Surprises from Warped Space

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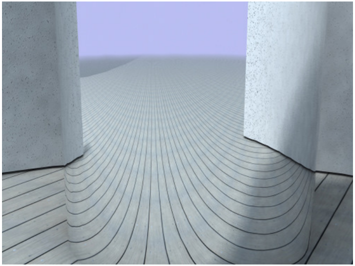

National Tsing Hua University
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Outlines

1. Motivation for extra spacial dimension(s)
2. Warped Extra Dimension (Randall-Sundrum)
3. Something unexpected
4. An unusual 2HDM in RS
5. Summary

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.

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

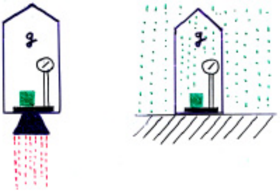
We are arrogant!

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

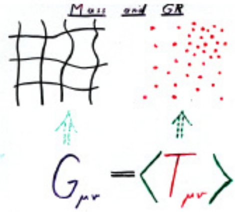
- Prominent problems: gauge hierarchy? Electroweak symmetry breaking?
  For example, GUT makes three couplings to one
- Prominent problems: Why 3 generations? Why $m_t \gg m_q, m_l \gg m_\nu$? Why $\theta^{12}_{CKM} \gg \theta^{23}_{CKM} \gg \theta^{13}_{CKM}$?
  For example, flavor symmetry to reduce 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 $\Longleftrightarrow$ 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 special profile of bulk fermion in RS, the 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

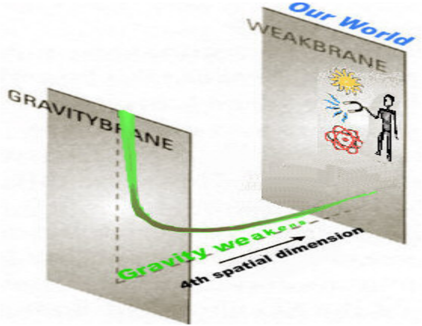
$$ds^2 = G_{AB}dx^A dx^B = e^{-2kr_c|\phi|}\eta_{\mu\nu}dx^\mu dx^\nu - r_c^2 d\phi^2, \; -\pi \le \phi \le \pi$$

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

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

Randall-Sundrum Model

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



- 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

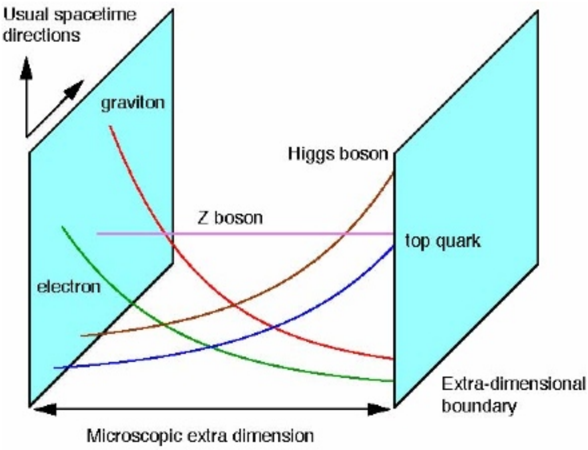
$$\left\langle M_{ij}^{f} \right\rangle = \frac{\lambda_{5,ij}^{f} v_W}{k r_c \pi} f_L^0(\pi, c_{f_i}^L) f_R^0(\pi, c_{f_j}^R)$$

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



Surprise 1: Problem with gravity

- Generally speaking, gravity does NOT respect any global symmetry, like $U(1)_L$, $U(1)_B$, etc.
- Therefore, one expects that gravity will generate the Mojorana mass term anyway

$$M_n \overline{\nu_R^C} \nu_R \,, \quad \text{or} \quad \frac{1}{\Lambda_\nu}(LH)^2$$

- That will ruin the hard earned Dirac neutrino configurations.

Another serious problem: Proton decay-1

- We also expect that gravity will generate the effective proton decay operators.

$$\overline{d^c} u \overline{Q^c} L,\ \overline{Q^c} Q \overline{u^c} e,\ \overline{Q^c} Q \overline{Q^c} L,\ \overline{d^c} u \overline{u^c} e,\ \overline{u^c} u \overline{d^c} e,\ uddn$$

- For example, consider the 4 $SU(2)$ doublets operator. In RS,

$$\frac{1}{\Lambda_P^2} \sim \int \frac{dy}{M_{Planck}^3} \psi_1 \psi_2 \psi_3 \psi_4$$
$$\sim 2 \int_0^\pi d\phi \left(\frac{k r_c (c_L + 1/2)}{r_c} \right)^2 exp[k r_c \phi (2 + 3 c_L^Q + c_L^L)]$$

Another serious problem: Proton decay-2

- No problem if all fermion zero modes are at UV. However, we have all the c's fixed by fermion masses and mixings.

$$\Lambda_P \sim M_{Planck} e^{-kr_c\pi}$$

- The realistic fermion configuration is not UV enough.
- The warping factor not only brings down the EW scale from the Planck scale. It takes the proton decay scale down to $\sim \mathcal{O}(100's)$ GeV as well.

Gauged discrete symmetry

- Similar problems occur in the study of black hole.
- In 1989, Krauss and Wilczek (PRL62,1221) proposed a mechanism such that a Z_n discrete symmetry will remain after the SSB of a $U(1)$.
- Arrange the SSB Higgs to carry a proper (higher) $U(1)$ charge.
- The SSB vacuum does a 2π $U(1)$ rotation to return the same configuration.
- However, the other filed with smaller charges are not able to complete a full rotation.
- If the charge is $1/N$ of the SSB Higgs, the Lagrangian possess a Z_N symmetry.
- Gravity has to respect the Z_N due to its gauge origin.

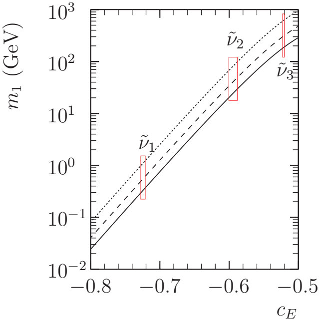
Surprise 2: KK fermion masses

- In general, KK excitations of gauge boson and fermions $\sim$ few TeV.
- The couplings to SM fields are suppressed.
- Very hard to test at LHC.
- However, [-+] KK fermion ($\tilde{\nu}_R$)can be relatively light. (Agashe et el, JHEP0308, 050)

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

Light KK [-+] Neutrinos

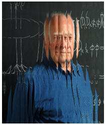
For the five representative configurations, we have an $e-$like neutrino $\tilde{\nu}_1 \sim (175 - 222)$ MeV, a $\mu-$like neutrino $\tilde{\nu}_2 \sim (16 - 24)$ GeV, and a $\tau-$like neutrino $\tilde{\nu}_3 \sim (168 - 180)$ GeV.



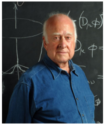
Bottom up: 3, 5, 10 TeV 1st [++]KK gauge boson.

Surprise 3: An Unusual 2HDM

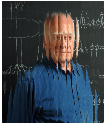
- Today, mainly on our recent finding of another unexpected outcome.
- We found that a composite Higgs could emerge from the condensation of third generation quarks.



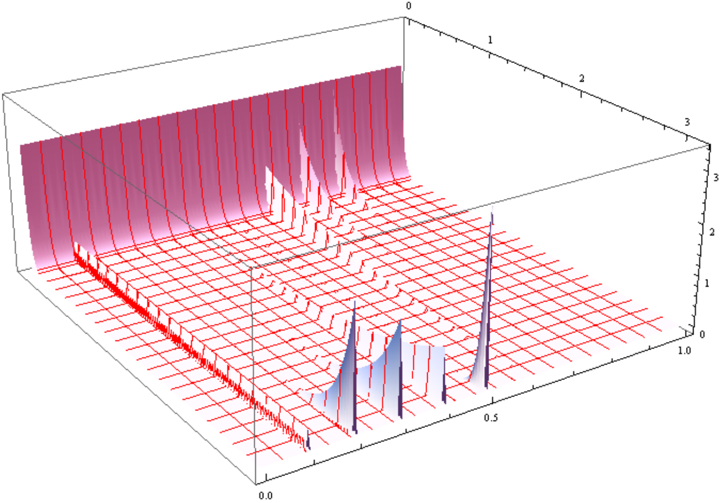
- I will discuss the resulting 2HDM.



Plus



One More Look at the Bulk Wave Function Profiles



Nambu-Jona-Lasinio term

- In the gauge (weak) eigenbasis, the coupling of the nth level KK gluon, $G^{(n)}$, to zero-mode fermions is given by

$$G_\mu^{A(n)} \left[\sum_i (g_f^n)_{ii}^L \, \bar{f}_{iL} T^A \gamma^\mu f_{iL} + (L \to R) \right], \qquad f = u,\, d\,,$$

  where g_f^n is proportional to the fermion-KK gauge overlapping and can be determined by their profiles.

- For small exchanging momenta, tree-level exchange of G_{KK}^1 leads to 4-Fermi interactions between zero mode fermions given by

$$\begin{aligned} & -\frac{g_i g_j}{M_{KK}^2} \left(\overline{Q_{iL}} T^A \gamma^\mu Q_{iL} \right) \left(\overline{f_{jR}} T^A \gamma_\mu f_{jR} \right) \\ & = \frac{g_i g_j}{M_{KK}^2} \left(\overline{Q_{iL}} f_{jR} \right) \left(\overline{f_{jR}} Q_{iL} \right) + O(1/N_c) \end{aligned}$$

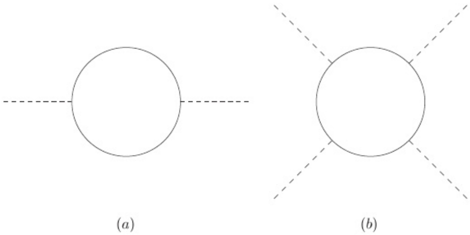
- In addition to the elementary scalar field H, below M_{KK}, the condensate can be viewed as a composite Higgs doublet.
- It has the same $SU(2)_L \times U(1)_Y$ quantum numbers as the SM Higgs. (ρ OK at tree level!)
- At M_{KK}, $\Phi \sim g_t < \bar{Q} t > / M_{KK}^2$ is a static auxiliary field.

$$\begin{aligned} \mathcal{L} &= |D_\mu H|^2 - m_0^2 H^\dagger H - \frac{1}{2}\lambda_0 (H^\dagger H)^2 \\ &\quad + \lambda_t \overline{Q_L} t_R \widetilde{H} + g_t \overline{Q_L} t_R \widetilde{\Phi} - M_{KK}^2 \Phi^\dagger \Phi + h.c. \end{aligned}$$

where $\widetilde{H} = i\sigma_2 H^*$, $\widetilde{\Phi} = i\sigma_2 \Phi^*$, $Q_L = (t, b)_L$, and m_0^2, λ_0 are the parameters in the brane Higgs scalar potential.

Bubble diagram

- At scales $\mu < M_{KK}$, quantum fluctuations generate a kinetic term for Φ as well as kinetic and mass term mixings between ϕ and H.
- Fermion bubble contribution to scalar (a) 2-point functions and (b) 4-point functions. The dashed lines can be either Φ or H fields.



Effective 2HDM

The effective Lagrangian takes the form

$$\begin{aligned}\mathcal{L} = & \left[1+\lambda_t^2\epsilon\right]|D_\mu H|^2 + \lambda_t g_t \epsilon\left[(D_\mu H)^\dagger D^\mu \Phi + h.c.\right] + g_t^2\epsilon|D_\mu \Phi|^2 \\ & - \left[m_0^2 - \lambda_t^2\Delta^2\right] H^\dagger H + \lambda_t g_t \Delta^2\left[H^\dagger\Phi + \Phi^\dagger H\right] - \left[M_{KK}^2 - g_t^2\Delta^2\right]\Phi^\dagger\Phi \\ & - \left[\frac{1}{2}\lambda_0 + \lambda_t^4\epsilon\right](H^\dagger H)^2 - 2\lambda_t^2 g_t^2\epsilon\left[\frac{1}{2}(H^\dagger\Phi + \Phi^\dagger H)^2 + H^\dagger H\Phi^\dagger\Phi\right] \\ & - 2\lambda_t^3 g_t\epsilon\, H^\dagger H(H^\dagger\Phi + \Phi^\dagger H) - 2\lambda_t g_t^3\epsilon\,\Phi^\dagger\Phi(H^\dagger\Phi + \Phi^\dagger H) - g_t^4\epsilon\,(\Phi^\dagger\Phi)^2 \\ & + \lambda_t\overline{Q_L}t_R\widetilde{H} + g_t\overline{Q_L}t_R\widetilde{\Phi} + h.c.\end{aligned}$$

Looks so complicated...

Effective 2HDM

- Here,

$$\epsilon = \frac{N_c}{16\pi^2} \ln\left(\frac{M_{KK}^2}{\mu^2}\right);$$
$$\Delta^2 = \frac{2N_c}{16\pi^2}(M_{KK}^2 - \mu^2),$$

  are calculated in the 1-loop approximation.
- $\epsilon \sim O(0.1)$ and $\Delta \sim O(0.3) M_{KK}$.
- We have also taken the cutoff to be M_{KK}, above which the 4-Fermi condensate approximation is no longer valid.

Effective 2HDM

- However, the transformations

$$H = \hat{H}\,,\ \Phi = -\frac{\lambda_t}{g_t}\hat{H} + \frac{1}{g_t\sqrt{\epsilon}}\hat{\Phi}$$

  will cast the kinetic terms into canonical diagonalized form.
- The resulting Lagrangian of the scalars is delightfully simple:

$$\mathcal{L} \supset |D_\mu \hat{H}|^2 + |D_\mu \hat{\Phi}|^2 - V(\hat{H}, \hat{\Phi})$$

  with

$$V(\hat{H},\hat{\Phi}) = \left(m_0^2 + \frac{\lambda_t^2}{g_t^2}M_{KK}^2\right)\hat{H}^\dagger\hat{H} - \frac{\lambda_t}{g_t^2\sqrt{\epsilon}}M_{KK}^2\left(\hat{H}^\dagger\hat{\Phi} + \hat{\Phi}^\dagger\hat{H}\right) + \left(\frac{M_{KK}^2}{g_t^2\epsilon} - \frac{\Delta^2}{\epsilon}\right)\hat{\Phi}^\dagger\hat{\Phi} + \frac{1}{2}\lambda_0(\hat{H}^\dagger\hat{H})^2 + \frac{1}{\epsilon}(\hat{\Phi}^\dagger\hat{\Phi})^2$$

Electroweak Symmetry breaking of 2HDM

- Define $\tan\beta = v_H/v_\phi$ and minimizing the potential yields:

$$\left(m_0^2 + \frac{\lambda_t^2}{g_t^2} M_{KK}^2\right) v_H - \frac{\lambda_t}{g_t^2\sqrt{\epsilon}} M_{KK}^2 v_\phi + \frac{\lambda_0}{2}|v_H|^2 v_H = 0,$$

$$\left(\frac{M_{KK}^2}{g_t^2\epsilon} - \frac{\Delta^2}{\epsilon}\right) v_\phi - \frac{\lambda_t}{g_t^2\sqrt{\epsilon}} M_{KK}^2 v_H + \frac{2}{\epsilon}|v_\phi|^2 v_\phi = 0.$$

We require that $v_H^2 + v_\phi^2 = (246\text{GeV})^2$.

Spectrum of Physical Scalars

- Charged and pseudoscalar sectors have the same mass matrix:

$$M_{\pm}^2 = M_A^2 = \begin{pmatrix} a + \frac{\lambda_0}{2} v_H^2 & c \\ c & b + \frac{1}{\epsilon} v_\phi^2 \end{pmatrix},$$

where

$$a = m_0^2 + \frac{\lambda_t^2}{g_t^2} M_{KK}^2 \,, b = \frac{1}{\epsilon}\left(\frac{M_{KK}^2}{g_t^2} - \Delta^2 \right), c = -\frac{\lambda_t}{g_t^2 \sqrt{\epsilon}} M_{KK}^2 .$$

- $det M_{\pm}^2 = 0$, the states with null eigenvalue are the Goldstone bosons to be eaten by $W^{\pm}$ and Z^0.
- At tree level, we have ($H^{\pm} = c_\beta h^{\pm} - s_\beta \phi^{\pm}, A^0 = c_\beta h_I - s_\beta \phi_I$)

$$M_{A^0}^2 = M_{H^\pm}^2 = \frac{2\lambda_t}{g_t^2 \sqrt{\epsilon} \sin 2\beta} M_{KK}^2$$

and mixing angle $\beta = \tan^{-1}(v_H / v_\Phi)$.

Degeneracy and Symmetry

- Without mass mixing term, $\hat{\Phi}$ and $\hat{H}$ have individual symmetries $SU(2)_{\hat{\Phi}L} \times SU(2)_{\hat{\Phi}R}$ and $SU(2)_{\hat{H}L} \times SU(2)_{\hat{H}R}$, and their cross product is a subgroup of $SO(8)$.
- SSB yields

$$\begin{aligned} SU(2)_{\hat{\Phi}L} \times SU(2)_{\hat{\Phi}R} &\xrightarrow{v_\phi} SU(2)_{D\hat{\Phi}} \\ SU(2)_{\hat{H}L} \times SU(2)_{\hat{H}R} &\xrightarrow{v_H} SU(2)_{D\hat{H}} \end{aligned}$$

  $SU(2)_D$ are analogous to the SM custodial $SU(2)$.
- The mixing term in $V(\hat{\Phi}, \hat{H})$ further reduces the symmetry to $SU(2)_V \subset SU(2)_{D\hat{\Phi}} \times SU(2)_{D\hat{H}}$.
- Three Goldstones form a triplet under this $SU(2)_V$. The 2 charged Higgs and the pseudoscalar form another triplet. The remaining two scalars are singlets. $3+3+1+1=8$

Neutral Scalars

- The mass squared matrix for the two scalars is given by

$$M_0^2 = \begin{pmatrix} a + \frac{3}{2}\lambda_0 v_H^2 & c \\ c & b + \frac{3}{\epsilon} v_\phi^2 \end{pmatrix}$$

- $TrM_0^2 = M_H^2 + k_1 v^2$ and $\det M_0^2 = k_2 M_H^2 v^2$, $k_{1,2}$ are ratios of $\mathcal{O}(1)$ parameters. Therefore one of the scalars $M_H \sim \mathcal{O}(\mathrm{TeV})$, while the other has mass $\sim \mathcal{O}(v)$
- It can be diagonalized

$$\begin{pmatrix} H_0 \\ h_0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \hat{H}_R \\ \hat{\Phi}_R \end{pmatrix}.$$

and

$$\tan 2\alpha = -\frac{2c}{a + \frac{3}{2}\lambda_0 v_H^2 - b - \frac{3}{\epsilon} v_\phi^2},$$

Top quark mass

- With the redefined scalar fields,

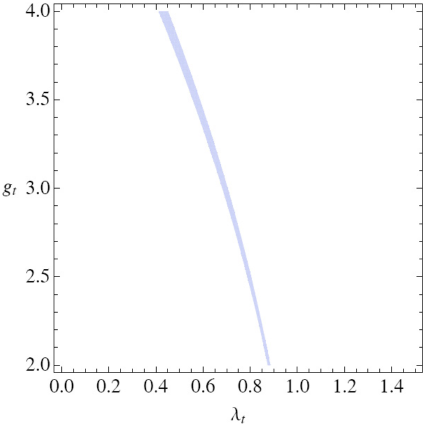
$$\mathcal{L}_Y = \lambda_t \overline{Q_L} t_R \widetilde{H} + g_t \overline{Q_L} t_R \widetilde{\Phi} + h.c. \rightarrow \frac{1}{\sqrt{\epsilon}} \overline{Q_L} t_R \widetilde{\hat{\Phi}} + h.c.$$

- Top quark gets its mass from coupling to $\hat{\Phi}$, which after symmetry breaking gives

$$m_t = \frac{v \cos\beta}{\sqrt{2\epsilon}}.$$

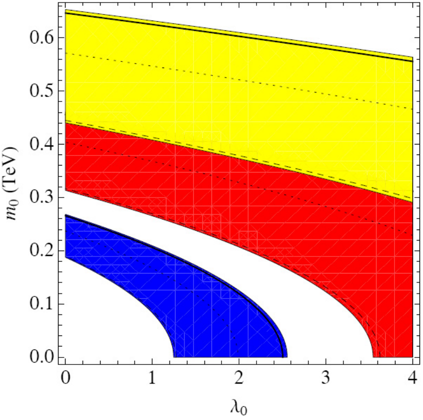
- $\tan\beta$ is determined by top mass!! $\cos\beta \sim \sqrt{\epsilon}$

$\{\lambda_t, g_t\}$



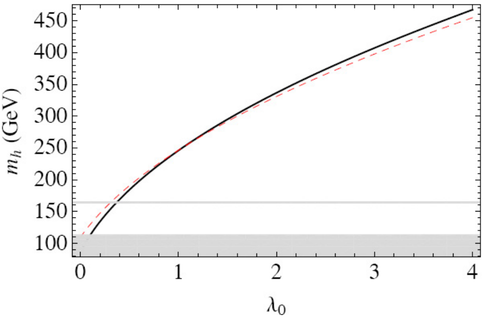
Allowed region in the $\{\lambda_t, g_t\}$ parameter space that satisfies m_t and 2nd Mini. Cond. M_{KK} lies between 1.5 to 4 TeV and m_t from 169.7 to 172.9 GeV.

$\{\lambda_0,\ m_0\}$



Allowed region in the $\{\lambda_0,\ m_0\}$ parameter space that satisfies 1st Mini. Cond. The (blue, red, yellow) correspond to $M_{KK} = \{1.5, 2.5, 3.5\}$ TeV. The lines (solid, dotted, dash) correspond to $g_t = \{2, 3, 4\}$.

SM like Higgs mass (Numerical)

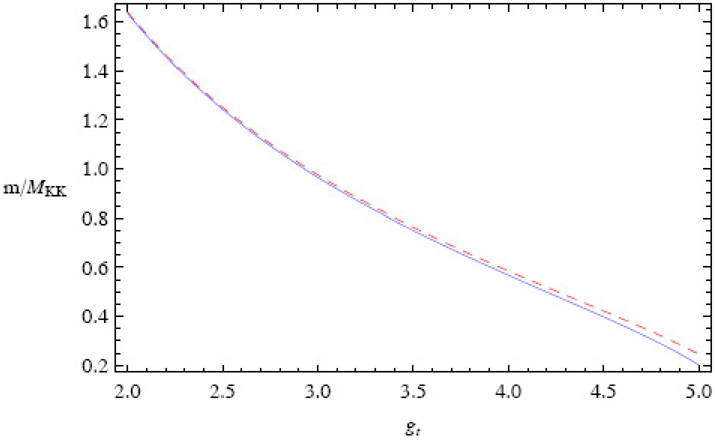


The mass of the lighter Higgs boson v.s. λ_0. The black line is for $M_{KK} = 1.5$ TeV and the red line is for $M_{KK} = 4$ TeV. The shaded regions are the LEP and Tevatron exclusions for the Higgs mass.

SM like Higgs mass

- The mass matrix for neutral scalar sector can be decomposed into
$$M_0^2 = M_\pm^2 + \begin{pmatrix} \lambda_0 v^2 \sin\beta & 0 \\ 0 & 4 m_t^2 \end{pmatrix}.$$
- Since the second term is much smaller than the first one, one expects taht the heavier $M_H \sim M_{H^\pm}$, and $\alpha \sim \beta$.
- By using $\alpha \sim \beta$, it can be derived that
$$M_{h_0}^2 \simeq \lambda_0 v^2 \sin^4\beta + 2\epsilon\, m_t^2.$$
- Also, the h^0 is very SM like. For example,
$$h^0 Z^0 Z^0 \text{ coupling } : \cos(\beta - \alpha)$$

Scalar Mass Splitting



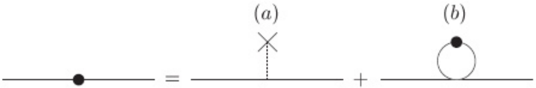
M_A, $M_{H^\pm}$, and M_{H^0} as a function of g_t and relative to M_{KK}. $M_{A^0} = M_{H^\pm}$ at tree level and are shown by the blue line; the heavier scalar state is the red dashed line.

Gap equation

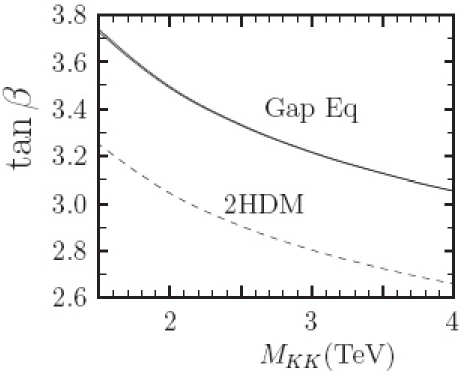
- An alternative way of obtaining m_t is via the gap equation,

$$
\begin{aligned}
m_t &= \frac{\lambda_t}{\sqrt{2}} v \sin\beta - i\frac{N_c g_L g_R}{2M_{KK}^2}\int \frac{d^4\ell}{(2\pi)^4}\frac{\mathrm{Tr}(\not\ell + m)}{\ell^2 - m_t^2} \\
&= \frac{\lambda_t}{\sqrt{2}} v \sin\beta + \frac{N_c g_L g_R m_t}{8\pi^2}\left[1 + \frac{m_t^2}{M_{KK}^2}\ln\frac{m_t^2}{M_{KK}^2}\right]
\end{aligned}
$$

- (a) Contribution from the brane Higgs (dash line) and the cross denotes the VeV. (b) The fermion bubble contribution.

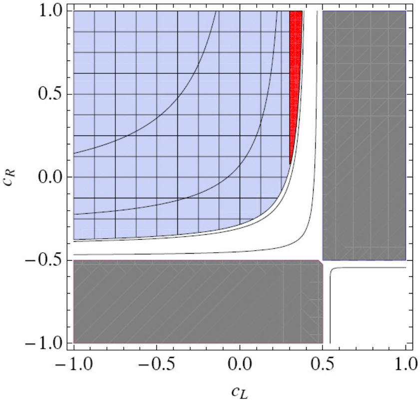


- The solutions for $\tan\beta$ v.s. M_{KK} in the 2HDM approach and from the gap equation.

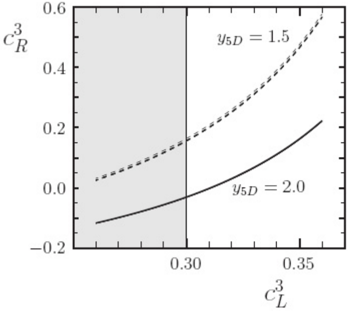


- This is consistent with the approximation of dropping $O(1/N_c)$ terms.

$c_L,\ c_R$ in 2HDM



Contours of g_t in c_L^3, c_R^3 plane for $M_{KK} = 1.5$ TeV. The solid lines are g_t contours for $g_t = \{4, 3, 2, 1, 0.125\}$ from top-left to bottom right. The dark regions are inconsistent with the condensate scenario. The small red region gives a good fit to $Z \to b_L \bar{b}_L$, without the additional P_{LR} symmetry.



The solution for bulk mass parameters c_L^3 and c_R^3 with two representative 5D Yukawa couplings. The KK mass is varied from 1.5 TeV to 4.0 TeV. The shaded areas are excluded by the $Z \to b_L \bar{b}_L$.

Flavor Changing Neutral Current -1

- The full Yukawa sector, including light quarks,

$$\mathcal{L}_Y = \lambda^d_{ij}\overline{Q_{Li}}d_{jR}H + g_t\overline{Q_{3L}}t_R\widetilde{\Phi} + \lambda^u_{ij}\overline{Q_{iL}}u_{jR}\widetilde{H} + h.c.$$

- After the rotation to go to canonical kinetic term, we have

$$\mathcal{L}_Y = \lambda^d_{ij}\overline{Q_{Li}}d_{jR}\hat{H} + \left(\lambda^u_{ij} - \lambda^u_{33}\right)\overline{Q_{iL}}u_{jR}\widetilde{\hat{H}} + \frac{1}{\sqrt{\epsilon}}\overline{Q_{3L}}t_R\widetilde{\hat{\Phi}} + h.c.$$

- After SSB, the up quark mass matrix is

$$\mathcal{M}^u_{ij} = -\frac{1}{\sqrt{2}}\begin{pmatrix} \lambda^u_{11}v_H & \lambda^u_{12}v_H & \lambda^u_{13}v_H \\ \lambda^u_{21}v_H & \lambda^u_{22}v_H & \lambda^u_{23}v_H \\ \lambda^u_{31}v_H & \lambda^u_{32}v_H & \frac{1}{\sqrt{\epsilon}}v_\phi \end{pmatrix}$$

Flavor Changing Neutral Current -2

- After little algebra, we can rewrite the Yukawa sector as,

$$\mathcal{L}_Y = -\frac{\sqrt{2}\mathcal{M}^d_{ij}}{v\sin\beta}\overline{Q_{Li}}d_{jR}\hat{H} - \frac{\sqrt{2}\mathcal{M}^u_{ij}}{v\sin\beta}\overline{Q_{iL}}u_{jR}\widetilde{\hat{H}} + \frac{1}{\sqrt{\epsilon}\cos\beta}\overline{Q_{3L}}t_R\left(\widetilde{\hat{\Phi}}\cos\beta - \widetilde{\hat{H}}\sin\beta\right) + h.c.$$

- It's clear that FCNC comes solely from the last term (no VEV, physical $H^\pm$ or A^0). And because $\alpha \sim \beta$, it is mainly H_0 in the combination.
- The light quark FCNCs are suppressed by
  - M_{KK} suppression if through H_0, $H^\pm$, and A^0
  - $\sin(\beta-\alpha)$ suppression if through h_0
  - Flavor structure of RS.
- From the first two terms, the h^0 Yukawa coupling is $-\sqrt{2}(M_{ij}/v)(\sin\alpha/\sin\beta)$, very close to the SM.

Conclusions

- RS model provides an interesting framework to address both the gauge hierarchy and flavor problems.
- However, unexpected outcomes: proton decay, very light KK fermions.
- Moreover, an unusual effective 2HDM could emerge from the $Q_3 t_3$ condensation below M_{KK}.
- The 2HDM is very predictable: $\tan\beta \sim 3$, close to the decoupled limit, no FCNC in down sector.