# The Composite Two Higgs Doublet Model

Andrea Wulzer ETHZ



# Introduction

The main question for the **LHC:** What is the **Nature** of **EWSB ?**

The answers from **LEP:**

- If strong-sector,  $\overline{S}$  m  $\bigcup$ ust be **tuned**
- Higgs model is **fine** for a **light** Higgs
- Not light enough though, **SUSY** in trouble (need for more complicated/tuned versions)











# The PNGB Higgs



### Elementary-Composite Couplings: *y<sup>R</sup>* are the Left- and Right-handed fermion linear couplings, which we will denote as "proto-Yukawa"  $\sim$  Schematically, the elementary fields to the elementary fields to the strong sector can be written as  $\sim$

$$
g_{SM} \cdot \Psi_{SM} \cdot \mathcal{O} = \left\{ \begin{array}{c} g A_{\mu} J^{\mu} \\ y_{L,R} f_{L,R} \mathcal{O}_{L,R} \end{array} \right\}
$$

we adopt **partiar compositeness** for fermions of  $\vert$ We adopt **partial compositeness** for fermions

 $\frac{1}{\sqrt{2}}$  , the Higgs therefore becomes a Pseudo-NGB (PNGB) and is free to acquire a potential, as we will also acquire a potential, as we will also acquire a potential, as we will also acquire a potential, as we will





#### electroweak observables. On the other hand, a more plane, a model is the more plane plane is. Because is the more plane is the more of that, EWPT still constrain significantly the structure of composite Higgs models. The first obvious constraint is given by the *S*-parameter *<sup>S</sup>*! <sup>∼</sup> *<sup>m</sup>*<sup>2</sup> EW Precision Observables ∼ *g*2 showing that the larger  $\bigcap_{\alpha=1}^{\infty}$  on  $\bigcap_{\alpha=1}^{\infty}$  because reason for  $\bigcap_{\alpha=1}^{\infty}$ interested in strongly coupled models. In strongly coupled models. In strongly coupled models. In the coupled <br>In the coupled models. In the coupled models. In the coupled models. In the coupled models. In the coupled mod bedding, *y<sup>L</sup>* is an isospin singlet while *y<sup>R</sup>* is a spurion of custodial isospin 1*/*2. Since *T*! corresponds to

product to reproduce *Yt*. A less constrained, and thus less tuned scenario, can arise in the case where

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interested in strongly coupled models.

 $\mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L} \mathcal{L}$ 

constraint is given by the *S*-parameter

interested in strongly coupled models.

Tree-Level contribution to  $S\colon$ Tree-Level contribution to  $\widehat{S}$ : Tree-Level contribution to  $S$ :  $\hskip1cm \Box$  $T_{\text{reco}}$  and contribution to  $\hat{S}$ .  $t$  evel contribution to  $S$ :  $\hbox{h}$ 

*v*2

 $\bigcup_{\nu} \mathcal{L}_{\nu}$  are continuous in Fig. . Notice that for  $y_R \sim g_\rho$ 

∼ *y*2

bedding, *y<sup>L</sup>* is an isospin singlet while *y<sup>R</sup>* is a spurion of custodial isospin 1*/*2. Since *T*! corresponds to

*gb*

*y<sup>L</sup>* and *y<sup>R</sup>* must be larger than *Yt*, giving potentially large effects. These can however be controlled by

just focus on the SO( $y_R \sim g_\rho$ 

the additional constraining power of *G/H*. For the choice *O<sup>L</sup>* = (2*,* 1)1*/*6, *O<sup>R</sup>* = (1*,* 2)1*/*<sup>6</sup> the expected

*v*2

*<sup>f</sup>* <sup>2</sup> *.* (24)

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These effects are computed by power computed by power computed by power countries that for our choice of em-

a violation of 2 units of isospin charge, selection rules dictate the four powers of *y<sup>R</sup>* in eq. (26). Now,

<sup>ρ</sup> *,* (25)

<sup>10</sup>. This might in general give rise to flavor problems which can be



 $Y_t \simeq y_L y_R / g_\rho$   $\left\{ \begin{array}{l} 0 \\ y_R \sim g_\rho \end{array} \right\}$ 

the experimental bounds, together with eq. (21) imply ξ *<* 0*.*05. This tight bound arises because δ*gb/g<sup>b</sup>*

invariant under O(4)  $\alpha$  *PLR* and not just SO(4), the contribution to  $\alpha$  in eq. (27) vanishes. (27) vanishes are contributed to  $\alpha$  in eq. (27) vanishes. (27) vanishes. (27) vanishes. (27) vanishes. (27) vanishes. (

# EW Precision Observables

**Avoided** by 
$$
P_{LR}
$$
 symmetry:  $\begin{array}{c} L \leftrightarrow R \\ b_L \rightarrow b_L \end{array}$ 

$$
\overline{b}_L i \not{\!\! D} b_L + \overline{b}_L [\delta_L \not{\!\! L} + \delta_R \not{\!\! R} + \delta_X \not{\!\! X}] b_L
$$

 $P_{LR}$  plus unbroken sym.  $\qquad \delta_L = \delta_R = \delta_X = 0$ 

Do we really need **another** symmetry ?

### **EW Precision Observables However on eigenstate of** *Precision* Observables

Now, the only correction to the current can come from the *J<sup>A</sup>* contribution, since *J<sup>V</sup>* and *J<sup>X</sup>* are conserved.

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where *E<sup>µ</sup>* and *D<sup>µ</sup>* are the *H* connection and *G/H* Goldstone field respectively []. *O*1*,*2*,*<sup>3</sup> are manifestly *PLR*

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**NO**,  $P_{LR}$  is accidental **!** is unaffected. Now in the fermion multiplet (2*,* 2)2*/*<sup>3</sup> the only eigenstate of *PLR* has electric charge −1*/*3,  $Use the SO(4)/SO(3) symmetry:$ fermion  $(y_L)$ ,  $q_L \mathcal{O}_L^A \equiv Q_A \mathcal{O}_L^A$ *Ai* (*i* = 1*,* 2*,* 3) transforming like a 3 of *SO*(3) and η = *QAU*<sup>∗</sup> *<sup>A</sup>*<sup>4</sup> transforming like a singlet. Then  $\psi_i = Q_A U_{Ai}^* \qquad \qquad \eta = Q_A U_{A4}^*$  $\mathcal{O}_1$  =  $\bar{\psi}\bar{\sigma}^{\mu}(\partial_{\mu}+\mathcal{E}_{\mu})\psi$   $\mathcal{O}_2 = \bar{\eta}\bar{\sigma}^{\mu}\partial_{\mu}\eta$  $\mathcal{O}_3$  =  $\bar{\psi}_i \bar{\sigma}^\mu \eta \mathcal{D}_{i\mu}$   $\mathcal{O}_4 = \bar{\psi}_i \bar{\sigma}^\mu \psi_j \mathcal{D}_{k\,\mu} \epsilon_{ijk}$ Can this term emerge with the full symmetry? invariant, and give no correction to *g<sup>b</sup>* upon weak gauging of the SM group. On the other hand *O*<sup>4</sup> breaks  $NO, P_{LR}$  is accidental ! and plays the  $SO(4)/SO(2)$  cymmetry:  $\mathcal{L}$  and  $\mathcal{L}$  construction  $\mathcal{L}$  $\delta_{\mathcal{A}}$  transformation  $\mathcal{A}$ <sup> $\mathcal{A}$ </sup> it is straightforward to write all the possible interactions at lowest derivative order  $\mathcal{L}$ *O<sub>2</sub>* = μ<sub>*iii*</sub> = *μ*<sub>j</sub><sup>2</sup> = *μ<sub>i</sub>*<sup>*y*</sup> = *μ*<sub>j</sub><sup>*D*</sup><sub>*iii*</sub> = *d*<sub>*i*</sub> = *<sup>A</sup>* does not contribute to the vector boson vertex, and in particular the coupling to the *Z*  $\begin{array}{cccc} \begin{array}{cccc} \hline \end{array} & \begin{array}{cccc} \hline \end{array} & \mathcal{A} & \mathcal{A} & \mathcal{A} & \mathcal{A} \end{array}$ for  $\mathcal{A}$  transformation  $\mathcal{A}$ , and using the dressed fermions of  $\mathcal{A}$  $A_4$  transformation  $A_4$ it is straightforward to write all the possible interactions at lowest derivative orders at lowest derivative<br>Interactions at lowest derivative orders at lowest derivative orders at lowest derivative orders at lowest der *<sup>O</sup>*<sup>3</sup> <sup>=</sup> <sup>ψ</sup>¯*i*σ¯*µ*η*Diµ <sup>O</sup>*<sup>4</sup> <sup>=</sup> <sup>ψ</sup>¯*i*σ¯*µ*ψ*jD<sup>k</sup> <sup>µ</sup>*%*ijk* (30) is unaffected. Now in the fermion multiplet (2*,* 2)2*/*<sup>3</sup> the only eigenstate of *PLR* has electric charge −1*/*3,  $Use the SO(4)/SO(3) symmetry:$  $(y_L)_A q_L O_L^A \equiv Q_A O_L^A$ *Ai* (*i* = 1*,* 2*,* 3) transforming like a 3 of *SO*(3) and η = *QAU*<sup>∗</sup> *<sup>A</sup>*<sup>4</sup> transforming like a singlet. Then invariant, and give no correction to *g<sup>b</sup>* upon weak gauging of the SM group. On the other hand *O*<sup>4</sup> breaks Can this term emerge with the full symmetry ?

where *E<sup>µ</sup>* and *D<sup>µ</sup>* are the *H* connection and *G/H* Goldstone field respectively []. *O*1*,*2*,*<sup>3</sup> are manifestly *PLR*

#### EW Precision Observables *PLR* and does indeed renormalize *g<sup>b</sup>* 11. Now, when is remarkable, and was independent in fact that when the Higgs scalar is itself and was independent<br>The Higgs scalar is its independent in the Higgs scalar is itself and was independent in the Higgs scalar is i EXTREMENT CONSERVABLES Goldstone residing into a bigger coset such as *SO*(5)*/SO*(4) or *SO*(6)*/SO*(4) × *SO*(2) the *PLR* arises as down sector, assuming that the right chiralities couple to a (1*,* 1)−1*/*3, we need to couple the quark doublet

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at the two derivative level we cannot write the analogue of *O*<sup>4</sup> since the Levi-Civita tensor of *SO*(4) has

In view of the latter result, in all the cases considered in previous literature *SO*(5)*/SO*(4) or *SO*(6)*/SO*(5)

11.

*<sup>A</sup>*5. Now we can still write the same *PLR* invariant contractions corresponding to *O*1*,*2*,*3. However,

four indices! One can easily extend this analysis to *SO*(6)*/SO*(4) × *SO*(2) with *O<sup>L</sup>* either in the 6 or 20!

invariant, and give no correction to *g<sup>b</sup>* upon weak gauging of the SM group. On the other hand *O*<sup>4</sup> breaks

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and in all the models studied in the present paper, experimental constraints allow a sizeable *y<sup>L</sup> > Yt*. In-

The situation might be better however. It was pointed out in ref.  $\mathcal{L}_{10}$  that when the strong sector is  $\mathcal{L}_{10}$ 

invariant under O(4)= SO(4) × *PLR* and not just SO(4), the contribution to δ*gb/g<sup>b</sup>* in eq. (27) vanishes.

an accidental symmetry of the lowest derivative interactions. This is very similar to the case of *C*2, an

again the main point is the impossibility of writing invariants that involve the Levi-Civita tensor.

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δ*g<sup>b</sup>*

*gb*

**NO**,  $P_{LR}$  is accidental !  $\mathsf{With} \ \mathcal{O}_L = \mathbf{5}_{2/3}\mathbf{:}$ Goldstone residing into a bigger coset such as *SO*(5)*/SO*(4) or *SO*(6)*/SO*(4) × *SO*(2) the *PLR* arises as **NO**,  $P_{LR}$  is accidental ! Use now the full  $SO(5)/SO(4)$  $\psi_i = Q_A U_{Ai}^* \qquad \quad \eta = Q_A U_{A5}^*$  $\frac{1}{2}$  a  $\frac{1}{2}$  and  $\frac{1}{2}$  in  $\text{With } \mathcal{O}_L = \mathbf{5}_{2/3}\colon$ idental symmetry of the  $|$  $J(5)/SO(4)$  and  $J(5)/SO(4)$  $\mathbf{5}_{2/3}$ :  $A5$  invariant contractions corresponding to  $A5$ avoided with appropriate UV assumptions, see [9] . Now *y<sup>R</sup>* is an *SO*(4) singlet under the custodial group and drops out of eq. (26). However *y<sup>L</sup>* transforms as (1*,* 2) under *SO*(4) and therefore one generically  $\mathsf{w}$ and in all the models  $\mathcal{O}_L = 5_{2/3}$ : *<sup>Q</sup>*¯σ¯*µ*∂*<sup>µ</sup><sup>Q</sup>* invariant under the *linearly realized <sup>O</sup>*(4) and corresponding to <sup>a</sup> linear combination of *<sup>O</sup>*1*,*2*,*3.

at the two derivative level we cannot write the analogue of *O*<sup>4</sup> since the Levi-Civita tensor of *SO*(4) has annot use the  $\epsilon$  tensor ! at tensor ! This result is more encouraging: for *y<sup>L</sup>* ∼ *Y<sup>t</sup>* and *y<sup>R</sup>* ∼ *g*<sup>ρ</sup> corresponding to a composite *tR*, the bound

η = *QAU*<sup>∗</sup>

Thus in these models a Higgs boson as heavy as 300 GeV could be envisaged.

*PLR* and does indeed renormalize *g<sup>b</sup>*

**four indication** of  $\delta q_b/q_b$  allows larger  $y_L \sim \sqrt{Y_t g_\rho}$ . **Reduction** of  $\delta g_b/g_b$  allows larger  $y_L \sim \sqrt{Y_t g_\rho}$ . four indices! One can easily extend this analysis to *SO*(6)*/SO*(4) × *SO*(2) with *O<sup>L</sup>* either in the 6 or 20!

again the main point is the impossibility of writing invariants that involve the Levi-Civita tensor.



#### Two Composite Higgses (*k* = 1*,* 2*,* 3) transforming as Φ → *L*Φ*R†* under *SO*(4) ∼ SU(2)*<sup>L</sup>* × SU(2)*R*. We will use the same symbol Φ for both parametrizations, as it will be clear from the context which one we use7. **The Figure of Two Composite Higgses** and **A**  $\mathbf{P}_{\text{max}}$  for both parametrizations, as it will be context which one we use  $\mathbf{P}_{\text{max}}$ *H*<sup>1</sup><sup>b</sup> = te l l i <sup>3</sup>)<sup>2</sup> = 174 GeV. IT IT IS EXAMPLE THE ONLY THE O , up to SU(2)*L*×U(1)*<sup>Y</sup>* rotations, the generic charge preserv-<sup>3</sup>*, v*<sup>2</sup>! <sup>4</sup>). In Higgs doublet notation this corresponds

preserving expectation value is Φ<sup>1</sup><sup>b</sup> = (0*,* 0*,* 0*, v*<sup>1</sup><sup>b</sup>

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*H*<sup>1</sup><sup>b</sup> =

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which in general arises from the non-linearities of an operators of an operators of an operators a contributio<br>Arises a contribution of an acontribution of an acontribution of an acontribution of an acontribution of an ac

proportional to the square of the order parameter *v*<sup>1</sup><sup>b</sup>

) %= 0. For *c<sup>T</sup>* ∼ *O*(1), generically generated by σ−model

4*v*<sup>2</sup>!

$$
\begin{aligned}\n\mathbf{S} & \mathbf{y}^{2} = (0, 0, 0, v_{4}^{1}) & H^{1} = \begin{pmatrix} 0 \\ v_{4}^{1} \end{pmatrix} \\
\mathbf{S} & \mathbf{y}^{2} = (0, 0, v_{3}^{2}, v_{4}^{2}) & H^{2} = \begin{pmatrix} 0 \\ v_{4}^{2} - iv_{3}^{2} \end{pmatrix} \\
\frac{c_{T}}{f^{2}} \left( \Phi^{1} \cdot \overleftrightarrow{D}_{\mu} \Phi^{2} \right)^{2} & \mathbf{y}^{2} = 2c_{T} \frac{(v_{4}^{1})^{2} (v_{3}^{2})^{2}}{f^{2} [(v_{4}^{1})^{2} + (v_{4}^{2})^{2} + (v_{3}^{2})^{2}]} \sim \frac{c_{T}}{2} \frac{v^{2}}{f^{2}} \\
\mathbf{S} & \mathbf{S} & \mathbf{S} & \mathbf{S} & \mathbf{S} & \mathbf{S} & \mathbf{S}\n\end{aligned}
$$
\n
$$
\begin{aligned}\n\mathbf{S} & \mathbf{S} & \math
$$

which in general arises from the non-linearities of an operators of an operators of an  $\alpha$  contribution of an  $\alpha$ 

interactions, this is phenomenologically unacceptable.

2

(*v*<sup>2</sup><sup>b</sup> 3)

<sup>3</sup> of SO(4) → SO(2)*<sup>c</sup>* breaking. Notice that a

2

Two discrete symmetries control the order parameter *v*<sup>1</sup><sup>b</sup>

4*v*<sup>2</sup><sup>b</sup>

<sup>∼</sup> *<sup>c</sup><sup>T</sup>*

]*,* (3)

 $\Phi$  for both parametrizations, as it will be context which one we use  $\Phi$  from the context which one we use

! 0

<sup>4</sup>), Φ<sup>2</sup><sup>b</sup> = (0*,* 0*, v*<sup>2</sup><sup>b</sup>

*H*<sup>2</sup><sup>b</sup> =

*v*2

3 of So(4) of So(4) → *SO(4)*c breaking. Notice that a society of So(4) → SO(

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<sup>2</sup>[Φ<sup>1</sup>b*†*

, up to *SU*(2)*<sup>L</sup>* × *U*(1)*<sup>Y</sup>* rotations, the generic charge

<sup>4</sup>). In matrix notation this corresponds

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) %= 0. For *c<sup>T</sup>* ∼ *O*(1), generically generated by σ−model

*<sup>f</sup>* <sup>2</sup> (4)

<sup>3</sup> and provide a useful organizing principle to

(*v*<sup>1</sup><sup>b</sup> 4)

#

contribution to *<sup>T</sup>*\$ is associated to Im (*H*<sup>1</sup>b*†*

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to,

! 0

*H*<sup>2</sup><sup>b</sup> =

as it will be clear from the context which one we use <sup>6</sup>.

proportional to the square of the order parameter *v*<sup>1</sup>!

In a model with two Higgs fields Φ<sup>1</sup>! and Φ<sup>2</sup>!

ing expectation value is Φ<sup>1</sup>! = (0*,* 0*,* 0*, v*<sup>1</sup>!

where, up to effects (*v/f*)2, we have *v* =

It is easy to check that the operator

<sup>4</sup>)<sup>2</sup> + (*v*<sup>2</sup><sup>b</sup>

! 0

<sup>4</sup>), Φ<sup>2</sup>! = (0*,* 0*, v*<sup>2</sup>!

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(*v*<sup>1</sup>! 4)

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### **Example 19 Two Composite Higgses**  $3$  and provide a useful organizing principle to  $\mathcal{A}$ contribution to *<sup>T</sup>*\$ is associated to Im (*H*<sup>1</sup>b*†* ) %= 0. For *cT* ∞ For *cT* ∞ *O*(1), generated by σ−model generated

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describe vacuum dynamics

Two discrete symmetries control the order parameter *v*<sup>1</sup><sup>b</sup>

) %= 0. For *cT* ∞ *CT*  $\sim$  *O*(1), generated by  $\sim$  0. For  $\sim$  0. For  $\sim$  0. For  $\sim$  0. For  $\sim$ 

(φ1*,* φ2*,* φ3*,* φ4) → (−φ1*,* φ2*,* −φ3*,* φ4) *,* (5)

*H*<sup>2</sup><sup>b</sup>

sector in all models under consideration. It acts like charge conjugation on the *SU*(2)*<sup>L</sup>* × *U*(1)*<sup>Y</sup>*

gauge bosons, and is thus broken when the SM fermions are taken into account. When fermions are

included, *C*<sup>1</sup> may become an approximate symmetry only when combined with parity *P*, and that

or simply *H* → *H*<sup>∗</sup> in doublet notation. *C*1, being a subgroup of *SO*(4), is respected by the strong

sector in all models under consideration. It acts like charge conjugation on the *SU*(2)*<sup>L</sup>* × *U*(1)*<sup>Y</sup>*

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is just *CP*. In particular in this scenario *CP* would have to be respected by the strong dynamics

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Throughout the paper *C*1*P* is defined to act as standatd *CP* on the SM states. In particular it acts

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describe vacuum dynamics vacuum dynamics vacuum dynamics vacuum dynamics vacuum dynamics vacuum dynamics vacuum<br>District vacuum dynamics vacuum dynamics vacuum dynamics vacuum dynamics vacuum dynamics vacuum dynamics vacuu

describe vacuum dynamics

interactions, this is phenomenologically unacceptable.

#### **Three ways** to control  $T$ : **Firm of** *Three* ways to control *T*: Two discrete symmetries control the order parameter *v*<sup>1</sup><sup>b</sup>  $\sim$  $\mathbf{S}$  and provide a useful organizing principle to  $\mathbf{S}$

 $(\phi_1, \phi_2, \phi_3, \phi_4) \rightarrow (-\phi_1, \phi_2, -\phi_3, \phi_4)$  $($ or,  $H \rightarrow H^*$ ) (φ1*,* φ2*,* φ3*,* φ4) → (−φ1*,* φ2*,* −φ3*,* φ4) *,* (5)  $C_1 \in SO(4)$  :  $\stackrel{(71, 72, 75, 74)}{=}$ 

like without extra phases on the SM Weyl fermions. We without extra phases on the SM Weyl fermions. We will fe<br>In the SM Weyl fermions. We will feel for the SM Weyl fermions. We will feel for the SM Weyl fermions. We will

sector in all models under consideration. It acts like charge conjugation on the *SU*(2)*<sup>L</sup>* × *U*(1)*<sup>Y</sup>*

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like without extra phases on the SM Weyl fermions.<br>The SM Weyl fermions on the SM Weyl fermions. The SM Weyl fermions. The SM Weyl fermions. The SM Weyl fermions

#### **Example 19 Two Composite Higgses**  $3$  and provide a useful organizing principle to  $\mathcal{A}$ contribution to *<sup>T</sup>*\$ is associated to Im (*H*<sup>1</sup>b*†* ) %= 0. For *cT* ∞ For *cT* ∞ *O*(1), generated by σ−model generated **•** *COI***IIDOSITE ENTIRES** and *COIIIDOSITE ENTIRES* and  $\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$ *• C*<sup>1</sup> is the *Z*<sup>2</sup> subgroup of *SO*(4) acting on quadruplets as

contribution to *<sup>T</sup>*\$ is associated to Im (*H*<sup>1</sup>b*†*

describe vacuum dynamics

Two discrete symmetries control the order parameter *v*<sup>1</sup><sup>b</sup>

) %= 0. For *cT* ∞ *CT*  $\sim$  *O*(1), generated by  $\sim$  0. For  $\sim$  0. For  $\sim$  0. For  $\sim$  0. For  $\sim$ 

*H*<sup>2</sup><sup>b</sup>

included, *C*<sup>1</sup> may become an approximate symmetry only when combined with parity *P*, and that

associated with the only broken by small effects such and only broken by small effects such as the light family

associated with the only broken by small effects such and only broken by small effects such as the light family

Throughout the paper *C*1*P* is defined to act as standatd *CP* on the SM states. In particular it acts

gauge bosons, and is thus broken when the SM fermions are taken into account. When fermions are

included, *C*<sup>1</sup> may become an approximate symmetry only when combined with parity *P*, and that

associated with the only broken by small effects such and only broken by small effects such as the light family Yukawas.<br>The contract family Yukawas as the light family Yukawas. The light family Yukawas as the light family

Throughout the paper *C*1*P* is defined to act as standatd *CP* on the SM states. In particular it acts

included, *C*<sup>1</sup> may become an approximate symmetry only when combined with parity *P*, and that

) %= 0. For *c<sup>T</sup>* ∼ *O*(1), generically generated by σ−model

) %= 0. For *c<sup>T</sup>* ∼ *O*(1), generically generated by σ−model

(φ1*,* φ2*,* φ3*,* φ4) → (−φ1*,* φ2*,* −φ3*,* φ4) *,* (5)

*,* Φ<sup>2</sup><sup>b</sup> plane, which without loss of generality we can choose to be Φ<sup>1</sup><sup>b</sup> → Φ<sup>1</sup><sup>b</sup>

contribution to *<sup>T</sup>*\$ is associated to Im (*H*<sup>1</sup>b*†*

describe vacuum dynamics vacuum dynamics vacuum dynamics vacuum dynamics vacuum dynamics vacuum dynamics vacuum<br>District vacuum dynamics vacuum dynamics vacuum dynamics vacuum dynamics vacuum dynamics vacuum dynamics vacuu

like without extra phases on the SM Weyl fermions. We will feel the SM Weyl fermions. We will feel the SM Weyl<br>And the SM Weyl fermions. We will feel the SM Weyl fermions. We will feel the SM Weyl feel the SM Weyl feel th

associated with the only broken by small effects such and only broken by small effects such as the light family Yukawas.

Throughout the paper *C*1*P* is defined to act as standatd *CP* on the SM states. In particular it acts

describe vacuum dynamics

interactions, this is phenomenologically unacceptable.

describe vacuum dynamics of the control of

#### **Three ways** to control  $T$ : **Firm of** *Three* ways to control *T*: Two discrete symmetries control the order parameter *v*<sup>1</sup><sup>b</sup>  $\sim$  $\mathbf{S}$  and provide a useful organizing principle to  $\mathbf{S}$  $\blacksquare$  **Three wavs** to control  $\widehat{T}$ : *(a)*  $\hat{T}$  ,  $\hat{T}$  , or simply *H* → *H*<sup>∗</sup> in doublet notation. *C*1, being a subgroup of *SO*(4), is respected by the strong  $\mathbf{S}$  is a large consideration. It acts like consideration on the  $\mathbf{S}$

 $C_1 \in SO(4)$  :  $(\phi_1, \phi_2, \phi_3, \phi_4) \rightarrow (-\phi_1, \phi_2, -\phi_3, \phi_4)$  $($ or,  $H \rightarrow H^*$ ) (φ1*,* φ2*,* φ3*,* φ4) → (−φ1*,* φ2*,* −φ3*,* φ4) *,* (5)  $C_1 \in SO(4)$ :  $(71, 72, 73, 74)$  (71, 72, 73, 74) sector in all models under consideration. It acts like charge conjugation on the *SU*(2)*<sup>L</sup>* × *U*(1)*<sup>Y</sup>* include  $(OI, H \rightarrow H^*)$  and the combined with parity  $P$ , and that parity  $P$ , and that  $P$  $\left(\textsf{or},\ \ H\to H^*\right)$ include  $\left(\mathsf{or},\;\, H\to H^*\right)$  $\left(\text{or, } H \to H^*\right)$ 

#### sector in all models under consideration. It acts like conjugation on the  $\alpha$  $\mathcal{B}$  and  $\mathcal{B}$  fermions are taken into a countries are taken into a contribution into a counter of  $\mathcal{B}$ sector in all models under consideration. It acts like charge conjugation on the *SU*(2)*<sup>L</sup>* × *U*(1)*<sup>Y</sup>* (φ1*,* φ2*,* φ3*,* φ4) → (−φ1*,* φ2*,* −φ3*,* φ4) *,* (5)  $\mathbf{g}$  like  $C$  also on the FW bosons  $\begin{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 &$ is in this fill and the EW bosons of the strong density  $\Gamma$  and  $\Gamma$  would have to be respected by the strong dynamics of  $\Gamma$  $\Lambda$ ste like  $\alpha$  else en the  $\text{EM}$  becount.  $\frac{1}{2}$   $\frac{1}{2}$  such a the  $\frac{1}{2}$  have to be respected by the strong dynamics d gauge bosons, and is the SM fermions are taken into account. When fermions are taken into account. When fermions are taken in included, *C*<sup>1</sup> may become an approximate symmetry only when combined with parity *P*, and that

is broken by termions, we impose  $C_1P\equiv CP$  $C$  is broken by fermions, we impose  $C_1 P = CP$ sector in all models under consideration. It acts like charge conjugation on the *SU*(2)*<sup>L</sup>* × *U*(1)*<sup>Y</sup>* sector in all models under consideration. It acts like charge conjugation on the *SU*(2)*<sup>L</sup>* × *U*(1)*<sup>Y</sup>* associated with the only broken by small effects such and only broken by small effects such as the light family <br>The contract family Yukawas. The light family Yukawas. The light family Yukawas. The light family Yukawas. Th Throughout the paper *C*<sub>1</sub>*P* is defined to act as standard  $\frac{1}{2}$  on the SM states. It acts is a state state of  $\frac{1}{2}$  $C$  is broken by fermions, we impose  $C_1P\!\equiv\! CP$ ≡ is broken by fermions, **we impose**  $C_1P\!\equiv\! CP$  would be a

*• C*<sup>2</sup> is a reflection in the Φ<sup>1</sup><sup>b</sup>

like without extra phases on the SM Weyl fermions. We without extra phases on the SM Weyl fermions. We will fe<br>In the SM Weyl fermions. We will feel for the SM Weyl fermions. We will feel for the SM Weyl fermions. We will

included, *C*<sup>1</sup> may become an approximate symmetry only when combined with parity *P*, and that

contribution to *<sup>T</sup>*\$ is associated to Im (*H*<sup>1</sup>b*†*

interactions, this is phenomenologically unacceptable.

*H*<sup>2</sup><sup>b</sup>

associated with the only broken by small effects such and only broken by small effects such as the light family Yukawas.

Throughout the paper *C*1*P* is defined to act as standatd *CP* on the SM states. In particular it acts

gauge bosons, and is thus broken when the SM fermions are taken into account. When fermions are taken in the

included, *C*<sup>1</sup> may become an approximate symmetry only when combined with parity *P*, and that

like without extra phases on the SM Weyl fermions. We without extra phases on the SM Weyl fermions. We will fe<br>the SM Weyl fermions. We will feel the SM Weyl fermions. We will feel the SM Weyl fermions. We will feel the S<br>

like without extra phases on the SM Weyl fermions.<br>The SM Weyl fermions on the SM Weyl fermions. The SM Weyl fermions. The SM Weyl fermions. The SM Weyl fermions

like <sup>ψ</sup> <sup>→</sup> <sup>ψ</sup>¯ without extra phases on the SM Weyl fermions.



<sup>7</sup>In the matrix notation, the complex doublet is embedded as Φ = (*H*˜ *, H*) where *H*˜ = *i*σ2*H*∗, while the interaction with

### Two Composite Higgses IN THE REST OF THE PAPER WE SHALL MOSTLY FOR THE PHENOMENOLOGY ON THE PHENOMENOLOGY OF THE PHENOMENOLOGY OF TH

In the rest of the paper we shall mostly focus on the phenomenology of models of class 1 and 2.

after both Higgses have taken arbitrary VEVs, implying *T*! = 0. Notice that for this to work only the

realized in the weakly coupled case, such as in Supersymmetry. In a renormalizable theory, the kinetic

**Three ways** to control  $T$ : e symmetry commute with  $\mathbf{S}$  and showled contain two SU(2) and showled contain two SU(2)  $\mathbf{S}$ **Extended** Custodial: to rotate Φ<sup>2</sup><sup>b</sup> parallel to Φ<sup>1</sup>b, or, which is the same, to a symmetry that constrains *c<sup>T</sup>* to vanish. Such  $\Phi_{\widehat{\mathbf{1}}} \rightarrow L\Phi_{\widehat{\mathbf{1}}}R_1^{\mathsf{T}}$ <sup>1</sup> and Φ<sup>2</sup><sup>b</sup> → *L*Φ<sup>2</sup>b*R†* **CALENDED CUSLOUIAI.**<br> $\Phi_{\widehat{\mathbf{2}}} \to L \Phi_{\widehat{\mathbf{2}}} R_2^{\dagger}$  $\blacksquare$ to rotate Φ<sup>2</sup><sup>b</sup> parallel to Φ<sup>1</sup>b, or, which is the same, to a symmetry that constrains *c<sup>T</sup>* to vanish. Such  $\Psi_1^* \to L \Psi_1^* R_1$  and showled contain the two SU(2)<sup>*R*</sup> $\Omega$ <sup>2</sup> doublets transform independently: i.e. Φ<sup>1</sup><sup>b</sup> → *L*Φ<sup>1</sup>b*R†*  $\Phi_{\widehat{\mathbf{2}}} \to L \Phi_{\widehat{\mathbf{2}}} R_2^{\dagger}$  $\frac{1}{2}$   $\left| \frac{1}{2} \right|$ 

realized in the weakly coupled case, such as in  $\mathcal{C}(\Omega)$  in a renormalizable theory, the kinetic t terms are the only operators that give a mass to the vector bosons, and these are invariant under SO(8),  $SO(3)_c$  is preserved by the VEV

Mechanism at work in the ren.THDM explicit broken to SU(2)*L* **CO(2)** by the gauge of SU(2)*L*. *Specifical contains two SU(2)* contains two SU(2)*R* under which we suggest that we suggest the specific set of SU(2)*R* under which we suggest that we suggest realized in the weakly coupled case, such as in Supersymmetry. In a renormalizable theory, the kinetic terms are the only operators that give a mass to the vector bosons, and these are invariant under SO(8), a symmetry clearly cannot commute with *SO*(4) and should contain two SU(2)*R*'s under which the two doublets transform in the form independent like  $\vert$ 

**Realized in**  $Sp(6)/SU(2) \times Sp(4)$ Realized in  $Sp(6)/SU(2) \times Sp(4)$ 

each doublet transforms as above so that custodial diagonal combination of the three SU(2)<sup>3</sup> is preserved



# **Two Composite Higgses** <sup>1</sup> *<sup>H</sup>*˜ <sup>+</sup> *<sup>Y</sup> <sup>u</sup>* <sup>3</sup> *<sup>H</sup>*˜ *<sup>H</sup>†*

selection rules from *SU*(3)*q<sup>L</sup>* ×*SU*(3)*u<sup>R</sup>* ×*SU*(3)*d<sup>R</sup>* and could in principle be motivated in a suitable model

composite fermions. There the selection rules of the global group *G* can enforce, at lowest order in the

Now, in the composite 2HDM the issues exemplified by eq. (6) and eq. (7) will both be present, but at

In composite Higgs models there are, a priori, extra sources of flavor violations in the Higgs sector [2, 7].

 $\overline{1}$  generically give rise to flavor changing couplings to the neutral Higgs only suppressed  $\overline{1}$ 

<sup>1</sup> *H* + *Y <sup>d</sup>*

*H/f* <sup>2</sup>)

<sup>3</sup> *HH†*

Higgs-Mediated FCNC:

(that is with zero derivatives) is <sup>11</sup> <sup>1</sup> <sup>∝</sup> *<sup>Y</sup> <sup>u</sup>* <sup>3</sup> ∝ *. . .* and similarly for the downs. However a more interesting possibility is  $\bar{q}_L(Y_1^u \tilde{H} + Y_3^u \tilde{H} H^{\dagger} H / f^2 + ...)u_R$ flavor violation *Y <sup>u</sup>*  $\frac{1}{2}$  realistic models of Goldstone Higgs where the Yukawas are generated by mixing elementary to  $\frac{1}{2}$ Effects of **compositeness:** (for 1 or 2 Higgses)

**Solution** is again MFV: (Agashe-Contino) **Solution** is again MFV: (Agashe-Contino)

 $\mathcal{N}$ ukawa couplings, a factorized flavor structure  $\mathcal{N}$ 

eliminates the leading contribution to Higgs mediated FCNC.

 $\bar{q}_L\big(Y_1^u\tilde{H}F_u(H^\dagger H/f^2)\big)u_R$ 

<sup>1</sup> <sup>∝</sup> *<sup>Y</sup> <sup>u</sup>* <sup>3</sup> ∝ *. . .* and similarly for the downs. However a more interesting possibility is  $g_{\text{unof}}$  can by  $G$  selection rules where  $\Box$ Enforced by  $G$  **selection rules** 

The matrices *Y u,d*

#### **Two Composite Higgses discussed in the Two Composite Higgses** couplings at microscopic scales where  $G_4$  breaking can be neglected, corresponding to some representation of  $G_4$ tions of **G, respectively r** couplings at microscopic scales where  $G_4$  breaking can be neglected, corresponding to some representation of  $G_4$ tions of **G, respectively r**

ated flavor transitions works as follows. The strong sector operators *Of<sup>L</sup>* , *Of<sup>R</sup>* in Eq. (9), which describe

discussion. The mixing (9) of the SM elementary fermions breaks both *G* and *H* explicitly but *G* invariance

ated flavor transitions works as follows. The strong sector operators *Of<sup>L</sup>* , *Of<sup>R</sup>* in Eq. (9), which describe

discussion. The mixing (9) of the SM elementary fermions breaks both *G* and *H* explicitly but *G* invariance

fermions are assumed to be linearly coupled to the strong sector through fermionic composite operators

*• C*<sup>1</sup> is the *Z*<sup>2</sup> subgroup of *SO*(4) acting on quadruplets as

rules to suppress Higgs mediated flavor violation in composite models.

Higgs-Mediated FCNC: *OfL,f<sup>R</sup>* . For one generation we have,  $\mathcal{L}_{\text{mix}} = (\bar{f}_L)_{\overline{\alpha}} (y_L^{\overline{\alpha}})^{I_{f_L}} \mathcal{O}_{I_{f_L}} + (\bar{f}_R) (y_R)^{I_{f_R}} \mathcal{O}_{I_{f_R}}$  $\Psi_L{}^{I_{f_L}} = (f_L)_{\overline{\alpha}} (y_L^{*\overline{\alpha}})^{I_{f_L}}/g_{\rho} \qquad \Psi_R{}^{I_{f_R}} = (f_R) (y_R^{*})^{I_{f_R}}/g_{\rho}$ come at higher order in the Yukawa or proto-Yukawa couplings and are normally subdominant and not very problematic [7].  $T\ddot{T}$  is why we neglect them in our discussion. SO(5)/SO(4),  $\{5,5\}$  **-** 2 - 1 = 1 SM fermions *f<sup>L</sup>* and *f<sup>R</sup>* to representations *G* of the operators to which they couple. This can be done most  $\mathcal{L}_{\rm mix} = (f_L)_{\overline{\alpha}} (y_L)$  $g_{\rho}$  (*I*<sub>f</sub>)  $\alpha$  */<sub>i</sub>f*)  $\alpha$  */<sub>i</sub>*  $U^{\dagger}\Psi$  transforms as in  $H.$ SM fermions *f<sup>L</sup>* and *f<sup>R</sup>* to representations *G* of the operators to which they couple. This can be done most  $\text{SO}(5)/\text{SO}(4), \{5,5\}$ <br> $\text{SO}(6)/\text{SO}(4)\times \text{SO}(2), \{\mathbf{20},\mathbf{1}\}$  $SO(6)/SO(4) \times SO(2)$ ,  $\{6, 6\}$   $\longrightarrow$   $3-1 = 2$ 1 or simply *H* → *H*<sup>∗</sup> in doublet notation. *C*1, being a subgroup of *SO*(4), is respected by the strong sector in all models under consideration. It acts like charge conjugation on the *SU*(2)*<sup>L</sup>* × *U*(1)*<sup>Y</sup>* gauge bosons, and is thus broken when the SM fermions are taken into account. When fermions are included, *C*<sup>1</sup> may become an approximate symmetry only when combined with parity *P*, and that is just *CP*. In particular in this scenario *CP* would have to be respected by the strong dynamics associated with the σ-model and only broken by small effects such as the light family Yukawas. Throughout the paper *C*1*P* is defined to act as standatd *CP* on the SM states. In particular it acts like <sup>ψ</sup> <sup>→</sup> <sup>ψ</sup>¯ without extra phases on the SM Weyl fermions.  $\mathcal{C}_2$  is a reflection in the  $\mathcal{C}_2$  $\frac{1}{2}$ even when fermions are included. In *SO*(6)*/SO*(4) × *SO*(2) and *SO*(6)*/SO*(4) the role of *C*<sup>2</sup> can be 1



#### Explicit Models r*Q,T* to which the *q<sup>L</sup>* = (*tL, bL*) and *t<sup>R</sup>* doublet and singlet are coupled to, are, respectively, in the r*Q,T* representations of the *SO*(6) symmetry group of the strong sector, while <u>Explicit Piouers</u>

 $\overline{\phantom{a}}$  are order one coefficients.

(spurions), whose transformation properties are extracted from the above equation. The *IQ,T* indices

in particular the Higgs fields being invariant. A second elementary group, under which *y<sup>R</sup>* is charged, is

potential therefore must be of the form

The central objects are the dressed spurions Υ*L,R*,

*nL,n<sup>R</sup>*

while *c*

*nL,n<sup>R</sup>*

α = 1*,* 2 are indices of the "elementary" *U*(2)<sup>e</sup>

the *SU*(2)*<sup>L</sup>* × *U*(1)*<sup>Y</sup>* gauge and fermion couplings. Among the latter, those associated to the top quark

mass will give the largest contributions. The structure will be determined by the *SO*(6) representations

*<sup>V</sup>* <sup>=</sup> *<sup>m</sup>*<sup>4</sup>

ρ

!

1

obtained by rotating Υ*L,R* with the Goldstone matrix in the appropriate representation. Because of the

have to classify all possible *SO*(4) × *SO*(2) invariants that can be built out of Υ*L,R* at a given order.

Among the latter ones, only those that are *only* invariant under *SO*(4)×*SO*(2) and *not* under *SO*(6) have

!

*nL,n<sup>R</sup>*

$$
L_{\text{mix}} = (\bar{q}_L)_{\overline{\alpha}} (y_L^{\overline{\alpha}})^{I_Q} Q_{I_Q} + (\bar{t}_R) (y_R)^{I_T} T_{I_T} + \text{h.c.}
$$

$$
\left(\begin{array}{cc}\n(\Upsilon_L)^{I_Q J_Q} & = & (y_L^* \frac{1}{\alpha})^{I_Q} (y_L^{\overline{\alpha}})^{J_Q}, \\
(\Upsilon_R)^{I_T J_T} & = & (y_R^*)^{I_T} (y_R)^{J_T}.\n\end{array}\right) \qquad \qquad \left(\begin{array}{c}\n(\Upsilon_L)^{\overline{I} \overline{J}} & \equiv & \left(U^{\mathbf{r}_Q \dagger}\right)^I \left(U^{\mathbf{r}_Q \dagger}\right)^J \left(U^{\mathbf{r}_T \dagger}\right)^J \left(U^{\mathbf{r}_T \dagger}\right)^{J} \\
(\Upsilon_R)^{I_J J_T} & = & (y_R^*)^{I_T} (y_R)^{J_T}.\n\end{array}\right)
$$

$$
V = \frac{m_{\rho}^4}{16\pi^2} \sum_{n_L, n_R} \frac{1}{(g_{\rho}^2)^{n_L + n_R}} \sum_{\delta} c_{\delta}^{n_L, n_R} \mathcal{I}_{n_L, n_R}^{\delta}
$$

are, respectively, in the r*Q,T* representations of the *SO*(6) symmetry group of the strong sector, while

*<sup>L</sup>* rotate, the strong sector and

<sup>Υ</sup>*L,R*#*<sup>K</sup> <sup>L</sup> ,* (36)

*<sup>n</sup>L,n<sup>R</sup> ,* (34)

**Red. The potential terms are H-invariants made of**  $\Upsilon$ **.**  $\overline{X}$   $\overline{Y}$  invariants made of  $\overline{Y}$ where *h*r*Q,T* takes, as before, a block-diagonal form. To construct the *SO*(6) invariants we therefore simply *<sup>n</sup>L,n<sup>R</sup>* , denotes *SO*(6) invariant operators constructed with the Goldstones and *nL,R* powers of Υ*L,R*,  $\begin{array}{ccc} \begin{array}{ccc} \end{array} & \text{rule} & \text{rule} \end{array}$ The potential terms are H-invariants made of  $\Upsilon.$ 

under these additional elementary symmetries forces it not to depend on *yL,R* directly, but on the following

It is straightforward to classify these invariants at each given order proceeding similarly to section 2.3.

#### Explicit Models (0*,*2), . . .). In the particular situation we will consider below where the spurion VEV respects both *C*1*P* and *C*<sup>2</sup> (θ = 0), imposing *C*<sup>2</sup> to the strong sector implies an accidental *C*1*P* in the potential. and *C*<sup>2</sup> (θ = 0), imposing *C*<sup>2</sup> to the strong sector implies an accidental *C*1*P* in the potential. sector in all models under consideration. It acts like charge conjugation on the *SU*(2)*<sup>L</sup>* × *U*(1)*<sup>Y</sup>*

(0*,*2), . . .). In the particular situation we will consider below where the spurion VEV respects both *C*1*P*

*<sup>y</sup>*4. Indeed, two operators, *<sup>I</sup>*<sup>5</sup>

(2*,*0) & *<sup>I</sup>*<sup>2</sup>

or simply *H* → *H*<sup>∗</sup> in doublet notation. *C*1, being a subgroup of *SO*(4), is respected by the strong

gauge bosons, and is thus broken when the SM fermions are taken into account. When fermions are taken into account. When fermions are taken in the SM fermions are taken in the SM fermions are taken in the SM fermions are t

*,* (48)

. This second symmetry is external to *SO*(4), it commutes with it and it may well be exact

even when fermions are included. In *SO*(6)*/SO*(4) × *SO*(2) and *SO*(6)*/SO*(4) the role of *C*<sup>2</sup> can be

VEV is therefore not uniquely determined in general. Assuming the VEV to be either *C*1*P* or *C*<sup>2</sup> invariant

$$
\text{Model A}: \{r_Q, r_T\} = \{20', 1\}
$$
\n
$$
20' = (9, 1) \oplus (4, 2) \oplus (1, 2) \oplus (1, 1)
$$

- we impose  $C_1P$  to align the VEVs that case, however, we now have two four-plets of *SO*(4) to which the doublet could mix, the *y<sup>L</sup>* spurion's **The vector impose**  $C_1P$  to align the VEVs in particular it and  $C_1P$  it acts in particular it acts in particular it acts in particular in particular in particular in particular in particular in particular in particula
- Operators in this representation and *X* = 2*/*3 can be coupled to *q<sup>L</sup>* as in the case of the 6. Differently from • **unique** generalized Yukawa like variance with extra phases of with the without the SM Weyl fermions. The SM Weyl fermions of the SM Weyl fermions. The SM Weyl fermions of the SM Weyl fermions. The SM Weyl fermions of the SM Weyl fermions. The SM Wey

*,* 1*}*

uniquely fixes the embedding,

Φ<sup>2</sup><sup>b</sup> → −Φ<sup>2</sup><sup>b</sup>

that case, however, we now have two four-plets of  $\vert$   $\rangle$  and  $\vert$   $\rangle$  spuriton  $\vert$  spuriton **• multiple**  $q_L$  embedding (pick one)

#### **I**1 Again obtained by counting, given the decomposition in eq. (47), the society of  $\mathbb{R}^d$ (0*,*2), . . .). In the particular situation we will consider below where the spurion VEV respects both *C*1*P* and *C*<sup>2</sup> (θ = 0), imposing *C*<sup>2</sup> to the strong sector implies an accidental *C*1*P* in the potential. and *C*<sup>2</sup> (θ = 0), imposing *C*<sup>2</sup> to the strong sector implies an accidental *C*1*P* in the potential. s. There are 6 of the m, one of them, one of which however should be removed given that it corresponds to the i

terms will be sufficient for our purposes, and are shown in table 5. The number of independent invariants is

(0*,*2), . . .). In the particular situation we will consider below where the spurion VEV respects both *C*1*P*

*<sup>y</sup>*4. Indeed, two operators, *<sup>I</sup>*<sup>5</sup>

(2*,*0) & *<sup>I</sup>*<sup>2</sup>

*,* (48)

*,* 1). For

$$
\text{Model A}: \{\mathbf{r}_Q, \mathbf{r}_T\} = \{\mathbf{20}', \mathbf{1}\}
$$

The results are similar to the ones obtained in the case of the 6: at the *y*<sup>2</sup> order imposing any one of

the trivial *SO*(6) invariant which does not contribute to the potential.

*,* 1*}*

with two 20!

 ${\bf 20'} ~=~ {\bf (9,1)} \oplus {\bf (4,2)} \oplus {\bf (1,2)} \oplus {\bf (1,1)}$ distinguish internal from residual symmetries because we are restricting to VEVs that preserve *C*1*P* and



#### **I1 Is an accidental symmetry of the posterior of the potential. Different case of two 6, the potential symmetry from the case of two 6, the case** (0*,*2), . . .). In the particular situation we will consider below where the spurion VEV respects both *C*1*P* and *C*<sup>2</sup> (θ = 0), imposing *C*<sup>2</sup> to the strong sector implies an accidental *C*1*P* in the potential. is an accidental symmetry of the potential. Differently from the case of two 6, there is no reason here to distinguish internal from residual symmetries because we are restricting to VEVs that preserve *C*1*P* and The results are similar to the ones obtained in the case of the 6: at the *y*<sup>2</sup> order imposing any one of the discrete symmetries automatically implies the other and also the *SO*(4) invariance. Moreover, *C*1*P ·C*<sup>2</sup>

distinguish internal from residual symmetries because we are restricting to VEVs that preserve *C*1*P* and

distinguish internal from residual symmetries because we are restricting to VEVs that preserve *C*1*P* and

is an accidental symmetry of the potential. Differently from the case of two 6, there is no reason here to

the discrete symmetries automatically implies the other and also the *SO*(4) invariance. Moreover, *C*1*P ·C*<sup>2</sup>

the discrete symmetries automatically implies the other and also the *SO*(4) invariance. Moreover, *C*1*P ·C*<sup>2</sup>

<sup>1</sup> <sup>=</sup> "αγδ*ij* (<sup>Υ</sup> <sup>20</sup>!

<sup>1</sup> <sup>=</sup> <sup>δ</sup>*ij*δ*kl*(<sup>Υ</sup> <sup>20</sup>!

<sup>1</sup> <sup>=</sup> <sup>δ</sup>*ik*δ*jl*(<sup>Υ</sup> <sup>20</sup>!

1 = "αγδικά του αγδικά" (Υ 2011)<br>1 = "αγδικά του αγδικά του αγδικά

1 = "αγδρόμεται στην προσπάθηκα" (1991)<br>1 = "αγδρόμεται στην προσπάθηκα" (1991)<br>1 = "αγδρόμεται στην προσπάθηκα" (1991)

<sup>1</sup> <sup>=</sup> <sup>δ</sup>αγδβδ(<sup>Υ</sup> <sup>20</sup>!

Table 5: The independent invariants that contribute to the Higgs potential, up to order *y*<sup>2</sup>

Operator

<sup>1</sup> <sup>=</sup> <sup>δ</sup>*ij*δ*kl*(<sup>Υ</sup> <sup>20</sup>!

the trivial *SO*(6) invariant which does not contribute to the potential.

<sup>1</sup> <sup>=</sup> <sup>δ</sup>*ik*δ*jl*(<sup>Υ</sup> <sup>20</sup>!

<sup>1</sup> <sup>=</sup> <sup>δ</sup>αγδβδ(<sup>Υ</sup> <sup>20</sup>!

<sup>1</sup> <sup>=</sup> "αγδβδ(<sup>Υ</sup> <sup>20</sup>!

<sup>1</sup> <sup>=</sup> "αγδ*ij* (<sup>Υ</sup> <sup>20</sup>!

*<sup>y</sup>*4. Indeed, two operators, *<sup>I</sup>*<sup>5</sup>

*L,R* for (r*Q,* r*<sup>T</sup>* ) = (20!

(2*,*0) & *<sup>I</sup>*<sup>2</sup>

*,* 1). For

$$
\text{Model A}: \{\mathbf{r}_Q, \mathbf{r}_T\} = \{\mathbf{20}', \mathbf{1}\}
$$

• accidental  $C_2$  and  $SO(4)$  in the potential  $r$ nta|  $C_2$  and  $SO(4)$ Operator <u>Intrinsic Residual Contribution (International Contribution)</u> Parity *SO*(4)

*SO*(2) as • accidenta  $C_2$  in the top Yukawa <sup>1</sup> <sup>=</sup> <sup>δ</sup>*ij*δ*kl*(<sup>Υ</sup> <sup>20</sup>! *<sup>L</sup>* )*ijkl* + + ! *C*<sup>2</sup> *C*1*P* 1 **|**  $\frac{1}{\sqrt{2}}$ *<sup>L</sup>* )*ijkl* + + ! *<sup>L</sup>* )*ijkl* + + !  $C_2$  in the Operator Intrinsic Residual Parity *SO*(4)

**L**  $\overline{a}$ <sup>2</sup>β − <sup>2</sup> → <sup>2</sup>

The coupled the coupled to  $\frac{1}{2}$  and  $\frac{1}{2}$  as in the case of the 6. Different case of the **e broken**  $C_2$  in the other Yukawas  $\begin{array}{|c|c|c|c|c|}\n\hline\n\end{array}$  **hroken**  $\begin{array}{|c|c|c|c|}\n\hline\n\end{array}$  in the other <sup>1</sup> <sup>=</sup> <sup>δ</sup>*ik*δ*jl*(<sup>Υ</sup> <sup>20</sup>!  $C_2$  in the



### **I11 Compared With the FX plicit Models** and with the previous section, and with the minimal one, less fine-tuning is  $\mathbb{R}^n$ (0*,*2), . . .). In the particular situation we will consider below where the spurion VEV respects both *C*1*P* and *C*<sup>2</sup> (θ = 0), imposing *C*<sup>2</sup> to the strong sector implies an accidental *C*1*P* in the potential. required to reach the same value of  $\mathbb{R}$  second, we see that the same value contribution to both  $\mathbb{R}^2$

$$
\text{Model A}: \{\mathbf{r}_Q, \mathbf{r}_T\} = \{\mathbf{20}', \mathbf{1}\}
$$

<sup>11</sup> *<* 0, *m*<sup>2</sup>



 $\frac{1}{\pi}$   $\begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{bmatrix}$  From the "**explicit**" potential:

*<sup>y</sup>*4. Indeed, two operators, *<sup>I</sup>*<sup>5</sup>

that the leading order potential is tunable, without sub-leading corrections. This is clearly an advantage

 $\overline{\phantom{a}}$  ratio being fixed, it is not possible to tune the  $\overline{\phantom{a}}$  . This means that the VEV of  $\overline{\phantom{a}}$ 

cannot be fine-tuned to be small, so that even if a *C*2-breaking vacuum existed, it would be difficult to make

(2*,*0) & *<sup>I</sup>*<sup>2</sup>

*.* (78)

*.* (79)

- check that it is **tunable**  $(\frac{v}{f} < 1)$ *f <* 1
- $\frac{f^{f^2}}{2}$   $\begin{bmatrix} 0 & 0 & \frac{1}{2} \\ 2 & 11 & 2 \end{bmatrix}$  **e** derive constraints on the spectrum

$$
m_h^2 \sim \frac{N_c}{16\pi^2} y_L^2 g_\rho^2 v^2 \sim (100 \text{ GeV})^2 \left(\frac{y_L}{1}\right)^2 \left(\frac{3}{N}\right)
$$

$$
n_1 = \left| -\frac{2}{3} \right| - \frac{4}{15} \left| -\frac{1}{2} \right| \qquad m_{H_2}^2 \sim \frac{N_c}{16\pi^2} y_L^2 g_\rho^2 f^2 \sim (200 \text{ GeV})^2 \left( \frac{y_L}{1} \right)^2 \left( \frac{3}{N} \right) \left( \frac{0.25}{\xi} \right)
$$

<sup>22</sup> *>* 0 , λ<sup>1</sup> *>* 0, leading to the splitting

# Explicit Models (0*,*2), . . .). In the particular situation we will consider below where the spurion VEV respects both *C*1*P* and *C*<sup>2</sup> (θ = 0), imposing *C*<sup>2</sup> to the strong sector implies an accidental *C*1*P* in the potential.

$$
Model \mathbf{A}: \{r_Q, r_T\} = \{20', 1\}
$$



*m<sup>T</sup>*

 $\overline{a}$ %

 $\overline{\phantom{a}}$  $\Big\}$  $\Big\}$  $\mid$ 

> $\ddot{\phantom{0}}$ gauge

*m<sup>T</sup>*

From the "**explicit**" potential: *H*2 *B***ZPIICIC** potential.

*<sup>y</sup>*4. Indeed, two operators, *<sup>I</sup>*<sup>5</sup>

(2*,*0) & *<sup>I</sup>*<sup>2</sup>

*.* (79)

*.* (79)

- check that it is **tunable**  $(\frac{v}{f} < 1)$ *f* ● check that it is **tunable**  $\left(\frac{v}{f} < 1\right)$ 1  $\cdot \int v$ *N*  $\geq 1$ ξ *f*  $\frac{1}{2}$  →  $\frac{1}{2}$   $\$ After EWSB, *H* gets an additional contribution through the λ<sup>4</sup> coefficient. From table 8 it turns out that  $\int$   $\frac{1}{1}$   $\int$   $\frac{1}{2}$   $\int$   $\frac{1}{$
- $\frac{L_{22}^2}{2}$   $\begin{array}{|c|c|c|}\n\hline\n0 & 0 & \frac{1}{2} \\
\hline\n2 & 11 & 2\n\end{array}$  **e** derive constraints on the spectrum addening consulations on the speculum *nstraints on the* S <del>γ σταν από του</del> και το κατά το κ<br>Γεγονότατα το κατά το κατά

Operators in this representation and *X* = 2*/*3 can be coupled to *q<sup>L</sup>* as in the case of the 6. Differently from that case, however, we now have two four-plets of *SO*(4) to which the doublet could mix, the *y<sup>L</sup>* spurion's VEV is therefore not uniquely determined in general. Assuming the VEV to be either *C*1*P* or *C*<sup>2</sup> invariant *m*<sup>2</sup> *<sup>H</sup>* <sup>−</sup> *<sup>m</sup>*<sup>2</sup> *H<sup>a</sup> m*<sup>2</sup> *H* # *m*<sup>2</sup> *h* 3*m*<sup>2</sup> *H* + 2 3 ξ ∼ ξ *.* (80) Custodial-breaking splitting come from gauge contributions (<sup>∝</sup> *<sup>g</sup>*!<sup>2</sup> ), and higher orders in *<sup>y</sup><sup>L</sup>* (<sup>∝</sup> *<sup>y</sup>*<sup>4</sup> Custodial-breaking splitting come from gauge contributions (<sup>∝</sup> *<sup>g</sup>*!<sup>2</sup> ), and higher orders in *<sup>y</sup><sup>L</sup>* (<sup>∝</sup> *<sup>y</sup>*<sup>4</sup> *mH<sup>±</sup>* − *m<sup>A</sup>* % *m<sup>T</sup>* % % % gauge ∼ # *v f* \$<sup>2</sup> # *g*! *yL* \$<sup>2</sup> # <sup>0</sup>*.*<sup>03</sup> # <sup>1</sup> *yL* \$<sup>2</sup> # ξ 0*.*25\$

*yL*

*g*ρ

*f*

*yL*

# <sup>0</sup>*.*<sup>005</sup> !*y<sup>L</sup>*

0*.*25\$

3

 $\sim$   $\pm$ 

0*.*25\$

|<br>|<br>|

*f*

∼

 $\overline{a}$ %

#### Explicit Models (0*,*2), . . .). In the particular situation we will consider below where the spurion VEV respects both *C*1*P* and *C*<sup>2</sup> (θ = 0), imposing *C*<sup>2</sup> to the strong sector implies an accidental *C*1*P* in the potential. included, *C*<sup>1</sup> may become an approximate symmetry only when combined with parity *P*, and that is just *CP*. In particular in this scenario *CP* would have to be respected by the strong dynamics

*<sup>y</sup>*4. Indeed, two operators, *<sup>I</sup>*<sup>5</sup>

(2*,*0) & *<sup>I</sup>*<sup>2</sup>

the SU(2)*<sup>L</sup>* gauge bosons comes from the covariant derivative<sup>8</sup> *<sup>D</sup>µ*<sup>Φ</sup> <sup>=</sup> <sup>∂</sup>*µ*<sup>Φ</sup> <sup>−</sup> *<sup>i</sup> <sup>W</sup><sup>a</sup>* <sup>σ</sup>*<sup>a</sup>*

associated with the σ-model and only broken by small effects such as the light family Yukawas.

like  $\mathbb{R}^n$   $\mathbb{R}^n$  with  $\mathbb{R}^n$  with  $\mathbb{R}^n$  with  $\mathbb{R}^n$  with  $\mathbb{R}^n$  fermions.

the SU(2)*<sup>L</sup>* gauge bosons comes from the covariant derivative<sup>8</sup> *<sup>D</sup>µ*<sup>Φ</sup> <sup>=</sup> <sup>∂</sup>*µ*<sup>Φ</sup> <sup>−</sup> *<sup>i</sup> <sup>W</sup><sup>a</sup>* <sup>σ</sup>*<sup>a</sup>*

*,* Φ<sup>2</sup><sup>b</sup> plane, which without loss of generality we can choose to be Φ<sup>1</sup><sup>b</sup> → Φ<sup>1</sup><sup>b</sup>

<sup>7</sup>In the matrix notation, the complex doublet is embedded as Φ = (*H*˜ *, H*) where *H*˜ = *i*σ2*H*∗, while the interaction with

even when fermions are included. In *SO*(6)*/SO*(4) × *SO*(2) and *SO*(6)*/SO*(4) the role of *C*<sup>2</sup> can be

sector in all models under consideration. It acts like charge conjugation on the *SU*(2)*<sup>L</sup>* × *U*(1)*<sup>Y</sup>*

or simply *H* → *H*<sup>∗</sup> in doublet notation. *C*1, being a subgroup of *SO*(4), is respected by the strong

gauge bosons, and is thus broken when the SM fermions are taken into account. When fermions are

sector in all models under consideration. It acts like charge conjugation on the *SU*(2)*<sup>L</sup>* × *U*(1)*<sup>Y</sup>*

included, *C*<sup>1</sup> may become an approximate symmetry only when combined with parity *P*, and that

gauge bosons, and is thus broken when the SM fermions are taken into account. When fermions are

is just *CP*. In particular in this scenario *CP* would have to be respected by the strong dynamics

Throughout the paper *C*1*P* is defined to act as standatd *CP* on the SM states. In particular it acts

associated with the σ-model and only broken by small effects such as the light family Yukawas.

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. This second symmetry is external to *SO*(4), it commutes with it and it may well be exact

. This second symmetry is external to *SO*(4), it commutes with it and it may well be exact

$$
\text{Model } \mathbf{B}: \ \{\mathbf{r}_Q, \ \mathbf{r}_T\} = \{\mathbf{6}, \mathbf{6}\}
$$

 $\bf (4,1)\oplus (1,2)$  $\mathbf{6} = (4,1) \oplus (1, \mathbf{2})$  $\mathbf \kappa = (\mathbf 4, \mathbf 1) \! \oplus \! (\mathbf 1, \mathbf 2)$ 

• we impose  $C_2$ 

*<sup>I</sup>* = *y<sup>R</sup>* (0*,* 0*,* 0*,* 0*,* cos θ*,i*sin θ) *.* (45)

*<sup>R</sup>* phase transformation, !*vR,I* can be aligned respectively along (1*,* 0) and (0*,* 1), allowing to

where *y<sup>R</sup>* is real. Both *C*1*P* and *C*<sup>2</sup> are preserved in the special case θ = 0.

- **unique** Yukawa because of  $C_2$  $\mathsf{se}$  of  $C_2$  is external to  $S_4$  $\overline{C_3}$
- Operators in this representation and *X* = 2*/*3 can be coupled to *q<sup>L</sup>* as in the case of the 6. Differently from  $\bullet$  unique embedding (again,  $C_2$ )  $\mathsf{p}\mathsf{b}\mathsf{edding}\ \mathsf{(again,}\ C_2) \begin{array}{c|c} \mathsf{p}\mathsf{b}\mathsf{c}\mathsf{c}\mathsf{c}\mathsf{d}\mathsf{d}\mathsf{c}\mathsf{d}\mathsf{c} \mathsf{c} \mathsf{c}$
- that case, however, we now have two four-plets of *SO*(4) to which the doublet could mix, the *y<sup>L</sup>* spurion's VEV is therefore not uniquely determined in general. Assuming the VEV to be either *C*1*P* or *C*<sup>2</sup> invariant • gives the **Composite Inert Higgs 7 2 Composite Inert Higgs** even when fermions are included. In *SO*(6)*/SO*(4) × *SO*(2) and *SO*(6)*/SO*(4) the role of *C*<sup>2</sup> can be

#### Explicit Models (0*,*2), . . .). In the particular situation we will consider below where the spurion VEV respects both *C*1*P* and *C*<sup>2</sup> (θ = 0), imposing *C*<sup>2</sup> to the strong sector implies an accidental *C*1*P* in the potential. or simply *H* → *H*<sup>∗</sup> in doublet notation. *C*1, being a subgroup of *SO*(4), is respected by the strong the trivial *SO*(6) invariant which does not contribute to the potential.

s. There are 6 of them, one of which however should be removed given that it corresponds to

The results are similar to the ones obtained in the case of the 6: at the *y*<sup>2</sup> order imposing any one of

Operator

*<sup>y</sup>*4. Indeed, two operators, *<sup>I</sup>*<sup>5</sup>

(2*,*0) & *<sup>I</sup>*<sup>2</sup>

(φ1*,* φ2*,* φ3*,* φ4) → (−φ1*,* φ2*,* −φ3*,* φ4) *,* (5)

*,* Φ<sup>2</sup><sup>b</sup> plane, which without loss of generality we can choose to be Φ<sup>1</sup><sup>b</sup> → Φ<sup>1</sup><sup>b</sup>

$$
\text{Model } \mathbf{B}: \{\mathbf{r}_Q, \mathbf{r}_T\} = \{\mathbf{6}, \mathbf{6}\}
$$

Peculiarities of the potential: is an accidental symmetry of the potential. Differently from the case of two 6, there is no reason here to distinguish internal from residual symmetries because we are restricting to VEVs that preserve *C*1*P* and

- **not tunable** at the **LO** is just *CP*. In particular in this scenario *CP* would have to be respected by the strong dynamics associated with the only broken by small effects such as the light family  $\mathcal{L}(\mathcal{A})$
- $\mathsf{val} \; C_1 P \; \mathsf{at} \; \mathbf{NLO}$  and  $\mathsf{val} \; C_1 P$ • accidental  $C_1P$  at **NLO** • accidental  $C_1P$  at **NLO**
- $\theta$  and  $\theta$   $\theta$  (4) to  $\theta$  and  $\theta$ VEV is therefore not uniquely determined in general. Assuming the VEV to be either *C*1*P* or *C*<sup>2</sup> invariant  $\bullet$  accidental  $SO(4)$  at **LO**  $\bullet$  accidental  $SO(4)$  at  $\textsf{\textbf{LO}}$

#### *I1***</sup> May** *Explicit Models* (0*,*2), . . .). In the particular situation we will consider below where the spurion VEV respects both *C*1*P* and *C*<sup>2</sup> (θ = 0), imposing *C*<sup>2</sup> to the strong sector implies an accidental *C*1*P* in the potential. *L***<sub>A</sub>***p***<sub>1</sub>,** *N***<sub>c</sub>** *y***<sub>2</sub>,** *N***<sub>c</sub>** *y***<sub>2**</sub> The individual contributions of the SO(6)*/*SO(4) × SO(2) operators of Table 5 are shown. The first line indicates the NDA pre-factor. We notice that the contributions to the operators *<sup>I</sup>*<sup>1</sup> *<sup>g</sup>* <sup>−</sup> *<sup>I</sup>*<sup>2</sup> *<sup>g</sup>* and *<sup>I</sup>*<sup>3</sup> *<sup>g</sup>* . The same applies to the corresponding *<sup>g</sup>*! operators. *{*contg*}* leading order *y2 contribution, for which no contribution, for which no contribution* appear, and is given by

Table 7: Contribution to the parameters of the general 2HDM potential eq. (62) from SU(2)*<sup>L</sup>* and U(1)*<sup>Y</sup>* gauge bosons.

*<sup>y</sup>*4. Indeed, two operators, *<sup>I</sup>*<sup>5</sup>

*<sup>g</sup>* . The same applies to the corresponding *<sup>g</sup>*! operators. *{*contg*}*

11 to be a factor ξ smaller than the subleading one, than the subleading one, those order  $\frac{1}{2}$ .

11 requires less two terms are of the two terms are of the same of

<sup>11</sup> requires less tuning if the two terms are of the same

(2*,*0) & *<sup>I</sup>*<sup>2</sup>

<sup>ρ</sup>*, } .* (63)

<sup>ρ</sup>*, } .* (63)

<sup>ρ</sup>*/*16π<sup>2</sup> with respect to

*.* (65)

*.* (65)

*,* (66)

*,* (66)

$$
\text{Model } \mathbf{B}: \ \{\mathbf{r}_Q, \ \mathbf{r}_T\} = \{\mathbf{6}, \mathbf{6}\}
$$

*<sup>R</sup>* contributions to *m*<sup>2</sup>

 $\Gamma$  this case the quartic  $\Lambda$  is dominated by the higher-order contributions:  $\Gamma$ 

leading order *y*<sup>2</sup> contribution, for which no cancellation appear, and is given by

Since canceling the *y*<sup>2</sup>

*<sup>L</sup>* and *y*<sup>2</sup>

Φ<sup>1</sup>!. The mass of *h* can be estimated as

Since canceling the *y*<sup>2</sup>

leading order in the derivative expansion.

than the triplet:

than the triplet:

positive in order for *m*<sup>2</sup>

positive in order for *m*<sup>2</sup>

### The 20! representation is the symmetric and traceless product of two 6, and it decomposes under *SO*(4)× **Spectrum:** the spectrum is expected to be the *C*2-even neutral scalar *h* which is contained in the first Higgs doublet Φ<sup>1</sup>!. The mass of *h* can be estimated as

$$
m_h^2 = Y_t^2 \frac{g_\rho^2}{16\pi^2} v^2 \sim (100 \text{ GeV})^2 \left(\frac{3}{N}\right)
$$

$$
m_{H_2}^2 \sim N_c \frac{g_\rho Y_t}{16\pi^2} m_\rho^2 \simeq (500 \text{ GeV})^2 \sqrt{\frac{3}{N}} \left(\frac{m_\rho}{2 \text{ TeV}}\right)^2
$$

$$
m_H^2 \simeq \left(1-\frac{\xi}{6}\right)m_{H^a}^2
$$

1 − ξενοδός<br>1 − ξενοδός<br>1 − ξενοδός

As discussed in the previous section and explicitly shown in eq. (65), the *y*<sup>2</sup> potential is SO(4)-invariant so

"

!!<br>!!

# Explicit Models (0*,*2), . . .). In the particular situation we will consider below where the spurion VEV respects both *C*1*P* and *C*<sup>2</sup> (θ = 0), imposing *C*<sup>2</sup> to the strong sector implies an accidental *C*1*P* in the potential.

*<sup>y</sup>*4. Indeed, two operators, *<sup>I</sup>*<sup>5</sup>

(2*,*0) & *<sup>I</sup>*<sup>2</sup>

. These splittings can be estimated as

Operators in this representation and *X* = 2*/*3 can be coupled to *q<sup>L</sup>* as in the case of the 6. Differently from

that case, however, we now have two four-plets of *SO*(4) to which the doublet could mix, the *y<sup>L</sup>* spurion's

VEV is therefore not uniquely determined in general. Assuming the VEV to be either *C*1*P* or *C*<sup>2</sup> invariant

$$
\textsf{Model B}: \ \{ {\bf r}_Q, \, {\bf r}_T \} = \{ {\bf 6}, {\bf 6} \}
$$

as *<sup>H</sup><sup>±</sup>* <sup>=</sup> (*H*<sup>2</sup> *<sup>±</sup> iH*1)*/*

Spontaneous *C*<sup>2</sup> Breaking

#### The 20! representation is the symmetric and traceless product of two 6, and it decomposes under *SO*(4)× **Spectrum:**  $\sqrt{2}$  and  $\sqrt{2}$  and  $\sqrt{2}$  order  $\sqrt{2}$  or  $\sqrt{2}$

$$
\left| \frac{m_{H^{\pm}} - m_A}{m_{H^{\pm}}} \right|_{\rm NLO} \sim \left( \frac{v}{f} \right)^2 \frac{Y_t}{g_\rho} \simeq 0.03 \sqrt{\frac{N}{3}} \left( \frac{\xi}{0.25} \right)
$$

Still assuming that *C*<sup>2</sup> symmetry is preserved by the couplings, we now consider the possibility that the

second Higgs Φ<sup>2</sup>! also acquires a VEV. In this case *C*<sup>2</sup> is spontaneously broken departing from the inert

Higgs scenario. Also, a VEV of Φ<sup>2</sup>! is compulsory in order for the alternative flavor scenarios (type-I, II, X

and Y, as in table 2.3) to be 2.3) to become viable. The discussion which follows applies to the discu

If the VEV of Φ<sup>2</sup>! is non-zero, so breaking the discrete symmetry (*C*<sup>2</sup> or *C*<sup>2</sup> *· C<sup>I</sup>* , depending on the

# **Conclusions**

Realistic composite THDM are easily constructed

Our examples have **peculiar** phenomenology, because of the many **accidental symmetries**

Some progresses on the **general understanding**  of the scenario, **better use** of symmetries

# **For the origin of the origin of the origin of the leading contribution of the leading contribution of the line**

corresponding to an effective minimal flavor violation in the zero derivative lagrangian. This feature lagrangi<br>This feature lagrangian flavor violation in the zero derivative lagrangian. This feature lagrangian is feature

 $N_{\rm eff}$  is the composite 2HDM the issues exemplified by eq. (6) and eq. (6) and eq. (7) will both be present, but at present, but at  $\alpha$ 

selection rules from *SU*(3)*q<sup>L</sup>* ×*SU*(3)*u<sup>R</sup>* ×*SU*(3)*d<sup>R</sup>* and could in principle be motivated in a suitable model

In composite Higgs models there are, a priori, extra sources of flavor violations in the Higgs sector [2, 7].

<sup>1</sup> *H* + *Y <sup>d</sup>*

Higgs-Mediated FCNC:

 $\mathbf{r}$  is the isomorphism is  $\mathbf{r}$  is 111  $\mathbf{r}$  is 11  $\bar{q}_L(Y_1^u \tilde{H} + Y_3^u \tilde{H} H^{\dagger} H / f^2 + \dots) u_R$ Effects of **compositeness:** (for 1 or 2 Higgses) Liet us discussed **compositeness:** (for flavor discusses) where *If<sup>L</sup>* and *If<sup>R</sup>* are *G* indices transforming in the conjugate representation of *OfL,R* while α denotes

*I hese operato* **P** *These operators are generated by CO <i>L* **Z** *CO L Z <i>CO L CO L Z <i>CO CO CO* 

rules to suppress Higgs mediated flavor violation in composite models.



#### **Two Composite Higgses** *L* **composite Hig**  $\overline{a}$ **Example 18 Two Composite Higgses Composite Higgses** energy via the exchange of the heavy modes excited by *OfL,f<sup>R</sup>* , see Fig. 2. By applying power counting as

hierarchical in order to reproduce the observed Yukawas. It is the observed Yukawas. It is the typical to estima<br>It is the observed Yukawas. It is the typical to estimate the typical to estimate the typical to estimate the

*yj*

Higgs-Mediated FCNC: *l*iate <sup>×</sup> *<sup>a</sup>ij* <sup>1</sup>*,*<sup>3</sup> (no sum over *<sup>i</sup>*, *<sup>j</sup>*)*, <sup>a</sup>ij*

*ds*)2, <sup>∆</sup>*<sup>S</sup>* <sup>=</sup> <sup>2</sup> transition, the coefficient is <sup>∼</sup> *<sup>m</sup>dms/v*2*m*<sup>2</sup>

 $\mathbf{r}$  is the isomorphism is  $\mathbf{r}$  is 111  $\mathbf{r}$  is 11  $\bar{q}_L(Y_1^u \tilde{H} + Y_3^u \tilde{H} H^\dagger H / f^2 + \dots) u_R$ Effects of **compositeness:** (for 1 or 2 Higgses) class of flavor violation can be under control with some not totally implausible tuning of parameters. On  $\begin{bmatrix} 1 & \text{F} & \$ for instance, *LRLR* 4-fermi interactions *R* ,<br>*g*<br>*g*<sup>1</sup> *m*<sup>2</sup>  $I/f^2 + \dots$ )  $\bar{a}$ <sub>z</sub> ( $V^u \tilde{H}$  +  $V^u \tilde{H} H^{\dagger} H / f^2$  +  $\bar{a}$  )  $\bar{a}$ *.* (11) **Effects of <b>compositeness:** (for I or 2 Higgses) degrees of mixing *y<sup>i</sup>* Assuming the strong sector does not have any flavor structure (*aij* ∼ *O*(1)) these mixings have to be

 $\mathcal{N}$ ukawa couplings, a factorized flavor structure  $\mathcal{N}$ 

$$
\Delta S = 2 \text{ transitions:} \quad \epsilon_L^i \epsilon_R^j \epsilon_L^k \epsilon_R^{\ell} \frac{g_{\rho}^2}{m_h^2} \frac{v^4}{f^4} \left( \bar{f}_L^i f_R^j \bar{f}_L^k f_L^{\ell} \right)
$$
  
vs resonance effects:

*g*2

*v*4

**The extra factor of** *v***4***f* **4 arises because on-shell flavor violating vertices with the higgs are**  $\frac{1}{2}$ **, and**  $\frac{1}{2}$ **, and \ For instance in the v.s. resonance effects:** 



*Lyj*

 $\mathcal{F}_{\mathcal{F}}$  instance for the (  $\mathcal{F}_{\mathcal{F}}$ 

with *aij*

degrees of mixing *y<sup>i</sup>*

For instance for the ( ¯

$$
\begin{array}{c}\n\mathcal{Y} \mathcal{Y} \math
$$

"

Both in the case with one or more Higgses the group theoretic mechanism to control the Higgs medi-

!

selection rules from *SU*(3)*q<sup>L</sup>* ×*SU*(3)*u<sup>R</sup>* ×*SU*(3)*d<sup>R</sup>* and could in principle be motivated in a suitable model

*<sup>R</sup>* of its chirality components to their composite counterparts.

In composite Higgs models there are, a priori, extra sources of flavor violations in the Higgs sector [2, 7].

<sup>1</sup> *H* + *Y <sup>d</sup>*

*.* (11)

<sup>ρ</sup> which is small enough for

<sup>1</sup>*,*<sup>3</sup> ∼ *O*(1)*.* (10)

*.* (12)

*.* (11)

<sup>ρ</sup> which is small enough for

<sup>ρ</sup> which is small enough for