Strongly Coupled Theories of the Electroweak Scale

Gustavo Burdman

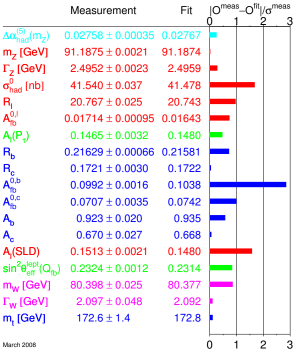
University of São Paulo

EWSB&LHC@IPhT, Saclay, October 27-29 2008

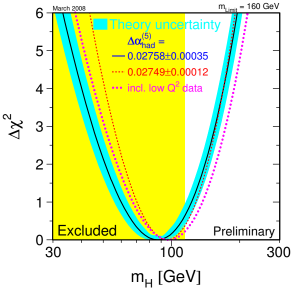
Outline

The great success of the SM

The Standard Model success



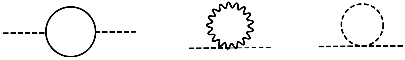
The SM Higgs is light



$m_h < 190$ 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 $\Lambda \to M_P \sim 10^{19}\ GeV$, 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

- SM with a light Higgs
- SUSY (MSSM, NMSSM, Folded, ...)
- Little Higgs, Twin Higgs
- LED, UED

Strongly Coupled

- Technicolor, Walking Technicolor
- Topcolor, Top See Saw
- Composite Higgs
- Randall-Sundrum

Spontaneous Chiral Symmetry Breaking in QCD

E.g. 2 flavors

$$\mathcal{L}_{\rm QCD} = \bar{Q}_L\, i\, \not{D} Q_L + \bar{Q}_R\, i\, \not{D} Q_R - \bar{Q}_L\, M\, Q_R + \text{h.c.}$$

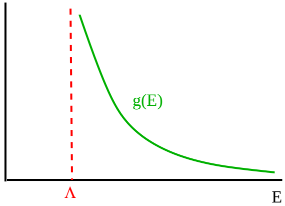
with

$$Q = \begin{pmatrix} u \\ d \end{pmatrix} \qquad\qquad M = \begin{pmatrix} m_u & 0 \\ 0 & m_d \end{pmatrix}$$

If $M = 0$, invariant under $SU(2)_L \times SU(2)_R$

$$\begin{aligned} Q_L &\longrightarrow e^{i\ell^a t^a}\, Q_L \\ Q_R &\longrightarrow e^{i r^a t^a}\, Q_R \end{aligned}$$

Spontaneous Chiral Symmetry Breaking in QCD



At low energies, $\Lambda \sim \Lambda_{\mathrm{QCD}}$, quark condensation

$$\langle \bar{Q}_L Q_R \rangle \neq 0$$

$$\Rightarrow SU(2)_L \times SU(2)_R \longrightarrow SU(2)_V$$

Spontaneous Chiral Symmetry Breaking in QCD

- Dynamical quark mass: $m_Q \simeq \Lambda_{\mathrm{QCD}}$
- 3 Broken generators $\Rightarrow$ 3 NGBs: (π^+, π^0, π^-)

Since $SU(2)_L \times SU(2)_R = SU(2)_V \times SU(2)_A \longrightarrow SU(2)_V$
Axial current does not annihilate vacuum

$$j_\mu^{5a} = \bar{Q}\gamma_\mu\gamma^5 Q$$

defines

$$\langle 0|j_\mu^{5a}|\pi^b(p_\mu)\rangle = i f_\pi \, p_\mu \delta_{ab}$$

But still conserved if $m_\pi = 0$.

Spontaneous Chiral Symmetry Breaking in QCD

Scaling:

- $\langle \bar{Q} Q \rangle \sim N_c \, \Lambda^3_{\rm QCD}$
- $f_\pi \sim \sqrt{N_c} \, \Lambda_{\rm QCD}$

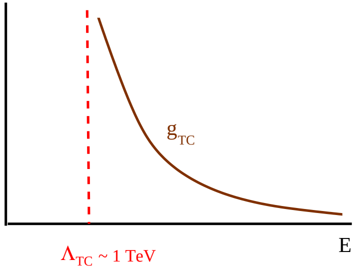
Explicit Symmetry Breaking:

- $M \neq 0 \;\; \Rightarrow m_\pi \neq 0$
- $\partial^\mu j^{5a}_\mu = f_\pi m^2_\pi$

Strong Dynamics at the TeV Scale

Analogy with QCD:

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



Basic Technicolor Model

Assume

- Assymptotically-free new interaction: $SU(N_T)$
- New fermions: $SU(2)_L$ doublet of techni-fermions

$$Q_L = \begin{pmatrix} T \\ B \end{pmatrix}_L \qquad (N_T, 1, 2, Y_Q)$$
$$T_R \qquad (N_T, 1, 1, Y_T)$$
$$B_R \qquad (N_T, 1, 1, Y_B)$$

- At Λ_{TC} we have $\langle \bar{Q}_L Q_R \rangle \neq 0 \qquad \Rightarrow$
    - Spontaneous breaking of global $SU(2)_L \times SU(2)_R$
    - But also SB of gauge symmetry $SU(2)_L \times U(1)_Y$

Basic Technicolor Model

Higgs Mechanism: $SU(2)_L \times SU(2)_R \longrightarrow SU(2)_V$

3 massless Nambu-Goldstone bosons

$$U = e^{i\pi^a\sigma^a/F_T} \qquad\qquad U \longrightarrow L\,U\,R^\dagger$$

and

$$\frac{F_T}{4}\,\mathrm{Tr}\left[(D_\mu U)^\dagger\, D^\mu\right] \longrightarrow \qquad \frac{gF_T}{2}\,W_\mu^+\partial^\mu\pi^- + \frac{gF_T}{2}\,W_\mu^-\partial^\mu\pi^+ + \frac{F_T}{2}\,\left(gW_\mu^3 + g'B_\mu\right)\partial^\mu\pi^0$$

with

$$\langle 0|j_\mu^{5a}|\pi^b\rangle = iF_T\,p_\mu\delta_{ab}$$

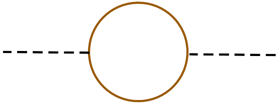
Technicolor Model – Gauge Boson Masses

NGBs eaten as gauge boson's longitudinal polarizations

$$\Rightarrow \qquad i\frac{g^2\,F_T^2}{4}\left(g_{\mu\nu} - \frac{q_\mu q_\nu}{q^2}\right)$$

Technicolor Model – Scales

From Pagels-Stokar formula (or Nambu–Jona-Lasinio model)

$F_T^2 \quad \hat{\simeq}$  $\hat{\simeq} \quad N_T$

More generally, if N_D doublets

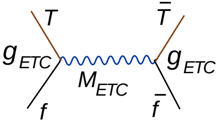
$$v = \sqrt{N_D}\, F_T = f_\pi \sqrt{\frac{N_T\, N_D}{N_c}}\, \frac{\Lambda_{\rm TC}}{\Lambda_{\rm QCD}}$$

E.g. for $N_D = 1$, $N_T = 3 \Rightarrow \Lambda_{\rm TC} \simeq 800$ GeV

Fermion Masses – Extended Technicolor

Need to enlarge TC $\longrightarrow$ Extended Technicolor (ETC)

- $G_{\rm ETC} \supset G_{\rm TC}$
- ETC interactions involve fermions and techni-fermions
- ETC broken at $\Lambda_{\rm ETC} \gg \Lambda_{\rm TC}$



- Fermion masses from

$$-\frac{g_{\rm ETC}^2}{M_{\rm ETC}^2}\,\bar{f}f\,\bar{T}T \qquad \Rightarrow \qquad m_f \sim \frac{g_{\rm ETC}^2}{M_{\rm ETC}^2}\,\Lambda_{\rm TC}^3$$

ETC Requires more realistic ETC Models

E.g. Farhi-Susskind:
Need $SU(3)_c$ color-triplet and color signlet techni-fermions

$$\begin{pmatrix} T^i \\ B^i \end{pmatrix}_L \qquad (N_T, 3, 2, y)$$

$$\begin{pmatrix} N \\ E \end{pmatrix}_L \qquad (N_T, 1, 2, -3y)$$

$$T^i_R \qquad (N_T, 3, 1, y+1)$$

$$B^i_R \qquad (N_T, 3, 1, y-1)$$

$$N_R \qquad (N_T, 1, 1, -3y+1)$$

$$E_R \qquad (N_T, 1, 1, -3y-1)$$

ETC Requires more realistic TC Models

- Condensates: $\langle \bar{T}^i_L T^i_R \rangle = \langle \bar{B}^i_L B^i_R \rangle = \langle \bar{N}_L N_R \rangle = \langle \bar{E}_L E_R \rangle \sim \Lambda^3_{\rm TC}$
- $\Rightarrow v^2 = 4\, F_T^2$
- Chiral Symmetry is now $SU(8)_L \times SU(8)_R$
  (gauge couplings $\longrightarrow 0$
- $\Rightarrow$ 63 - 3 = 60 NGB's in the spectrum !

Back to ETC

ETC gauge boson exchange leads to

- Four technifermion operators

$$\frac{\alpha_{ab}}{\Lambda^2_{\rm ETC}} \left(\bar{T}\gamma_\mu \hat{t}^a T\right)\left(\bar{T}\gamma^\mu \hat{t}^b T\right) \qquad \Rightarrow \qquad M_{\tilde{\pi}}$$

- Mixed four-fermion operators

$$\frac{\beta_{ab}}{\Lambda^2_{\rm ETC}} \left(\bar{T}\gamma_\mu \hat{t}^a f\right)\left(\bar{f}\gamma^\mu \hat{t}^b T\right) \qquad \Rightarrow \qquad m_f$$

- Four-fermion operators

$$\frac{\gamma_{ab}}{\Lambda^2_{\rm ETC}} \left(\bar{f}\gamma_\mu \hat{t}^a f\right)\left(\bar{f}\gamma^\mu \hat{t}^b f\right) \qquad \Rightarrow \qquad \mathrm{FCNCs}$$

Bounds from FCNCs in ETC Models

From γ terms

$$\frac{\gamma}{\Lambda^2_{\rm ETC}}(\bar{s}\gamma^5 d)(\bar{s}\gamma^5 d) \quad \Rightarrow \quad \text{Contributes to } K^0 - \bar{K}^0 \text{ mixing}$$

Even with $\gamma \sim \sin\theta_c \sim 10^{-2}$, the bound is $\Lambda_{\rm ETC} > 1000$ TeV

OK for light fermions. But for $m_c \simeq 1$ GeV, we need

$$m_f \sim \beta\, N_T \frac{\Lambda^3_{\rm TC}}{\Lambda^2_{\rm ETC}}$$

If $\beta \sim O(1)$ and $\Lambda_{\rm TC} \sim O(1)$ TeV $\Rightarrow \Lambda_{\rm ETC} \sim 30$ TeV

Solutions to TC/ETC Flavor Problem

- Techni-GIM Models:
  - Assume ETC gauge are degenerate $\Rightarrow$ GIM
  - One ETC gauge group per hypercharge ETC_L, ETC_U, ETC_D.
  - Fermion masses come from small breakings of large global symmetry
- Walking TC:
  Near conformal behavior of TC between ETC and TC scales, enhances $\langle \bar{F}_L F_R \rangle$

Walking Technicolor

Fermion masses from ETC

$$m_f \sim \beta\, N_T \frac{\langle \bar{F} F \rangle}{\Lambda^2_{\rm ETC}}$$

Need to keep $\Lambda_{\rm ETC}$ high, but enhance m_f. How? Enhance $\langle \bar{F} F \rangle$

- Running effects between $\Lambda_{\rm TC}$ and $\Lambda_{\rm ETC}$

$$\langle \bar{F} F \rangle_{ETC} = \left(e^{\int_{\Lambda_{\rm TC}}^{\Lambda_{\rm ETC}} \frac{d\mu}{\mu}\, \gamma(\mu)} \right) \langle \bar{F} F \rangle_{TC}$$

with anomalous dimension $\gamma(\mu) = \gamma(\alpha(\mu))$.

Walking Technicolor

If TC is QCD-like:

$$\gamma(\mu) \sim \alpha(\mu) \sim \frac{c}{\ln \mu} \quad \text{and} \quad c \lesssim O(1)$$

which gives

$$\langle \bar{F} F \rangle_{ETC} \simeq \left[\ln \left(\frac{\Lambda_{\rm ETC}}{\Lambda_{\rm TC}} \right) \right]^{c} \langle \bar{F} F \rangle_{TC}$$

Walking Technicolor

But if TC is close to a conformal fixed point with

$$\alpha(\mu) \sim \alpha^* = \text{constant}$$

then $\gamma(\mu)$ is constant and the enhancement is

$$\langle \bar{F} F \rangle_{ETC} \simeq \left(\frac{\Lambda_{\rm ETC}}{\Lambda_{\rm TC}} \right)^{\gamma} \langle \bar{F} F \rangle_{TC}$$

Enhances m_f keeping $\Lambda_{\rm ETC}$ high. E.g. for $\gamma \sim 1$

$$m_f \simeq \beta \, N_T \frac{\Lambda_{\rm TC}^2}{\Lambda_{\rm ETC}}$$

$\Rightarrow O(1)$ GeV masses are OK. But top quark too heavy for WTC

Top Condensation – Topcolor

- Top Condesation: New interaction leads to

$$\langle \bar{t}t \rangle \neq 0$$

  Breaks EW symmetry, gives dynamica mass to top
- But, to get m_t right $\Lambda \sim 10^{15}$ GeV
  Or if $\Lambda \sim 1$ TeV $\Rightarrow m_t \simeq 600$ GeV
- Topcolor-assisted Technicolor:
  - TC breaks (most of) EW symmetry
  - ETC gives masses up to $O(1)$ GeV
  - Topcolor interaction $\Rightarrow \langle \bar{t}t \rangle \neq 0$, responsible for m_t.

Top Condensation – Topcolor

- Top See-saw:
  - Topcolor + Singlet fermion without TC
  - χ_L and χ_R have quantum numbers of t_R

$$(\bar{t}_L \bar{\chi}_L) \begin{pmatrix} m_{tt} & m_{t\chi} \\ m_{\chi t} & m_{\chi\chi} \end{pmatrix} \begin{pmatrix} t_R \\ \chi_R \end{pmatrix}$$

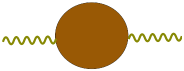
  - m_{tt} and $m_{t\chi}$ dynamically generated via condensates $m_{t\chi} \sim 600$ GeV. The seesaw results in

$$m_t \simeq \frac{m_{t\chi}\, m_{\chi t}}{m_{\chi\chi}}$$

OK if $m_{\chi t}/m_{\chi\chi} \lesssim 0.3$

TC and Precision Bounds

Electroweak Precision Constraints



- E.g. Techni-fermions give

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

- But

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

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

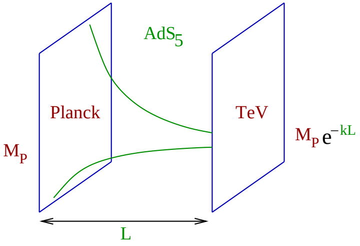
Ingredients to build Strongly Coupled Theories in AdS_5

- 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 ⇒ 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

Natural EWSB

If the Higgs is localized at (or near) the TeV brane ($y = \pi R$)

$$S_H = \int d^4x \int_0^{\pi R} dy \sqrt{-g}\, \delta(y - \pi R) \left[g_{\mu\nu} \partial^\mu H^\dagger \partial^\nu H - \lambda \left(|H|^2 - v_0^2 \right)^2 \right]$$

Even if $v_0 \simeq M_{\rm Planck}$, the v.e.v. (and mass) of the physical Higgs is

$$v = e^{-k\pi R} v_0$$

To solve the hierarchy problem need Higgs 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

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

Flavor in Warped Extra Dimensions

- Fermion *bulk mass* $\Rightarrow$ zero-mode localization:

$$M_f = c\, k, \qquad c \sim O(1)$$

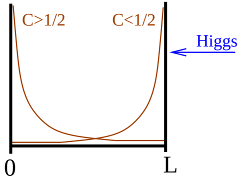
- The zero-mode fermion wave-function is

$$F^L_{\rm ZM}(y) = \frac{1}{\sqrt{2\pi R}}\, f^L_0(0) e^{\left(\frac{1}{2} - c_L\right) ky}$$

- If $c_L > 1/2 \Rightarrow$ fermion localized near $y = 0$, Planck brane.
  If $c_L < 1/2 \Rightarrow$ fermion localized near $y = \pi R$, TeV brane.

Fermion Masses in Bulk RS Models

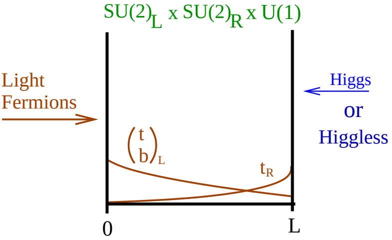
- $O(1)$ flavor breaking in bulk can generate fermion mass hierarchy:



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

EWSB from Fourth-Generation in AdS_5

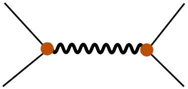
Top-condensation models (Nambu; Bardeen, Hill, Lindner):
EWS broken by $\langle \bar{t}t \rangle \neq 0$

- Top quark is too light: $m_t \sim 600$ GeV if $\Lambda \sim O(1)$ TeV. Or $\Lambda \sim 10^{15}$ GeV if $m_t \sim 200$ GeV.
- $\Rightarrow$ Heavy fourth generation $M_4 \sim 600$ GeV.
- Problems:
  - All of 4th Gen must condense, but What's the underlying interaction ?
  - Fermion masses ?

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



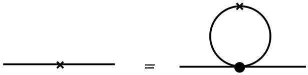
E.g. KK gluon exchange $\longrightarrow \langle \bar{U} U \rangle \neq 0$

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

EWSB from Fourth-Generation in AdS$_5$

If $g_U > g_U^{\rm crit.}, \Rightarrow \langle \bar{U}_L U_R \rangle \neq 0$

$\Rightarrow$ Solution to the gap equation:



This implies

- Electroweak Symmetry Breaking
- Dynamical m_U

We can also write an effective theory at low energy for the Higgs.

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

Higgsless EWSB in AdS$_5$

Break EWS by Boundary Conditions (Csaki,Grojean,Pilo,Terning)

- BCs on branes $\Rightarrow SU(2)_L \times SU(2)_R \times U(1)_X \rightarrow U(1)_{\rm EM}$
  - TeV brane: $SU(2)_L \times SU(2)_R \rightarrow SU(2)_V$: Preserves custodial symmetry.
  - Planck brane: $SU(2)_R \times U(1)_X \rightarrow U(1)_Y$: Allows fermion mass terms on TeV brane.
- Z and W are KK modes. $\rho \sim 1$
- Fermion masses:
  - vector-like mass terms on TeV brane.
  - Isospin symmetry broken on Planck brane.
  - E.g.: top quark is TeV-brane localized $\Rightarrow$ larger mass (larger overlap with chiral-symmetry breaking).

Higgsless EWSB in AdS_5

EWPC:

- S parameter is large
- S can be made small by de-localizing fermions
- $Z \to b_L \bar{b}_L$ requires protective symmetry.
  Still, deviates some from data

Higgsless EWSB in AdS$_5$

Signals:

- Unitarization of $WW, WZ, \ldots$ scattering done by KK resonances
- Couplings of $V^{(n)}$'s to $W^{\pm}$ and Z must satisfy sum rules (to cancel E^2, E^4 behavior). E.g. for $WW \to WW$:

$$\begin{aligned} g_{WWWW} &= g_{WWZ}^2 + g_{WW\gamma}^2 + \sum_n (g_{WWV^{(n)}})^2 \\ &= \frac{3}{4M_W^2}\left[{g_{WWZ}}^2 M_Z^2 + \sum_n (g_{WWV^{(n)}})^2 M_n^2 \right] \end{aligned}$$

- KK gauge bosons $\Rightarrow$ narrow resonances, lighter ($M_{V^{(1)}} \lesssim 1$ TeV) than in Techni-color or other strongly coupled models.

Summary/Outlook

Summary/Outlook

- TeV Scale could be a window to new strong interactions

Summary/Outlook

- TeV Scale could be a window to new strong interactions
- Weakly coupled theories in AdS_5 map to
  Strongly Coupled 4D Dynamics

Summary/Outlook

- TeV Scale could be a window to new strong interactions
- Weakly coupled theories in AdS_5 map to Strongly Coupled 4D Dynamics
- RS Bulk Models: EWSB *and* Flavor

Summary/Outlook

- TeV Scale could be a window to new strong interactions
- Weakly coupled theories in AdS_5 map to Strongly Coupled 4D Dynamics
- RS Bulk Models: EWSB *and* Flavor
- Resonant spectrum $\simeq$ few TeV

Summary/Outlook

- TeV Scale could be a window to new strong interactions
- Weakly coupled theories in AdS_5 map to Strongly Coupled 4D Dynamics
- RS Bulk Models: EWSB *and* Flavor
- Resonant spectrum $\simeq$ few TeV
- Couplings to KK gauge bosons to fermions reveal flavor theory

Summary/Outlook

- TeV Scale could be a window to new strong interactions
- Weakly coupled theories in AdS_5 map to Strongly Coupled 4D Dynamics
- RS Bulk Models: EWSB *and* Flavor
- Resonant spectrum $\simeq$ few TeV
- Couplings to KK gauge bosons to fermions reveal flavor theory
- Models and Signals defined by mechanism of Higgs localization, flavor

Summary/Outlook

- TeV Scale could be a window to new strong interactions
- Weakly coupled theories in AdS_5 map to
  Strongly Coupled 4D Dynamics
- RS Bulk Models: EWSB *and* Flavor
- Resonant spectrum $\simeq$ few TeV
- Couplings to KK gauge bosons to fermions reveal flavor theory
- Models and Signals defined by mechanism of
  Higgs localization, flavor
- If LHC reveals Strongly Coupled TeV scale
  $\Rightarrow$ Model Building in AdS_5 should be a useful tool