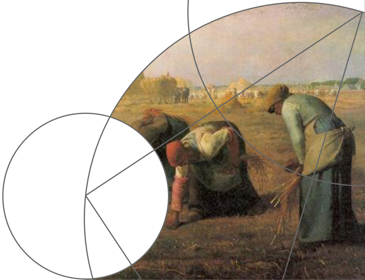
Violation of Lepton Flavor Universality as a probe of Composite Sectors

Adrián Carmona
Institute for Theoretical Physics, ETH Zurich

arXiv:1410.8555, **JHEP 1505 (2015) 002** and work in progress

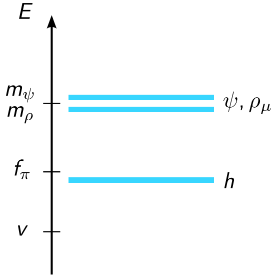
6^{th} Higgs Hunting

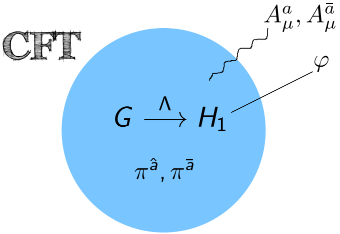
July 30, 2015



Composite Higgs

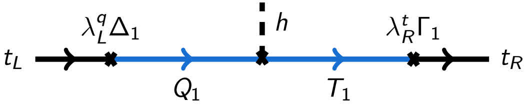
- One interesting solution to the hierarchy problem is making the Higgs composite, the remnant of some new strong dynamics
  [Kaplan, Georgi '84]
- It is particularly compelling when the Higgs is the pNGB of some new strong interaction. Something like pions in QCD
  [Agashe, Contino, Pomarol '04]



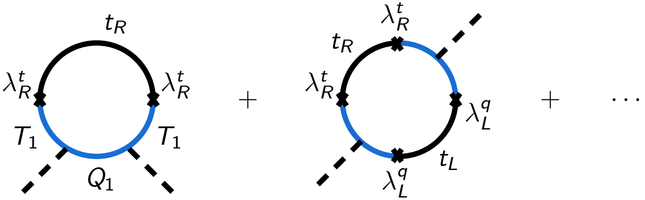


The Higgs Effective Potential

- The coupling to the elementary sector breaks the global symmetry, generating a Higgs potential at the loop level
- The gauge contribution is aligned in the direction that preserves the EW symmetry [Witten '83]
- However, the linear mixings needed to generate the fermion masses



can be also responsible for a viable EWSB

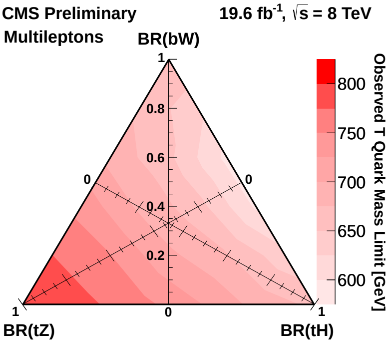


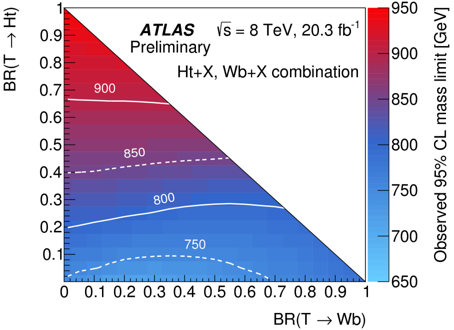
Light Top Partners at the LHC

In general

$$m_H \sim 125 \text{ GeV and } m_{\text{top}} \sim 170 \text{ GeV} \Rightarrow \text{light top partners} \lesssim 1 \text{ TeV}$$

which leads to some tension with current top partner searches performed by ATLAS and CMS



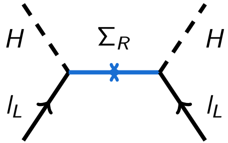


Lepton Sector

It is not necessarily true that the lepton sector has to be fully elementary

- The lepton mixing matrix is non-hierarchical (flavor-symmetries?)
- Neutrinos can be Majorana and exhibit a seesaw mechanism

Let us consider e.g. a type-III seesaw



$$\Sigma_R \sim \mathbf{3}_0$$

In a P_{LR} symmetric case, for each lepton generation ℓ, we have

$$\ell_R \sim (\mathbf{1},\mathbf{1}), \qquad l_L^\ell \sim (\mathbf{2},\mathbf{2}), \qquad \Sigma_R^\ell \sim (\mathbf{3},\mathbf{3})$$

which could in principle fill a complete $\mathbf{14} = (\mathbf{1},\mathbf{1}) \oplus (\mathbf{2},\mathbf{2}) \oplus (\mathbf{3},\mathbf{3})$

A Minimal Lepton Sector

Different chiralities will talk to different conformal operators but we can still have just one operator for both RH fields, Σ_R^ℓ and ℓ_R,

$$\mathcal{L} \supset \frac{\lambda_L^\ell}{\Lambda^{\gamma_L^\ell}} \bar{l}_L^\ell \mathcal{O}_L^\ell + \frac{\lambda_R^\ell}{\Lambda^{\gamma_R^\ell}} \bar{\Psi}_R^\ell \mathcal{O}_R^\ell + \text{h.c.}, \quad \mathcal{O}_L^\ell \sim \mathbf{5}, \quad \mathcal{O}_R^\ell \sim \mathbf{14}$$

Since the Majorana mass is generated at the UV $\|\mathcal{M}_\mathrm{M}\| \sim M_\mathrm{Planck}$, we need sizable $\epsilon_R^\ell \sim \lambda_R^\ell (\mu/\Lambda)^{\gamma_R^\ell}$ to obtain not too small neutrino masses

$$M_\nu \sim v^2 \epsilon_L^2 \epsilon_R^2 \mathcal{M}_\mathrm{M}^{-1}$$

A Minimal Lepton Sector

Different chiralities will talk to different conformal operators but we can still have just one operator for both RH fields, Σ_R^ℓ and ℓ_R,

$$\mathcal{L} \supset \frac{\lambda_L^\ell}{\Lambda^{\gamma_L^\ell}} \bar{l}_L^\ell \mathcal{O}_L^\ell + \frac{\lambda_R^\ell}{\Lambda^{\gamma_R^\ell}} \bar{\Psi}_R^\ell \mathcal{O}_R^\ell + \text{h.c.}, \quad \mathcal{O}_L^\ell \sim \mathbf{5}, \quad \mathcal{O}_R^\ell \sim \mathbf{14}$$

Since the Majorana mass is generated at the UV $\|\mathcal{M}_\text{M}\| \sim M_\text{Planck}$, we need sizable $\epsilon_R^\ell \sim \lambda_R^\ell (\mu/\Lambda)^{\gamma_R^\ell}$ to obtain not too small neutrino masses

$$M_\nu \sim v^2 \epsilon_L^2 \epsilon_R^2 \mathcal{M}_\text{M}^{-1}$$

Just the overall size of the neutrino masses ask for partially composite ℓ_R, for all three generations!

A Minimal Lepton Sector

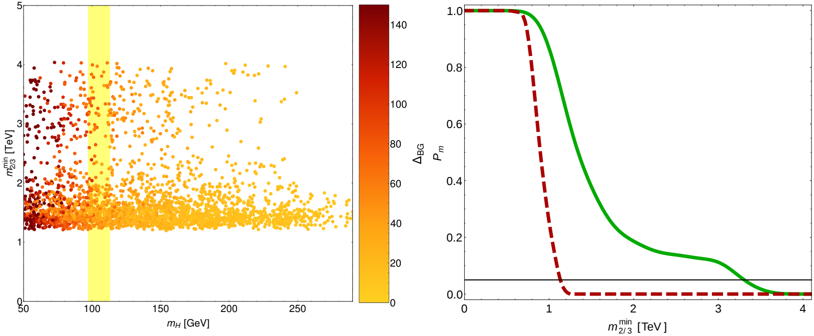
This has a number of interesting consequences:

1. Since the RH fields mix with a **14**, the ℓ_R contribution to the Higgs quartic is $\mathcal{O}(\epsilon_R^2)$, which can be sizeable even for not so big ϵ_R
   - In particular, this can partially cancel a bigger top contribution and make thus the top partners heavier
   - Moreover, the lepton contribution can even trigger the EWSB, allowing for minimal quark setups that were not allowed before
2. Embeding this setup in a MFV scenario allows for only one flavon (connecting the LH and RH sectors) and thus no FCNC or LFV
3. Finally, the different values of ϵ_R^ℓ can reproduce the observed violation of lepton flavor universality, [LHCb arXiv:1406.6482]

$$R_K = \frac{\mathcal{B}(B^+ \to K^+ \mu^+ \mu^-)}{\mathcal{B}(B^+ \to K^+ e^+ e^-)} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

Lifting Top Partners

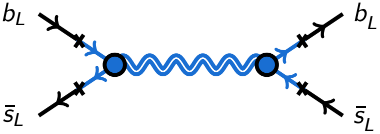
Quarks: $\mathbf{5}-\mathbf{1}-\mathbf{5}-\mathbf{1}$ Leptons: $\mathbf{5}-\mathbf{14}$

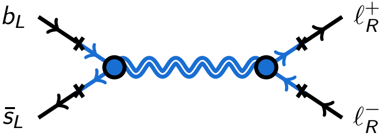


$$Y_*^l = 0.7, \quad Y_*^q = 0.7, \quad f_\pi = 0.8 \text{ TeV}, \quad g_\psi \sim 4.4$$

Violation of Lepton Flavor Universality

$$M_\nu \sim v^2(\epsilon_L^\ell \epsilon_R^\ell)^2 \mathcal{M}_{\rm M}^{-1}, \qquad M_\ell \sim v\epsilon_L^\ell \qquad \Rightarrow \qquad \epsilon_R^\tau \leq \epsilon_R^\mu \leq \epsilon_R^e$$

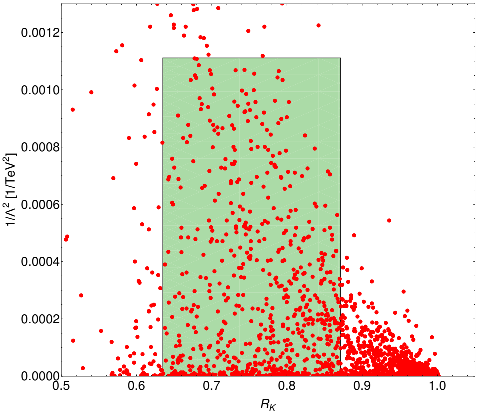




$$\mathcal{O}_1 \sim \frac{g_\rho^2}{m_\rho^2}(\epsilon_L^b)^2(\epsilon_L^s)^2 \leq 1/\Lambda_{\rm max}^2 \qquad\qquad \mathcal{O}_{LR}^\ell \sim \frac{g_\rho^2}{m_\rho^2}\epsilon_L^b\epsilon_L^s(\epsilon_R^\ell)^2$$

Violation of Lepton Flavor Universality

$$M_\nu \sim v^2(\epsilon_L^\ell \epsilon_R^\ell)^2 \mathcal{M}_{\mathrm{M}}^{-1}, \qquad M_\ell \sim v\epsilon_L^\ell \qquad \Rightarrow \qquad \epsilon_R^\tau \leq \epsilon_R^\mu \leq \epsilon_R^e$$



Conclusions

- The inclusion of a lepton sector in CHMs can in some cases significantly change the picture
- Minimality can link disparate features like the size of neutrino masses and the masses of top partners
- This is welcome in the framework of MFV
- Violation of LFU could be the first probe of these scenarios!

Back-up Slides

Partial Compositeness

The fermionic Lagrangian reads

$$\mathcal{L} = \mathcal{L}_{\text{el}} + \mathcal{L}_{\text{mix}} + \mathcal{L}_{\text{comp}}$$

with

$$\mathcal{L}_{\text{el}} = \bar{l}_L^\ell i\not{D} l_L^\ell + \bar{\ell}_R i\not{D}\ell_R + \bar{\Sigma}_R^\ell i\not{D}\Sigma_R^\ell - \frac{1}{2}\left[\mathcal{M}_{\text{M}}^{\ell\ell'}\,\text{Tr}\left(\bar{\Sigma}_R^{\ell c}\Sigma_R^{\ell'}\right) + \text{h.c.}\right]$$

and

$$\mathcal{L}_{\text{mix}} = \frac{\lambda_L^\ell}{\Lambda^{\gamma_L^\ell}}\bar{l}_L^\ell \mathcal{O}_L^\ell + \frac{\lambda_R^\ell}{\Lambda^{\gamma_R^\ell}}\bar{\Psi}_R^\ell \mathcal{O}_R^\ell + \text{h.c.}$$

For $\gamma_R^\ell < 0$, we get a large correction to the RH kinetic terms

$$\frac{\lambda_R^{\ell 2}}{\Lambda^{2\gamma_R^\ell}}\int \text{d}^4p\,\text{d}^4p\ \bar{\Psi}_R^\ell(-p)\langle\mathcal{O}_R^\ell(p)\bar{\mathcal{O}}_R^{\ell'}(-q)\rangle\Psi_R^{\ell'}(q)$$

$$\sim \delta_{\ell\ell'}\lambda_R^{\ell 2}\left(\frac{\mu}{\Lambda}\right)^{2\gamma_R^\ell}\int \text{d}^4x\ \bar{\Psi}_R(x) i\not{\partial}\Psi_R(x)$$

R_K

In order to compute R_K we use the following effective Hamiltonian

$$\mathcal{H}_{\rm eff} = -\frac{4\,G_F}{\sqrt{2}}(V_{ts}^* V_{tb}) \sum_i \hat{C}_i^\ell \mathcal{O}_i^\ell(\mu),$$

with the relevant operators being

$$\begin{aligned}
\mathcal{O}_7 &= \frac{e}{16\pi^2} m_b\,(\bar{s}\sigma_{\alpha\beta}P_R b)\,F^{\alpha\beta}, & \mathcal{O}_7' &= \frac{e}{16\pi^2} m_b\,(\bar{s}\sigma_{\alpha\beta}P_L b)\,F^{\alpha\beta},\\
\mathcal{O}_9^\ell &= \frac{\alpha_{\rm em}}{4\pi}(\bar{s}\gamma_\alpha P_L b)\left(\bar{\ell}\gamma^\alpha \ell\right), & \mathcal{O}_9^{\ell\prime} &= \frac{\alpha_{\rm em}}{4\pi}(\bar{s}\gamma_\alpha P_R b)\left(\bar{\ell}\gamma^\alpha \ell\right),\\
\mathcal{O}_{10}^\ell &= \frac{\alpha_{\rm em}}{4\pi}(\bar{s}\gamma_\alpha P_L b)\left(\bar{\ell}\gamma^\alpha \gamma_5 \ell\right), & \mathcal{O}_{10}^{\ell\prime} &= \frac{\alpha_{\rm em}}{4\pi}(\bar{s}\gamma_\alpha P_R b)\left(\bar{\ell}\gamma^\alpha \gamma_5 \ell\right),
\end{aligned}$$

and $\hat{C}_i = C_i^{\rm SM} + C_i^{\rm NP}$. Using $C_9^{\rm SM} = 4.228$ and $C_{10}^{\rm SM} = -4.410$, we get

$$R_K \approx \frac{|C_{10}^{\rm SM} + C_{10}^\mu + C_{10}^{\prime\mu}|^2 + |C_9^{\rm SM} + C_9^\mu + C_9^{\prime\mu}|^2}{|C_{10}^{\rm SM} + C_{10}^e + C_{10}^{\prime e}|^2 + |C_9^{\rm SM} + C_9^e + C_9^{\prime e}|^2}$$

R_K

In order to compute R_K we use the following effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}(V_{ts}^{*} V_{tb}) \sum_i \hat{C}_i^{\ell} \mathcal{O}_i^{\ell}(\mu),$$

with the relevant operators being

$$\begin{aligned}
\mathcal{O}_7 &= \frac{e}{16\pi^2} m_b \left(\bar{s}\sigma_{\alpha\beta} P_R b\right) F^{\alpha\beta}, & \mathcal{O}_7' &= \frac{e}{16\pi^2} m_b \left(\bar{s}\sigma_{\alpha\beta} P_L b\right) F^{\alpha\beta}, \\
\mathcal{O}_9^{\ell} &= \frac{\alpha_{\text{em}}}{4\pi} \left(\bar{s}\gamma_\alpha P_L b\right) \left(\bar{\ell}\gamma^\alpha \ell\right), & \mathcal{O}_9^{\ell\prime} &= \frac{\alpha_{\text{em}}}{4\pi} \left(\bar{s}\gamma_\alpha P_R b\right) \left(\bar{\ell}\gamma^\alpha \ell\right), \\
\mathcal{O}_{10}^{\ell} &= \frac{\alpha_{\text{em}}}{4\pi} \left(\bar{s}\gamma_\alpha P_L b\right) \left(\bar{\ell}\gamma^\alpha \gamma_5 \ell\right), & \mathcal{O}_{10}^{\ell\prime} &= \frac{\alpha_{\text{em}}}{4\pi} \left(\bar{s}\gamma_\alpha P_R b\right) \left(\bar{\ell}\gamma^\alpha \gamma_5 \ell\right),
\end{aligned}$$

and $\hat{C}_i = C_i^{\text{SM}} + C_i^{\text{NP}}$. Using $C_9^{\text{SM}} = 4.228$ and $C_{10}^{\text{SM}} = -4.410$, we get

$$R_K \approx \frac{|C_{10}^{\text{SM}} + C_{LR}^{\mu}|^2 + |C_9^{\text{SM}} + C_{LR}^{\mu}|^2}{|C_{10}^{\text{SM}} + C_{LR}^{e}|^2 + |C_9^{\text{SM}} + C_{LR}^{e}|^2}$$