A Concrete Composite 2-Higgs Doublet Model

Stefania De Curtis

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Based on:

DC, Delle Rose, Moretti, Yagyu, Phys. Lett. B786 (2018); JHEP 1812 (2018) 051

DC, Redi, Tesi JHEP 1204 (2012) 042

Motivations and Outline

- The 125 GeV Higgs-like signal observed at the LHC could not be the "fundamental" Standard Model Higgs

- 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

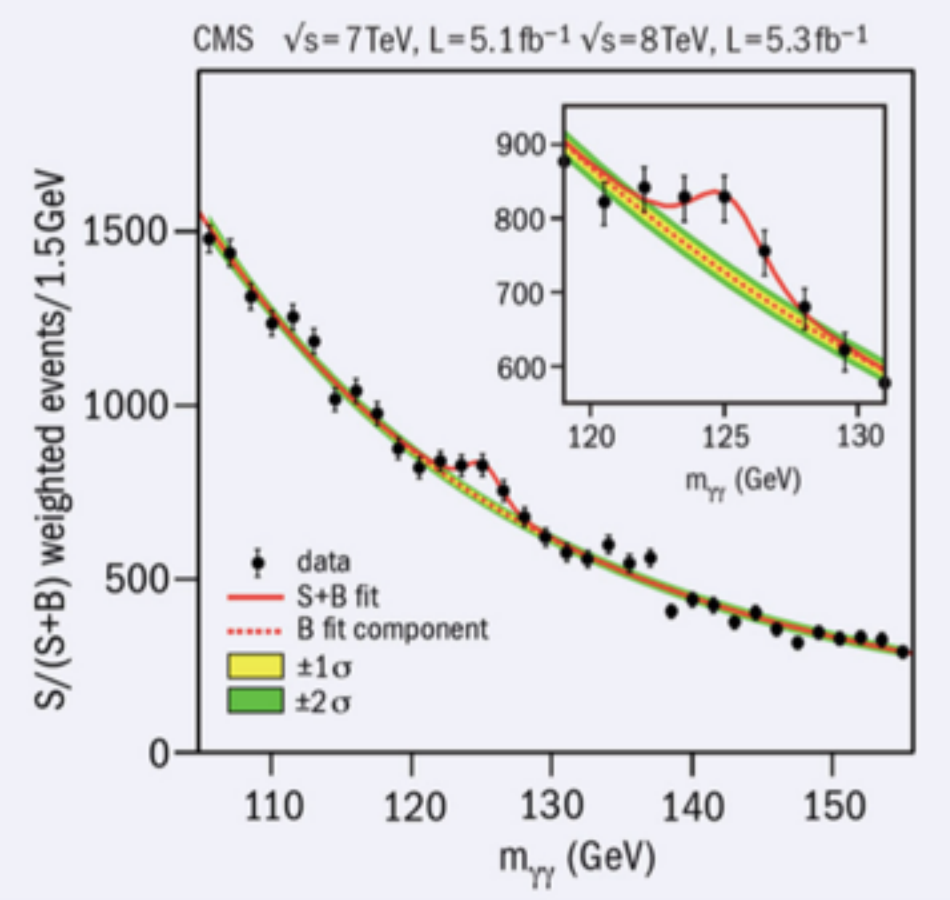
- Minimal realisation: the 4-Dimensional Composite Higgs Model (4DCHM) describing also new fermion and vector composite resonances

- Ideal targets for the LHC program: could produce visible effects (new resonances) without large conflict with indirect bounds

- More than one composite Higgs? A concrete composite pNGB realisation of a 2HDM is here presented

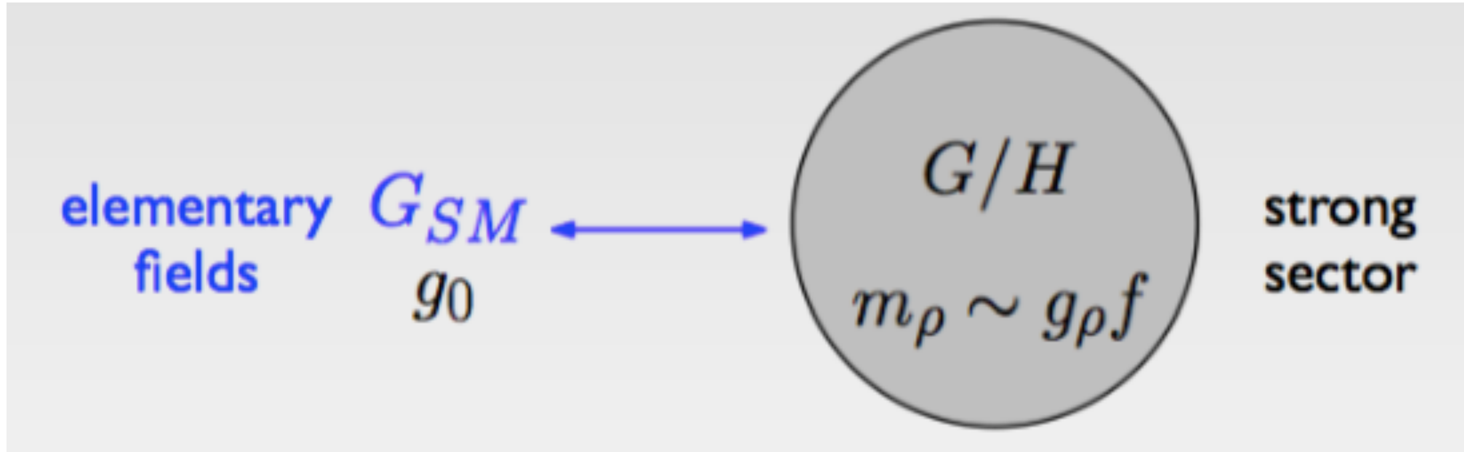
- The properties of $h,H,A,H^{\pm}$ are derived in terms of the fundamental parameters of the strong sector

We found the Higgs boson



- ☑ Is it the SM Higgs ?
- ☑ Is it an elementary/composite particle ?
- ☑ Is it natural ?
- ☑ Is it unique ?
- ☑ Is it the first supersymmetric particle ever observed ?
- ☑ Is it the only responsible for the masses of all the elementary particles ?
- ☑ Is it a portal to a hidden world ?

Higgs as a Composite pseudo Nambu Goldstone Boson



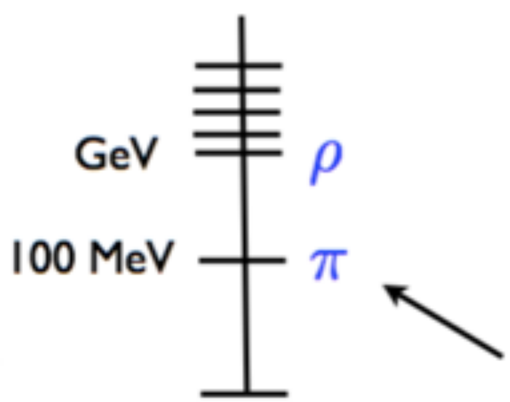
The basic idea

- Higgs as Goldstone Boson of G/H in a **strong** sector

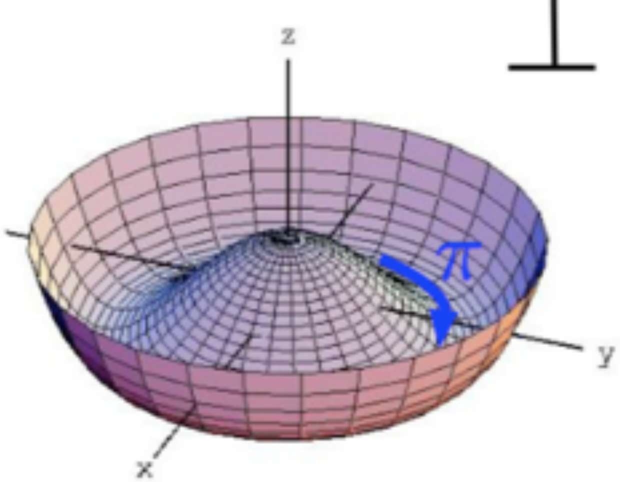
(Georgi, Kaplan '80s)

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

Spectrum:



pseudo Nambu Goldstone
bosons (pNGB)

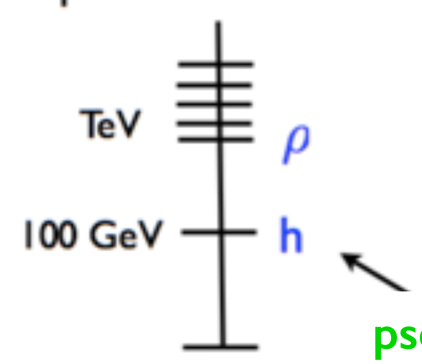


Mass protected by the
global QCD symmetry!

$\pi \to \pi + \alpha$

→ Can the light Higgs be a kind of a pion
from a new strong sector?

We'd like the spectrum of the new strong sector to be:



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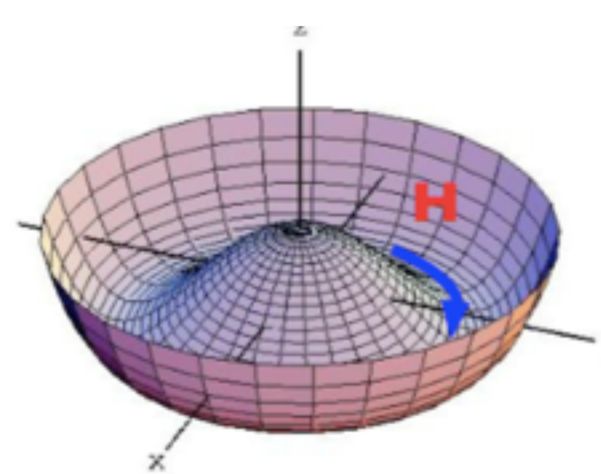


e.g. SO(5) → SO(4)

4 Goldstones
⇓
Higgs doublet

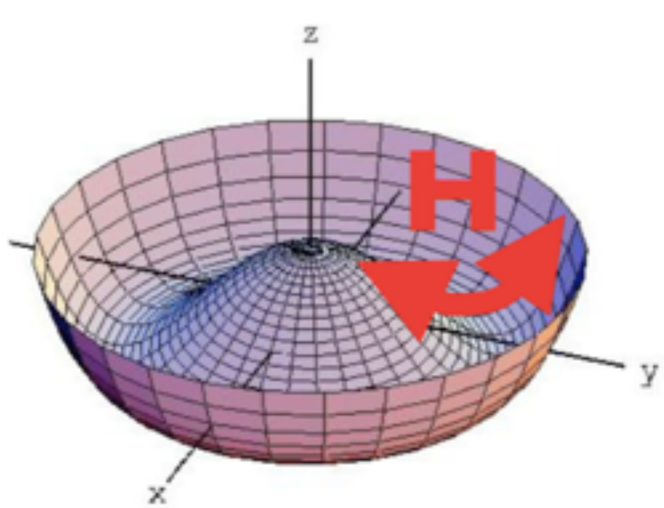
Higgs as a Composite pseudo Nambu Goldstone Boson

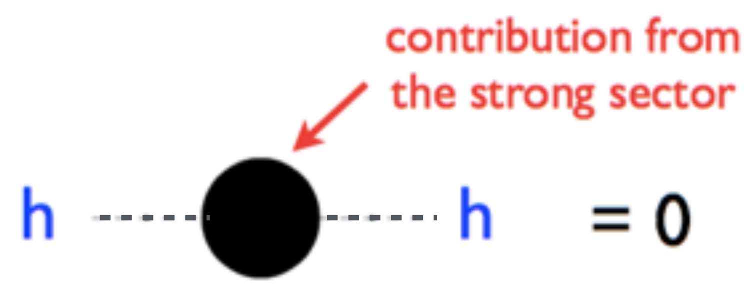
How to get an Higgs mass?

- G is only an approximate global symmetry $g_0 \rightarrow V(h)$

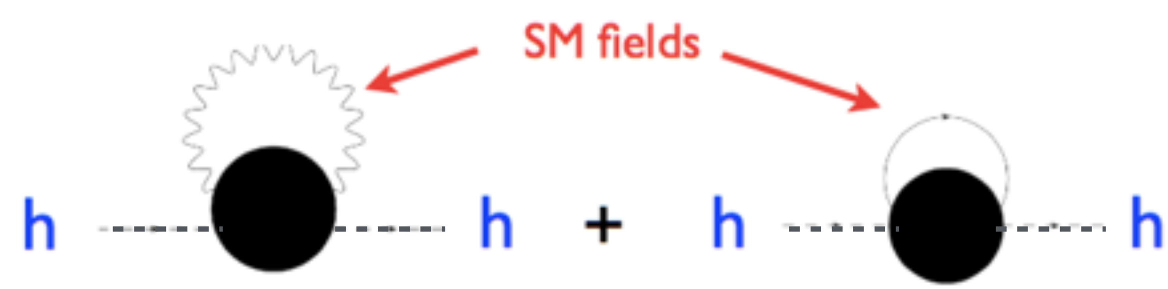
SM-field couplings to the strong sector break the global G

SM loop effects $\rightarrow$ EWSB minimum





= 0 it's a Goldstone

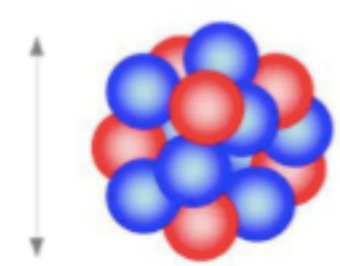


- EWSB as in the SM
- And the hierarchy problem?

no Higgs mass term at tree level

$$\rightarrow \delta m_h^2 \sim \frac{g_0^2}{16\pi^2}\Lambda_{com}^2$$

$$l \sim 1/\Lambda_{com}$$



Composite Higgs Models

From now on, composite=pseudo-Goldstone

How to construct a *complete* Composite Higgs Model?

- $G/H \supset \mathbf{4}$, $G_{SM} \subset H$
- Computable Higgs mass: finite 1-loop effective potential
- Need for composite resonances!
- Not too large tuning $\xi = \frac{v^2}{f^2}$, $v = 246$ GeV, $f \sim 1$ TeV (compositeness scale)

MINIMAL MODEL with $SU(2)_C$

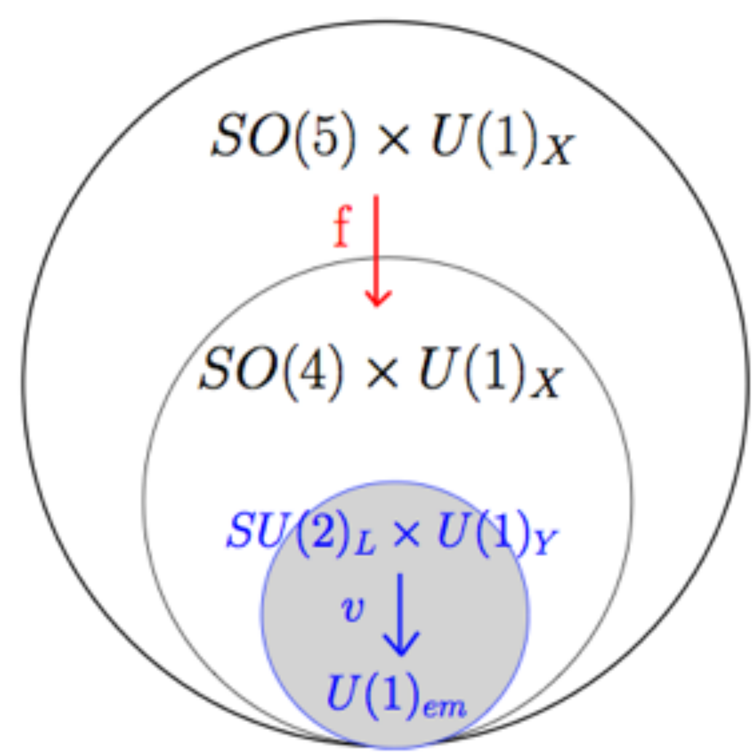
Agashe, Contino, Pomarol (hep-ph/0412089)

MCHM5

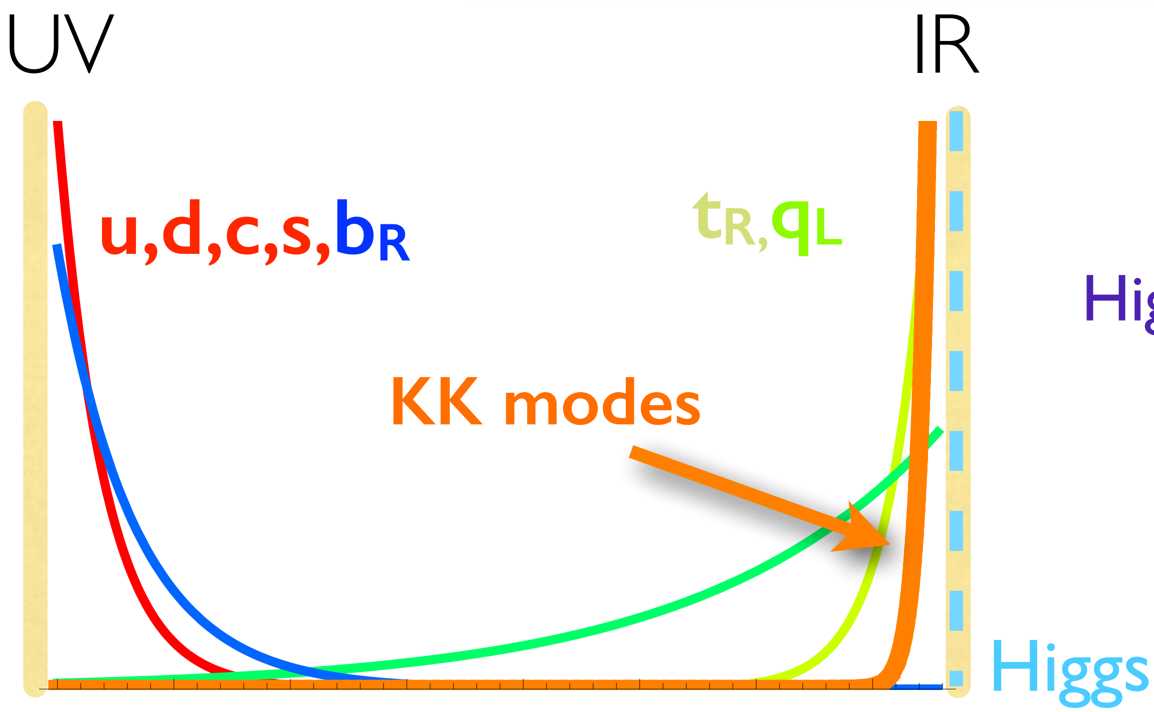
$$\frac{SO(5)}{SU(2)_L \times SU(2)_R} \quad \rightarrow \quad \text{GB: } (\mathbf{2}, \mathbf{2})$$

Higgs = pseudo-GB

$(m_h \ll m_\rho)$



Composite Higgs Models in 5D



Compositeness degree ~
localisation toward the IR brane

Realised by Randall-Sundrum scenario

$$ds^2 = e^{-2kry}(-dt^2 + dx^2) + dy^2$$

Higgs= fifth component (A_5) of the 5D gauge field

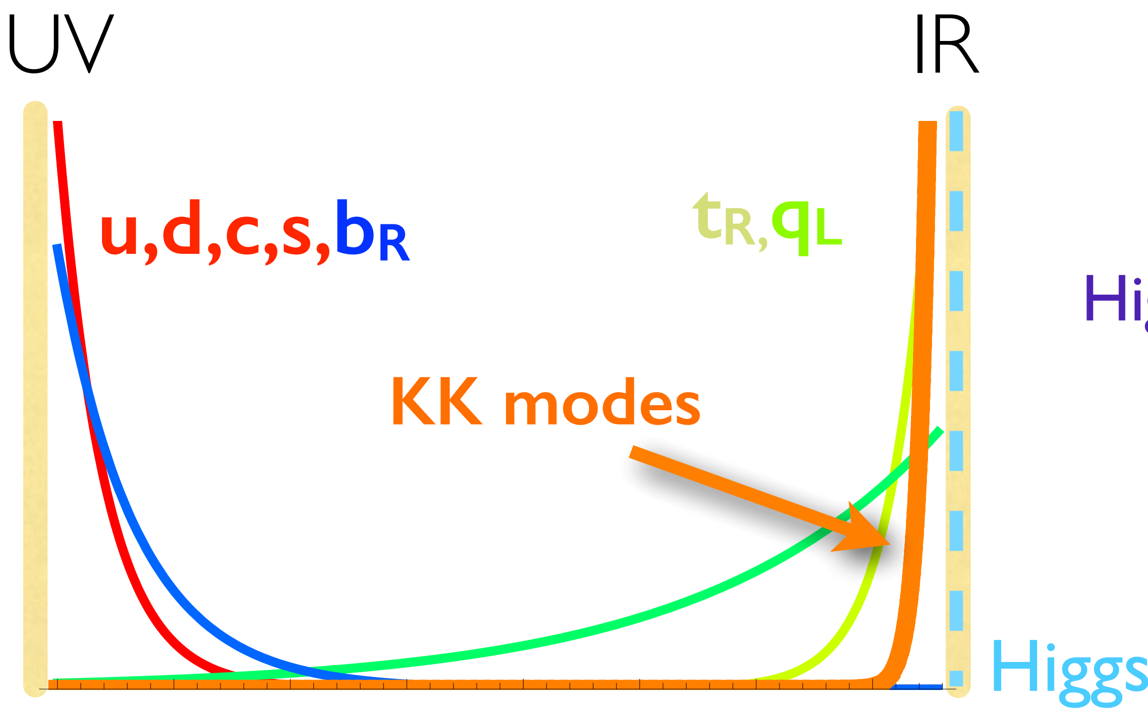
Symmetry breaking by boundary conditions

resonances = ∞ (KK modes)

Through AdS/CFT correspondence 5D models are dual to 4D strongly coupled theories

Composite physics is largely independent on the 5D bulk → only lowest modes relevant

Composite Higgs Models in 5D



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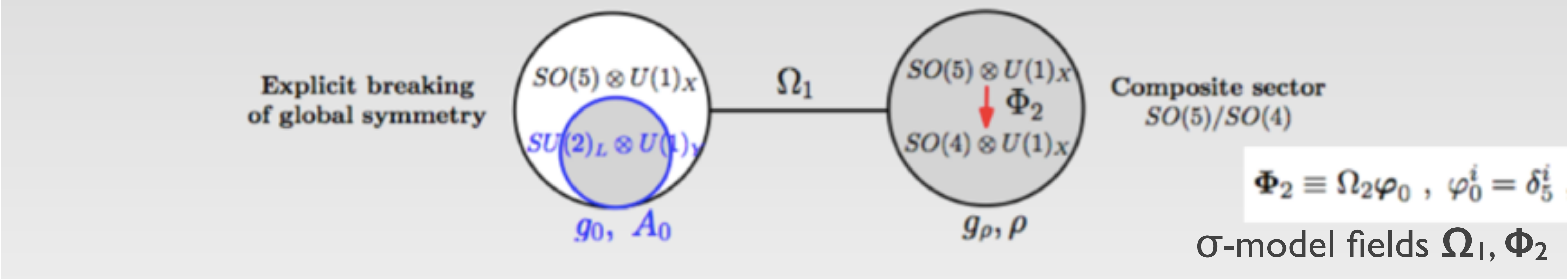
➡ Go for an **effective 4D description** with one level of resonances deconstruction of a 5D model

Elementary Sector	⟷	**Strong Sector**
$A_\mu, \psi \in SU(2) \times U(1)_Y$	$\mathcal{L}_{\text{mix}} = g_0 A_\mu J^\mu_\rho + \Delta \bar{\psi} \Psi$	$\rho_\mu, \Psi \in G_{\text{strong}}$
$g_0 < 1$		$m_\rho,\ 1 < g_\rho < 4\pi$

4DCHM = Minimal 4D realisation of MCHM5

DC, Redi, Tesi '12

Agashe, Contino, Pomarol '04



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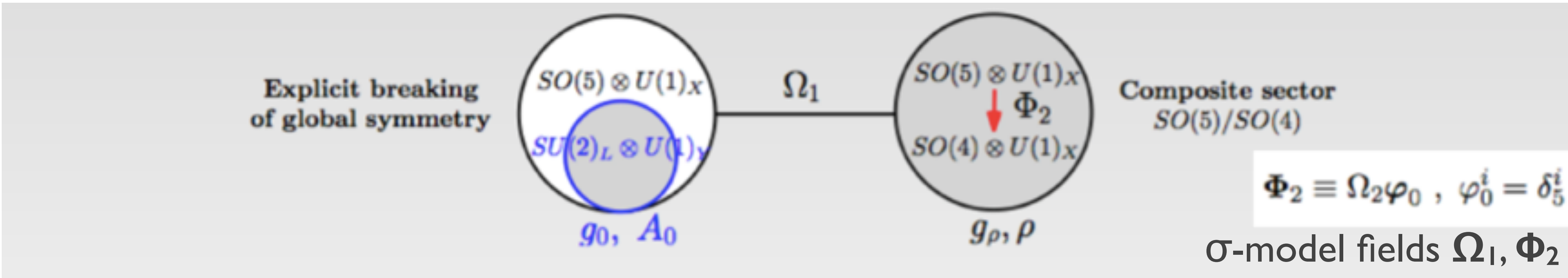
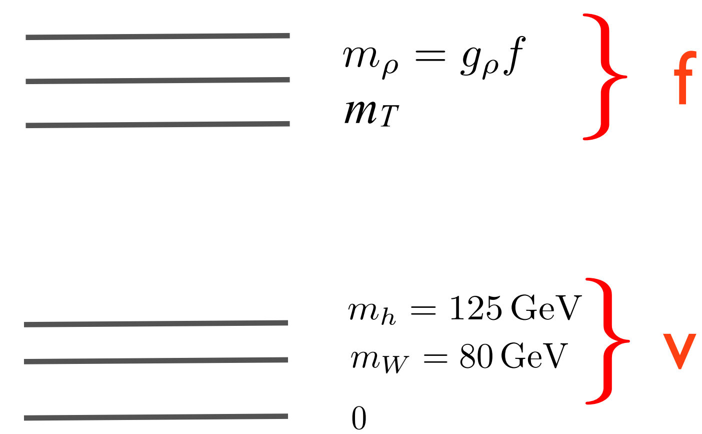


Low-energy Lagrangian *a la* CCWZ + ρ new spin-1 resonances as gauge fields of the "hidden gauge symmetry" + $T, \tilde{T}$ extra composite fermions

Strong sector: resonances + Higgs bound state

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

Spectrum :



g_ρ = strong coupling

4DCHM = Minimal 4D realisation of MCHM5

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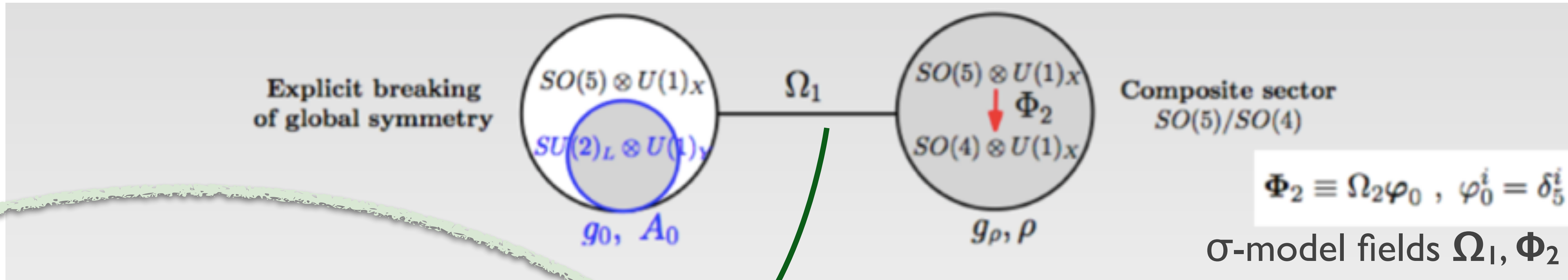
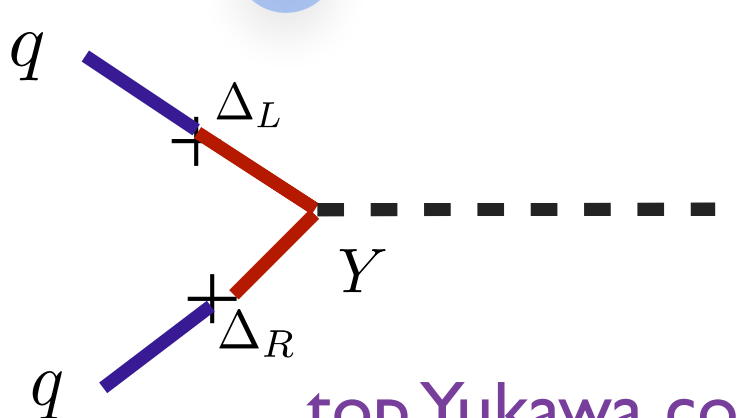


Linear elementary-composite fermion mixings Δ
→ partial compositeness mostly for the 3rd generation quarks

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



top Yukawa coupling

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

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

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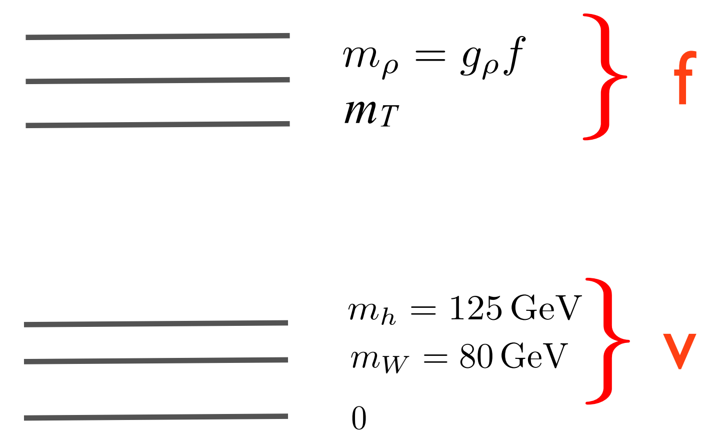
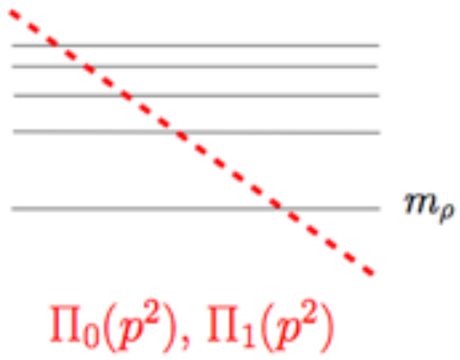


g_ρ = strong coupling

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)

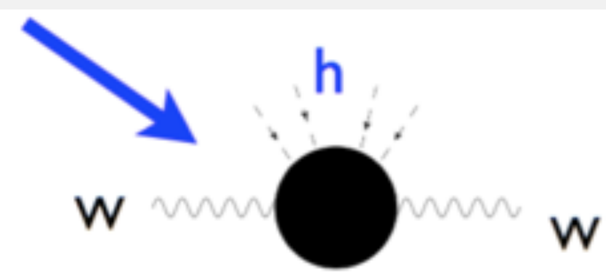
Integrate out the composite sector and get a low-energy Lagrangian with form-factors

(Agashe, Contino, Pomarol '04)

Gauge Sector

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

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



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

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

EW scale

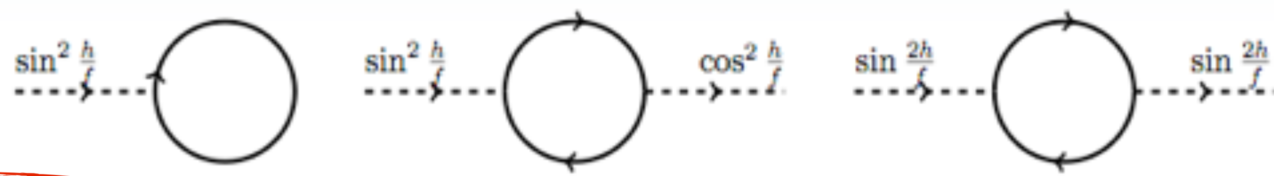
$$v^2 = f^2 \sin^2\frac{\langle h\rangle}{f}$$

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

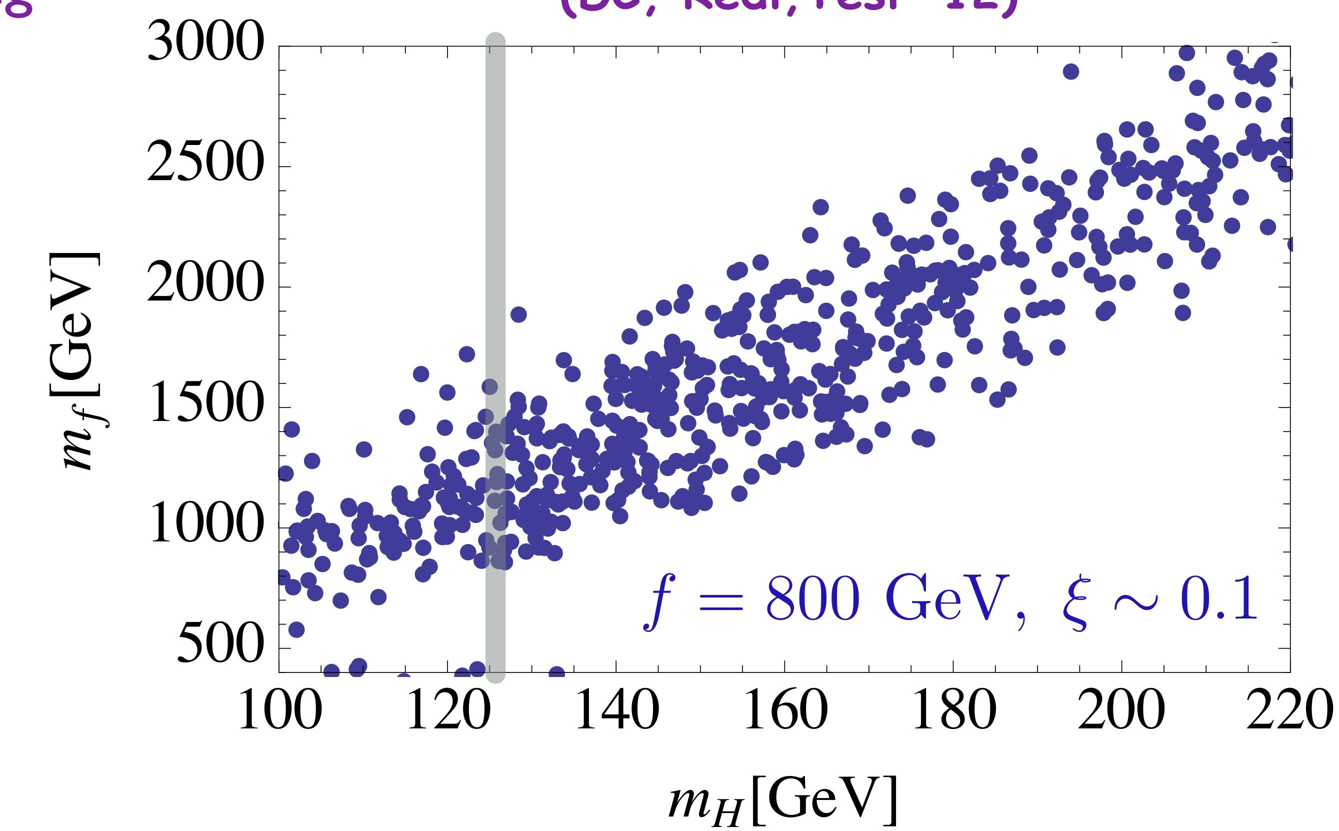
lightest extra-fermion mass

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

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

$\Delta > \Delta_{min} \sim 1/\xi$

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)
...	...	...

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)

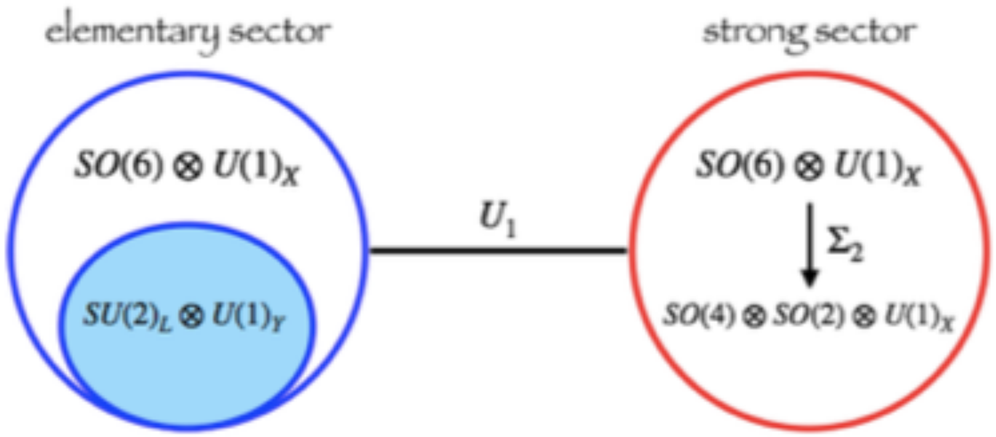
- Besides CP, one can impose a C_2 discrete symmetry (analogous of Z_2 in the elementary 2HDM) which distinguishes the 2 Higgs doublets: $(H_1,H_2) \to (H_1,-H_2)$. One of them does not couple to the SM fields → **INERT CASE**

- 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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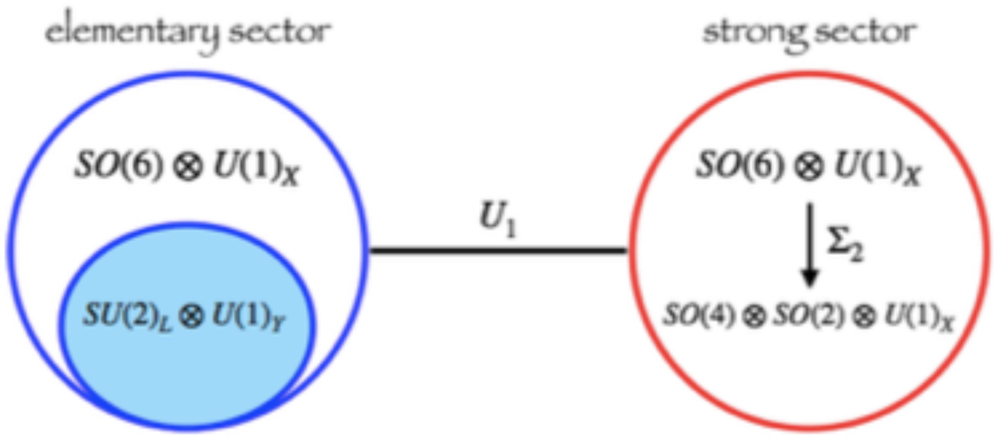

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$$U_i = \exp i\frac{f}{f_i^2}\Pi$$

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

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

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

GB matrix

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

$=U_1U_2$

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

8 broken SO(6) generators

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

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

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

$$v^2 \equiv v_1^2 + v_2^2$$

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

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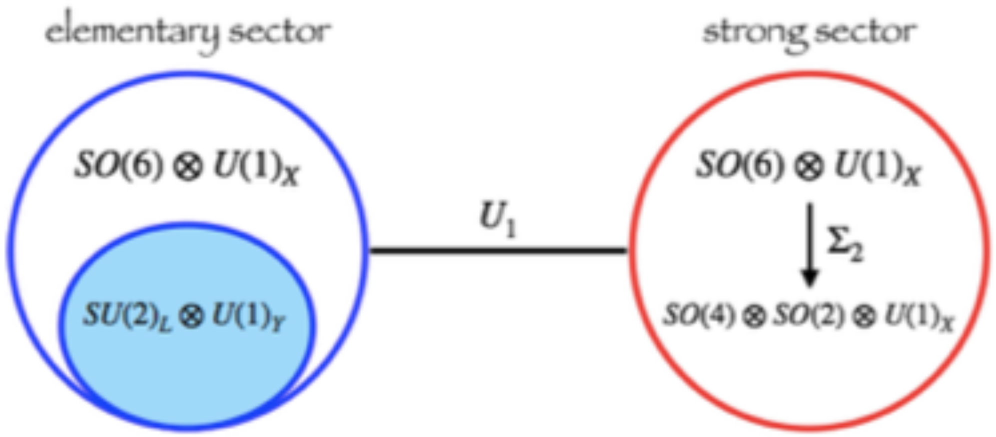

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$h^4_\alpha = h_\alpha + v_\alpha$

$$v^2 \equiv v_1^2 + v_2^2$$

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

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

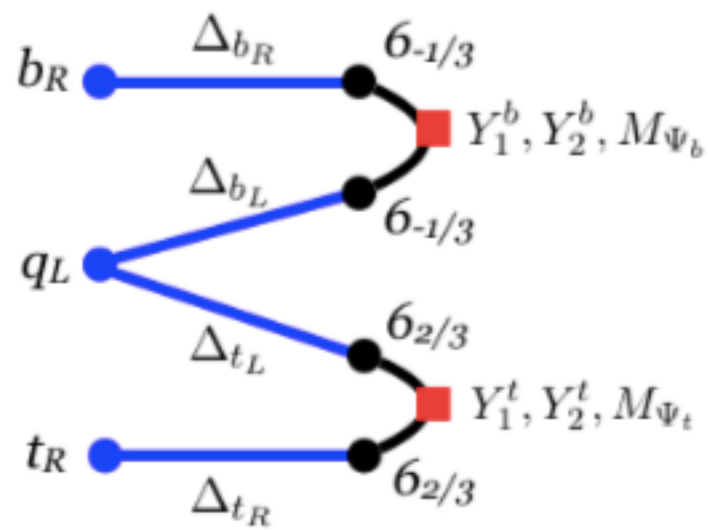
$$m_W^2 = \frac{g^2}{4}f^2\sin^2\frac{v}{f}$$

$\to v_{\rm SM}^2$

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



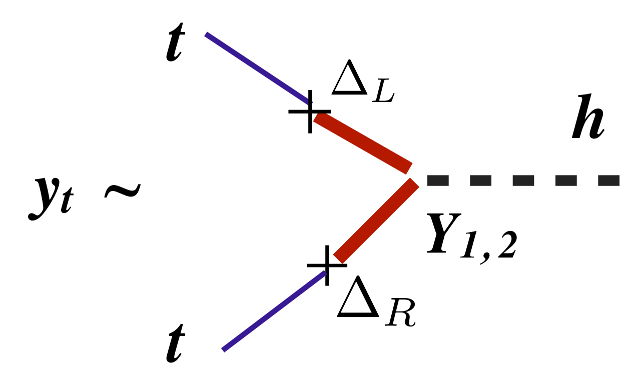
for the top

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

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



Custodial Symmetry

- 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

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

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

Custodial Symmetry

- ☑ 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

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

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

Flavour structure

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 composite 2HDM higher dim. operators contribute to Higgs mediated FCNCs

Composite Higgs and Flavour

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

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

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 !

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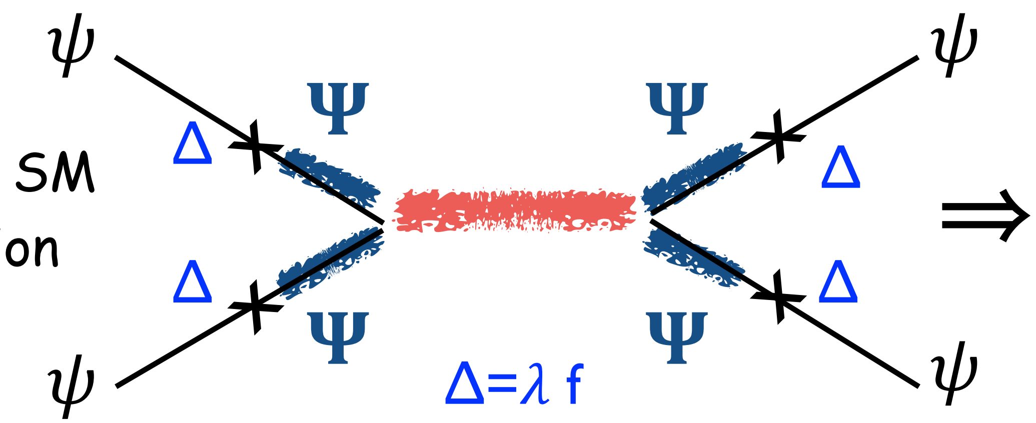
BUT in composite scenarios four-fermion operators are generated integrating out the composite fermions and vectors

ψ is a SM fermion



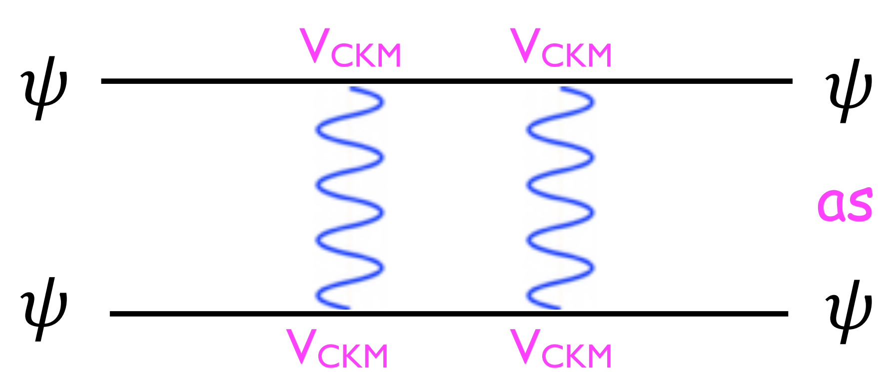
⇒

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

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)

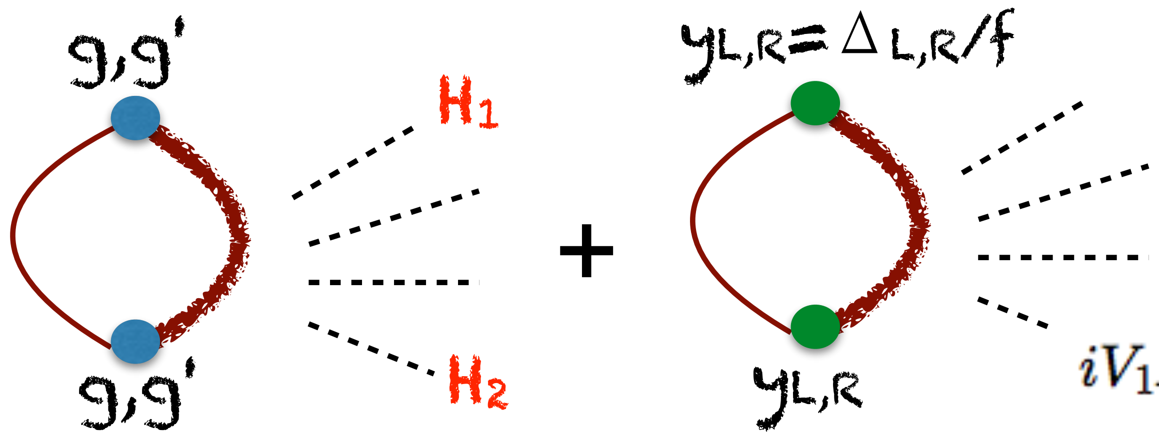


as in the SM

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

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

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

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)

Present bounds on the CHM parameters

- **Higgs coupling measurements**

For SO(5)/SO(4):

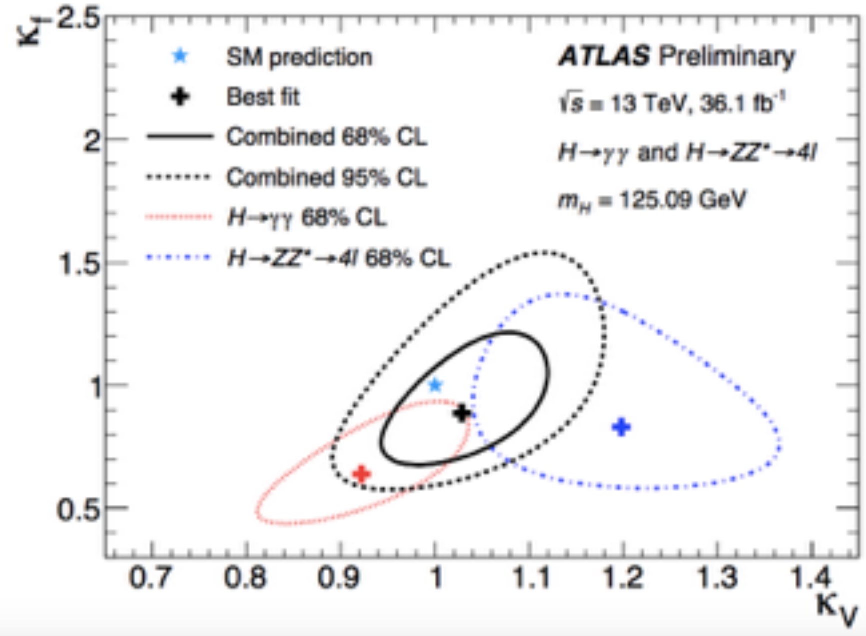
$$g_{HVV} = g_{HVV}^{\rm SM}\sqrt{1-\xi};\ g_{Hff} = g_{Hff}^{\rm SM}\frac{(1-2\xi)}{\sqrt{1-\xi}}$$

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

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 ≥ 600 GeV ($\xi \leq 0.17$)**



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

couplings still constrained at ≳10% level

$\xi \leq 0.2$

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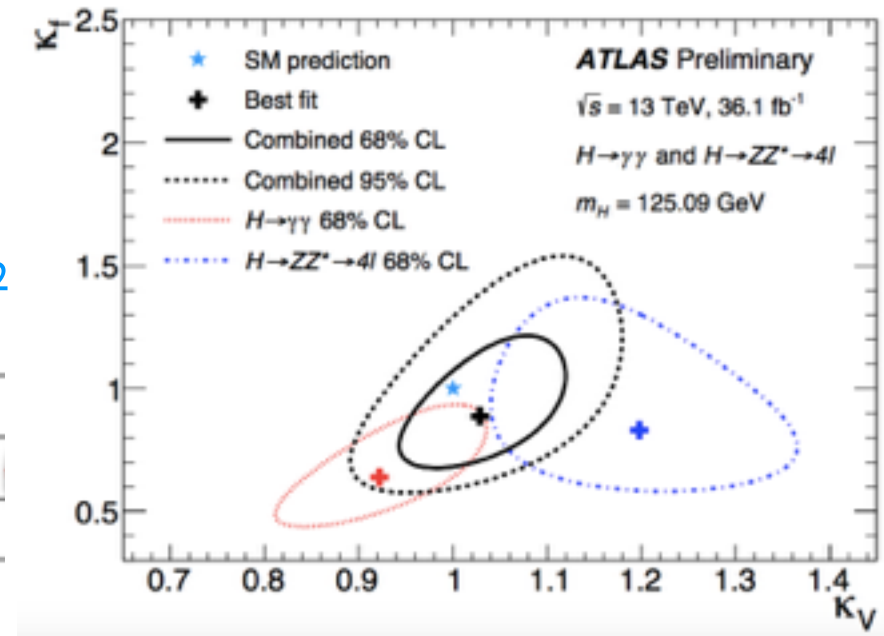

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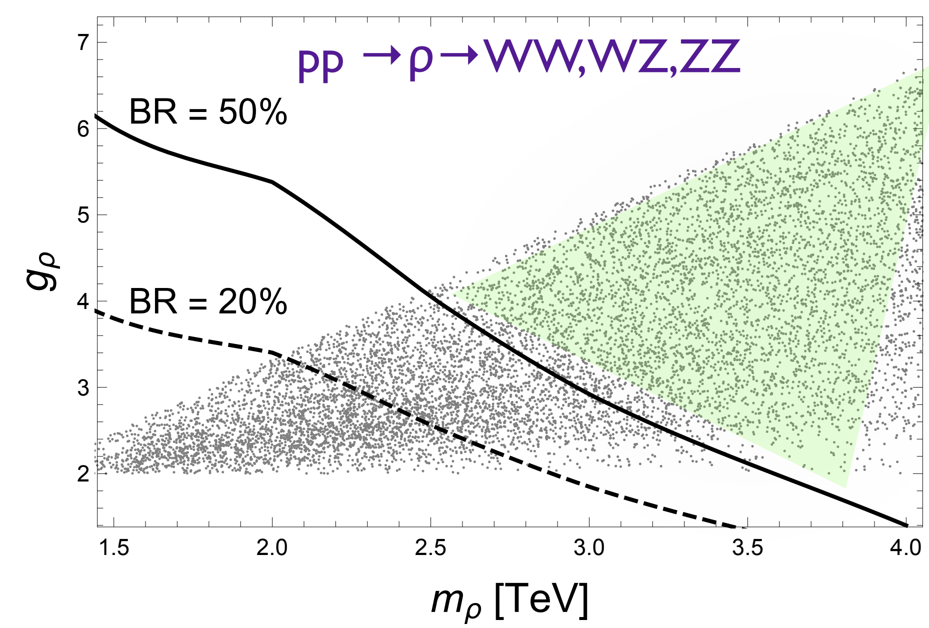
- **Direct searches of heavy spin-1 resonances**

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

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

Very conservative: narrow width approximation, BR=50%

OK with bounds from EWPTs



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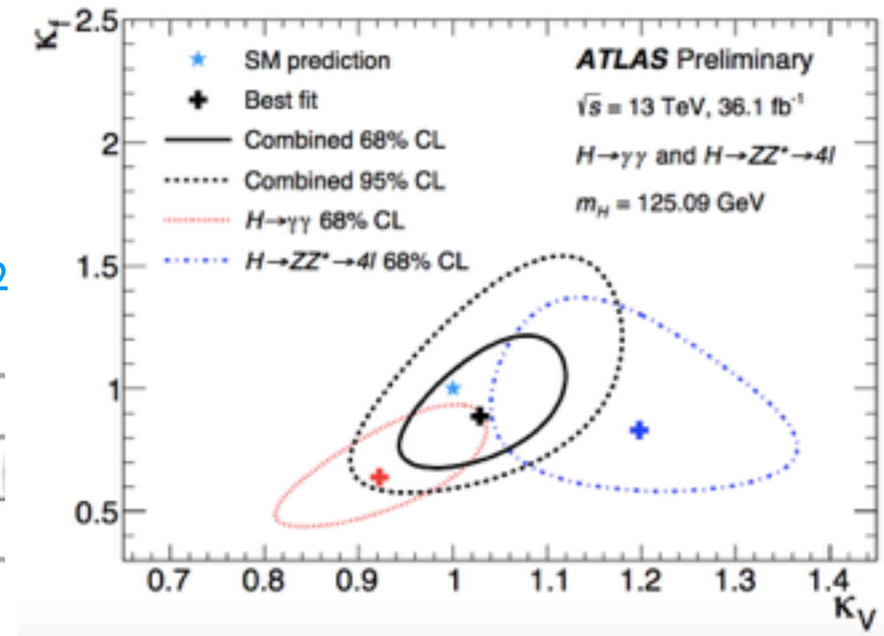

$\kappa_V = \frac{g_{hVV}}{g_{hVV}^{SM}}$

couplings still constrained at $\gtrsim$10% level

$\xi \leq 0.2$

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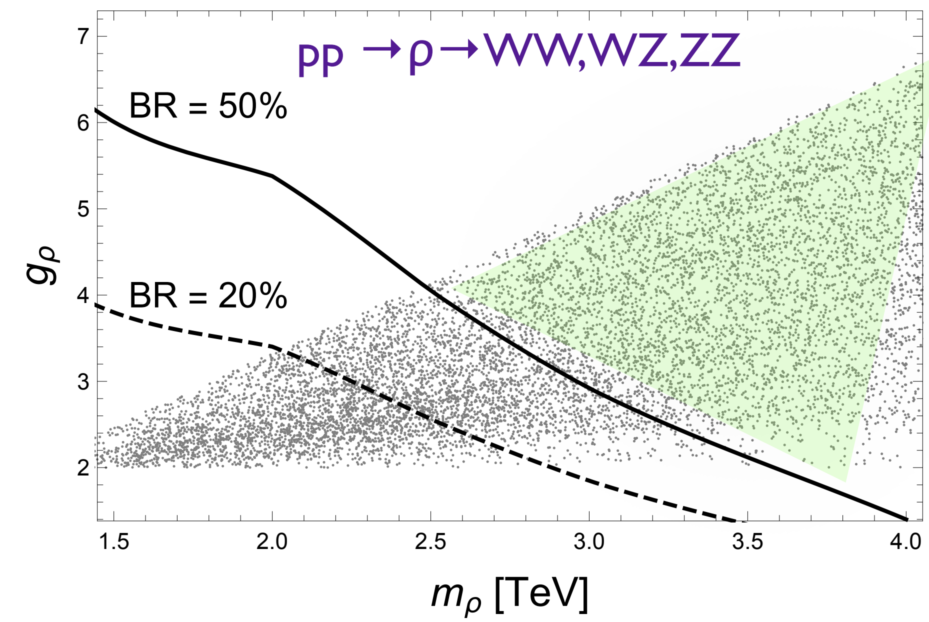


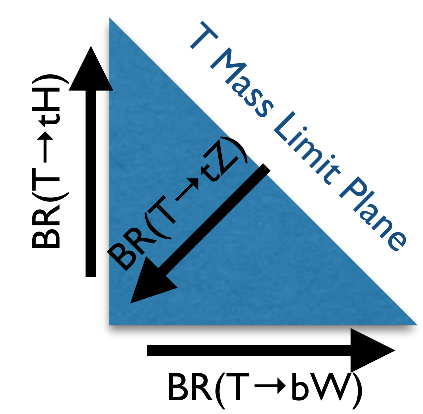
In our analysis: **$m_\rho \geq$ 2.5 TeV** as function of g_ρ →

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**

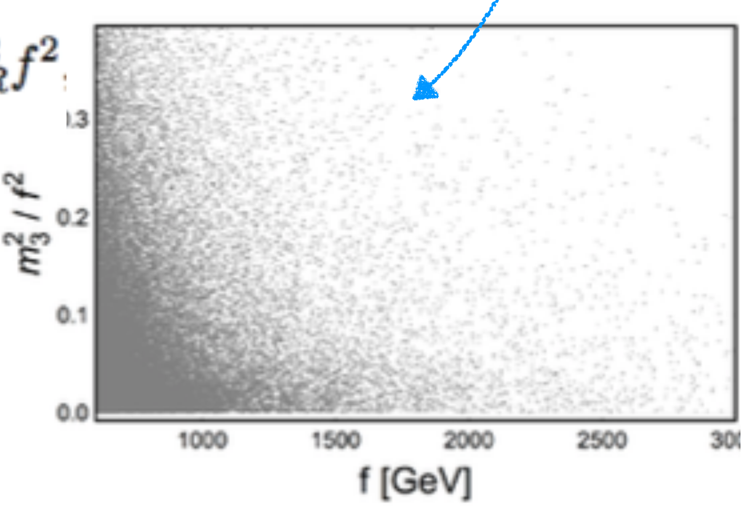
Parameters of the model

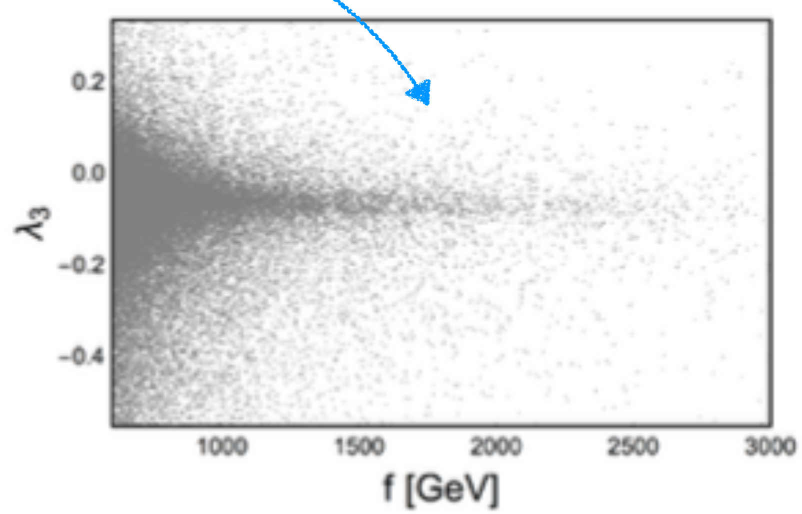
Up to the fourth order in the pNGB fields we get the same structure of the E2HDM potential

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

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

$\not{C}_2$ 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 $v^2=v_1^2+v_2^2$
- Impose $120 < m_h(\text{GeV}) < 130$
- Impose $165 < m_{top}(\text{GeV}) < 170$

2-Higgs Doublets as pNGBs

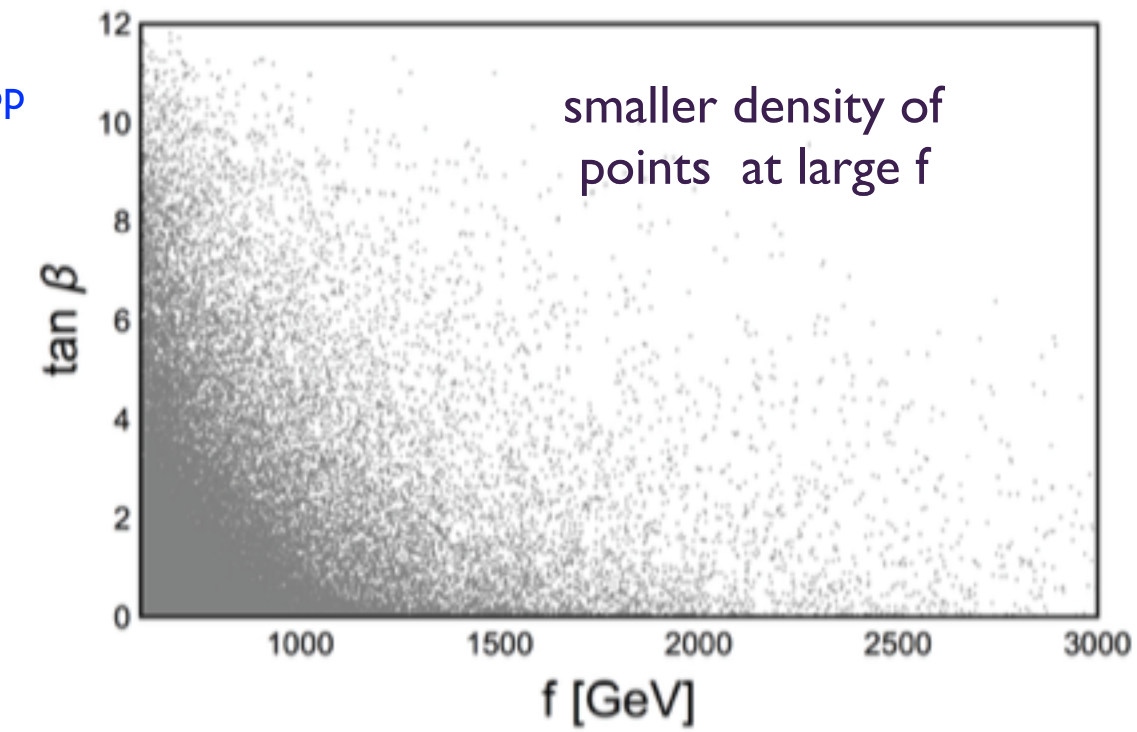
WE GOT SOLUTIONS !

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

- CP , $\not{Z}_2$
- 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 $\tan\beta = v_2/v_1 \lesssim 10$

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

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



- Tuning: the minimal tuning $\Delta \sim 1/\xi = f^2/v_{\rm SM}^2$ is not sufficient to depart from $v_{SM} \sim f$ and other cancellations must be advocated → higher order terms in the fermion couplings $y_{L,R}$ are needed

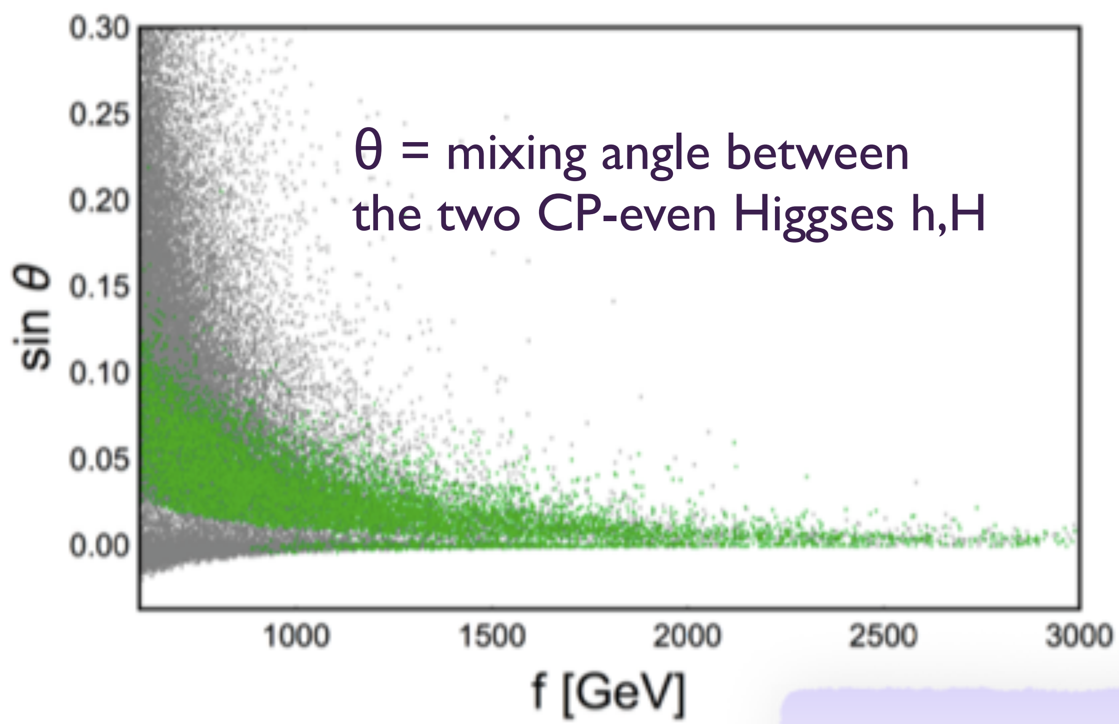
Higgs Boson Masses

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



θ = mixing angle between the two CP-even Higgses h,H

- CP-odd states:

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

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

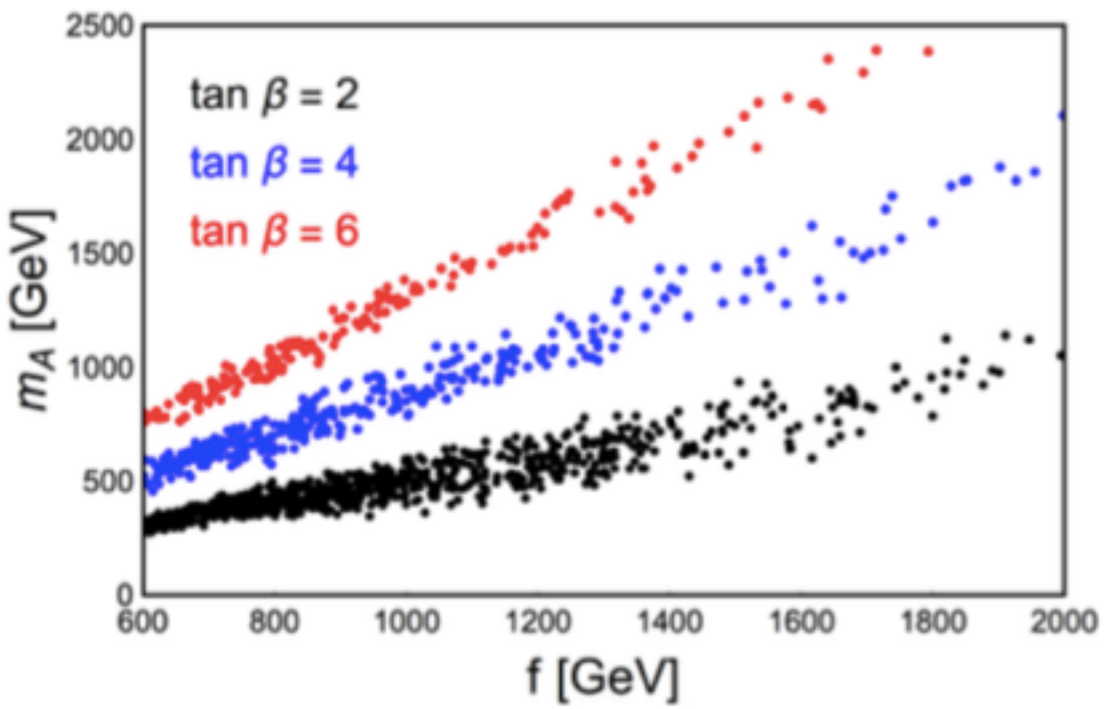
f ⟶ ∞ SM limit

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

Masses of the extra-Higgses



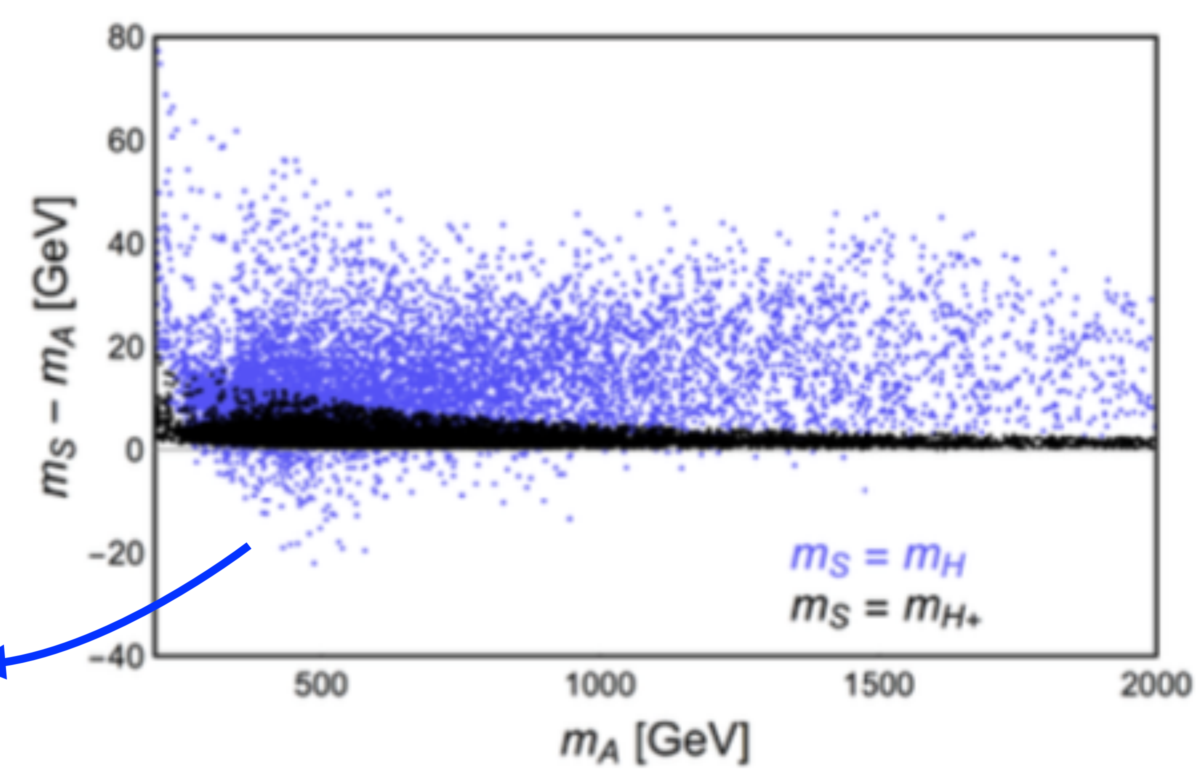
m_A grows linearly with f

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

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 $H \rightarrow A Z^*$ accompanied by the absence of $A \rightarrow W^{\pm *} H^{\mp}$ could be a hint of ℂ2HDM

$A \rightarrow H Z^*$ 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

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

fixed by the strong dynamics and correlated to other observables

The fermion masses are also predicted:

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

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

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$m_{Q,T}$ ~ heavy fermion masses

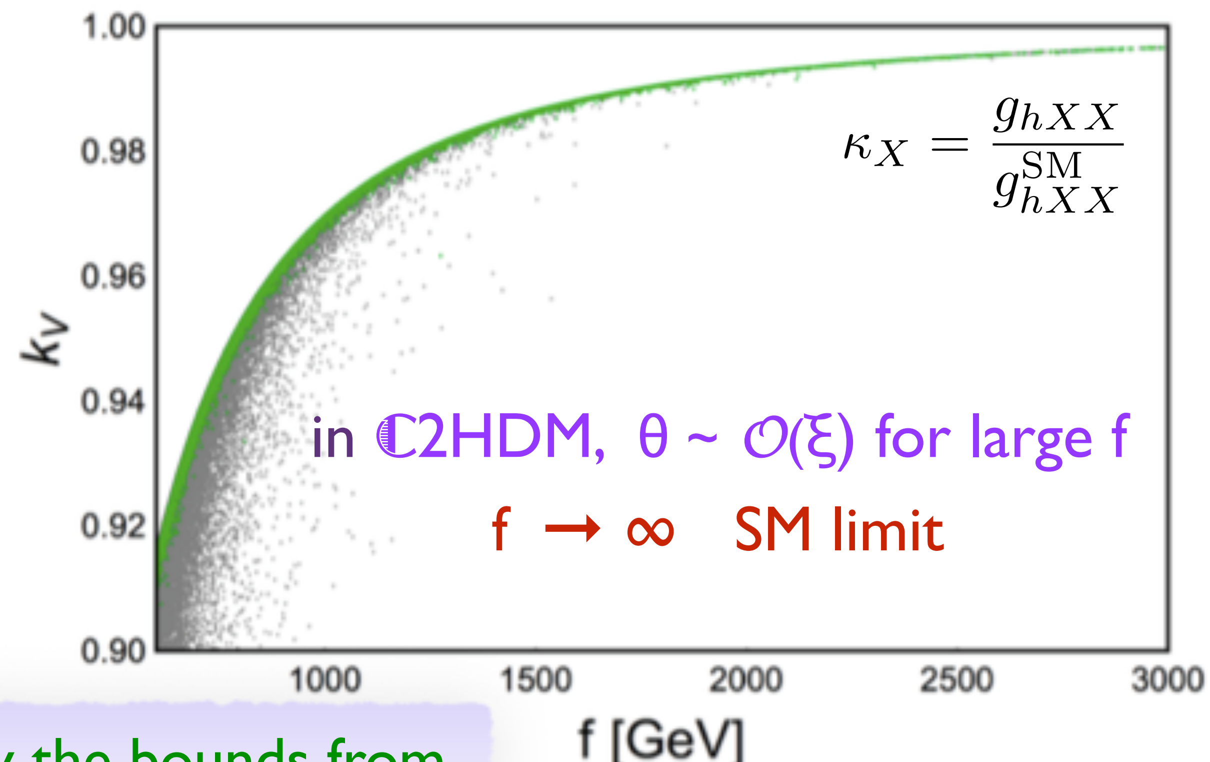
$\tan\beta = v_2/v_1$

- 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

$$k_V \simeq (1-\xi/2) \cos\theta$$

V=W,Z



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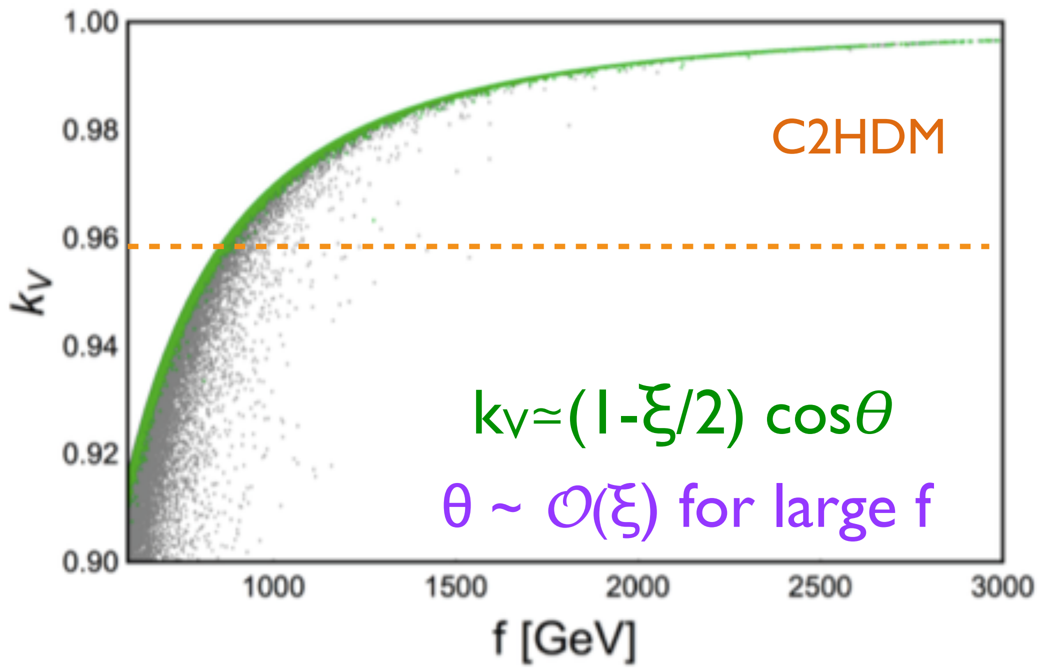
E2HDM or ℂ2HDM ?



If a deviation in k_V is measured (few %)

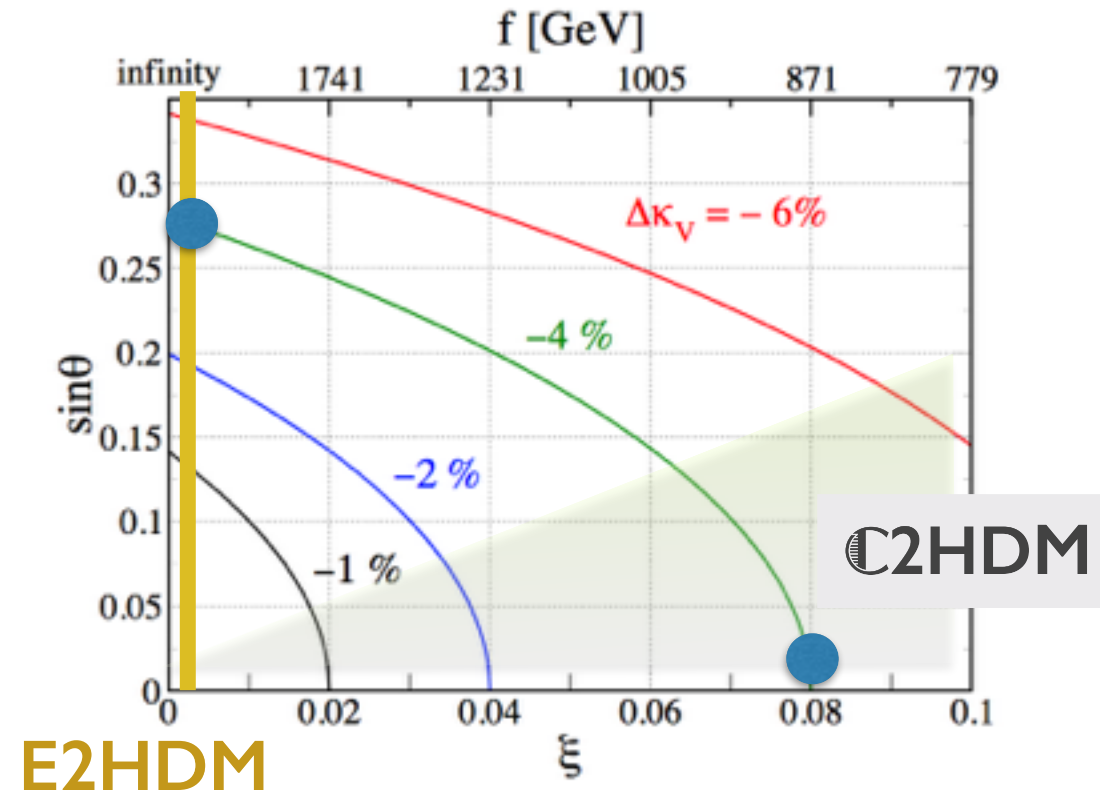
it requires a mixing $\theta \neq 0$ in the E2HDM

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

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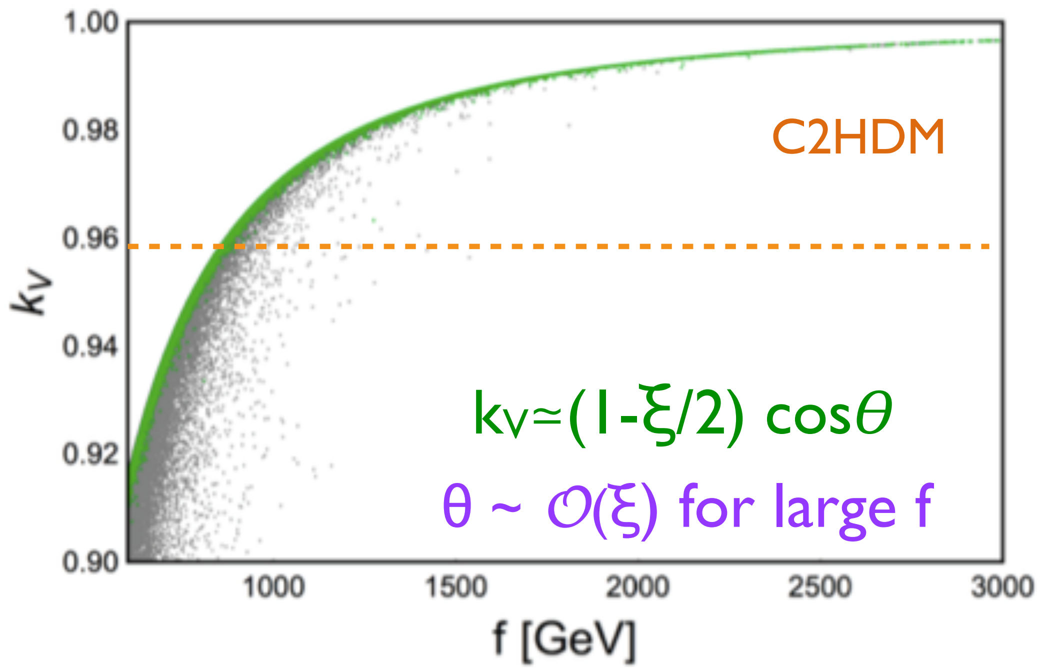

$k_V \simeq (1-\xi/2)\cos\theta$

$\theta \sim \mathcal{O}(\xi)$ for large f

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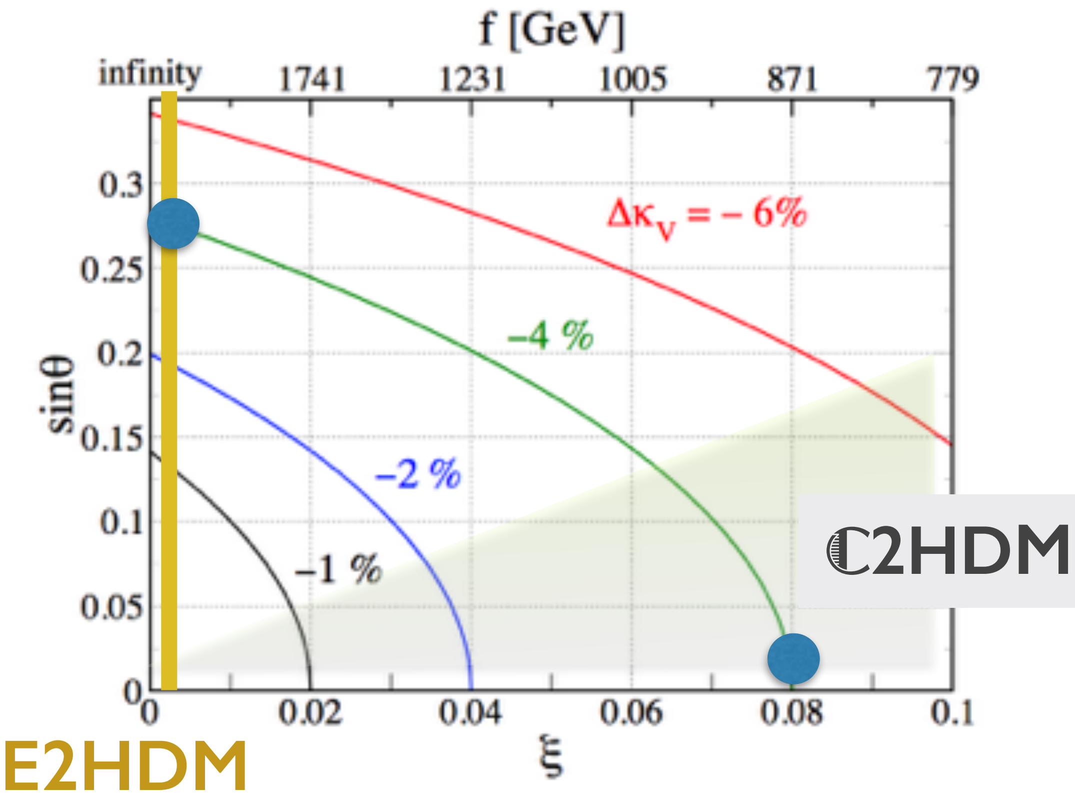
→ $\sin\theta \simeq 0$, f = 870 GeV within the ℂ2HDM

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



Similarly, for the H production:

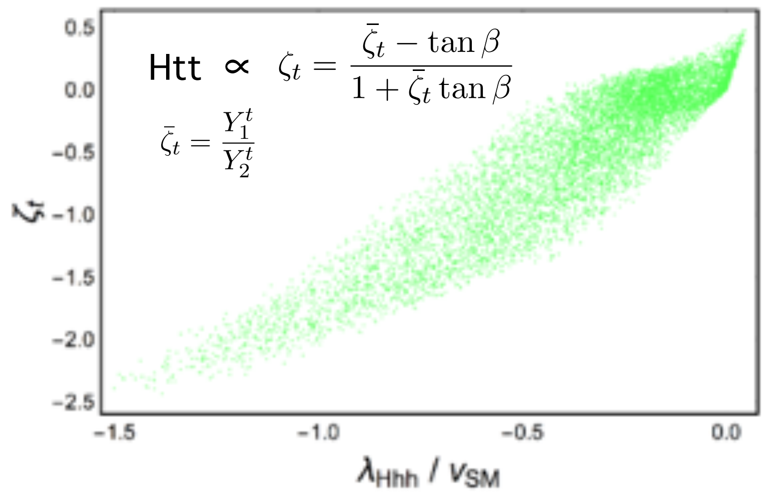
Higgs-strahlung and vector-boson fusion would be very suppressed in the ℂ2DHM, unlike in the E2HDM due to $\sin\theta$ dependence

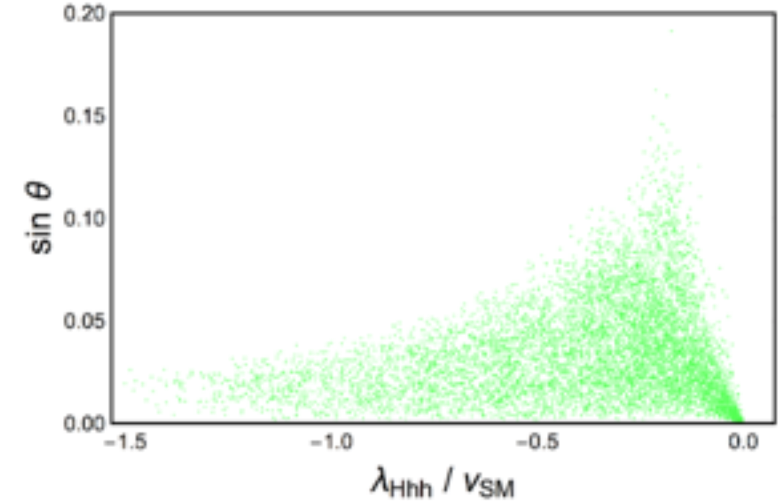
A close scrutiny of the H signatures would be a key to disentangle between the two models

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

LHC phenomenology of the extra pNGB Higgses

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





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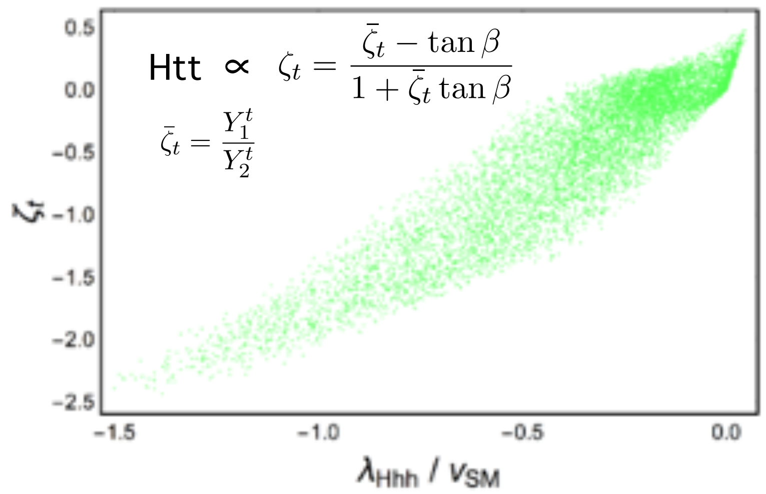
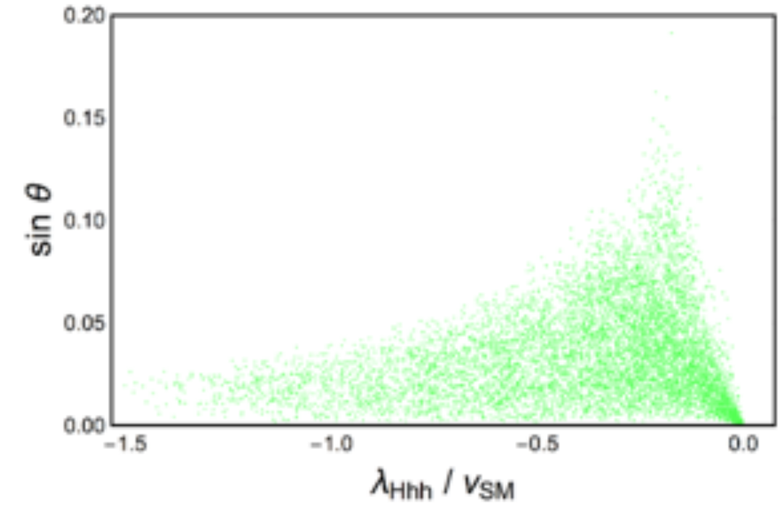
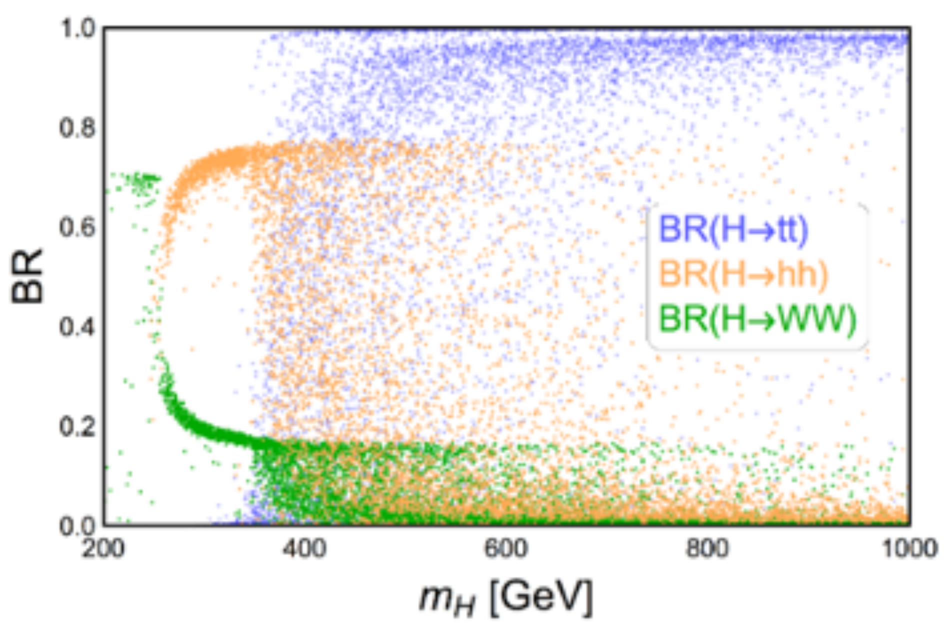




☑ CP-even H



H → tt represents the main decay mode

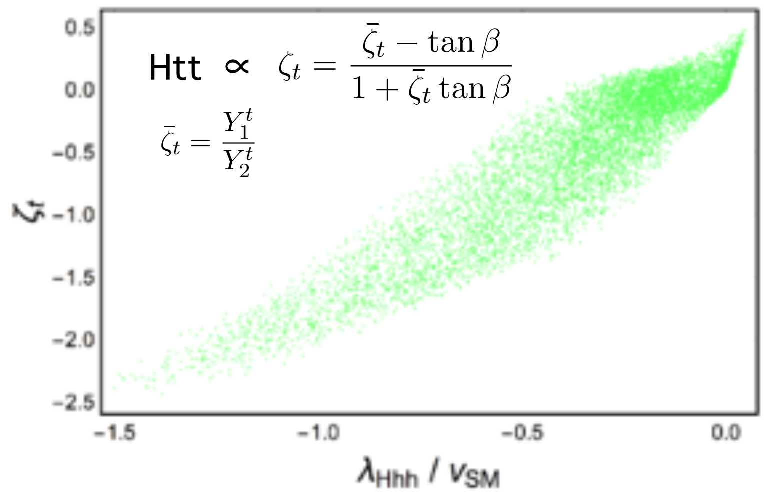
Below the tt threshold, H → hh dominates

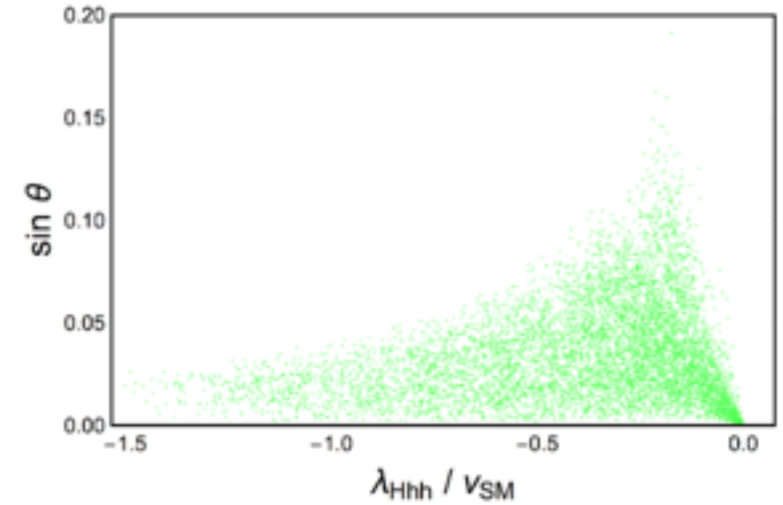
BR(H→hh) ~ 80%, BR(H→VV) ~ 20% (sinθ predicted to be small)

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

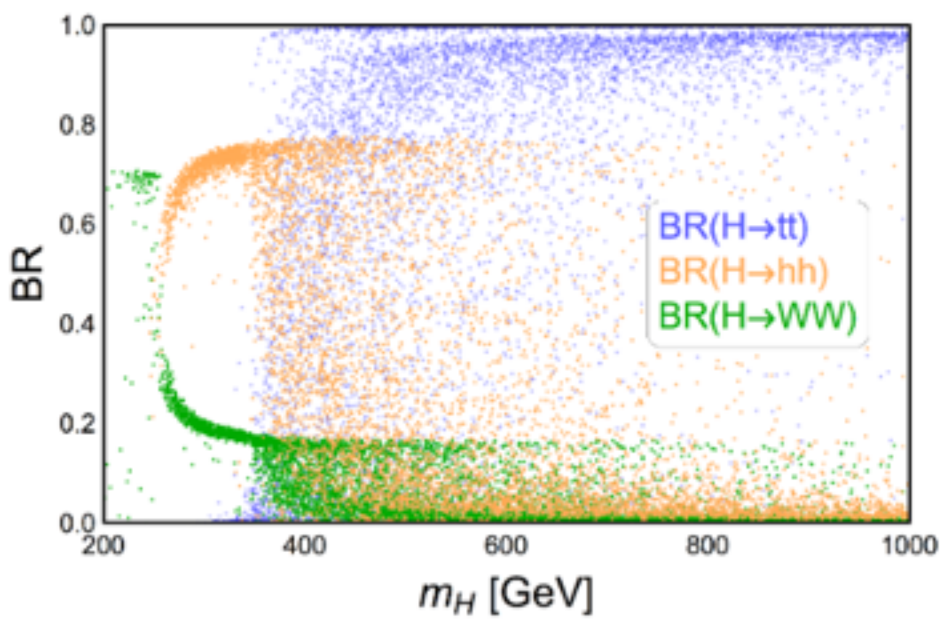
LHC phenomenology of the extra pNGB Higgses

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





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

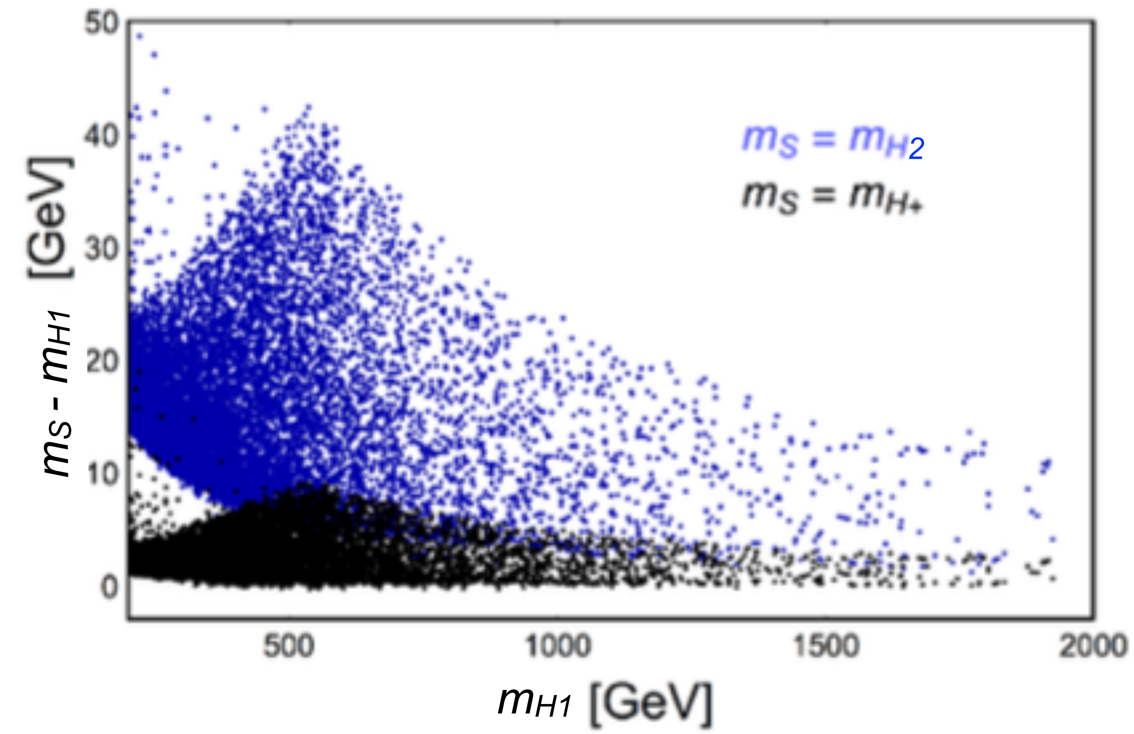
$H^+ \to bt$ is the main decay mode as $m_{H+} > m_t$

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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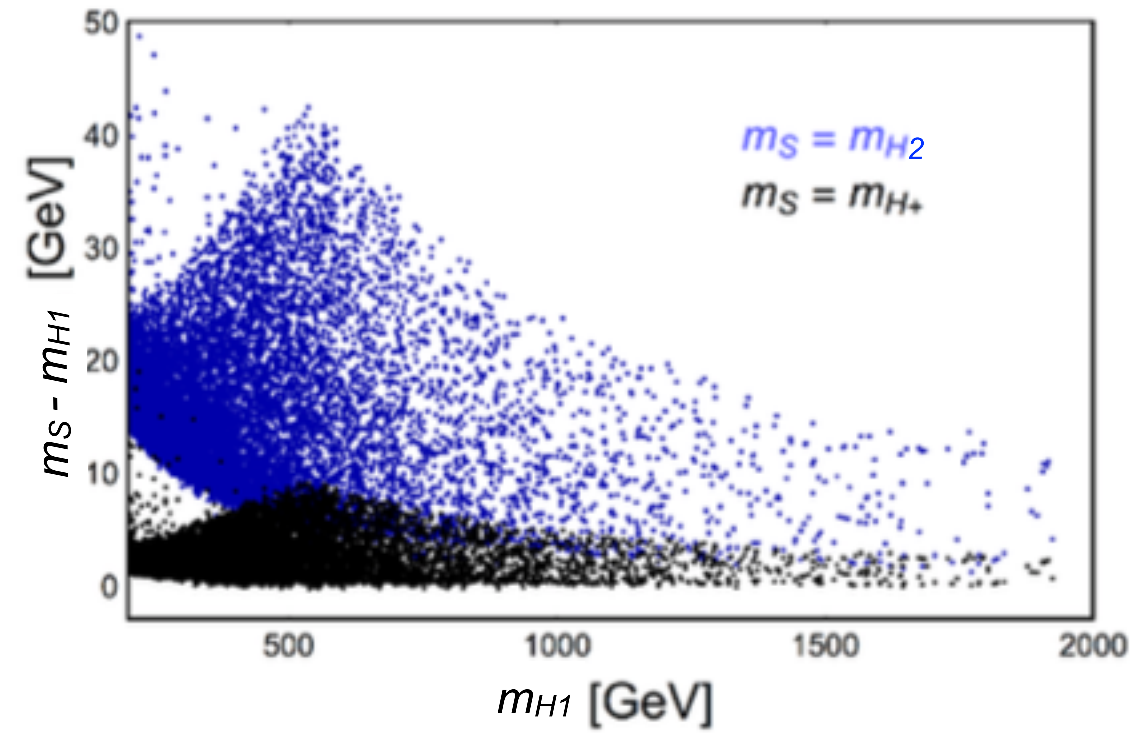
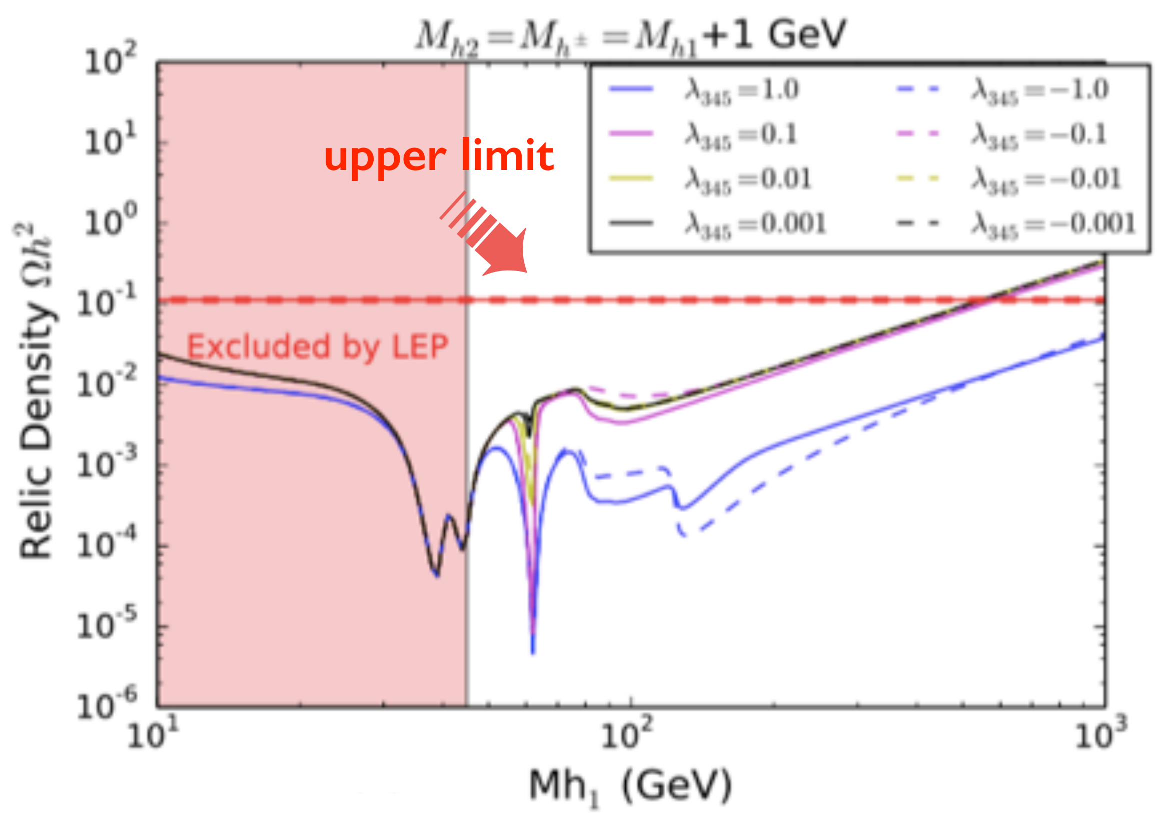


If C_2 is preserved also by lighter quarks and leptons can H_1 be a dark matter candidate ?

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

H_1 can be a dark matter candidate for

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

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

Waiting for BSM signals

Let's continue in exploring new (but also old) ideas to explain what the SM fails to explain

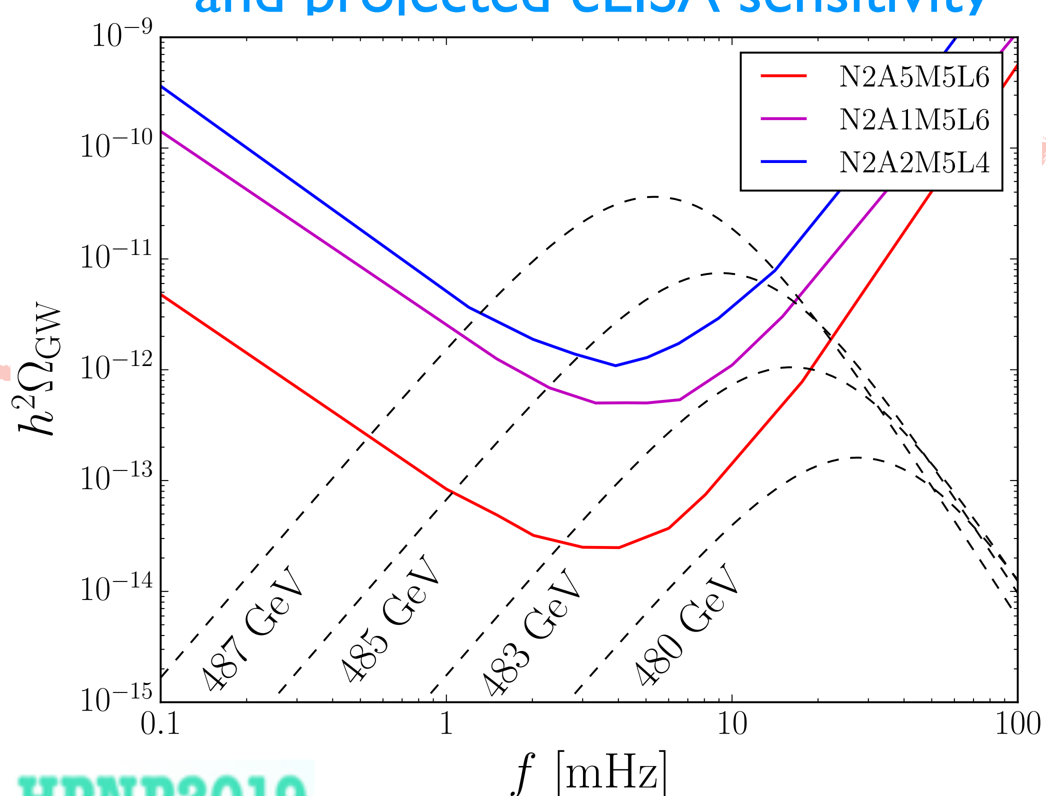
Future developments: EW Baryogenesis

☑ **B violation:** SM sphalerons

☑ **C,CP violation:** CKM phase is not enough, new sources of CPV from complex Yukawas in the strong sector or from non-trivial fermion embeddings

☑ **Out of equilibrium:** (strong) first order phase transition

Gravitational wave spectrum $m_A = m_{H+}$ and projected eLISA sensitivity



EWBG in elementary 2HDM:

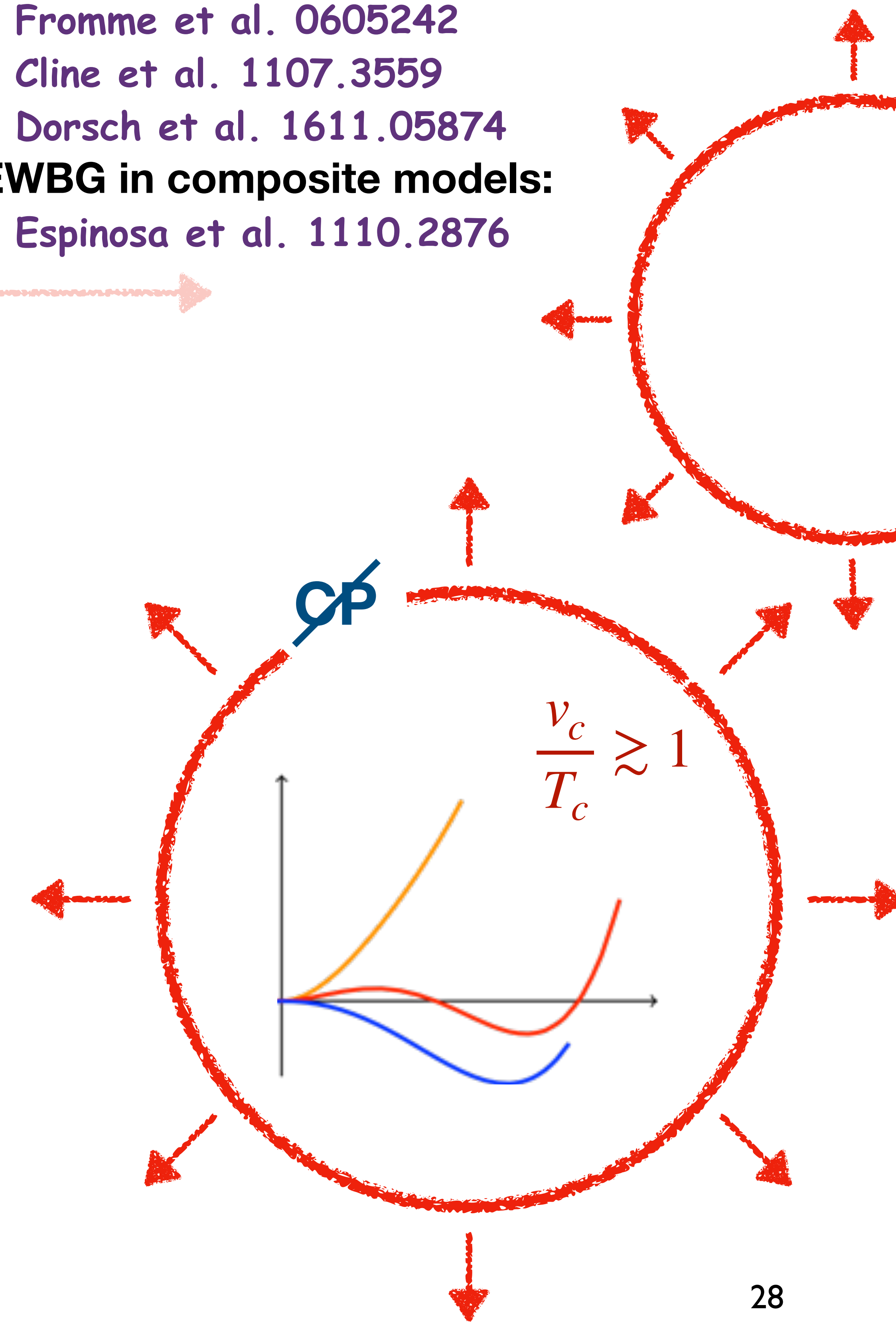
Fromme et al. 0605242

Cline et al. 1107.3559

Dorsch et al. 1611.05874

EWBG in composite models:

Espinosa et al. 1110.2876



BACKUP SLIDES

ℂ2HDM versus MSSM

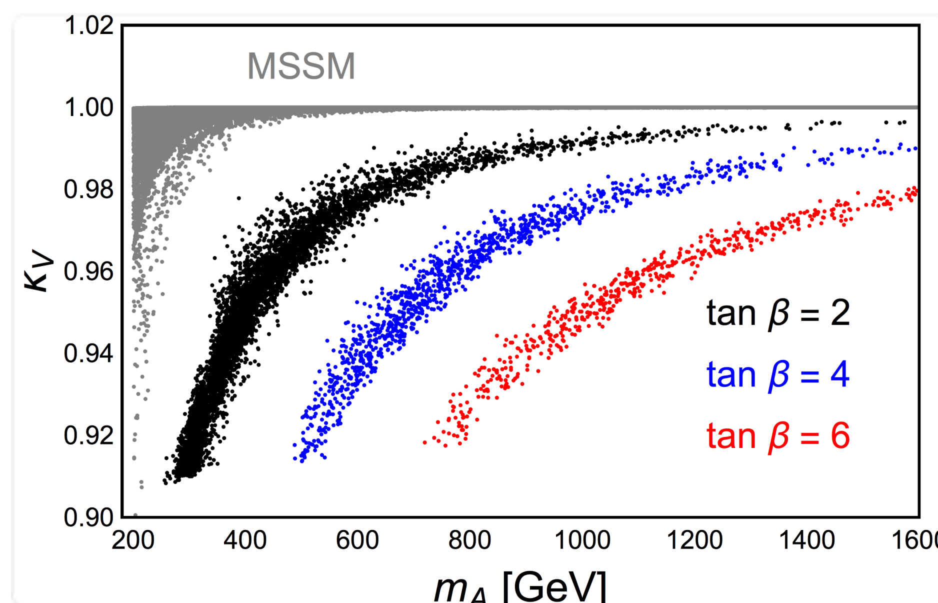
	Supersymmetry	Compositeness
dynamics	*weak*	*strong*
nature of the Higgs	*elementary*	*bound state* $\varphi \sim \langle \bar{\Psi}\Psi \rangle$
quadratic divergences	*fermion/boson interplay*	*no elementary scalars*
lightness of the Higgs	$m_\varphi \sim m_Z$	*pseudo Nambu-Goldstone*
Higgs structure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

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

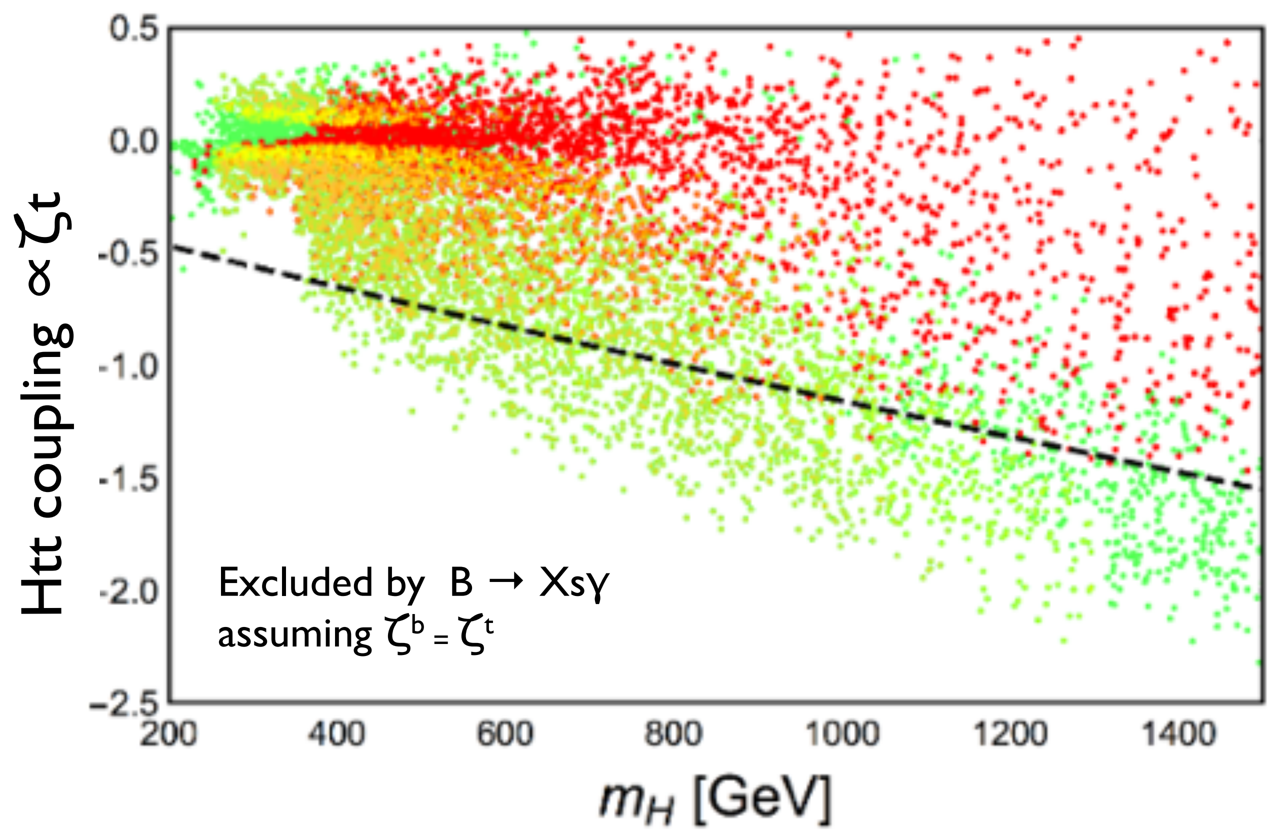
Several observables can be used to discriminate between ℂ2HDM and MSSM:

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

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



H signal/exclusion at the HL-LHC



- satisfy the present bounds from direct and indirect searches
- in addition have κ_{VV} , $\kappa_{\gamma\gamma}$ and κ_{gg} within the 95%CL projected uncertainty at L = 3000 fb^{-1}
- in addition 95% CL excluded by the direct search $gg \to H \to hh \to bb\gamma\gamma$ at L = 3000fb^{-1}

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

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 → $\tau\nu$ mediated by $H^\pm$ (relevant for small masses and/or large $H^+\tau\nu$ couplings, not here)
- ☑ Transition b → s γ: B → Xs γ - relevant parameters are ξ^t_{H+} and ξ^b_{H+}
- ☑ Bs → $\mu^+\mu^-$ - relevant coupling is ξ^t_{H+}

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

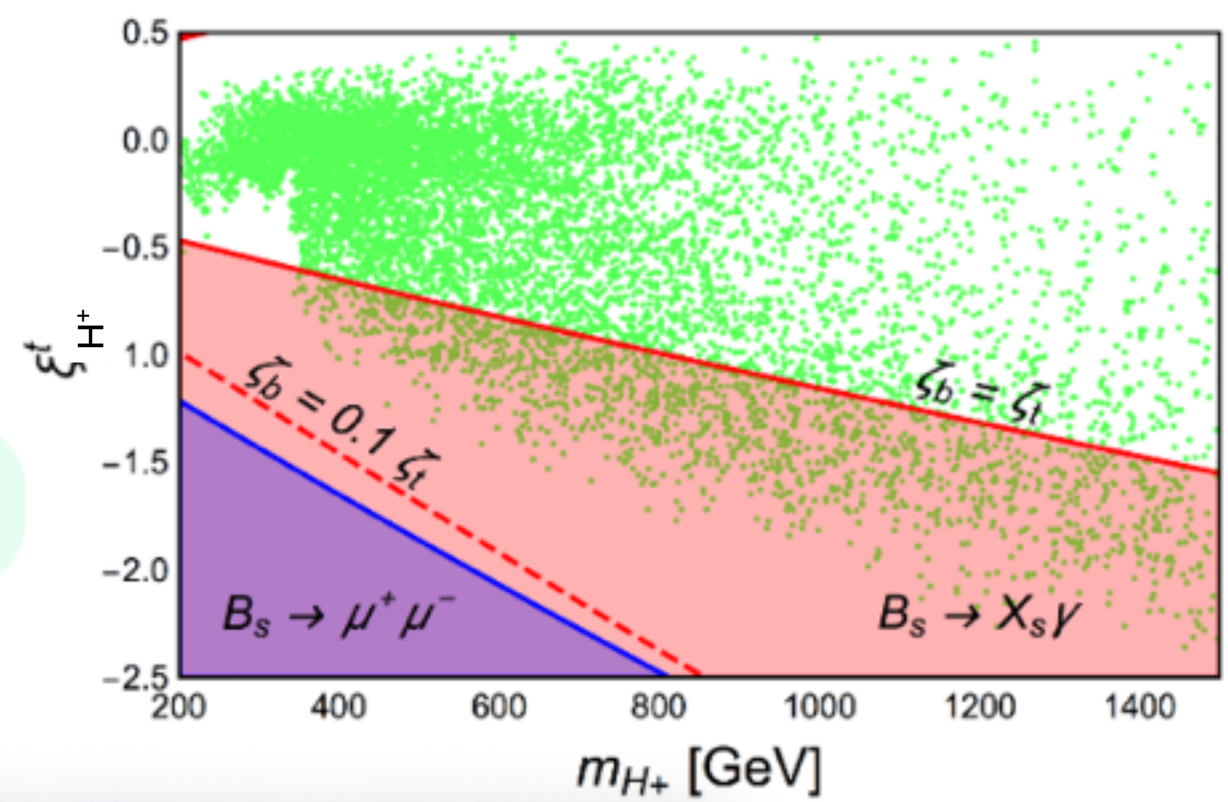
We implement partial compositeness for t,b,τ

$\xi^{d,l}_{H+}$ are not related directly to the Higgs potential (negligible contribution to v and m_h)

→ 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

CP violation in C2HDM

- 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 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

- If also C_2 is broken by the strong sector, the T parameter gets an unacceptable contribution for a generic vacuum structure

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

Conclusion:

In the C2HDM the T parameter can be protected by either (approximate) CP or (approximate or exact) C2 **(Mrazek et al.11)**

Typical mass spectrum of the C2HDM

$$m^2_{H,A,H\pm} \simeq m_3^2 \frac{1+t_\beta^2}{t_\beta} + \mathcal{O}(\lambda v^2)$$

top Yukawa

$$m_3^2 \simeq \left(\frac{Y_1}{Y_2}\right) \frac{N_c y_t^2}{8\pi^2} \frac{1+t_\beta^2}{(1+t_\beta \zeta_t)^2} \frac{m_{l_1}^2 m_{l_2}^2}{m_{l_1}^2 - m_{l_2}^2} \log \frac{m_{l_1}^2}{m_{l_2}^2}$$

$-Y_1/Y_2$

Y_1= C_2 breaking term

m_{l_1}, m_{l_2}= lightest top partner masses

$$m_h^2 \simeq \frac{g^{*2}}{16\pi^2} y_t^2 v^2$$

$g^* = m_f / f$