COMPOSITE 2HDM AT THE LHC: SINGLE & DOUBLE HIGGS

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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***

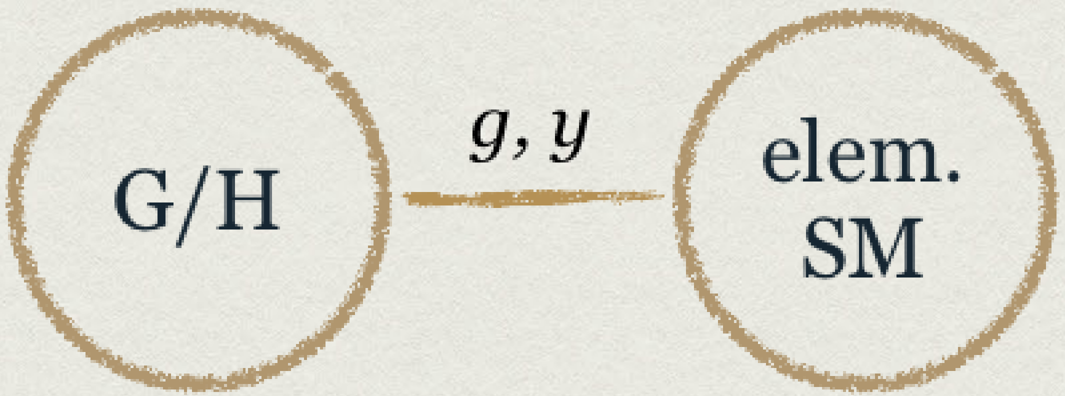
S. De Curtis, SM, R. Nagai, K. Yagyu, ***JHEP 10 (2021) 040***

S. De Curtis, L. Delle Rose, F. Egle, SM, M.M. Muhlleitner, K. Sakurai, ***arXiv:2310.10471***

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

Composite 2HDM: Compositeness alternative to MSSM

Two sites structure:



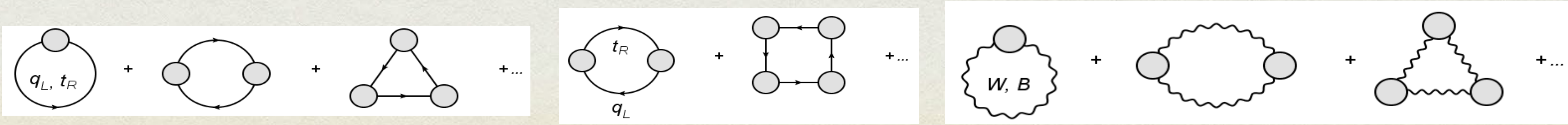
We borrow this idea from QCD: ie,

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, …	New spin 1 and ½ states $\sim$ 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 (here, 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*

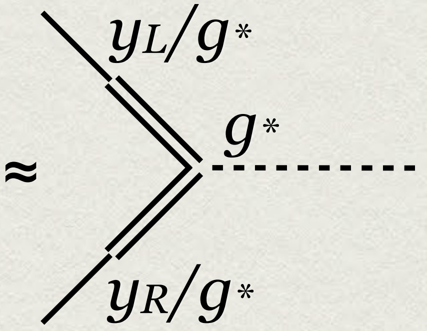
G	H	N_G	NGBs rep.$[H]$ = rep.$[\mathrm{SU}(2)\times\mathrm{SU}(2)]$
SO(5)	SO(4)	4	$\mathbf{4}=(\mathbf{2},\mathbf{2})$
SO(6)	SO(5)	5	$\mathbf{5}=(\mathbf{1},\mathbf{1})+(\mathbf{2},\mathbf{2})$
SO(6)	SO(4) × SO(2)	8	$\mathbf{4}_{+\mathbf{2}}+\bar{\mathbf{4}}_{-\mathbf{2}}=2\times(\mathbf{2},\mathbf{2})$
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) × 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	$\mathbf{4}_{-5}+\bar{\mathbf{4}}_{+\mathbf{5}}=2\times(\mathbf{2},\mathbf{2})$
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 (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):

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

GBs

$\Sigma = U_1 \Sigma_2 U_1^T$

All the parameters real $\rightarrow$ 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 (VLTs), 1 bottom partner (VLB) and 1 exotic fermion with Q = 5/3 (per representations)*

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

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

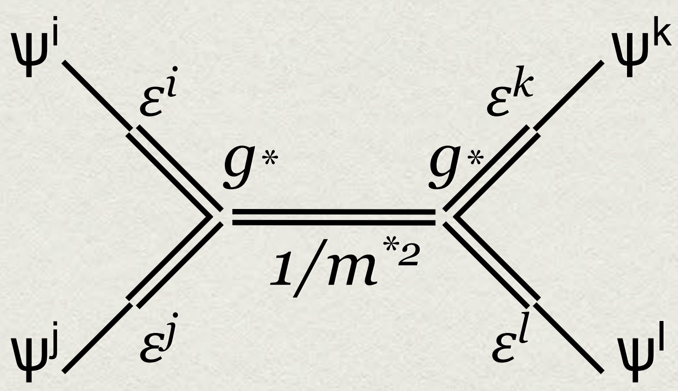
no freedom in the coefficient, fixed by the coset

possible solutions:

- CP (*which we assume, see later*)
- 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 gauge 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 $\Delta S = 2$, $\quad \sim \frac{1}{m^{*2}} \frac{m_d}{v} \frac{m_s}{v}$

do not require an excessive and unnatural tuning of the parameters

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, it will: DM candidate)
- 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

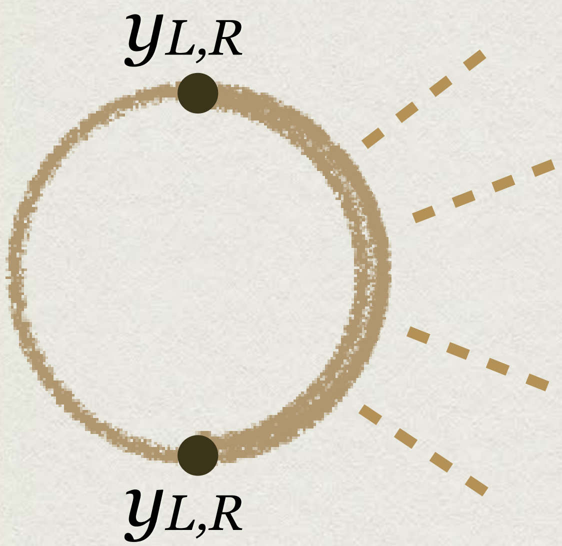
$$Y_u^{ij} Q^i u^j \left(a_{1u} H_1 + a_{2u} H_2\right) + Y_d^{ij} Q^i d^j \left(a_{1d} H_1 + a_{2d} H_2\right) + Y_e^{ij} L^i e^j \left(a_{1e} H_1 + a_{2e} H_2\right) + h.c.$$

(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 bosonic resonances (ie, W's, Z's, see below.) Question is then, what does such compositeness-driven EWSB *predicts*?



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

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

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

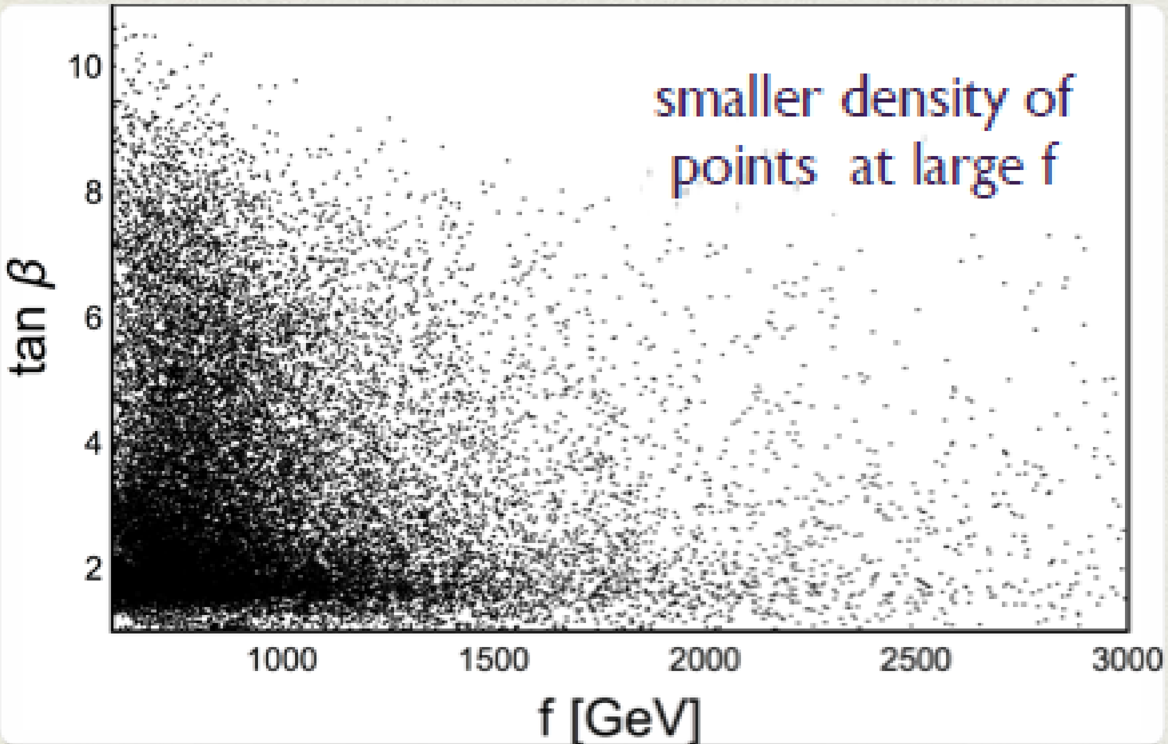
Any C_2 breaking in the strong sector induces (all real, following CP conservation in strong sector):

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

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

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

Can heavy Higgs mass spectra reveal C2HDM from MSSM?



- tan β predicted by the strong sector
- m(h) and m(top) require tan β ~ O(1)
- larger tuning at large *f* : *Δ ~ 1/ξ*
- *No inverted hierarchy unlike E2HDMs*

& (typically) m(H)>2m(h)

- 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

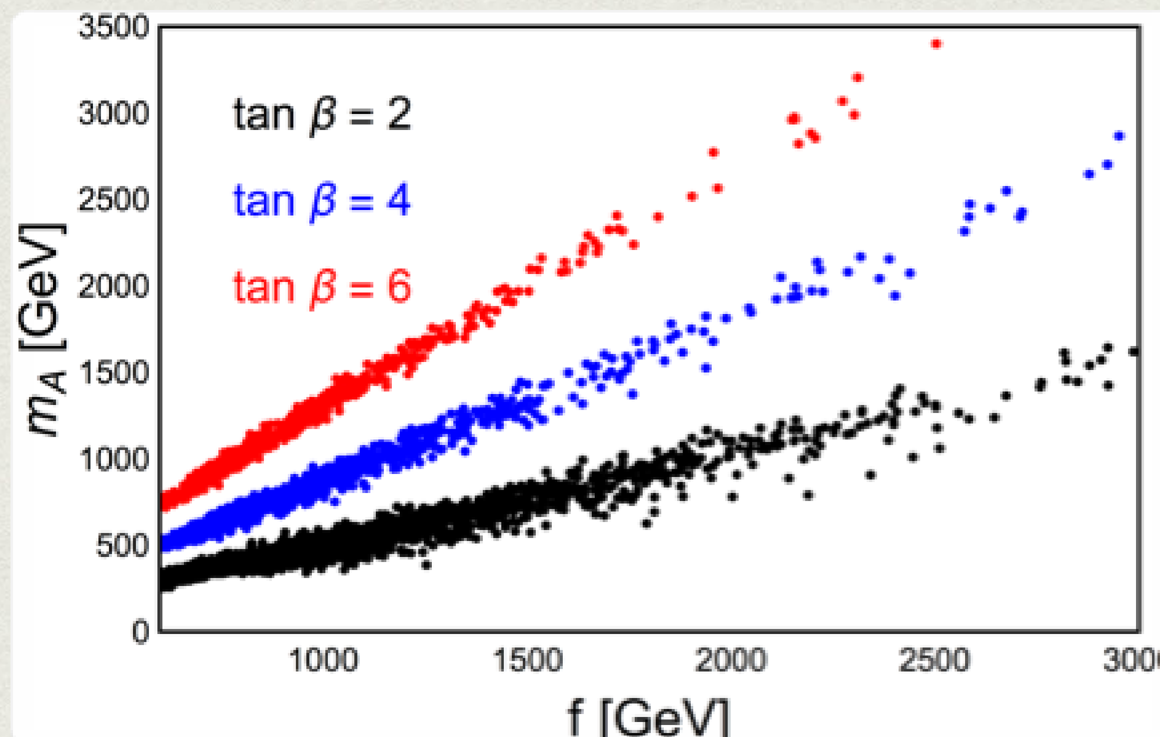
unconstrained

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

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

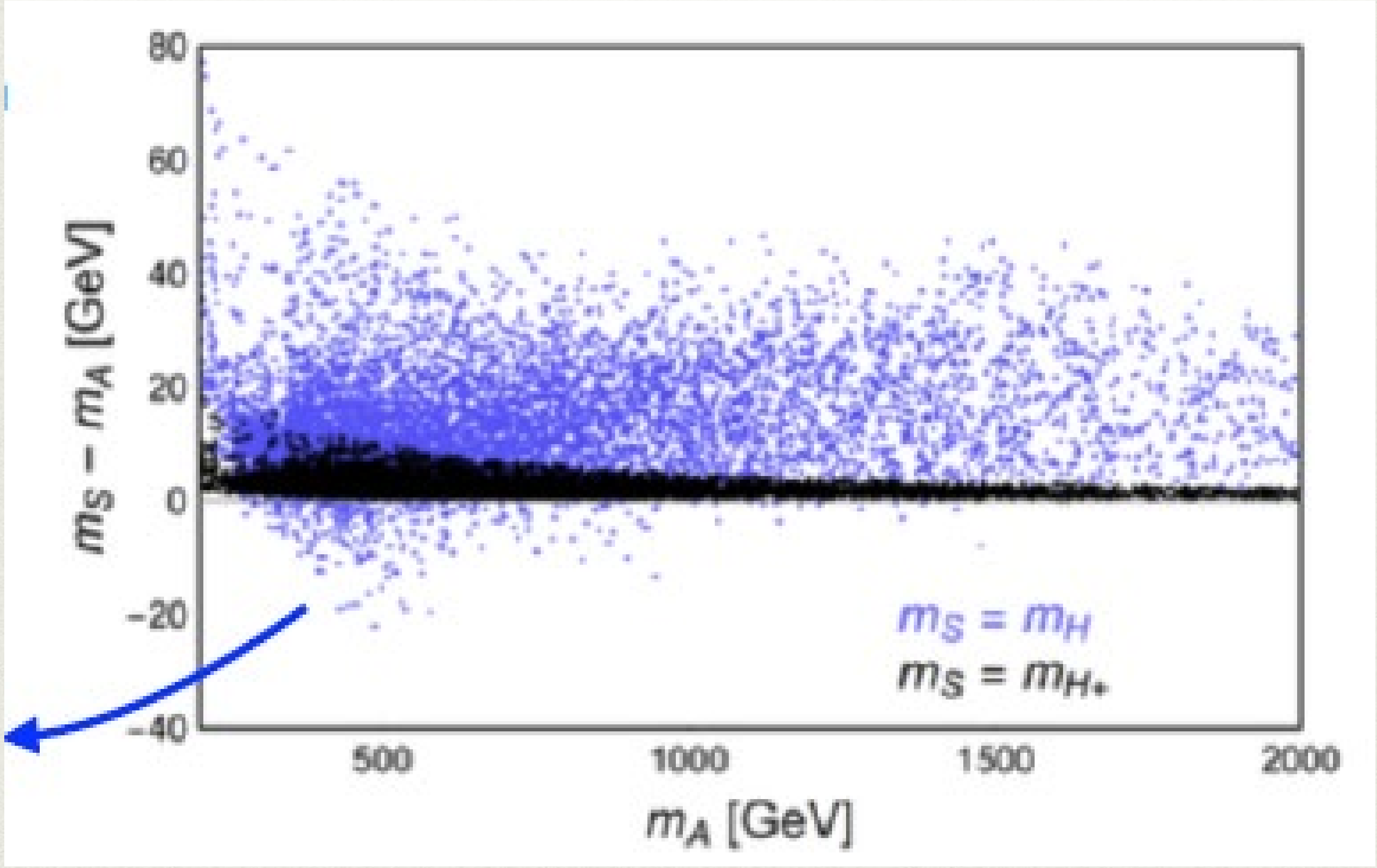
$$T_2 \sim s_\beta(m_2^2 - M^2 c_\beta^2 + \lambda_i' v^2)$$

(tadpole conditions: minimal fine-tuning required)



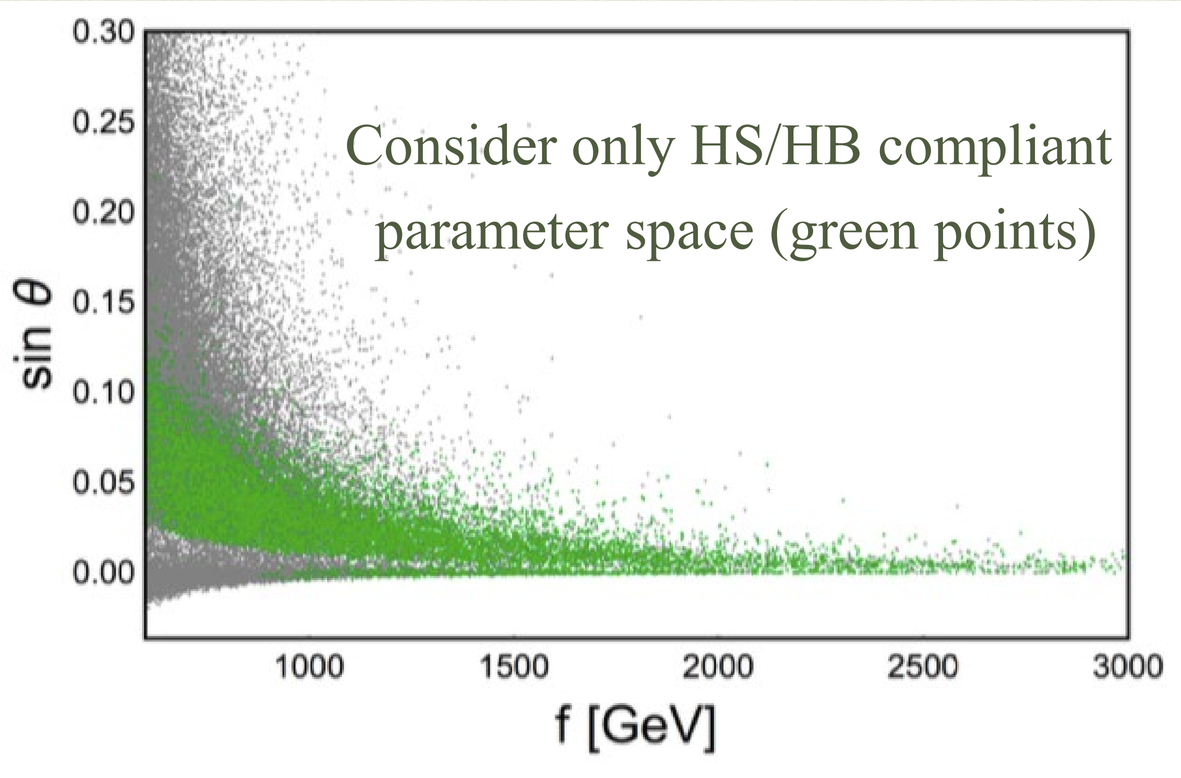
Chain Higgs decays more frequent in C2HDM than MSSM

- m_{H+} and m_A : very close in both scenarios (high degeneracy):
  very sharp prediction in the C2HDM, $m^2_{H^\pm} - m^2_A \simeq \frac{\Delta_L^4}{m_*^4} v^2$
- in the MSSM (max 15 GeV)



$H \rightarrow A Z^*$ (or $A \rightarrow H Z^*$) can disentangle between the two scenarios

Mixing in the CP-even Higgs sector also predicted



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

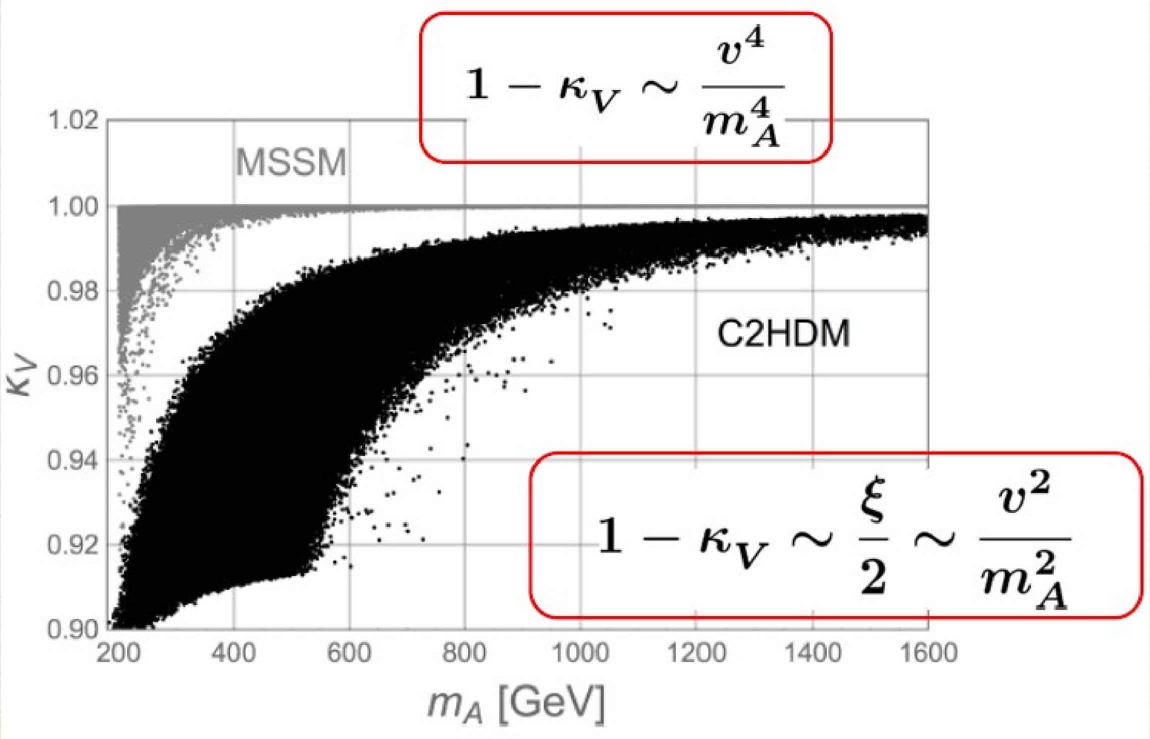
Delayed alignment (at high masses) in the C2HDM wrt the MSSM

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 the MSSM

a relevant deviation is present even for no mixing

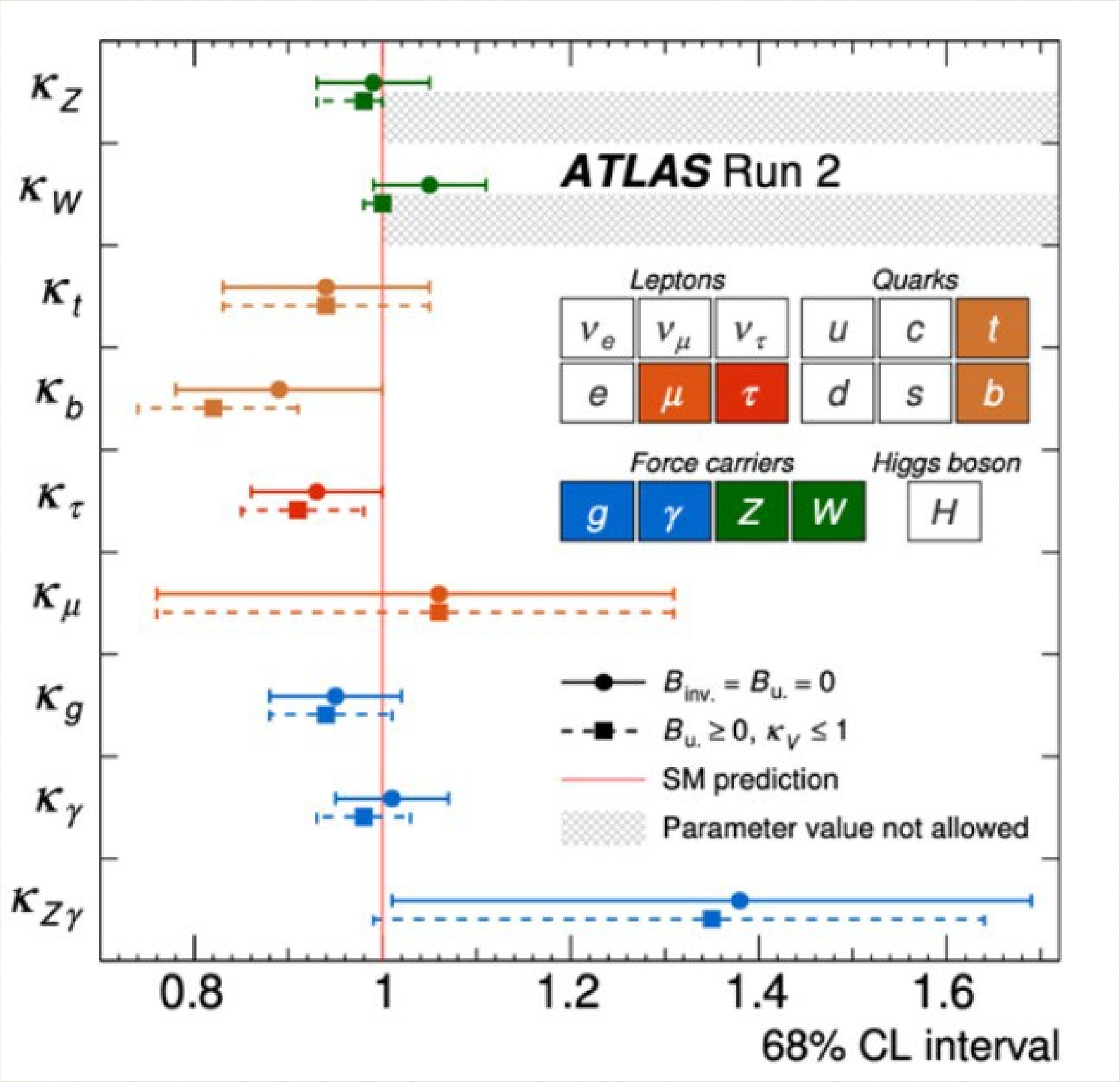


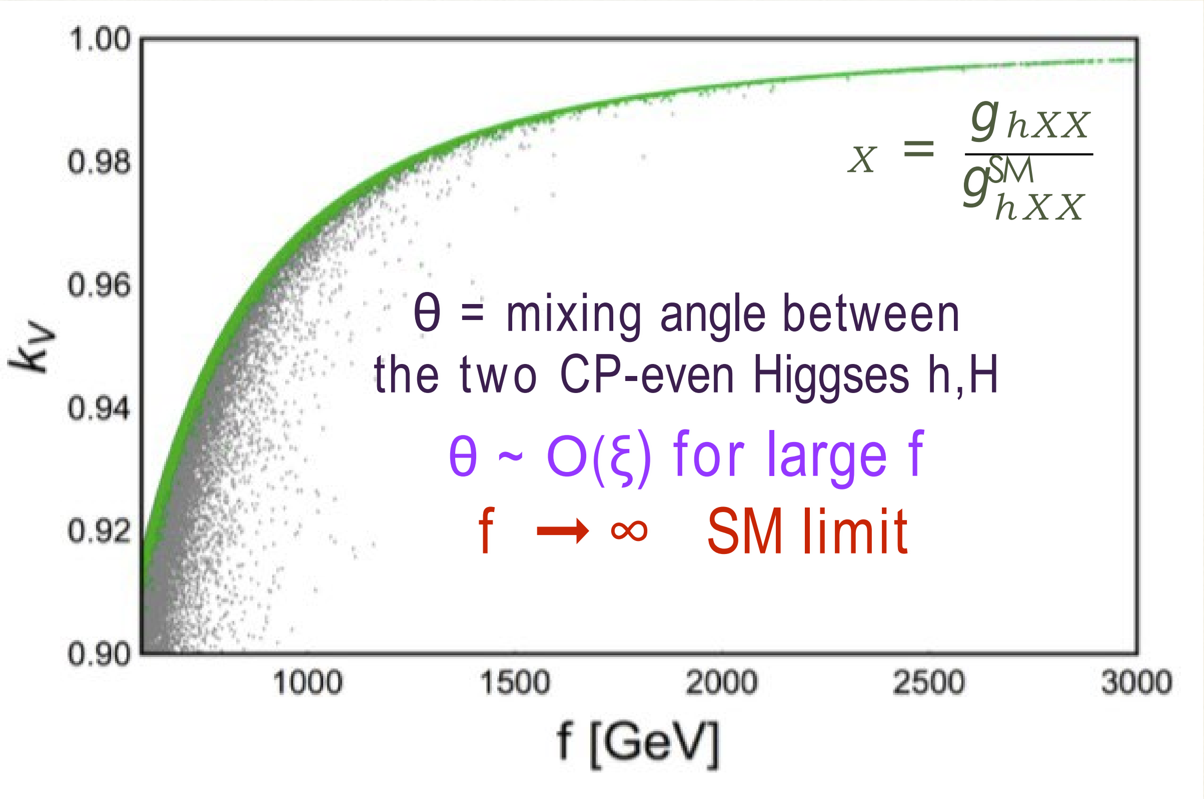
C2HDM - FACING THE DATA

- h couplings to SM particles:

corrections of order ξ to the hVV couplings.
Also modified by the mixing angle θ

$k_V \simeq (1-\xi/2)\cos\theta$ V=W,Z $\xi = v^2/f^2$





green points satisfy the present bounds
tested against HiggsBounds and HiggsSignals packages

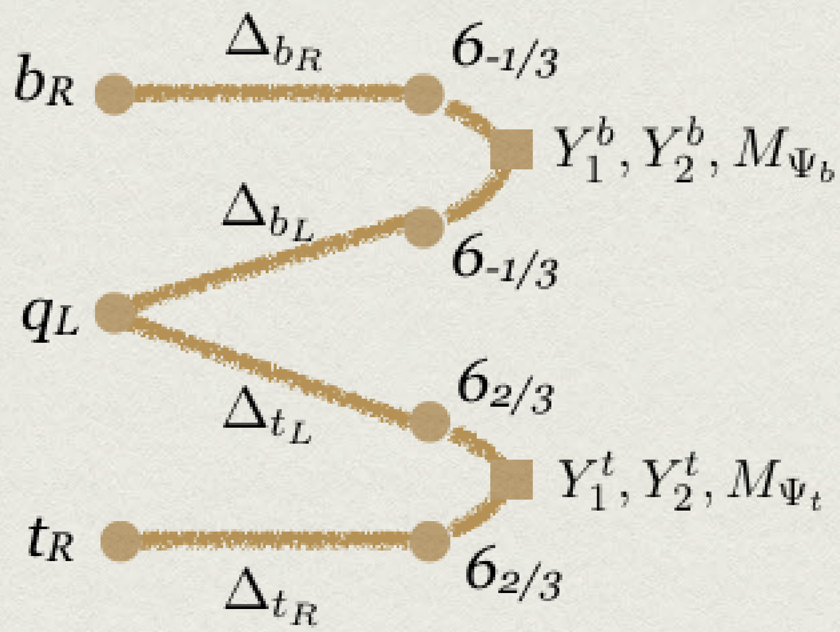
NOW: the Higgs couplings are constrained at 10-20% level

ξ ≤ 0.1 f ≥ 750 GeV

HL-LHC: the Higgs couplings will be constrained at 2-4% level
ξ ≤ 0.04 f ≥ 1200 GeV

Sampling the parameter space (also 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 λ_j (j=1,…,7) are determined by the parameters of the strong sector

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

Yukawas — linear mixings — heavy fermion mass parameters

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

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

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

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

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

Y_t

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

(Higgs & top mass are lowest order)

Heavy fermion spectrum

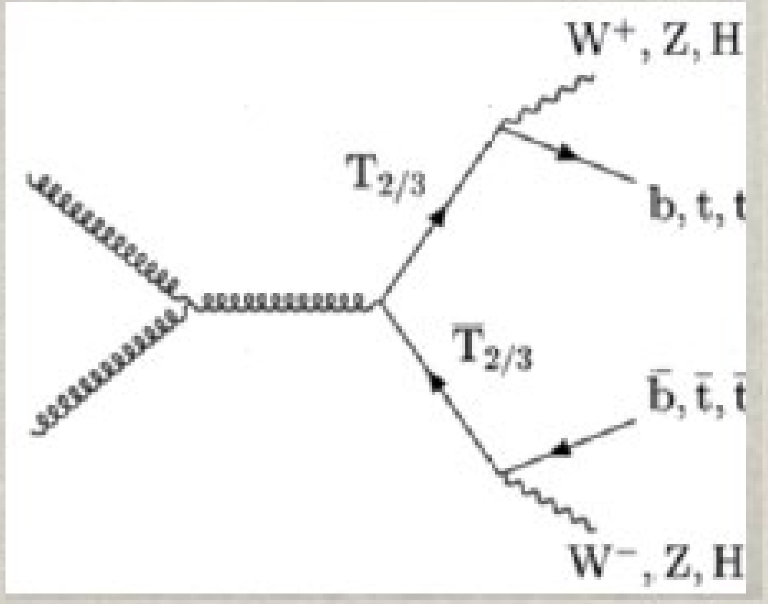
4 top partners with $Q = 2/3$: $X_{2/3}$, $T_{2/3}$, $\tilde{T}_1$, $\tilde{T}_2$;

1 bottom partner with $Q = -1/3$: $B_{-1/3}$;

1 exotic fermion with $Q = 5/3$: $X_{5/3}$.

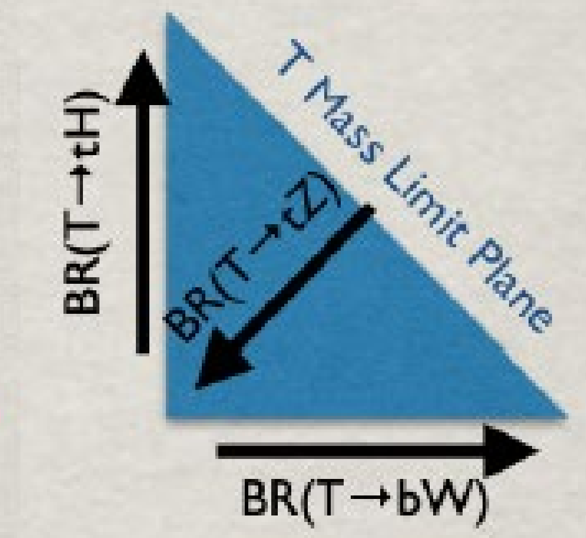
- Count must be doubled because of 2 representations
- Diagonalisation of mass matrix of the 9 fermions with charge 2/3 only numerical

Mass bounds on new heavy fermions: $T_{2/3}$, $B_{-1/3}$, $X_{5/3}$



Pair production searches set $\sigma \times$ BR limits depending on the extra-fermion mass and on the BR assumption

← only SM decay channels considered →

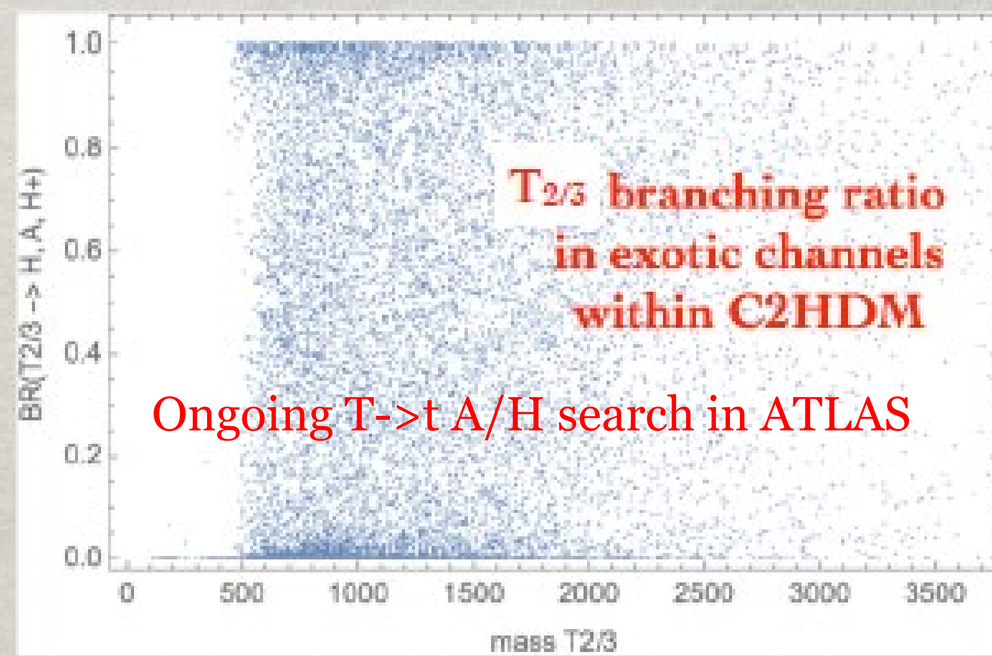


In C2HDM the $T_{2/3}$ can decay in Ht, At, $H^+\bar{b}$ with BR~1 thus softening the bounds based on the SM decay channel only

However, from a recent ATLAS analysis [hep-exp 2212.05263] seems difficult to allow $M_{T2/3} < 1.3$ TeV

Search for pair-produced vector-like quarks using events with exactly one lepton (e or μ), at least four jets including at least one b-tagged jet, and large missing transverse momentum

(upgrade of a previous analysis using 139 fb^{-1} and neural networks trained at several BRs)



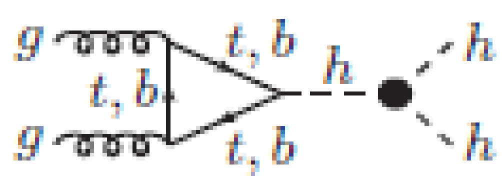
A recasting of the bounds is under study

For the phenomenological analysis we take $M_{T2/3} \geq 1.3$ TeV

Di-Higgs(SM)@Run 3/HL-LHC high priority: can reveal C2HDM?

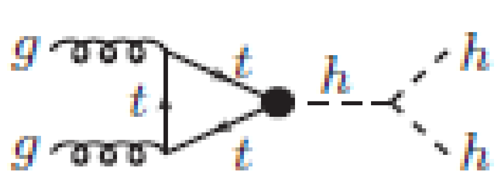
Recall VLTs are heavy (rest mass for LHC pair production is 2.6 TeV)

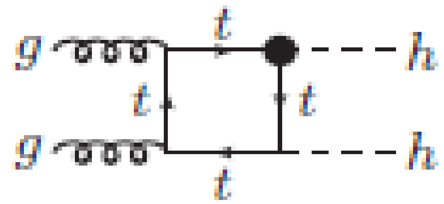
1. **modified Higgs trilinear coupling**



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

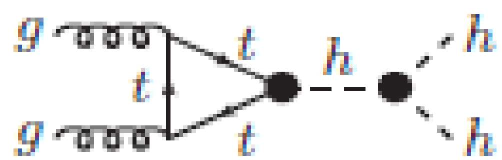
2. **one modified** tth **coupling**





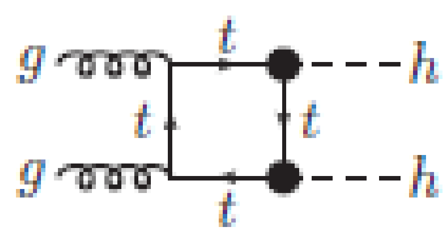
$\mathcal{A}_i \propto \kappa_{htt}$

3. **modified Higgs trilinear coupling +** **modified** tth **coupling**



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

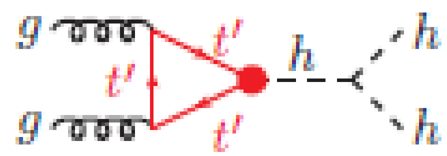
4. **two modified** tth **couplings**



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

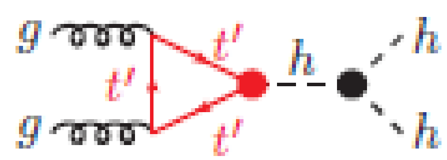
See also De Curtis talk

5. **VLQ triangle**



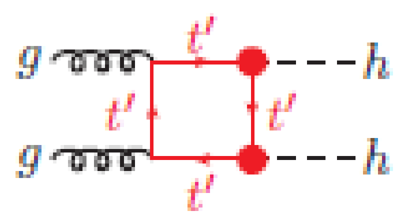
$\mathcal{A}_i \propto \kappa_{ht't'}$

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



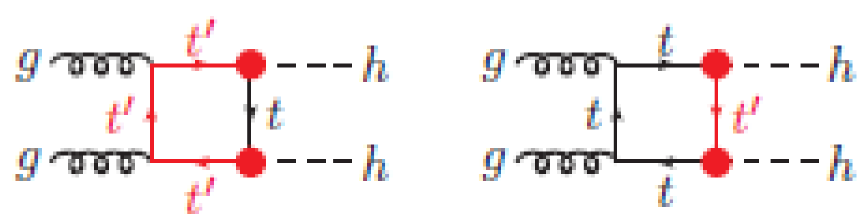
$\mathcal{A}_i \propto \kappa_{hhh}\kappa_{ht't'}$

7. **VLQ box**

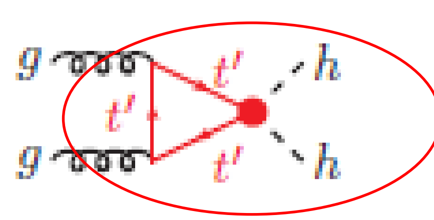


$\mathcal{A}_i \propto \kappa_{ht't'}^2$

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 (SM et al, 2307.05550)

Recall triangle vs box cancellation in the SM

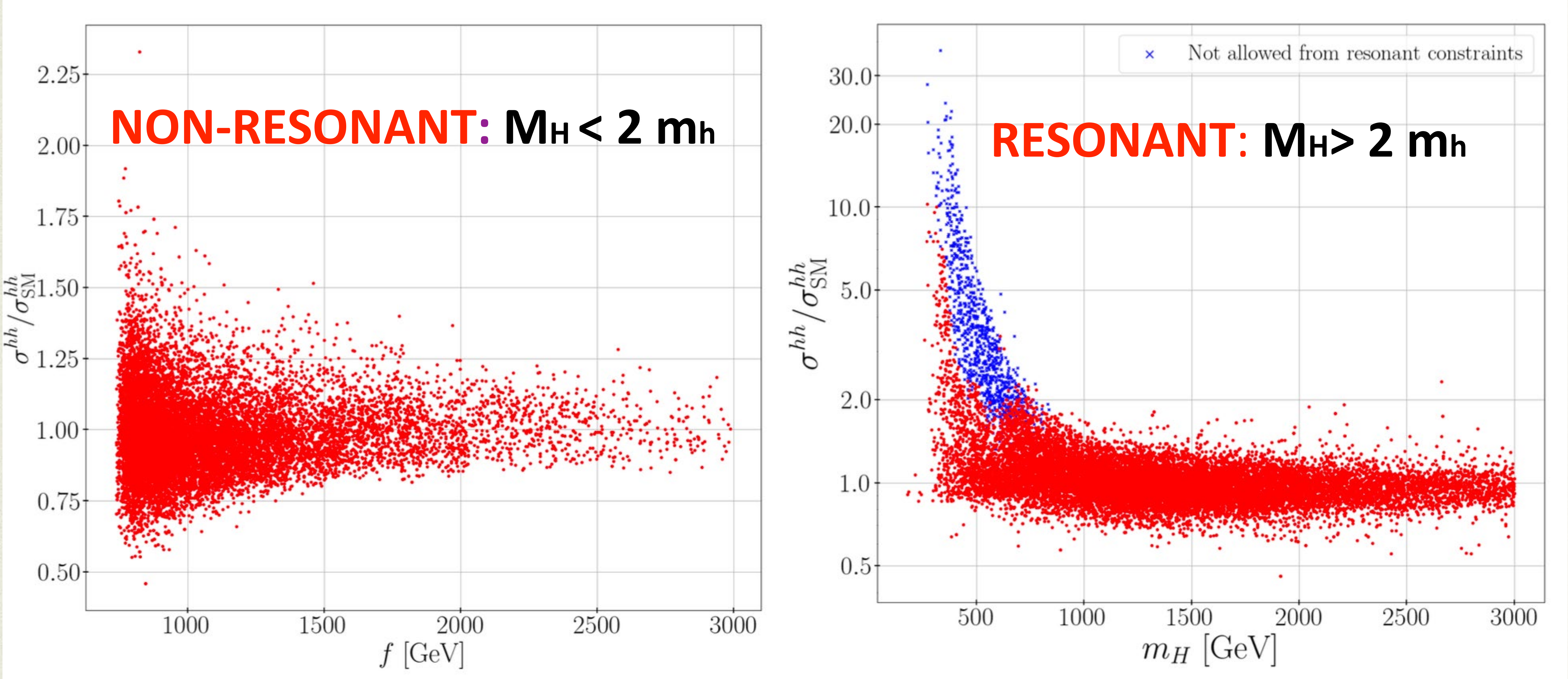
Typical of theories with pNGBs

Phenomena at play in C2HDM:

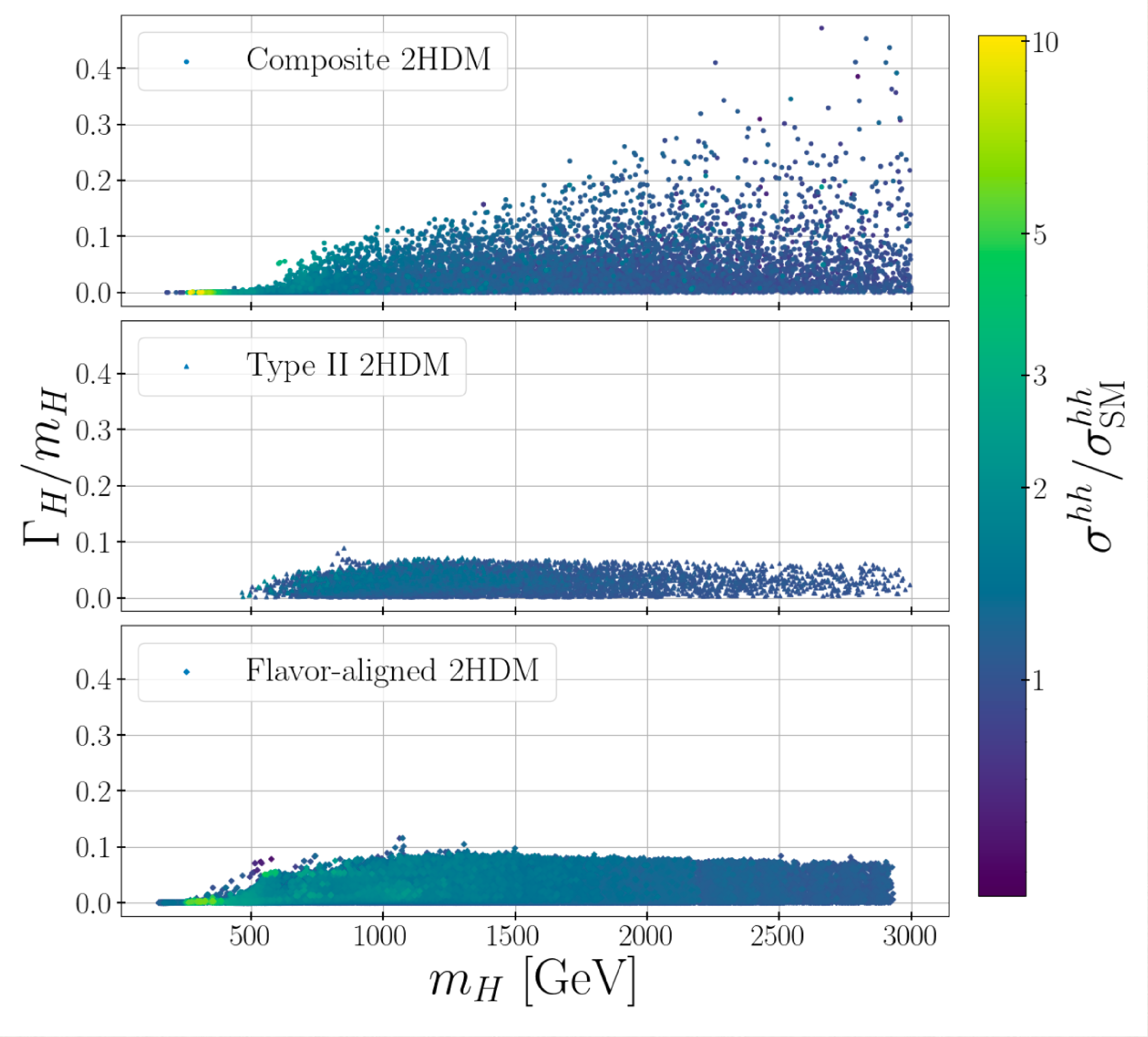
1. Modified hhh ($\kappa(\lambda)$) & tth couplings ($\kappa(t)$) - small deviations
2. Heavy top contributions *T(i)* (*i*=l, .. ,8) + quartic tthh - naturally present in CHMs
3. H contribution - present in MSSM, 2HDM, etc. - but wider

(see next slide)

Inclusive results for $\sigma(hh)/\sigma(h(SM)h(SM))$:



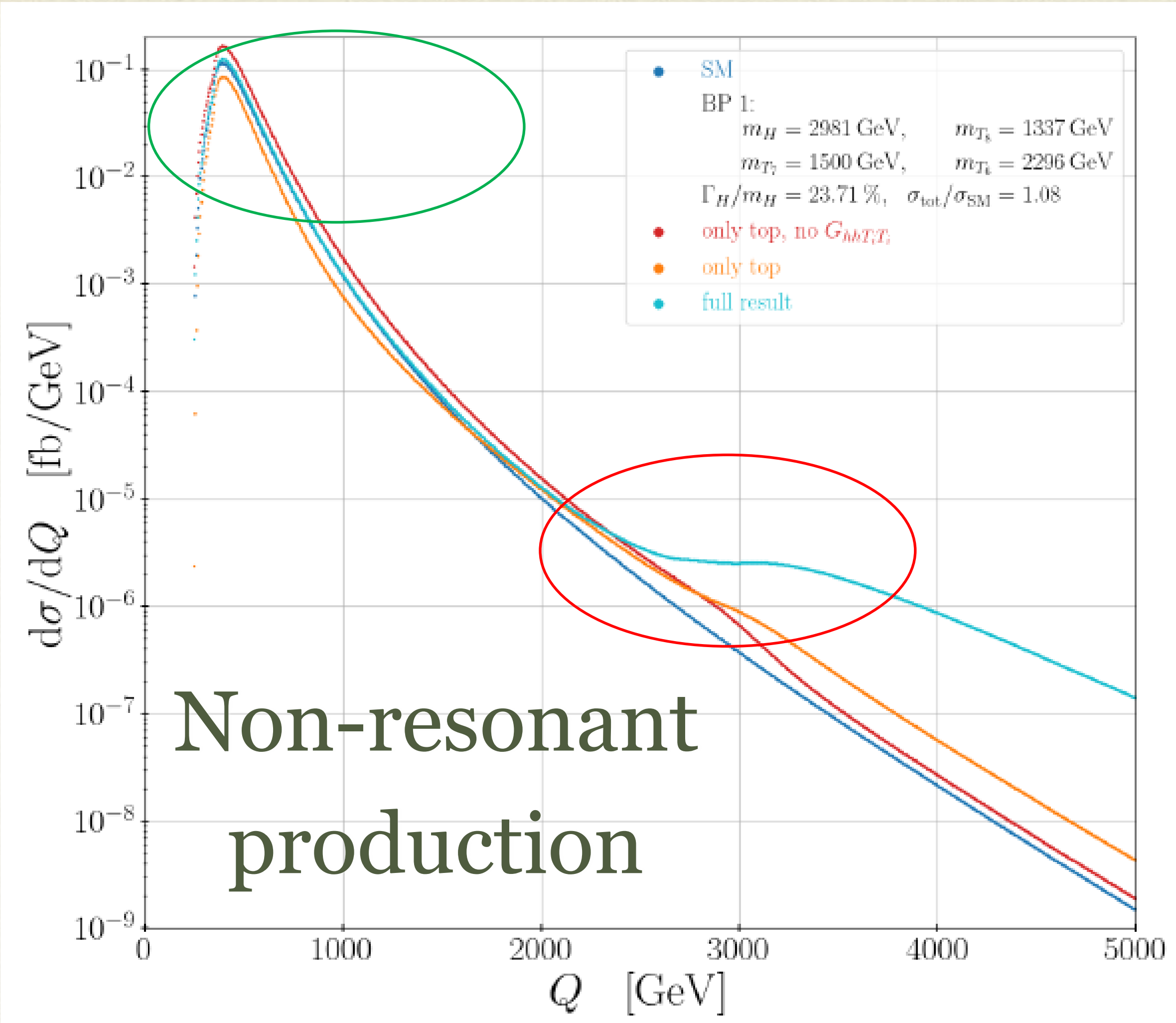
Currently LO (based on HPAIR), working on C2HDM NLO *K*-factors

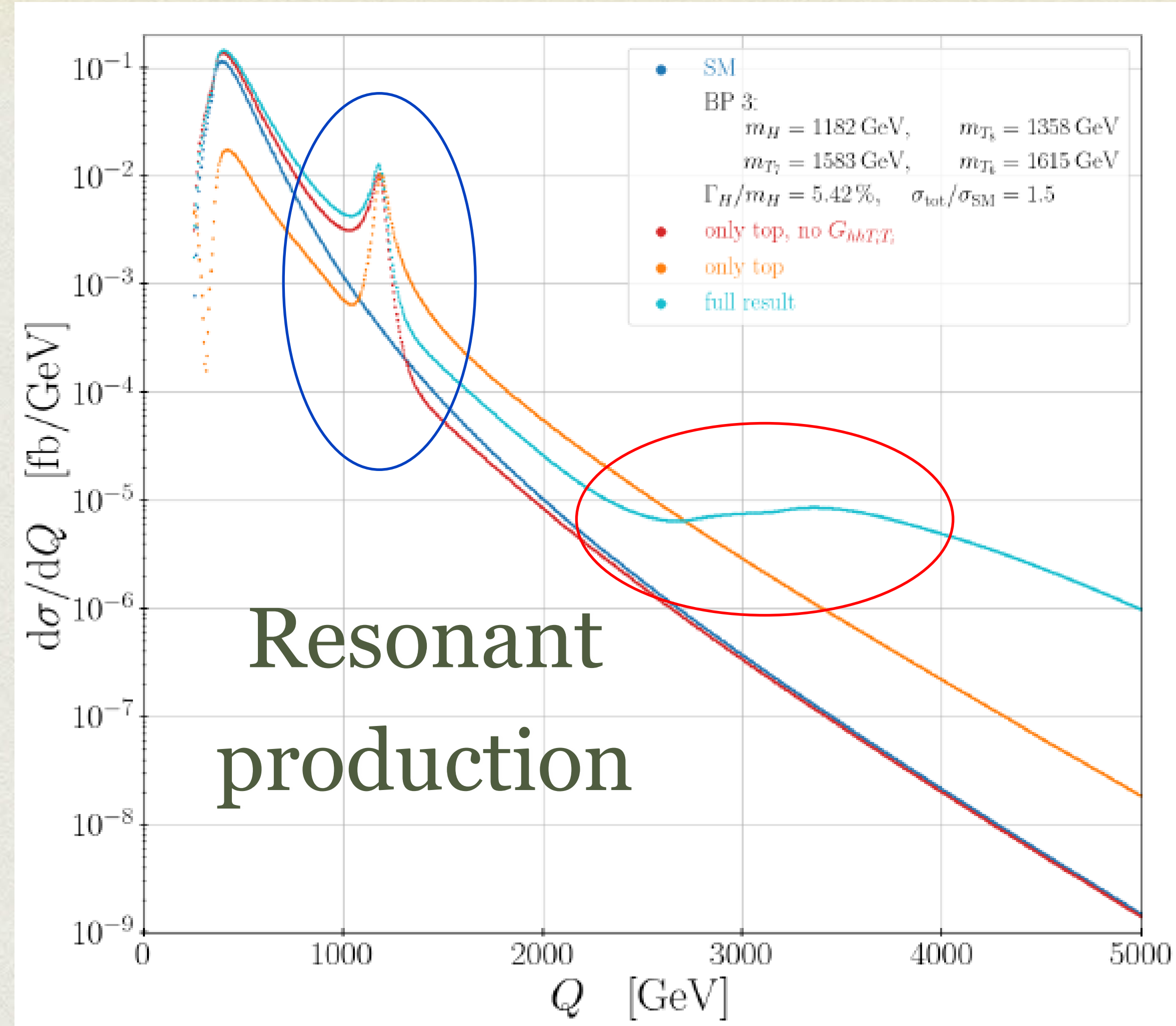


C2HDM: i) low-energy remnant of strongly interactive theory, **Γ**(H)/M(H) can be up to ~30%

ii) also H-> *t T(7,8)* can open with *T(7,8)* lowest-lying VLTs

→ large interference effects



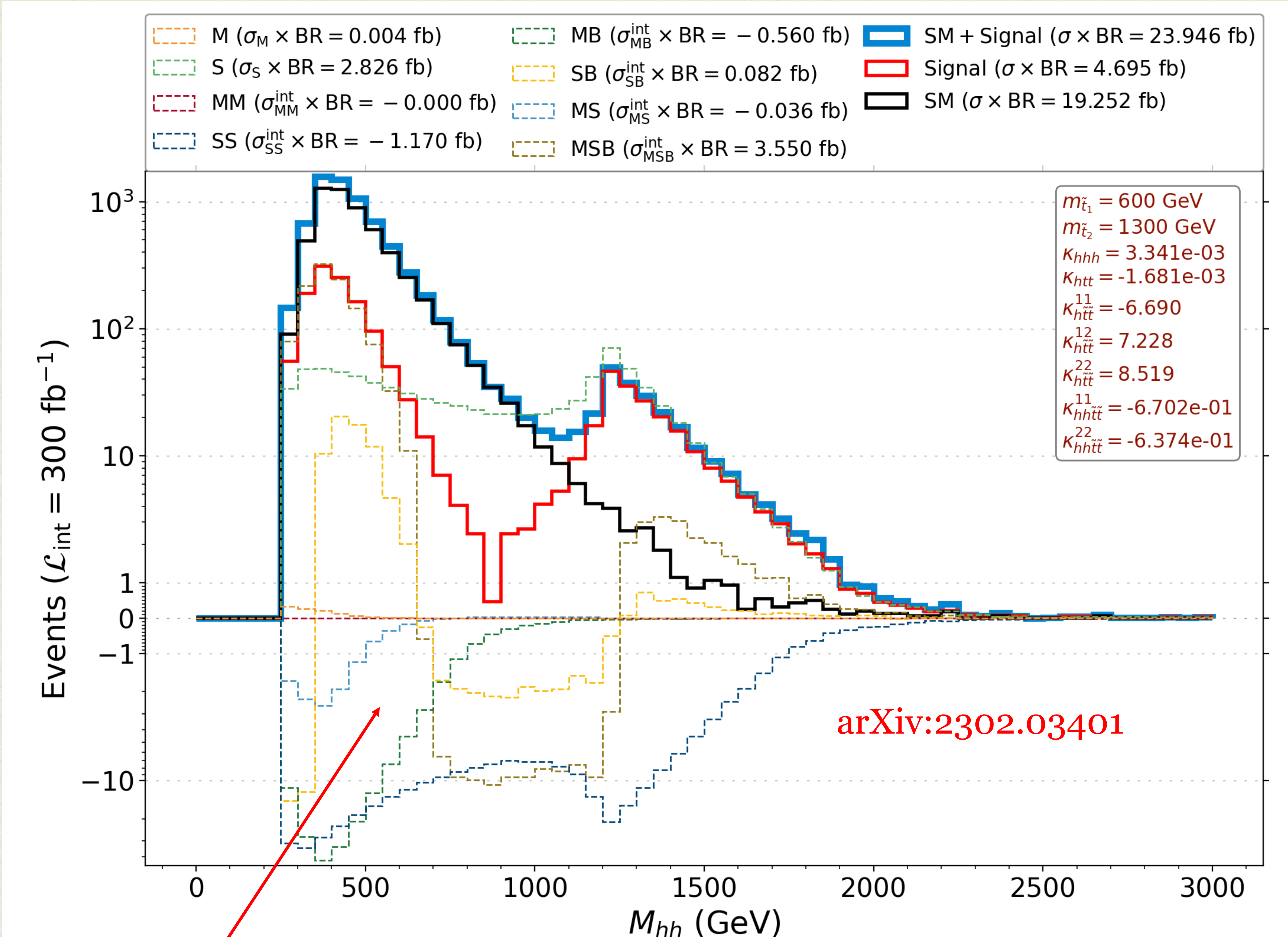


Loop-induced thresholds at 2m(VLQ), low mass tail & BW distortions

Need to surpass: i) EFT paradigms (HEFT, SMEFT) in non-resonant searches
ii) NWA/BW approximation in resonant searches

Developing Simplified Model library (with amplitude decomposition for interpretation) mappable onto: i) fundamental theories (done for SUSY, in progress for Compositeness)
ii) new EFTs in decoupling (SMEFT+, i.e., SMEFT approach with SM+VLTs as low energy limit

Experimental sensitivity: Run 3 to resonant case and HL-LHC for non-resonant one



Done for SUSY (stops) in progress for Compositeness (VLTs)

CONCLUSIONS AND PERSPECTIVES

- C2HDM is simplest natural 2HDM alternative to MSSM in the context of CHMs

- O(6)/SO(4)xSO(2) scenario with a broken C_2 which realising a(n Aligned) C2HDM notably different from MSSM: *delayed Higgs alignment, lifted mass degeneracy amongst BSM Higgses (ie, chain decays)* (also *different mass spectra for top companions* – see backup slides)

- Top companions in compositeness (VLTs) very constrained by LHC direct searches (on-shell production): could they show up first indirectly (via loops)?

- Di-Higgs(SM) production (Run 3 & especially HL-LHC): significant VLT effects in both resonant & non-resonant production (ie, interferences with long tails)

- Outlook: (i) reverse engineering of decayed *hh* signals (decode spectra) & (ii) SMEFT+ implementation

BACKUP SLIDES

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*

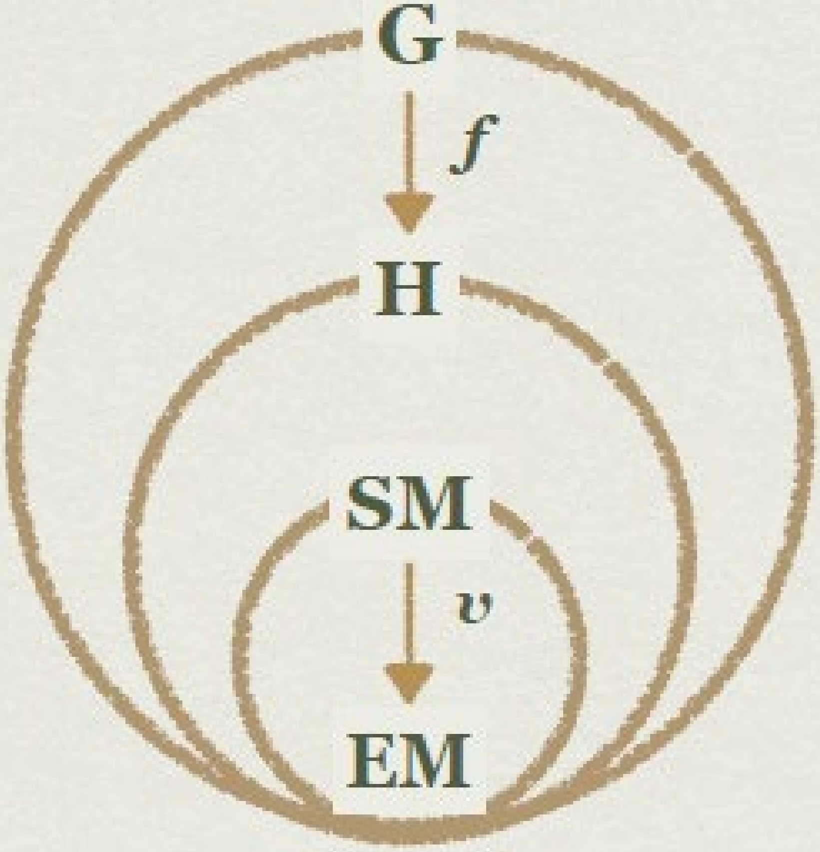
(Recall that Nature likes doublets.)

MSSM VS C2HDM

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

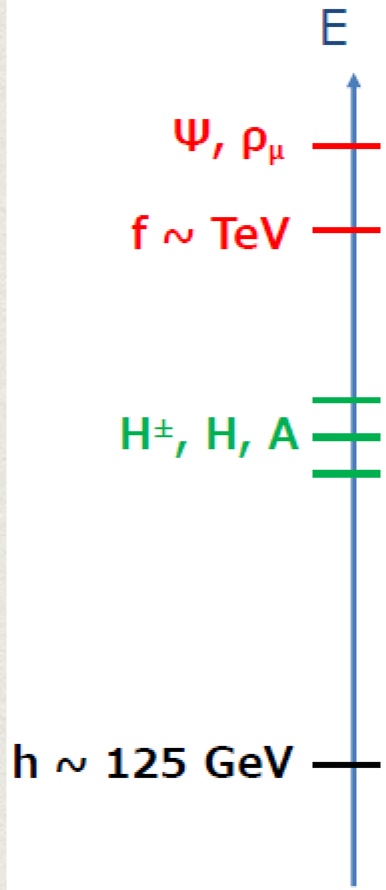
Q: can you distinguish the two paradigms by looking at 2HDM dynamics?

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:



Y_1: C_2 breaking term

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

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

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

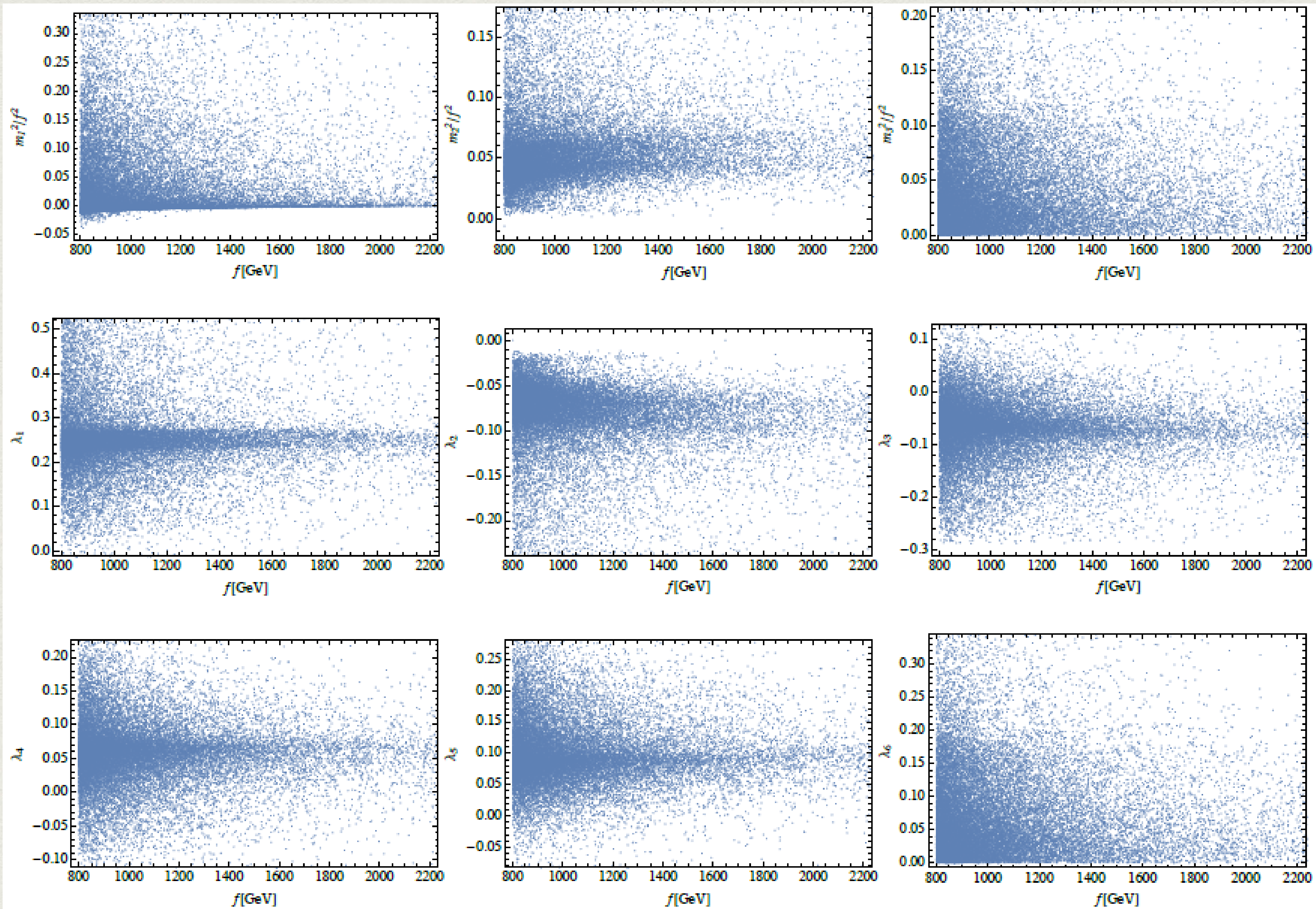
★f → ∞ : All extra Higgses are decoupled

→ (elementary) SM limit.

★To get M≠0, we need C_2 breaking

(Yukawa alignment is required →A2HDM).

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

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

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

- tan β (vev ratio) basis dependent

with

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

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

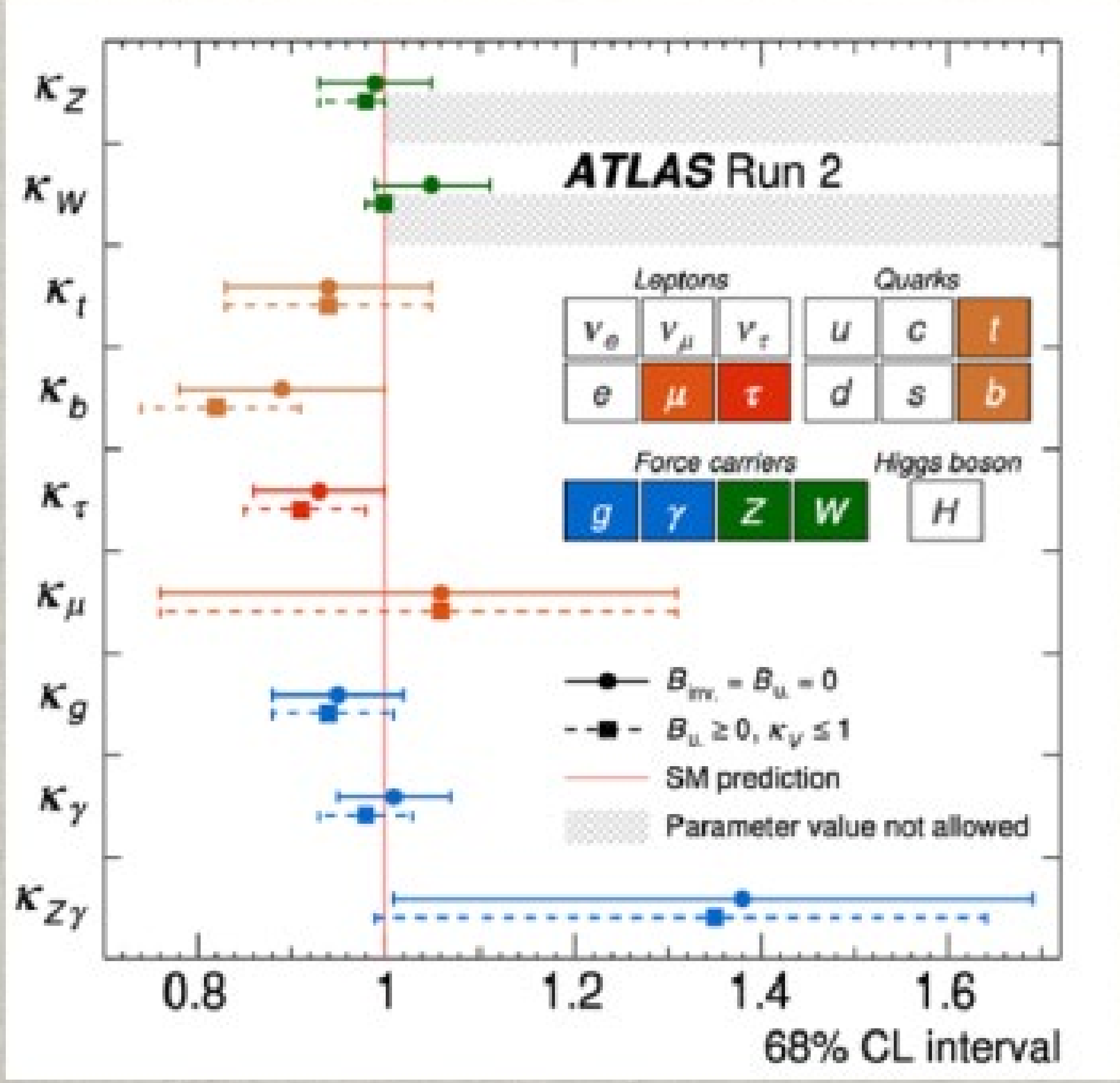
The parameter θ denotes the mixing between the physical components of the two CP-even states while ζ_f represents the normalised coupling to the fermion f of the CP-even scalar that does not acquire a VEV in the Higgs basis. Since θ is predicted to be small, ζ_f controls the interactions of the Higgs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

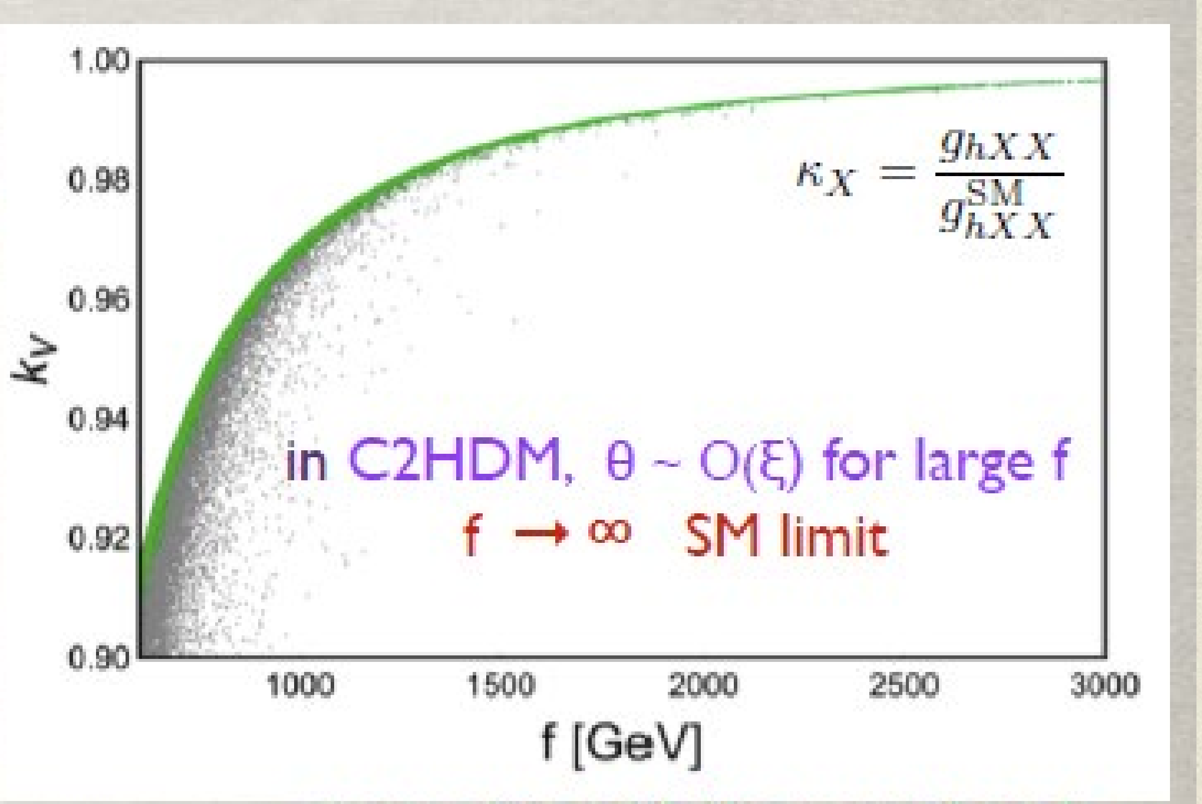
C2HDM - facing the data

- h couplings to SM particles:

dictated by symmetries (as in QCD chiral Lagrangian) Ex: corrections of order ξ to the hVV couplings. Also modified by the mixing angle θ

$k_V \simeq (1-\xi/2)\cos\theta$ V=W,Z $\xi = v^2/f^2$





green points satisfy the present bounds

NOW: the Higgs couplings are constrained at 10-20% level

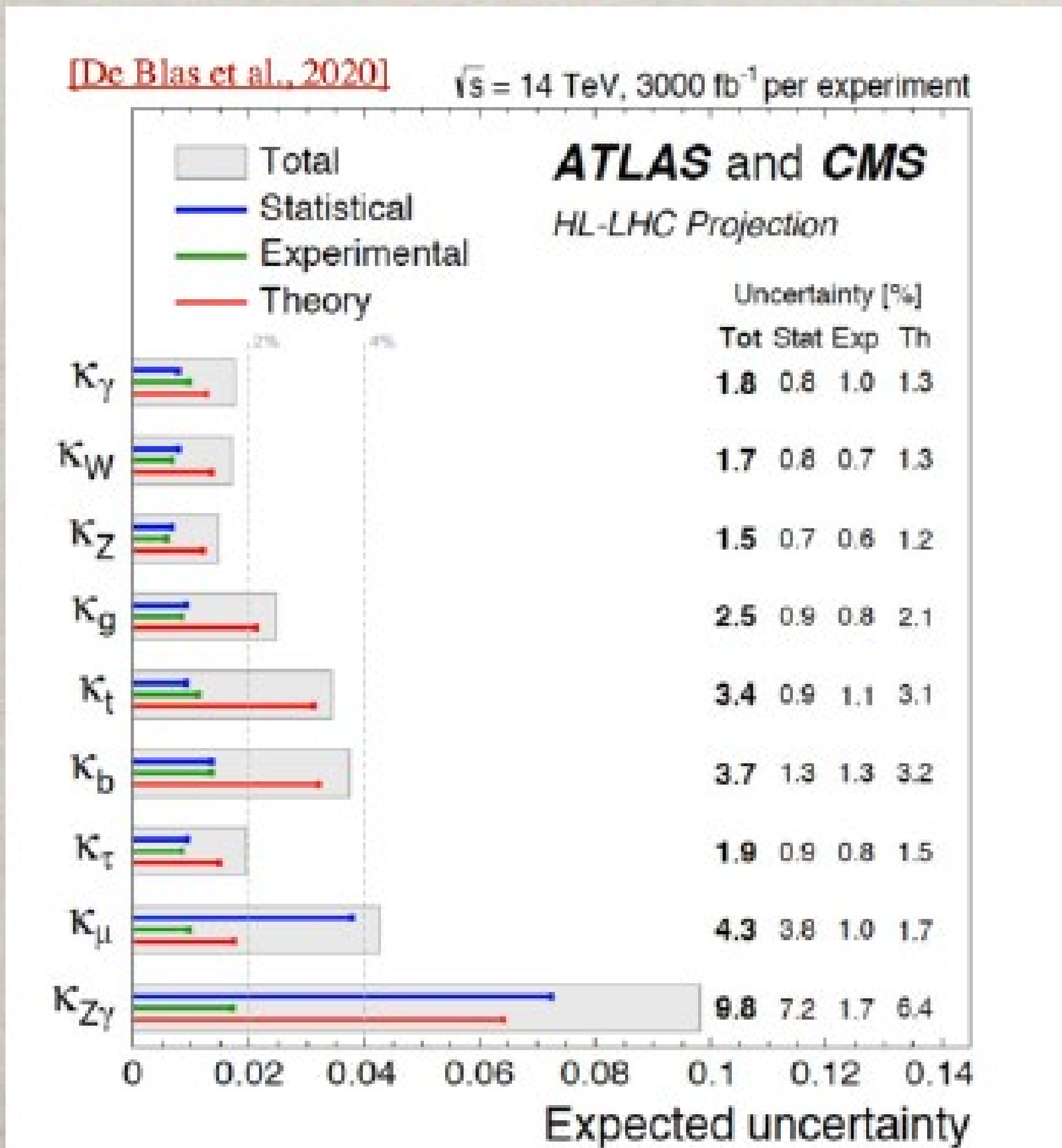
$\xi \leq 0.1$ f $\geq$ 750 GeV

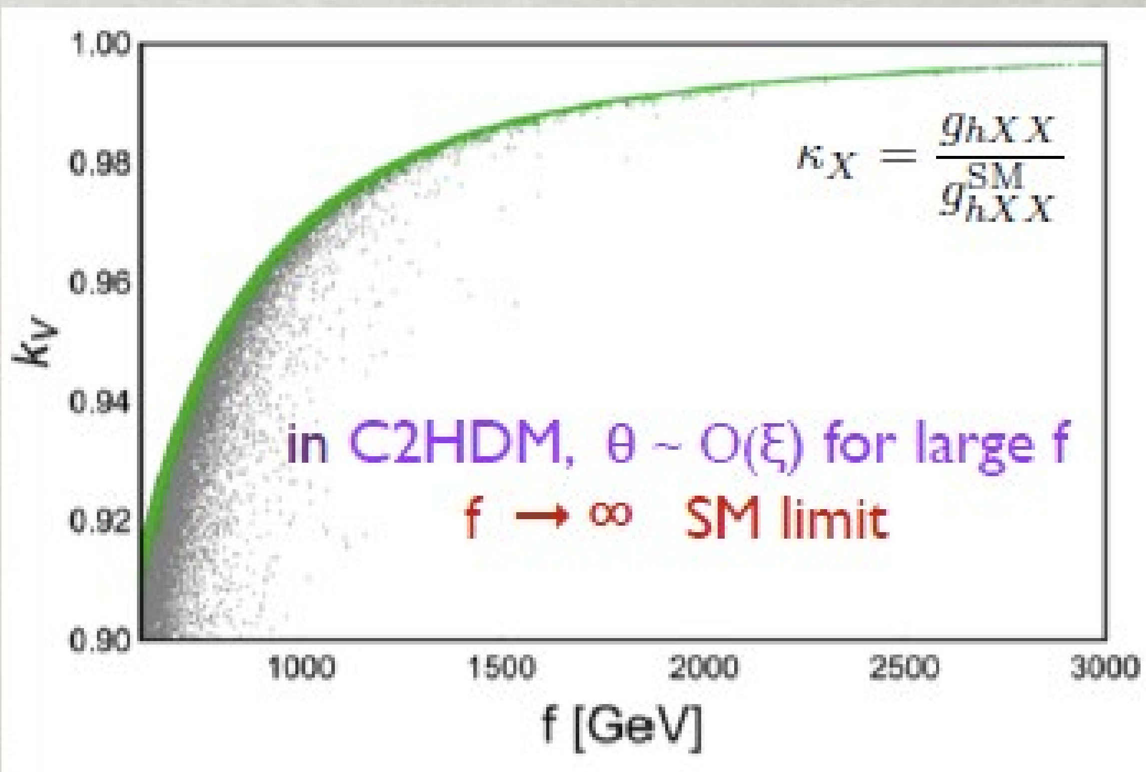
C2HDM - facing the data

- h couplings to SM particles:

dictated by symmetries (as in QCD chiral Lagrangian) Ex: corrections of order ξ to the hVV couplings. Also modified by the mixing angle θ

$k_V \simeq (1-\xi/2)\cos\theta$ V=W,Z $\xi = v^2/f^2$





green points satisfy the present bounds

HL-LHC : the Higgs couplings will be constrained at 2-4% level

$\xi \leq 0.04$ f ≥ 1200 GeV

CHMs NOT ruled out

Higgs Boson Masses

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

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

$\tan\beta = v_2/v_1$

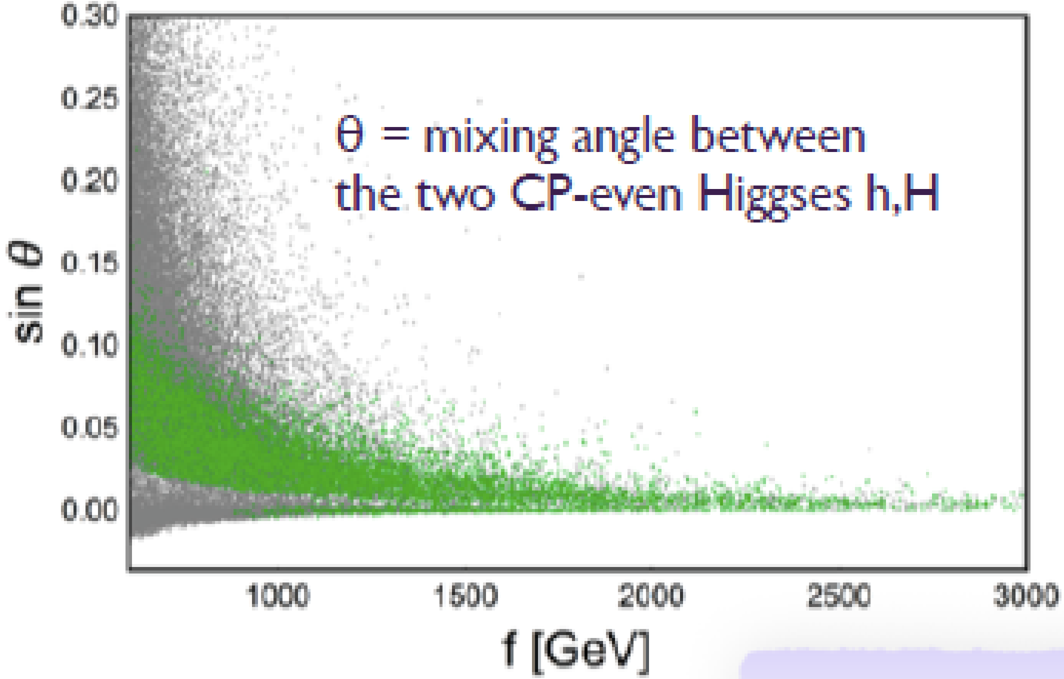
- CP-even states:

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

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

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

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



- **CP-odd & charged Higgses**

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

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

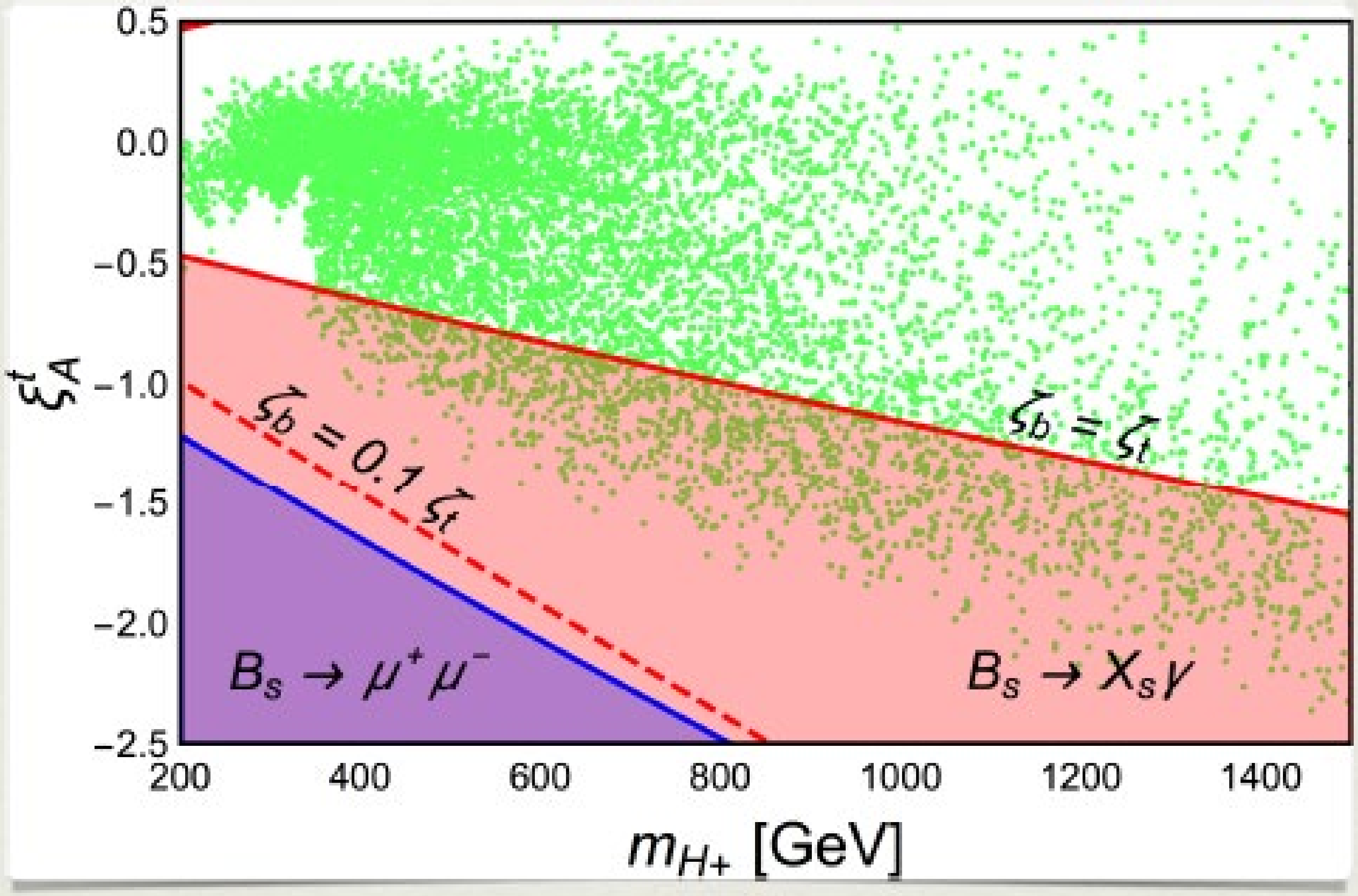
f → ∞   SM limit

H, A, $H^\pm$ decouple and h → h^{SM}

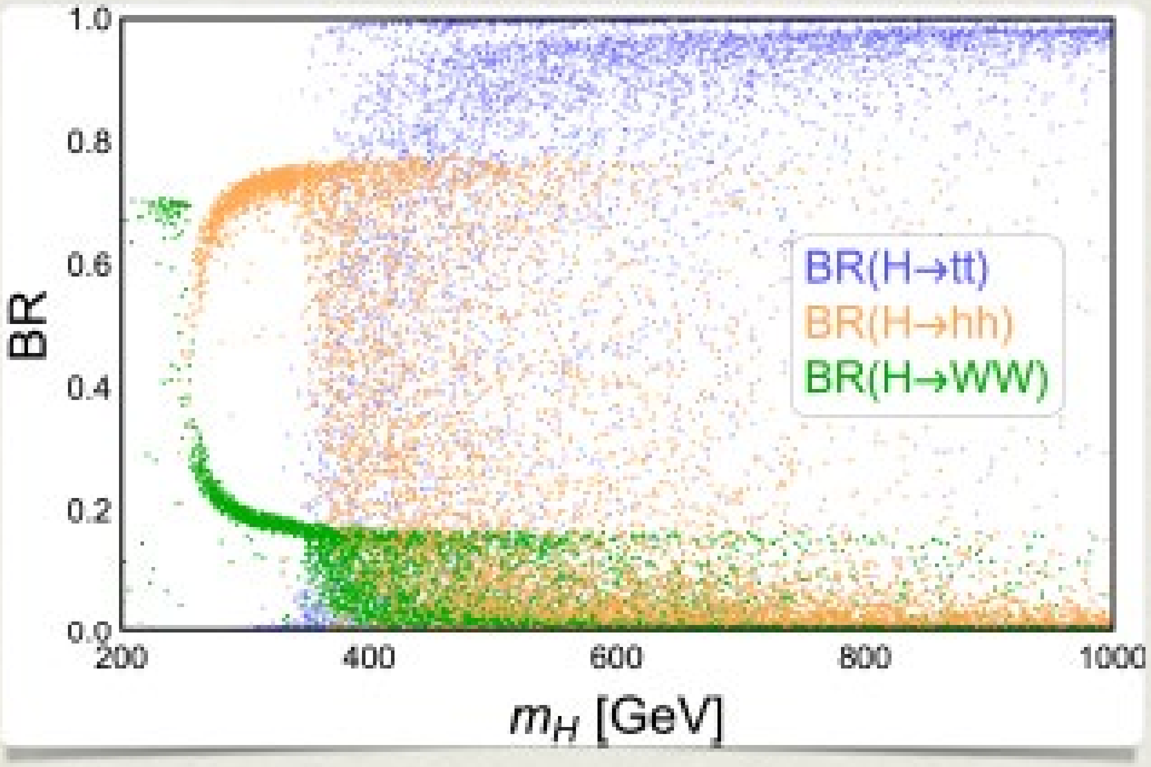
green points satisfy the bounds from direct and indirect Higgs searches

tested against HiggsBounds and HiggsSignals

Flavour constraints



Heavy Higgs decay modes

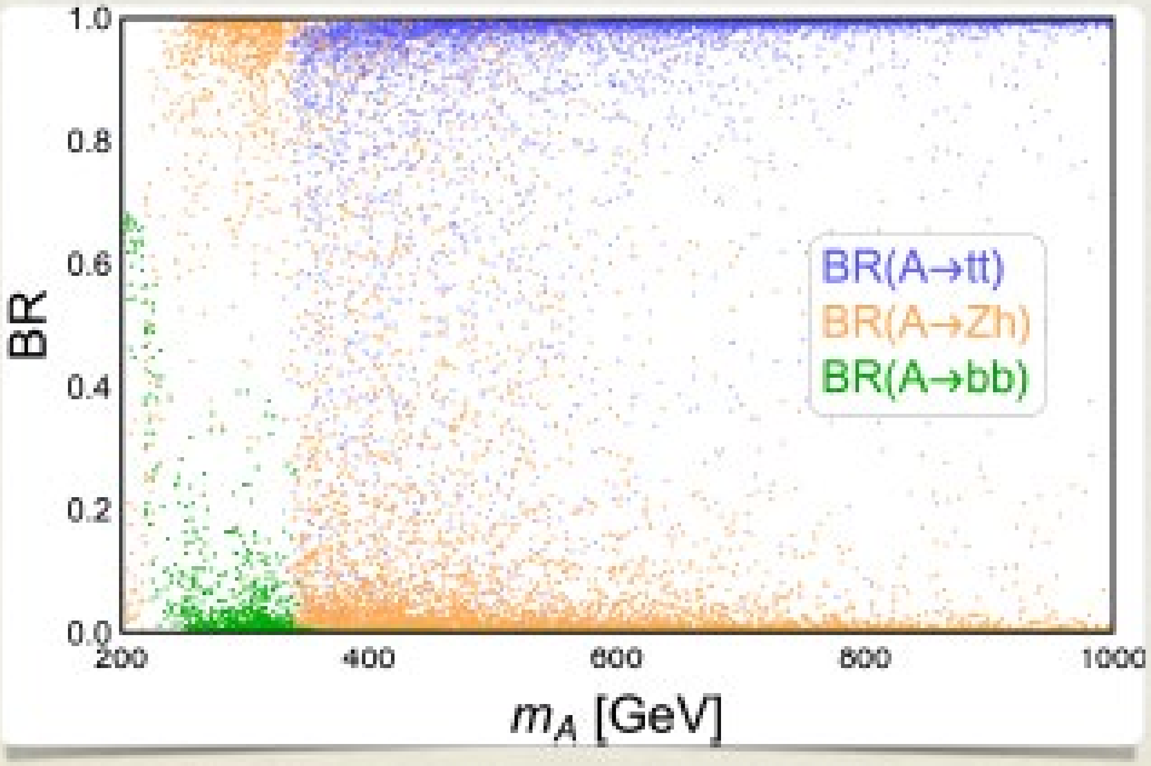


$H \to tt$ represents the main decay mode below the tt threshold, $H \to hh$ dominates *(BR(H→hh) ~ 80%, BR(H→VV) ~ 20%)*

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

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

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



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

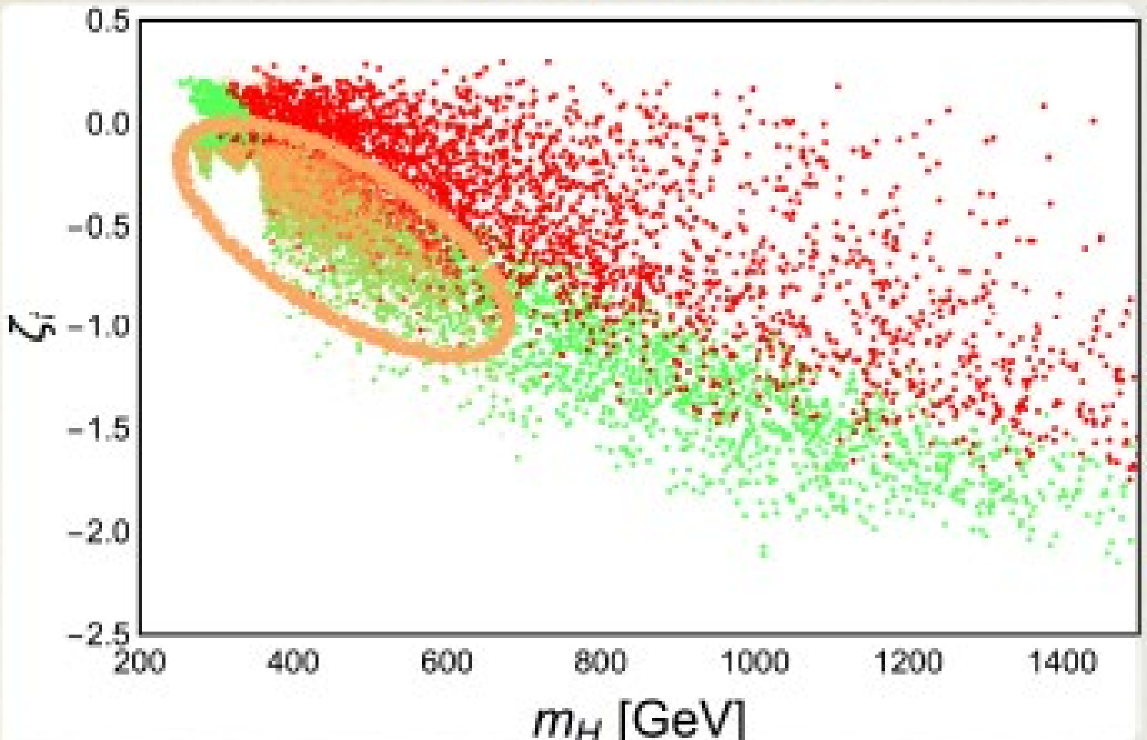
$$\mathrm{BR}(A \to b\bar{b}) \approx 8 \times 10^{-4}(\frac{\zeta_b^2}{\zeta_t^2})$$

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

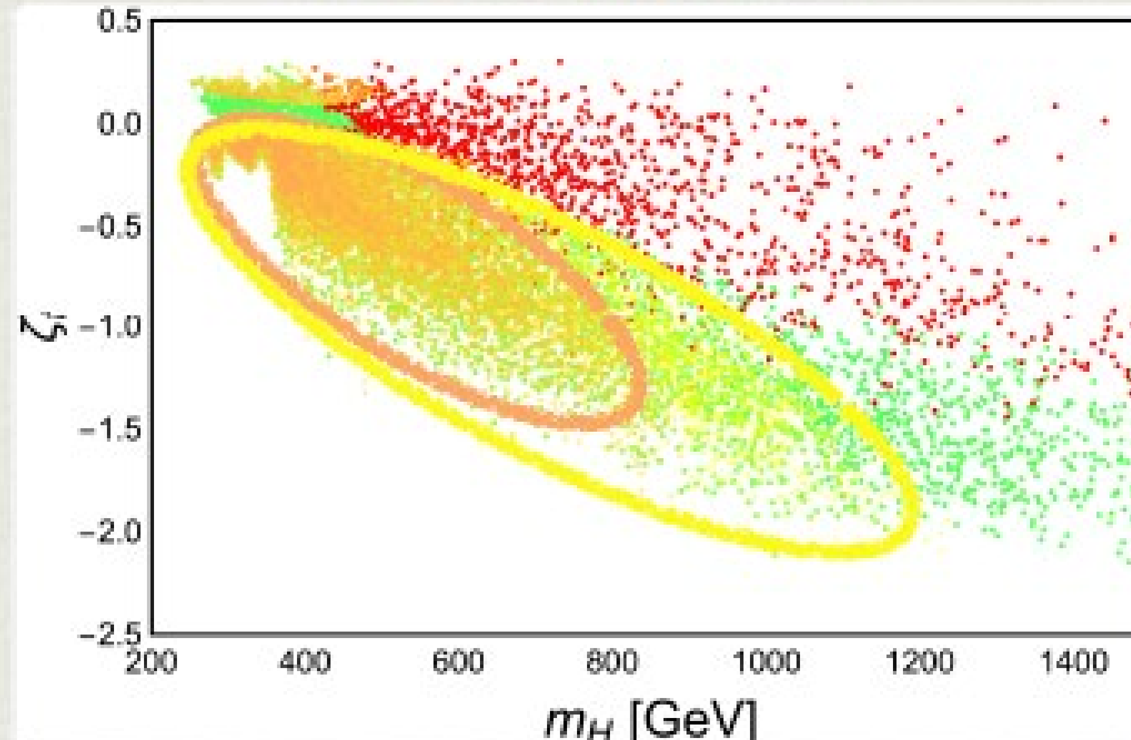
interplay between indirect and direct searches

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

end of Run 3



HL-LHC and HE-LHC



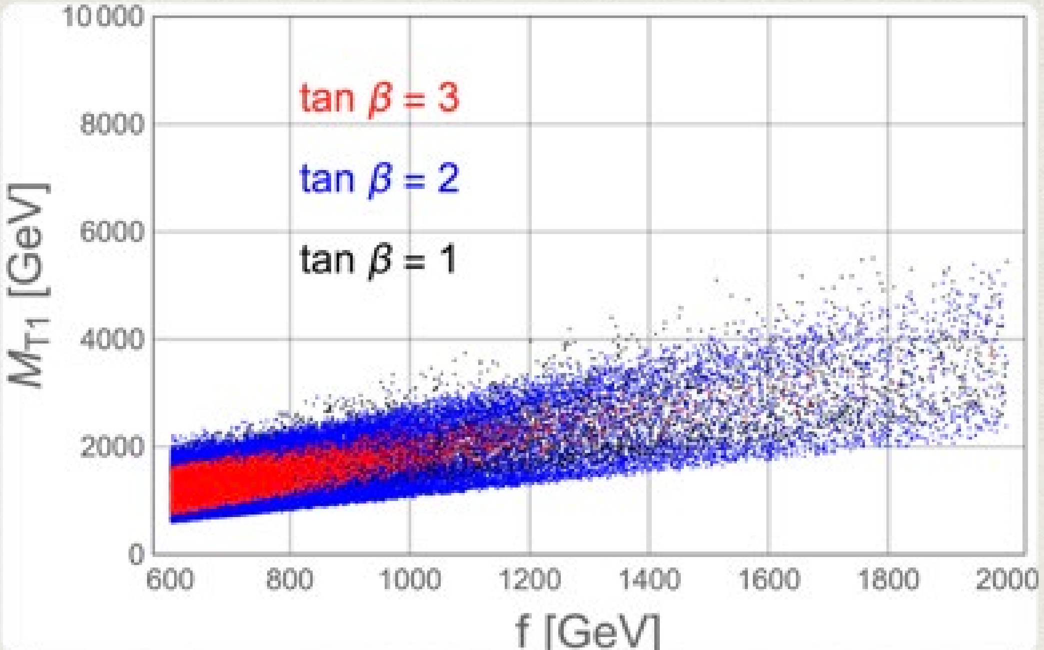
PRELIMINARY

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

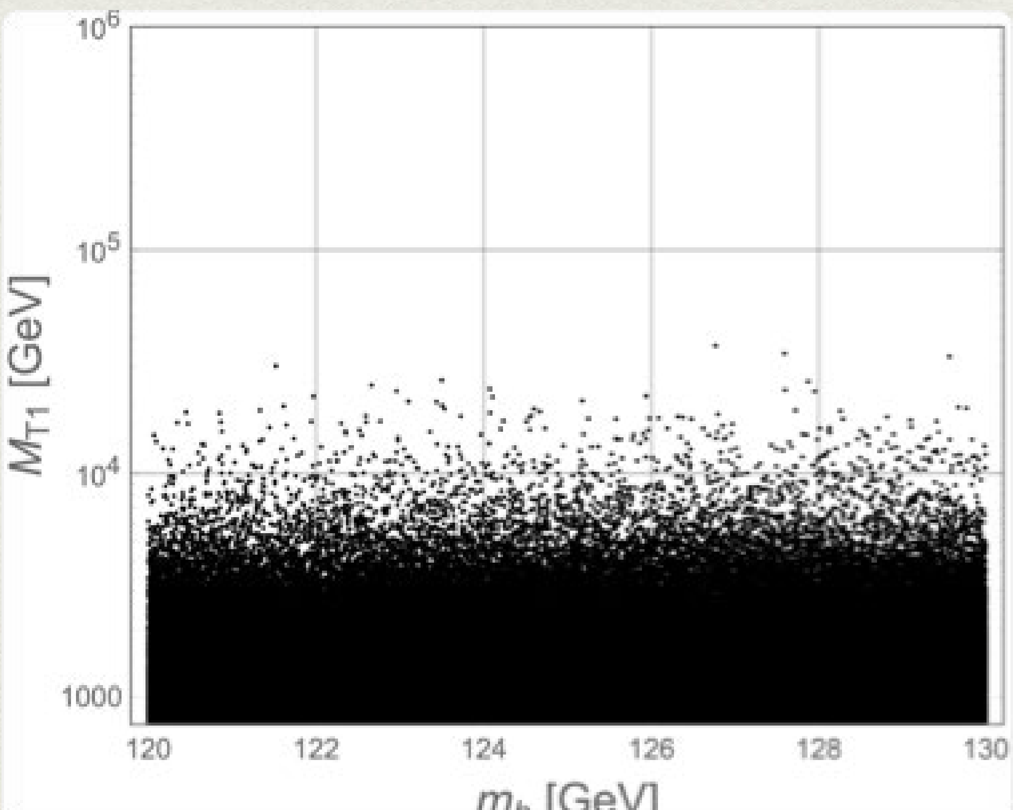
colour legend:

- **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)*

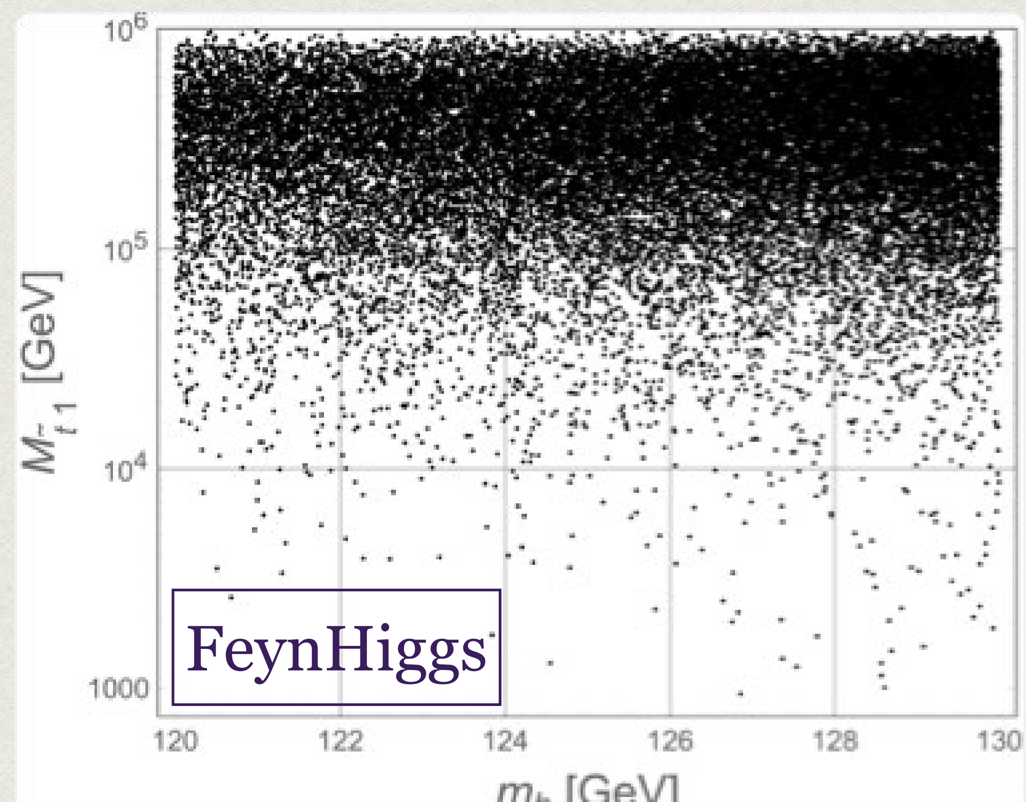
C2HDM: lightest top partner T_1



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 $\tilde{t}_1$



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

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

- 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

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

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

- Yukawa interactions

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

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

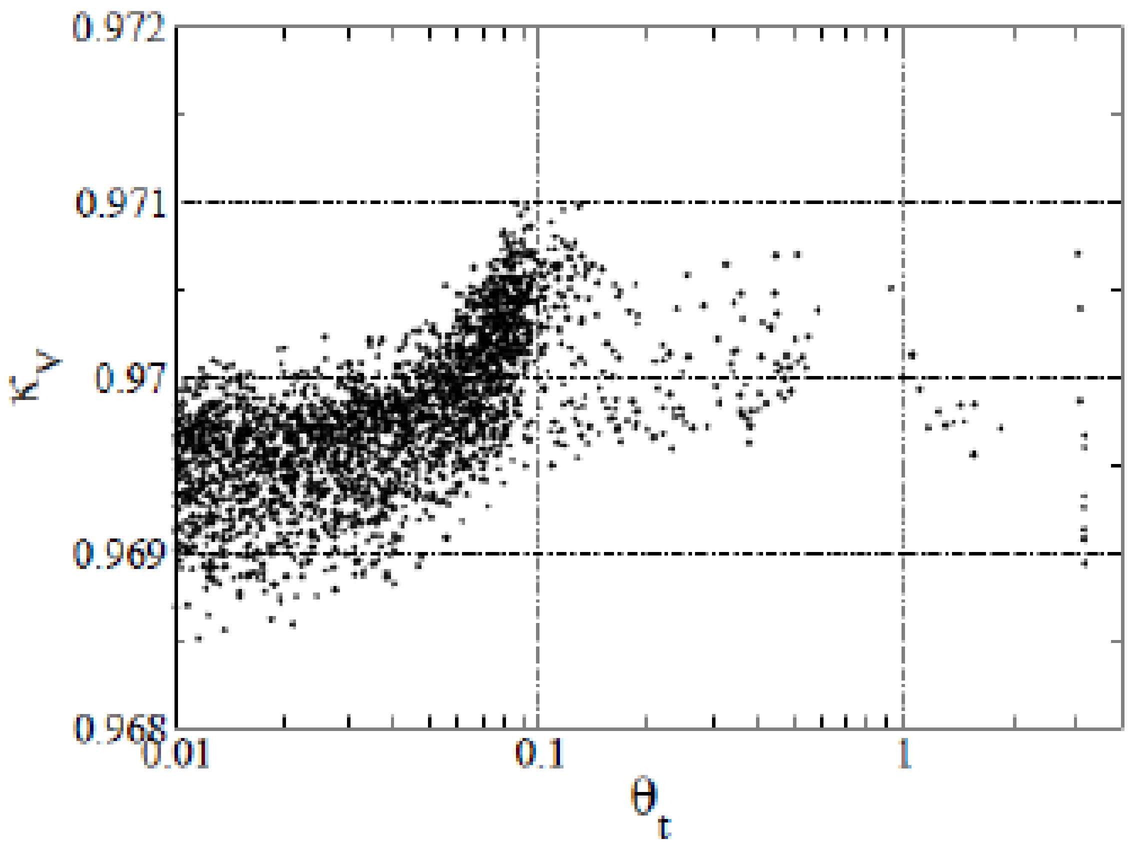
- All the potential & Yukawa sector parameters are determined by the strong sector.
- Both potential & Yukawa sector contain the CPV phase from the common origin.

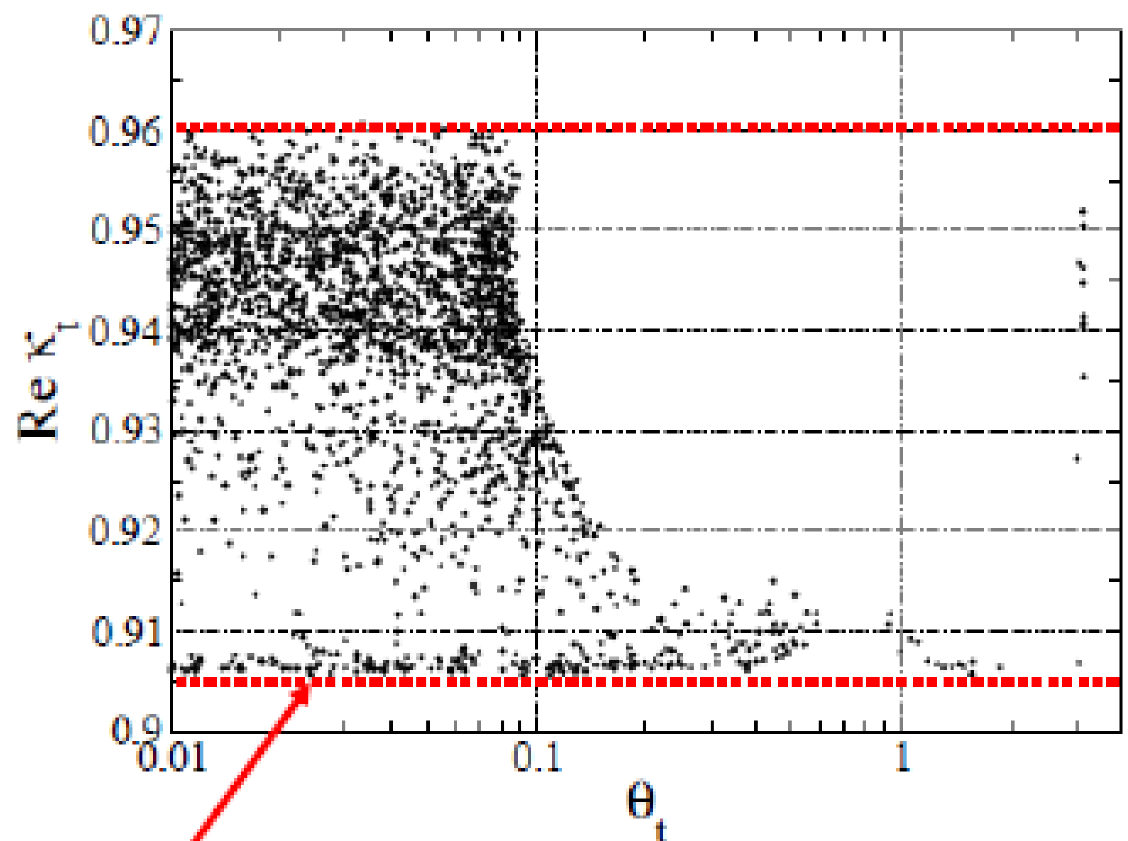
h(125) couplings

- f = 1 TeV

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

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

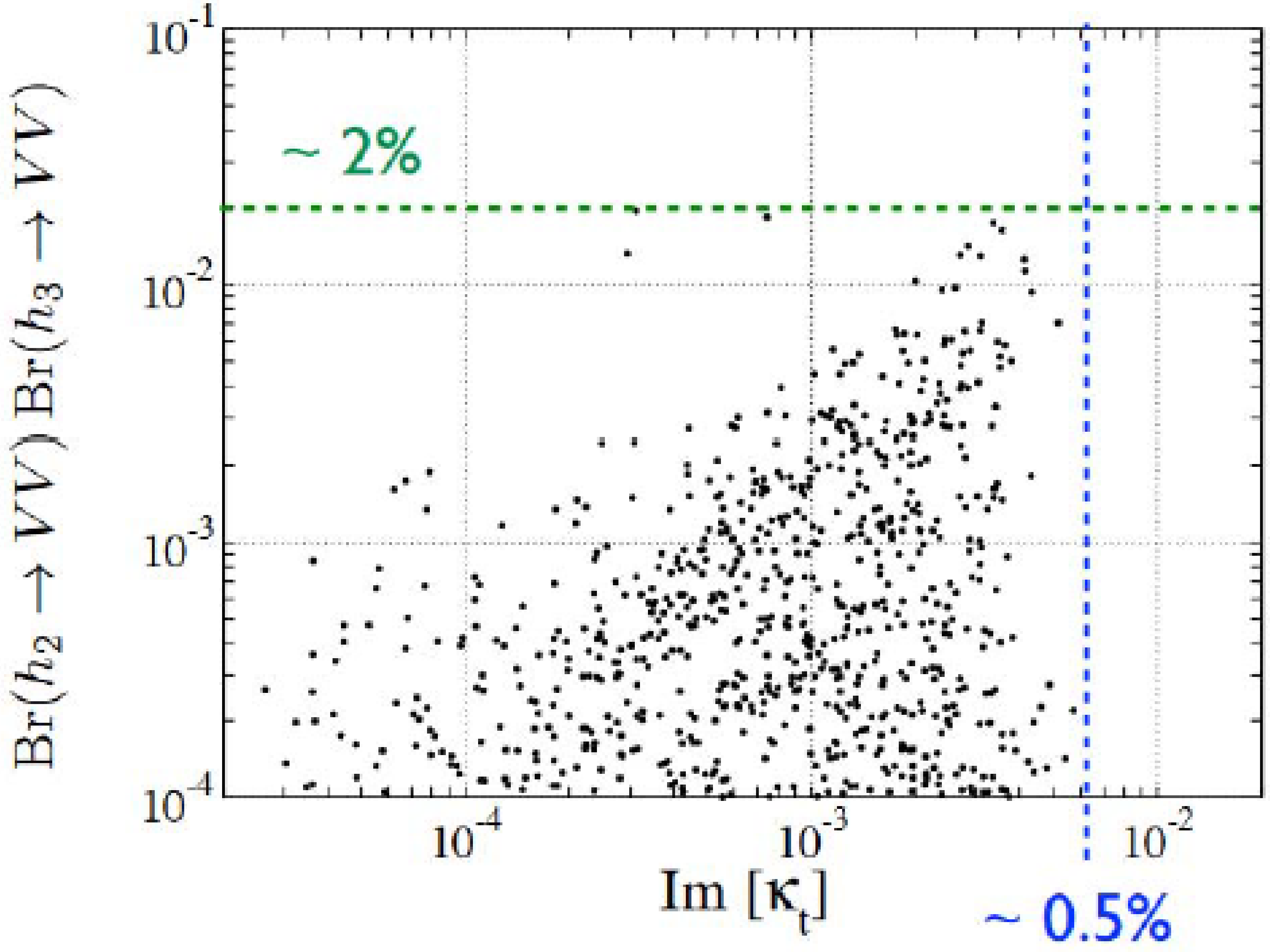


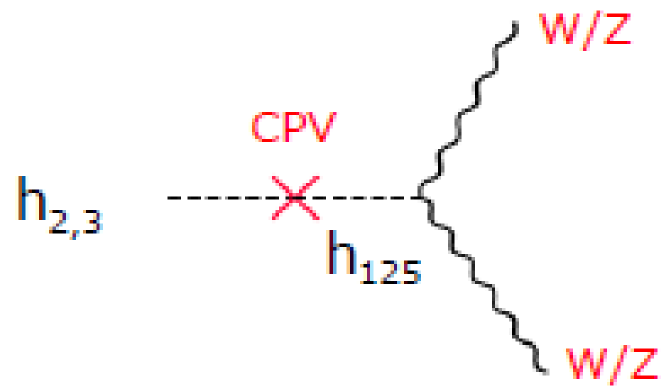


$$\sim 1 - \frac{3}{2}\xi$$

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!