Phenomenology of Large Volume Compactifications in Type IIB String Theory

Kerim Suruliz (DAMTP, Cambridge)

SUSY 07, Karlsruhe, July 31, 2007

based on:

hep-th/0704xxx, J. Conlon, C. Kom, KS, B. Allanach, F. Quevedo
hep-th/0701154, D. Cremades, M.-P. Garcia del Moral, F. Quevedo, KS
hep-th/0610129, J. Conlon, S. Abdussalam, F. Quevedo, KS

...
Plan of Talk

- Motivation.
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- Motivation.
- Moduli stabilisation and Large Volume models.
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- Spectra and Phenomenology.
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- Moduli stabilisation and Large Volume models.
- Spectra and Phenomenology.
- Summary and Conclusions.
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- Low energy supersymmetry as a solution to the hierarchy problem.
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- SUSY must be broken: soft terms - gaugino and scalar masses, A-terms etc.
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- SUSY must be broken: soft terms - gaugino and scalar masses, A-terms etc.
- What does string theory predict for the supersymmetry breaking pattern?
- Moduli stabilisation and supersymmetry breaking closely related.
- Take the top down approach: study classes of string theory models with stabilised moduli and try to find firm predictions.
Review of Moduli Stabilisation

K. Suruliz (DAMTP, Cambridge)

July 2007
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Closed string moduli are divided into complex structure (shape) and Kähler (size) moduli.
Flux Compactifications and the KKLT Scenario

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The Kähler moduli fixed by non-perturbative contributions to superpotential (KKLT scenario).
Obtained in [hep-th/0502058] (Balasubramanian, Berglund, Conlon and Quevedo) by taking into account leading order $\alpha'$ correction to Kähler potential $K$:

$$K = -2 \log(V + \xi)$$
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Needs at least two Kähler moduli, $T_b$ and $T_s$. The volume is

$$V \propto (T_b + T_b^*)^{3/2} - (T_s + T_s^*)^{3/2}$$
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$$V \propto (T_b + T_b^*)^{3/2} - (T_s + T_s^*)^{3/2}$$

- $T_b$ overall volume, $T_s$ small 'blow-up' cycle.
The superpotential is

\[ W = W_0 + A_s e^{-a_s T_s} \left( + A_b e^{-a_b T_b} \right) \]
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Full scalar potential

\[ V = \frac{e^{-2a_s \tau_s}}{\mathcal{V}} - \frac{e^{-a_s \tau_s}}{\mathcal{V}^2} + \frac{\xi}{\mathcal{V}^3} \]

(the axion in \( T_s \) fixes the middle sign)
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A minimum is found at

\[ \tau_s = \mathcal{O}(1) \]
\[ \mathcal{V} \sim e^{a_s \tau_s} \]
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m_s & \sim \frac{M_P}{\sqrt{V}} \\
m_{soft} & \sim m_{3/2} \sim \frac{M_PW_0}{V}.
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With $W_0 \approx 1$ (no fine tuning), need $\mathcal{V} \sim 10^{15} l_s^6$ - this is easily obtainable. Large volume is a natural source of hierarchies.
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With $V \sim 10^{15}$ (in $l_s^6$) get $m_s \sim 10^{11}$GeV. Intermediate scale scenario $\implies$ no gauge coupling unification.
Assume local brane model giving the matter content of the MSSM: magnetised D7 branes.
Compactifications

Standard formalism for computing gravity mediated soft terms in SUGRA.
Soft Terms in Large Volume Compactifications

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- Requires knowledge of:

\[ K(h, \phi) = \hat{K}(h) + \tilde{K}_i(h)\phi_i\phi_i^*. \]

Also need gauge kinetic functions \( f_a \).
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- From there one computes

\[ M_a = \frac{1}{2} \frac{F^m\partial_m f_a}{\text{Re} f_a}. \]

\[ m_i^2 = (m_{3/2}^2 + V_0) - F^m\bar{F}^{\bar{n}}\partial_m\partial_{\bar{n}}\tilde{K}_i, \]

etc.
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Magnetic fluxes $F$ responsible for chirality. Their presence gives unknown corrections to the gauge kinetic functions and Kähler potentials.
In the diluted flux limit $F = 0$ (i.e. $\tau_s \gg \epsilon$),

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\begin{align*}
M_i &= M \\
m_a &= \frac{M}{\sqrt{3}} \\
A &= -M \\
B &= -\frac{4M}{3}.
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Introduce now perturbations due to corrections $\epsilon_\alpha$ to $\tilde{K}$.

\[
\begin{align*}
M_i &= M(1 + \epsilon_i) \\
ma &= \frac{M}{\sqrt{3}}(1 + \epsilon_a) \\
A_{abc} &= -\frac{1}{\sqrt{3}}(ma + mb + mc)
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Use micrOMEGAs to compute all of these.
The spectra with $m_\tilde{g} \approx 900\text{GeV}$ fixed in order to set overall scale, with 20% fluctuations at high scale.
On the whole fairly similar to an SPS1 type mSUGRA spectrum, but there are some important differences.
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- Spectrum more ‘bunched’ - the particle masses have less time to run since the string scale is intermediate and approximate unification takes place there.
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The gaugino mass ratio at the low scale is

\[ M_1 : M_2 : M_3 = (1.5 - 2) : 2 : 6. \]

In mSUGRA one has 1 : 2 : 6.
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- Discrimination of models - two approaches. Counting observables and kinematic observables.
OS dilepton and trilepton events.
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The number of dilepton (and thus trilepton) events varies a lot even when the overall spectrum mass scale is fixed - $m_{\tilde{g}} \approx 900 \text{GeV}$.
Many of the OS dileptons come from the decay chain
\[ \tilde{\chi}_2^0 \rightarrow \tilde{\ell}^\pm \ell^\mp \rightarrow l^\pm l^\mp \tilde{\chi}_1^0. \]
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Depending on the mass differences \( m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0} - m_{\tilde{l}^R}, m_{\tilde{l}^R} - m_{\tilde{\chi}_1^0} \), we may see many or few dileptons.
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If there are not many dileptons, the spectrum will be hard to reconstruct as lepton observables are cleanest (\( \sim 90\% \) tagging efficiency for \( e, \mu \)).
We consider a spectrum with many OSSF dilepton events, so that the chain $\tilde{\chi}_2^0 \rightarrow \tilde{l}^\pm l^\mp \rightarrow l^\pm l^\mp \tilde{\chi}_1^0$ can be reconstructed.
Spectrum Reconstruction

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- The gluino is at $m_{\tilde{g}} = 909$ GeV.
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Squark masses (all in GeV):

$$m_{\tilde{d}_L} = 800, m_{\tilde{u}_L} = 792, \ldots$$
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The slepton and neutralino masses are

$$m_{\tilde{e}_R, \tilde{\mu}_R} = 270, ...$$

$$m_{\tilde{\chi}_1^0} = 233, m_{\tilde{\chi}_2^0} = 303, m_{\tilde{\chi}_3^0} = 460, m_{\tilde{\chi}_4^0} = 483.$$
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The chargino masses are $m_{\tilde{\chi}_1^+} = 303, m_{\tilde{\chi}_2^+} = 480$. 
Use the standard techniques: $ll$ endpoint, $qll$ endpoint and threshold, $ql$ endpoint.
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Generate \(100 \text{fb}^{-1}\) of data with backgrounds (except \(W+\text{jets}\) and \(Z+\text{jets}\)).

Cuts are as in ATLAS TDR:

1. Four hard jets with \(P_T > 100, 50, 50, 50\) GeV.
2. Isolated lepton \(P_T > 10\) GeV.
3. \(E_T^{\text{miss}} > 0.2M_{\text{eff}}\), with

\[
M_{\text{eff}} = P_{T1} + P_{T2} + P_{T3} + P_{T4} + E_T^{\text{miss}}.
\]
Dilepton endpoint at

\[ M_{ll}^{\text{max}} = \sqrt{\frac{(m_{\tilde{\chi}^0_2}^2 - m_{\tilde{l}_R}^2)(m_{\tilde{\chi}^0_1}^3 - m_{\tilde{l}_R}^2)}{m_{\tilde{l}_R}^2}} \]
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Can be reconstructed with very good accuracy, ±0.15GeV.
qll, ql endpoints use the decay chain $\tilde{q}_L \rightarrow q\tilde{\chi}^0_2 \rightarrow q\tilde{l}^\pm l^\mp \rightarrow ql^\pm l^\mp \tilde{\chi}^0_1$. 
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• Use lighter $qll$ mass, since the hardest jet probably came from $\tilde{q}_R \rightarrow q\tilde{\chi}_1^0$. 


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- (Lighter) $qll$ invariant mass has an endpoint at

$$M_{qll}^{max} = \sqrt{\frac{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2)}{m_{\tilde{\chi}_2^0}^2}}$$
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Smeared due to jet finding algorithm, combinatorics etc.
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Smeared due to jet finding algorithm, combinatorics etc.

Heavier ql invariant mass should give endpoint at

$$M_{ql}^{max} = \sqrt{\frac{(m_{\tilde{q}_L}^2 - m_{\tilde{\chi}_2^0}^2)(m_{\tilde{\chi}_2^0}^2 - m_{l_R}^2)}{m_{\tilde{\chi}_2^0}^2}}$$
Fit histograms using MINUIT and MINOS.
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Assuming that we can get rid of systematic errors, obtain

\[ M_{ll}^{max} = 69.4 \pm 0.15 \text{GeV} \]
\[ M_{qll}^{max} = 467.6 \pm 6.0 \text{GeV} \]
\[ M_{ql}^{max} = 330.5 \pm 4.0 \text{GeV} \]
\[ M_{qll}^{min} = 202.8 \pm 10.0 \text{GeV} \].
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\]

Now fit mass differences: this is done by random generation of masses for \( \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{l}_R, \tilde{q}_L \), calculating \( M_{ll}^{max}, M_{qll}^{max}, M_{ql}^{max}, M_{qll}^{min} \) and using an \( e^{-\chi^2/2} \) probability distribution.
Spectrum Reconstruction V

- Can reconstruct mass differences well:

- $\chi^2 / \text{ndf}$

- M2-M1 abs
  - Constant: $4.0 \pm 248.3$
  - Mean: $0.4 \pm 567.7$
  - Sigma: $0.1 \pm 22.3$

- LR-M1 abs
  - $\chi^2 / \text{ndf}$: $105.1 / 61$
  - Constant: $6.8 \pm 391.8$
  - Mean: $0.02 \pm 37.28$
  - Sigma: $0.016 \pm 1.621$

- QL-M1 abs
  - $\chi^2 / \text{ndf}$: $800.2 / 48$
  - Constant: $248.3 \pm 4.0$
  - Mean: $567.7 \pm 0.4$
  - Sigma: $22.3 \pm 0.1$

K. Suruliz (DAMTP, Cambridge)
SPECTRUM RECONSTRUCTION V

- Can reconstruct mass differences well:

![Histograms of mass differences](image)
Fitting the mass difference graphs gives

\begin{align*}
    m_{\tilde{\nu}_R} - m_{\tilde{\chi}_1^0} &= 37.3 \pm 1.6 \text{GeV} \\
    m_{\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} &= 69.4 \pm 1.0 \text{GeV} \\
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\end{align*}
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Can we discriminate this from a generic mSUGRA scenario?
Answer: yes - use the ratio \( M_1 : M_2 : M_3 = 1 : 2 : 6 \).
In mSUGRA $m_\tilde{g} \approx 6m_{\tilde{\chi}^0_1}$ and $m_{\tilde{\chi}^0_2} \approx 2m_{\tilde{\chi}^0_1}$. 
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Thus

$$\frac{m_{\tilde{g}} - m_{\tilde{\chi}^0_1}}{m_{\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1}} \approx 5.$$
Comparison with mSUGRA II

- In mSUGRA $m_\tilde{g} \approx 6m_{\tilde{\chi}_1}$ and $m_{\tilde{\chi}_2} \approx 2m_{\tilde{\chi}_1}$.
- Thus
  
  \[
  \frac{m_\tilde{g} - m_{\tilde{\chi}_1}}{m_{\tilde{\chi}_2} - m_{\tilde{\chi}_1}} \approx 5.
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- In mSUGRA also have $\frac{m_{\tilde{q}_L}}{m_\tilde{g}} \lesssim 1$. 
In mSUGRA $m\tilde{g} \approx 6m\tilde{\chi}_1^0$ and $m\tilde{\chi}_2^0 \approx 2m\tilde{\chi}_1^0$.

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Thus expect

\[
\frac{m_\tilde{q}_L - m_\tilde{\chi}_1}{m_\tilde{\chi}_2 - m_\tilde{\chi}_1} \lesssim 5.
\]

However, we measured

\[
\frac{m_\tilde{q}_L - m_\tilde{\chi}_1}{m_\tilde{\chi}_2 - m_\tilde{\chi}_1} = 8.11 \pm 0.31.
\]
Conclusions

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Thank you for your attention