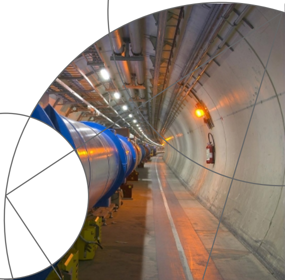
Flavor, Minimality and Naturalness in Composite Higgs Models

Adrián Carmona Bermúdez
Institute for Theoretical Physics, ETH Zurich

In collaboration with F. Goertz
A naturally light Higgs without light Top Partners arXiv:1410.8555

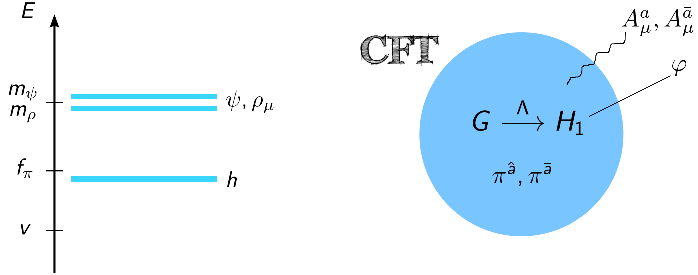
ERC Workshop "EFT for Collider Physics, Flavor Phenomena and EWSB", Mainz



November 11, 2014

Composite Higgs

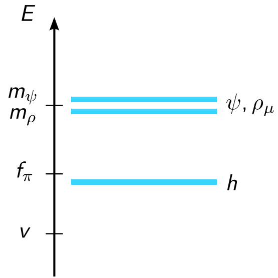
- One interesting possibility is that the Higgs is composite, the remnant of some new strong dynamics [Kaplan, Georgi '84]
- It is particularly compelling when the Higgs is the pNGB of some new strong interaction. Something like pions in QCD [Agashe, Contino, Pomarol '04]

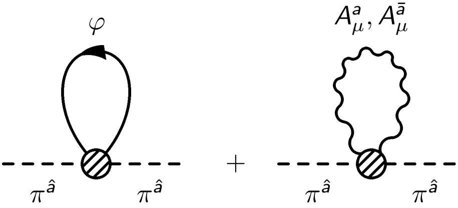


They can naturally lead to a light Higgs $m_\pi^2 = m_h^2 \sim g_{\rm el}^2 \Lambda^2 / 16\pi^2$

Composite Higgs

- One interesting possibility is that the Higgs is 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]





They can naturally lead to a light Higgs $\quad m_\pi^2 = m_h^2 \sim g_{\mathrm{el}}^2 \Lambda^2 / 16\pi^2$

Partial Compositeness

Another compelling feature of these models is that they can address the flavor puzzle through partial compositeness [Kaplan '91]

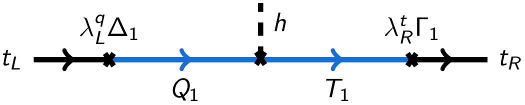
$$\mathcal{L}_{\text{mix}} = \lambda_L^q \bar{q}_L \mathcal{O}_L^q + \lambda_R^t \bar{t}_R \mathcal{O}_R^t + \text{h.c.} \quad \langle 0|\mathcal{O}_L^q|Q_n\rangle = \Delta_n \quad \langle 0|\mathcal{O}_R^t|T_n\rangle = \Gamma_n$$

inducing at low energies

$$\mathcal{L}_{\text{mix}} = \lambda_L^q \Delta_1 \bar{q}_L Q_{1R} + \lambda_R^t \Gamma_1 \bar{t}_R T_{1R} + \text{h.c.} + \ldots$$

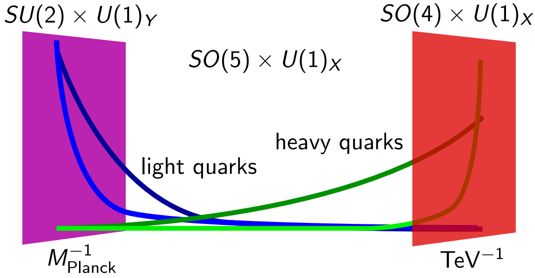
The SM states will be a mixture of elementary and composite states, with masses after EWSB

$$m_t \sim \frac{v}{\sqrt{2}} \frac{\lambda_L^q \Delta_1}{m_{Q_1}} \frac{\lambda_R^t \Gamma_1}{m_{T_1}} \frac{Y}{f_\pi}$$



AdS/CFT correspondence

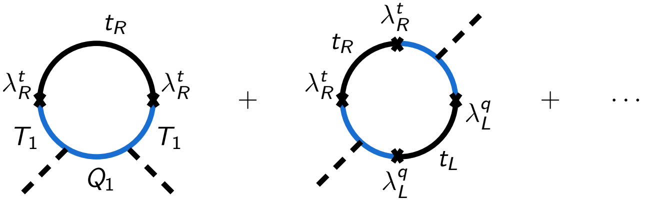
- Models with warped extra dimensions are weakly duals to strongly coupled 4D theories [Maldacena '98]
- They provide a calculable framework for composite Higgs models



- The 5D realizations of models where the Higgs is a pNGB are models of gauge-Higgs unification (GHU), $\pi^{\hat{a}}(x) \sim A_5^{\hat{a}}(x)$

The CW Higgs Effective Potential

- The coupling to the elementary sector breaks the global symmetry, generating a Higgs potential at the loop level
- Fermions give a negative contribution to the Higgs potential, controlled by the size of their linear mixings to the composite sector

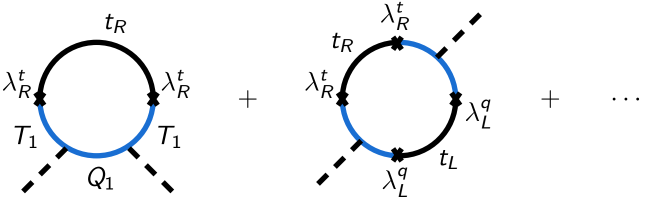


- Top quark also responsible for triggering the EWSB
  [Contino,da Rold,Pomarol, '06]

$$V(h) \cong \frac{9}{2} \int \frac{d^4 p}{(\pi)^4} \log \Pi_W - 2N_c \int \frac{d^4 p}{(2\pi)^4} \log \left(p^2 \Pi_{t_L} \Pi_{t_R} - \Pi_{t_L t_R}^2 \right)$$

The CW Higgs Effective Potential

- The coupling to the elementary sector breaks the global symmetry, generating a Higgs potential at the loop level
- Fermions give a negative contribution to the Higgs potential, controlled by the size of their linear mixings to the composite sector

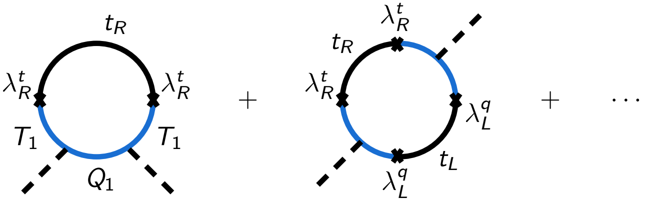


- Top quark also responsible for triggering the EWSB
  [Contino,da Rold,Pomarol, '06]

$$m_h \approx \sqrt{\frac{N_c}{\pi^2}} m_t \frac{m_q^*}{f_\pi}$$

The CW Higgs Effective Potential

- The coupling to the elementary sector breaks the global symmetry, generating a Higgs potential at the loop level
- Fermions give a negative contribution to the Higgs potential, controlled by the size of their linear mixings to the composite sector



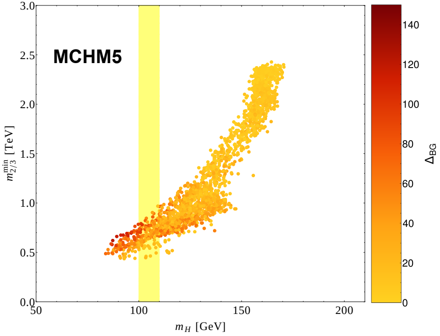
- Top quark also responsible for triggering the EWSB
  [Contino,da Rold,Pomarol, '06]

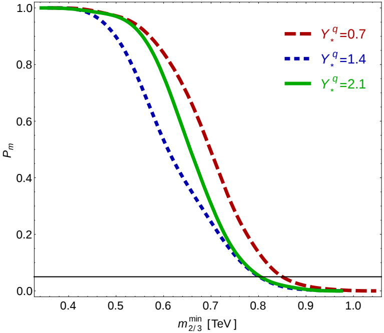
$$m_h \approx \sqrt{\frac{N_c}{\pi^2}}\, m_t \frac{m_q^*}{f_\pi}$$

Light Top Partners at the LHC!

Light Top Partners at the LHC

For most minimal representations and $f_\pi \lesssim 1$ TeV, light top partners are well below the TeV

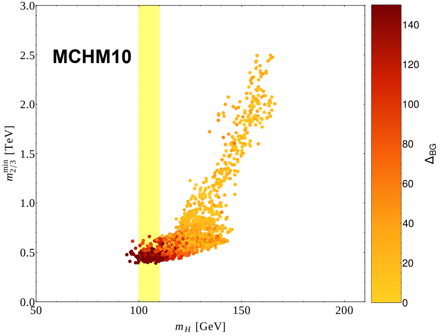


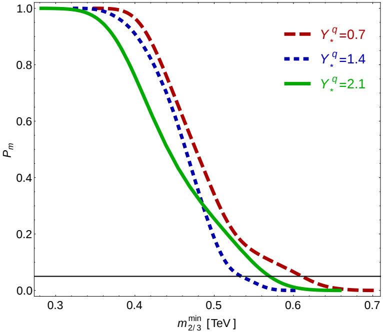


$f_\pi = 0.8$ TeV, $g_\psi \sim 4.4$. $Y_q^* = 0.7$ is the maximum allowed "Yukawa" (IR brane mass)

Light Top Partners at the LHC

For most minimal representations and $f_\pi \lesssim 1$ TeV, light top partners are well below the TeV

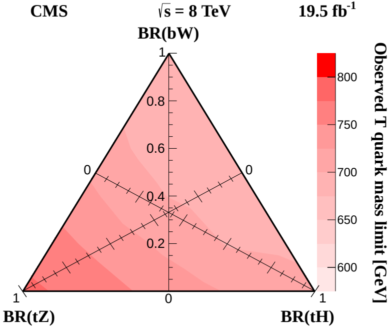


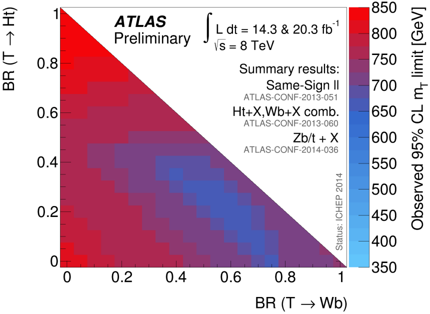


$f_\pi = 0.8$ TeV, $g_\psi \sim 4.4$. $Y_q^* = 0.7$ is the maximum allowed "Yukawa" (IR brane mass)

Light Top Partners at the LHC

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





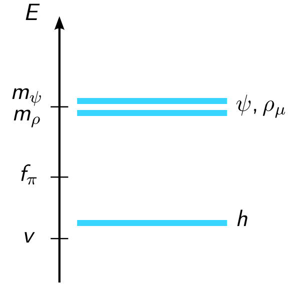
Understanding the Higgs potential

1. The contributions of gauge bosons are completely fixed by the breaking of the strong sector

$$SO(5) \times U(1)_X \to SO(4) \times U(1)_X$$

2. The fermion contributions relay to a large extent on the $SO(5)$ representations of $\mathcal{O}_L^q$ and $\mathcal{O}_R^t$

$$\begin{aligned}
\mathbf{4} &= (\mathbf{2},\mathbf{1}) \oplus (\mathbf{1},\mathbf{2}) \\
\mathbf{5} &= (\mathbf{1},\mathbf{1}) \oplus (\mathbf{2},\mathbf{2}) \\
\mathbf{10} &= (\mathbf{3},\mathbf{1}) \oplus (\mathbf{1},\mathbf{3}) \oplus (\mathbf{2},\mathbf{2}) \\
\mathbf{14} &= (\mathbf{1},\mathbf{1}) \oplus (\mathbf{2},\mathbf{2}) \oplus (\mathbf{3},\mathbf{3})
\end{aligned}$$



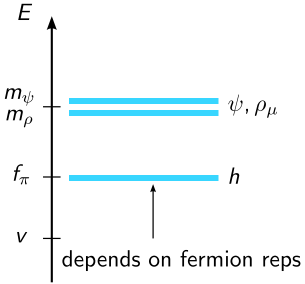
Understanding the Higgs potential

1. The contributions of gauge bosons are completely fixed by the breaking of the strong sector

$$SO(5) \times U(1)_X \to SO(4) \times U(1)_X$$

2. The fermion contributions relay to a large extent on the $SO(5)$ representations of $\mathcal{O}_L^q$ and $\mathcal{O}_R^t$

$$\mathbf{4} = (\mathbf{2}, \mathbf{1}) \oplus (\mathbf{1}, \mathbf{2})$$
$$\mathbf{5} = (\mathbf{1}, \mathbf{1}) \oplus (\mathbf{2}, \mathbf{2})$$
$$\mathbf{10} = (\mathbf{3}, \mathbf{1}) \oplus (\mathbf{1}, \mathbf{3}) \oplus (\mathbf{2}, \mathbf{2})$$
$$\mathbf{14} = (\mathbf{1}, \mathbf{1}) \oplus (\mathbf{2}, \mathbf{2}) \oplus (\mathbf{3}, \mathbf{3})$$



Spurion Analysis

in the $\mathrm{MCHM}_{5,10}$

We can promote $y_L \equiv \lambda_L^q \Delta_1$ and $y_R \equiv \lambda_R^t \Gamma_1$ to fields transforming under $SO(5)$ making the full Lagrangian $SO(5)$ invariant before EWSB

Building all possible $SO(5)$ invariants and using NDA we obtain

$$V^{(5)}(h) = \alpha \sin^2(h/f_\pi) - \beta \cos^2(h/f_\pi) \sin^2(h/f_\pi)$$

with

$$\alpha \sim \frac{N_c m_\psi^4}{16\pi^2} \left(\frac{c_L^t}{2} |\epsilon_L|^2 - c_R^t |\epsilon_R|^2 \right) \qquad m_\psi \equiv g_\psi f_\pi$$

$$\beta \sim \frac{N_c m_\psi^4}{16\pi^2} \left(\frac{c_L'^t}{4} |\epsilon_L|^4 + c_R'^t |\epsilon_R|^4 - c_{LR}'^t |\epsilon_L|^2 |\epsilon_R|^2 \right) \qquad \epsilon_{L,R} \equiv y_{L,R}/g_\psi$$

with $\alpha \sim |\epsilon|^2$ and $\beta \sim |\epsilon|^4$

Spurion Analysis

in the $\mathrm{MCHM}_{5,10}$

We can promote $y_L \equiv \lambda_L^q \Delta_1$ and $y_R \equiv \lambda_R^t \Gamma_1$ to fields transforming under $SO(5)$ making the full Lagrangian $SO(5)$ invariant before EWSB

Building all possible $SO(5)$ invariants and using NDA we obtain

$$V^{(5)}(h) = \alpha \sin^2(h/f_\pi) - \beta \cos^2(h/f_\pi) \sin^2(h/f_\pi)$$

with

$$\begin{aligned} \alpha &\sim \frac{N_c m_\psi^4}{16\pi^2} \left(\frac{c_L^t}{2} |\epsilon_L|^2 - c_R^t |\epsilon_R|^2 \right) & m_\psi \equiv g_\psi f_\pi \\ \beta &\sim \frac{N_c m_\psi^4}{16\pi^2} \left(\frac{c_L'^t}{4} |\epsilon_L|^4 + c_R'^t |\epsilon_R|^4 - c_{LR}'^t |\epsilon_L|^2 |\epsilon_R|^2 \right) & \epsilon_{L,R} \equiv y_{L,R}/g_\psi \end{aligned}$$

with $\alpha \sim |\epsilon|^2$ and $\beta \sim |\epsilon|^4$ α is typically much larger than β !!

Spurion Analysis

in the $\text{MCHM}_{5,10}$

EWSB requires $\alpha = \beta \cos(2v/f_\pi)$ and thus $\alpha \lesssim \beta$. We need to tune both terms contributing to

$$\alpha \sim \left(\frac{c_L^t}{2} |\epsilon_L|^2 - c_R^t |\epsilon_R|^2 \right) \sim |\epsilon|^2 \left(\frac{c_L^t}{2} - c_R^t \right) \qquad |\epsilon_L| \approx |\epsilon_R| = |\epsilon|$$

to make it of order $\beta \sim |\epsilon|^4$. This leads to a total tuning

$$\Delta^{(5)} \sim \frac{1}{|\epsilon|^2 \sin^2(v/f_\pi)}$$

The Higgs mass read

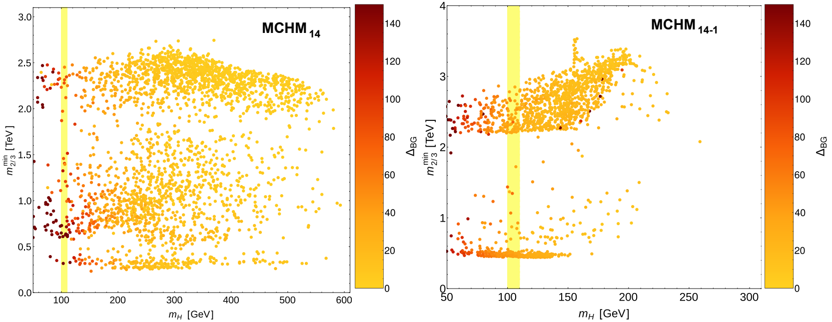
$$\begin{aligned} m_h^2 &= \frac{8}{f_\pi^2} \beta \cos^2(v/f_\pi) \sin^2(v/f_\pi) \sim \frac{N_c}{2\pi^2} |y|^4 v^2 \\ \Rightarrow \quad & m_h \sim \frac{v}{\sqrt{2}} \sqrt{\frac{N_c}{\pi^2}} |y|^2 \sim \sqrt{\frac{N_c}{\pi^2}} m_t \frac{m_q^*}{f_\pi} \end{aligned}$$

Lifting Partner Masses

It was pointed out that the presence of light partners could be avoided choosing larger fermionic representations e.g. $\mathcal{O}_L^q \sim \mathbf{14}$ and $\mathcal{O}_R^t \sim \mathbf{1}$

[Panico, Redi, Tesi, Wulzer, '13] [Pappadopulo, Thamm, Torre, '13]

In this case α and β are order $|\epsilon_L|^2$. No longer need to tune α vs β, although this leads typically to a too heavy Higgs $\Rightarrow$ ad-hoc tuning



What about leptons?

What about leptons?

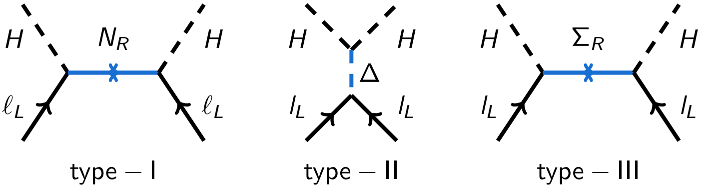
Looking at their masses we could naively conclude that $m_\ell \ll m_t \Rightarrow y^\ell_{L,R} \ll y^t_{L,R}$. However ...

1. Contrary to the quark case, the PMNS lepton mixing matrix is non-hierarchical (+ severe constraints on LFV)

   $\rightarrow$ Flavor symmetry acting on the lepton sector [delAguila,AC,Santiago '10]

   - Additional Yukawa suppresion $\rightarrow$ composite τ_R, i.e., $y^\tau_R \sim y^t_{L,R}$
   - Strongly elementary LH sector $\rightarrow y^\ell_L \sim 0$

2. Neutrinos could also be Majorana particles $\rightarrow$ See-saw mechanism

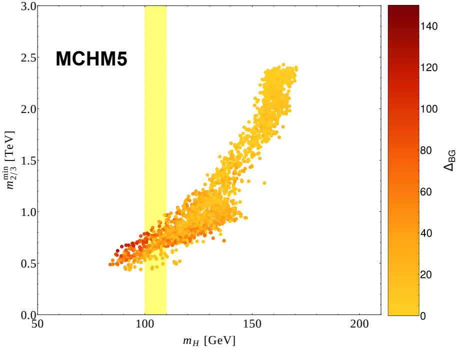


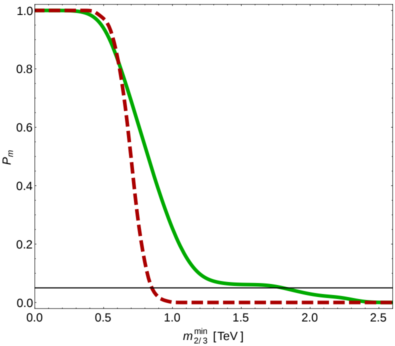
$\rightarrow$ We need to embed the new heavy dof in irreps of SO(5)

MCHM_5^{5-14}

We consider the MCHM_5 for quarks, with $f_\pi = 0.8$ TeV and $g_\psi \sim 4.4$

$$l_L^\tau \sim \mathbf{5}_{-1}, \qquad \tau_R \sim \mathbf{14}_{-1}$$



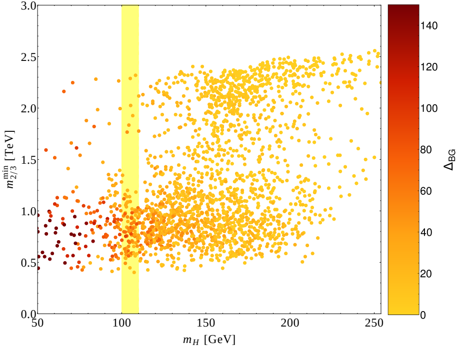


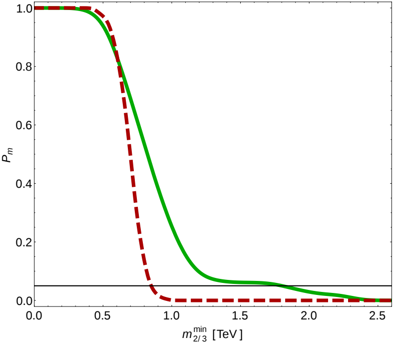
$$Y_q^* = 0.7, \qquad Y_l^* = 0.35$$

MCHM_5^{5-14}

We consider the MCHM_5 for quarks, with $f_\pi = 0.8$ TeV and $g_\psi \sim 4.4$

$$l_L^\tau \sim \mathbf{5}_{-1}, \qquad \tau_R \sim \mathbf{14}_{-1}$$





$$Y_q^* = 0.7, \qquad Y_l^* = 0.35$$

mMCHM$^{\rm III}$

The most minimal implementation of the type-III seesaw in a $SO(5) \times U(1)_X$ composite Higgs model is

$$l_L^\ell \sim \mathbf{5}_{-1}, \qquad \Sigma_R^\ell \text{ and } \ell_R \sim \mathbf{14}_{-1}, \qquad \ell = e, \mu, \tau$$

- For quarks, there was no reason to use a **14** besides being open-minded and trying to exhaust all possibilites
- However, for leptons, it is the minimal irrep where one can accommodate at the same time a $\mathbf{3}_0$ of $SU(2)_L \times U(1)_Y$ and a P_{LR} protected RH charged lepton

mMCHM$^{\rm III}$

The most minimal implementation of the type-III seesaw in a $SO(5) \times U(1)_X$ composite Higgs model is

$$l_L^\ell \sim \mathbf{5}_{-1}, \qquad \Sigma_R^\ell \text{ and } \ell_R \sim \mathbf{14}_{-1}, \qquad \ell = e, \mu, \tau$$

- For quarks, there was no reason to use a **14** besides being open-minded and trying to exhaust all possibilites
- However, for leptons, it is the minimal irrep where one can accommodate at the same time a $\mathbf{3}_0$ of $SU(2)_L \times U(1)_Y$ and a P_{LR} protected RH charged lepton

The overall size of the neutrino masses ask for IR localized ℓ_R !!

mMCHM$^{\mathrm{III}}$

The most minimal implementation of the type-III seesaw in a $SO(5) \times U(1)_X$ composite Higgs model is

$$l_L^\ell \sim \mathbf{5}_{-1}, \qquad \Sigma_R^\ell \text{ and } \ell_R \sim \mathbf{14}_{-1}, \qquad \ell = e, \mu, \tau$$

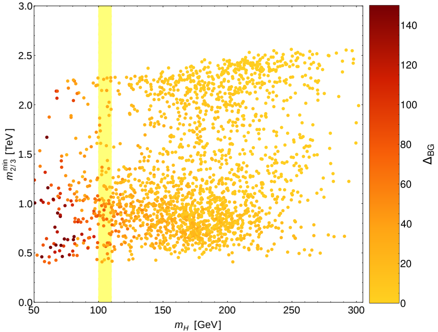
- For quarks, there was no reason to use a **14** besides being open-minded and trying to exhaust all possibilites
- However, for leptons, it is the minimal irrep where one can accommodate at the same time a $\mathbf{3}_0$ of $SU(2)_L \times U(1)_Y$ and a P_{LR} protected RH charged lepton

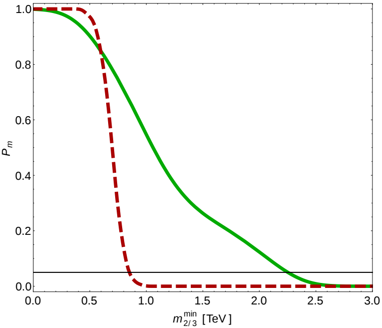
The overall size of the neutrino masses ask for IR localized ℓ_R !!

This happens for all three generations !!

$\text{mMCHM}_5^{\text{IIII}}$

As all the RH charged leptons are partially composite they can overcome the relative color suppression in the Higgs potential $N_g = 3 = N_c$

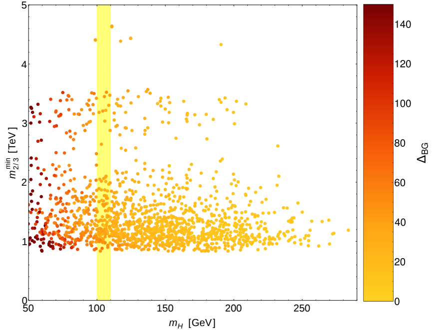


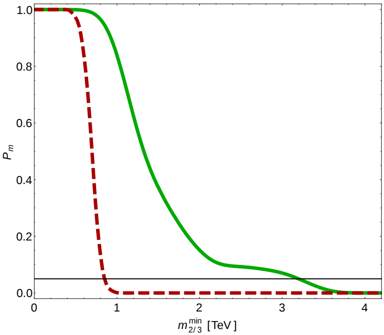


$$Y_*^l = 0.35, \quad Y_*^q = 0.7, \quad f_\pi = 0.8 \text{ TeV}, \quad g_\psi \sim 4.4$$

mMCHM$_{5-1}^{\mathrm{III}>}$

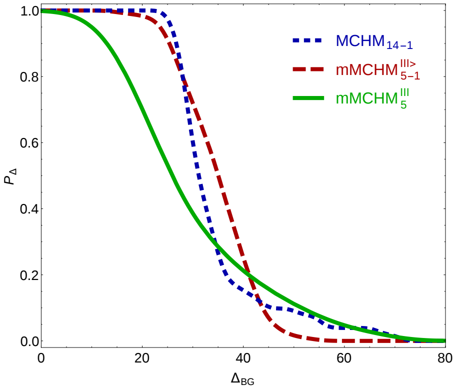
Leptons can even be the main source of the Higgs mass, allowing for the most minimal quark model $q_L \sim \mathbf{5}_{-2/3}, t_R \sim \mathbf{1}_{-2/3}$





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

Comparison of Tuning



- $\mathrm{mMHCM}_5^{\mathrm{III}}$ allows to reconcile minimal tuning with absence of ultra-light partners
- $\mathrm{mMCHM}_{5-1}^{\mathrm{III}>}$ features least dof of all $SO(5)/SO(4)$ models

$$Y_*^q = 0.7, \quad f_\pi = 0.8 \text{ TeV}, \quad g_\psi \sim 4.4, \quad m_{2/3}^{\mathrm{min}} > 1 \text{ TeV}$$

Conclusions and Outlook

- Models of composite Higgs offer a nice solution of the hierarchy problem as well as a rationale behind EWSB
- A 125 GeV Higgs puts the simplest models in the quark sector under constraint
- Leptons can play a very important role in EWSB
- Lepton sector allows to build very economical MCHMs that

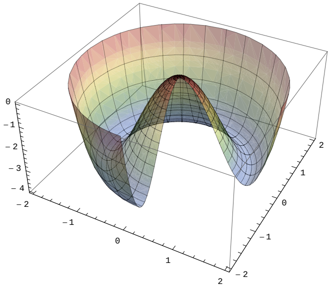
  $\rightarrow$ do not require ultra-light partners

  $\rightarrow$ feature a Higgs which is naturally light

Backup Slides

Probing the EWSB

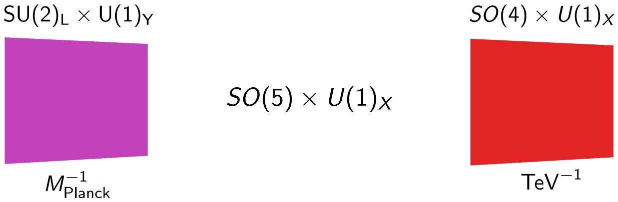
The discovery of the Higgs boson and the measurement of its couplings offer a unique possibility to study the precise mechanism of EWSB



This could help to solve some very important unsolved questions:

What is the origin of the Higgs mass? Is there a mechanism stabilizing the EW scale? How are neutrino masses generated? Why fermion masses span so many orders of magnitude? What is the origin of DM?

Gauge-Higgs Unification



$T^{\hat{a}} \in \mathrm{Alg}(SO(5)/SO(4))$ are broken at both branes $\Rightarrow$ zero-modes for $A_5^{\hat{a}}$

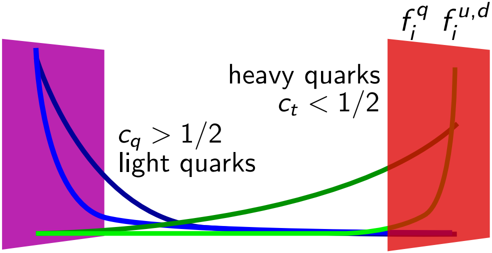
- We can identify the Higgs with the scalar components of the 5D gauge fields along $SO(5)/SO(4)$

$$\text{vector field} \rightarrow A_\mu^{\hat{a}} \quad \xleftrightarrow{\text{Lorentz symmetry}} \quad A_5^{\hat{a}} \leftarrow \text{scalar field}$$

- The 5D gauge symmetry prevents the Higgs to get a mass
- The explicit breaking of the 5D gauge symmetry will induce a calculable potential at the quantum level

Bulk Fermions

We can explain the huge hierarchy existing between the different fermion masses



$$(m_{u,d})_{ij} \sim \frac{v}{\sqrt{2}} Y_* f_i^q f_j^{u,d}$$

We also obtain naturally the hierarchical mixing observed the quark sector

$$\left| U_L^{u,d} \right|_{ij} \sim f_i^q / f_j^q \qquad \left| U_R^{u,d} \right|_{ij} \sim f_i^{u,d} / f_j^{u,d} \qquad i \leq j$$

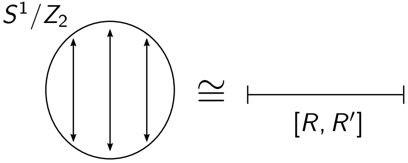
Bulk Fermions

The smallest irrep of the 5D Clifford algebra

$$\{\Gamma^M, \Gamma^N\} = 2g^{MN} \qquad M, N = \mu, 5$$

is four-dimensional

1. 5D fermions $\psi(x, z)$ are vector-like and a bulk mass $c = MR$ is allowed
2. We can still get a 4D chiral spectrum



$$\psi_L(x, -\phi) = Z\psi_L(x, \phi) \qquad Z^2 = 1$$

$$\psi_L(x, R^{(\prime)}) = 0 \quad \partial_z \psi_L(x, R^{(\prime)}) = 0$$

After KK decomposition, we can have a chiral massless state

$$\psi_L(x, z) = f_L^{(0)}(z)\psi_L^{(0)}(x) + \sum_{n=1}^{\infty} f_L^{(n)}(z)\psi_L^{(n)}(x)$$

5D calculation

The contribution of all KK resonances can be traded by an integral

$$
\begin{aligned}
V(h) &= \sum_r \frac{N_r}{2} \sum_{k=1}^{\infty} \int \frac{\mathrm{d}^4 p}{(2\pi)^4} \log(p^2 + m_{r,n}^2(h)) \\
&= \sum_r \frac{N_r}{(4\pi)^2} \int_0^{\infty} \mathrm{d}p \; p^3 \log \rho_r(-p^2)
\end{aligned}
$$

with $\rho_r(w^2),\ w \in \mathbb{C}$, holomorphic in $\mathrm{Re}(w) > 0$ and with roots in the real axis encoding the physical spectrum $\rho_r(m_{r,n}^2(h)) = 0,\ n \in \mathbb{N}$.

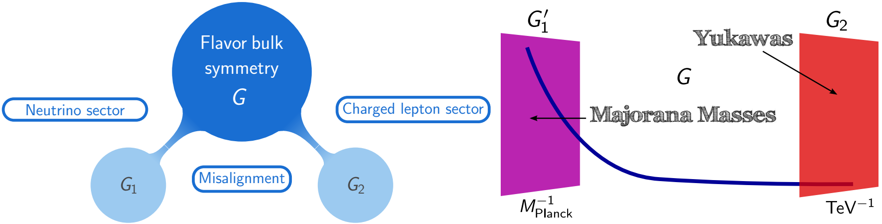
To compute them, we use the freedom of 5D gauge transformations to "gauge away" the Higgs vev except from the IR brane. We then

- Solve bulk equations of motion with zero vev
- Apply UV boundary conditions
- Impose IR boundary conditions for a non-vanishing vev

The determinant of the subsequent system of equations give us ρ_r

Flavor Symmetries

The largeness of the neutrino mixing angles strongly suggest the presence of a bulk symmetry making $(\lambda_L^l)_i = \lambda_L^l$ and $(\lambda_R^N)_i = \lambda_R^N$. Also helpful to deal with flavor constraints

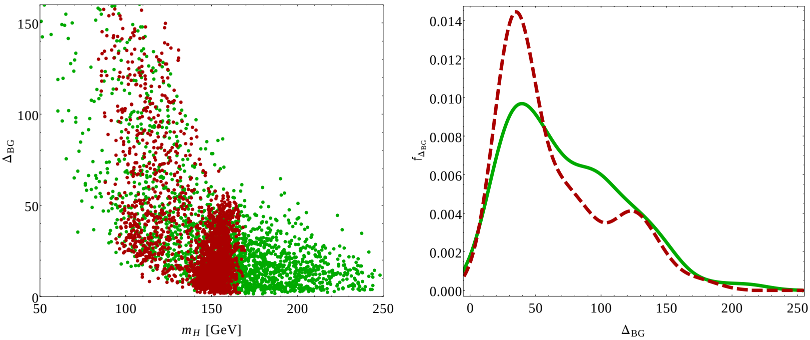


1. The misalignment between the two sectors leads to a definite mixing pattern at leading order $\sim$ PMNS
2. Subleading terms destabilizing the predicted mixing angles or leading to dangerous LFV processes can require $v_{\text{flavon}}/\Lambda_{\text{NP}} \ll 1$

A composite τ

We consider the MCHM$_5$ for quarks, with $f_\pi = 0.8$ TeV and $g_\psi \sim 4.4$

$$l_L^3 \sim \mathbf{5}_{-1}, \qquad \tau_R \sim \mathbf{14}_{-1}$$



$$y_q^* = 1.4, \qquad y_l^* = 0.35$$

A Very Minimal MCHM

Being more concrete, we consider 5D multiplets of $SO(5)\times U(1)_X$

$$\zeta_{1\tau} \sim \mathbf{5_{-1}} = \tau_1'[-,+] \oplus \begin{pmatrix} \nu_1^\tau[+,+] & \tilde{\tau}_1[-,+] \\ \tau_1[+,+] & \tilde{Y}_1^\tau[-,+] \end{pmatrix}$$

$$\zeta_{2\tau} \sim \mathbf{14_{-1}} = \tau_2'[-,-] \oplus \begin{pmatrix} \nu_2^\tau[+,-] & \tilde{\tau}_2[+,-] \\ \tau_2[+,-] & \tilde{Y}_2^\tau[+,-] \end{pmatrix}$$

$$\oplus \begin{pmatrix} \hat{\lambda}_2^\tau[-,-] & \nu_2^{\tau\prime\prime}[+,-] & \tau_2^{\prime\prime\prime}[+,-] \\ \hat{\nu}_2^\tau[-,-] & \tau_2^{\prime\prime}[+,-] & Y_2^{\tau\prime\prime\prime}[+,-] \\ \hat{\tau}_2[-,-] & Y_2^{\tau\prime\prime}[+,-] & \Theta_2^{\tau\prime\prime\prime}[+,-] \end{pmatrix}$$

with UV and IR brane terms

$$\mathcal{S}_{\rm UV} = -\frac{1}{2}\sum_{j=e,\mu,\tau}\int d^4x \left\{a^4(z) M_\Sigma^j \operatorname{Tr}\left(\bar{\Sigma}_{jR}\Sigma_{jR}^c\right)\right\}_{\rm UV} + \text{h.c.},$$

$$\mathcal{S}_{\rm IR} = \sum_{j=e,\mu,\tau}\int \mathrm{d}^4x \left\{a^4(z)\left[M_S^j\left(\overline{\zeta}_{1jL}^{(\mathbf{1},\mathbf{1})}\zeta_{2jR}^{(\mathbf{1},\mathbf{1})}\right)_{55} + M_B^j\left(\overline{\zeta}_{1jL}^{(\mathbf{2},\mathbf{2})}\zeta_{2jR}^{(\mathbf{2},\mathbf{2})}\right)_{55}\right]\right\}_{\rm IR}$$

A Very Minimal MCHM

Being more concrete, we consider 5D multiplets of $SO(5) \times U(1)_X$

$$\zeta_{1\tau} \sim \mathbf{5_{-1}} = \tau_1'[-,+] \oplus \begin{pmatrix} \boxed{\nu_1^\tau[+,+]} & \tilde{\tau}_1[-,+] \\ \boxed{\tau_1[+,+]} & \tilde{Y}_1^\tau[-,+] \end{pmatrix}$$

$$\zeta_{2\tau} \sim \mathbf{14_{-1}} = \boxed{\tau_2'[-,-]} \oplus \begin{pmatrix} \nu_2^\tau[+,-] & \tilde{\tau}_2[+,-] \\ \tau_2[+,-] & \tilde{Y}_2^\tau[+,-] \end{pmatrix}$$

$$\oplus \begin{pmatrix} \boxed{\hat{\lambda}_2^\tau[-,-]} & \nu_2^{\tau\prime\prime}[+,-] & \tau_2^{\prime\prime\prime}[+,-] \\ \boxed{\hat{\nu}_2^\tau[-,-]} & \tau_2^{\prime\prime}[+,-] & Y_2^{\tau\prime\prime\prime}[+,-] \\ \boxed{\hat{\tau}_2[-,-]} & Y_2^{\tau\prime\prime}[+,-] & \Theta_2^{\tau\prime\prime\prime}[+,-] \end{pmatrix}$$

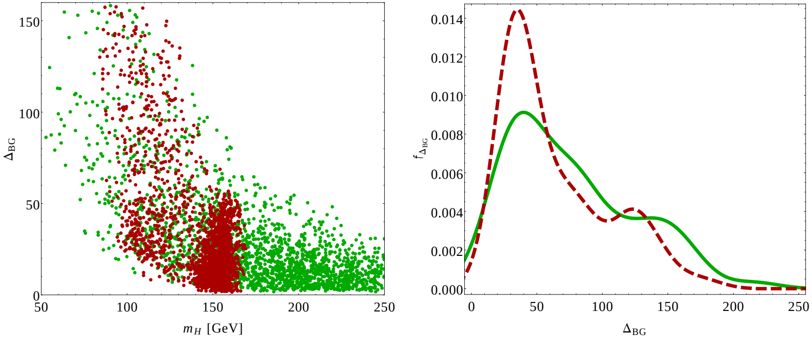
with UV and IR brane terms

$$\mathcal{S}_{\mathrm{UV}} = -\frac{1}{2} \sum_{j=e,\mu,\tau} \int \mathrm{d}^4x \left\{ a^4(z) M_\Sigma^j \operatorname{Tr}\left(\bar{\Sigma}_{jR} \Sigma_{jR}^c\right) \right\}_{\mathrm{UV}} + \mathrm{h.c.},$$

$$\mathcal{S}_{\mathrm{IR}} = \sum_{j=e,\mu,\tau} \int \mathrm{d}^4x \left\{ a^4(z) \left[M_S^j \left(\bar{\zeta}_{1jL}^{(\mathbf{1},\mathbf{1})} \zeta_{2jR}^{(\mathbf{1},\mathbf{1})} \right)_{55} + M_B^j \left(\bar{\zeta}_{1jL}^{(\mathbf{2},\mathbf{2})} \zeta_{2jR}^{(\mathbf{2},\mathbf{2})} \right)_{55} \right] \right\}_{\mathrm{IR}}$$

A Very Minimal MCHM

- As all the RH charged leptons are partially composite they can overcome the relative color suppression in the Higgs potential
- We consider quarks in *small* reps, e.g. MCHM_5 or MCHM_{10}



$$y_*^l = 0.35, \quad y_*^q = 1.40, \quad f_\pi = 0.8 \text{ TeV}, \quad g_\psi \sim 4.4$$

A Very Minimal MCHM

- As all the RH charged leptons are partially composite they can overcome the relative color suppression in the Higgs potential
- We consider quarks in *small* reps, e.g. MCHM_5 or MCHM_{10}

$$y_*^l = 0.70, \quad y_*^q = 0.70, \quad f_\pi = 0.8 \text{ TeV}, \quad g_\psi \sim 4.4$$