SUPERSYMMETRY
VS
COMPOSITENESS

2HDMs tell the story

Luigi Delle Rose

S. De Curtis, LDR, S. Moretti, K.Yagyu, arXiv:1803.01865
S. De Curtis, LDR, S. Moretti, A. Tesi, K. Yagyu, arXiv:1805.xxxxx

INTRODUCTION - Q&A

Q. Is the discovered Higgs the SM one?

Q. Is it elementary or composite?

Q. Any other scalar accompanying it?
(*minimality is not always a good guiding principle*)

Q. Which is the mechanism behind EWSB?

Q. How can we address the hierarchy problem?

Q. Do we really understand it?

Q. … ? … ? … ? … ?

INTRODUCTION - Q&A

Q.	Is the discovered Higgs the SM one?	A.	we don’t know
Q.	Is it elementary or composite?	A.	we don’t know
Q.	Any other scalar accompanying it? (*minimality is not always a good guiding principle*)	A.	we don’t know
Q.	Which is the mechanism behind EWSB?	A.	we don’t know
Q.	How can we address the hierarchy problem?	A.	<u>*Susy*</u> and <u>*compositeness*</u> are the best-known paradigms
Q.	Do we really understand it?	A.	probably not
Q.	… ? … ? … ? … ?	A.	we don’t know

LHC is doing a great job in helping us answering these questions

Future machine will do much better

INTRODUCTION

mainly motivated by the hierarchy problem we consider

SUSY **COMPOSITE**

Their phenomenology is very rich and interesting:
effects in the Higgs couplings, extended scalar sector, new resonances

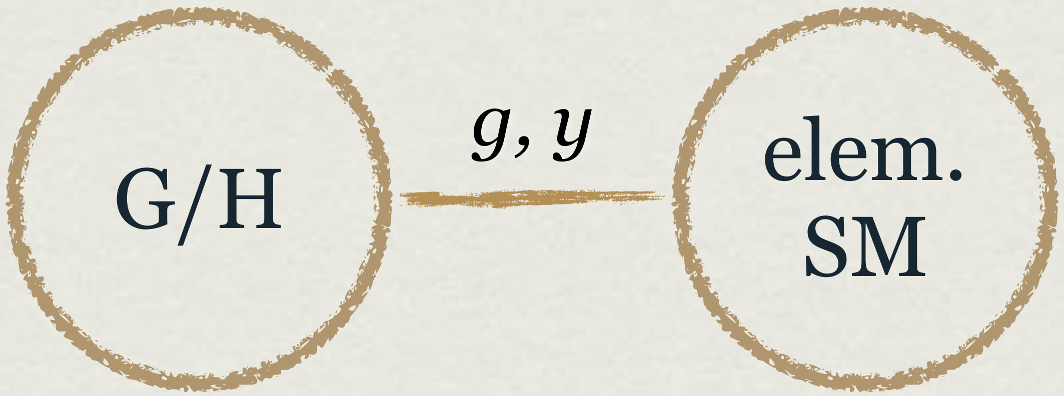
we consider a Composite 2HDM and the MSSM as
minimal realisations of EWSB based on a 2HDM structure

a composite 2HDM is the simplest natural 2HDM alternative to SUSY

What do we know about the

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

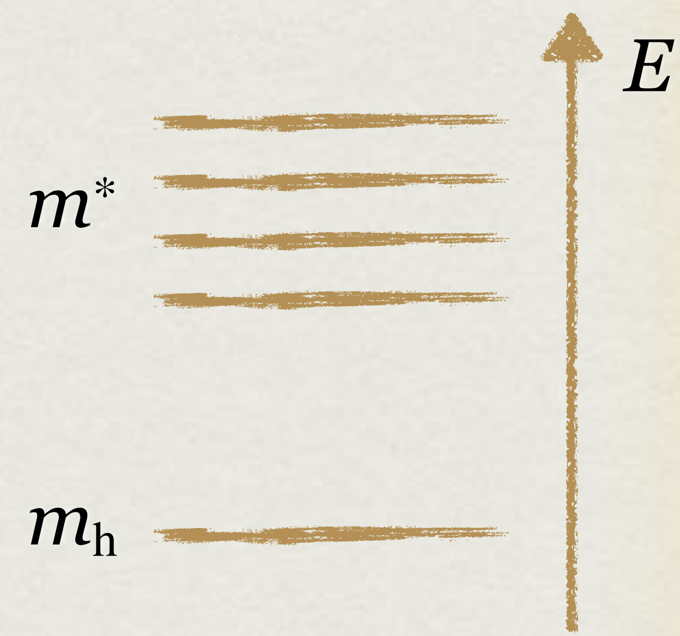
Symmetry fixes (almost) everything



we borrow this idea from QCD

Nature has already realised this mechanism

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



a large separation with the Higgs can be achieved if we identify it with a NGB state

the mixing breaks the global symmetry and generates a one-loop effective potential

Cooking recipe

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

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) $\times$ SO(2)	8	$\mathbf{4_{+2}} + \bar{\mathbf{4}}_{\mathbf{-2}} = 2\times(\mathbf{2},\mathbf{2})$
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) $\times$ 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) $\times$ 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) $\times$ U(1)	8	$\mathbf{4}_{-5} + \bar{\mathbf{4}}_{\mathbf{+5}} = 2\times(\mathbf{2},\mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$

Mrazek et al., 2011

Cooking recipe

- **G/H** **SO(6)/SO(4)xSO(2)**
  - *the coset delivers 8 NGBs (2 Higgs doublets)*
  - *spin 1/2 and 1 resonances*
- **elementary/composite mixing**
  - *no freedom in the gauge sector*
  - *partial compositeness among fermions (different reps. under G)*
- **discrete symmetries**

  CP, C_2
- **constraints**

  calculability of the effective potential, absence of FCNC, constraints from flavour observables, Higgs data and direct searches

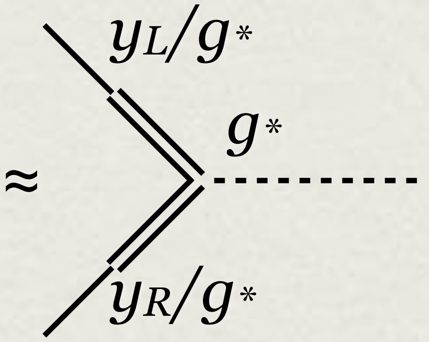
Partial compositeness

linear interactions between composite and elementary 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 the IR $\quad -\mathcal{L} = m^* \bar{T}\, T + y\, f\, \bar{t}\, T \quad \longrightarrow$ ***partial compositeness***

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

$$\begin{aligned} \mathcal{L}_{\rm mix} + \mathcal{L}_{\rm strong} &= \Delta^I_L \bar{q}^{\mathbf{6}}_L \Psi^I_R + \Delta^I_R \bar{t}^{\mathbf{6}}_R \Psi^I_L \\ &+ \bar{\Psi}^I i \not{D} \Psi^I - \bar{\Psi}^I_L M^{IJ}_\Psi \Psi^J_R - \bar{\Psi}^I_L \left(Y^{IJ}_1 \Sigma + Y^{IJ}_2 \Sigma^2 \right) \Psi^J_R \end{aligned}$$

at least 2 heavy resonances are needed for a UV finite potential

$$\Sigma = U i \sigma_2 U^T \qquad U = \exp(i \frac{\Pi}{f})$$

$$\Pi = \sqrt{2} h^{\hat{a}}_\alpha T^{\hat{a}}_\alpha = -i \begin{pmatrix} 0_{4\times4} & h^{\hat{a}}_1 & h^{\hat{a}}_2 \\ -h^{\hat{a}}_1 & 0 & 0 \\ -h^{\hat{a}}_2 & 0 & 0 \end{pmatrix}$$

$$v^2 = v_1^2 + v_2^2$$

$$m_W^2 = \frac{g^2}{4} f^2 \sin^2 \frac{v}{f}$$

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

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

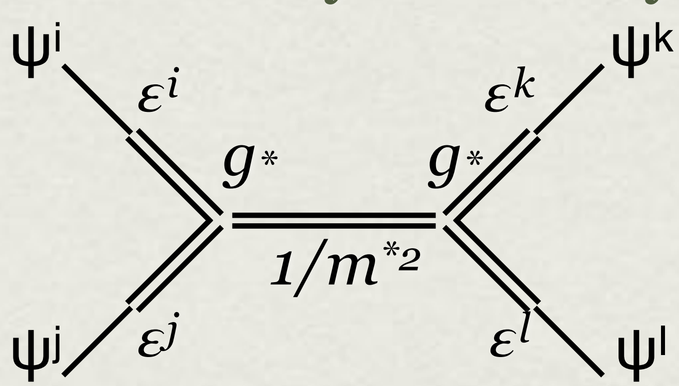
no freedom in the coefficient, fixed by the coset

possible solutions:

- CP
- C_2: ($H_1 \to H_1$, $H_2 \to -H_2$) which forbids H_2 to acquire a vev

FCNC

FCNC mediated by the heavy resonances



$$\sim \epsilon^i_L \epsilon^j_R \epsilon^k_L \epsilon^l_R \left(\frac{g^*}{m^*}\right)^2 a^{ijkl}, \quad a^{ijkl} \sim O(1)$$

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.*
- *flavour symmetries can also help to control these observables*

An issue with Higgs-mediated FCNC

the most general lagrangian is built from the H invariants in $\mathbf{r_L}$ x $\mathbf{r_R}$

$$-\mathcal{L}_{\rm yuk} = a^A_{ij} (\bar{q}^i_L)_{\mathbf{r_L}} \, U P_A U^\dagger \, (t^j_R)_{\mathbf{r_R}} + \text{h.c.} \qquad U \equiv \exp(i\frac{\Pi}{f})$$

FCNC may arise if there are

- several non trivial invariants in the product $\mathbf{r_L}$ x $\mathbf{r_R}$
- multiple embeddings of the SM fermions in $\mathbf{r_{L,R}}$

*For instance, **6** = **4** + **2**, provides three invariants (**4·4**, **2·2**, **2**∧**2**) in **6** x **6***

and two independent embeddings for t_R

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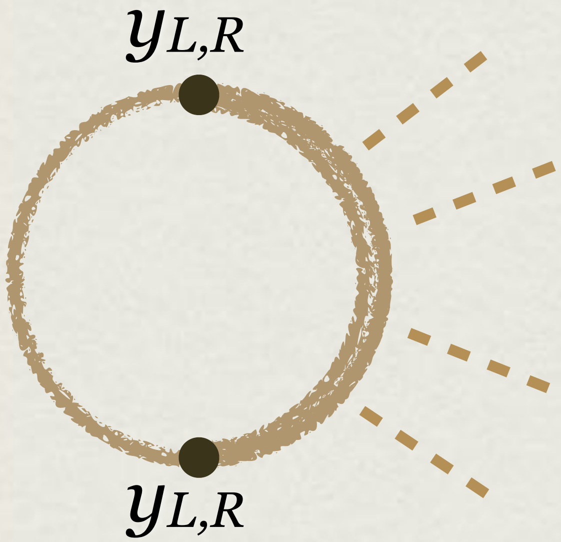
FCNC can be removed by

1. assuming C_2 in the strong sector and in the mixings *inert C2HDM*
2. requiring (flavour) alignment in the Yukawa couplings $Y_1^{IJ} \propto Y_2^{IJ}$

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

the ratio a_1/a_2 is predicted by the strong dynamics

The effective potential



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

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

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

without any tuning, the minimum of the potential is v ~ f

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

while, in the tuned direction,

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

C_2 breaking in the strong sector induces:

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

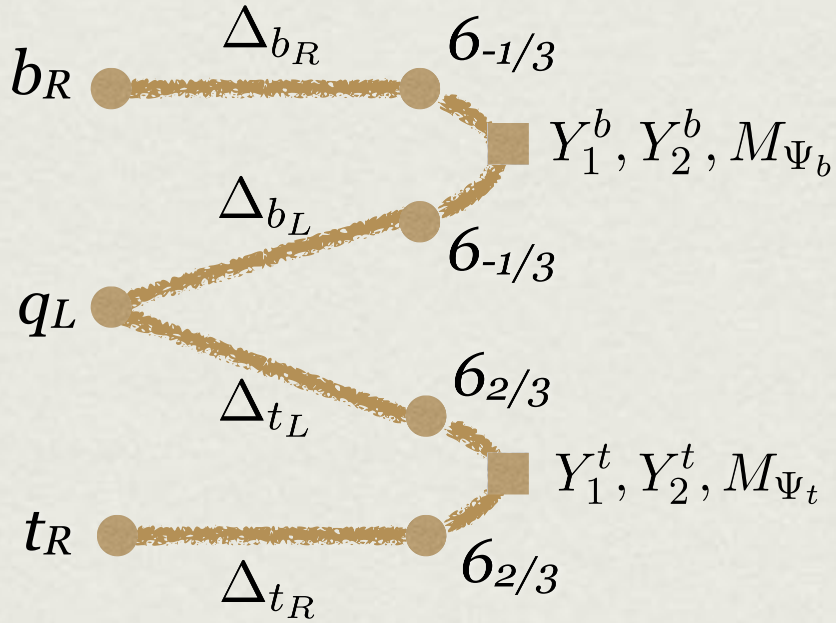
$$\lambda_6 = \lambda_7 = \frac{5}{3}\frac{m_3^2}{f^2}$$

it is not possible to realise a 2HDM-like scenario with a softly broken Z_2

Sampling the parameter space

C2HDM: we adopt the L-R structure based on the 2-site models which represents the minimal choice for a realistic and calculable effective potential

De Curtis et al., 2012



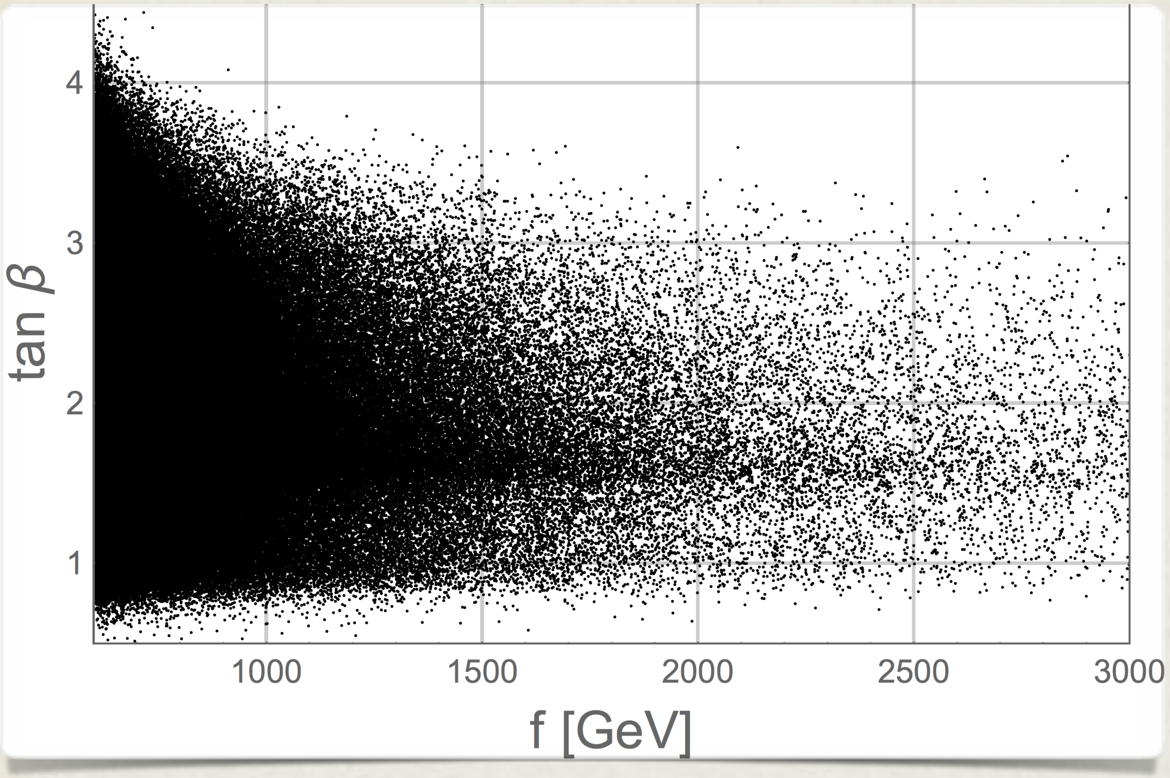
$$X = f,\, Y_1,\, Y_2,\, M_\Psi,\, \Delta_L,\, \Delta_R$$

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

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

MSSM: we use FeynHiggs 2.14.1 and scan the parameter space according to LHCHXSWG-2015-002:

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



- tan β is 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

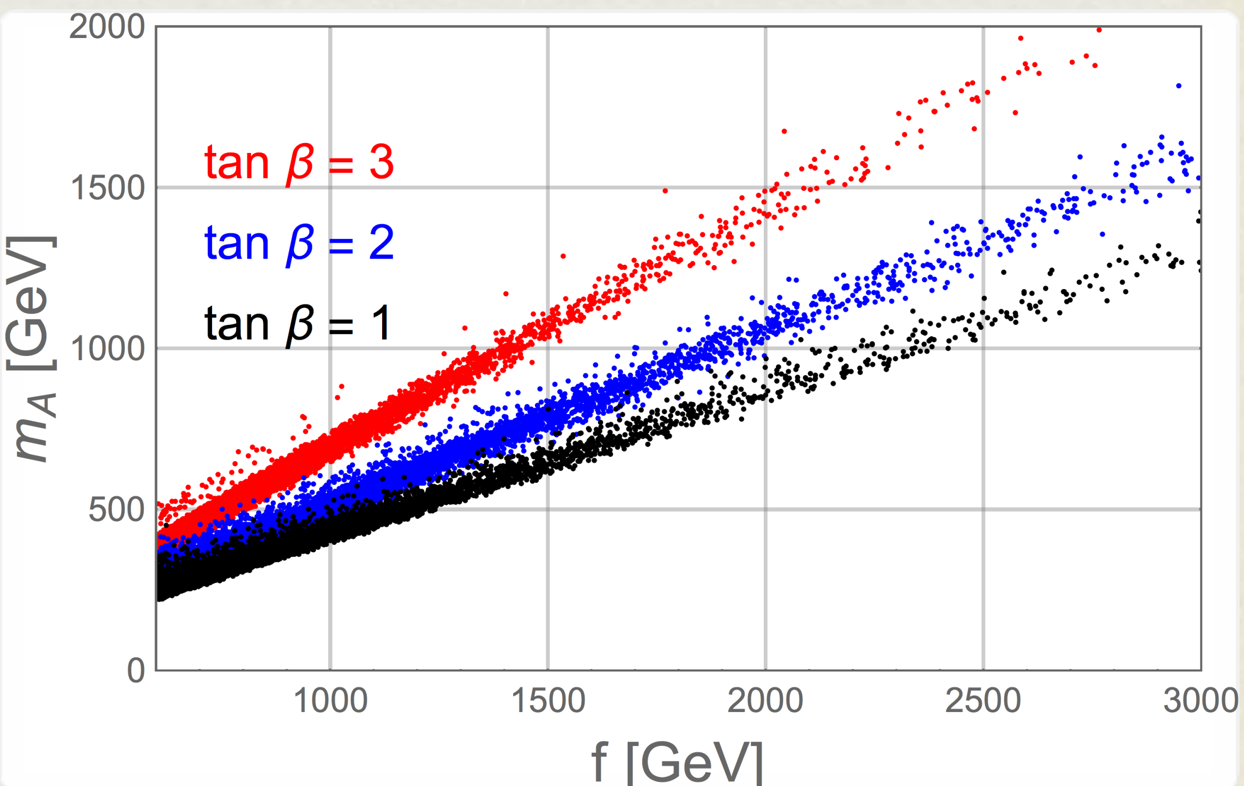
- m_H, m_A, m_{H+} grow with f (and tan β)

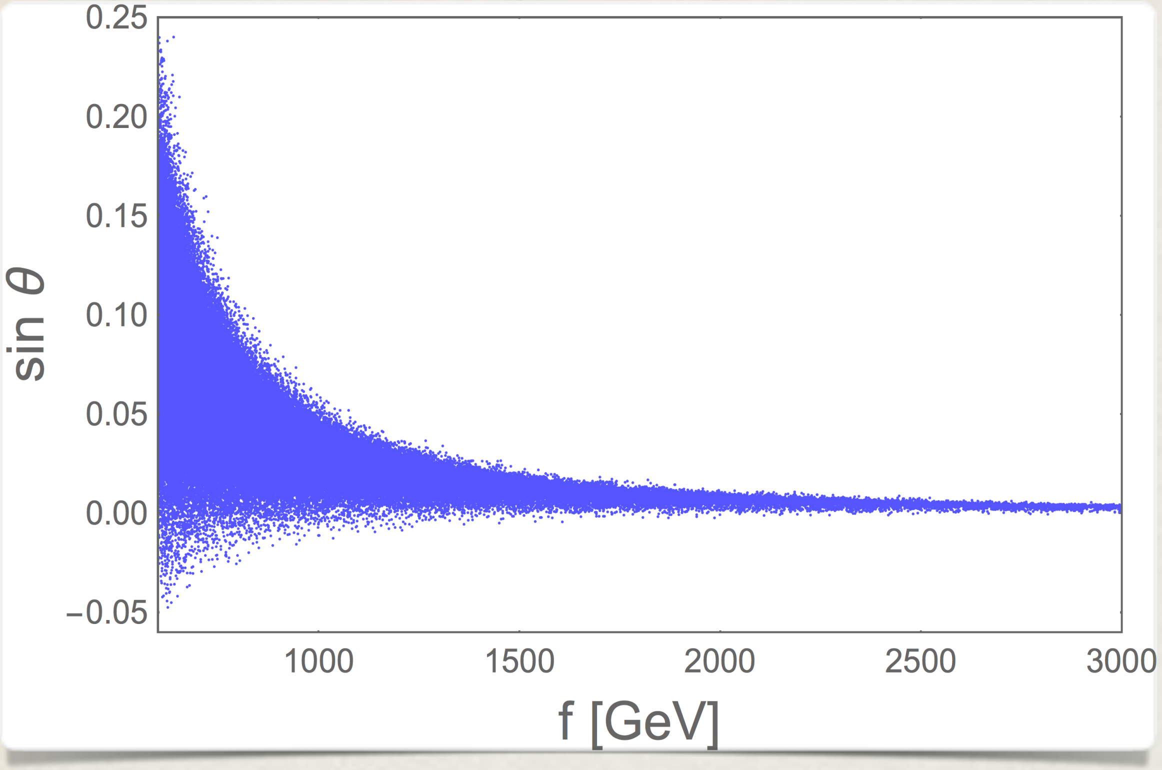
$$\mathcal{M}^2 = \begin{pmatrix} \Lambda_1 v^2 & \Lambda_6 v^2 \\ \Lambda_6 v^2 & \mathcal{M}_{22}^2 \end{pmatrix}$$

fixed by minimisation of V

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

- In the limit f → ∞ (+ EWSB), we recover the SM (not the E2HDM)





mixing between the CP-even states *h*, *H*

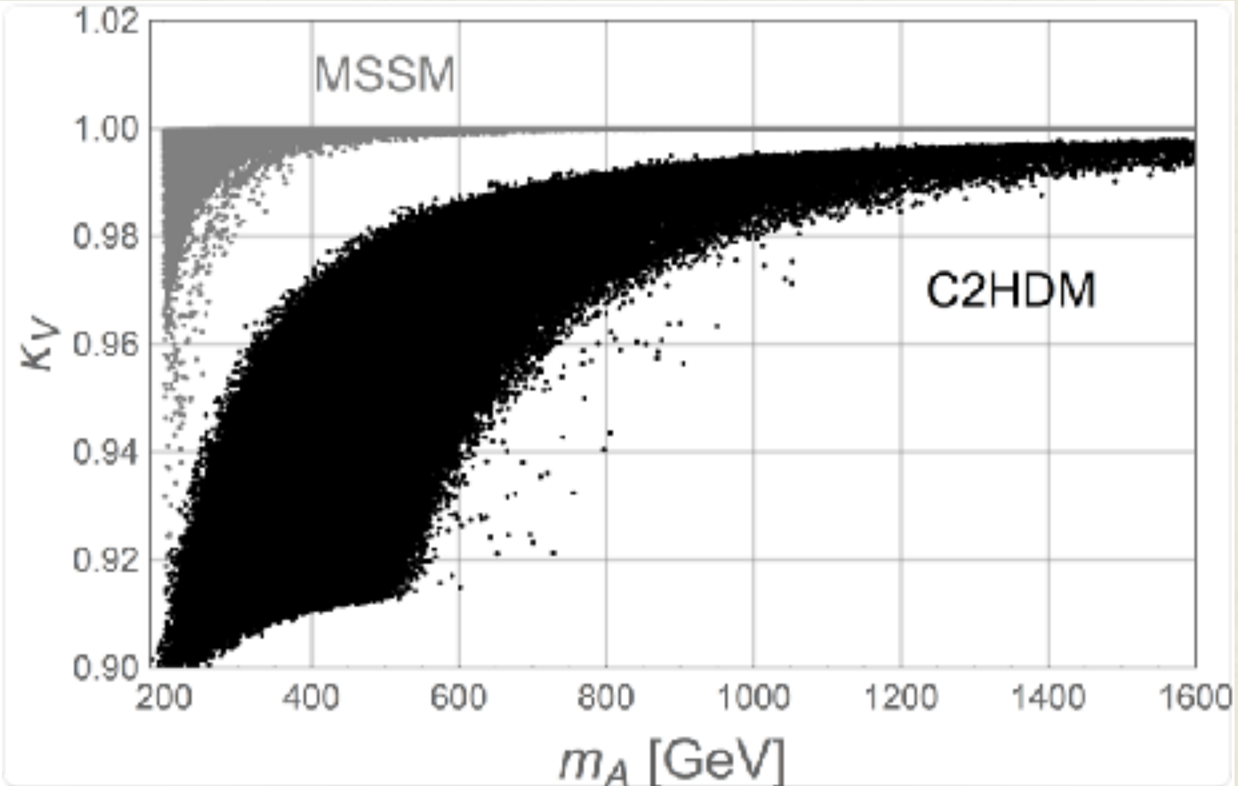
$$\tan 2\theta = -2\frac{\Lambda_6 v^2}{\mathcal{M}_{22}^2 - \Lambda_1 v^2} \sim c\frac{v^2}{f^2}$$

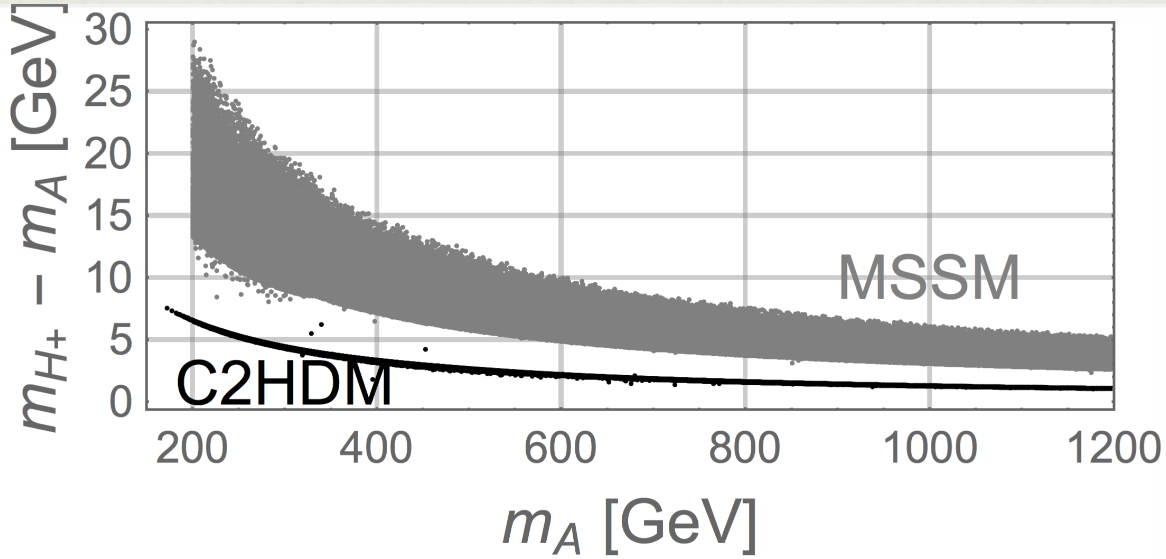
the SM-like Higgs coupling to W,Z

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

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

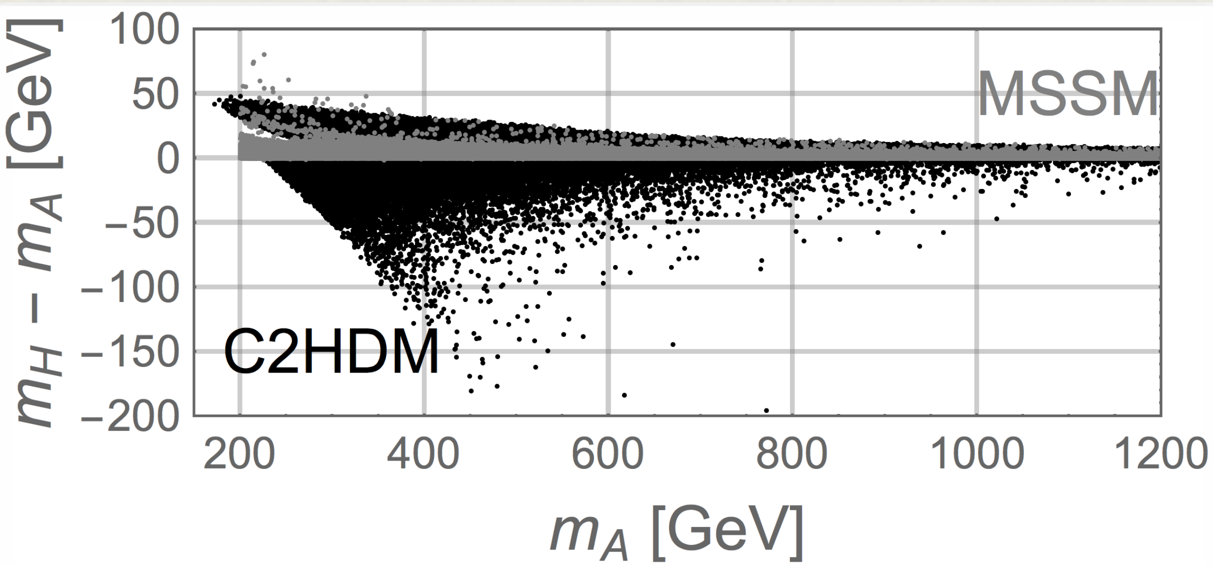
a relevant deviation is present even for no mixing





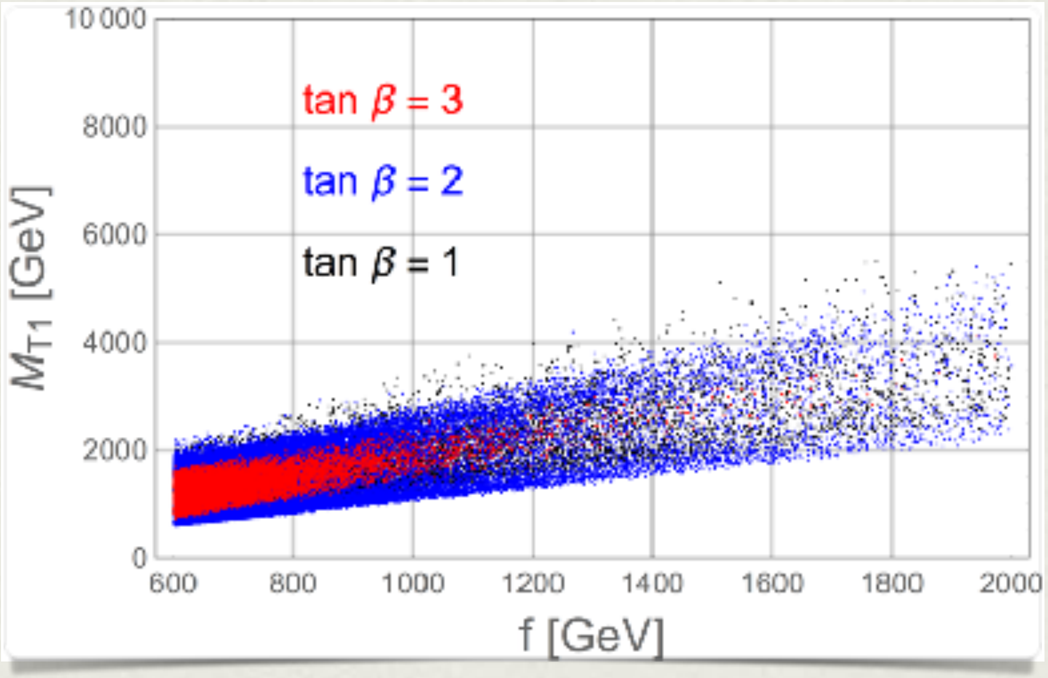
- m_{H+} and m_A are very close in both scenarios
- very sharp prediction in the C2HDM:

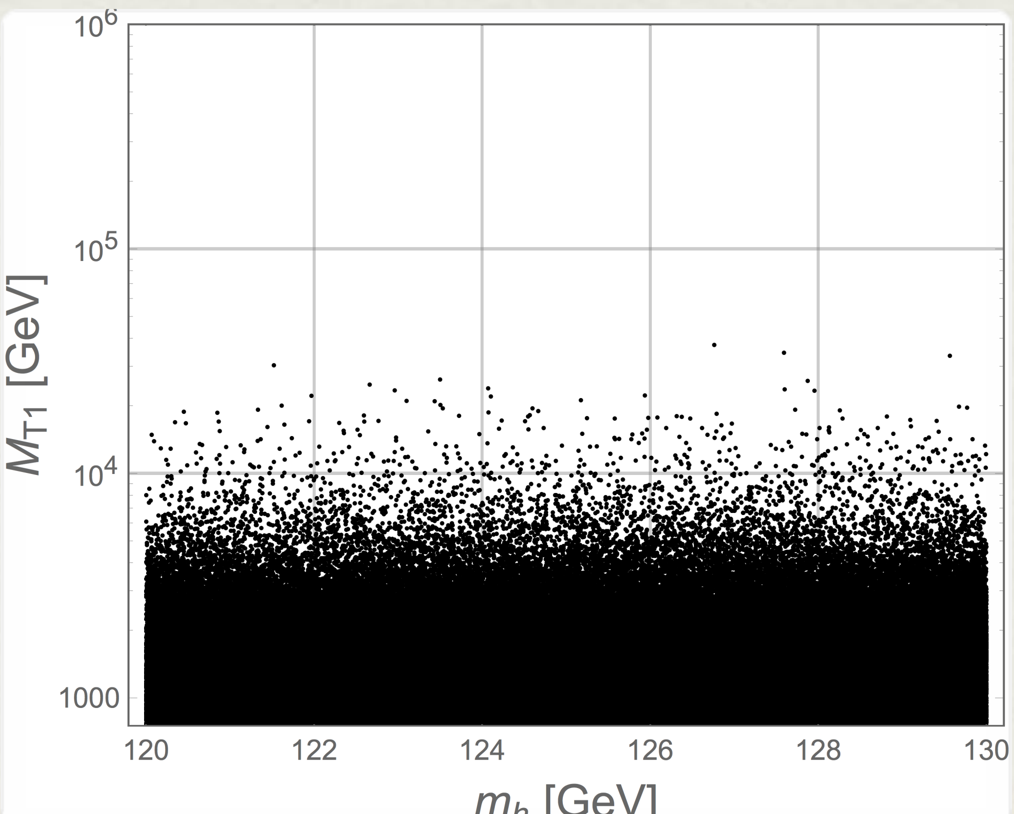
$$m_{H^\pm}^2 - m_A^2 \simeq \frac{\Delta_L^4}{m_*^4} v^2$$



- larger mass prediction in the C2HDM
- A → H Z can be an interesting channel discriminating the two scenarios
- H → A Z* could also be useful

C2HDM: lightest top partner T_1

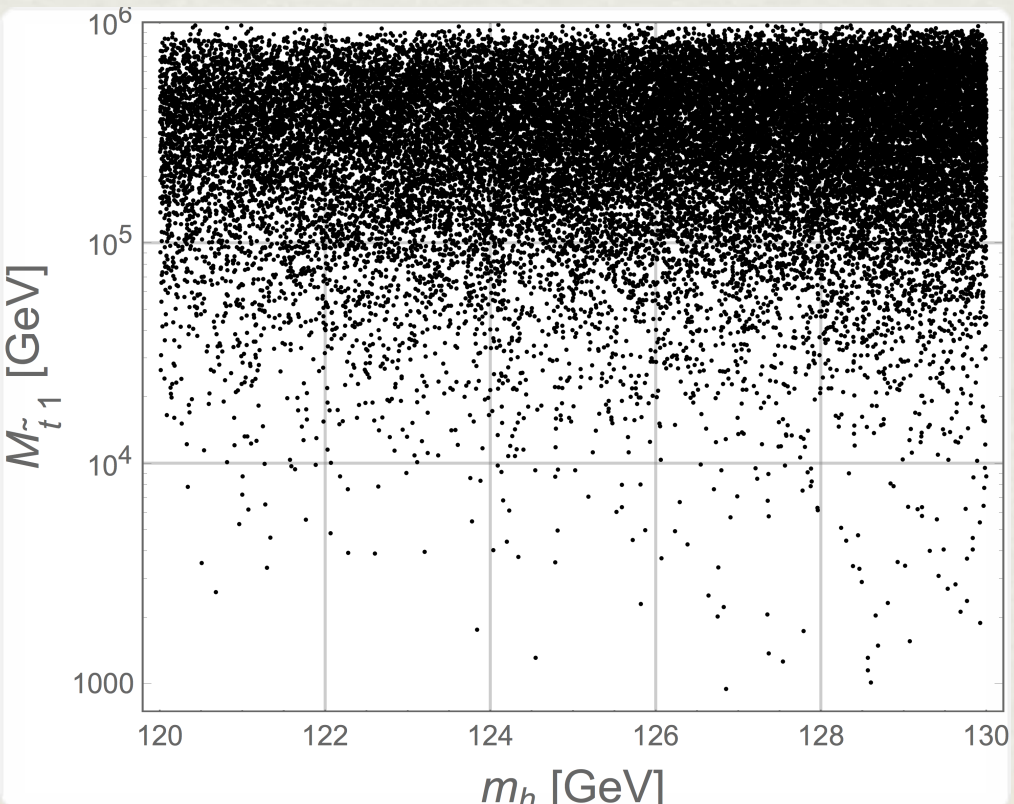




the heavy resonance in the **6** of SO(6) delivers 4 top partners, 1 bottom partner and 1 exotic fermion with Q = 5/3

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

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



CONCLUSIONS AND PERSPECTIVES

- a C2HDM is the simplest natural 2HDM alternative to SUSY
- we considered the SO(6)/SO(4)xSO(2) scenario with a broken C_2 which realises a (type-III) Composite 2HDM
- several observables can be used to discriminate between C2HDM and MSSM: k_V, mass spectrum, top partners, ...
- other interesting scenarios: exact C_2, spontaneously broken C_2, broken CP
- phenomenological study of the C2HDM: constraints and predictions for the LHC and future colliders