AdS/QCD and AdS/Technicolor

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October, 2007

based on arXiv:0705.3533 with K. Yoshioka

Outline

- ☐ Motivation
- ☐ The idea of (minimal and extended) Technicolor model
- ☐ D-brane construction and Holographic description
- ☐ Compute the masses of W, Z bosons and STU parameters
- ☐ Summary and Discussions

Motivation

- ☐ Technicolor is an attractive idea to stabilize the weak scale.
- ☐ It utilizes the strong gauge interactions and then it is difficult to compute quantitatively.
- ☐ Moreover, simple models are excluded out because of large deviations in precision tests (STU parameters) and large FCNC.
- ☐ The Walking Technicolor is expected to avoid these problems, but more difficult to compute. For example S-parameter has not been computed as far as I heard.
- ☐ String realization of Technicolor using D-branes provides a new way to analyze Technicolor strong theory!
- ☐ This is based on a strong/weak duality. A strong Technicolor theory has a dual in terms of a weak gravitational theory. (AdS/CFT, AdS/QCD, ...)

☐ Motivation

☐ The idea of (minimal and extended) Technicolor model

☐ D-brane construction and Holographic description

☐ Compute the masses of W, Z bosons and STU parameters

☐ Summary and Discussions

Minimal Technicolor

□ We prepare a gauge theory (technicolor $SU(N_{TC})$ gauge theory) whose gauge coupling becomes strong around the weak scale.

□ Minimal Model [Weinberg '79, Susskind '79]
The technicolor sector :

	$SU(N_{TC})$	$SU(2)_L$	$SU(2)_R \supset U(1)_Y$
T_L	□	□	
T_R	□		□ $= (1/2, -1/2)$

Similar to QCD, the technicolor quarks T condensate $\langle \overline{T} T \rangle = \Lambda_{TC}^3$ which break $SU(2)_L \times SU(2)_R(U(1)_Y) \to SU(2)_D(U(1)_{EM})$.

- The weak scale is stabilized since it is given by the technicolor scale.
- $M_W = gF_{TC}/2 = 80.4$ GeV $\to F_{TC} \sim 250$ GeV
(Pion decay constant $f_\pi \sim 100$ MeV)

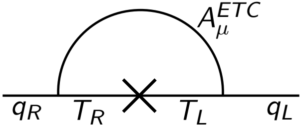
Extended Technicolor

☐ To introduce masses of SM quarks and leptons, the Extended Technicolor is proposed.[Eichten-Lane'80,Dimopoulos-Susskind'79]

$SU(N+3) \to SU(N+2) \to SU(N+1) \to SU(N) \to$ confinement

$$m_q \sim \frac{g_{ETC}^2 \langle \overline{T}_R T_L \rangle_{m_{ETC}}}{m_{ETC}^2}$$

$m_C \to m_{ETC} \lesssim$ few TeV



☐ However, large FCNC is expected

$$\frac{g_{ETC}^2 \theta_{sd}^2}{m_{ETC}^2} (\bar{s}\Gamma^\mu d)(\bar{s}\Gamma'_\mu d), \qquad (\Gamma_\mu, \Gamma'_\mu = \gamma_\mu(1 \pm \gamma_5)/2)$$

$\Delta M_K \to m_{ETC} \gtrsim 1300$ TeV, (with $g_{ETC}\sqrt{Re\theta_{sd}^2} \sim 1$)

☐ the Walking Technicolor [Holdom, '81]

$$\langle \overline{T}_R T_L \rangle_{(m_{ETC})} = \langle \overline{T}_R T_L \rangle_{(\Lambda_{TC})} \ \exp \int_{\Lambda_{TC}}^{m_{ETC}} \gamma_m$$

If $\beta_{TC} \sim 0$, $\gamma_m \sim 1$ and $\langle \overline{T}_R T_L \rangle_{(m_{ETC})} \gg \langle \overline{T}_R T_L \rangle_{(\Lambda_{TC})}$.

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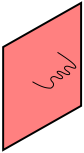
D-brane



□ D-brane is defined as the boundary which open strings can end. The massless modes from open string consist a super Yang-Mills theory.
e.g. 4 dim. N=4 $SU(N_c)$ SYM on $N_c \times$ D3-brane

□ On the other hand, D-brane is a black hole solution in supergravity.
e.g. $AdS_5 \times S^5$ ($R^4 \propto N_c$, after $\alpha' \to 0$ limit) is the D3-brane near horizon geometry.

□ Therefore these two different descriptions for D-brane which gives the conjecture [Maldacena '97]

AdS/CFT, (Holography)

4 dim. N=4 $SU(N_c)$ SYM	$\leftrightarrow$	sugra on $AdS_5 \times S^5$	
$\lambda = g_{YM}^2 N_c$	$\leftrightarrow$	R^4/l_s^4	$\gg 1$

Technicolor gauge on D-branes

☐ We first have to realize pure Yang-Mills gauge theory (which will be identified as technicolor gauge theory).

☐ $N_{TC}\times$ D4-brane $\rightarrow$ 5 dim. $SU(N_{TC})$ SYM
$\downarrow$ S^1 with anti-periodic b.c. for fermions
$N_{TC}\times$ D4-branes on S^1 $\rightarrow$ 4 dim. $SU(N_{TC})$ YM (+ infinite KK modes)

☐ We also know the black hole metric for this.

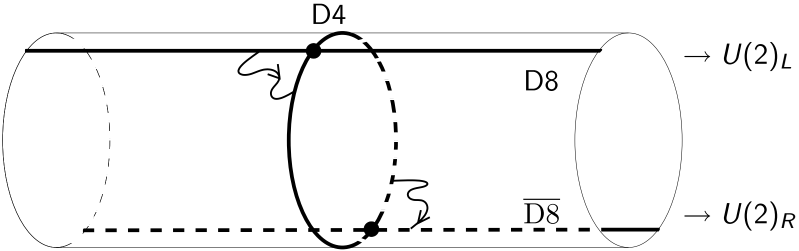
4 dim. $SU(N_{TC})$ YM (+ KK) with large 't Hooft	$\leftrightarrow$	gravity in $N_{TC}\times$D4 on S^1 black hole background

☐ We further need to introduce techni-quarks.

TechniQuarks from D-branes

[e.g. Sakai-Sugimoto '04]

☐ We introduce 2× D8-branes and 2× anti-D8-branes.



2× D8-branes $\rightarrow U(2) \supset SU(2)_L$

2× anti-D8-branes $\rightarrow U(2) \supset SU(2)_R \supset U(1)_Y$

D4-D8 string → Left handed massless chiral fermion → L-handed techniquark

D4-anti-D8 string → Right handed massless chiral fermion → R-handed techniquark

Technicolor on D-branes

□ The minimal Technicolor is realized on D-branes.

	$SU(N_{TC})$	$U(2)_L$	$U(2)_R$	
A_μ^{TC}	*adj.*			D4 − D4
T_L	□	□		D4 − D8
T_R	□		□	D4 − $\overline{\text{D8}}$
A_μ^L		*adj.*		D8 − D8
A_μ^R			*adj.*	$\overline{\text{D8}}$ − $\overline{\text{D8}}$

4 dim. $SU(N_{TC})$ YM (+ KK) + TechniQuarks $+U(2)_L \times U(2)_R$ (large 't Hooft)	$\leftrightarrow$	gravity in $N_{TC}\times$D4 on S^1 black hole background + 2× (D8,anti-D8) branes (weak coupling)

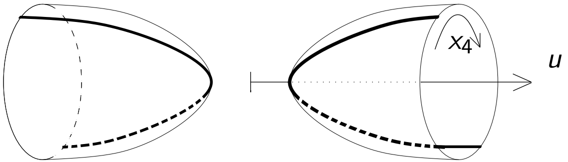
- Later, we assume $U(2)_L$ is broken to $SU(2)_L$ and $U(2)_R$ is broken to $U(1)_Y$ by Higgsing at (arbitrary) high energy.
- We can introduce SM quarks and lepton which then becomes the extended technicolor. (But I am afraid there is no time.)

Holographic Dual

☐ The near horizon geometry of D4-branes on S^1 with anti-periodic b.c. for fermions is [Witten]

$$ds^2 = \left(\frac{u}{R}\right)^{\frac{3}{2}} \left(dx_{M_4}^2 + f(u)dx_4^2\right) + \left(\frac{R}{u}\right)^{\frac{3}{2}} \left(\frac{du^2}{f(u)} + u^2 d\Omega_4^2\right)$$

$$f(u) = 1 - \frac{u_K^3}{u^3}, \qquad e^{\phi} = g_s \left(\frac{u}{R}\right)^{\frac{3}{4}}, \qquad x_4 \sim x_4 + \frac{2\pi}{M_K}$$



$(R^3 = \pi g_s N_{TC} l_s^3)$

$(M_K = 3u_k^{1/2}/2R^{3/2})$

The D8-brane in this geometry should already describe the electroweak sym br.

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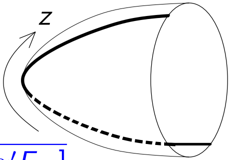
W and Z boson masses

□ $U(2)_L \times U(2)_R$ gauge bosons come from D8-D8 and anti-D8-anti-D8. The action for D8 (anti-D8) branes is given by DBI action in this geometry.

□ We first need the induced metric on D8-brane. D8-brane is located at constant x_4. Then

$$ds^2 = \left[\frac{u_K}{R}\right]^{\frac{3}{2}} K(z)^{\frac{1}{2}} dx_{M_4}^2 + R^{\frac{3}{2}} u_K^{\frac{1}{2}} K(z)^{\frac{-1}{2}} \left[\frac{4}{9} K(z)^{\frac{-1}{3}} dz^2 + K(z)^{\frac{2}{3}} d\Omega_4^2\right]$$

$$u^3 \equiv u_K^3 K(z), \qquad K(z) \equiv 1 + z^2$$



□ The DBI actioon is

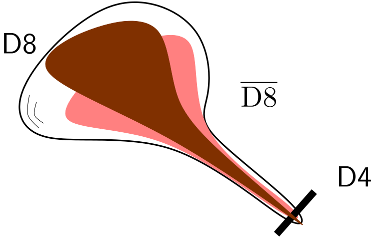
$$S = -T_8 \int d^9 x e^{-\phi} \sqrt{\det[g_{ab} + \partial_a X_4 \partial_b X_4 + 2\pi\alpha' F_{ab}]}$$

A_μ, A_z, A_θ and X_4 are $U(2)$ adjoint gauge and scalar fields on D8-brane.

Integrating over S^4 and keeping quadratic terms, the action becomes YM in a curved space.

$$S = \frac{-1}{g_5^2} \int d^4x \int_{-z_R}^{z_L} dz \, \mathrm{Tr} \left[\frac{1}{4} K(z)^{\frac{-1}{3}} F_{\mu\nu}^2 + \frac{M_K^2}{2} K(z) F_{\mu z}^2 \right] + \cdots ,$$

We have the maximal values z_L and z_R because the extra dimensions are assumed to be compactified.



We assume that $U(2)_L$ is broken to $SU(2)_L$ around $z = z_L$ and $U(2)_R$ is broken to $U(1)_Y$ around $z = z_R$.

Higgsless picture

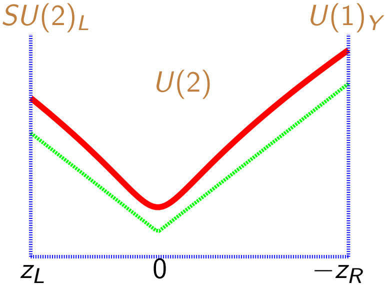
☐ If we look at the effective 5 dim action, this is similar to a Higgsless model.

- There are two throats, instead, which correspond to D8 and $\overline{\mathrm{D8}}$ and are connected smoothly at IR region.
- Two UV cuts represent the volumes of D8 and $\overline{\mathrm{D8}}$.
- $U(2)$ gauge fields come from D8 and live in the bulk.

5 dim. metric is

$$ds^2 = K(Z)^{\frac{2}{3}} dx_4^2 + K(Z)^{-\frac{2}{3}} dz^2$$

$$K(Z)^{\frac{1}{3}} = (1+z^2)^{\frac{1}{3}} \neq z$$



- The b.c. at two UVs determines the gauge symmetry at the UV scale.
- The b.c. at IR is not given by hand.

W and Z boson masses

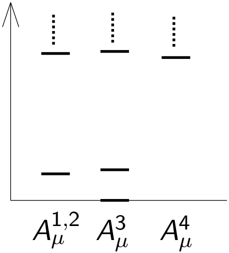
□ We should get γ, W and Z bosons, their masses and coupling constants.

□ The mode expansions
$A^a_\mu(x,z) = \sum_n A^{a,n}_\mu(x)\psi_n(z)$:

$A^3_\mu \quad \rightarrow \gamma,\ Z$, KK

$A^{1,2}_\mu \quad \rightarrow W$, KK

$A^4_\mu \quad \rightarrow$ KK



□ The masses and gauge couplings are read

$$m_\gamma = 0, \quad m_Z = m_W/c_W, \quad m_W = c \cdot g_{SU(2)_L} f_{TC},$$

$$g_{SU(2)_L} \simeq g_5/z_L^{1/6}, \quad g_{U(1)_Y} = t_W g_{SU(2)_L},$$

$$t_W = (z_L/z_R)^{1/6}, \quad m_{KK} \sim M_K,$$

$(L = \frac{1}{4g^2}F^2)$

STU parameters

☐ We summarize them into STU parameters. To do that, we have to know how many parameters we have. We have four M_K, z_L, z_R, $g_5(l_s, g_s)$.

- Two of z_L, z_R and $g_5(l_s, g_s)$ are used to fix SM gauge couplings $g_{SU(2)_L}$ and $g_{U(1)}$ coupling. (This automatically realizes correct Weinberg angle.)
- M_K is fixed to realize the SM Z-boson mass m_Z.

We have one free parameter, say z_L. As z_L large, m_K becomes heavier. Then we expect STU are becoming small enough since we can ignore the corrections from composite states. However because of perturbative unitarity, we cannot take arbitrary large z_L.

Numerical results & Oblique parameters

☐ $z_L = 10^6$:
$z_R = 35.26 \cdot z_L,\ M_K = 2.437$ TeV
$m_K \geq 2.0$ TeV
$S = 0.47,\ T, U \sim 0$

z_L	S	$M_{W'}$(GeV)
10^4	2.26	917
10^5	1.02	1359
10^6	0.47	2002
10^7	0.22	2943

- exp. $S = -0.13 \pm 0.10,\ T = -0.13 \pm 0.11,\ U = 0.20 \pm 0.12$
  Without the fundamental Higgs field, the perturbative unitarity is lost around a few TeV.

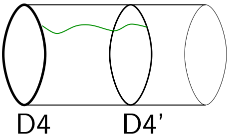
Summary & Discussion

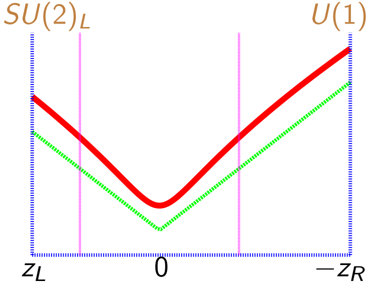
☐ We constructed a Technicolor model using various D-branes.

☐ Applying AdS/CFT, we studied the dynamical electroweak symmetry breaking from gravity side.

☐ We computed m_W, m_Z and gauge couplings. The oblique S parameter is around 0.5.

☐ SM fermions are introduced by introducing another D4 branes.





- S is reduced by flavor D4-brane effects.
- We estimated the order of fermion masses. Top and Bottom quark have strong interactions with KK modes which may induce large Zbb coupling deviation. FCNC?
- We assumed the stabilization of moduli related with the positions of D-branes.

☐ We don't know yet how to compute $\langle \overline{T}_R T_L \rangle_{(m_{ETC})}$.

$$\langle \overline{T}_R T_L \rangle_{(m_{ETC})} = \langle \overline{T}_R T_L \rangle_{(\Lambda_{TC})} \ \exp \int_{\Lambda_{TC}}^{m_{ETC}} \gamma_m$$

☐ This is the first step to go to a more realistic model.

D-brane configuration : SM sector

□ SM matters are introduced by further adding D4-branes which are parallel to but separated from techni D4-branes.

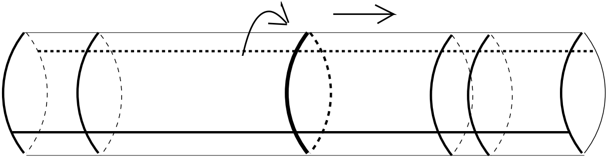
$3_{\rm generation} \times (1_{\rm lepton} + 3_{\rm quark}) \times$ D4-branes

	$SU(N_{TC})$	$SU(2)_L$	$U(1)_R$	$U(1)_l$
q_L		□		1
q_R			$(1/2, -1/2)$	1

L lepton

R lepton

$$U(1)_Y = U(1)_R + U(1)_l/2 + U(1)_b/3$$



Fermion masses

□ $SU(N_{TC}+3) \to SU(N_{TC}+2) \to SU(N_{TC}+1) \to SU(N_{TC}) \to$ confinement

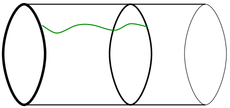
$$m_q \sim g_{ETC}^2 \frac{\langle \overline{Q}_L Q_R \rangle}{m_{ETC}^2}$$

□ In our D-brane configuration, there is massive gauge fields from open string stretching between the techni D4 and flavor D4-branes.

$$m_{ETC} = l_s^{-2} \int_0^{z_i} dz \sqrt{-\det g} \sim N_{TC} g_{TC}^2 z_i^{\frac{2}{3}} M_K,$$

$$m_q \sim \frac{g_{ETC}^2 \langle \overline{Q}_L Q_R \rangle_{ETC}}{N_{TC}^2 g_{TC}^4 z_i^{\frac{4}{3}} M_K^2} \propto z_i^{\frac{-4}{3}} M_K$$

$$M_K \sim \mathrm{TeV} \to z_i \sim (10, 10^{2.5}, 10^{4.5})$$



top quark ($z_i \sim 10$) strongly interacts with composite states.