Chances for SUSY-GUT in the LHC Epoch

Marco Chianese

Università degli Studi di Napoli Federico II - INFN

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in collaboration with Z. Berezhiani, G. Miele and S. Morisi*

* at this workshop
Several phenomena or open problems suggest the presence of physics beyond Standard Model (SM):

- hint of gauge unification;
- structure of fermion masses;
- hierarchy problem;
- baryogenesis.

The Supersymmetric Grand Unified Theories (SUSY-GUTs) are able to address part of these problems.

After the 8 TeV LHC run I, we try:

- to reanalyze the room still remaining for SUSY-GUT inspired models;
- to determine the upper bound $M_{UB}$ for the energy below which SUSY signatures have to show up.
Assumptions

• To perform our study, we require:

• One step gauge unification at a single energy scale $M_{\text{GUT}}$, without intermediate symmetry scales;

$M_{\text{GUT}} = 2 \text{ TeV}$

$M_{\text{SUSY}} = 2 \text{ TeV}$

SU(5) Bottleneck

band at 3 $\sigma$
Assumptions

• To perform our study, we require:

  • One step gauge unification at a single energy scale $M_{GUT}$, without intermediate symmetry scales;

  • Consistency of third family fermion masses and possible Yukawa $b$-$\tau$ unification;

\[
y_b(M_{GUT}) = y_\tau(M_{GUT}) \left( 1 + \mathcal{O} \left( \frac{y_\mu(M_{GUT})}{y_\tau(M_{GUT})} \right) \right)
\]
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• To perform our study, we require:
  
  • One step gauge unification at a single energy scale $M_{GUT}$, without intermediate symmetry scales;

  $y_{b}(M_{GUT}) = y_{\tau}(M_{GUT}) \left(1 + \mathcal{O}\left(\frac{y_{\mu}(M_{GUT})}{y_{\tau}(M_{GUT})}\right)\right)$

  • Consistency of third family fermion masses and possible Yukawa $b$-$\tau$ unification;

  • Consistency with the experimental limit on proton decay;

  • Absence of special fine tunings among the parameters in the GUT scenario, implying couplings $\mathcal{O}(1)$ above $M_{GUT}$.
We have developed a Mathematica code, which resolves all the RGEs up to 2-loop order with numerical iterative method.

\[
\frac{d}{dt} X_i = \frac{1}{16\pi^2} \beta_{X_i}^{(1)}(X_j) + \frac{1}{(16\pi^2)^2} \beta_{X_i}^{(2)}(X_j)
\]

The analysis takes into account all the matching and threshold relations at 1-loop level.

We consider the general possibility of:

- several SUSY thresholds (multi-scale approach);
- GUT threshold.

Only the third generation Yukawa couplings are relevant.
The set of input parameters are

\[ \{\tilde{m}_h, \tilde{m}_g, \tilde{m}_{sq}, \chi, \tan \beta\} \]

SUSY thresholds

\[ \tilde{m}_h \equiv \text{higgsinos} \]
\[ \tilde{m}_g \equiv \text{gluinos} \]
\[ \tilde{m}_{sq} \equiv \text{squarks} \]

Two other constrained masses.

At \( M_{\text{GUT}} \)

\[ \frac{\tilde{m}_g}{\tilde{m}_W} = 1 \]
\[ \frac{\tilde{m}_{sq}}{\tilde{m}_{sl}} = \frac{\tilde{m}_{10}}{\tilde{m}_5} \]

IRR: \[ \bar{5} + 10 \]
The mass matrix of the Higgs scalars $H_u$ and $H_d$ involves mass parameters of different origin.

\[
\mathcal{M}^2 = \begin{pmatrix}
\tilde{M}^2_u + \mu^2 & \mu B_\mu \\
\mu B_\mu & \tilde{M}^2_d + \mu^2
\end{pmatrix}
\]

**SUSY $\mu$-term**
\[
\mu^2 = \mathcal{O}(\tilde{m}_h)
\]

**F-term**
\[
\mu B_\mu = \mathcal{O}(\tilde{m}_g)
\]

**D-term**
\[
\tilde{M}^2_{u,d} = \mathcal{O}(\tilde{m}_{sq})
\]
Higgs sector and SUSY thresholds

- The mass matrix of the Higgs scalars $H_u$ and $H_d$ involves mass parameters of different origin.

\[ M^2 = \begin{pmatrix} M_u^2 + \mu^2 & \mu B_{\mu} \\ \mu B_{\mu} & M_d^2 + \mu^2 \end{pmatrix} \]

### SUSY $\mu$-term
\[ \mu^2 = \mathcal{O}(\tilde{m}_h) \]

### F-term
\[ \mu B_{\mu} = \mathcal{O}(\tilde{m}_g) \]

### D-term
\[ M_{u,d}^2 = \mathcal{O}(\tilde{m}_{sq}) \]

- A fine-tuning condition has to be imposed in order to get the SM Higgs.

\[
- m^2 = \frac{1}{2} \left( 2\mu^2 + \tilde{M}_u^2 + \tilde{M}_d^2 - \sqrt{4\mu^2 B_{\mu}^2 + (\tilde{M}_u^2 - \tilde{M}_d^2)^2} \right) \sim -(100 \text{ GeV})^2
\]

\[ \tilde{m}_h \sim \tilde{m}_g \sim \tilde{m}_{sq} \]

same order of magnitude
• The set of input parameters are

\[ \{ \tilde{m}_h, \tilde{m}_g, \tilde{m}_{sq}, \chi, \tan \beta \} \]

GUT threshold

• The Higgs \( \Sigma \), which breaks SU(5) down to the MSSM, can have mass \( M_\Sigma \) smaller than \( M_{GUT} \).

\[ V_\Sigma = \frac{M_\Sigma}{2} \Sigma^2 + \frac{\lambda_\Sigma}{2} \Sigma^3 \]

\[ \chi = \frac{M_{GUT}}{M_\Sigma} \]

\[ \lambda_\Sigma = \frac{\sqrt{2\pi\alpha_{GUT}}}{\chi} = \mathcal{O}(1) \]

Naturalness
The set of input parameters are

\[ \{ \tilde{m}_h, \tilde{m}_g, \tilde{m}_{sq}, \chi, \tan \beta \} \]

Yukawa matching condition

In the transition between SM and MSSM we have to impose

\[
\begin{align*}
\nu_u &= \langle H^0_u \rangle \\
\nu_d &= \langle H^0_d \rangle \\
\tan \beta &= \frac{\nu_u}{\nu_d}
\end{align*}
\]

\[
\begin{align*}
m_t &= y_t \nu \sin \beta \\
m_b &= y_b \nu \cos \beta \\
m_\tau &= y_\tau \nu \cos \beta
\end{align*}
\]
The set of input parameters are

\[ \{ \tilde{m}_h, \tilde{m}_g, \tilde{m}_{sq}, \chi, \tan \beta \} \]

The outputs are

\[ \{ \alpha_3(M_Z), M_{GUT}, \alpha_{GUT}, y_t(M_{GUT}), y_b(M_{GUT}), y_\tau(M_{GUT}) \} \]

These two values must be compatible with the experimental measurements.

**EW measurement**

\[ \alpha_3^{\text{exp}}(M_Z) = 0.1184 \pm 0.0007 \]

**proton decay**

\[ \frac{M_{GUT}}{\sqrt{\alpha_{GUT}}} \geq 3 \cdot 10^{16} \text{ GeV} \]
Proton decay

• We take into account the 6d operators describing the proton decay mediated by leptoquarks.

\[
\Gamma (p \rightarrow e^+ \pi^0) = \frac{\pi}{4} \frac{\alpha_{\text{GUT}}^2}{M_{\text{GUT}}^4} \frac{m_p}{f^2} \alpha_H^2 |1 + D + F|^2 \left( 1 - \frac{m^2_{\pi}}{m^2_p} \right)^2 \left[ (A_R^{(1)}) + (A_R^{(2)}) \left( 1 + |V_{ud}|^2 \right)^2 \right]
\]

Hisano, Kobayashi, Nagata, PL B716 (2012)

\[
\tau_p/\text{Br} (p \rightarrow e^+ \pi^0) > 1.29 \cdot 10^{34} \text{ yr}
\]

\[
\frac{M_{\text{GUT}}}{\sqrt{\alpha_{\text{GUT}}}} \gtrsim 3 \cdot 10^{16} \text{ GeV}
\]

Super-Kamiokande, PR D85:112001 (2012)

• We do not consider the 5d operators since they are strongly model dependent.
\[ \chi = 1 \]

\[ \chi = 10 \]

The p-decay bound is given by:

\[ \frac{M_{\text{GUT}}}{\sqrt{\alpha_{\text{GUT}}}} \geq 3 \times 10^{16} \text{GeV} \]
SUSY mass spectrum

\[ \chi = 1 \]

\[ \chi = 10 \]
Surface $\tilde{m}_g = \tilde{m}_{sq}$

$\chi = 1$

$\tilde{m}_g = \tilde{m}_{sq}$

$\tilde{m}_h$ (TeV) vs. $\tilde{m}_g$ (TeV) for $\chi = 1$

$\tilde{m}_h$ (TeV) vs. $\tilde{m}_g$ (TeV) for $\chi = 10$
Surface $\tilde{m}_g = \tilde{m}_{sq}$

$\chi = 1$

$\chi = 10$
Larger values for GUT threshold $\chi$ are not allowed since:

- naturalness requirement implies $\lambda_\Sigma \sim O(1)$;
- $M_{GUT}$ unnaturally approaches $M_{Plack}$.

\[ M_{UB} \sim 20 \text{ TeV} \]
Conclusions

• After LHC run I (8 TeV), for planning new colliders it is of interest:
  • to reanalyze the room still remaining for SUSY-GUT inspired models;
  • to determine the upper bound $M_{UB}$ for the energy below which SUSY signatures have to show up.

• Assuming one step unification (SU(5) bottleneck), under natural assumptions we have obtained general bounds on SUSY mass spectrum.

• We claim that if a SUSY-GUT model is the proper way to describe physics beyond the SM, the lightest gluino or higgsino cannot have a mass larger than

$M_{UB} \sim 20$ TeV
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$$M_{UB} \sim 20 \text{ TeV}$$

Thanks for your attention