Mariano Quirós

Institute of High Energy Physics (IFAE)

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The simplest and perhaps more elegant solution to the naturalness problem is provided by SUPERSYMMETRY. Howie Baer, Tianjin Li,… talks @ this conference.

It provides a technical solution to the hierarchy problem: TeV scale is not sensitive to UV physics.

The pros of SUSY are well known by this audience,… but of course there are also some cons:

1. SUSY does not explain why $\text{TeV} \ll M_{Pl}$
2. Not clear mechanism of SUSY BREAKING
3. Not clear solution to the $\mu$ problem
Contents

- A (well known) alternative to SUSY: warped extra dimension
- First order phase transitions: confinement/deconfinement, electroweak
- Gravitational wave signatures
- Collider phenomenology
- Gapped continuum KK modes
- Conclusions
An alternative to SUSY

- Proposed in 1999 by Randall and Sundrum (RS)
  - It was based on a 5D space with line element
    \[ ds^2 = e^{-2A} \eta_{\mu\nu} dx^\mu dx^\nu - dy^2, \quad A = ky \]
    \[ TeV = e^{-ky_1} M_{Pl}, \quad ky_1 \sim 35 \]
    \[ AdS \leftrightarrow CFT \quad correspondence \]
    \[ h(y) \propto e^{aky}, \quad a > 2 \]
- The Higgs is mainly localized on the IR brane (composite):
- Heavy (light) fermions are mainly localized on the IR (UV) brane: composite (elementary)
- Zero mode gauge bosons are flat
- KK modes are mainly localized on the IR brane (composite)
• In RS model the brane distance has to be stabilized by a bulk field $\phi$ breaking conformal invariance with bulk and brane potentials fixing its VEVs

\[
\phi_\alpha^T = s_{2W} c_K^2 k y_1 \frac{(a - 1)^2}{a(2a - 1)} \frac{m_Z^2}{m_{KK}^2}
\]

\[
\alpha T = s_{2W} c_K^2 k y_1 a(2a - 1) \frac{m_Z^2}{m_{KK}^2}
\]

\[
\alpha S = 2 s_{2W} c_W^2 c_K^2 a^2 - 1 \frac{m_Z^2}{m_{KK}^2}
\]

\[
c_{KK} = \frac{m_{KK}}{k} e^{ky_1}, \quad ky_1 \approx 35
\]

W. Goldberger, M. Wise, 9907218

• It then appears a “light state”: the radion/dilaton with interesting Higgs-like phenomenology

• The RS model has problems when confronting the electroweak precision measurements, e.g. oblique observables
Using the RPP fit for the $S$ and $T$ parameters

\[
S = 0.02 \pm 0.07 \quad T = 0.06 \pm 0.06 \quad r \simeq 0.92
\]

$9 \text{ TeV} \leq m_{KK} \leq 15 \text{ TeV}, a \to \infty$

$5 \text{ TeV} \leq m_{KK} \leq 10 \text{ TeV}, a = 2$

Leads to

\[
m_{KK} \gtrsim 10 \text{ TeV}
\]

- Creates a little hierarchy problem
- Too heavy for detection at LHC
WAY OUT 1: CUSTODIAL MODELS

• Promote the custodial symmetry to gauge symmetry in the bulk broken by orbifold boundary conditions

• The simplest one is:

\[ SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L} \]

\[ G \rightarrow H_{UV}(H_{IR}) \]

G. Senjanovic talk @ this conference

\[ W_L^{1,2,3} = (N, N) \]
\[ W_R^{1,2} = (D, N) \]

\[ Z = \frac{1}{\sqrt{g_R^2 + g_X^2}} [g_R W_R^3 - g_X \mathcal{X}] = (D, N) \]

\[ B = \frac{1}{\sqrt{g_R^2 + g_X^2}} [g_R W_R^3 + g_X \mathcal{X}] = (N, N) \]

K. Agashe et al., 0308036

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\[ Higgs = \text{PNGB} \]

R. Contino et al., 0306259

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B. Batell talk @ this conference Friday 14:30

<table>
<thead>
<tr>
<th>Model</th>
<th># PGB (A_5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SO(4)/SO(3)</td>
<td>6-3=3 (Higgsless SM)</td>
</tr>
<tr>
<td>SU(3)/SU(2)×U(1)</td>
<td>8-4=4 (H_{SM})</td>
</tr>
<tr>
<td>SO(5)/SO(4)</td>
<td>10-6=4 (H_{SM})</td>
</tr>
<tr>
<td>SO(6)/SO(5)</td>
<td>15-10=5 (H_{SM} + singlet)</td>
</tr>
<tr>
<td>SO(6)/SO(4)×SO(2)</td>
<td>15-6-1=8 (H_u, H_d)</td>
</tr>
</tbody>
</table>
WAY OUT 2: NON-CUSTODIAL MODELS

• Another possibility is to have large back reaction on the metric such as to create a singularity

• Typical example is the metric

\[ A(y) = ky - \frac{1}{\nu^2} \log(1 - y/y_s) \]

• Which is AdS on the UV: \( y = 0 \)

• Strong departure from conformality on the IR: \( y = y_s \)

• Singularity admissible as it supports finite temperature in the form of a black-hole horizon

\[ J. \ Cabrer \ et \ al., \ 1103.1388 \]
\[ S. \ Gubser, \ 0002160 \]
• The improvement in EWPD comes from the fact that the Higgs profile in flat coordinates is \( f_{hA}^{(0)}(y) \propto e^{-A}h(y) \to 0, \ (y \to y_s) \)

• Then the Higgs profile has a maximum away from the IR brane

![Graph showing Higgs profile](image)

**A. Carmona et al., 1107.1500**

**J. Cabrer et al., 1103.1388**

\[ \nu = 0.55, \ m_{KK} \leq 3 \ TeV, \ \Delta m_{KK} = 0.5 \ TeV \]

\[ \nu = 5, \ m_{KK} \leq 12 \ TeV, \ \Delta m_{KK} = 1 \ TeV \]
First order phase transitions

- In this theories there is the confinement/deconfinement phase transition \( P. \text{Creminelli et al., 0107141} \)

- We have to introduce the notion of effective potential as a function of the radion field \( E. \text{Megias et al., 1806.04877} \)

\[
\begin{align*}
    ds^2 &= - [1 + 2F(x,y)]^2 dy^2 + e^{-2[A+F(x,y)]} \eta_{\mu\nu} dx^\mu dx^\nu, \quad F(x,y) = F(y)r_1(x)
\end{align*}
\]

**Units of k**

\[
\begin{align*}
    r_1(x) &\rightarrow \mu(x)
\end{align*}
\]
• At finite temperature the system allows for an additional gravitational solution with a black hole (BH) singularity located in the bulk

\[ ds_{BH}^2 = -\frac{1}{h(y)}dy^2 + e^{-2A(y)}(h(y)dt^2 - d\vec{x}^2) \]

*blackening factor* \( h(y_h) = 0 \)

• In the AdS/CFT correspondence this BH metric describes the high temperature phase of the system where the radion is sent to its symmetric phase

• The phase transition starts when the free energy of the BH deconfined phase equals the free energy of the confined phase

\[ F_d(T) = E_0 + F_{\text{min}} - \frac{\pi^2}{90} g_d^{\text{eff}} T^4 \]

\[ F_c(T) = -\frac{\pi^2}{90} g_c^{\text{eff}} T^4 \]

Potential depth \( \text{all fields} \) \hspace{2cm} \text{Depth in the BH phase} \hspace{2cm} \text{all fields except IR ones}
Deconfinement/confinement phase transition

\[ F_{\text{min}} = -\frac{\pi^2}{8} a_h(T) N^2 T^4, \quad a_h \approx 0.15 \text{ (back reaction effect)} \]

Potential depth

Depth in the BH phase

P. Creminelli et al., 0107141
$S_4$ and $S_3/T$

$O(4)$ bounce  $O(3)$ bounce

$T_n$ (tunneling temperature)

E. Megias et al., 1806.04877
• When the radion phase transition happens the nucleation temperature is smaller than the VEV: then $\langle \mu \rangle / T_n \gg 1$ and the phase transition is very strong first order

• The cooling triggers a brief period of cosmological inflation with few e-folds of inflation

• During the phase transition the energy density is approximately conserved

• The universe ends up in the confined phase at the reheat temperature $T_R > T_n$

• In most cases (but not always) the reheat temperature is around the TeV
The electroweak phase transition

- The confinement/deconfinement phase transition is tightly connected to the electroweak phase transition

- This is the case e.g. when the Higgs, radion and right-handed top are localized toward the IR brane (only exist in the confined phase)

- In this case the nucleation temperature of the radion phase transition is essentially unaffected by the SM degrees of freedom

- When the BH horizon moves beyond the IR brane during the radion phase transition the Higgs potential appears as

$$V(\mu, \mathcal{H}) = V_{\text{eff}}(\mu) + \left( \frac{\mu}{\langle \mu \rangle} \right)^4 V_{\text{SM}}(\mathcal{H}, T)$$
• The minimum of the SM Higgs potential is at

\[ v(T) = v \sqrt{1 - T^2/T_{EW}^2}, \quad T_{EW} \simeq m_{\phi}/\left(m_W^2/v^2 + m_Z^2/2v^2 + m_t^2/v^2\right)^{1/2} \simeq 150 \, \text{GeV} \]

• Depending on the relationship between the tunneling and reheat temperatures, and the EW temperature the EWBG scenario will be different.

• Two cases: \( T_R > T_{EW} \) and \( T_R < T_{EW} \)

• Of course one or another case depends on the choice of the model parameters
Sequential phase transitions

\[ T_R > T_{EW} \]

- Generic prediction in most models
- Even if \( T_n < T_{EW} \) the reheat temperature can be large
- Electroweak symmetry is restored after reheating
- Electroweak baryogenesis should proceed as in the SM case

Simultaneous phase transitions

\[ T_R < T_{EW} \]

- The reheating does not restore EW symmetry and the Higgs lies at the minimum of the potential \( V(\mathcal{H}, T_R) \)
- The EW phase transition is strong enough if \( T_R < T_\mathcal{H} \simeq 140 \text{ GeV} \)
- In the window \( T_\mathcal{H} < T_R < T_{EW} \) the EWPT is too weak for EWBG

G. Nardini et al., 0706.3388

- If \( T_R < T_\mathcal{H} \) EWPT is strong enough for EWBG
Gravitational waves

A cosmological first order phase transition generates a stochastic gravitational wave background (SGWB)

The power spectrum depends on phase transition quantities

\[ \alpha \simeq \frac{E_0}{3(\pi^2 N^2/8) a_h(T_n) T_n^4} \quad \frac{\beta}{H_*} \simeq T_n \left. \frac{dS_E}{dT} \right|_{T=T_n} \]

In the next two decades several GW observatories will have the potential to observe, or constrain, the SGWB produced in our benchmark models
Benchmark points in our model
Collider phenomenology

- The lightest BSM state is the radion

- Radion couples to the SM fields $X$ as the Higgs with a reduction coefficient which is model dependent

$$\mathcal{L}_R^{XX} = c_X \mathcal{L}_{HXX}, \quad X = \gamma, g, f, Z, W, H$$

- The coefficients are model dependent and less than 1

<table>
<thead>
<tr>
<th>Scen.</th>
<th>$m_{rad}$/TeV</th>
<th>$m_G$/TeV</th>
<th>$c_\gamma$</th>
<th>$c_g$</th>
<th>$c_V$</th>
<th>$c_H$</th>
<th>$c_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B2</td>
<td>0.915</td>
<td>4.80</td>
<td>0.472</td>
<td>0.164</td>
<td>0.0649</td>
<td>0.259</td>
<td>0.259</td>
</tr>
<tr>
<td>B8</td>
<td>0.745</td>
<td>4.19</td>
<td>0.542</td>
<td>0.146</td>
<td>0.0744</td>
<td>0.298</td>
<td>0.298</td>
</tr>
<tr>
<td>C1</td>
<td>0.890</td>
<td>3.08</td>
<td>0.532</td>
<td>0.179</td>
<td>0.0904</td>
<td>0.362</td>
<td>0.362</td>
</tr>
<tr>
<td>C2</td>
<td>0.751</td>
<td>2.77</td>
<td>0.595</td>
<td>0.162</td>
<td>0.101</td>
<td>0.404</td>
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<tr>
<td>D1</td>
<td>0.477</td>
<td>4.50</td>
<td>3.791</td>
<td>0.475</td>
<td>0.397</td>
<td>1.586</td>
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<tr>
<td>E1</td>
<td>0.643</td>
<td>4.16</td>
<td>0.562</td>
<td>0.124</td>
<td>0.0746</td>
<td>0.298</td>
<td>0.298</td>
</tr>
</tbody>
</table>
• The radion is a heavy narrow weakly coupled resonance

<table>
<thead>
<tr>
<th>Scen.</th>
<th>$\Gamma_{R\rightarrow WW}$</th>
<th>$\Gamma_{R\rightarrow ZZ}$</th>
<th>$\Gamma_{R\rightarrow hh}$</th>
<th>$\Gamma_{R\rightarrow t\bar{t}}$</th>
<th>$\Gamma_{R\rightarrow b\bar{b}}$</th>
<th>$\Gamma_{R\rightarrow \tau\bar{\tau}}$</th>
<th>$\Gamma_{R\rightarrow \gamma\gamma}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B_2</td>
<td>1220</td>
<td>610</td>
<td>5.70</td>
<td>2670</td>
<td>0.825</td>
<td>0.129</td>
<td>0.0385</td>
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<tr>
<td>B_8</td>
<td>786</td>
<td>389</td>
<td>9.01</td>
<td>2680</td>
<td>0.917</td>
<td>0.138</td>
<td>0.0143</td>
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<tr>
<td>D_1</td>
<td>4960</td>
<td>2350</td>
<td>362</td>
<td>28000</td>
<td>17.73</td>
<td>2.49</td>
<td>0.378</td>
</tr>
</tbody>
</table>

all widths are in MeV

• Mainly coupled to W and Z gauge bosons and top quark

• The heavy radion phenomenology is very model dependent and it is in general easy to avoid the present bounds as we have found in our benchmark points

• Still the bounds on KK modes start to be very demanding
Bounds from ATLAS & CMS start to be very strong

\[ g_{gKKqq} = -0.2g_s, \quad g_{gKKtLtL} = g_s, \quad \Gamma_{gKK} = 30\% \]
Gapped continuum KK modes

- Experimental searches normally assume that new particles are isolated (narrow) resonances that can be produced on-shell.

- A possible “explanation” for elusiveness: KK states are a TeV gapped continuum of states instead of isolated particles. A theory in that direction is the clockwork mechanism, or its 5D version, where TeV is the fundamental scale, and Planck is a derived scale. The KK modes have a TeV mass gap and a (quasi continuum) spacing of 30 GeV. 

  - C. Csaki et al., 1811.06019

- A theory in that direction is the clockwork mechanism, or its 5D version, where TeV is the fundamental scale, and Planck is a derived scale. The KK modes have a TeV mass gap and a (quasi continuum) spacing of 30 GeV.

  - G. Giudice et al., 1711.08437

- Similar to Linear Dilaton scenarios, dual to Little String theories

  - I. Antoniadis et al., 1102.4043

S. Chan Park talk @ this conference Friday 15:00
The class of models we have considered here share some properties:

$$A(y) = ky - \frac{1}{\nu^2} \log(1 - y/y_s)$$

1. They reproduce RS in the UV and therefore they can explain conventionally the hierarchy with a fundamental Planck scale and a warped TeV scale.

2. For $\nu > 1$ they yield discrete KK spectra with TeV spacing.

3. For $\nu < 1$ they yield ungapped continuum spectra similar to unparticles.

4. For $\nu = 1$ they yield gapped continuum spectra.

H. Georgi, 0703260

A. Falkowski et al., 0806.1737
J.A. Cabrer et al., 0907.5361
• Their Green functions generalize from *particle propagator* with isolated poles

\[
\frac{1}{p^2 - m^2 + i\epsilon} = \mathcal{P} \frac{1}{p^2 - m^2} + i \pi \delta(p^2 - m^2)
\]

• … to Green functions with an *isolated pole* (the zero mode) and a *continuum of states*, instead of a discrete sum of KK modes, with a mass gap \(m\)

\[
G_A(p^2, m^2) = Re G_A(p^2, m^2) + i Im G_A(p^2, m^2) \theta(p^2 - m^2)
\]

• This is the behavior of gapped unparticles where the gap was usually produced by EW breaking

• Here the gap is TeV, and is linked to the solution of the hierarchy problem
The continuum spectrum shows up in the spectral density function

\[ p \equiv \sqrt{s}, \quad \rho = \text{mass gap} \]

![Graphs showing spectral density functions for various particles](image_url)
Phenomenology of continuum KK modes

- The mass gap is different for different states

<table>
<thead>
<tr>
<th>field</th>
<th>gauge boson</th>
<th>fermion</th>
<th>graviton radion Higgs</th>
</tr>
</thead>
<tbody>
<tr>
<td>mass gap</td>
<td>$\frac{1}{2}\rho$</td>
<td>$</td>
<td>c_f</td>
</tr>
</tbody>
</table>

As for light fermions $c_f > 1/2$, the easiest produced continuum is for gauge bosons
• Normal searches at LHC are based on bumps in the invariant mass of final state

• However here, in production of fermions from DY processes via gluon KK continuum, there is just an increase in the cross section: \( \sigma(q\bar{q} \rightarrow g^* \rightarrow f\bar{f}), \quad p = \sqrt{s} \)

\[
\frac{\sigma}{\sigma_{SM}}(q\bar{q} \rightarrow f_{IR}\bar{f}_{IR}) \quad \text{Strong increase with energy}
\]

\[
\frac{\sigma}{\sigma_{SM}}(q\bar{q} \rightarrow f_{UV}\bar{f}_{UV}) \quad \text{Little increase with energy}
\]

Phenomenology in progress…
Conclusions

- Warped extra dimensions is an interesting alternative to solve the hierarchy problem (dual to CFT, ...)

- It triggers a confinement/deconfinement first order phase transition, and possibly a first order EW phase transition

- Gravitational waves are useful tools to detect the existence of first order phase transitions, and thus of new physics

- An exploring possibility to solve the elusiveness of signals at LHC is a continuum of KK states (related to CFT, unparticles, ..)