# Supersymmetric extensions of the SM after the first LHC results

## Master's project in theoretical physics

(in progress, to be completed by September 17, 2013)

Giulia Cusin

Supervisor: Prof. Fabio Zwirner

Università degli Studi di Padova, Italy
Dept. of Physics and Astronomy G. Galilei

July 8, 2013

# Outline

- Why supersymmetry
- LHC 8 TeV results vs minimal supersymmetry
  - (Not so) light Higgs
  - The missing superpartner problem
- Supersymmetry and naturalness
  - Minimal supersymmetry
  - R-parity violation
  - Dirac gauginos
- Supersymmetry and heavy superpartners
  - Split-supersymmetry
  - High-scale susy: prediction of the Higgs mass
- Program for the next months
  - Properties of models with Dirac gauginos
  - Hierarchies in special no-scale supergravities

# Why supersymmetry?

On a purely theoretical ground

- general symmetry of a 4D relativistic QFT (Haag, Lopuszansky and Sohnius)
- linearly realized, it gives a rationale for elementary scalars, living in N=1 multiplets with chiral fermions
- its local version, supergravity, contains Einstein's general relativity and fits naturally in superstrings

Motivations from particle phenomenology

- SUSY can solve the SM hierarchy problem if superparticle masses are at the weak scale
- SUSY can provide viable DM candidates: neutralino LSP in MSSM, gravitino, etc
- gauge coupling unification in MSSM could be a hint and not just a coincidence
- some SUSY models can be predictive concerning the lightest Higgs mass

# The MSSM

## Main features

- gauge group $SU(3) \times SU(2) \times U(1)$ $\longrightarrow$ vector multiplets

$$\textbf{gauginos} \quad (\widetilde{g},\, \widetilde{W},\widetilde{B})$$

- chiral multiplets containing the three SM generations and two Higgs doublets

$$\text{squarks}\,(\widetilde{q})\,, \quad \text{sleptons}\,(\widetilde{l})\,, \quad \text{higgsinos}\,(\widetilde{H}_{1,2})$$

- R-parity conserving superpotential

$$W = Qh^U U^c H_2 + Qh^D D^c H_1 + Lh^E E^c H_1 + \mu H_1 H_2$$

- explicit soft susy breaking (often with universality assumption)

gaugino and scalar masses + cubic scalar couplings (A-terms)

# Minimal SUSY and LHC: Higgs boson

- First fact: (not so) light Higgs

$$m_h^{exp} = 125\,GeV$$

Minimal SUSY

$$m_h < m_Z|cos(2\beta)| \qquad \delta m_h^2 \sim y_t^2 m_t^2 log\left(\frac{m_{\tilde{t}}^2}{m_t^2}\right) \quad \rightarrow m_{\tilde{t}} \gtrsim TeV$$

$$m_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1 - sin^2(2\beta)}} - m_{H_d}^2 - m_{H_u}^2 - 2|\mu|^2$$

$\rightarrow\sim$ 1% fine-tuning (0.1 % without A-terms)

- Second fact: very SM-like Higgs

  (So far) no significant deviations from the SM predictions for the observed Higgs couplings
  No hints for other neutral and charged states

# The missing superpartner problem

LHC searches

- At LHC, direct superpartner limits are close to 1.5 TeV for vanilla MSSM squarks ang gluinos
- Gluino critical for naturalness
  - large production cross section at LHC
  - a heavy gluino pulls upward the masses of all colored sparticles, including the stop $\rightarrow$ pulls up the soft Higgs mass $\rightarrow$ pulls up the weak scale $\rightarrow$ fine tuning is needed
- The absence of significant deviations from the SM predictions is confirmed by flavour experiments

The above features seems to lead to a heavy spectrum for most s-particles

# What to do?

We are in a puzzling situation!

Two main options are being considered

Natural SUSY

- Minimal natural SUSY
- R-parity violation
- Dirac gauginos

Heavier s-particles

- Split-supersymmetry
- High-scale SUSY
- Other options?

# What to do?

We are in a puzzling situation!

Two main options are being considered

Natural SUSY

- Minimal natural SUSY
- R-parity violation
- Dirac gauginos

Heavier s-particles

- Split-supersymmetry
- High-scale SUSY
- Other options?

# Dirac gauginos: main features

## Building blocks

- Extended N=2 supersymmetry in the gauge sector
- Spontaneous breaking of SUSY in a hidden sector with $U(1)'$ gauge group, through non vanishing D-term
- Breaking mediated by supersoft operators
- Dirac tree level masses for gauginos, finite 1-loop masses for scalars

supersoft operators $\int d^2\theta\,\sqrt{2}\frac{W'_\alpha W_j^\alpha A_j}{M_p}$ $\qquad \int d^2\theta\,\frac{W'_\alpha W'^\alpha}{M_p^2}A_j^2$

scalar masses $m_i^2 = \frac{C_i(r)\alpha_i M_i^2}{\pi}\log\left(\frac{\delta_i^2}{M_i^2}\right)$

$W'_\alpha$ field-strengh of the $U(1)'$ factor

$m_D = \frac{\langle D'\rangle}{M_p}$ and $\delta_i$ mass for the new scalar fields in the gauge sector (EPS)

# Dirac gauginos: why attractive and what we discuss

## Good features

- supersoft terms depending on few parameters (vs MSSM)
- 1-loop corrections to $m_{H_u}$ lower than in MSSM

$$\delta m^2_{H_u} = -\frac{3\lambda_t^2}{8\pi^2} m_{\tilde{t}^2} \log \frac{M_3^2}{m^2_{\tilde{t}}} \quad \leftrightarrow \quad \Lambda^2 \text{ in MSSM}$$

## Troubles: any improvements? ⟵in the next months

- how to obtain the measured value for the Higgs mass?
- what about unification? ⟵ new matter content to be added!
- what is the fine-tuning situation after quantum corrections?

↑

supersoft-breaking operators⟶ different masses for gluinos and scalars ⟶ threshold corrections to the stop mass going as

$$\log\left(\frac{m_{gluino}}{m_{scalar}}\right)$$

# Hierarchy in special no-scale SUGRA

## "Traditional" no-scale model

### Classical breaking of SUSY on a Minkowski space

- hidden sector with one chiral superfield $T$, acting as a scale-modulus

$$K = -3\log(T+\overline{T}) \qquad W = k = const$$

$$V = e^G(G^T G_{T\overline{T}} G^{\overline{T}} - 3) = 0 \quad \forall T$$

- vanishing classical vacuum energy
- sliding gravitino mass
- coupling with the superfields of the observable sector

$$K = -3\log(T+\overline{T}) + \sum_i |C_i|^2 (T+\overline{T})^{n_i} + \sum_i |H_i|^2 (T+\overline{T})^{h_i} + \left[ H_u H_d (T+\overline{T})^h + h.c. \right]$$

$$W = W_{MSSM} + k$$

- SUSY-breaking masses for MSSM matter and Higgs proportional to gravitino mass and depending on descrete parameters $n_i, h_i, h$

## “Variant” no-scale model ← in progress!

- The Higgs fields are treated as moduli, inserting them in the no-scale structure

$$K = -\frac{3}{2}\log\left[(T+\bar{T})^2 - (H_d + \overline{H_u})^2\right] + \sum_i |C_i|^2 Y^{n_i}$$

$$W = W_{MSSM} + k$$

where

$$Y \equiv (T+\overline{T})^2 - (H_d + \overline{H_u})^2$$

- At tree-level we have vanishing masses for $T$ and for the Higgs fields

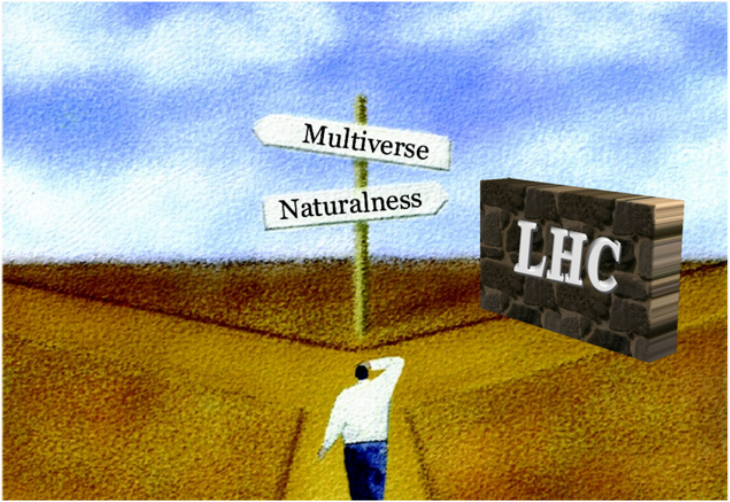
### Future developments

- we study the 1-loop structure of the scalar potential
- for a proper choice of the model parameters → spectrum with heavy scalars and light Higgs?
- we want to check if it would be possible to generate the correct values for the Higgs mass and for the cosmological constant with a better fine-tuning situation with respect to the traditional model

# Conclusions

LHC will tell us which of the two roads is the preferred one by Nature

But there are still open theoretical ends to be further explored!




This picture is taken from Villadoro's talk in Padova, April 2013

# Back-up slides

# “Traditional” no-scale model

$$K = -3\log(T+\overline{T}) + \sum_i |C_i|^2 (T+\overline{T})^{\lambda_i} + \left[H_u H_d (T+\overline{T})^h + h.c.\right]$$

$$f_{ab} = \delta_{ab} T$$

$$W = k + d_{\alpha\beta\gamma} C^\alpha C^\beta C^\gamma$$

where $d_{\alpha\beta\gamma} C^\alpha C^\beta C^\gamma = h^U Q U^c H_u + h^D Q D^c H_d + h^E L E^c H_d$ (no $\mu$-term)

## Spectrum

gravitino mass $m_{3/2}^2 = \dfrac{|k|^2}{(T+\overline{T})^3}$

squark/slepton masses $m_i^2 = m_{3/2}^2 (1+\lambda_i)$

diagonal Higgs masses $m_{H_i}^2 = m_{3/2}^2 (1+\lambda_{H_i})$

Higgsino mass $m_{\tilde{h}}^2 = m_{3/2}^2 (h+1)^2 (T+\overline{T})^{2h-h_1-h_2}$

Higgs mixing mass $m_3^2 = m_{3/2} m_{\tilde{h}} (2-h+h_1+h_2)$

A-terms $A_{ikj} = m_{3/2}(3+h_i+h_k+h_j)$

gaugino mass $(\mathcal{M}_{1/2})_{AB} = m_{3/2}\delta_{AB}$

# Some more details about MSSM

From minimization of the scalar potential

$$\sin 2\beta = -\frac{2m_3^2}{m_1^2 + m_2^2} \qquad \text{where } m_1^2 = |\mu|^2 + m_{H_u}^2$$

$$m_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1 - sin^2(2\beta)}} - m_{H_d}^2 - m_{H_u}^2 - 2|\mu|^2$$

One loop correction to $m_h$

$$\delta m_h^2 = \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\log\left(\frac{M_s^2}{m_t^2}\right) + \frac{X_t^2}{M_s^2}\left(1 - \frac{X_t^2}{12M_s^2}\right)\right]$$

$$M_s^2 = \frac{1}{2}\left(m_{\tilde{t}_1}^2 + m_{\tilde{t}_2}^2\right)$$

$$X_t = A_t - \mu\, ctg\beta$$

- $m_t^4$ dependence
- logarithmic sensitivity to stop quark mass
- dependence of Higgs mass on $X_t$, maximal value at $X_t = \sqrt{6}M_s$

# Natural supersymmetry

## Minimal supersymmetry

- One loop corrections to $m_{H_u}$ $\rightarrow$ only need light higginos, stops and gluinos $\rightarrow$ internal hierarchy
- but...additional fine tuning in the parameter space to keep this hierarchy after considering 1 loop corrections!

## R-parity violation

- R parity is replaced by an alternative discrete symmetry that still manages to forbid proton decay at the level of renormalizable Lagrangian
- Collider searches for SUSY can be compleately different from MSSM ones

## Dirac gauginos

- Extended N=2 supersymmetry in the gauge sector
- Spontaneous breaking of SUSY in a hidden sector with $U(1)'$ gauge group, through non vanishing D-term
- Breaking mediated by supersoft operators

# Minimal (natural) supersymmetry

One loop corrections to $m_{H_u}$

$$m_z^2 = -2(m_{H_u}^2 + |\mu|^2) + \dots$$

$$\delta m_{H_u}^2 \sim \frac{-3y_t^2 m_{\tilde{t}}^2}{4\pi^2}\left(1 + \frac{a^2}{2}\right) \log \frac{\Lambda}{m_{\tilde{t}}}$$

$$\delta m_{\tilde{t}}^2 = \frac{8\alpha_s}{3\pi} M_3^2 \log \frac{\Lambda}{M_3}$$

$\rightarrow$ only need light higginos, stops and gluinos $\rightarrow$ internal hierarchy

but...additional fine tuning in the parameter space to keep this hierarchy after considering 1 loop corrections!

For low $\Lambda$ the situation is much better, but it get worse if $\Lambda$ is raised up (i.d. gravity mediation models)

# SUSY and heavy superpartners

We give up naturalness!

We simply want SUSY give us good DM candidates and a good coupling unification

Split-supersymmetry

- heavy scalars (and gravitino)
- light fermions at TeV scale $m_0$, as dictated by the WIMP miracles
- this scheme reproduces sucessful unification, indipendent on the masses of the scalars

High-scale supersymmetry

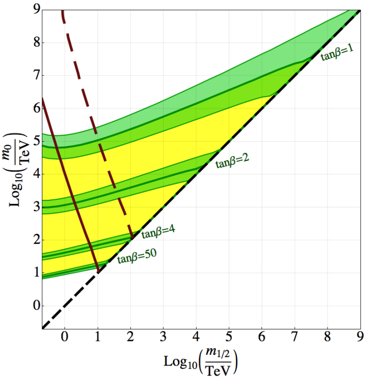
- Interesting works on high-energy SUSY in the MSSM context, given particular boundary conditions on $tg(\beta)$ ($\rightarrow$ symmetries in the Higgs sectors)
- SUSY at high-scale ($> 10^{10}\, GeV$) gives us a good prediction for the Higgs mass, and the result seems to be rather model-independent

# Split-supersymmetry

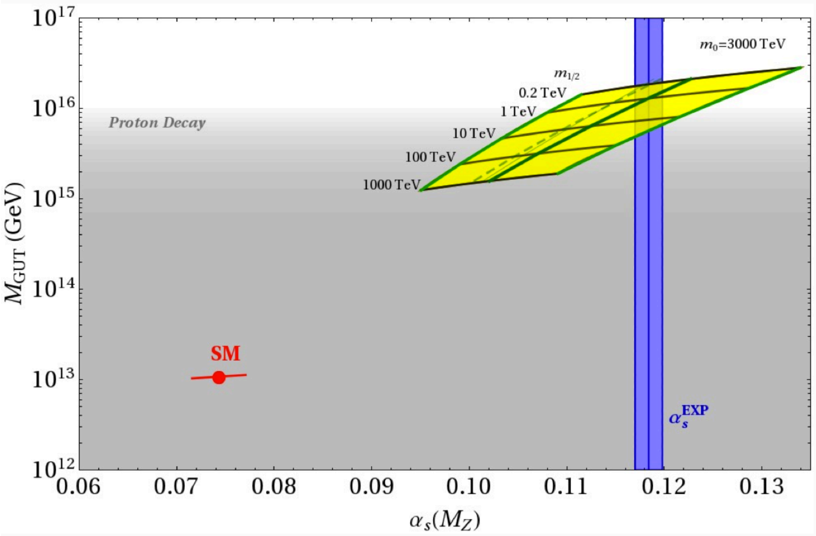
Bounds on $m_0$ in model with split supersymmetry, coming from the experimental Higgs mass and unification

After Higgs discovery we have constraints on $m_0$

- it is possible to study the phenomenology of these model in a sensitive way
- the predictions are different from the Natural SUSY ones: let us see what LHC will indicate us about the naturalness of the Higgs sector



# Minimal susy and unification



# The missing superpartner problem at LHC