PHENOMENOLOGY OF A COMPOSITE 2HDM

Stefano Moretti

NExT Institute (Soton & RAL) and Uppsala

S. De Curtis, L. Delle Rose, SM, K.Yagyu, ***Phys. Lett. B786 (2018) 189***

S. De Curtis, L. Delle Rose, SM, K. Yagyu, ***JHEP 1812 (2018) 051***

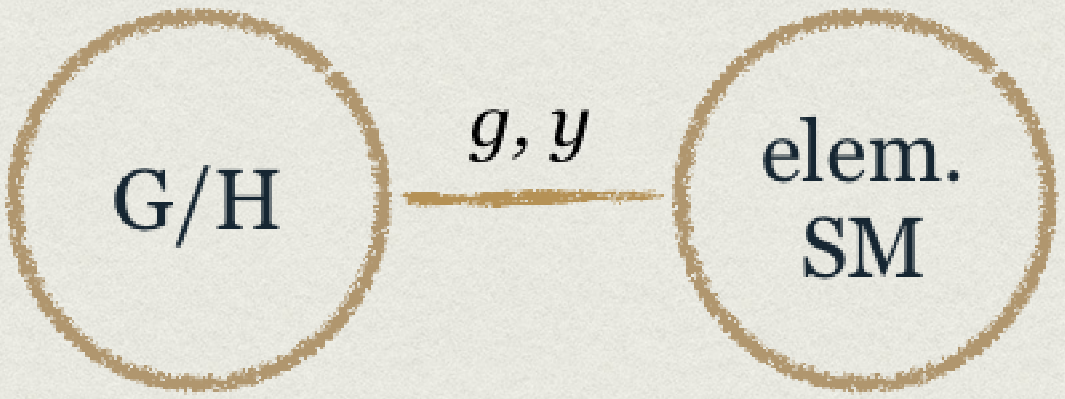
S. De Curtis, SM, R. Nagai, K. Yagyu, ***JHEP 10 (2021) 040***

S. De Curtis, L. Delle Rose, SM, ***in preparation***

S. De Curtis, L. Delle Rose, F. Egle, SM, M.M. Muhlleitner, K. Sakurai, ***in preparation***

Compositeness, nothing new?

Two sites structure:



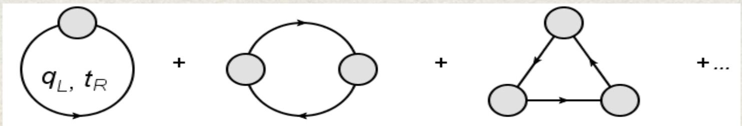
We borrow this idea from QCD: ie,

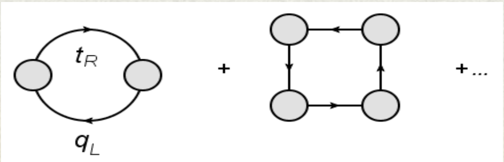
Nature has already realised this mechanism

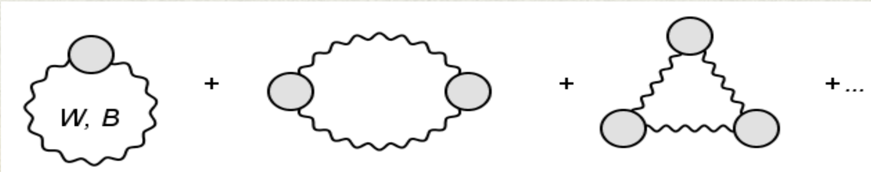
The coset delivers a set of states at a common mass scale: m^*

A large separation between new fermions/vector states and Higgses can be achieved if we identify these with pNGBs: m_{h}

<u>Partial compositeness</u>: composite/elementary mixing (g,y) connect two sites, eventually generating a one-loop effective scalar potential a la Coleman-Weinberg (which we calculated)







In essence:

	Pion Physics	Composite pNGB Higgs
Fundamental Theory	QCD	QCD-like theory
Spontaneous sym. breaking	$SU(2)_L \times SU(2)_R \to SU(2)_V$	$G \to H$ (spontaneous at compositeness scale f)
pNGB modes	$(\pi^0, \pi^\pm) \sim 135$ MeV	$h \sim 125$ GeV
Other resonances	$\rho \sim 770$ MeV, $\cdots$	New spin 1 and ½ states ~ Multi-TeV

- Need to choose the correct G->H (spontaneous) breaking to have required NGBs
- Need to break H (explicitly, so pNGBs) via *g* (gauge) and *y* (Yukawa) mixings to generate effective (ie, one-loop) scalar potential for EWSB
- Gauge contribution significant but positive, then look closely at Yukawas (negative)

Model construction

- **G/H** **SO(6)/SO(4) x SO(2)**
  - *the coset delivers 8 NGBs (2 complex Higgs doublets)*
  - *new spin 1/2 and 1 resonances too*

G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4}=(\mathbf{2},\mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5}=(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4}_{+2}+\bar{\mathbf{4}}_{-2}=2\times(\mathbf{2},\mathbf{2})$
SO(7)	SO(6)	6	$\mathbf{6}=2\times(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$
SO(7)	G_2	7	$\mathbf{7}=(\mathbf{1},\mathbf{3})+(\mathbf{2},\mathbf{2})$
SO(7)	SO(5) × SO(2)	10	$\mathbf{10}_0=(\mathbf{3},\mathbf{1})+(\mathbf{1},\mathbf{3})+(\mathbf{2},\mathbf{2})$
SO(7)	$[\mathrm{SO}(3)]^3$	12	$(\mathbf{2},\mathbf{2},\mathbf{3})=3\times(\mathbf{2},\mathbf{2})$
Sp(6)	Sp(4) × SU(2)	8	$(\mathbf{4},\mathbf{2})=2\times(\mathbf{2},\mathbf{2}),(\mathbf{2},\mathbf{2})+2\times(\mathbf{2},\mathbf{1})$
SU(5)	SU(4) × U(1)	8	$\mathbf{4}_{-5}+\bar{\mathbf{4}}_{+5}=2\times(\mathbf{2},\mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14}=(\mathbf{3},\mathbf{3})+(\mathbf{2},\mathbf{2})+(\mathbf{1},\mathbf{1})$

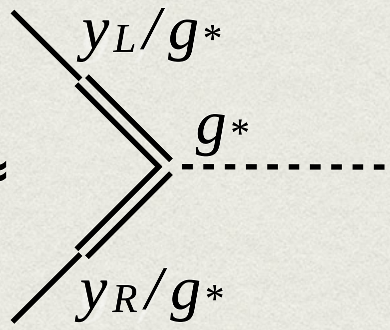
Mrazek et al., 2011

Partial compositeness (y)

Linear interactions between composite and elementary (top) operators

$$\mathcal{L}_{\rm int} = g J_\mu W^\mu$$
$$\mathcal{L}_{\rm int} = y_L\, q_L\, \mathcal{O}_L + y_R\, t_R\, \mathcal{O}_R$$

$y_{top} \approx$



In our scenario with G/H = SO(6)/SO(4)xSO(2) and fermions in the **6** of SO(6):

$$\begin{aligned}\mathcal{L}_{\rm mix} + \mathcal{L}_{\rm strong} \;=\;& \Delta_L^I \bar{q}_L^{\mathbf{6}} \Psi_R^I + \Delta_R^I \bar{t}_R^{\mathbf{6}} \Psi_L^I \\ +\;& \bar{\Psi}^I i \not{D} \Psi^I - \bar{\Psi}_L^I M_\Psi^{IJ} \Psi_R^J - \bar{\Psi}_L^I \left(Y_1^{IJ} \Sigma + Y_2^{IJ} \Sigma^2\right) \Psi_R^J\end{aligned}$$

GBs

$\Sigma = U_1 \Sigma_2 U_1^T$

All the parameters real → CP invariant scenario

- *Mixings, masses & Yukawas of heavy tops*
- *At least 2 heavy (I,J=1,2) top resonances are needed for UV finiteness*
- *Heavy resonances in the **6** of SO(6) delivers 4 top partners, 1 bottom partner and 1 exotic fermion with Q = 5/3*

Custodial symmetry

The predicted leading order correction to the T parameter arises from the non-linearity of the GB Lagrangian. In the SO(6)/SO(4)xSO(2) model is

$$\hat{T} \propto 16 \times \frac{v^2}{f^2} \times \frac{\mathrm{Im}[\langle H_1\rangle^\dagger \langle H_2\rangle]^2}{(|\langle H_1\rangle|^2 + |\langle H_2\rangle|^2)^2}$$

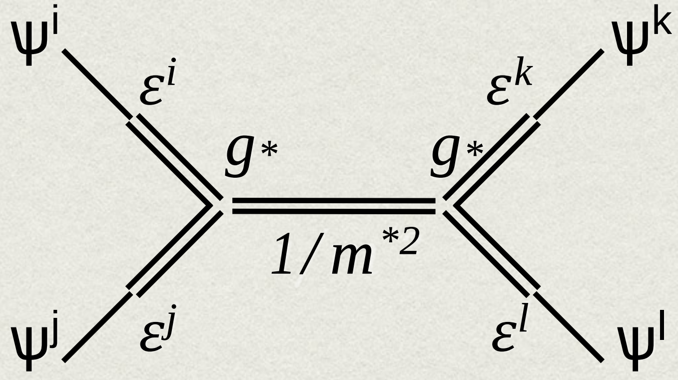
no freedom in the coefficient, fixed by the coset

possible solutions:

- CP (*which we assume*)
- C_2: $H_1 \to H_1$, $H_2 \to -H_2$ forbidding H_2 to acquire a vev (*which we don't*)

FCNCs

FCNCs mediated by the heavy resonances



$$\sim \epsilon_L^i \epsilon_R^j \epsilon_L^k \epsilon_R^l \left(\frac{g^*}{m^*}\right)^2 a^{ijkl}, \quad a^{ijkl} \sim O(1)$$

for example, for ΔS = 2, $\sim \frac{1}{m^{*2}} \frac{m_d}{v} \frac{m_s}{v}$

- *does not require an excessive and unnatural tuning of the parameters*

Issues with Higgs-mediated FCNCs

FCNCs can be removed by

- assuming C_2 in the strong sector and in the mixings (ie, $Y_1=0$): *inert C2HDM* (not considered here)
- broken C_2 in the strong sector requires (flavour) *alignment* $Y_1^{IJ} \propto Y_2^{IJ}$ propagating to each type of fermions in the low energy Lagrangian

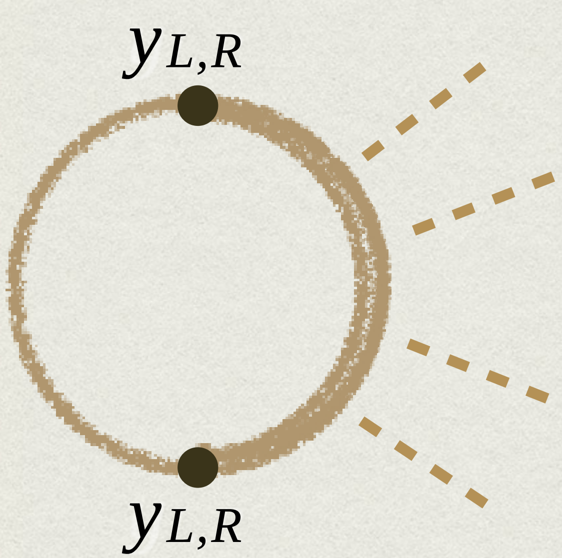
$$Y_u^{ij} Q^i u^j \left(a_{1u} H_1 + a_{2u} H_2\right) + Y_d^{ij} Q^i d^j \left(a_{1d} H_1 + a_{2d} H_2\right) + Y_e^{ij} L^i e^j \left(a_{1e} H_1 + a_{2e} H_2\right) + h.c.$$

(the ratios a_1/a_2 are predicted by the strong dynamics)

The scalar potential

The entire effective potential is fixed by the parameters of the strong sector and the scalar spectrum is entirely predicted by the strong dynamics

Note: here integrate out heavy composite resonances (both fermionic & bosonic)
Question is then, what does such compositeness-driven EWSB *predicts*?



The potential up to the fourth order in the Higgs fields:

$$V = m_1^2 H_1^\dagger H_1 + m_2^2 H_2^\dagger H_2 - \left[m_3^2 H_1^\dagger H_2 + \text{h.c.} \right]$$
$$+ \frac{\lambda_1}{2}(H_1^\dagger H_1)^2 + \frac{\lambda_2}{2}(H_2^\dagger H_2)^2 + \lambda_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + \lambda_4 (H_1^\dagger H_2)(H_2^\dagger H_1)$$
$$+ \frac{\lambda_5}{2}(H_1^\dagger H_2)^2 + \lambda_6 (H_1^\dagger H_1)(H_1^\dagger H_2) + \lambda_7 (H_2^\dagger H_2)(H_1^\dagger H_2) + \text{h.c.}$$

Light (SM-like) Higgs (ie, no inverted mass hierarchy):

without any tuning, the minimum of the potential is $v \sim f$

$$m_\Pi^2 \sim \frac{g^{*2}}{16\pi^2} y^2 f^2$$

while, in the tuned direction,

$$m_h^2 \sim \frac{g^{*2}}{16\pi^2} y^2 v^2$$

$$m_h^2 \sim \frac{N_c}{16\pi^2} g_\rho^2 m_t^2$$

(after reproducing top mass)

Heavy Higgs masses: $M^2 \equiv \frac{m_3^2}{s_\beta c_\beta} \sim \frac{1}{16\pi^2} Y_1 Y_2 \sim \frac{f^2}{16\pi^2}$

Any C_2 breaking in the strong sector induces (all real, following CP conservation in strong sector):

$$m_3^2 \neq 0, \lambda_6 \neq 0, \lambda_7 \neq 0$$

$$\lambda_6 = \lambda_7 = \frac{5}{3} \frac{m_3^2}{f^2}$$

it is not possible to realise a C2HDM scenario with a softly broken Z_2

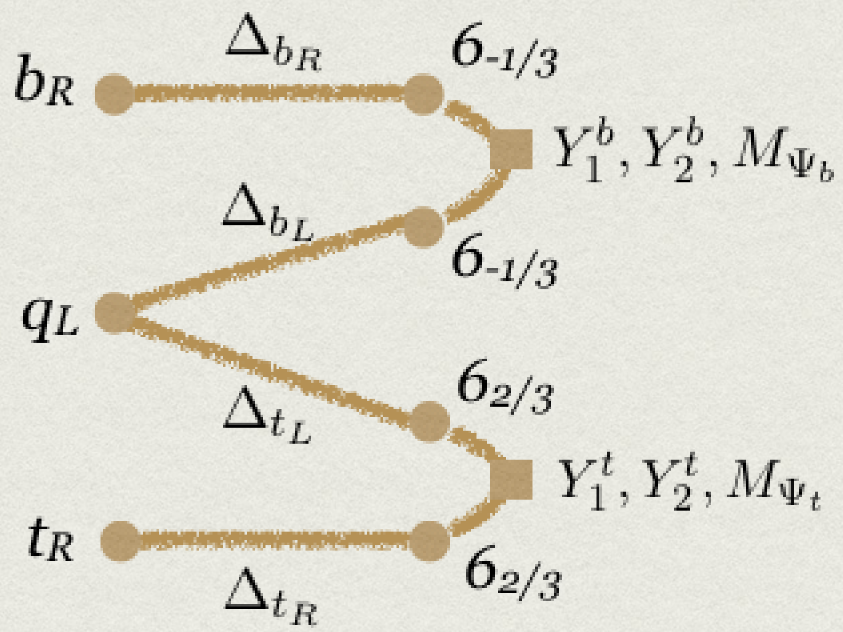
Sampling the parameter space (now include b)

C2HDM: we adopt the L-R structure based on the 2-site models which represents the minimal choice for a calculable effective potential *(De Curtis et al., 2012)*

m_i^2 (i=1,..,3) and λj (j=1,…,7) are determined by the parameters of the strong sector

$$f,\quad Y_1^{12},\quad Y_2^{12},\quad \Delta_L^1,\quad \Delta_R^2,\quad M_\Psi^{11},\quad M_\Psi^{22},\quad M_\Psi^{12},\quad g_\rho$$

Yukawas — linear mixings — heavy fermion mass parameters



$$X = f,\, Y_1,\, Y_2,\, M_\Psi,\, \Delta_L,\, \Delta_R$$

$$600\,\mathrm{GeV} < f < 3000\,\mathrm{GeV} \qquad |X| < 10 f$$

$$m_W^2 = \frac{1}{4}\frac{g_W^2 g_\rho^2}{g_W^2+g_\rho^2} f^2 \sin^2\frac{v}{f} \qquad v^2 = v_1^2 + v_2^2 \qquad \tan\beta = v_2/v_1$$

g^2 — $V_{sm}^2 \sim (246\ \mathrm{GeV})^2$

$$m_t = \frac{v}{\sqrt{2}} \frac{\Delta_L \Delta_R}{m_\Psi^2} \frac{Y_1 s_\beta + Y_2 c_\beta}{f}$$

Y_t

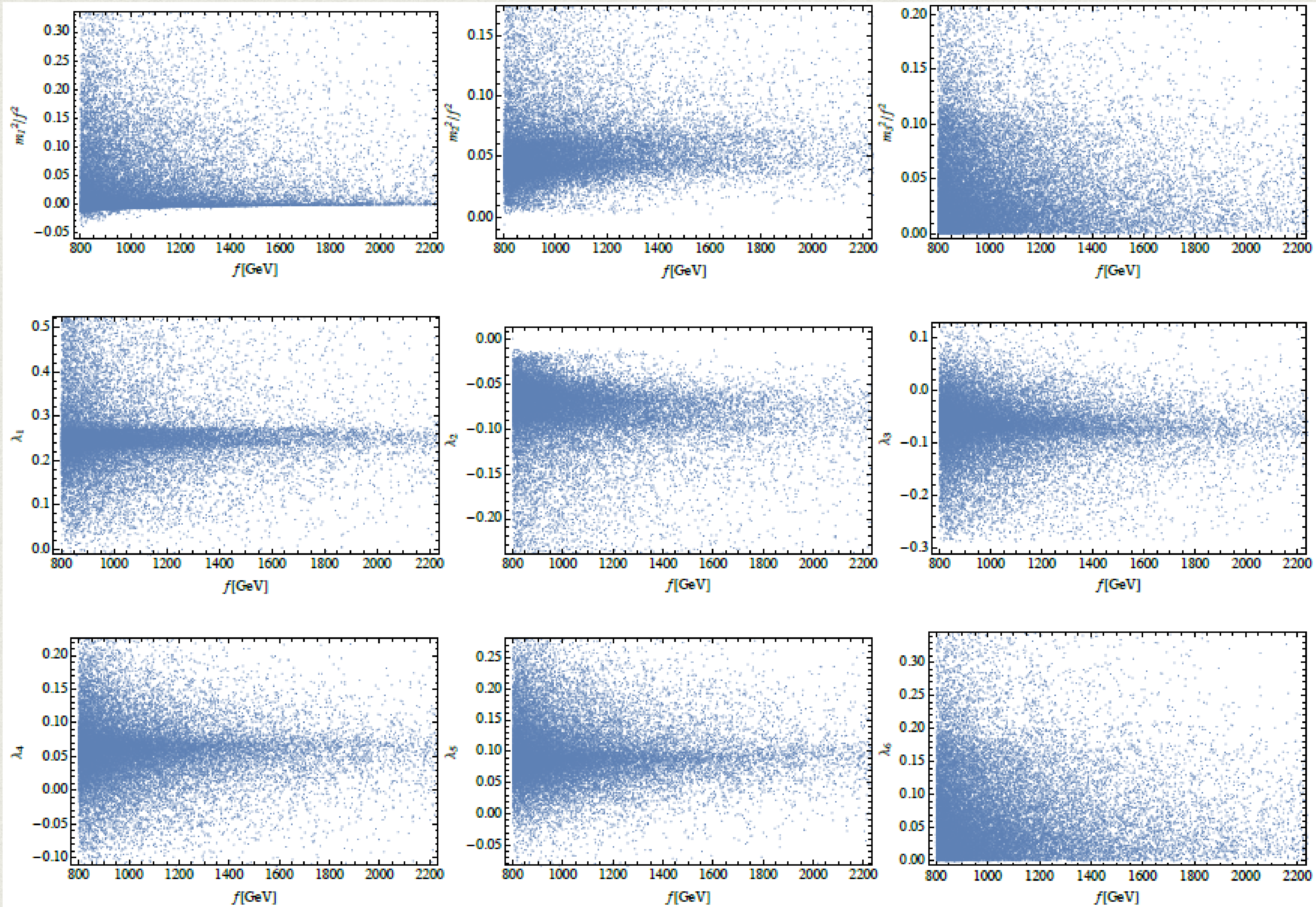
$$120\,\mathrm{GeV} < m_h < 130\,\mathrm{GeV}$$
$$165\,\mathrm{GeV} < m_t < 175\,\mathrm{GeV}$$

(Higgs & top mass are lowest order)

Will compare to MSSM (FeynHiggs 2.14.1 and LHCHXSWG-2015-002 prescriptions)

- 2loop + NNLL resummation — $2 < \tan\beta < 45, \quad 200\,\mathrm{GeV} < m_A < 1600\,\mathrm{GeV}$
- soft SUSY breaking = M_{SUSY} — $1\,\mathrm{TeV} < M_{\mathrm{SUSY}} < 100\,\mathrm{TeV} \qquad |X_t| < 3 M_{\mathrm{SUSY}}$

The entire effective potential is fixed by the parameters of the strong sector



Checked all theoretical constraints (vacuum stability, triviality, unitarity)

Yukawa sector $\xi \equiv v_{\rm SM}^2/f^2$

$$-\mathcal{L}_{\rm Yukawa} = \sum_{f=u,d,l} \frac{m_f}{v_{\rm SM}} \bar{f} \left[\xi_h^f\, h + \xi_H^f\, H - 2iI_f \xi_A^f\, A\gamma^5\right] f$$
$$+ \frac{\sqrt{2}}{v_{\rm SM}} \left[V_{ud}\, \bar{u} \left(-\xi_A^u m_u P_L + \xi_A^d m_d P_R\right) dH^+ + \xi_A^l\, m_l\, \bar{\nu} P_R l\, H^+\right] + \text{h.c.},$$

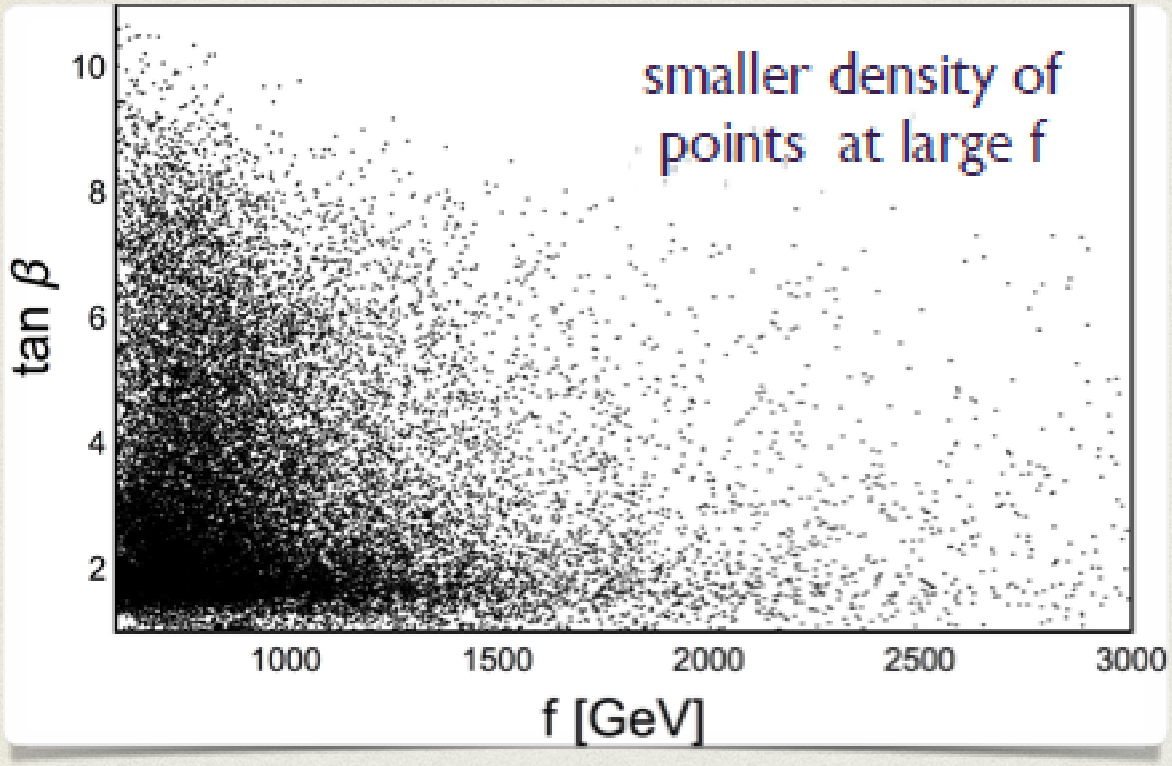
where $I_f = 1/2(-1/2)$ for $f = u\,(d,l)$ and the ξ^f coefficients are

$$\xi_h^f = (1 + c_f^h\, \xi) \cos\theta + (\zeta_f + c_f^H\, \xi) \sin\theta\,, \quad \xi_H^f = -(1 + c_f^h\, \xi) \sin\theta + (\zeta_f + c_f^H\, \xi) \cos\theta\,,$$
$$\xi_A^f = \zeta_f + \xi \left[-\frac{\tan\beta}{2} \frac{1 + \bar{\zeta}_t^2}{(1 + \bar{\zeta}_f\, \tan\beta)^2},\right]$$

with

$$c_f^h = -\frac{1}{2}\frac{3 + \bar{\zeta}_f\, \tan\beta}{1 + \bar{\zeta}_f\, \tan\beta}\,, \quad c_f^H = \frac{1}{2}\frac{\bar{\zeta}_f(1 + \tan^2\beta)}{(1 + \bar{\zeta}_f\, \tan\beta)^2}\,,$$
$$\zeta_f = \frac{\bar{\zeta}_f - \tan\beta}{1 + \bar{\zeta}_f\, \tan\beta}\,, \qquad \bar{\zeta}_f = -\frac{Y_1^f}{Y_2^f}\,.$$

The parameter θ denotes the mixing between the physical components of the two CP-even states while ζ_f represents the normalised coupling to the fermion f of the CP-even scalar that does not acquire a VEV in the Higgs basis. Since θ is predicted to be small, ζ_f controls the interactions of the Higgs states $H, A, H^\pm$ at the zeroth order in ξ.



- tan β (usual vev ratio) predicted by the strong sector
- m_h and m_{top} require tan β ~ O(1)
- larger tuning at large *f*
- values of tan β in the C2HDM and MSSM cannot be directly compared (next slide)

- m_H, m_A, m_{H+} grow with *f* (and tan β)

$$\mathcal{M}^2 = \begin{pmatrix} \Lambda_1 v^2 & \Lambda_6 v^2 \\ \Lambda_6 v^2 & \mathcal{M}_{22}^2 \end{pmatrix}$$

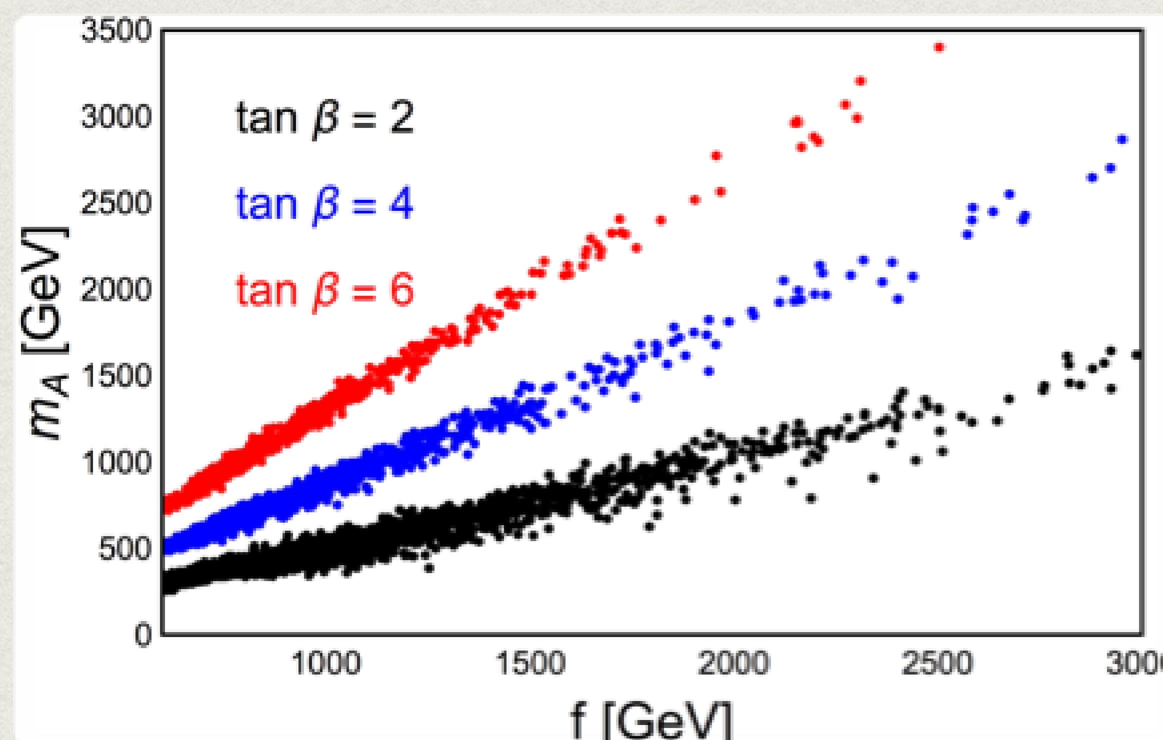
fixed by minimisation of V

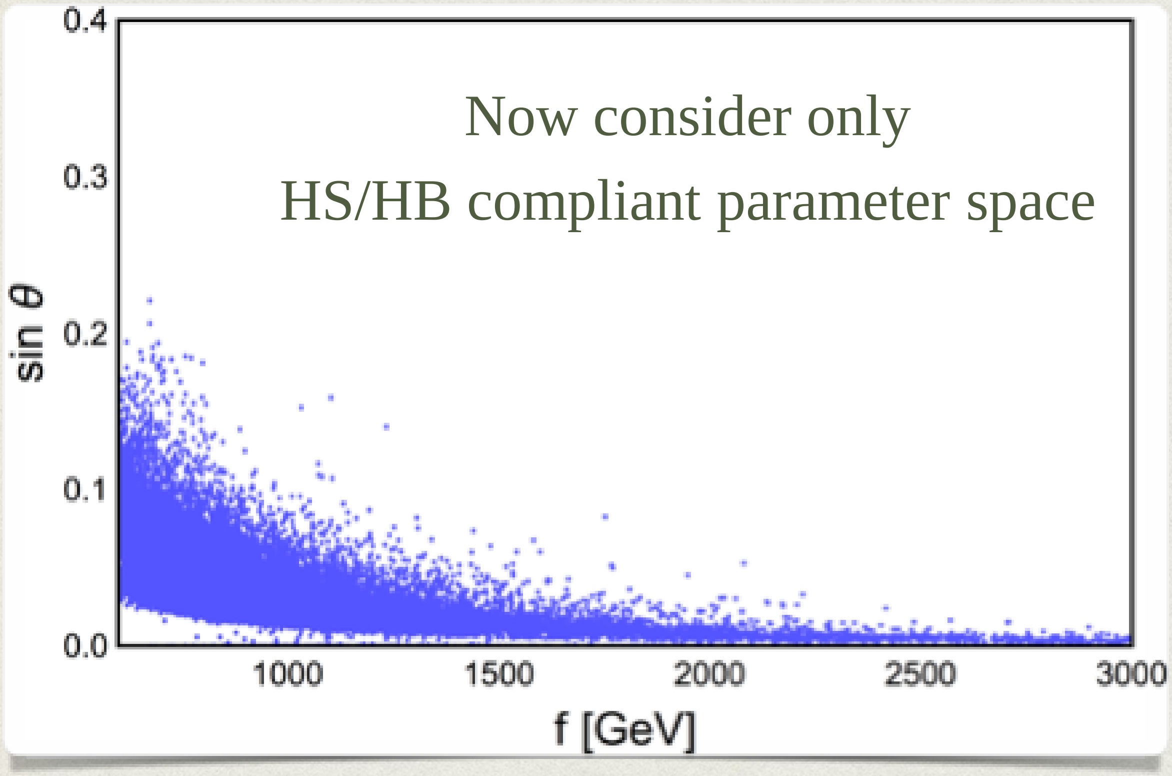
unconstrained

$\mathcal{M}_{22} \sim f$

$$T_1 \sim c_\beta(m_1^2 - M^2 s_\beta^2 + \lambda_i v^2)$$
$$T_2 \sim s_\beta(m_2^2 - M^2 c_\beta^2 + \lambda_i' v^2)$$

(tadpole conditions: some fine-tuning required)





Mixing between the CP-even states *h*, *H*:

$$\tan 2\theta = -2\frac{\Lambda_6 v^2}{\mathcal{M}_{22}^2 - \Lambda_1 v^2} \sim c\frac{v^2}{f^2}$$

SM-like h requires large f while

very non-SM-like h requires small f

Comment: $\tan\beta$ is basis-dependent. In the E2HDM it is uniquely identified if the Z_2 properties are specified ex. Type-I or Type-II

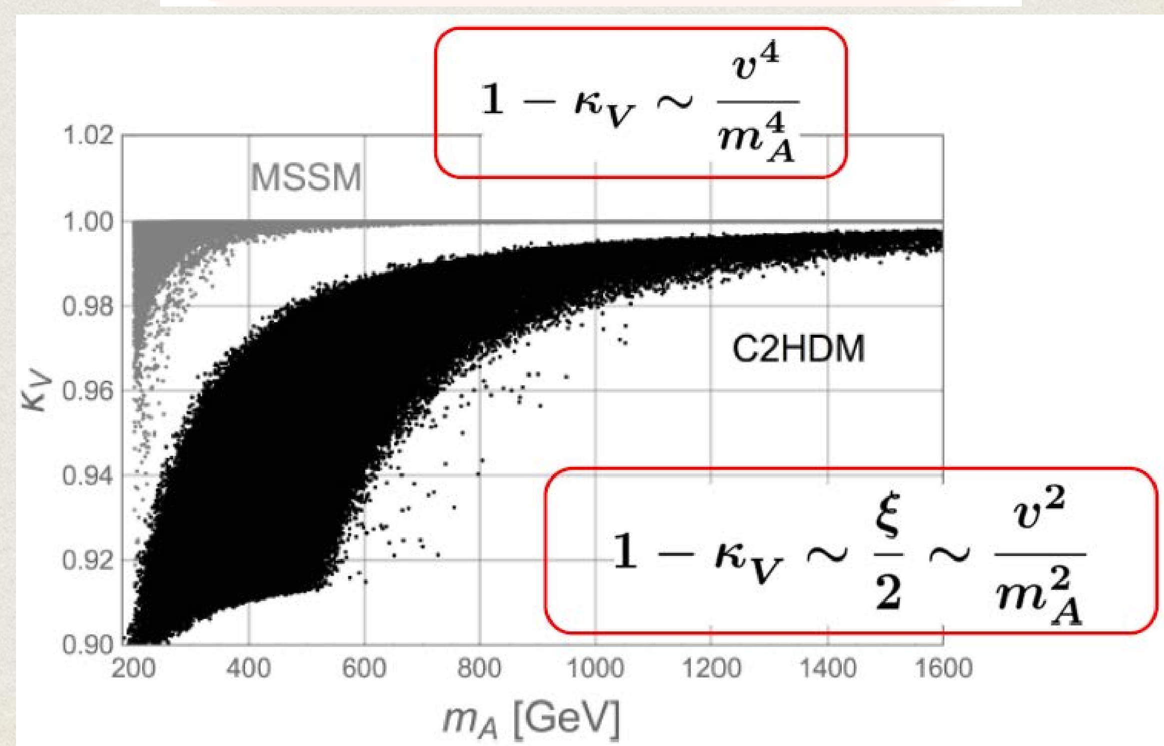
A comparison of the two scenarios for fixed $\tan\beta$ values is not correct

The SM-like Higgs *h* coupling to *W*,*Z*

$$\kappa_V = \left(1 - \frac{\xi}{2}\right)\cos\theta, \quad \xi \equiv \frac{v_{\rm SM}^2}{f^2}$$

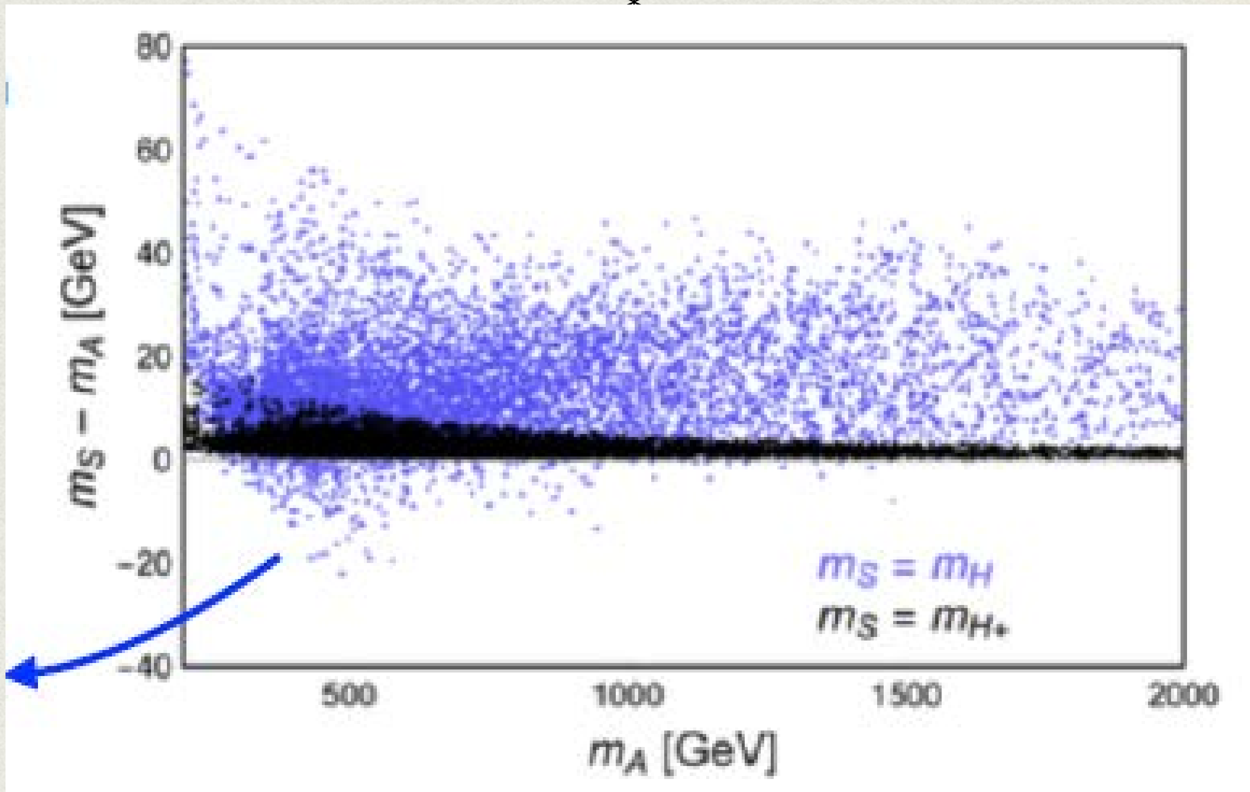
the alignment limit is approached more slowly in the C2HDM than in MSSM

a relevant deviation is present
even for no mixing

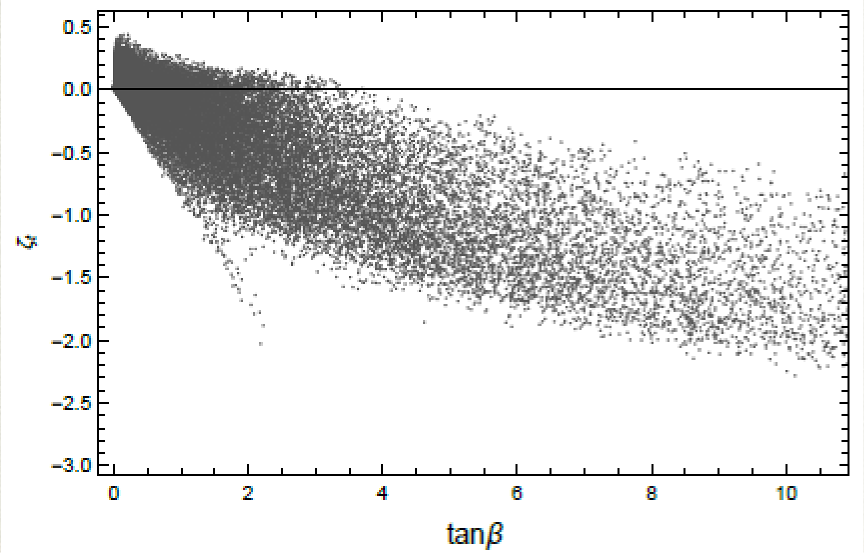


Can heavy Higgs mass spectra reveal C2HDM from MSSM?

- m_{H+} and m_A : very close in both scenarios (high degeneracy): very sharp prediction in the C2HDM, $m_{H^\pm}^2 - m_A^2 \simeq \frac{\Delta_L^4}{m_*^4} v^2$
- m_H and m_A: larger mass splitting prediction in the C2HDM than in the MSSM (max 15 GeV)
- $H \to A\, Z^*$ can be a channel discriminating the two scenarios
- $A \to H\, Z^*$ could also be useful

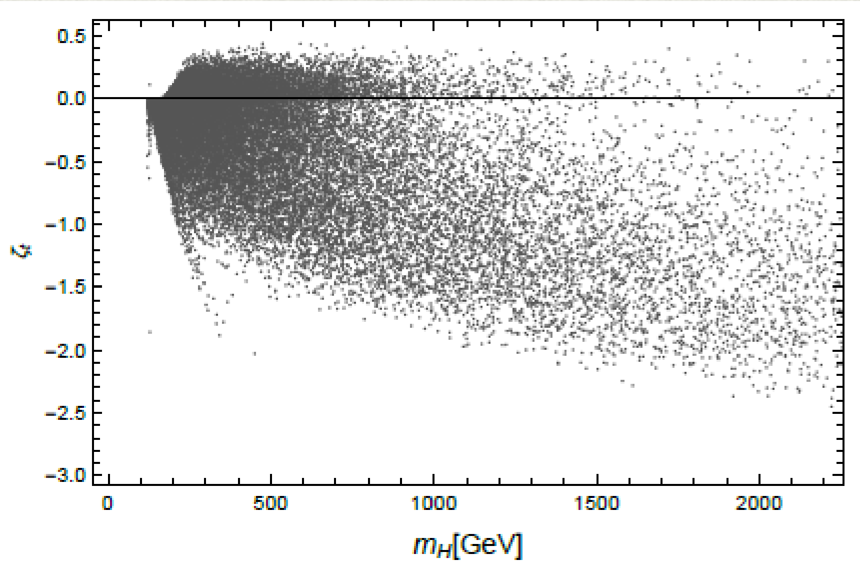


Can correlate to Yukawas, tan β:



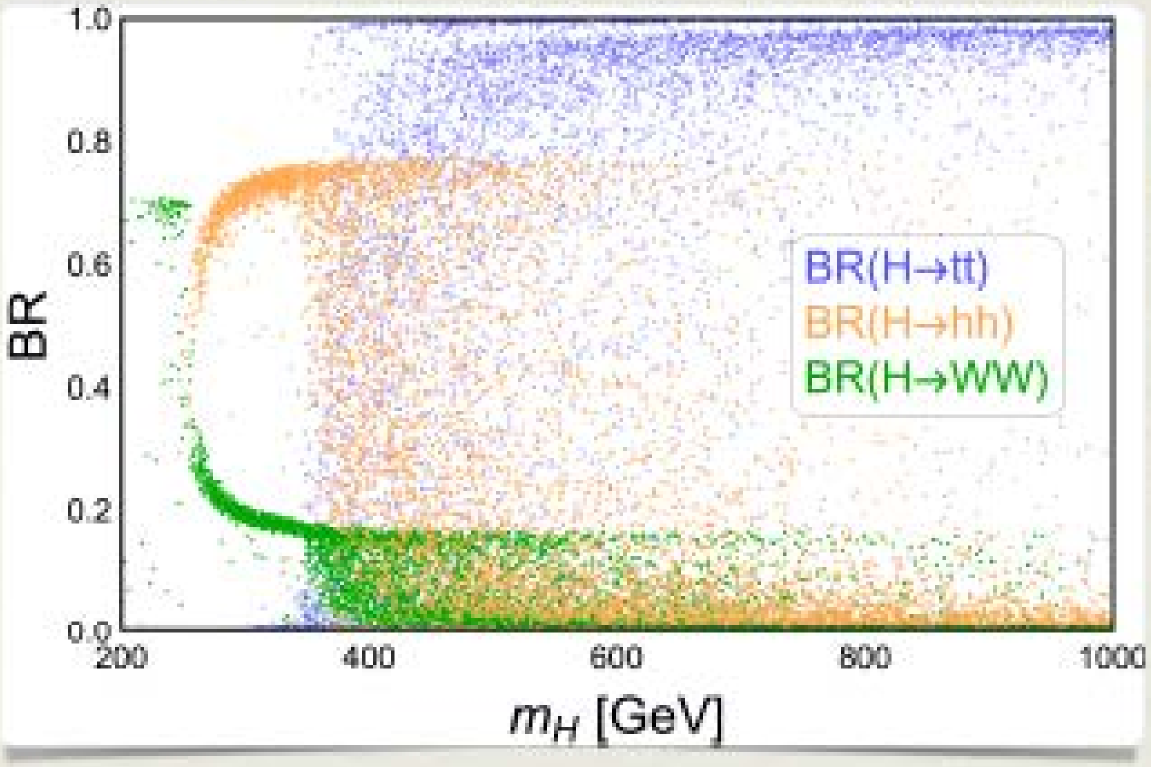
correlation between ζ_t and $\tan\beta$ for all values of $f > 700$ GeV

m_H:



correlation between ζ_t and the mass of the heavy CP-even boson

Heavy Higgs decay modes



$H \to tt$ represents the main decay mode

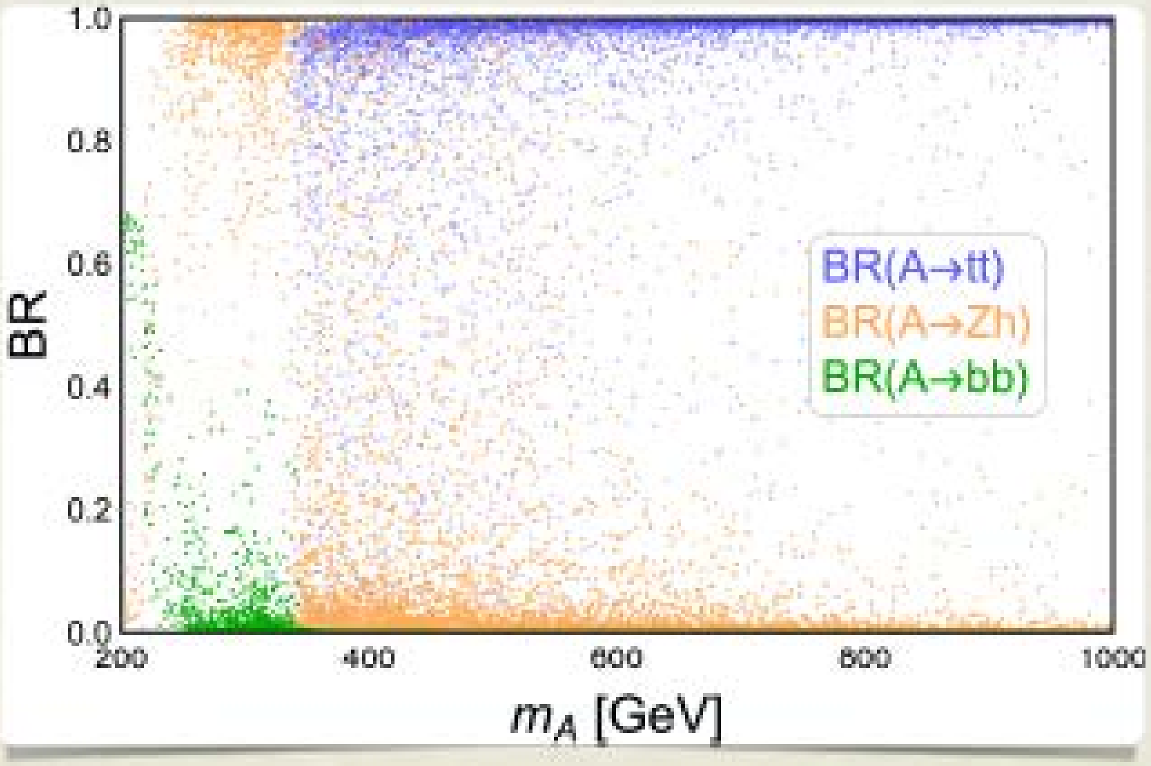
below the tt threshold, $H \to hh$ dominates

(BR(H→hh) ~ 80%, BR(H→VV) ~ 20%)

$$\Gamma(H \to t\bar{t}) \approx \frac{3y_t^2}{16\pi}|\zeta_t|^2 m_H$$

$$\Gamma(H \to hh) \approx \frac{9}{32\pi m_H}(v_{\rm SM}^2 \Lambda_6^2)$$

$$\Gamma(H \to W^+W^-) \approx 2\Gamma(H \to ZZ) \approx \frac{1}{16\pi m_H}\sin^2\theta \frac{m_H^4}{v_{\rm SM}^2}$$



$$\mathrm{BR}(A \to t\bar{t}) \approx 1$$

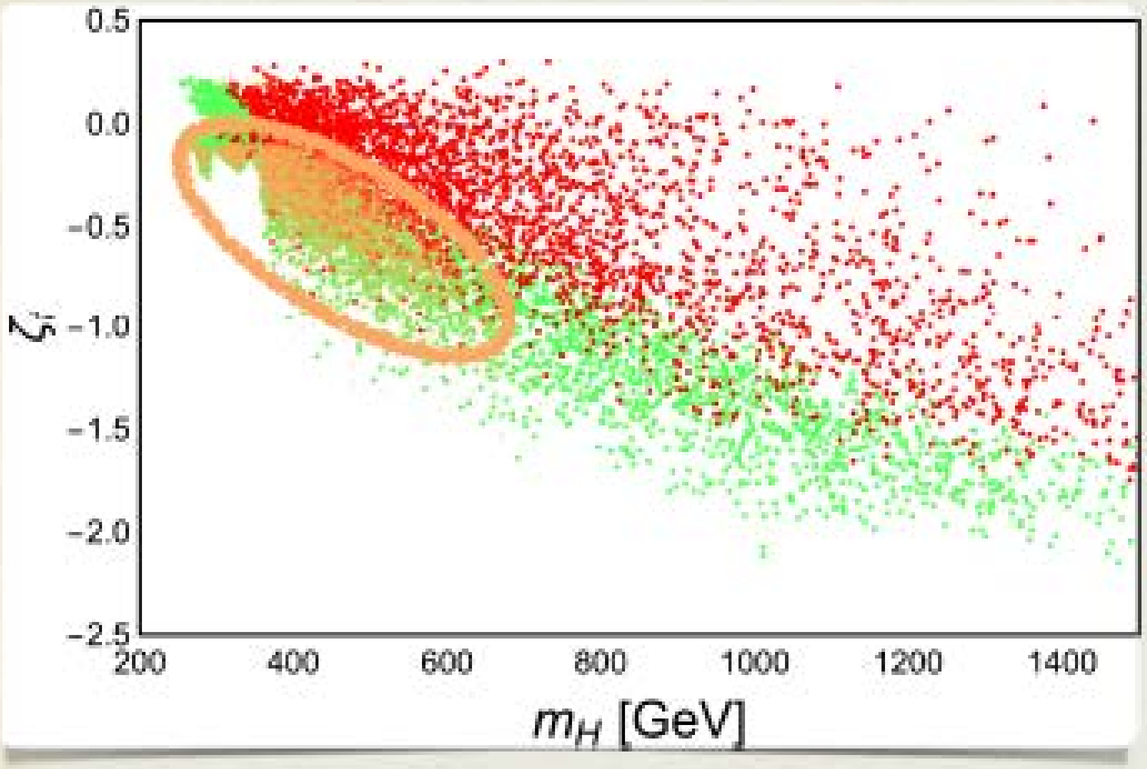
$$\mathrm{BR}(A \to b\bar{b}) \approx 8 \times 10^{-4}(\frac{\zeta_b^2}{\zeta_t^2})$$

$$\mathrm{BR}(A \to \tau^+\tau^-) \approx 4 \times 10^{-5}(\frac{\zeta_\tau^2}{\zeta_t^2})$$

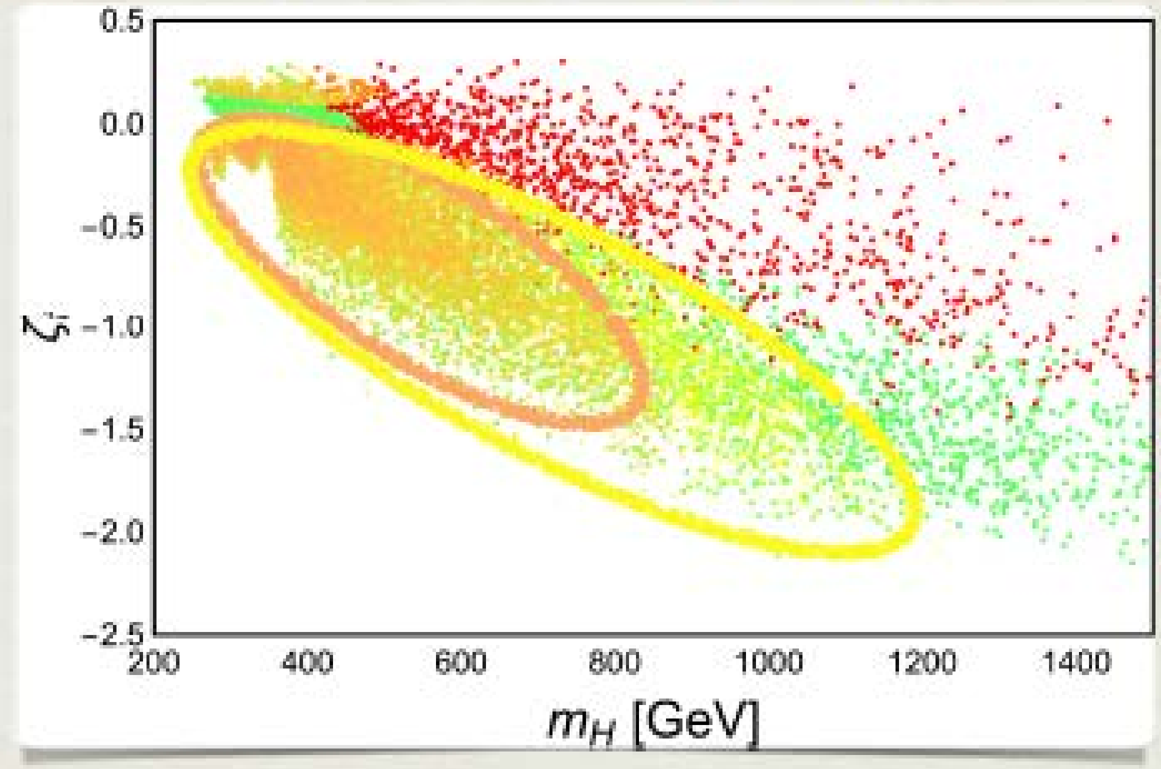
interplay between indirect and direct searches

$gg \to H \to hh \to bb\gamma\gamma$

end of Run 3



HL-LHC and HE-LHC



PRELIMINARY

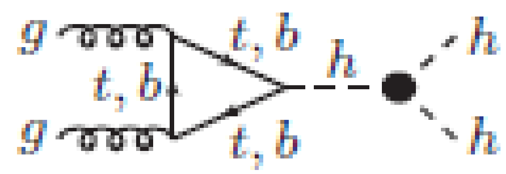
the *Htt* and *Hhh* couplings are strongly correlated and carry the imprint of compositeness

colour legend:

- **green**: *points that pass present constraints at 13 TeV*
- **red**: *points that have κ_V, κ_γ and κ_g within 95% CL projected uncertainty at L = 300 fb^{-1} (left) and L = 3000 fb^{-1} (right) (arXiv:1307.7135)*
- ***orange****: points that are 95% CL excluded by direct search at L = 300 fb^{-1} (left) and L = 3000 fb^{-1} (right) (CMS PAS HIG-17-008)*
- ***yellow****: points hat are 95% CL excluded by direct search at the HE-LHC (right)*

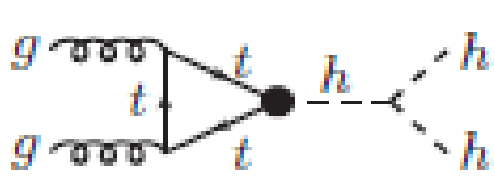
Can di-Higgs at the LHC reveal C2HDM?

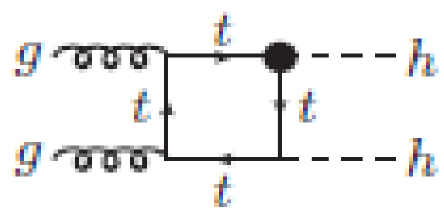
1. modified Higgs trilinear coupling



$\mathcal{A}_i \propto \kappa_{hhh}$

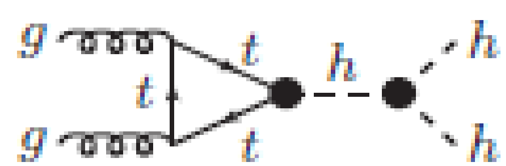
2. one modified tth coupling





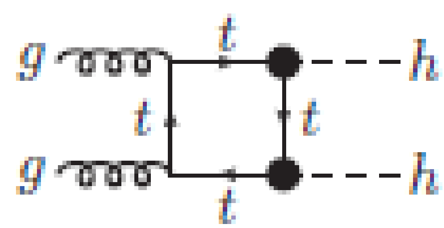
$\mathcal{A}_i \propto \kappa_{htt}$

3. modified Higgs trilinear coupling + modified tth coupling



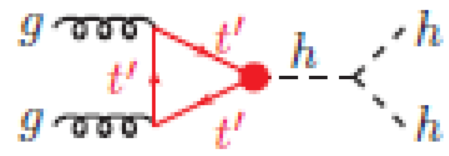
$\mathcal{A}_i \propto \kappa_{hhh}\kappa_{htt}$

4. two modified tth couplings



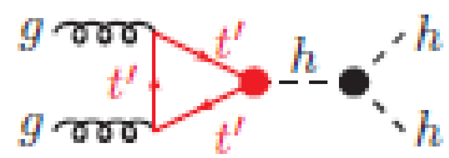
$\mathcal{A}_i \propto \kappa_{htt}^2$

5. **VLQ triangle**



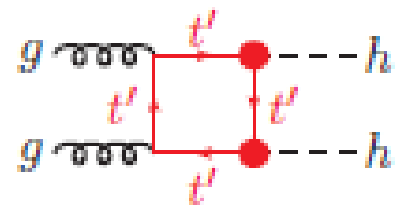
$\mathcal{A}_i \propto \kappa_{ht't'}$

6. **modified Higgs trilinear coupling + VLQ triangle**



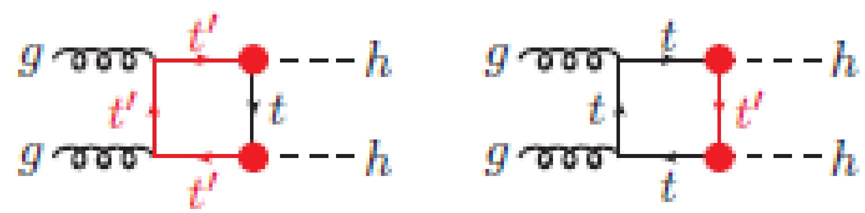
$\mathcal{A}_i \propto \kappa_{hhh}\kappa_{ht't'}$

7. **VLQ box**

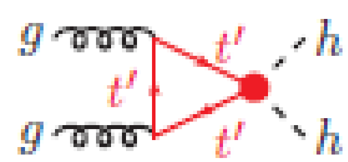


$\mathcal{A}_i \propto \kappa^2_{ht't'}$

8. **VLQ-top box**



9. **VLQ 4-leg effective vertex**

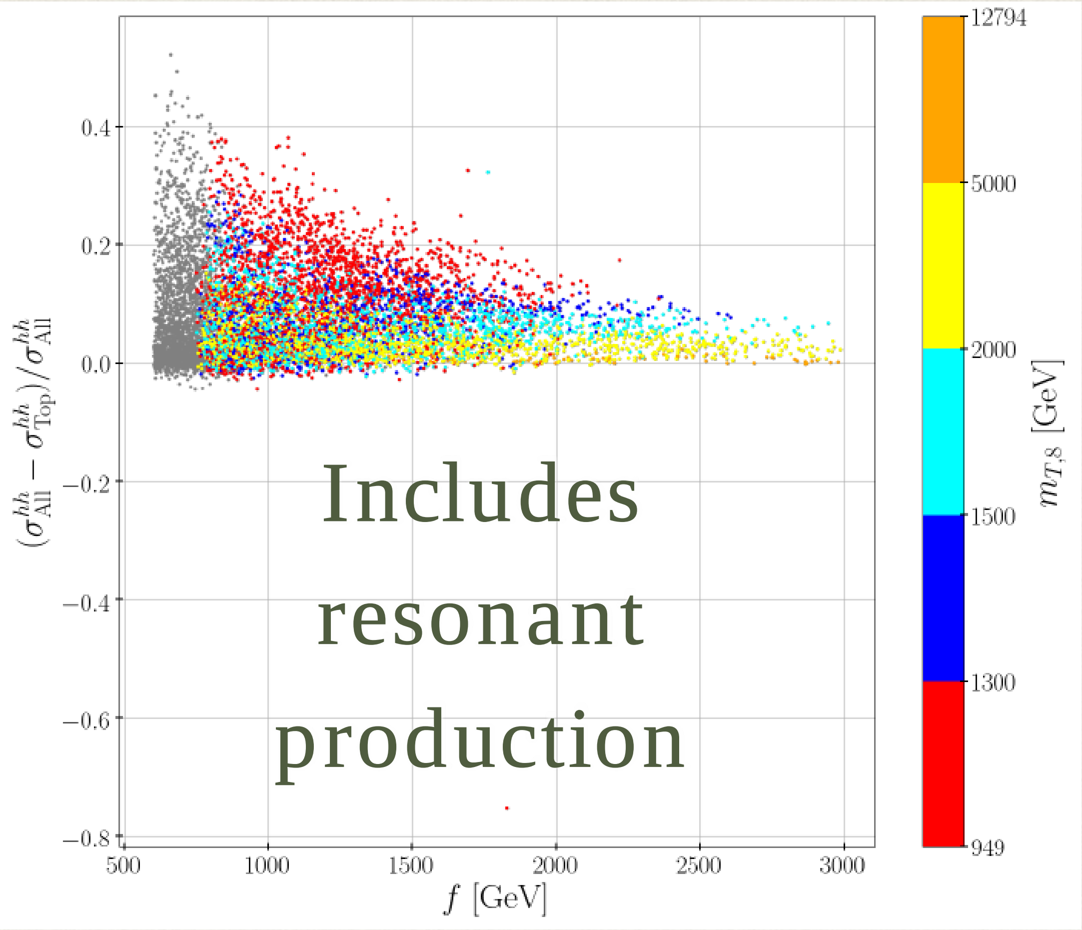


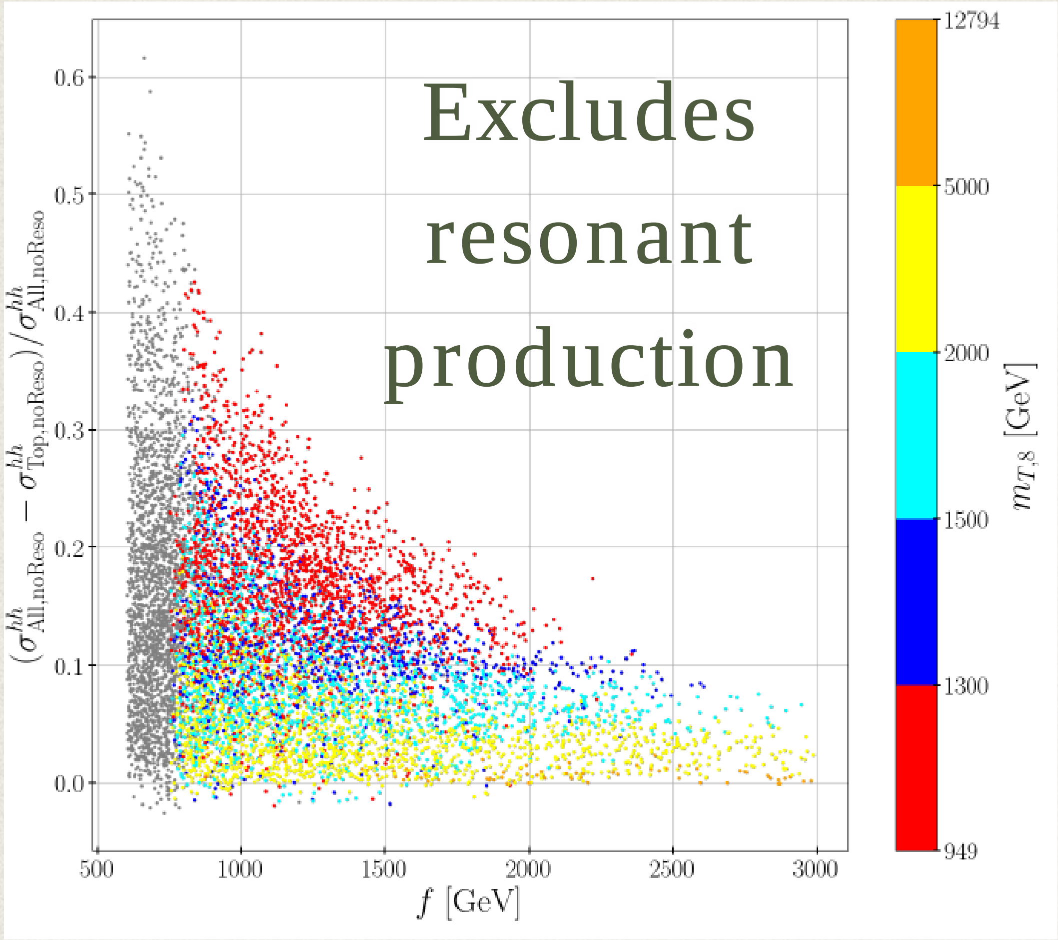
$\mathcal{A}_i \propto \kappa_{hht't'}$

Can we see VLQ loop effects by looking at di-Higgs mass, pT, etc.

Different from squark loop effects (PV functions, spin) – threshold shape

Recall triangle vs box cancellation in the SM





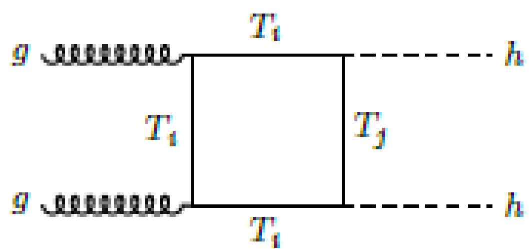
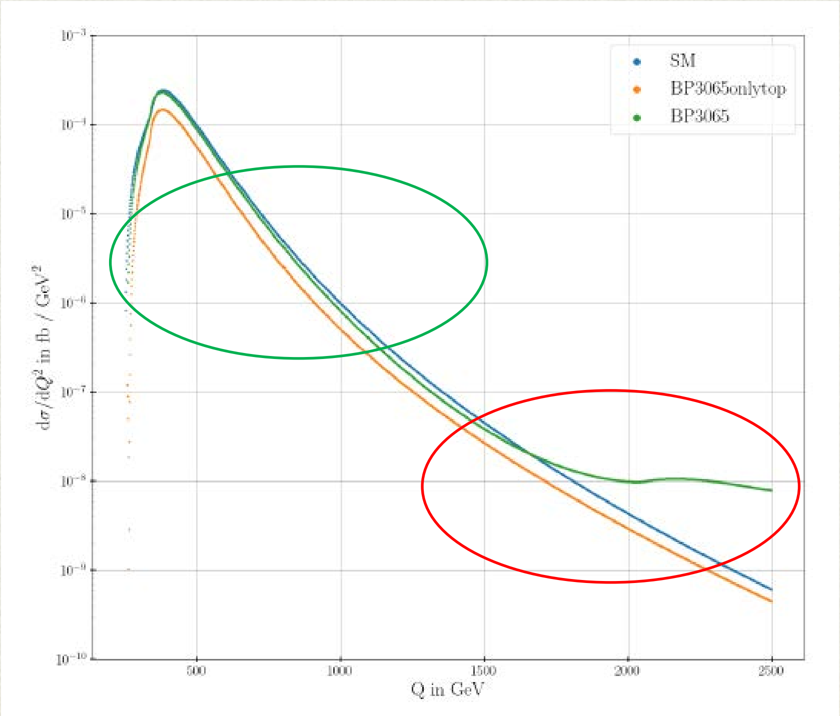


Figure 1: Box diagram

Box can induce thresholds at 2m(VLQ) & low mass tail



CPV in Strong Sector

- We introduce SO(6) 6-plet fermions for the explicit Lagrangian:

$$\mathcal{L}_{\rm str} = \bar{\Psi}^6 (i\not{D} - m_\Psi)\Psi^6 - \bar{\Psi}^6_L (Y_1 \Sigma + Y_2 \Sigma^2)\Psi^6_R + \text{h.c.}$$

$$+\Delta_L \bar{q}^6_L \Psi^6_R + \Delta_R \bar{t}^6_R \Psi^6_L + \text{h.c.}$$

where $(q^6_L)_t = (\Upsilon^t_L)^T q_L\,, \quad t^6_R = (\Upsilon^t_R)^T t_R$

$$\Upsilon^t_L = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 & 1 & i & 0 & 0 \\ 1 & -i & 0 & 0 & 0 & 0 \end{pmatrix} \qquad \Upsilon^t_R = \begin{pmatrix} 0 & 0 & 0 & 0 & \cos\theta_t & i\sin\theta_t \end{pmatrix}$$

- CPV sources can be introduced in the strong sector parameters.

For simplicity, we consider a non-zero θ_t as a CPV source (others → real).

CPV in Higgs potential

- Higgs potential

$$V_{\rm eff}(\Phi_1,\Phi_2) = m_1^2\Phi_1^\dagger\Phi_1 + m_2^2\Phi_2^\dagger\Phi_2 - \left[m_3^2\Phi_1^\dagger\Phi_2 + {\rm h.c.}\right]$$
$$+\frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \quad +\lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1)$$
$$+\frac{\lambda_5}{2}(\Phi_1^\dagger\Phi_2)^2 + \lambda_6(\Phi_1^\dagger\Phi_1)(\Phi_1^\dagger\Phi_2) + \lambda_7(\Phi_2^\dagger\Phi_2)(\Phi_1^\dagger\Phi_2) + {\rm h.c.} \quad + \mathcal{O}(\Phi_{1,2}^6)$$

$$\mathrm{Im}\,[\lambda_6] = \mathrm{Im}\,[\lambda_7] = \frac{4}{3}\frac{\mathrm{Im}[m_3^2]}{f^2} \propto \sin 2\theta_t, \quad \mathrm{Im}[\lambda_5] \sim 0$$

- Yukawa interactions

$$\zeta_t = \frac{Y_1}{Y_2}$$

$$\mathcal{L}_{\rm eff}^Y \propto -\bar{q}_L\left[(\cos\theta_t + i\zeta_t\sin\theta_t)\tilde{\Phi}_1 + (\zeta_t\cos\theta_t + i\sin\theta_t)\tilde{\Phi}_2\right]t_R + {\rm h.c.} + \mathcal{O}(\Phi_{1,2}^3)$$

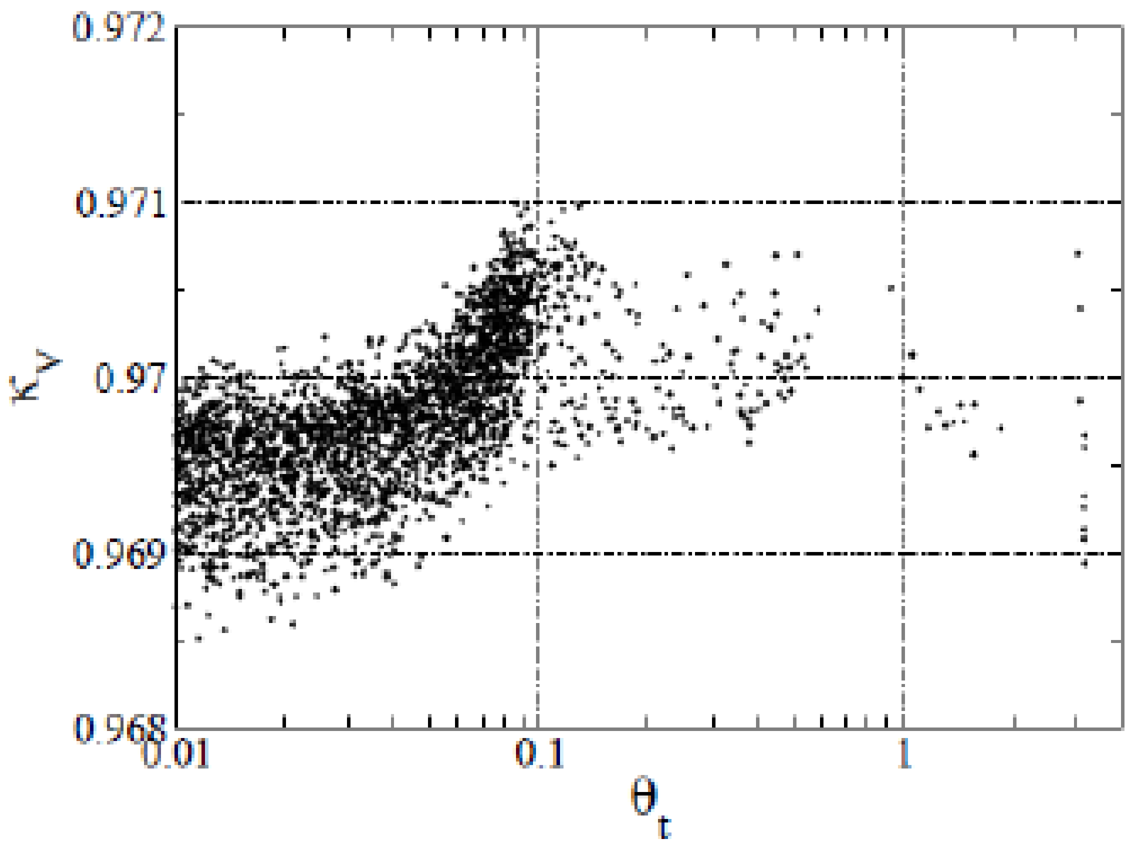
- All the potential & Yukawa sector parameters are determined by the strong sector.
- Both potential & Yukawa sector contain the CPV phase from the common origin.

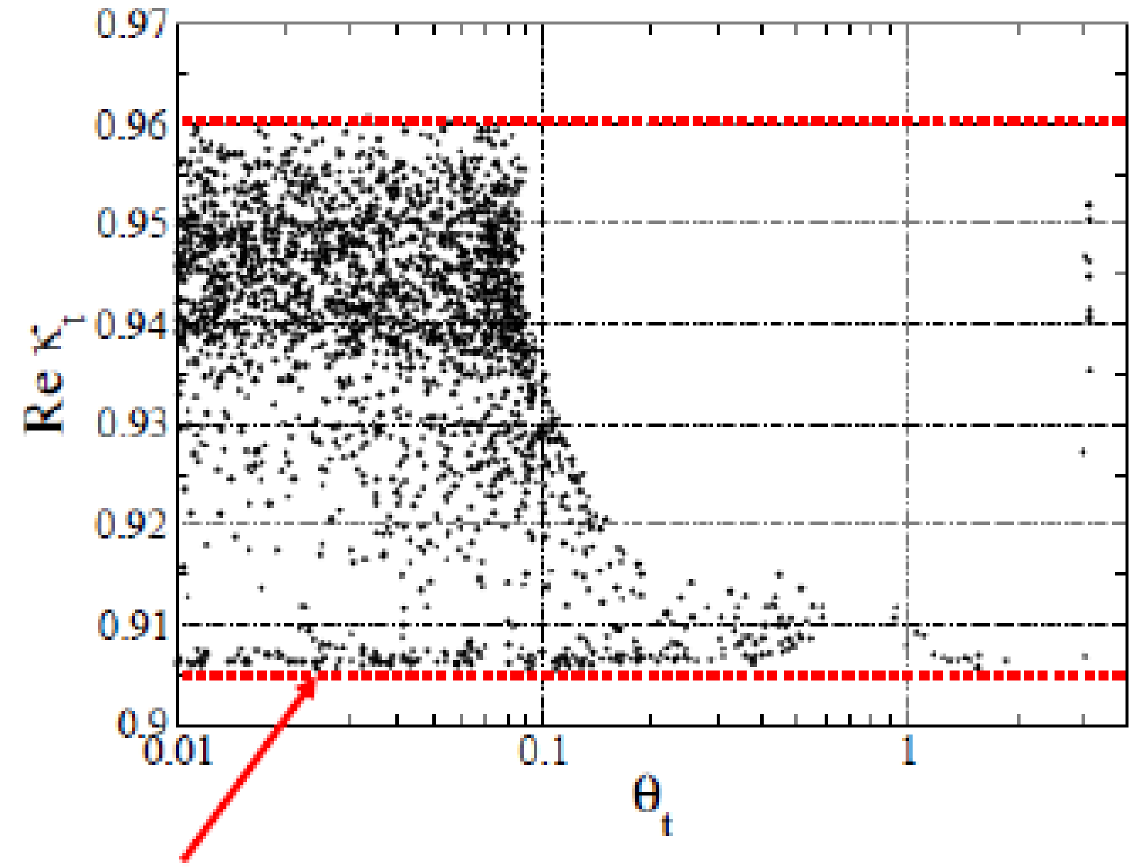
h(125) couplings

- f = 1 TeV

$$\kappa_V \simeq 1 - \frac{\xi}{2}\left(1 - \frac{1}{2}\sin^2 2\beta \sin^2 2\theta_t\right)$$

$$\mathrm{Re}\,\kappa_t \simeq 1 - \xi\left(\frac{3}{2} + \frac{\zeta_t \tan\beta}{1 - \zeta_t \tan\beta}\right)$$

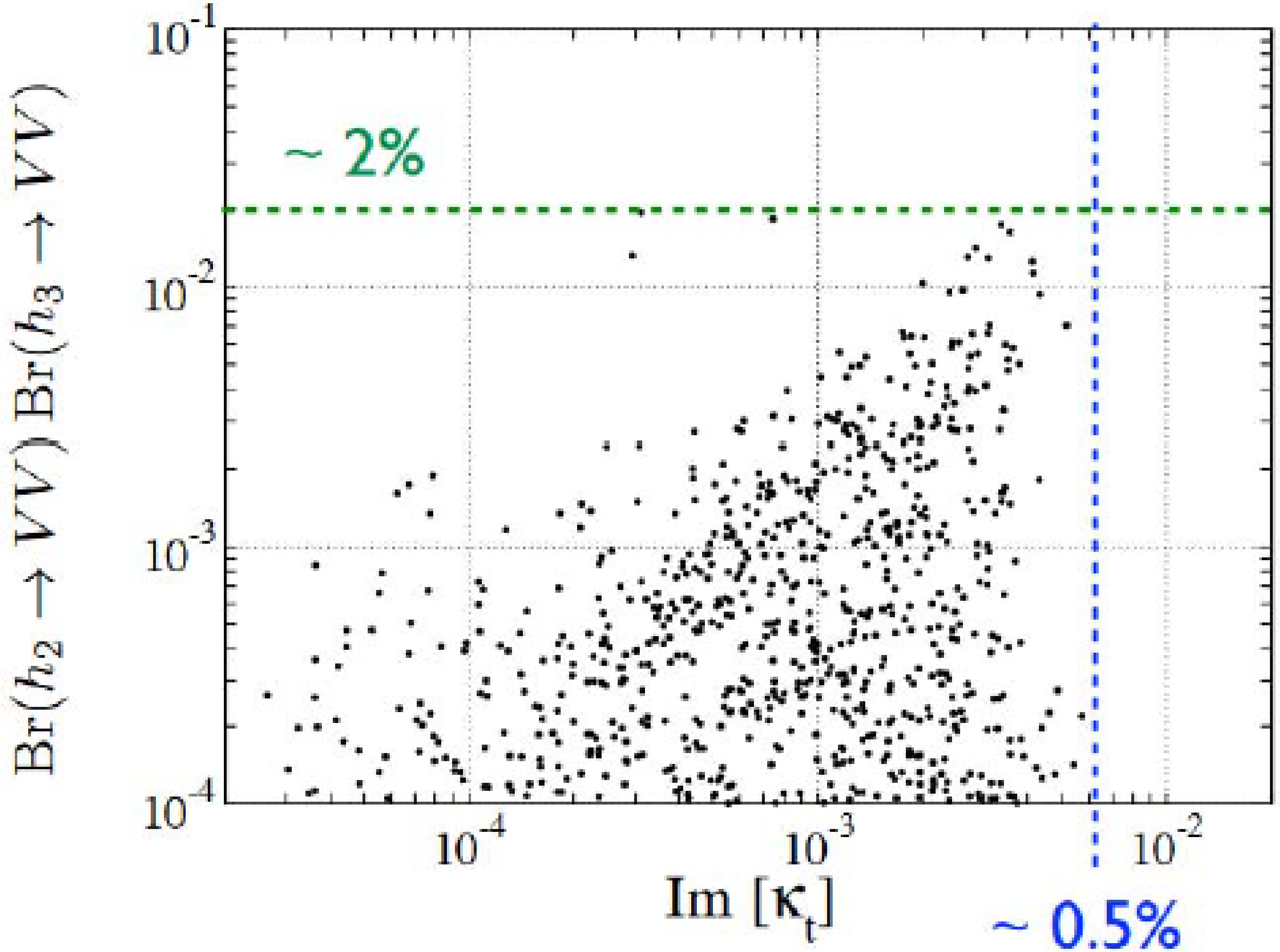


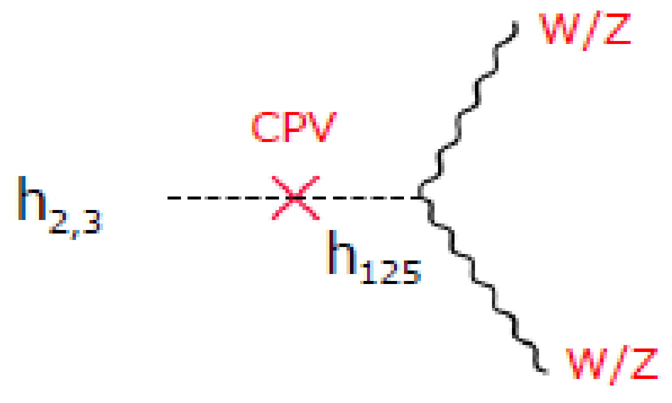


$$\sim 1 - \frac{3}{2}\xi$$

Peculiar signature: h(125), h(2), h(3) -> VV

Keus, King, Moretti, KY (2015)





- Both heavier neutral Higgs boson can decay into diboson.
- Correlation b/w Im[κ_t] and product of BRs can be important to test the CPV C2HDM!

CONCLUSIONS AND PERSPECTIVES

- A C2HDM is the simplest natural 2HDM alternative to its SUSY version (MSSM) in the context of CHMs

- We considered the SO(6)/SO(4)xSO(2) scenario with a broken C_2 which realises a(n Aligned) C2HDM – notably different from standard E2HDMs

- Higgs mass spectra *disappointingly similar*, yet existing observables can be used to discriminate between C2HDM and MSSM: k_V (delayed decoupling), heavy Higgs inter-decay patterns, (lighter) top partner spectrum in di-Higgs

- Complete phenomenological study of the C2HDM in progress (VLT/VLB decays to additional Higgses, etc.) including CPV

- Other interesting scenarios: exact C_2, etc., all making their way into tools

INTRODUCTION

Mainly motivated by the hierarchy problem we consider

SUPERSYMMETRY (SUSY)	**COMPOSITENESS**
solves it via top/stop cancellations in Higgs mass whatever the energy	solves it because whatever energy goes into Higgs constituents' motion

Both generates scalar/Higgs potential dynamically

We consider a Composite 2HDM and the MSSM as minimal realisations of EWSB based on a 2HDM structure

Composite 2HDM (C2HDM) simple natural alternative to the MSSM (SUSY)

What do we know about the

- MSSM? it provides 2 Higgs doublets and … *we know pretty much everything*
- C2HDM? it provides 2 Higgs doublets and … *I am going to tell you something*

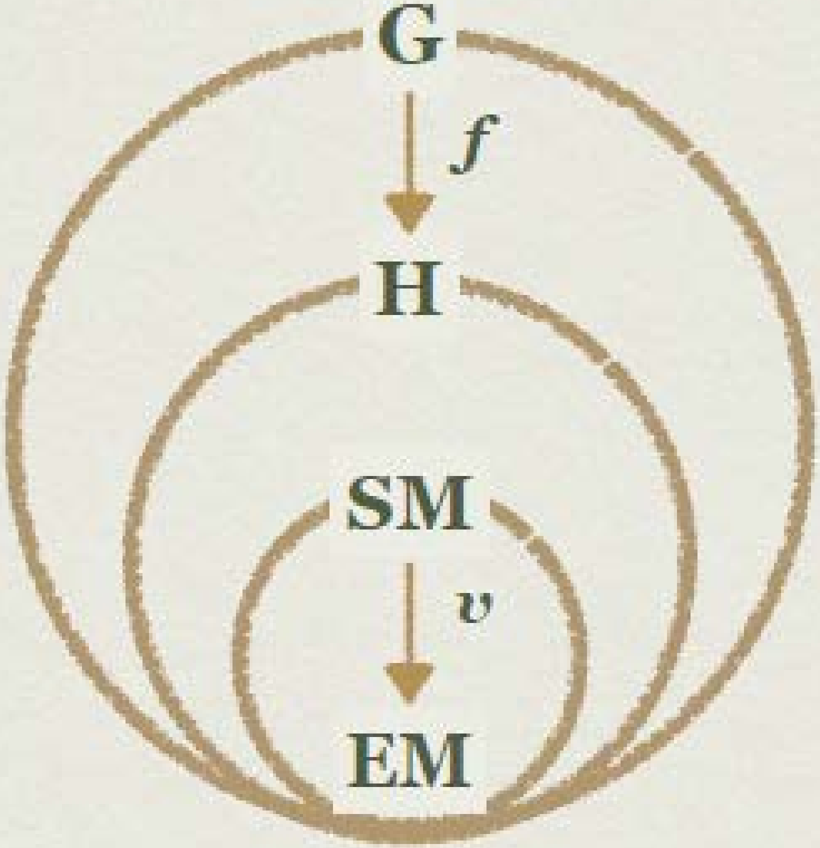
(Recall that Nature likes doublets.)

MSSM VS C2HDM

	Supersymmetry (Weak dynamics)	Compositeness (Strong dynamics)
Nature of Higgs	Elementary scalar Φ	Bound state $\langle\bar{\psi}\psi\rangle \sim \Phi$
Quadratic div. Light Higgs	Chiral symmetry $m_h \sim m_Z$ (ie, $\lambda \sim g$)	No elementary Higgs Pseudo Nambu-Goldstone (pNGBs)
Higgs structure	2HDM (aka MSSM) required for $m_{u,d}$	2HDM depending on a ~~global symmetry~~

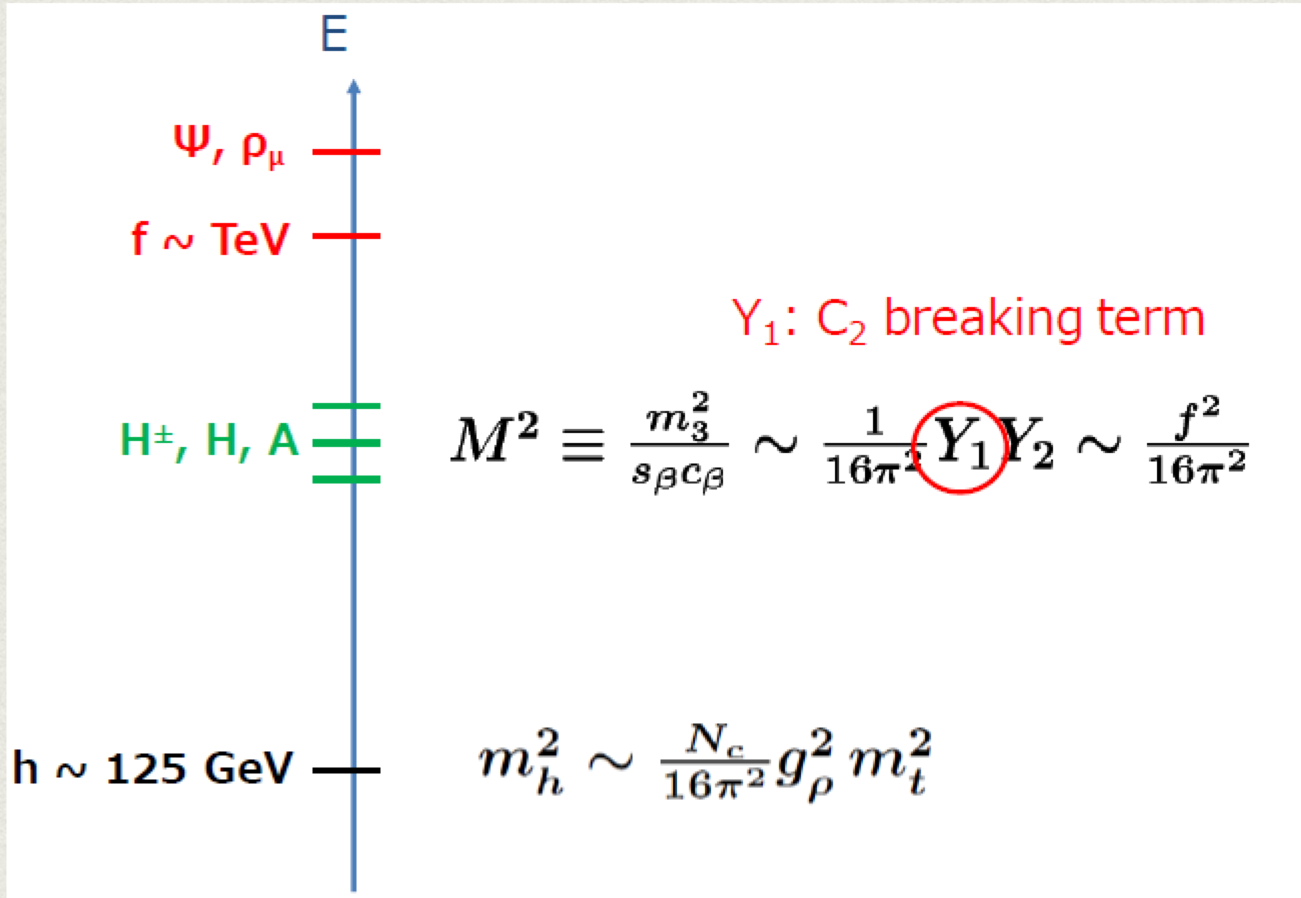
Q: can you distinguish the two paradigms by looking at 2HDM dynamics?

Basic rules for a Composite Higgs Model



- a global symmetry G above f (~ TeV) is spontaneously broken down to a subgroup H
- the structure of the Higgs sector is determined by the coset G/H
- H should contain the custodial group
- the number of NGBs (dim G - dim H) must be larger than (or at least equal to) 4
- the symmetry G must be explicitly broken to generate the mass for the (otherwise massless) NGBs

To recap:



★ For $m_h \sim 125$ GeV , we need $g_\rho \sim 5$.

★f → ∞ : All extra Higgses are decoupled

→ (elementary) SM limit.

★To get M≠0, we need C_2 breaking

(Yukawa alignment is required →A2HDM).

Present bounds on the CHM parameters

- **Higgs coupling measurements**

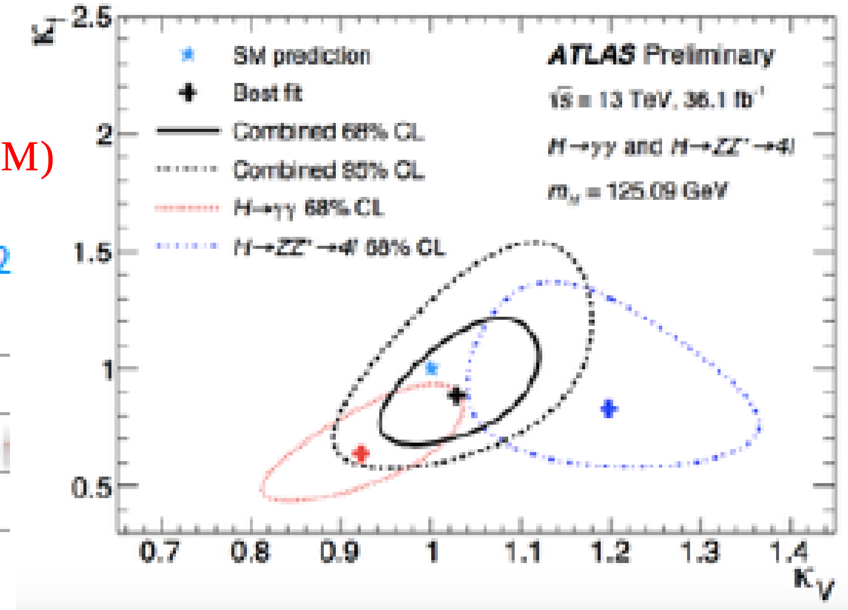
For SO(5)/SO(4): (leading corrections, can be adapted to C2HDM)

$$g_{HVV} = g_{HVV}^{SM}\sqrt{1-\xi};\quad g_{Hff} = g_{Hff}^{SM}\frac{(1-2\xi)}{\sqrt{1-\xi}} \qquad \xi = v^2/f^2$$

CMS Projection for precision of Higgs coupling measurement

L (fb^{-1})	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ
300	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]
3000	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]

In our analysis: $f \geq 600$ GeV ($\xi \leq 0.17$)



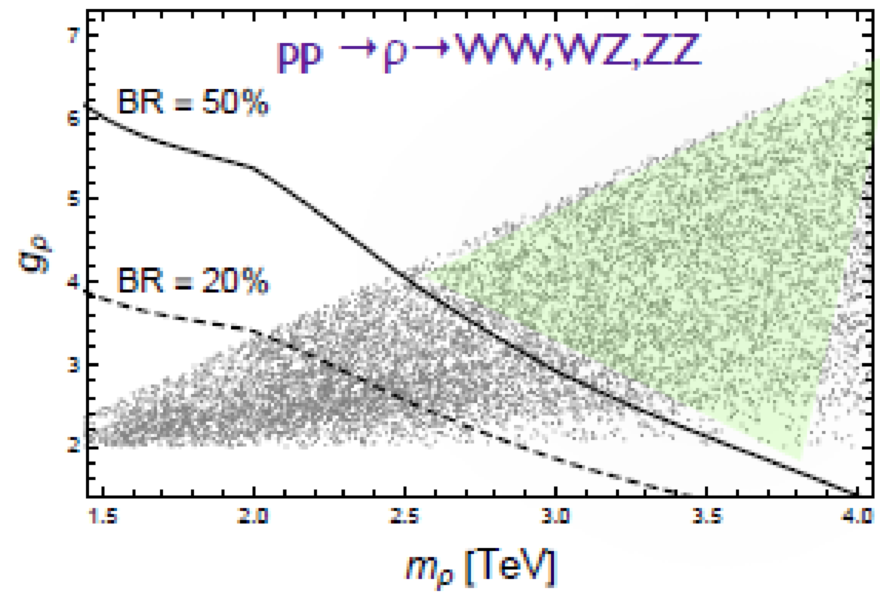
$\kappa_V = \frac{g_{hVV}}{g_{hVV}^{SM}}$

couplings still constrained at ≳10% level

$\xi \leq 0.2$

- **Direct searches of heavy spin-1 resonances**

Search for new vector resonances decaying in di-bosons in 36.7 fb^{-1} data at $\sqrt{s}$ = 13 TeV recorded with ATLAS (1708.04445) adapted to our composite 2HDM parameters



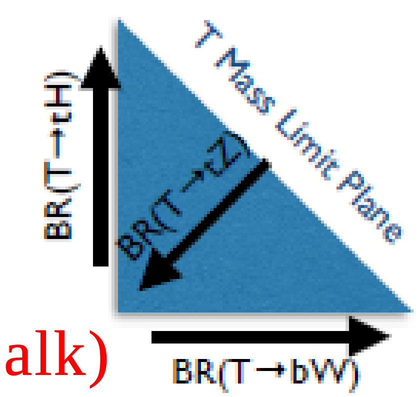
In our analysis: $m_\rho \geq 2.5$ TeV as function of g_ρ →

Very conservative: narrow width approximation, BR=50%

OK with bounds from EWPTs

- **Direct searches for partners of the 3rd generation quarks**

Lower mass bounds depend on the BR assumption: m_T(Wb=50%) > 1-1.2 TeV



BSM (pseudo)calars decays relax bounds: In our analysis: $m_T \geq 1$ TeV

(See Aurelio's talk)

Higgs Boson Masses

Same physical Higgs states as in the E2HDM: $h, H, A, H^{\pm}$

h → SM-like Higgs

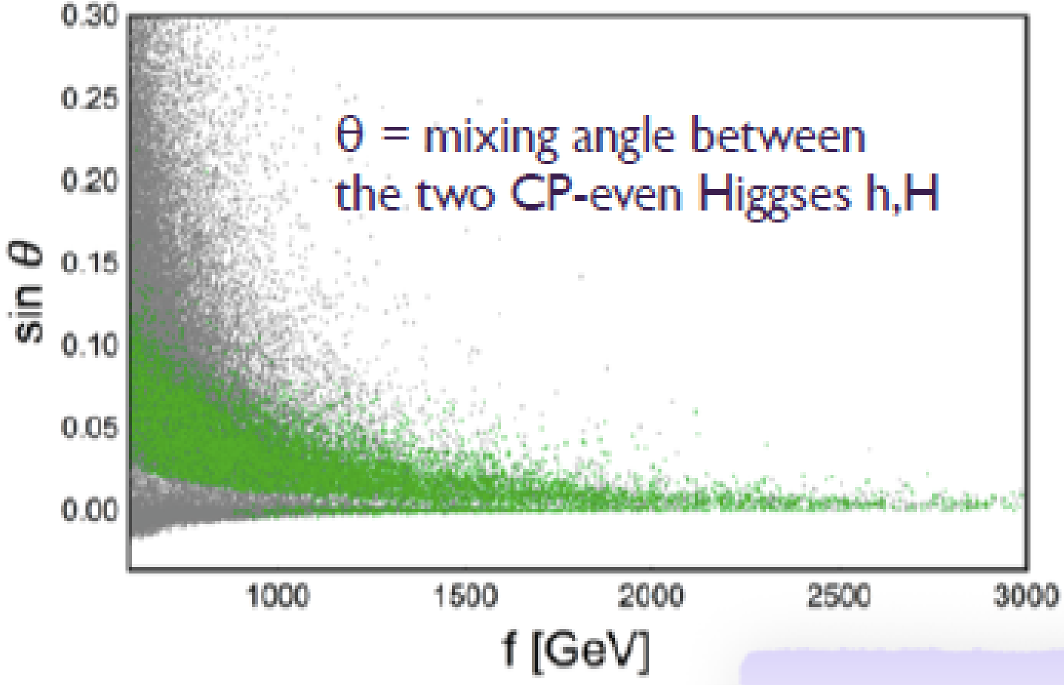
- They are identified in the Higgs basis after a rotation by an angle β: only one doublet provides a VEV and contains the GBs of W,Z $\quad \tan\beta = v_2/v_1$
- CP-even states:

$$m_h^2 = c_\theta^2 \mathcal{M}_{11}^2 + s_\theta^2 \mathcal{M}_{22}^2 + s_{2\theta} \mathcal{M}_{12}^2$$
$$m_H^2 = s_\theta^2 \mathcal{M}_{11}^2 + c_\theta^2 \mathcal{M}_{22}^2 - s_{2\theta} \mathcal{M}_{12}^2$$

$$\tan 2\theta = 2 \frac{\mathcal{M}_{12}^2}{\mathcal{M}_{11}^2 - \mathcal{M}_{22}^2}$$

The tadpole conditions involve only $\mathcal{M}_{11}$ and $\mathcal{M}_{12}$ while $\mathcal{M}_{22}$ is ~ unconstrained thus

$m_h \sim \mathcal{M}_{11} \sim v \quad m_H \sim \mathcal{M}_{22} \sim f$ and θ is predicted to be small: $\mathcal{O}(\xi)$ for large f



- **CP-odd & charged Higgses**

$m_A = \mathcal{M}_{22} + \mathcal{O}(v) \sim f$

$m_{H^\pm} = \mathcal{M}_{22} + \mathcal{O}(v) \sim f$

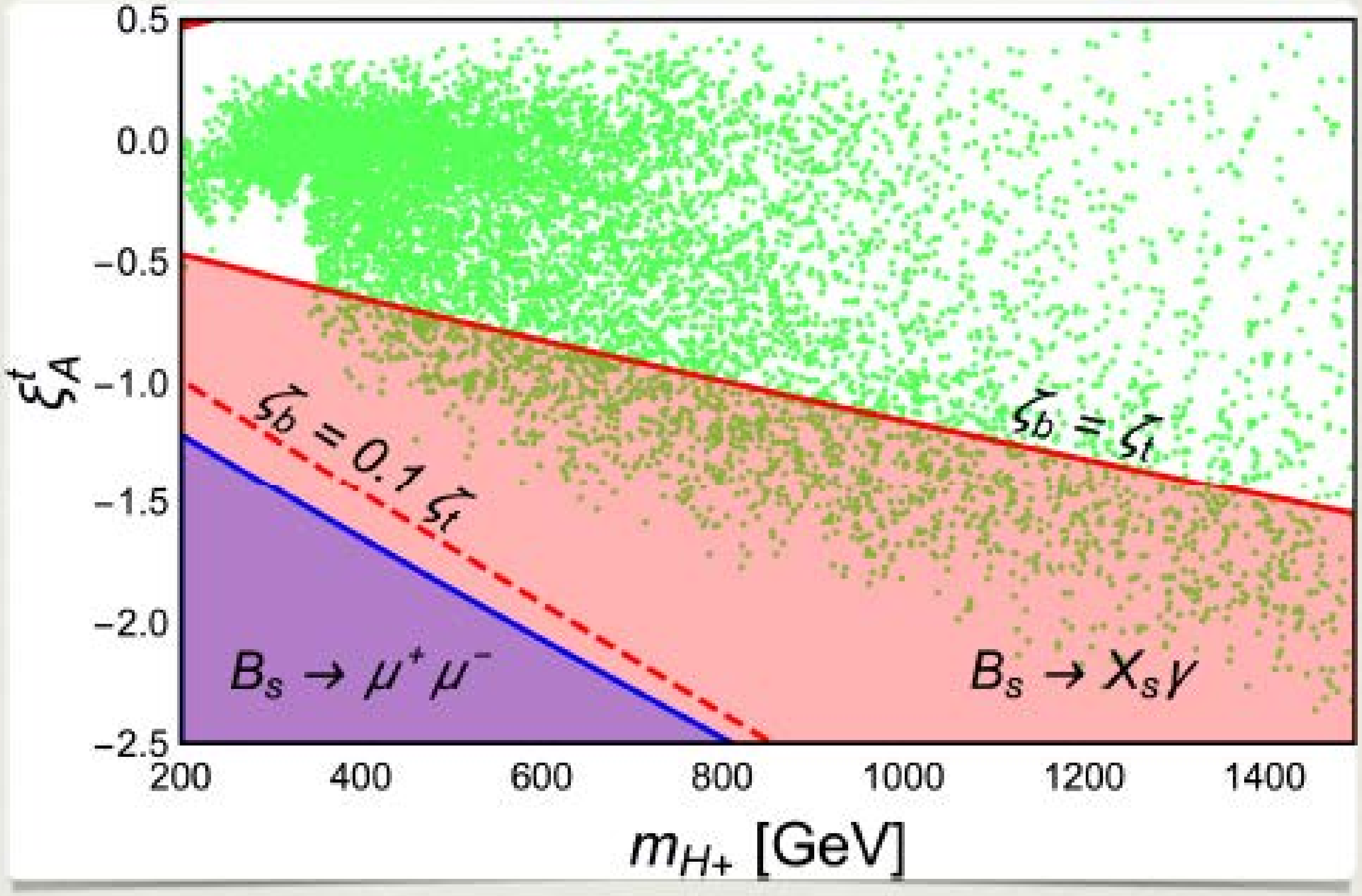
f → ∞ SM limit

$H, A, H^{\pm}$ decouple and $h \to h^{SM}$

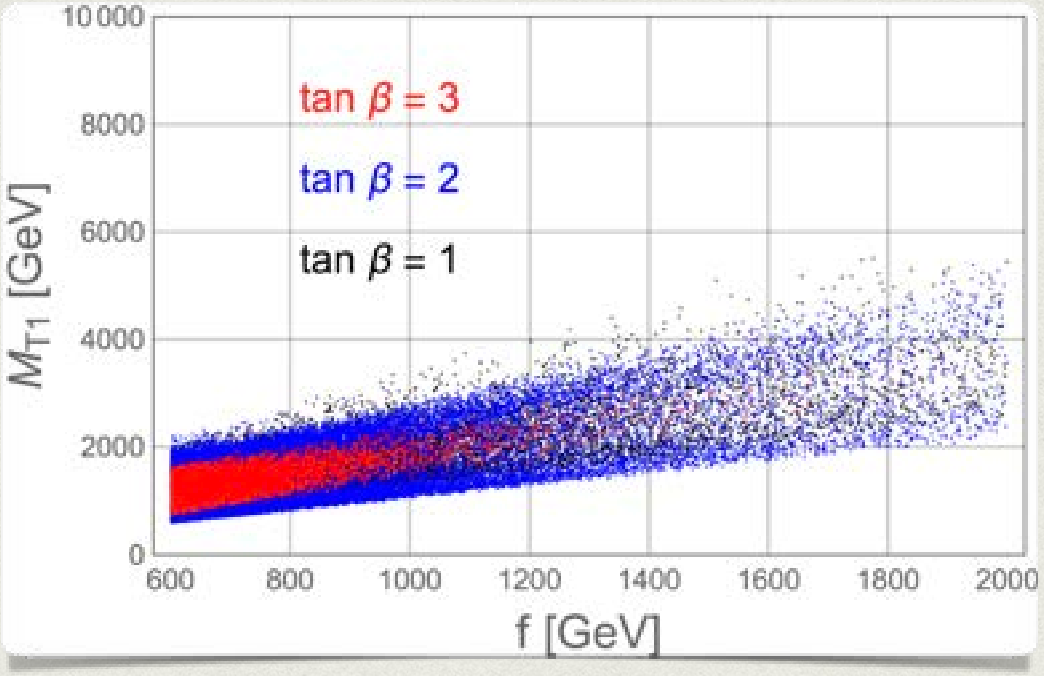
green points satisfy the bounds from direct and indirect Higgs searches

tested against HiggsBounds and HiggsSignals

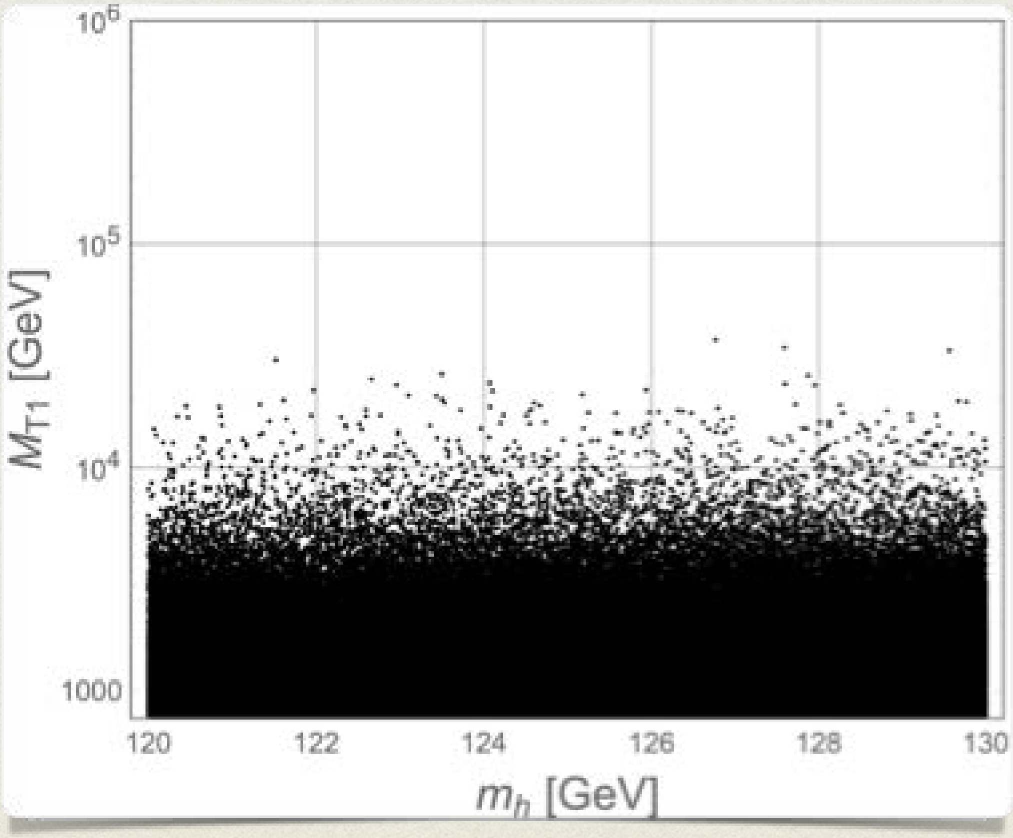
Flavour constraints



C2HDM: lightest top partner T_1



Reproducing the observed value of m_h requires a fermionic top partner in the C2HDM lighter than the scalar one in the MSSM



MSSM: lightest stop $\tilde{t}_1$