

Europe/Paris timezone

LIO international conference on Flavour, Composite models and Dark matter

23-27 novembre 2015 **IPNL**

Flavor in Composite Higgs Models

Alberto Parolini

KIAS

26/11/2015

1. Motivation ξ*ia* **l**. Motiva **1. Motivation** .*^B*

Address SM Hierarchy Problem: mechanism to protect Higgs mass. \overline{f}

• Naturalness \implies new physics at the TeV ⇒ new physics at the TeV

- Environmental Selection
- Finite Naturalness, …
- Cosmological Relaxation
- ??

Motivation Line Motiva Motivation .*^B*

Address SM Hierarchy Problem: mechanism to protect Higgs mass. \overline{f}

- Environmental Selection
- Finite Naturalness, …
- Cosmological Relaxation

• Naturalness \implies new physics at the TeV ⇒ new physics at the TeV

flavour robustness of

• ??

Introduction

Strong dynamics breaking EW symmetry.

Coupling to quarks:

• linear mixing (partial compositeness)

 $\bar{q}_L \mathcal{O}_{q_L} + \bar{u}_R \mathcal{O}_{q_R}$

• bilinear mixing (TC-like)

 $\bar{q}_L q_R \mathcal{O}$

Partial Compositeness mpositeness and *M* ∈ (0.82) and *M* ∈ (0.82) and *M* ∈ (0.82) and *M* ⊆ (0.82) and **Partial Compositer Partial Compositenes** *Mab* (0.80) .*^B* $\overline{}$ sitene λ*AB*

$$
\mathcal{L} = \bar{\psi} i \partial \psi + \bar{\mathcal{O}} i \partial \mathcal{O} + \epsilon \bar{\psi} \mathcal{O} + \ldots + h.c.
$$

CFT φ \in = γ\$ + *... ,* γ = dim (*O*) − 5*/*2 (0.84) $O \in CFT$

$$
\frac{d\epsilon}{d\log\mu} = \gamma \epsilon + \dots, \qquad \gamma = \dim(\mathcal{O}) - 5/2
$$

effective low energy description

$Partial$ Compositeness **+ 2000** $\frac{1}{2}$ $\frac{$ $\mathcal{L}(\mathcal{D})$ d log *µ* $\frac{1}{2}$ = $\frac{1}{2}$ $\frac{1}{2}$

$$
\mathcal{L} = \bar{\psi} i \partial \psi + \bar{\mathcal{O}} (i \partial - m_M) \mathcal{O} + \epsilon \bar{\psi} \mathcal{O} + h.c.
$$

 $\tan\phi =$ ϵ \overline{m}_M

 $\frac{\epsilon}{\cos \theta}$ $\qquad \qquad$ $\text{light} = \psi \cos \phi + \mathcal{O} \sin \phi$ ${\rm light}=\psi\cos\phi+{\cal O}\sin\phi$ heavy $= -\psi \sin \phi + \mathcal{O} \cos \phi$

$Partial$ Compositeness
 $|$ $\mathcal{L}(\mathcal{D})$ d log *µ* $\frac{1}{2}$ = 0.83)

$$
\mathcal{L} = \bar{\psi} i \partial \psi + \bar{\mathcal{O}} (i \partial - m_M) \mathcal{O} + \epsilon \bar{\psi} \mathcal{O} + h.c.
$$

$Partial$ Compositeness **+ 2000** $\frac{1}{2}$ $\frac{$ $\mathcal{L}(\mathcal{D})$ d log *µ* $\frac{1}{2}$ = $\frac{1}{2}$ $\frac{1}{2}$

$$
\mathcal{L} = \bar{\psi} i \partial \psi + \bar{\mathcal{O}} (i \partial - m_M) \mathcal{O} + \epsilon \bar{\psi} \mathcal{O} + h.c.
$$

$Partial$ Compositeness **+ 2000** $\frac{1}{2}$ $\frac{$ $\mathcal{L}(\mathcal{D})$ d log *µ* $\frac{1}{2}$ = $\frac{1}{2}$ + $\frac{1}{$

$$
\mathcal{L} = \bar{\psi} i \partial \psi + \bar{\mathcal{O}} (i \partial - m_M) \mathcal{O} + \epsilon \bar{\psi} \mathcal{O} + h.c.
$$

$$
\tan \phi = \frac{\epsilon}{m_M} \qquad \qquad \text{light} = \psi \cos \phi + \mathcal{O} \sin \phi
$$
\n
$$
\text{heavy} = -\psi \sin \phi + \mathcal{O} \cos \phi
$$

- Flavor hierarchies
- GIM-like mechanism suppressing FCNC and CP Agashe, Perez, Soni 0408134 Cacciapaglia et al. 0709.1714 Redi, Weiler 1106.6357

Flavor constraints

Panico Wulzer 1506.01961

$$
m_* > O(1) \text{ TeV}
$$

$$
m_* > 10 \text{ TeV} \qquad \varepsilon_K
$$

 $m_* > O(10)$ TeV $\Delta F = 0$

Alberto Parolini 6 26/11/2015

Flavor constraints: lepton sector *m* $\frac{1}{2}$ 10 TeV ε*K*² (10 TeV εκπαιδίας της Συναλίας τη

Feruglio et al 1509.03241

Flavor constraints: lepton sector *m* $\frac{1}{2}$ 10 TeV ε*K*² (10 TeV εκπαιδίας της Συναλίας τη

Feruglio et al 1509.03241

$$
m_* > O(10)
$$
 TeV e EDM
 $m_* > O(10)$ TeV $\mu \rightarrow e\gamma$

 $Y_L^* = 0$ is a (stable) solution

An alternative model

Strong dynamics breaking EW symmetry.

Coupling to quarks:

• linear mixing (partial compositeness)

 $\bar{q}_L \mathcal{O}_{q_L} + \bar{u}_R \mathcal{O}_{q_R}$

• bilinear mixing (TC-like) 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1 1.1

An alternative model

^L ⁼ ^λ*u*(Λ*HC*)Λ[*O*] *f* $\frac{1}{2}$ + $\frac{1}{2}$ + employing "*O*# ⁼ ^Λ[*O*] *HCv/f* and Λ*HC* \$ 4π*f*, [*O*] being the dimension of the operator *O*. If we assume G. Cacciapaglia, H. Cai, T. Flacke, S. Lee, AP, H. Serodio1501.03818 JHEP 1506 (2015) 085

Mixed couplings:

 \bullet linear mixing for $\sf top$ (potentially bottom) $\bar q_L {\cal O}_{q_L} + \bar u_R {\cal O}_{q_R}$ \mathcal{O}_{q_R}

• bilinear mixing for **other quarks** (charm mass is compatible with $\Lambda_{UV} \lesssim 10^5 \text{ TeV}$) $\bar{q}_L q_R \mathcal{O}$ **quarks** $qLqR$

2. Higgs as a pNGB ggs as a pN **∣G** Finggs as a pinciple of the state of the state \overline{a} and \overline{a} and \overline{a} are not all \overline{a} and \overline{a} are \overline{a} PNGB
Dinamagna *G* = SO(5) × U(1)*^X H* = SO(4) × U(1)*^X Y* = *T*3*^R* + *X, H^s* (0.33) *G/H, SO*₂ and π **b**/ π (0.34) π $a p NGB$ 0 0 00 2*/*3

H, dim $G/H \ge 4$, $\mathrm{SO}(5)/\mathrm{SO}(4) \Rightarrow \mathsf{V}(\mathsf{h})$ =0 at tree level α / $, \quad \text{and} \quad \text{or} \quad 11 \leq 1, \quad \text{or}$ $\mathcal{C})^{\prime}$ $\mathcal{L}(\mathcal{O})/\mathcal{O}(\mathcal{O}(1))$. $\mathcal{O}(\mathcal{O})$ at the $\mathcal{O}(\mathcal{O})$ \Rightarrow V(h)=0 at tree level • G/H , dim $G/H \ge 4$, SO(5)/S $50(4)$ 8 \rightarrow $\sqrt{(1)}$ \rightarrow at the server G/H , dim $G/H \ge 4$, $SO(5)/SO(4) \Rightarrow V(h)=0$ at tree level \bullet *G/H*, dim $\dim G$ ϕ 4, $SO(5)/SO(4) \Rightarrow V(h)=0$ at tree level *a*_/4 = 3^{*/*} a_{[/]</sup> = 12 ²/₂ + 6−2*/*²/₂ + 6−2*/*₂ + 7^{*/2*} + 6−2*/*² + 6−2*/*²}

 $G = \text{SO}(5) \times U$ (1) $X \hspace{1.6cm} Y$ Ω $\frac{1}{2}$ $\mathcal{O}($ $\mathcal{L}_{\mathcal{L}_{\mathcal{L}}}$ \rightarrow $\mathop{\rm U}(1)_X$ $G = SO(5) \times U(1)_X$ $Y = T_{3R} + X$ $\frac{1}{\sqrt{2}}$ $\times \text{U}(1)_X$ $\mathbf{U} \cap \mathbf{U}$ \overline{H} ÷ *Nc|yt|* $SO(4) \times U(1)$ ∼ $V \cap T$ (1.36) ⁸π² ^Λ² ^δ*m*² $H = SO(4)$ *^f ^ha*ˆ*Ta*^ˆ *, U* → *gUh†* $b = 30(5) \times 0(1)X$ *f* $I = 13R + X$ $H = SO(4) \times U(1)_X$

$\mathrm{SU}(2)\times \mathrm{U}(1)\subseteq G_{SM}\subseteq H$ *i* $f(2) \times U(1) \subset G_{SM} \subset H$ *f* $\mathcal{O}(2) \times$ *i* $U(1) \subseteq$ G *bcq*(*^m* $SU(2) \times U(1) \subseteq G_{SM} \subseteq H$ $SU(2) \times U(1) \subseteq G_{SM} \subseteq H$ $-$ ² $M = -$ ²

 \Rightarrow V(h) \neq 0 . \Rightarrow **V**(h) \neq 0 *,* (0.39)

 $\Rightarrow \quad V(n) \neq 0$ -*i* f and f and f and f and f and f and f . dial compositeness (at least for the top)
 u and the top of the t ²*^f* ^π*aT^a* artial compositeness and least for the top) Partial compositeness (at least for the top)

Alberto Parolini 10 26/11/2015 **Alberto Parolini** *Nc|yt|* **Alberto Parolini**

The Model be ΛUV and Eventual at a scale ΛUV and Eventual as coupling between pairs of the effective Lagrangian as couplings between pairs of the effective Lagrangian as couplings between pairs of the effective Lagrangian as coupl

$$
\psi = \begin{pmatrix} Q \\ \tilde{T} \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} i & B - i & X_{5/3} \\ B + X_{5/3} \\ i & T + i & X_{2/3} \\ -T + X_{2/3} \\ \sqrt{2} & \tilde{T} \end{pmatrix}
$$

$$
\mathcal{L}_{comp} = i\overline{Q}_{L,R}(\not{D} + \not{E})Q_{L,R} + i\overline{\tilde{T}}_{L,R}\not{D}\tilde{T}_{L,R} - M_4(\overline{Q}_LQ_R + \overline{Q}_RQ_L) \n- M_1(\overline{\tilde{T}}_L\tilde{T}_R + \overline{\tilde{T}}_R\tilde{T}_L) + ic_L\overline{Q}_L^i\gamma^\mu d_\mu^i \tilde{T}_L + ic_R\overline{Q}_R^i\gamma^\mu d_\mu^i \tilde{T}_R + \text{h.c.} \n-\mathcal{L}_{mix} = y_{L4,1}f\overline{q}_{3L}^5U\psi_R + y_{R4,1}f\overline{t}_R^5U\psi_L + \text{h.c.}
$$

$$
\mathcal{L}_Y = \bar{q}_{L,\alpha} \lambda_{\alpha,\beta}^u u_{R,\beta} \mathcal{O}_u + \bar{\tilde{q}}_{L,\alpha} \lambda_{\alpha,\beta}^d d_{R\beta} \mathcal{O}_d + h.c.
$$

Alberto Parolini 11 26/11/2015 where *E^µ* and *d^µ* denote the CCWZ Cartan-Maurer one-forms (*c.f.*, *e.g.*, Ref.[48] for the explicit expresthese terms are generated independent independent independent on the partial composite $\frac{26}{11/2015}$ where *E^µ* and *d^µ* denote the CCWZ Cartan-Maurer one-forms (*c.f.*, *e.g.*, Ref.[48] for the explicit expressions). Masses and couplings deriving from this Lagrangian are detailed in Appendix A. The terms in

[−]*Lmix* ⁼*yL*4*,*1*fq*⁵

Up Sector Mass Matrix **The fermionic field content defined above can be split into up and down sectors as a bove can be split into up a** ^h [∈] SO(4). It is convenient to define ^Σ ⁼ *^U ·* (0 0 0 0 1)*^t* also define

$$
\xi_{\uparrow} = \begin{pmatrix} u & c & t & T & X_{2/3} & \tilde{T} \end{pmatrix}^T
$$
 $v = s_{\epsilon} f \simeq 246 \text{ GeV}$

$$
M_{\rm up} = \begin{pmatrix} \tilde{m}[\epsilon]_{11} & \tilde{m}[\epsilon]_{12} & \tilde{m}[\epsilon]_{13} & 0 & 0 & 0 \\ \tilde{m}[\epsilon]_{21} & \tilde{m}[\epsilon]_{22} & \tilde{m}[\epsilon]_{23} & 0 & 0 & 0 \\ \tilde{m}[\epsilon]_{31} & \tilde{m}[\epsilon]_{32} & \tilde{m}[\epsilon]_{33} & fy_{L4} \cos^2 \frac{\epsilon}{2} & fy_{L4} \sin^2 \frac{\epsilon}{2} & -f \frac{y_{L1}}{\sqrt{2}} \sin \epsilon \\ 0 & 0 & f \frac{y_{R4}^*}{\sqrt{2}} \sin \epsilon & M_4 & 0 & 0 \\ 0 & 0 & -f \frac{y_{R4}^*}{\sqrt{2}} \sin \epsilon & 0 & M_4 & 0 \\ 0 & 0 & fy_{R1}^* \cos \epsilon & 0 & 0 & M_1 \end{pmatrix}
$$

Alberto Parolini 12 26/11/2015 the 6 × 6 (or 4 × 4) matrix, but actually only block diagonalizes it. Nevertheless, this is enough since in **La** *L*
 La La La *L***

La La** *L* **La La** *L***

La La** *L* **La La** *L* **La La** *L* **La L**

Up Sector Mass Matrix this new basis the heavy eigenstates are diagonal and they can be safely integrated out at tree level. For the up-quark sector we get, up to *^O*(*s*³ $\overline{}$ Up Sector Mass Matrix

$$
U_{uL}^{\dagger} M_{\rm up} U_{uR} \simeq \begin{pmatrix} m_U & 0 \\ 0 & D_M \end{pmatrix} \qquad m_U = V_{uL} M_U V_{uR}^{\dagger}
$$

$$
m_U \simeq \frac{s_{2\epsilon}}{2} m_{\rm UV}^u + m_t \Pi, \quad \Pi = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}
$$

$$
V_{uL,R} \sim \begin{pmatrix} O(1) & O(1) & O(\frac{m_c}{m_t}) \\ O(1) & O(1) & O(\frac{m_c}{m_t}) \\ O(\frac{m_c}{m_t}) & O(\frac{m_c}{m_t}) & 1 \end{pmatrix}
$$

Alberto Parolini 13 26/11/2015 Alberto Parolini

2. Up Sector Couplings We loosely identify *M*[∗] ∼ *M*⁴ ∼ *M*¹ ∼ *|M*¹ − *M*4*|* ∼ *f*, following our assumption of light top partners. [√]2*MTMT*˜ *mb*Σ*^d*

$$
\Sigma_u \sim \left(\begin{array}{ccc} m_c^2 & m_c^2 & m_c m_t \\ m_c^2 & m_c^2 & m_c m_t \\ m_c m_t & m_c m_t & m_t^2 \end{array} \right)
$$

$$
y_u \simeq \frac{m_U}{f s_{2\epsilon}/2} \left(1 - \frac{1}{2} s_{2\epsilon}^2 \right) + B_u \,, \qquad \qquad B_u \sim \frac{\Sigma_u}{M_*^2}
$$

$$
\delta A_{NC}^{tL}\big|_{3\times3}\simeq\frac{g}{c_W}\frac{\Sigma_u}{M_*^2}\,,\quad \delta A_{NC}^{tR}\big|_{3\times3}\simeq-\frac{g}{c_W}\frac{\Sigma_u}{M_*^2}
$$

Alberto Parolini 14 26/11/2015 Exact expressions are lengthy and are not reported here. They are obtained as outlined in Appendix A.2.

Flavor Preserving as expected [57, 58, 59]. In the limit *yL*¹ = *yL*4, *yR*¹ = *yR*⁴ and *c^L* = *c^R* = 1*/* formulae that can be considered as an expression of more general complex of more general complications of more general complications of more general complications of more general complications of more general complications

$$
\delta g_{Zt_L} \simeq -\frac{g}{c_W} \left(\frac{m_t}{M_*}\right)^2 \frac{\left(1 - s_{\phi R}^2\right)^2}{2s_{\phi R}^2}, \quad \delta g_{Zt_R} \simeq -\frac{g}{c_W} \left(\frac{m_t}{M_*}\right)^2 \frac{\left(2 - s_{\phi L}^2\right)}{2}
$$

Flavor Preserving as expected [57, 58, 59]. In the limit *yL*¹ = *yL*4, *yR*¹ = *yR*⁴ and *c^L* = *c^R* = 1*/* formulae that can be considered as an expression of more general complex of more general complications available. Such deviation, however, also enters the coupling to charged currents: besides the coupling threatening threatening threatening threatening threatening threatening threatening threatening threatening threatening

$$
\delta g_{Zt_L} \simeq -\frac{g}{c_W} \left(\frac{m_t}{M_*}\right)^2 \frac{\left(1 - s_{\phi R}^2\right)^2}{2s_{\phi R}^2}, \quad \delta g_{Zt_R} \simeq -\frac{g}{c_W} \left(\frac{m_t}{M_*}\right)^2 \frac{\left(2 - s_{\phi L}^2\right)}{2}
$$

$$
\text{CKM unitarity:} \qquad \qquad |\delta A_{CC}^L|^{1/2} \sim \left| \frac{m_t}{M_*} \frac{(1 - s_{\phi R}^2)}{\sqrt{2} s_{\phi R}} \right| \lesssim 10^{-1}
$$

Flavor Preserving as expected [57, 58, 59]. In the limit *yL*¹ = *yL*4, *yR*¹ = *yR*⁴ and *c^L* = *c^R* = 1*/* formulae that can be considered as an expression of more general complex of more general complications available. Such deviation, however, also enters the coupling to charged currents: besides the coupling threatening 1*/*2

$$
\delta g_{Zt_L} \simeq -\frac{g}{c_W} \left(\frac{m_t}{M_*}\right)^2 \frac{\left(1 - s_{\phi R}^2\right)^2}{2s_{\phi R}^2}, \quad \delta g_{Zt_R} \simeq -\frac{g}{c_W} \left(\frac{m_t}{M_*}\right)^2 \frac{\left(2 - s_{\phi L}^2\right)}{2}
$$

CKM unitarity:
$$
|\delta A_{CC}^L|^{1/2} \sim \left|\frac{m_t}{M_*} \frac{\left(1 - s_{\phi R}^2\right)}{\sqrt{2s_{\phi R}}}\right| \lesssim 10^{-1}
$$

 α

$$
\delta g_{Zb_L} = 0 \,, \quad \delta g_{Zb_R} = -\frac{g s_{2\epsilon}^2}{8 c_W} \left(\frac{y_{L4} f m_{UV33}^d}{M_4^2 + y_{4L}^2 f^2} \right)^2 \simeq -\frac{g}{2 c_W} s_{\phi L}^2 c_{\phi L}^2 \left(\frac{m_b}{M_*} \right)^2
$$

 $\overline{}$ b coupli 1*/*2 ano
≀ # $\begin{array}{c} \begin{array}{c} 1 \\ 1 \end{array} \end{array}$ # $\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1-\frac{1}{\sqrt{1+\frac{1$ *M*[∗] (*1 − s*2)
φ*R*
2 *s*² φ*R* r<mark>ameter</mark>: a: $\ddot{\mathbf{r}}$ Loop effects in Zbb couplings and S,T parameters: as in conventional CHM

2. Flavor Violating with **B**
 Bu given in Eq.(2.16). The contribution of a Higgs exchange to the operator α because *[|]Bd[|]* [∼] !(*mb/M*∗)³ [∼] ¹⁰−7(1 TeV*/M*∗)3. Flavour violating *^Z* interactions are controlled by

*uL*δ*AtL NC*_{*V*} *NC*^{*u*} liated

$$
\text{Higgs mediated up FCNC} \qquad \qquad \frac{1}{m_H^2} \bigg(\frac{m_c}{M_*} \bigg)^4 \simeq \frac{10^{-12}}{\text{TeV}^2} \left(\frac{1 \text{ TeV}}{M_*} \right)^4
$$

$$
\text{Z mediated up FCNC} \qquad \frac{g^2}{16 c_W^2 m_Z^2} \bigg(\frac{m_c}{M_*} \bigg)^4 \simeq \frac{10^{-11}}{\text{TeV}^2} \left(\frac{1 \text{ TeV}}{M_*} \right)^4
$$

Z mediated down FCNC *m*² edia¹ *m^Z m^V* \mathbb{R}^2 **Z** mediated down FCNC

$$
\frac{10^{-4}}{\text{TeV}^2} \left[(V_{dL33}^* V_{dL31})^2 \mathcal{Q}_1^{db} + (V_{dL33}^* V_{dL32})^2 \mathcal{Q}_1^{sb} + (V_{dL32}^* V_{dL31})^2 \mathcal{Q}_1^{ds} \right]
$$

2. Flavor Violating: Top Couplings

for the flavour violation has the flavour structure from the flavour structure from the direct Yukawa couplings. As it can be a simple from the direct Yukawa coupling \mathbb{R} structure from the direct Yukawa couplings. As for the flavour violation has the flavour structure from the flavour structure from the direct Yukawa couplings. As it can be a simple from the direct Yukawa coupling \mathbb{R} and \mathbb{R} are the direct Yukawa couplings. LHC Run I

$$
y_{tc,L} \simeq y_{tc,R} \sim \frac{m_c m_t}{f M_*} \simeq 10^{-4} \qquad \qquad \mathcal{B}(t \to hc) < 6 \div 8 \times 10^{-3}
$$

$$
(\delta A_{NC}^{tL,R})_{32} \simeq \frac{g}{c_W} \frac{m_t m_c}{M_*^2} \simeq 10^{-4} \qquad \qquad \mathcal{B}(t \to Zc) < 5 \times 10^{-4}
$$

Flavor Violating Processes: heavy resonances $\overline{}$ *m^t* \cdot **h** *M*[∗] **Property resonances** and α

$$
\mathcal{L} = \Phi(g_B \bar{Q}Q + g_S \bar{\tilde{T}} \tilde{T}) + \frac{1}{2} m_{\Phi}^2 \Phi^2
$$

$$
\mathcal{L} \simeq \left(\frac{\tilde{g}}{m_{\Phi}}\right)^2 \left(\frac{m_c}{m_t}\right)^4 \left(\frac{m_t}{M_*}\right)^2 \mathcal{Q}_4^{uc} \simeq \left(\frac{1 \text{ TeV}}{M_*}\right)^2 \left(\frac{\tilde{g}}{m_{\Phi}/\text{TeV}}\right)^2 \times \frac{10^{-10}}{\text{TeV}^2} \mathcal{Q}_4^{uc}
$$

$$
\mathcal{L} \simeq \left(\frac{g_B s_{\phi L}^2 c_{\phi L}}{m_{\Phi}}\right)^2 \left(\frac{m_b}{M_*}\right)^2 \left[z_4^{db} \mathcal{Q}_4^{db} + z_4^{sb} \mathcal{Q}_4^{sb} + z_4^{ds} \mathcal{Q}_4^{ds}\right]
$$

$$
\simeq \left(\frac{1 \text{ TeV}}{M_*}\right)^2 \left(\frac{g_B}{m_{\Phi}/\text{TeV}}\right)^2 \times \frac{10^{-5}}{\text{TeV}^2} \left[z_4^{db} \mathcal{Q}_4^{db} + z_4^{sb} \mathcal{Q}_4^{sb} + z_4^{ds} \mathcal{Q}_4^{ds}\right]
$$

$$
z_4^{d_{\alpha}d_{\beta}} = V_{dL3\alpha}^* V_{dL3\beta} \sum_{\gamma\delta} V_{dR\gamma\beta} V_{dR\delta\alpha}^*
$$

Alberto Parolini 26/11/2015

- + vector resonances
- $+$ Zbb, Zcc, \ldots
- + CP and CP
- + Higgs couplings
- + W FV couplings
- + UV four fermion operators (qq)(qq) $\Lambda_{UV} \lesssim 10^5$ TeV

\sum ummary we have of its couplings. In composite Higgs models, relative deviations in its couplings to \sum

- + vector resonances $\frac{1}{2}$ sector: in the correction is universal and it has the form in the f
	- $+$ Zbb, Zcc, \dots
	- $+$ CP and \mathcal{L} *ySM* − *y*
	- + Higgs couplings *m/v* " ¹ [−] ¹ [−] ²*s*²
	- + W FV couplings
- + UV four fermion operators (qq)(qq) This value is still allowed for the *h*¯*bb* coupling [80]. For light quarks the Yukawa couplings are not construction in the same precision in the same

Up sector: OK flavour bounds require the mixing angles to be small, so that a certain amount of alignment seems to be small, so that any \sim op sector: $\mathsf{U}\mathsf{N}$

Down sector: $|z_4^{db}| < 1 \div 10^{-2}$, $|z_4^{sb}| < 1 \div 10^{-1/2}$, $|z_4^{ds}| < 10^{-4} \div 10^{-6}$ $|V_{dR}^*|$ $|V_{dL33}^* V_{dL13}| < 10^{-1}$, $|V_{dL33}^* V_{dL23}| < 10^{-1/2}$, $|V_{dL13}^* V_{dL23}| < 10^{-5/2}$ $|V_{dL13}| < 10^{-1}$, $|V_{dL23}| < 10^{-1/2}$, *,* (3.42) $|V_{di}^*|$ $|V_{dL33}^*V_{dL31}| < 10^{-1} \div 10^{-3}, \quad |V_{dL33}^*V_{dL32}| < 1 \div 10^{-2},$ $|V^*_{dL32}V_{dL31}| < 10^{-3} \div 10^{-5}$.

Summary

- + vector resonances
- + Zbb, Zcc, … $t = 7bh$, $7cc$
- + CP and CP t CP and \mathcal{Q} boson FCNCs and \mathcal{Q} boson FCNCs is more interested in the sonance is more interest.
- + Higgs couplings model dependent. The product dependent. The product contributions is no way to avoid such contributions in general. The such contributions in general. The such contributions in general. The such contributions in general. T
	- + W FV couplings
	- + UV four fermion operators (qq)(qq)

Up sector: OK \blacksquare moreover many special case \bigcap K

Down sector:

$$
V_{dL,R} \sim \begin{pmatrix} O(1) & O(1) & O(\frac{m_s}{m_b}) \\ O(1) & O(1) & O(\frac{m_s}{m_b}) \\ O(\frac{m_s}{m_b}) & O(\frac{m_s}{m_b}) & 1 \end{pmatrix}
$$

- 1. Different top partners, different cosets
- 2. Vector-like quarks
- 3. Different origin of bottom mass
- 4. Fully composite right top

Additional top partners Δ dditional top partners. partners, we restrict to custodians [46] for a zero tree level correction to *Z*¯*bLbL*: the minimal options Additional top partners. For the down sector we obtain the following Higgs couplings couplings of the Higgs coupling couplings. For the following coupling \mathbb{R}^n

for instance $14 = 1 + 4 + 9$ f_{c} we focus on partners in the 9 with a mass $\frac{1}{2}$ and $\frac{1}{2}$ and $\frac{1}{2}$ $\frac{1}{100}$ moderne we obtain the following flavour-violating couplings of the Higgs of the Higgs of the Higgs of the Higgs solution $\frac{1}{100}$ tance 1 ϵ ² $1 + 4$ $+$ 9

$$
\mathcal{L} \simeq -\frac{s_{\phi 9L}^2 c_{\phi L}^3}{c_{\phi 9L}^2} \frac{\epsilon^2}{f} h \bar{b}_L \left(m_{\text{UV31}}^d d_R + m_{\text{UV32}}^d s_R + m_{\text{UV33}}^d b_R \right)
$$

$$
\propto \left(\bar{d}_L \bar{s}_L \bar{b}_L \right) \left(\begin{array}{ccc} 0 & 0 & 0 \\ 0 & 0 & 0 \\ m_{\text{UV31}}^d & m_{\text{UV32}}^d & m_{\text{UV33}}^d \end{array} \right) \left(\begin{array}{c} d_R \\ s_R \\ b_R \end{array} \right)
$$

$$
\mathcal{L} \;\;\simeq\;\; \frac{1}{m_H^2} \bigg(\frac{\epsilon m_b}{f} \bigg)^2 \left[z_4^{db} \mathcal{Q}_4^{db} + z_4^{sb} \mathcal{Q}_4^{sb} + z_4^{ds} \mathcal{Q}_4^{ds} \right] \simeq \frac{10^{-4}}{\text{TeV}^2} \left[z_4^{db} \mathcal{Q}_4^{db} + z_4^{sb} \mathcal{Q}_4^{sb} + z_4^{ds} \mathcal{Q}_4^{ds} \right]
$$

Alberto Parolini 23 t

3. Bottom mass to make the mass shortcom mass, we do not new resonance. We thus control \mathbb{R} and Eq.(2.5) and Eq.(2.8) with Eq.(2.8) with Eq.(2.5) and Eq.(2.5) and Eq.(2.8) with Eq.(2.8) with Eq.(2.8) with Eq.(2.8) with Eq.(2.8) with **WITH THE TENNIS EMBEDDING, its U/1, matching is 2***/3, matching the charge of with the charge of with the charge of with term could have been with the charge of* μ **WITH THE TEAM THIS EMBEDDING, its U/1, matching the charge is 2***/3, matching the charge of with the charge of w*

Main motivation: dynamical explanation of structure of 3x3 down unitary transformation.

$$
\mathcal{L} = y_R f \,\bar{\psi}_L U^t d_{3R}^{14} \Sigma + h.c. = \frac{1}{2} y_R f s_\theta \bar{B}_L b_R + h.c.
$$
\n
$$
\int \int \text{Tr}[\bar{Q}_{14} d_{3R}^{14}] \qquad Q_{14} = U(Q_1 + Q_4 + Q_9) U^t
$$

3. Bottom mass to make the mass shortcom mass, we do not new resonance. We thus control \mathbb{R} and Eq.(2.5) and Eq.(2.8) with Eq.(2.8) with Eq.(2.5) and Eq.(2.5) and Eq.(2.8) with Eq.(2.8) with Eq.(2.8) with Eq.(2.8) with Eq.(2.8) with \mathbf{r} mass, we do not neglect to add any new resonance. We thus complement Eq.(2.5) and Eq.(2.5) with Eq.(2.8) with Eq.(2.8) with \mathbf{r} \blacksquare

Main motivation: dynamical explanation of structure of 3x3 down unitar *M*ain motivation: dyna n *Main motivation: dynamical explanation of structure of 3x3 down unitary transformation.*

$$
\mathcal{L} = y_R f \bar{\psi}_L U^t d_{3R}^{14} \Sigma + h.c. = \frac{1}{2} y_R f s_\theta \bar{B}_L b_R + h.c.
$$

$$
d_{3R}^{14}=\frac{b_R}{2\sqrt{2}}\left(\begin{array}{cccccc} 0 & 0 & 1 & i & 0 \\ 0 & 0 & -i & 1 & 0 \\ 1 & -i & 0 & 0 & 0 \\ i & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{array}\right)
$$

$$
\mathcal{L} = \bar{d}_{\alpha L} m_{\alpha \beta}^d d_{\beta R} + h.c. , \quad m^d = m_{UV}^d \frac{s_{2\epsilon}}{2} + \Pi \frac{f y_R s_{\phi L}}{2} s_\epsilon
$$

• Top partial compositeness and direct Yukawas (in pNGB composite Higgs models)

• Analysis of indirect bounds

Generalizations

- Additional partners
- Bottom partial compositeness (without partners)
- vector-like quarks

• …

Thank You