A Minimal Model of Supersymmetry Breaking

CERN 2008

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Supersymmetry not an exact symmetry - Needs to be broken.

1. Moduli/Gravity mediated SUSY Breaking (MMSB) at a high ($\sim 10^{11} GeV$) scale by moduli - communicated to visible sector by gravitational strength interactions. Arnowitt, Chamseddin, Nath

2. 'Anomaly' Mediated SUSY Breaking (AMSB) as in 1. but communicated to Visible sector by loop effects. Randall, Sundrum; Giudice et al

3. Gauge Mediated SUSY Breaking (GMSB) happens at low ($< 10^{10} GeV$) scale in a hidden sector communicated via gauge interactions to visible sector. Typically needs a mesenger sector. Dine, Nelson; +...

Experimental inputs:

- CC is tiny $\sim O((10^{-3} eV)^4)$
- No light scalars with gravitational strength coupling
- SUSY partner masses $\gtrsim O(100 GeV)$
- Lightest Higgs $> 114 GeV$
- Flavor changing neutral currents (FCNC) suppressed
- No large CP violating phases

Theory of SUSY breaking must satisfy these.

Better still these should emerge naturally from the theory!

SUSY breaking must be discussed within a SUGRA context.

Global SUSY when broken leads to large +ve CC.

Cannot be cancelled except within SUGRA context.

SUGRA can only be a complete theory within string theory

Include (generic) string theory inputs into the theory

Couplings of (SM or MSSM) and hidden sector functions of moduli

Moduli need to be stable to avoid Brans-Dicke scalars and violations of equivalence principle.

1. MMSB: Most natural in string theory context. Generically - FCNC probem.

2. ‘AMSB’: Needs sequestering to suppress 1. -ve slepton squared masses.

3. GMSB: No FCNC. Need messengers and hidden sector (NOT AS IN 1). String theory embedding? mu and Bmu problem?

Both 2 and 3 achieve absence of FCNC because SUSY breaking communicated by gauge interactions which are flavor neutral.

Both require some suppression of mSUGRA.

AMSB Naturally avoids FCNC like GMSB and unlike MMSB.

But leads to negative squared slepton masses.

Needs SUSY breaking mechanism such as in MMSB.

However what exactly is AMSB?

Original papers appear to depend on Weyl (or conformal) compensator formalism.

But Weyl anomalies need to be cancelled.

Usual arguments need to be revised.

Alternative. Dine and Seiberg (hep-th/0701023), SdA (0801.0578)

A Minimum model even if classically sequestered will have mSUGRA soft masses from quadratic divergences.

$\kappa^2 \equiv 8\pi G_N = M_P^{-2} = 1.$

Action depends on $K(\Phi^A, \bar{\Phi}^{\bar{A}})$, $W(\Phi^A)$, $f(\Phi^A).A = 1, \ldots N$

$I, J \ldots$MSSM fields $N_v \sim 10^2$, $i, j, \ldots$ closed string moduli fields and dilaton $h_{21} + h_{11} + 1$. r, s open string moduli.

$$\begin{aligned}\Delta m^2_{I\bar{J}} &= -R_{I\bar{J}k\bar{l}} F^k F^{\bar{l}} - R_{I\bar{J}K\bar{L}} F^K F^{\bar{L}} \\ &\quad -R_{I\bar{J}r\bar{s}} F^r F^{\bar{s}} + \frac{1}{3} F_I F_{\bar{J}} + K_{I\bar{J}} m^2_{3/2}. \\ &\quad + \ldots\end{aligned}$$

Evaluate at a minimum with

$$F^A \bar{F}^{\bar{B}} K_{A\bar{B}} - 3m^2_{3/2} = 0 \Longrightarrow |F^A| \lesssim m_{3/2}$$

Note: $F^I \sim m_{3/2} Q^I \sim m_{3/2} 10^{-16}$.

1. MMSB $F^m \sim m_{3/2}$, $\Longrightarrow \Delta m_s^2 \sim m_{3/2}^2$, $m_{3/2} \gtrsim 100 GeV$. FCNC problem not resolved - Dilaton dominance - not with all moduli stabilized. No scale models $\Delta m_S^2 = 0$, etc. Cancellation between first and last terms.

2. 'AMSB': Classically second term neglegible. Quantum effects $\rightarrow$ singularity at origin of field space. Effect $\propto \frac{\alpha}{4\pi}\frac{F^I}{Q^I} \sim \frac{\alpha}{4\pi} m_{3/2}$. Need $m_{3/2} \gtrsim 10^4 GeV$ and MMSB suppressed.

3. GMSB: Need to suppress MMSB (i.e. classical effects). Choose min. with $m_{3/2} \ll 100 GeV$. $F^k, F^r \sim m_{3/2}$. Quantum effects give $m_s \sim \frac{\alpha}{4\pi}\frac{F^r}{\phi^r}$. i.e. need $\frac{F^r}{\phi^r} \gtrsim 10^4 GeV$.

Consider GKP-KKLT type model - MSSM on a stack of D3 branes

$$\begin{aligned}
K &= -3\ln(T+\bar{T}-(z^{Q}_{I\bar{J}}Q^I\bar{Q}^{\bar{J}} \\
&\quad +(x_{IJ}Q^IQ^J+h.c.)+\ldots) \\
&\quad -\ln(S+\bar{S})+k(z,\bar{z}) \\
&= K_{mod}+Z_{I\bar{J}}\Phi^I\Phi^{\bar{J}}+\frac{1}{2}(X_{IJ}\Phi^I\Phi^J+h.c.)+\ldots \\
K_{mod} &= -3\ln(T+\bar{T})-\ln(S+\bar{S})+k(z,\bar{z}), \\
&\quad Z_{I\bar{J}}=\frac{3z_{I\bar{J}}}{T+\bar{T}},\ X_{IJ}=\frac{3x_{IJ}}{T+\bar{T}}.
\end{aligned}$$

Grana, Grimm, Haack, Louis

$z_{I\bar{J}}$ independent of z^{α} and x_{IJ} linear to order calculated.

Assume structure valid for chiral models too!

Moduli superpotential:

$$W_{mod} = W_{flux}(S,z) + \sum_n A_n(S,z) e^{-a_n T}$$

MSSM superpotential:

$$\begin{aligned} W_{MSSM} &= \tilde{\mu} H_u H_d + y_{uij} Q^i H_u U^{cj} \\ &\quad + y_{Dij} Q^i H_d D^{cj} + y_{Eij} L^i H_d E^{cj}. \end{aligned}$$

Moduli Potential:

$$\begin{aligned} V_{mod} &= \frac{e^{k(z,\bar{z})}}{(S+\bar{S})(T+\bar{T})^2} \times \\ &\quad \{\frac{1}{3}|\partial_T W_{mod}|^2 - 2\Re \partial_T W_{mod} \bar{W}_{mod}\} \\ &\quad + |F^S|^2 K_{S\bar{S}} + F^z F^{\bar{z}} k_{z\bar{z}} \end{aligned}$$

Local minimum with zero cosmological constant (CC)

SUSY breaking only in the T direction

$$V_{mod}|_0 = 0,\ F|_0^S = F^z|_0 = 0,\ F^T|_0 \neq 0.$$

But T modulus - the scalar partner of the goldstino- has zero mass.

Will be lifted after refinetuning because of quantum effects.

CC fine tunining:

$$F^T F^{\bar{T}} K_{T\bar{T}}|_0 = 3m_{3/2}^2,$$

Need to have $\partial_T W|_0 = 0$ (or $\ll m_{3/2}$)

$$R_{T\bar{T}I\bar{J}} = \frac{1}{3} K_{T\bar{T}} Z_{I\bar{J}} + O(H^2)$$

so

$$m^2_{I\bar{J}} = m^2_{3/2} Z_{I\bar{J}} - F^T F^{\bar{T}} R_{T\bar{T}I\bar{J}} = 0$$

Similarly $B\mu$ A-terms are also zero.

Quadratically divergent quantum effects - need cutoff.

$$\begin{aligned} \Lambda &\sim M_{GUT} \sim M_{KK} \sim 10^{16} GeV \sim 10^{-2} M_P \\ \frac{\Lambda^2}{16\pi^2} &\sim 10^{-6} M_P^2. \end{aligned}$$

Coupling constant unification - only piece of experimental evidence for SUSY!

Should be taken seriously even at cost of additional fine tuning.

Quadratic divergence issues and mSUGRA

Coeff of divergence:

$$\mathrm{Str}M^2(\Phi) \equiv \sum_J (-1)^{2J}(2J+1)\mathrm{tr}M^2(\Phi) \neq 0$$

$$\begin{aligned} V|_0 &= (F^m \bar{F}^{\bar{n}} K_{m\bar{n}} - 3m_{3/2}^2)(1 + \frac{(N-5)\Lambda^2}{16\pi^2}) \\ &+ \frac{\Lambda^2}{16\pi^2}(m_{3/2}^2(N-1) - F^T \bar{F}^{\bar{T}} R_{T\bar{T}}), \\ m_{I\bar{J}}^2 &= V|_0 Z_{I\bar{J}} + (m_{3/2}^2 Z_{I\bar{J}} - F^T F^{\bar{T}} R_{T\bar{T}I\bar{J}}) \times \\ & (1 + \frac{(N-5)\Lambda^2}{16\pi^2}) \\ & - \frac{\Lambda^2}{16\pi^2}('' R^{2}'')O(m_{3/2}^2) \end{aligned}$$

Gaillard and Jain, Ferrara Kounnas Zwirner, Choi, Lee, Munoz hep-ph/9709250.

Classical CC=0 gives

1 loop CC:

$$\frac{\Lambda^2}{16\pi^2} m_{3/2}^2 (N - N_v - 3) = 10^{-6} m_{3/2}^2 M_P^2 (h_{21} - 1)$$

N (N_v) total (visible sector) Chiral superfields.

Need to re-finetune Classical CC to $-ve$ value to cancel this.

A class of solutions:

$$\begin{aligned} |F^T| &= \sqrt{3} m_{3/2} + O(h_{21} \frac{\Lambda^2}{16\pi^2} m_{3/2}) \\ |F^S| &\sim O(\frac{\Lambda}{4\pi} m_{3/2}) \\ |F^z| &\sim O(\frac{1}{\sqrt{h_{21}}} \frac{\Lambda}{4\pi} m_{3/2}) \end{aligned}$$

$$
\begin{aligned}
m'^2_{I\bar{J}} &\sim \frac{\Lambda^2}{16\pi^2} m^2_{3/2}[(h_{21} - 2N_v)Z_{I\bar{J}} + O(?)Z'_{I\bar{J}}] \\
&\sim 10^{-6} m^2_{3/2}[(h_{21} - 2N_v)Z_{I\bar{J}} + O(?)Z'_{I\bar{J}}]
\end{aligned}
$$

Need $h_{21} > 2N_v \sim 10^2$. Generically second term as large as first - need fine tuning at 10^{-3} level. In general expect tuning of fluxes to achieve this.

A terms:

$$
\begin{aligned}
A_{IJK} &= e^{K_m/2} \frac{W_m^*}{|W_m|} \{F^i D_i y_{IJK} (1 + \frac{N-5}{16\pi^2}\Lambda^2) \\
&\quad - \frac{\Lambda^2}{16\pi^2} O(F^T)\}
\end{aligned}
$$

Classical A-terms vanish.

Second term is $\propto y_{IJK}$ but in general first is not. But in our case it is.

μ and $B\mu$ terms:

Again classically zero. Leading quantum effect:

$$\mu_{IJ} = -\bar{F}^{\bar{\alpha}} \partial_{\bar{\alpha}} X_{IJ} = O(\sqrt{h_{21}} \frac{\Lambda}{4\pi} m_{3/2})$$

$$B\mu_{IJ} = V_{classical}|_0 X_{IJ} \sim O(h_{21} \frac{\Lambda^2}{16\pi^2} m_{3/2}^2) \sim O(\mu^2).$$

Gaugino masses:

Again classically zero. Leading quantum effect.

$$\frac{m_a}{g_a^2} = F^m \partial_m f_a \sim F^S \partial_S f_a \sim O(1) \frac{\Lambda}{4\pi} m_{3/2}$$

This (quantum) mSUGRA contribution too low.

Consistency Issues

To cancel quantum contribution to CC need

$$Ae^{-aT} \sim a^{-1}(T+\bar{T})^{1/2} h_{21} \frac{\Lambda^2}{16\pi^2} m_{3/2}$$

Also

$$\frac{1}{T} \sim M_{KK} \sim \Lambda \sim 10^{-2} \Longrightarrow T \lesssim O(10^2)$$

$A \sim O(1)$, $m_{3/2} \sim 10 TeV \sim 10^{-14} M_P$, estimate $a \gtrsim O(1/10)$ $N \sim 10-100$.

SUSY breaking and AMSB/GMSB

$$m_{\Phi}^2(X) = 2\sum_a c^i \left(\frac{\alpha_X^a}{4\pi}\right)^2 (b^a - b'^a)\frac{|F_X|^2}{|X|^2}$$

b'(b) beta function coeff above(below) X -Giudice Rattazzi. Here

$$X^2 = H_u H_d \;\Rightarrow\; \frac{F_X}{X} = \frac{1}{2}\left(\frac{F_u}{v_u} + \frac{F_d}{v_d}\right)$$

$$F_u = \mu v_d + m_{3/2} v_u,\; F_d = \mu v_u + m_{3/2} v_d$$

Assuming $\mu \ll m_{3/2}$

$$m_{\Phi}^2(X) = 2\sum_a c_{\Phi}^a \left(\frac{\alpha_X^a}{4\pi}\right)^2 (b^a - b'^a) m_{3/2}^2.$$

AMSB contribution sum of two terms:

True AMSB contribution:

$$\frac{m_a}{g_a^2} \sim -\frac{b'_a}{8\pi^2}\frac{1}{3}F^i K_i - \sum_r \frac{T_a(r)}{4\pi^2}F^i \partial_i(\ln(e^{-K_{mod}/3}Z_r)$$

GMSB like contribution:

$$\frac{m_a}{g_a^2} \sim \frac{(b^a - b'^a)}{8\pi^2} m_{3/2}$$

In our case the sum gives

$$\frac{m_a}{g_a^2} = -\frac{b_a}{8\pi^2} m_{3/2}$$

mSUGRA + 'AMSB'

$$\Lambda \sim 10^{16} GeV = 10^{-2} M_P$$

$$h_{21} = 3 - 5 \times 10^{2}, \, m_{3/2} \sim 10 - 30 TeV$$

$$\mu \sim \frac{B\mu}{\mu} \sim m_s \gtrsim 100 - 500 GeV$$

$$m_1 \sim m_2 \lesssim 100 GeV, \, m_3 \sim 400 - 1000 GeV$$

Model has features of all three standard mechanisms

- Origin of susy breaking in moduli - transmitted by gravity as in mSUGRA

- Soft parameters quantum effect as in AMSB and GMSB

- Gaugino masses from quantum mSUGRA + 'AMSB'

- 'AMSB' has features of both standard AMSB and GMSB

- $m_{3/2} \sim 10 TeV$ as in AMSB

Tuning issues

Tuning (in addition to CC and $m_{3/2}$) 1 part in 10^3?

But high $m_{3/2}$ compared to EW scale!

To get low value additional tuning

by a factor $\left(\frac{m_{3/2}(high)}{m_{3/2}(low)}\right)^6$ needed Douglas.

So even if classical mSUGRA solution existed

Need additional tuning by $\left(\frac{10^4}{10^2}\right)^6 = 10^{12}$

In GMSB no FCNC tuning needed. So factor is 10^9.

GMSB on another branch? Dine et al

Also need additional sector.

Important to find concrete string theory models.

How generic is this?

In IIB MSSM can also be on 7-branes.

Detailed exposition in LVS - Conlon, Quevedo,...

(To get GUT scale need to fine tune - but see Blumenhagen et al)

Classical soft terms suppressed

$m_s \sim m_{3/2}/\ln m_{3/2}$. As in Choi, Nilles,...

But with GUT scale Λ quadratic divergence contribution of same order.

Gaugino mass: suppressed classical plus quantum effect.

Qualitative phenomenology should be similar to above

Generic property:

Kaehler potential for Kaehler T^i (and complex structure z^α) moduli satisfies.

$$K_A K^A = 3$$

Broken by α' and quantum corrections.

Classical shift symmetries imply W independent of T^i giving no-scale property.

Broken by NP quantum corrections.

If perturbative string theory is to make sense corrections must be small.

Results may be generic consequences of these properties.

Predictive models?

Anything beyond the above - flux dependent.

Eg: sparticle couplings

$$A_{IJK}(z^{\alpha}) = a(z^{\alpha})Y_{IJK}(z^{\alpha}) + \epsilon Y'_{IJK}(z^{\alpha})$$

Models must be such that FCNC violating second term suppresed.

a, Y' predictions - but flux dependent!

Can have very large number of solutions satisfying std model constraints.