

# Dirac gaugino models and the Higgs

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# Introduction

I'll use this opportunity to introduce myself to the FRIF:

- New chargé de recherche au LPTHE.
- Part of the « Physique des Particules Élémentaires » group.
- Karim Benakli, Pietro Slavich and I form the Beyond the Standard Model (BSM) subgroup.
- On the off chance that I seem familiar, I was a postdoc at the LPTHE from 2007-9 so this is my second Journées de la FRIF.

# Why do we need BSM?

It is legitimate to ask: why do we need physics beyond the Standard Model?

The long-term and time-independent answers are:

♣ It is incomplete:

- It does not provide a dark matter candidate.
- Dark energy remains a mystery.
- CP violation and electroweak baryogenesis in the Standard Model do not explain the matter/antimatter asymmetry of the universe.
- It cannot reconcile quantum physics and gravity.

◇ There are also puzzles:

- Coupling to a higher energy theory generically leads to the hierarchy problem: what protects the electroweak scale?
- Measurements of neutron dipole moments are tiny, whereas in the SM we would expect them to be several orders of magnitude larger (although it doesn't make an actual prediction). This is the Strong CP problem, which people expect to be solved by a new particle – the axion – which has not yet been observed. This would require new physics at  $\gtrsim 10^9$  GeV.
- The Standard Model has many parameters with no obvious origin yet the generations fall into patterns with similar repeated properties. We have no explanation for flavour.
- The tiny values of neutrino masses and their oscillations suggest new physics at high energies.

However, as ever more data and experiments are performed, there are more reasons to be excited:

♠ Some hints:

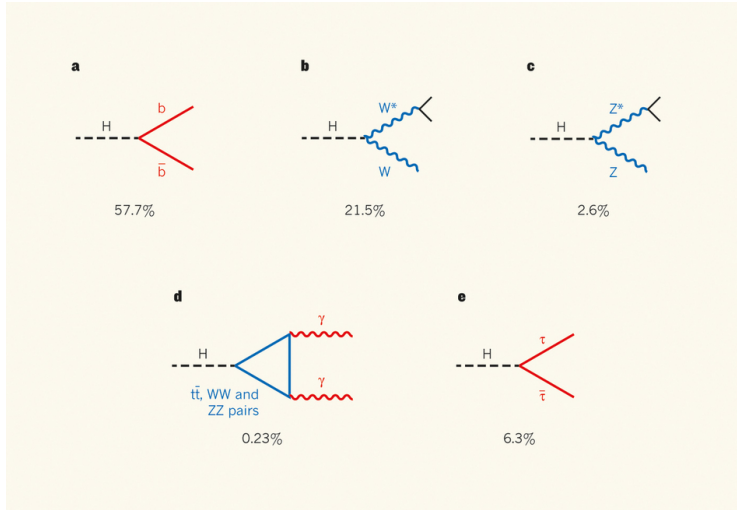
- The measured muon magnetic moment is 3.4 standard deviations from its predicted value. This points at relatively light electroweak-charged new particles (which enter in loops).
- Similar discrepancy in some decays of B-mesons reported by BaBar hinting at CP-violation beyond the standard model.
- Several dark matter detection experiments (DAMA, CoGeNT, CRESST) have reported signals.
- Forward-backward asymmetry at the Tevatron.
- Excess of multi-lepton events from CMS.

♡ Many anomalous astrophysical observations:

- Transparency of the universe to gamma rays.
- White dwarf cooling.
- PeV-neutrinos at IceCUBE.
- 130-GeV gamma-ray line (at  $4\sigma$ ).
- Positron flux in Pamela/AMS.
- ...

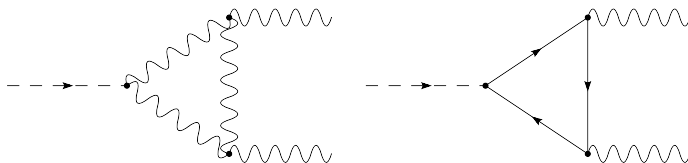
# The Higgs: a place to search for new physics

The Higgs has several decay channels which are predicted quite precisely in the Standard Model:



# New physics and the Higgs

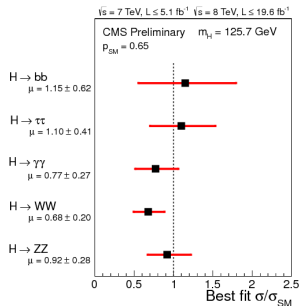
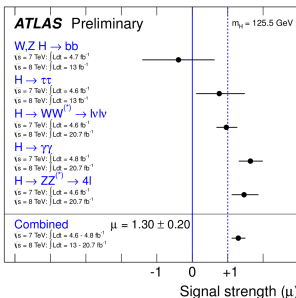
Extra (rather light) particles would lead to deviations from the Standard Model predictions, e.g. by enhancing the diphoton decay:



Higgs production can also be affected by new coloured particles or mixing with heavier Higgses.

# The Higgs at the LHC

So far, there are no clear signs of deviations from the Standard Model ...



... but neither do we rule out new physics.

# Higgs questions for new physics

- The main challenge for new physics from the Higgs is to explain its mass.
- However, we also do not know whether it is really the Standard Model Higgs - we do not have a good measurement of the Higgs self-couplings and it is interesting to ask whether these can be predicted to be different, and if deviations would ever be detectable.
- Is there only one Higgs? Could there be charged Higgses?
- How would these affect the hierarchy problem?



# Overview

- ~~Status of BSM.~~
- Motivation for this talk: Dirac gauginos as non-minimal supersymmetric models.
- What has been achieved so far.
- Dirac gaugino models and the Higgs.
- Future directions.

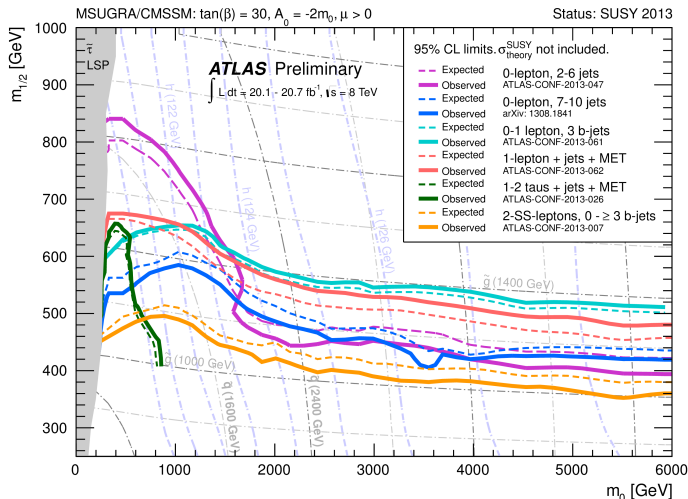
# Supersymmetry

Supersymmetry (SUSY) remains the best motivated candidate for physics beyond the standard model (either immediately or at much higher energies):

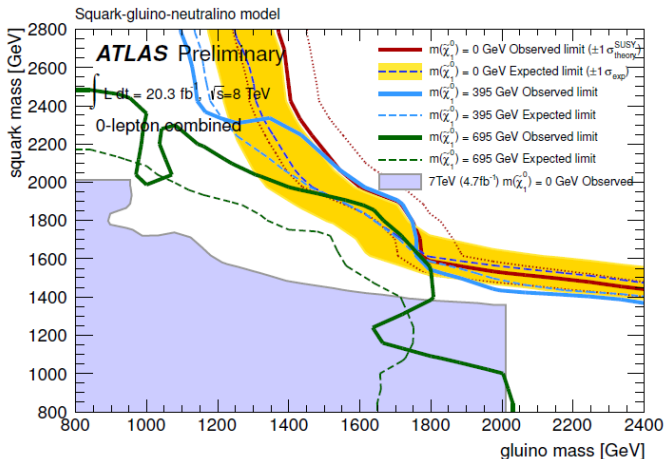
- It provides a compelling solution to the hierarchy problem: cancellation of contributions from fermions and bosons.
- It provides dark matter candidates.
- In the MSSM or in Split SUSY, the gauge couplings apparently unify!
- It is required for consistency by string theory, the leading candidate for a quantum theory of gravity.
- There is no compelling alternative!

# Minimal SUSY and the LHC

However, minimal models of SUSY at the LHC are becoming increasingly constrained:



# Minimal SUSY and the LHC II



# SUSY and the LHC

- Limits are really only coming from new coloured particles: there could easily be many electroweakly-charged particles just above the electroweak scale, where the best limits still come from LEP ( $\mathcal{O}(100)$  GeV).
- Squark limits only apply to first two generations of squarks: third generation – most important for the “naturalness” of SUSY – may remain light. This suggests a connection with flavour physics.
- Gluino bounds do look somewhat “unnatural” now.
- The simple bounds may be evaded in many ways, e.g. if there is a compressed spectrum or R-parity violation.

Bottom line: now is the time to be considering non-minimal SUSY models.

Of these, recently **Dirac gauginos** have become a leading and exciting candidate.

## What are Dirac gauginos?

- In the MSSM have Majorana gauginos described by one Weyl fermion  $\lambda$  in adjoint rep of each gauge group, mass term  $\mathcal{L} \supset -\frac{1}{2}M_\lambda\lambda\lambda + \text{h.c.}$
- To make give a Dirac mass, add an extra adjoint fermion  $\chi$  to give mass term

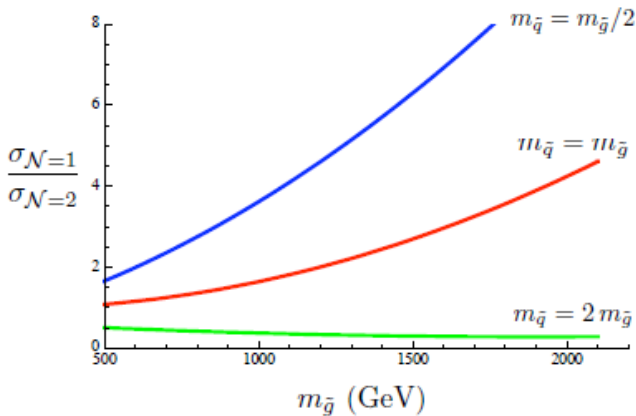
$$\mathcal{L} \supset -m_D\chi\lambda + \text{h.c.}$$

- This also requires a scalar  $\Sigma$  by supersymmetry, fit in an adjoint chiral multiplet  $(\Sigma, \chi)$  which transform into each other under supersymmetry.
- Can relate to a second supersymmetry transforming the gauge bosons to  $\chi$  rather than  $\lambda$ .

# Motivation

One motivation, as mentioned above, is they allow the relaxation of LHC search bounds:

Production of squarks is suppressed since no chirality flip is possible. Gluino production is enhanced a little relative to MSSM, but this is greatly suppressed when  $m_{\tilde{q}_{1,2}} \gg m_{\tilde{g}}$ .



## Motivation: bottom up

In addition:

- They typically suppress processes such as  $B \rightarrow s\gamma$  and  $\Delta F = 2$  meson oscillations.
- They allow for increased **naturalness**: supersoft masses do not lead to large corrections to stop mass – we can more naturally accommodate a heavier gluino, compatible with LHC searches.
- They allow new Higgs couplings, permitting increased Higgs mass  $\rightarrow$  compatibility with e.g. light stops.
- There would have been/could still be clear signals from accompanying adjoint scalars if light (this would have been a surprise).
- If gauginos are found at the LHC, we will have to determine whether they are Majorana or Dirac in nature, and this is very difficult to do directly: maybe only possible at ILC.
- Challenge is to study the possible spectra and Higgs properties.



# Motivation: top down

Some attractive theoretical motivations!

## ♣ Simpler models of SUSY breaking:

- Nelson-Seiberg Theorem: existence of R symmetry (chiral symmetry under which bosons are also charged:  $\Phi \rightarrow e^{i\alpha R} \Phi$ ,  $\theta \rightarrow e^{i\alpha} \theta$ ,  $W \rightarrow e^{2i\alpha} W$ ) required for F-term SUSY breaking
- Dirac gaugino mass may preserve R, Majorana does not: [Fayet, 78] suggested this as the original way to obtain gaugino masses!

## ♡ Alternatively Majorana gaugino mass may be too small:

- Many O'Raifeartaigh models
- Models of low-scale SUSY

## ♠ Adjoints are ubiquitous in top-down models:

- Gauge fields in higher dimensions
- Brane positions/motions

## ◇ Relationship with $N \geq 2$ SUSY.

# Status

Studying non-(N)MSSM SUSY models is typically hard due to lack of tools - and sometimes theory. However, now is the time to be doing this!

On the theory side,

- Dirac gauginos usually considered in context of gauge mediation; have explored many possibilities [Benakli and MDG 0811.4409, 0909.0017, 1003.4957], [Abel and MDG 1102.0014 ].
- Increasing numbers of people interested in this class of models (too many to mention all, but include Weiner, Kribs, Martin, Villadoro, Arvanitaki, Csaki, ...), e.g. effect of Seiberg dualities, lepton number as R-symmetry, detailed studies of naturalness, ...
- We now understand the technical aspects well: RGEs at two loops [MDG 1206.6697], how the masses are generated [Benakli, MDG and Maier 1104.2695], etc.
- Have performed a study of dark matter [Belanger, Benakli, MDG, Moura 0905.1043].
- Have examined flavour constraints [Dudas, MDG, Heurtier, Tziveloglou 1312.2011].
- However: despite many different models (not yet mapped out) there are no scenarios appropriate for collider studies such as the CMSSM yet.

On the tools/collider side:

- Have been some studies (e.g. Martin and Kribs; Heikinheimo, Kellerstein, Sanz '11) of collider bounds for simplified models.
- We now have the tools for numerically studying general theories: SARAH, PYR@TE, FeynRules, CalcHEP, MadGraph, MicrOmegas, ...
- Since 2012 at my instigation these have incorporated the possibility of Dirac gauginos (see [Benakli, MDG, Staub 1211.0552]).

# MSSM with Adjoints

Names		Spin 0	Spin 1/2	Spin 1	$SU(3), SU(2), U(1)_Y$
Quarks ( $\times 3$ families)	$\mathbf{Q}$ $u^c$ $d^c$	$\tilde{\mathbf{Q}} = (\tilde{u}_L, \tilde{d}_L)$ $\tilde{u}_L^c$ $\tilde{d}_L^c$	$(u_L, d_L)$ $u_L^c$ $d_L^c$		$(\mathbf{3}, \mathbf{2}, 1/6)$ $(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$ $(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$
Leptons ( $\times 3$ families)	$\mathbf{L}$ $e^c$	$(\tilde{\nu}_{eL}, \tilde{e}_L)$ $\tilde{e}_L^c$	$(\nu_{eL}, e_L)$ $e_L^c$		$(\mathbf{1}, \mathbf{2}, -1/2)$ $(\mathbf{1}, \mathbf{1}, 1)$
Higgs	$\mathbf{H}_u$ $\mathbf{H}_d$	$(H_u^+, H_u^0)$ $(H_d^0, H_d^-)$	$(\tilde{H}_u^+, \tilde{H}_u^0)$ $(\tilde{H}_d^0, \tilde{H}_d^-)$		$(\mathbf{1}, \mathbf{2}, 1/2)$ $(\mathbf{1}, \mathbf{2}, -1/2)$
Gluons	$\mathbf{W}_{3\alpha}$		$\lambda_{3\alpha}$ $[\equiv \tilde{g}_\alpha]$	$g$	$(\mathbf{8}, \mathbf{1}, 0)$
W	$\mathbf{W}_{2\alpha}$		$\lambda_{2\alpha}$ $[\equiv \tilde{W}^\pm, \tilde{W}^0]$	$W^\pm, W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
B	$\mathbf{W}_{1\alpha}$		$\lambda_{1\alpha}$ $[\equiv \tilde{B}]$	$B$	$(\mathbf{1}, \mathbf{1}, 0)$
DG-octet	$\mathbf{O}_g$	$\mathbf{O}_g$ $[\equiv \Sigma_g]$	$\chi_g$ $[\equiv \tilde{g}']$		$(\mathbf{8}, \mathbf{1}, 0)$
DG-triplet	$\mathbf{T}$	$\{T^0, T^\pm\}$ $[\equiv \{\Sigma_0^W, \Sigma_W^\pm\}]$	$\{\chi_T^0, \chi_T^\pm\}$ $[\equiv \{\tilde{W}'^\pm, \tilde{W}'^0\}]$		$(\mathbf{1}, \mathbf{3}, 0)$
DG-singlet	$\mathbf{S}$	$\mathbf{S}$ $[\equiv \Sigma_B]$	$\chi_S$ $[\equiv \tilde{B}']$		$(\mathbf{1}, \mathbf{1}, 0)$

# Supersymmetric Couplings

Here are the most general renormalisable superpotential couplings:

- SUSY couplings contained in superpotential:

$$W = W_{\text{Yukawa}} + W_{\text{Higgs}} + W_{\text{Adjoint}}$$

- No new Yukawas:

$$W_{\text{Yukawa}} = Y_{\text{U}}^{ij} \mathbf{Q}_i \cdot \mathbf{H}_u \mathbf{u}_j^c + Y_{\text{D}}^{ij} \mathbf{Q}_i \cdot \mathbf{H}_d \mathbf{d}_j^c + Y_{\text{E}}^{ij} \mathbf{L}_i \cdot \mathbf{H}_d \mathbf{e}_j^c$$

- Two new Higgs couplings (c.f. NMSSM):

$$W_{\text{Higgs}} = \mu \mathbf{H}_u \cdot \mathbf{H}_d + \lambda_S \mathbf{S} \mathbf{H}_d \cdot \mathbf{H}_u + 2\lambda_T \mathbf{H}_d \cdot \mathbf{T} \mathbf{H}_u$$

- Several possible new Adjoint couplings which violate R:

$$W_{\text{Adjoint}} = \text{LS} + \frac{M_S}{2} \mathbf{S}^2 + \frac{\kappa_S}{3} \mathbf{S}^3 + M_T \text{tr}(\mathbf{T} \mathbf{T}) + \lambda_{ST} \text{Str}(\mathbf{T} \mathbf{T}) \\ + M_O \text{tr}(\mathbf{O} \mathbf{O}) + \lambda_{SO} \text{Str}(\mathbf{O} \mathbf{O}) + \frac{\kappa_O}{3} \text{tr}(\mathbf{O} \mathbf{O} \mathbf{O}).$$

# Getting 126 GeV

- In limit of large  $m_S, m_T$ , can integrate out adjoint scalars to obtain

$$m_h^2 \simeq M_Z^2 c_{2\beta}^2 + \frac{v^2}{2} (\lambda_S^2 + \lambda_T^2) s_{2\beta}^2 + \frac{3}{2\pi^2} \frac{m_t^4}{v^2} \left[ \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} + \frac{\mu^2 \cot^2 \beta}{m_{\tilde{t}_1} m_{\tilde{t}_2}} \left( 1 - \frac{\mu^2 \cot^2 \beta}{12 m_{\tilde{t}_1} m_{\tilde{t}_2}} \right) \right] \\ + v^2 \left[ \lambda_1 c_\beta^4 + \lambda_2 s_\beta^4 + 2(\lambda_3 + \lambda_4 + \lambda_5) c_\beta^2 s_\beta^2 + 4(\lambda_6 c_\beta^2 + \lambda_7 s_\beta^2) s_\beta c_\beta \right] \\ \xrightarrow{\tan \beta \rightarrow \infty} M_Z^2 + \lambda_2 v^2 + \frac{3}{2\pi^2} \frac{m_t^4}{v^2} \log \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}$$

Can enhance the Higgs mass naturally!

- At small  $\tan \beta$ , do not need heavy stops or large stop mixing etc: for large  $\lambda_S$  or  $\lambda_T$  we can take just the tree-level part:  $m_h^2 \simeq M_Z^2 c_{2\beta}^2 + \frac{v^2}{2} (\lambda_S^2 + \lambda_T^2) s_{2\beta}^2$   
 $\rightarrow \lambda_S \sim 0.7$  to obtain correct Higgs mass as at small  $\tan \beta$  as in NMSSM/ $\lambda$ SUSY.
- Also the origin of the potential may be a maximum rather than saddlepoint as in MSSM
- For large  $\tan \beta$ , scalar and triplet scalars can do the same job if they are heavy (e.g. for  $\lambda_S = 1.8$  or  $\lambda_T = 1.2$  with no stop contribution)

$$32\pi^2 \lambda_2 \supset 2\lambda_S^4 \log \frac{m_S^2}{v^2} + (g_2^4 - 4g_2^2 \lambda_T^2 + 10\lambda_T^4) \log \frac{m_T^2}{v^2} \\ + \frac{4\lambda_S^2 \lambda_T^2}{m_S^2 - m_T^2} \left[ m_S^2 \log \frac{m_S^2}{v^2} - m_T^2 \log \frac{m_T^2}{v^2} - (m_S^2 - m_T^2) \right]$$

# Unification

- MSSM one-loop beta-function coefficients are  $(b_3, b_2, b_1 = (5/3)b_Y) = (3, -1, -11)$ , lead to unification of couplings at  $10^{16}$  GeV with perturbative couplings  $\alpha_{\text{GUT}} \sim 1/24$ .

$$\frac{1}{g_i^2(\mu)} = \frac{1}{g_i^2(M_{\text{SUSY}})} + \frac{b_i}{8\pi^2} \log \mu/M_{\text{SUSY}}$$

- Triumph of the MSSM (modulo two-loop discrepancy...) that we might like to preserve!!
- Adding complete GUT multiplets (as in gauge mediation) does not alter this (beta-function coefficients decreased by  $(1, 1, 1)$  per pair of  $\text{SU}(5)$  messengers).
- Adding adjoint fields does (except for  $S$ , a singlet):  $T$  decreases  $b_2$  by 2,  $O_g$  decreases  $b_3$  by 3

## Four alternatives

1. Abandon matter and gauge unification
2. Modify our definition of “unification” ...
3. Add extra “bachelor” states to make up complete GUT adjoint multiplets [Fox, Nelson and Weiner, 02], allows matter and gauge unification
4. Add minimal extra states to restore gauge unification

# Messengers to the Rescue

- Gauge mediation requires messenger fields - these could also restore gauge unification!
- Require at least 2 pairs of messengers in (anti) fundamental of  $SU(2)$  and  $SU(3)$  for adjoint scalar masses (see later)
- Easy to find sets of messengers that satisfy this, e.g.

$$\begin{array}{ll}
 4 \times [(1, 1)_1 + (1, 1)_{-1}] & \text{at } m_1 = 3 \cdot 10^{12} \text{ GeV} \\
 4 \times [(1, 2)_{1/2} + (1, \bar{2})_{-1/2}] & \text{at } m_2 = 1.3 \cdot 10^{13} \text{ GeV} \\
 2 \times [(3, 1)_{1/3} + (\bar{3}, 1)_{-1/3}] & \text{at } m_3 = 10^{13} \text{ GeV} \\
 M_U \sim 9.9 \cdot 10^{17} \text{ GeV} & \alpha_U^{-1} \sim 4.77
 \end{array}$$

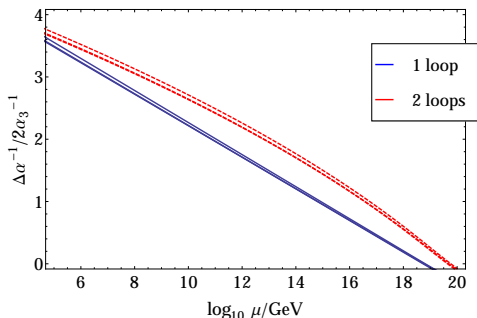
- High messenger scale required to allow perturbativity up to GUT scale

# F-theory Unification

- If we modify our definition of unification, in the heterotic string, we could “unify” the hypercharge at a different Kac-Moody level.
- Alternatively, we can modify our definition of unification to the F-theory criterion

$$\Delta\alpha^{-1} \equiv 5\alpha_1^{-1} - 3\alpha_2^{-1} - 2\alpha_3^{-1} = 0$$

This entails simply adding a vector-like pair of electron fields  $(1, 1)_{\pm 1}$  to the model, following [\[Davies, 2012\]](#)



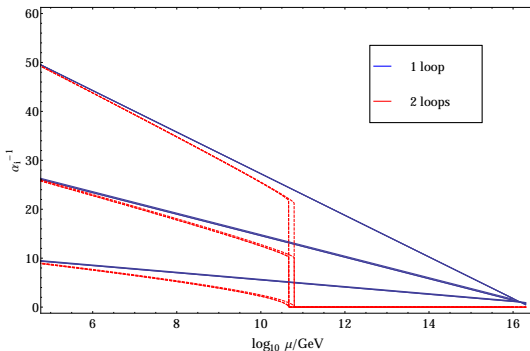
Unfortunately at two loops the couplings seem to unify beyond the Planck scale.



## Other unification schemes

Can consider other schemes for unification with gravity mediation. E.g. Adding “bachelor” states at low scale

$$24 \rightarrow 8_0 + 3_0 + 1_0 + (3, 2)_{-5/6} + (\bar{3}, 2)_{5/6}$$

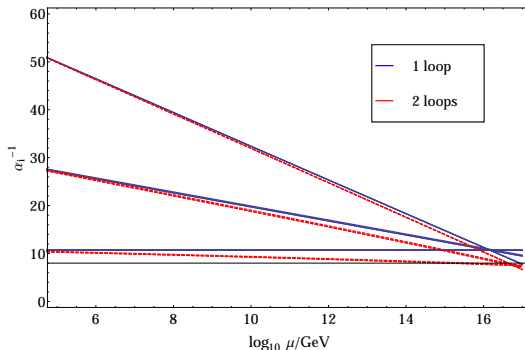


## Other unification schemes II

Or just add

$$(\mathbf{1}, \mathbf{2})_{1/2} + (\mathbf{1}, \mathbf{2})_{-1/2} + 2 \times (\mathbf{1}, \mathbf{1})_{\pm 1}$$

This could come from  $(\text{SU}(3))^3$  (would need also four SM singlets).



## Toward a GUT scenario

- The latter configuration is particularly interesting. Let us add to the minimal Dirac gaugino MSSM a pair of doublets  $R_u, R_d$  and two non-chiral selectrons  $\hat{E}_i, \hat{\bar{E}}_i, i = 1, 2$ . The most general higgs potential is then

$$\begin{aligned}
 W \supset & (\mu + \lambda_S S) H_d H_u + 2\lambda_T H_d T H_u \\
 & + (\mu_R + \lambda_{SR} S) R_u R_d + 2\lambda_{TR} R_u T R_d + \mu_{\hat{E}ij} \hat{E}_i \hat{\bar{E}}_j \\
 & + (\mu_u + \lambda_{Su} S) R_u H_u + 2\lambda_{Tu} R_u T H_u + (\mu_d + \lambda_{Sd} S) R_d H_d + 2\lambda_{Td} R_d T H_d \\
 & + Y_{\hat{E}i} R_u H_d \hat{E}_i + Y_{\hat{\bar{E}}i} R_d H_u \hat{\bar{E}}_i
 \end{aligned}$$

We can now take one of two directions:

- An extended MRSSM  $\rightarrow$  removing  $\mu, \mu_R, \lambda_S, \lambda_T$  and related couplings, where an R-symmetry is preserved by the Higgs sector.
- Charge the new fields under lepton number, so that we have new heavy vector-like leptons and sleptons. The superpotential becomes

$$\begin{aligned}
 W \supset & (\mu + \lambda_S S) H_d H_u + 2\lambda_T H_d T H_u \\
 & + (\mu_R + \lambda_{SR} S) R_u R_d + 2\lambda_{TR} R_u T R_d + (\mu_{\hat{E}ij} + \lambda_{SEij} S) \hat{E}_i \hat{\bar{E}}_j \\
 & + Y_{\hat{E}i} R_u H_d \hat{E}_i + Y_{\hat{\bar{E}}i} R_d H_u \hat{\bar{E}}_i \\
 & + Y_{LFV}^{ij} L_i \cdot H_d \hat{E}_j + Y_{EFV}^j R_u H_d E_j
 \end{aligned}$$

## Lepton flavour violation

The mass matrix for the fermions becomes

$$\mathcal{L}_{\text{leptons}} \supset - \begin{pmatrix} \bar{r}_u & \hat{e}_i & e_i^L \end{pmatrix} \begin{pmatrix} \mu_R & \frac{v c_\beta}{\sqrt{2}} Y_{\hat{E}_i} & -\frac{v c_\beta}{\sqrt{2}} Y_{\text{EFV}} \\ \frac{v s_\beta}{\sqrt{2}} Y_{\hat{E}_i} & \mu_E & 0 \\ 0 & -\frac{v c_\beta}{\sqrt{2}} Y_{\text{LFV}} & -\frac{v c_\beta}{\sqrt{2}} Y_E \end{pmatrix} \begin{pmatrix} r_d^+ \\ \hat{e}_i \\ e_{Ri} \end{pmatrix}$$

When we diagonalise, will find new couplings with e.g. the Higgs:

$$\mathcal{L} \supset - \frac{h c_\beta}{\sqrt{2}} \left[ L_{ij} \bar{e}_i P_L e_j + R_{ij} \bar{e}_i P_R e_j \right]$$

Generate effective operators

$$\sigma_L^{ij} \bar{e}_i \sigma^{\mu\nu} P_L e_j F_{\mu\nu} + \sigma_L^{ij} \bar{e}_i \sigma^{\mu\nu} P_R e_j F_{\mu\nu}$$

where

$$\sigma_{L,R} \sim \frac{1}{32\pi^2} Y_{\text{EFV}} Y_{\text{LFV}} Y_{\hat{E}} \frac{v}{\mu_{R,E}^2}$$

## Loop processes

- These operators are relevant for both  $\mu \rightarrow e\gamma$  and EDMs:
- Assuming no tuning,

$$\begin{aligned}\text{Br}(\mu \rightarrow e\gamma) &\simeq 6 \times 10^{12} |\sigma_{L,R}|^2 < 2.4 \times 10^{-12} \\ \rightarrow \sigma_{L,R} &\lesssim 6 \times 10^{-13} \text{GeV}^{-1}\end{aligned}$$

- Whereas with the new EDM measurement

$$d_e = 2\text{Im}(\sigma_{L,R}) < 4.5 \times 10^{-15} \text{GeV}^{-1}$$

- Hence we need

$$\text{Im}(Y_{\text{EFV}} Y_{\text{LFV}} Y_{\hat{E}}) \lesssim 10^{-8} \rightarrow Y_{\text{EFV}} \lesssim 10^{-2 \div 3}$$

## Tree-level processes

When we diagonalise the mass matrices, we now have vector-like electrons so the Z-couplings are no-longer diagonal:

$$j_Z^\mu \supset \bar{e}_i \gamma^\mu \left[ \left( \frac{1}{2} - s_W^2 \right) P_L - s_W^2 P_R \right] e_i + \left( \frac{1}{2} - s_W^2 \right) \bar{e}_6 \gamma^\mu e_6 + \sum_{i=4,5} -s_W^2 \bar{e}_i \gamma^\mu e_i$$

$$\supset \sum_i^6 \bar{e}_i \gamma^\mu \left( \frac{1}{2} P_L - s_W^2 \right) e_i + \frac{1}{2} \bar{q}_R^i q_R^j \bar{e}_i \gamma^\mu P_R e_j - \frac{1}{2} q_L^{ik} \bar{q}_L^{jk} \bar{e}_i \gamma^\mu P_L e_j$$

This allows  $\mu \rightarrow eZ \rightarrow e^- e^+ e^-$ :

$$\text{BR}(\mu \rightarrow 3e) = 2 \times 10^{-4} c_\beta^2 \left[ |Y_{LFV}^{2k} \bar{Y}_{LFV}^{1k}|^2 + |Y_{EFV}^2 \bar{Y}_{EFV}^1|^2 \right]$$

$$< 1.0 \times 10^{-12}$$

This gives

$$|Y_{LFV}^{2k} \bar{Y}_{LFV}^{1k}|^2 \lesssim 10^{-8}$$

$$Y_{LFV}^{ik} \sim Y_{EFV}^j \lesssim 10^{-2} \quad (1)$$

which can even be relaxed a little for large  $\tan \beta$ .

## Other aspects of flavour

- On the other hand, the usual SUSY contributions to flavour-violating processes are suppressed: whenever we have a chirality-flip on a gaugino, this is forbidden (e.g.  $\mu \rightarrow e\gamma$  etc).
- N.b. since we do not have a completely R-symmetric model, we still have chirality-flips from Higgsinos (in the MRSSM these processes are forbidden completely).
- The flavour story is quite interesting but that's another talk ... see [Dudas, MDG, Heurtier, Tziveloglou 1312.2011].

## Aside: the FSSM

A pure LPTHE collaboration: [Benakli, Darmé, MDG, Slavich '13]:

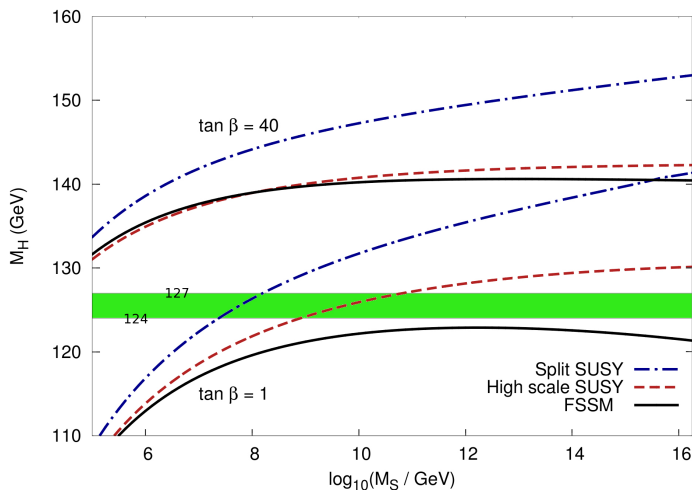
- An alternative that we can consider with the same field content is to take the scalars of the theory (except one, fine-tuned, Higgs) to be heavy at some scale  $M_S$ .
- We can then also add a Majorana gaugino mass at  $M_S$  with a small Dirac mass such that the fermions  $\chi$  – the “fake gauginos” – are the only SUSY partners that are light and remain at  $\sim \text{TeV}$ :

$$m_{\text{gaugino}} \sim \begin{pmatrix} M_S & \epsilon M_S \\ \epsilon M_S & \epsilon^2 M_S \end{pmatrix}$$

- This “Fake Split-SUSY Model” (FSSM) gives a prediction for the Higgs mass that is different from Split SUSY which is much more compatible with the observed value.



## FSSM cont'd



# Introducing the CMDGSSM

We can now specify a minimal set of boundary conditions at the GUT scale:

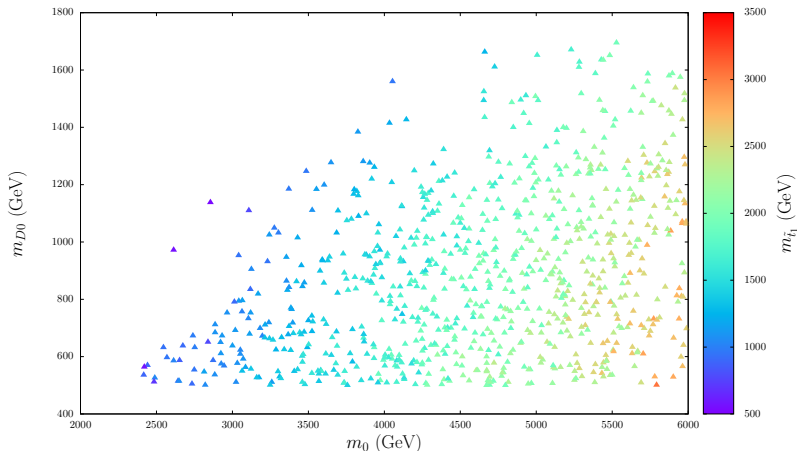
- As in the CMSSM/mSUGRA, we have  $m_0, \tan \beta$  but instead of  $m_{1/2}$  we have  $m_D$ . We set  $A_0 = 0$  due to SUSY preserving R-symmetry.
- We also choose to take non-universal Higgs masses, and so specify  $\mu, B_\mu$ .
- Since we have two new tadpole conditions from  $v_S, v_T$  we specify  $m_{S0}$  (singlet scalar mass) and  $m_{T0}$  (triplet scalar mass) at the GUT scale. We set the octet scalar mass equal to the triplets, and take  $B_T = B_S = B_O = 0$  for minimality.
- We have the Yukawa couplings  $Y_{\hat{E}i}, Y_{\hat{E}i}, Y_{LFV}^{ij}, Y_{EFV}^j$  which are equivalent to lepton Yukawas; they are constrained to be  $\lesssim 0.01$  and so irrelevant for spectrum-generator purposes.
- We have a choice of  $\mu_R, \mu_E \rightarrow$  can either adjust for precision gauge unification; set to be equal to the Higgs  $\mu$ ; set at convenient values. The Higgs mass and coloured particle spectrum is largely independent of this choice.
- We have a choice of couplings  $\lambda_S, \lambda_T, \lambda_{SR}, \lambda_{TR}, \lambda_{SEij}$ : can take  $N = 2$  values, or  $(SU(3))^3$  values, or choose freely.

## First forays

- We can now start to explore the parameter space using SPheno code produced by SARAH for this model, which calculates two-loop RGEs and one-loop pole masses.
- One important technical limitation is due to the Higgs mass: if we enhance it using heavy stops, then the accuracy of the spectrum generator is no longer trustworthy.
- We instead choose to explore the corner of parameter space with  $\lambda_S \sim 0.7$ , small  $\tan \beta$  so that no sparticle contributing significantly to the Higgs mass is heavier than about 2 TeV.
- For convenience we take  $\lambda_T \sim 0$  and set  $\mu_R \sim \mu_E \sim \text{TeV}$ , scan over  $\lambda_S, \tan \beta$  within a narrow range and otherwise scan randomly over  $\mu, B\mu, m_0, m_D, m_{S0}, m_{T0}$ .
- We keep only points with the correct Higgs mass satisfying the constraints from HiggsBounds.

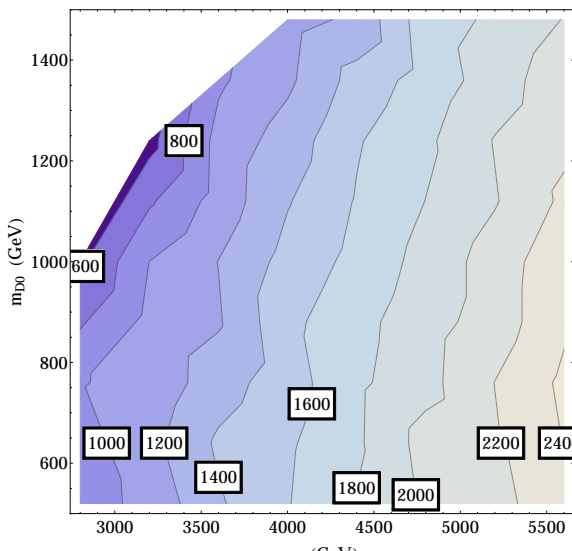
## $m_0 - m_D$ plane and stop masses

We find no models in the with small  $m_0$  and large  $m_D$  since the bino mass is important in the Higgs mass calculation. We do find many models with light stops:



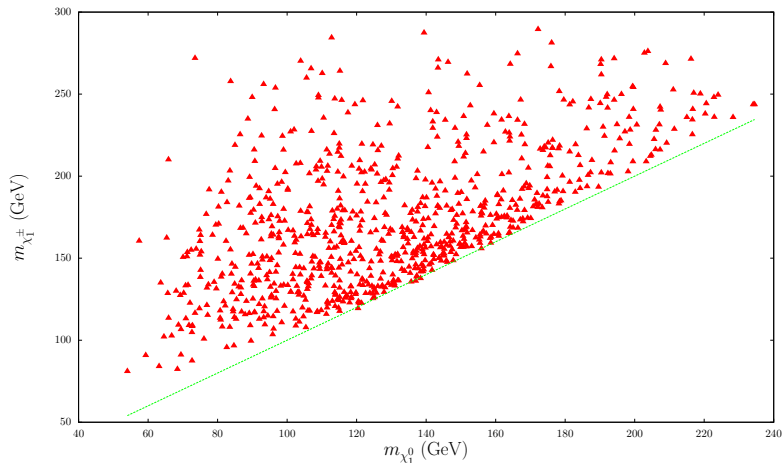
## $m_0 - m_D$ plane II

Same plot as on previous slide, clearly showing contours of stop mass:



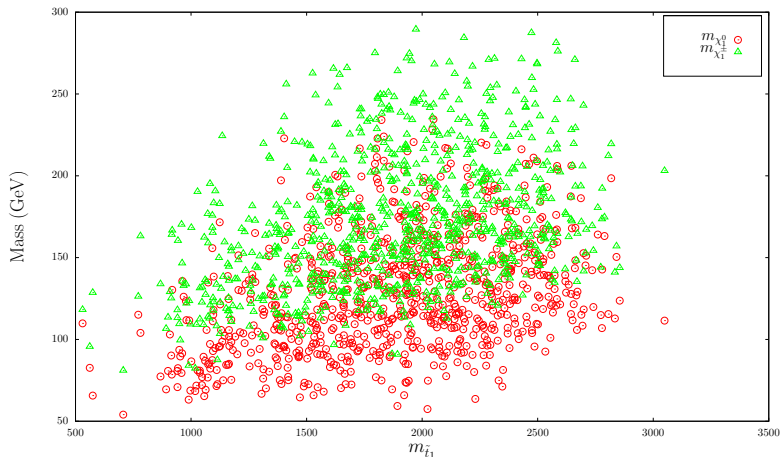
## Charginos and neutralinos

The neutralinos are typically light due to the restriction on the bino mass from the Higgs mass. Also the scans preferentially find models with light  $\mu$ , leading to light charginos.



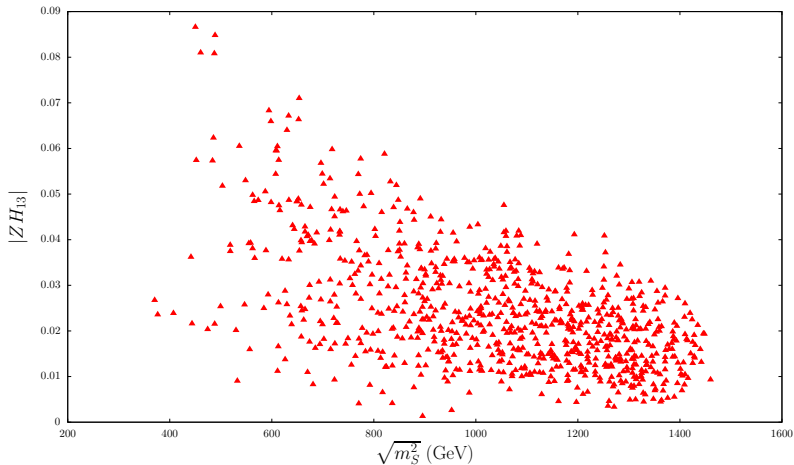
# Charginos, neutralinos and stops

Here we show the correlation of the neutralino and chargino masses with the lightest stop mass:



# Higgs mixing

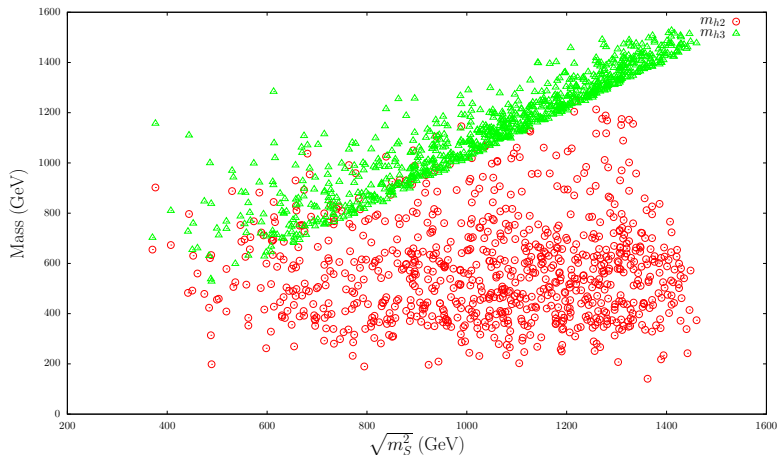
The models we find are typically “ $\lambda$ SUSY in disguise”:





# Higgs masses

We often find a relatively light second Higgs:



# Predictions

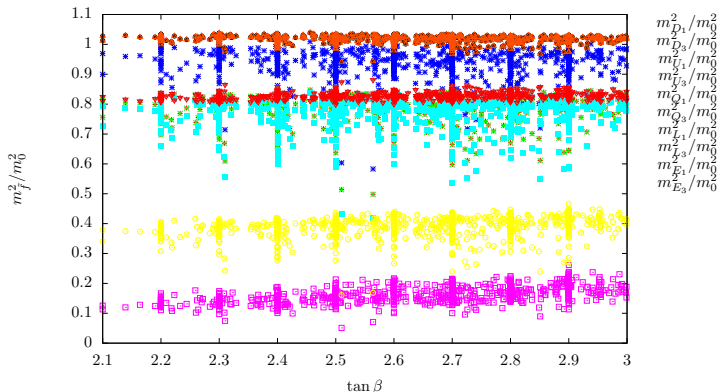
- Unification takes place at  $(1.8 \pm 0.4) \times 10^{17}$  GeV
- We have a compressed pattern of soft masses (with deviations of a few percent):

$$\begin{aligned} m_{U33}^2 : m_{Q33}^2 : m_{Q11}^2 : m_{Dii}^2 : m_{Eii}^2 : m_{U11}^2 : m_{Lii}^2 \\ = 0.16 : 0.39 : 0.77 : 0.79 : 0.83 : 0.93 : 1.02 \end{aligned}$$

- Hence sleptons are heavy and quasi-degenerate with the first two generations of squarks. This is because the Dirac gaugino masses do not enter into the squark RGEs.
- While the lightest stop masses are  $1.9 \pm 0.5, 2.9 \pm 0.6$  TeV.
- The gaugino masses are in the ratio  $0.22 : 0.9 : 3.5$ , i.e. the Wino barely runs from  $m_D$  (as can be seen from the one-loop RGE, which is zero for small  $\lambda_T$ ).

# Squark masses

Over the range of  $\tan \beta$  scanned, the squark masses vary little:



# Conclusions

- Dirac gauginos have many attractive phenomenological and theoretical advantages over their Majorana counterparts, and can arise naturally in many different contexts (strong dynamics, higher dimensions, string theory, ...)
- There now exists a tool (SARAH with SPheno) to seriously study many aspects of their phenomenology which can interface with other tools.
- Now have a GUT scenario with a minimal number of parameters that we can in future confront with bounds.
- This is part of the long program of research into these and other beyond-MSSM theories which is now gathering momentum.

# Future Possibilities

Many possible avenues for future work:

- Work in progress with P. Slavich: calculation of two-loop corrections to Higgs mass and implementation in codes.
- Prepare for the next run of the LHC at 13 TeV: connection with collider limits.
- Modifications of Higgs sector
- Models to realise messenger mass patterns
- Explicit D-term SUSY sectors (e.g. 4 – 1 model)
- Warped models
- Gauge messengers
- Gravity mediation, embedding in string models, Dirac gravitinos,....