Unusual Two Higgs Doublet Model from Warped Space

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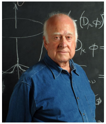

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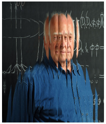


Randall-Sundrum Model

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

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

k: 5D curvature $\sim M_{planck}$, r_c: radius of extra dimension.

- Two branes are localizes at $\phi = 0$(UV) and $\phi = \pi$(IR). The elementary Higgs H on the IR brane.
- The hierarchy among fermions is due to the special profile of bulk fermion, without fine tuning in Yukawa couplings.
- All physical quantities in terms of Planck unit

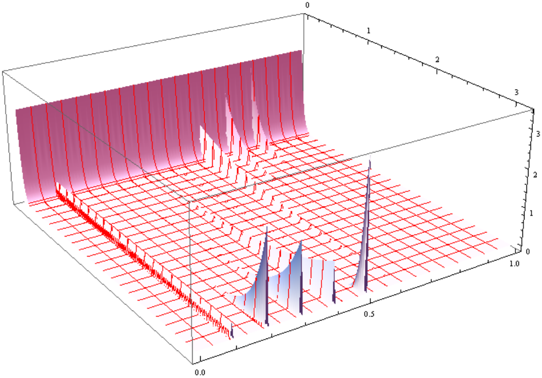
Fermion Masses in RS

- 5D action for fermions (E_a^A: the veilbien.)

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

- 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)
- The task is find configuration(s) $\{c_L^1, c_L^2, c_L^3, c_R^1, c_R^2, c_R^3\}$ that fits all the known fermion masses and the CKM/PMNS matrices. (See PRD78,096003, PRD79,056007, PRD80,113013)

the Bulk Wave Function Profiles



$g_{Gtt}^{L/R}$, the coupling of the 1st KK gluon, $G_{KK}^{(1)}$, to LH/RH zero-mode fermions is proportional to the wavefunction overlapping and can be determined by their profiles.

Nambu-Jona-Lasinio term

- Tree-level exchange of $G^{(1)}_{KK}$ leads to 4-Fermi interactions between zero mode fermions

$$\frac{g_i g_j}{M^2_{KK}} \left(\overline{Q_{iL}} f_{jR}\right) \left(\overline{f_{jR}} Q_{iL}\right) + O(1/N_c)$$

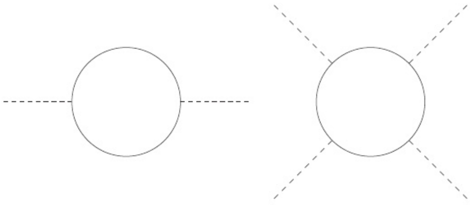
- Besides H, the condensate $\Phi = g_t < \bar{Q} t > / M^2_{KK} \Rightarrow$ composite Higgs doublet below M_{KK}, where $g_t \equiv \sqrt{g^L_{Gtt} g^R_{Gtt}}$.
- Φ and SM Higgs have the same $SU(2)_L \times U(1)_Y$ quantum numbers. $\Rightarrow \rho$ is OK at tree level!
- At M_{KK}, Φ is a static auxiliary field.

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

m_0^2, λ_0 are the usual parameters in the Higgs 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.



(a) (b)

Effective 2HDM

- 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 diagonal 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 the loop factors $\epsilon \sim O(0.1)$, $\Delta \sim O(0.3)M_{KK}$, and

$$V(\hat{H},\hat{\Phi}) = A\hat{H}^\dagger\hat{H} + \frac{1}{2}\lambda_0(\hat{H}^\dagger\hat{H})^2 + B\hat{\Phi}^\dagger\hat{\Phi} + \frac{1}{\epsilon}(\hat{\Phi}^\dagger\hat{\Phi})^2 + C(\hat{H}^\dagger\hat{\Phi} + \hat{\Phi}^\dagger\hat{H})$$

  where

$$A = m_0^2 + \frac{\lambda_t^2}{g_t^2}M_{KK}^2\,, B = \frac{1}{\epsilon}\left(\frac{M_{KK}^2}{g_t^2} - \triangle^2\right)\,, C = -\frac{\lambda_t M_{KK}^2}{g_t^2\sqrt{\epsilon}}$$

Electroweak Symmetry breaking of 2HDM

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

$$A(g_t, \lambda_t, m_0)v_H + C(g_t, \lambda_t)v_\phi + \frac{\lambda_0}{2}|v_H|^2 v_H = 0$$
$$B(g_t)v_\phi + C(g_t, \lambda_t)v_H + \frac{2}{\epsilon}|v_\phi|^2 v_\phi = 0$$

  We require that $v_H^2 + v_\phi^2 = (246\text{GeV})^2$.
- Above the cutoff, M_{KK}, the 4-Fermi condensate approximation is no longer valid.
- There are 14 free parameters in the general 2HDM with sever FCNC problems.

Spectrum of Physical Scalars

- Scalar mass matrix:

$$M_{\pm}^2 = M_A^2 = \begin{pmatrix} A + \frac{\lambda_0}{2} v_H^2 & C \\ C & B + \frac{v_\phi^2}{\epsilon} \end{pmatrix}, M_0^2 = M_{\pm}^2 + \begin{pmatrix} \lambda_0 v^2 \sin\beta & 0 \\ 0 & 4 m_t^2 \end{pmatrix}.$$

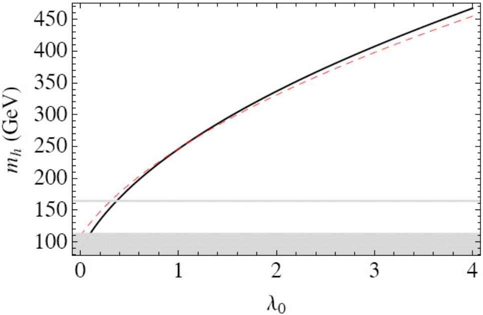
- For $H^{\pm}, A^0$, the mixing angles is β, and (at tree level)

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

- $Tr M_0^2 = M_{H^\pm}^2 + k_1 v^2$ and $\det M_0^2 = k_2 M_{H^\pm}^2 v^2$, $k_{1,2} \sim \mathcal{O}(1)$. Therefore $M_{H^0} \sim \mathcal{O}(\mathrm{TeV})$, while $M_{h^0} \sim \mathcal{O}(v)$
- Since the second term in M_0^2 is much smaller than the first one, one expects $M_{H^0} \sim M_{H^\pm}$, mixing angle $\alpha \sim \beta$ and

$$M_{h^0}^2 \simeq \lambda_0 v^2 \sin^4\beta + 2\epsilon\, m_t^2.$$

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 and the Top quark mass

- Also, the h^0 is very SM like. For example, the $h^0 Z^0 Z^0$ coupling is $\cos(\beta - \alpha)$
- With the redefined scalar fields,

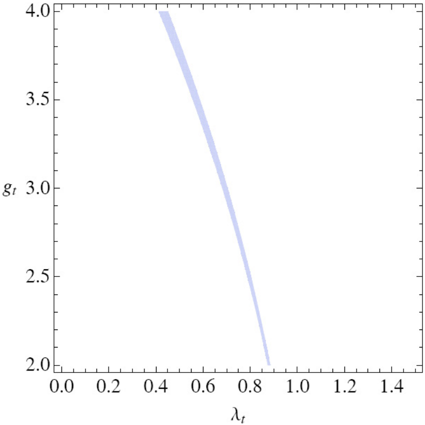
$$\mathcal{L}_Y = \lambda_t \overline{Q_L} t_R \widetilde{H} + g_t \overline{Q_L} t_R \widetilde{\Phi} + h.c. \rightarrow \frac{1}{\sqrt{\epsilon}} \overline{Q_L} t_R \widetilde{\hat{\Phi}} + h.c.$$

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

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

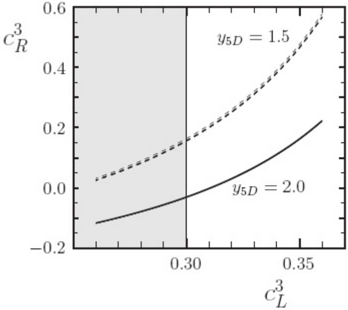
- $\tan\beta$ is determined by top mass!! $\cos\beta \sim \sqrt{\epsilon}$, or $\tan\beta \sim 3.0$.

$\{\lambda_t, g_t\}$



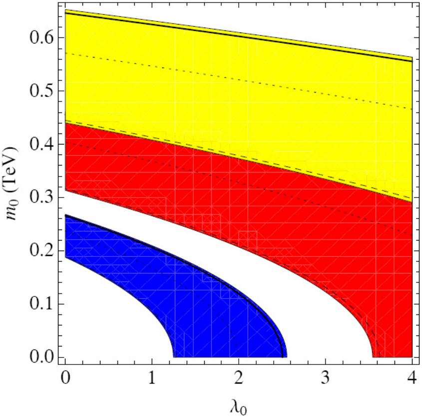
Allowed region in the $\{\lambda_t, g_t\}$ parameter space that satisfies m_t and 2nd Mini. Cond. M_{KK} lies between 1.5 to 4 TeV and m_t from 169.7 to 172.9 GeV.

location, location, location



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 $Z \to b_L \bar{b}_L$.

$\{\lambda_0,\ m_0\}$



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 $g_t = \{2, 3, 4\}$.

Flavor Changing Neutral Current

- In terms of $\hat{H}, \hat{\Phi}$, the Yukawa sector is

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

- FCNC comes solely from the last term (no VEV, physical $H^{\pm}$ or A^0). Since $\alpha \sim \beta$, mainly H_0 in the combination.
- Light quark FCNCs are suppressed by (1) M_{KK}, if through H_0, $H^{\pm}$, and A^0 (2) small $\sin(\beta - \alpha)$, if through h^0
- 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.
- Light(heavy) fermion results from the UV(IR) peaking profiles. KK gauge boson peaks near IR.
- factor $\sim (3-5)$ enhancement for the $SU(3)_c$ coupling between the first KK gluon, t_R, and Q_3.
- A composite Higgs could emerge from the $Q_3 t_R$ condensation below M_{KK}.
- The 2HDM is very predictive: $\tan\beta \sim 3$, close to the decoupled limit, no(suppressed) FCNC in down(up) sector.