Single-sector gauge mediation, warped extra dimensions, and the Large Hadron Collider

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Warped extra dimension models: much studied over last few years. [Randall, Sundrum 99, ...]

Alternative to CMSSM, mSUGRA,....

AdS/CFT interpretation of these models: very attractive (but not exactly rigorous). [Arkani-Hamed, Porrati, Randall 00; Rattazzi, Zaffaroni 00]

Extra dim’l th’s are nonrenorm’ble ⇒ EFT.

Q’s: How to complete in UV? Give more rigor to AdS/CFT map? Model-bldg. insight from underlying th. (UT)?
Best candidate string/M-th.

AdS spacetime solns now exist. (warped string = flux background = $N_c$ D3’s backreaction)

They realize AdS/CFT (firm footing).

Our goal:
marry warped string constructions & warped phen’l models.
Nontrivial YM dynamics (="CFT") takes on a gravitational meaning (="AdS").

Everybody has heard about $AdS_5 \times S^5$.

A far more interesting example is the Klebanov-Strassler construction [00].

It is based on the Klebanov-Witten construction:

$$AdS_5 \times T^{1,1}.$$ 

KW dual gauge theory: $\mathcal{N} = 1$ SCFT.
Type IIB theory is formulated on:

4d Minkowski $\times$ conifold.

The conifold has a cone-like geometry, with $T^{1,1}$ base:
$T^{1,1}$ is a quotient manifold:

\[ T^{1,1} = [SU(2) \times SU(2)]/U(1) \]

The “1, 1” denotes the $U(1)$ quotient:

\[ H = (\sigma_3 \otimes 1) + (1 \otimes \sigma_3). \]
Warping spacetime

- $N_c$ D3’s at tip.
- Gravitating $\Rightarrow$ backreact on geometry, warp it.
- Geometry $\rightarrow AdS_5 \times T^{1,1}$. 
Warping spacetime

- $N_c$ D3’s at tip.
- Gravitating $\Rightarrow$ backreact on geometry, warp it.
- Geometry $\rightarrow AdS_5 \times T^{1,1}$. 

\[\text{BACKREACTION}\]

\[\text{WARPS}\]
Advantage of $T^{1,1}$

Comparison, $AdS_5 \times X_5$

<table>
<thead>
<tr>
<th>5d space $X_5$</th>
<th>$S^5$</th>
<th>$T^{1,1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Killing spinors</td>
<td>32</td>
<td>8</td>
</tr>
<tr>
<td>dual FT</td>
<td>$\mathcal{N} = 4$ SCFT</td>
<td>$\mathcal{N} = 1$ SCFT</td>
</tr>
</tbody>
</table>

Progress! ... Goal is softly broken $\mathcal{N} = 1$ SUSY.
There is a singularity at the tip of the conifold. In the dual gauge theory, this is reflected by the absence of an IR cutoff.
Klebanov-Strassler resolve the singularity with the deformed conifold.

They show that it is equivalent to confinement in the IR of the dual gauge theory.

\[
\varepsilon^{2/3}
\]
Conformal symmetry breaking

- On the gravity side of the duality, this breaks half the Killing spinors.
- On the gauge theory side, this breaks the fermionic conformal charges, reducing to $\mathcal{N} = 1$ SUSY gauge theory.
- Now we are “very close” to the real world.
- I.e., semi-realistic susy $AdS_5$ models.
Introduction of $N_f$ D7 probe branes allows for a weakly coupled $U(N_f)$ gauge theory in the dual.

$$g_f^2 \sim (\text{volume})^{-1}.$$
D7 probes = flavors

- Embed D7s $\rightarrow$ “techniquarks” of dual gauge theory.
- Bound states $\Rightarrow$ models w/ compositeness + SUSY.

\[ Q = \text{techniquark} \]

\[ Higgs (\text{NGB}) \]

\[ \text{D7–D3} \]
\[ \text{D7–D3} \]
\[ \text{D7–D7} \]

\[ \text{U}(N_C) \text{ binding} \]
Noncompact $\rightarrow$ compact CY

- Recent studies of the low-E EFT (4d, 5d):
  - Sakai, Sonnenschein 03
  - Kuperstein 04
  - Levi, Ouyang 05
  - Gherghetta, JG 06
  - Acharya, Benini, Valandro 06

- In [★]: include UV regulator.

- METHOD: Giddings, Kachru, Polchinski 02.

- Cap conifold w/ compact Calabi-Yau...
The CY and the KS tip are, respectively, to be thought of as refinements of the UV and IR branes of, say, Randall-Sundrum 1.
Now I discuss applications of these ideas.

**GOAL:** String-inspired, realistic low-E theory.

- The models are:
  - MSSM in bulk.
  - Deformed AdS$_5$.
- SUSY breaking: use non-supersymmetric variants of KS string refinement.
  [Borokhov, Gubser 02; Kuperstein, Sonnenschein 03]
Slice of $\text{AdS}_5$:

\[ ds^2_5 = A^2(z) \left( -dt^2 + d\vec{x}^2 + dz^2 \right), \]
\[ A^2(z) = \frac{1}{z^2}. \]

- 1+3 dim's: $t$, $\vec{x}$.
- 5th dim.: $1 \leq z \leq z_{\text{IR}}$.
- Warp factor: $A^2(z)$ (units of AdS curvature).
- UV brane: $z_{\text{UV}} = 1$.
- IR brane: $z_{\text{IR}} = m_P/(0.1 \text{ to } 10 \text{ TeV})$. 
Deforming AdS$_5$

- Deform AdS according to the dim’l reduc. of Kup.-Sonn. soln.:

\[ ds^2_5 = A^2(z) \left( -dt^2 + d\vec{x}^2 + dz^2 \right), \]

\[ A^2(z) = \frac{1}{z^2} \left( 1 - \epsilon \cdot \left( \frac{z}{z_{IR}} \right)^4 \right). \]

- Domain: $1 \leq z \leq z_{IR}$.
- Dial 1: $\epsilon \sim 0.1$. [$\epsilon = 0.05$ in following.]
- Dial 2: $z_{IR} = m_P/(1-100 \text{ TeV})$.
- SUSY lim.: $\epsilon \to 0$.
- Interpretation: DSB in the $SU(N_c)$. 
A few per cent violence in the IR: Will it matter?

* Ratio deformed/undeformed warp factor. *
* Unchanged except very near IR brane. *
- Solutions parameterized by boundary mass $b$.
- LO profile $\sim z^{b-1}$, unchanged.
- Zero modes lifted:
  \[
  \tilde{m} \approx \sqrt{\epsilon (b - 1)(b + 10)} z_{\text{IR}}^{-1} \quad (b > 1)
  \]
  \[
  \tilde{m} \approx \sqrt{\epsilon (1 - b)(b + 10)} (z_{\text{IR}})^{b-2} \quad (0 < b < 1)
  \]
- KK modes still $\sim \pi/z_{\text{IR}}$. 
Masses of quasi-zeromode scalars

The graph shows the masses of quasi-zeromode scalars as a function of the parameter $b$. The axes are labeled as $m$ (GeV) on the y-axis and $b$ on the x-axis. The masses are indicated at 100 TeV, 10 TeV, and 1 TeV, with the UV and IR regions labeled on the graph.
Fermions

- Exact zeromodes persist.

\[
0 = (\gamma^\alpha \partial^\alpha + \gamma_5 \partial_z + cA) \hat{\psi}, \quad \hat{\psi} \equiv A^2 \psi,
\]

\[
f_{\pm} = N_{\pm} A^{-2}(z) \exp \left( \mp c \int_{1}^{z} dz' A(z') \right).
\]

- Profile virtually unchanged:

\[
N_{\pm} z^{\frac{1}{2} \mp c_{\pm}} \left[ 1 + \frac{\epsilon z'^{4}}{4 z'^{4}_{\text{IR}}} \left( 1 - \frac{1}{2} c_{\pm} \right) \right].
\]

- \( m = 0 \)'s protected by chiral symmetries.

- \( \Rightarrow \) massless gauginos.

- \( Z_2 \) projection \( \rightarrow \) chiral/\( \mathcal{N} = 1 \) light spectrum.
Generational hierarchies

- **Higgses at UV brane** (why? ... later.).
- **Dial 3:** Bulk fermion masses $c_{L,R}$.
- **Use profiles** $\sim z^{1/2-c_L}, z^{1/2+c_R}$ for ferm. hier.

$$Y_{4d} = \frac{1}{2} Y_{5d} \sqrt{\frac{1 - 2c_L}{z^{-1-2c_L} - 1}} \sqrt{\frac{1 + 2c_R}{z^{1+2c_R} - 1}}.$$

![Diagram showing generational hierarchy and Higgses at UV and IR branes.](image-url)
Scalar-fermion correlation

- SUSY implies boundary scalar mass $b$:

\[ b = \frac{3}{2} - c_L. \]

- $O(\epsilon)$ deviations in this relation $\rightarrow$ $O(\epsilon^2)$ mass/profile corrections ... neglect.

- Scalar/fermion profiles approx. same.

- $\Rightarrow$ scalar partners of light fermions IR localized ($b > 1$), [HEAVY]

- partners of heavy fermions UV localized ($b < 1$). [LIGHT]
 Scalars: INVERTED HIERARCHY

[worried? ... good.]

Gen. 1 spartners

Splitting adjustable

Gen. 2 spartners

LHC Reach (few TeV)

Gen. 3 spartners

Gen. 1 & 2 scalars beyond LHC reach.
Dual interpretation

- IR-localized generations 1 & 2 $\Rightarrow$ composite.
- Scalars feel the SUSY-breaking strong dynamics directly.
  \[
  \tilde{m}_\phi \sim \Lambda_{SU(N)} \sim m_{KK}
  \]
- Fermions protected by chiral symmetry.
Third generation, higgses, gauginos

- Composite 1st & 2nd generations $\rightarrow$ messengers with $F$-terms:

\[ F \sim \tilde{m}_\phi \Lambda_{SU(N)} \]

- Equivalent to “single-sector” dynamical SUSY-breaking.
  [Arkani-Hamed, Luty, Terning 97-98]

- Third generation elementary $\Rightarrow$
  only feel SM gauge mediation.

- Similarly for Higgses and gauginos.

- Gravity dual of 1-loop gaugino mass:
  $G_3$ flux background.
Example spectrum

- Gen. 1 sleptons (10.2 TeV)
- Gens. 1 & 2 squarks (5.9 TeV)
- Gen. 2 sleptons (5.1 TeV)
- LHC Reach (few TeV)
- Gen. 3 sparticles, gauginos, higgsinos, higgses (115 GeV – 1.6 TeV)
Example spectrum

<table>
<thead>
<tr>
<th>Particle (\bar{e}_L, \bar{e}<em>R, \tilde{\nu}</em>{eL})</th>
<th>Masses (10160, 10150, 10160) GeV (5145, 5130, 5145) GeV (5905, 5885, 5970, 5890) GeV (5905, 5885, 5970, 5890) GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\tilde{\mu}_L, \tilde{\mu}<em>R, \tilde{\nu}</em>{\mu L}) (\tilde{d}_L, \tilde{d}_R, \tilde{u}_L, \tilde{u}_R) (\tilde{s}_L, \tilde{s}_R, \tilde{c}_L, \tilde{c}_R)</td>
<td>(\tilde{g}) (1615) GeV (1354, 1369, 1253, 1369) GeV (511, 630, 633) GeV (478, 593) GeV (288, 480, 511, 598) GeV (115, 646, 646, 651) GeV (2.35) eV</td>
</tr>
<tr>
<td>(\tilde{\tau}_1, \tilde{\tau}<em>2, \tilde{\nu}</em>{\tau L}) (\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm) (\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0) (h^0, A^0, H^0, H^\pm) (\tilde{G})</td>
<td></td>
</tr>
</tbody>
</table>
FCNC constraints

- Nondegenerate squarks very dangerous.
- We keep gen. 1 vs. 2 squarks degenerate.
- ⇒ little 1-2 hierarchy \((m_c/m_u)\) in 5d Yukawas.
- Gen. 1-3 and 2-3 mixing constraints ⇒ KK scale cannot be too large.
- Still solve BIG hierarchies, e.g. \(m_t/m_e\), w/ localization!
| $|\delta^d|$ | model  | 95% CL (bound) | experiment |
|-------|-------|---------------|------------|
| 12/LL  | $2.1 \times 10^{-4}$ | $1.4 \times 10^{-2}$ |            |
| 12/RR  | $2.1 \times 10^{-4}$ | $9.0 \times 10^{-3}$ |            |
| 12/LR  | $8.5 \times 10^{-12}$ | $9.0 \times 10^{-5}$ |            |
| 12/RL  | $4.9 \times 10^{-13}$ | $9.0 \times 10^{-5}$ |            |
| 13/LL  | $2.2 \times 10^{-2}$ | $9.0 \times 10^{-2}$ | $\Delta m_B, \beta$ |
| 13/RR  | $2.1 \times 10^{-2}$ | $7.0 \times 10^{-2}$ | $\Delta m_B, \beta$ |
| 13/LR  | $3.6 \times 10^{-8}$ | $1.7 \times 10^{-2}$ |            |
| 13/RL  | $5.1 \times 10^{-11}$ | $1.7 \times 10^{-2}$ |            |
| 23/LL  | $1.6 \times 10^{-1}$ | $1.6 \times 10^{-1}$ | $b \rightarrow sX, \Delta m_{B_s}$ |
| 23/RR  | $1.6 \times 10^{-1}$ | $2.2 \times 10^{-1}$ | $b \rightarrow sX, \Delta m_{B_s}$ |
| 23/LR  | $2.6 \times 10^{-7}$ | $4.5 \times 10^{-3}$ |            |
| 23/RL  | $6.4 \times 10^{-9}$ | $6.0 \times 10^{-3}$ |            |
Consider $d\tilde{m}_{Q3}^2/dt$, w/ gen. 1 & 2 squarks at scale $\Lambda$.

1-loop:

$$\beta^{(1)}_{\tilde{m}_{Q3}^2} \approx -\frac{\alpha_s}{4\pi} \frac{32}{3} M_3^2 \quad (\text{IR} \nearrow).$$

2-loop:

$$\beta^{(2)}_{\tilde{m}_{Q3}^2} \approx \frac{\alpha_s^2}{(4\pi)^2} \frac{4 \cdot 32}{3} \Lambda^2 \quad (\text{IR} \searrow).$$

$\tilde{m}_{Q3}^2(\text{TeV}) > 0$ constraint:

$$\left( \sqrt{\frac{\pi}{\alpha_s(\Lambda)}} \approx 6 \right) : \quad \Lambda \lesssim 6 M_3.$$
LHC predictions

- Typical cascade decay from $gg \rightarrow \tilde{g}\tilde{g}$:

  \[
  \begin{align*}
  & \sim g \quad \sim t_1 \quad \sim \chi_{1+} \quad \sim \chi_{10} \\
  & \text{tbar} \quad \text{b} \quad \text{W}^+ \quad \nu_l^+ \\
  & \text{W}^- \quad \text{bbar} \quad \text{nu} \quad l^- \\
  & \text{nubar} \quad \text{l}^- \\
  & \sim \Gamma \quad \text{gamma} \\
  \end{align*}
  \]

- The $\tilde{\chi}_{1}^0$ decays give rise to the distinctive signal:

  \[ p\bar{p} \rightarrow \gamma\gamma + \not{E}_T + X. \]
Limit from $p\bar{p} \rightarrow 2\gamma + \not{E}_T$ [Tevatron 2005]

Neutralino Mass (GeV/c$^2$)

CDF 202 pb$^{-1}$
DØ 263 pb$^{-1}$

GMSB $\gamma\gamma + \not{E}_T$
$M=2\Lambda$, $N=1$, $\tan\beta=15$, $\mu>0$

PROSPINO NLO
QCD Uncertainty

$\sigma \times BR \ (\gamma+X)$ (pb)

expected limit
observed limit

Chargino Mass (GeV/c$^2$)
At Tevatron energy 1.96 TeV, PYTHIA says:

\[ \sigma \times BR = 2.5 \times 10^{-5} \text{ pb} \]
\[ \sim 0 \text{ events at DØ+CDF w/ 2 fb}^{-1}. \]

No constraint.
At LHC energy 14 TeV, PYTHIA says: 
\[ \sigma \times BR = 3.5 \times 10^{-2} \text{ pb}. \]

1000 times the rate of Tevatron!

Obtain \( \sim 35 \) events w/ 1 fb\(^{-1}\) (\( \sim \) 1st year).

Backgrounds larger at LHC: Will we see the signal?

Compare to gauge mediation.
Compare to GMED
Backgrounds

- **Real:**
  \[ pp \rightarrow \{ gg, q\overline{q} \} \rightarrow \gamma \gamma, \]

- **Fake: (mainly \( j \sim \pi^0 \):**
  \[ pp \rightarrow \gamma j_{\text{fake}}, \quad pp \rightarrow j_{\text{fake}} j_{\text{fake}}. \]

  channel \[
  \begin{array}{ccc}
  \gamma \gamma & \gamma j & jj \\
  \text{cross section} & 0.15 \mu b & 0.12 \text{ mb} & 55 \text{ mb}
  \end{array}
  \]

- **Comparable since**
  \[ j_{\text{fake}} / j \sim 10^{-3} \]
MET

[SUSY = solid, SM(\(\gamma\gamma\)) = dashed]
$p_T$ [SUSY = solid, SM($\gamma\gamma$) = dashed]
Cuts

Distributions suggest:

\[ p_{T,\gamma} \geq 40 \text{ GeV}, \quad \not{E}_T \geq 60 \text{ GeV} \]

Don’t lose much signal.

Background eliminated.
MET (signal) \[w/\text{ cuts} = \text{solid}, \ w/o \text{ cuts} = \text{dashed}\]
pT (signal)  [w/ cuts = solid, w/o cuts = dashed]
MET w/ cuts [SUSY = solid, SM(\(\gamma\gamma\)) = dashed]
pT w/cuts  [SUSY = solid, SM(\gamma\gamma) = dashed]
## Summary w/cuts

<table>
<thead>
<tr>
<th>Integrated Luminosity</th>
<th>SUSY</th>
<th>SM $2\gamma$</th>
<th>SM $2\gamma$ + fakes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 fb$^{-1}$</td>
<td>27.6</td>
<td>0.0285</td>
<td>$\lesssim 0.1$</td>
</tr>
<tr>
<td>10 fb$^{-1}$</td>
<td>276</td>
<td>0.285</td>
<td>$\lesssim 1$</td>
</tr>
</tbody>
</table>
Why Higgses on UV brane?

- Suppose $H_{1,2} \rightarrow$ IR brane.
- Gen. 1 & 2 UV localized.
- Gauge mediated $\tilde{m}_{1,2}, M_i \ (i = 1, 2, 3) \sim 1$ TeV
  $\Rightarrow$ KK scale 100 TeV.
- No SUSY at IR end $\rightarrow$ problems...
Why Higgses on UV brane?

- 2HDM many new parameters: 3 $m^2$'s, 7 $\lambda$'s.
- Many new sources of FCNC's.
- Hierarchy problem:
  - Gen. 3 now IR localized $\rightarrow$ 100 TeV $\tilde{m}_3$.
  - KK modes 100 TeV.
  - Unsuppressed coupling to Higgs for both.
  - Recall $\lambda_t \sim 1$ and $\Delta m^2_{h0} \sim \ln(\tilde{m}_t/m_t)$.
  - Destabilizes EW scale.
The mass scale of Gen. 1,2 sfermions are fixed by the quark and lepton masses and two additional parameters ($z_{IR}$, $\epsilon$).

The rest of the sparticles are fixed by three other parameters ($F$, $N_{mess.}$, $\tan \beta$).
Conclusions

- Gravitational dual for single-sector models.
- A single parameter ($\epsilon$) for SUSY-breaking in bulk.
- Lower rates distinguish model from gauge mediation.
- Backgrounds negligible w/ simple cuts.

BIGGEST CONSTRAINTS:
- FCNC’s and
- tachyonic squarks.