

What do we expect from SUSY

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- 1. Introduction: soft SUSY-breaking terms and flavour universality
- Gauge Mediation and the status of pure Gauge Mediation
 3 types of experimental constraints
- Living with heavy (few TeV) scalars: return of generic gravity models without flavour universality Comments on fine-tuning.
- 4. Conclusions
- ---- Here will not consider models which try to split flavours by making stops much lighter than first two generations; no `flavoured' gauge mediation.

Also will mostly stick to the MSSM reasoning.

Soft SUSY breaking terms (MSSM)

Majorana gaugino masses (complex):

 M_1 , M_2 , M_3 Squark and slepton squared masses (3 × 3 matrices, real): m_Q^2 , $m_{\bar{u}}^2$, $m_{\bar{d}}^2$, m_L^2 , $m_{\bar{e}}^2$

Higgs-sector masses (real):

 $\mathcal{L}_{eff} \supset m_u^2 |H_u|^2 + m_d^2 |H_d|^2 + (B_\mu H_u H_d + c.c.)$

The μ -parameter (not a soft term; complex):

 $\mathcal{W}_{eff} \supset \mu H_u H_d$

Trilnear scalar self-couplings (complex):

 $\mathcal{L}_{eff} \supset a_u^{ij} H_u Q^i \bar{u}^j + a_d^{ij} H_d Q^i \bar{d}^j + a_L^{ij} H_d L^i \bar{E}^j$

Flavour universality

Dangerous flavour-chaging (FCNC) processes in SUSY extensions of the SM are automatically evaded if one assumes (or can justify) the universal flavour structure of the soft terms:

$$\mathbf{m}_{\mathbf{Q}}^{2} = \begin{pmatrix} m_{Q}^{2} & 0 & 0 \\ 0 & m_{Q}^{2} & 0 \\ 0 & 0 & m_{Q}^{2} \end{pmatrix}, \ \mathbf{m}_{\bar{\mathbf{u}}}^{2} = \begin{pmatrix} m_{\bar{u}}^{2} & 0 & 0 \\ 0 & m_{\bar{u}}^{2} & 0 \\ 0 & 0 & m_{\bar{u}}^{2} \end{pmatrix}, \ \mathbf{m}_{\bar{\mathbf{d}}}^{2} = \begin{pmatrix} m_{\bar{d}}^{2} & 0 & 0 \\ 0 & m_{\bar{d}}^{2} & 0 \\ 0 & 0 & m_{\bar{d}}^{2} \end{pmatrix}$$
$$\mathbf{m}_{\mathbf{L}}^{2} = \begin{pmatrix} m_{L}^{2} & 0 & 0 \\ 0 & m_{L}^{2} & 0 \\ 0 & 0 & m_{L}^{2} \end{pmatrix}, \ \mathbf{m}_{\bar{\mathbf{e}}}^{2} = \begin{pmatrix} m_{\bar{e}}^{2} & 0 & 0 \\ 0 & m_{\bar{e}}^{2} & 0 \\ 0 & 0 & m_{\bar{e}}^{2} \end{pmatrix}$$

and also that the trilinear couplings $\mathbf{a} \propto \mathbf{yukawa}$:

$$\mathbf{a}_{\mathbf{u}} = \left(\begin{array}{ccc} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a_{u} \end{array}\right) \ , \ \mathbf{a}_{\mathbf{d}} = \left(\begin{array}{ccc} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a_{d} \end{array}\right) \ , \ \mathbf{a}_{\mathbf{L}} = \left(\begin{array}{ccc} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & a_{L} \end{array}\right)$$

at the high scale M_{mess} or M_{Pl} .

Flavour universality

Gauge mediation is automatically flavour universal.

At the messenger scale it is *flavour-independent by construction*:

$$m_{\tilde{f}}^{2}(M_{mess}) = 2 \sum_{i=1}^{3} C_{i}k_{i} \frac{\alpha_{i}^{2}(M_{mess})}{(4\pi)^{2}} \Lambda_{S}^{2} \times 1_{3\times3}$$
$$a_{u/d/L}(M_{mess}) = A_{0}(M_{mess}) \times yukawa = 2loop \simeq 0$$

Below the messenger scale, this universality is not de-tuned by the RGE:

$$\mathbf{m}_{\mathbf{Q}}^{2} = \begin{pmatrix} m_{Q_{1}}^{2} & 0 & 0 \\ 0 & m_{Q_{1}}^{2} & 0 \\ 0 & 0 & m_{Q_{3}}^{2} \end{pmatrix} , \ \mathbf{m}_{\bar{\mathbf{u}}}^{2} = \begin{pmatrix} m_{\bar{u}_{1}}^{2} & 0 & 0 \\ 0 & m_{\bar{u}_{1}}^{2} & 0 \\ 0 & 0 & m_{Q_{3}}^{2} \end{pmatrix} , \ \mathbf{m}_{\bar{\mathbf{d}}}^{2} = \begin{pmatrix} m_{\bar{d}_{1}}^{2} & 0 & 0 \\ 0 & m_{\bar{d}_{1}}^{2} & 0 \\ 0 & 0 & m_{\bar{d}_{3}}^{2} \end{pmatrix}$$
$$\mathbf{m}_{\mathbf{L}}^{2} = \begin{pmatrix} m_{L_{1}}^{2} & 0 & 0 \\ 0 & m_{L_{1}}^{2} & 0 \\ 0 & 0 & m_{L_{3}}^{2} \end{pmatrix} , \ \mathbf{m}_{\bar{\mathbf{e}}}^{2} = \begin{pmatrix} m_{\bar{e}_{1}}^{2} & 0 & 0 \\ 0 & m_{\bar{e}_{1}}^{2} & 0 \\ 0 & 0 & m_{\bar{e}_{3}}^{2} \end{pmatrix}$$

Flavour universality

Gravity mediation is not. It is not guaranteed to be flavour-blind.

One can *set* it to be flavour-blind by assuming a minimal form of the Kahler potential, e.g. in the CMSSM one *chooses:*

$$M_{3} = M_{2} = M_{1} = m_{1/2},$$

$$\mathbf{m}_{\mathbf{Q}}^{2} = \mathbf{m}_{\mathbf{u}}^{2} = \mathbf{m}_{\mathbf{d}}^{2} = \mathbf{m}_{\mathbf{L}}^{2} = \mathbf{m}_{\mathbf{e}}^{2} = m_{0}^{2} \mathbf{1}, \qquad m_{H_{u}}^{2} = m_{H_{d}}^{2} = m_{0}^{2},$$

$$\mathbf{a}_{\mathbf{u}} = A_{0} \mathbf{y}_{\mathbf{u}}, \qquad \mathbf{a}_{\mathbf{d}} = A_{0} \mathbf{y}_{\mathbf{d}}, \qquad \mathbf{a}_{\mathbf{e}} = A_{0} \mathbf{y}_{\mathbf{e}},$$

$$b = B_{0} \mu,$$

But even then, this universality would generally be de-tuned by the RG evolution down from the Planck scale to the Flavour Symmetry Breaking (flavour messenger scale). See e.g. Calibbi, Lalak, Pokorski, Ziegler 1203.1489

...unless one assumes some underlying symmetry from unknown higher theory...

2. Gauge mediation



Messenger fields are coupled to the SUSY-breaking sector and to the SM sector. Importantly, in the SM sector they are coupled only to gauge multiplets, not to the matter fields.

Gauge mediation manifestly does not give raise to new flavour changing processes since SM gauge interactions are flavour blind.

LSP of gauge mediation is gravitino. Contrary to gravity mediation the NLSP is neutralino or stau and it will ultimately decay into gravitino (inside or outside of the detector). A possibility of gravitino dark matter.

Gaugino masses are generated by:



Scalar masses squared are generated by:



[in a one-scale model $\Lambda_G \simeq \Lambda_S = \frac{F}{M_{\text{mess}}}$.]

Pure General Gauge Mediation

Abel, Dolan, Jaeckel, VVK 0910.2674 and 1009.1164

GGM models with 3 input parameters, Λ_G , Λ_S and M_{mess} . and $B_0 = 0, A_0 = 0$.

EWSB and Z-mass determine μ and $\tan\beta$. Take $\mu\Lambda_G = \text{Real}$.

This is a vanilla gauge mediation with automatic flavour and CP-conservation and minimal number of parameters — theoretically sound and predictive .

Gaugino and scalar masses are determined via

$$M_{\tilde{\lambda}_i}(M_{mess}) = k_i \frac{\alpha_i(M_{mess})}{4\pi} \Lambda_G$$

$$m_{\tilde{f}}^2(M_{mess}) = 2 \sum_{i=1}^3 C_i k_i \frac{\alpha_i^2(M_{mess})}{(4\pi)^2} \Lambda_S^2$$

Pre-LHC: Pure GGM compact parameter space



Yellow is excluded by tachyons; Black is excluded by pre-LHC direct search limits. In the blue region SoftSUSY has not converged and in the green region a coupling reaches a Landau pole during RG evolution. The red dotted line indicates the ordinary gauge mediation scenario where $\Lambda_G = \Lambda_S$.











LHC searches

- Jets and Missing Energy searches of gluinos and squarks (at 940 GeV and 1380 GeV in simplified models)
- Serches of stable (or long-lived) charged superpartners: $\tilde{\tau}$ (a) model-independent Drell-Yan -based exclusion $m_{\tilde{\tau}} \ge 223 \text{GeV}$

(b) more model-dependent exclusion $m_{ au} \geq 314 {
m GeV}$

• Higgs exclusions and the possibility of 125 GeV Higgs.

Jets and MET searches of SUSY (ATLAS & CMS)



ATLAS 4.7 fb⁻¹ at $\sqrt{s} = 7$ TeV complete 2011 sample

Searches for long-lived stau's



The model-independent limit on pair-produced stau is $m_{\tilde{\tau}} \geq 223 \text{GeV}$.

The model-dependent GMSB limit is $m_{\tilde{\tau}} \geq 314 \text{GeV}$.

Pure GGM @ M=10⁸ GeV what's left of...



88 125-127 GeV Higgs world













Pure GGM, or what's left of it:

Vanilla gauge mediation – pGGM – highly predictive, falsifiable & clean theoretical set-up:

- Jets & MET + long-lived stau + Higgs searches give complimentary info and coverage of the parameter space.
- 2. Higgs @ 125 GeV pushes scalars to ~4-6-8 TeV region.
- 3. Starting to run out of parameter space for these models even though extreme top end hard to exclude at the LHC-

=> need to re-examine theoretical motivation for gauge mediation => re-examine need for flavour and CP-universality.

Return of general gravity models SUSY with sfermions in the TeV range:

In the remaining part of the talk I'll argue that:

If we accept having all squarks and sleptons in the TeV (or 10 TeV) range – there is no immediate need to restrict our SUSY models at the high scale to be flavour-universal (same for CP).

In gravity mediation expect that roughly the same effect ~ F/M_{Pl} governs all *diagonal* and *off-diagonal* entries for masses of *squarks* and of *sleptons* as well as the *a-terms* (at the high input scale):

i.e. if the input for squark masses is a few TeV => from universality of gravity it is likely that same few TeV is the input value for slepton masses. Also no a priori difference between diagonal and off-diagonal elements.

Flavour violation

Experimental constraint MEGA collaboration:



Already at $m_{\tilde{l}_R} = 3$ TeV get $1.2 \times 10^{-6} \times 10^{-6}$

The off-diagonal ratio can be ~ 1

Flavour violation

Fine-tuning in $Br(\mu \rightarrow e\gamma)$

Take a non-diagonal \mathbf{m}^2_Q matrix and diagonalise it:

$$\mathbf{m}_{\mathbf{L}}^{2} = \begin{pmatrix} m_{0}^{2} & \delta m^{2} & 0\\ \delta m^{2} & m_{0}^{2} & 0\\ 0 & 0 & m_{0}^{2} \end{pmatrix} \Longrightarrow \begin{pmatrix} m_{1}^{2} & 0 & 0\\ 0 & m_{2}^{2} & 0\\ 0 & 0 & m_{0}^{2} \end{pmatrix}$$

where $m_{1,2}^2 = m_0^2 \pm \delta m^2$. The measure of flavour fine-tuning is

$$\frac{m_1^2}{\mathsf{Br}} \frac{\partial \mathsf{Br}}{\partial m_1^2} \simeq \frac{m_0^2}{\delta m^2} \simeq \left(\frac{100 \,\mathrm{GeV}}{m_0}\right)^2 \sqrt{\frac{10^{-5}}{\mathsf{Br}}} = 10 \times \left(\frac{1 \,\mathrm{TeV}}{m_0}\right)^2$$

Check against the usual fine-tuning arising from the EW scale

$$\frac{m_1^2}{v^2} \frac{\partial v^2}{\partial m_1^2} \simeq \frac{m_0^2}{m_z^2} \simeq 500 \quad \text{at } m_0 = 2,000 \text{ GeV}$$

they run in opposite directions with m_0 .

Flavour violation

More extreme (most extreme) constraint areises from $K^0 \leftrightarrow \overline{K}^0$



At $m_{\tilde{q}} = 10$ TeV the off-diagonal mass-squared ratio is ~ 0.02 On the other hand it gives a huge fine-tunning for lighter scalars.

Flavour versus EW-scale fine-tuning

Measures of fine-tuning: $\Delta_{\mu \to e\gamma} = \frac{m_0^2}{\delta m^2} \simeq 10^3 \times \left(\frac{100 \text{ GeV}}{m_0}\right)^2$ and $\Delta_{K^0\leftrightarrow\overline{K}^0} = \frac{m_0^2}{\delta m^2} = 10^4 \times \frac{100 \text{ GeV}}{2m_0} \text{ vs the usual } m_Z\text{-scale fine-tuning}$ $\Delta_{m_Z} = \frac{m_0^2}{m_z^2}$ m_0 (GeV)

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CP violation

Allow general CP-violating phases into the underlying SUSY theory

$$\operatorname{Arg}(a_d^*M_i), \quad \operatorname{Arg}(a_u\mu), \quad \operatorname{Arg}(a_d\mu), \quad \operatorname{Arg}(a_L\mu)$$

not assuming any need to impose CP-universality: How heavy should the SUSY scalars be to decouple CP-violation?

Experimental limits on EDM's of neutron, electron and mercury atom:

$$d_n < 2.9 \times 10^{-26} e \text{ cm} \quad \text{for a review see Ibrahim \& Nath}$$

$$d_e < 1.7 \times 10^{-27} e \text{ cm}$$

$$d_n < 2 \times 10^{-28} e \text{ cm}$$

$$f_{f_L} = \int_{\tilde{g}, \tilde{\chi}^+, \tilde{\chi}^0}^{\tilde{g}} \int_{f_R}^{\tilde{g}} \int_{\tilde{g}}^{\tilde{g}} \int_{\tilde{g}}^{\tilde{g}}$$

CP violation

plot from Abel, Khalil, Lebedev 0103320



We thus conclude: Scalar masses > 2.5 TeV – to – 10 TeV make CP-violation go away!

Conclusions

SUSY with sfermions in the TeV range:

Part 1: status of pure Gauge Mediation models & experimental constraints => 4 - 8TeV squarks (driven by 125 GeV Higgs, but also by direct searches)

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SUSY with sfermions in the TeV range:

Part 1: status of pure Gauge Mediation models & experimental constraints => 4 - 8TeV squarks (driven by 125 GeV Higgs, but also by direct searches)

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Part 2: A strong argument in favour of *generic* Gravity Mediation (or other completely general models).

-This is not `the' Split SUSY – scalar masses are ~1-10 TeV not at MPlanck.

- Fine-tuning arising from stabilising the electro-weak scale is complemented by fine-tuning to erase FCNC and CP, the latter favour large scalar masses.



B and mu in pGGM

In pure GGM we have no direct couplings of the SUSY-breaking sector to the Higgs sectorand $B_{\mu} \approx 0$ at the messenger scale.

From this B_{μ} is generated radiatively at the electroweak scale.

 $\tan\beta$ and μ are obtained from the requirement of electroweak symmetry breaking.

 B_{μ} is responsible for communicating the vev of H_u to H_d , hence the ratio of these two vevs, tan β is large.

Alternatively, one can use a more common approach where $\tan \beta$ is an arbitrary input and B_{μ} at the high scale is obtained from it. This is no longer a simple vanilla gauge mediation, but not much changes apart from $\tan \beta$ not constrained to be large.

Pure GGM: generating B and tan(beta)



Left: radiative generation of B .

Right: $\tan \beta$ obtained from the electroweak breaking. Contours of $\tan \beta = 20, 30, 40, 50$.