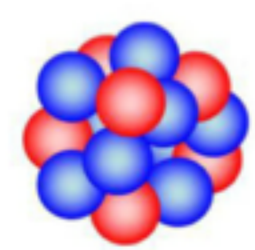
- G is only an approximate global symmetry $g_0 \ \rightarrow \ V(h)$
- EWSB as in the SM

- And the hierarchy problem?

no Higgs mass term at tree level

$$\rightarrow \delta m_h^2 \sim \frac{g_0^2}{16\pi^2}\Lambda_{com}^2$$

$l \sim 1/\Lambda_{com}$



Characteristics of a Composite Higgs

It is not a true (SM-like) Higgs...

$$\mathcal{L} = \frac{1}{2}(\partial_\mu h)^2 + V(h) + \frac{v^2}{4}\mathrm{Tr}\left[(D_\mu\Sigma)^\dagger(D^\mu\Sigma)\right]\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + \cdots\right)$$

$$- \frac{v}{\sqrt{2}}\sum_{i,j}\left(\bar{u}_L^i \bar{d}_L^i\right)\Sigma\begin{pmatrix}\lambda_{ij}^u u_R^j \\ \lambda_{ij}^d d_R^j\end{pmatrix}\left(1 + c\frac{h}{v} + \cdots\right) + \mathcal{L}_{SM,\not{h}}$$

$$\Sigma = e^{i\frac{\sigma^a\chi^a}{v}}$$

- SM Higgs for a $a = b = c = 1$
- GB Higgs $a = \sqrt{1 - v^2/f^2},\ b = 1 - 2\ v^2/f^2$ SM limit $f \to \infty$
- Composite Higgs only partly unitarizes *WW* scattering $A(s,t,u) \sim \dfrac{s+t}{f^2}$
- Up to effects v^2/f^2, the scalar h behaves as the SM Higgs
- Technicolor limit $f = v$

Extended Composite Higgs Models

J.Mrazek et al.1105.5403; DC,Moretti,Yagyu,Yildirim 1602.06437

- We characterise models where EWSB is driven by 2 Higgs doublets as pNGBs of new dynamics above the weak scale

- We focus on models based on SO(6)/SO(4)xSO(2). The unbroken group contains the custodial SO(4). The spectrum of the GBs is completely fixed by the coset and it is given by 2 Higgs 4-plets

- The low-energy effective Lagrangian stands on few specific assumptions about the strong sector: the global symmetries, the SSB pattern, the sources of explicit breaking. At the leading 2-derivative order, the non-linear σ-model interactions are fixed in terms of a unique parameter f (compositeness scale)

- Elementary fields are linearly coupled to the strong sector (partial compositeness)

$$\mathcal{L}_{\rm mix} = g_0\ (\psi_{\rm SM}\ \mathcal{O}) \qquad \psi_{\rm SM} = (A_\mu, f) \qquad g_0 = g, y$$

- The SM fields have a degree of mixing ~ g_0/g_ρ. Realistic models $g_0 < g_\rho < 4\pi$

- $\mathcal{L}_{\rm mix}$ breaks the global symm. of the strong sector, the Higgses become pNGBs and acquire a potential

Extended Composite Higgs Models

- Crucial property is the presence of discrete symmetries in addition to the custodial SO(4), to control the T-parameter (this because in non-minimal models, even though the non-linear interactions satisfy SO(4), a contribution to T can arise for a generic vacuum structure J.Mrazek et al.1105.5403)

- Discrete symmetries also protect from Higgs-mediated Flavour Changing Neutral Currents

- Besides CP, impose a C_2 discrete symmetry (J.Mrazek et al.1105.5403) distinguishes the 2 Higgs doublets and restricts the form of the Higgs potential and the Yukawa couplings (analogous of Z_2 in E2HDM)

- Two classes of models: 1) exact discrete C_2 symmetry (inert case) — the second Higgs does not couple to the SM fields 2) softly-broken C_2 symmetry (active case) which controls the T parameter and FCNC

The model - 2 Higgs Doublets as pNGBs

J.Mrazek et al.1105.5403; DC,Moretti,Yagyu,Yildirim 1602.06437

Analogue of the construction in non-linear sigma models developed by Callan-Coleman-Wess-Zumino (CCWZ)

The kinetic Lagrangian invariant under the SO(6) is:

GB matrix $U = \exp\left(i\frac{\Pi}{f}\right)$

$$\mathcal{L}_{\rm kin} = \frac{f^2}{4}(d^{\hat{a}}_\alpha)_\mu (d^{\hat{a}}_\alpha)^\mu \qquad (d^{\hat{a}}_\alpha)_\mu = i\,{\rm tr}(U^\dagger D_\mu U T^{\hat{a}}_\alpha)$$

$\alpha = 1,2 \quad \hat{a} = 1,..,4$

are the 8 broken SO(6) generators

$$\Pi \equiv \sqrt{2} h^{\hat{a}}_\alpha T^{\hat{a}}_\alpha = -i \begin{pmatrix} 0_{4\times 4} & h^{\hat{a}}_1 & h^{\hat{a}}_2 \\ -h^{\hat{a}}_1 & 0 & 0 \\ -h^{\hat{a}}_2 & 0 & 0 \end{pmatrix} \qquad \Phi_\alpha \equiv \frac{1}{\sqrt{2}} \begin{pmatrix} h^2_\alpha + i h^1_\alpha \\ h^4_\alpha - i h^3_\alpha \end{pmatrix}$$

$$\boxed{h^4_\alpha = \tilde{h}_\alpha = h_\alpha + v_\alpha}$$

covariant derivative: $D_\mu = \partial_\mu - i g T^a_L W^a_\mu - i g' Y B_\mu$

$$\boxed{v^2 \equiv v_1^2 + v_2^2}$$

the gauge boson masses are generated by the VEVs of the fourth components of the Higgs fields

$$m_W^2 = \frac{g^2}{4} f^2 \sin^2 \frac{v}{f} \rightarrow v^2_{\rm SM}$$

The model - 2 Higgs Doublets as pNGBs

Similarly to E2HDM, define the Higgs basis: only one doublet contains v and the NGs of W,Z

$$\begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} \Phi \\ \Psi \end{pmatrix} \qquad \Phi = \begin{pmatrix} G^+ \\ \frac{v+h_1'+iG^0}{\sqrt{2}} \end{pmatrix}, \quad \Psi = \begin{pmatrix} H^+ \\ \frac{h_2'+iA}{\sqrt{2}} \end{pmatrix}$$

A CP-odd
$h'_{1,2}$ CP-even

$\tan\beta = v_2/v_1$

By expanding the kinetic term up to O(1/f²) we get non canonical forms for $G_0,\ G^{\pm},\ h_2'$ we rescale according to:

$$G^+ \to \left(1-\frac{\xi}{3}\right)^{-1/2} G^+, \quad G^0 \to \left(1-\frac{\xi}{3}\right)^{-1/2} G^0, \quad h_2' \to \left(1-\frac{\xi}{3}\right)^{-1/2} h_2'$$

$$\xi = \frac{v_{\rm SM}^2}{f^2}$$

The mass eigenstates of the CP-even scalars are defined by introducing the mixing angle Θ

$$\begin{pmatrix} h_1' \\ h_2' \end{pmatrix} = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

identified with the Higgs discovered at the LHC

determined by the mass matrix from the Higgs potential

Higgs potential in C2HDM

- The Higgs potential is generated at loop level
  - — gauge boson loops give a positive squared-mass term
  - — fermion loops can provide a negative squared-mass term and trigger EWSB

- Studied by J.Mrazek et al. 1105.5403 in the SO(6)/SO(4)xSO(2) model for several reps. of fermion fields **assuming** that all the explicit breaking is associated with the couplings of the strong sector to the SM fields due to Yukawa (y) and gauge (g) couplings (by relaxing this hypothesis the parameter space could be enlarged)

- They obtain the general E2HDM potential with parameters expressed in terms of those in the strong sector and the explicit breaking ones (at each order in y and g, it is parameterized by a limited number of coefficients which depend on the fermion representation)

$$
\begin{aligned}
V(\Phi_{\hat{1}},\Phi_{\hat{2}}) = \; & \frac{1}{2}m_{11}^2\,\mathrm{Tr}[\Phi_{\hat{1}}^\dagger\Phi_{\hat{1}}] + \frac{1}{2}m_{22}^2\,\mathrm{Tr}[\Phi_{\hat{2}}^\dagger\Phi_{\hat{2}}] + \frac{1}{2}\,\mathrm{Tr}[\Phi_{\hat{1}}^\dagger\Phi_{\hat{2}}(m_{12}^2 + i\,\tilde{m}_{12}^2\sigma_3)] \\
& + \frac{1}{4}\lambda_1\,\mathrm{Tr}^2[\Phi_{\hat{1}}^\dagger\Phi_{\hat{1}}] + \frac{1}{4}\lambda_2\,\mathrm{Tr}^2[\Phi_{\hat{2}}^\dagger\Phi_{\hat{2}}] + \frac{1}{4}\lambda_3\,\mathrm{Tr}[\Phi_{\hat{1}}^\dagger\Phi_{\hat{1}}]\,\mathrm{Tr}[\Phi_{\hat{2}}^\dagger\Phi_{\hat{2}}] \\
& + \frac{1}{4}\lambda_4\,\mathrm{Tr}^2[\Phi_{\hat{1}}^\dagger\Phi_{\hat{2}}] + \frac{1}{4}\tilde{\lambda}_4\,\mathrm{Tr}^2[\Phi_{\hat{1}}^\dagger\Phi_{\hat{2}}\sigma_3] + i\,\frac{1}{4}\lambda_5\,\mathrm{Tr}[\Phi_{\hat{1}}^\dagger\Phi_{\hat{2}}]\,\mathrm{Tr}[\Phi_{\hat{1}}^\dagger\Phi_{\hat{2}}\sigma_3] \\
& + \frac{1}{4}\,\mathrm{Tr}[\Phi_{\hat{1}}^\dagger\Phi_{\hat{1}}]\,\mathrm{Tr}[\Phi_{\hat{1}}^\dagger\Phi_{\hat{2}}(\lambda_6 + i\tilde{\lambda}_6\sigma_3)] + \frac{1}{4}\,\mathrm{Tr}[\Phi_{\hat{2}}^\dagger\Phi_{\hat{2}}]\,\mathrm{Tr}[\Phi_{\hat{1}}^\dagger\Phi_{\hat{2}}(\lambda_7 + i\tilde{\lambda}_7\sigma_3)]
\end{aligned}
$$

$$V = \frac{m_\rho^4}{16\pi^2} \sum_{n_R, n_L} \frac{1}{(g_\rho^2)^{n_R+n_L}} \sum_\delta c_\delta^{(n_R,n_L)} \, \mathcal{I}^\delta_{(n_R,n_L)}$$

pre-factors

small coupling expansion

SO(6) invariant operators constructed with the NGBs

J.Mrazek et al.1105.5403

Contribution to the parameters of the general C2HDM potential from fermions in the **6**

operator	$\mathcal{I}^1_{(0,1)}$	$\mathcal{I}^1_{(1,0)}$	$\mathcal{I}^1_{(2,0)}$	$\mathcal{I}^4_{(2,0)}$	$\mathcal{I}^5_{(2,0)}$	$\mathcal{I}^1_{(1,1)}$	$\mathcal{I}^5_{(1,1)}$	$\mathcal{I}^6_{(1,1)}$	$\mathcal{I}^1_{(0,2)}$	$\mathcal{I}^4_{(0,2)}$
$\frac{1}{16\pi^2}\times$	$-\frac{y_L^2 g_\rho^2}{2}$	$y_R^2 g_\rho^2$	$\frac{y_R^4}{4}$	$\frac{y_R^4}{4}\left(\frac{g_\rho}{4\pi}\right)^2$	$\frac{y_R^4}{4}\left(\frac{g_\rho}{4\pi}\right)^2$	$\frac{y_R^2 y_L^2}{4}$	$y_R^2 y_L^2\left(\frac{g_\rho}{4\pi}\right)^2$	$-y_R^2 y_L^2\left(\frac{g_\rho}{4\pi}\right)^2$	$-\frac{y_L^4}{2}$	$-y_L^4\left(\frac{g_\rho}{4\pi}\right)^2$
m_{11}^2/f^2	1	$\cos^2\theta$	0	0	0	$\cos^2\theta$	$\cos^2\theta$	0	1	1
m_{22}^2/f^2	1	$\sin^2\theta$	0	0	0	$\sin^2\theta$	$\sin^2\theta$	0	1	1
m_{12}^2/f^2	0	0	0	0	$\sin 4\theta$	0	0	0	0	0
$\tilde{m}_{12}^2/f^2$	0	0	0	0	0	$-\sin 2\theta$	0	$\frac{1}{2}\sin 2\theta$	0	0
λ_1	$-\frac{1}{3}$	$-\frac{1}{3}\cos^2\theta$	$2\cos^4\theta$	$2\cos^4\theta$	0	$-\frac{4}{3}\cos^2\theta$	$-\frac{7}{12}\cos^2\theta$	0	$-\frac{7}{12}$	$-\frac{11}{24}$
λ_2	$-\frac{1}{3}$	$-\frac{1}{3}\sin^2\theta$	$2\sin^4\theta$	$2\sin^4\theta$	0	$-\frac{4}{3}\sin^2\theta$	$-\frac{7}{12}\sin^2\theta$	0	$-\frac{7}{12}$	$-\frac{11}{24}$
λ_3	0	0	$\sin^2\theta$	$-\sin^2\theta$	0	0	$-\frac{1}{4}$	0	0	$-\frac{1}{4}$
λ_4	$-\frac{2}{3}$	$-\frac{1}{3}$	0	$2\sin^2 2\theta$	0	$-\frac{4}{3}$	$-\frac{1}{3}$	0	$-\frac{7}{6}$	$-\frac{2}{3}$
$\tilde{\lambda}_4$	0	0	0	0	0	0	0	0	$\frac{1}{2}$	0
λ_5	0	0	0	0	0	0	0	0	0	0
λ_6	0	0	0	0	$-\frac{1}{3}\sin 4\theta$	0	0	0	0	0
$\tilde{\lambda}_6$	0	0	0	0	0	$\frac{2}{3}\sin 2\theta$	0	$-\frac{1}{12}\sin 2\theta$	0	0
λ_7	0	0	0	0	$-\frac{1}{3}\sin 4\theta$	0	0	0	0	0
$\tilde{\lambda}_7$	0	0	0	0	0	$\frac{2}{3}\sin 2\theta$	0	$-\frac{1}{12}\sin 2\theta$	0	0

power counting estimate of the pre-factors up to the fourth-order

The result depends on:

- the fermionic repr.
- the explicit breaking assumption
- the order of the expansion in the degree of mixing g_0/g_ρ with $g_0 = g, g', y_L, y_R$

Higgs potential in C2HDM

DC, Moretti, Yagyu, Yildirim 1602.06437

- Here we assume the most general CP-conserving E2HDM form for the potential. The masses and couplings of the Higgses are free parameters

- We will however highlight parameter space regions where differences can be found between E2HDM and C2HDM (the compositeness implemented in the kinetic terms and interactions with SM fields)

- To avoid FCNC's at tree level we impose a discrete C_2 symmetry $(\Phi_1, \Phi_2) \to (+\Phi_1, -\Phi_2)$ which could be exact (inert case) or softly broken (active case)

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

m_3^2 and λ_5 are real, M defined by $M^2 = \dfrac{m_3^2}{s_\beta c_\beta}$ is the soft-breaking C_2 parameter

(The C_2 symm. also avoids anomalous contributions to the T parameter from dim-6 operators E.Bertuzzo et al.1206.2623)

Mass spectrum for the Active C2HDM

The mass matrices for charged states and the CP-odd scalars are diagonalised by a β-angle rotation

$\tan\beta = v_2/v_1$

$$\boxed{m_{H^\pm}^2 = M^2 - \frac{v^2}{2}(\lambda_4+\lambda_5), \quad m_A^2 = M^2 - v^2\lambda_5}$$

The mass matrix for the CP-even scalars is diagonalised by a Θ-angle rotation

$$\tan 2\theta = \frac{2(M_{\rm even})^2_{12}}{(M_{\rm even})^2_{11} - (M_{\rm even})^2_{22}}$$

$$(M_{\rm even})^2_{11} = v^2(\lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + 2\lambda_{345} c_\beta^2 s_\beta^2),$$

$$(M_{\rm even})^2_{22} = \left(1+\frac{\xi}{3}\right)[M^2 + v^2(\lambda_1+\lambda_2 - 2\lambda_{345})s_\beta^2 c_\beta^2],$$

$$(M_{\rm even})^2_{12} = v^2\left(1+\frac{\xi}{6}\right)[-\lambda_1 c_\beta^2 + \lambda_2 s_\beta^2 + c_{2\beta}\lambda_{345}]\, s_\beta c_\beta$$

$$\lambda_{345} = \lambda_3+\lambda_4+\lambda_5.$$

$$\boxed{\begin{aligned} m_h^2 &= c_\theta^2(M_{\rm even})^2_{11} + s_\theta^2(M_{\rm even})^2_{22} + 2s_\theta c_\theta(M_{\rm even})^2_{12},\\ m_H^2 &= s_\theta^2(M_{\rm even})^2_{11} + c_\theta^2(M_{\rm even})^2_{22} - 2s_\theta c_\theta(M_{\rm even})^2_{12}\end{aligned}}$$

Decoupling limit for large M: the extra Higgses get degenerate with M and Θ→0

(the usual 2HDM notation is recovered with Θ=α-β-π/2)

λ_i parameters in terms of the masses of the physical Higgs bosons

$$\lambda_1 = \frac{1}{v^2 c_\beta^2}\left[m_h^2 c_{\beta+\theta}^2 + m_H^2 s_{\beta+\theta}^2 - M^2 s_\beta^2 + \frac{\xi}{3} s_\beta (m_h^2 c_{\beta+\theta} s_\theta - m_H^2 s_{\beta+\theta} c_\theta)\right],$$

$$\lambda_2 = \frac{1}{v^2 s_\beta^2}\left[m_h^2 s_{\beta+\theta}^2 + m_H^2 c_{\beta+\theta}^2 - M^2 c_\beta^2 - \frac{\xi}{3} c_\beta (m_h^2 s_{\beta+\theta} s_\theta + m_H^2 c_{\beta+\theta} c_\theta)\right],$$

$$\lambda_3 = \frac{1}{v^2}\left[\frac{2 s_{\beta+\theta} c_{\beta+\theta}}{s_{2\beta}}(m_h^2 - m_H^2) + 2m_{H^\pm}^2 - M^2 - \frac{\xi}{3 s_{2\beta}}(m_h^2 s_\theta c_{2\beta+\theta} - m_H^2 c_\theta s_{2\beta+\theta})\right]$$

$$\lambda_4 = \frac{1}{v^2}(M^2 + m_A^2 - 2m_{H^\pm}^2),$$

$$\lambda_5 = \frac{1}{v^2}(M^2 - m_A^2).$$

mh=125GeV, v=245GeV

Total of 7 free parameters:

mH, mA, mH+, sinΘ , tanβ , M, ξ (or f)

Mass spectrum for the Inert C2HDM

$$m_{H^\pm}^2 = m_2^2 + \frac{v^2}{2}\lambda_3, \qquad m_H^2 = \left(1 + \frac{\xi}{3}\right)\left({m_2}^2 + \frac{v^2}{2}\lambda_{345}\right)$$

$$m_A^2 = {m_2}^2 + \frac{v^2}{2}(\lambda_3 + \lambda_4 - \lambda_5), \qquad m_h^2 = \lambda_1 v^2.$$

m_3=M=0 (C_2 symm) and <Φ_2>=0, m_2 sets the scale for the mass of the inert Higgs

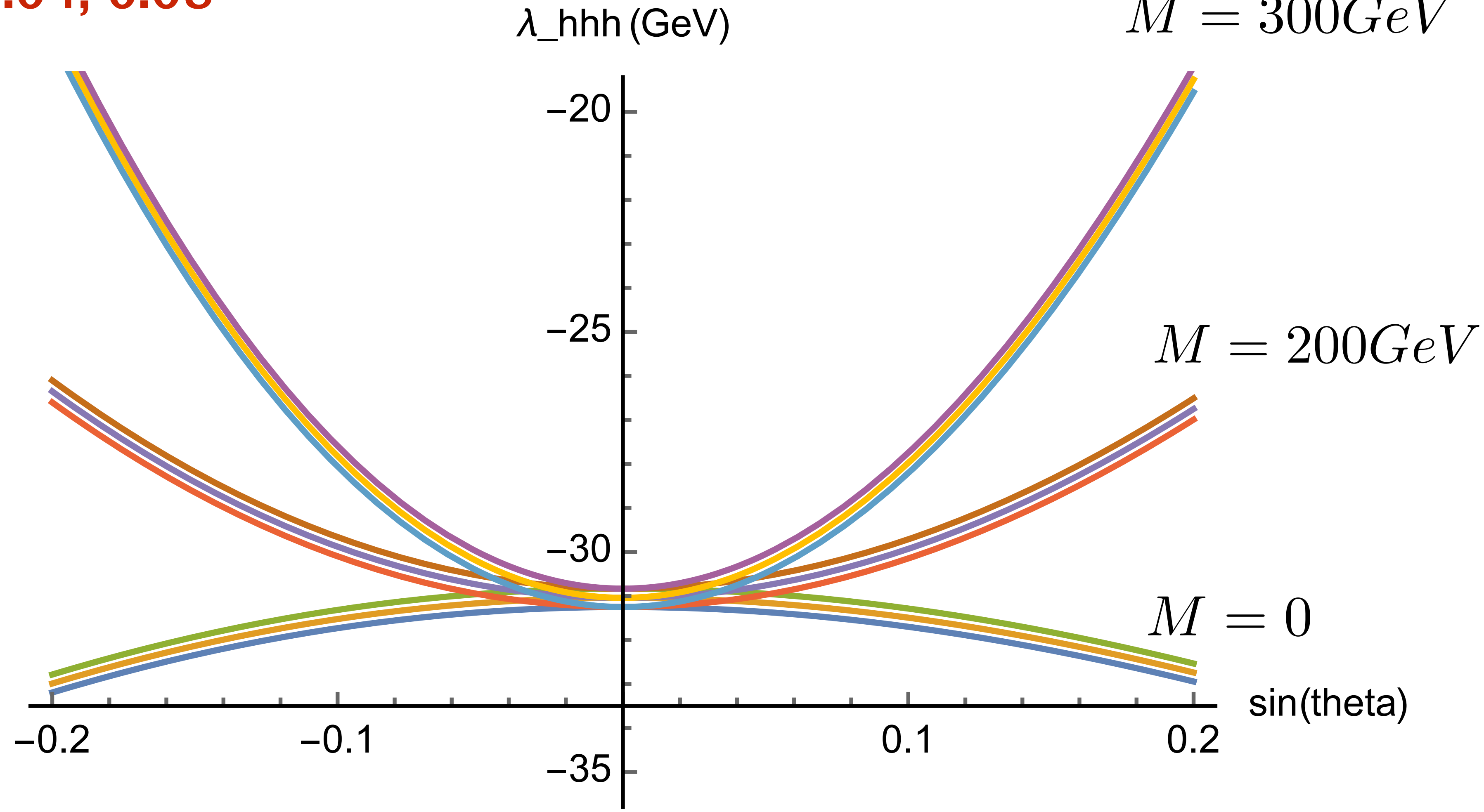
$\Phi_2 \equiv$H possible candidate for composite neutral dark matter

Trilinear Higgs self-coupling - role of M

$$\lambda_{hhh} = \frac{1}{4v_{\rm SM}s_{2\beta}}\left[(s_{2\beta+3\theta} - 3s_{2\beta+\theta})m_h^2 + 4s_\theta^2 s_{2\beta+\theta}M^2\right] + \frac{\xi}{12v_{\rm SM}}\left[c_\theta m_h^2 + 2s_\theta^2 M^2(c_\theta + 2s_\theta\cot 2\beta)\right] + \mathcal{O}(\xi^2)$$

tanβ=1 (nearly independent of tanβ for small Θ)

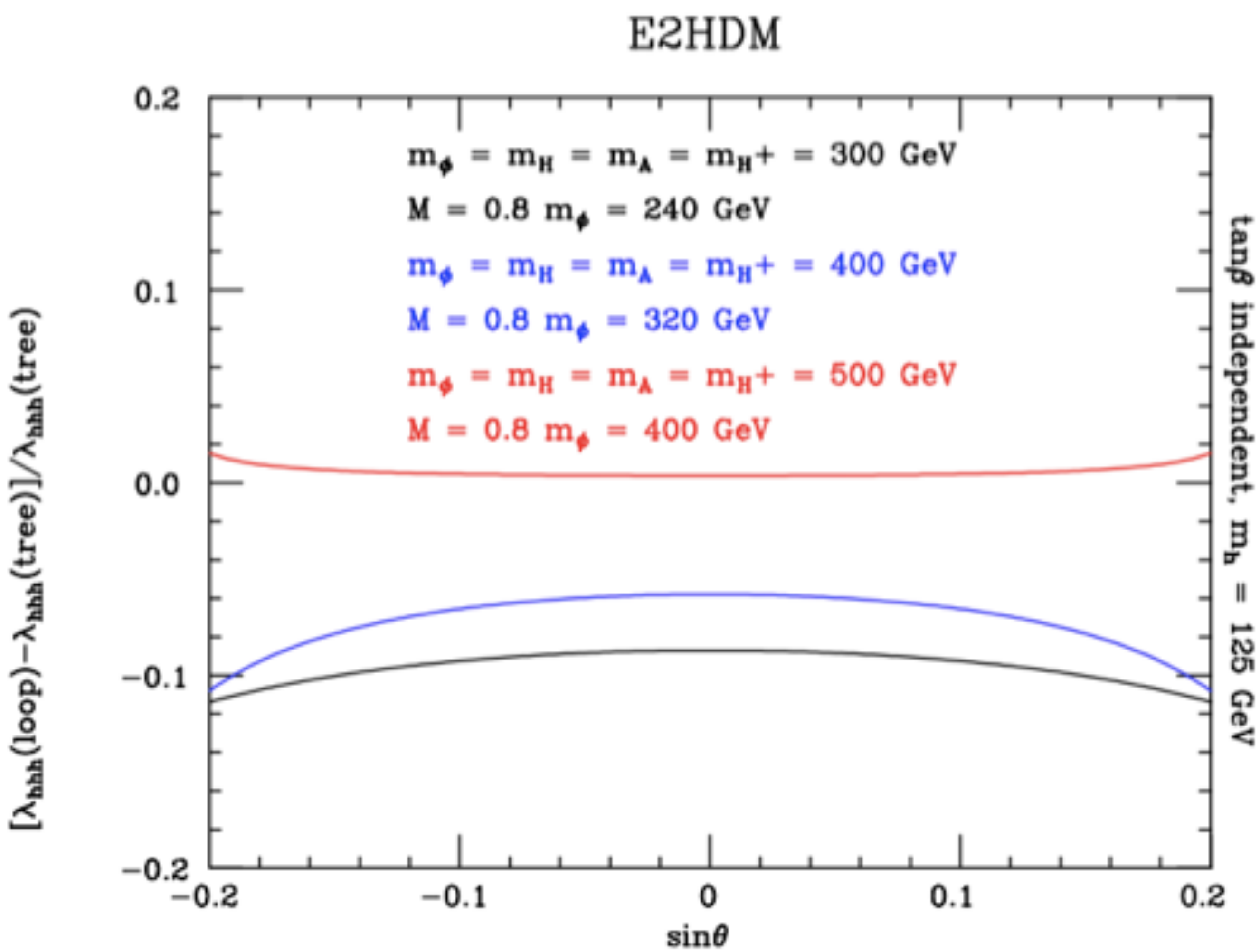
ξ=0, 0.04, 0.08



λ_{hhh} one-loop

S.Kanemura et al. 0408364

- ☑ The quantum effect of additional particles in loop diagrams for λ_{hhh} can be enhanced when they show the non-decoupling property and can become as large as plus 100% for $M \ll m_\Phi$
- ☑ Under control in the decoupling limit $M \approx m_\Phi = m_H = m_{H^+} = m_A$



Deviations ~10% for $M=0.8\ m_\Phi$ and $m_\Phi=300$GeV. Lower for larger masses

We will set $M=0.8\ m_\Phi$ in our analysis

C2HDM coupling deviations

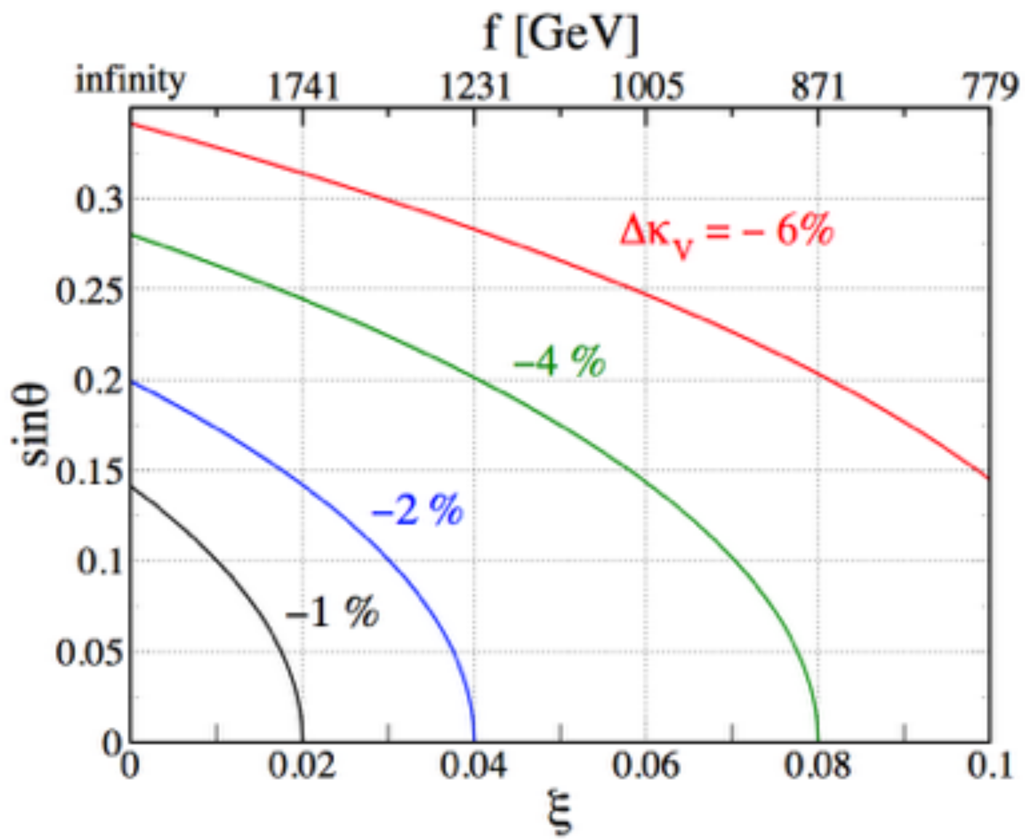
Even without introducing fermions, the pattern of deviations from the SM-like properties can be different between C2HDMs and E2HDMs

Introduce a scaling factor k_X for the hXX couplings as $\kappa_X = g^{\rm NP}_{hXX}/g^{\rm SM}_{hXX}$

- ☑ In the C2HDM, at the first order in ξ we get $\kappa_V = (1-\xi/2)c_\theta$ (V=W,Z)
- ☑ E2HDM is obtained with $\xi=v^2/f^2\to 0$ or $f\to\infty$, while SM has $\kappa_X = 1$
- ☑ Two sources giving $\kappa_X \neq 1$ in C2HDM: non zero value of ξ and/or θ
- ☑ Conversely, only $\theta\neq 0$ gives $\kappa_X \neq 1$ in E2HDM

Therefore, for a given value of k_X, the value of θ is determined in E2HDM while only the combination (θ,ξ) is determined in C2HDM

C2HDM coupling deviations



Contours for the deviations in the hVV coupling $\Delta\kappa_V = \kappa_V - 1$

$\kappa_V = g_{hVV}/g_{hVV}^{\rm SM} = (1-\xi/2)c_\theta$

Ex. $\Delta\kappa_V = -2\%$ corresponds to sinθ=0.2 in the E2HDM but can be reproduced by (sinθ,ξ)=(0,0.04) in the C2HDM

Even in the case of no-mixng between h and H, a non-zero deviation in hVV coupling is present in the C2HDM

Vertex	Coefficient
$H^\pm \overleftrightarrow{\partial}_\mu A W^{\mp\mu}$	$\frac{g}{2}$
$H^\pm\partial_\mu h W^{\mp\mu}$	$\mp i\frac{g}{2}(1-\frac{5}{6}\xi)\sin\theta$
$h\partial_\mu H^\pm W^{\mp\mu}$	$\pm i\frac{g}{2}(1-\frac{1}{6}\xi)\sin\theta$
$H^\pm\partial_\mu H W^{\mp\mu}$	$\mp i\frac{g}{2}(1-\frac{5}{6}\xi)\cos\theta$
$H\partial_\mu H^\pm W^{\mp\mu}$	$\pm i\frac{g}{2}(1-\frac{1}{6}\xi)\cos\theta$
$A\partial_\mu h Z^\mu$	$-\frac{g_Z}{2}(1-\frac{5}{6}\xi)\sin\theta$
$h\partial_\mu A Z^\mu$	$\frac{g_Z}{2}(1-\frac{1}{6}\xi)\sin\theta$
$A\partial_\mu H Z^\mu$	$-\frac{g_Z}{2}(1-\frac{5}{6}\xi)\cos\theta$
$H\partial_\mu A Z^\mu$	$\frac{g_Z}{2}(1-\frac{1}{6}\xi)\cos\theta$
$H^+\overleftrightarrow{\partial}_\mu H^- Z^\mu$	$-i\frac{g_Z}{2}c_{2W}$
$H^+\overleftrightarrow{\partial}_\mu H^- A^\mu$	$-ie$

Coefficients of the scalar-scalar-gauge type vertices

Perturbative Unitarity in C2HDM

DC,Moretti,Yagyu,Yildirim 1602.06437

- The s-wave amplitudes $A(V_LV_L \to V_LV_L)$ grow with energy due to the modified hVV coupling and lead to perturbative unitarity violation

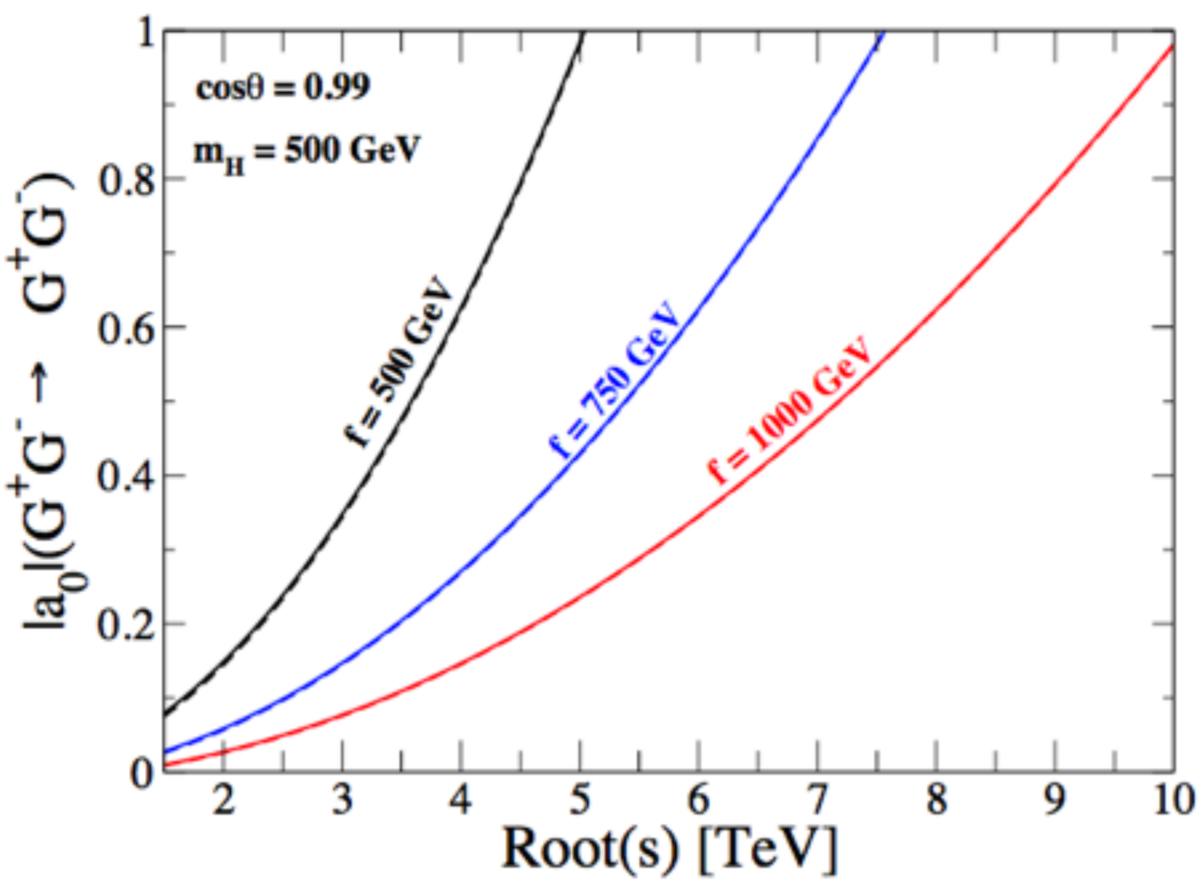
$$a_0(W_L^+W_L^- \to W_L^+W_L^-) = \frac{s}{32\pi v_{\rm SM}^2}\xi - \frac{1}{8\pi v_{\rm SM}^2}(m_h^2 c_\theta^2 + m_H^2 s_\theta^2)(1-\xi) + \mathcal{O}(g^2, s^{-1}).$$

- The study of unitarity bounds gives an indication of the scale at which effects of the strong sector become relevant

- Use of the Equivalence Theorem

$|a_0|<1/2$ gives a unitarity cut-off on energy

Ex: f=1TeV (ξ=0.06)
Λ~7TeV



Perturbative Unitarity in C2HDM

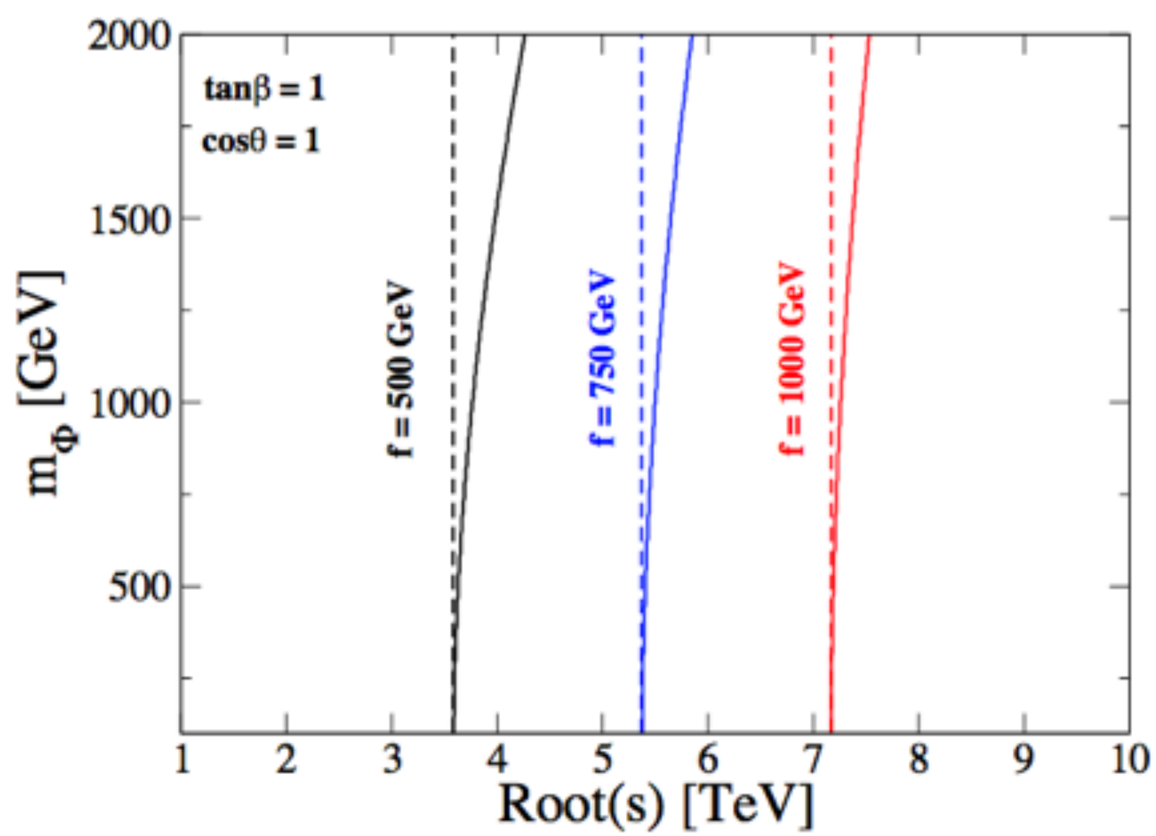
ϕ scattering angle

$$\mathcal{M}(H^+H^- \to H^+H^-) = \frac{s}{2v_{\rm SM}^2}\xi(1+c_\phi) - \frac{m_{H^\pm}^2}{v_{\rm SM}^2}\xi\left(\frac{2}{3}+4c_\phi\right) + \lambda_{H^+H^-H^+H^-} + \mathcal{O}(s^{-1})$$

from kinetic term
due to NGB nature

from kinetic term and potential

from potential



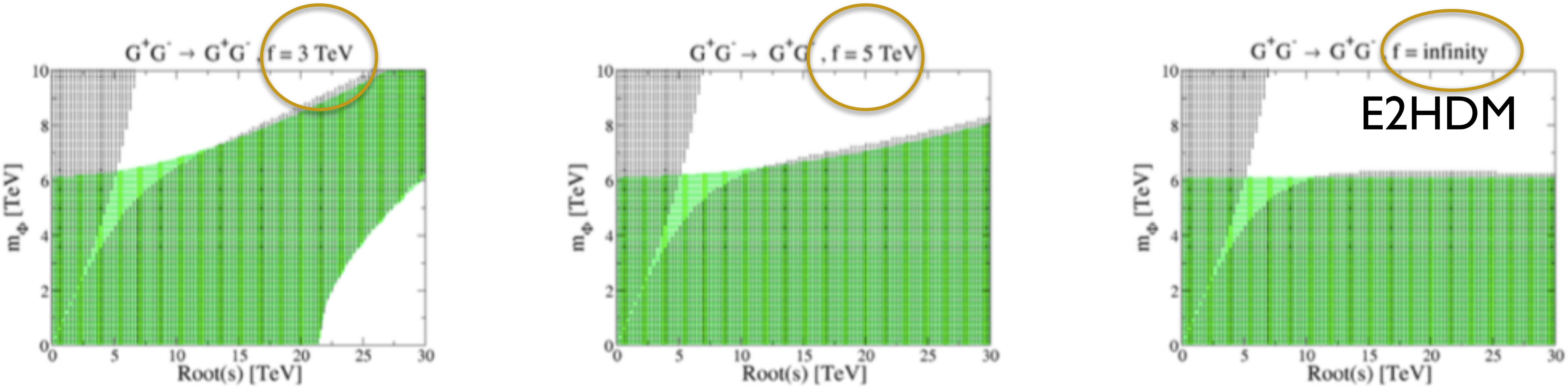
Unitarity bound from the requirement
$|a_0(H^+H^- \to H^+H^-)| < 1/2$
for $M = m_A = m_H = m_{H^+} = m_\Phi$

dashed lines neglecting $O(s^0\xi)$ terms

$O(s^0\xi)$ contributions are not so important as long as we consider $m_\Phi \lesssim 1$ TeV

Neglecting $O(s^0\xi)$ makes the calculation of all the 2→2 body scattering amplitudes simpler and it is safe in the parameter region relevant for the phenomenology at the LHC

Perturbative Unitarity in C2HDM from G+G-→G+G-



grey regions: exact formulae

green regions: neglecting O(1/s) terms

mH=mA=mH+=M=mΦ

cosΘ=0.99, tanβ=1

- The results are in good agreement for $\sqrt{s}>m_\Phi$
- The region $\sqrt{s}\simeq m_\Phi$ is excluded due to the resonant effects

Compare C2HDM (left, center) with E2HDM (right):

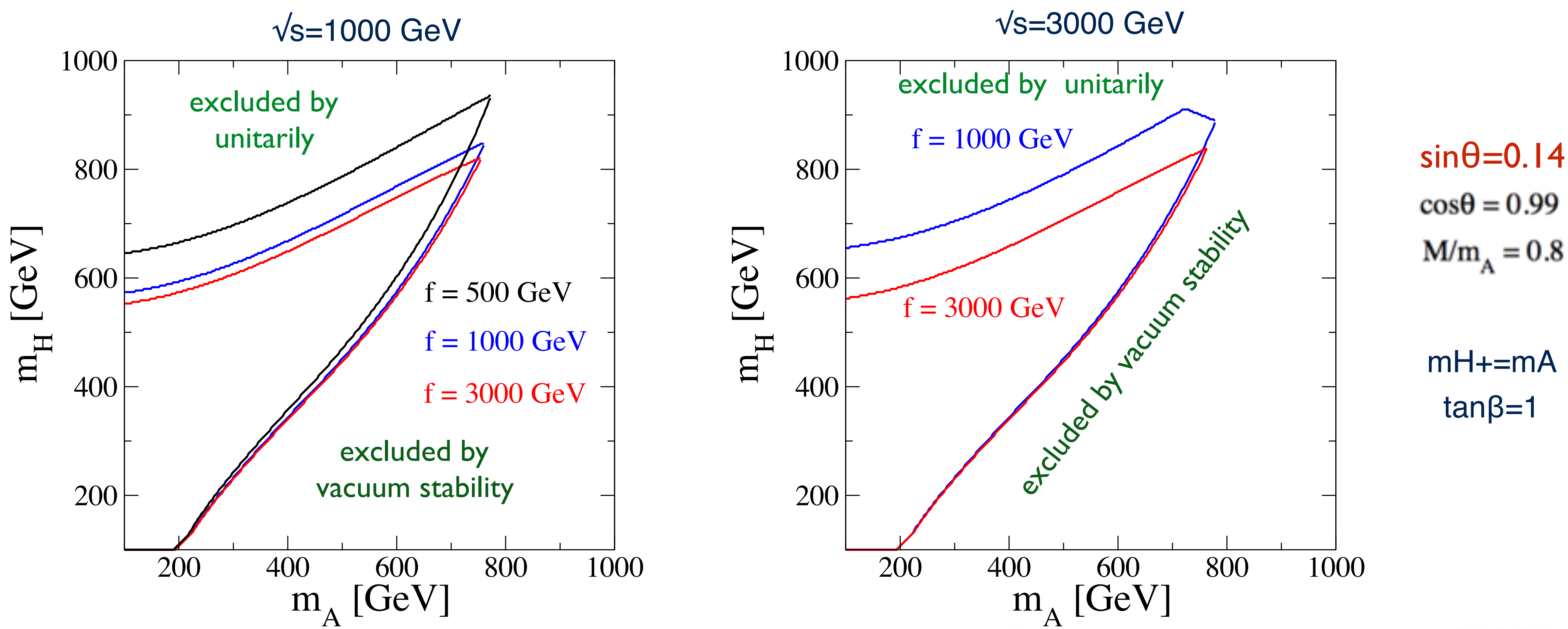
- Energy cut-off ~20TeV for f=3TeV in C2HDM
- Below the cut-off the bound on the mass is less stringent in the C2HDM due to a partial cancellation between the s term and the mH^2 one

Perturbative Unitarity in C2HDM

DC, Moretti, Yagyu, Yildirim 1602.06437

- ☑ We calculate all the 2→2 body elastic (pseudo)scalar scattering amplitudes in the C2HDM
There are 14 neutral, 8 singly charged and 3 double charged states
- ☑ We also impose the vacuum stability condition (scalar potential bounded from below in any direction)

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \sqrt{\lambda_1\lambda_2} + \lambda_3 + \mathrm{MIN}(0, \lambda_4 \pm \lambda_5) > 0$$



E2HDM corresponds to f →∞
(indistinguishable from f=3000GeV)

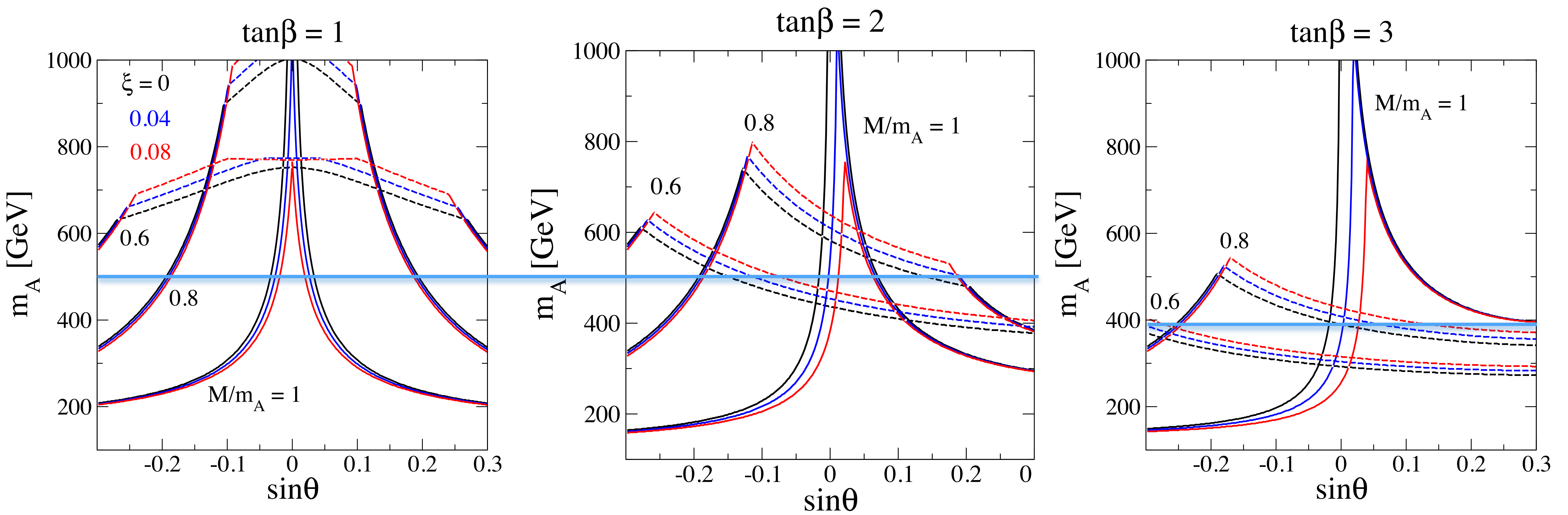
More parameter space becomes available to the C2HDM with respect to the E2HDM for smaller f values

Perturbative Unitarity and Vacuum Stability in C2HDM

outside the alignment limit $\sin\theta \to 0$

$m_{H+}=m_A=m_H$

$M/m_A=1, 0.8, 0.6$



below solid (dashed) lines : allowed by vacuum stability (unitarity)

C2HDM bounds are for $\sqrt{s}$=1000 GeV and f =1250(850)GeV corresponding to ξ=0.04(0.08)

E2HDM corresponds to f →∞(ξ=0)

for mϕ=500GeV, M=0.8mA, tanβ=1,2

-0.2<sinΘ<0.2 is allowed

larger tanβ values require lower mϕ

Effective Yukawa Lagrangian for C2HDM

DC, Moretti, Yagyu, Yildirim 1610.02087

- The kinetic term of the pNGB is uniquely determined by the structure of the global symmetry breaking SO(6)/SO(4)xSO(2)

- For the Yukawa sector we need to assume the embedding for SM fermions into SO(6) multiplets. It is justified by the partial compositeness assumption where the SM fermions mix with the composite ones in a SU(2)xU(1) invariant form. The low-energy Lagrangian is obtained after integrating out the composite fermions

- We use here the **6**-plet reprs of SO(6) for SM quarks and leptons

$$
\begin{aligned}
(\Psi_{2/3})_L \equiv Q_L^u &= (-id_L, -d_L, -iu_L, u_L, 0, 0)^T, \\
(\Psi_{-1/3})_L \equiv Q_L^d &= (-iu_L, u_L, id_L, d_L, 0, 0)^T, \\
(\Psi_{2/3})_R \equiv U_R &= (0, 0, 0, 0, 0, u_R)^T, \\
(\Psi_{-1/3})_R \equiv D_R &= (0, 0, 0, 0, 0, d_R)^T, \\
(\Psi_{-1})_L \equiv L_L &= (-i\nu_L, \nu_L, ie_L, e_L, 0, 0)^T, \\
(\Psi_{-1})_R \equiv E_R &= (0, 0, 0, 0, 0, e_R)^T.
\end{aligned}
$$

$$Q = T_3^L + T_3^R + X$$

- In order to reproduce the correct electric charge we have added an additional $U(1)_X$ symmetry.

Effective Yukawa Lagrangian for C2HDM

- The Yukawa Lagrangian is given in terms of Σ, the 15-plet of pNGB, SO(6) adjoint, the 6-plet of fermions

$$\mathcal{L}_Y = f\left[\bar{Q}_L^u(a_u\Sigma - b_u\Sigma^2)U_R + \bar{Q}_L^d(a_d\Sigma - b_d\Sigma^2)D_R + \bar{L}_L(a_e\Sigma - b_e\Sigma^2)E_R\right] + \text{h.c.}$$

$$\Sigma = U\Sigma_0 U^T$$

U=pNGB matrix

$$\Sigma_0 = \begin{pmatrix} 0_{4\times4} & 0_{4\times2} \\ 0_{2\times4} & i\sigma_2 \end{pmatrix}$$

transforms linearly under SO(6)

$$\Sigma \to g\Sigma g^T$$

a_f and b_f are 3x3 complex matrices in the flavor space

- Masses of fermions (at the first order in ξ) → $m_f = v_{\rm SM}\left[a_f c_\beta + b_f s_\beta\left(1-\frac{\xi}{2}\right)\right]$

- In general FCNCs appear at tree level due to the existence of two independent Yukawa couplings a_f and b_f (both doublets couple to each fermion type).

  To avoid it, impose a C_2 discrete symmetry (J.Mrazek et al. 1105.5403)

$$U(\pi_1^{\hat{a}}, \pi_2^{\hat{a}}) \to C_2 U(\pi_1^{\hat{a}}, \pi_2^{\hat{a}}) C_2 = U(\pi_1^{\hat{a}}, -\pi_2^{\hat{a}})$$

$$C_2 = \text{diag}(1,1,1,1,1,-1)$$

$\pi_1^{\hat{a}}$ C_2-even

$\pi_2^{\hat{a}}$ C_2-odd

$$(\pi_1^{\hat{a}}, \pi_2^{\hat{a}}) \to (\pi_1^{\hat{a}}, -\pi_2^{\hat{a}})$$

- Depending on the C_2 charge of the right-handed fermions, we define 4-independent Types of Yukawa interactions, like the Z_2 symm. in E2HDM

Effective Yukawa Lagrangian for C2HDM

$$\mathcal{L}_Y = \sum_{f=u,d,e} \frac{m_f}{v_{\rm SM}} \bar{f}\left(\bar{X}_f^h h + \bar{X}_f^H H - 2iI_f \bar{X}_f^A \gamma_5 A\right) f$$
$$+ \frac{\sqrt{2}}{v_{\rm SM}} \bar{u} V_{ud} (m_d \bar{X}_d^A P_R - m_u \bar{X}_u^A P_L) d\, H^+ + \frac{\sqrt{2}}{v_{\rm SM}} \bar{\nu} m_e \bar{X}_e P_R\, e\, H^+ + \text{h.c.}$$

$\bar{X}_f^\phi$ are diagonal in the mass eigenbasis of fermions

	U_R	D_R	E_R	(a_u, b_u)	(a_d, b_d)	(a_e, b_e)	$\bar{X}_u^h$	$\bar{X}_d^h$	$\bar{X}_e^h$	$\bar{X}_u^H$	$\bar{X}_d^H$	$\bar{X}_e^H$	$\bar{X}_u^A$	$\bar{X}_d^A$	$\bar{X}_e^A$
Type-I	$-$	$-$	$-$	$(0,\surd)$	$(0,\surd)$	$(0,\surd)$	ζ_h	ζ_h	ζ_h	ζ_H	ζ_H	ζ_H	ζ_A	ζ_A	ζ_A
Type-II	$-$	$+$	$+$	$(0,\surd)$	$(\surd,0)$	$(\surd,0)$	ζ_h	ξ_h	ξ_h	ζ_H	ξ_H	ξ_H	ζ_A	ξ_A	ξ_A
Type-X	$-$	$-$	$+$	$(0,\surd)$	$(0,\surd)$	$(\surd,0)$	ζ_h	ζ_h	ξ_h	ζ_H	ζ_H	ξ_H	ζ_A	ζ_A	ξ_A
Type-Y	$-$	$+$	$-$	$(0,\surd)$	$(\surd,0)$	$(0,\surd)$	ζ_h	ξ_h	ζ_h	ζ_H	ξ_H	ζ_H	ζ_A	ξ_A	ζ_A

$$\zeta_h = \left(1 - \frac{3}{2}\xi\right) c_\theta + s_\theta \cot\beta, \quad \xi_h = \left(1 - \frac{\xi}{2}\right) c_\theta - s_\theta \tan\beta,$$
$$\zeta_H = -\left(1 - \frac{3}{2}\xi\right) s_\theta + c_\theta \cot\beta, \quad \xi_H = -\left(1 - \frac{\xi}{2}\right) s_\theta - c_\theta \tan\beta,$$
$$\zeta_A = \left(1 + \frac{\xi}{2}\right) \cot\beta, \quad \xi_A = -\left(1 - \frac{\xi}{2}\right) \tan\beta.$$

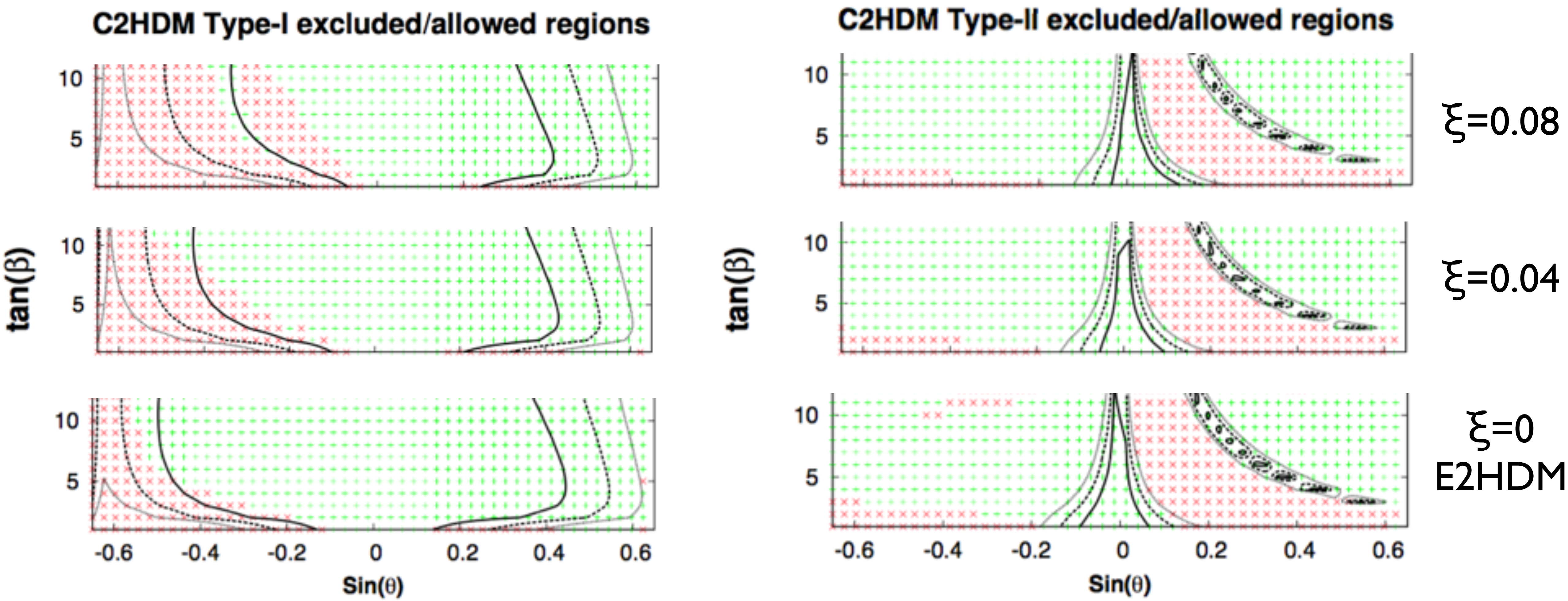
Ex. in all Types:

$$\kappa_t = g_{htt}/g_{htt}^{\rm SM} = \bar{X}_u^h = \zeta_h$$

corrections O(ξ) are predominately negative

Present collider bounds for the C2HDM Type-I and Type-II

$m_A = m_{H^+} = m_H = M = 500\,\text{GeV}$ $m_h = 125\,\text{GeV}$



green/red regions are 95%CL allowed/excluded from LEP, Tevatron, LHC data by using HiggsBounds package

—— 68%CL
- - - - - 95%CL
· · · · · · 99%CL

$\Delta\chi^2$-contours by HiggsSignal package

Type-I reveals a better compliance with the LHC data

Type-II disfavoured for $|\sin\theta|>0.2$ and $\tan\beta>10$

Type-X and Type-Y very similar to Type-II

ξ dependence is only marginally evident for Type-I

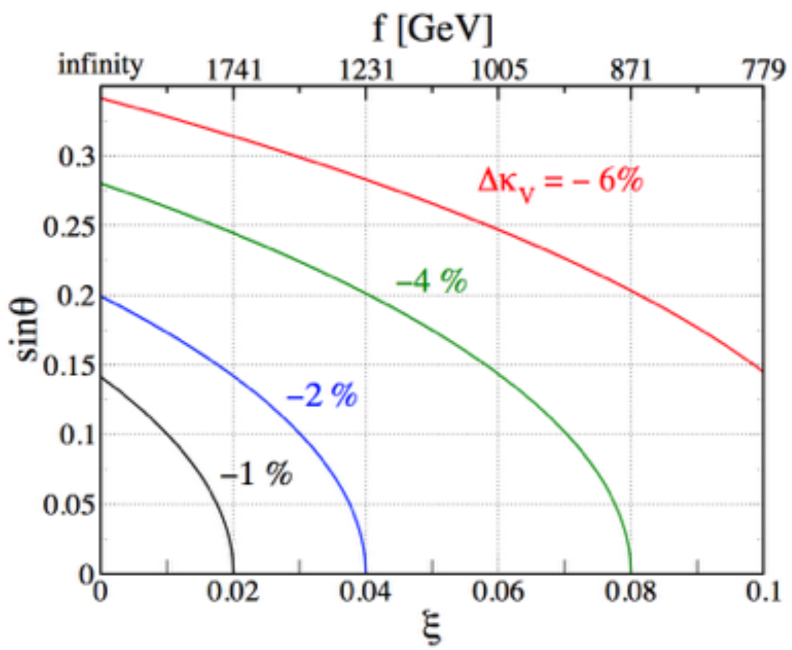
Choose: $\xi \lesssim 0.08$ $|\sin\theta| \lesssim 0.2$ and small $\tan\beta$ also compliant with unitarity and stability bounds with $m_\Phi = 500\,\text{GeV}$

Deviations in Higgs boson couplings

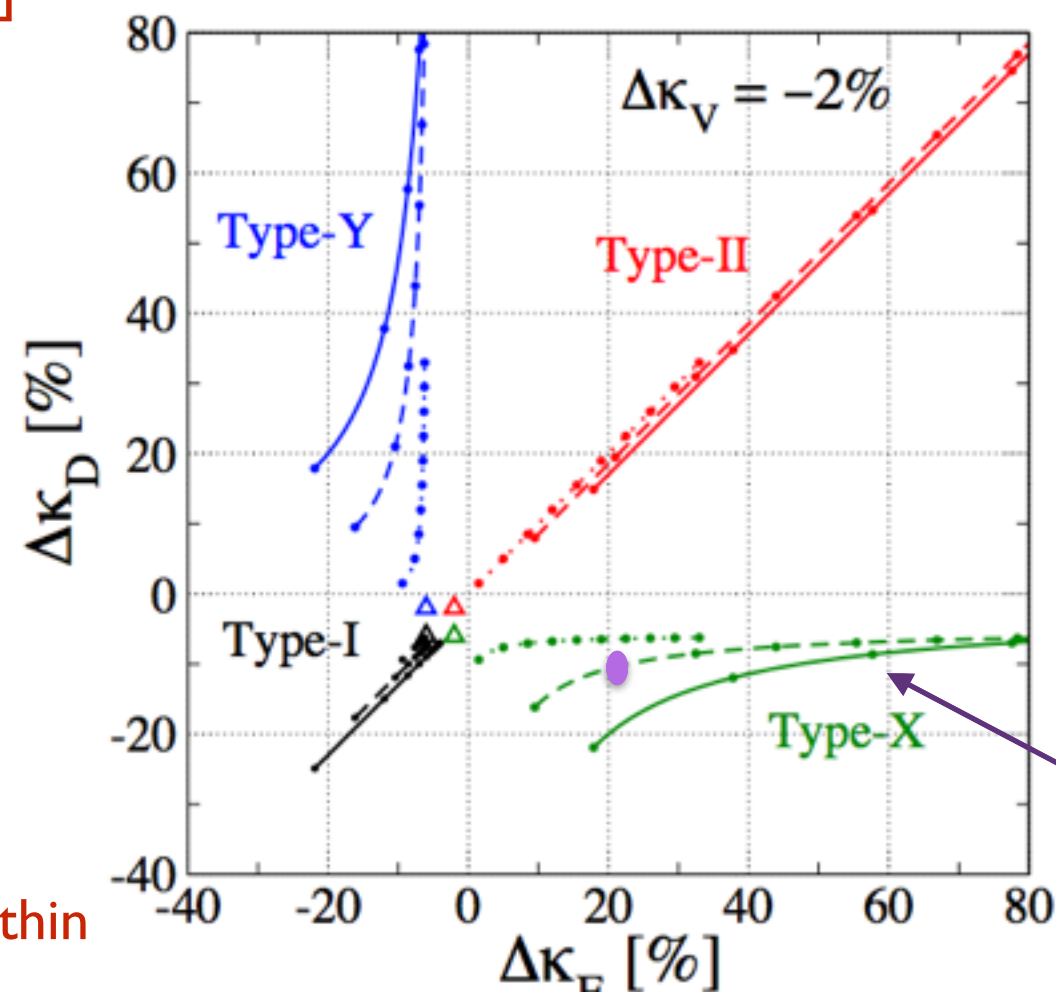
$$\Delta\kappa_X = g_{hXX}/g_{hXX}^{\rm SM} - 1$$

DC, Moretti, Yagyu, Yildirim 1610.02087

Suppose a deviation Δk_V is measured at the LHC, it is an indirect evidence for a non-minimal Higgs sector



$|\Delta k_V| > 2\%$ difficult to be explained within E2HDM because of the theor. and exp. bounds on $\sin\Theta$, but possible in C2HDM



E=charged lepton
D=down-type quark

ξ=0
ξ=0.03
ξ=0.04

Dots on the lines refer to tanβ =1 to 10 with steps of 1 away from (0,0)

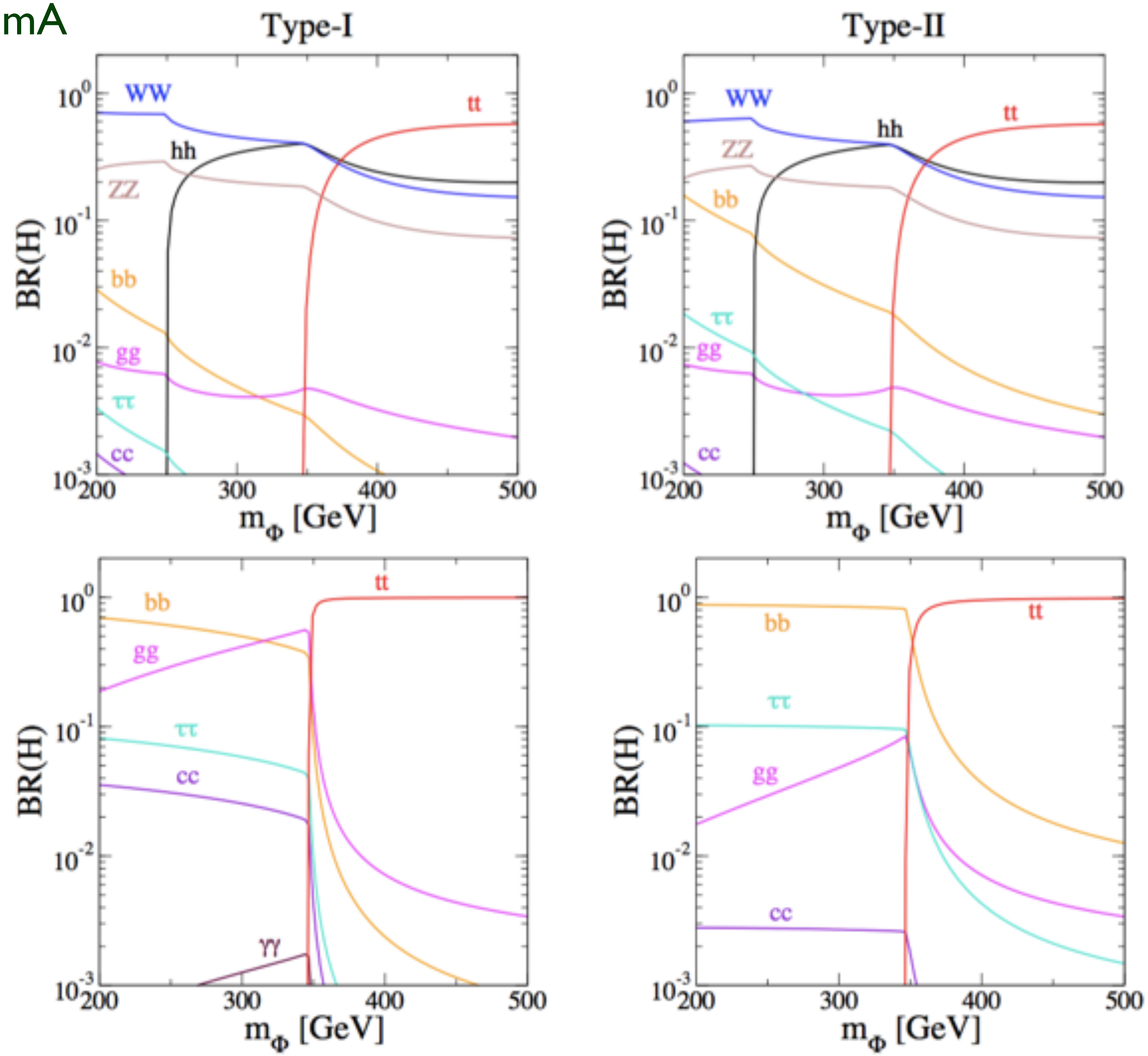
If $|\Delta k_V| \lesssim 2\%$ by looking at the pattern of the deviations in Δk_E and Δk_D we can discriminate between E2HDM and C2HDM and among the four Types of Yukawa interactions

Ex: if Δk_V=-2%, Δk_D=-10%, Δk_E=20% then → Type-X C2HDM with tanβ =2 and ξ=0.03

Decays of the extra-Higgs boson H

mϕ=mH=mH+=mA
M=0.8mA,
tanβ=2

Δk_V = -2%



E2HDM
(sinΘ=-0.2, ξ=0)

C2HDM
(sinΘ=0, ξ=0.04)

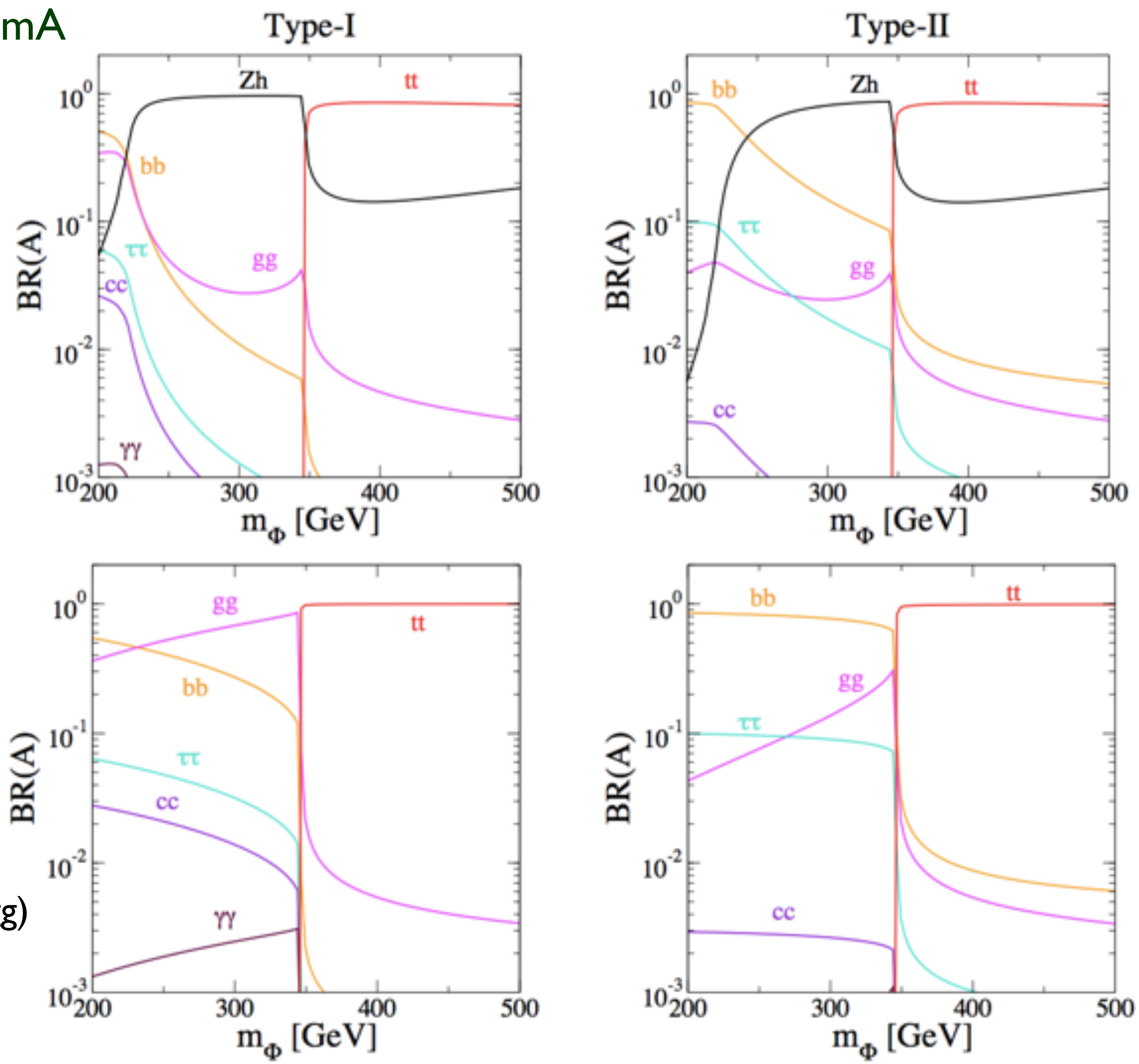
Below the tt threshold, H→hh, WW, ZZ are the dominant channels in E2CHM while they are absent in the C2HDM with sinΘ=0 (in all the 4 Yukawa Types)

Decays of the extra-Higgs boson A

mϕ=mH=mH+=mA
M=0.8mA,
tanβ=2

Δk_V = -2%

the three body decay
A→Z*h→ffh is
taken into account
for mA<mZ+mh



E2HDM
(sinΘ=-0.2, ξ=0)

C2HDM
(sinΘ=0, ξ=0.04)

Similar to H with
BR(A→gg)>BR(H→ gg)

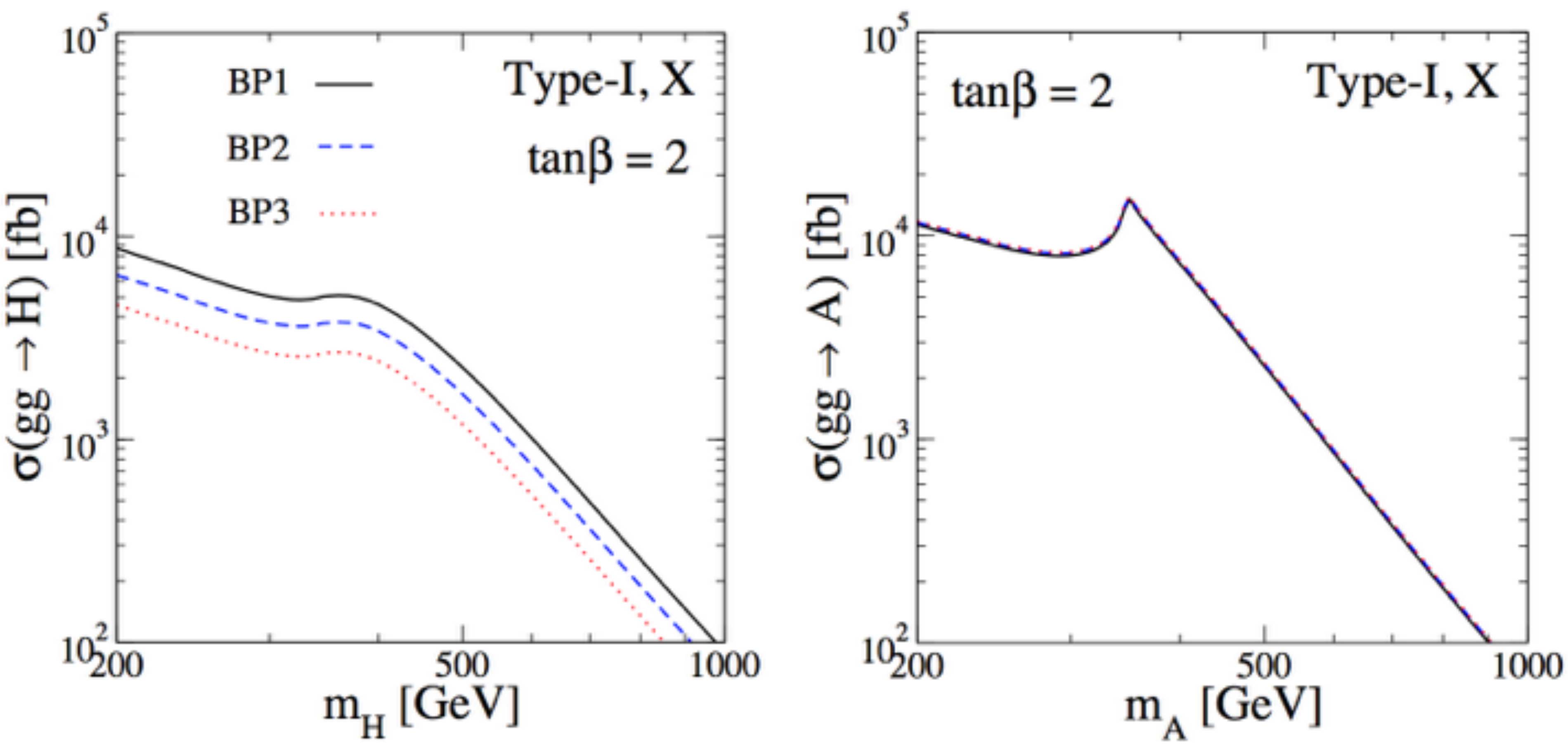
Below the tt threshold, A→Zh can be the dominant channels in E2HDM while it is absent in the C2HDM with sinΘ=0 (in all the 4 Yukawa Types)

Productions of the extra-Higgs bosons at the LHC
σ (gg→H/A)

$$\sigma(gg \to \phi^0) = \frac{\Gamma(\phi^0 \to gg)}{\Gamma(h_{\rm SM} \to gg)} \times \sigma(gg \to h_{\rm SM}), \quad (\phi^0 = H \text{ or } A)$$

with the mass of h_{SM} artificially set at $m_{\phi 0}$

E2HDM: BP1(sinΘ=-0.2, ξ=0) C2HDM: BP2(sinΘ=-0.1, ξ=0.03), BP3(sinΘ=0, ξ=0.04)



Similar for Type-II,Y differences for large tanβ ~ 10

√s=13 TeV

Sizeable differences between E2HDM and C2HDM in gluon fusion H production

For the A production the differences are marginal

mainly due to the sinΘ dependence in the top Yukawa couplings →

$$\zeta_H = -\left(1 - \frac{3}{2}\xi\right) s_\theta + c_\theta \cot\beta \qquad \zeta_A = \left(1 + \frac{\xi}{2}\right)\cot\beta;$$

☑ SCENARIO 1: A deviation in the hVV and/or hff couplings is established during the Run2 of the LHC, then an investigation of the 2HDM is called for

- ✓ If $|\Delta k_V|$ >2% then E2HDM unlikely could explain it because of the theor. and exp. bounds on sinΘ, but it could be possible within the C2HDM
- ✓ If $|\Delta k_V| \lesssim 2\%$ a dedicated scrutiny of the decay patterns of all potentially accessible heavy Higgs states could enable to separate the E2HDM from the C2HDM through the combination of the differences in the BRs and production cross sections

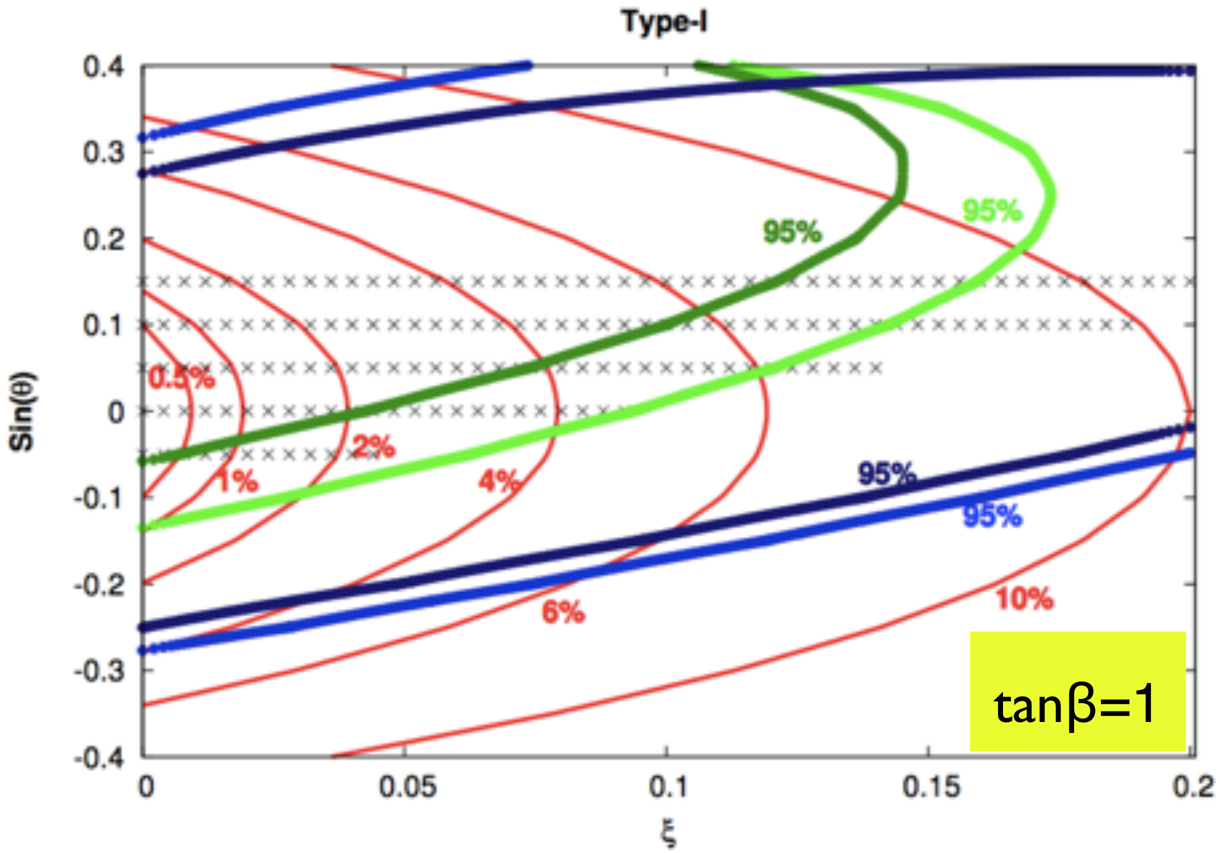
☑ SCENARIO 2: ☹ No additional Higgs states will have been discovered at the LHC, neither after 3000 fb^{-1}, nor deviations in the Higgs couplings

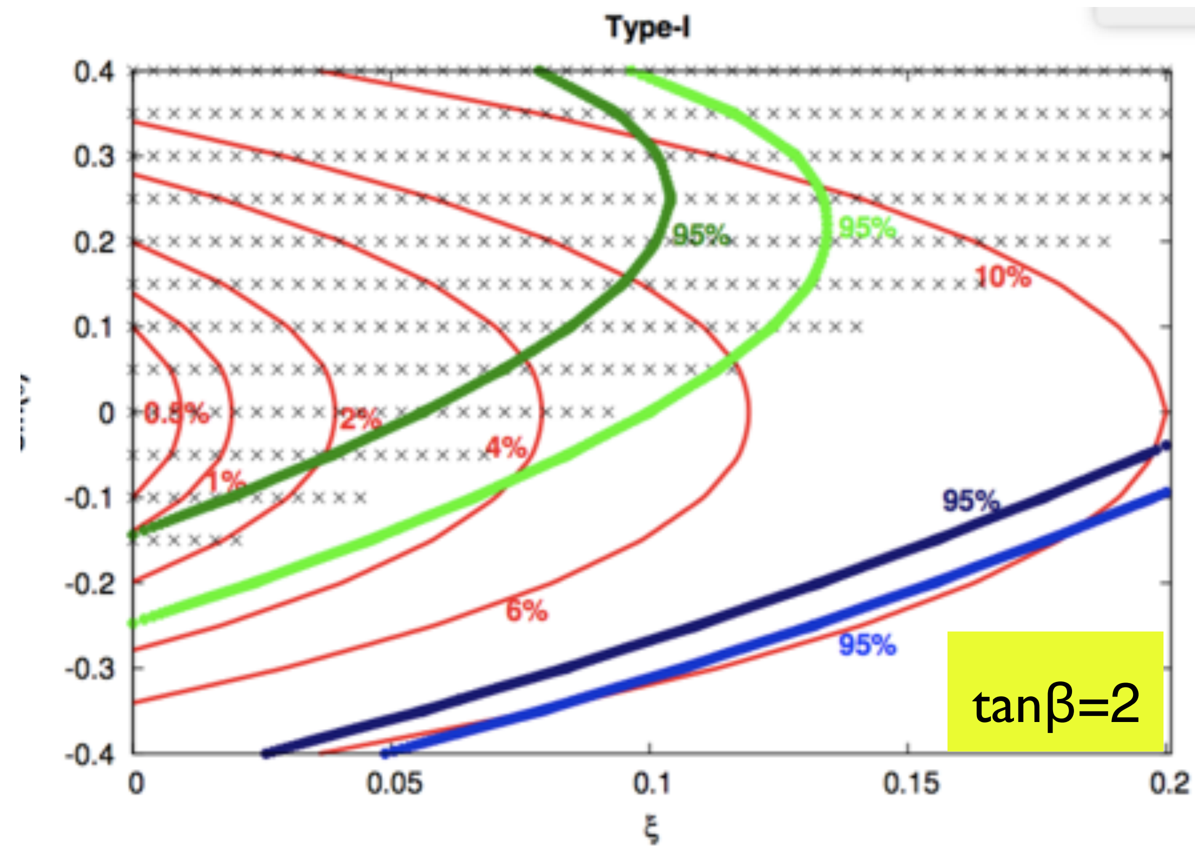
- ✓ e+e- colliders will have a great task. The Higgs boson h discovered at the LHC will be produced in single-mode (via Higgs-strahlung ee→Zh, Vector Boson Fusion ee →eeh and associated production via top quarks ee→tth) and double-mode (via ee→Zhh, ee→eehh, ee→tthh)
- ✓ Because of the small background, the Higgs boson couplings will be measured with an extremely good accuracy ~ 0.5%(2.5%) for hZZ(htt) at ILC(500,500)

Future e+e$^-$ machines will have the potential to discriminate between the E2HDM and C2HDM by studying the SM-h cross-sections

Present and future LHC bounds for the C2HDM Type-I

m_A=mH+=mH=500GeV   M=0.8m_A mh=125GeV





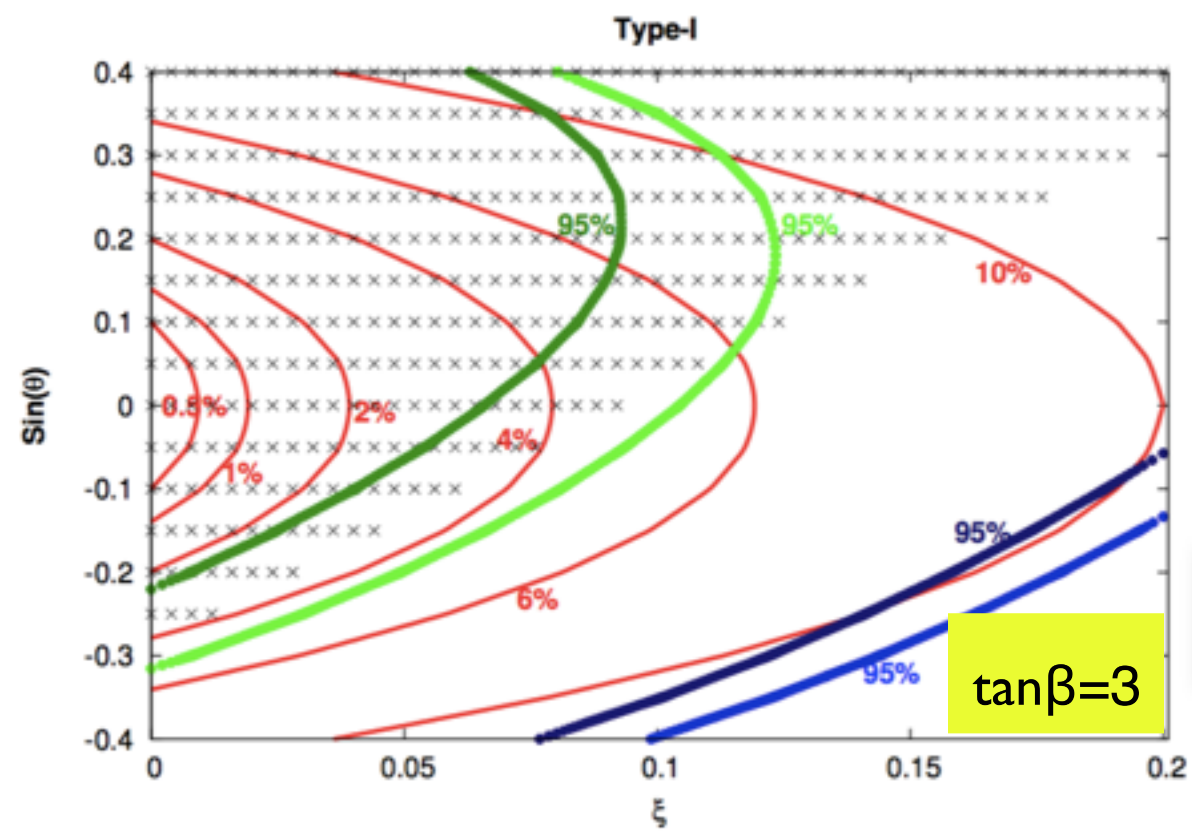
×××= regions 95%CL allowed by current collider data (HiggsBounds tool)

compatibility with the observed Higgs signals (SM) extrapolated at

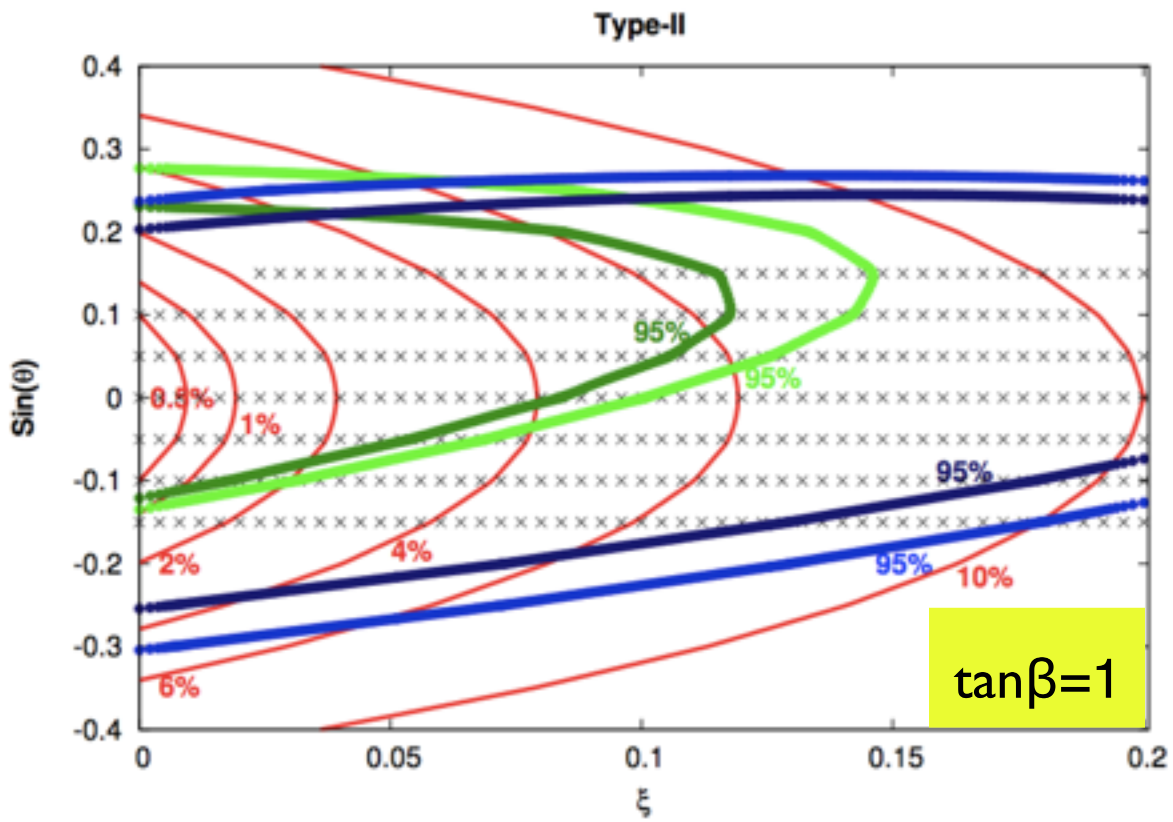
300fb^{-1} 3000fb^{-1}

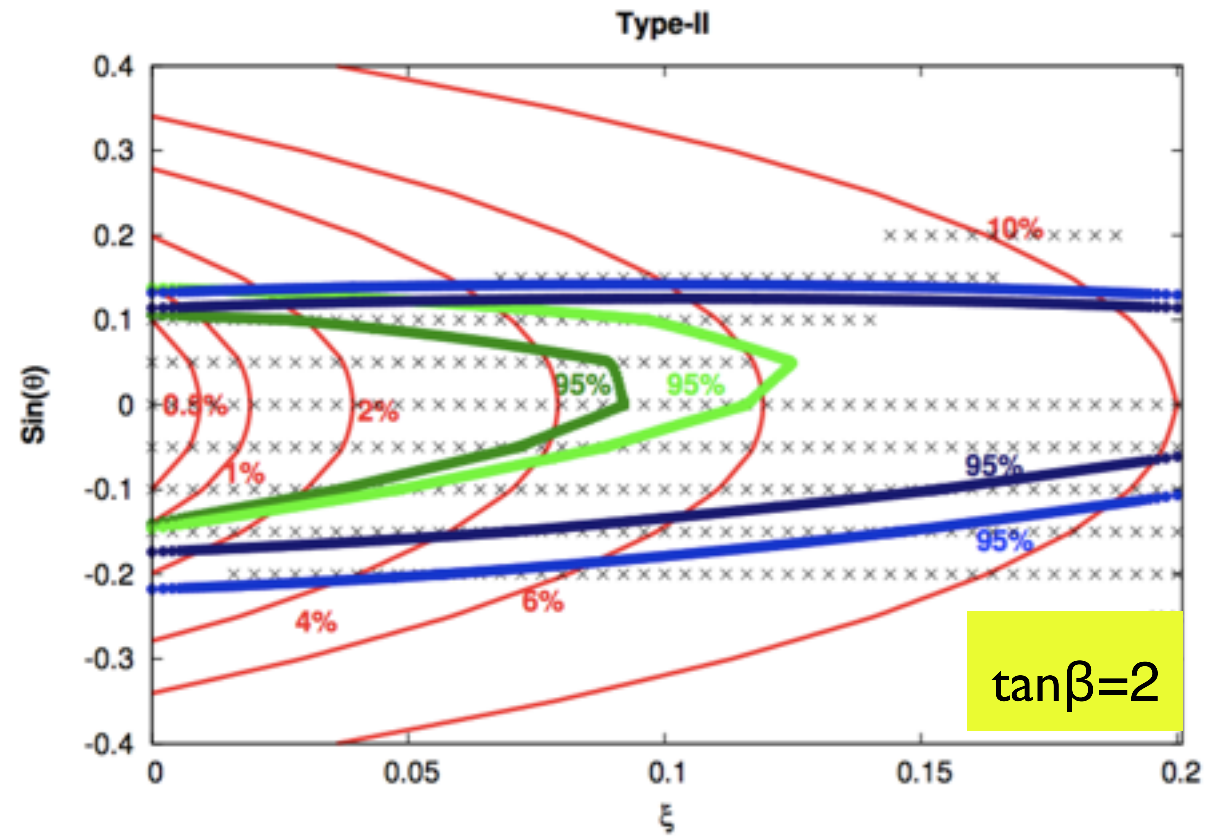
contours of

$$|\Delta k_V| = |g_{hVV}^{\rm C2HDM}/g_{hVV}^{\rm SM} - 1|$$



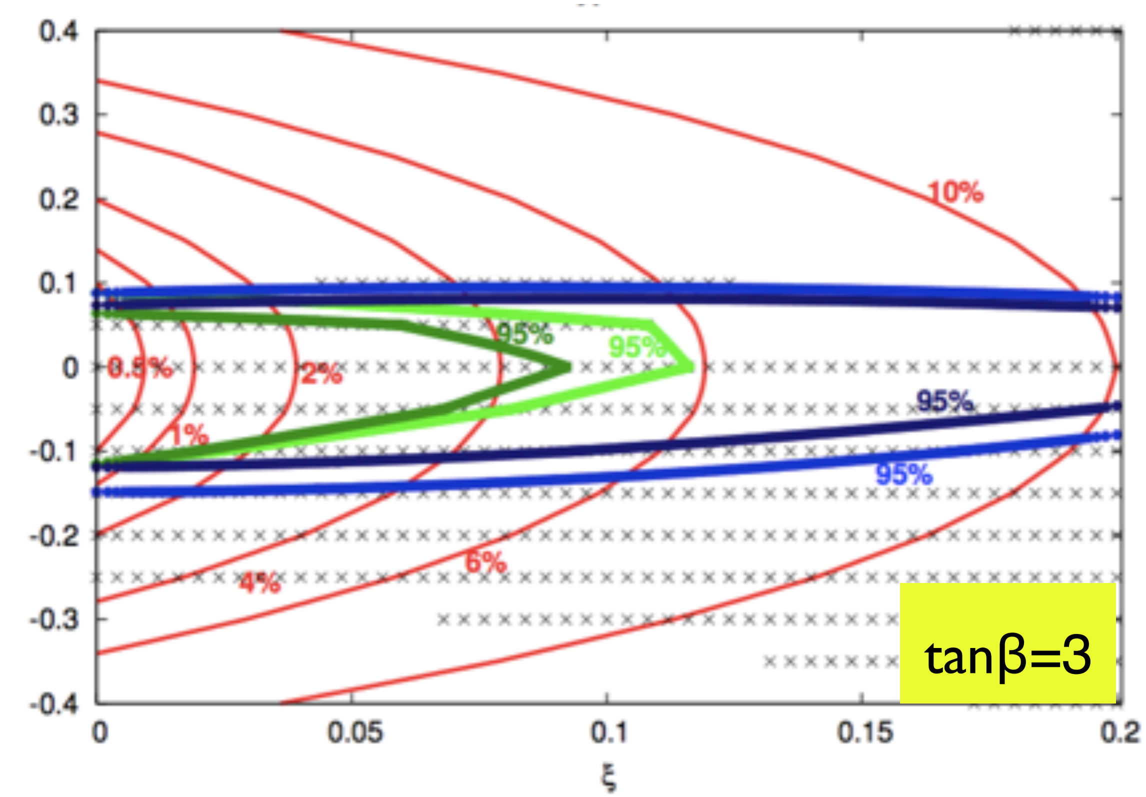
Same analysis for the C2HDM Type-II



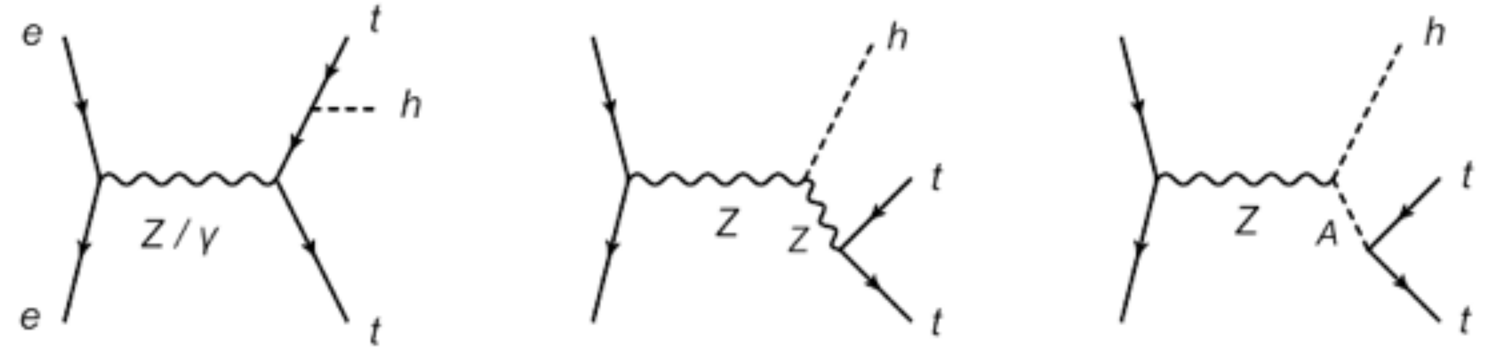


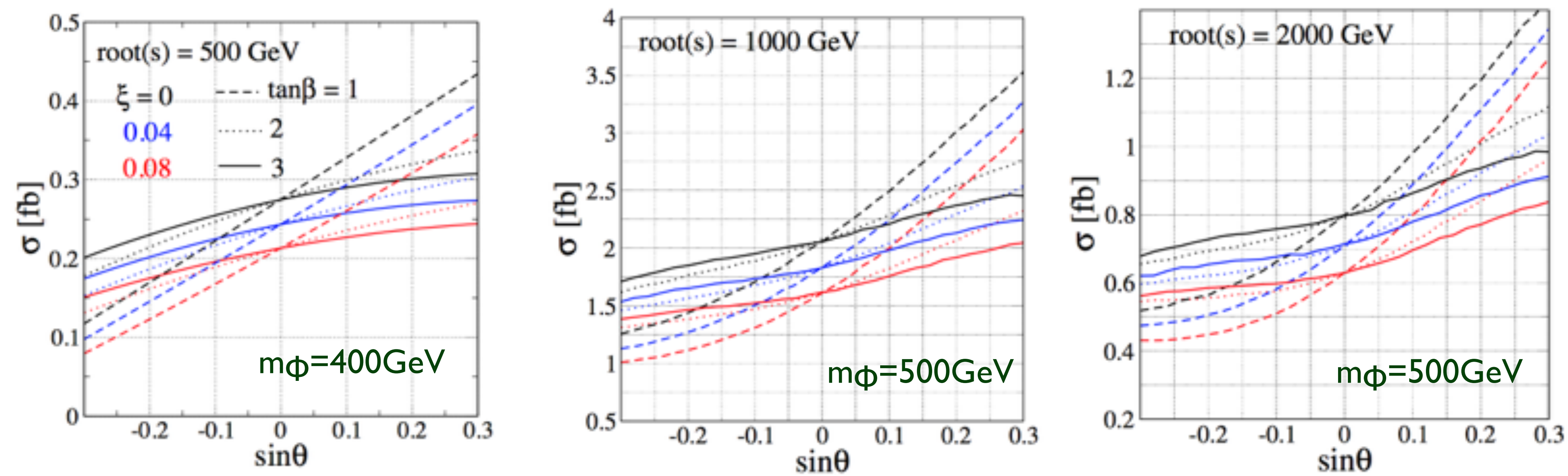
Assumption: no new Higgs boson detected and the properties of SM-like one are greatly constrained

After HL-LHC there remains scope to distinguish C2HDM from E2HDM (ξ=0) at future e+e- colliders



Associated Higgs Boson production with top quarks
e+e-→tth





At $\sqrt{s}$=1,2TeV the on-shell production of A is realised and the cross section get enhanced. The ξ dependence acts like an overall rescaling with negative deviations >20% for ξ=0.08

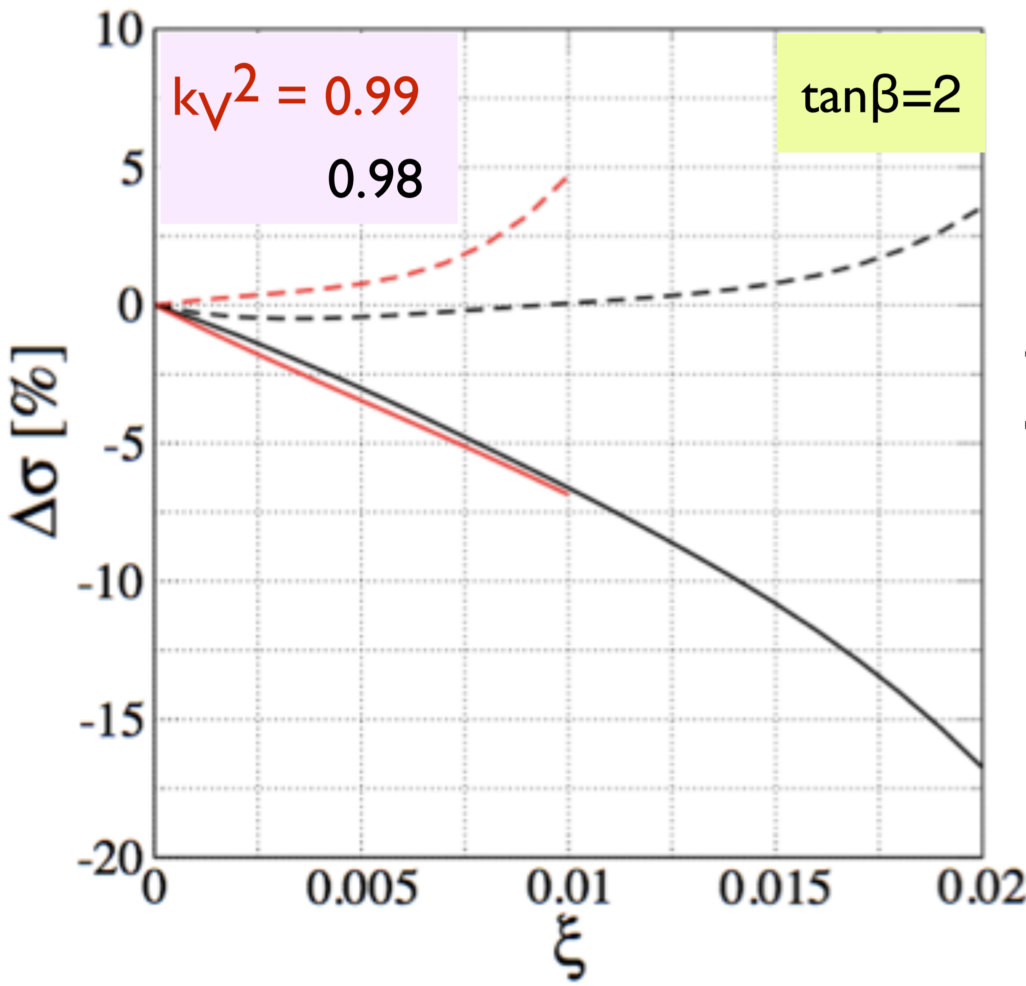
The C2HDM predicts cross sections for e+e-→tth that cannot be realised in the E2HDM

Differences in e+e-→tth cross-section for fixed k_V^2= 0.99, 0.98

$\sqrt{s}$=1000GeV, mA=mH+=mH=500GeV M=0.8 m_A mh=125GeV

$$\Delta\sigma = (\sigma_{\mathrm{C2HDM}}/\sigma_{\mathrm{E2HDM}} - 1)$$

$$k_V = g_{hVV}/g_{hVV}^{\mathrm{SM}}$$



Δk_V=-0.5%

Δk_V= -1%

-------- sinΘ<0

——— sinΘ>0

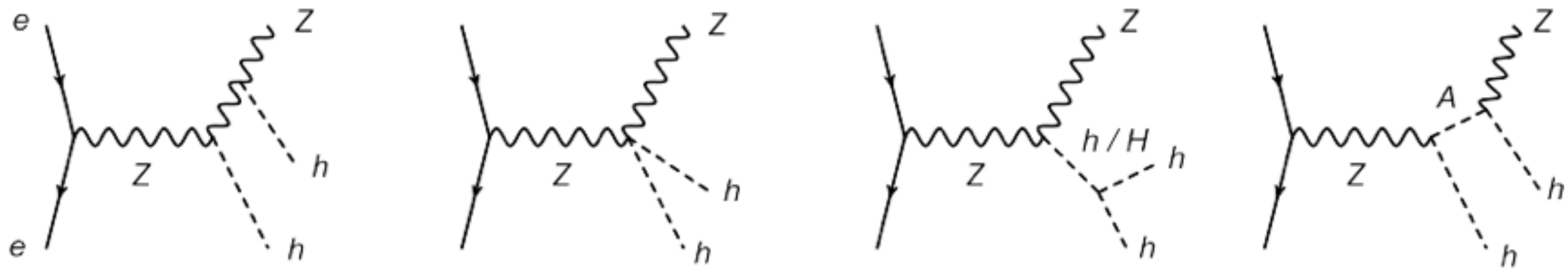
the sign of sinΘ not determined by measuring k_V

the lines correspond to values of Type-I C2HDM parameters allowed by unitarity and stability bounds and after 3000 fb-1 at the LHC

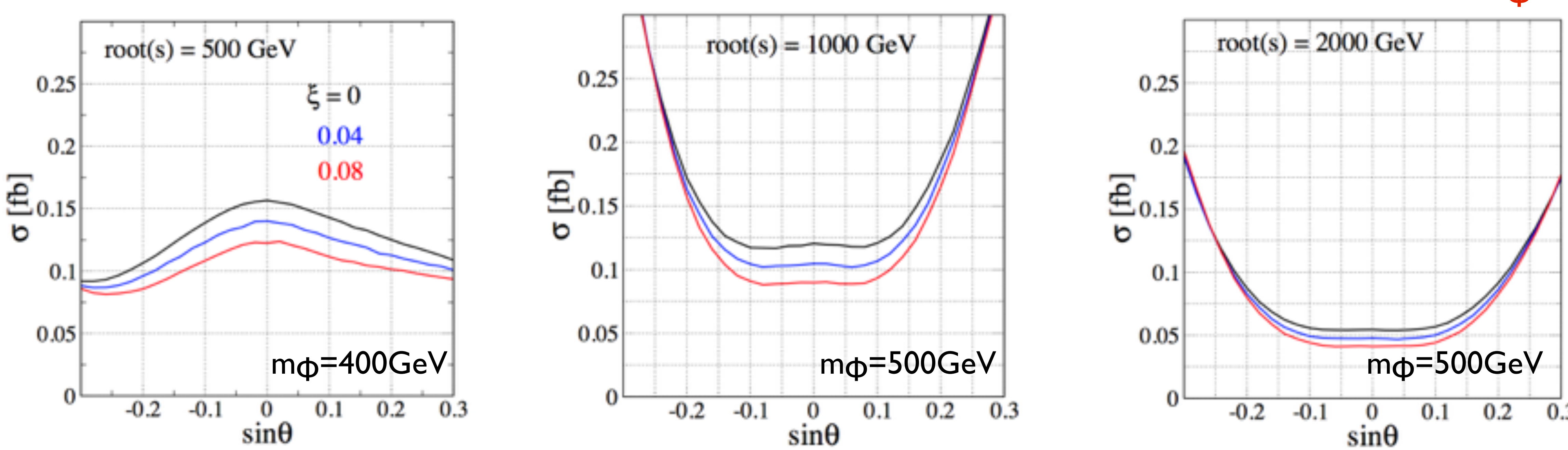
Even with very small deviations in k_V precisely determined via HS and VBF, the differences between E2HDM and C2HDM in e+e-→ tth cross section can be ~15%

Double Higgs Boson production: e+e-→Zhh

sensitive to triple-Higgs couplings and to the extra Higgs boson exchanges



M=0.8mϕ tanβ=2

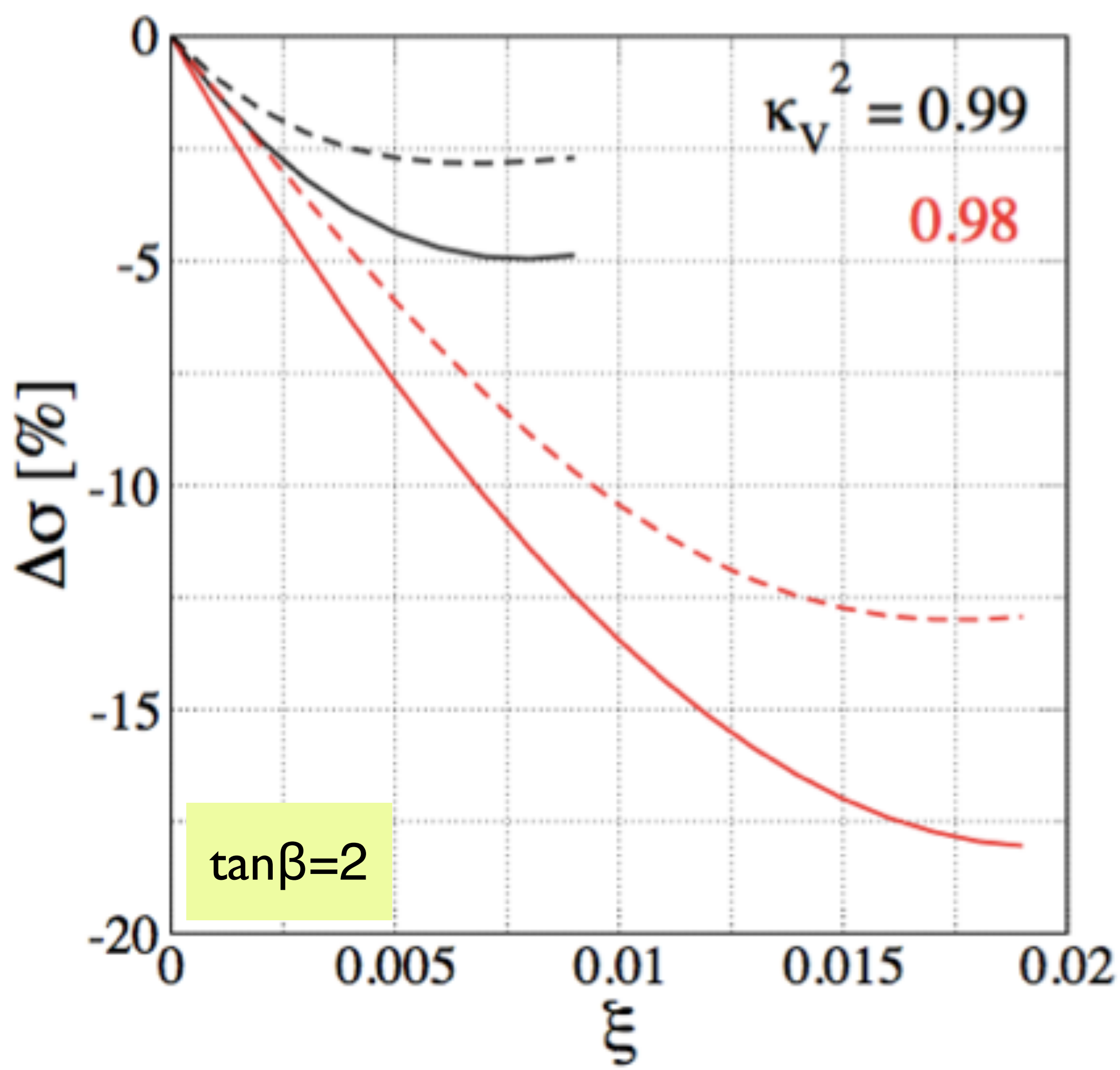


At $\sqrt{s}$=1,2TeV the on-shell production of H,A is realised, followed by H→hh and A→Zh respectively, both proportional to sinΘ

The ξ dependence remains comparable at all energies being in the 20-30% range

Differences in cross section for e+e-→Zhh

$\sqrt{s}$=1000GeV mA=mH+=mH=500GeV M=0.8 mA mh=125GeV



$$\Delta\sigma = (\sigma_{\rm C2HDM}/\sigma_{\rm E2HDM} - 1)$$

$$k_V = g_{hVV}/g_{hVV}^{\rm SM}$$

sinΘ>0 ———— Δk_V=-0.5%

sinΘ<0 - - - - - Δk_V= -1%

the lines correspond to values of Type-I C2HDM parameters allowed by unitarity and stability bounds and after 3000 fb^{-1} at the LHC

Large negative differences between C2HDM and E2HDM are predicted also for ≲1% deviations in the hVV coupling

Summary and Conclusions

☑ C2HDM amplitudes grow with $\sqrt{s}$ in bosonic scattering processes. Perturbative unitarity is broken at a certain energy scale depending on the compositeness scale f. However for LHC (e+e-) energies and m$\Phi \lesssim$500GeV, UV completion is not necessary for Higgs studies

☑ In presence of a deviation in hVV couplings from SM prediction, E2HDM would require non-zero mixing case, while C2HDM could achieve this with zero mixing case

☑ If deviations are measured at collider experiments, we have indirect evidence for a non-mimiml Higgs sector possible belonging to a E2HDM or C2HDM

☑ Differences in the decay BR's and production cross sections for the extra Higgs bosons could enable us to distinguish a C2HDM from E2HDM at both hadron and lepton colliders

BACKUP SLIDES

Strong sector: resonances + Higgs bound state

Extra particle content:
- Spin 1 resonances
- Spin 1/2 resonances

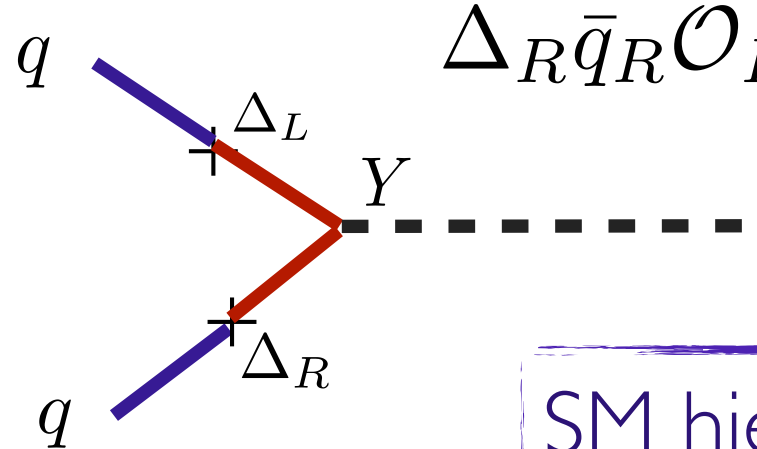
Spectrum:

$m_\rho = g_\rho f$ } f

$m_h = 125\,\mathrm{GeV}$
$m_W = 80\,\mathrm{GeV}$
0 } v

$g_\rho =$ strong coupling

Linear elementary-composite couplings (partial compositeness)



$$\Delta_R \bar{q}_R \mathcal{O}_L + \Delta_L \bar{q}_L \mathcal{O}_R + Y \bar{\mathcal{O}}_L H \mathcal{O}_R$$

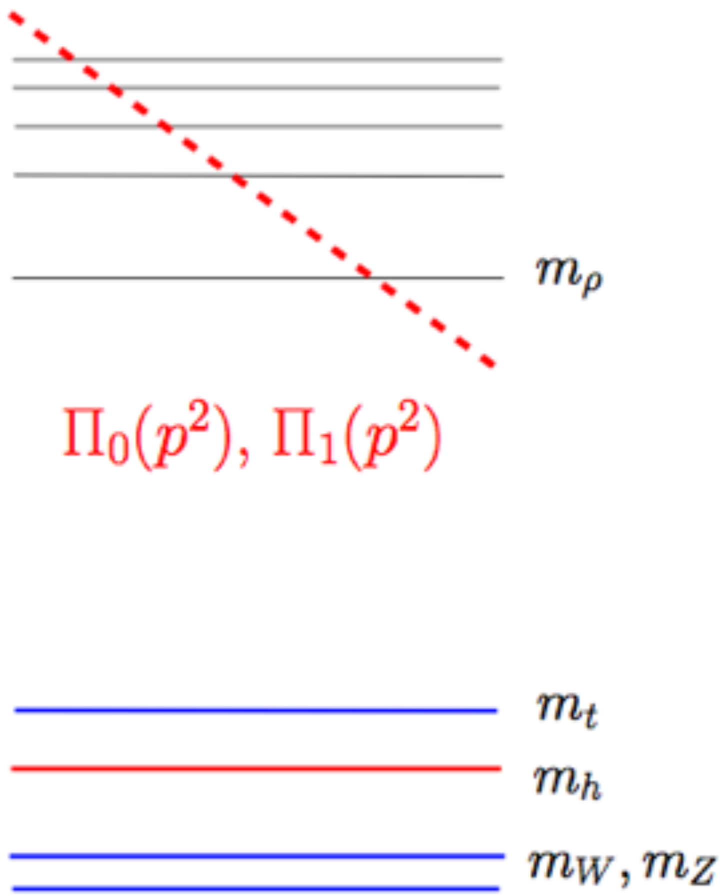
$$y_{SM} = \epsilon_L \cdot Y \cdot \epsilon_R \qquad \epsilon = \frac{\Delta}{m_Q}$$

SM hierarchies are generated by the mixings:
light quarks elementary, top strongly composite

$$m_t \sim \frac{v}{\sqrt{2}} \frac{\Delta_{t_L}}{m_\psi} \frac{\Delta_{t_R}}{m_\chi} \frac{Y_T}{f}$$

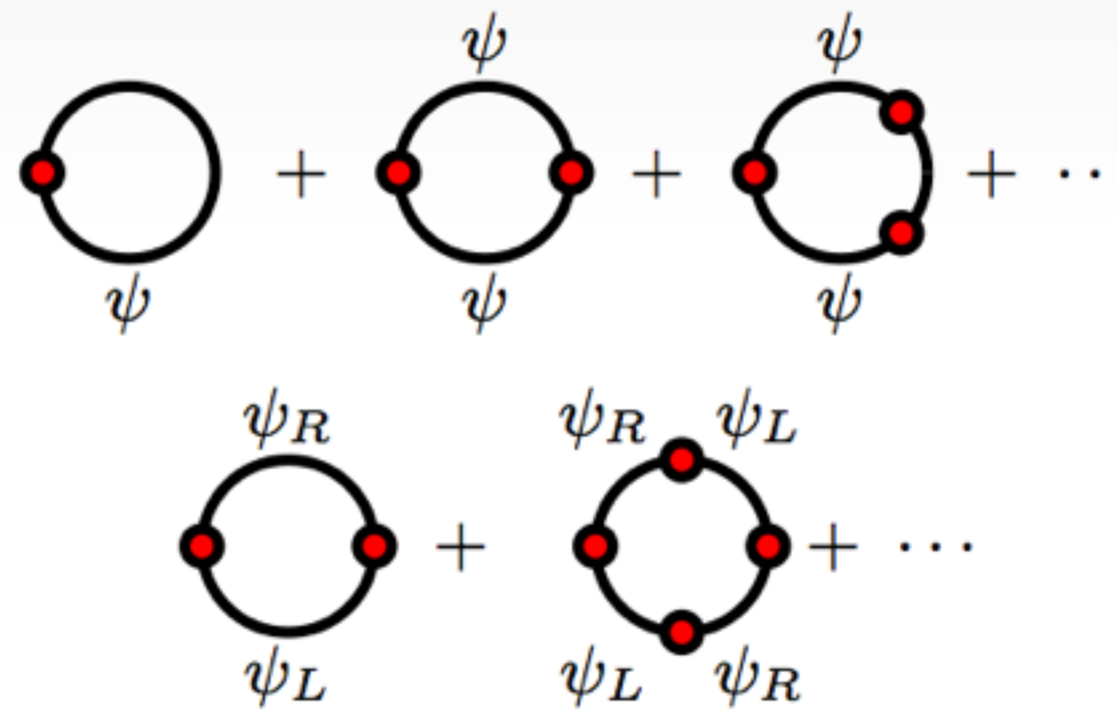
And the Higgs mass?

Integrate out the composite sector and get a low-energy Lagrangian with form-factors Agashe, Contino, Pomarol '04



Contribution from the gauge loops subleading

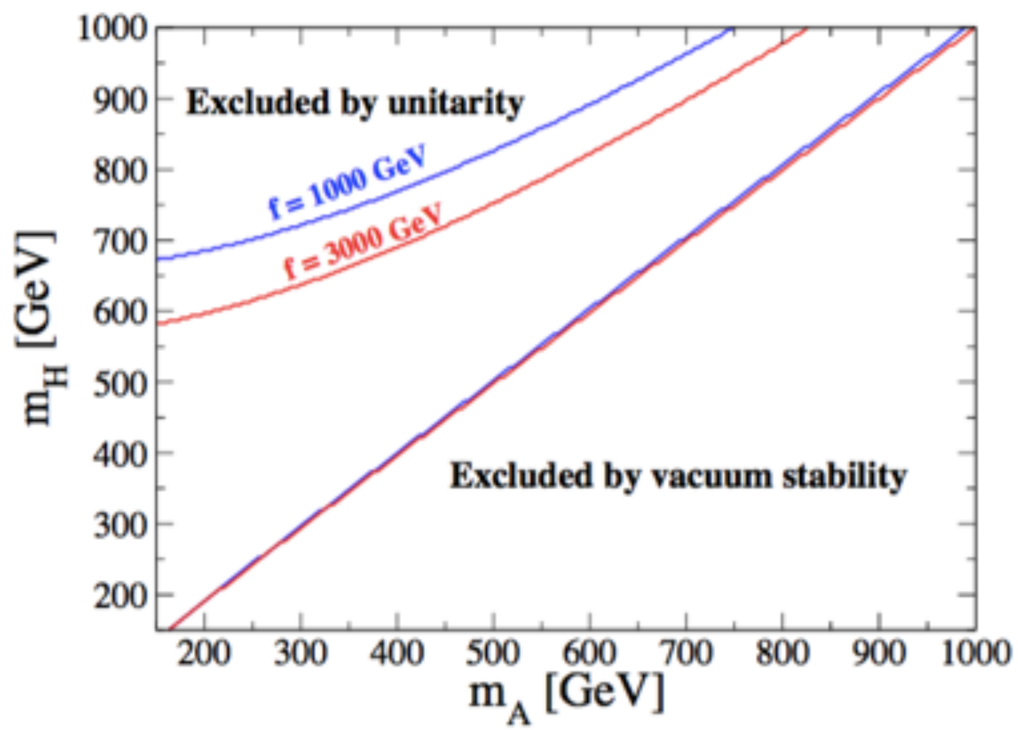
Quantum loops generate $V(h)$



$$m_H \sim 0.3\, y_t \frac{m}{f} v$$

Perturbative Unitarity in the inert C2HDM

- In the inert model (C_2 symm) there is no m_3 term in the potential (M=0) and $\langle\Phi_2\rangle=0$. H is the inert Higgs, not coupled to quarks and leptons



$\sqrt{s}=3000$ GeV

mH+=mA=m2

$\lambda_2=0.1$

mh < mA

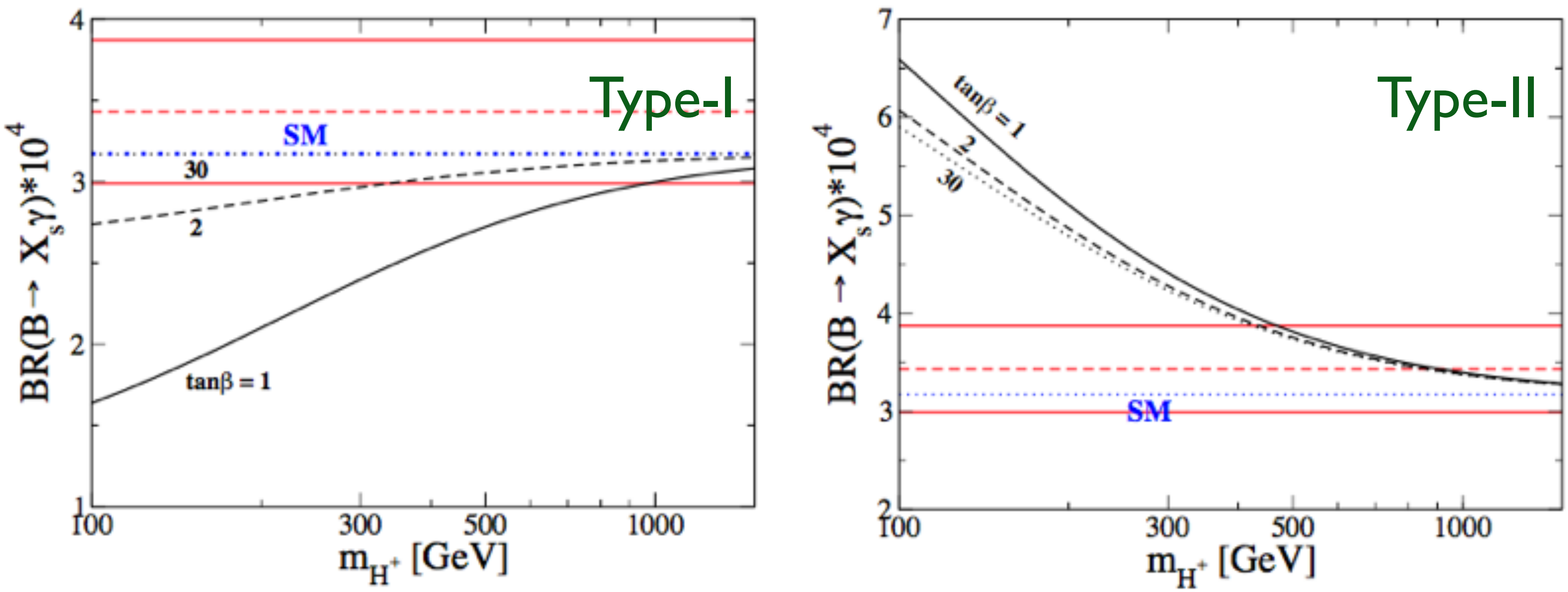
- A different choice of parameters leading to a different mass spectrum with mH<mh is possible

Ex. for mH=m2=100GeV the upper limit from unitarity on mH+=mA is about 700GeV

A dark-matter-motivated scenario is available as it is consistent with the unitarity bounds derived

Constraints on 2HDM from B —> X$_s$γ

A.G.Akeroyd et al.1605.05881



Predictions for Br(B —> X$_s$γ) at NLO QCD within the SM and the 2HDM for tanβ =1,3,30

The red lines delimit the 2σ allowed region from exp. results

95%CL bounds from NNLO calculation (M.Misiak et al.1503.01789)

Type-I (Type-X): M$_{H+}$>100(200)GeV for tanβ =2.5(2), no bound for tanβ>3

Type-II (Type-Y): M$_{H+}$>480GeV for tanβ>2

Loose bounds on m$_{H+}$ in Type-I for tanβ≳2

Trilinear Hhh coupling

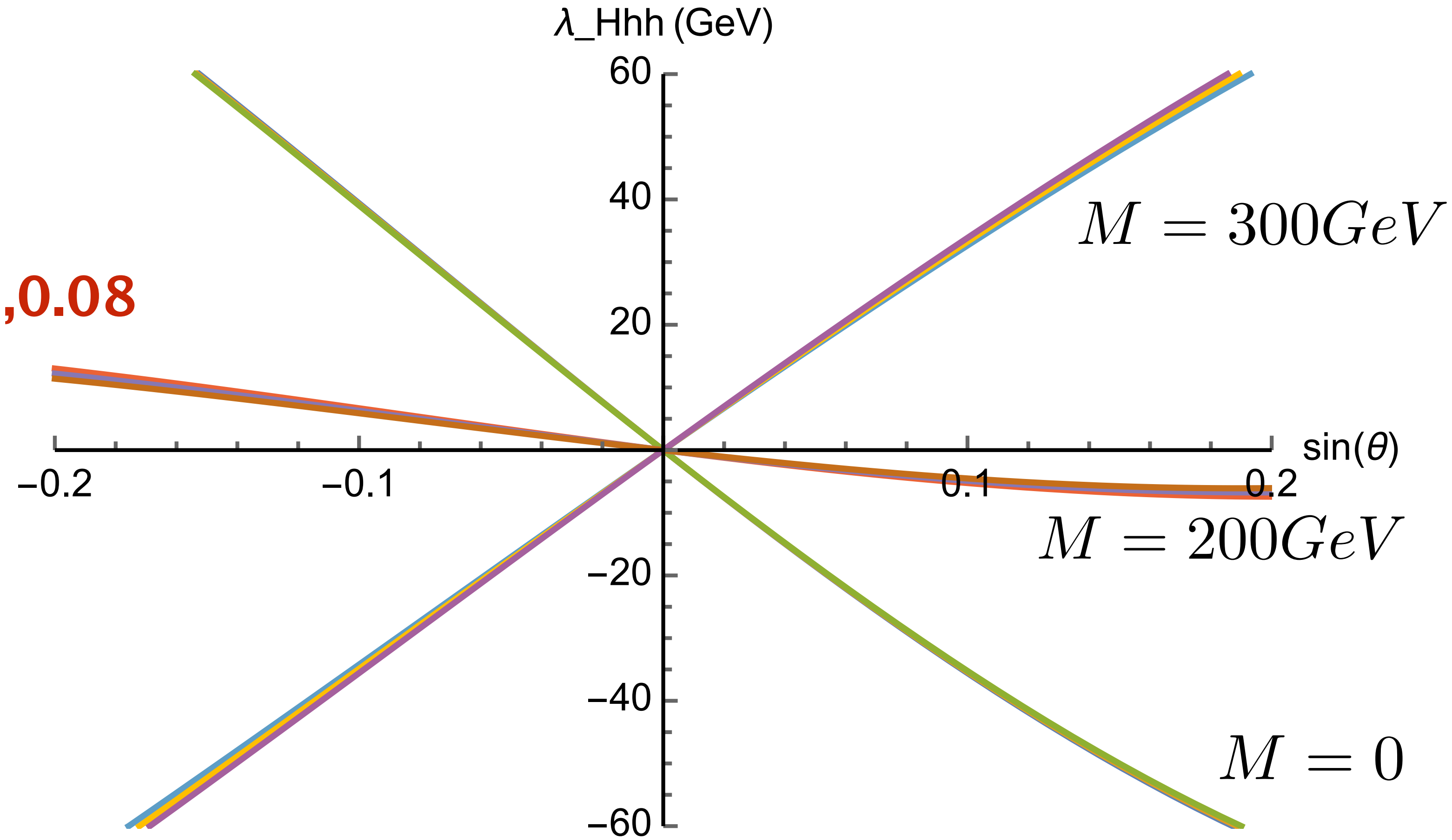
$$\lambda_{Hhh} = \frac{s_\theta}{2v_{\rm SM} s_{2\beta}}\left[-s_{2(\beta+\theta)}(2m_h^2 + m_H^2) + (s_{2\beta} + 3s_{2(\beta+\theta)})M^2\right]$$
$$+\frac{\xi}{12v_{\rm SM}} s_\theta \left[m_H^2 - 2m_h^2 + (1 + 3c_{2\theta} + 6\cot 2\beta s_{2\theta})M^2\right] + \mathcal{O}(\xi^2)$$

nearly independent on tanβ for small Θ

tanβ=1

m_H=400GeV

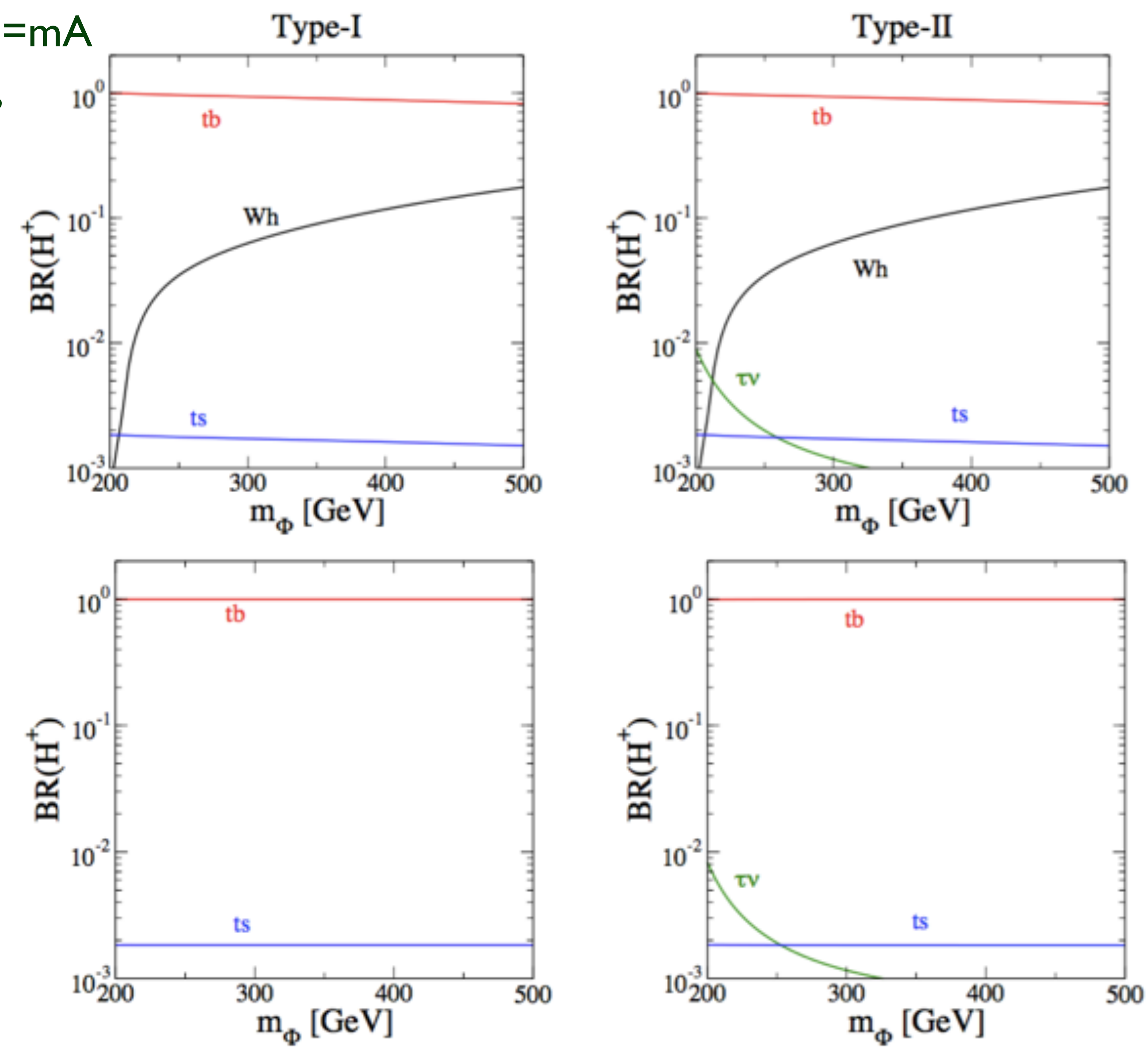
ξ=0, 0.04,0.08



Decays of the extra-Higgs boson H+

mϕ=mH=mH+=mA
M=0.8mA,
tanβ=2

Δk_V = -2%



E2HDM
(sinΘ=-0.2, ξ=0)

C2HDM
(sinΘ=0, ξ=0.04)

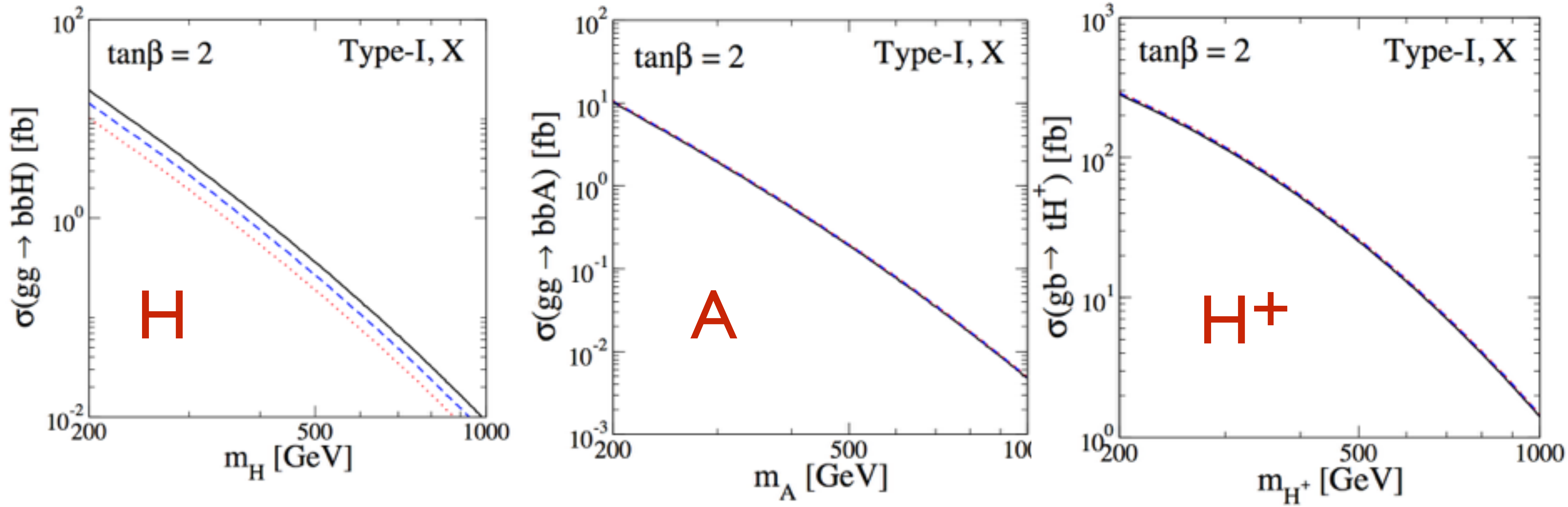
H+→W+h is a relevant channel in E2ChM while it is absent in the C2HDM with sinΘ=0
(in all the 4 Yukawa Types)

Productions of the extra-Higgs bosons at the LHC

σ ($gg \to bbH/A$)   and σ ($gb \to tH+$)

$\sqrt{s}$=13 TeV

E2HDM: BP1($\sin\Theta$=-0.2, ξ=0)   C2HDM: BP2($\sin\Theta$=-0.1, ξ=0.03), BP3($\sin\Theta$=0, ξ=0.04)



Relevant differences between E2HDM and C2HDM only for H production

(for all Types and all tanβ values)