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The Leptonic Sector in Composite Higgs Models

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F. del Aguila, A. Carmona, J.S. arXiv:0911.xxxx

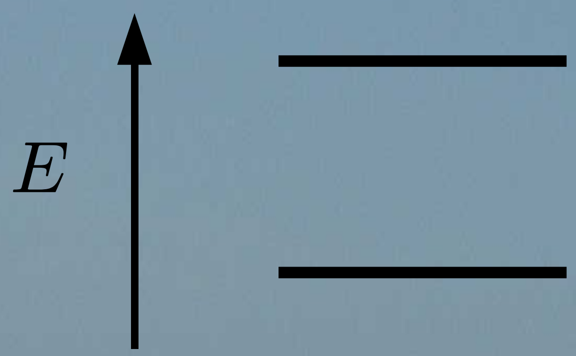
The LHC is here!

- The LHC is finally ready to study the mechanism of EWSB
- Composite Higgs models are a likely candidate
  - Natural realization of EWSB
  - Potentially interesting collider implications
- Weak realization in 5D models with warped ED
  - Quark sector well studied
  - What about the lepton sector?

This talk!

Composite Higgs Models

- Two scale symmetry breaking: **Georgi, Kaplan, et al. 84-85**



$f \sim \text{TeV} \quad G \to H$

- $\text{SM} \subset H$
- Higgs is a pNGB in G/H

v **EWSB**

$$0 \longleftarrow \frac{v}{f} \longrightarrow 1$$

SM **TC**

- Flavor under control if elementary sector couples linearly

Kaplan 91

5D realization of CHM

- Models of gauge-Higgs unification in warped ED realize the composite Higgs idea

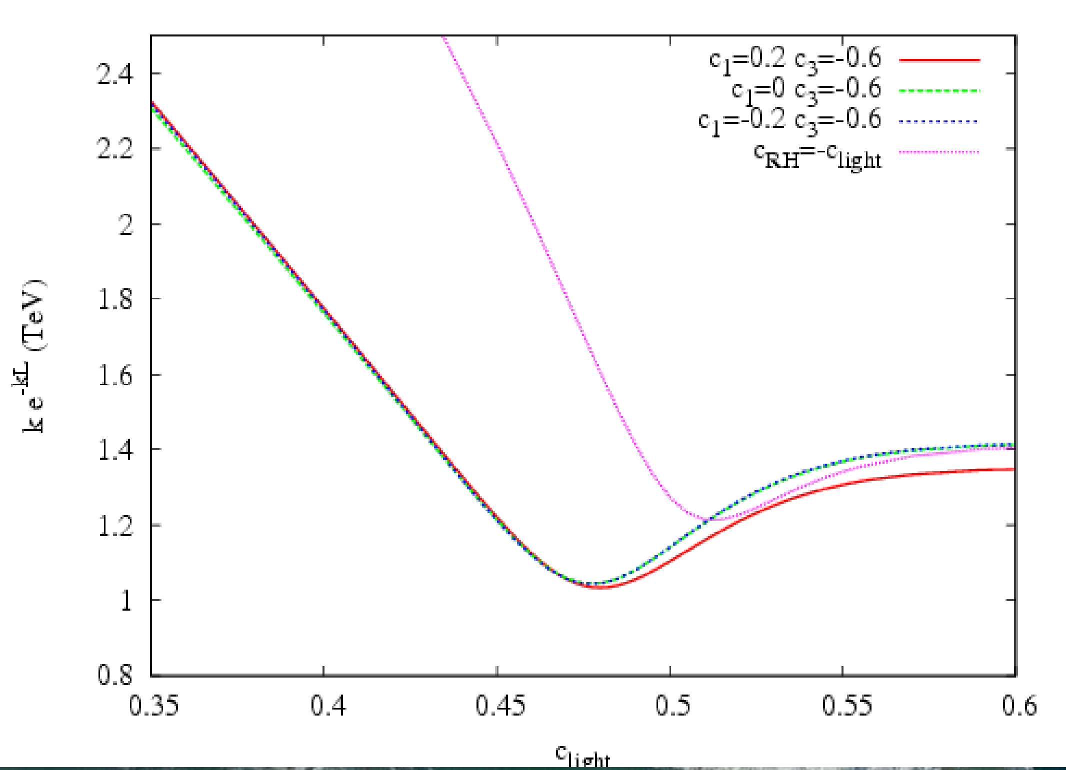
$$ds^2 = \left(\frac{R}{z}\right)^2 (\eta_{\mu\nu} dx^\mu dx^\nu - dz^2), \quad R \leq z \leq R'$$

  - Gauge symmetry broken on both branes contains a massless zero mode for $A_5 \longleftrightarrow$ Composite Higgs
  - Finite (calculable) potential generated at loop level
  - Minimal realistic models have been constructed based on SO(5)/SO(4) symmetry breaking pattern

Agashe, Contino, Pomarol '05

EW constraints on CHM

- T and Zbb protected by custodial (and LR) symmetry



Agashe, Delgado, May, Sundrum '03
Agashe, Contino, Da Rold, Pomarol '06

- Main constraint: S plus fermionic contribution to T and Zbb (1 loop)

Carena, Pontón, J.S., Wagner '06-07

$$m_{\rm gauge} \gtrsim 3.5\ \mathrm{TeV}$$

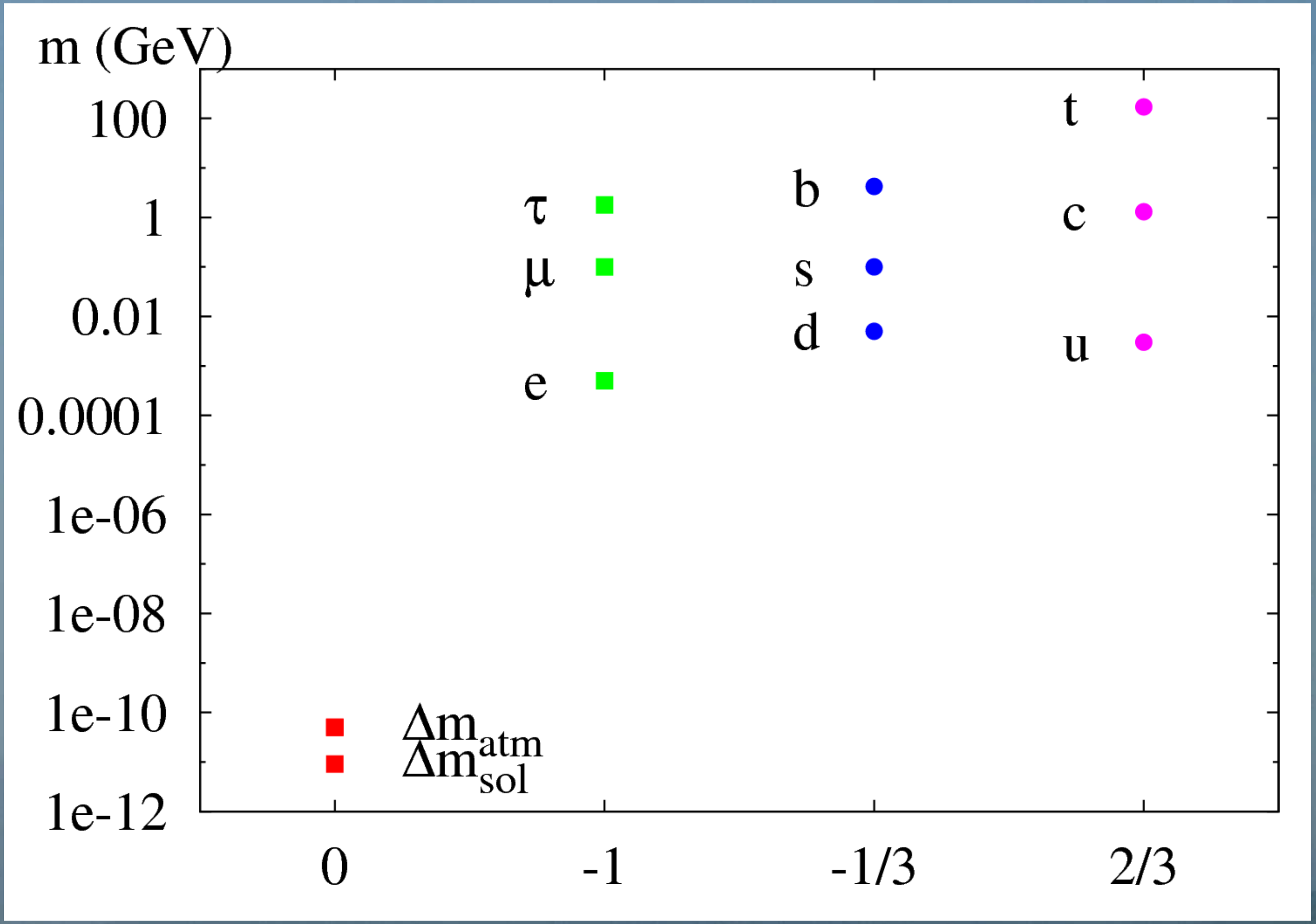
- Fermions are expected to be much lighter

$$m_{\rm fermion} \gtrsim 0.5\ \mathrm{TeV}$$

What about leptons?

- Most models focus on the quark sector
  - top is expected to be also composite
  - Masses and mixing angles naturally hierarchical
- Why is the leptonic spectrum so different?

What about leptons?



What about leptons?

$$|V_{\mathrm{CKM}}| = \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & \sim 1 & 0.04 \\ xx & xx & \gtrsim 0.7 \end{pmatrix}$$

$$|U_{\mathrm{PMNS}}| = \begin{pmatrix} 0.8 - 0.84 & 0.53 - 0.6 & 0 - 0.17 \\ 0.29 - 0.52 & 0.51 - 069 & 0.61 - 0.76 \\ 0.26 - 0.5 & 0.46 - 0.66 & 0.64 - 0.79 \end{pmatrix}$$

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$$|V_{\rm CKM}| = \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & \sim 1 & 0.04 \\ xx & xx & \gtrsim 0.7 \end{pmatrix}$$

Goes well with hierarchical masses

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???????????

What about leptons?

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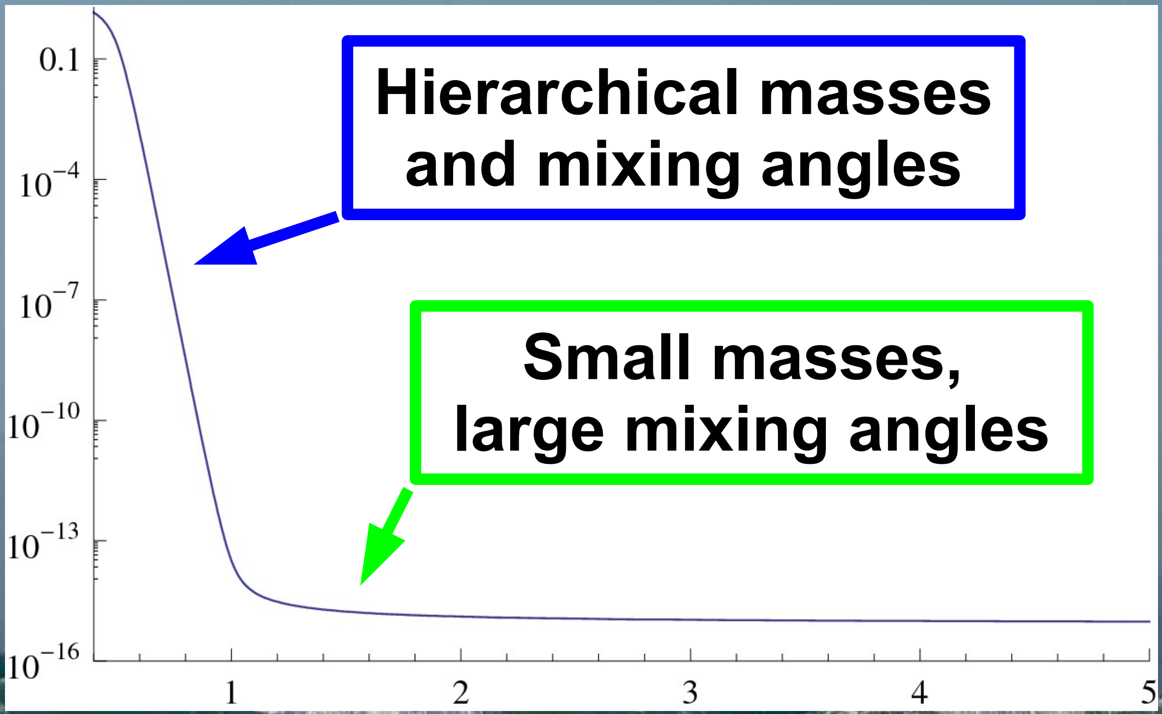
What about leptons?

- Why is the leptonic spectrum so different?
  - The pattern changes for tiny neutrino Dirac masses

Agashe, Okui, Sundrum 08; Carena, Medina, Shah, Wagner 09

λ_{eff}



Localization

What about leptons?

- Why is the leptonic spectrum so different?
  - The pattern changes for tiny neutrino Dirac masses

Agashe, Okui, Sundrum 08; Carena, Medina, Shah, Wagner 09

- But:
  - Flavor?
  - Why neutrinos so different?

What about leptons?

- Why is the leptonic spectrum so different?
  - Global symmetries (A4, T') in simple RS models

    Csaki, Delauny, Grojean, Grossman 08; Chen, Mahanthappa, Yu 09

  - Use see-saw to generate the right neutrino scale
  - Discrete symmetries predict the mixing pattern
  - Added bonus: flavor protection (very useful in models with warped extra dimensions)

What about leptons?

$$|U_{\mathrm{PMNS}}| = \begin{pmatrix} 0.8 - 0.84 & 0.53 - 0.6 & 0 - 0.17 \\ 0.29 - 0.52 & 0.51 - 069 & 0.61 - 0.76 \\ 0.26 - 0.5 & 0.46 - 0.66 & 0.64 - 0.79 \end{pmatrix}$$

$$U_{\mathrm{HPS}} = \begin{pmatrix} \sqrt{\frac{2}{3}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} = \begin{pmatrix} 0.82 & 0.58 & 0 \\ -0.41 & 0.58 & -0.71 \\ -0.41 & 0.58 & 0.71 \end{pmatrix}$$

Tri-Bi-Maximal mixing

Harrison, Perkins, Scott 02

Leptons in the $MCHM_5$

- Roadmap
  - 5D realization of CHM: SO(5)/SO(4) (x U(1))
  - Use identical structure for the quark and lepton sectors for $MCHM_5$ **Contino, Da Rold, Pomarol 07**
  - Impose a global A_4 x G_{FN} symmetry
  - Compute spectrum: lepton masses and mixings
  - Compute constraints: PMNS, EWPT, LFV
  - Study collider implications (in progress)

Leptons in the $MCHM_5$

- Lepton sector in $MCHM_5$: based on 5's of SO(5)

$$\zeta_1 = \begin{pmatrix} \widetilde{X}_1 & \nu_1 \\ \tilde{\nu}_1 & e_1 \end{pmatrix} \oplus \nu_1'$$

Recall

$$SO(4) \sim SU(2)_L \times SU(2)_R$$

$$5 = (2,2) \oplus 1$$

Leptons in the MCHM_5

- Lepton sector in MCHM_5: based on 5's of SO(5)

$$Y = \frac{1}{2} \quad -\frac{1}{2} \quad 0$$

$$\zeta_1 = \begin{pmatrix} \widetilde{X}_1 & \nu_1 \\ \tilde{\nu}_1 & e_1 \end{pmatrix} \oplus \nu_1'$$

$$Y = -\frac{1}{2} \quad -\frac{3}{2} \quad 0$$

$$\zeta_3 = \begin{pmatrix} \nu_3 & \tilde{e}_3 \\ e_3 & \widetilde{Y}_3 \end{pmatrix} \oplus e_3'$$

Different quantum numbers governed by an extra U(1)

Leptons in the MCHM$_5$

- Lepton sector in MCHM$_5$: based on 5's of SO(5)

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Leptons in the $MCHM_5$

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Leptons in the $MCHM_5$

- Impose a global A_4 symmetry
- A_4: even permutations of 4 elements
  - 3 one-dimensional plus 1 three-dimensional representations:

$$(1), \quad (1'), \quad (1'') = (1')^*, \quad (3)$$

Leptons in the $MCHM_5$

- Impose a global A_4 symmetry

$$(3) \qquad \zeta_1 = \begin{pmatrix} \widetilde{X}_1 & \nu_1 \\ \tilde{\nu}_1 & e_1 \end{pmatrix} \oplus \nu'_1 \qquad\qquad (3) \qquad \zeta_2 = \begin{pmatrix} \widetilde{X}_2 & \nu_2 \\ \tilde{\nu}_2 & e_2 \end{pmatrix} \oplus \nu'_2$$

$$(3) \qquad \zeta_3 = \begin{pmatrix} \nu_3 & \tilde{e}_3 \\ e_3 & \widetilde{Y}_3 \end{pmatrix} \oplus e'_3 \qquad\qquad (1, 1', 1'') \qquad \zeta_\alpha = \begin{pmatrix} \nu_\alpha & \tilde{e}_\alpha \\ e_\alpha & \widetilde{Y}_3 \end{pmatrix} \oplus e'_\alpha$$

$\zeta_{1,2,3}$ **family independent localization**

Leptons in the $MCHM_5$

- Global A_4 broken by brane scalars to Z_2 and Z_3 (to ensure TBM mixing)

$$UV : \langle \phi \rangle = (\tilde{v}, 0, 0) \qquad IR : \langle \phi' \rangle = (v', v', v')$$

- Write the most general terms allowed by the symmetries

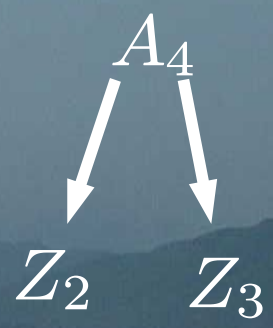
$$\begin{aligned}
-\mathcal{L}_{UV} &= \frac{x_\eta}{2\Lambda}\eta\overline{\psi}_{\nu_2'}\overline{\psi}_{\nu_2'} + \frac{x_\nu}{2\Lambda}\phi\overline{\psi}_{\nu_2'}\overline{\psi}_{\nu_2'} + x_l\chi_{l_1}\psi_{l_3} + \text{h.c.} + \dots \\
-\mathcal{L}_{IR} &= \left(\frac{R}{R'}\right)^4 \left[\frac{y_b^\alpha}{\Lambda'}\left\{\left(\phi'^\dagger\chi_{l_3}\right)^\alpha\psi_{l_\alpha} + \left(\phi'^\dagger\chi_{\tilde{l}_3}\right)^\alpha\psi_{\tilde{l}_\alpha}\right\} + \frac{y_s^\alpha}{\Lambda'}\left(\phi'^\dagger\chi_{e_3'}\right)^\alpha\psi_{e_\alpha'}\right. \\
&+ \left.\frac{y_b}{\Lambda'}\left\{\eta'^*\chi_{l_1}\psi_{l_2} + \eta'^*\chi_{\tilde{l}_1}\psi_{\tilde{l}_2}\right\} + \frac{y_s}{\Lambda'}\eta'^*\chi_{\nu_1'}\psi_{\nu_2'}\right] + \text{h.c.} + \dots
\end{aligned}$$

Leptons in the MCHM$_5$

- After A$_4$ breaking

$$
\begin{aligned}
-\mathcal{L}_{UV} &\to \frac{1}{2}\psi_{\nu'_2}\hat{\theta}^\dagger_M\psi_{\nu'_2} + x_l\chi_{l_1}\psi_{l_3} + \text{h.c.} + \ldots \\
-\mathcal{L}_{IR} &= \left(\frac{R}{R'}\right)^4 \Big[\sqrt{3}\frac{v'}{\Lambda'}\left(\chi^\alpha_{l_3}y^\alpha_b\psi_{l_\alpha} + \chi^\alpha_{\tilde{l}_3}y^\alpha_b\psi_{\tilde{l}_\alpha} + \chi^\alpha_{e'_3}y^\alpha_s\psi_{e'_\alpha}\right) \\
&\quad + y_b\frac{v'_\eta}{\Lambda'}\left(\chi_{l_1}\psi_{l_2} + \chi_{\tilde{l}_1}\psi_{\tilde{l}_2}\right) + y_s\frac{v'_\eta}{\Lambda'}\chi_{\nu'_1}\psi_{\nu'_2}\Big] + \text{h.c.} + \ldots\ .
\end{aligned}
$$

$$
\hat{\theta} = U_{\text{HPS}} \begin{pmatrix} \epsilon_t + \epsilon_s & 0 & 0 \\ 0 & \epsilon_s & 0 \\ 0 & 0 & \epsilon_t - \epsilon_s \end{pmatrix} U^\dagger_{\text{HPS}}
$$



Leptons in the MCHM$_5$

- After A_4 breaking
  - Yukawas suppressed by $v'/\Lambda' \sim 0.1 - 0.01$
  - Charged lepton Yukawas: diagonal and hierarchical
  - Neutrino Yukawas: proportional to the identity
  - The only source of mixing is the (UV localized) neutrino Majorana mass

$$\mathcal{M}^{\nu}_{M} \propto U_{\mathrm{HPS}} \begin{pmatrix} \epsilon_t + \epsilon_s & 0 & 0 \\ 0 & \epsilon_s & 0 \\ 0 & 0 & \epsilon_t - \epsilon_s \end{pmatrix} U^{\dagger}_{\mathrm{HPS}}$$

Leptons in the MCHM_5

- Scales:
  - Neutrino Majorana mass

$$M_M^{\nu} \sim R^{-1}\frac{\tilde{v}}{\Lambda} f_{R;UV}^2 \sim 10^{12-15}\ \mathrm{GeV}$$

For moderately IR localized ν_R

  - Dirac (Yukawa) masses

$$M_D \sim v\frac{v'}{\Lambda'} f_{L;IR} \times f_{R;IR} \sim \begin{cases} 1 - 30\ \mathrm{GeV}\ (\nu) \\ 10^{-4} - 1\ \mathrm{GeV}\ (l) \end{cases}$$

ν_R, τ_R **need a sizable IR localization**

Leptonic spectrum in the MCHM_5

- Neutrino masses generated through see-saw

$$M^{\nu}_{\mathrm{eff}} = -M^{\nu}_{D}(M^{\nu}_{M})^{-1}(M^{\nu}_{D})^{\mathrm{T}}$$
$$\propto (M^{\nu}_{M})^{-1} = U_{\mathrm{HPS}} M_{\mathrm{diag}} U^{\dagger}_{\mathrm{HPS}}$$

TBM mixing

- Charged lepton masses naturally hierarchical (suppressed with respect to v) and diagonal in current eingenstate basis: <u>No tree level LFV</u>
- Small corrections if fermion KK modes and non-linear Higgs effects taken into account

Higher order corrections

- Can higher dimension operators destabilize this pattern?
  - New corrections are $\sim \frac{\tilde{v}^2}{\Lambda^2}$
  - Corrections to TBM mixing and LFV
  - Easy to classify to all orders

$$\langle\phi\rangle^3 \sim \langle\phi\rangle \qquad \langle\phi'\rangle^2 \sim 1 + \langle\phi'\rangle$$

    - New structure for the Majorana mass
    - Diagonal but non-universal neutrino Yukawas
    - Non-diagonal charged lepton Yukawas

New in GHU!

Higher order corrections

- As expected, there is more flavor violation in composite Higgs models than in simple RS

Csaki, Falkowski, Weiler 08

- But there is an extra flavor protection from custodial + LR symmetry + splitting in two sectors (neutrino and charged lepton sectors)

Agashe 09

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Agashe 09

Motivated by Zbb protection

Higher order corrections

- Extra flavor protection: protected couplings to the Z

Agashe 09

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Constraints on the model

- Fix the IR scale to 1.5 TeV (m_{KK}~3.5 TeV)
- Check constraints:
  - Lepton masses
  - EWPT: $\delta g/g \lesssim 0.2\%$
  - Lepton mixing: $U_{\rm PMNS}$
  - Tree level LFV: $\mu \to 3e, \quad \mu \leftrightarrow e, \ldots$
  - One loop LFV: $\mu \to e\gamma$

Constraints on the model

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  - Lepton masses — **Requires IR localized** ν_R, τ_R
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Sizable but OK for
$v/\Lambda \lesssim 0.1, c_3 \gtrsim 0.55$

Constraints on the model

- Fix the IR scale to 1.5 TeV (m_{KK}~3.5 TeV)
- Check constraints:
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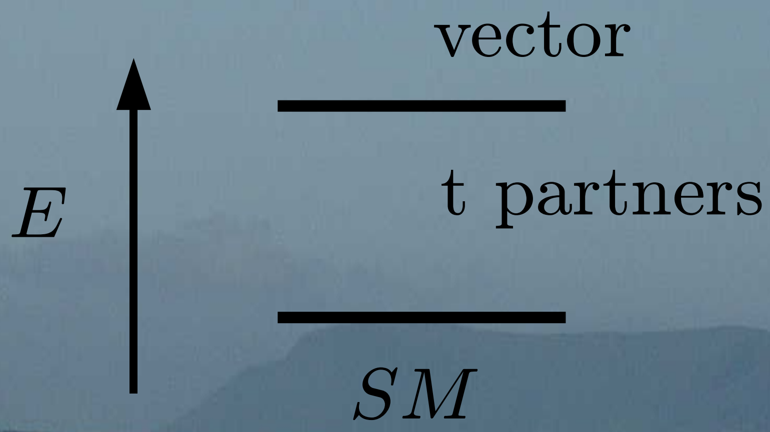
Requires IR localized ν_R, τ_R

- New light leptonic resonances!



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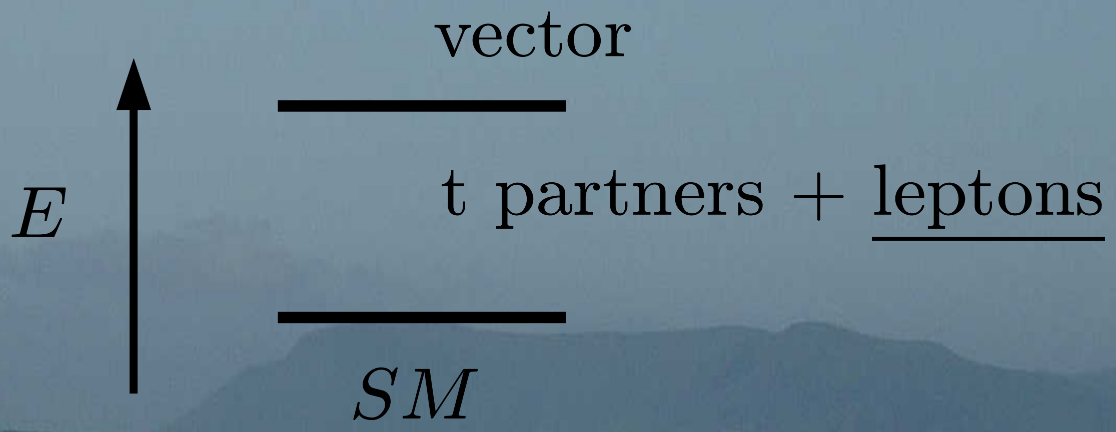

Conclusions

- Fully realistic composite Higgs model from 5D:
  - Correct EWSB and quark spectrum
  - Correct lepton spectrum with discrete symmetries
    - Hierarchical charged lepton masses
    - Correct neutrino masses and mixing
    - Double layer of flavor protection
      - A4 symmetry
      - Custodial + LR symmetry+ structure of MCHM5
  - New quark and lepton resonances at the LHC!
  - LFV close to observable limits