Walking Technicolor & AdS/CFT

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Introduction

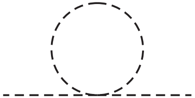
- Electro-Weak Symmetry Breaking (EWSB) is the most urgent problem in high energy physics
- $SU(2)_L \times U(1)_Y \to U(1)_{\rm e.m.}$ leads to masses for $W^{\pm}$, Z, while the photon A is massless
- Higgs mechanism is a proposed solution:

$$|D^{\mu}\varphi|^2 - \lambda \left(|\varphi|^2 - \frac{v^2}{2} \right)^2 , \quad D_{\mu} = \partial_{\mu} - ig\frac{\tau^a}{2}W^a_{\mu} - ig'\frac{1}{2}B_{\mu}$$

EWSB due to non-zero VEV: $\langle \varphi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$

Introduction

- Quadratic divergence of mass term for Higgs implies fine-tuning:



$\sim \Lambda^2$

- Triviality of ϕ^4-theory
- SUSY can help: logarithmic divergence instead
- What about EWSB induced by strongly coupled dynamics?

Outline of Talk

Part I:

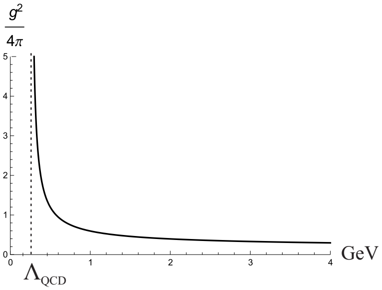
- Technicolor
- Extended Technicolor
- Walking Technicolor
- Precision Electro-Weak Parameters

Part II:

- AdS/CFT
- Bottom-Up Approach
- Top-Down Approach

Part I: Technicolor

- Hierarchy problem: $\frac{\Lambda_{\rm EW}}{\Lambda_{\rm Planck}} \sim 10^{-16}$
- We never ask why $\frac{\Lambda_{\rm QCD}}{\Lambda_{\rm Planck}} \sim 10^{-20}$
- The reason is dimensional transmutation: $\Lambda_{\rm QCD} \sim \Lambda_{\rm UV} e^{-\frac{8\pi^2/b_0}{g^2(\Lambda_{\rm UV})}}$



- Could $\Lambda_{\rm EW}$ be similarly generated by strong dynamics?

Part I: Technicolor

- Technicolor was first thought of as a scaled up version of QCD with gauge group $SU(N_{TC})$
- Techniquarks:

$$T = \begin{pmatrix} U_L \\ D_L \end{pmatrix} \in (N_{TC}, 2)_{Y_L}$$

$$U_R \in (N_{TC}, 1)_{Y_U}, \ D_R \in (N_{TC}, 1)_{Y_D}$$

- Condensate $\langle \bar{T}_L T_R \rangle \sim F_T^3$ induces EWSB, producing masses

$$m_W^2 \sim g^2 F_T^2 = m_Z^2 \cos^2 \theta_W$$

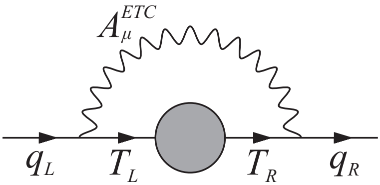
- No hierarchy problem!
- No fundamental scalars

Part I: Technicolor

- How to generate mass terms for Standard Model fermions?
- Try to introduce an operator of the schematic form $\bar{T}_R T_L \bar{q}_L q_R$
- Non-zero $\langle \bar{T}_L T_R \rangle \Rightarrow$ masses for Standard Model quarks
- But this operator is dimension six, thus irrelevant, so adding it defeats the purpose!

Part I: Extended Technicolor

- Extended Technicolor unifies $SU(3)$, $SU(N_{TC})$, and flavor symmetries into the ETC gauge group G_{ETC}
- At a high scale $\Lambda_{ETC} = M_{ETC}/g_{ETC}$, symmetry breaking occurs $G_{ETC} \to SU(3) \times SU(N_{TC})$
- Masses for Standard Model fermions are generated through:



$$m_q \sim \frac{g_{ETC}^2}{M_{ETC}^2}\langle \bar{T}_L T_R \rangle \sim \Lambda_{ETC}^{-2}\langle \bar{T}_L T_R \rangle$$

Part I: Extended Technicolor

- Integrating out A_μ^{ETC} also generates terms of the form $\bar{q}q\bar{q}q$
- The most stringent constraint comes from the K^0-$\bar{K}^0$ system, due to the operator

$$\Lambda_{ETC}^{-2}\bar{d}\Gamma^\mu s\bar{d}\Gamma_\mu s$$

- Comparing with data $\Delta m_K = K_L - K_S < 3.5 \times 10^{-18}$ TeV gives that $\Lambda_{ETC} > 1000$ TeV
- This leads to too small masses for SM quarks (FCNC problem)

Let us look at the expression for m_q again more carefully:

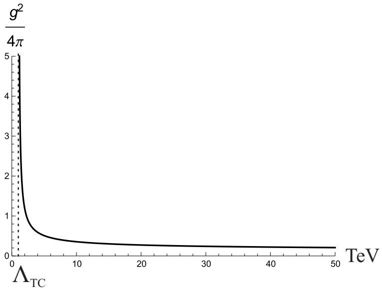
$$m_q \sim \Lambda_{ETC}^{-2} \langle \bar{T}_L T_R \rangle_{ETC},$$

$$\langle \bar{T}_L T_R \rangle_{ETC} = \langle \bar{T}_L T_R \rangle_{TC} \exp \left(\int_{\Lambda_{TC}}^{\Lambda_{ETC}} \frac{d\mu}{\mu} \gamma(\mu) \right),$$

where γ is the anomalous dimension of the operator $\bar{T}_L T_R$

Part I: Extended Technicolor

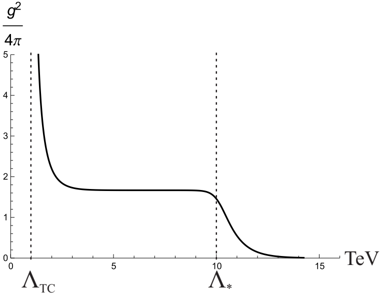
- For Technicolor models that are QCD-like, the classical estimate $\gamma = 0$ is a good approximation:



- However, if Technicolor remains strongly coupled over a sizeable region, this is no longer true, and the condensate can get enhanced

Part I: Walking Technicolor

- Walking Technicolor has a "walking" region where it remains strongly coupled:



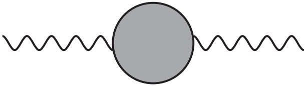
- This enhances the condensate by a factor $\left(\frac{\Lambda_*}{\Lambda_{TC}}\right)^{\gamma}$ and can therefore solve the problem with FCNC

Part I: Walking Technicolor

- Walking Technicolor has spontaneously broken approximate scale invariance
- Could this lead to a light scalar, the dilaton (pseudo-Goldstone of dilatations), in the spectrum?
- Such a light scalar would couple to the Standard Model fields in a similar way as the Higgs, and therefore it would be hard to distinguish the two at low energies!

Part I: Precision Electro-Weak Parameters

- Properties of the EW sector have been measured extremely accurately
- Technicolor models contribute:



- We can define parameters $\hat{S}$, $\hat{T}$, $\hat{U}$:

$$\Pi(q^2) = \Pi(0) + q^2\Pi'(0) + \frac{1}{2}(q^2)^2\Pi''(0) + \cdots ,$$

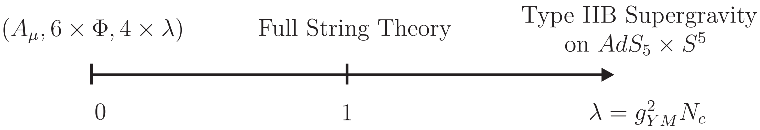
$$\hat{S} = \frac{g}{g'}\Pi'_{W^3B}(0),$$

$$\hat{T} = \frac{1}{M_W^2}\left(\Pi_{W^3W^3}(0) - \Pi_{W^+W^-}(0)\right),$$

$$\hat{U} = \left(\Pi'_{W^+W^-}(0) - \Pi'_{W^3W^3}(0)\right)$$

Part II: AdS/CFT

- AdS/CFT is a duality between $\mathcal{N} = 4$ SYM and Type IIB String Theory on $\mathrm{AdS}_5 \times S^5$:



- Allows to study strongly coupled dynamics in field theory
- The extra bulk dimension (the radius r) is related to energy scale in the field theory, and thus the bulk is in a sense a geometrical representation of the RG flow of the dual theory

Part II: AdS/CFT

What does this have to do with Walking Technicolor?

- The walking region can be thought of as the theory flowing near an IR fixed point
- This near conformality means that we can apply ideas from AdS/CFT

These fall into two classes:

- Phenomenological bottom-up models where the matter content in the bulk is put in by hand
- Top-down models which have their origin in string theory constructions, and therefore are on firmer ground

Part II: Bottom-Up Approach

- The simplest possible way to model the walking region would be to take AdS and put hard cut-offs in the IR and the UV, i.e. the space ends abruptly at r_{IR} and r_{UV}
- r_{IR} is then a very crude way to model confinement (at scale Λ_{TC}), while r_{UV} models the end of the walking region (at scale Λ_*)
- In this model, we can compute precision electro-weak parameters, such as the S-parameter
- However, if we try to compute the mass of the dilaton, it is zero

Part II: Bottom-Up Approach

Let us consider something a little more sophisticated:
(DE, Piai 2011)

- Put a scalar Φ in the bulk and let it backreact on the geometry:

$$\text{Scalar potential:} \quad V(\Phi) = \frac{1}{2}\partial_\Phi W^2 - \frac{4}{3}W^2,$$
$$W(\Phi) = -\frac{3}{2} - \frac{\Delta}{2}\Phi^2 + \frac{\Delta}{3\Phi_I}\Phi^3$$

- The metric is given by (A is the warp factor)

$$ds^2 = dr^2 + e^{2A(r)}dx_{1,3}^2$$

Part II: Bottom-Up Approach

- Any solution to the first order equations

$$\partial_r \Phi = \partial_\Phi W, \quad \partial_r A = -\frac{2}{3} W$$

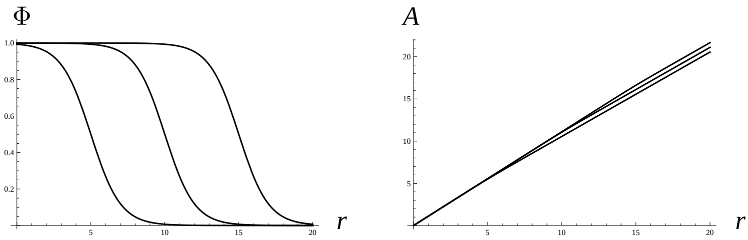
solves the equations of motion

- One-parameter (r_*) family of solutions:

$$\begin{aligned}\Phi(r) =& \frac{\Phi_I}{e^{\Delta(r-r_*)} + 1}, \\ A(r) =& \frac{1}{9}\left(9r + \Phi_I^2 \frac{e^{\Delta(r+r_*)}}{(e^{\Delta r} + e^{\Delta r_*})^2} + \Phi_I^2 \Delta r - \Phi_I^2 \log[1 + e^{\Delta(r-r_*)}]\right) \\ & - \frac{1}{9}\Phi_I^2 \left(\frac{1}{2\cosh(\Delta r_*) + 2} - \log\left(1 + e^{-\Delta r_*}\right)\right)\end{aligned}$$

Part II: Bottom-Up Approach

- Background functions Φ and A for $\Delta = 1$, $\Phi_I = 1$, varying r_*:



- Interpolates between two AdS $\Rightarrow$ flows from a UV fixed point to an IR fixed point
- As for the simpler model, confinement is modelled by a hard IR cut-off

Part II: Bottom-Up Approach

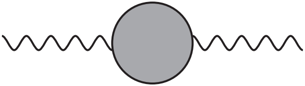
How to model EWSB?

- Consider a simpler version $U(1)_L \times U(1)_R \to U(1)_V$
- Introduce gauge fields A_μ^L and A_μ^R in the bulk
- Symmetry breaking occurs because of different boundary conditions for A_μ^V and A_μ^A:

$$\partial_r A_\mu^V(r_{IR}) = 0, \quad A_\mu^A(r_{IR}) = 0$$

Part II: Bottom-Up Approach

- Holography enables us to compute contributions from the strongly coupled sector to $\Pi(q^2)$:

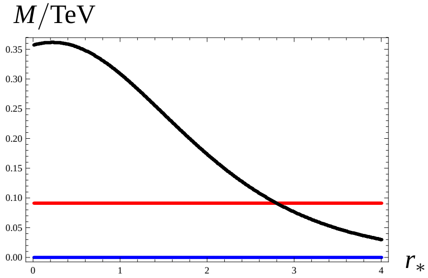


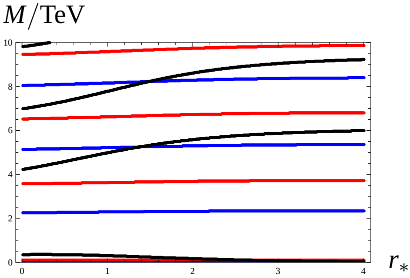
- By looking at the zeros of $\Pi(q^2)_{V,A}$, we obtain the spectrum of spin-1 states
- Analogue of $\hat{S}$-parameter ($\hat{T}$ and $\hat{U}$ don't exist):

$$\hat{S} = \frac{g}{g'} \Pi'_{LR}(0)$$

- Experimental constraint: $\hat{S} < 0.003$

Spectrum as a function of r_* (vector is blue, axial-vector is red, scalar is black):





Part II: Bottom-Up Approach

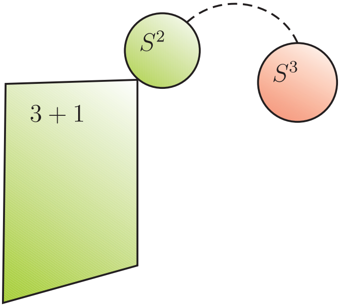
	$\varepsilon = 0.07,\ \Phi_I = 1,\ \Delta = 1$						
r_*	1.5	2.	2.2	2.3	2.4	2.5	2.6
M_Z	0.0912	0.0912	0.0912	0.0912	0.0912	0.0912	0.0912
m	0.2410	0.1731	0.1490	0.1378	0.1272	0.1172	0.1078
$\hat{S}$	0.0026	0.0026	0.0026	0.0026	0.0026	0.0026	0.0026
Λ_*	3.9	6.5	7.9	8.7	9.6	10.7	11.8
M_{V1}	2.3	2.3	2.3	2.3	2.3	2.3	2.3
M_{V2}	5.3	5.3	5.3	5.3	5.3	5.3	5.3
M_{V3}	8.2	8.3	8.3	8.3	8.3	8.3	8.3
M_{A1}	3.7	3.7	3.7	3.7	3.7	3.7	3.7
M_{A2}	6.7	6.7	6.7	6.7	6.8	6.8	6.8
M_{A3}	9.7	9.7	9.8	9.8	9.8	9.8	9.8
M_1	5.3	5.6	5.7	5.7	5.7	5.8	5.8
M_2	8.2	8.6	8.7	8.8	8.8	8.9	8.9

Table: Numerical results for $\Delta = 1 = \Phi_I = 1$, $\varepsilon = 0.07$, $r_2 \to +\infty$ by varying r_*. All masses are in TeV.

Part II: Top-Down Approach

Let us consider a top-down model obtained from string theory

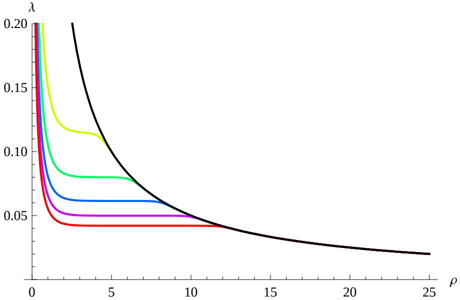
- D5 system:



- D5-branes wrapped on S^2
- This gives us an $\mathcal{N}=1$ SUSY field theory

Part II: Top-Down Approach

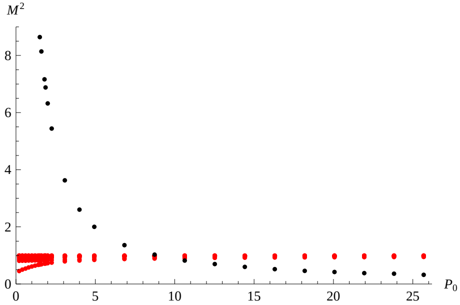
- We can define a 4d gauge coupling λ (inverse of size of the S^2)
- Walking backgrounds:
  (DE, Nunez, Piai 2009)



- Two scales: gaugino condensate and end of walking region ρ_*

Part II: Top-Down Approach

Scalar spectrum for different values of $P_0 \simeq 2\rho_*$ (in units of $g_s\alpha' N_c$):



Light scalar whose mass is suppressed by the length of the walking region

Summary

- Technicolor models offer a mechanism for Electro-Weak Symmetry Breaking through strongly coupled dynamics
- Walking Technicolor models may imply the existence of a light scalar, the dilaton, that would be difficult to distinguish from the Higgs at low energies
- It is nowadays comparatively easy to build bottom-up holographic models incorporating this scenario while agreeing with the experimental constraints
- Top-down models of walking obtained from string theory exist, but it would be interesting to find more examples, in order to see which generic features emerge