Sparticle Spectra from LARGE-Volume String Compactifications

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Talk Structure

- LARGE Volume Models
- Computing Soft Terms
- Sparticle Spectra and Phenomenology
- Conclusions

LARGE Volume Models

- Moduli stabilisation is a central problem in string phenomenology.
- Moduli are ubiquitous in string compactifications and describe the geometry of the extra dimensions.
- Moduli are naively massless scalars which generate unphysical fifth forces.
- LARGE volume models are an attractive method of moduli stabilisation, supersymmetry breaking and hierarchy generation.

LARGE Volume Models

In IIB flux compactifications, the appropriate 4-dimensional supergravity theory is

$$
\begin{aligned}
K &= -2\ln\left(\mathcal{V}+\frac{\xi}{g_s^{3/2}}\right) - \ln\left(i\int \Omega\wedge\bar{\Omega}\right) - \ln\left(S+\bar{S}\right), \\
W &= \int G_3\wedge\Omega + \sum_i A_i e^{-a_i T_i}.
\end{aligned}
$$

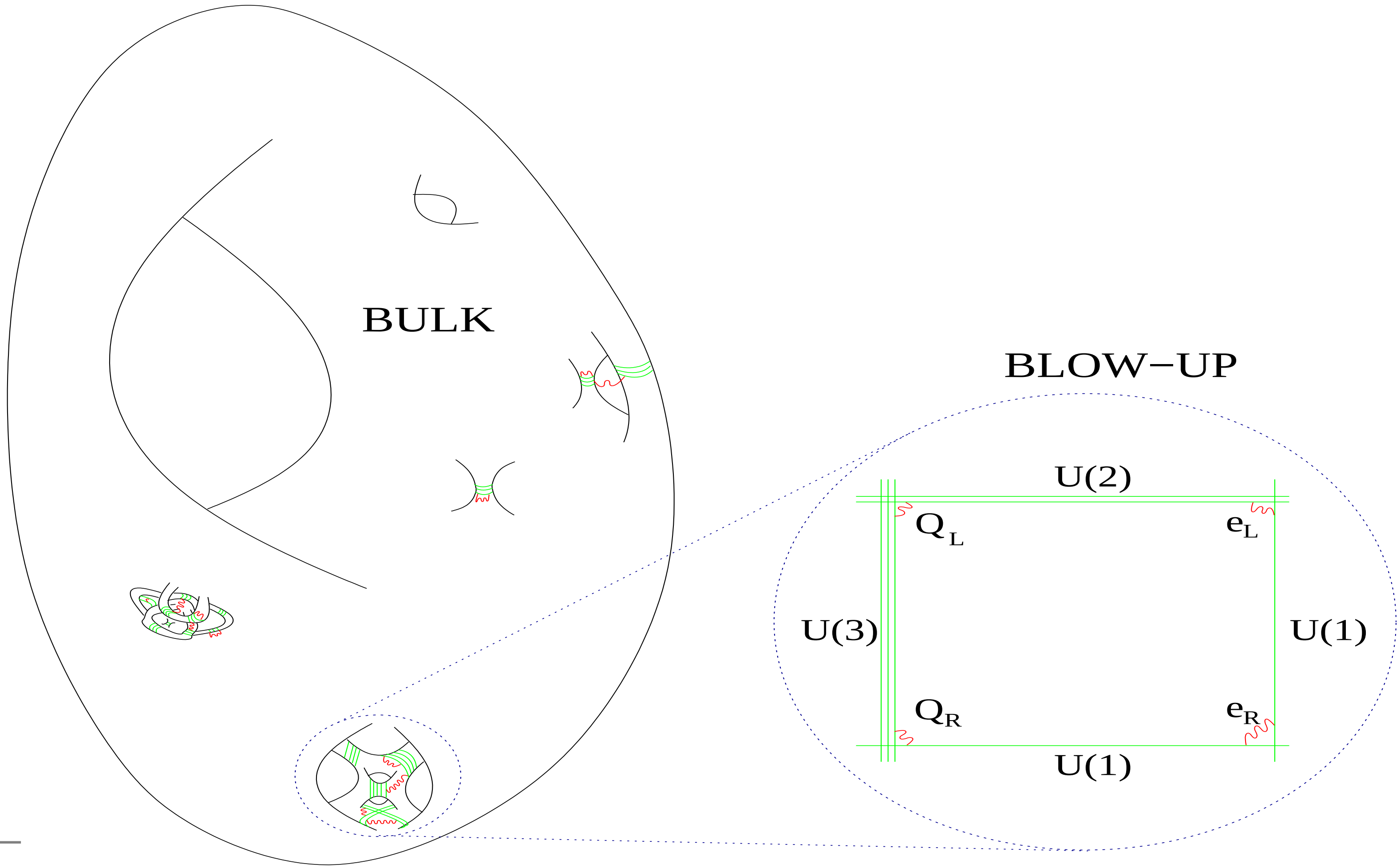
Consistent inclusion of α' corrections in the Kähler potential gives dramatic changes in the structure of the potential

$\Longrightarrow$ a new minimum appears at exponentially large volume $\mathcal{V} \gg 1$

LARGE Volume Models: Geometry

The simplest example has two moduli, τ_b and τ_s.

$\mathcal{V} = \tau_b^{3/2} - \tau_s^{3/2}$ (a Swiss cheese form).



Moduli Stabilisation: LARGE Volume

The supergravity potential is:

$$V = \underbrace{\frac{\sqrt{\tau_s} a_s^2 |A_s|^2 e^{-2a_s\tau_s}}{\mathcal{V}} - \frac{a_s |A_s W_0| \tau_s e^{-a_s\tau_s}}{\mathcal{V}^2}} + \frac{\xi |W_0|^2}{g_s^{3/2}\mathcal{V}^3}.$$

$$V = -\frac{|W_0|^2 \left(\ln \mathcal{V}\right)^{3/2}}{\mathcal{V}^3} + \frac{\xi |W_0|^2}{g_s^{3/2}\mathcal{V}^3}.$$

A minimum exists at

$$\mathcal{V} \sim |W_0| e^{c/g_s}, \qquad \tau_s \sim \ln \mathcal{V}.$$

This minimum is non-supersymmetric AdS and at exponentially large volume.

LARGE Volume Models

- The stabilised volume is naturally exponentially large.
- The large volume lowers the string scale and gravitino mass through

$$m_s = \frac{M_P}{\sqrt{\mathcal{V}}}, \qquad m_{3/2} = \frac{M_P}{\mathcal{V}}.$$

- With $\mathcal{V} = 10^{14} l_s^6$ and $m_s = 10^{11}$GeV, the weak hierarchy is naturally generated through TeV-scale supersymmetry.
- $m_s = 10^{11}$GeV also generates the correct scales for the axion decay constant $f_a \sim 10^{11}$GeV and the neutrino suppression scale $\Lambda \sim 10^{14}$GeV.

LARGE Volume Models

We take the overall volume to be $\mathcal{V} = 10^{14} l_s^6$.

The mass scales present are:

- Planck scale: $M_P = 2.4 \times 10^{18}$GeV.
- Neutrino/dimension-5 suppression scale: $\Lambda \sim 10^{14}$GeV.
- String scale: $M_S = \frac{M_P}{\sqrt{\mathcal{V}}} \sim 10^{11}$GeV.
- Axion decay constant $f_a \sim M_S \sim 10^{11}$GeV.
- KK scale $M_{KK} = \frac{M_P}{\mathcal{V}^{2/3}} \sim 10^9$GeV.
- Gravitino mass $m_{3/2} = \frac{M_P}{\mathcal{V}} \sim 30$TeV.
- Soft terms $m_{susy} \sim \frac{m_{3/2}}{\ln(M_P/m_{3/2})} \sim 1$TeV.

From strings to LHC

To compute sparticle spectra from the high-scale theory, what needs to be done?

1. Stabilise moduli and break supersymmetry
2. Compute the high-scale soft breaking terms
3. Run the soft terms to low energy using RGEs (SoftSUSY)
4. Study soft term phenomenology with Monte Carlo event generation (Herwig/PYTHIA)
5. Detector simulation (PGS)
6. Data analysis (ROOT)

SUSY Breaking and Soft Terms

- Computing gravity-mediated soft terms starts by expanding the supergravity K and W in terms of the matter fields C^α,

$$
\begin{aligned}
W &= \hat{W}(\Phi) + \mu(\Phi) H_1 H_2 + \frac{1}{6} Y_{\alpha\beta\gamma}(\Phi) C^\alpha C^\beta C^\gamma + \ldots, \\
K &= \hat{K}(\Phi, \bar{\Phi}) + \tilde{K}_{\alpha\bar{\beta}}(\Phi, \bar{\Phi}) C^\alpha C^{\bar{\beta}} + [Z H_1 H_2 + h.c.] + \ldots, \\
f_a &= f_a(\Phi).
\end{aligned}
$$

- If we know $\tilde{K}_{\alpha\bar{\beta}}$ and $Y_{\alpha\beta\gamma}$, computing soft terms is straightforward.

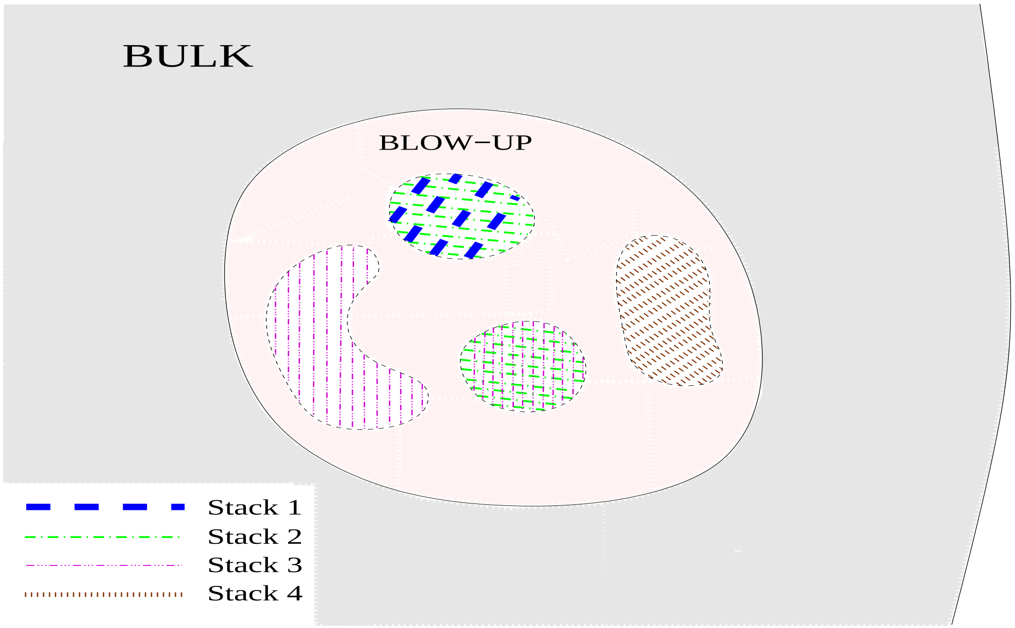
SUSY Breaking and Soft Terms

- Soft scalar masses $m^2_{i\bar{j}}$ and trilinears $A_{\alpha\beta\gamma}$ are given by

$$\begin{aligned}
\tilde{m}^2_{\alpha\bar{\beta}} &= (m^2_{3/2} + V_0)\tilde{K}_{\alpha\bar{\beta}} \\
&\quad - \bar{F}^{\bar{m}} F^n \left(\partial_{\bar{m}} \partial_n \tilde{K}_{\alpha\bar{\beta}} - (\partial_{\bar{m}} \tilde{K}_{\alpha\bar{\gamma}}) \tilde{K}^{\bar{\gamma}\delta} (\partial_n \tilde{K}_{\delta\bar{\beta}}) \right) \\
A'_{\alpha\beta\gamma} &= e^{\hat{K}/2} F^m \Big[\hat{K}_m Y_{\alpha\beta\gamma} + \partial_m Y_{\alpha\beta\gamma} \\
&\quad - \left((\partial_m \tilde{K}_{\alpha\bar{\rho}}) \tilde{K}^{\bar{\rho}\delta} Y_{\delta\beta\gamma} + (\alpha \leftrightarrow \beta) + (\alpha \leftrightarrow \gamma) \right) \Big].
\end{aligned}$$

SUSY Breaking and Soft Terms

- We consider a stack of (magnetised) branes all wrapping an identical cycle.
- Chiral fermions stretch between differently magnetised branes.



SUSY Breaking and Soft Terms

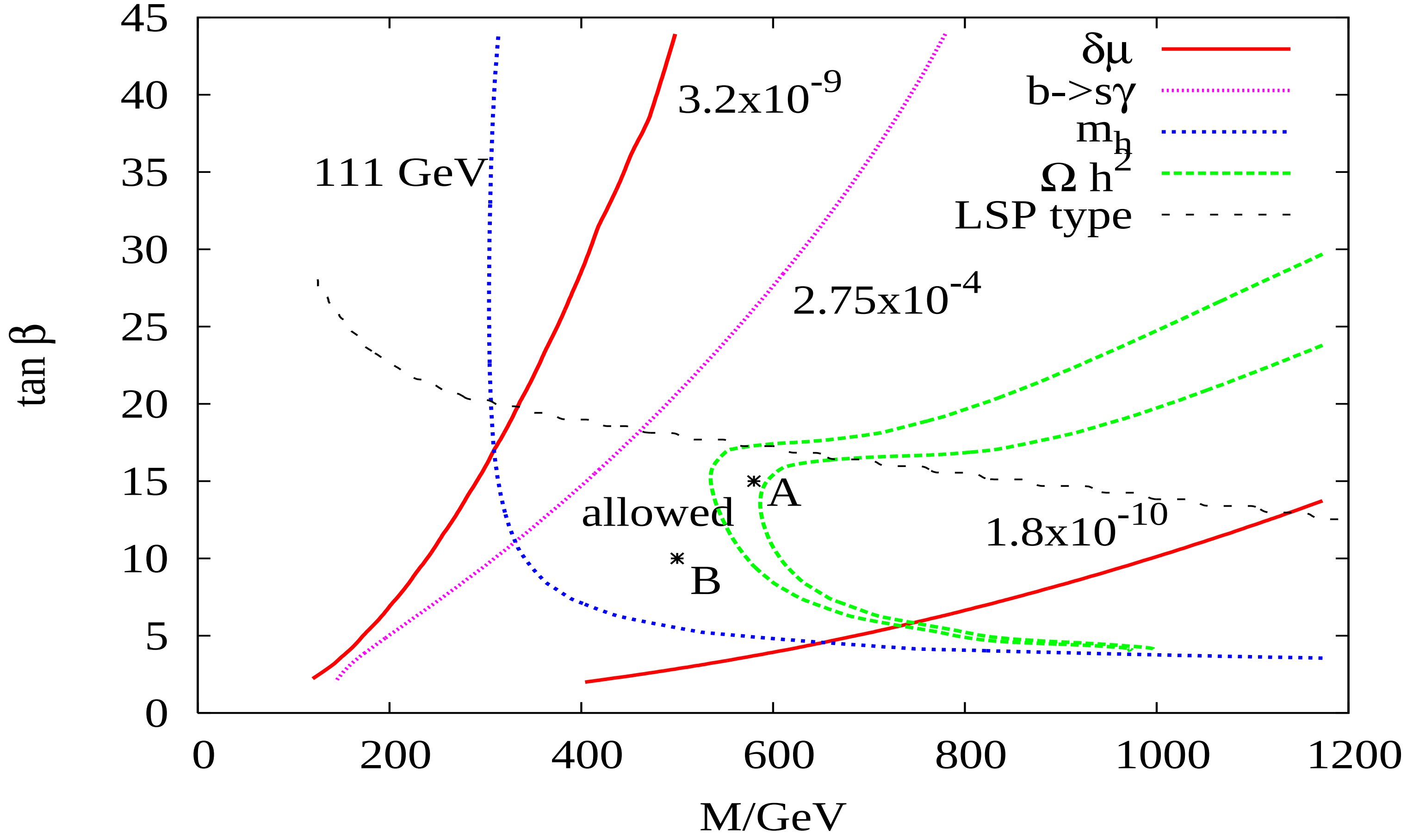
- To leading order (neglect brane magnetic fluxes)

$$
\begin{aligned}
\tilde{K}_{\alpha\bar{\beta}} &\sim \frac{\tau_s^{1/3}}{\mathcal{V}^{2/3}} k_{\alpha\bar{\beta}}(U,\bar{U}). \\
f_a &= T_s/4\pi.
\end{aligned}
$$

- We can compute the soft terms to get

$$
\begin{aligned}
M_i &= \frac{F^s}{2\tau_s} \equiv M, \\
m_{\alpha\bar{\beta}} &= \frac{M}{\sqrt{3}} \tilde{K}_{\alpha\bar{\beta}}, \\
A_{\alpha\beta\gamma} &= -M\, \hat{Y}_{\alpha\beta\gamma}, \\
B &= -\frac{4M}{3}.
\end{aligned}
$$

SUSY Breaking and Soft Terms



Soft Terms: Spectra

- Magnetic fluxes on the brane world-volumes are necessary for chirality.
- They also affect soft terms

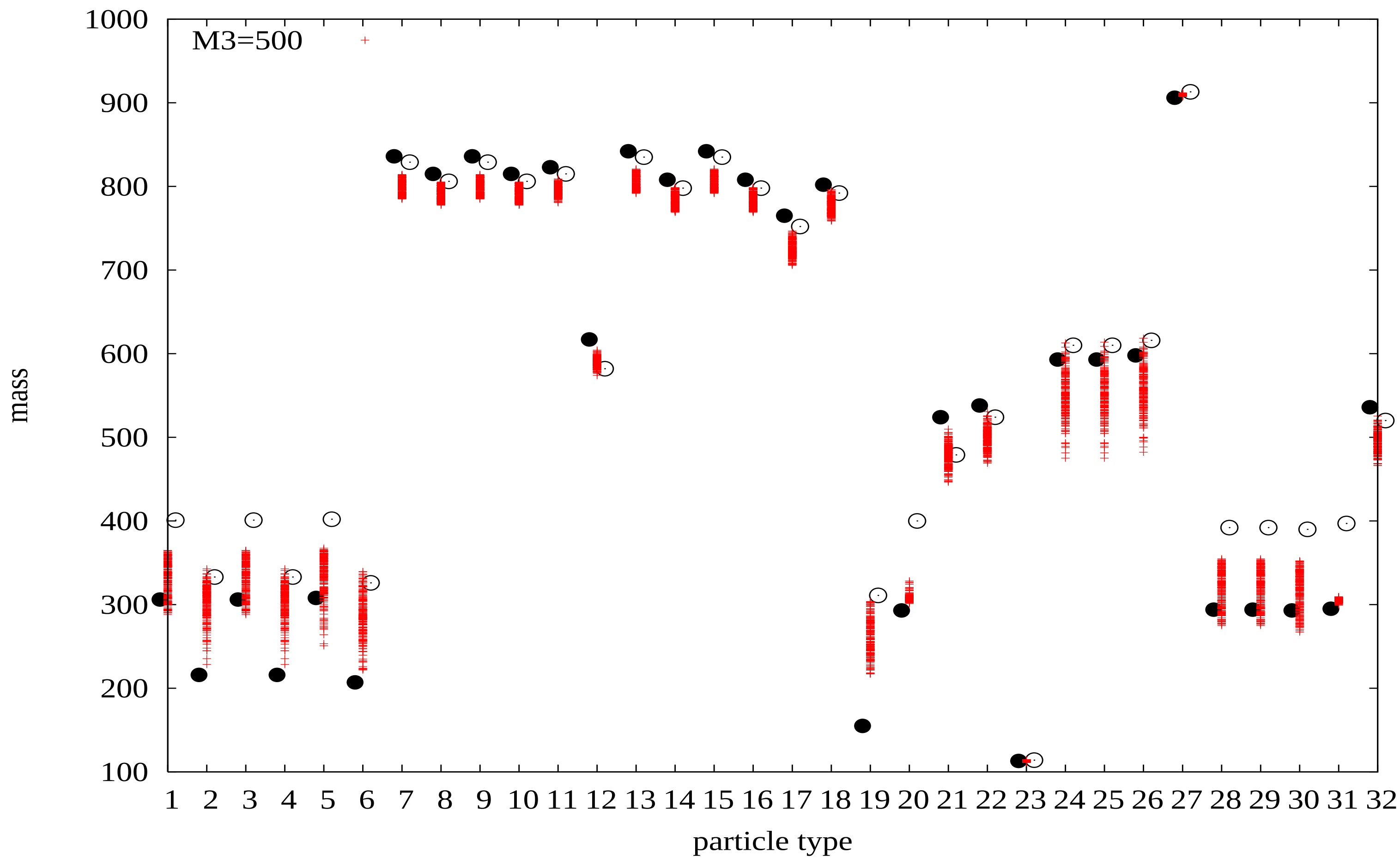
$$f_a = \frac{T}{4\pi} \quad \rightarrow \quad f_a = \frac{T}{4\pi} + h_a(F)S,$$

$$\tilde{K}_{\alpha\bar{\beta}} \sim \frac{\tau_s^{1/3}}{\mathcal{V}^{2/3}} k_{\alpha\bar{\beta}}(U,\bar{U}) \quad \rightarrow \quad \frac{(\tau_s+\epsilon)^{1/3}}{\mathcal{V}^{2/3}} k_{\alpha\bar{\beta}}(U,\bar{U}).$$

- For gauge couplings we ‘know’ the effect of fluxes.
- For scalar masses we parametrise flux effects by ϵ and allow ϵ to vary.
- The magnitude of variation is determined by high-scale non-universality of the gauge couplings.

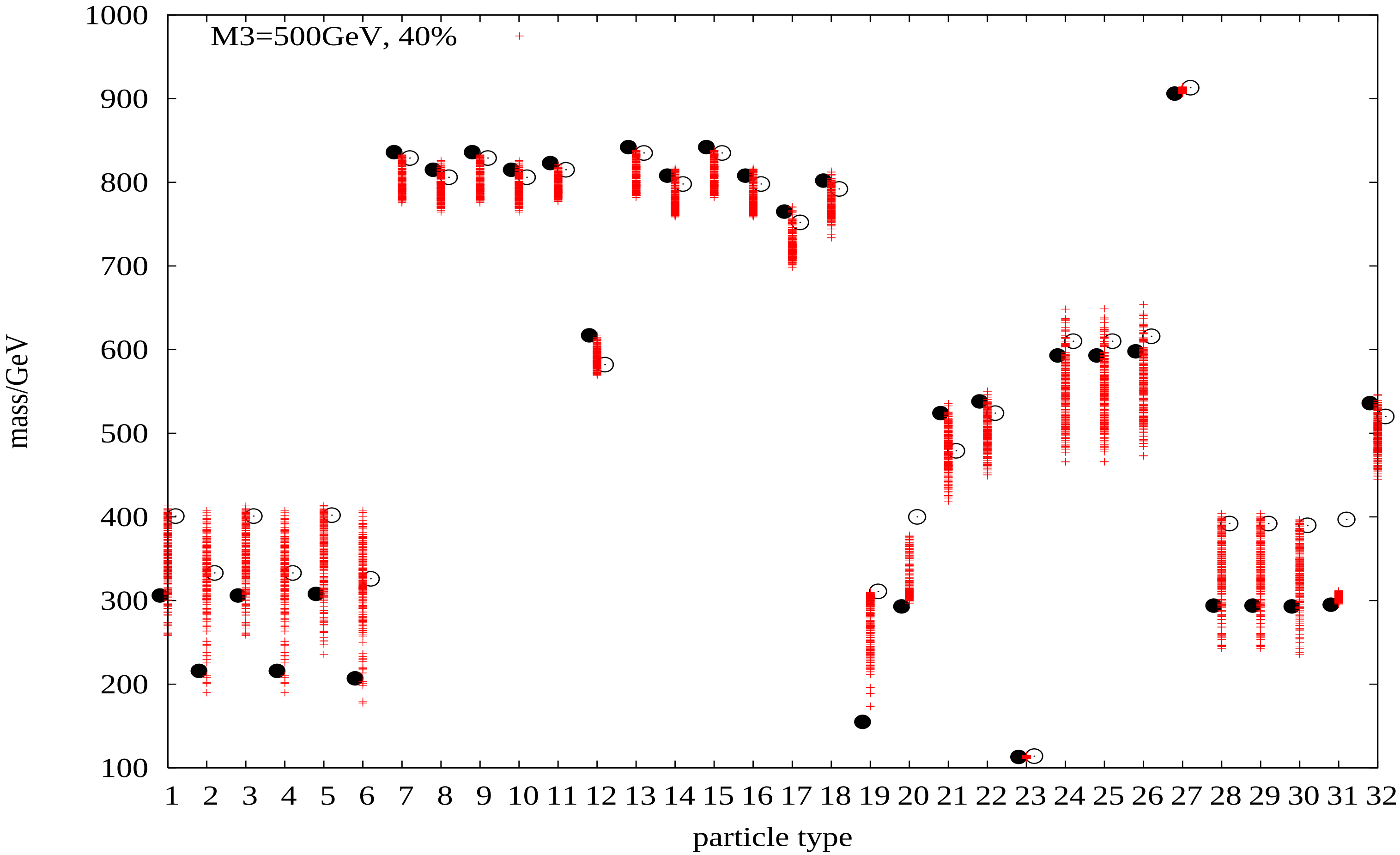
Soft Terms: Spectra

- We run the soft terms to low energy with a 20% high scale variation:



Soft Terms: Spectra

- We run the soft terms to low energy with a 40% high scale variation:



Soft Terms: Spectra

Gauginos:

- The gaugino mass ratios are most predictive:

$$M_1 : M_2 : M_3 = 1.5 \rightarrow 2 : 2 : 6.$$

- This comes from the higher-dimensional brane geometry.
- Bino uncertainty is due to the U(1) normalisation.
- Gaugino mass ratios are protected against uncertainties in the spectrum:

$$\frac{M_3^2(\mu)}{M_2^2(\mu)} = \frac{g_3^2(\mu)}{g_2^2(\mu)}.$$

Soft Terms: Spectra

Gauginos:

- The bino mass is significantly heavier than in mSUGRA.
- This follows from the assumption of dilute fluxes: in absence of magnetic fluxes, gaugino masses are universal at intermediate scale.
- Small perturbations about this cannot make bino as light as in mSUGRA.

Soft Terms: Spectra

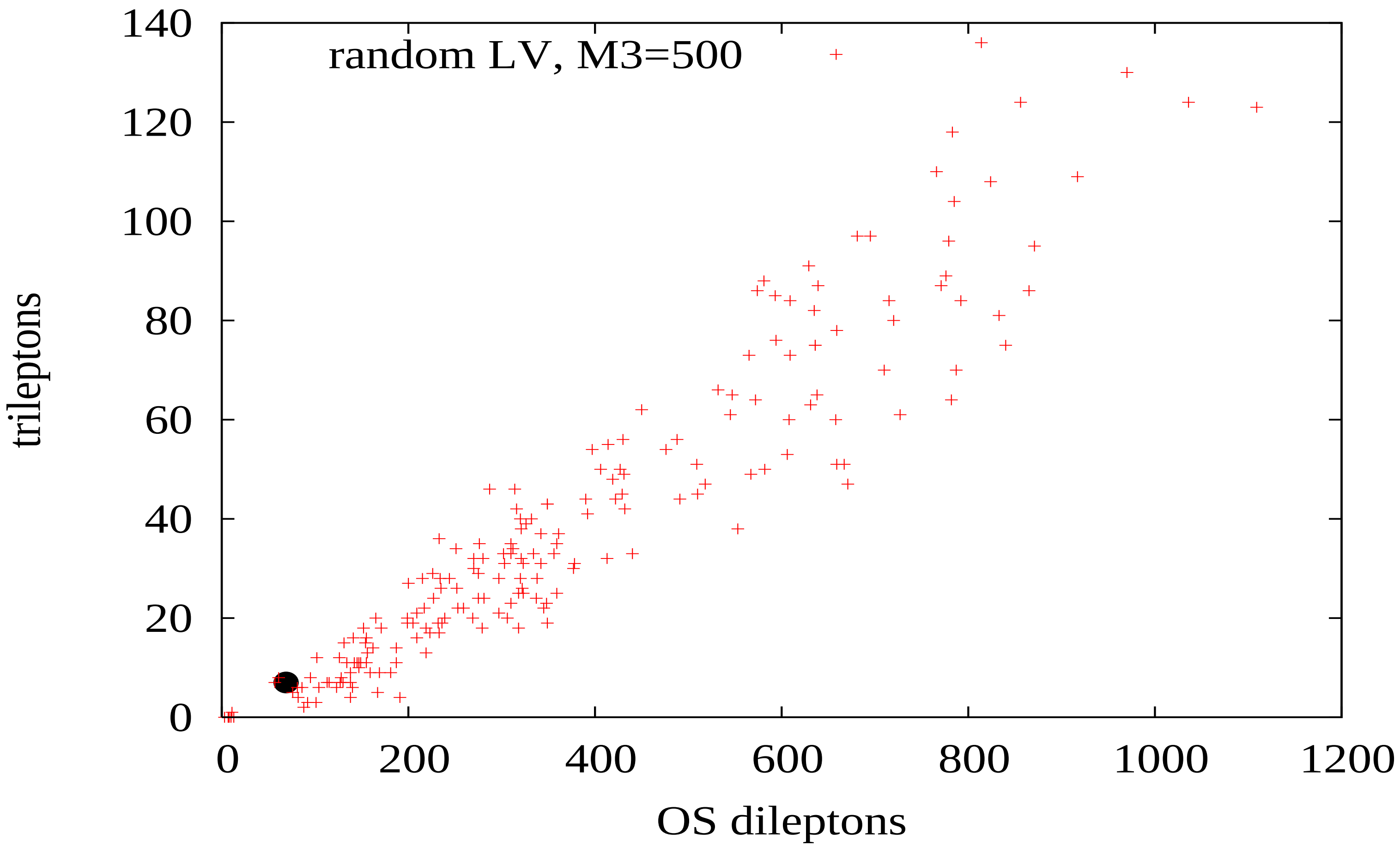
Scalars:

- RG running starts at the intermediate rather than GUT scale.
- The spectrum is more compressed than typical mSUGRA spectra: squarks tend to be lighter and sleptons tend to be heavier.
- $$\left(\frac{m_{\tilde{q}}}{m_{\tilde{g}}}\right)_{LV} < \left(\frac{m_{\tilde{q}}}{m_{\tilde{g}}}\right)_{MSUGRA}$$

  RGE squark focussing behaviour is less efficient.

Soft Terms: Phenomenology

- How predictive is this spectrum for colliders?



Soft Terms: Phenomenology

- All models have the same production scale ($m_{\tilde{g}} \sim 900$GeV) and come from the same high-scale theory!
- There is a big variation in the number of observed di/tri-lepton events.
- But - number of events passing cuts depends on decay modes.
- Di-lepton pairs come from the chain

$$\tilde{\chi}_2 \rightarrow \tilde{l} l^{\pm} \rightarrow \tilde{\chi}_1 l^{\pm} l^{\mp}.$$

- Small changes in slepton masses give large changes in branching ratios.

Conclusions I

- LARGE volume models stabilise moduli and break supersymmetry at a hierarchically small scale with no fine-tuning.
- Soft terms and sparticle spectra can be computed.
- We can calculate all the way 'from string theory to the LHC'.
- Gaugino mass ratios are most robust:

$$M_1 : M_2 : M_3 = 1.5 \rightarrow 2 : 2 : 6$$

- Scalar masses are more uncertain due to brane fluxes.

Conclusions II