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Lepton Flavor in Composite Higgs Models

Florian Goertz[a,*]

[a] *Max-Planck-Institut für Kernphysik, Saupfercheckweg 1, 69117 Heidelberg, Germany*

E-mail: fgoertz@mpi-hd.mpg.de

In these proceedings, I will present the status of lepton flavor physics in composite Higgs models with partial compositeness in the light of recent data in the lepton sector. I will consider anarchic flavor setups, scenarios with flavor symmetries, and minimal incarnations of the see-saw mechanism that naturally predict non-negligible lepton compositeness. The focus will be on lepton flavor violating processes, dipole moments, and on probes of lepton flavor universality, all providing stringent tests of partial compositeness. The expected size of effects in the different approaches to lepton flavor and the corresponding constraints will be discussed, including 'UV complete', effective, and holographic descriptions.

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1. Introduction

The concept of partial compositeness (PC) [1–4] in composite Higgs (CH) models offers an attractive means to explain the flavor hierarchies. In such a framework, the Higgs is a composite pseudo Nambu-Goldstone boson (pNGB) of a spontaneously broken global symmetry of a new confining sector. Linear mixings of the Standard Model (SM) fermions with composite resonances can then address the observed mass spectra. At the same time, dangerous flavor-changing neutral currents (FCNCs) are suppressed by a 'geometric' GIM mechanism [2, 5–8].

In spite of obvious similarities, the lepton sector is distinct from the quark sector due to the leptonic mixing angles being sizable [9] and all leptons being significantly lighter than the weak scale [with neutrino masses even $\lesssim 1$ eV]. Thus, one could expect that leptons are largely elementary and behave SM-like, not affecting the one-loop Higgs potential or not extremely well-measured observables. However, as we will show, different explicit models addressing the lepton masses and mixings predict some lepton compositeness, changing the picture. Moreover, stringent flavor limits lead to relevant bounds even for basically elementary leptons.

PC for leptons has been studied in [10–36], mostly from a low-energy perspective and via holographic methods. Ultra-violet (UV) completions have been envisaged, too, considering the constituents and dynamics forming the bound states that mix with the SM-like fermions [37–45]. A subclass, dubbed "minimal fundamental PC" (MFPC) [41, 42, 46], e.g. assumes the composite fermions to consist of an elementary fermion $\mathcal{F}$ and a scalar $\mathcal{S}$. In contrast to 3-fermion states, the scaling dimension of the composite operator O_F is then expected close to the canonical $[O_F]_0 = [\mathcal{F}] + [\mathcal{S}] = 5/2 \ll 3[\mathcal{F}] = 9/2$, realizing the top mass without large anomalous dimension [47].

2. Partial Compositeness: Effective Description and Different Embeddings of Leptons

While also commenting on predictions of MFPC, to capture a broad range of potential UV completions for the phenomenological study and to make contact with the large set of previous works in an effective/holographic SO(5)/SO(4) setup, we will stick to an effective description of PC. Below the scale $\Lambda_{\rm UV}$ where the elementary/composite-sector interactions are generated, PC for leptons can in fact be described via linear mixings of the SM-like elementary fields with composite operators $O^l_{L,R}$ of the confining sector

$$\mathcal{L}_{\rm mix} = (\lambda^\ell_L/\Lambda_{\rm UV}^{\gamma^\ell_L})\, \bar{l}^\ell_L O^\ell_L + (\lambda^\ell_R/\Lambda_{\rm UV}^{\gamma^\ell_R})\, \bar{l}^\ell_R O^\ell_R + (\lambda^{\nu_\ell}_R/\Lambda_{\rm UV}^{\gamma^{\nu_\ell}_R})\, \bar{\nu}^\ell_R O^{\nu_\ell}_R \;+ \text{h.c.}, \tag{1}$$

eventually responsible for lepton masses. Here, $\ell = e, \mu, \tau$, with an obvious analogue for quarks, $\lambda^l_{L,R}$ are ($O(1)$) couplings and $\gamma^l_{L,R} = [O^l_{L,R}] - 5/2$ are the anomalous dimensions of the composite operators. Moreover, l^ℓ_L, l^ℓ_R, and ν^ℓ_R correspond to the embeddings of the SM-like fields into irreducible representations of the global symmetry, as SO(5) in the Minimal Composite Higgs Model (MCHM) [2], according to the operators they mix with.

Small differences in $\gamma^i_{R,L}$ lead to hierarchical fermion masses (and possibly mixings) [6, 12, 48, 49] from an anarchic UV structure, after integrating out the resonances excited by $O^l_{L,R}$, inducing

$$m_l \sim g_* v/\sqrt{2}\, \epsilon^l_L \epsilon^l_R\,, \quad \text{where } \epsilon^l_{L,R} \sim \lambda^l_{L,R}/g_*\, (\mu/\Lambda_{\rm UV})^{\gamma^l_{L,R}} \tag{2}$$

defines the 'degree of compositeness' of a chiral SM-like field. Here, g_* is the coupling of the resonances and $\mu \sim \Lambda_c \sim$ TeV the IR scale where the composites condense (see [50] for more details).[1]

Basic Anarchic Setup Similar to the quark sector, leptons in CH models can be realized just by assuming anarchic values for the dimensionless input parameters, generating the hierarchies in charged-lepton masses after condensation by the UV-scale suppression, $\Lambda_{UV} \gg \mu$ in Eq. (1). The leptonic mixing matrix and neutrino masses could be kept non-hierarchical by appropriate assumptions on the PC structure, as envisaged in Refs [14, 17, 18, 22, 26, 36]. However, even though PC suppresses FCNCs, it remains a challenge to evade the stringent flavor constraints, as we will see, pushing the pNGB decay constant $f \sim \Lambda_c/4\pi$ above the TeV scale.

Models with Flavor Symmetries Flavor symmetries can be used to refine the anarchic approach, properly generating the particular form of the leptonic mixing matrix and of neutrino masses together with hierarchical charged-lepton masses and a flavor protection going beyond the geometric GIM (see below). Popular flavor groups G_f are summarized in Tab. 1. The discovery of a non-zero θ_{13} angle [51–54] lead to a broadening to (product) groups beyond the early A_4, S_4, or (double tetrahedral) T', and to considering spontaneous breaking of such symmetries. Interestingly, models with flavor symmetries often feature a suppression of the Yukawa couplings in the composite sector (inducing lepton masses after mixing), since those control the breaking of G_f (see, e.g., [20]). Moreover, left-handed (LH) lepton compositeness is bound to be small due to lack of custodial

[1] It would be interesting to examine the emergence of a hierarchical spectrum explicitly in a setup of MFPC.

Table 1: Popular choices for flavor symmetry G_f in the lepton sector, where below $X \in \{A_5, \Delta(96), \Delta(384)\}$.

G_f	$A_4 \times Z_N$	$S_4 \times Z_N^n$	$X \times Z_N$	$\Delta(27) \times Z_4 \times Z_4'$	S_3	T'	$U(N)$
Ref.	[16, 20, 21, 28]	[24, 25, 29]	[25]	[33]	[31]	[19]	[27, 36]

protection of $Z\bar{\ell}_L\ell_L$ couplings. In turn, the τ_R mixes quite significantly with the composite sector to generate m_τ, which can lead to interesting LHC/Higgs signatures [23, 32, 55, 56]. However, non-negligible compositeness in the charged lepton sector can also emerge beyond such models of flavor symmetries, simply from the scale of neutrino masses – as in minimal realizations of a seesaw in the CH framework that we will discuss now.

Minimal Seesaw Model and Composite Leptons In the CH framework, a very minimal realization of the lepton sector is possible, explaining the tiny neutrino masses via a type-III seesaw with heavy fermionic $SU(2)_L$ triplets and providing at the same time an efficient flavor protection. Employing such triplets, a *unification* of the right-handed (RH) lepton sector is possible and a single, symmetric, representation of SO(5) can host both the charged RH leptonic $SU(2)_L$ singlet and the RH seesaw triplet [32, 34, 35]. This leads to a more minimal model for leptons, featuring less new particles and less parameters, than conventional analogues to minimal viable (MCHM$_5$-like) quark sectors, which require in fact mixings with *four* fundamental **5**'s of SO(5) [4, 20].

Here, the PC Lagrangian of Eq. (1) only contains linear interactions with *two* operators, embedding $l_L^\ell \sim \mathbf{5} = (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1})$ and $l_R^\ell \sim \mathbf{14} = (\mathbf{3},\mathbf{3}) \oplus (\mathbf{2},\mathbf{2}) \oplus (\mathbf{1},\mathbf{1})$, where the former hosts the LH SM doublet in the $(\mathbf{2},\mathbf{2})$ of $SU(2)_L \times SU(2)_R$ and the latter contains now both the see-saw triplet Σ_ℓ and RH singlet in the $(\mathbf{3},\mathbf{3})$ and $(\mathbf{1},\mathbf{1})$, see [34, 35]. Adding a Majorana mass term in the elementary sector

$$\mathcal{L}_{\rm el} = -\frac{1}{2}\left[M_\Sigma^{\ell\ell'} \mathrm{Tr}\left(\bar{\Sigma}_{\ell R}^c \Sigma_{\ell' R}\right) + \mathrm{h.c.}\right], \quad \Sigma_\ell = \begin{pmatrix} \hat{\nu}^\ell/\sqrt{2} & \hat{\lambda}^\ell \\ \hat{\ell} & -\hat{\nu}^\ell/\sqrt{2} \end{pmatrix}, \; \ell = e, \mu, \tau\,, \tag{3}$$

explains the tiny neutrino masses via large $M_\Sigma^{\ell\ell'} \gg v$. If now $l_R^\ell \supset \Sigma_\ell$ in Eq. (1) would be fully elementary, an effective Majorana mass of $O(M_{\rm Pl})$ - the fundamental UV scale of the theory - would emerge, resulting in a significantly too strong suppression of neutrino masses (note that also the Dirac mass is PC-suppressed). This calls for a non-negligible compositeness of l_R^ℓ, bringing down the effective Majorana mass [34, 35, 50]. A hierarchy $0 \ll \epsilon_R^\tau \ll \epsilon_R^\mu \ll \epsilon_R^e$ follows from the fact that charged lepton hierarchies require $\epsilon_L^e \ll \epsilon_L^\mu \ll \epsilon_L^\tau \ll 1$ (where the sizable RH compositeness leads to a cancellation of the corresponding ϵ_R^ℓ exponential in (2) [24, 34, 35]) while the neutrino mass matrix $\mathcal{M}_\nu \sim v g_* \epsilon_L^\ell (M_\Sigma^{\ell\ell'}/\epsilon_R^\ell \epsilon_R^{\ell'})^{-1} v g_* \epsilon_L^{\ell'}$ should be non-hierarchical.

This will lead to interesting signatures, like lepton flavor universality (LFU) violation in RH couplings within the first generations, as we will discuss below, while being save from flavor and precision constraints. This is because the minimal amount of two SO(5) representations, hosting all leptons, allows for a flavor symmetry broken by a *single* spurion in the strong sector, making it possible to diagonalize the latter [34, 35], while $Z\bar{\ell}_R\ell_R$ is custodially protected [23, 55]. Moreover, the moderate compositeness, together with an (group-theoretically) enhanced contribution of the **14** representation, leads to a sizable leptonic impact on the pNGB Higgs mass [32]. This allows to address the significant tension of minimal CH models with bounds on top-partners of $m_{t'} \gtrsim 1.3$ TeV [57–59] via lifting the partners for given m_h (and f), see left panel of Fig. 1. Here, a scan of the mass of the lightest top partner versus m_h (at $f = 1$ TeV) is performed, comparing the minimal seesaw model (including a minimal quark-sector, colored points) with the MCHM$_5$ (gray points) [32, 34]. While for $m_h(1\text{ TeV}) \approx 105$ GeV (yellow stripe) the latter is in strong tension with LHC limits, the former remains basically unconstrained (even at minimal Barbieri-Giudice tuning $\Delta_{\rm BG}$ [60]), see [34, 35] and [50] for more details.[2]

3. Lepton Flavor: Predictions, Constraints, and Discussion

Lepton Flavor Violation (LFV) and Dipole Moments In CH models, the decay $\mu \to e\gamma$ is induced by penguin-loops involving heavy resonances [14, 22], generating the dipole operator (with here $\ell = \mu$, $\ell' = e$)

$$O_{\ell\ell'}^\gamma \equiv ev\, F_{\mu\nu} \bar{\ell}_L \sigma^{\mu\nu} \ell'_R\,. \tag{4}$$

The latest 90% CL limit on the branching ratio (BR) reads $\mathrm{BR}(\mu \to e\gamma) < 4.2 \times 10^{-13}$ [65], being 5 orders stronger than for the tau decay [9]. In the *anarchic scenario*, the BR scales as (see also [22, 26, 66, 67])

$$\mathrm{BR}(\mu \to e\gamma) = 96\pi^2 e^2 v^6/m_\mu^2 \left(\left|C_{\mu e}^\gamma\right|^2 + \left|C_{e\mu}^\gamma\right|^2\right), \quad C_{\ell\ell'}^\gamma \sim \sqrt{2}/32\pi^2\, g_*^3/m_*^2\, \epsilon_L^\ell \epsilon_R^{\ell'}\,, \tag{5}$$

[2] For a survey of (collider) constraints on CH see [61] and for other setups addressing the top-partner issue [62–64].

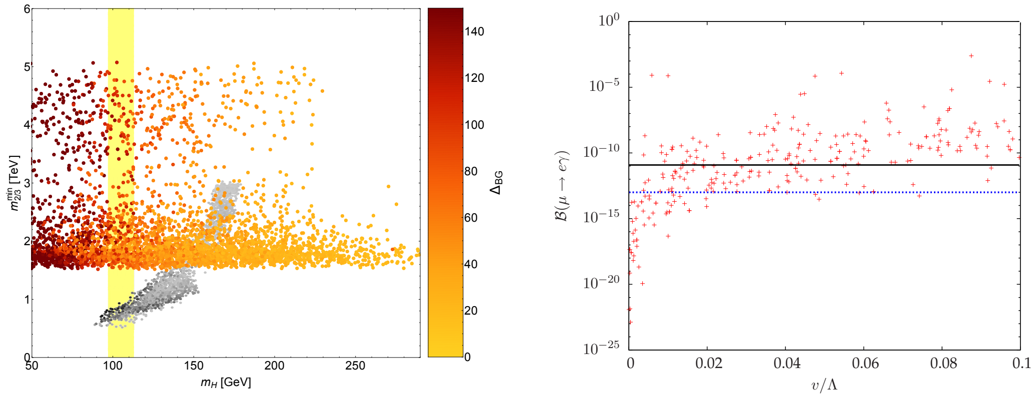

Figure 1: Left: Lightest top-partner mass (and tuning Δ_{BG}) vs. m_h in the minimal seesaw model (colored points) and the MCHM$_5$ (gray), for $f = 1$ TeV. Right: BR$(\mu \to e\gamma)$ in MCHM$_5$-like setup with A_4 flavor symmetry vs. A_4-breaking vev (over the cutoff) v/Λ for $m_* \sim 3$ TeV, $g_* \sim 4$ (from [20]). The solid (dashed) line shows the MEGA (projected MEG) limit.

with m_* the mass scale of the resonances. The experimental constraint above then leads to the bound

$$g_*^3/m_*^2 \sqrt{|\epsilon_L^\mu \epsilon_R^e|^2 + |\epsilon_L^e \epsilon_R^\mu|^2} \lesssim 10^{-7}/\text{TeV}^2 \quad \Longrightarrow \quad \boxed{m_*/g_* \gtrsim 20\,\text{TeV} \quad (\text{BR}(\mu \to e\gamma))}\,, \tag{6}$$

consistent with Refs [36, 66], where we employed Eq. (2) and (conservatively) set $\epsilon_R^\ell = \epsilon_L^\ell$. This would push the anarchic scenario far beyond LHC reach. The electric dipole moment of the electron d_e, being proportional to the *imaginary part* of the (1,1) component of the dipole coefficient of Eq. (4) and scaling as [36, 66]

$$d_e \sim \text{Im}(c_e)\, e/16\pi^2\, g_*^3/m_*^2\, \epsilon_L^e \epsilon_R^e\, v/\sqrt{2}\,, \tag{7}$$

where c_e contains the phase of the setup, provides another bound. The recent $d_e < 1.1 \times 10^{-29} e\,$cm from ACMEII [68] gives

$$\boxed{m_*/g_* \gtrsim \sqrt{\text{Im}(c_e)}\, 75\,\text{TeV} \quad (\text{eEDM})}\,, \tag{8}$$

agreeing with the limits of Refs [36, 66], after updating them. Finally, constraints from $\mu - e$ conversion in Gold bound FCNC couplings to the Z boson $\sim \epsilon_{L,R}^\mu \epsilon_{L,R}^e$. Setting again $\epsilon_R^\ell = \epsilon_L^\ell$, the SINDRUMII 90% CL limit of $\Gamma(\mu Au \to eAu)/\Gamma_{\text{capture}}(\mu Au) < 7 \times 10^{-13}$ [69] delivers a (weaker) bound (see [36, 66]) of

$$\boxed{m_*/\sqrt{g_*} \gtrsim 3\,\text{TeV} \quad (\mu Au \to eAu)}\,. \tag{9}$$

We note that constraints from $\mu \to eee$, probing the same operator, are a factor ~ 3 less strong, while corresponding tau decays and d_μ as well as $(g-2)_\mu$ are even less constraining, see e.g. [36, 66].

In setups with *flavor symmetries*, as in Tab. 1, the bounds from LFV are typically much weaker. For example, in models where leptons transform appropriately under a spontaneously broken A_4 symmetry [16, 20], one can rotate to a flavor-diagonal basis to leading order and the constraints above are reduced to the 1 TeV scale (see also [28]). This is shown quantitatively in the right panel of Fig. 1, where for small A_4-breaking (elementary) vev over the cutoff v/Λ and $m_* \sim 3$ TeV, $g_* \sim 4$, most points are in agreement with a bound of BR$(\mu \to e\gamma) < 5{\times}10^{-13}$. Similar statements hold for the *minimal seesaw model* with analogous flavor protection, as discussed.

In *MFPC*, the flavor structure is induced by the fundamental constituents. If e.g. the techni-color (TC) scalars $\mathcal{S}$ acquire mass solely from TC interactions (and their potential conserves flavor) [41], the coefficient of the dipole operator in (4) will be diagonal and real in the same basis as the SM-fermion Yukawa matrix, $C_{\ell\ell'}^\gamma \propto y_{\ell\ell'}^{\text{SM}}$ (to leading approx.). This pushes BR$(\mu \to e\gamma)$ and d_e below the limits, even for very low TC scale [41].

Lepton Flavor Universality Moving to LFU-violating observables, we focus on the prominent ratios $R_{K^{(*)}} \equiv \text{BR}(B \to K^{(*)}\mu^+\mu^-)/\text{BR}(B \to K^{(*)}e^+e^-)$, constrained at LHCb as $R_K = 0.846^{+0.060}_{-0.054}$ and $R_{K^*} = 0.69^{+0.11}_{-0.07}$ [71, 72] (for $1.1 < q^2/\text{GeV}^2 < 6$), which strongly disfavors $R_{K^{(*)}} > 1$, while in the SM $R_K \approx R_{K^*} \approx 1$. In CH models, corrections typically emerge via electroweak-resonance induced 4-fermion operators [34, 36, 46, 70, 73–75]

$$O_{XY}^{q^1q^2\ell^1\ell^1} = (\bar{q}_X^1 \gamma_\mu q_X^2)(\bar{\ell}_Y^1 \gamma^\mu \ell_Y^2)\,, \quad \text{with coefficients} \;\; C_{XY}^{q^1q^2\ell^1\ell^2} \sim g_*^2/m_*^2\, \epsilon_X^{q^1} \epsilon_X^{q^2} \epsilon_Y^{\ell^1} \epsilon_Y^{\ell^2}\,, \tag{10}$$

where $X,Y = L,R$. The LHCb results already notably constrain μ_R compositeness (for some $\epsilon_X^s \epsilon_X^b > 0$) and μ_L/e_L compositeness together with a non-negligible $\epsilon_R^s \epsilon_R^b > 0$ [70]: reaching $R_{K,K^*} < 1$ requires μ_L or e_L compositeness and basically LH b–s compositeness *or* e_R compositeness, irrespectively of the b–s chirality [70] (see also [73, 76]). Focusing on LH muons/RH electrons, we find a good fit [76–78] for

$$g_*^2/m_*^2\, \epsilon_L^s \epsilon_L^b \epsilon_L^\mu \epsilon_L^\mu \sim 10^{-3}/\text{TeV}^2 \quad \text{or} \quad g_*^2/m_*^2\, \epsilon_X^s \epsilon_X^b \epsilon_R^e \epsilon_R^e \sim 4 \cdot 10^{-3}/\text{TeV}^2\,. \tag{11}$$

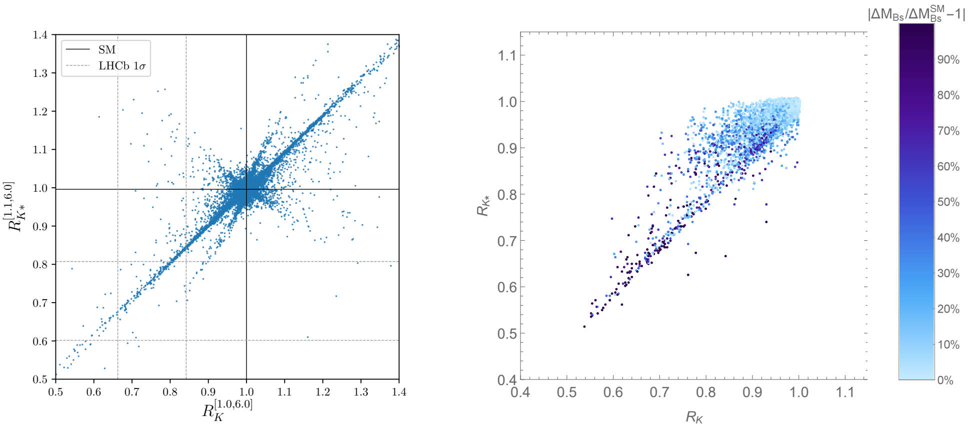

Figure 2: MFPC [46] (left) and minimal seesaw [70] (right) prediction in the $R_K - R_{K^*}$ plane for 1 TeV$< f <$ 3 TeV and f = 1.2 TeV.

Trying to realize one of these patterns led to some efforts in the CH community, envisaging in particular enhanced muon compositeness [36, 46, 73–75].[3] In *MFPC*, after imposing constraints from $\mathrm{BR}(K^+ \to e^+\nu)/\mathrm{BR}(K^+ \to \mu^+\nu)$ and the Z-boson partial width (MFPC lacks custodial protection), the predictions in the $R_K - R_{K^*}$ plane are shown in the left panel of Fig. 2 [46]. The best fit is in principle reachable, and similar conclusions were obtained in (*not-quite anarchic*) holographic [74, 75] and 4D effective [73] setups. It would then be interesting to find a motivated model that makes a clearer prediction for LFU violation. This is provided by the *minimal seesaw model*, which predicts moderate RH electron compositeness leading strictly to $R_{K,K^*} < 1$ (see the right panel of Fig. 2 [70]). A good fit of $R_{K,K^*} \sim 0.8$ is obtained relatively easily, while respecting other constraints due to small LH lepton compositeness and RH custodial protection.

In conclusion, the different patterns of predictions discussed above [combined with searches for (light) resonances] offer a promising means to get a better handle on the nature of leptons.

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[3]Note that the $R_{D^{(*)}}$ anomalies could also be tackled in CH via leptoquark states [79–81], see also [82, 83].