# Chances for SUSY-GUT in the LHC Epoch

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

* at this workshop

# Beyond Standard Model

- 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.

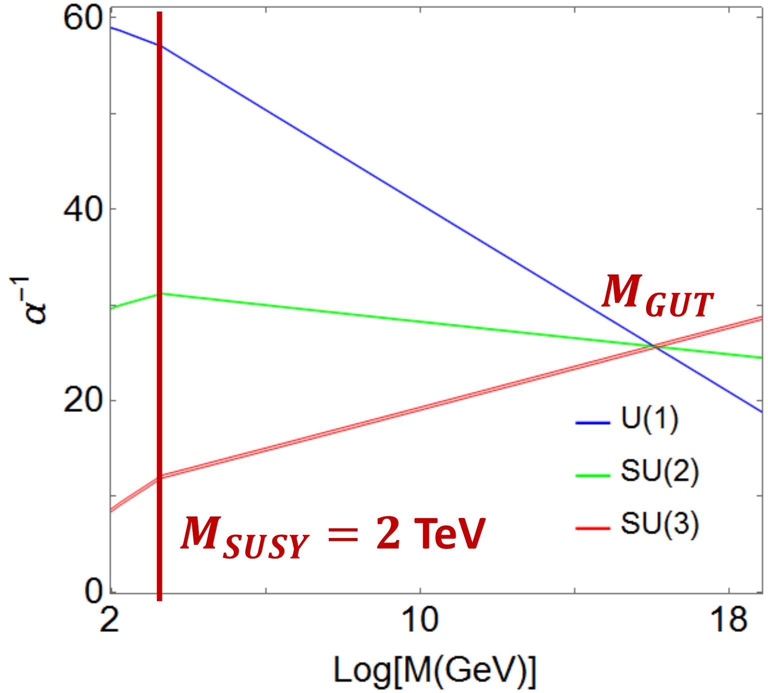
- After the 8 TeV LHC run I, we try:

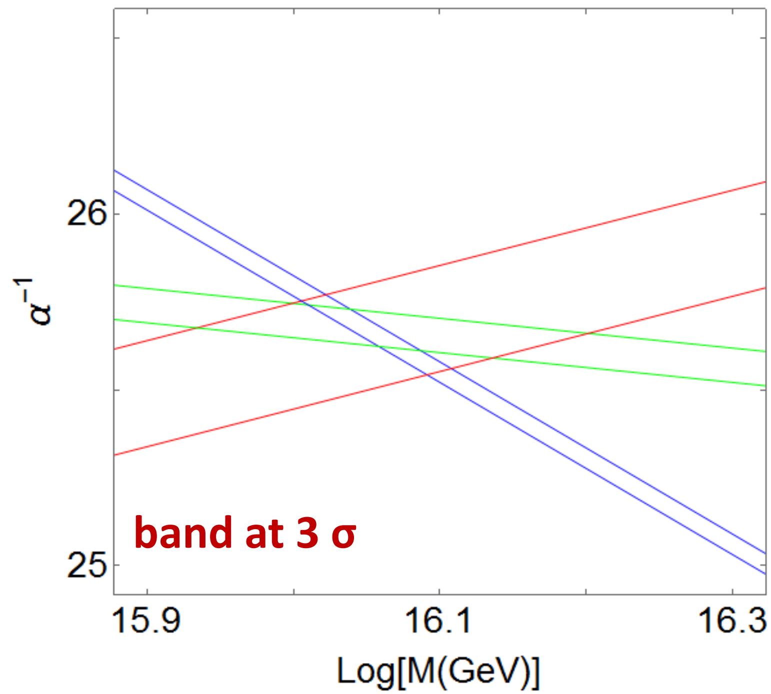
    - to reanalyze the room still remaining for SUSY-GUT inspired models;
    - to determine the **upper bound** $M_{UB}$ for the energy below which SUSY signatures have to show up.

# Assumptions

- To perform our study, we require:
  - One step gauge unification at a single energy scale $M_{GUT}$, without intermediate symmetry scales;

→ **SU(5) Bottleneck**



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  - Consistency of third family fermion masses and possible Yukawa b-τ unification;

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  - 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 $M_{GUT}$.

    → **Naturalness**

# Renormalization Group Equations

- We have developed a *Mathematica* code, which resolves all the RGEs up to **2-loop order** with numerical iterative method.

$$\frac{d}{dt}X_i = \frac{1}{16\pi^2}\beta^{(1)}_{X_i}(X_j) + \frac{1}{(16\pi^2)^2}\beta^{(2)}_{X_i}(X_j)$$

- 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.

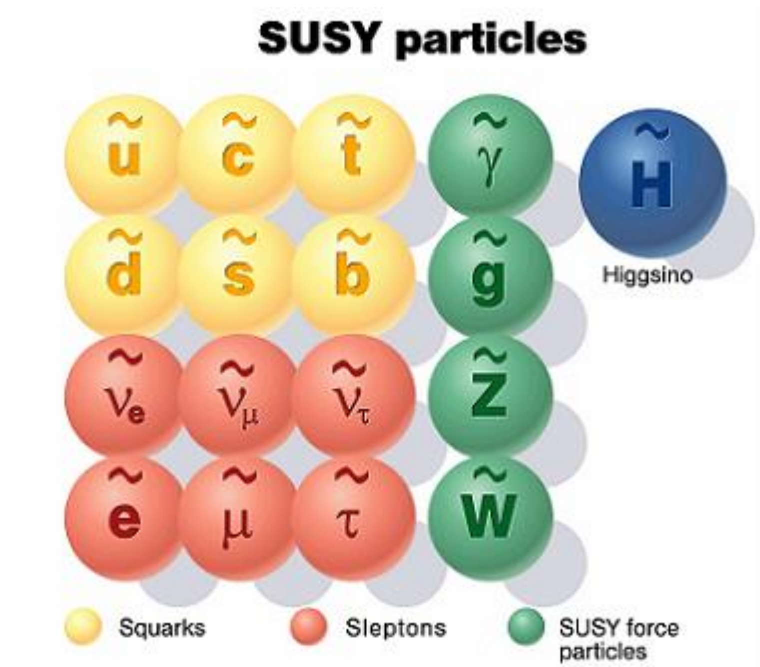
- Only the third generation Yukawa couplings are relevant.

# Input and output parameters

- The set of input parameters are

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

**SUSY thresholds**




$\tilde{m}_h \equiv$ higgsinos

$\tilde{m}_g \equiv$ gluinos

$\tilde{m}_{sq} \equiv$ squarks

**SUSY μ-term**
**F-term**
**D-term**

- Two other constrained masses.

**At $M_{GUT}$**

**SU(5)** → $\frac{\tilde{m}_g}{\tilde{m}_W} = 1$ $\quad \frac{\tilde{m}_{sq}}{\tilde{m}_{sl}} = \frac{\tilde{m}_{10}}{\tilde{m}_5}$

**IRR:** $\overline{\mathbf{5}} + \mathbf{10}$

# Higgs sector and SUSY thresholds

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

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

**SUSY μ-term**

$$\mu^2 = \mathcal{O}\left(\tilde{m}_h\right)$$

**F-term**

$$\mu B_\mu = \mathcal{O}\left(\tilde{m}_g\right)$$

**D-term**

$$\tilde{M}_{u,d}^2 = \mathcal{O}\left(\tilde{m}_{sq}\right)$$

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**SUSY μ-term** | **F-term** | **D-term**

$$\mu^2 = \mathcal{O}\left(\tilde{m}_h\right) \qquad \mu B_\mu = \mathcal{O}\left(\tilde{m}_g\right) \qquad \tilde{M}_{u,d}^2 = \mathcal{O}\left(\tilde{m}_{sq}\right)$$

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

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

→ $$\tilde{m}_h \sim \tilde{m}_g \sim \tilde{m}_{sq}$$

**same order of magnitude**

# Input and output parameters

- The set of input parameters are

$$\{\widetilde{m}_h, \widetilde{m}_g, \widetilde{m}_{sq}, \chi, \tan\beta\}$$

**GUT threshold**

- The Higgs Σ, 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**

# Input and output parameters

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**Yukawa matching condition**

- In the transition between SM and MSSM we have to impose

$$v_u = \langle H_u^0 \rangle$$

$$v_d = \langle H_d^0 \rangle$$

$$\tan\beta = \frac{v_u}{v_d}$$

$$m_t = y_t v \sin\beta$$

$$m_b = y_b v \cos\beta$$

$$m_\tau = y_\tau v \cos\beta$$

# Input and output parameters

- 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**

$$\alpha_3^{\exp}(M_Z) = 0.1184 \pm 0.0007$$

**proton decay**

$$\frac{M_{\rm GUT}}{\sqrt{\alpha_{\rm GUT}}} \gtrsim 3 \cdot 10^{16}\,\mathrm{GeV}$$

→ compatibility constraints ←

# Proton decay

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

$$\Gamma\left(p \to e^+\pi^0\right) = \frac{\pi}{4}\frac{\alpha_{\rm GUT}^2}{M_{\rm GUT}^4}\frac{m_p}{f_\pi^2}\alpha_H^2|1+D+F|^2\left(1-\frac{m_\pi^2}{m_p^2}\right)^2\left[\left(A_{\rm R}^{(1)}\right)+\left(A_{\rm R}^{(2)}\right)\left(1+|V_{ud}|^2\right)^2\right]$$

*Hisano, Kobayashi, Nagata, PL B716 (2012)*

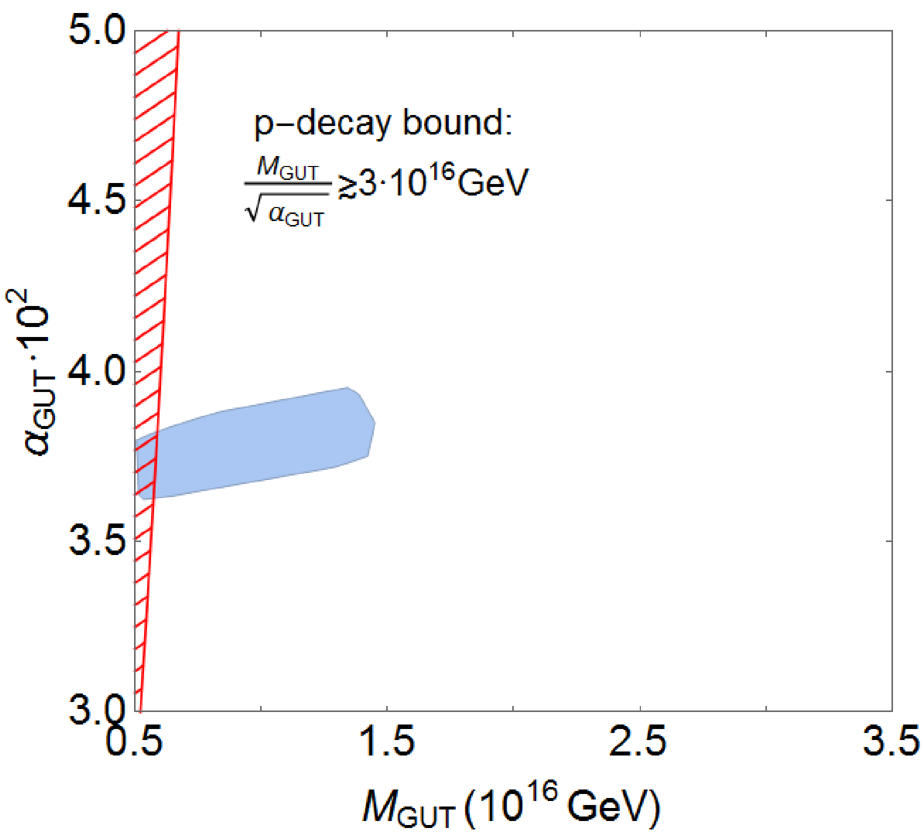
$$\tau_p/{\rm Br}\left(p \to e^+\pi^0\right) > 1.29\cdot 10^{34}\ {\rm yr} \quad \Rightarrow \quad \frac{M_{\rm GUT}}{\sqrt{\alpha_{\rm GUT}}} \gtrsim 3\cdot 10^{16}\ {\rm GeV}$$

*Super-Kamiokande, PR D85:112001 (2012)*

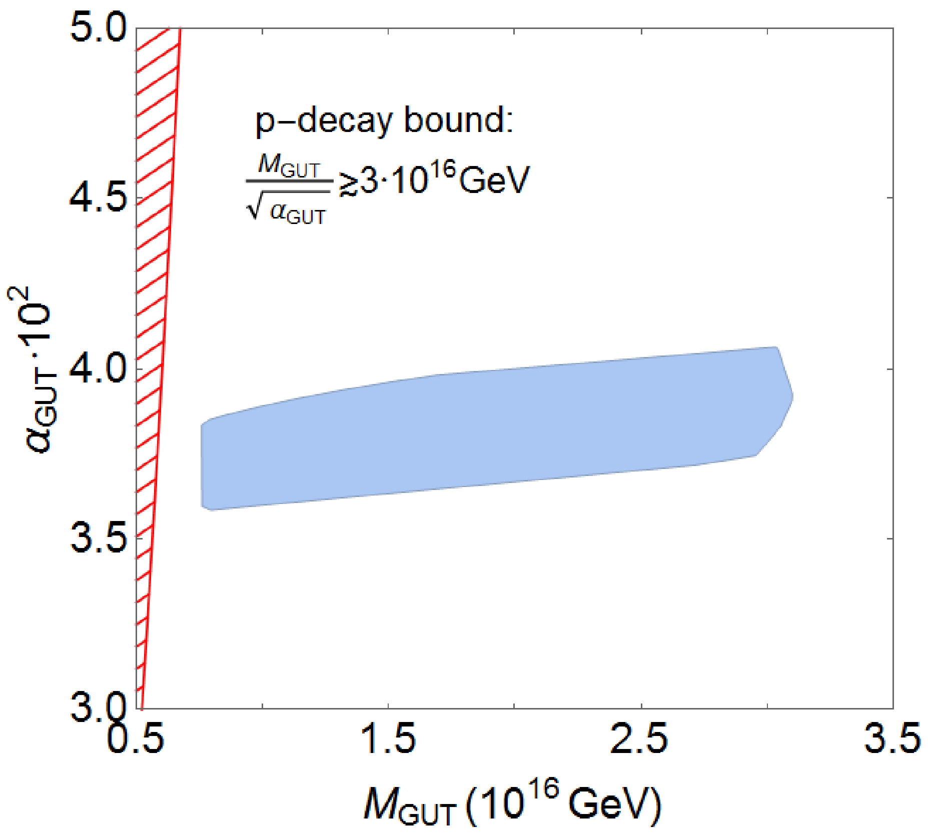
- We do not consider the **5d** operators since they are strongly model dependent.

# GUT region

$\chi = 1$




$\chi = 10$



# SUSY mass spectrum

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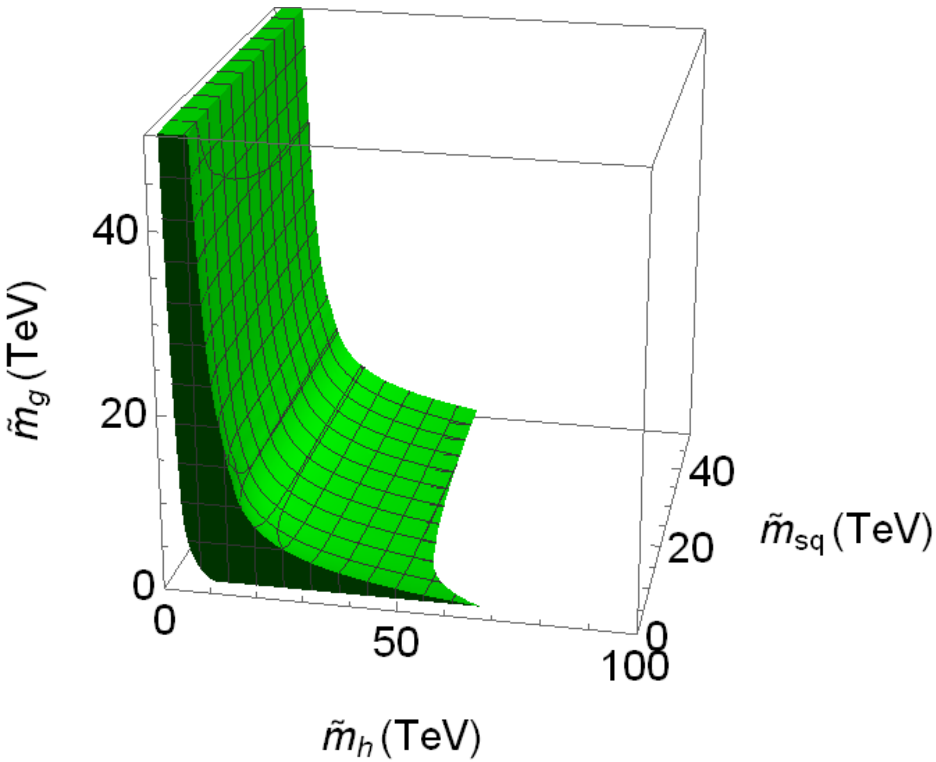


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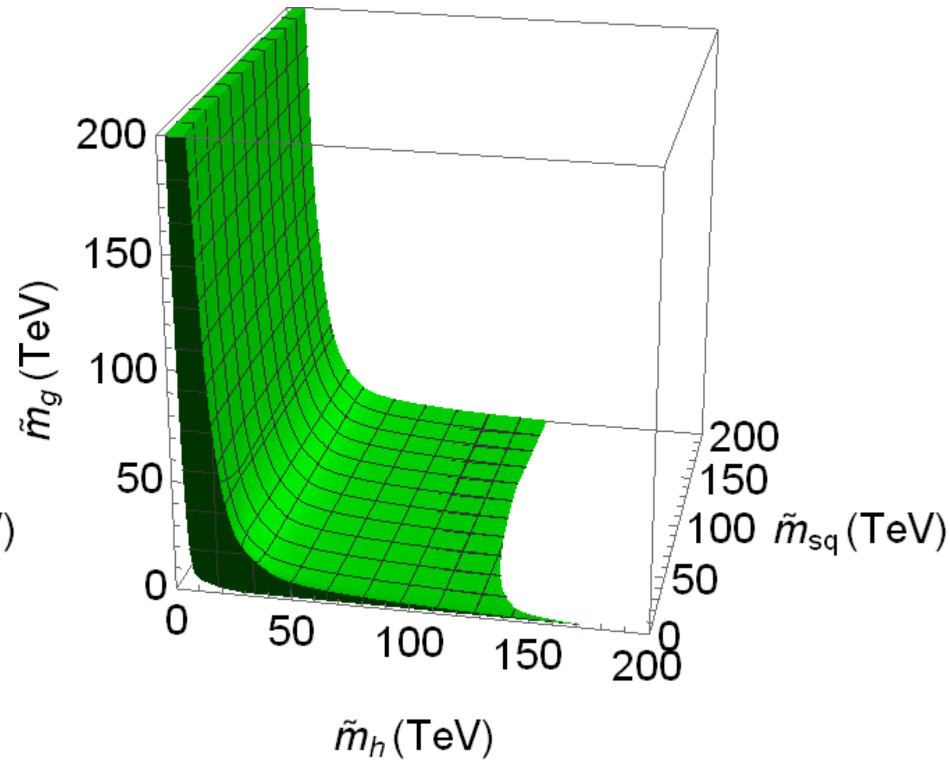

# Surface $\tilde{m}_g = \tilde{m}_{sq}$

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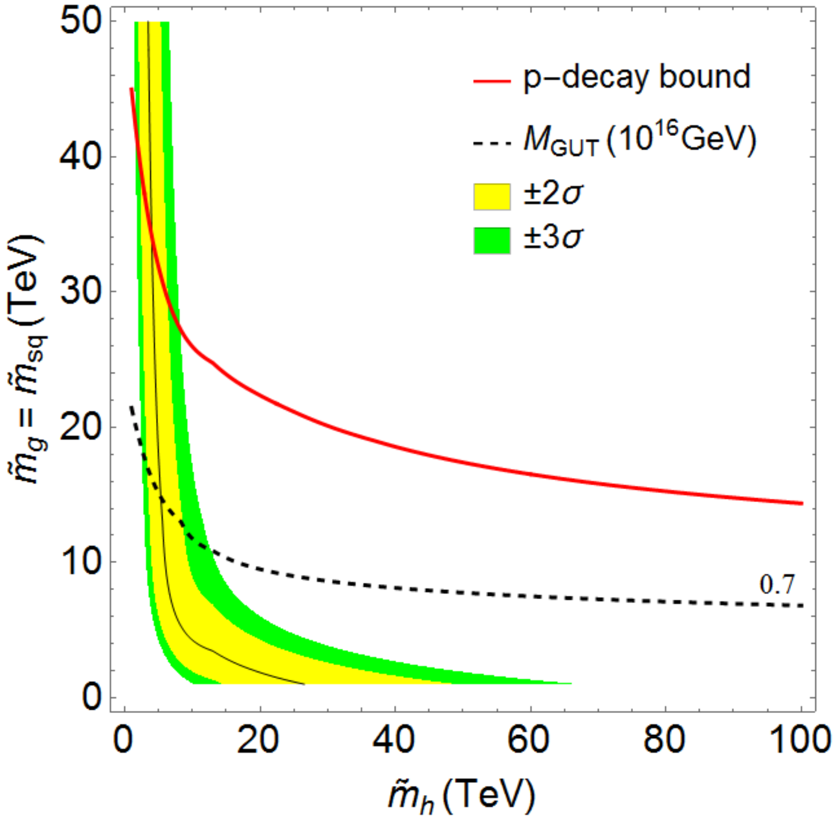


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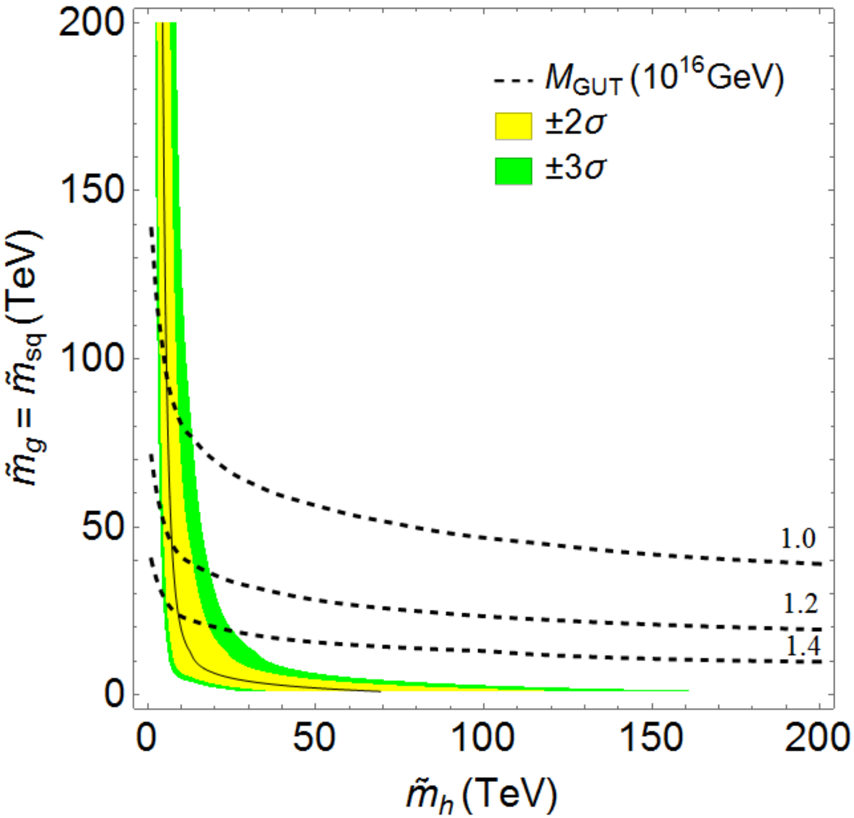

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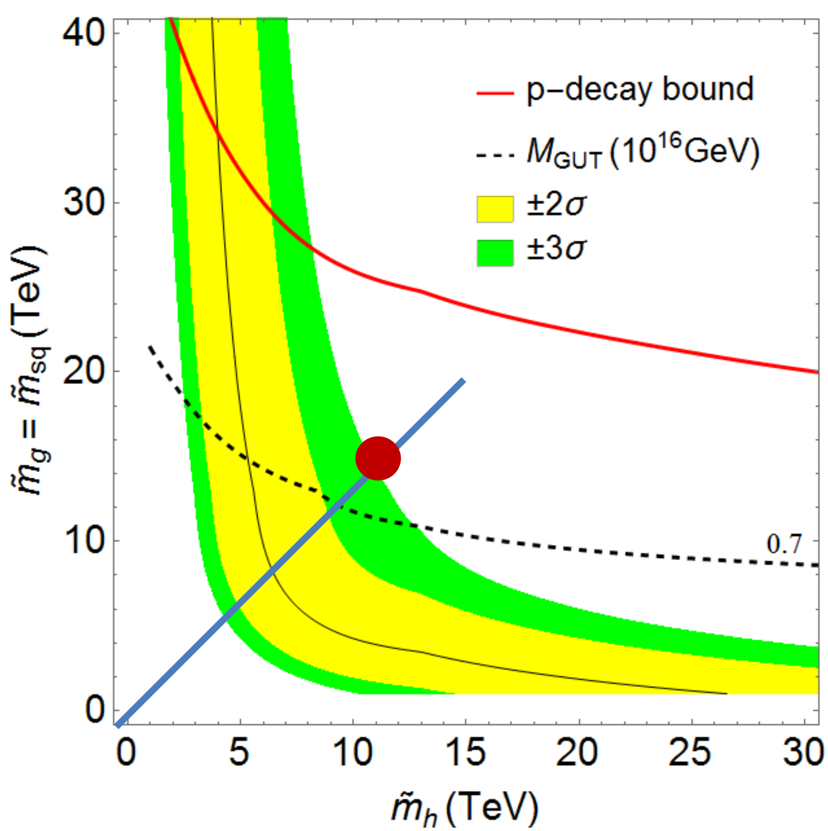


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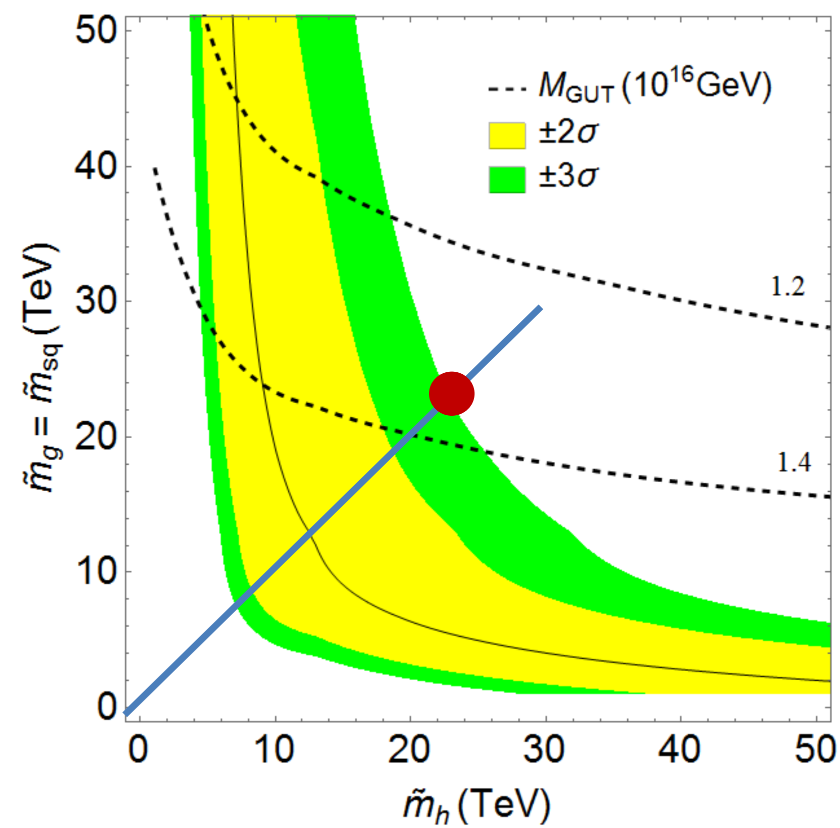
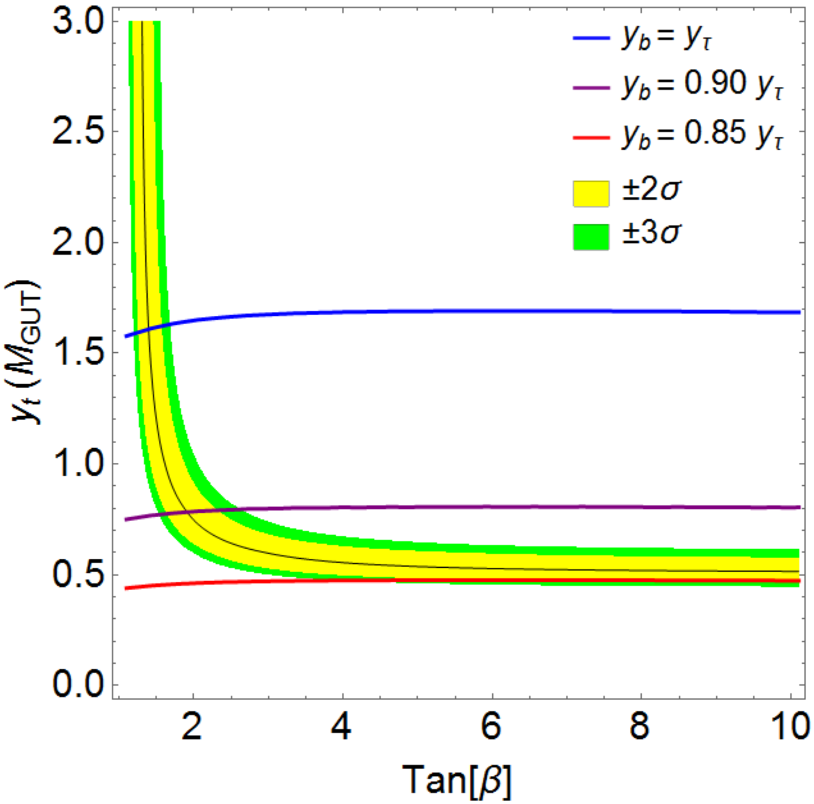
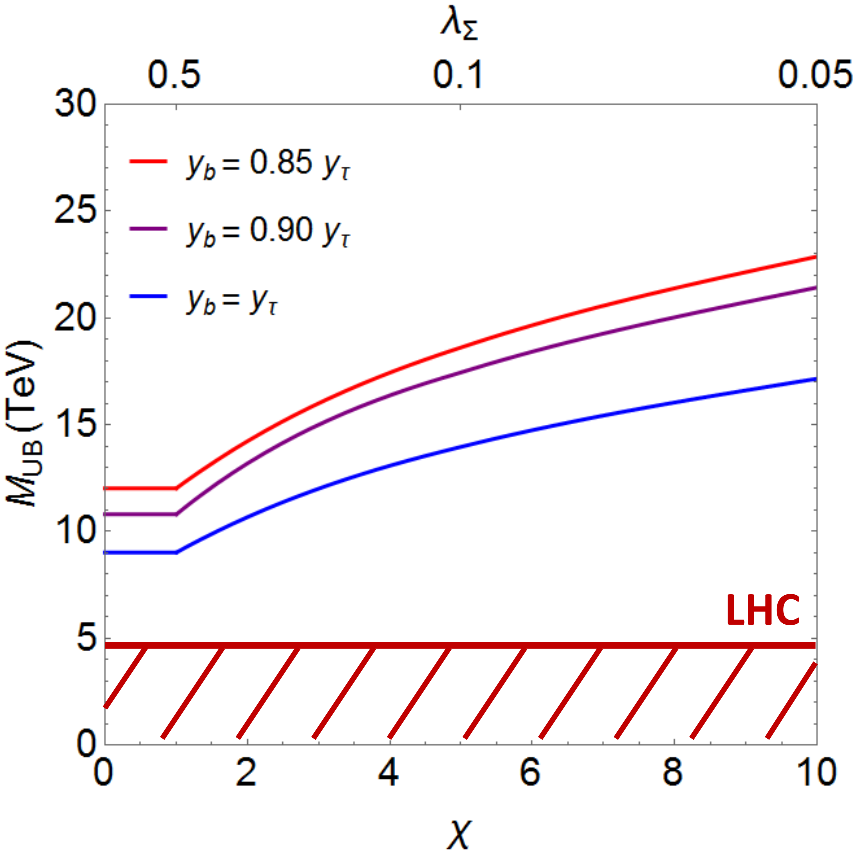


# Upper bound for SUSY physics




- Larger values for GUT threshold $\chi$ are not allowed since:
  - naturalness requirement implies $\lambda_\Sigma \sim \mathcal{O}(1)$;
  - $M_{GUT}$ unnaturally approaches $M_{Plack}$.

→ $M_{UB} \sim 20$ **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 lighest gluino or higgsino cannot have a mass larger than

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# Thanks for your attention