Strongly Coupled Theories of the TeV Scale

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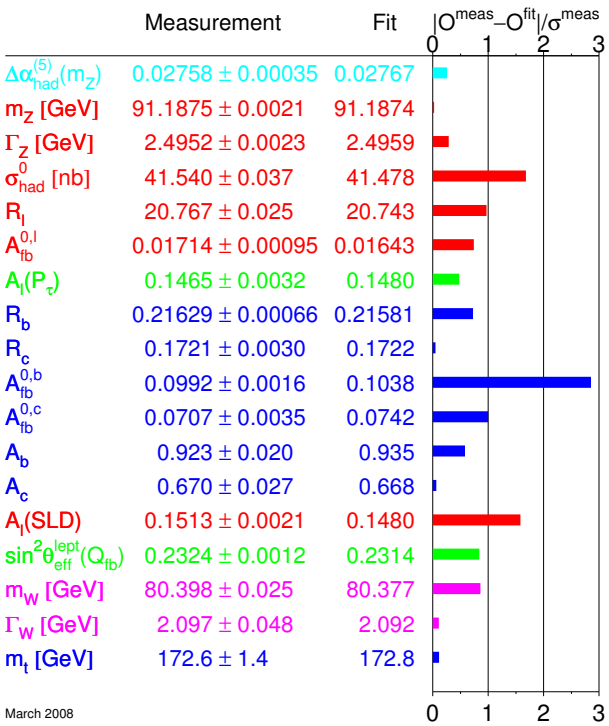
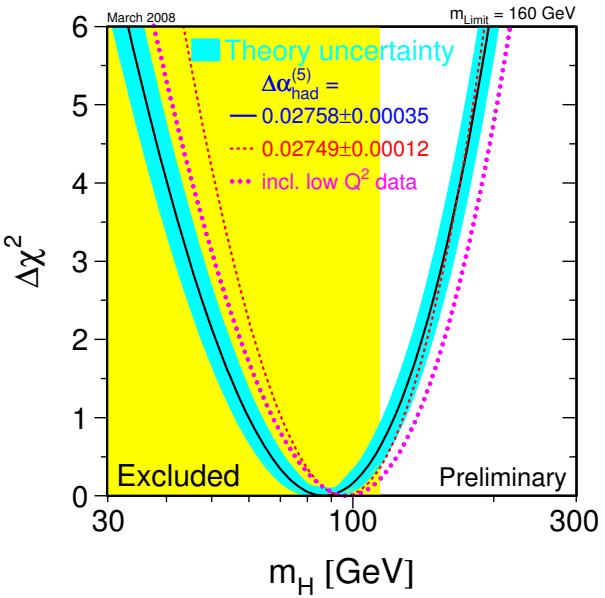
Outline

The great success of the SM

The Standard Model success



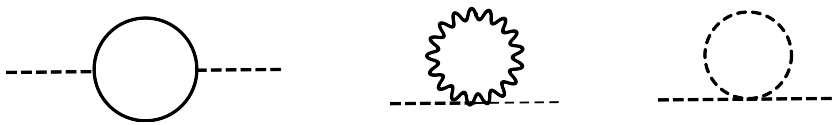
The SM Higgs is light



$m_h < 190$ GeV @ 95% C.L.

The Stability of the Weak Scale

But if Higgs elementary scalar quantum corrections drive m_h up



$$\delta m_h^2 \sim \frac{c^2}{16\pi^2}\Lambda^2$$

- We need $\Rightarrow m_h \lesssim 1$ TeV
- But if $\Lambda \longrightarrow M_P \sim 10^{19}\ GeV$, unnatural

$\Rightarrow$ Gauge Hierarchy Problem

Mechanism to Stabilize the Weak Scale

Need a mechanism to keep v and M_P separate.

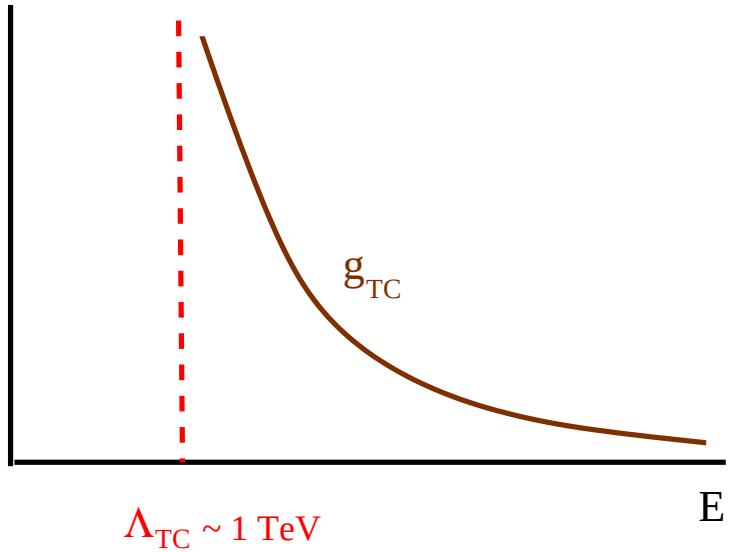
New physics at $\Lambda \sim 1$ TeV is:

Weakly Coupled	Strongly Coupled
• SM with a light Higgs	• Technicolor, Walking Technicolor
• SUSY (MSSM, NMSSM, Folded, ...)	• Topcolor, Top See Saw
• Little Higgs, Twin Higgs	• Composite Higgs
• LED, UED	• Randall-Sundrum

Strong Dynamics at the TeV Scale

Analogy with QCD:

- New Strong Interaction: Technicolor
- Strong at $M_W \ll M_P$
- Breaks Electroweak symmetry: $\langle \bar{F} F \rangle \neq 0$



Strong Dynamics at the TeV Scale

TC Problem I: Fermion Masses

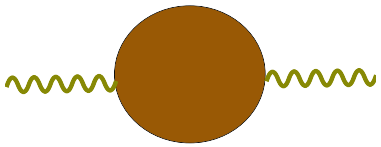
- Need Extended Technicolor (ETC):
  $G_{\rm ETC} \supset G_{\rm TC}$ with $\Lambda_{\rm ETC} \gg \Lambda_{\rm TC}$

$$m_f \simeq \frac{g^2_{\rm ETC}}{\Lambda^2_{\rm ETC}} \langle \bar{F} F \rangle$$

- Needs Walking (Walking TC):
  For heavier fermions (e.g. m_c, m_τ) needs to enhance $\langle \bar{F} F \rangle$
- But m_t requires $\Lambda_{\rm ETC}$ too low
  $\Rightarrow$ Topcolor, Top See Saw (Hill, Dobrescu)

Strong Dynamics at the TeV Scale

TC Problems II: Electroweak Precision Constraints



- E.g. Techni-fermions give

$$S \sim \frac{N}{6\pi}$$

- But

$$S^{\text{exp.}} \leq 0.1$$

Strong Dynamics and AdS/CFT

AdS/CFT Correspondence (Maldacena):

- Originally:

  $AdS_5 \times S^5$ String Theory $\leftrightarrow \mathcal{N} = 4$ 4D SU(N) Theory (CFT)

- In general: Assume 5D theory in $AdS_5 \leftrightarrow$ 4D CFT (Arkani-Hamed, Porrati, Randall)

- Need

$$g^2 N \gg 1$$

  to ignore string corrections.

- $\Rightarrow$ Holographic dual is 4D strongly coupled theory

Strong Dynamics from a Slice of AdS$_5$

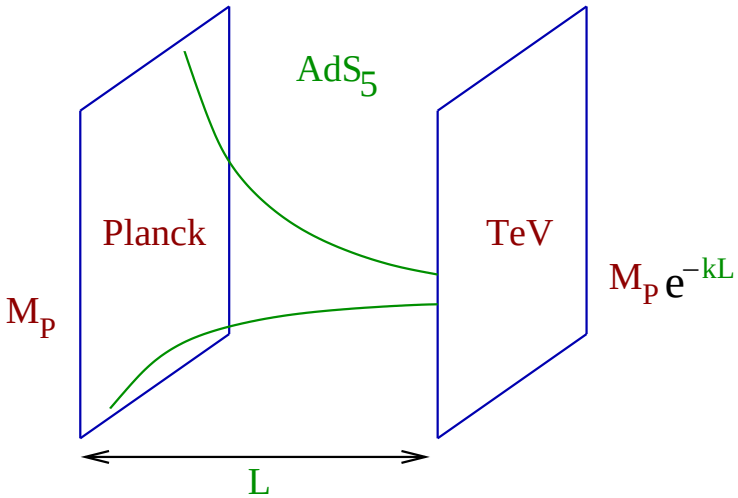
Ingredients to build Strongly Coupled Theories in AdS$_5$

- UV cutoff in the 4D Theory $\leftrightarrow$ UV ("Planck") boundary
- Break 4D Conformal Invariance in the IR $\leftrightarrow$ IR boundary
- 4D Strongly Coupled Gauge Theory described by 5D Weakly Coupled Theory

Solving the Hierarchy Problem in AdS$_5$

Metric in extra dimension $\Rightarrow$ small energy scale from M_P (Randall-Sundrum)

$$ds^2 = e^{-2\kappa|y|}\,\eta^{\mu\nu}dx_\mu dx_\nu - dy^2$$



Corrections to m_h OK
If Higgs close to TeV brane

Need Higgs IR localization

Bulk AdS_5 Models

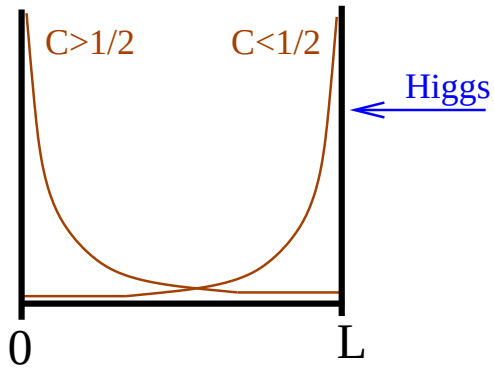
Allowing Gauge and Matter fields in 5D bulk
(Gherghetta-Pomarol, Grossman-Neubert)

- Avoid effects of Higher Dimensional Operators only suppressed by IR/TeV scale
- Natural Models of Flavor:
  Zero-mode fermion localization $\leftrightarrow$ fermion mass

$$M_f^{(5D)} = ck, \qquad c \simeq O(1)$$

Fermion Masses in Bulk RS Models

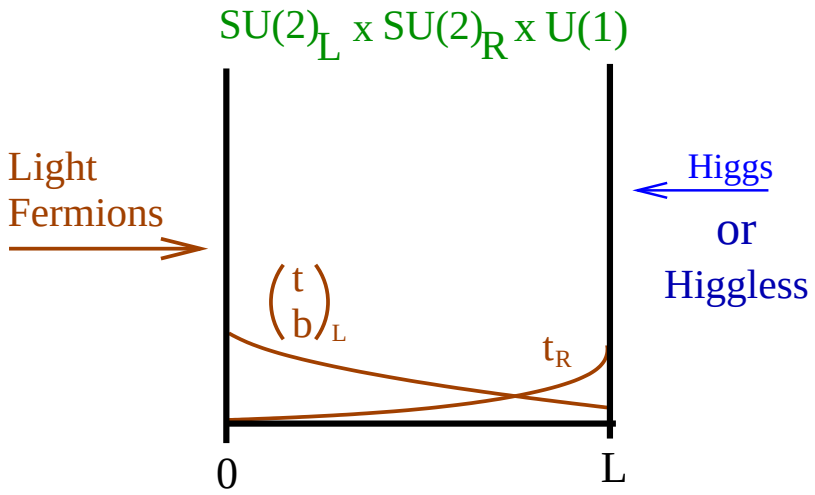
- $O(1)$ flavor breaking in bulk can generate fermion mass hierarchy:



TeV localization $\longrightarrow$ larger Yukawas,
Planck localization $\longrightarrow$ suppressed Yukawas.

- Heavier fermions couple stronger to gauge KK modes:
  - $G^{(1)} \longrightarrow t\bar{t}$ dominates
  - Tree-level flavor violation

The Bulk RS Picture



Models of EWSB *and* Flavor

- EWPC: T OK, but $S \simeq N/\pi$ at tree-level

$$M_{KK} \gtrsim (2-3)\ \mathrm{TeV}$$

- $Z \to \bar{b}b$ require discrete symmetry ($L \leftrightarrow R$) (Agashe, Contino, Da Rold, Pomarol)
- Potentially important bounds and/or effects from flavor violation

Dynamical Origin of the Higgs Sector

What localizes the Higgs to/near the IR/TeV brane ?

- Gauge-Higgs Unification
- Zero-mode Fermion Condensation
- Higgsless

Gauge-Higgs Unification in AdS$_5$

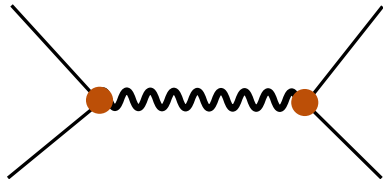
Extract H from a 5D gauge field

- $A^a_M \rightarrow (A^a_\mu, A^a_5)$
- Bulk Gauge group:
  - $G_{\rm bulk} \supset G_{\rm SM}$
  - Needs to include custodial symmetry.
- Minimal model (Agashe, Contino, Pomarol):
  $SO(5) \times U(1) \longrightarrow SO(4) \times U(1)$ by BCs
- Higgs is **4** of $SO(4)$: 4 d.o.f. $\leftrightarrow$ complex $SU(2)_L$ doublet
- H localized near TeV brane.
  m_h protected by bulk gauge symmetry (H pseudo-NGB)

Fermion Condensation

Fourth-Generation Condensation in AdS_5 (G.B. Da Rold)

- Fourth Generation in the AdS_5 bulk
- Choose zero-mode fermions IR localized $\Rightarrow$ strongly coupled to KK gauge bosons



E.g. KK gluon exchange $\longrightarrow \langle \bar{U} U \rangle \neq 0$

- EWSB
- $m_U^{(0)} \sim (600 - 700)$ GeV (ala Bardeen-Hill-Lindner)
- Heavy Higgs: $m_h \simeq (600 - 900)$ GeV

Fermion Condensation (cont.)

- All other fermion masses: Bulk higher dimensional operators

$$\frac{C^{ijk\ell}}{M_P^3}\,\bar{\Psi}_L^i(x,y)\Psi_R^j(x,y)\bar{\Psi}_R^k(x,y)\Psi_L^\ell(x,y)$$

- Phenomenology dominated by 4th generation
  - $V^{(1)} \to \bar{U}U$ (broader KK gauge bosons)
  - Flavor physics: E.g. new sources of CPV in mixing, ...
  - Additional contributions to S, T

Higgsless Models

Higgsless RS Bulk Models (Csaki, Grojean, Murayama, Pilo, Terning)

- Boundary Condition breaking
$$SU(2)_L \times SU(2)_R \times U(1)_X \rightarrow U(1)_{EM}$$
- IR localized mass terms $\Rightarrow$ fermion masses
- Kaluza-Klein modes of gauge fields unitarize amplitudes.
$\Rightarrow$ KK modes "light": $M_{KK} \lesssim$ 1 TeV
- Phenomenology in the Gauge boson sector:
  - $V_L V_L$ scattering
  - Sum Rules
- Corresponds to Walking Technicolor Models

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- If LHC reveals Strongly Coupled TeV scale
  $\Rightarrow$ Model Building in AdS_5 should be a useful tool