A quivery road towards Natural Gauge Mediation

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Based on work in collaboration with
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Outline

- SUSY models and a Higgs at ~126 GeV

- Quivers, SUSY breaking and D-terms

- An electroweak quiver...

- ...and its phenomenology

- Summary and open questions

The Higgs boson mass in the MSSM

- In the MSSM, in the limit of quasi-degenerate L/R stops, the one-loop Higgs mass can be written as

$$m_h^2 \simeq m_z^2 \cos 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v_{ew}^2}\left[\ln\frac{M_S^2}{m_t^2} + \frac{X_t^2}{M_S^2}\left(1 - \frac{X_t^2}{12 M_S^2}\right)\right]$$

Tree-level limit

One-loop contribution

→ The loop contributions must become comparable to the tree-level ones.

- Take the (unmixed) stops to be heavy, for $m_h \sim 125.5$ GeV, typically $M_s > 5$ TeV.

Naturalness and heavy (undetectable) spectrum issues

- Consider maximal stop mixing : $X_t = A_t - \mu \cot\beta \sim \sqrt{6}\, M_s$.

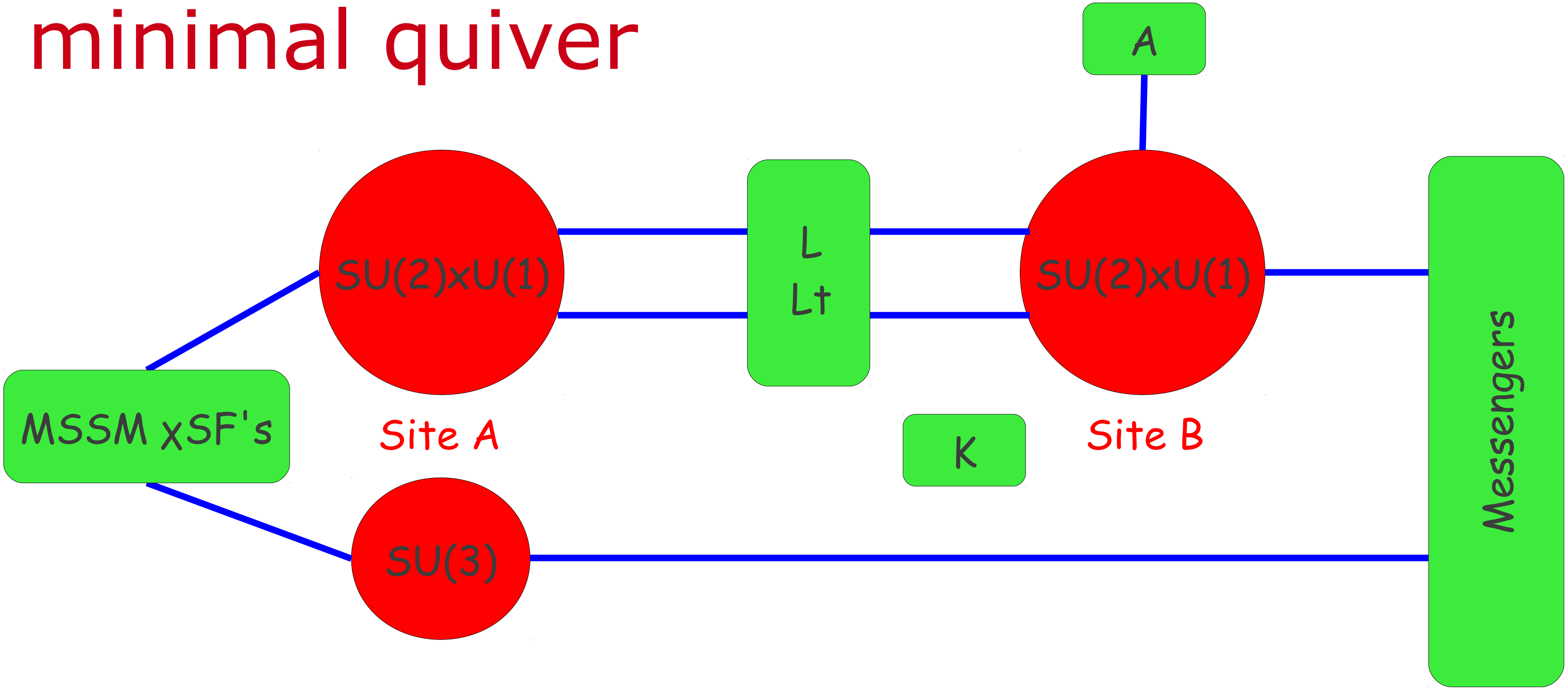
Feasibility depends on the supersymmetry breaking mechanism

e.g. Brümmer, Kraml, Kulkarni (2012)

- In particular, in GMSB A_t is zero at the messenger scale

Essentially impossible to get maximal stop mixing.

A minimal quiver



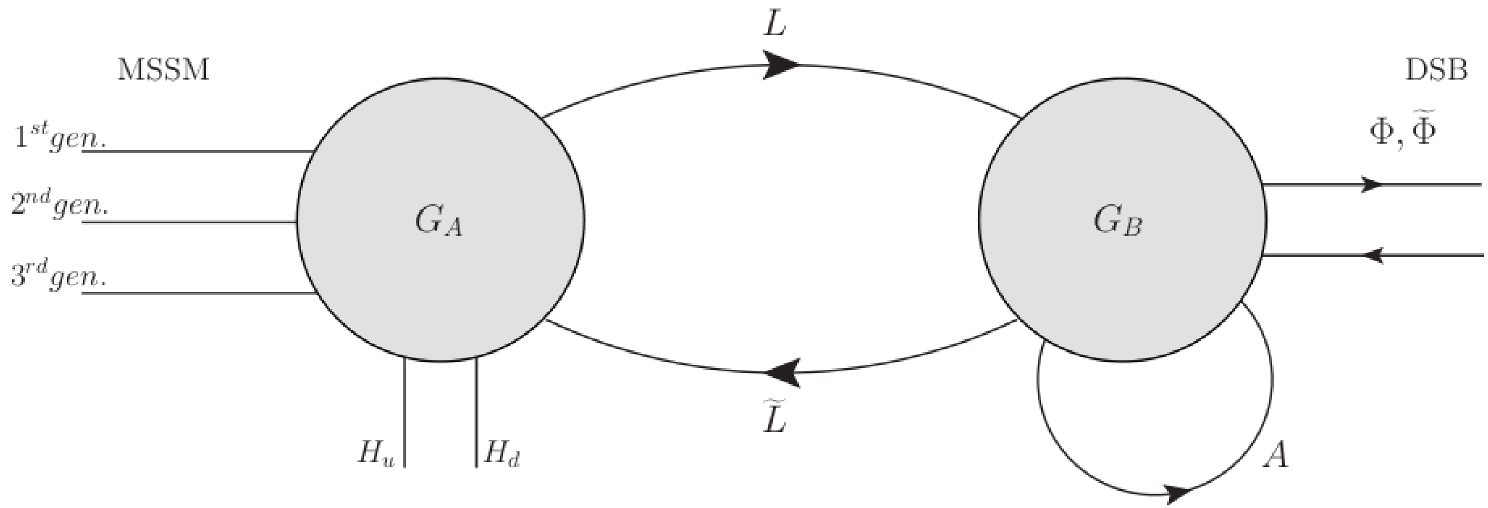
- Start form the usual mGMSB setup.

- Interject between SU(2)xU(1) and the messenger sector another SU(2)xU(1) gauge group and only charge the messengers under site B and SU(3).

- Introduce a pair of bifundamentals L, Lt to break $(SU(2)xU(1))^2$ down to the diagonal.

- Finally, introduce a B-adjoint A and a singlet K to give masses to all L, Lt components.

Minimal QGMSB : basic setup



We consider an EW quiver with all MSSM χSFs charged under site A and messengers under site B. The superpotential we adopt reads :

$$W_{\rm SSM} = Y_u\, \hat{u}\, \epsilon_{ij} \hat{q}^i\, \hat{H}_u^j \, - Y_d\, \hat{d}\, \epsilon_{ij} \hat{q}^i\, \hat{H}_d^j \, - Y_e\, \hat{e}\, \epsilon_{ij} \hat{l}^i\, \hat{H}_d^j \, + \mu \epsilon_{ij}\, \hat{H}_u^i\, \hat{H}_d^j$$

$$W_{\rm Quiver} = \frac{Y_K}{2} \hat{K}(\, \hat{L}_i^j\, \hat{\tilde{L}}_j^i \, - V^2) + Y_A\, \hat{L}_i^j\, \hat{A}_j^k\, \hat{\tilde{L}}_k^i$$

NB1 : full MSSM quiver left for the future (work in progress, technically challenging!)
NB2 : the model can be combined with any supersymmetry breaking mechanism.

Minimal QGMSB : some features

Minimizing the resulting scalar potential we get

$$SU(2)_A \otimes SU(2)_B \rightarrow SU(2)_L \quad , \quad U(1)_A \otimes U(1)_B \rightarrow U(1)_Y$$

with the MSSM χSFs transforming in the usual way under the MSSM gauge group, and the heavy gauge bosons picking up masses as

$$m^2_{v,i} = 2(g^2_{A,i} + g^2_{B,i})v^2$$

Moreover, in our GMSB framework :

- Site B gauginos/scalars and linking scalars pick up standard GMSB masses.

- Site A gauginos are massless at the messenger scale.

- Site A scalar soft masses get modified as SUSY breaking is mediated along the quiver :

The site A soft masses can be suppressed wrt to minimal GMSB
→ interesting for the LHC :)

Minimal QGMSB : the Higgs mass

The key point is that once we integrate out the linking field scalars, an effective D-term Lagrangian is generated in the low-energy theory.

e. g. Batra, Delgado, Kaplan, Tait (2004)

So, instead of being bounded by m_z , the tree-level Higgs mass now becomes

$$m_{h,0}^2 = \left[m_z^2 + \left(\frac{g_1^2 \Delta_1 + g_2^2 \Delta_2}{2} \right) v_{ew}^2 \right] \cos 2\beta$$

where

$$\Delta_1 = \left(\frac{g_{A1}^2}{g_{B1}^2} \right) \frac{m_L^2}{m_{v1}^2 + m_L^2} \quad , \quad \Delta_2 = \left(\frac{g_{A2}^2}{g_{B2}^2} \right) \frac{m_L^2}{m_{v2}^2 + m_L^2}$$

- Site A must be stronger than site B.

- The linking field soft mass must be as close as possible to the heavy gauge boson mass, without getting too large : they introduce some (milder) additional fine-tuning.

Blum, d'Agnolo, Fan (2012)

Implementing a quiver framework

We can use the SARAH package to do part of the hard work for us!

Staub (2008, 2012, 2013)

What we get as output :

- Two-loop renormalization group equations for ***all*** model parameters.

- One-loop tadpole equations.

- One loop sparticle mass and two-loop Higgs mass calculation routines.

→ All of these in fortran form, straightforwardly taken over by the SPheno spectrum generator to do the numerics.

Well, there's still quite a bit of work to be done, e.g. :

- Include important threshold corrections, not computed by default.
→ For MSSM scalars coming from integrating out the linking field scalars.

- Supply whatever pieces of the effective action are needed.
→ The extra D-terms have been added by hand.

The parameter space

$$2.1 \times 10^5 \ \text{GeV} \leq M \leq 3.0 \times 10^5 \ \text{GeV}$$

(Because it works!) (Because it works!)

$$4.0 \times 10^4 \ \text{GeV} \leq \Lambda_{1,2} \leq 1.9 \times 10^5 \ \text{GeV}$$

(LEP chargino bound) (For light sleptons)

$$1.9 \times 10^5 \ \text{GeV} \leq \Lambda_3 \leq 2.1 \times 10^5 \ \text{GeV}$$

(gluino mass > 1.6 TeV) (Stop mass < 2 TeV)

$$1 \times 10^7 \ \text{GeV}^2 \leq m_L^2 \leq 1 \times 10^8 \ \text{GeV}^2$$

(For Higgs mass) (For fine-tunning)

$$1.5 \times 10^4 \ \text{GeV} \leq v \leq 4 \times 10^4 \ \text{GeV}$$

(Because it works!) (For Higgs mass)

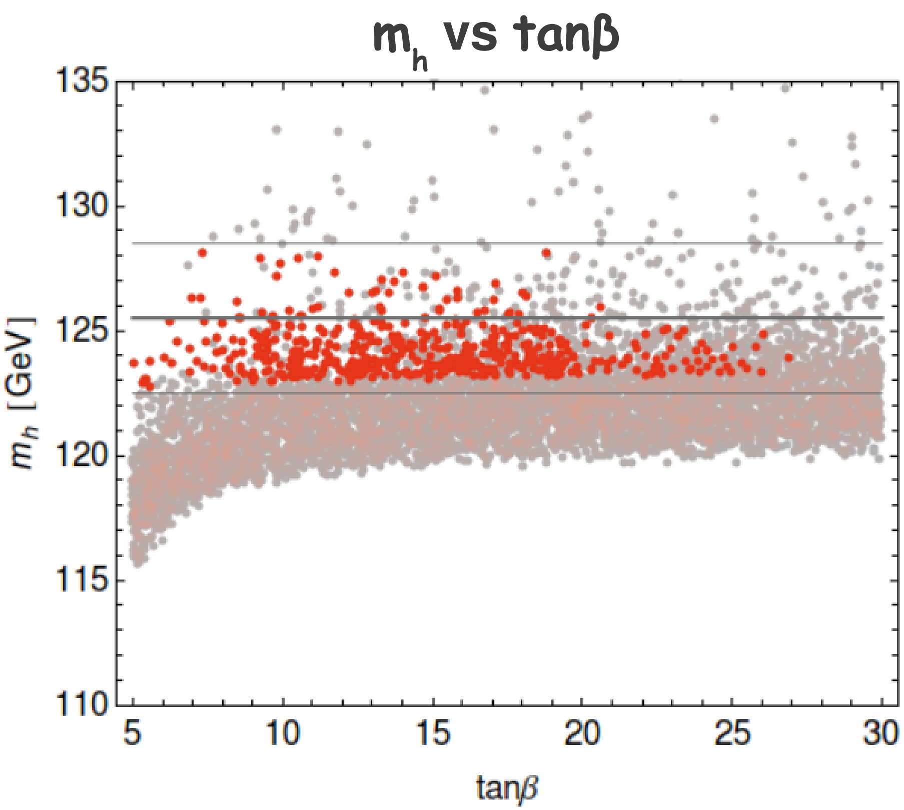
$$5 \leq \tan\beta \leq 30$$

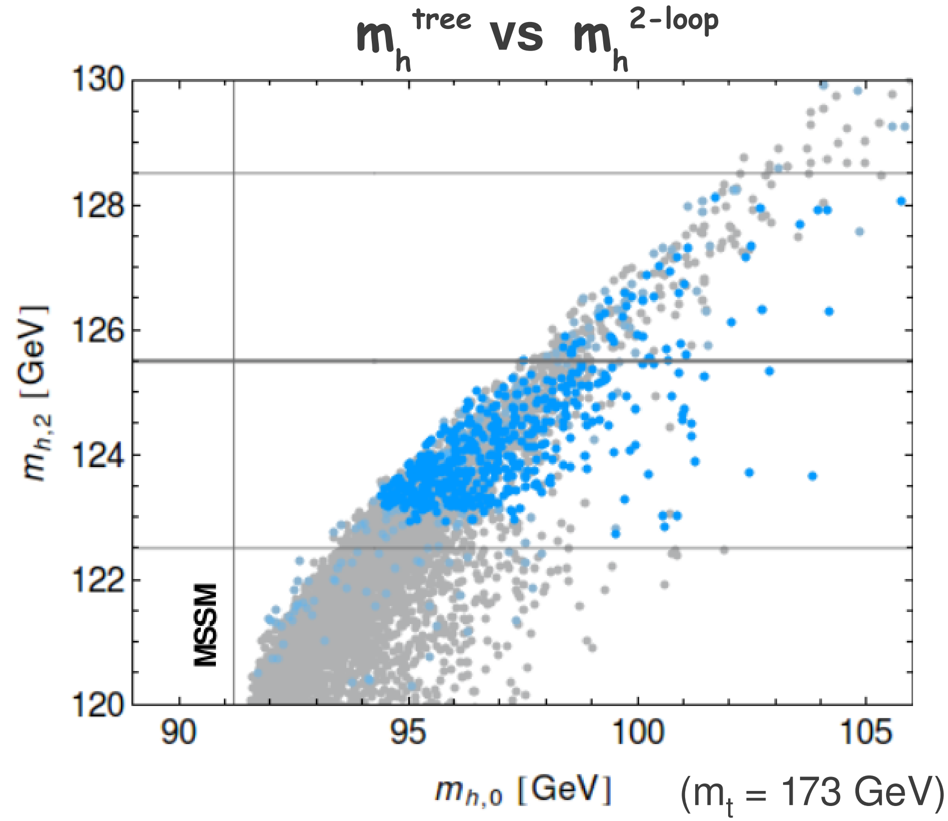
(Standard MSSM region)

(For Higgs mass)

$$0.8 \leq \theta_1, \theta_2 \leq 1.4$$

The Higgs boson mass





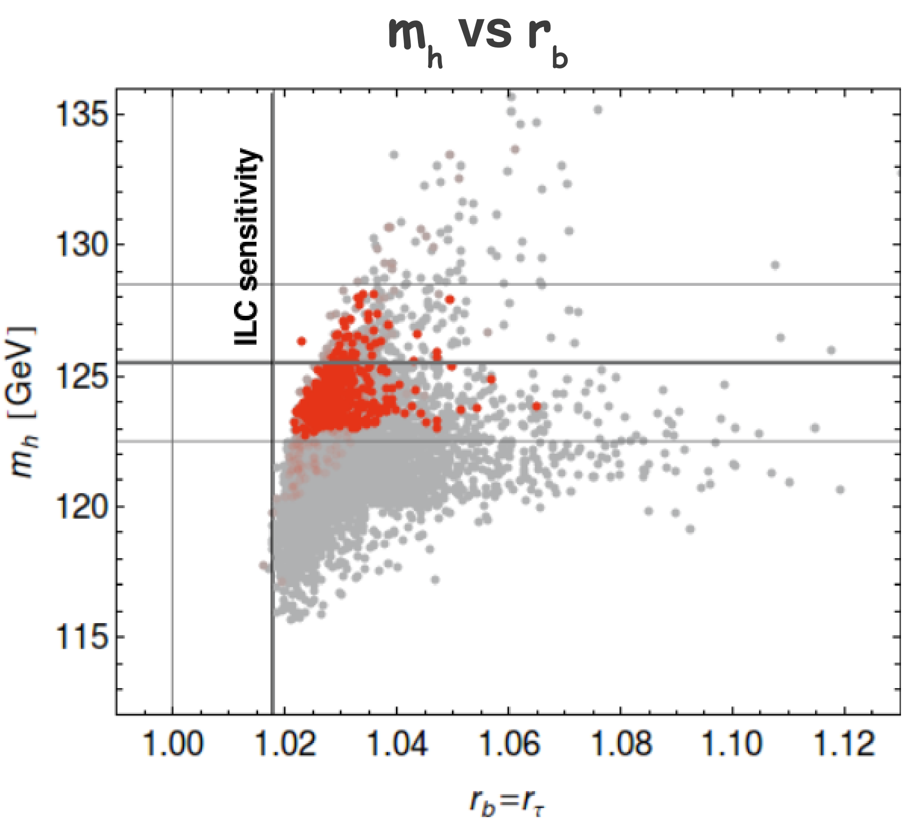
NB: The density of points has no statistical significance!

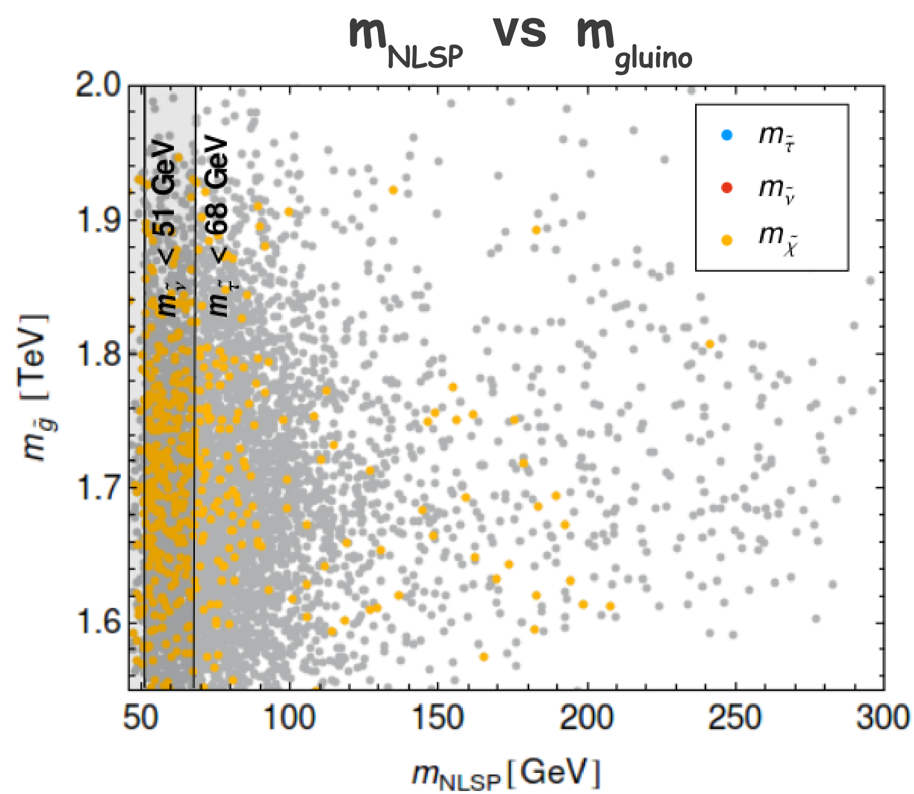
→ We have imposed stops to be lighter than 2 TeV.

→ A Higgs mass of ~126 GeV can be easily accommodated in both variants, even for small values of tanβ.

→ The gluino bound turns out to be *the* crucial factor.

The Higgs couplings and the NLSP





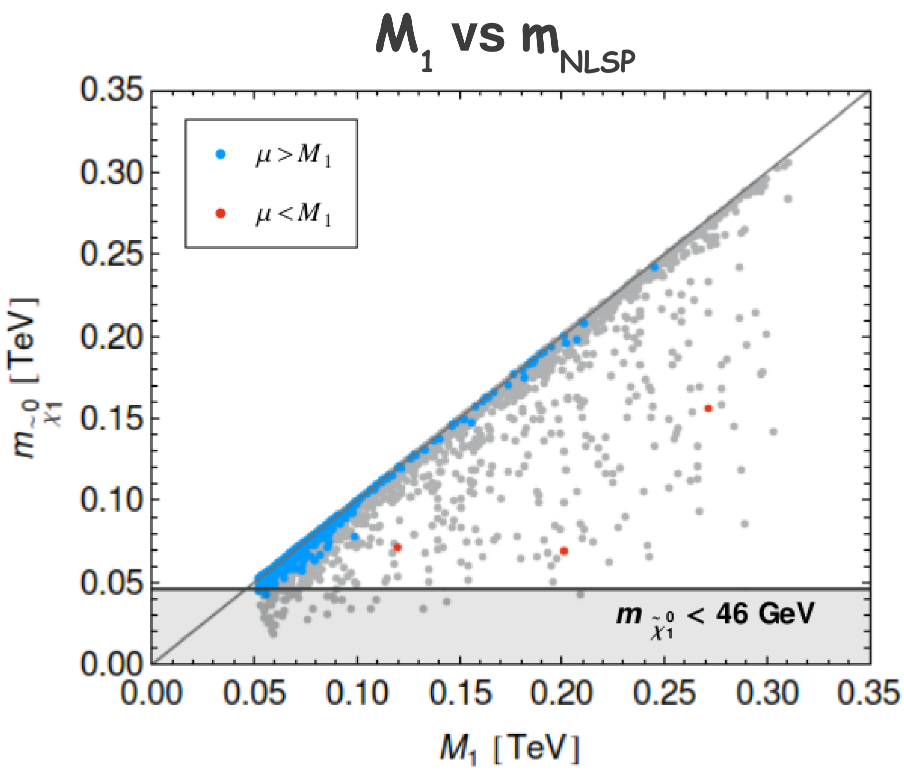
Do the D-terms dangerously enhance d-type higgs couplings? Not really...

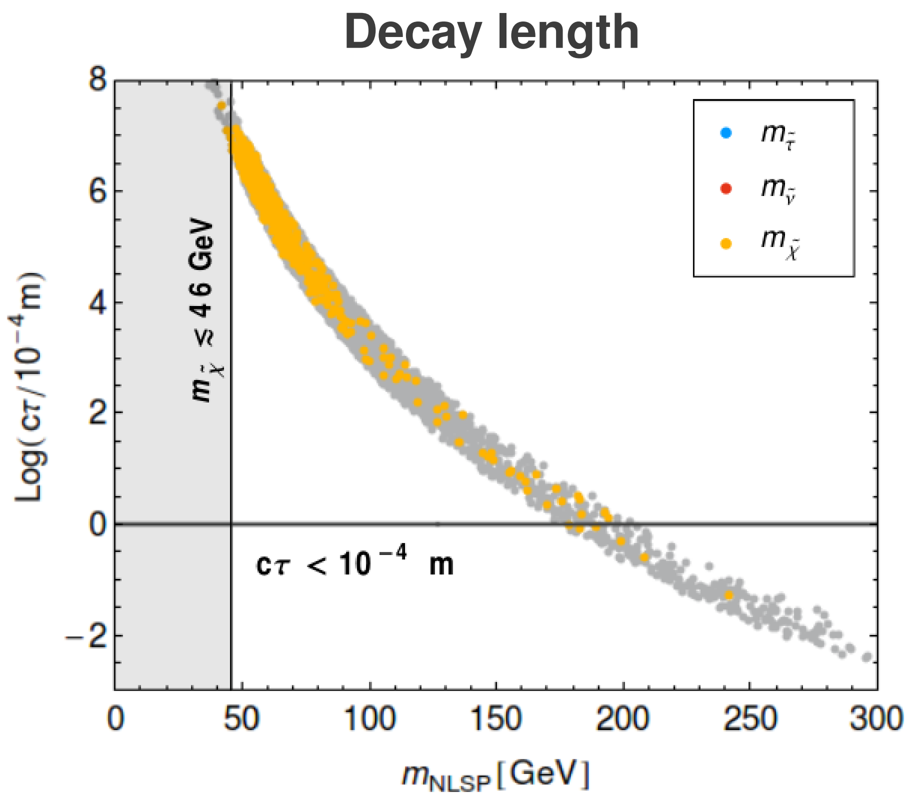
→ h → bb was is very uncertain. h → ττ didn't even exist until recently.

→ The D-term contribution is often taken to be too large.

→ At the LHC, we can expect and O(10%) sensitivity.
→ But the ILC can test essentially the full mechanism!

Nature of neutralino NLSPs and decays





→ By far mostly Bino NLSPs, with some Higgsinos appearing here and there.

→ Both prompt and desplaced NLSP decays are possible.

→ The NLSP nature determines the basic search channels : Binos decay to photons and gravitinos, so look for $\gamma\gamma + E_T^{Miss}$ (+j) or for $\gamma bb + E_T^{Miss}$ in the case of Higgsinos. For sleptons, we look for $l + E_T^{Miss}$.

Open questions

- With the minimal $(SU(2) \times U(1))^2$ setup, the linking soft mass seems to be too low if computed properly : need to devise ways to raise it! Could the (more theoretically motivated) full quiver do the trick?

- Funnily, substantial enhancement of the Higgs mass is possible, but the stop mass still needs to be relatively high due to the gluino mass bound! Ways to bring it down?

- The full quiver should also help with this issue: the stops should be lighter. Maybe possible to restore universality in strong/EW GMSB scales.

- What is the role of kinetic mixing in this story? It should be there!

- A more detailed collider phenomenology of such models? The tools are in principle there.

- What about dark matter phenomenology? Does the gravitino have the correct properties?

Is all this going too far?

What do *you* think :)

Thank you!

Some constraints more concretely

- Low-energy observables (computed by SPheno).

Observable	Accepted range
$B_s \to X_s \gamma$	$[2.78, 4.32] \times 10^{-4}$
δa_μ	$< 20 \times 10^{-10}$
$\Delta\rho$	$< 1.2 \times 10^{-3}$
$BR(B_s \to \mu^+\mu^-)$	$< 7.7 \times 10^{-9}$

- Gluinos heavier than 1600 GeV (from jets + E_T^{Miss}, a bit severe but safe!).

- LEP chargino searches.

- Higgs mass should lie within the region [122.5,128.5] GeV (Th+Exp uncertainties).

- Higgs observables have been checked by interfacing with HiggsBounds.

- Higgs signal strengths have been computed by linking to HiggsSignals.

The trilinear couplings

In our electroweak quiver, the β-functions for the trilinears are given by

$$16\pi^2 \frac{d}{dt} A_t \simeq A_t \left[9 y_t^* y_t + y_b^* y_b - \frac{16}{3} g_3^2 - 3 g_{A2}^2 - \frac{13}{15} g_{A1}^2 \right] + y_t \left[\frac{32}{3} g_3^2 m_{\tilde{g}} + 6 g_{A2}^2 m_{\tilde{W}_A} + \frac{26}{15} g_{A1}^2 m_{\tilde{B}_A} \right] + 2 a_b y_b^* y_t$$

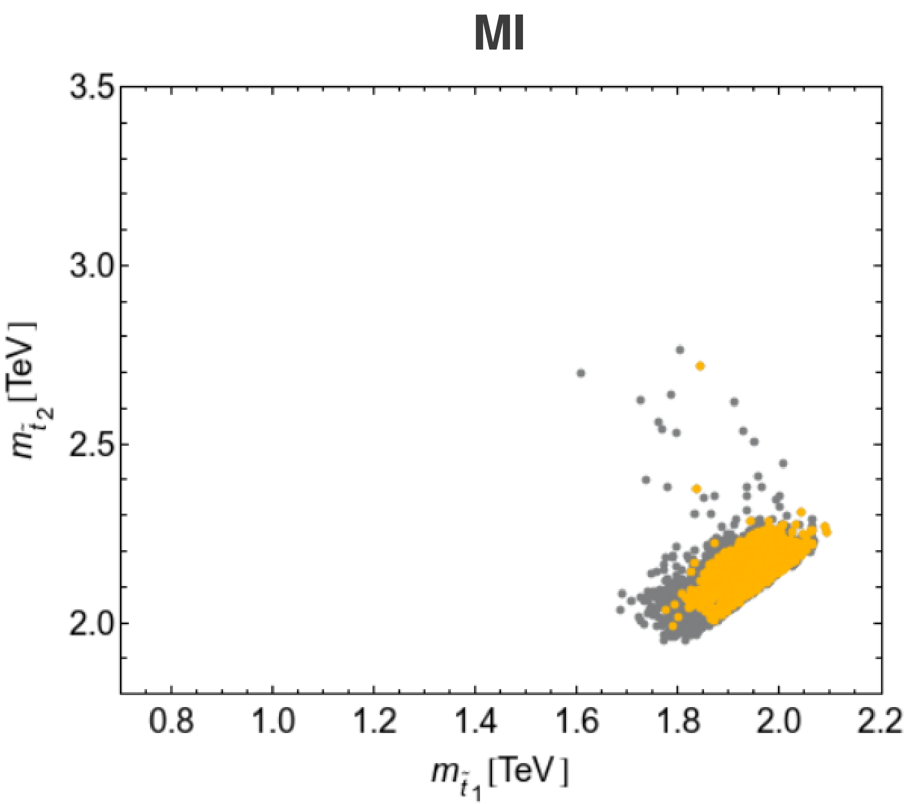
To be compared to the MSSM expressions

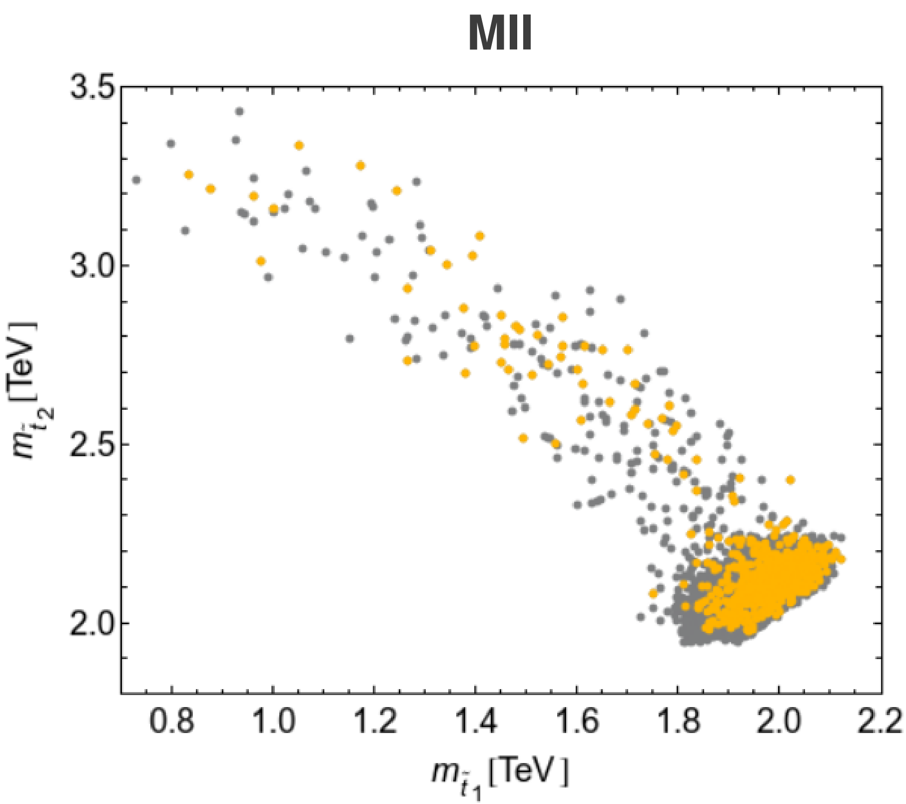
$$16\pi^2 \frac{d}{dt} A_t \simeq A_t \left[18 y_t^* y_t + y_b^* y_b - \frac{16}{3} g_3^2 - 3 g_2^2 - \frac{13}{15} g_1^2 \right] + y_t \left[\frac{32}{3} g_3^2 m_{\tilde{g}} + 6 g_2^2 m_{\tilde{W}} + \frac{26}{15} g_1^2 m_{\tilde{B}} \right] + 2 a_b y_b^* y_t$$

→ MI tends to predict slightly larger trilinears.
(Far from the maximal mixing regime though...)

→ Interestingly though, MII predicts quite a bit of L/R stop splitting.

Stop splitting in MI and MII





→ Notice the tail in MII, which ends up giving roughly the same M_s value.

→ Compensates the larger trilinears of MI, so both models roughly predict the same Higgs masses.

→ Note that the NLSP decays promptly to the gravitino.

The additional fine-tuning

If one requires e.g. no more than 10% additional fine-tuning, the latter can be estimated through

$$\frac{g_{SM}^2 \Delta}{16\pi^2} \frac{m_L^2}{m_h^2} < 10$$

Blum, d'Agnolo, Fan (2012)

→ Note that we have stayed fairly conservative on this side.

→ Also note that these numbers always contain some degree of arbitrariness!