Electroweak Symmetry Breaking in Gauge-Higgs Unification Models

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Work with M. Peskin

- Do we ‘understand’ Electroweak symmetry breaking?
    - Standard model Higgs potential is put in by hand

- One viable explanation is Higgs as a composite Goldstone boson under a strongly interacting theory.
- We would like to advance this theory using its dual formulation in AdS5 and make it more predictive.
- Gauge-Higgs unification framework
    - Higgs field as the fifth component of a gauge field
    - Higgs potential is determined dynamically and can be computed from other parameters in the Lagrangian Hosotani

What do we want to achieve?

- Little Hierarchy

  Higgs potential will depend on a non-linear sigma model field U

$$U = \exp\left(\frac{2i\Pi \cdot T}{f}\right) \qquad h \in \Pi$$

  Then, it is natural that $v = 0$ or $v \sim f$, but we need $0 < v \ll f$ since BSM particles should be much heavier than v.

  → Therefore, we must be *near a second-order phase transition* in the phase diagram of the model.

- In SM, seemingly unrelated numbers determine the masses

$$\frac{y_t^2}{2} = \left(\frac{m_t}{v}\right)^2, \quad \frac{g^2}{4} = \left(\frac{m_W}{v}\right)^2, \quad 2\lambda = \left(\frac{m_h}{v}\right)^2$$

  Are they related? Can we properly generate those numbers?

5D Geometry

AdS5 bulk

UV

$k = 1/z_0 \sim 100\ \mathrm{TeV}$

UV cutoff scale

IR

$k_R = 1/z_R \sim 1\ \mathrm{TeV}$

Scale of the strong interaction

SO(5) x U(1) Model Agashe, Contino, Pomarol

SM gauge symmetry

$SU(2)_L \times U(1)_Y$

AdS5 bulk

$SO(5) \times U(1)_X$

Custodial symmetry protects T

$SO(4) \times U(1)_X$

UV

$k = 1/z_0 \sim 100 \text{ TeV}$

UV cutoff scale

IR

$k_R = 1/z_R \sim 1 \text{ TeV}$

Scale of the strong interaction

$SO(5)/SO(4)$: Higgs as Goldstone bosons (A_5 zero mode)

$$Y = T_R^3 + X \quad \text{and} \quad Q = T_L^3 + T_R^3 + X$$

From VEV to Twisted Boundary Conditions

- Consider a non-zero background 5D gauge field

$$A_M(x^\mu, z) = (0, 0, 0, 0, A_5(z))$$

- By a gauge transformation,
  we can remove the background field in the bulk.
  But it modifies boundary conditions at either $z = z_0$ or $z = z_R$
  by a transformation

$$U_W = \exp\left[ig_5 \int_{z_0}^{z_R} dz A_5^a(z) T^a\right]$$

- By integrating out fermions & gauge fields,
  we can compute the Coleman-Weinberg potential of Higgs.
  It will depend on U_W

Fermions: Warm-up with SU(2)

- In 5D, fermion mass term is allowed: $m = ck$
- Consider two doublets and their CW potentials

$$\Psi_t = \begin{pmatrix} ++ \\ -- \end{pmatrix} \quad \to \quad V_t(\theta) = -2\int \frac{d^4p}{(2\pi)^4} \log\left[1 + \frac{\sin^2\theta}{F_t(p^2, c_t)}\right]$$

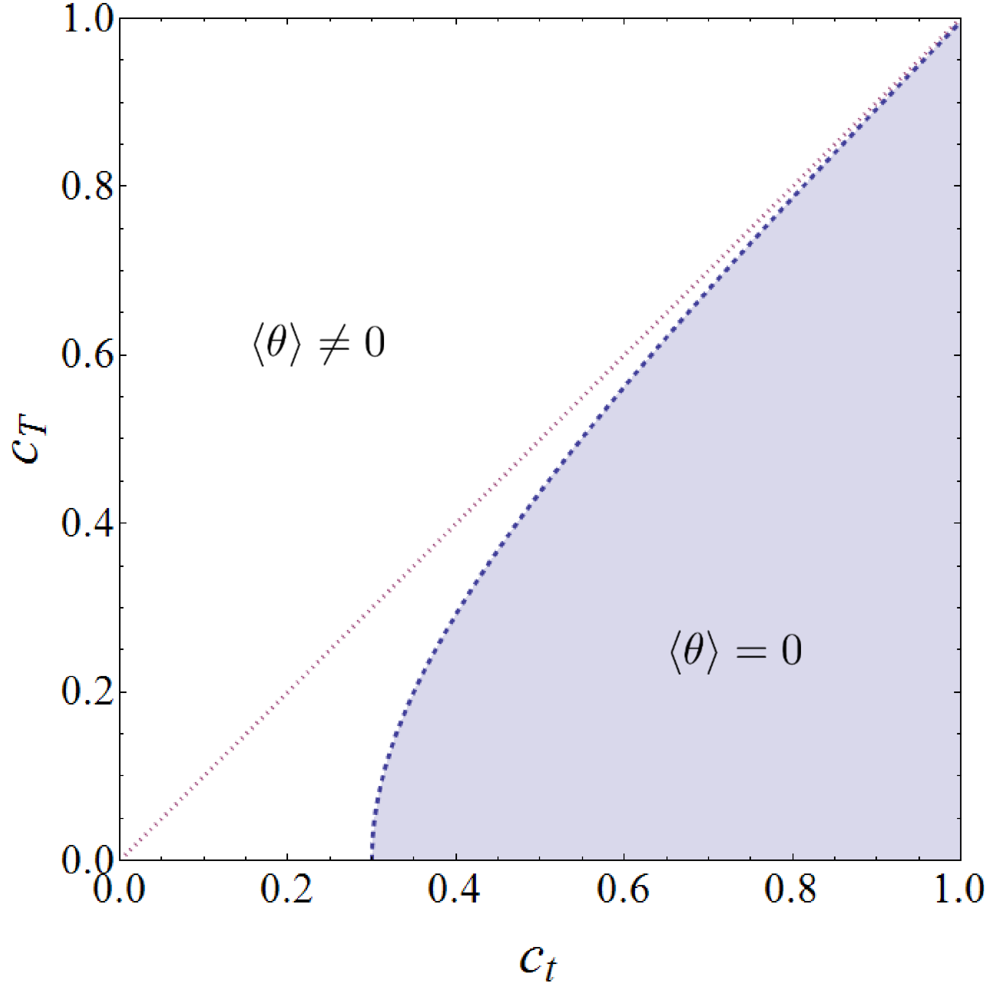
$$\theta = \frac{v}{\sqrt{2}f}$$

$$\Psi_T = \begin{pmatrix} +- \\ -+ \end{pmatrix} \quad \to \quad V_T(\theta) = -2\int \frac{d^4p}{(2\pi)^4} \log\left[1 - \frac{\sin^2\theta}{F_T(p^2, c_T)}\right]$$

1) Note, $F_{t,T} \to e^{p(z_R - z_0)}$ for large momentum, so V convergent

2) Competition between $+\sin^2\theta$ and $-\sin^2\theta$
$\to$ Second-order phase transition

SU(2) Phase Diagram



Dotted blue line : Line of 2[nd]-order phase transition

Fermions in SO(5)xU(1)

- Embedded in $\mathbf{5_{2/3}} = (\mathbf{2},\mathbf{2})_{\mathbf{2/3}} \oplus (\mathbf{0},\mathbf{0})_{\mathbf{2/3}}$

$$\Psi_t = \begin{bmatrix} \begin{pmatrix} \chi_t(-+) & t_L(++) \\ \chi_b(-+) & b_L(++) \end{pmatrix} \\ t_R(--) \end{bmatrix}, \qquad \Psi_T = \begin{bmatrix} \begin{pmatrix} \chi_T(-+) & T(+-) \\ \chi_B(-+) & B(+-) \end{pmatrix} \\ T'(-+) \end{bmatrix}$$

- Custodial symmetry for $Z \to bb$ Agashe, Contino, Da Rold, Pomarol

Boundary Gauge Kinetic Term

- In the setup so far, a single parameter g_5 sets the strength of the new forces and the coupling of the $SU(2)_L \times U(1)_Y$ gauge interactions.
- Introduce a UV-localized kinetic term for gauge fields.

$$S_{UV} = \int d^4x dz \left(\sqrt{-g} \left[-\frac{1}{4} a z_0 \delta(z - z_0) g^{mp} g^{nq} F_{mn} F_{pq} \right] \right)$$

- This gives a knob to control the weak gauge coupling

$$g^2 = \frac{g_5^2 k}{\log(z_R/z_0) + a_L}$$

- Two boundary terms a_L, a_Y for $SU(2)_L \times U(1)_Y$

Top Quark, W, and Higgs Mass

- Top Yukawa coupling

$$\left(\frac{m_t}{v}\right)^2 = \frac{g_5^2 k}{8} f(c_t), \quad f(c) = \left(\frac{1-2c}{1-(z_0/z_R)^{1-2c}}\right)\left(\frac{1+2c}{1-(z_0/z_R)^{1+2c}}\right)$$

- W boson

$$\left(\frac{m_W}{v}\right)^2 = \left(\frac{\log(z_R/z_0)}{\log(z_R/z_0)+a_L}\right) \times \frac{g_5^2 k}{8} f(1/2)$$

- Higgs boson

$$\left(\frac{m_h}{v}\right)^2 = \frac{g_5^4 k^2}{64\pi^2}\left[B(c_t, c_T) + \left(-\log\frac{v^2}{f^2} - \frac{3}{2}\right) C(c_t, c_T)\right]$$

Allowed Parameter Space

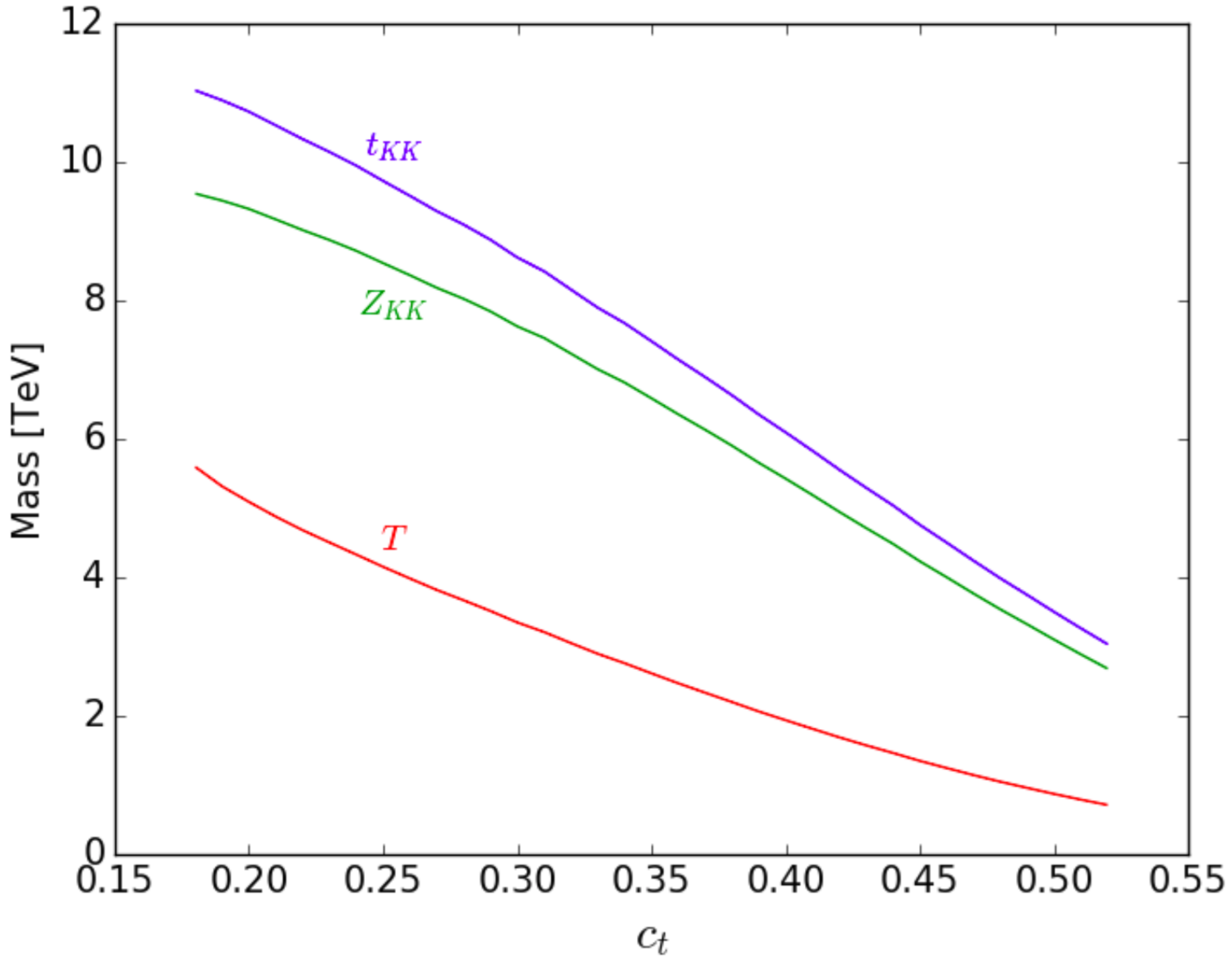
- There are 8 parameters and 5 observables
- In terms of one dimensionful parameter and other numbers,

$$k_R \quad \text{and} \quad k/k_R,\, c_t,\, c_T,\, g_5^2 k,\, g_X^2 k,\, a_L,\, a_Y$$

$$v \quad \text{and} \quad e,\ g,\ y_t,\ \lambda$$

- Higgs potential is almost independent of a_Y
- Observables at TeV scale $\rightarrow$ weakly dependent on k/k_R
- Therefore, we have a quasi-1-dimensional parameter space.
- Assume $k/k_R \sim 100$ (potentially constrained by flavor physics)

Mass Spectra of Kaluza-Klein States



Precision Electroweak Analysis

- S parameter receives a tree-level correction

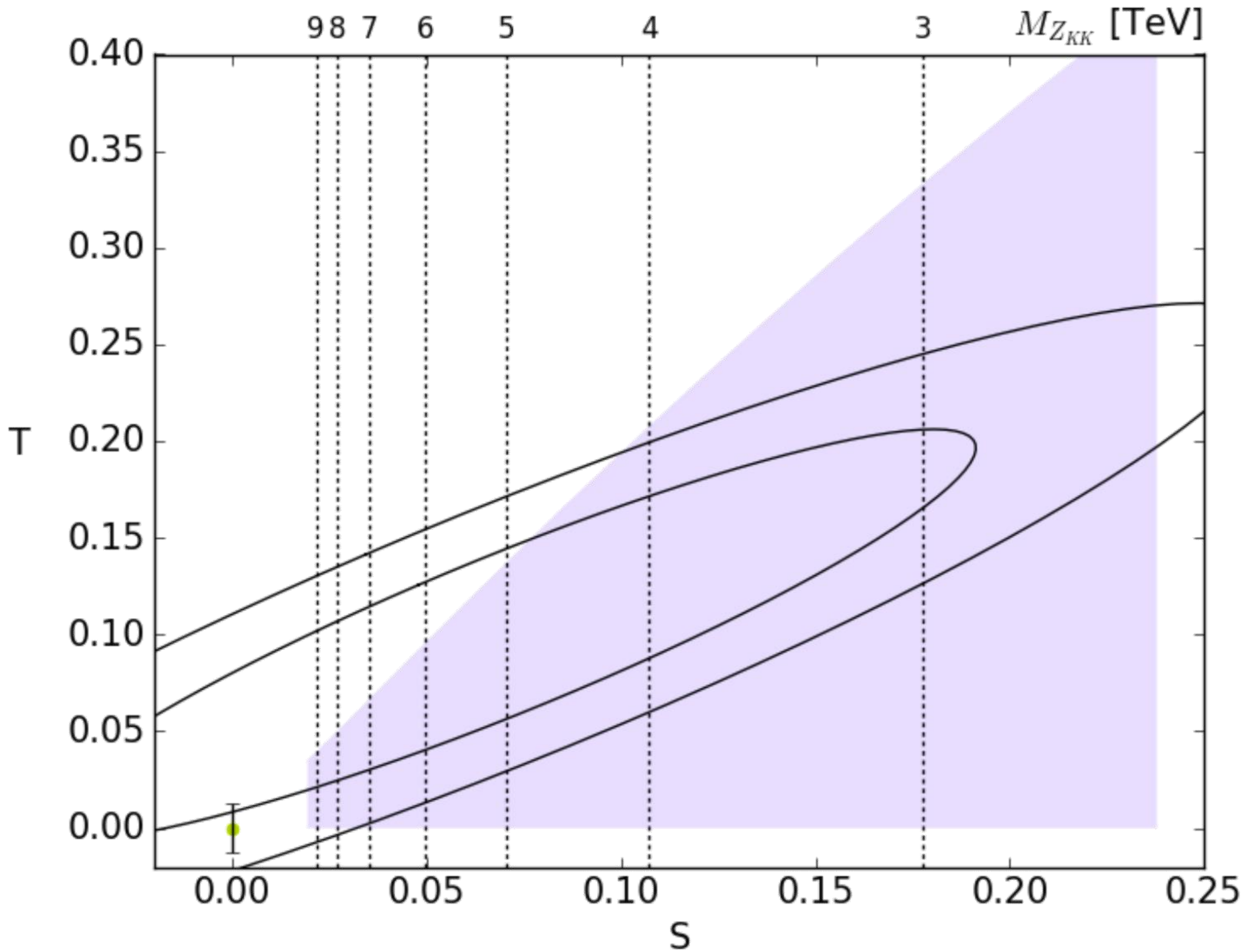
$$S = \pi v^2 z_R^2 \left(\frac{3}{2} - \frac{1}{k\pi R + a_Y} \right)$$

- Fermion loop correction to T parameter
  - It has been argued that the loop correction is convergent so the first KK correction is a good estimate. Carena, Ponton, Santiago, Wagner
  - However, full 5D calculation shows that it is divergent.
  - The divergent term is subleading in m_t^2.
    Using a cutoff Λ, we can estimate the correction

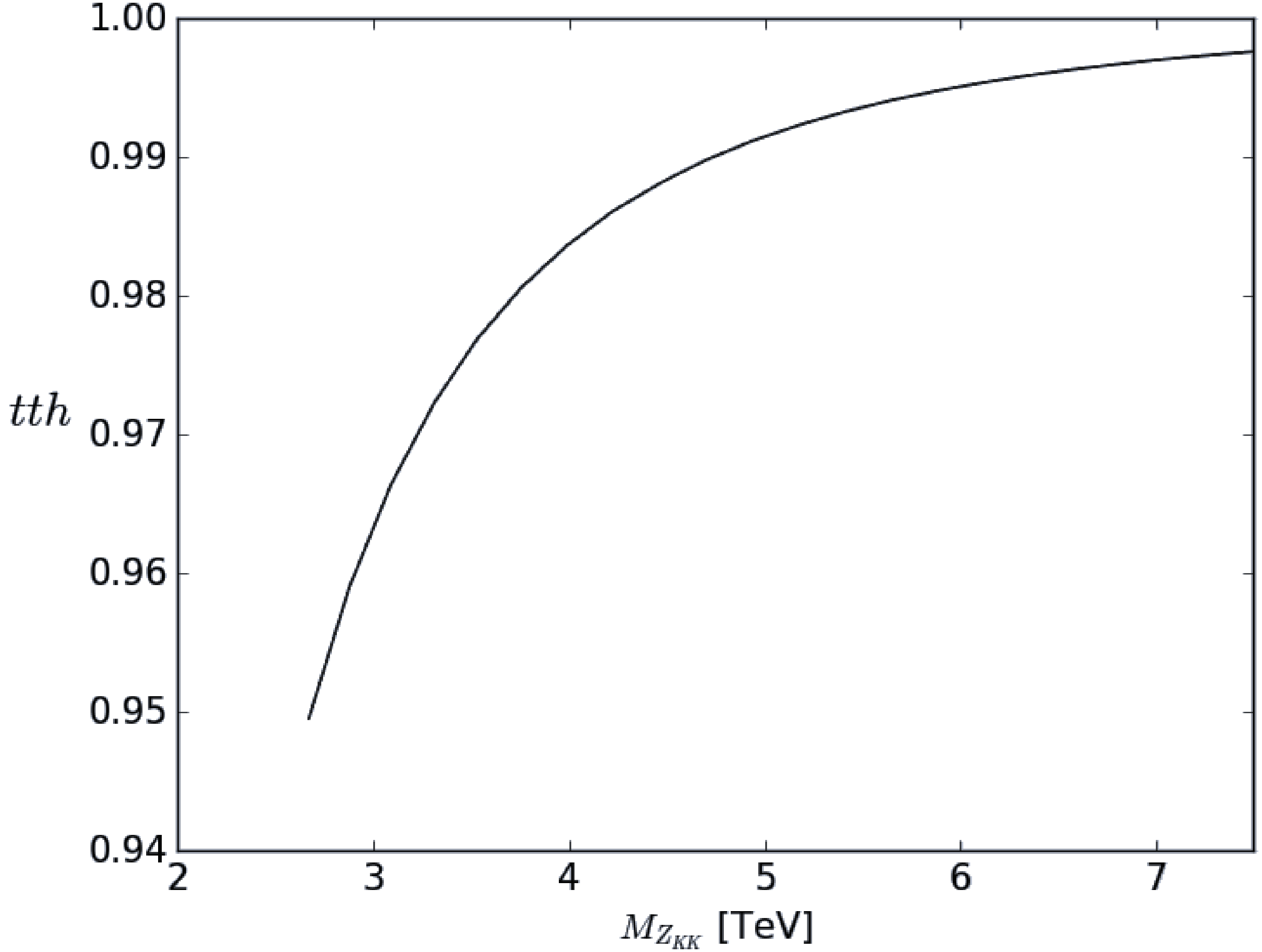
    $$T = \frac{3m_t^2}{16\pi s_w^2 c_w^2 m_Z^2} \left[1 + \beta(c_t) m_t^2 z_R^2 \left(\log\left(\frac{\Lambda^2}{m_t^2} \right) - 1 \right) \right]$$

    $\beta(c)$ is calculable. We will use $\Lambda \sim k_R$

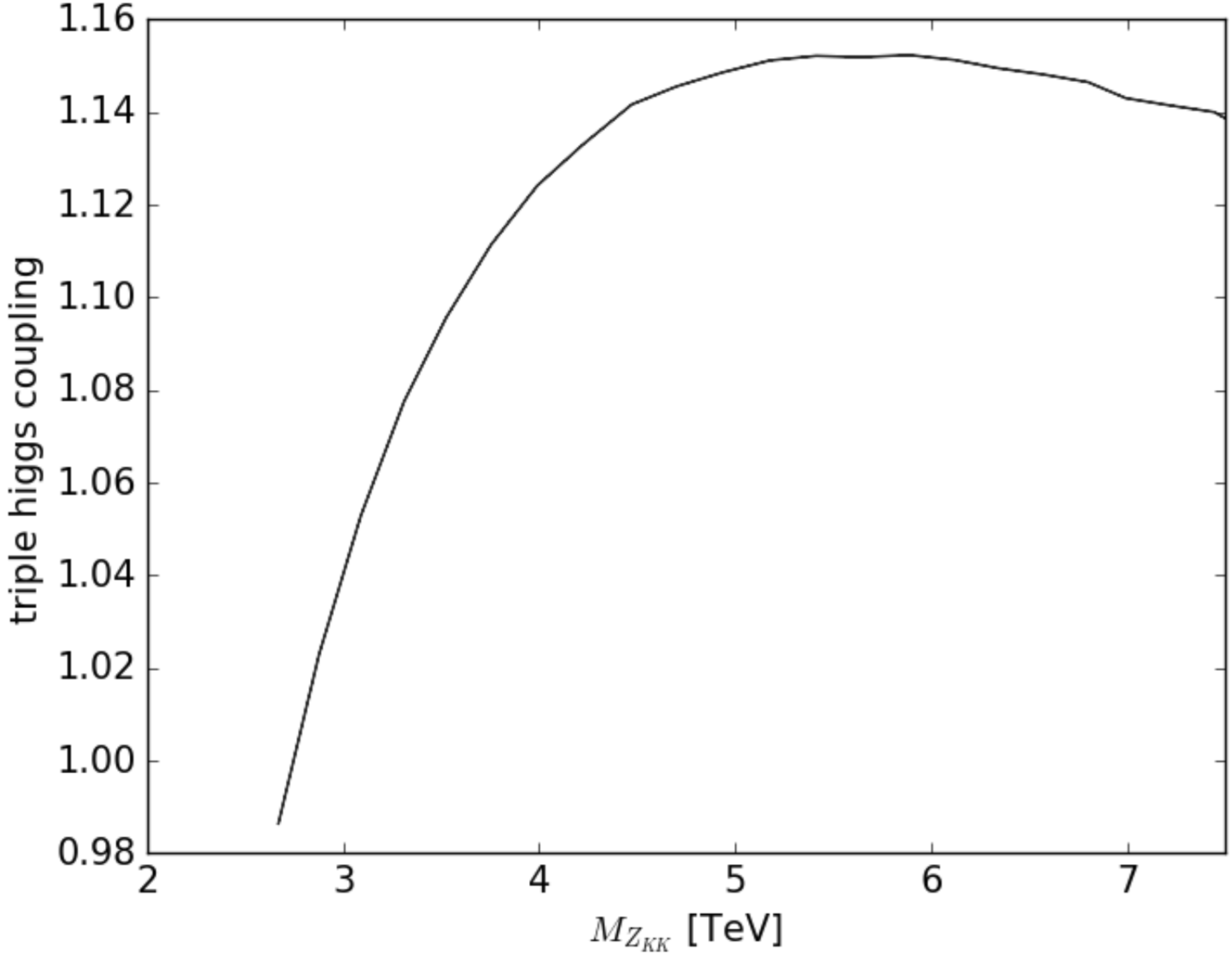
Precision Electroweak Analysis



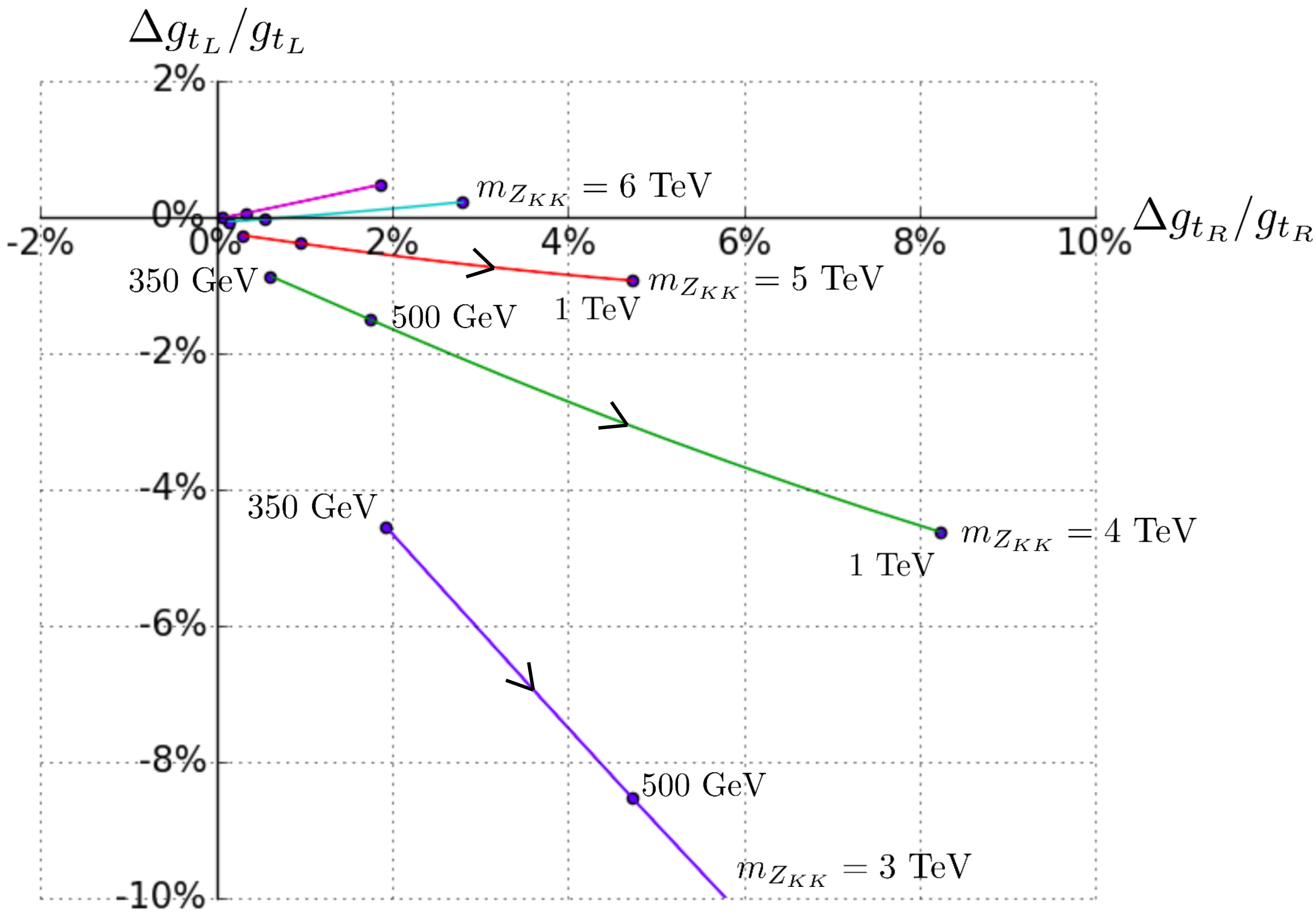
tth Coupling



Triple Higgs Coupling



Effective ttZ coupling from $e_L^- e_R^+ \to t_L\bar{t}_R,\ t_R\bar{t}_L$



Summary

- Gauge-Higgs unification based on $SO(5) \times U(1)_X$ in AdS5 as a dual formulation of a 4D composite Higgs model
- Higgs effective potential is calculable with twisted b.c.
- Competing potentials can generate the little hierarchy
- Constrained most significantly by S parameter
- Resonance masses and coupling deviations are correlated.

THANK YOU

Back-up Slides

Fermions in SO(5)

- Embedded in $\mathbf{5_{2/3}} = (\mathbf{2},\mathbf{2})_{\mathbf{2/3}} \oplus (\mathbf{0},\mathbf{0})_{\mathbf{2/3}}$

$$\Psi_t = \begin{bmatrix} \begin{pmatrix} \chi_t(-+) & t_L(++) \\ \chi_b(-+) & b_L(++) \end{pmatrix} \\ t_R(--) \end{bmatrix}, \qquad \Psi_T = \begin{bmatrix} \begin{pmatrix} \chi_T(-+) & T(+-) \\ \chi_B(-+) & B(+-) \end{pmatrix} \\ T'(-+) \end{bmatrix}$$

- Custodial symmetry for $Z \to bb$ Agashe, Contino, Da Rold, Pomarol
- Coleman-Weinberg potentials from the fermions

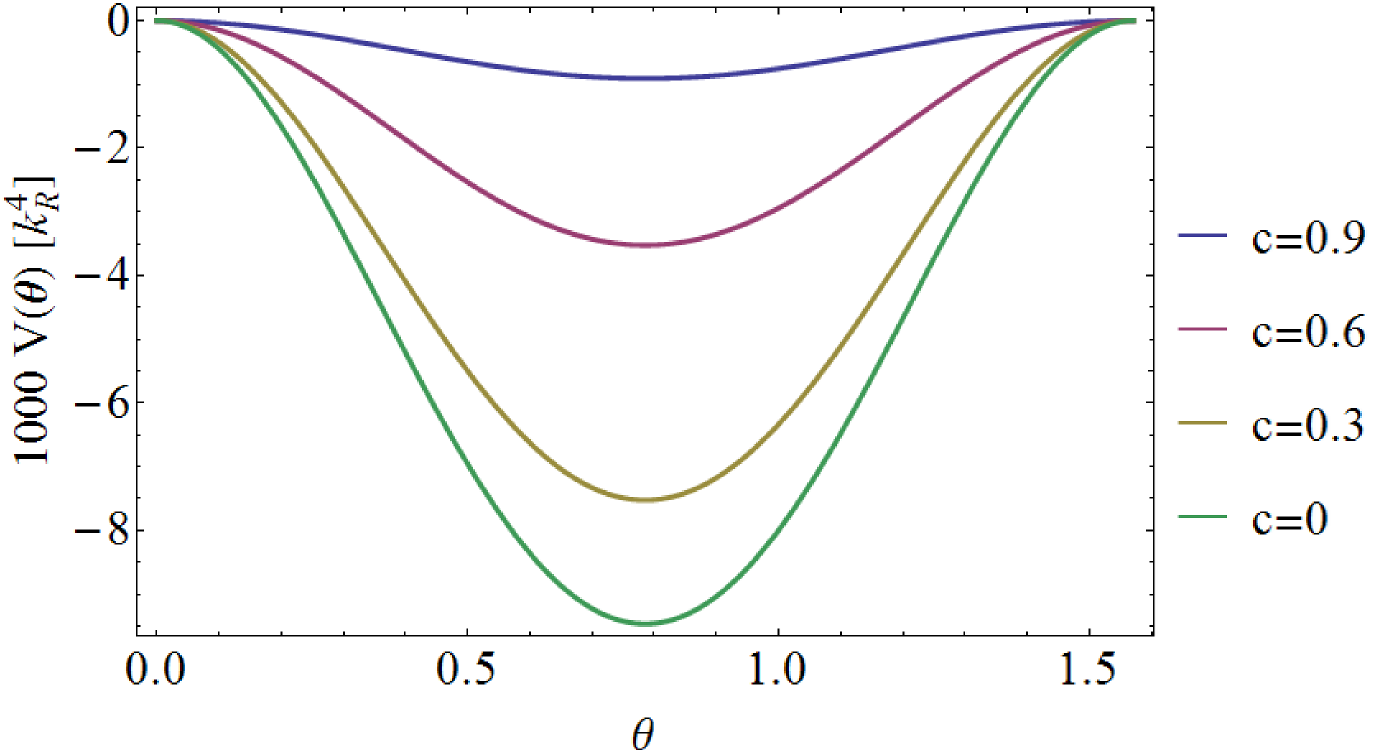
$$V_t(h) = -3 \times 2 \int \frac{d^4p}{(2\pi)^4} \log\left[1 + \frac{\frac{1}{2}\sin^2 2\theta}{F_A(p^2, c_t)}\right]$$

$$V_T(h) = -3 \times 2 \int \frac{d^4p}{(2\pi)^4} \log\left[1 - \frac{1-\cos^4\theta}{F_R(p^2, c_T)}\right]$$

$$\theta = \frac{v}{\sqrt{2}f}$$

Note, $F_{A,R} \to e^{p(z_R - z_0)}$ for large momentum, so V convergent

- Without the Top partner multiplet, the Higgs potential looks like



Potential minimum always at $\theta = \dfrac{\pi}{4} \;\rightarrow\; v \sim f$

- Small $\epsilon^2 = \frac{1}{2}\sin^2 2\theta$ expansion:

$$V_t(h) = -A_t(c_t)\epsilon^2 + \frac{1}{2}B_t(c_t)\epsilon^4 + \frac{1}{2}C_t(c_t)\epsilon^4 \log\frac{1}{\epsilon^2}$$

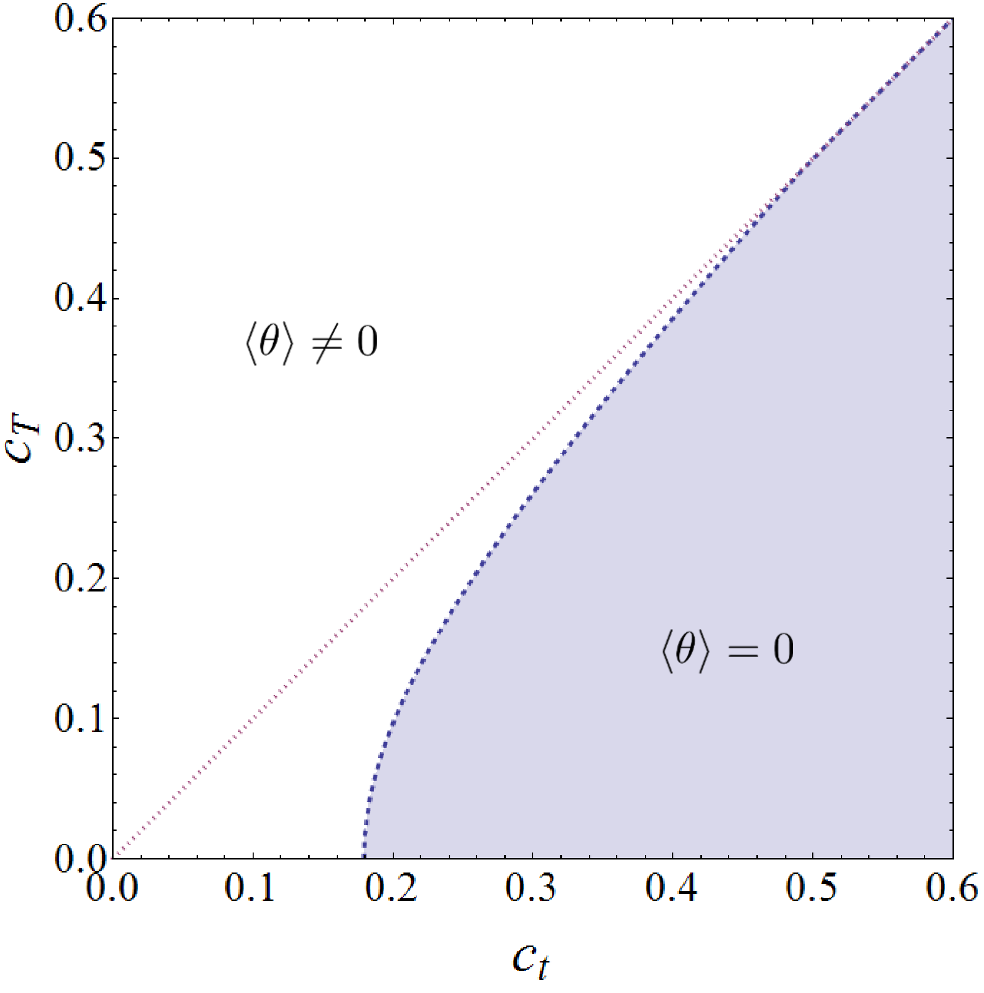
$$V_T(h) = A_T(c_T)\epsilon^2 + \frac{1}{2}B_T(c_T)\epsilon^4$$

- Competition between $A_t(c_t)$ and $A_T(c_T)$ determines vev
- Including (small) gauge field contribution,

$$V_{total}(h) = -A\epsilon^2 + \frac{1}{2}B\epsilon^4 + \frac{1}{2}C\epsilon^4 \log\frac{1}{\epsilon^2}$$

- The line of second-order phase transitions : $A(c_t, c_T) = 0$
- Therefore, if (c_t, c_T) are fine-tuned to be near that line, we can achieve the little hierarchy $v/f \ll 1$

Phase Diagram



Dotted blue line : $A(c_t, c_T) = 0$