COMPOSITENESS
VS
SUPERSYMMETRY

(2HDMs tell the story)

Stefano Moretti, NExT Institute (Soton & RAL)

S. De Curtis, L. Delle Rose, SM, K.Yagyu, arXiv:1803.01865
S. De Curtis, L. Delle Rose, SM, A. Tesi, K. Yagyu, arXiv:1809.xxxxx

INTRODUCTION

Mainly motivated by the hierarchy problem we consider

SUSY **COMPOSITENESS**

Their phenomenology is very rich and interesting:
altered SM-like Higgs couplings, extended scalar sector, new resonances

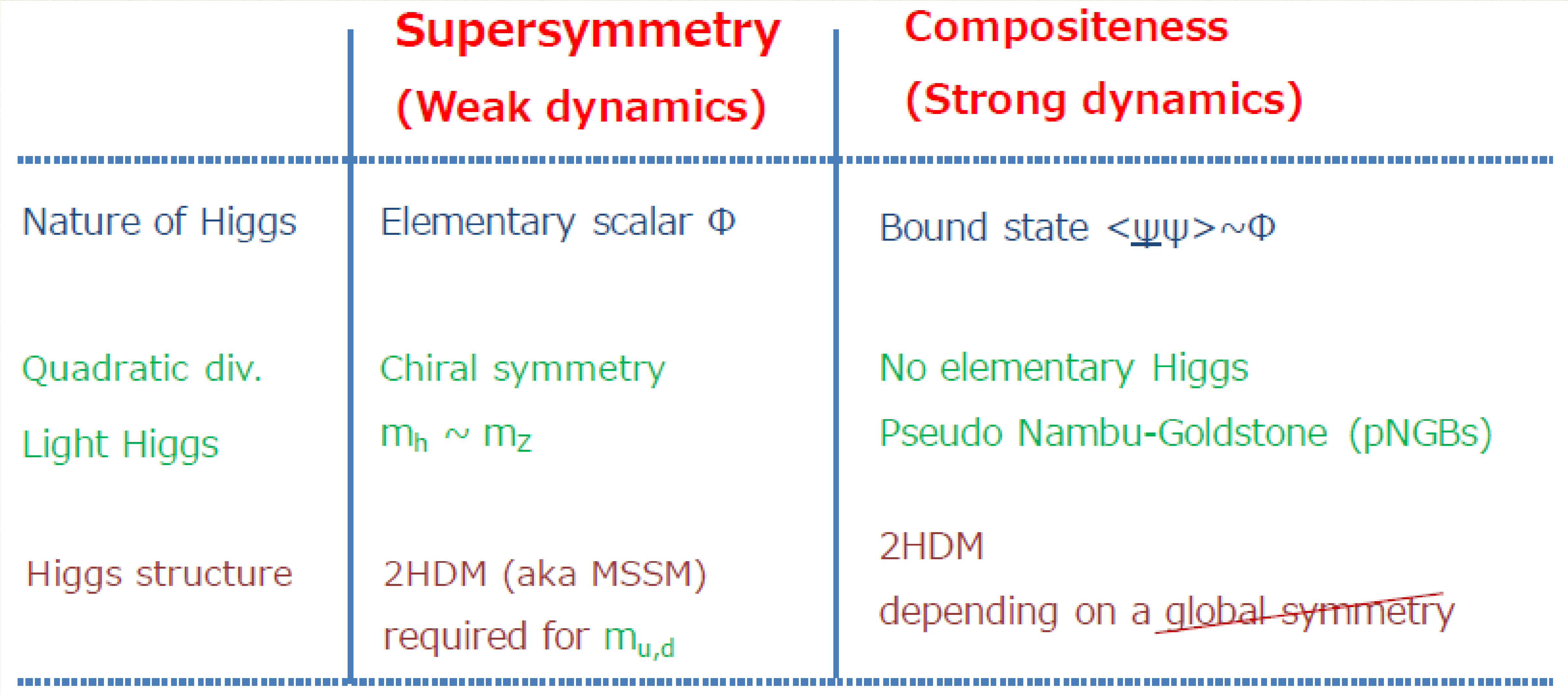
we consider a Composite 2HDM and the MSSM as
minimal realisations of EWSB based on a 2HDM structure

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*

C2HDM VS MSSM

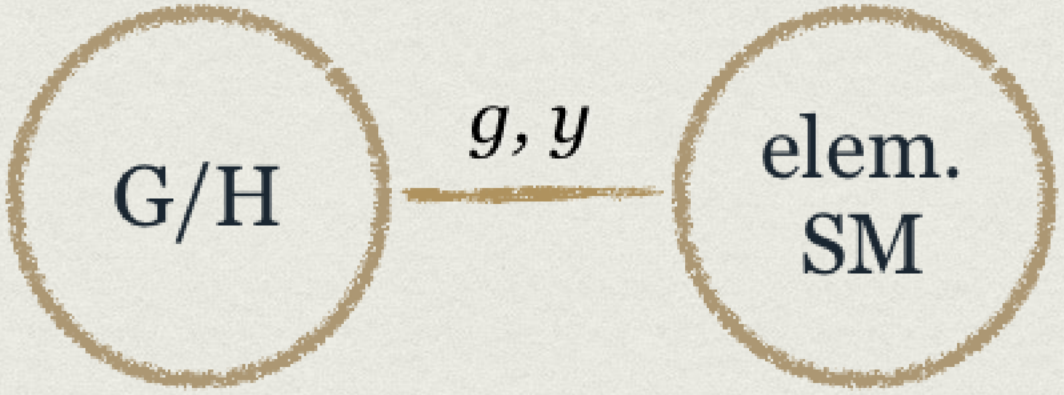


	Supersymmetry **(Weak dynamics)**	**Compositeness** **(Strong dynamics)**
Nature of Higgs	Elementary scalar Φ	Bound state $\langle\underline{\psi}\psi\rangle \sim \Phi$
Quadratic div.	Chiral symmetry	No elementary Higgs
Light Higgs	$m_h \sim m_Z$	Pseudo Nambu-Goldstone (pNGBs)
Higgs structure	2HDM (aka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

Can you distinguish the two paradigms by looking at 2HDM dynamics?

Nothing new?

Two sites structure:



We borrow this idea from QCD: ie,

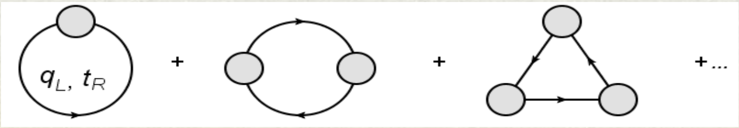
Nature has already realised this mechanism

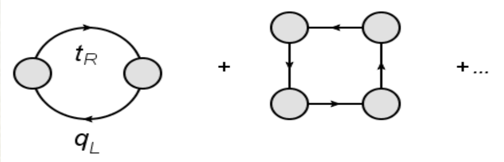
The coset delivers a set of states at a common mass scale: m^*

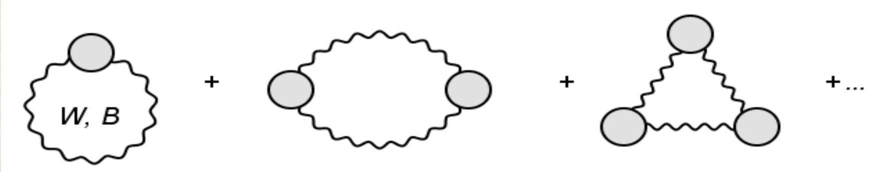
A large separation between new fermions/vector states and Higgses can be achieved if we identify these with pNGBs: m_h

Partial compositeness: composite/elementary mixing breaks the global symmetry H and generates a one-loop effective potential with the scalar part a la Coleman Weinberg (which we calculate for the first time)

Can use CCWZ (see Nagai's talk)

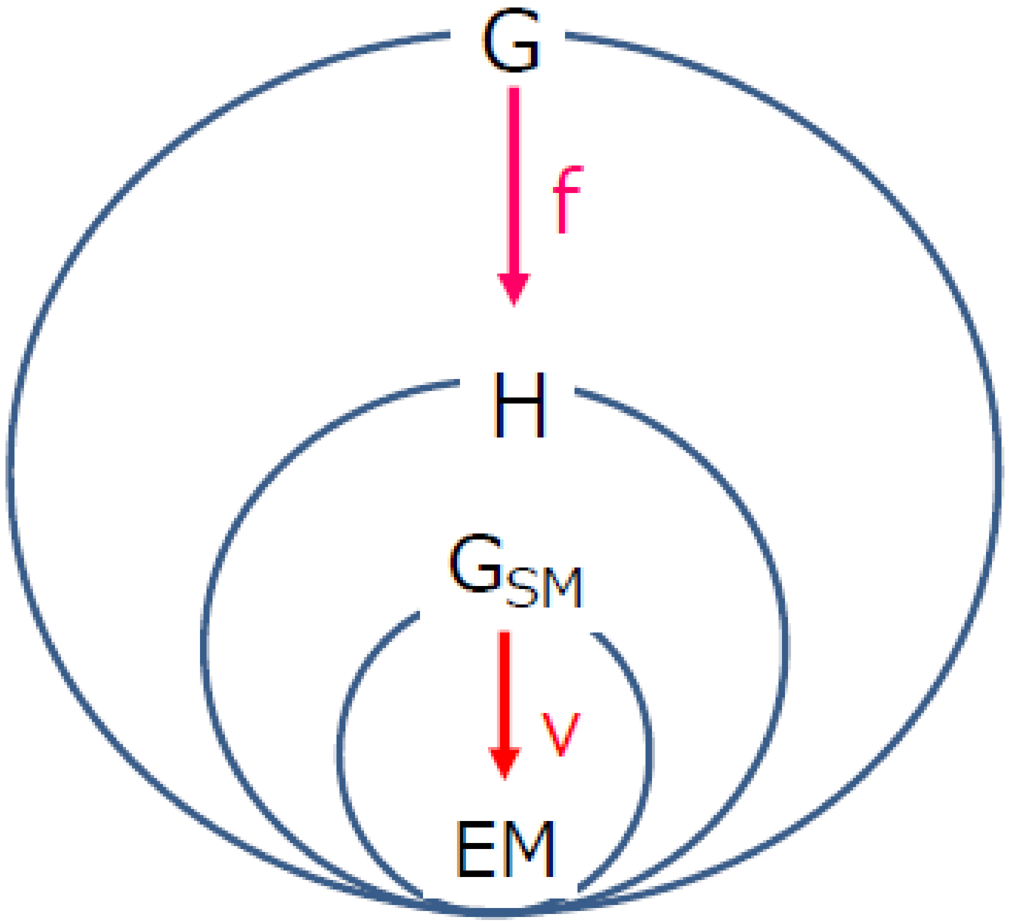




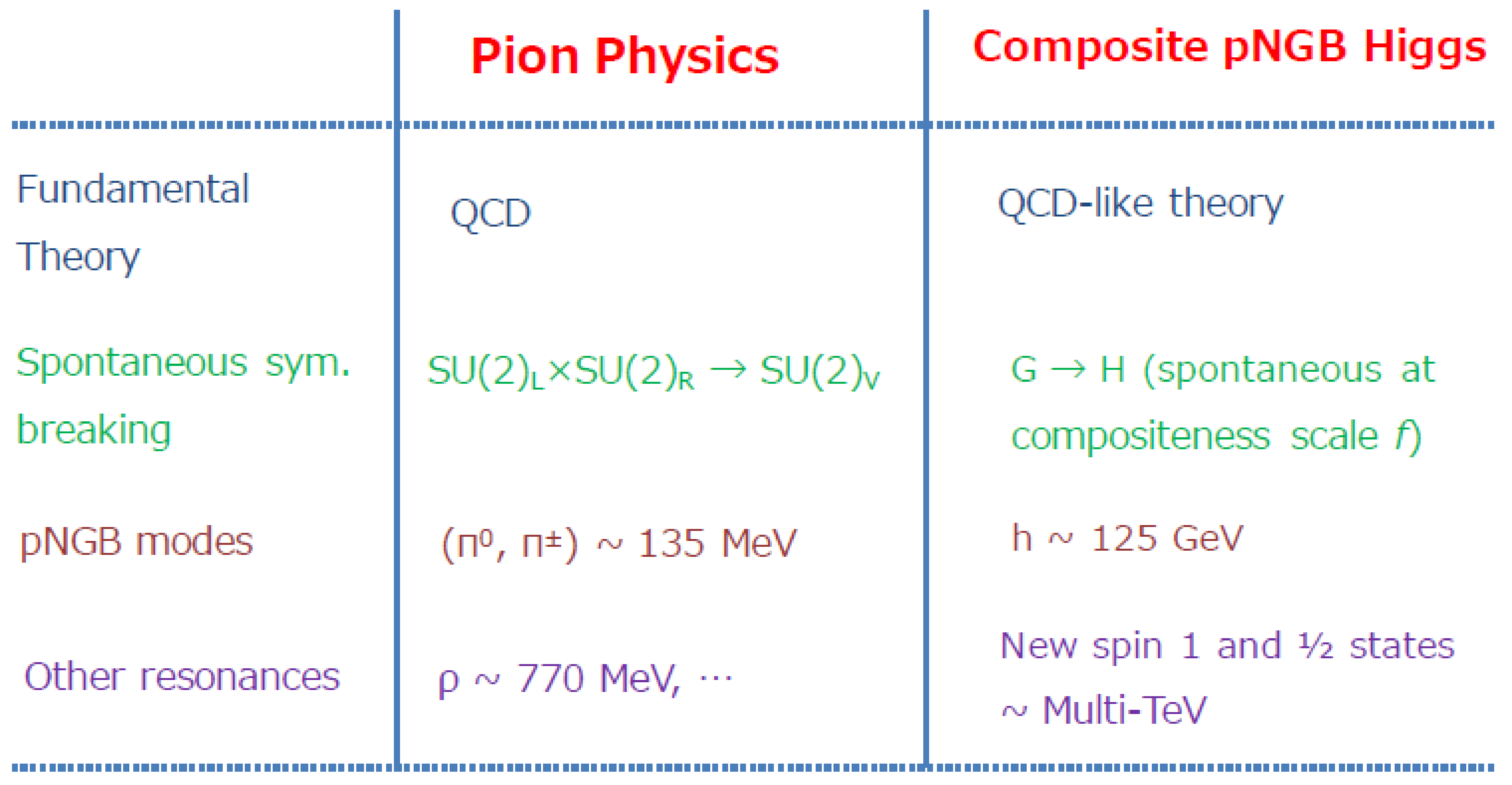


Basic rules for a Composite Higgs Model with NGBs

- ☐ Suppose there is a global symmetry G at scale above *f* (~TeV) which is spontaneously broken down into a subgroup H
- ☐ The structure of the Higgs sector is determined by the coset G/H
- ☐ H should contain the custodial $SO(4) \simeq SU(2)_L \times SU(2)_R$ symmetry
- ☐ The number of NGBs (dimG-dimH) must be 4 or larger



In essence:

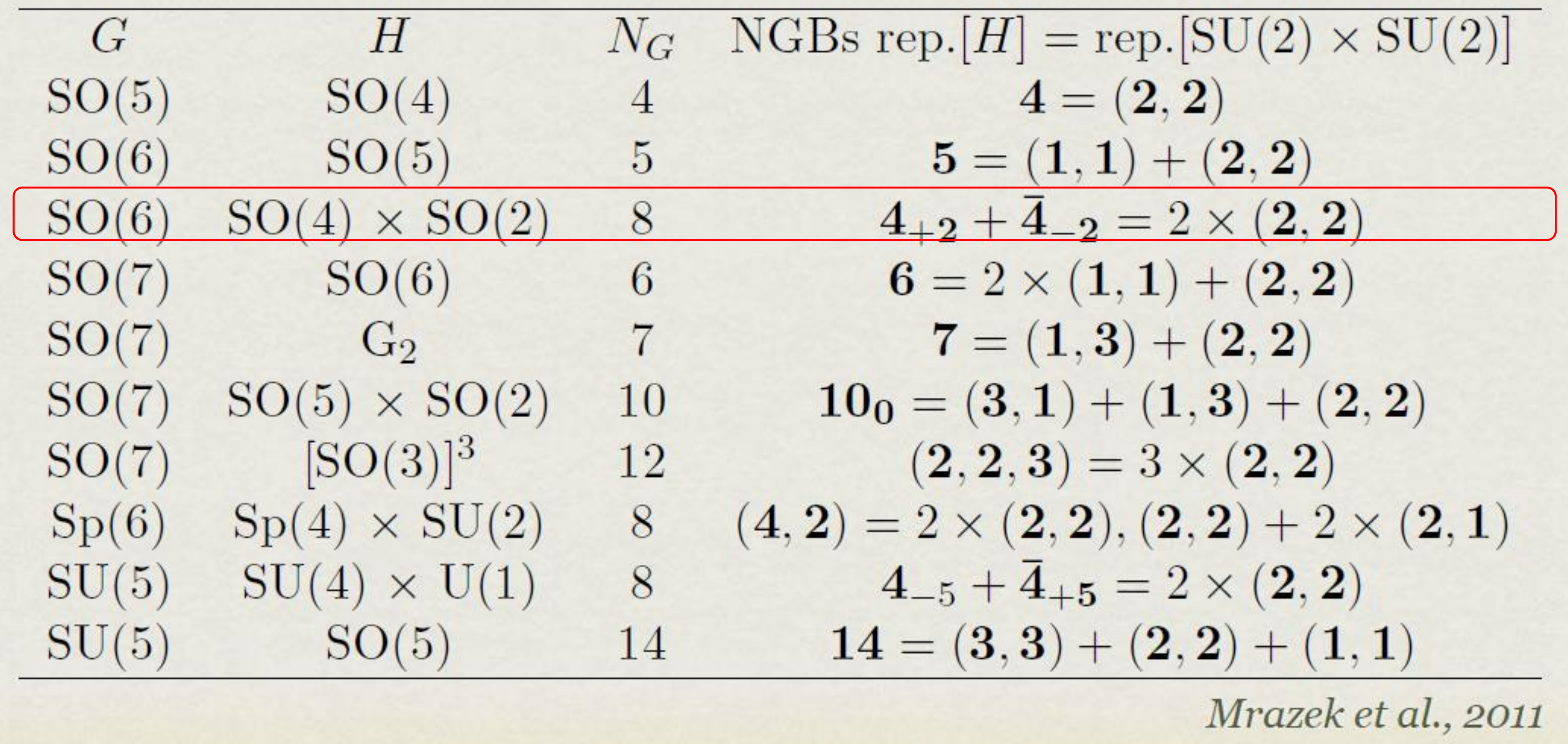


	Pion Physics	**Composite pNGB Higgs**
Fundamental Theory	QCD	QCD-like theory
Spontaneous sym. breaking	$SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$	$G \rightarrow H$ (spontaneous at compositeness scale f)
pNGB modes	$(\pi^0, \pi^\pm) \sim 135$ MeV	$h \sim 125$ GeV
Other resonances	$\rho \sim 770$ MeV, $\cdots$	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 (ignore here), look at Yukawa (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	$\mathbf{10}_{\mathbf{0}} = (\mathbf{3},\mathbf{1}) + (\mathbf{1},\mathbf{3}) + (\mathbf{2},\mathbf{2})$
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	$\mathbf{4}_{-\mathbf{5}} + \bar{\mathbf{4}}_{+\mathbf{5}} = 2\times(\mathbf{2},\mathbf{2})$
SU(5)	SO(5)	14	$\mathbf{14} = (\mathbf{3},\mathbf{3}) + (\mathbf{2},\mathbf{2}) + (\mathbf{1},\mathbf{1})$

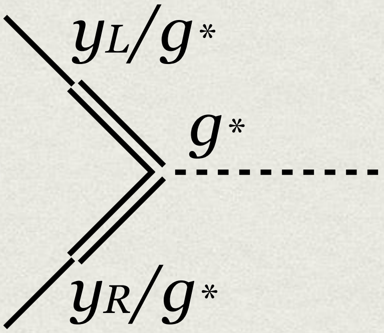
Mrazek et al., 2011

Partial compositeness (y)

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

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

at least 2 heavy (I=1,2)
resonances are needed for
a UV finite potential

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

$$\Pi = \sqrt{2} h_\alpha^{\hat{a}} T_\alpha^{\hat{a}} = -i \begin{pmatrix} 0_{4\times4} & h_1^{\hat{a}} & h_2^{\hat{a}} \\ -h_1^{\hat{a}} & 0 & 0 \\ -h_2^{\hat{a}} & 0 & 0 \end{pmatrix}$$

$$v^2 = v_1^2 + v_2^2$$
$$m_W^2 = \frac{g^2}{4} f^2 \sin^2 \frac{v}{f}$$

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

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

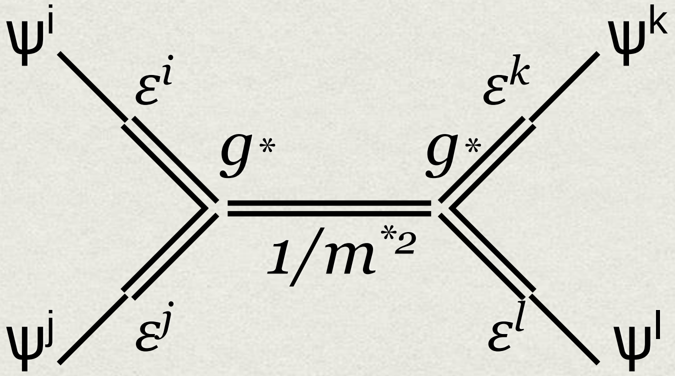
no freedom in the coefficient,
fixed by the coset

possible solutions:

- CP (which we assume)
- C_2: $H_1 \to H_1$, $H_2 \to -H_2$ forbidding H_2 to acquire a vev (see later)

FCNCs

FCNCs mediated by the heavy resonances



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

- *does not require an excessive and unnatural tuning of the parameters*
- *flavour symmetries can also help to control these observables*

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

Issues with Higgs-mediated FCNCs

FCNCs can be removed by

- assuming C₂ in the strong sector and in the mixings (ie, Y_1=0): *inert C2HDM* (not considered here)
- broken C₂ in the strong sector requires (flavour) *alignment* $Y_1^{IJ} \propto Y_2^{IJ}$

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

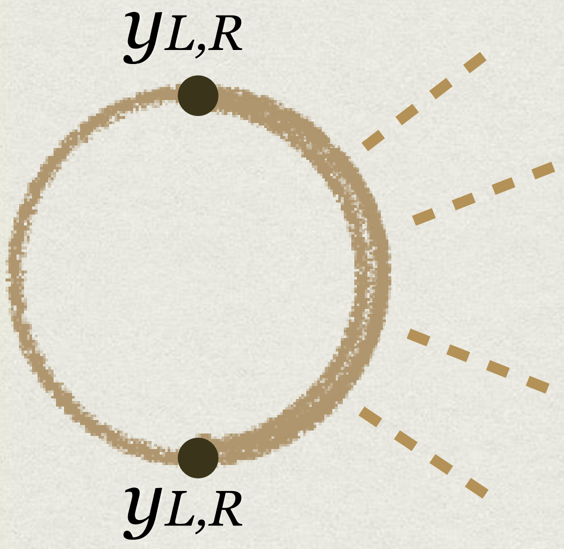
(the ratio a_1/a_2 is predicted by the strong dynamics)

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

Note: *effective* also because integrate out heavy composite resonances (fermions and vectors)

Question is then, what does compositeness-driven EWSB predicts?

The effective potential



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:

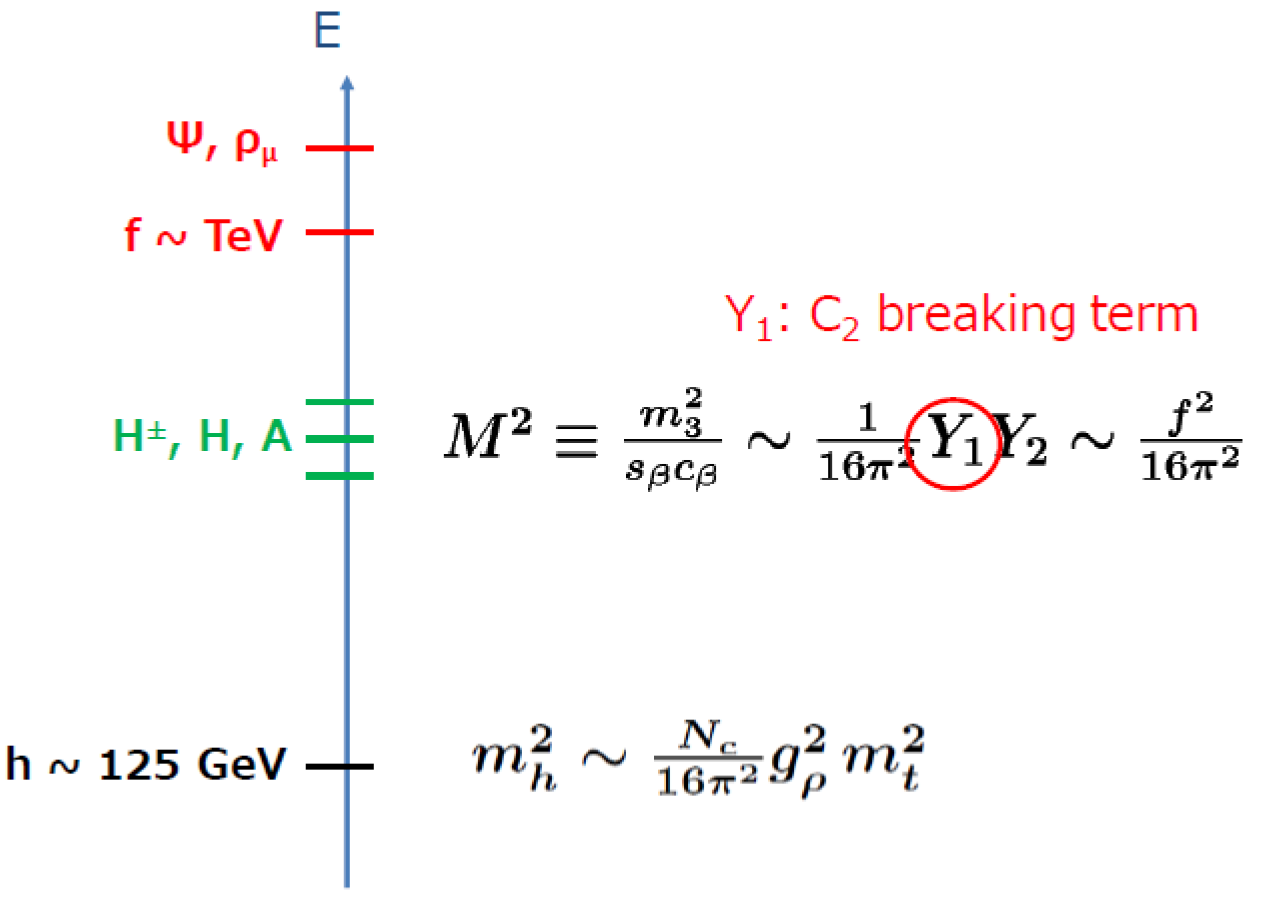
$$M^2 \equiv \frac{m_3^2}{s_\beta c_\beta} \sim \frac{1}{16\pi^2} Y_1 Y_2 \sim \frac{f^2}{16\pi^2}$$

Any C₂ 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 C2HDM-like scenario with a softly broken Z₂

To recap:



Y$_1$: C$_2$ breaking term

$$M^2 \equiv \frac{m_3^2}{s_\beta c_\beta} \sim \frac{1}{16\pi^2} \enclose{circle}{Y_1} Y_2 \sim \frac{f^2}{16\pi^2}$$

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

★ For m_h ~ 125 GeV , we need g_ρ ~ 5.

★f → ∞ : All extra Higgses are decoupled

→ (elementary) SM limit

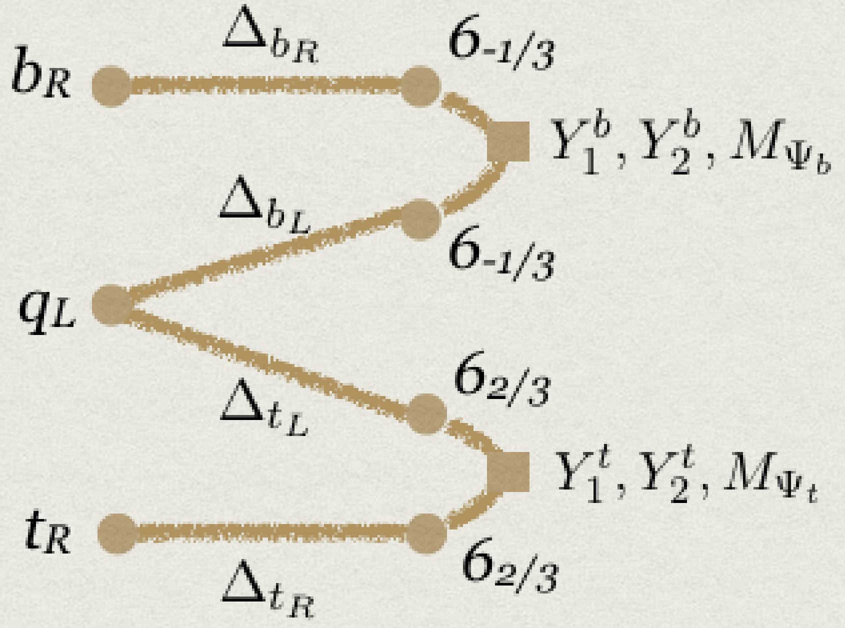
★To get M≠0, we need C$_2$ breaking

(Yukawa alignment is required →A2HDM).

Sampling the parameter space (now include b)

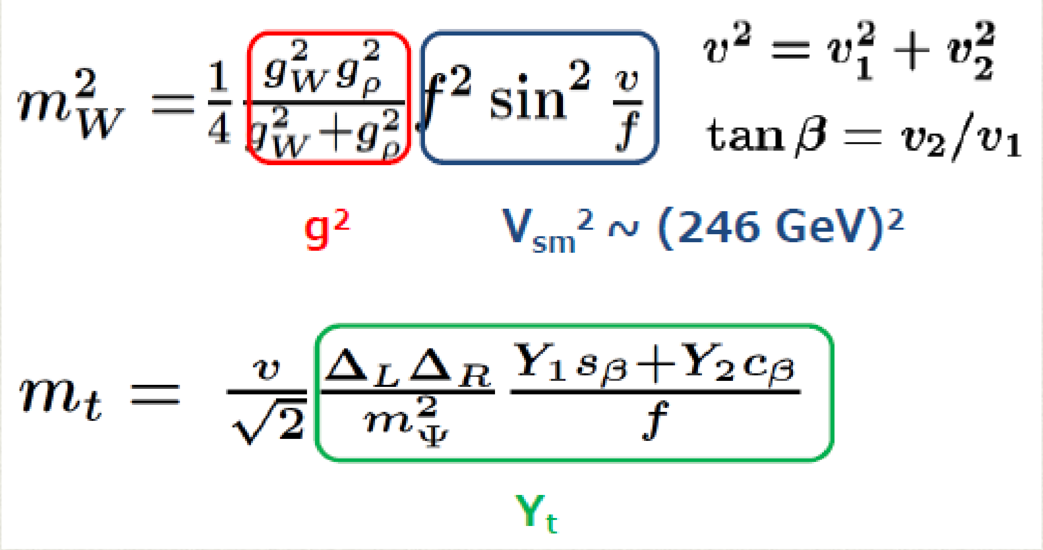
C2HDM: we adopt the L-R structure based on the 2-site models which represents the minimal choice for a realistic and calculable effective potential

De Curtis et al., 2012



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

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



$$m_W^2 = \frac{1}{4}\underbrace{\boxed{\frac{g_W^2 g_\rho^2}{g_W^2+g_\rho^2}}}_{g^2}\underbrace{\boxed{f^2 \sin^2\frac{v}{f}}}_{V_{sm}^2 \sim (246\text{ GeV})^2}$$

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

$$\tan\beta = v_2/v_1$$

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

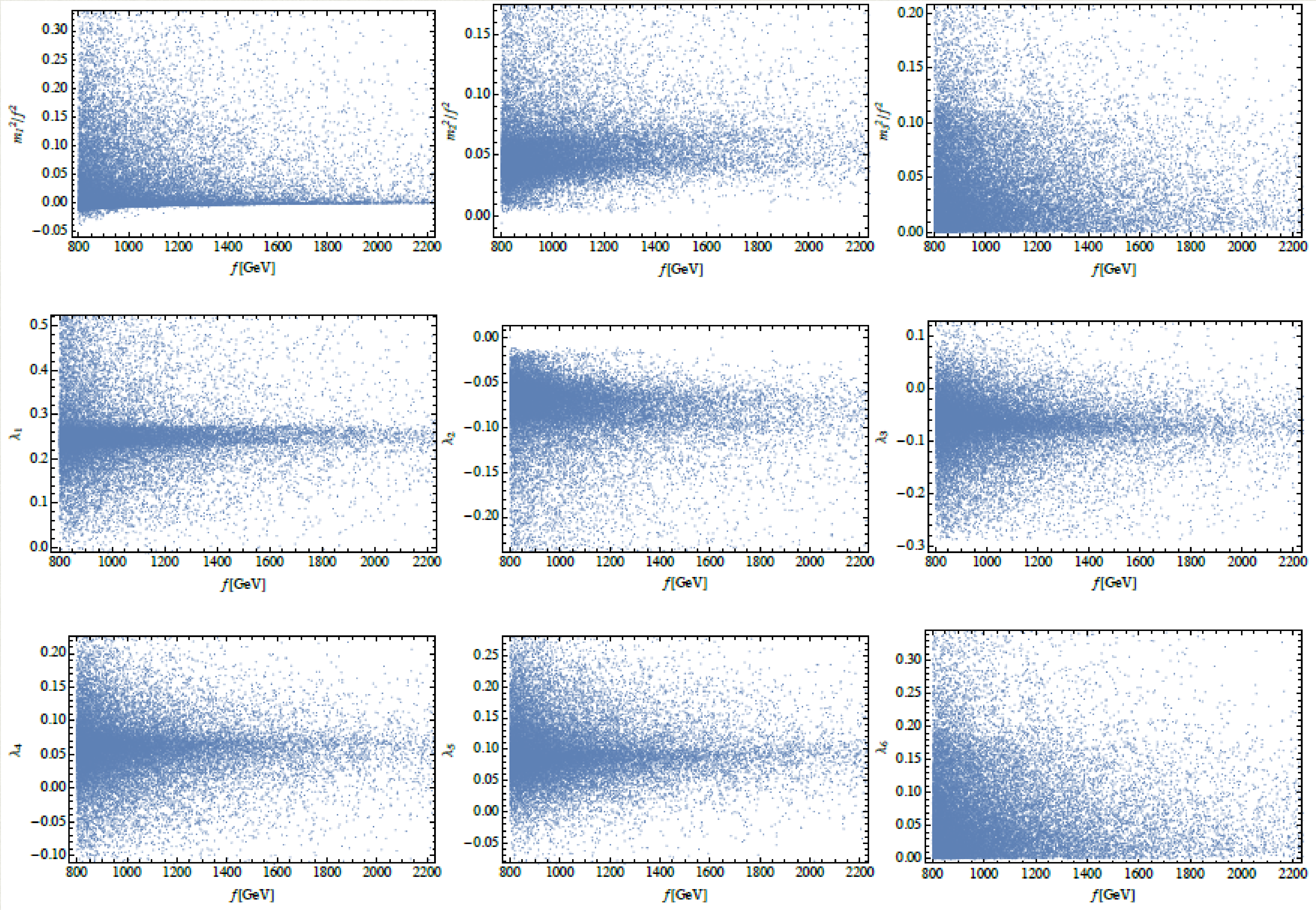
$$120\,\text{GeV} < m_h < 130\,\text{GeV}$$

$$165\,\text{GeV} < m_t < 175\,\text{GeV}$$

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

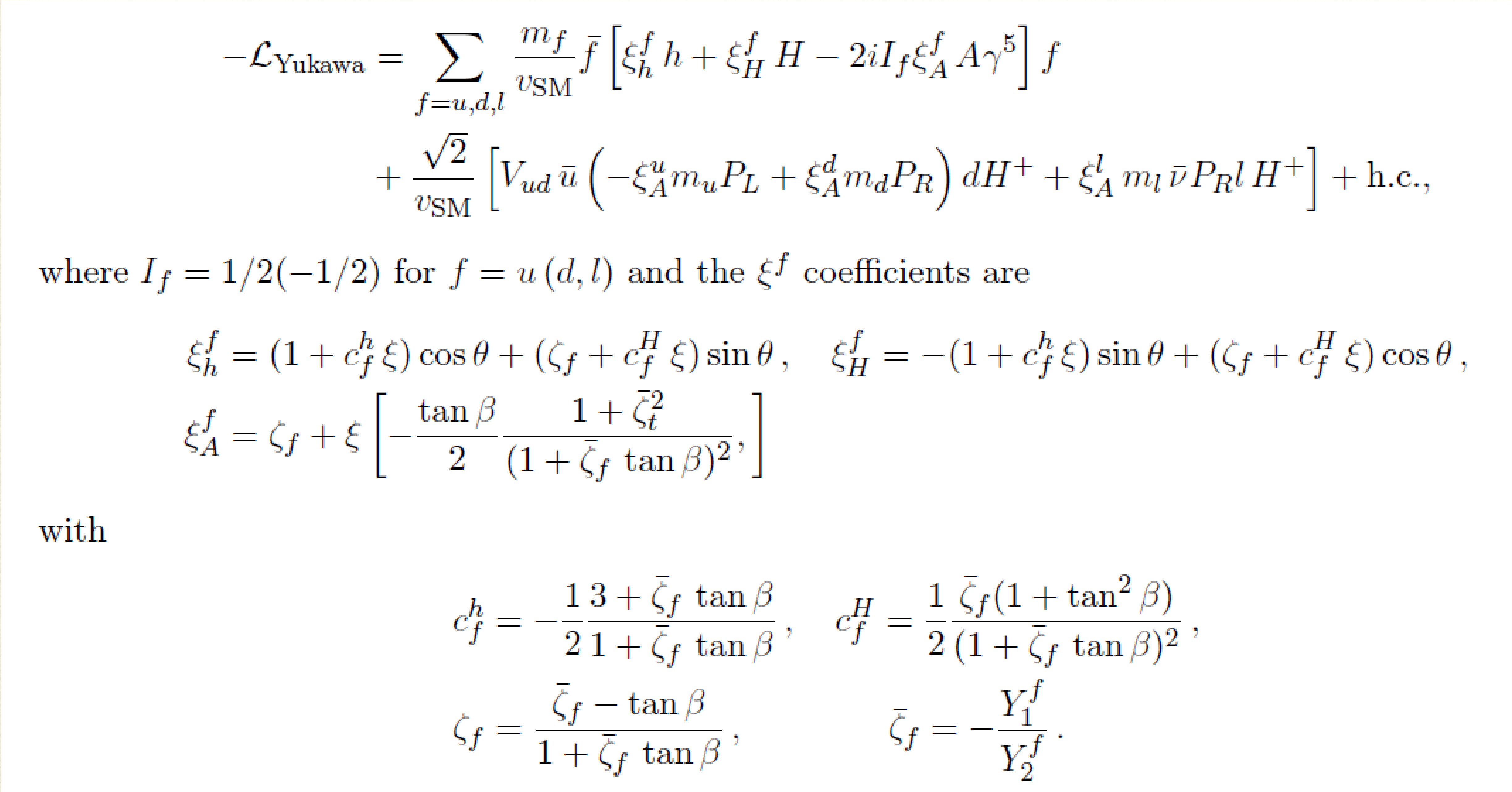
- 2loop + NNLL resummation $\quad 2 < \tan\beta < 45, \quad 200\,\text{GeV} < m_A < 1600\,\text{GeV}$
- soft SUSY breaking = M_{SUSY} $\quad 1\,\text{TeV} < M_{\text{SUSY}} < 100\,\text{TeV} \qquad |X_t| < 3M_{\text{SUSY}}$

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

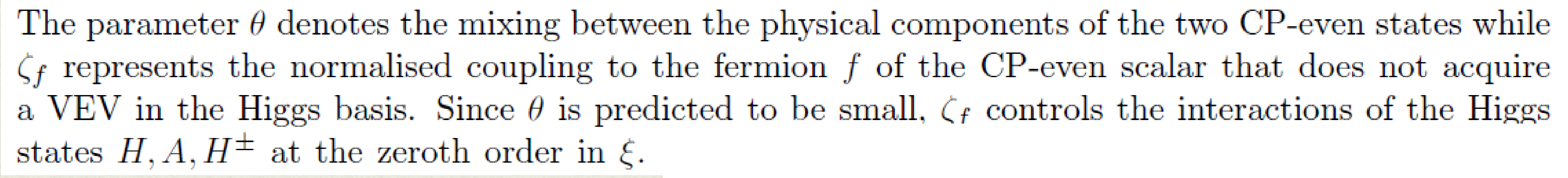
$$\xi_h^f = (1 + c_f^h\, \xi) \cos\theta + (\zeta_f + c_f^H\, \xi) \sin\theta\,, \quad \xi_H^f = -(1 + c_f^h\, \xi) \sin\theta + (\zeta_f + c_f^H\, \xi) \cos\theta\,,$$

$$\xi_A^f = \zeta_f + \xi \left[-\frac{\tan\beta}{2} \frac{1 + \bar{\zeta}_t^2}{(1 + \bar{\zeta}_f\, \tan\beta)^2}, \right]$$

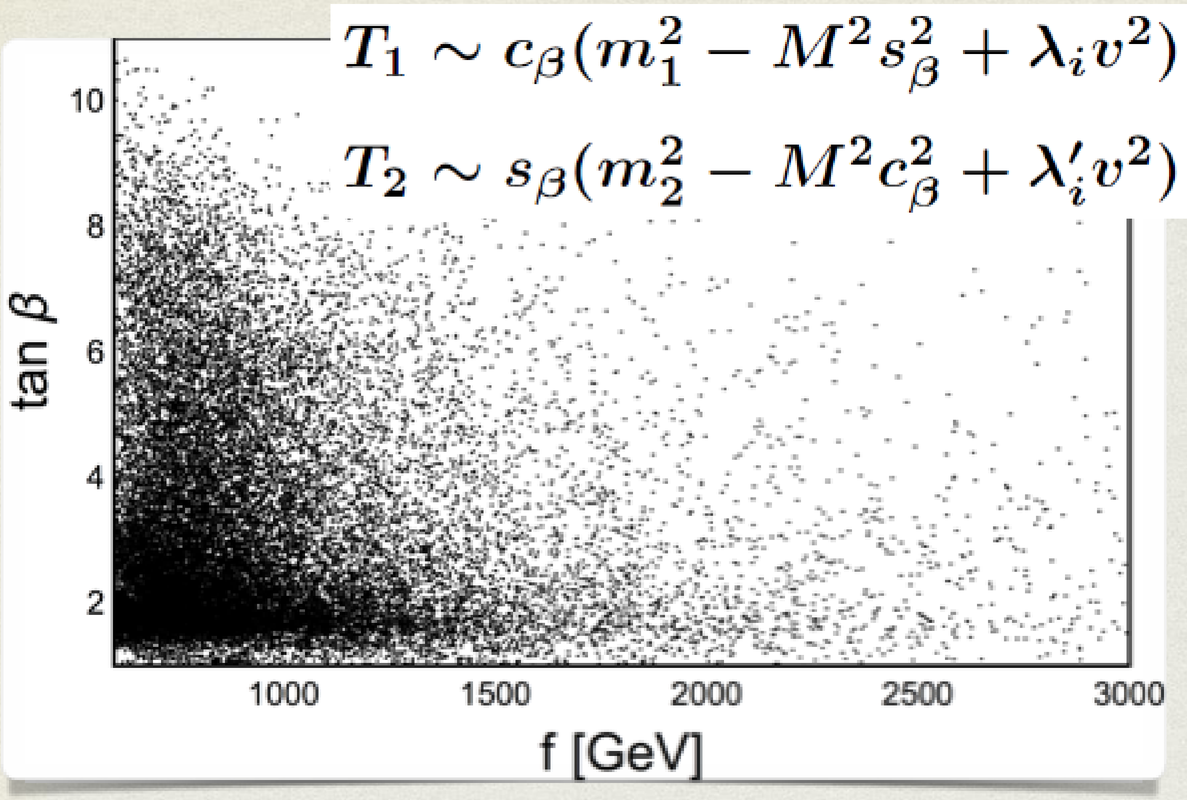
with

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

$$\zeta_f = \frac{\bar{\zeta}_f - \tan\beta}{1 + \bar{\zeta}_f\, \tan\beta}\,, \qquad \bar{\zeta}_f = -\frac{Y_1^f}{Y_2^f}\,.$$



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.



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

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

- 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 (see next slide)!

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

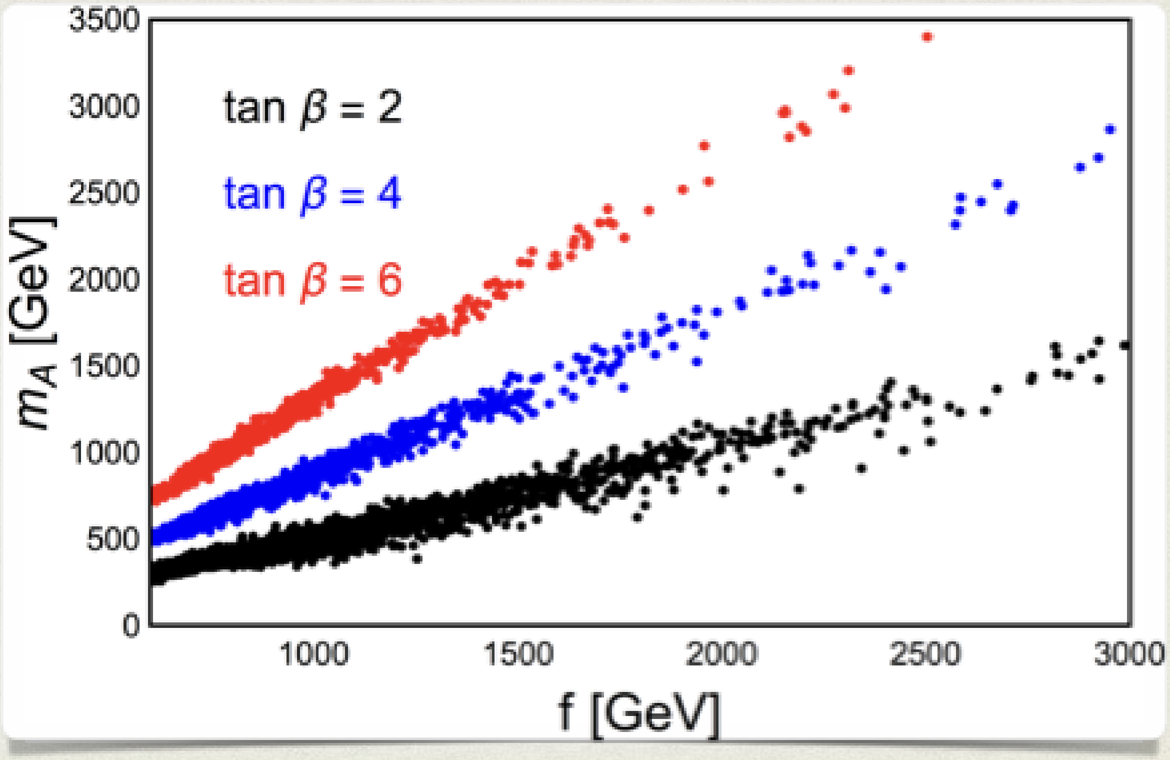
$$\mathcal{M}^2 = \begin{pmatrix} \Lambda_1 v^2 & \Lambda_6 v^2 \\ \Lambda_6 v^2 & \mathcal{M}_{22}^2 \end{pmatrix}$$

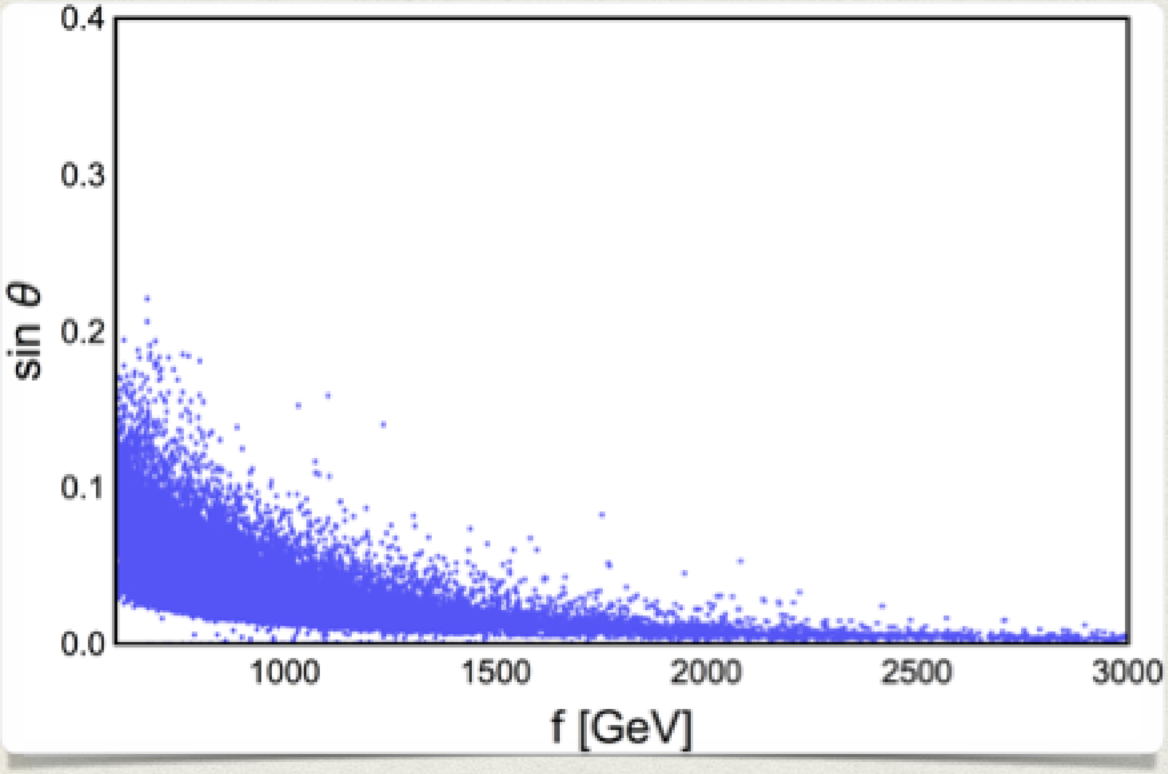
fixed by minimisation of V

unconstrained

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

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





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

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

SM-like h requires large f while

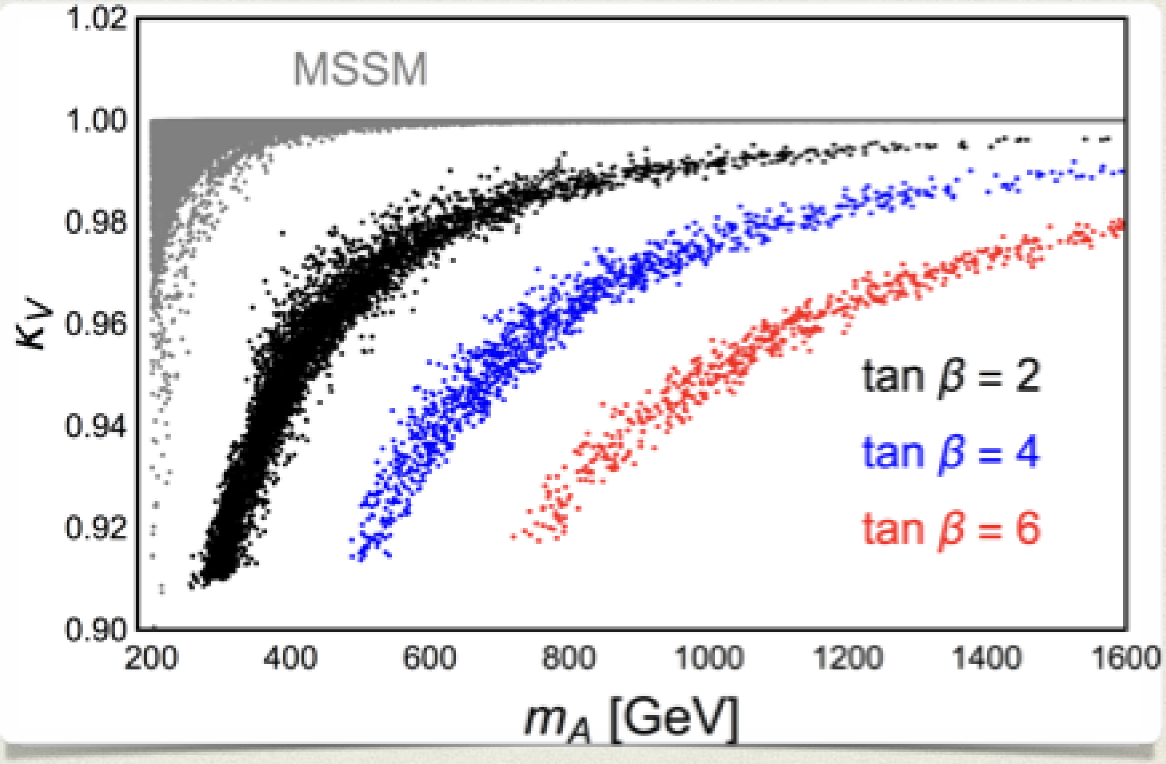
very non-SM-like h requires small f

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

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

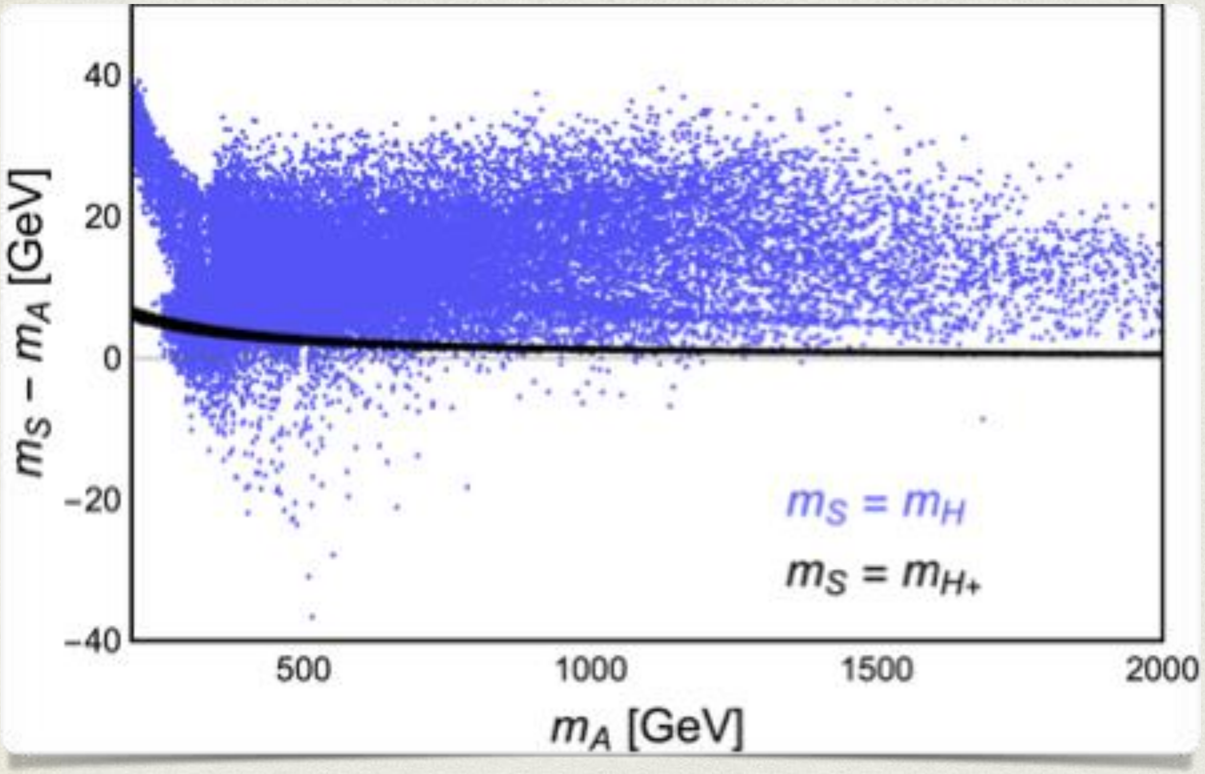
the alignment limit is approached more slowly in the C2HDM than in MSSM

a relevant deviation is present even for no mixing



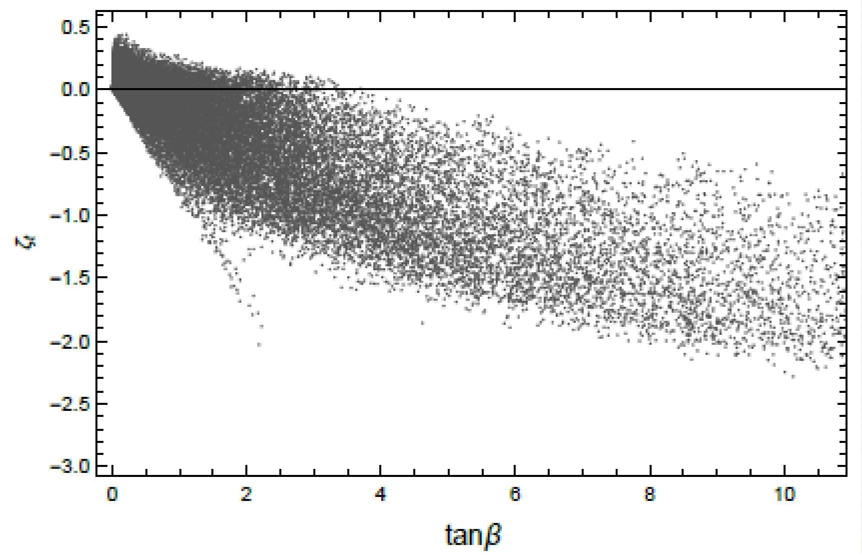
Can heavy Higgs mass spectra reveal C2HDM from MSSM?

- m_{H+} and m_A : very close in both scenarios (high degeneracy): very sharp prediction in the C2HDM, $m_{H^\pm}^2 - m_A^2 \simeq \frac{\Delta_L^4}{m_*^4} v^2$



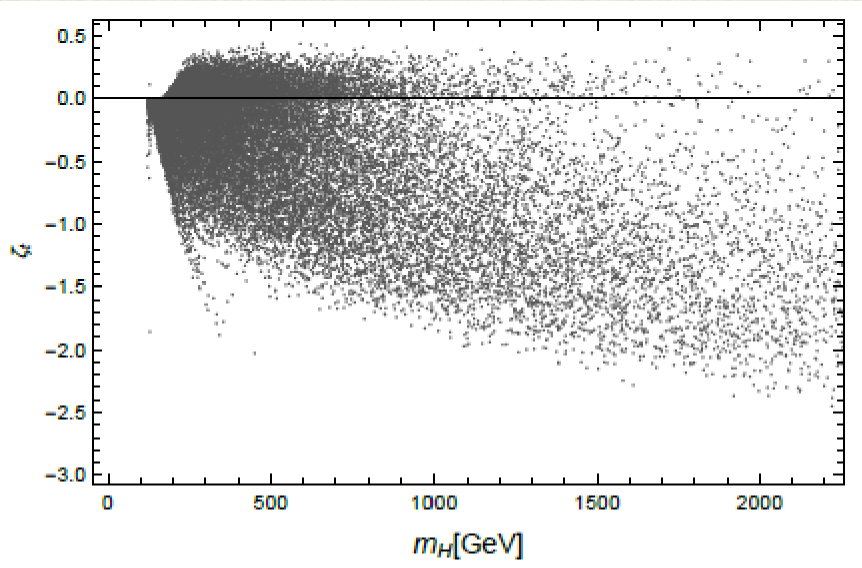
- m_H and m_A: larger mass splitting prediction in the C2HDM than in the MSSM (max 15 GeV)
- $H \to A Z^*$ can be an interesting channel discriminating the two scenarios
- $A \to H Z^*$ could also be useful

Recall, can do:



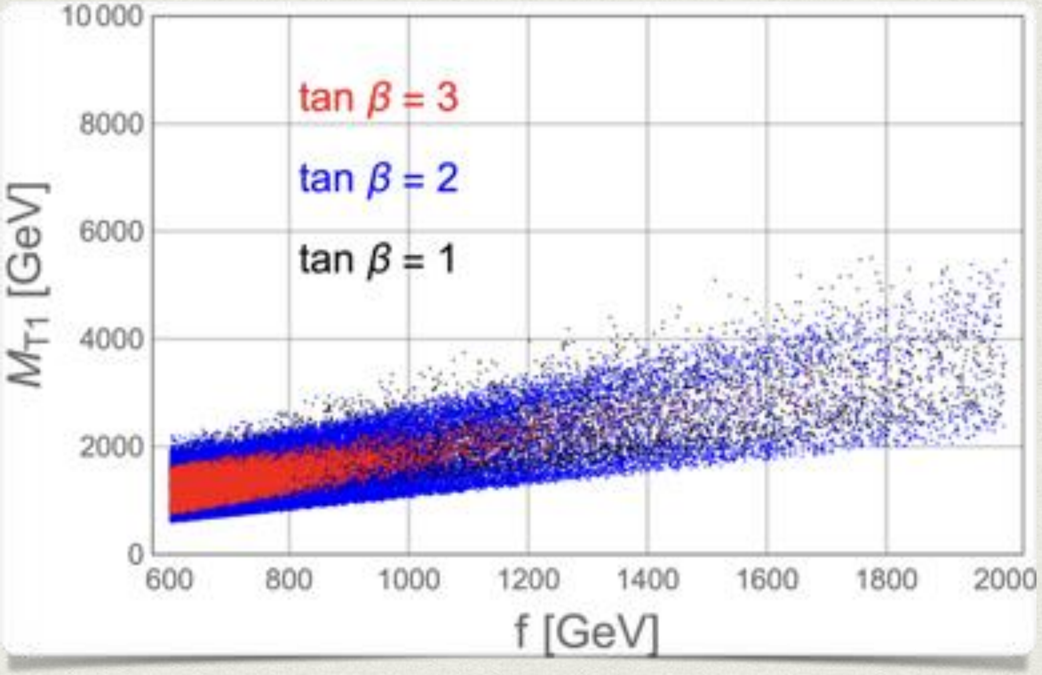
correlation between ζ_t and $\tan\beta$ for all values of $f > 700$ GeV

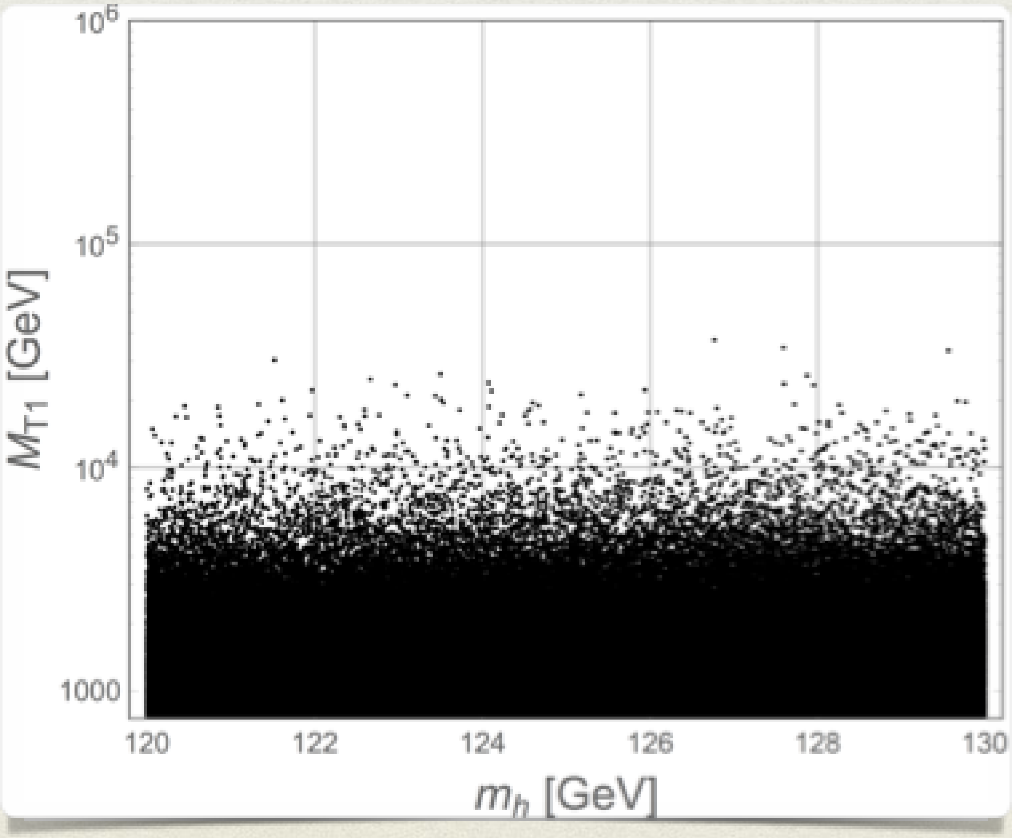
Can also do:



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

C2HDM: lightest top partner T_1

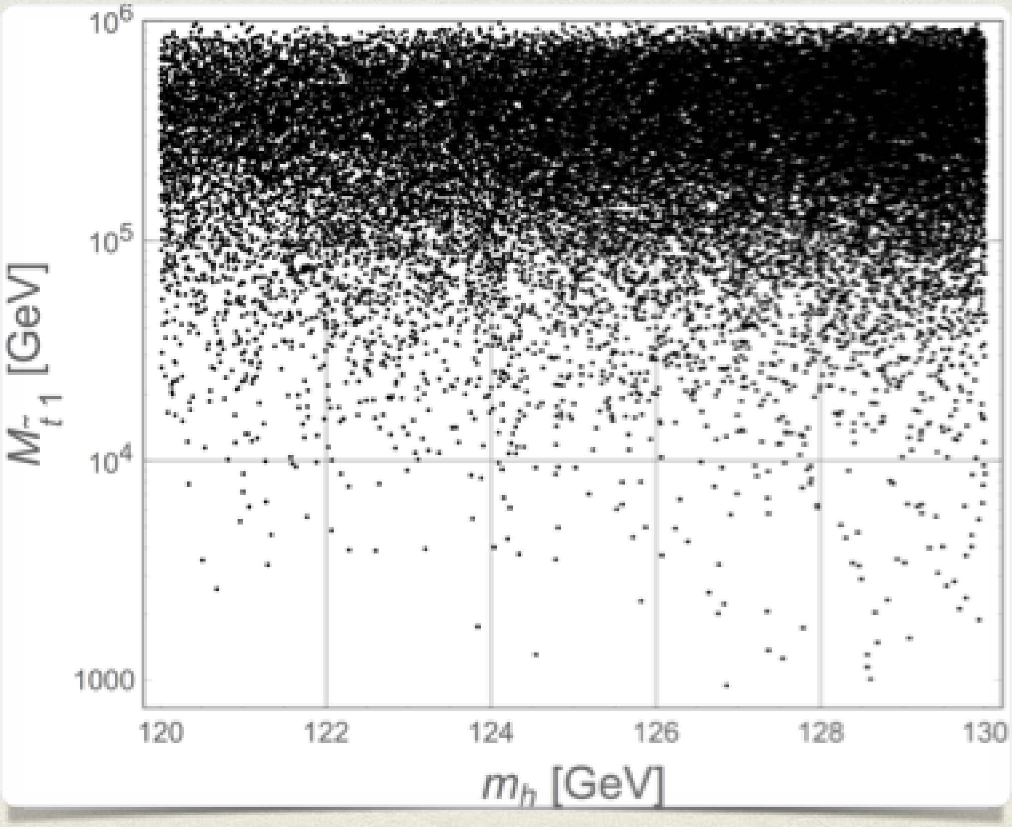




the heavy resonance in the **6** of SO(6) delivers 4 top partners, 1 bottom partner and 1 exotic fermion with Q = 5/3

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 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 (Aligned) C2HDM
- Several existing observables can be used to discriminate between C2HDM and MSSM: k_V (delayed decoupling), heavy Higgses' intern-decay patterns, (lightest) top partner spectrum
- Complete phenomenological study of the C2HDM in progress (fine tuning, new specific observables, …)
- Other interesting scenarios: exact C_2, broken CP, etc.