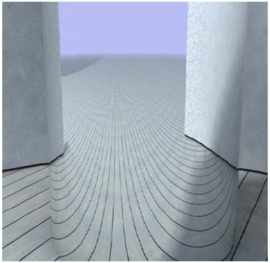
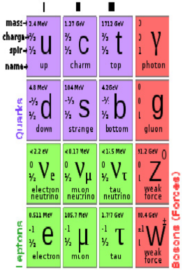
Flavor in Warped Space

We-Fu Chang





National Tsing Hua University
(Based on works done with John Ng, A. Spray, and J. Wu)

Nanning, Nov.18, LHEP2010

Outlines

1. Flavor and Warped Extra Dimension (Randall-Sundrum)
2. Quark sector in RS
3. Lepton sector in RS

Free Parameters and problems in SM

- There are 27(+2) free parameters in SM
- Roughly speaking, one group of free parameters involves gauge interaction and how the symmetries are broken.

$$\begin{aligned} 4 &: \alpha_1, \alpha_2, \alpha_3, G \\ +2 &: M_W, m_H \end{aligned}$$

- The second class (will be referred as general flavor problem) involes fermion masses and mixings.

$$\begin{aligned} +6+6 &: m_e, m_\mu, m_\tau, 3m_\nu s, m_u, m_c, m_t, m_d, m_s, m_b \\ +1+4+4 &: \theta_{QCD}, U_{CKM}, U_{PMNS} \\ (+2) &: \text{Majorana phases} \end{aligned}$$

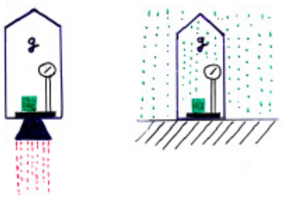
We are arrogant!

The ultima dream of HEP theorist is to reduce the number of free parameters as many as possible.

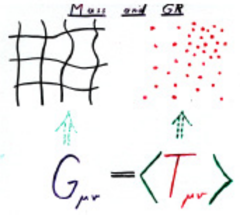
- Prominent problems: gauge hierarchy? Electroweak symmetry breaking?
  For example, GUT makes three couplings to one
- Prominent problems: Why 3 generations? Why $m_t \gg m_q, m_l \gg m_\nu$? Why $\theta^{12}_{CKM} \gg \theta^{23}_{CKM} \gg \theta^{13}_{CKM}$?
  For example, flavor symmetry to reduce the 21(+2) flavor parameters to only few
- ... etc

Mass and gravity

(Pictures stolen from Fritzsch's talk)



Equivalence principle
Eötvös exp, $< 10^{-9}$



Einstein Eq
Need unify concept of mass.

Gravity and mass $\Longleftarrow\!\Longrightarrow$ Quantum Physics

Planck Mass

$$M_p = \sqrt{\frac{\hbar c}{G}} = 1.2 \times 10^{19}\ \text{GeV} \sim 0.02\ \text{mg}$$

Our ultimate goal: All physical quantities be calculated in terms of Planck units.

RS Model is one of the promising candidates

- Randall-Sundrum (PRL83, 3370) can explain the hierarchy between EW and M_{planck}

$$EW \sim ke^{-kr_c\pi}, \; kr_c \sim 11.7$$

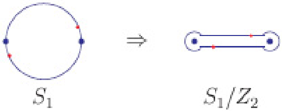
where k is the 5D curvature $\sim M_{planck}$ and r_c is the radius of the compactified fifth dimension.

- Due to the same warping factor, the mass and mixing hierarchy among fermions can be achieved without fine tuning in Yukawa couplings.
- And the number of free parameters (in flavor sector) is smaller than in SM

Introduction to the Randall-Sundrum Model

- RS assumes a 1+4 dim with a warp or conformal metric, AdS.
- 5D interval (S_1/Z_2) is given by

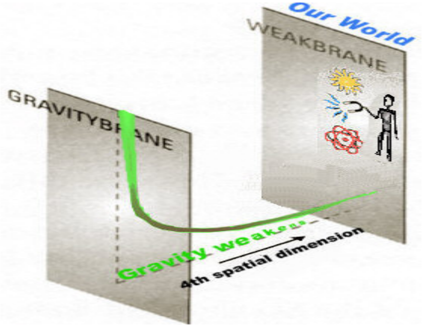
$$ds^2 = G_{AB}dx^A dx^B = e^{-2kr_c|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 d\phi^2, \; -\pi \leq \phi \leq \pi$$



- Two branes are localizes at $\phi = 0$(UV) and $\phi = \pi$(IR)
- The metric is

$$G_{AB} = \begin{pmatrix} e^{-2\sigma}\eta_{\mu\nu} & 0 \\ 0 & -r_c^2 \end{pmatrix}, \; \sigma \equiv kr_c|\phi|$$

Due to the metric, matters tend to stay near the IR brane.



From Planck to EW

- A Higgs scalar on the IR brane.

$$\int d^4x d\phi \sqrt{G} \frac{\delta(\phi-\pi)}{r_c} \left[G^{\mu\nu} (D_\mu \Phi(x))^\dagger D_\nu \Phi(x) + \lambda \left(|\Phi(x)|^2 - v^2 \right)^2 \right]$$
$$= \int d^4x d\phi e^{-4\sigma} \delta(\phi-\pi) \left[e^{2\sigma} (D_\mu \Phi(x))^\dagger D_\nu \Phi(x) + \lambda \left(|\Phi(x)|^2 - v^2 \right)^2 \right]$$

- After SSB, $\Phi(x)$ acquires a VEV, $\langle \Phi \rangle = v \sim$ the Planck scale. Re-scaling the Higgs field to $H(x) = e^{-kL}\Phi(x)$, the effective 4D action becomes

$$\int d^4x \left[(D_\mu H(x))^\dagger D^\mu H(x) + \lambda \left(|H(x)|^2 - v_W^2 \right)^2 \right]$$

$v_w = ve^{-k\pi r_c} = 174 GeV$.

Bulk Fermion

- 5D action for fermions is

$$\int d^4x d\phi \sqrt{G} \left[E_a^A \bar{\Psi} \gamma^a D_A \Psi - c\, k\, \mathrm{sgn}(\phi) \bar{\Psi}\Psi \right]$$

where E_a^A is the veilbien, and a dimensionless bulk mass c.

$$\Psi_{L,R}(x,\phi) = \frac{e^{\frac{3}{2}\sigma}}{\sqrt{r_c}} \sum_n \Psi_n^{L,R}(x) \hat{\phi}_n^{L,R}(\phi)\,, \; \langle \hat{\phi}_n | \hat{\phi}_m \rangle = \delta_{m,n}$$

spectrum determined by B.C.'s (+: Neumann /-: Dirichlet).
- Desired chirality for zero mode set by orbifold parity.
- The coefficients $c_{L,R}$ control the zero modes peak at either UV or IR
- SM chiral zero modes localized near UV brane $\Rightarrow$ small overlap after SSB. No need to fine tune Yukawa's. Fermion masses are naturally small. (except 3rd generation quarks)

Fermion Masses in RS

- The fermion masses are given by

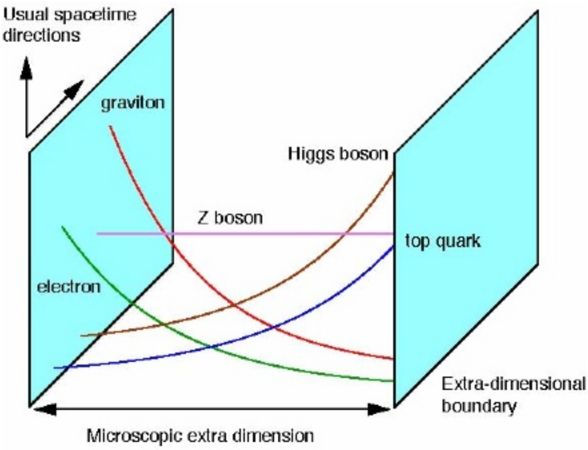
$$\left\langle M_{ij}^{f} \right\rangle = \frac{\lambda_{5,ij}^{f} v_W}{k r_c \pi} f_L^0(\pi, c_{f_i}^L) f_R^0(\pi, c_{f_j}^R)$$

where $v_W = 174$ GeV, and

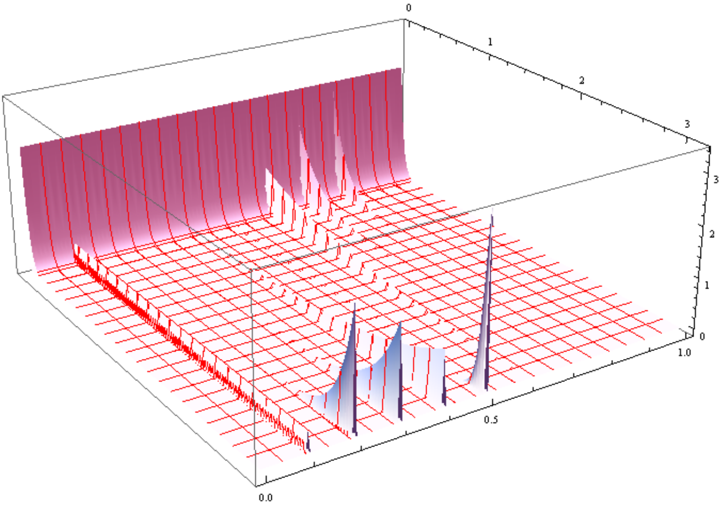
$$f_{L,R}^0(\phi, c_{L,R}) \propto \exp\left[k r_c \phi (1/2 \mp c_{L,R})\right]$$

- The Yukawa couplings λ_{ij} are arbitrary complex numbers with $|\lambda| \sim \mathcal{O}(1)$.
- The task is find configurations that fit all the known fermion masses and the CKM/PMNS matrices.

Bulk Wave Function



One More Look at the Bulk Wave Function Profiles



Electroweak Precision Tests

- The main problem is that the new KK modes will modify EWPT
- The S, T parameters will receive tree level corrections
- It's known that $\rho = 1$ is protected by a custodial $SU(2)$ symmetry
- Promote that to a bulk gauge symmetry
- Tree level KK gauge effects are suppressed
- The gauge symmetry is now $SU(2)_L \times SU(2)_R \times U(1)_X$
- Take $X = B - L$

Custodial RS model

- Break $SU(2)_R \to U(1)_R$ by orbifold B.C.

	UV	IR
$\tilde{W}_\mu^{1,2}$	$-$	$+$
other Gauge Fields	$+$	$+$

- $U(1)_R \times U(1)_X \to U(1)_Y$ by VEV on UV brane. We have a Z' and B_μ

$$Z'_\mu = \frac{g_5 \tilde{W}_\mu^3 - g'_5 \tilde{B}_\mu}{\sqrt{g_5^2 + g_5'^2}}$$

and

$$B_\mu = \frac{g'_5 \tilde{W}_\mu^3 + g_5 \tilde{B}_\mu}{\sqrt{g_5^2 + g_5'^2}}$$

- B_μ is the SM hypercharge gauge boson and broken with $SU(2)_L$ on the IR brane by Higgs (a bi-doublet)

Quark Representation

- Zero modes have parity $(++)$
- Usual assignment doesn't work

$$\begin{matrix} SU(2)_L & SU(2)_R \\ \begin{pmatrix} t_L \\ b_L \end{pmatrix} & \begin{pmatrix} t_R \\ b_R \end{pmatrix} \end{matrix}$$

  because t_R is a zero mode and $SU(2)_R$ is broken on UV
- d_R and t_R must have their own $(-+)$ partners

$$\begin{matrix} SU(2)_L & SU(2)_R & SU(2)_R \\ \begin{pmatrix} t_L \\ b_L \end{pmatrix} & \begin{pmatrix} \mathbf{T_R} \\ b_R \end{pmatrix} & \begin{pmatrix} t_R \\ \mathbf{B_R} \end{pmatrix} \end{matrix}$$

General Configurations

- We have found several realistic configurations. For example,

$$\begin{aligned}\nu_Q &= \{0.634, 0.556, 0.256\}\\ \nu_U &= \{-0.664, -0.536, 0.185\}\\ \nu_D &= \{-0.641, -0.572, -0.616\}\end{aligned}$$

- The u and d quark mass matrices (at TeV scale)

$$\langle|M_u|\rangle = \begin{pmatrix} 0.000897 & 0.049 & 0.767 \\ 0.010 & 0.554 & 8.69 \\ 0.166 & 9.06 & 142.19 \end{pmatrix},$$

$$\langle|M_d|\rangle = \begin{pmatrix} 0.0019 & 0.017 & 0.0044 \\ 0.022 & 0.196 & 0.050 \\ 0.352 & 3.209 & 0.813 \end{pmatrix}$$

(in GeV), where we have used $ke^{-kr_c\pi} = 1.5\,TeV$

RS Quark Masses

- Statistic average: $\lambda_5 = \rho e^{i\theta}$,

$$\rho \in \left[1/\sqrt{2}, \sqrt{2}\right], \theta \in [0, 2\pi]$$

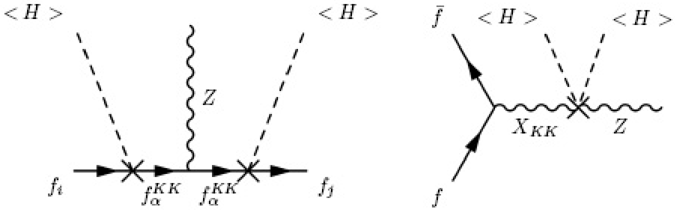
- The CKM matrix elements for the above

$$|V^L_{us}| = 0.16(14)\,,\ |V^L_{ub}| = 0.009(11)\,,\ |V^L_{cb}| = 0.079(74)$$
$$|V^R_{us}| = 0.42(24)\,,\ |V^R_{ub}| = 0.12(10)\,,\ |V^R_{cb}| = 0.89(13)$$

- Note the RH rotations are larger than the LH ones
- Appears to be true from the numerical searches we found
- How to test it?

FCNC in the minimal Constrained RS model

- Besides the direct production of the KK Z (≥ 2.5 TeV) is tree level FCNC
- FCNC $Z - f_{KK}$ and $Z - Z'_{KK}$ mixing



- Going to the mass basis the unitarity is broken $\rightarrow$ FCNC

$t \longrightarrow Z + jets$

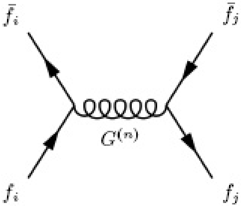
- The BR is:

$$Br(t \to Zc(u)) = 1.8677 \times \left(|Q_Z(t_L)\hat{\kappa}^L_{tc(u)}|^2 + |Q_Z(t_R)\hat{\kappa}^R_{tc(u)}|^2 \right)$$

- LH and RH decays are different. $\kappa^R > \kappa^L$ in the configs we found.
- But $Br(t_R \to Z + c(u)_R) < Br(t_L \to Z + c(u)_L)$ by factor $\sim 2 - 10$ due to the destructive interference.
- The BR is $\sim 10^{-5}$ c.f. SM $\sim 10^{-13}$
- Compare the decays in $t\bar{t}$ vs single tW channels.

$\triangle F = 2$ FCNC

- Server constraint come from $\triangle F = 2$ FCNC mediated by tree-level exchange of KK gluons.



- The fermions are in the weak eigenbasis. Go to the mass basis,

$$G_\mu^{(n)} \left[\sum_{a,b} (\hat{g}_f^n)^L_{ab}\, \bar{f}'_{aL} \gamma^\mu f'_{bL} + (L \leftrightarrow R) \right] , \qquad f = u,\, d\,,$$

- Summing all KK Gluon contribution

$$\mathfrak{S}^{\omega,\xi}_{ab,cd} = \sum_{n=1}^{\infty} \frac{(\hat{g}_f^n)^\omega_{ab} (\hat{g}_f^n)^\xi_{cd}}{m_n^2} , \qquad \omega,\, \xi = L,\, R$$

- The effective $\Delta F = 2$ Hamiltonian beyond SM

$$\mathcal{H}_{eff}^{NP} = \sum_{i=1}^{5} C_i(\Lambda) Q_i^{ab} + \sum_{i=1}^{3} \tilde{C}_i(\Lambda) \tilde{Q}_i^{ab} \,,$$

Λ:the scale of new physics, and

$$\begin{aligned} Q_1^{ab} &= \bar{\psi}_{aL}^{\alpha} \gamma_\mu \psi_{bL}^{\alpha} \bar{\psi}_{aL}^{\beta} \gamma^\mu \psi_{bL}^{\beta} \,, Q_2^{ab} = \bar{\psi}_{aR}^{\alpha} \psi_{bL}^{\alpha} \bar{\psi}_{aR}^{\beta} \psi_{bL}^{\beta} \,, \\ Q_3^{ab} &= \bar{\psi}_{aR}^{\alpha} \psi_{bL}^{\beta} \bar{\psi}_{aR}^{\beta} \psi_{bL}^{\alpha} \,, Q_4^{ab} = \bar{\psi}_{aR}^{\alpha} \psi_{bL}^{\alpha} \bar{\psi}_{aL}^{\beta} \psi_{bR}^{\beta} \,, \\ Q_5^{ab} &= \bar{\psi}_{aR}^{\alpha} \psi_{bL}^{\beta} \bar{\psi}_{aL}^{\beta} \psi_{bR}^{\alpha} \,, \end{aligned}$$

α, β: colour indices, a, b: generation indices. The operator $\tilde{Q}_{1,2,3}^{ab}$ are obtained from $Q_{1,2,3}^{ab}$ by the $L \leftrightarrow R$.

- From KK Gluons,

$$C_1(\Lambda) = \frac{1}{6} \mathfrak{S}_{ab,ab}^{LL} \,, \qquad \tilde{C}_1(\Lambda) = \frac{1}{6} \mathfrak{S}_{ab,ab}^{RR} \,, \qquad C_4(\Lambda) = -\mathfrak{S}_{ab,ab}^{LR} \,,$$

- The 95% allowed range of the Wilson coefficients from UTfit contributing in the $\Delta F = 2$ tree-level gluon exchange processes, and their typical values at $\Lambda = 4$ TeV in each configuration. All values are given in units of GeV^{-2}.

Parameter	95% allowed range	Config. I	Config. II	Config. III
Re C_K^1	$[-9.6, 9.6] \cdot 10^{-13}$	$4.3 \cdot 10^{-17}$	$1.8 \cdot 10^{-15}$	$-4.2 \cdot 10^{-15}$
Re C_K^4	$[-3.6, 3.6] \cdot 10^{-15}$	$-1.4 \cdot 10^{-16}$	$-2.8 \cdot 10^{-16}$	$-1.8 \cdot 10^{-15}$
Re C_K^5	$[-1.0, 1.0] \cdot 10^{-14}$	$4.6 \cdot 10^{-17}$	$9.4 \cdot 10^{-17}$	$6.0 \cdot 10^{-16}$
Im C_K^1	$[-4.4, 2.8] \cdot 10^{-15}$	$2.6 \cdot 10^{-18}$	$1.8 \cdot 10^{-15}$	$-1.0 \cdot 10^{-15}$
Im C_K^4	$[-1.8, 0.9] \cdot 10^{-17}$	$1.5 \cdot 10^{-19}$	$8.8 \cdot 10^{-18}$	$-1.8 \cdot 10^{-18}$
Im C_K^5	$[-5.2, 2.8] \cdot 10^{-17}$	$-4.9 \cdot 10^{-20}$	$-2.9 \cdot 10^{-18}$	$6.0 \cdot 10^{-19}$
$\lvert C_D^1 \rvert$	$< 7.2 \cdot 10^{-13}$	$1.3 \cdot 10^{-13}$	$3.1 \cdot 10^{-13}$	$1.6 \cdot 10^{-14}$
$\lvert C_D^4 \rvert$	$< 4.8 \cdot 10^{-14}$	$1.7 \cdot 10^{-15}$	$8.8 \cdot 10^{-15}$	$4.0 \cdot 10^{-14}$
$\lvert C_D^5 \rvert$	$< 4.8 \cdot 10^{-13}$	$5.7 \cdot 10^{-16}$	$2.9 \cdot 10^{-15}$	$1.3 \cdot 10^{-14}$
$\lvert C_{B_d}^1 \rvert$	$< 2.3 \cdot 10^{-11}$	$7.5 \cdot 10^{-13}$	$7.7 \cdot 10^{-14}$	$4.8 \cdot 10^{-13}$
$\lvert C_{B_d}^4 \rvert$	$< 2.1 \cdot 10^{-13}$	$1.9 \cdot 10^{-13}$	$4.8 \cdot 10^{-14}$	$1.7 \cdot 10^{-13}$
$\lvert C_{B_d}^5 \rvert$	$< 6.0 \cdot 10^{-13}$	$6.2 \cdot 10^{-14}$	$1.6 \cdot 10^{-14}$	$5.6 \cdot 10^{-14}$
$\lvert C_{B_s}^1 \rvert$	$< 1.1 \cdot 10^{-9}$	$9.0 \cdot 10^{-11}$	$4.1 \cdot 10^{-11}$	$4.0 \cdot 10^{-11}$
$\lvert C_{B_s}^4 \rvert$	$< 1.6 \cdot 10^{-11}$	$9.4 \cdot 10^{-12}$	$7.6 \cdot 10^{-13}$	$5.8 \cdot 10^{-12}$
$\lvert C_{B_s}^5 \rvert$	$< 4.5 \cdot 10^{-11}$	$3.1 \cdot 10^{-12}$	$2.5 \cdot 10^{-13}$	$1.9 \cdot 10^{-12}$

1st KK Gluon at LHC

- For the three configurations and for $m_1 = 4.0$ TeV, the widths into the $\bar{t}t$ pairs are: $\{769.3, 635.4, 747.4\}$ GeV.
- The decay branching ratios of $G^{(1)}$

Branching ratios	Config. I	Config. II	Config. III
Top quarks	0.83	0.83	0.84
Bottom quarks	0.16	0.16	0.15
All Light quarks	0.01	0.01	0.01

- Top quark spin,

$$\frac{d\Gamma_s}{d\cos\theta} = \frac{m_1}{192\pi}\sqrt{1-4x_t^2}\Big\{ (|\hat{g}_L|^2 + |\hat{g}_R|^2)(1-x_t^2)$$
$$+6\,\mathrm{Re}\,(\hat{g}_L\hat{g}_R^*)\,x_t^2 + 2(|\hat{g}_R|^2 - |\hat{g}_L|^2)\,x_t\sqrt{1-4x_t^2}\,\mathbf{s}\cdot\hat{\mathbf{p}}\Big\}$$

with $x_t \equiv m_t/m_1$ and $\mathbf{s}$ the measured top spin three-vector, and $\mathbf{p}$ the three-momentum of the same top quark in the rest frame of $G^{(1)}$.

Summary for the quark sector

- The RS model can accommodate good quark mass matrices without fine tuning Yukawa
- $U_R > U_L$
- Tree level FCNC best probed in $t \to Z + jets$. The BR is $\sim 10^{-5}$ makes it very interesting at the LHC
- Predicts that LH decays are dominant.
- $\triangle F = 2$ is OK if with NP $\Lambda = 4$ TeV. And the discovery of 1st KK gluon at LHC is possible
- $G^{(1)}$ decay branching ratios: ~ 0.84 for top, ~ 0.15 for $b\bar{b}$.
- Top spin is useful to probe into the flavor structure of the RS scenario.

Dirac Neutrino in (4+n)-dim

- Neutrinos are massive. How about adding RH neutrinos to SM to write down $y_\nu \bar{L} \nu_R H$?
- Hierarchy among the Yukawa $y_t \sim 1 \Leftrightarrow y_\nu \lesssim 10^{-12}$
- Dim-4 operator is no good in 4D SM. But small y^ν_{eff} can be naturally made in models with extra spatial dimension(s).
- Bulk RH neutrinos in ADD model can make y^ν_{eff} small due to the same volume dilution that brings $M_G \Rightarrow$ TeV.

$$y_\nu \sim \int dy\, y_5\, \delta(y)_{SM}\, \phi(y)\,,\; y_5 \sim \mathcal{O}(1)$$

Dirac Neutrino Masses in RS

- The neutrino masses are given by

$$\langle M^{\nu}_{ij} \rangle = \frac{\lambda^{\nu}_{5,ij} v_W}{k r_c \pi} f^0_L(\pi, c^L_{\nu_i}) f^0_R(\pi, c^R_{\nu_j})$$

where $v_W = 174$ GeV, and

$$f^0_{L,R}(\phi, c_{L,R}) \propto \exp\left[k r_c \phi (1/2 \mp c_{L,R})\right]$$

- The Yukawa couplings λ_{ij} are arbitrary complex numbers with $|\lambda| \sim \mathcal{O}(1)$.
- The task is find configurations that fit the PMNS matrix

$$\triangle m^2_{21} = 7.67^{+0.67}_{-0.61} \times 10^{-5}\,\mathrm{eV}^2,\ |\triangle m_{31}|^2 = 2.46^{+0.47}_{-0.42} \times 10^{-3}\,\mathrm{eV}^2$$
$$\theta_{12} = 34.5^{+4.8}_{-4.0},\ \theta_{23} = 42.3^{+11.3}_{-7.7},\ \theta_{13} = 0.0^{+12.9}_{-0.0},\ \delta_{CP} \in [0,\ 2\pi]$$

Numerical solutions

Also, lepton flavor violation bounds
$Br(\mu \to 3e) < 10^{-12}$, $Br(\tau \to l_1 l_2 \bar{l}_3) < 10^{-7}$

Config.	c_L	c_E	c_{ν_R}
1	{0.5876, 0.5476, 0.5001}	{−0.7245, −0.5882, −0.5216}	{−1.247, −1.223, −1.278}
2	{0.5880, 0.5456, 0.5014}	{−0.7211, −0.5917, −0.5213}	{−1.333, −1.246, −1.223}
3	{0.5865, 0.5454, 0.5006}	{−0.7242, −0.5899, −0.5217}	{−1.223, −1.355, −1.245}
4	{0.5877, 0.5377, 0.5006}	{−0.7249, −0.5947, −0.5203}	{−1.321, −1.250, −1.224}
5	{0.5830, 0.5328, 0.5018}	{−0.7276, −0.6005, −0.5229}	{−1.254, −1.224, −1.384}

Config.	Charged lepton masses (MeV)	Neutrino masses (meV)	δ_{CP}	$\{\theta_{12}, \theta_{23}, \theta_{13}\}$ (°)
1	{0.4959, 104.7, 1780}	{1.4, 8.9, 50}	−0.47	{39, 36, 2.7}
2	{0.4959, 104.7, 1779}	{0.22, 8.5, 47}	2.5	{32, 42, 6.6}
3	{0.4959, 104.7, 1779}	{0.26, 9.0, 47}	1.3	{35, 38, 1.9}
4	{0.4959, 104.7, 1780}	{0.13, 8.7, 47}	2.4	{35, 53, 9.7}
5	{0.4959, 104.7, 1780}	{0.096, 9.1, 53}	1.5	{37, 49, 12}

Only normal hierarchy is viable in our search.

Some subtleties

- Bulk leptons are in the representation

$$L_i = \begin{pmatrix} \nu_{iL}[+,+] \\ e_{iL}[+,+] \end{pmatrix},\ E_i = \begin{pmatrix} \tilde{\nu}_{iR}[-,+] \\ e_{iR}[+,+] \end{pmatrix},\ \nu_{iR}[+,+]$$

  Only [+,+] fields have zero modes.

- Gauged discrete Z_3 symmetry forbids proton decay and lepton number violation.

$$\overline{d^c} u \overline{Q^c} L,\ \overline{Q^c} Q \overline{u^c} e,\ \overline{Q^c} Q \overline{Q^c} L,\ \overline{d^c} u \overline{u^c} e,\ \overline{u^c} u \overline{d^c} e,\ uddn,$$
$$M_n \overline{\nu_R^C} \nu_R,\ \frac{1}{\Lambda_\nu}(LH)^2,\ \cdots$$

- The bulk EW symmetry is now extended to

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times U(1)_x$$

- and the $U(1)_x$ is SSB to Z_3 by a UV Higgs.

KK fermion masses

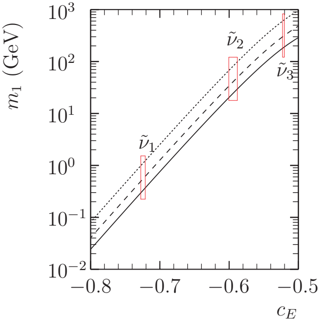
- In general, KK excitations of gauge boson and fermions $\sim$ few TeVs.
- The couplings to SM fields are suppressed.
- Very hard to test at LHC.
- However, [-+] KK fermion ($\tilde{\nu}_R$) can be relatively light.

$$\frac{J_{c_E+1/2}(m_n/k)}{Y_{c_E+1/2}(m_n/k)} = \frac{J_{c_E-1/2}(m_n e^{kr_c\pi}/k)}{Y_{c_E-1/2}(m_n e^{kr_c\pi}/k)}$$

Its mass is determined by the bulk mass parameter.

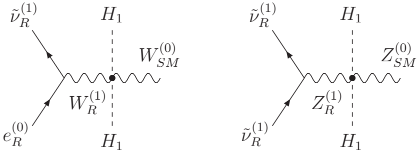
Light KK [-+] Neutrinos

For the five representative configurations, we have an $e-$like neutrino $\tilde{\nu}_1 \sim (175 - 222)$ MeV, a $\mu-$like neutrino $\tilde{\nu}_2 \sim (16 - 24)$ GeV, and a $\tau-$like neutrino $\tilde{\nu}_3 \sim (168 - 180)$ GeV.



Bottom up: 3, 5, 10 TeV 1st [++]KK gauge boson.

Effective coupling



- Light KK neutrinos couple to SM W

$$W\tilde{\nu}_{iR}e_{iR} \quad : \quad r_i\, g_L/\sqrt{2}$$

$$\{r_1,\, r_2,\, r_3\} \sim \{2.0\times 10^{-3},\, 0.15,\, 1.0\}\times 10^{-3}\times\left(\frac{3\,\text{TeV}}{M_{-+}}\right)^2$$

- Light KK neutrinos couple to SM Z ($Z\overline{\tilde{\nu}_R}\nu_R$ is suppressed)

$$Z\bar{\tilde{\nu}}_{iR}\tilde{\nu}_{iR} \quad : \quad \frac{g_L}{\cos\theta_W}\gamma^\mu\left[z_{Li}\hat{L}+z_{Ri}\hat{R}\right]$$

$$\{z_1,\, z_2,\, z_3\}_{L/R} \sim \{0.97,\, 0.93,\, 0.91\}\times 10^{-2}\times\left(\frac{3\,\text{TeV}}{M_{-+}}\right)^2$$

Life time

- $\tilde{\nu}_3$ decays predominantly into τW.

$$\Gamma_{\tilde{\nu}_3} \sim 1.5 \times 10^{-6} \text{ GeV}$$

- For $\tilde{\nu}_1$, the dominant decay channel is $\tilde{\nu}_1 \to e e^+ \nu_e$:

$$\tau_{\tilde{\nu}_1} \sim 2.3 \times 10^4 \times \left(\frac{M_{KK}}{3\,\text{TeV}}\right)^4 \times \left(\frac{200\,\text{MeV}}{M_{\tilde{\nu}_1}}\right)^5 \text{sec}$$

- $\tilde{\nu}_2 \to \mu \bar{l} \nu_l$, $\mu \bar{d} u$, $\mu \bar{s} c$. $\tau_{\tilde{\nu}_2} \sim 1.2 \times 10^{-15}$ sec. for $M_{\tilde{\nu}_2} = 20$ GeV and $M_{KK} = 3$TeV,

Evade the low energy tests

- Our r_1 is well within $|r_1|^2 < 10^{-6}$ set by no extra peaks in the e^+ spectrum of $K^+ \to e^+\tilde{\nu}_1$ decay for a (160-220) MeV ν.
- By kinematics, $\tilde{\nu}_1$ does not modify G_F, best determined by the muon decay, at tree level.
- At the Z pole. LEP measured

$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_\nu^{SM}} = 2.9840 \pm 0.0082\,.$$

- $\tilde{\nu}_2$ decays into charged final states immediately. Only $\tilde{\nu}_1$ can escape the detector.

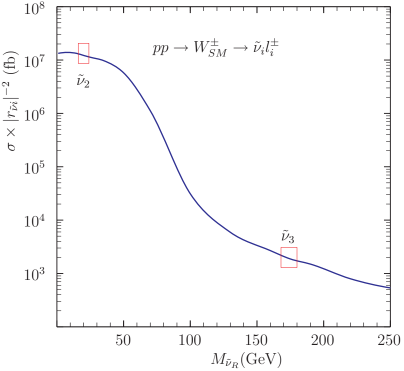
$$z_{L1}^2 + z_{R1}^2 \leq 0.096 \text{ (95\% CL)}$$

much larger than our estimates above.

Convolute the parton level $\hat{\sigma}$ with PDF(MSTW2008) to get the production cross-section at LHC

$$\sigma(pp \to \tilde{\nu}_i e_i^+) = \int dx_1 dx_2\, 2 f_u(x_1) f_d(x_2) \hat{\sigma}(x_1 x_2 s) \theta(1 - x_{N_i})$$

The total $\tilde{\nu}_R$ production cross section $\sim$ 0.3fb and $\sim$ 0.001fb for $\tilde{\nu}_2$ and $\tilde{\nu}_3$ respectively at $\sqrt{s} = 14$ TeV (both $\tilde{\nu} l^\pm$ are included).



Searching for the $\tilde{\nu}$ at LHC

- $\tilde{\nu}_1$ is much lighter than a GeV. Too large background for $\tilde{\nu}_1$ at LHC.
- $\tilde{\nu}_2$ can be detected via $u\bar{d} \to \tilde{\nu}_2 \mu^+ \to \mu^+ \mu^- e(\tau)\bar{\nu}$.
- Apparent lepton flavor violation plus missing energy, with the $\mu^+\mu^-$ pair not in resonance.
- These are characteristic heavy neutrino signatures.
- Similarly, $\tilde{\nu}_3$ can be detected via $u\bar{d} \to \tau^+ \tilde{\nu}_3 \to \tau^+ \tau^- W$.
- Where a W jet plus τ jets are expected and the τ jets are not in resonance.

Summary of the lepton sector

- RS model can accommodate good fermion mass matrices without fine tuning Yukawa.
- Small Dirac neutrino masses are natural in RS model.
- A gauged discrete symmetry to forbid the gravity induced Majorana neutrino masses and proton decays.
- This model predicts normal hierarchy and a nonzero $\theta_{13}\,(1^o - 13^o)$.
- Predicts three light KK neutrinos at 170 MeV, 20 GeV, and 180 GeV.
- 20 GeV $\tilde{\nu}_2$ may be probed at LHC.
- RS provides a framework to explain two hierarchies in the same time.

Conclusion

- RS provides a framework to explain two hierarchies in the same time.
- And it can be tested.

Extra -1

As of today, there are roughly 6,882,000,000 people in the world....

..... and every single one is UNIQUE!

Extra -2

And we have no idea why there are aliens among us??

Although any two persons have 99.9% of their DNA in common.

However, it's easy to tell the differences between two species.

We share 98.5% of DNA sequences with chimps.

Extra -4: $B_q^0 - \bar{B}_q^0$ Mixing

- One very sensitive probe to NP in the meson sector comes from the B_q^0-$\bar{B}_q^0$ mixing ($q = d,\, s$)
- The contribution of NP to $\Delta B = 2$ transitions can be parametrized in a model-independent way as the ratio of the full (SM + NP) amplitude to the SM one

$$\frac{\langle B_q^0|\mathcal{H}_{eff}^{full}|\bar{B}_q^0\rangle}{\langle B_q^0|\mathcal{H}_{eff}^{SM}|\bar{B}_q^0\rangle} = 1 + \frac{\langle B_q^0|\mathcal{H}_{eff}^{NP}|\bar{B}_q^0\rangle}{\langle B_q^0|\mathcal{H}_{eff}^{SM}|\bar{B}_q^0\rangle} \equiv C_q\, e^{2i\phi_q}\,, \qquad q = d,\, s\,,$$

- For the configurations of solutions we found, KK gluons are not manifest in the B_q^0-$\bar{B}_q^0$ mixing, and the SM effects are expected to be dominant.

Parameter	Config. I	Config. II	Config. III
C_d	1.13	1.02	1.08
ϕ_d [°]	-2.48	-0.24	-3.02
C_s	1.68	1.36	1.29
ϕ_s [°]	0.61	0.12	0.04