Paolo Lodone

*SNS of Pisa
and INFN*

(in collaboration with:
R. Barbieri, E. Bertuzzo, M. Farina, D. Pappadopulo)

Can the Supersymmetric Flavour Problem decouple in case of a Non Standard Supersymmetric Spectrum?

Main ref: R. Barbieri et al, “A Non Standard Supersymmetric Spectrum” [1004.2256].
1/7) Motivation: naturalness

- **Higgs mass Problem**

MSSM: \( m_h \lesssim m_Z |\cos 2\beta| + \text{rad. corr.} \) \( \leftrightarrow \text{finetuning} \)

\( \rightarrow \) alleviated if \( m_h^{(\text{tree})} \uparrow \)

- **Supersymmetric Flavour Problem**

Ameliorated by hierarchical sfermions.
Obstruction: \( \text{finetuning} \) (+ colour cons.)

\( \rightarrow \) alleviated if \( m_h^{(\text{tree})} \uparrow \)

Related issues?
Idea: Non Standard Supersymmetric Spectrum

Motivated? Naturally implemented? Phenomenological consequences?
2/7) Hierarchical sfermions and flavour physics

- No degeneracy nor alignment: \( m_{\tilde{q}_{1,2}} > \text{hundreds of TeV} \)
  
  [Dine, Kagan Samuel 1990] [Pomarol Tommasini 1996] [Cohen, Kaplan, Nelson 1996]

- If \( \delta_{12}^{LL} \approx \frac{|m_1^2 - m_2^2|}{(m_1^2 + m_2^2)/2} \approx \lambda \approx 0.22 \) and \( \delta^{LL} \approx \delta^{RR} \gg \delta^{LR} : \)

  - Recent analysis:
    [Giudice, Nardecchia, Romanino 2009]

  - If as above but \( \delta^{LL} \gg \delta^{RR}, \delta^{LR} \) (or \( \delta^{RR} \gg \delta^{LL}, \delta^{LR} \) ) :

    \[
    \Delta C = 2 \Rightarrow m_{\tilde{q}_{1,2}} \gtrsim 3 \text{ TeV} \\
    \text{Im } \Delta S = 2, \; \sin \phi_{CP} \approx 0.3 \Rightarrow m_{\tilde{q}_{1,2}} \gtrsim 12 \text{ TeV}.
    \]

\[
\Rightarrow m_{\tilde{f}_{1,2}} \gtrsim 20 \div 30 \; \text{TeV} \quad m_{\tilde{f}_3} \approx 0.5 \div 1 \; \text{TeV}
\]

may be a way to solve the flavour problem
3/7) Bounds on $m^2_{f_1,2}$ in the MSSM:

I) naturalness

$$ \frac{\partial m_h^2}{\partial t} \approx \frac{\alpha'}{4\pi} Tr(Y \tilde{m}_{1,2}^2) + \frac{\alpha^2}{16\pi^2} \tilde{m}_{1,2}^2 \quad \& \quad \frac{m^2_{\tilde{q}_{1,2}}}{m_h^2} \frac{\delta m_h^2}{\delta m_{\tilde{q}_{1,2}}^2} < \Delta $$

No particular condition at $M=M_{\text{susy}}$

Vert. degeneracy at $M=M_{\text{susy}}$ for $1^{\text{st}}$ and $2^{\text{nd}}$ gen.

[Barbieri, Giudice, 1988][Dimopoulos, Giudice 1995]
3/7) Bounds on $m_{f_{1,2}}^2$ in the MSSM: II) colour conservation

$$\frac{d}{dt}m_{f}^2 = -8\sum_{i} \tilde{\alpha}_i C_i M_i^2 + 8 \left[ \left( \frac{1}{2} N_5 + \frac{3}{2} N_{10} \right) \sum_{i} \tilde{\alpha}_i^2 C_i \right] \tilde{m}_{1,2}^2 + (N_5 - N_{10}) \frac{3}{5} Y_f \tilde{\alpha}_1 \left( \frac{4}{3} \tilde{\alpha}_3 - \frac{3}{4} \tilde{\alpha}_2 - \frac{1}{12} \tilde{\alpha}_1 \right) \tilde{m}_{1,2}^2.$$

Large $m_{1-2}$ draws $m_{f3}^2$ negative at low energies!

Way out*:

- $M_{\text{susy}} \ll M_{\text{GUT}}$
- Larger $m_{\tilde{h}}^{(\text{tree})}$

(because larger allowed $m_3(M_{\text{susy}})$ and $M_g$ !)


*without peculiar initial cond. [Feng 2009][Bagger 2009]
4/7) Supersymmetry without a light Higgs boson
(to keep the success of EWPT, no effective theories)

- **Extra U(1)**
  
  \[ m_h^2 \leq (m_Z^2 + \frac{g_x^2 v^2}{2(1 + \frac{M_X^2}{2M_{\phi}^2})}) \cos^2 2\beta \]

- **Extra SU(2)**
  
  \[ m_h^2 \leq m_Z^2 \left( g'^2 + \frac{\Delta g^2}{g'^2 + g^2} \right) \cos^2 2\beta \]
  \[ \Delta = \frac{1 + \frac{M_X^2}{M_{\phi}^2}}{1 + \frac{M_X^2}{M_{\phi}^2}} \]

- **\[ \Delta f = \lambda S H_1 H_2 \]**
  
  \[ m_h^2 \leq m_Z^2 (\cos^2 2\beta + \frac{2\lambda^2}{g^2 + g'^2} \sin^2 2\beta) \]

[P.L. 2010] [Barbieri et al 2010]

- \( \Lambda = \) scale at which some coupling gets semiperturbative
- In gauge extensions \( M_{\phi,\Sigma}/M_X \) is maximized consistently with naturalness of the higher vev

With low \( \Lambda \), \( m_h \) can be sign. raised

[Batra, Delgado, Kaplan, Tait 2004]
[Barbieri, Hall, Nomura, Rychkov 2007]
5/7) Bounds with larger $m_h^{(tree)}$:

I) naturalness

\[ U(1) \quad m_h^{max} = 180 \text{ GeV} \quad \text{SU(2)} \quad m_h^{max} = 250 \text{ GeV} \quad \lambda\text{Susy} \quad m_h^{max} = 250 \text{ GeV} \]

$\tilde{m}$ is $m_{\tilde{f}_{1,2}}$ with vertical degeneracy among $\tilde{f}$'s at $M_{\text{susy}}$

$\Rightarrow \quad m_{\tilde{f}_{1,2}} \gtrsim 20 \text{ TeV} \quad \text{OK in } \lambda\text{Susy at } M = 100\div1000 \text{ TeV}$
5/7) Bounds with larger \( m_{h}^{(tree)} \):

II) colour conservation (can the SUSY Flavour Problem decouple?)

- RGE for \( m_3 \):
  \[
  \frac{dm_{Q_3}^2}{d \log \mu} = -\frac{1}{16\pi^2} \frac{32}{3} g_3^2 M_g^2 + \frac{8}{(16\pi^2)^2} \left( \frac{1}{15} g_1^4 + 3 g_2^4 + \frac{16}{3} g_3^4 \right) \hat{m}_{1,2}^2
  \]

- Imposing \( m_3(G_F r^2) > 0 \):

We neglect lighter gauginos; \( M_g = \text{gluino mass at low energy.} \)

[Arkani-Hamed, Murayama 1997]
5/7) Bounds with larger $m_h^{(tree)}$:

II) colour conservation (can the SUSY Flavour Problem decouple?)

- Fix maximum $m_3$ from:
  \[
  \frac{\partial \log v^2}{\partial \log m_3^2} \approx \frac{6 (m_t/175 \text{ GeV})^2}{16\pi^2} \frac{m_3^2}{m_h^2/2} \log \frac{M}{200 \text{ GeV}} \leq 10
  \]

- Then impose positive squared masses:

**MSSM**

**λSUSY with $m_h=250$ GeV**

Bound from threshold effects: $m_H/m_L<25$

[Agashe, Graesser 1998]
6/7) Phenomenological consequences: I) gluino pair production and decay

A typical configuration

See also [Barbieri, Pappadopulo 2009]

3 relevant semi-inclusive BR's

\[ \tilde{g} \rightarrow t\bar{t}\chi \]
\[ \tilde{g} \rightarrow t\bar{b}\chi \] (\(tb\chi\))
\[ \tilde{g} \rightarrow bb\chi \]

with \( B_{tt} + 2B_{tb} + B_{bb} \approx 1 \)
and \( \chi = \chi_{LSP} + W, Z' \)’s

⇒ multi top events
⇒ spherical events
⇒ 4 b’s always, sometime only

More in general

\[ m_{\tilde{g}} = 400 \div 1800 \text{ GeV} \]
\[ m_{\tilde{t}_1} < m_{\tilde{t}_2} < 800 \text{ GeV} \quad \theta_t = 0 \div \pi/2 \]
\[ \mu = 100 \div 400 \text{ GeV} \]
\[ M_1, M_2 = 100 \div 500 \text{ GeV} \]
\[ m_{\tilde{b}_R} \lesssim 600 \text{ GeV} \]

(s-lepton masses almost always unimportant)
6/7) Phenomenological consequences: II) unconventional Higgs sector

\[ h \rightarrow ZZ \rightarrow l^+l^- l^+l^- \quad \text{Easy and very much non-susy like} \]
\[ H \rightarrow hh \rightarrow 4V \rightarrow l^+l^- 6j \quad BR \propto \lambda^2 \text{ much larger than normal} \]
\[ A \rightarrow hZ \rightarrow VVZ \rightarrow l^+l^- 4j \]
6/7) Phenomenological consequences: III) DM relic abundance

See also “The well tempered neutralino”  
[Arkani-Hamed, Delgado, Giudice 2006]

A strong effect of the s-channel heavier Higgs exchange  
No “well-temperament”

\[ M_1(GeV) \]

\[ M_2 \text{ large} \]

\[ \text{MSSM } m_h = 120 \text{ GeV} \]
\[ \lambda \text{Susy: } m_h = 200 \text{ GeV} \]

Direct detection affected by \( \sigma \propto \frac{1}{m_h^4} \)

and different mixing

dark blu: CDMS now light blu: “XENON100”
7/7) Conclusions

- Higgs mass problem and SUSY Flavour problem may be related and point towards a Non Standard Supersymmetric Spectrum:

  \[ m_h = 200 \div 250 \text{ GeV} \]
  \[ m_{\tilde{f}_{1,2}} \gtrsim 20 \div 30 \text{ TeV} >> m_{\tilde{f}_3} \]

- **Naturally** possible in non minimal extensions (at least in \( \lambda \)SUSY)
- The Supersymmetric Flavour Problem can decouple (**no em/colour breaking**) thanks not only to low \( M \) but also to large \( m_h \).
- Peculiar phenomenology:

  \[
  \begin{align*}
  \tilde{g} & \rightarrow t\bar{t}\chi, \ t\bar{b}\chi (t\bar{b}\chi), \ b\bar{b}\chi \\
  h & \rightarrow ZZ, \ H \rightarrow hh, \ hh\!h
  \end{align*}
  \]

  DM: no “well-temperament”
  Direct Detection affected
Backup Slides
B1) Comparison of the three models:

From a bottom-up point of view, \(m_h\) can be significantly raised.

<table>
<thead>
<tr>
<th>(m_h^{max}/m_Z)</th>
<th>Price to pay</th>
</tr>
</thead>
<tbody>
<tr>
<td>(U(1))</td>
<td>2</td>
</tr>
<tr>
<td>(SU(2))</td>
<td>2</td>
</tr>
<tr>
<td>(SU(2))</td>
<td>3</td>
</tr>
<tr>
<td>(\lambda)SUSY</td>
<td>2</td>
</tr>
<tr>
<td>(\lambda)SUSY</td>
<td>3</td>
</tr>
</tbody>
</table>

[P.L. 2010]
B2) Electroweak precision tests

- Gauge ext U(1): \( M_X \gtrsim 5 \text{ TeV} \) 
  \((m_h = 2m_Z)\)

- Gauge ext SU(2): \( \frac{M_X}{5 \text{ TeV}} \gtrsim \frac{g_X}{g_Z} \)

\[ \lambda_{\text{SUSY}}: \]

---

E. Salvioni, A. Strumia, G. Villadoro, F. Zwirner (2010)
B3) What about unification?

\[ \Lambda \sim M \sim 10^4 \text{ TeV} \]
\[ m_{1,2} = 20 \text{ TeV} \]

At \[ M \approx 10^4 \text{ TeV} : \]
\[ g_1 \approx 0.5, \quad g_2 \approx 0.7, \quad g_3 \approx 0.85 \]

May it be a “sufficient” unification?

(we cannot say what happens here)

[suggested by R. Barbieri, 2010]
B4) Extra naturalness bounds (tree + loop)

- Gauge ext U(1):
  \[ M_X \geq 0.40 \, M_\phi \]

- Gauge ext SU(2):
  \[ M_X \geq 0.22 \, M_\Sigma \]

- \( \lambda \text{SUSY}: \quad m_s \lesssim 1 \text{ TeV} \)
  (but no problem)
B5) DM: other deformations

\[ M_1(\text{GeV}) \quad M_2 \text{ large} \quad M_2 = 200 \text{ GeV} \]

\[ \lambda_{\text{Susy}}: \quad m_h = 250 \text{ GeV} \]

dark blu: CDMS now
light blu: "XENON100"
B6) EWPT in U(1) case

*extra U(1) case*

excluded at 90%

Salvioni, Strumia, Villadoro, Zwirner