Gauge-Higgs unification and holography

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Similiarities between RS and composite models

Randall-Sundrum models

- gauge symmetry broken by boundary conditions leads to massless scalar A_5 and tower of massive KK modes
- localisation of fermion zero modes leads to hierarchical effective Yukawa couplings and suppressed FCNCs

Composite models

- spontaneously broken global symmetry induces massless GB in addition to strongly coupled resonances
- partial compositeness as the origin of flavour hierarchies in the SM Yukawa couplings and suppressing FCNCs

From string theory: AdS/CFT correspondence

AdS/CFT duality conjecture

type IIB string theory on $\mathrm{AdS}_5 \times S^5$ $\quad\Longleftrightarrow\quad$ $\mathcal{N} = 4$ supersymmetric $SU(N)$ gauge theory on 4D Minkowski space

- duality based on equal symmetry structure: space-time vs. internal
- implies equal correlation functions for observables if

$$\frac{R^4}{l_s^4} = 4\pi g^2 N$$

l_s: string scale, g: $SU(N)$ gauge coupling

Note: $\mathcal{N} = 4$ supersymmetric $SU(N)$ theory is conformal
➢ scale-invariant

Phenomenological application

in the limit of weakly coupled (i. e. classical) gravity:

AdS$_5$ background in RS $\Longleftrightarrow$ strongly coupled 4D conformal field theory

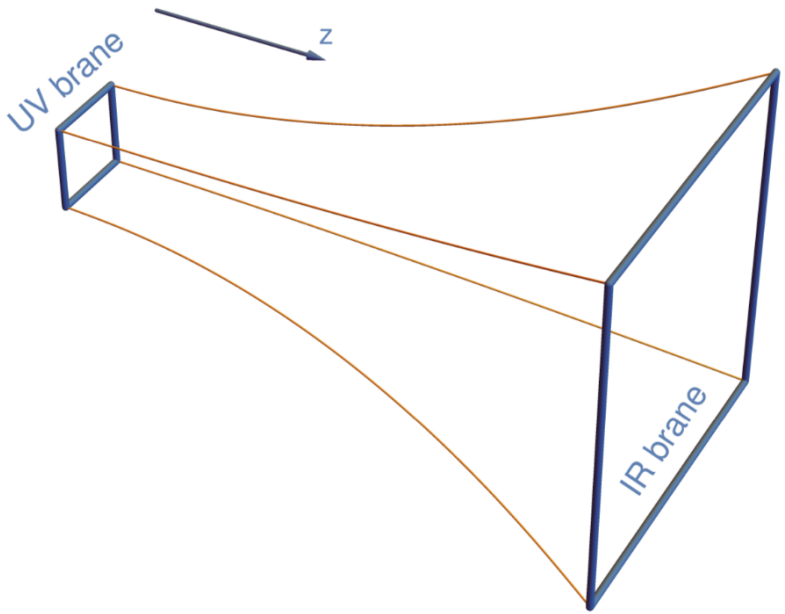
AdS$_5$ metric

$$ds^2 = \left(\frac{R}{z}\right)^2 (\eta_{\mu\nu} dx^\mu dx^\nu - dz^2)$$

coordinate transformation $z \to e^\alpha z$ leads to rescaling of effective metric that can be undone by rescaling $x \to e^\alpha x$

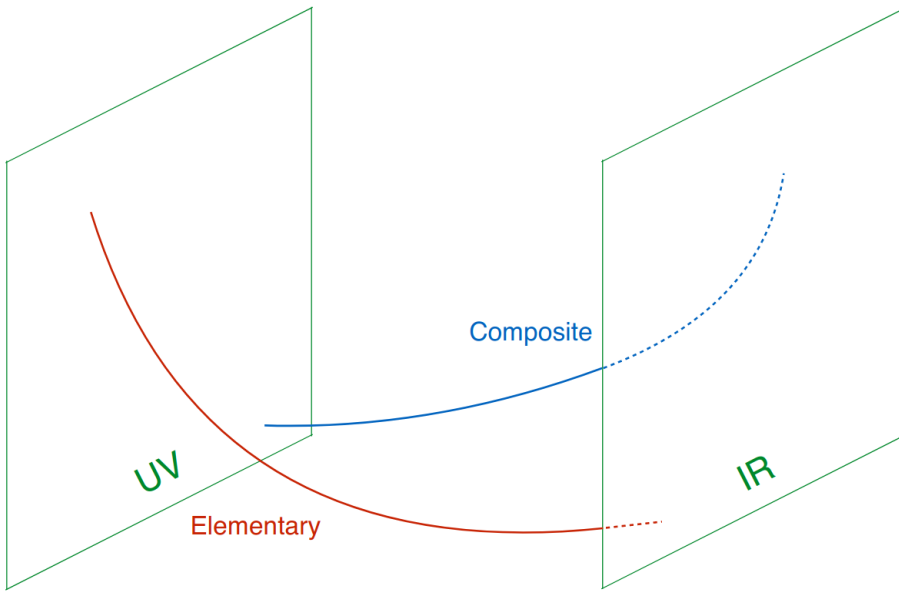
motion alsong $z \Longleftrightarrow$ rescaling 4D coordinates

equivalent to change of energy scales



Holographic picture of extra dimension

- 5th dim. corresponds to RG flow in 4D conformal field theory (CFT)
- branes correspond to scales where CFT is broken
  - UV brane: $\Lambda \sim 1/R$ UV cutoff
  - IR brane: spontaneous CFT breaking by confinement at scale $\Lambda \sim 1/R'$
- IR-localised $\Leftrightarrow$ composite states
- UV-localised $\Leftrightarrow$ elementary states
- 5D gauge $\Leftrightarrow$ 4D global symmetry weakly gauged for A_μ zero mode
- fermion localisation along bulk $\Leftrightarrow$ degree of partial compositeness



Symmetry breaking: 5D vs. 4D

Symmetry breaking by BCs

- $A_\mu(R) = 0$: no gauged symmetry below cutoff
- $A_\mu(R') = 0$: dynamical gauge symmetry breaking by confining CFT
- $A_\mu(R, R') = 0$: global symmetry spontaneously broken by confinement

➢ A_5 zero mode corresponds to massless Goldstone boson

$$A_5(x, z) = (az + bz \log z) A_5(x)$$

peaked towards IR brane, i, e. composite!

➢ **gauge-Higgs unification**

Ingredients for a realistic RS model

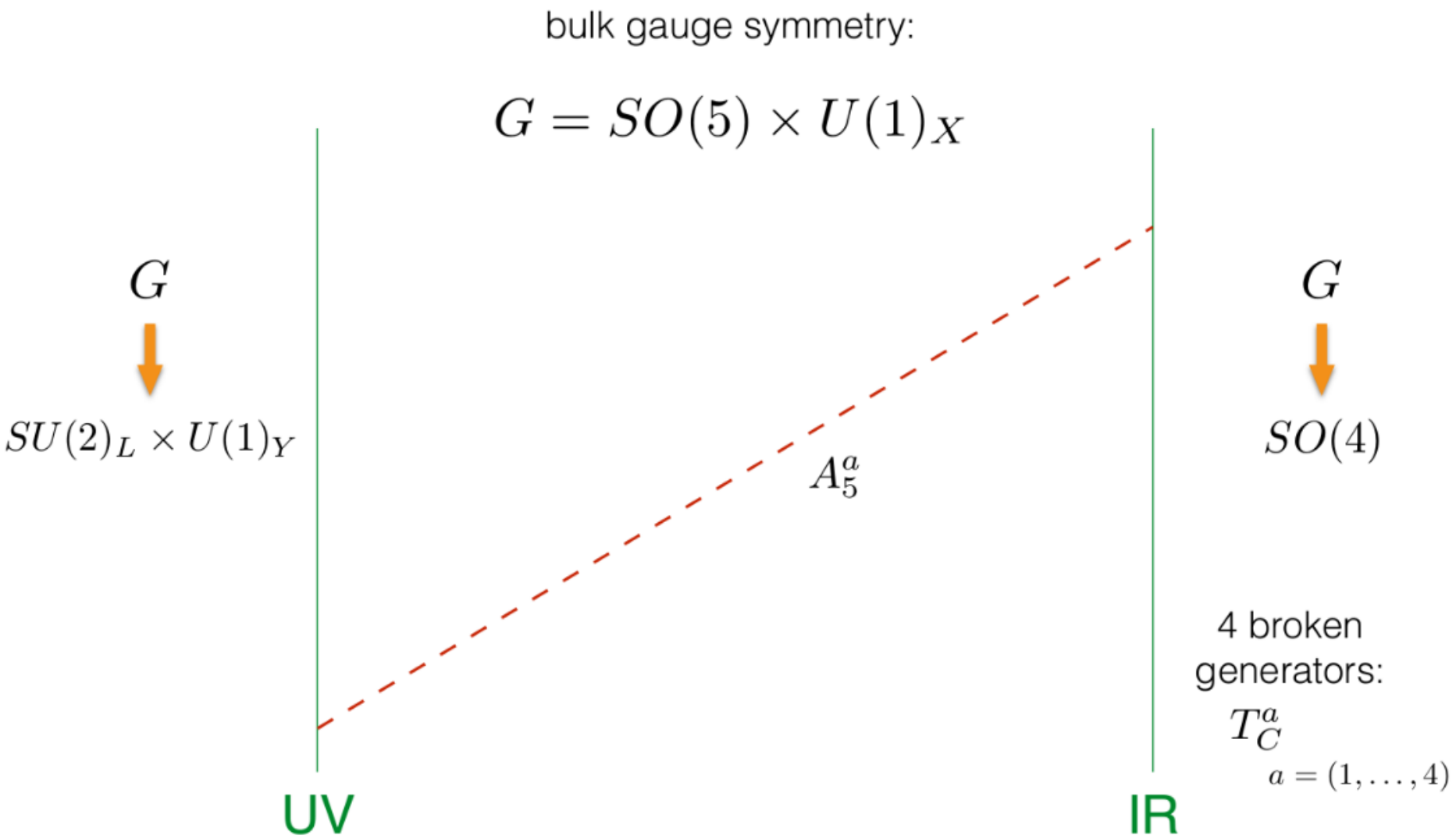
Concept: apply knowledge from our study of composite models to build realistic RS model using AdS/CFT correspondence

Lessons from composite Higgs models (MCHM)

- requirement of custodial symmetry
  ➢ $SO(5) \times U(1)_X$ global symmetry
- Higgs as pseudo-GB of $SO(5) \to SO(4)$
- gauged SM group $SU(2)_L \times U(1)_Y$
- partially composite fermions

➢ **translate to RS model using AdS/CFT duality**

Bulk gauge symmetry and boundary conditions



Relevant scales

KK scale $M_{\mathsf{KK}} \sim 2/R'$

- mass gap of strong dynamics, scale of lightest resonances

dimensionless KK coupling $g_* = g_5/\sqrt{R}$

- interaction strength of KK resonances
- strength of Higgs interactions incl. Yukawas

dimensionless 4D gauge coupling $g = g_5/\sqrt{R'}$

- interaction strength of zero-mode gauge bosons

scale of global symmetry breaking

$$f = \frac{M_{\mathsf{KK}}}{g_*} \sim \frac{2}{g_* R'}$$

cutoff scale for IR dynamics (incl. Higgs) $g_* f \leq 4\pi f$

Effective Higgs potential

- tree-level potential for A_5 forbidden by 5D gauge invariance
- radiatively generated since gauge symmetry is broken by BCs
- AdS/CFT: UV-brane BCs $\Leftrightarrow$ explicit symmetry breaking by cutoff
- contributions to A_5 effective potential must connect $A_5^{(0)}$ (localised at IR brane) to symmetry breaking effects on UV brane
- appearance of non-local "Wilson line"

$$\Omega(z) = \exp\left(i g_5 \int_R^z dz' \, A_5^a T^a \right)$$

- energy cutoff by finite size of extra dimension

➢ 5D gauge symmetry protects A_5 Higgs from quadratic divergences

Fermions

- P_{LR}-symmetric fermion represenations to protect $Zb_L\bar{b}_L$ vertex

$$\Psi_q \sim \mathbf{5}_{2/3} \to (\mathbf{2},\mathbf{2})_{2/3} + (\mathbf{1},\mathbf{1})_{2/3}$$
$$\Psi_u \sim \mathbf{5}_{2/3} \to (\mathbf{2},\mathbf{2})_{2/3} + (\mathbf{1},\mathbf{1})_{2/3}$$
$$\Psi_d \sim \mathbf{10}_{2/3} \to (\mathbf{2},\mathbf{2})_{2/3} + (\mathbf{1},\mathbf{3})_{2/3} + (\mathbf{3},\mathbf{1})_{2/3}$$

- conditions for choice of BCs
  - zero modes only for SM fermions
  - BCs on UV brane respect $SU(2)_L \times U(1)_Y$ symmetry
  - BCs on IR brane respect $SO(4) \times U(1)_X$ symmetry
- size of effective Yukawa couplings determined by choice of 5D bulk mass parameters determining zero mode localisation
- RS-GIM mechanism suppressing FCNCs

Practical implications of holography

Why is AdS/CFT useful?

- guiding principle for 5D model building from 4D composite models
- 5D dual of strongly coupled composite model is weakly coupled and therefore calculable

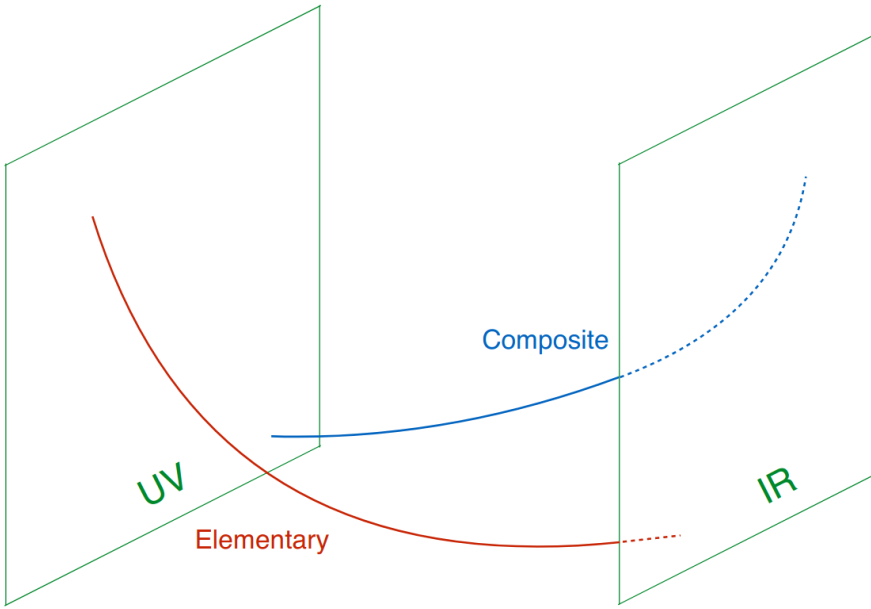
➢ explicit calculations of Higgs potential, precision observables etc. become possible and replace NDA estimates

➢ applications beyond models of EW symmetry breaking
c. f. AdS/QCD

Summary

Study goal: gauge-Higgs unification & holography

- AdS/CFT correspondence
- realistic RS model
- gauge-Higgs unification



Reading assignment

- chapter 4.7, 4.9, 4.10 of C. Csaki, S. Lombardo, O. Telem, *TASI Lectures on Non-Supersymmetric BSM Models*, `arXiv:1811.04279`