Lepton Masses in Holographic Composite Higgs Models

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F. del Aguila, A. Carmona, J.S., JHEP 1008 ('10) and PLB 695 ('11)

Composite Higgs Models

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

E

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

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

v **EWSB**

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

SM **TC**

Nice flavor structure from partial compositeness:

Kaplan 91

- Masses and mixing angles naturally hierarchical
- Flavor violation scales with SM masses and mixing angles

5D realization of CHM

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

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

  - Gauge symmetry broken on both branes contains a massless zero mode for $A_5 \longleftrightarrow$ Composite Higgs
  - Minimal realistic models (quark sector) have been constructed based on SO(5)/SO(4) symmetry breaking pattern

Agashe, Contino, Pomarol '05

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 lepton spectrum so different?
  - Leptons charged under global symmetry
    - Parallel the quark sector
    - Masses via see-saw mechanism
    - Charged sector like quarks
    - Flavor protection: symmetries (flavor, conformal) + structure in model space

Leptons in the MCHM$_5$

- Lepton sector in MCHM$_5$: based on 5's of SO(5)
- Impose a global A_4 symmetry

Neutrino sector

$$\underset{}{\overset{(3)}{\zeta_1 = \left(\begin{matrix} \widetilde{X}_1 \\ \tilde{\nu}_1 \end{matrix} \;\; \boxed{\begin{matrix} \nu_1 \\ e_1 \end{matrix}}\right) \oplus \boxed{\nu_1'}}} \qquad \overset{(3)}{\zeta_2 = \left(\begin{matrix} \widetilde{X}_2 \\ \tilde{\nu}_2 \end{matrix} \;\; \boxed{\begin{matrix} \nu_2 \\ e_2 \end{matrix}}\right) \oplus \boxed{\nu_2'}}$$

Charged lepton sector

$$\overset{(3)}{\zeta_3 = \left(\boxed{\begin{matrix} \nu_3 \\ e_3 \end{matrix}} \;\; \begin{matrix} \tilde{e}_3 \\ \widetilde{Y}_3 \end{matrix}\right) \oplus \boxed{e_3'}} \qquad \overset{(1,1',1'')}{\zeta_\alpha = \left(\boxed{\begin{matrix} \nu_\alpha \\ e_\alpha \end{matrix}} \;\; \begin{matrix} \tilde{e}_\alpha \\ \widetilde{Y}_3 \end{matrix}\right) \oplus \boxed{e_\alpha'}}$$

Leptons in the $MCHM_5$

- Global A_4 broken by brane scalars to Z_2 and Z_3 (extra Z_8 to forbid some operators)

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

- 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

$$
\begin{aligned}
-\mathcal{L}_{UV} &\to \frac{1}{2}\psi_{\nu_2'}\hat{\theta}_M^{\dagger}\psi_{\nu_2'} + x_l\chi_{l_1}\psi_{l_3} + \text{h.c.} + \ldots \\
-\mathcal{L}_{IR} &= \left(\frac{R}{R'}\right)^4 \Bigg[\sqrt{3}\frac{v'}{\Lambda'}\left(\chi^{\alpha}_{l_3}y^{\alpha}_{b}\psi_{l_\alpha} + \chi^{\alpha}_{\tilde{l}_3}y^{\alpha}_{b}\psi_{\tilde{l}_\alpha} + \chi^{\alpha}_{e_3'}y^{\alpha}_{s}\psi_{e'_\alpha}\right) \\
&\quad + y_b\frac{v'_\eta}{\Lambda'}\left(\chi_{l_1}\psi_{l_2} + \chi_{\tilde{l}_1}\psi_{\tilde{l}_2}\right) + y_s\frac{v'_\eta}{\Lambda'}\chi_{\nu_1'}\psi_{\nu_2'}\Bigg] + \text{h.c.} + \ldots\ .
\end{aligned}
$$

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

Leptons in the $MCHM_5$

- After A_4 breaking

$$
\begin{aligned}
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-\mathcal{L}_{IR} &= \left(\frac{R}{R'}\right)^4 \left[\sqrt{3}\frac{v'}{\Lambda'}\left(\chi^\alpha_{l_3}y^\alpha_b\psi_{l_\alpha} + \chi^\alpha_{\tilde{l}_3}y^\alpha_b\psi_{\tilde{l}_\alpha} + \chi^\alpha_{e_3'}y^\alpha_s\psi_{e_\alpha'}\right)\right. \\
&\left. + y_b\frac{v_\eta'}{\Lambda'}\left(\chi_{l_1}\psi_{l_2} + \chi_{\tilde{l}_1}\psi_{\tilde{l}_2}\right) + y_s\frac{v_\eta'}{\Lambda'}\chi_{\nu_1'}\psi_{\nu_2'}\right] + \text{h.c.} + \ldots\ .
\end{aligned}
$$

- 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 (diagonalized by U_{HPS})

Leptonic spectrum in the MCHM$_5$

- Neutrino masses generated through see-saw

$$M^\nu_{\rm eff} = -M^\nu_D (M^\nu_M)^{-1} (M^\nu_D)^{\rm T}$$
$$\propto (M^\nu_M)^{-1} = U_{\rm HPS} M_{\rm diag} U^\dagger_{\rm HPS}$$

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 have suppression $\sim \dfrac{\tilde{v}^2}{\Lambda^2}$
  - Corrections to TBM mixing and LFV
  - Easy to classify to all orders

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

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

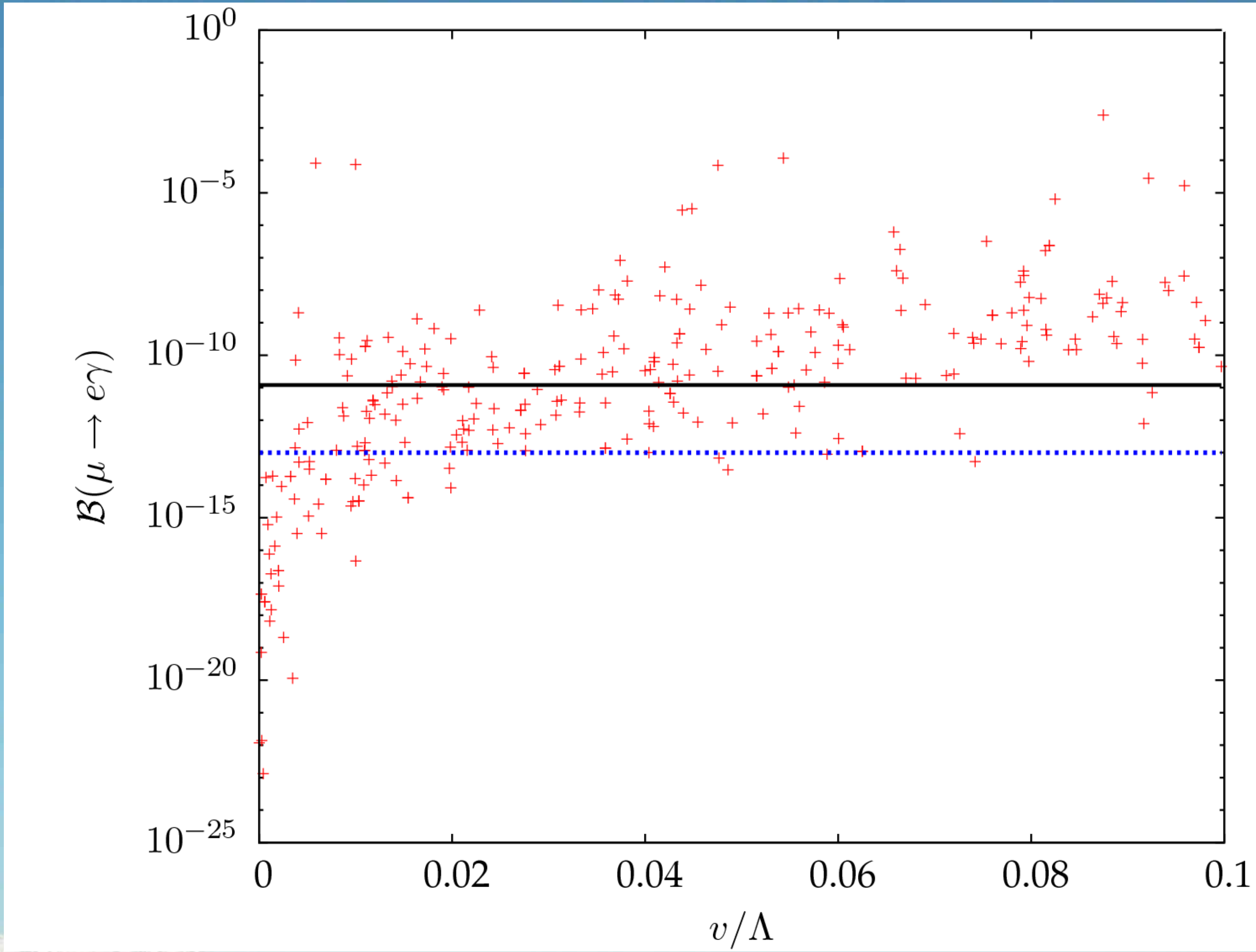
New in GHU!

Constraints on the model

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

Sizable but OK for
$v/\Lambda \lesssim 0.1, c_3 \gtrsim 0.55$

Constraints on the model



Constraints on the model

Corrections to tri-bimaximal mixing and flavor universality generated from higher dimensional operators $\propto \frac{v}{\Lambda}$

A4 breaking
Cut-off scale

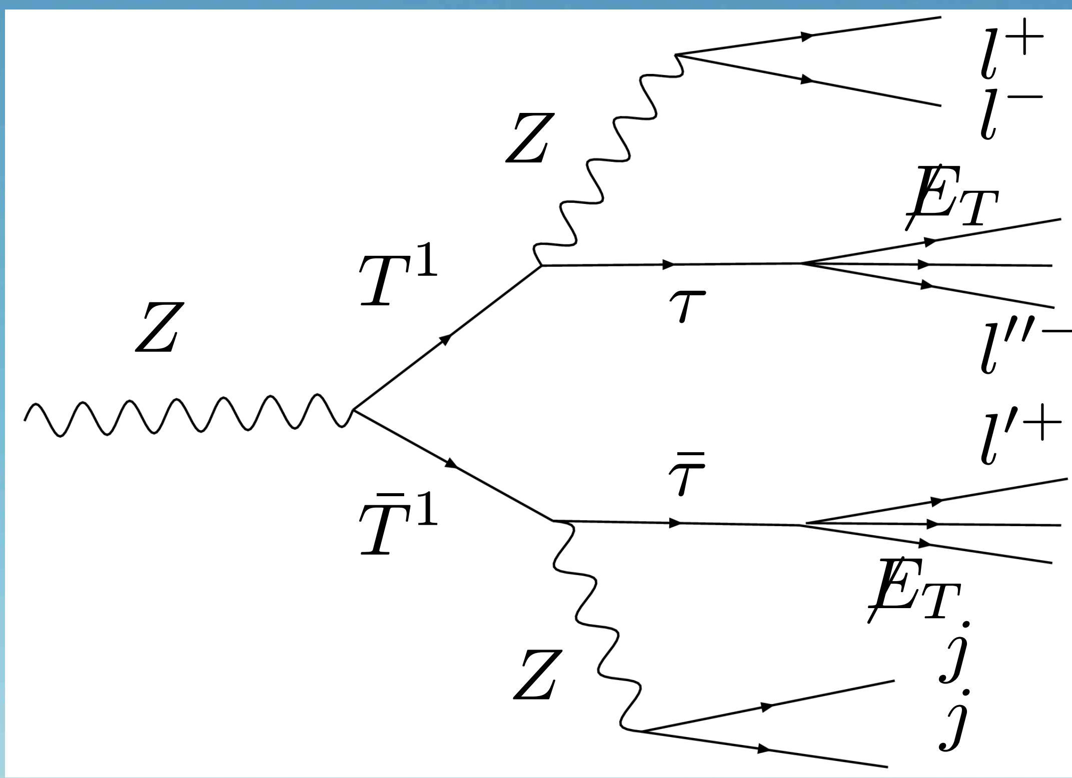
$\mu \to e\gamma \propto \frac{v^3}{\Lambda^3}$ requires $\frac{v}{\Lambda} \lesssim 0.01 - 0.1$

$m_\tau \propto \frac{v}{\Lambda}$ suppressed $\Rightarrow \tau$ very composite

Tau custodians: new light lepton resonances with strong coupling to the tau (LHC implications of high-scale see-saw!)

Tau custodians at the LHC

Signature $pp \to l^+ l^- l'^+ l''^- jj \not{E}_T$ $l, l', l'' = e, \mu$

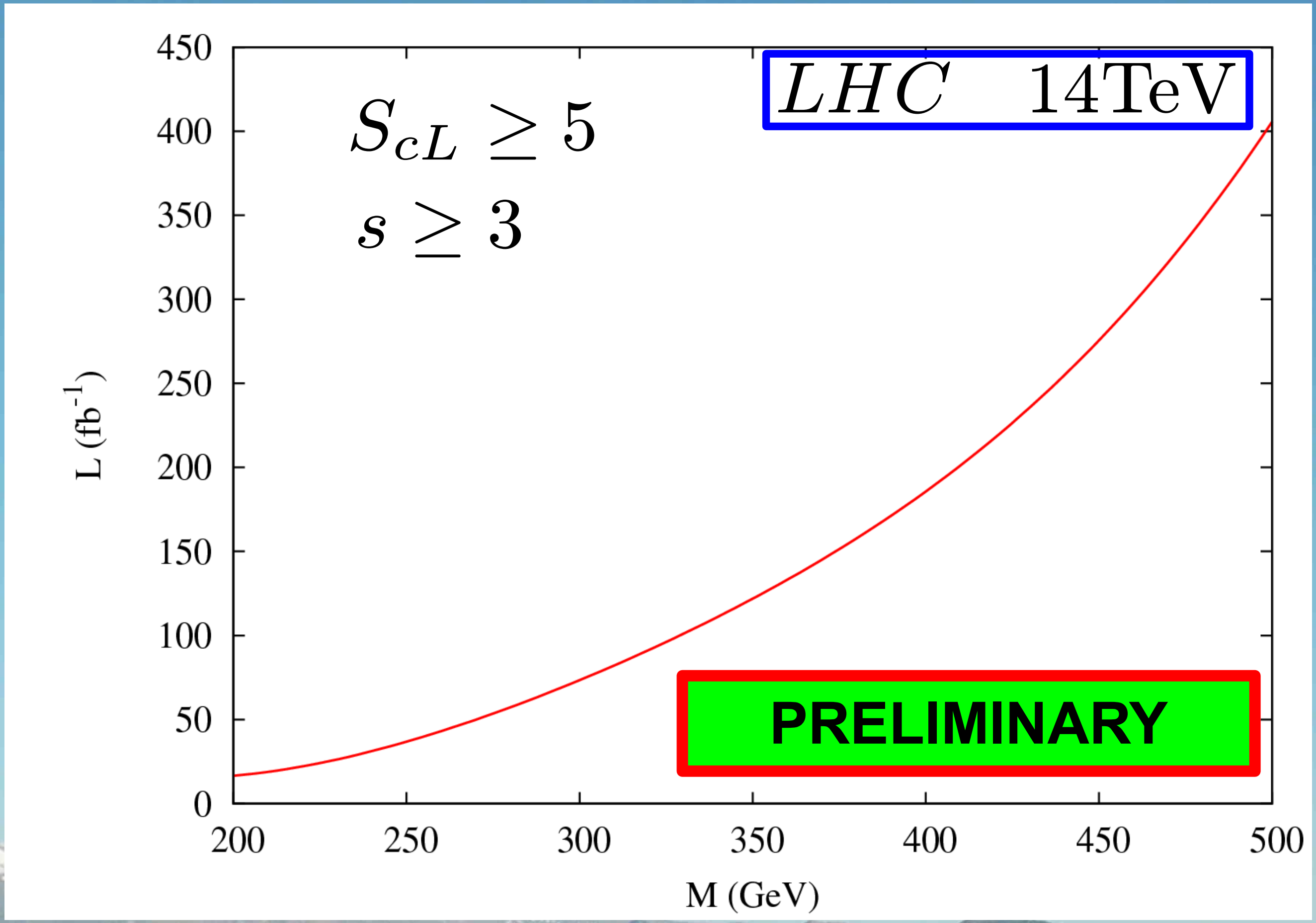


Very collimated

Very collimated

Tau custodians at the LHC

Discovery luminosity $S_{cL} \equiv \sqrt{2\left[(s+b)\ln\left(1-\frac{s}{b}\right)-s\right]}$



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 from (high-scale) see-saw
    - Double layer of flavor protection
      - A4 symmetry
      - Custodial + LR symmetry+ structure of MCHM5
  - New lepton resonances at the LHC!
  - LFV close to observable limits

Backup slides

Quantum numbers

	A_4	Z_8		A_4	Z_8
ζ_1	$\mathbf{3}$	1	$\phi(\mathrm{UV})$	$\mathbf{3}$	4
ζ_2	$\mathbf{3}$	2	$\eta(\mathrm{UV})$	$\mathbf{1}$	4
ζ_3	$\mathbf{3}$	1	$\phi'(\mathrm{IR})$	$\mathbf{3}$	5
ζ_α	$\mathbf{1}, \mathbf{1}', \mathbf{1}''$	4	$\eta'(\mathrm{IR})$	$\mathbf{1}$	7

Lower bounds on θ_{13}

- Large corrections to θ_{13} can be accommodated (how natural is that?)

$$\frac{v}{\Lambda} = 0.5 \qquad\qquad \delta_2 = 8 \ll 4\pi^2 \ \text{(NDA)}$$

$$\frac{\eta\phi^2}{\Lambda^3}\overline{\nu}'^{c}_{2R}\nu'_{2R} + \text{h.c.} \to \overline{\nu}'^{c}_{2R}\begin{pmatrix} \delta_1+\delta_2+\delta_3 & 0 & 0 \\ 0 & \delta_1+\omega\delta_2+\omega^2\delta_3 & 0 \\ 0 & 0 & \delta_1+\omega^2\delta_2+\omega\delta_3 \end{pmatrix}\nu'_{2R} + \text{h.c.},$$

$$\sin^2 2\theta_{13} = 0.125$$