EWSB in Extra Dimensional Models

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Kitano rules

1. Concentrate on EWSB & fermion masses.
2. Model must be better than Glashow's.
3. Viable? Check predictability.

★ Ignore meaningless calculations.

Suggested approach for this workshop

1. Identify the problems.
2. Discuss their seriousness.
   - ★ Possible to postpone in LHC physics?
   - ★ If claim so, need a reason.
3. Discuss/summarize possible solutions.
4. Discuss LHC predictions associated to each solution.
5. Discuss situations 1.5 years later.

My task

- Give a basis for such discussions.
- By reviewing:
  - ★EWSB in **RS and GHU models**.
  - ★$\rightarrow$ EWSB in **extra dimensional models**.

EWSB in Extra Dimensions

- The same as in SM? Yes: **UED models.**
- No:
  - ★ EWSB by Wilson-line phases.
    - ✳ **GHU models.**
      - ✦ When warped (or +BKT), dual to technicolor with PNGB Higgs.
      - ✦ Lightest A_5 = Techni-dilaton resonance? (→量子数ちょっと違う)
  - ★ EWSB by boundary conditions.
    - ✳ **Higgsless models**.
      - ✦ When warped, dual to technicolor without PNGB. (?)
      - ✦ Lightest KK A_μ = rho-meson resonance.
    - ✳ **Dirichlet Higgs model**.
      - ✦ Higgsless with a bulk Higgs.
      - ✦ Lightest KK Higgs = "Higgs impostor."

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UED

UED Models

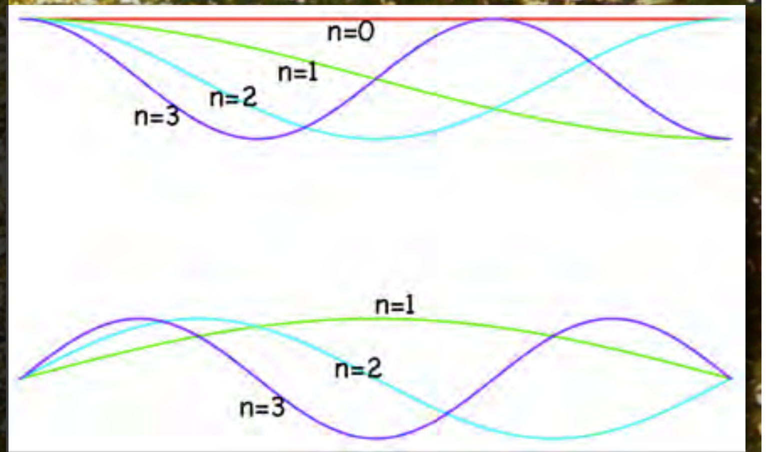
- Put all SM fields in bulk. (Review available if requested.)
- EWSB is **no better** than in SM. By bulk potential:
  - ✳ $V(\Phi) = -m_D^2|\Phi|^2 + \lambda_D|\Phi|^4$.
- ★ Relatively safe but boring.
  - ✳ No reason for negative mass^2.
  - ✳ Need higher dim'nal op to lift-up potential: $\lambda_D = \lambda_4/\Lambda^{D-4}$.
- Or even worse fine-tuning. In (4+n)-dimensions,
  - ✳ $m_H^2 = O(\Lambda^{2+n}/m_{KK}^n) - O(\Lambda^{2+n}/m_{KK}^n)$.
- Heavy Higgs allowed by KK top contributions to T-parameter. (Shown later)

Review: mUED Model

Appelquist, Cheng, Dobrescu, 01

- An extra dimension compactified on S^1/Z_2 (~line segment).
- All SM fields propagate in bulk.
  - ★ Neumann: $\partial_y \Phi|_{bd}=0$ on SM d.o.f.
    - ✳ quarks, leptons, gauge fields $\mathbf{A_\mu}$
    - ✳ Higgs field (We change this later.)
  - ★ Dirichlet: $\Phi|_{bd}=0$ on non-SM d.o.f.
    - ✳ Extra quarks and leptons with opposite chirality,
    - ✳ Extra dimensional component $\mathbf{A_5}$ (unphysical)

KK mass: $M_n = n/R$



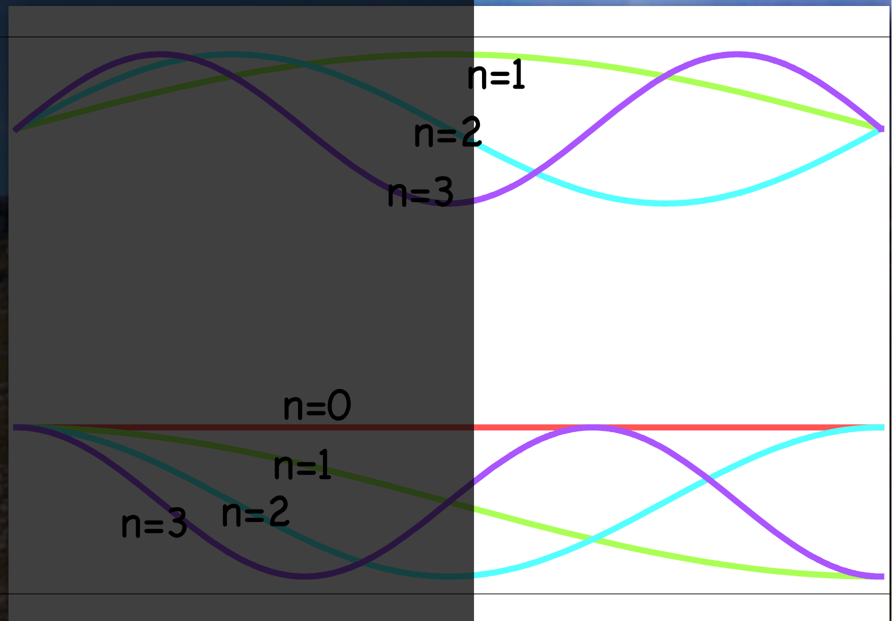
KK parity

KK Expansion in Ordinary UED, Review

$$S_{\rm free} = \int d^4x \int_0^{\pi R} dy\, \Phi^\dagger \left(\Box + \partial_y^2 - m_\Phi^2\right)\Phi = \sum_{n=0}^{\infty} \int d^4x\, \Phi_n^\dagger \left(\Box - \frac{n^2}{R^2} - m_\Phi^2\right)\Phi_n$$

$$\partial_y^2 \to -\frac{n^2}{R^2}$$

- A 5D field = infinite 4D KK modes.
  - ★ Dirichlet: $\Phi|_{\rm bd} = 0$,
    - ✳ $\Phi(x,y) = \Sigma_{n=1}\, \Phi_n(x)$ sin(ny/R),
    - ✳ m_{KK} = 1/R, 2/R, ...
  - ★ Neumann: $\partial_y\Phi|_{\rm bd} = 0$,
    - ✳ $\Phi(x,y) = \Sigma_{n=0}\, \Phi_n(x)$ cos(ny/R),
    - ✳ m_{KK} = 0, 1/R, 2/R, ...



Backup: Z_2 orbifold parity

- Z_2 on Gauge field: $A_\mu \to A_\mu$, $A_5 \to -A_5$。

$$\mathcal{B}_\mu(x,-y) = \mathcal{B}_\mu(x,y), \qquad \mathcal{B}_5(x,-y) = -\mathcal{B}_5(x,y),$$
$$\mathcal{W}_\mu(x,-y) = \mathcal{W}_\mu(x,y), \qquad \mathcal{W}_5(x,-y) = -\mathcal{W}_5(x,y),$$

- If $\psi \to \pm\gamma^5\psi$, current $J^M \propto \bar{\psi}\gamma^M\psi$ transforms the same as gauge field: $J^\mu \to J^\mu$, $J^5 \to -J^5$.

★ Choose **+** for $SU(2)_W$ **doublet**:

✳ $\psi_L \to +\psi_L$、 $\psi_R \to -\psi_R$ (zero mode for **left handed**)

★ Choose **−** for $SU(2)_W$ **singlet**:

✳ $\psi_L \to -\psi_L$、 $\psi_R \to +\psi_R$ (zero mode for **right handed**)

$$L(x,-y) = \gamma^5 L(x,y), \qquad E(x,-y) = -\gamma^5 E(x,y),$$
$$Q(x,-y) = \gamma^5 Q(x,y), \qquad U(x,-y) = -\gamma^5 U(x,y),$$
$$D(x,-y) = -\gamma^5 D(x,y),$$

Backup: Fermion KK

N N D

$$L(x,y) = c_0\, l_L^{(0)}(x) + \sum_{n=1}^{\infty} c_n \cos\frac{ny}{R}\, L_L^{(n)}(x) + \sum_{n=1}^{\infty} c_n \sin\frac{ny}{R}\, L_R^{(n)}(x)$$

$$Q(x,y) = c_0\, q_L^{(0)}(x) + \sum_{n=1}^{\infty} c_n \cos\frac{ny}{R}\, Q_L^{(n)}(x) + \sum_{n=1}^{\infty} c_n \sin\frac{ny}{R}\, Q_R^{(n)}(x),$$

$$E(x,y) = c_0\, e_R^{(0)}(x) + \sum_{n=1}^{\infty} c_n \cos\frac{ny}{R}\, E_R^{(n)}(x) + \sum_{n=1}^{\infty} c_n \sin\frac{ny}{R}\, E_L^{(n)}(x),$$

$$U(x,y) = c_0\, u_R^{(0)}(x) + \sum_{n=1}^{\infty} c_n \cos\frac{ny}{R}\, U_R^{(n)}(x) + \sum_{n=1}^{\infty} c_n \sin\frac{ny}{R}\, U_L^{(n)}(x),$$

$$D(x,y) = c_0\, d_R^{(0)}(x) + \sum_{n=1}^{\infty} c_n \cos\frac{ny}{R}\, D_R^{(n)}(x) + \sum_{n=1}^{\infty} c_n \sin\frac{ny}{R}\, D_L^{(n)}(x),$$

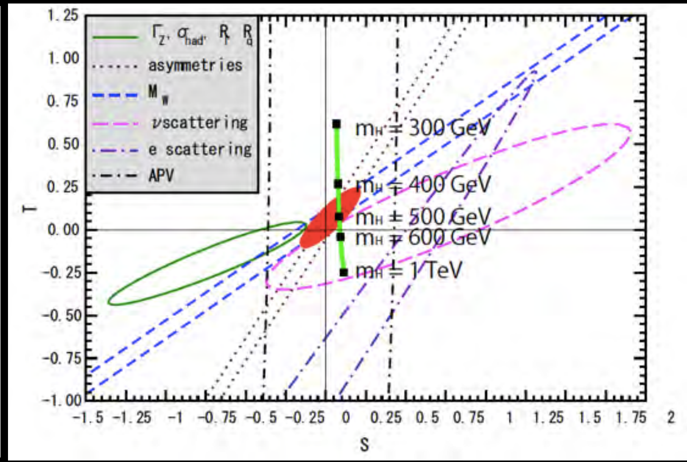
UED allows heavy Higgs

$$S \simeq \frac{1}{6\pi}\log\frac{m_H}{m_{H,\mathrm{ref}}} + \frac{1}{6\pi}\sum_{n=1}^{\infty}\frac{m_t^2}{n^2/R^2}$$

$$T \simeq -\frac{3}{8\pi c_W^2}\log\frac{m_H}{m_{H,\mathrm{ref}}} + \frac{m_t^2}{4\pi^2\alpha v_{\mathrm{EW}}^2}\sum_{n=1}^{\infty}\frac{m_t^2}{n^2/R^2}$$

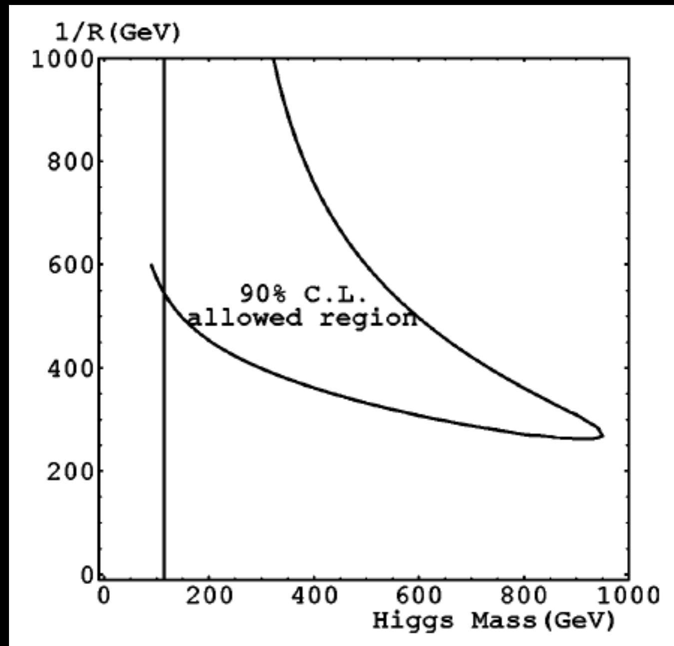
(Higgs loop omitted)

1.6



※緑線は $m_H = m_{KK}$ の場合。

- Heavy Higgs: m_H >500GeV requires lower KK scale: m_{KK} < 600GeV.
  - ★ Being killed by Tobioka-san.
  - ★ mHED with LKP DM: m_{KK} ~ 1.5TeV.



Appelquist, Yee (03)

ちなみに

- UED のこの辺の問題が気になるので↓
  - ★ No reason for negative mass^2.
  - ★ Need higher dimensional operator to lift-up potential: $\lambda_D = \lambda_4/\Lambda^{D-4}$.
  - ★ Worse fine-tuning: mH2 = O(Λ2+n/mKKn)−O(Λ2+n/mKKn).
- UED で EWSB をヒッグス場の Dirichlet 境界条件で起こしたらどうか？というのが最近推してる Dirichlet Higgs model です。
  - ✤ Haba, Oda, Takahashi, arXiv:0910, 1005.
  - ✤ Nishiwaki, Oda, arXiv:1011. (Unitarity issues.)
- 興味を持たれた方はセミナーへ呼んでください。
  - ★ 重いヒッグス、軽いKK: $m_H = m_{KK} \sim 500$GeV。 $g_{\text{1st KK Higgs}} = 0.9\, g_{SM}$
  - ★ WW縦波散乱の $O(E^2)$ は KK-Higgs exchanges で完全に相殺。
    - ✳ スカラー場を用いた Higgsless に相当。

UEDまとめ

- 基本的に m_{KK} < 600GeV ぐらいまでは既に死につつある。
  - ★ したがって m_H > 500GeV ぐらいのところは死につつある。
  - ★ LHC signal は KK resonances だが、LKP が安定なので single production できない。(SUSYと似たシグナル。)
- EWSB は標準模型と一緒 (ただしより悪いfine-tuing)。そこを変えて Dirichlet Higgs だと概念的には Higgsless に似たものとなる。
  - ★ 後者は KK Higgs の single production が特徴。

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ここまでで

白いところを話した。

GHU

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これから
白いところを話す。

EWSB by GHU

- Symmetry breaking by Wilson-line phase.
- Gauge hierarchy (technically) solved.
  - ★ No divergence can occur in Higgs effective potential due to non-locality.
  - ★ Historically, “deconstruction of 6D GHU led to development of little Higgs models.”

GHU Models

	flat	warped
$SU(3)_L$	Antoniadis, Benakli, Quiros (01); Hall, Nomura, Smith (02); Burdman, Nomura (03); Haba, Hosotani, Kawamura, Yamashita (04); …	Contino, Nomura, Pomarol (03); Hosotani, Mabe (05); Hosotani, Noda, Sakamura, Shimasaki (06); …
$SO(5)$	Panico, Safari, Serone (11).	Agashe, Contino, Pomarol (05); Contino, Da Rold, Pomarol (07); Medina, Shar, Wagner (07); Hosotani, Oda, Ohnuma, Sakamura (08).

First warped effective potential by Oda, Weiler (06)

Constraints on GHU

- Following constraints restricts parameter space:
  - ★ |S,T-parameters| <~ 0.1
  - ★ [Z-b_L-b_L^{bar} coupling] <~ 10^{-3}. (Related to T)
    - ✳ Can be suppressed at tree level by custodial symmetry in SO(5)-based models.
  - ★ [Anomalous W-t_R-b^{bar} coupling] <~ 10^{-3}.
    - ✳ Leads to: $b \to s\gamma$.

$SU(3)_L$ vs SO(5)

- 黒板に絵を描く。
- To account for large top-Yukawa, one typically has composite q_L and t_R (being finite near IR brane).
  ★ Usually b_R is elementary (living near UV-brane). Still suffers from tree-level T (& Zbb^{bar}).
- Custodial symmetry wanted.
  ★ Exact SO(4) = $SU(2)_L \times SU(2)_R$ at IR-brane, where EWSB takes place.
  ★ Leading to SO(5) model broken to SO(4) at IR-brane by Wilson-line phase.

Flat vs warped

- Naively, $m_h \sim m_W \sim m_{KK}$ in flat model.
- In warped space: $m_h \sim m_W \sim (kL)^{-1/2}\, m_{KK}$ $(\sim m_{KK}/6)$
- Flat models dead? No.
  - ★ Add many bulk fermions. (Ugly.) Or else,
  - ★ Add **boundary kinetic terms** for gauge bosons (and fermions).
    - ✳ Can be regarded as truncation of warped space. (絵)
- However,
  - ★ Flat model with BKTs is effective theory valid slightly above TeV.
  - ★ Cannot address **flavor problems**, which involve much higher scales.
    - ✳ In warped models, light generations localized at UV-brane.

Fermions in SO(5) models in market

Symmetry broken by hand or by Higgs.

Wilson-line breaking.
Brane masses by hand.

		UV-brane $SU(2)_L \times U(1)_Y$	bulk $SO(5) \times U(1)_X$	IR-brane $SO(4) \times U(1)_X$ $SO(4)=SU(2)_L \times SU(2)_R$
warped	Agashe, Contino, Pomarol (05)	-	(q_L, t_R, b_R) in $(\mathbf{4}_{1/3}, \mathbf{4}_{1/3}, \mathbf{4}_{1/3})$	an extra $\mathbf{4}_{1/3}$
	Contino, Da Rold, Pomarol (07) model I	extra $\mathbf{2}_{1/6}$ to kill extra q_L'	(q_L, q_L') in $(\mathbf{5}_{2/3}, \mathbf{5}_{-1/3})^1$ (t_R, b_R) in $(\mathbf{5}_{2/3}, \mathbf{5}_{-1/3})^2$	brane masses
	Medina, Shar, Wagner (07)	-	(q_L, t_R, b_R) in $(\mathbf{5}_{2/3}, \mathbf{5}_{2/3}, \mathbf{10}_{2/3})$	many #O(10) extra $\mathbf{4}$'s & $\mathbf{1}$'s
	Hosotani, Oda, Ohnuma, Sakamura (08)	extra pairs of $\mathbf{2}_{7/6}$, $\mathbf{2}_{1/6}$, $\mathbf{2}_{1/6}$, required by anomaly cancellation	(q_L, t_R, b_R) in $(\mathbf{5}_{2/3}, \mathbf{5}_{-1/3})$, irrespectively.	-
flat with BKT	Panico, Safari, Serone (11) model I	-	(q_L, t_R, b_R) in $\mathbf{10}_{2/3}$	no mass allowed
	PSS (11) model II	q_L' killed by extra $\mathbf{2}_{1/6}$ or Dirichlet BC	(q_L, q_L') & (t_R, b_R) in $(\mathbf{5}_{2/3}, \mathbf{5}_{-1/3})$	no mass allowed

Basically dead due to Zbb^bar
Agashe, Contino, Da Rold, Pomarol (06)

Typical LHC signals

- Light Higgs: $m_H < 200$GeV.
- Lightest particle BSM is KK-quarks:
  - ★ 500GeV < m_q < 1TeV,
  - ★ with EM charge: −1/3, 2/3, or 5/3.
- KK gauge bosons slightly heavier: ~ few TeV.
- Other issues.
  - ★ Composite top (and bottom). Yukawa deviation.
  - ★ Strong coupling becomes strongly coupled for colored KK.
    - ✳ Problem? 一応軽い人たちは摂動的ではあるが…

GHU まとめ

- 概念的にはとても美しい EWSB。
  - ★ 理想は綺麗、実現は汚い, as usual in 素粒子模型。（Gauge mediation を思い出そう。）
  - ★ PNGBのいるテクニカラーのデュアル？
  - ★ フェルミオンの質量を入れようとすると汚くなってくる。（テクニカラーと同じ問題。）
    - ✳ テクニカラーと違って計算できるので計算してみると本当に死ぬ。悪即斬。
- KK gluon が強結合になるのはどうなのか。

Higgsless

は、棚橋さんがやったのでいいですよね？

- Comments to add:
  - ★ When warped (or flat+BKT), dual to technicolor without PNGB (?)
  - ★ Lightest KK A_μ = rho-meson resonance.

全体のまとめ

- これから数年かけて LHC が EWSB sector を決定する。
- SM と同じなら UED, 違ってたら（余次元の範囲では）
  - ★ Wilson-line breaking:
    - ✳ GHU.
  - ★ Boundary breaking:
    - ✳ Higgsless,
    - ✳ Dirichlet Higgs.
- わくわくしますね。Prediction して当てるように頑張ろう。（Postdiction ではなく。）

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