A MODEL FOR NEUTRINO AND CHARGED LEPTON MASSES IN EXTRA DIMENSIONS

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NEUTRINO PHYSICS : SESSION IV

OUTLINE

A. INTRODUCTION

: Fundamental questions in ν-physics

: mechanisms for generating tiny light ν-masses

B. Our idea

: What is new?

: extra dim + fat brane

(ADD + UED)

C. MODEL & FORMALISM

: One family model

: extension to more families

D. PHENOMENOLOGICAL IMPLICATIONS

E. CONCLUSIONS

A. INTRODUCTION

ν-SECTOR : $\sqrt{\Delta m^2_{12}} \sim 10^{-2}$ eV

$\sqrt{\Delta m^2_{23}} \sim 5 \times 10^{-2}$ eV

Charged lepton Sector : $m_e \sim 1$ MeV

$m_\mu \sim 100$ MeV

$m_\tau \sim 2{,}000$ MeV

Hierarchy :

Charged leptons : 2,000 : 100 : 1

Possible ν- mass hierarchy : 5 : 1 : 1

MIXING ANGLES :

ν- Sector : Two angles large, one small

Quark-sector : All angles small

QUESTIONS:

: Why the ν-masses so small compared to quarks and charged lepton masses?

: Why there can be practically no hierarchy among the ν-masses, while large hierarchy among the quarks and charged lepton masses?

: Why, unlike the quark sector, the mixing angles are large in ν-sector?

: Are ν's Majorana or Dirac?

MECHANISM FOR UNDERSTANDING TINY ν-MASSES

① SEE-SAW

$$\mathcal{L} = f\,\bar{\ell}\,H\,N_R + M\,N_R\,N_R$$

$N_R \to M_N$

$$m_\ell \sim f\langle H\rangle$$

$$m_\nu \sim \frac{m_\ell^2}{M_N}$$

: does not naturally lead to lack of hierarchy among ν-masses

: ν's Majorana $\Rightarrow \beta\beta$ decay, CL, $m_{ee} \lesssim 0.3\,\text{eV}$

② EXTRA DIMENSION

ADD model, large submm extra dim

$$\mathcal{L} = \int dy\, f_5\, \bar{\ell}\,H\,N_R \Rightarrow \frac{f_5}{\sqrt{\pi r}}\,(\bar{\ell}\,H\,N_R)$$

$\bar{\ell}\,H$: 4D wall; N_R: extra dim

$$f = \frac{f_5}{\sqrt{\pi r}} \text{ small,}$$

because r is large ($\sim$ submm.)

: does not explain hierarchy among charged lepton masses.

B. OUR MODEL

⇓

: Combine ADD WITH UED

: Gravity and RH ν propagate in submm size extra dim

: SM particles live in a fat brane, instead of a 4D wall

⇒ ν's get masses as in ADD

⇒ Three SM families live in fat branes of sizes (R_1, R_2, R_3)

⇒ lead to hierarchies among the charged lepton masses.

MODEL AND FORMALISM

: one extra dim, y, of size $r \sim$ submm, S^1

: gravity propagate all the way in y

: SM singlet RH ν, N propagate in y in the space S^1/Z_2 orbifold

: All SM particles of 1st family, as well as the Higgs doublet, H lives in the S^1/Z_2 orbifold of size R

$r \sim$ submm, $R \sim$ TeV^{-1}

Fields : $\ell \equiv \begin{pmatrix} \nu_e \\ e \end{pmatrix}$, e_R, H, N ← SM singlet

$$\ell(x,y) = \frac{1}{\sqrt{\pi R}} \left\{ \ell_L^0(x) + \sqrt{2} \sum_{n=1}^{\infty} \left[\ell_L^n(x) \cos\frac{ny}{R} + \ell_R^n(x) \sin\frac{ny}{R} \right] \right.$$

$$e_R(x,y) = \frac{1}{\sqrt{\pi R}} \left\{ e_R^0(x) + \sqrt{2} \sum_{n=1}^{\infty} \left[e_R^n(x) \cos\frac{ny}{R} + e_L^n(x) \sin\frac{ny}{R} \right] \right.$$

$$H(x,y) = \frac{1}{\sqrt{\pi R}} \left\{ H^0(x) + \sqrt{2} \sum_{n=1}^{\infty} H^n(x) \cos\frac{ny}{R} \right\}$$

$$N(x,y) = \frac{1}{\sqrt{\pi R}} \left\{ N_R^0(x) + \sqrt{2} \sum_{n=1}^{\infty} \left[N_R^n(x) \cos\frac{ny}{R} + N_L^n(x) \sin\frac{ny}{R} \right] \right.$$

$$S_1^{int} = \int d^4x \int_0^{\pi R} dy \left[y_5 \bar{l}(x,y) H(x,y) e(x,y) + \tilde{y}_5 \bar{l}(x,y) \tilde{H}(x,y) N(x,y) \right] + h.c.$$

$$\Rightarrow S_1^{int} = \int d^4x \left[\frac{1}{\sqrt{\pi R}} y_5 \bar{e}_L e_R \frac{1}{\sqrt{2}} (v+h) + \frac{1}{\sqrt{\pi r}} \tilde{y}_5 \bar{\nu}_L N_R \frac{1}{\sqrt{2}} (v+h) \right] + h.c.$$

$$y_4 \equiv \frac{y_5}{\sqrt{\pi R}} \;, \quad \tilde{y}_4 \equiv \frac{\tilde{y}_5}{\sqrt{\pi r}}$$

$$\Rightarrow m_e = y_4 \frac{v}{\sqrt{2}} \;, \quad m_{\nu e} = \tilde{y}_4 \frac{v}{\sqrt{2}}$$

: Even though $y_5 \sim \tilde{y}_5$, $\tilde{y}_4$ is hierarchially small compared to y_4

$$\Rightarrow m_{\nu e} << m_e$$

: $$\frac{m_{\nu e}}{m_e} = \left(\frac{\tilde{y}_5}{y_5} \right) \sqrt{\frac{R}{r}} \sim \sqrt{\frac{R}{r}}$$

With $R^{-1} \sim$ TeV, $r \sim$ submm $\sim 1/10^{-3}$ eV

$$\Rightarrow m_{\nu e} \sim 10^{-2} \text{ eV}$$

Problem :

$N(x,y) \Rightarrow N_R^0,\ N_R^1,\ N_R^2,\ \cdots\cdots$
$\qquad\qquad\quad\ N_L^1,\ N_L^2,\ \cdots\cdots$

zero mass

mass $\sim 10^{-3}$ ev

: $\nu_{Le}^{(0)}$ combine with N_R^0 to make a massive Dirac ν_e

: But, $N_R^{(n)}$, $N_L^{(n)}$ will mix with ν_e, and will alter its SM coupling

To SOLVE THIS

: introduce a bulk SM singlet scalar field $\Phi(x,y)$; $\Phi(x,-y) = -\Phi(x,y)$

$$\Phi(x,y) = \sum_{n=1}^{\infty} \Phi^n(x) \sin\frac{ny}{r}$$

$\Rightarrow$ Additional bulk interaction

Additional bulk interaction:

$$S_1' = \tilde{Y}_5 \int d^4x \int_0^{\pi r} dy \; \bar{N}(x,y)\, N(x,y)\, \Phi(x,y)$$

: Assume only $\Phi^1(x)$ has a large TeV scale VEV

$$\Rightarrow S_1' = M \bar{N}_L^n N_R^m \left[\delta_{n-m-1,0} + \delta_{n-m+1,0}\right]$$

where $M \equiv \dfrac{\tilde{Y}_5 \langle \Phi^1 \rangle}{\sqrt{\pi r}}$

Mass matrix:

Fields : $(\nu_{eL}^0, N_L^1, N_L^2, \cdots)$

$(N_R^0, N_R^1, N_R^2, \cdots)$

For simplicity,
take only first two KK excitations

Mass matrix

$$(\nu_{eL}^{0}, \bar{N}_L^{1}, \bar{N}_L^{2}) \begin{pmatrix} m & \sqrt{2}\,m & \sqrt{2}\,m \\ 0 & m' & M \\ 0 & M & 2m' \end{pmatrix} \begin{pmatrix} N_R^{0} \\ N_R^{1} \\ N_R^{2} \end{pmatrix}$$

$m' \sim \frac{1}{R}$, $M \sim$ Tev scale

$\Rightarrow$ neutrino masses : m, $\underbrace{M, M}$ Two Tev scale massive neutrinos (N_1, N_2)

one light neutrino, ν_e

$\Rightarrow$ Mixing between ν_e and N_i are $O\left(\frac{m}{M}\right)$

: Including upto n^{th} KK excitations,

$\Rightarrow$ one light neutrino of mass $\sim m$ and n Tev scale massive neutrinos

$\Rightarrow$ ONE FAMILY MODEL

: ν's are Dirac

: hieranchy bet. light ν and charged lepton mass.

C. INCORPORATING MORE FAMILIES

Two Family Model

Bulk doublets: $l_e(x,y)$, $l_\mu(x,y)$, $H(x,y)$
$e_R(x,y)$, $\mu_R(x,y)$

Bulk singlets: $N(x,y)$, $N'(x,y)$, $\Phi(x,y)$

Additional bulk interactions:

$$S_{12} = \int d^4x \int_0^{\pi R} dy \Big[y_{5(e,\mu)} \bar{l}_e(x,y) H(x,y) \mu(x,y) + \tilde{y}_{5(e\mu)} \bar{l}_e(x,y) \tilde{H}(x,y) N'(x,y) + (e \leftrightarrow \mu) \Big] + h.c.$$

$$S'_{12} = \tilde{Y}'_5 \int d^4x \int_0^{\pi r} dy\, M'_0 \Big[\bar{N}(x,y) N'(x,y) + \bar{N}'(x,y) N(x,y) \Big] \Phi(x,y)$$

Fields: $(\nu^0_{eL}, \nu^0_{\mu L}, N^1_L, N'^1_L, N^2_L, N'^2_L, \dots)$
$(N^0_R, N^1_R, N'^1_R, N^2_R, N'^2_R, \dots)$

$\Rightarrow$ Two light neutrinos, $m_{\nu_e} \sim m$, $m_{\nu_\mu} \sim p$
and n Tev scale neutrinos of mass $\sim M, M'$
$\therefore$ Mixing bet. light and heavy $\sim O(m/M)$

Three Family Model

$l_e(x,y)$, $l_\mu(x,y)$, $l_\tau(x,y)$, $H(x,y)$: Doublets

$e_R(x,y)$, $\mu_R(x,y)$, $\tau_R(x,y)$: Singlets

$N(x,y)$, $N'(x,y)$, $N''(x,y)$, $\Phi(x,y)$

$\Rightarrow$ Three light neutrinos of masses
m_{ν_e}, m_{ν_μ}, m_{ν_τ}

+ n TeV scale neutrinos of mass $\sim M, M', M''$

: Mixing between light and heavy, $\sim O(m/M)$

HIERARCHY BETWEEN THE CHARGED LEPTON MASSES :

$$m_e : m_\mu : m_\tau = \sqrt{\frac{1}{R_1}} : \sqrt{\frac{1}{R_2}} : \sqrt{\frac{1}{R_3}}$$

$$\Rightarrow R_1^{-1} : R_2^{-1} : R_3^{-1} \sim 1\ \text{TeV} : 10^4\ \text{TeV} : 10^6\ \text{TeV}$$

D. PHENOMENOLOGICAL IMPLICATIONS

: ν's are Dirac $\Rightarrow$ no neutrinoless double beta decay
(expected future expt. limit, $m_{ee} \sim 0.01$ eV)

: KK excitations of SM particles at TeV scale
(in ADD model, no KK excitation of SM particles)
Current limit from Tevatron, ~ 350 GeV

: KK excitations of only 1st family (?) at LHC energy
(different from UED)

: Unification scale somewhat higher than UED

: where do the gauge bosons live ? (R')

$$S_{gauge} = \int d^4x \int_0^{\pi R_i} dy \frac{1}{(\sqrt{\pi R_i})^2 \sqrt{\pi R'}} g_5 \bar{f}_i(x,y) \Gamma^m T^a f_i(x,y) A_{\mu a}$$

$$\Rightarrow \int d^4x \frac{g_5}{\sqrt{\pi R'}} \left[\bar{f}_i^0(x) \gamma^m T^a f_i^0(x) A_{\mu a}^{(x)} + \text{KK terms} \right]$$

$\Rightarrow R' > R_i$ to have universal gauge couplings

$\Rightarrow \mu' < \mu_i \Rightarrow$ KK excitations of gauge bosons lighter than KK excitation of fermions

$\Rightarrow$ Testable at LHC

CONCLUSIONS

: A new model for neutrino and charged lepton masses in extra dim

: Three families live in fat branes of three different sizes of TeV^{-1} scale or smaller

: Gravity and SM singlet neutrinos propagate in submm size extra dim

: model combines ADD with UED

: hierarchy of charged lepton masses from the hierarchy of fat branes

: ν'masses from submm extra dim., hence not hierarchial

: explain $m_\nu \ll m_\ell$

: ν's are Dirac particle $\Rightarrow$ no neutrinoless $\beta\beta$ decay

: KK excitations of the gauge bosons lighter than KK excitations of fermions (LHC)

+ : KK excitations of only the gauge bosons and possibly the 1st family in LHC reach.

FURTHER WORK IN PROGRESS

: Flavor violation

: Higher dim. operators

: Stability of fat branes