The $\mu$ problem
&
a non standard Higgs spectrum

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Outline

Main topics

- Susy = light Higgs boson? The NMSSM with large $\lambda$
- The generation of the $\mu$ term (scale invariant superpotential)

Experimental constraints
  - LEP bounds
  - EWPTs
  - DM direct detection

The naturalness of the theory

Higgs signatures at the LHC

Conclusions & Outlook

Based on
R. Franceschini and S. Gori
“Solving the $\mu$ problem with a heavy Higgs boson”
JHEP 1105:084,2011 [arXiv: 1005.1070]
Susy = light Higgs boson?

In the MSSM

- At the one loop
  \[ m_h^2 \leq m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2} y_t^4 v^2 \sin^4 \beta \log \left( \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right) \]

- The MSSM is SM like in most part of the parameter space

LEP bound: \( m_h \geq 114.4 \) GeV

Necessity of rather heavy stops!

Fine tuning!

( since the stops contribute at one loop also to \( m_Z \) )

"Susy little hierarchy problem"
Susy = light Higgs boson?

In the MSSM

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- The MSSM is SM like in most part of the parameter space
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Necessity of rather heavy stops!
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(since the stops contribute at one loop also to \( m_Z \))
"Susy little hierarchy problem"

In the NMSSM

- At the one loop
\[ m_h^2 \leq m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \frac{3}{4\pi^2} y_t^4 v^2 \sin^4 \beta \log \left( \frac{m_{t_1} m_{t_2}}{m_t^2} \right) \]
- If \( \lambda \) is perturbative until \( M_{\text{GUT}} \), we can gain only \(~ 20 \text{ GeV} \) if compared to the MSSM

What if we take large \( \lambda \)?

- Effective field theory valid up to tens of TeV (above which, one or more Higgs reveals its composite nature)
- It can be still compatible with the unification of the gauge couplings

Barbieri, Hall, Nomura, Rychkov – PRD 75
(Harnik, Kribs, Larson, Murayama - PRD 70, Chang, Kilic, Mahbubani -PRD 71, Birkedal, Chacko, Nomura - PRD 71)
The model

A particular fat Higgs model

Low energy effective field theory:

\[ W = \lambda S H_1 \cdot H_2 + \frac{k}{3} S^3 \]

\[ V_{\text{soft}} = m_1^2 |H_1|^2 + m_2^2 |H_2|^2 + \mu_S^2 |S|^2 - (A\lambda S H_1 H_2 + G\frac{k}{3} S^3 + h.c.) \]
\[ + \ \frac{1}{8} g_1^2 (|H_2|^2 - |H_1|^2)^2 + \frac{1}{8} g_2^2 (H_1^\dagger T^i H_1 + H_2^\dagger T^i H_2)^2 \]

No dimensionfull parameters in the superpotential

The \( \mu \) problem

\( \mu = \lambda \langle S \rangle \)

If \( \lambda \) is large, is \( \mu \) still at (or just above) the EW scale?

Free parameters

\( \lambda, k, A, G, m_1^2, m_2^2, \mu_S^2 \)

Traded for \( \tan \beta, \mu, v \), thanks to the minimization conditions

\( \lambda \) perturbative until \( \sim O(10 \text{ TeV}) \)
The mass of the lightest Higgs boson

\[ \lambda = 2 \]
\[ k = 1.2 \]
\[ \tan \beta = 1.5 \]

Assuming \( G = A \)

(large differences are not possible by the constraints on the potential)

Minimum allowed value for \( \mu \)

Kanehata, T. Kobayashi, Y. Konishi, O. Seto, T. Shimomura
arXiv:1103.5109

\[ V(v_1, v_2, s) < V(0, 0, 0) = 0 \]

NO absolute minimum of the potential

No correct EWSB

Allowed

Condition of conservation of EM is automatically satisfied

\( \mu \) problem & a non-standard \( H \) spectrum
**Generation of the μ term**

\[ \mu = \lambda \ s \]

Is it constrained to be at around the EW scale by the conditions we have to impose to the scalar potential?

- \( V(v_1, v_2, s) < V(0, 0, 0) = 0 \) and absence of spontaneous CP breaking. In the **large \( \lambda \) limit**:
  \[
  \mu^2 \gtrsim \frac{\lambda^2 v^2}{2} \sin^2 2\beta - \frac{m_Z^2}{4} \cos^2 2\beta
  \]

- The absence of a tachionic Higgs and \( V(v_1, v_2, s) < V(0, 0, 0) = 0 \) in the **large \( \lambda \) limit** and for \( k < \lambda \):
  \[
  \mu \lessapprox \frac{v \lambda \sin 2\beta}{2} \frac{3(\rho - 4)\rho + \sqrt{8(\rho - 1)(5\rho - 7)} + 9}{(\rho - 5)(\rho - 1)} \approx \frac{3}{2} v \lambda \sin 2\beta + O(\rho) v \lambda
  \]

  \[ \rho = k/\lambda \]

The mass of the chargino is rather constrained

\[
\frac{\lambda v}{\sqrt{2}} \sin 2\beta \lesssim \mu \lesssim \frac{3 \lambda v}{2} \sin 2\beta
\]

Where \( \lambda v \) is the scale of the lightest Higgs mass

**μ is just above the EW scale**

**Note:**

- \( \lambda \rightarrow \infty \)
- \( \mu \rightarrow A \sin(2\beta)/2 \)

Large \( \lambda \)

Higgs and chargino not seen at LEP

\[ \mu \text{ problem & a non standard H spectrum} \]
Experimental constraints (1)

Is this theory viable in spite of the several experimental constraints?

- **LEP bounds** on Higgs, chargino and neutralino masses

Not strong constraints after having ensured that the Higgs is not tachionic

The lightest neutralino is massless for

\[ \mu^2 = \frac{\lambda v^2 \lambda^2 \sin 2\beta}{k} \]
Is this theory viable in spite of the several experimental constraints?

- **LEP bounds** on Higgs, chargino and neutralino masses

  Not strong constraints after having ensured that the Higgs is not tachionic

- **EWPTs**: main contribution to the T parameter is due to the Neutralinos

\[
\mu^2 = \frac{\lambda v^2 \lambda^2 \sin 2\beta}{k/2}
\]

The lightest neutralino is massless for

- \( k = 1.2 \)
- Perturbative until \( \sim 10\text{TeV} \)
- Preference for smaller values of \( \tan\beta \) and \( \lambda \)

(We assume gauginos quite heavier than Higgsinos)
Experimental constraints (1)

Is this theory viable in spite of the several experimental constraints?

- **LEP bounds** on Higgs, chargino and neutralino masses

  Not strong constraints after having ensured that the Higgs is not tachionic

- **EWPTs**: main contribution to the T parameter is due to the Neutralinos

  In spite of a large Higgs mass, the theory can be consistent with EWPTs because of the positive NP contributions to T

The lightest neutralino is massless for

$$\mu^2 = \frac{\lambda v^2 \lambda^2 \sin 2\beta}{2}$$
Experimental constraints (2)

- Dark matter direct detection experiments

Computed using two different values for the quark form factors (from chiral perturbation theory (arXiv:0801.3656), or from QCD on the lattice (arXiv:0907.4177))

Both in the case of large/small Higgs mass $\mu \sim (200-300)$ GeV is favored

- Large values of $\lambda$ and small values of the charged Higgs mass are favored
- A large $m_{\chi_1}$ is typically excluded
Summary of the constraints

- $k = 1.2$
- To have in general smaller contributions to the $T$ parameter

- Correct EWSB;
- LEP bounds;
- EWPTs;
- DM direct detection

In blue the allowed region

Ranges for the mass of chargino and of the charged Higgs boson are rather limited
Summary of the constraints

\[ k = 1.2 \]

to have in general smaller contributions to the T parameter

- Correct EWSB;
- LEP bounds;
- EWPTs;
- DM direct detection

\( \lambda = 1.5 \)

\( \lambda = 2 \)

Ranges for the mass of chargino and of the charged Higgs boson are rather limited

In blue the allowed region

Here we will do our analysis
In a generic theory the EW scale depends on several dimensionful parameters $v^2 = v^2(a_j)$.

For small variations of these parameters it is natural to have also small variations of the EW scale.

Definition of fine tuning $\Delta_{ai}$

$$\Delta_{a_j} \equiv \left| \frac{a_i^2}{v^2} \frac{d v^2(a_i)}{d a_j^2} \right|$$

Barbieri, Giudice, Nucl.Phys.B306

In our theory, we have to compute the fine tuning with respect to $(\mu_s, m_1, m_2, G, A)$.

Only the latter is relevant:

Heavy squarks are allowed (but not required) with a moderate level of fine tuning:

$$\Delta = \left| \frac{m_Q^2}{v^2} \frac{d v^2}{d m_Q^2} \right| \sim \left| \frac{m_Q^2}{v^2} \frac{d v^2}{d m_2^2} \frac{d m_2^2}{d m_Q^2} \right| \Rightarrow \Delta \sim \frac{m_Q^2}{v^2} 3 \log^2 \frac{\Lambda_{\text{mess}}}{\text{TeV}} \frac{d v^2}{d m_2^2}$$

Not huge dependence for large values of $\lambda$. Theory is much less tuned for a heavy Higgs boson.
Production of the Higgs bosons at the LHC

1. Gluon gluon fusion

Reduced couplings squared with up-type quarks:

Significantly coupled

The two heavier states are sufficiently coupled

Possibility of producing at the LHC all the three Higgs bosons through gluon gluon fusion
2. Vector boson fusion

Reduced couplings squared with gauge bosons:

- The heaviest state is rather decoupled
- Difficulty of producing the heaviest Higgs boson at the LHC through vector boson fusion
Decays of the lightest Higgs boson

Three main decay modes:

- Rather reduced decay of the Higgs into $W^+W^-$ Higgs not found at the LHC yet.
- Higgs could be observed earlier in the non-SM decay $h \rightarrow a_1a_1 \rightarrow \tau \bar{\tau}b\bar{b}$
- A large fraction of Higgs bosons decay invisibly into two LSPs

$\lambda = 2$
$k = 1.2$
$\tan \beta = 1.5$
A benchmark point

A typical configuration:

\[ \lambda = 2 \]
\[ k = 1.2 \]
\[ \tan \beta = 1.5 \]
\[ \mu = 240 \text{ GeV} \]
\[ m_{H^+} = 520 \text{ GeV} \]

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Conclusions

Scale invariant NMSSM as an effective field theory valid up to \(~10\) TeV

- It raises dramatically the mass of the lightest Higgs boson: \(M_{h_1} \sim (200-300)\) GeV
- It generates a \(\mu\) term that scales as the lightest Higgs mass (it addresses naturally the \(\mu\) problem)

In spite of the large Higgs mass, EWPTs can be easily satisfied

Predictions: in the region of parameter space allowed by the experiments (LEP, EWPTs, DM direct detection)
- Lightest chargino rather close in mass to the lightest Higgs boson
- Lightest neutralino with a mass smaller than \(~100\) GeV
- Lightest Higgs boson mainly decaying into two pseudoscalars \(h \rightarrow a_1 a_1 \rightarrow \tau \bar{\tau} b \bar{b}\)

- Possibility of discovery the heavier Higgs bosons produced through gluon gluon fusion

Outlook: detailed study of the collider signature of the model
\( \lambda = 2 \)
\( k = 1.2 \)
\( \tan \beta = 1.5 \)
$k = 1.2$

$\lambda = 1.5$

$\cot \beta = 1.1$

$\cot \beta = 1.3$

$\cot \beta = 1.5$

$\cot \beta = 2$

$k = 1.2$

$\lambda = 2$