A Concrete Composite 2-Higgs Doublet Model

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Based on: DC,Redi,Tesi, JHEP 1204 (2012) 042
DC,Delle Rose,Moretti,Yagyu, Phys. Lett. B786 (2018); JHEP 1812 (2018) 051
DC,Delle Rose,Panico, 1909.07894

Theory Challenges in Higher-Order NEw Physics Calculations

Karlsruhe Institute of Technology (KIT)
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Outline

- From a theoretical point of view the SM is unsatisfactory. Explore BSM solutions: Higgs as a pseudo Nambu Goldstone boson (pNGB) from a strong dynamics can provide an elegant solution for naturalness

- More than one composite Higgs? Look for a pNGB realisation of extended Higgs scenarios

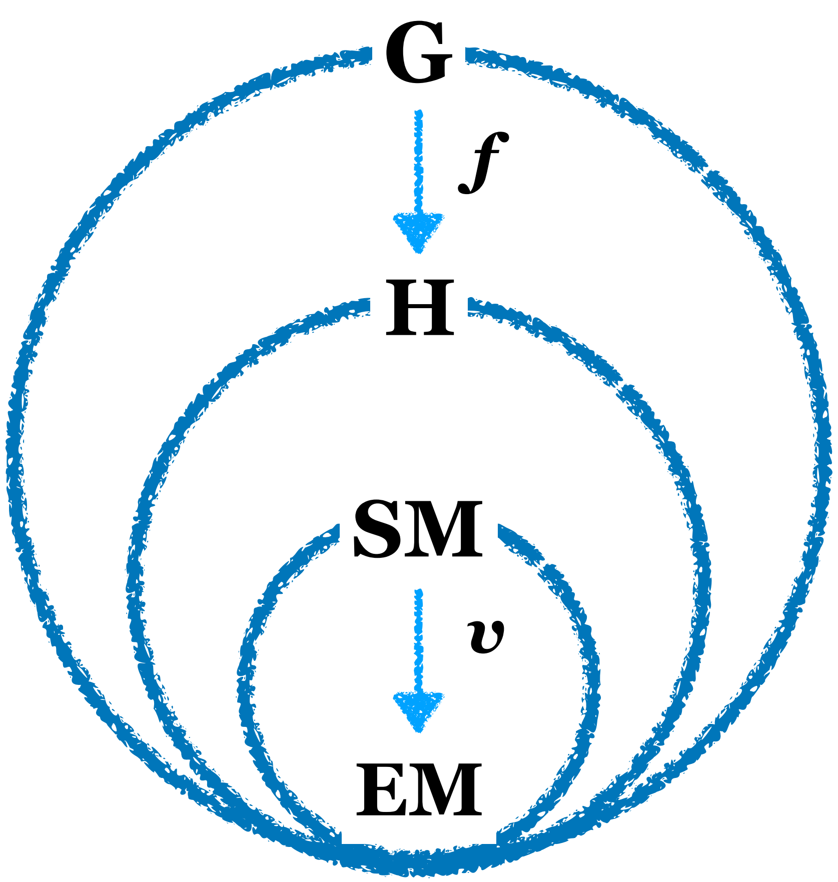
- In a Composite 2HDM (C2HDM) the properties of $h, H, A, H^{\pm}$ are derived in terms of the fundamental parameters of the strong sector and compared with the Elementary 2HDM ones

- Further developments: Composite Dynamics in the Early Universe

— a strong first-order EW Phase Transition can trigger EW Baryogenesis in a CHM based on SO(6)/SO(5)

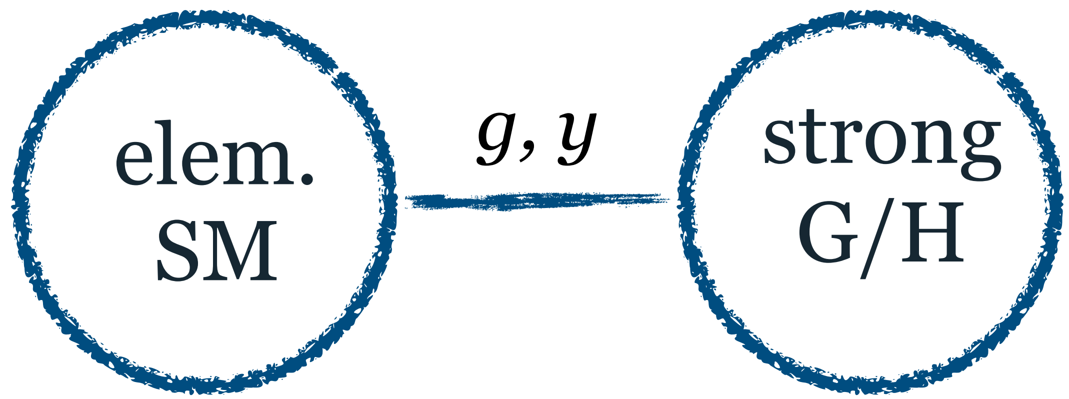
— it generates Gravitational Wave signatures ➞ interplay between Gravitational Interferometry and Collider experiments in testing the Higgs sector

Basic rules for Composite NGB Higgs models

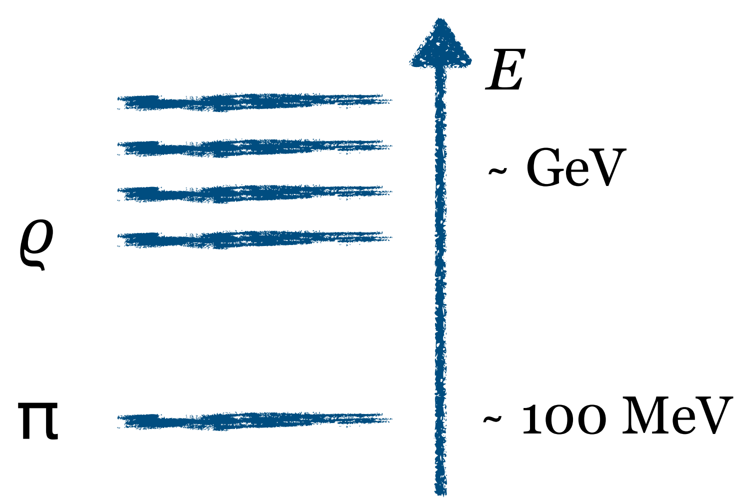


- a global symmetry G above f (~ TeV) is spontaneously broken down to a subgroup H
- the structure of the Higgs sector is determined by the coset G/H
- H should contain the custodial group
- the number of NGBs (dim G - dim H) must be larger than (or at least equal to) 4
- the symmetry G must be explicitly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

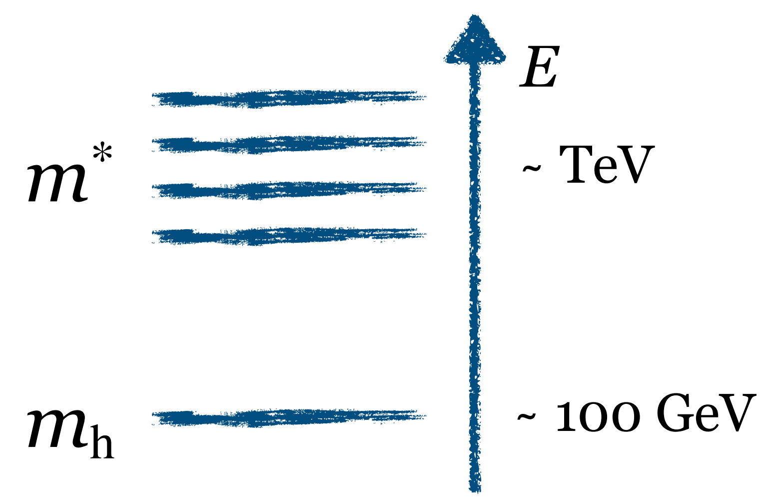
Mass spectra



inspired by QCD
where one observes that the
(pseudo) scalars are the lightest states



the Higgs could be a kind of pion
arising from a new strong sector



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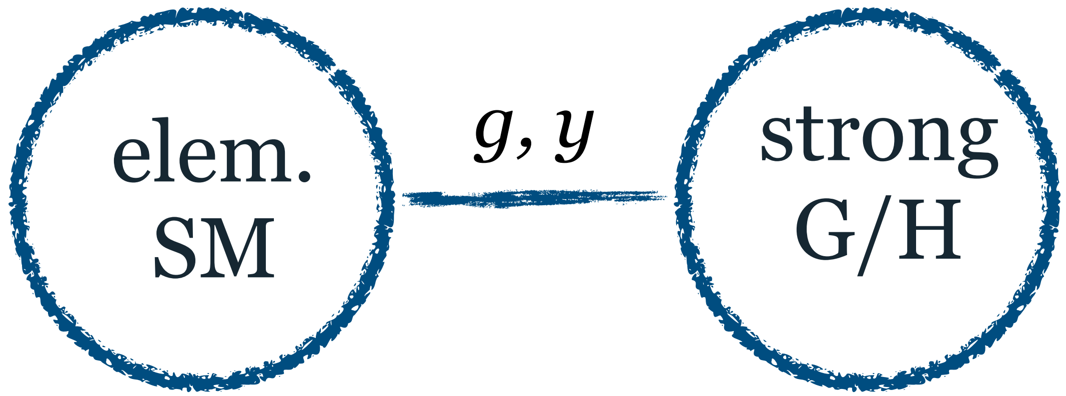

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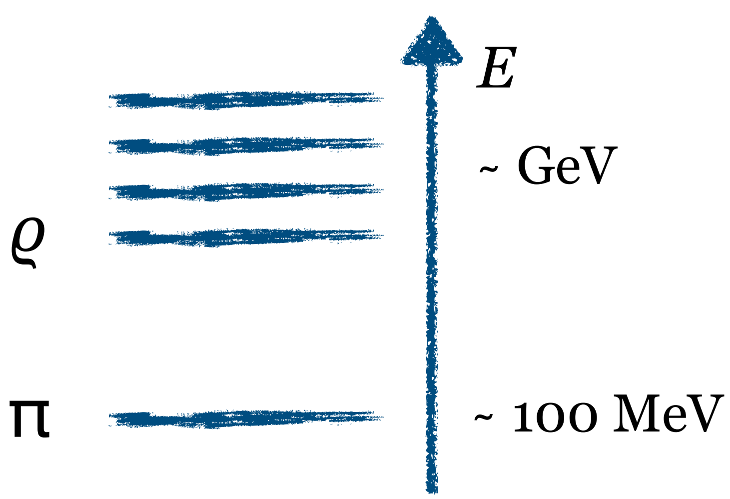

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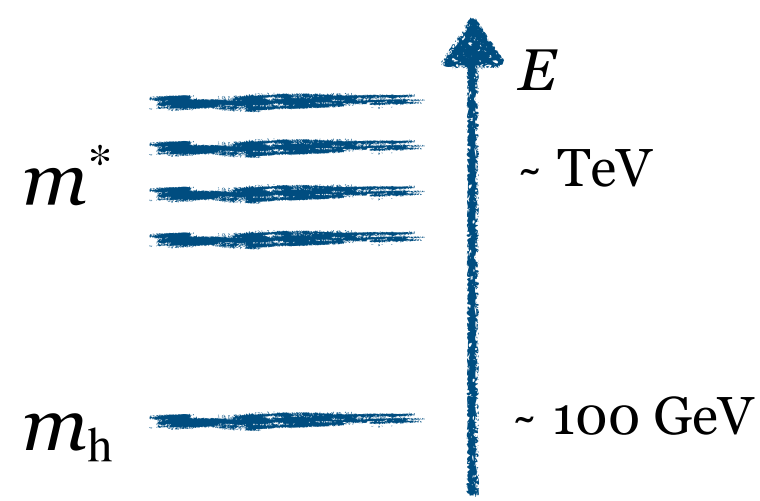
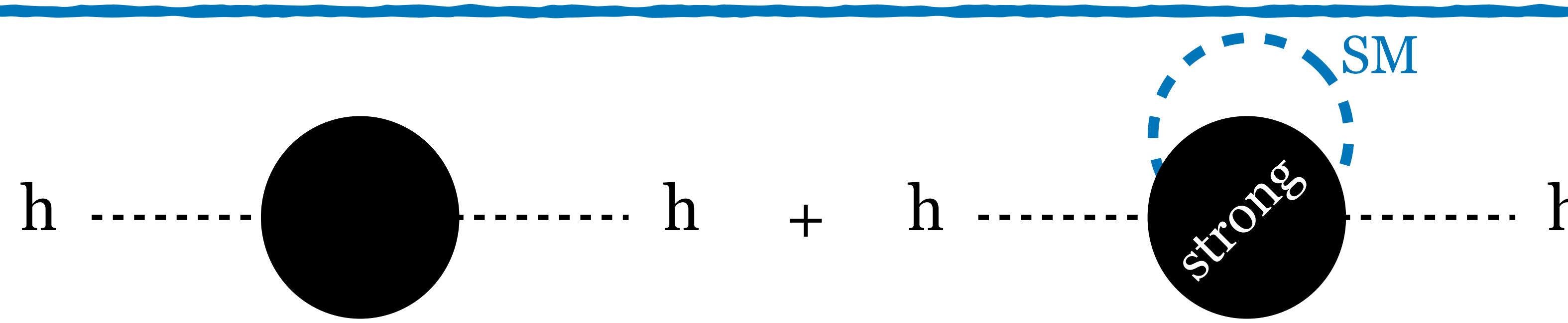


Higgs mass =



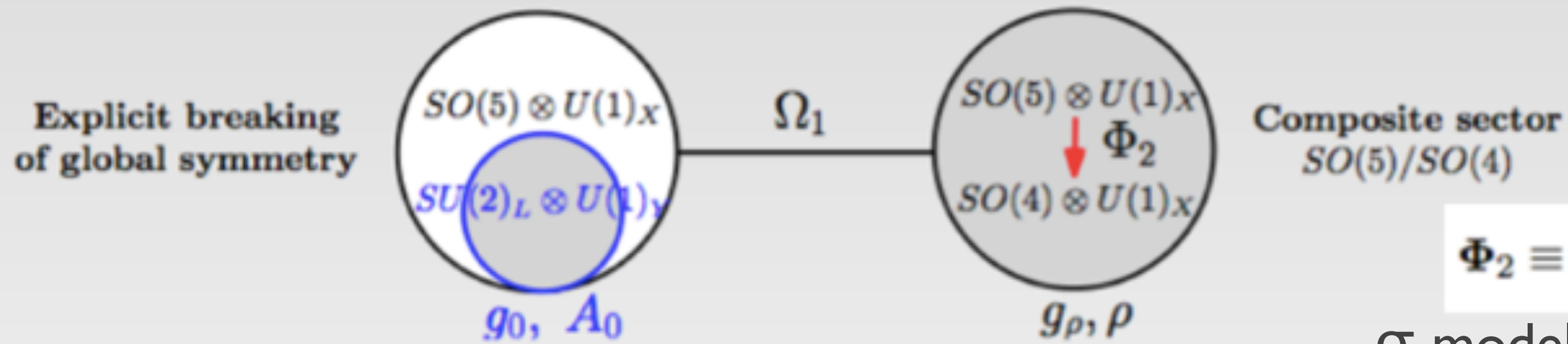
= 0 its a GB!

$m_h^2 \sim g^2/16\pi^2 f^2$

4DCHM = Minimal 4D realisation of MCHM5

DC, Redi, Tesi '12

Agashe, Contino, Pomarol '04



$$\Phi_2 \equiv \Omega_2 \varphi_0 \ , \ \varphi_0^i = \delta_5^i$$

σ-model fields Ω_1, Φ_2

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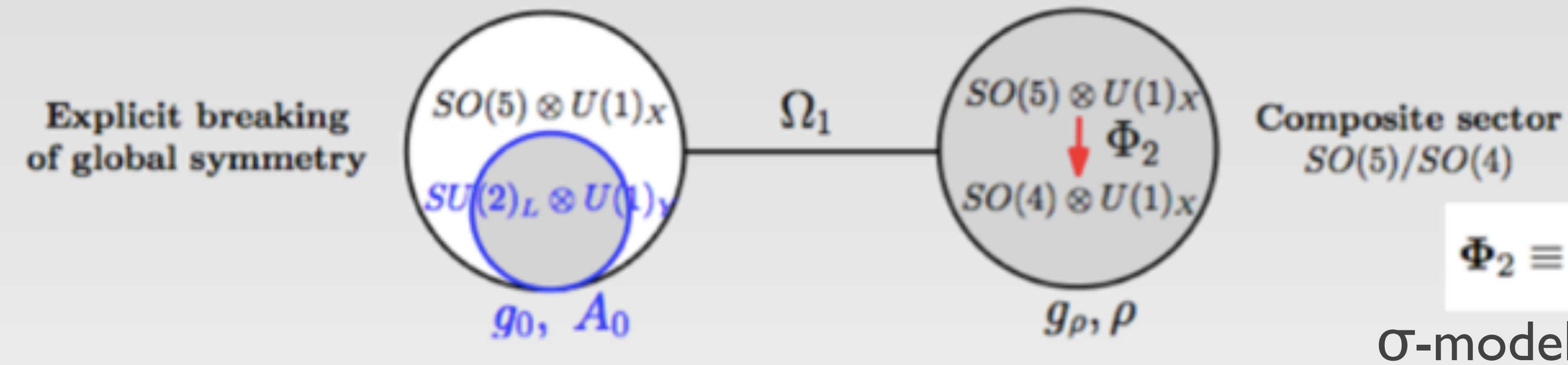
DC, Redi, Tesi '12 | Agashe, Contino, Pomarol '04



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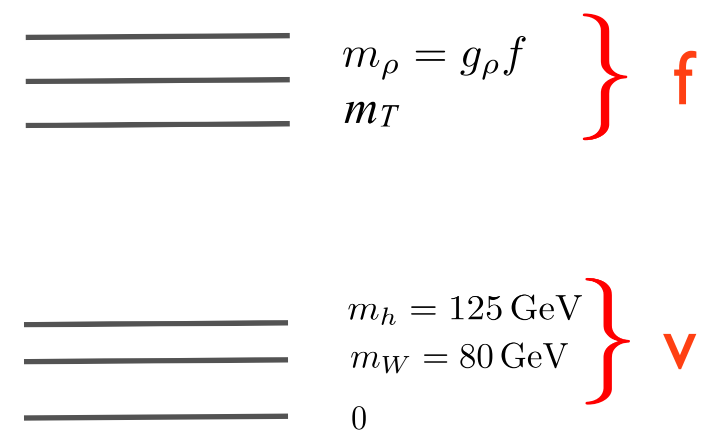
Low-energy Lagrangian *a la* CCWZ + ρ new spin-1 resonances as gauge fields of the "hidden gauge symmetry" + $T, \tilde{T}$ extra composite fermions

Strong sector: resonances + Higgs bound state

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

Spectrum :



g_ρ = strong coupling

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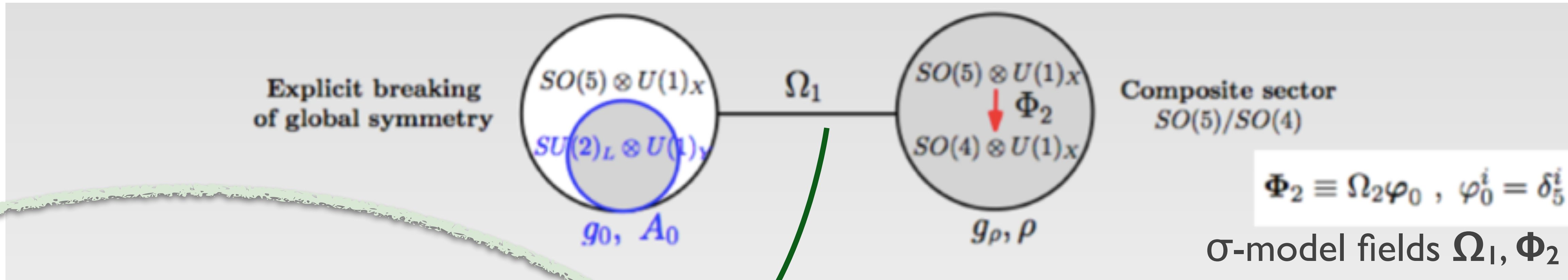
DC, Redi, Tesi '12 — Agashe, Contino, Pomarol '04

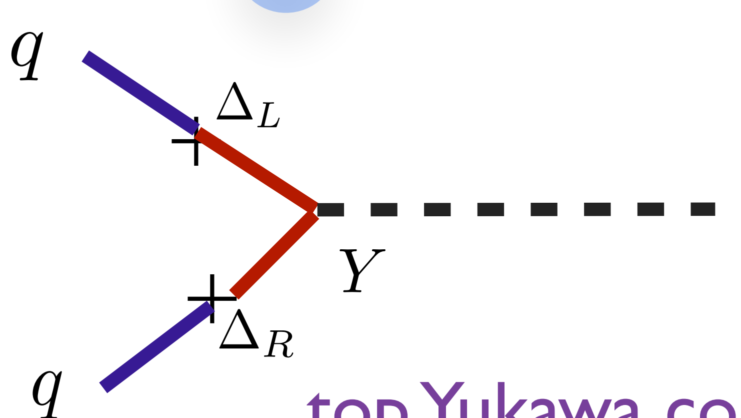


Low-energy Lagrangian *a la* CCWZ + ρ new spin-1 resonances as gauge fields of the "hidden gauge symmetry" + $T, \tilde{T}$ extra composite fermions

Linear elementary-composite fermion mixings Δ

→ partial compositeness mostly for the 3rd generation quarks

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



top Yukawa coupling

$$m_t \sim \frac{v}{\sqrt{2}} \frac{\Delta_{t_L}}{m_T} \frac{\Delta_{t_R}}{m_{\tilde{T}}} \frac{Y_T}{f}$$

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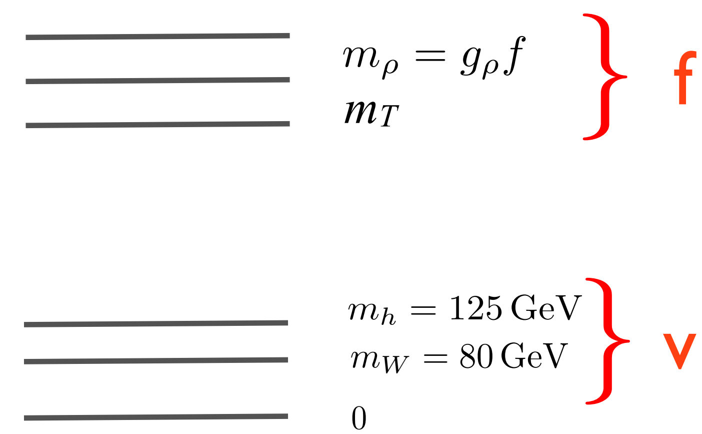
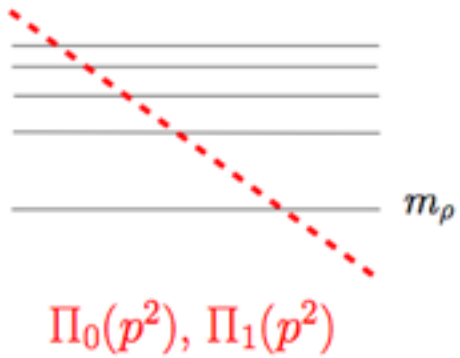


g_ρ = strong coupling

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

And the Higgs mass?

Δ_L, Δ_R, g_0 g_{0Y} break the global G symmetry



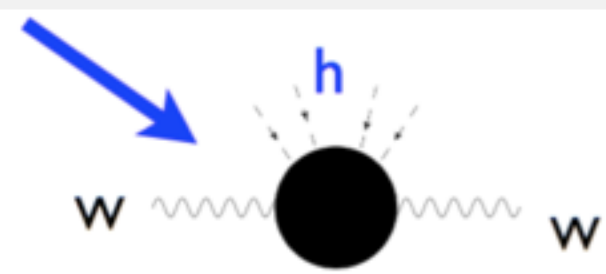
Quantum loops generate V(h)

Integrate out the composite sector and get a low-energy Lagrangian with form-factors

(Agashe, Contino, Pomarol '04)

Gauge Sector

$$\mathcal{L} = \frac{P^T_{\mu\nu}}{2}\left[\left(\Pi_0(p) + \frac{s_h^2}{4}\Pi_1(p)\right) A^a_\mu A^a_\nu + \left(\Pi_B(p) + \frac{s_h^2}{4}\Pi_1(p)\right) B_\mu B_\nu + 2 s_h^2\, \Pi_1(p)\, \widehat{H}^\dagger T^a_L Y \widehat{H}\, A^a_\mu B_\nu\right], \qquad s_h^2 = \sin^2\frac{h}{f}$$



Encode the strong-sector contribution to the gauge propagator in the h-background

- $\Pi_i(p)$ form factors of the composite sector

from m_W^2 and $\Pi_1(0) = f^2$

EW scale

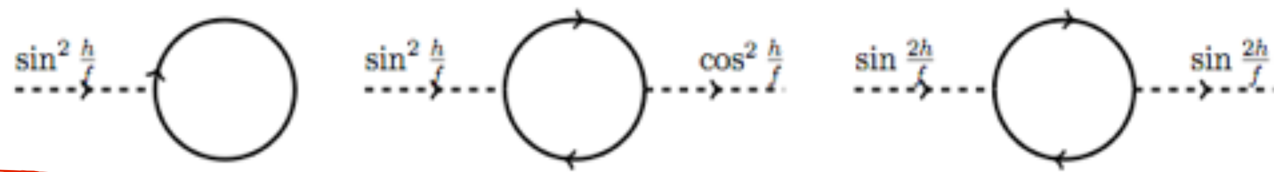
$$v^2 = f^2 \sin^2\frac{\langle h\rangle}{f}$$

- SM couplings

$$\frac{1}{g^2} = -\Pi_0'(0) = \frac{1}{g_0^2} + \frac{1}{g_\rho^2}$$

$$\frac{1}{g'^2} = -\Pi_B'(0) = \frac{1}{g_{0Y}^2} + \frac{1}{g_\rho^2} + \frac{1}{g_{\rho X}^2}$$

Coleman-Weinberg effective potential generated at 1-loop



$$V(h) \approx \alpha\, s_h^2 - \beta\, s_h^2 c_h^2$$

s_h=sin(h/f)

EWSB $\longrightarrow$ $\langle s_h \rangle = \frac{v}{f} = \sqrt{\frac{\beta - \alpha}{2\beta}} \neq 0$

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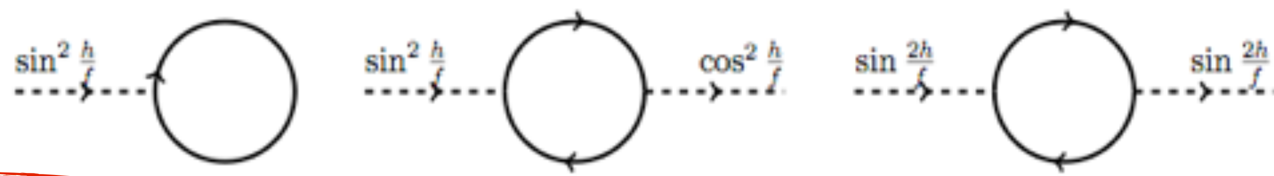

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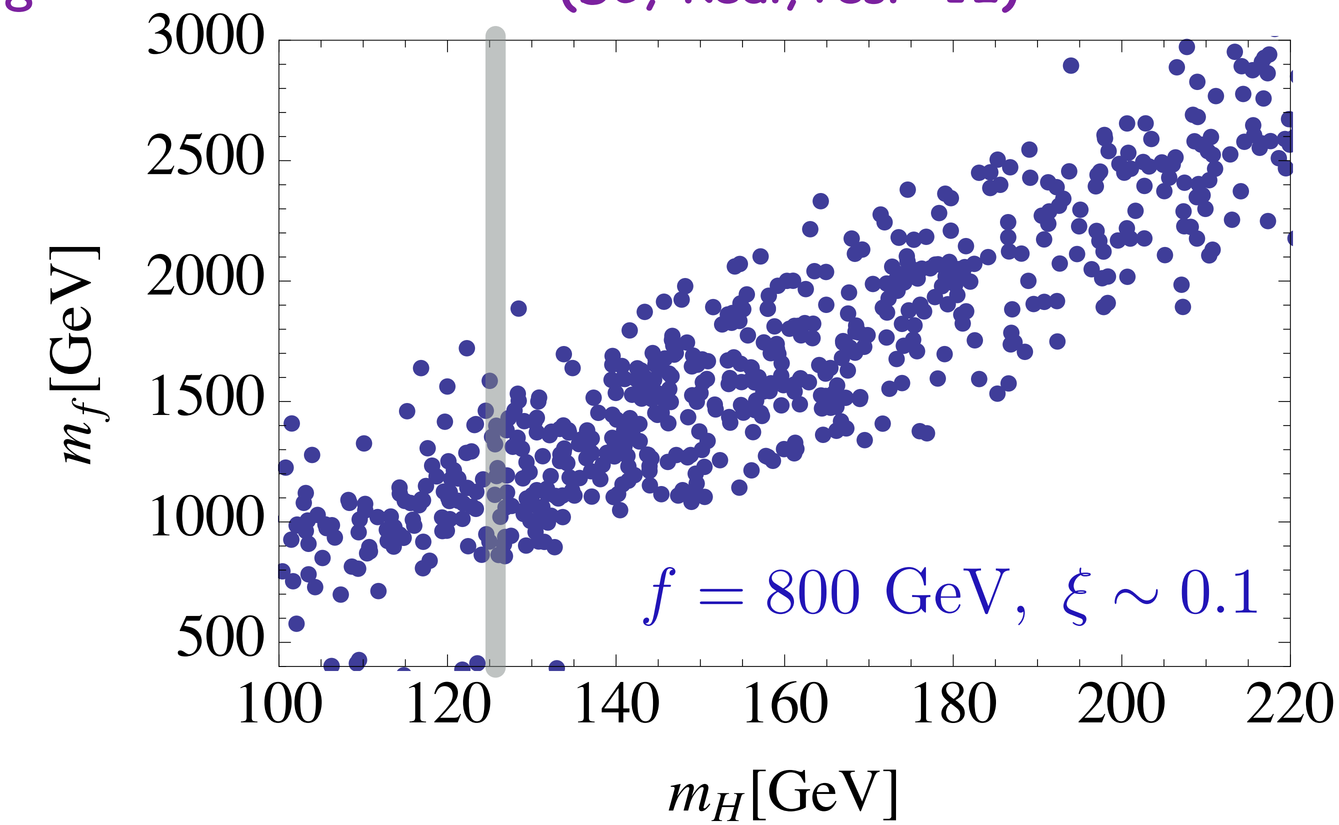
lightest extra-fermion mass

Higgs mass $\quad m_H \sim 0.3\, y_t \frac{m_f}{f} v$

top Yukawa coupling

Correlation with the lightest extra-fermion mass

(DC, Redi,Tesi '12)



125 GeV Higgs asks for light (in the TeV region) fermionic partners

→ we are still in the ballpark with LHC bounds

Heaviest extra-fermions require a larger f value and a larger tuning

$\xi = v^2/f^2$

Extended Composite Higgs Models

Models with a larger Higgs structure with respect to the SM have been largely discussed
Supersymmetry, requires two Higgs doublets with specific Yukawa and potential terms
2HDMs offer a rich phenomenology in EW and flavour physics

Look for a pNGB realisation of extended Higgs scenarios

The structure of the Higgs sector is determined by the coset G/H

G	H	PGB
SO(5)	SO(4)	4=(2,2)
SO(6)	SO(5)	5=(2,2)+(1,1)
SO(6)	SO(4)xSO(2)	8=(2,2)+(2,2)
SO(7)	SO(6)	6=(2,2)+(1,1)+(1,1)
	G_2	7=(1,3)+(2,2)
...	...	...

➡ Minimal = One Doublet

➡ Doublet + Singlet
Gripaios et al.09; Redi,Tesi 12

➡ Two Doublets
Mrazek et al.11
Bertuzzo et al.13
DC et al. 16; 18

SU(5) →SU(4) x U(1)

New players in the game

Composite 2-Higgs Doublet Models

J.Mrazek et al. '11; DC,Moretti,Yagyu,Yildirim '16, DC,Delle Rose,Moretti,Yagyu '18

- EWSB is driven by 2 Higgs doublets as pNGBs of SO(6)/SO(4)xSO(2). The unbroken group contains the custodial SO(4)

- The presence of discrete symmetries in addition to the custodial SO(4) is crucial to control the T-parameter and to protect from Higgs-mediated FCNCs (J.Mrazek et al.11)

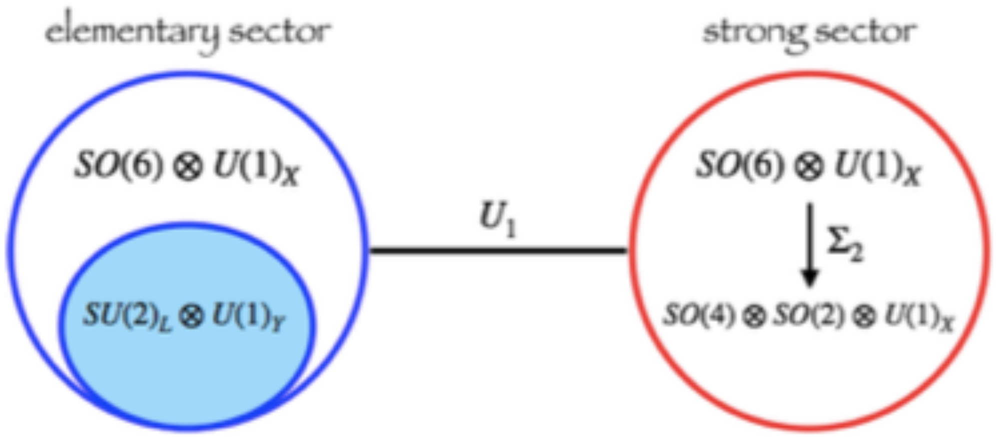
- Besides CP, one can impose a C_2 discrete symmetry (analogous of Z_2 in the elementary 2HDM) which distinguishes the 2 Higgs doublets: $(H_1,H_2) \rightarrow (H_1,-H_2)$. One of them does not couple to the SM fields → **INERT CASE**

- If C_2 is not a symmetry of the strong sector, alignment conditions on the strong Yukawa couplings must be imposed to suppress FCNCs (composite version of an Aligned 2HDM Pich,Tuzón,'09)

- Bounds from flavour observables, Higgs data and direct searches must be satisfied

A Concrete Composite 2-Higgs Doublet Model

DC, Delle Rose, Moretti, Yagyu '18



☑ The construction of the effective theory follows the same steps of the minimal 4DCHM (two-site model)

☑ The Lagrangian of the GBs + gauge sector is: (non-linear σ-models + resonances)

$$\mathcal{L}^{\rm gauge}_{\rm C2HDM} = \frac{f_1^2}{4}{\rm Tr}|D_\mu U_1|^2 + \frac{f_2^2}{4}{\rm Tr}|D_\mu \Sigma_2|^2 - \frac{1}{4g_\rho^2}(\rho^A)_{\mu\nu}(\rho^A)^{\mu\nu} - \frac{1}{4g_{\rho X}^2}(\rho^X)_{\mu\nu}(\rho^X)^{\mu\nu}$$

$$- \frac{1}{4g_A^2}(A^A)_{\mu\nu}(A^A)^{\mu\nu} - \frac{1}{4g_X^2}X_{\mu\nu}X^{\mu\nu},$$

A, X=elementary gauge fields

ρ^A,ρ^X=composite gauge fields

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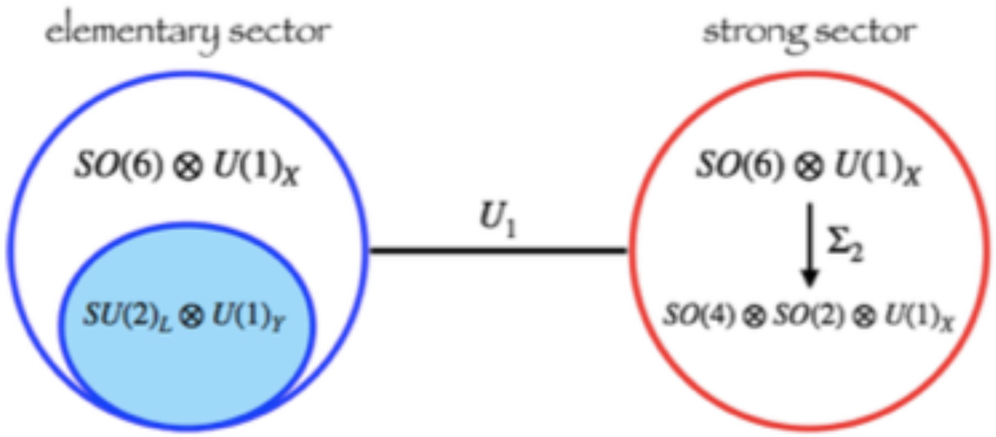

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$$U_i = \exp i\frac{f}{f_i^2}\Pi$$

$$\Sigma_2 = U_2\Sigma_0 U_2^T$$

$\Sigma_0 = -i/\sqrt{2}(\delta_I^5\delta_J^6 - \delta_J^5\delta_I^6)$

$I, J = 1,..,6$

GB matrix

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

$=U_1 U_2$

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

8 broken SO(6) generators

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

$$\Phi_\alpha \equiv \frac{1}{\sqrt{2}}\begin{pmatrix} h_\alpha^2 + i h_\alpha^1 \\ h_\alpha^4 - i h_\alpha^3 \end{pmatrix}$$

$h^4_\alpha = h_\alpha + v_\alpha$

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

$$f^{-2} = f_1^{-2} + f_2^{-2}$$

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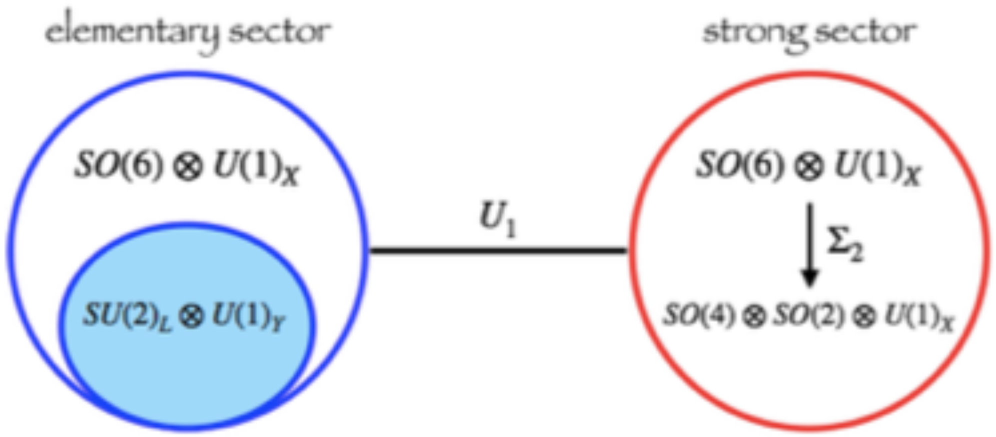

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$h^4_\alpha = h_\alpha + v_\alpha$

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

$$f^{-2} = f_1^{-2} + f_2^{-2}$$

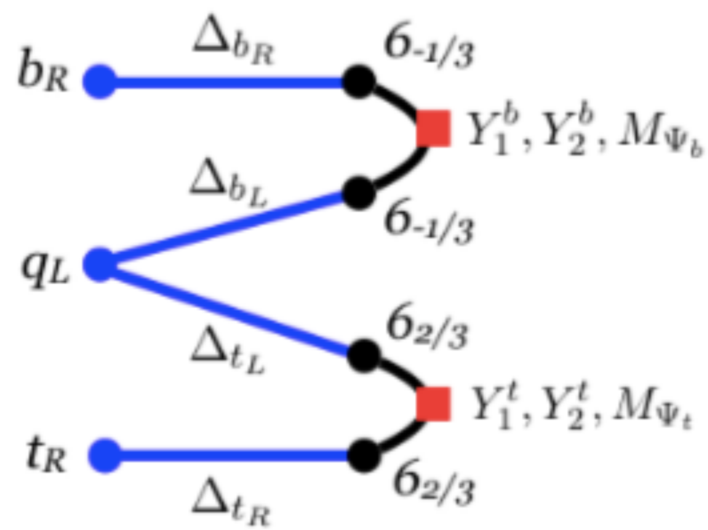
☑ gauge boson masses generated by the VEVs of the fourth components of the Higgs fields

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

A Concrete Composite 2-Higgs Doublet Model

DC, Delle Rose, Moretti, Yagyu '18

- Fermion sector: embed the 3rd generation quarks into SO(6) reps.
- Partial Compositeness = linear couplings $\Delta_{L,R}$ between composite and elementary fermions



for the top

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

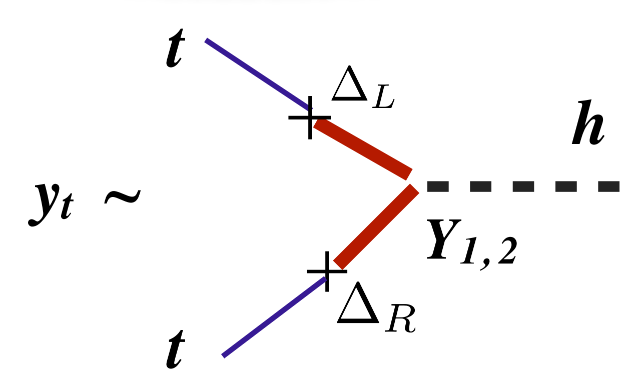
GBs

$$\Sigma = U_1 \Sigma_2 U_1^T$$

- at least 2 heavy fermions ψ needed for an UV finite effective potential $I,J=1,2$

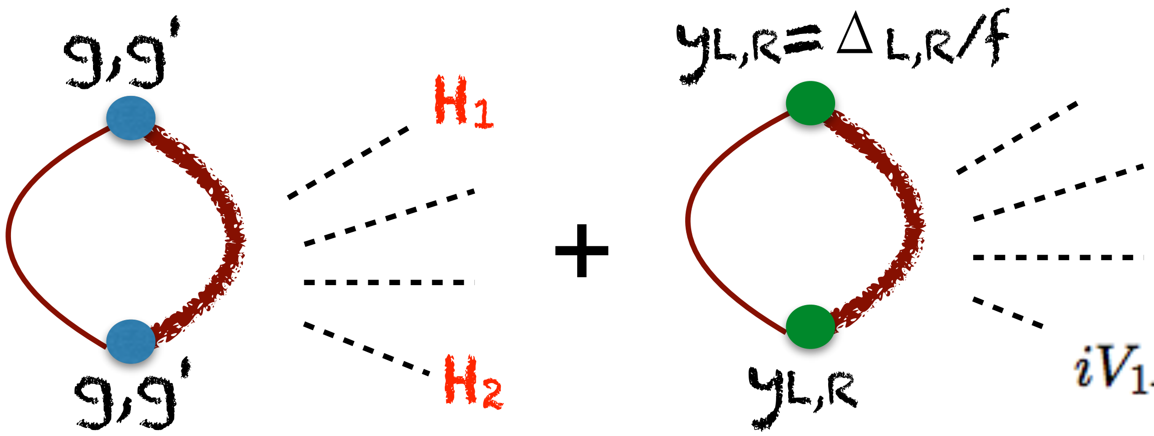
- These are all the possible invariants

- All the parameters real → CP invariant scenario



The Higgs Potential

The SM fields are linearly coupled to operators of the strong sector and explicitly break its symmetry
A potential for the Higgses is radiatively generated



The derivation follows the same steps of the minimal scenario → by integrating out the heavy resonances and deriving the form factors

$$iV_{1\text{-loop}} = \frac{1}{f^4}\int \frac{d^4k}{(2\pi)^4}\left[\frac{3}{2}V_G(H_1,H_2) - 2N_c V_F(H_1,H_2)\right] + \ldots$$

By expanding up to the fourth order in 1/f, V_G and V_F show the same structure of the Higgs potential in the elementary 2HDM

m_i^2 (i=1,..,3) and λ_j (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

$f_1=f_2$, $g_\rho = g_{\rho X}$ and assuming a LR structure for the fermion Lagrangian as in the minimal model

(partial compositeness for the top)

2-Higgs Doublets as pNGBs

WE GOT SOLUTIONS !

A realistic Aligned 2HDM can be realised in a composite scenario

- The vanishing of the two tadpoles of the CP-even Higgs bosons requires tuning which is larger for large f (as expected)
- The requirements to reconstruct m_h and m_{top} select values of $\tan\beta = v_2/v_1 \lesssim 10$
- Same physical Higgs states as in the elementary 2HDM: h, H, A, $H^{\pm}$ (h=SM-like Higgs)

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- Same physical Higgs states as in the elementary 2HDM: $h, H, A, H^\pm$ (h=SM-like Higgs)
- They are identified in the Higgs basis after a rotation by β: only one doublet provides a VEV and contains the GBs of W,Z
- CP-even states: h, H

  $m_h \sim v \quad m_H \sim f + \mathcal{O}(v)$

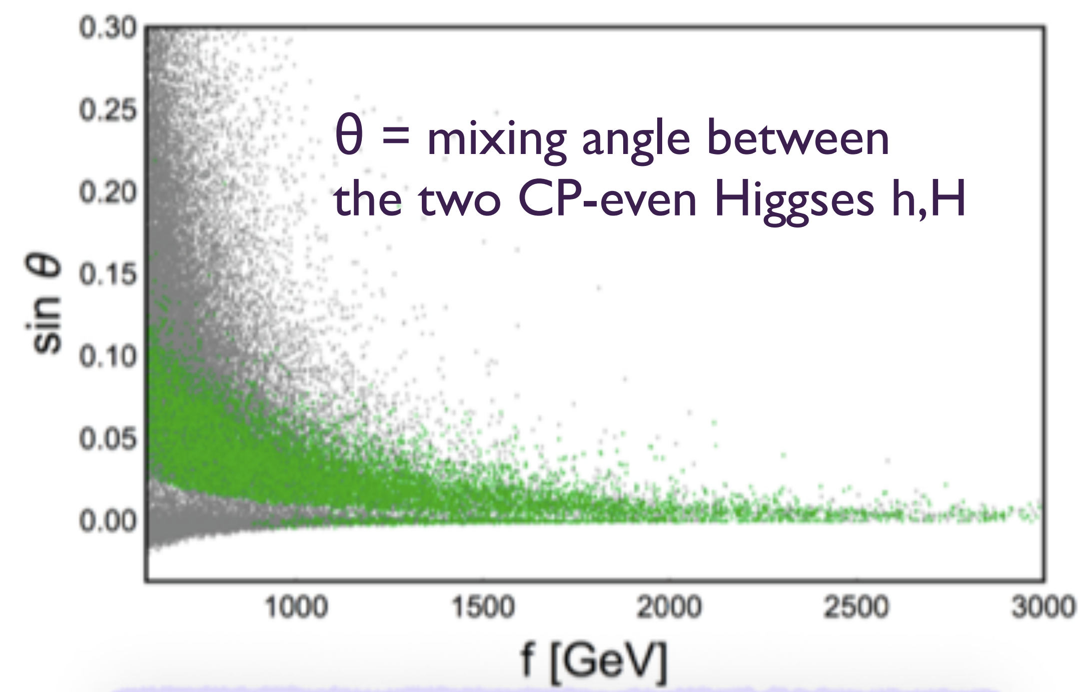
  θ is predicted to be small: $\mathcal{O}(\xi)$ for large f

  $\xi = v^2/f^2$
- CP-odd states: $A, H^\pm$

  $m_A \sim m_{H\pm} \sim f + \mathcal{O}(v)$

$f \to \infty$ SM limit

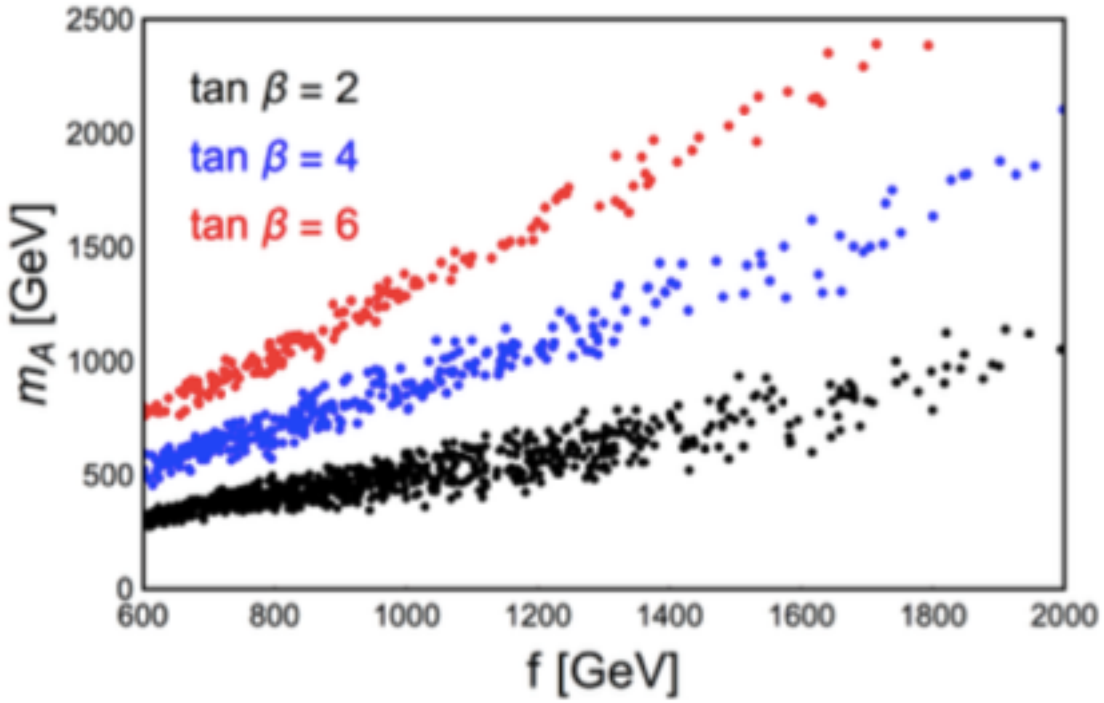
$H, A, H^\pm$ decouple and $h \to h^{SM}$



green points satisfy the bounds from direct and indirect Higgs searches

tested against HiggsBounds and HiggsSignals

Masses of the extra-Higgses



m_A grows linearly with f

$m^2_A \propto f^2(1+\tan^2\beta)$

Mass Splittings

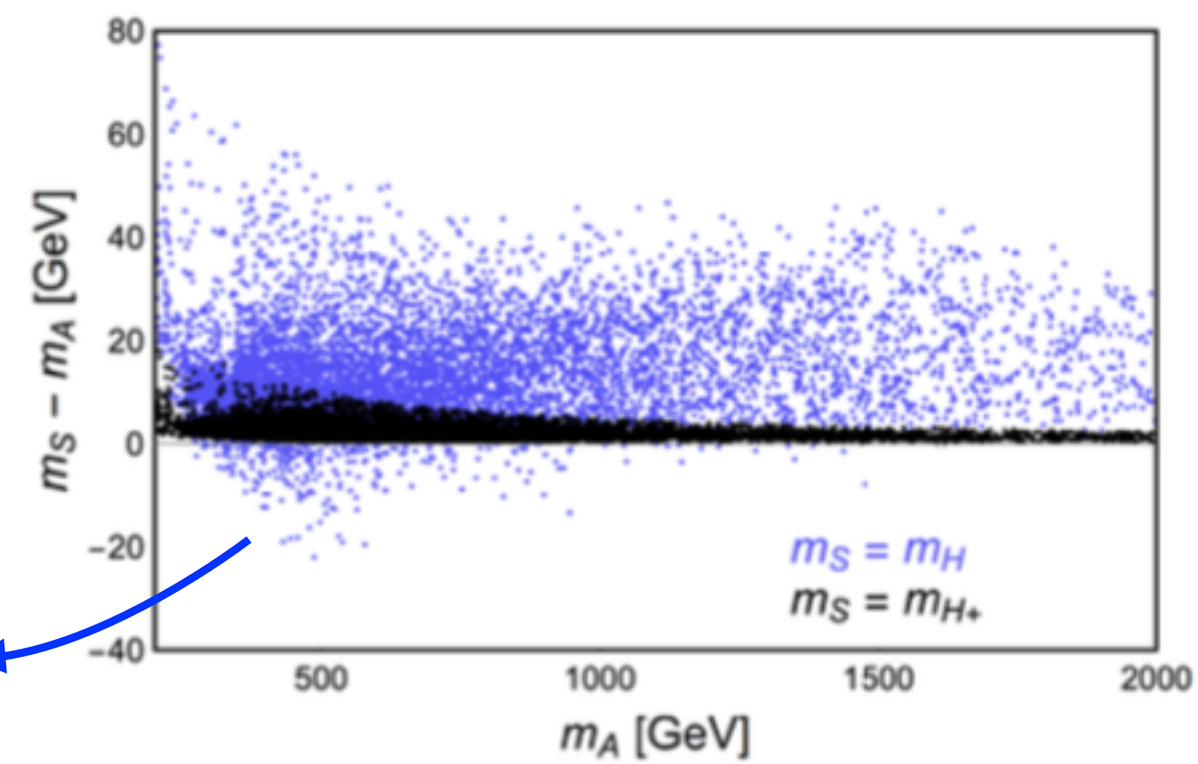
$m_{H\pm}$ and m_A are predicted to be highly degenerate:
very sharp prediction in the C2HDM:

$$m^2_{H^\pm} - m^2_A \propto \frac{g_Y^2}{16\pi^2} g_\rho^2$$

larger m_H-m_A splitting in the C2HDM than in the MSSM

-20 GeV < m_H-m_A < 60 GeV

Ex: a signal $H \to A\, Z^*$ accompanied by the absence of $A \to W^{\pm *} H^{\mp}$ could be a hint of C2HDM



$A \to H\, Z^*$ could also be useful

Higgs Boson Couplings

- Couplings to SM fermions:
  Assuming flavour alignment ($Y_1 \propto Y_2$) to guarantee the absence of tree level FCNCs

$$-\mathcal{L}_{\rm Yukawa} = \sum_{f=u,d,l} \frac{m_f}{v_{\rm SM}} \bar{f} \left[\xi_h^f \, h + \xi_H^f \, H \right] f \quad + \text{ A, } H^{\pm} \text{ couplings}$$

fixed by the strong dynamics and correlated to other observables

The fermion masses are also predicted:

$$m_t = \frac{v_{\rm SM}}{\sqrt{2}} \frac{\Delta_L \Delta_R}{m_Q m_T} \frac{M_\Psi^2}{\tilde{m}_Q \tilde{m}_T} \frac{Y_1 s_\beta + Y_2 c_\beta}{f} [1+\mathcal{O}(\xi)]$$

$m_{Q,T}$ ~ heavy fermion masses
$\tan\beta = v_2/v_1$

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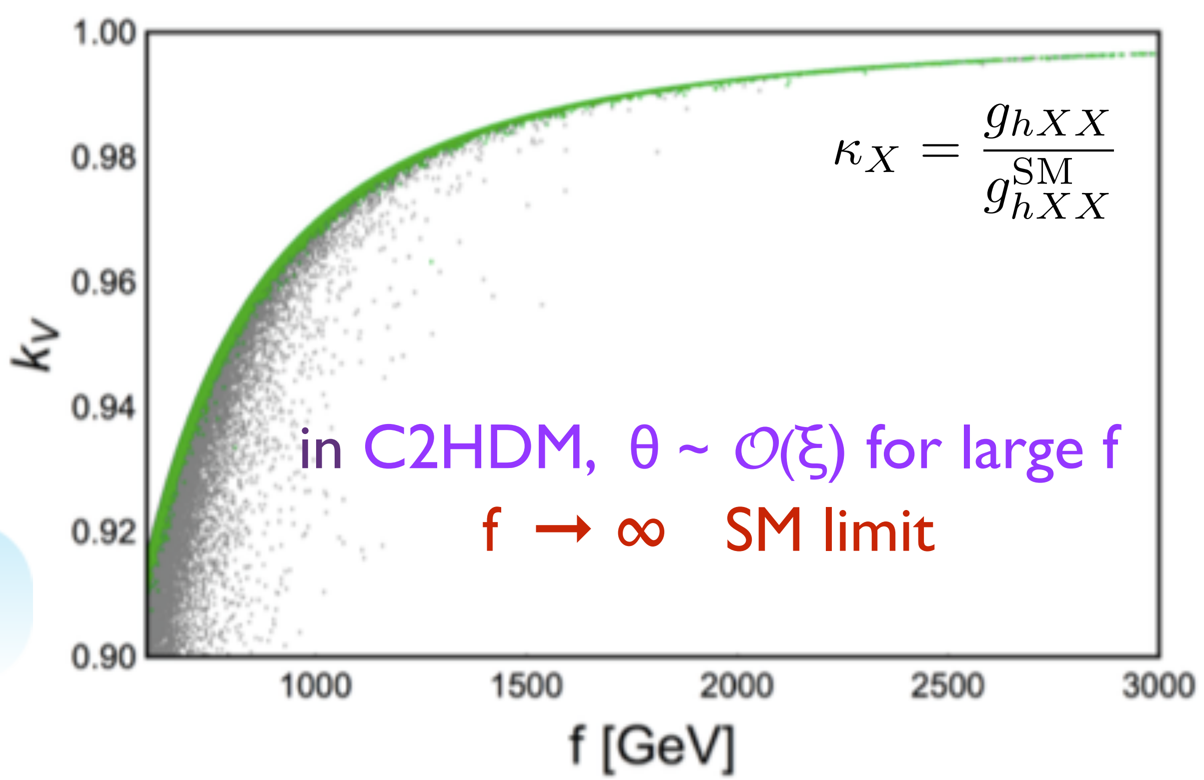
- Couplings to SM gauge bosons:

In C2HDM, due to the non-linearities of the derivative terms, we get corrections of order ξ to the hVV couplings. Also modified by the mixing angle θ as in the E2HDM

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

θ is predicted to be ≤ 0.1 → a deviation in k_V can be addressed by a suitable value of f

Different H,A,$H^{\pm}$ phenomenology with respect to the E2HDM **(see Shinya's talk)**

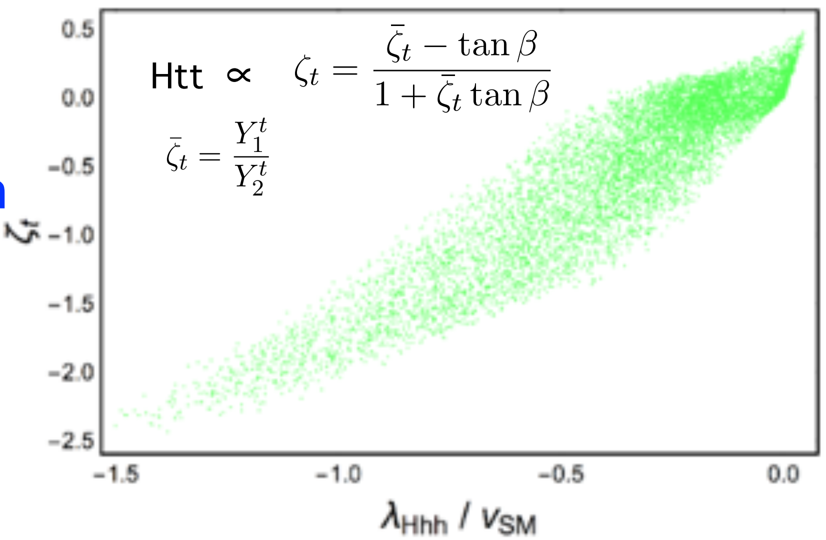


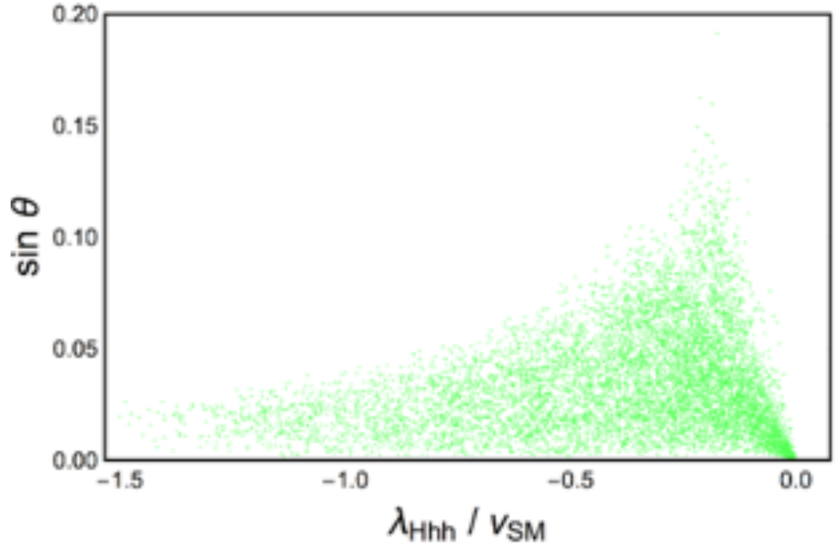
green points satisfy the present bounds

LHC phenomenology of the extra pNGB Higgses

Mainly determined by the couplings to fermions and trilinear couplings due to θ~0

Htt and Hhh are strongly correlated in C2HDM and carry the imprint of compositeness →





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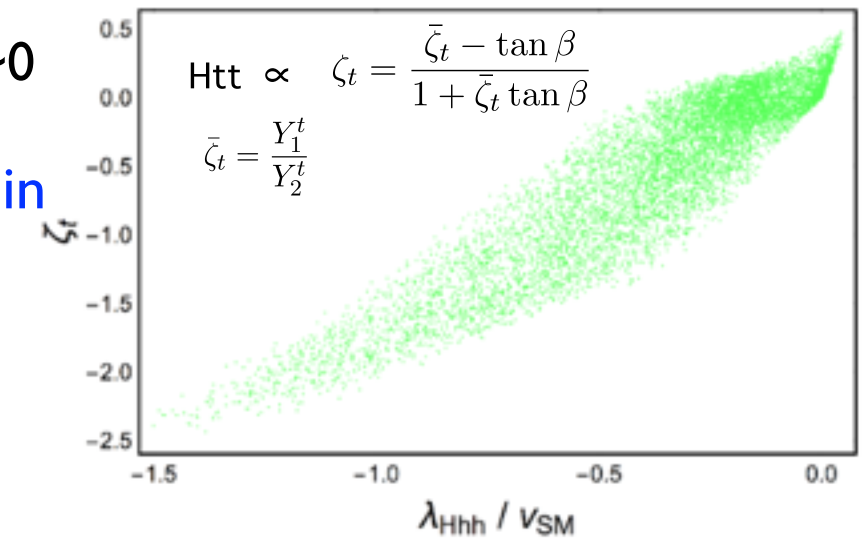
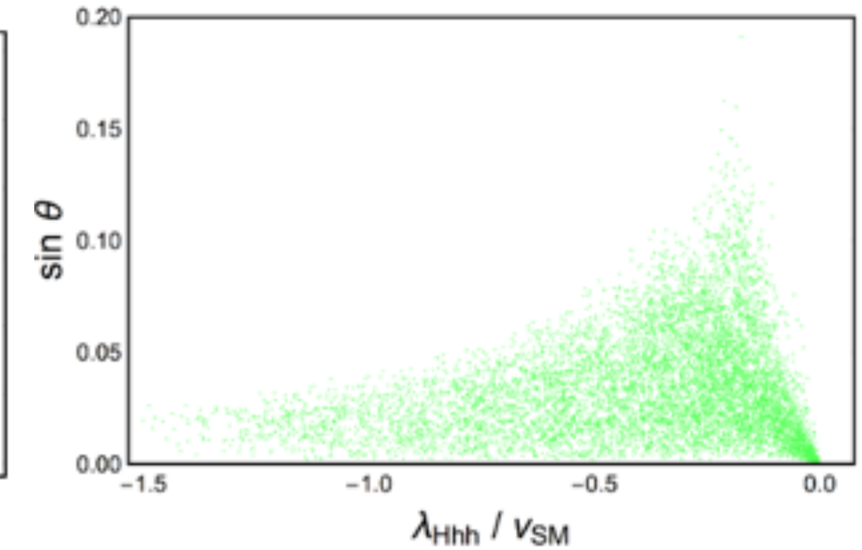
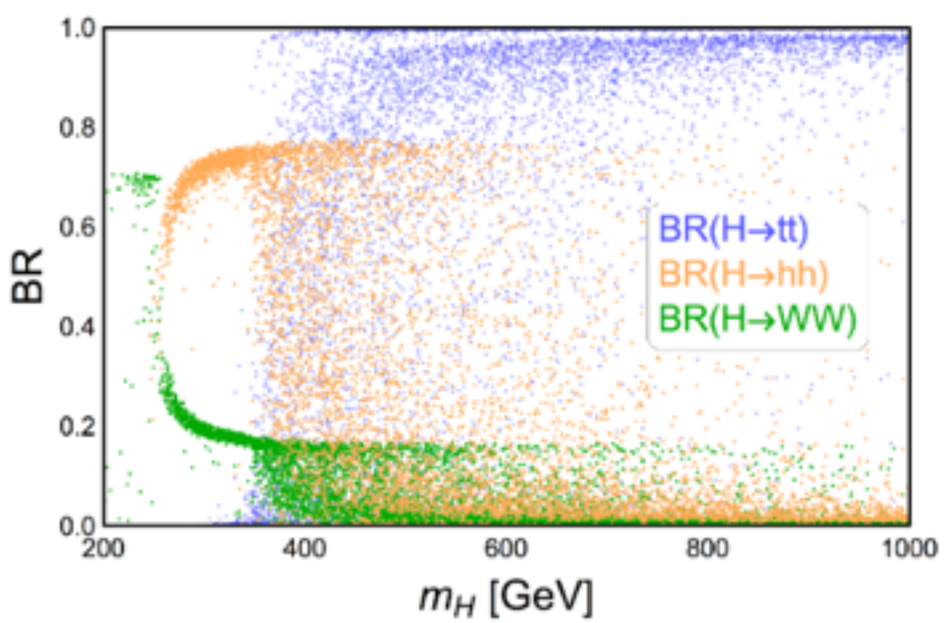




CP-even H



H → tt represents the main decay mode

Below the tt threshold, H → hh dominates

BR(H→hh) ~ 80%, BR(H→VV) ~ 20% (sinθ predicted to be small)

BR(H →ZZ)~ 1/2 BR(H →WW) not shown in the plot

CP-odd A

A→ tt represents the main decay mode

A→ Zh dominates below the tt threshold

Charged $H^\pm$

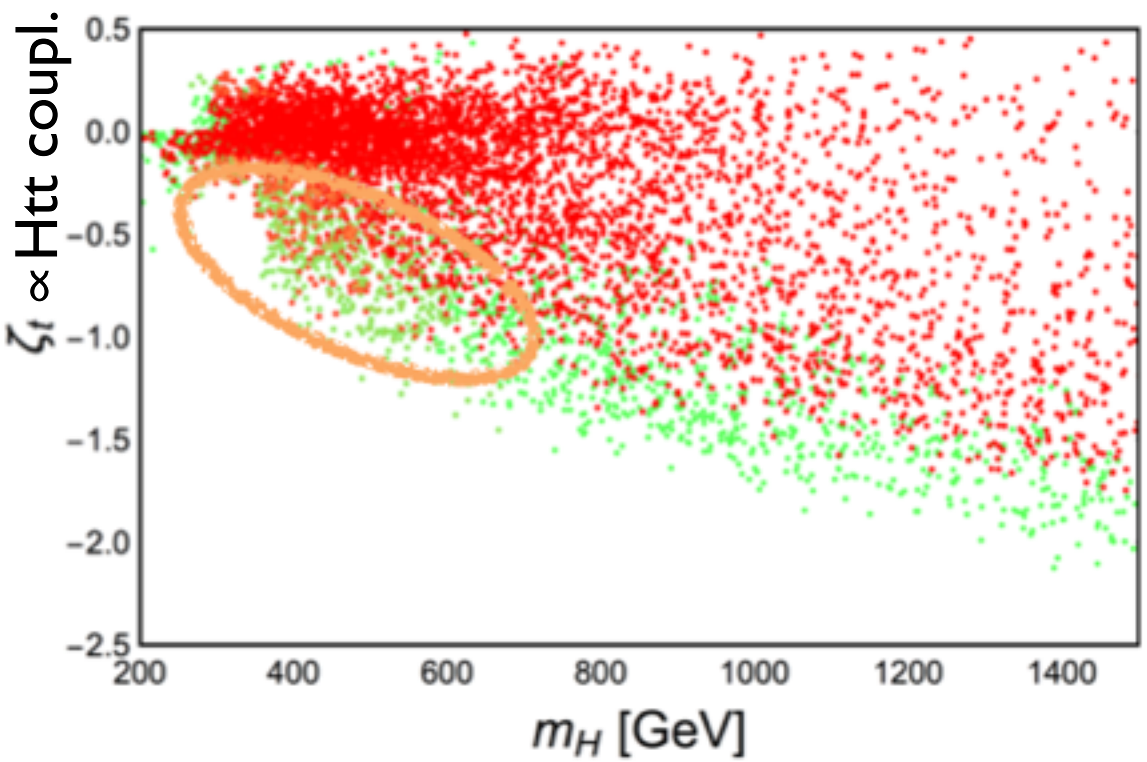
$H^+ \to W^+ h$ and $H^+ \to bt$ are the relevant decay channels

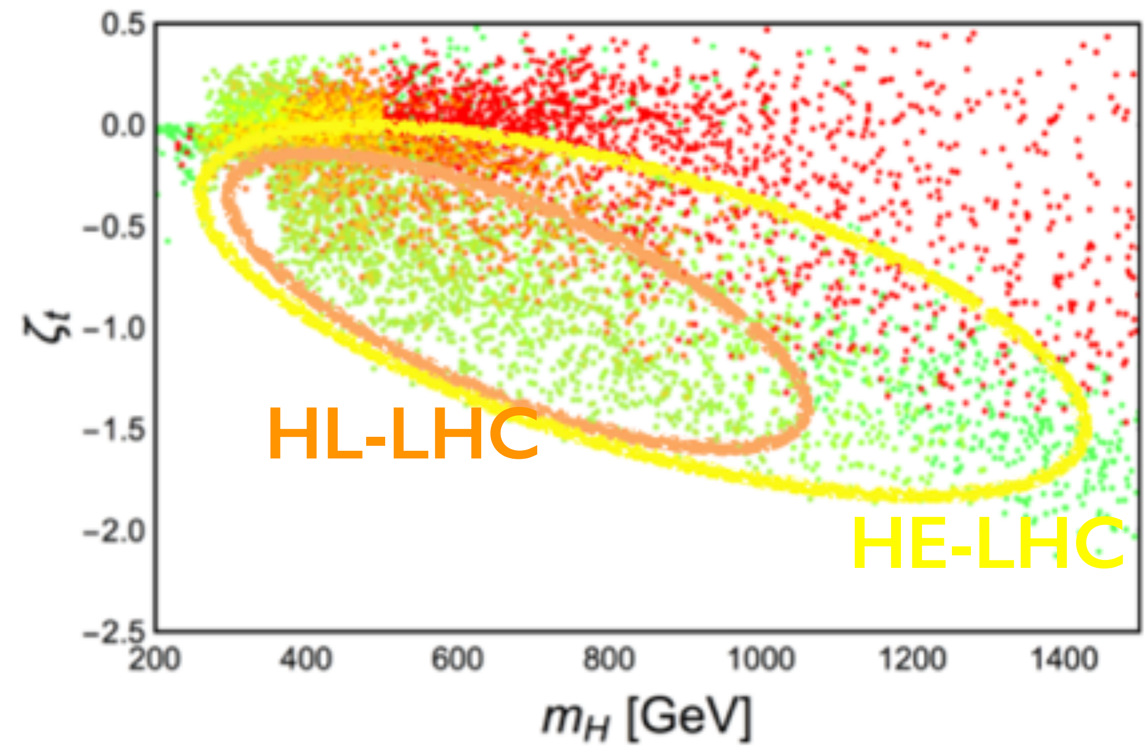
$H^+ \to bt$ is the main decay mode as $m_{H+} > m_t$

Different decay modes with respect to the E2HDM (see Shinya's talk)

Present and Future H indirect/direct bounds @ LHC

(contribution to BSM Physics at the HL-LHC and HE-LHC)





H production at the LHC dominated by gluon fusion + top loop

- satisfy the present bounds from direct and indirect searches at 13 TeV
- in addition have κ_{VV} , $\kappa_{\gamma\gamma}$ and κ_{gg} within the 95%CL projected uncertainty at 14 TeV with L = 3000 fb^{-1}
- in addition 95% CL excluded by the direct search $gg \to H \to hh \to bb\gamma\gamma$ at 14 TeV with L = 300fb^{-1} (left) and L = 3000fb^{-1} (right)
- 95% CL excluded by the same search at the HE-LHC at 27 TeV with L = 15ab^{-1}

CP violation in C2HDM

(work in progress)

(in collaboration with Ryo Nagai)

- Differently form the gauge sector which is fixed by the symmetry group of the strong dynamics, for the fermion sector one can choose different group representations for the fermionic fields

- We choose to embed the SM fermions into the fundamental **6** of SO(6) which decomposes into (**4**,**1**) ⊕ (**1**,**2**) of SO(4) x SO(2)

- The left-handed doublet q_L has a unique embedding into the (**4**,**1**)$_{2/3}$ while the right-handed component t_R can be embedded in two different ways because the fundamental **6** contains two $SU(2)_L$ singlets. An extra angle θ_t parametrises this ambiguity (analogously θ_b for the b_R)

$$(t_R^{\mathbf{6}})^A = t_R(\Upsilon_R^t)^A \qquad A=1,..,6 \qquad \langle \Upsilon_R^t \rangle = (0,0,0,0,\cos\theta_t, i\sin\theta_t)$$

- If $\theta_t \neq 0$ a physical phase is responsible for CP violation (in addition one can consider complex couplings in the strong sector interactions as further CPV sources)

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Warning:

If both C_2 and CP are broken by the strong sector, the T parameter gets a contribution for a generic vacuum structure

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

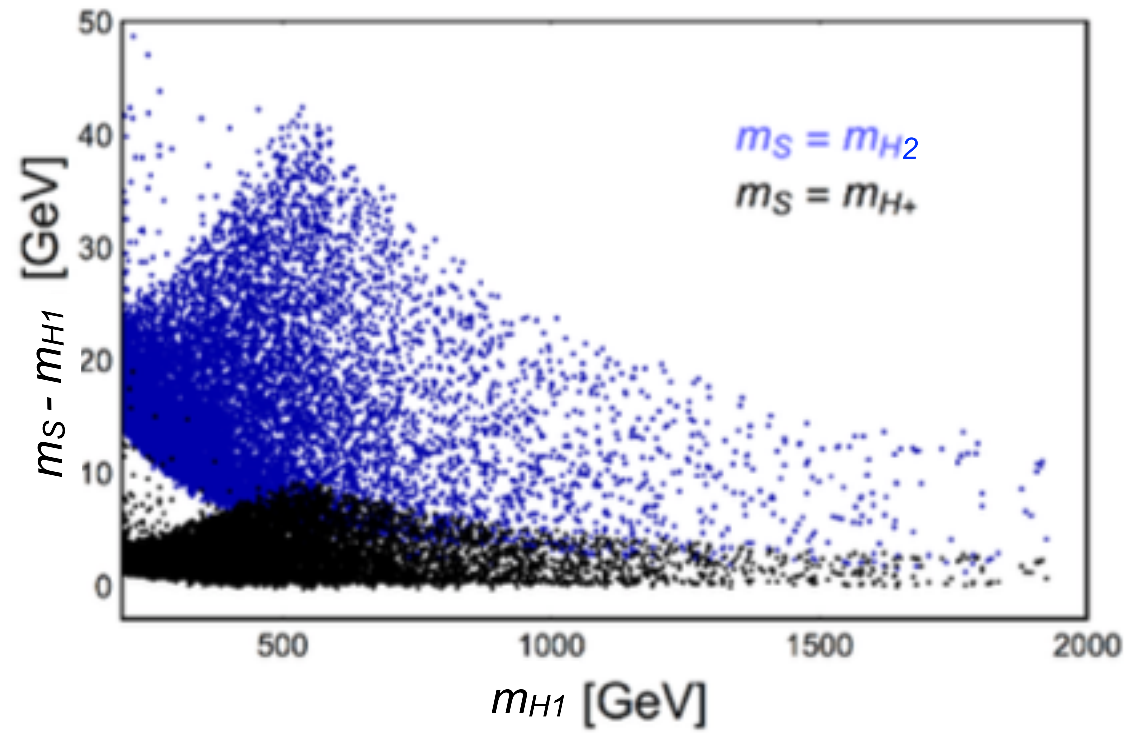
We have to play with this in the C2HDM → Our preliminary study suggests that we can find solutions where CP is violated and T is protected

C_2-symmetric scenario

If Y_1=0 we get a C_2-symmetric scenario → a composite version of the IDM
(only one Higgs doublet develops a VEV)

- m_2 gives the mass to the second Higgs doublet
- no spontaneous breaking of C_2 is realised
- H_1 is lighter than H_2 and $H^\pm$

If C_2 is preserved also by lighter quarks and leptons
can H_1 be a dark matter candidate ?



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To reproduce the DM relic density with a neutral component of an inert Higgs doublet we need λ_{345} for any mass point, also important to extract bounds from direct detection

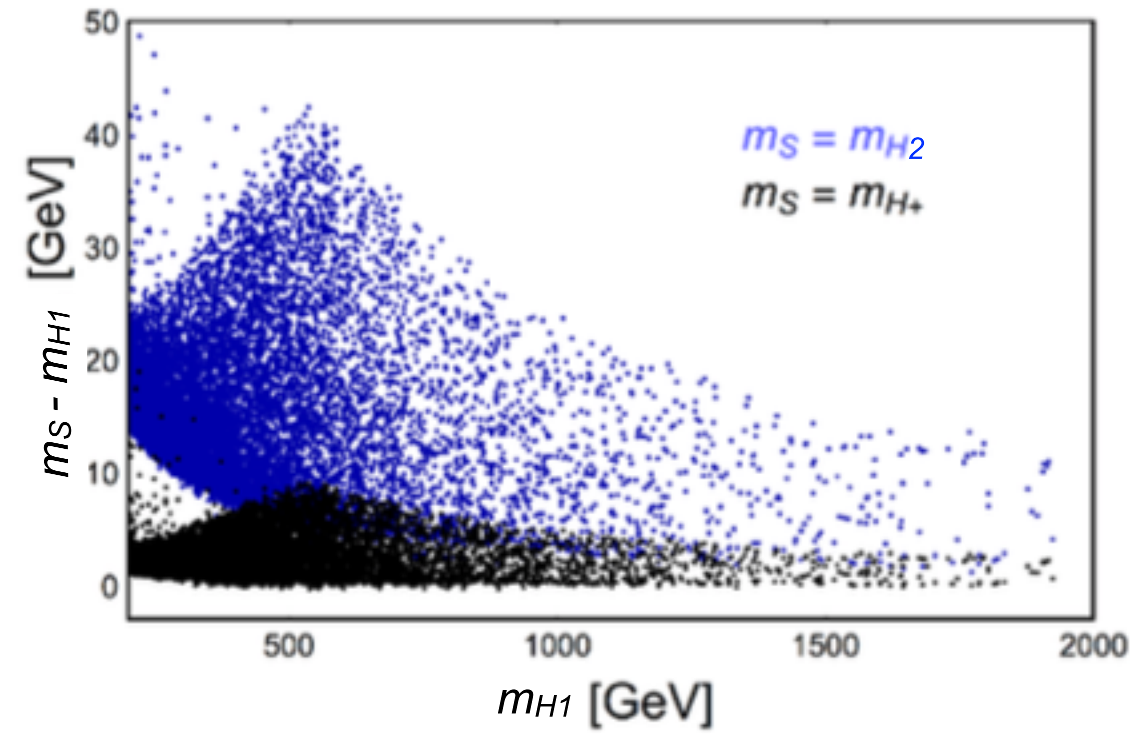
use the analysis by Belyaev et al. '16 →

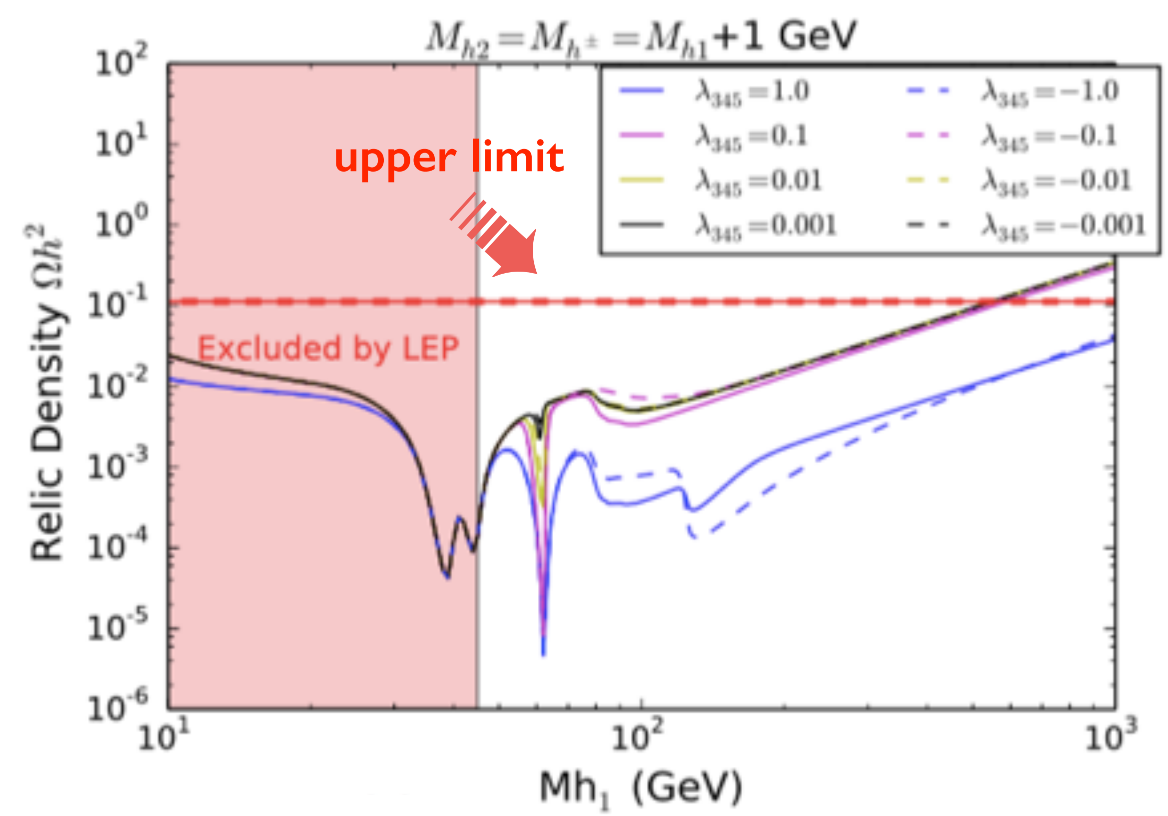
The relic density upper limit is exceeded by
$m_{H1} \gtrsim$ 600GeV if $|\lambda_{345}| \lesssim 0.1$ ($m_{H1} \gtrsim$ 200GeV from DD)

C2HDM can predict $|\lambda_{345}|$ ~1 for large m_{H1} (~ 1TeV)

H_1 can be a dark matter candidate for

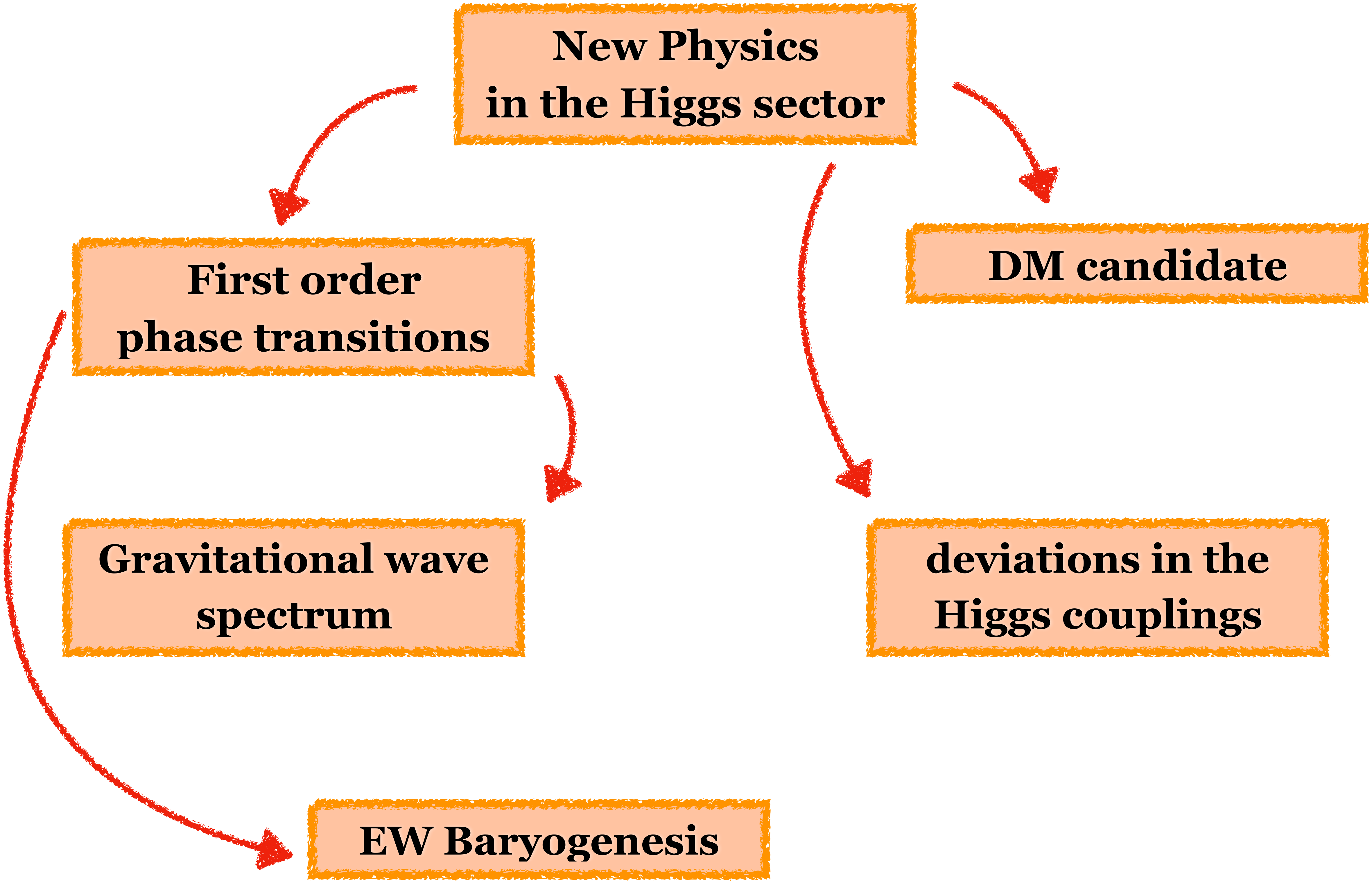
$200 \lesssim m_{H1}(\text{GeV}) \lesssim 1000$





Further developments:
Composite Dynamics in the Early Universe

(DC, Delle Rose, Panico, 1909.07894)



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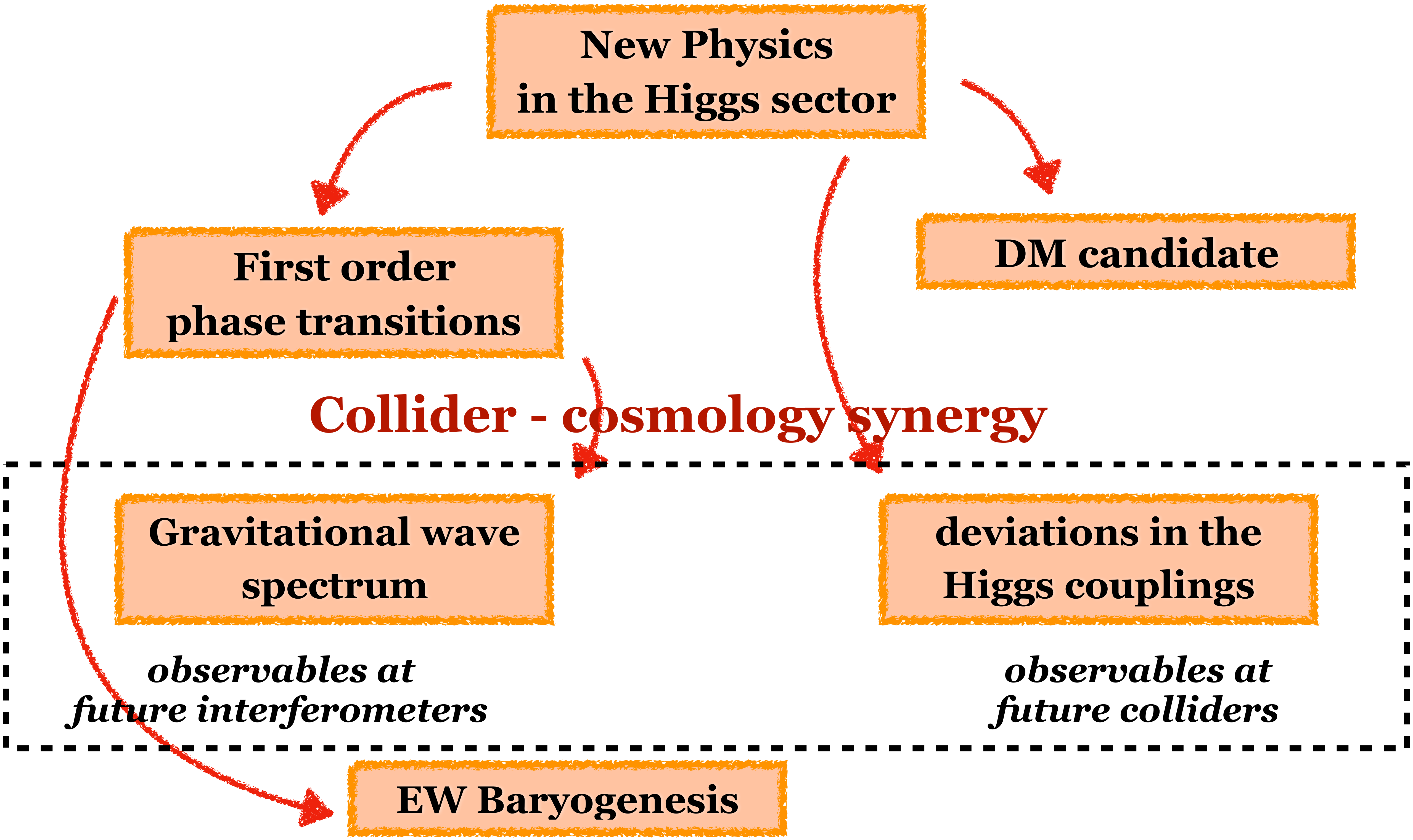
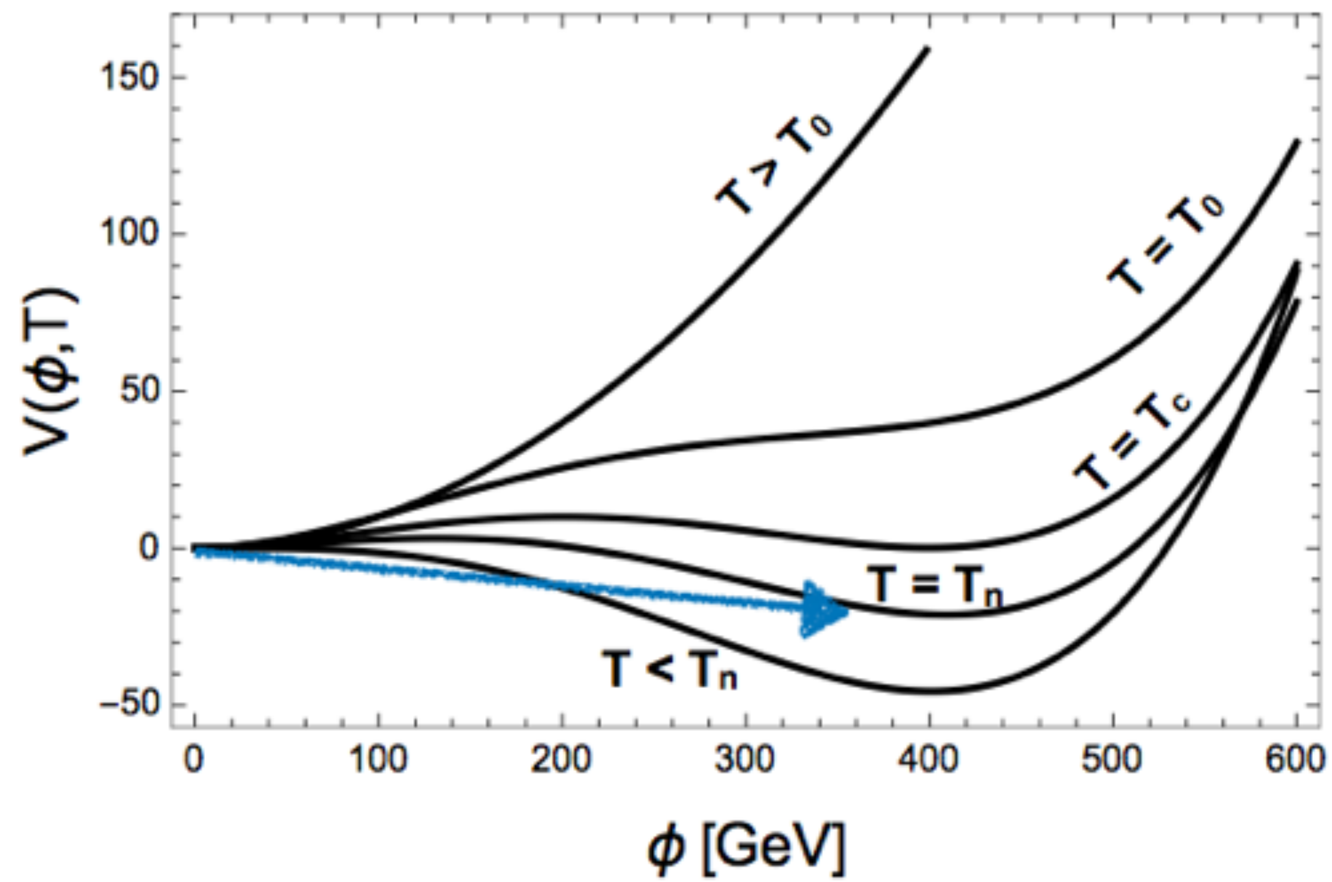


Strong EW Phase Transition can trigger Baryogenesis

Thermal History

- The EW symmetry is restored at $T > T_0$ below T_0 a new (local) minimum appears
- At a critical T_c the two minima are degenerate and separated by a barrier (two phases coexist)
- The transition starts at the bubble nucleation temperature $T_n < T_c$



Sakharov Conditions for Baryogenesis

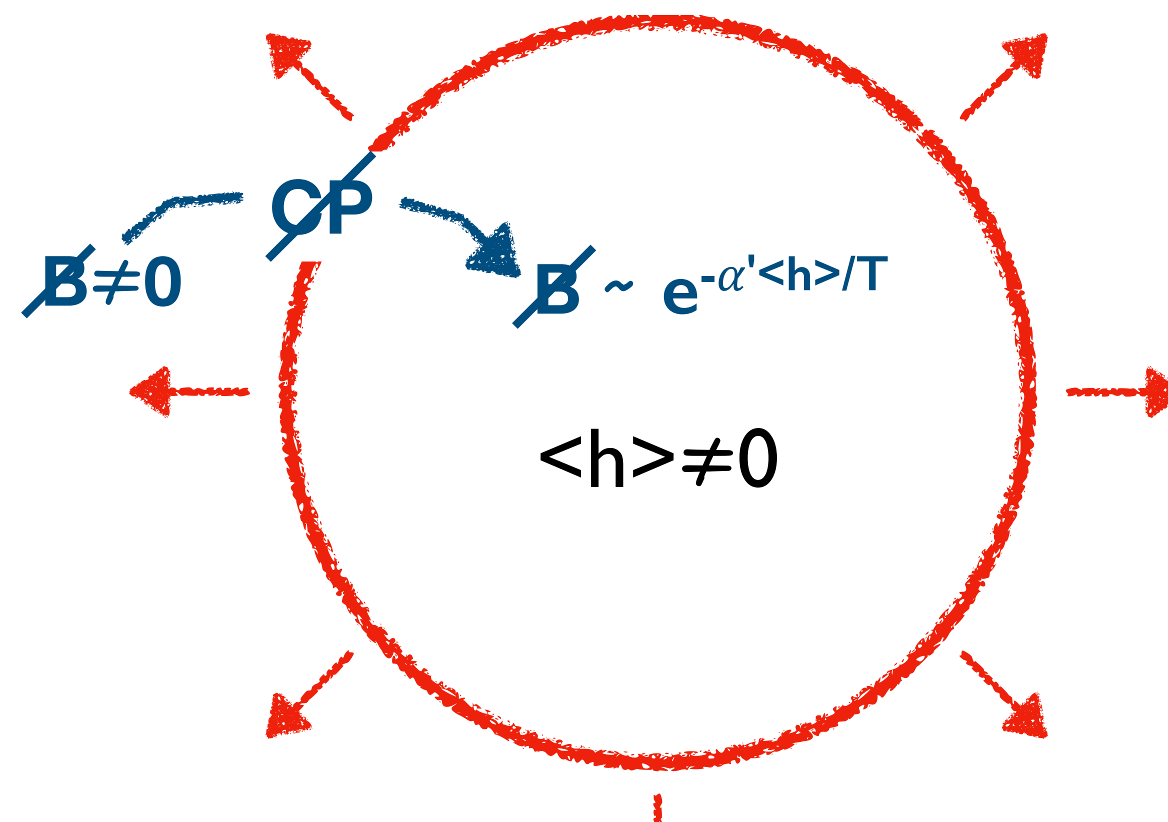
- B violation
- C and CP violation
- **Out of equilibrium dynamics:** (strong) 1st order phase transition

In the SM phase transition is a smooth crossover, also not enough CP violation from CKM

→ **NP needed !!**

Ex: by adding a dim-6 Higgs operator

(Grojean, Servant, Wells, '04)



The SM + scalar singlet

(Espinosa, Konstandin, Riva '11)

Higgs + singlet effective potential (Z_2 symmetric) in the high-temperature limit

$$V(h,\eta,T) = \frac{\mu_h^2}{2}h^2 + \frac{\lambda_h}{4}h^4 + \frac{\mu_\eta^2}{2}\eta^2 + \frac{\lambda_\eta}{4}\eta^4 + \frac{\lambda_{h\eta}}{2}h^2\eta^2 + \left(c_h\frac{h^2}{2} + c_\eta\frac{\eta^2}{2}\right)T^2$$

portal interaction thermal corrections

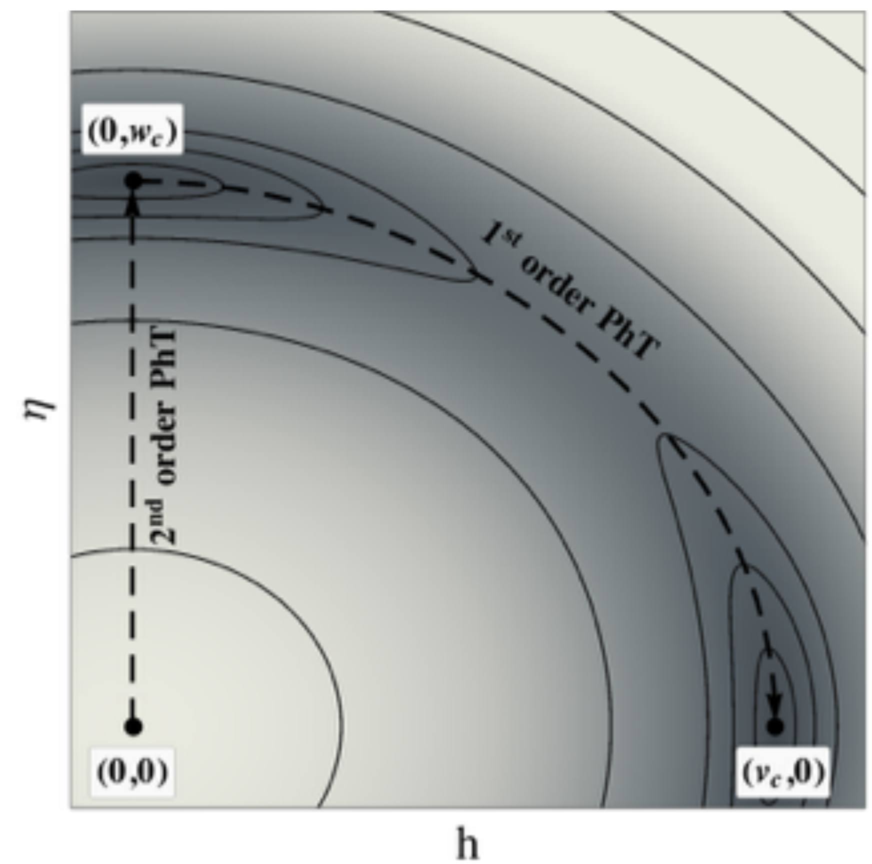
thermal masses (count the dof coupled to the scalars)

$$c_h = \frac{1}{48}(9g^2 + 3g'^2 + 12y_t^2 + 24\lambda_h + 2\lambda_{h\eta}) \qquad c_\eta = \frac{1}{12}(4\lambda_{h\eta} + \lambda_\eta)$$

- ☑ EW symmetry restored at very high T: <h, η> = (0,0)
- ☑ Two interesting patterns of symmetry breaking (as the Universe cools down):

1. (0,0) → (v,0) one-step PhT
2. (0,0) → (0,w) → (v, 0) two-step PhT

The two-step is stronger due to a tree-level barrier between the two minima → <η> varies during the PhT



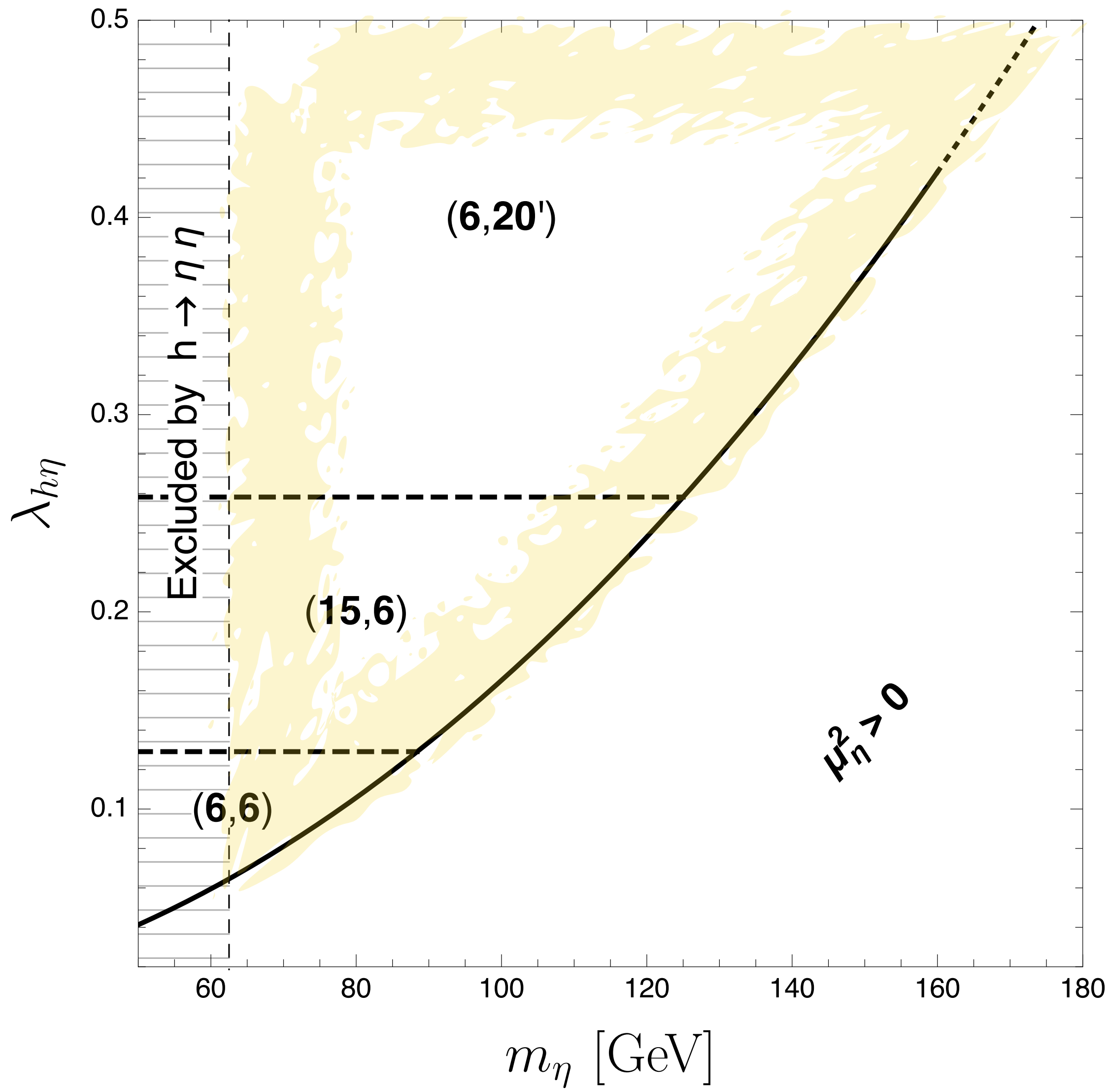
Is it possible to realise it in a CHM scenario based on SO(6)/SO(5)?

extended pNGB Higgs sector with an additional scalar

Classification of repr. of composite fermionic operators

(DC, Delle Rose, Panico, 1909.07894)

- ☑ **4** — not suitable for the top quark: large Zb_Lb_L coupling
- ☑ **10** — no potential for the scalar singlet η
- ☑ **6, 15, 20'** — viable representations for the top quark



☑ (q_L, t_R) ~ $(\mathbf{6}, \mathbf{6})$

Typically predicts $\lambda_\eta \simeq 0, \quad \lambda_{h\eta} \simeq \lambda_h/2$ unless of large tuning in bottom and gauge sectors

Due to the form of the invariants, sharp upper bounds $\lambda_{h\eta} < \lambda_h\,, \qquad m_\eta < m_h/\sqrt{2}$

☑ (q_L, t_R) ~ $(\mathbf{15}, \mathbf{6})$

Less-tuned scenario: no need to rely on bottom and gauge. Upper bounds $\lambda_{h\eta} < 2\lambda_h, \quad m_\eta < m_h$

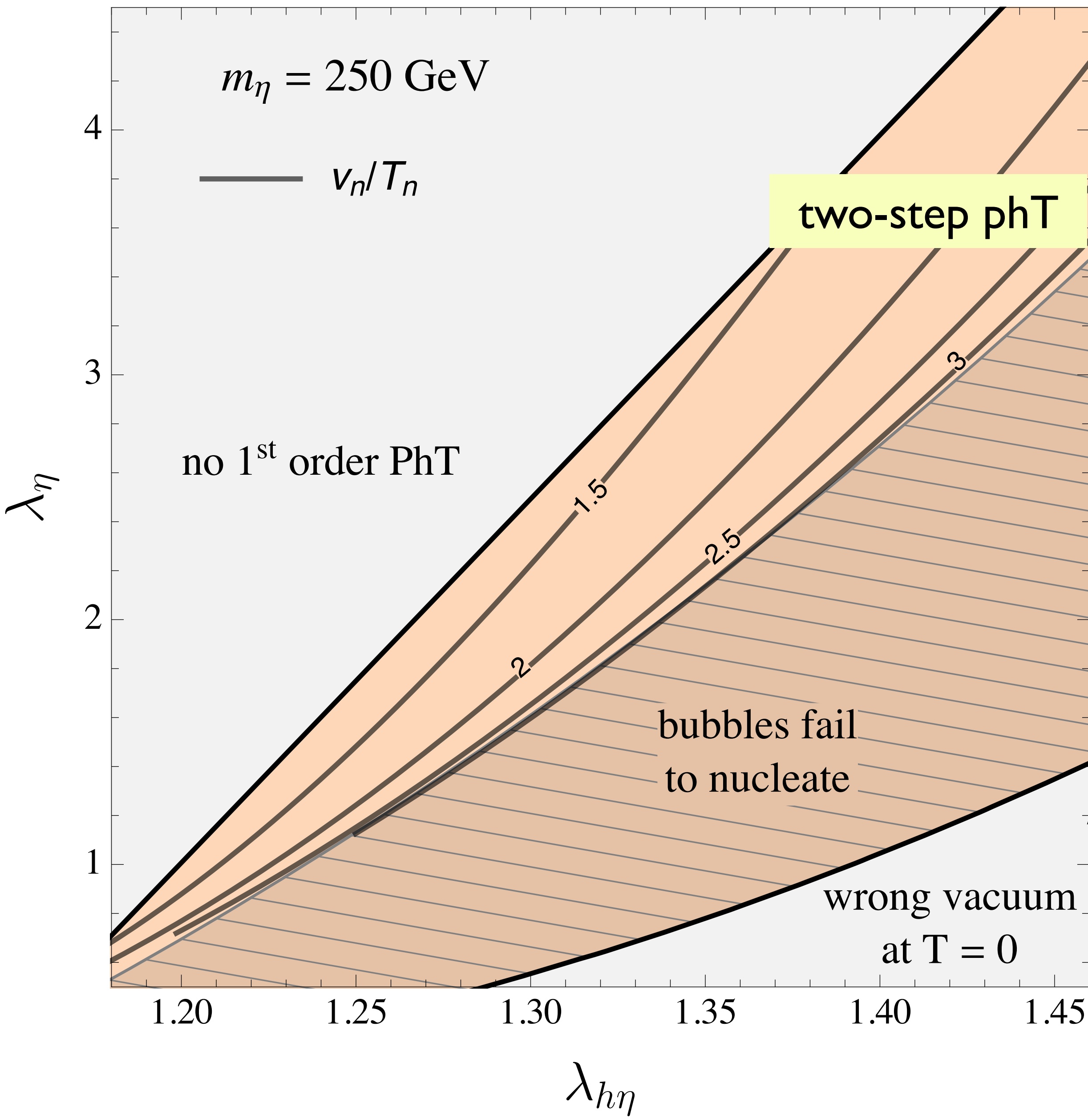
No EW Baryogenesis can be realised (see later)

☑ (q_L, t_R) ~ $(\mathbf{6}, \mathbf{20'})$

large parameter space available without tuning

Properties of the EWPhT

$(q_L, t_R) \sim (6, 20')$ (DC, Delle Rose, Panico, 1909.07894)



Bubbles fail to nucleate if the rate of bubble formation does not balance the Hubble expansion (ex. $\lambda_{h\eta}$ too large produces a high barrier)
The system remains trapped in the metastable vacuum (0,w) and no EWSB occurs

(0,w) is the global minimum at T=0

The EWPhT starts at $T_n < T_c$ determined by requiring:
Probability of nucleation of bubbles / Hubble volume ~ 1

The computation of T_n requires to solve (numerically) a two-field bounce equation
T_n is one of the parameter characterising the amplitude and the frequency peak of the GW spectrum

—— Strength of the phase transition
v_n/T_n $(v_n = \langle h \rangle|_{T_n})$
a crucial parameter for EWBG

EW Baryogenesis

- The out-of-equilibrium dynamics fulfils only one of the Sakharov's conditions to realise baryogengesis → a strong source of $\not{C}\not{P}$ is also needed to explain the observed baryon asymmetry

(Espinosa,Gripaios,Kostandin,Riva,'12)

BONUS

- An additional source of $\not{C}P$ is present in CHMs due to the non-linear dynamics of the GBs → ex: dimension 5 operator $\eta h\, \bar{t}_L t_R$ can have a complex coefficient

$$\mathcal{O}_t = y_t \left(1 + i\frac{b}{f}\eta\right)\frac{h}{\sqrt{2}}\bar{t}_L t_R + \text{h.c.}$$

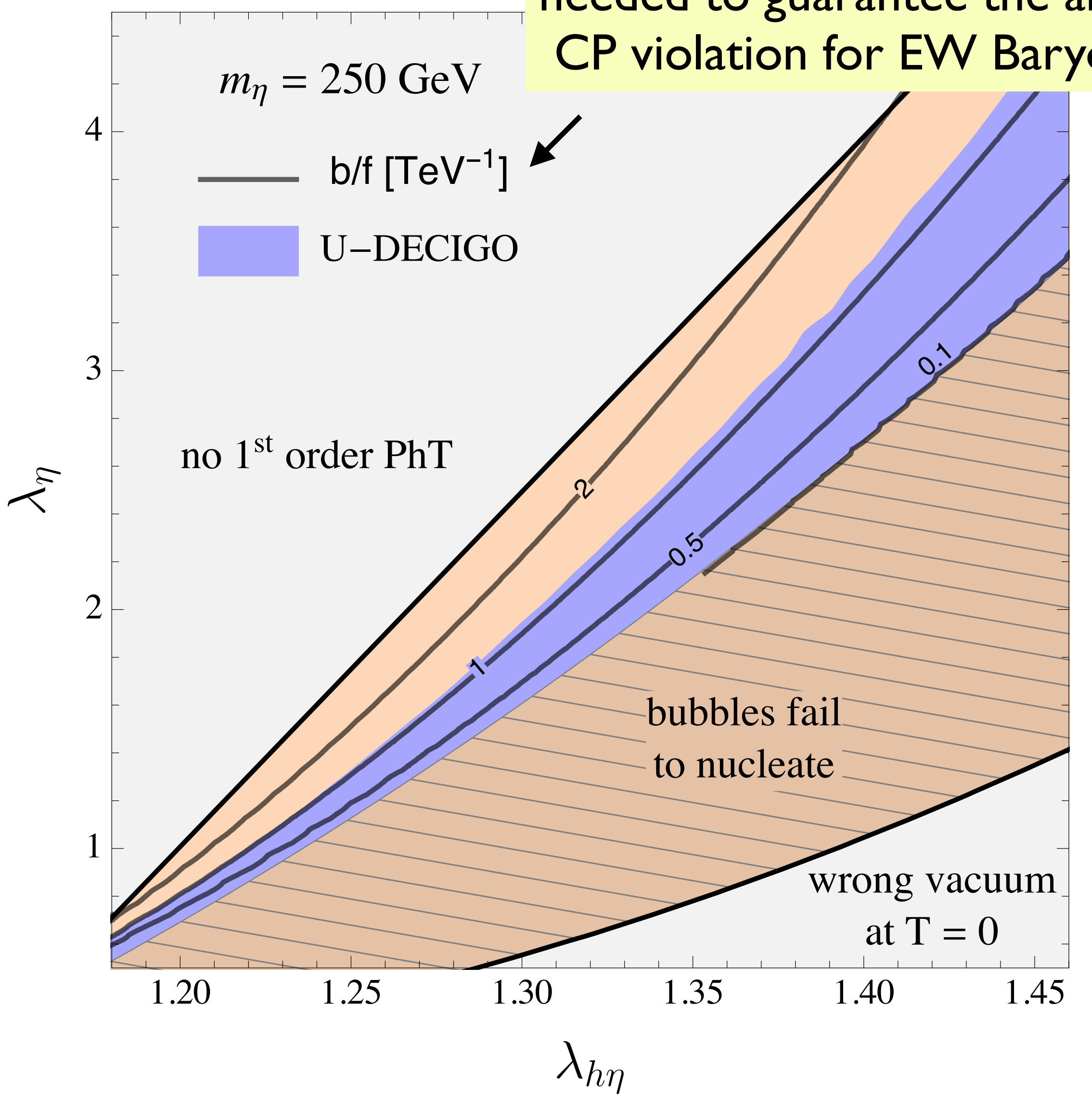
- It induces a phase in the top mass which becomes physical during the EW phase transition at T ≠ 0 when η changes its VEV. This is realised on the bubble walls during the two-step phase transition (0,0) → (0,w) → (v, 0)

- The baryon asymmetry depends on the variation of the phase of the top mass, on the strength of the PhT, the bubble width, the bubble wall velocity. To reproduce the observed baryon asymmetry b/f ≲ TeV^{-1} is enough

$$(n_B - n_{\bar{B}})/n_\gamma \simeq 6 \times 10^{-10}$$

Strong EWPhT, EWBG and GW spectrum linked by a CHM scenario

b/f ~ phase in the top mass - needed to guarantee the amount of CP violation for EW Baryogenesis



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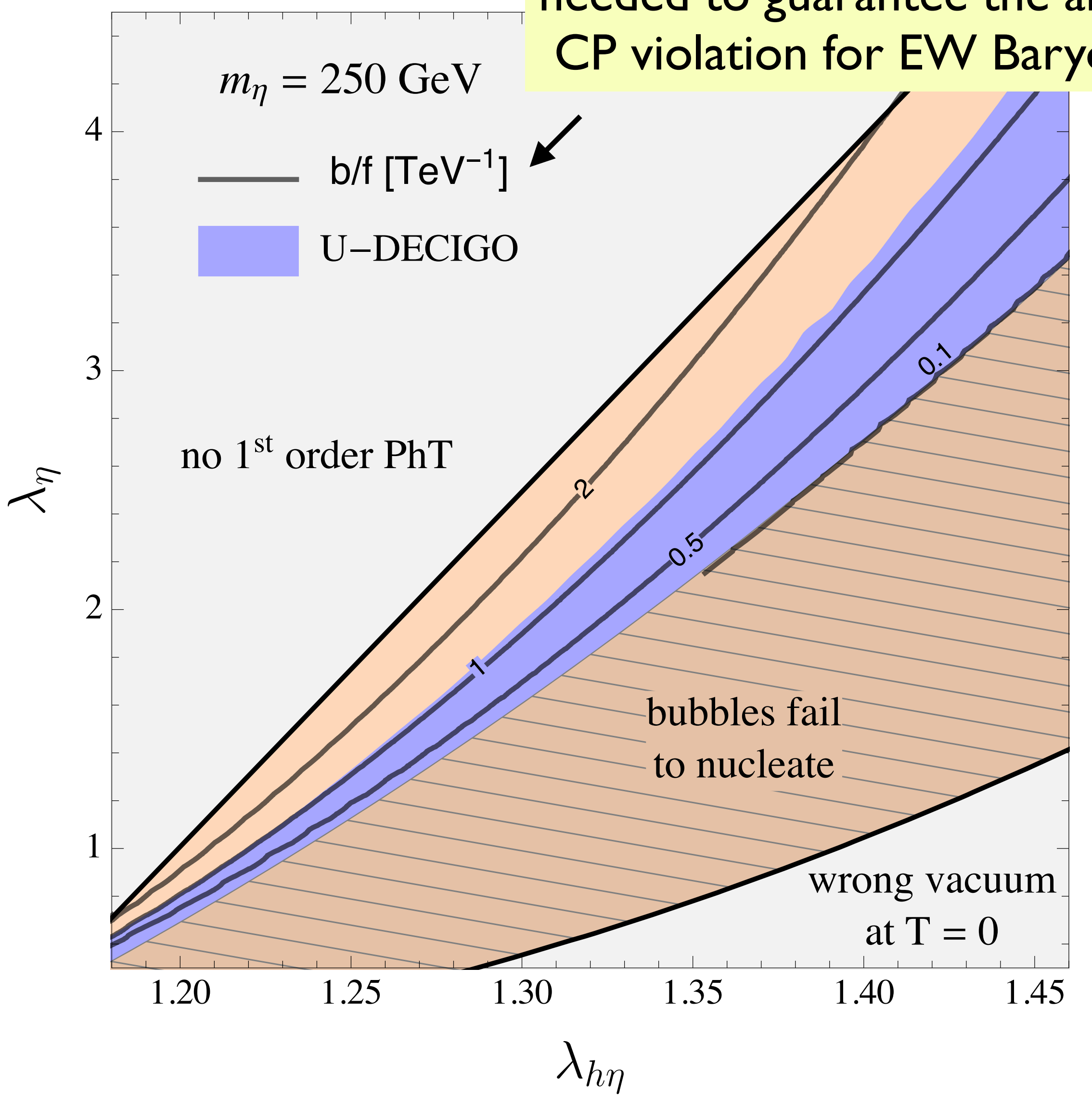


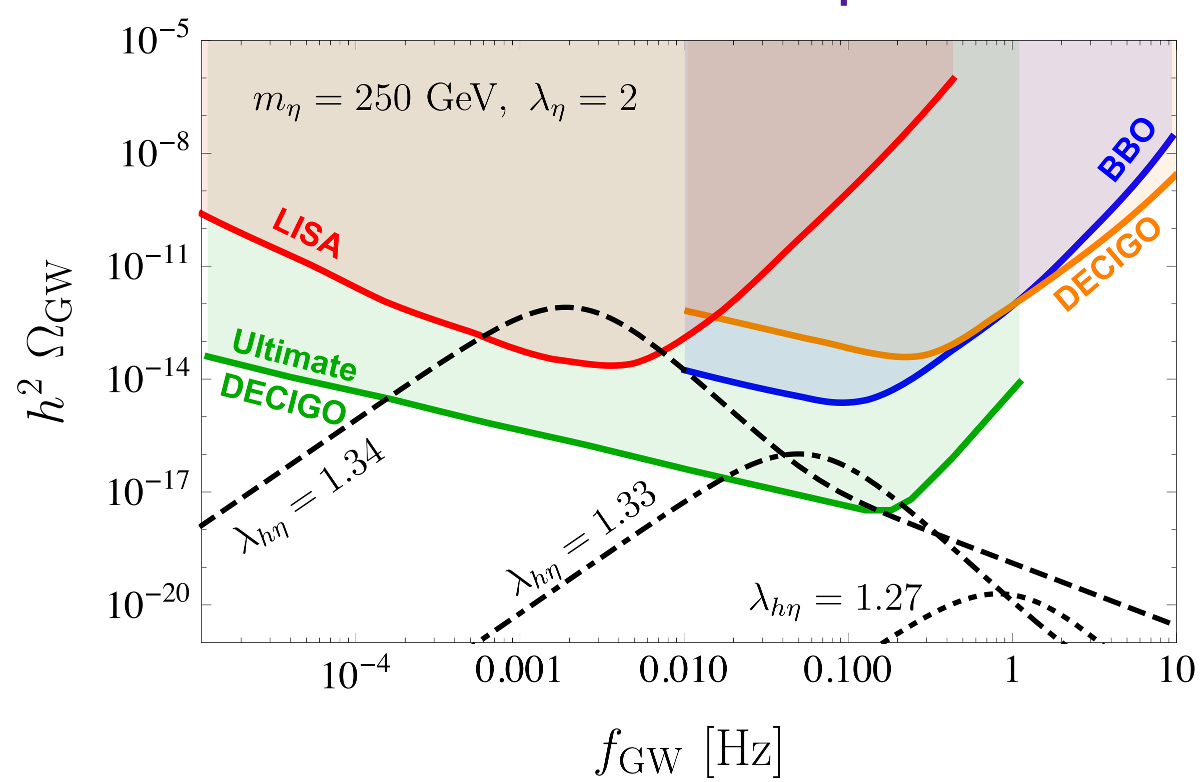
The bubbles expand, collide incoherently …

→ Stochastic Background of GW's :

(bubble collisions, sound waves in the plasma, magnetohydrodynamic turbulence effects)

(Grojean, Servant '06, Caprini, Durrer, Servant '08, '09)

Gravitational Wave Spectrum



same region where the EWBG could be achievable

peak frequencies within the sensitivity reach of future experiments for a significant part of the parameter space

Conclusions

☑ Higgs as a pseudo Nambu-Goldstone Boson is a compelling possibility for stabilising the EW scale

☑ Realistic scenarios can be built and analysed with the full spectrum including new particles

☑ A concrete realisation of a composite aligned 2HDM is now available with parameters determined by the underlying strong dynamics

☑ Non-minimal CHMs can link the dynamics of a strong first order EWPhT to the structure of GW spectrum and the possibility to realise EW Baryogenesis

Waiting for BSM signals from Colliders

Future space-based gravitational interferometry experiments could provide a complementary way to test the Higgs sector

BACKUP SLIDES

Custodial Symmetry and FCNCs in C2HDM

- ☑ No custodial violation in renormalisable elementary 2HDM (E2HDM)
- ☑ In CHMs the non-linearities of the GB Lagrangian lead to dimension 6 operators

$$\mathscr{L}_{d\geq 6} \supset \frac{c_{ij}\tilde{c}_{kl}}{f^2}(H_i^\dagger \overleftrightarrow{D}_\mu H_j)(H_k^\dagger \overleftrightarrow{D}_\mu H_l)$$

contribute to the T parameter for generic VEVs of the 2 Higgs doublets

Possible solutions:

- ☑ CP → assumed here
- ☑ C_2 : that forbids H_2 to acquire a VEV ($H_1 \to H_1$, $H_2 \to -H_2$) → NOT assumed here

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

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- ☑ If CP is the only discrete symmetry, the Yukawa couplings of the elementary 2HDM are:

$$\mathscr{L}_{2\mathrm{HDM}} \supset Y_u^{ij}\bar{q}_L^i(a_{1u}\tilde{H}_1 + a_{2u}\tilde{H}_2)u_R^j + Y_d^{ij}\bar{q}_L^i(a_{1d}H_1 + a_{2d}H_2)d_R^j$$

No tree level FCNC if a's are the identity in flavour space = Aligned Yukawa Couplings (Pich, Tuzón, '09)

- ☑ **In C2HDM higher dim. operators contribute to Higgs mediated FCNCs**

Thanks to the pNGB nature of the Higgs doublets, the Yukawa terms including all the non-linearities can be recast as (Agashe, Contino '09)

BONUS

$$Y_u^{ij}\bar{q}_L^i(a_{1u}F_1^u[H_i] + a_{2u}F_2^u[H_i])u_R^j + \ldots$$

The ratio a_1/a_2 predicted by the strong dynamics after integrating out the heavy resonances

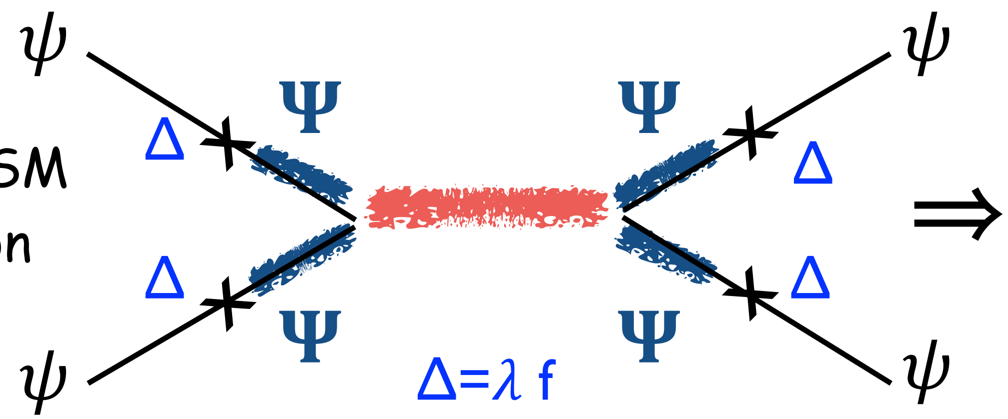
$F_{1,2}[H]$ are trigonometric polynomials starting with $H_{1,2}$ → like in the elementary case

The assumption of aligned Yukawa couplings is not a stronger requirement in the composite scenario than in the elementary one !

Composite Higgs and Flavour

In composite scenarios four-fermion operators are generated integrating out the composite fermions and vectors

ψ is a SM fermion

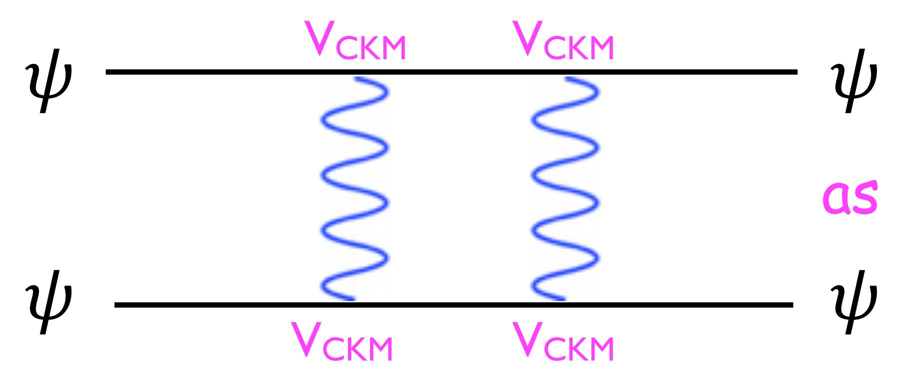


$$\frac{x_{ijkl}}{f^2}\psi_i\psi_j\psi_k\psi_l$$

They can mediate FCNCs at tree-level if the flavour coefficients $x^{ijkl} \sim (\lambda\lambda)^{ij}\,(\lambda\lambda)^{kl}$ are generic

These effects are suppressed if a partial alignment of λ^{ij} with the CKM matrix is realised

(Redi, Weiler 11; Barbieri et al.12)



as in the SM

We will work under these assumptions to realise a flavour symmetric composite sector

Present bounds on the CHM parameters

- **Higgs coupling measurements**

For SO(5)/SO(4):

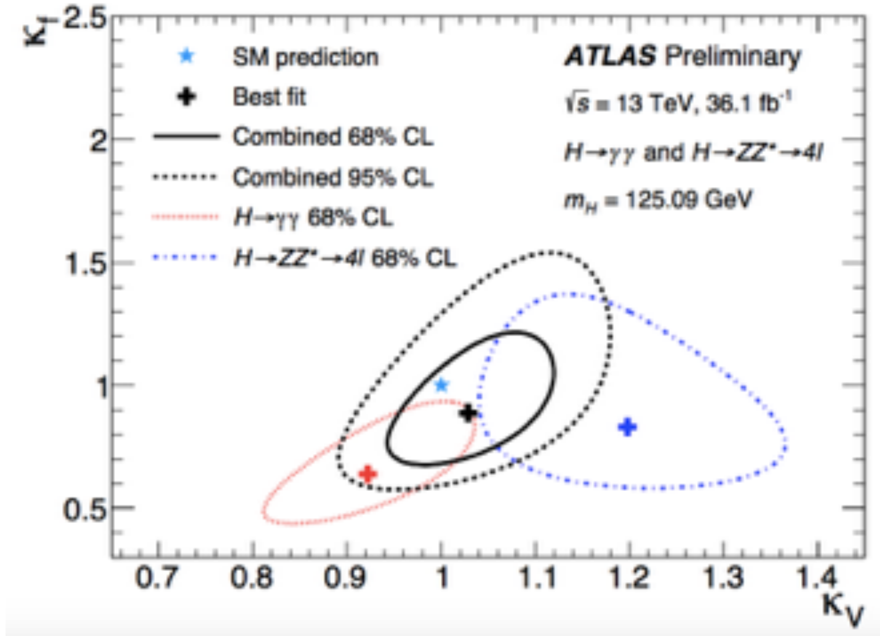
$$g_{HVV} = g_{HVV}^{\rm SM}\sqrt{1-\xi};\; g_{Hff} = g_{Hff}^{\rm SM}\frac{(1-2\xi)}{\sqrt{1-\xi}}$$

$\xi = v^2/f^2$

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)**



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

couplings still constrained at $\gtrsim$10% level

$\xi \leq$0.2

Present bounds on the CHM parameters

- **Higgs coupling measurements**

For SO(5)/SO(4):

$$g_{HVV} = g_{HVV}^{SM}\sqrt{1-\xi};\ g_{Hff} = g_{Hff}^{SM}\frac{(1-2\xi)}{\sqrt{1-\xi}}$$

$\xi = v^2/f^2$

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]
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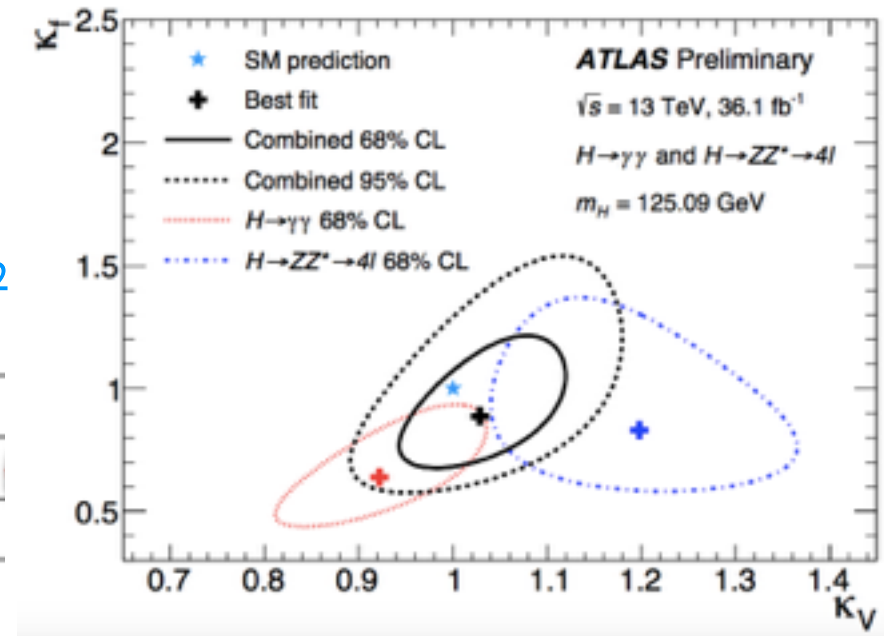


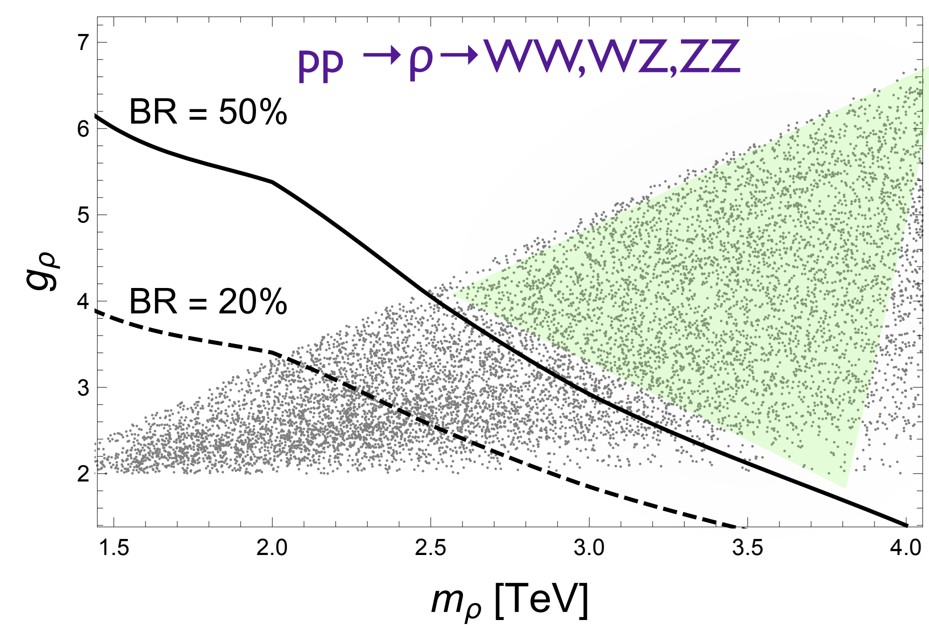
couplings still constrained at ≳10% level

ξ ≤0.2

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

- **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_ρ ≥ 2.5 TeV** as function of g_ρ →

Very conservative: narrow width approximation, BR=50%

OK with bounds from EWPTs

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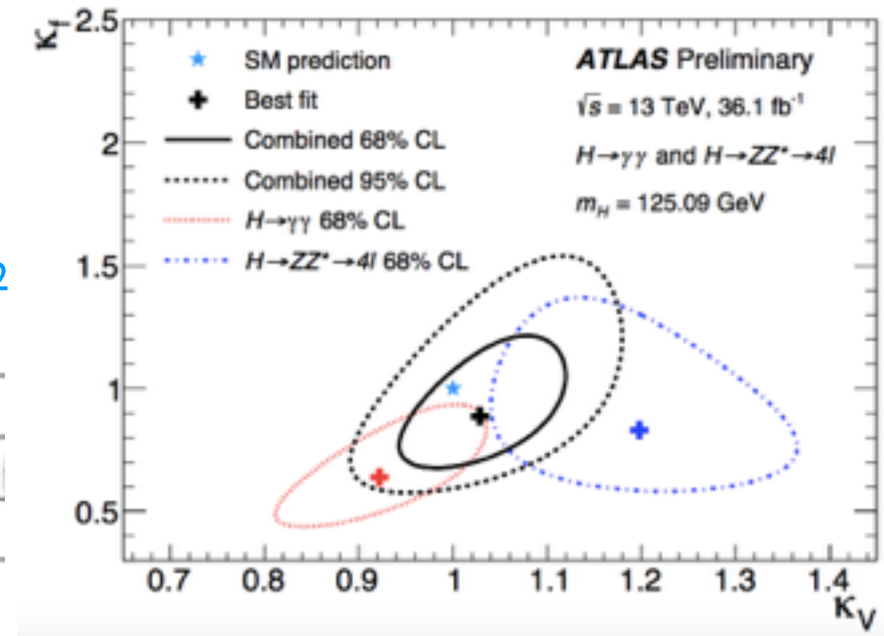

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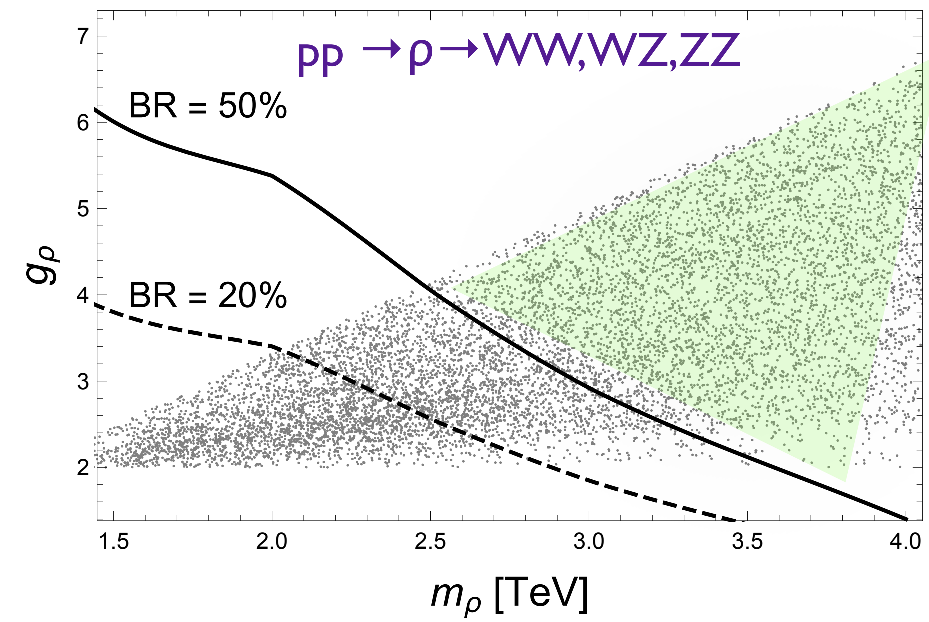


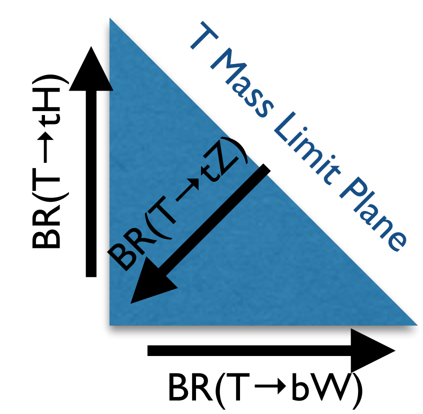
In our analysis: **$m_\rho \geq 2.5$ TeV** as function of g_ρ →

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



In our analysis: **$m_T \geq 1$ TeV**

C2HDM versus MSSM

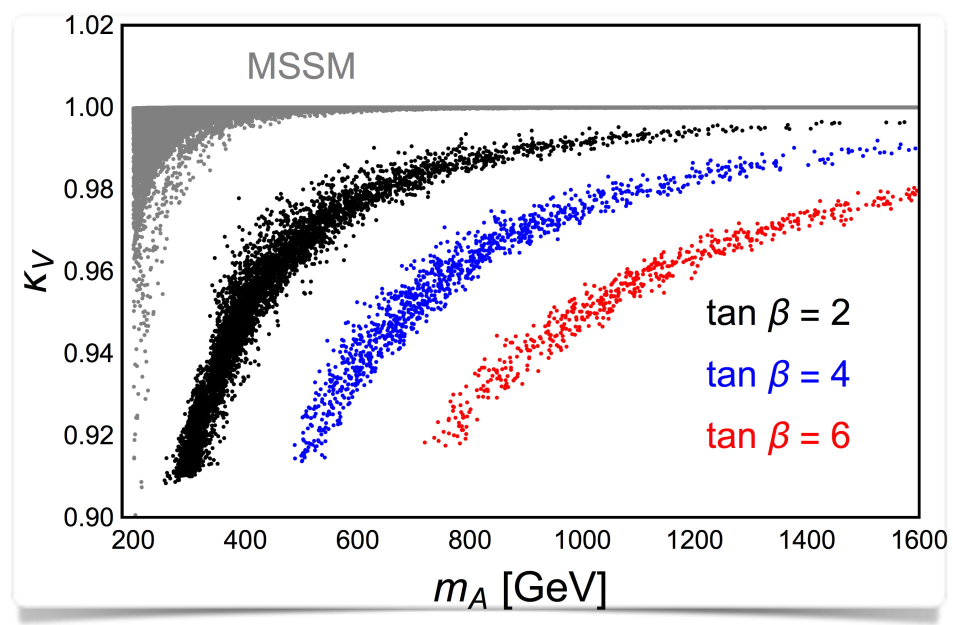
	Supersymmetry	Compositeness
dynamics	*weak*	*strong*
nature of the Higgs	*elementary*	*bound state* $\varphi \sim \langle\bar{\Psi}\Psi\rangle$
quadratic divergences	*fermion/boson interplay*	*no elementary scalars*
lightness of the Higgs	$m_\varphi \sim m_Z$	*pseudo Nambu-Goldstone*
Higgs structure	*2HDM required*	*2HDM depending on the (broken) global symmetry*

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

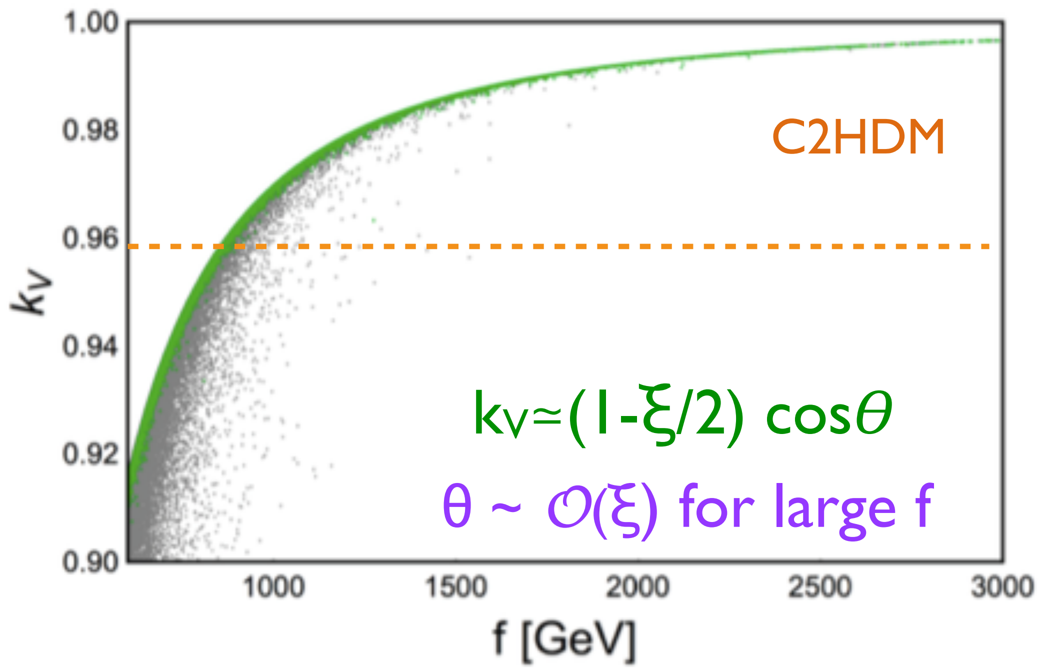
Several observables can be used to discriminate between ℂ2HDM and MSSM:

- k_V (delayed decoupling)
- mass spectrum
- heavy Higgses' decay patterns
- (lightest) top partner spectrum

(DC, Delle Rose, Moretti, Yagyu, '18)

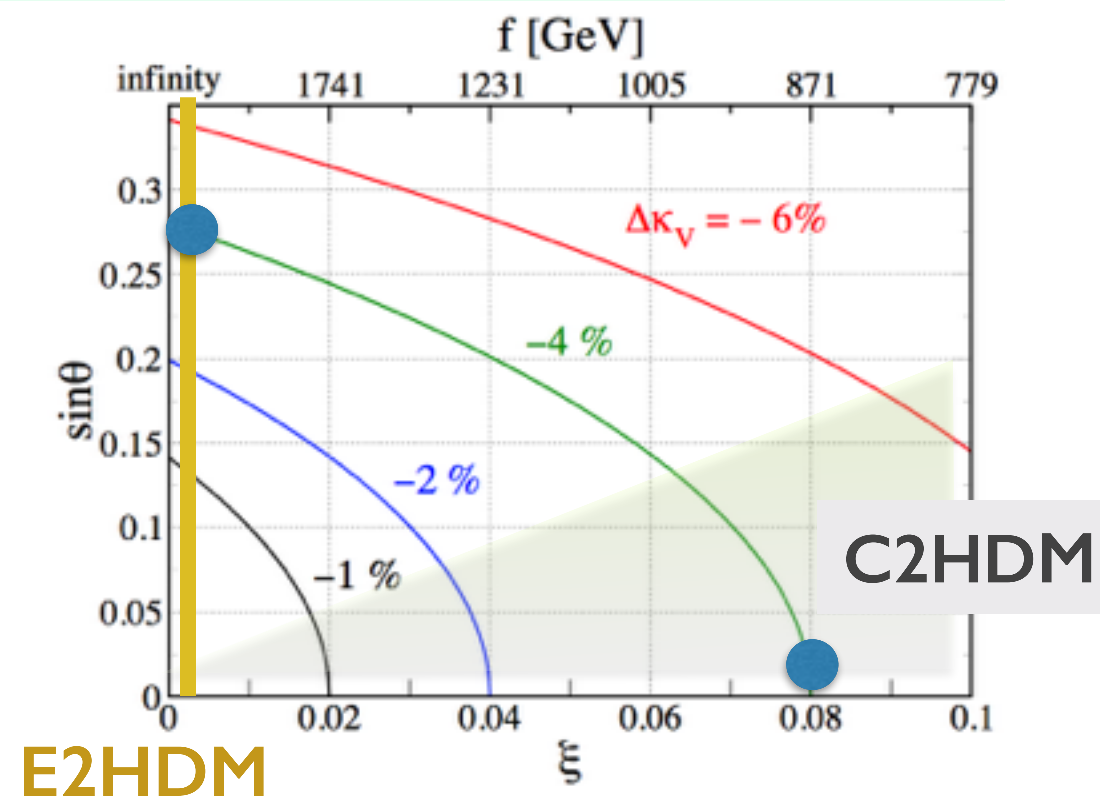


E2HDM or C2HDM ?



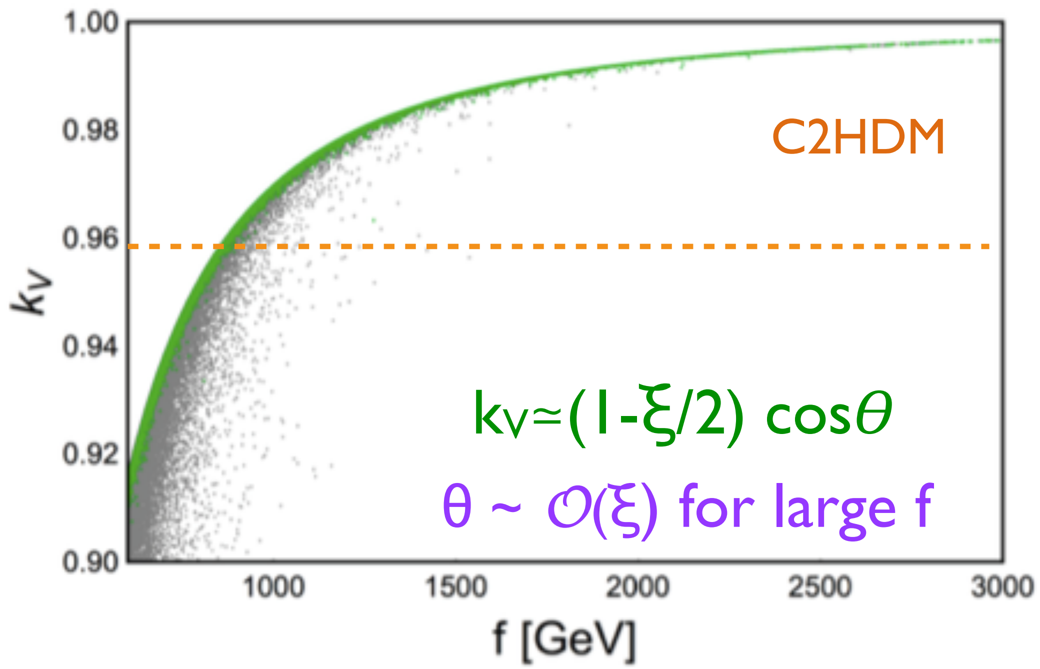
If a deviation in k_V is measured (few %)
it requires a mixing $\theta \neq 0$ in the E2HDM
while it can be explained with $\theta \sim 0$ and f ~1 TeV

Ex: k_V=0.96
→ $\sin\theta \simeq 0.28$ within the E2HDM
→ $\sin\theta \simeq 0$, f = 870 GeV within the C2HDM



Even if $\sin\theta$ is predicted to be ≤0.1 a deviation in k_V can be addressed in the C2HDM by a suitable value of f

E2HDM or C2HDM ?



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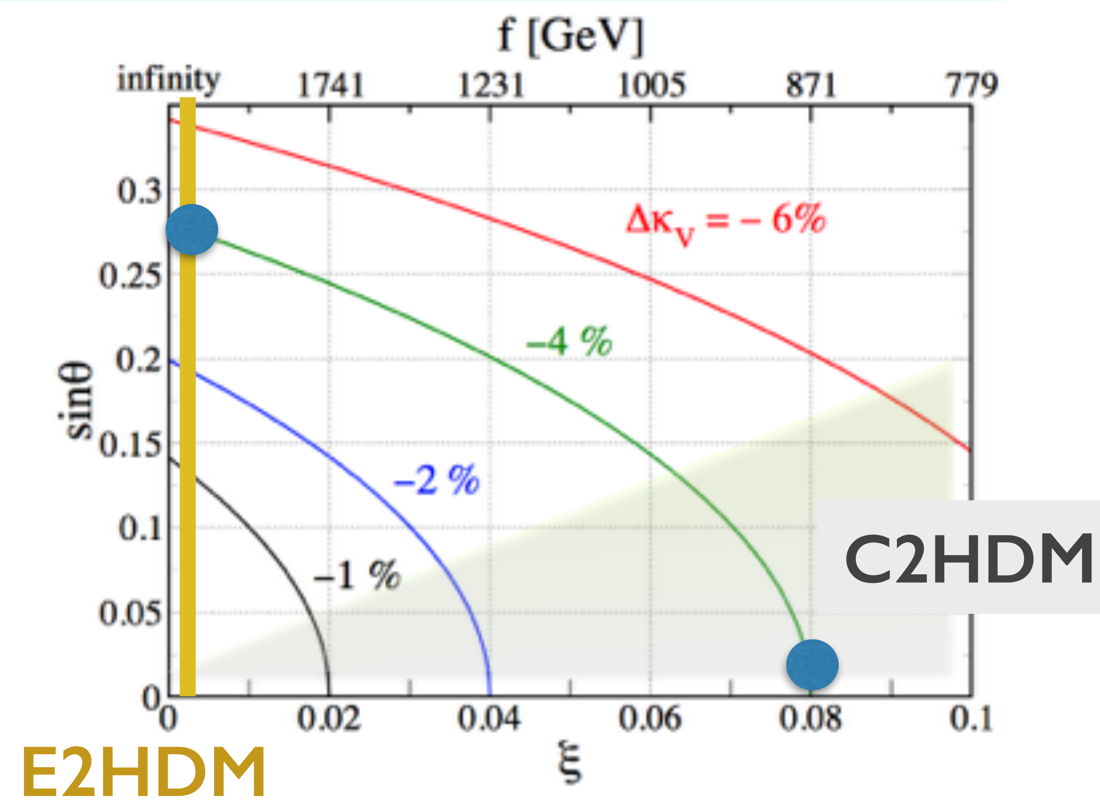
$H \to W^+W^-, ZZ$; $A \to Z^* H$; $H^\pm \to W^{\pm *} h$ decays would be suppressed within C2HDM as compared to E2HDM



Similarly, for the H production:

Higgs-strahlung and vector-boson fusion would be very suppressed in the C2DHM, unlike in the E2HDM due to $\sin\theta$ dependence

A close scrutiny of the H signatures would be a key to disentangle between the two models

Even if $\sin\theta$ is predicted to be ≤ 0.1 a deviation in k_V can be addressed in the C2HDM by a suitable value of f

Flavour Constraints

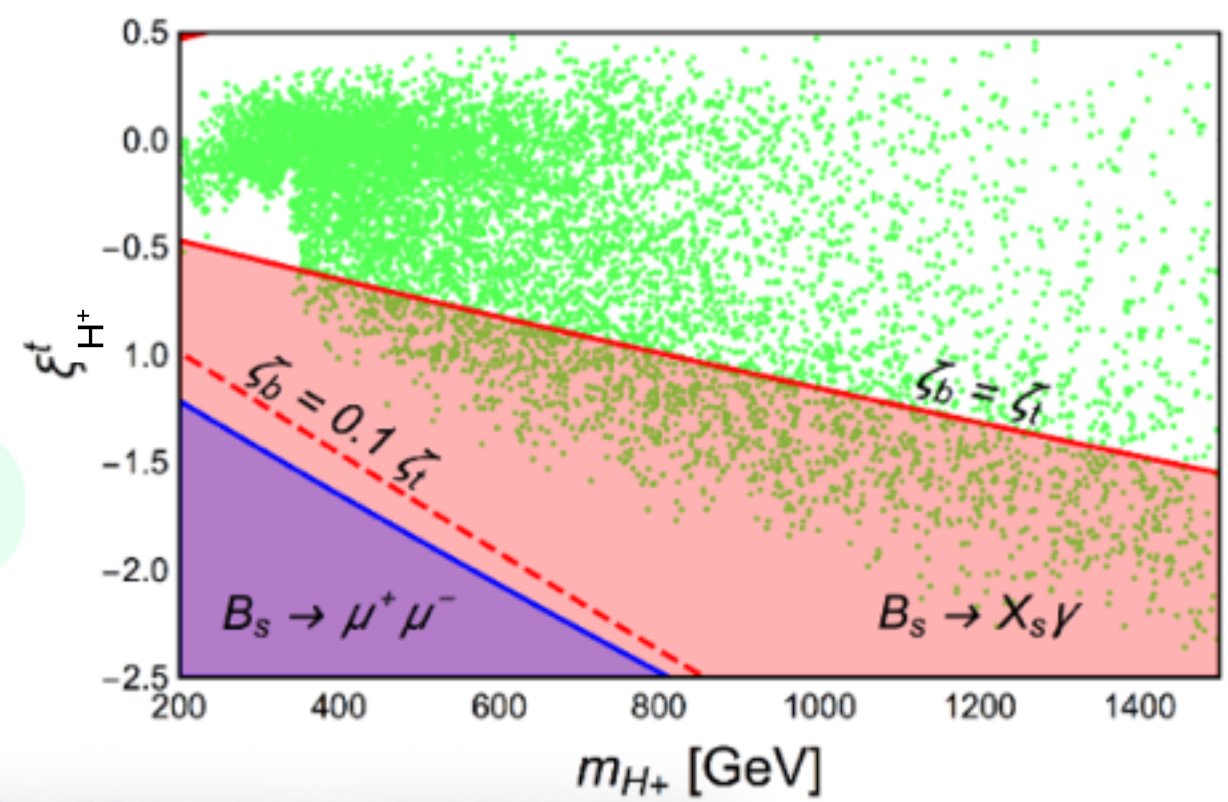
For a flavour symmetric composite sector ($Y_1^{ij} \propto Y_2^{ij}$), the heavy Higgses can only mediate tree level charged current processes and loop effects in neutral ones

The Higgses have interactions with fermions aligned in flavour space
All the flavour constraints are due to a rescaling of the SM rates

- ☑ Meson decays: B, D $\rightarrow \tau\nu$ mediated by $H^{\pm}$ (relevant for small masses and/or large $H^{+}\tau\nu$ couplings, not here)
- ☑ Transition $b \rightarrow s\gamma$: $B \rightarrow X_s\gamma$ - relevant parameters are ξ^{t}_{H+} and ξ^{b}_{H+}
- ☑ $B_s \rightarrow \mu^{+}\mu^{-}$ - relevant coupling is ξ^{t}_{H+}

$\xi^{f}_{H+} \sim \zeta^{f} + O(\xi)$

We implement partial compositeness for t,b,τ
$\xi^{d,l}_{H+}$ are not related directly to the Higgs potential (negligible contribution to v and m_h)
$\rightarrow$ they can be taken small to reduce the effects in the charged currents



Excluded regions in the C2HDM (m_{H+}, ξ^{t}_{H+}) plane by flavour constraints are below the lines

(2σ constraints from Enomoto, Watanabe '16, Misiak et al. '15

green points satisfy the bounds from direct and indirect Higgs searches

tested against HiggsBounds and HiggsSignals

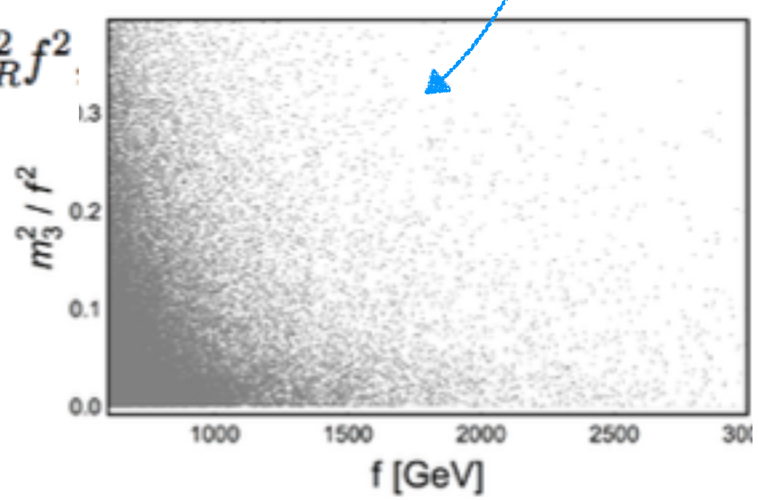
Parameters of the model

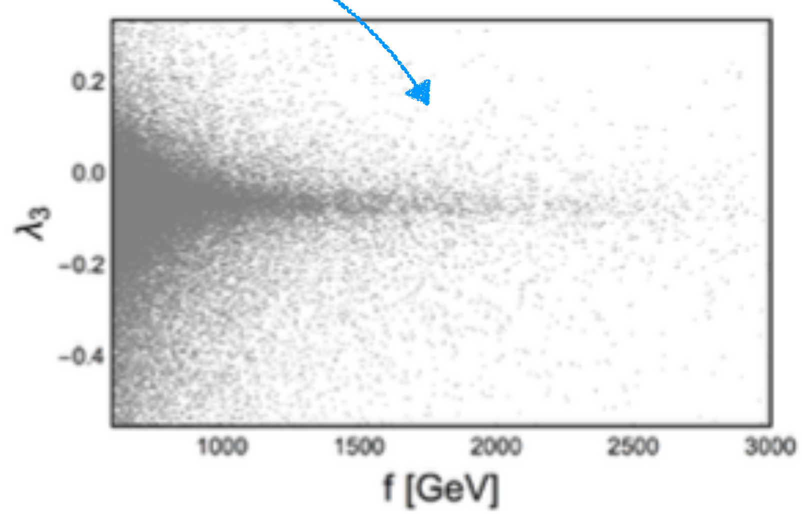
Up to the fourth order in the pNGB fields we get the same structure of the E2HDM potential

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

$$m_3^2|_{\text{fermion}} \sim \frac{N_c}{16\pi^2} y_L^2 y_R^2 f^2$$

$\not{C}_2$ appears at the quartic order in $y_{L,R}$





the quartic couplings are in the perturbative domain

$$600\,\text{GeV} \le f \le 3000\ \text{GeV},\ 0 \le X \le 10f,\ 2 \le g_\rho \le 10$$

C_2 breaking in the strong sector ($Y_1 \neq 0$) induces m_3^2, λ_6, λ_7 $\neq 0$
It is not possible to have a softly broken Z_2 scenario

To study the EWSB dynamics and the scalar spectrum →

- Impose the potential to be minimum for: $f \sin(v/f) = v_{SM} = 246$GeV
- Impose $120 < m_h(\text{GeV}) < 130$
- Impose $165 < m_{top}(\text{GeV}) < 170$

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