TOP-DOWN BSM REVIEW

March 8, 2013

Rencontres de Moriond, La Thuile

Outline

- Avenues for the hierarchy problem
- Some SUSY preferred models from LHC data and the BEH scalar mass

  - Flavor and inverted hierarchy/natural SUSY
  - Mini-split SUSY
  - low-scale SUSY breaking dynamics
  - String/F-theory inspired SUSY spectra
- Conclusions

Avenues for the hierarchy problem

The **hierarchy problem** guided (misguided ?) BSM physics for the last 30 years. Traditional solutions fall into three categories :

a) low-energy **supersymmetry** (SUSY) $M_{SUSY} \sim TeV$

b) strong dynamics (technicolor, RS, composite BEH scalar models)

c) TeV strings/quantum gravity, with or without SUSY,

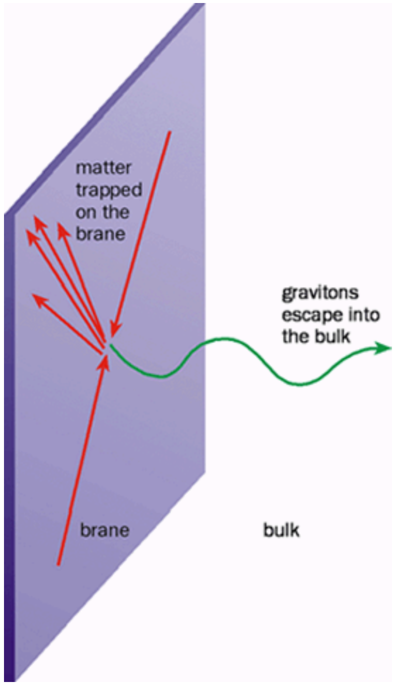
$$M_s \sim M_\star \sim TeV$$

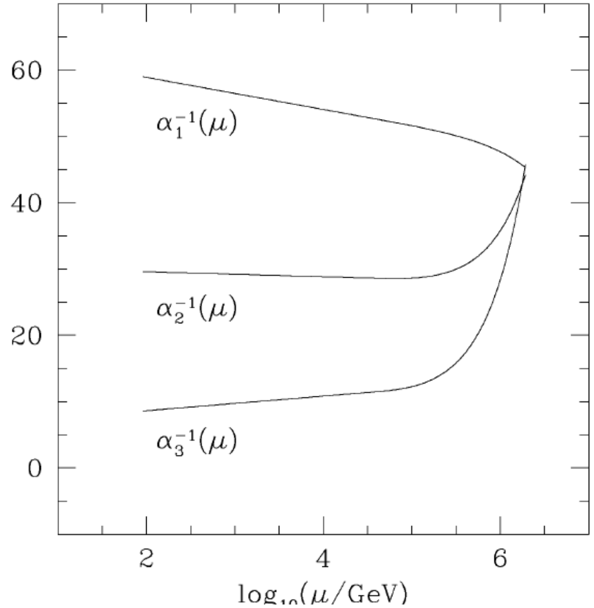
Obs : however, in string theory, it is possible that

$$M_{SUSY} \sim M_s \sim 10^{16} - 10^{17}\ GeV$$

(see talk A. Sagnotti)

c) Extra dimensions provide spectacular low-energy physics: (sub) mm size gravitational (perpendicular) dimensions, TeV-size + possibly unification of gauge couplings from parallel dimensions, KK dark matter, etc





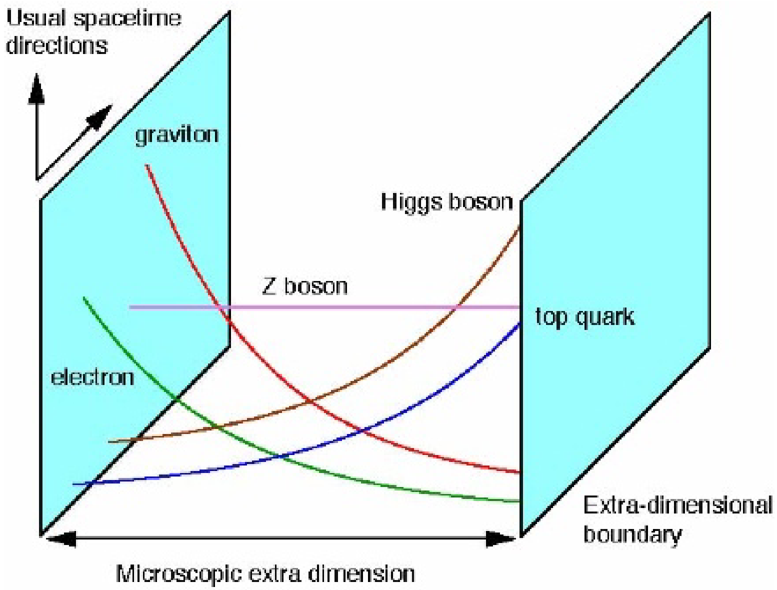
Current constraints: $R_\perp < 0.02mm \quad , \quad R_{||}^{-1} > 1.5 - 2\ TeV$

(see K.Takuda and M. Marionneau talks)

b) Modern realizations of strong dynamics: holographic models.
There is a 5d-4d (AdS-CFT) holographic dictionary:
- States localized on the TeV/infrared brane: composite

Ex: 5d KK states : resonances of the 4d strongly-coupled theory
- States localized on the Planck/UV brane; elementary

• Geometric localization leads to flavor structure
• Electroweak and FCNC effects asks for $\Lambda_{IR} > 1.5 - 2\, TeV$



E. Dudas – E. Polytecnique, Rencontres de Moriond 2013

One example:

Composite BEH scalar models (Agashe et al, 2005):

- Gauge symmetry SU(3) x SO(5) x U(1)' broken by boundary conditions to :
- SM on the Planck brane.
- SU(3) x SO(4) x U(1)' on the TeV brane.
- Higgs is the 5th component of a gauge boson, pseudo-goldstone boson* of SO(5)/SO(4).
- It behaves as a composite state (localized on IR brane).
- Lightest KK states in the model ; color fermions with electric charges -1/3,2/3 and 5/3 and masses between 0.5 and 1.5 TeV. The q=5/3 state decays mainly into $W^+t \to W^+W^+b$, giving a pair of same-sign leptons in the final state.

$*$ Talks A.Azatov,L.Merlo

a) SUSY hints from LHC searches and BEH scalar mass

- LHC direct SUSY searches and BEH scalar mass set new limits on superpartner masses for simple (simplified) SUSY models (talks J. Marrouche, M.Verducci)

  Popular models: mSUGRA, CMSSM, minimal gauge mediation with TeV superpartner masses have some difficulties in accomodating the data in a natural way★.
- However, from a UV viewpoint (supergravity, string theory), popular models are rather unpopular.

  It is important to theoretically analyze and experimentally search for non-minimal SUSY models.

★ See talks M.Carena, U.Ellwanger, D.Kazakov…

Inverted hierarchy/Natural SUSY

One old possibility which became popular recently because of LHC constraints: inverted hierarchy/natural SUSY models:
- third generations squarks and gauginos in the TeV range (light stops).
- First two generation scalars much heavier (10-15 TeV). They affect little the tuning of the electroweak scale.

This is actually natural in most flavor models and holographic constructions. Simplest example: U(1) gauged flavor symmetry. Quark mass matrices given by

$$h_{ij}^U \sim \epsilon^{q_i+u_j+h_u} \quad , \quad h_{ij}^D \sim \epsilon^{q_i+d_j+h_d} \ ,$$

where typically $\epsilon = \frac{\langle \Phi \rangle}{M} \sim \lambda = 0.22$ and q_i are charges of left-handed quarks, etc.

Quarks masses and mixings are given by ($q_{13} = q_1 - q_3$,etc)

$$\frac{m_u}{m_t} \sim \epsilon^{q_{13}+u_{13}} \;,\; \frac{m_c}{m_t} \sim \epsilon^{q_{23}+u_{23}} \;,\; \frac{m_d}{m_b} \sim \epsilon^{q_{13}+d_{13}} \;,\; \frac{m_s}{m_b} \sim \epsilon^{q_{23}+d_{23}}$$

$$\sin\theta_{12} \sim \epsilon^{q_{12}} \quad , \quad \sin\theta_{13} \sim \epsilon^{q_{13}} \quad , \quad \sin\theta_{23} \sim \epsilon^{q_{23}} \; .$$

Good fit to to data ⇨ larger charges for the lighter generations

$$q_1 \; > q_2 \; > q_3 \quad , \quad u_1 \; > u_2 \; > u_3 \quad , \quad d_1 \; > d_2 \; > d_3$$

Scalar masses are of the form

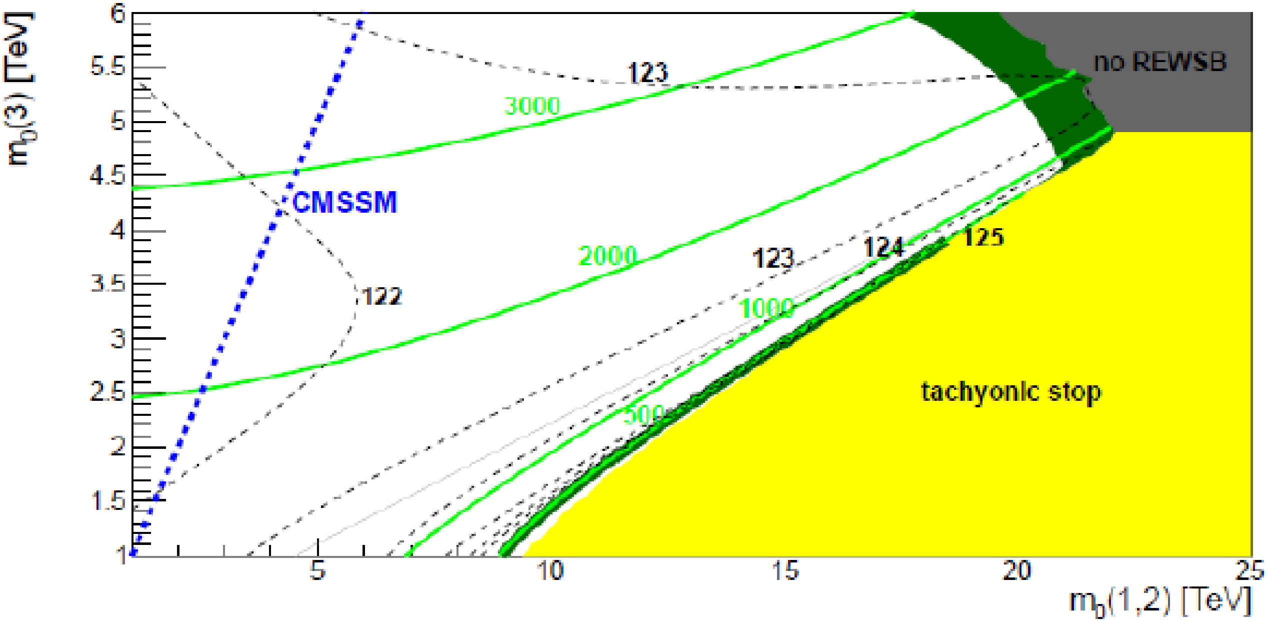
$$m_{ij}^2 \;=\; X_i \langle D \rangle \;+\; a_{ij} \langle F \rangle$$

If $< D >>>< F >$ then an inverted hierarchy is generated.

Nowdays, FCNC constraints seriously these models;
need some degeneracy 1-2 generations ⇨ $q_1 = q_2 \;, q_3 = 0$
additional symmetries (discrete subgroups of SU(2)).

Inverted hierarchy can also be realized in 5d and string models.

Large stop mixing can be generated from RG running (see M. Badziak et al, 2012)



Inverted hierarchy example. Higgs mass (black dashed), stop mass (solid green) for $\mu > 0, \tan\beta = 10, M_{1/2} = 1, A_0 = -2$ (TeV). Yellow "tachyonic stop" and grey "no REWSB" ($\mu^2 < 0$) regions are excluded. Dark green region: $\Omega_{\rm DM} h^2 < 0.1288$.

Mini-split SUSY models

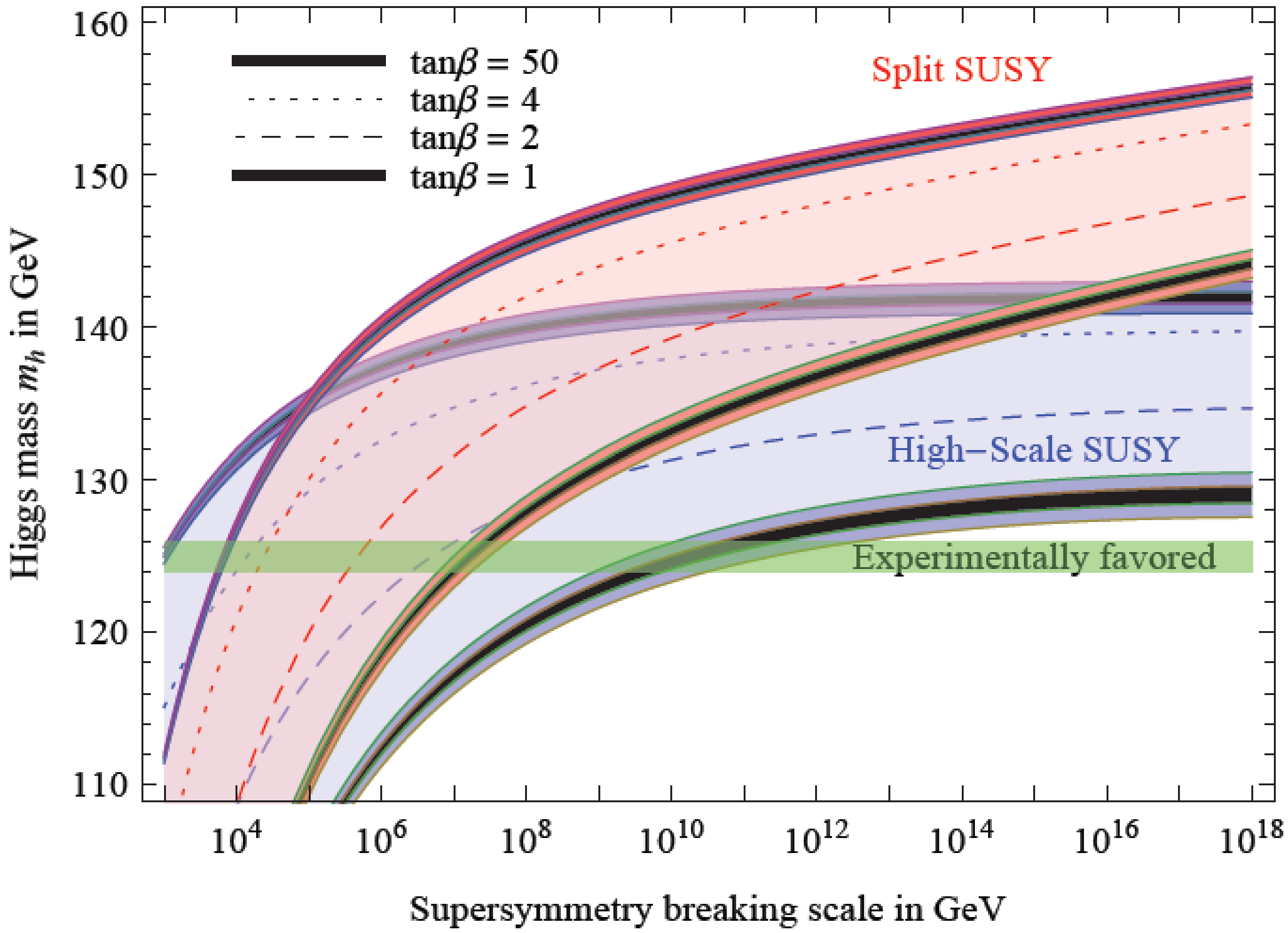
- Versions of split-SUSY with:
- scalar and higgsino masses at 100-1000 TeV
- gaugino masses in the TeV range (loops suppression).
- Natural realization in models with « pure gravity mediation » or « strong moduli stabilization », in which
- scalar masses fixed by gravitino mass $m_0 \sim m_{3/2}$
- gaugino masses given by anomaly mediation

$$M_{1/2}^a = \frac{b_a g_a^2}{16\pi^2} m_{3/2}$$

➢ Strong correlation between :

-BEH scalar mass and gravitino mass

- Relic density of (wino) LSP and gravitino mass $m_{3/2} < 10^3 TeV$



BEH scalar mass versus scalar masses in split and high-scale SUSY models (from Giudice-Strumia (2011))

Low-scale SUSY breaking dynamics

. Earlier work, see e.g. Brignole,Feruglio,Zwirner; Brignole,Casas,Espinosa,Navarro

- SUSY breaking in MSSM is usually parametrized by a spurion superfield $S = \theta^2 m_{soft}$ ⇒ soft terms.
- Possible to write effective lagrangians which contain also the couplings of the SUSY breaking sector to SM Fields; promote S to a full superfield $S \to \frac{m_{soft}}{f} X$ where

$$X = x + \sqrt{2}\theta G + \theta^2 F_X$$

G is the goldstino and x the scalar (sgoldstino) partner.
Two options:
i) x is light enough ⇒ part of the low-energy theory
ii) x is very heavy ⇒ it can be « integrated out ».
The result is a constrained superfield (Siegel,Komargodski-Seiberg)

$$X = \frac{GG}{2F_X} + \sqrt{2}\theta G + \theta^2 F_X \quad , \quad X^2 = 0 \qquad (1)$$

The lagrangian contains MSSM+soft terms+Goldstino couplings in a very compact form

$$\mathcal{L} \;=\; \mathcal{L}_{MSSM} + \mathcal{L}_X + \mathcal{L}_m + \mathcal{L}_{AB} + \mathcal{L}_g \quad \text{where}$$

$$\mathcal{L}_H = \sum_{i=1,2} \frac{m_i^2}{f^2} \int d^4\theta \; X^\dagger X \;\; H_i^\dagger e^{V_i} H_i \;,$$

$$\mathcal{L}_m = \sum_{\Phi} \frac{m_\Phi^2}{f^2} \int d^4\theta \; X^\dagger X \Phi^\dagger e^V \Phi \;, \;\; \Phi = Q, U_c, D_c, L, E_c$$

$$\mathcal{L}_{AB} = \frac{B}{f} \int d^2\theta \;\; X H_1 H_2 + (\frac{A_u}{f} \int d^2\theta \;\; X Q U_c H_2 + \cdots)$$

$$\mathcal{L}_g = \sum_{i=1}^{3} \frac{1}{16\, g_i^2\, \kappa} \frac{2\, m_{\lambda_i}}{f} \int d^2\theta \, X \, \mathrm{Tr}\, [\, W^\alpha W_\alpha]_i + h.c.$$

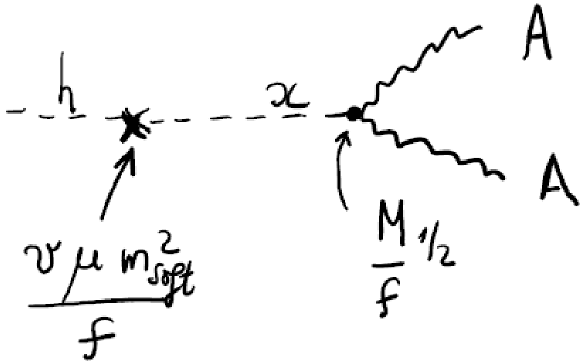
Some novelties:

- There are new, goldstino-independent couplings, for ex. new quartic BEH couplings

$$V = \left(|\mu|^2 + m_1^2\right) |h_1|^2 + \left(|\mu|^2 + m_2^2\right)|h_2|^2 + (B\, h_1 . h_2 + \text{h.c.})$$
$$+ \frac{g_1^2 + g_2^2}{8}\left[|h_1|^2 - |h_2|^2\right]^2 + \frac{g_2^2}{2}|h_1^\dagger\, h_2|^2$$
$$+ \frac{1}{f^2}\left|m_1^2\,|h_1|^2 + m_2^2\,|h_2|^2 + B\, h_1 . h_2\right|^2$$

(Antoniadis,E.D., Ghilencea, Tziveloglou, 2010)

- There is a mixing sgoldstino x-BEH scalar



Enhanced BEH scalar couplings to gauge fields

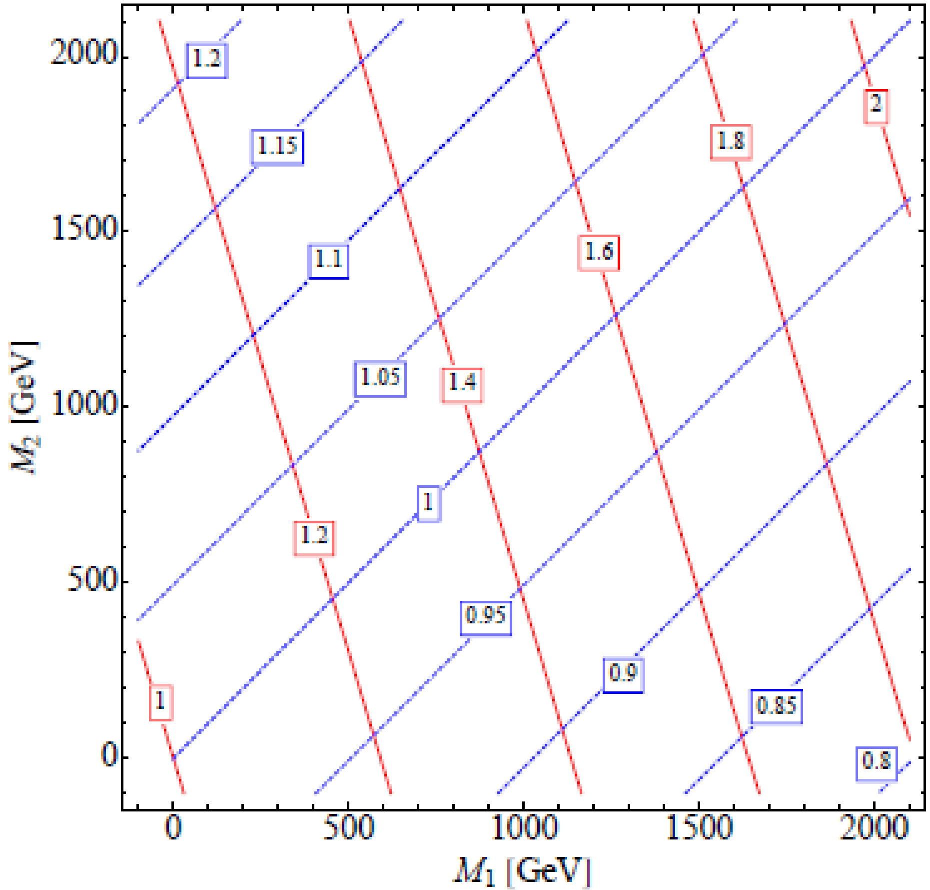
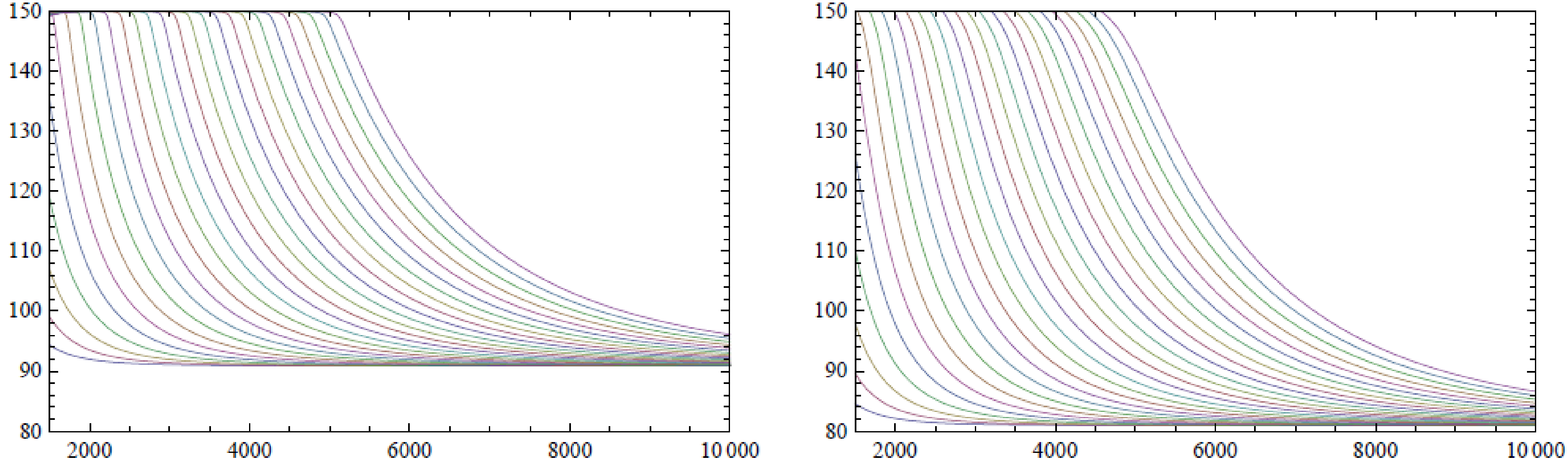


Figure 1: The $h \to \gamma\gamma$ and $h \to Z\gamma$ partial decay widths, normalized with respect to their corresponding SM values, i.e. $\Gamma_{h\gamma\gamma}/\Gamma^{SM}_{h\gamma\gamma}$ (red solid lines) and $\Gamma_{hZ\gamma}/\Gamma^{SM}_{hZ\gamma}$ (blue dashed lines), are shown as functions of the bino and wino masses. The values of these normalized partial widths correspond to the maximum values given the assumption that the gluon production cross section does not deviate from the SM value by more than 30%. The gluino mass M_3 has been set to 1 TeV.

(E.D., Petersson, Tziveloglou, 2012)



(a) m_h as function of $\sqrt{f}$ and μ as a parameter, for $\tan\beta = 50$.

(b) m_h as function of $\sqrt{f}$ and μ as a parameter, for $\tan\beta = 5$.

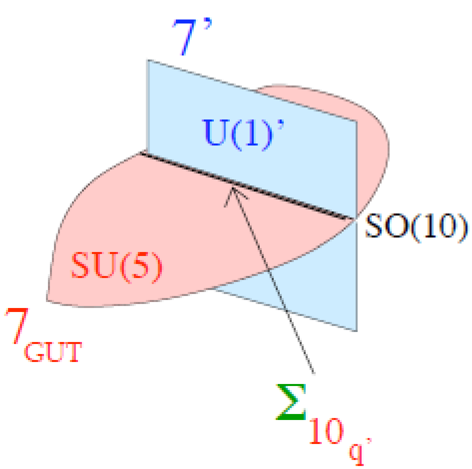
Tree-level Higgs masses (GeV) as functions of $\sqrt{f}$.

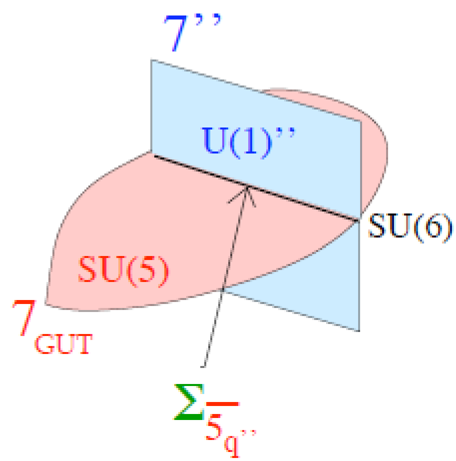
In both figures, $M_A = 150$ GeV and μ increases upwards from 400 to 3000 GeV in steps of 100 GeV.

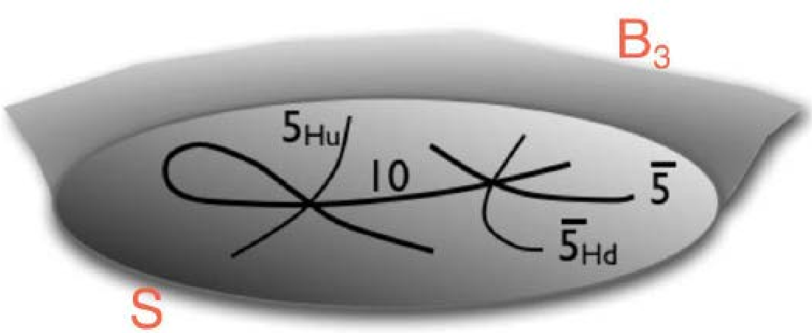
String/F-theory inspired SUSY spectra

There are various possibilities. A recent one (Madrid group) :

- local, SU(5) GUT F-theory models
- internal U(1) and hypercharge fluxes
- GUT modulus SUSY breaking







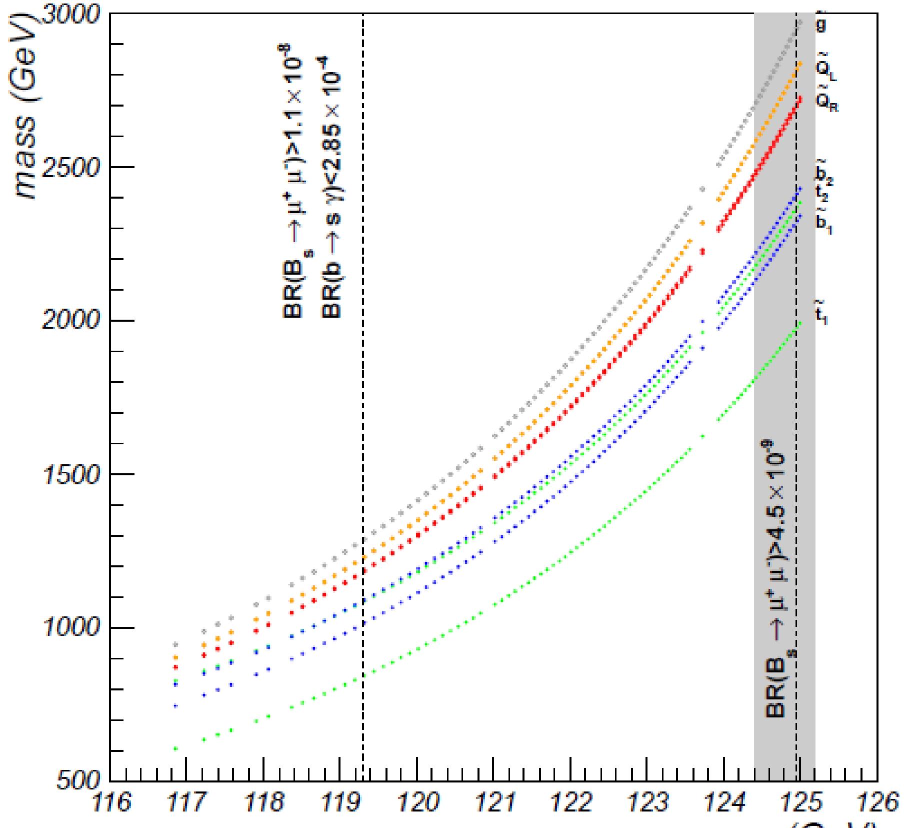
Scanning over one parameter flux, they found the soft terms relations:

$$M_{1/2} = \sqrt{2} m_0 = -\frac{2}{3} A = -B$$

that generate maximal stop mixing $A \simeq -2\, m_0$

- Radiative electroweak symmetry breaking forces large $\tan\beta \sim 40$

Squark and gluino masses versus the BEH scalar mass



Conclusions

- It is important to search for alternatives to SUSY:
Xtra dimensions,TeV strings, strong dynamics/compositeness…

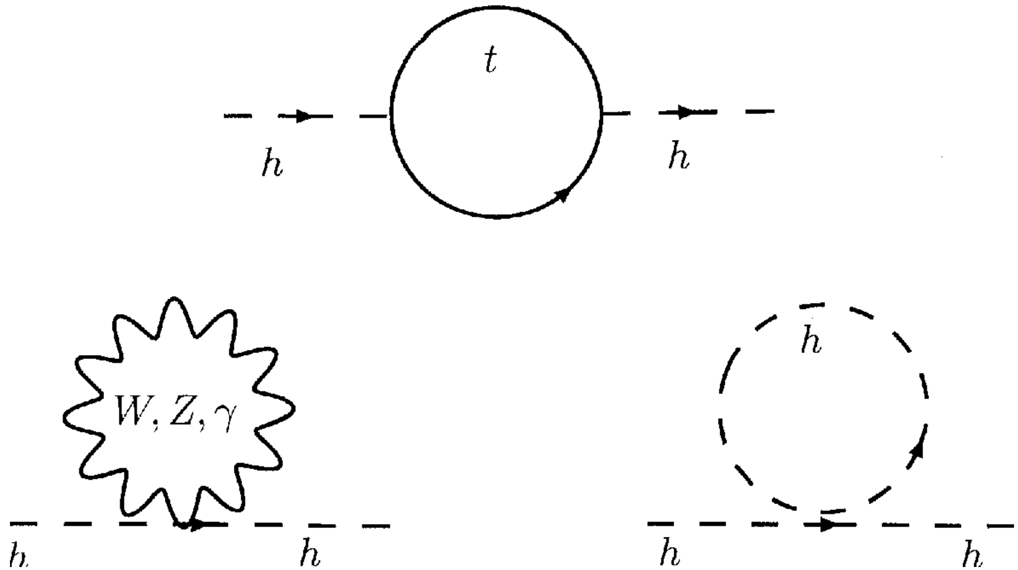
- It is fair to give a last chance to natural solutions
to the hierarchy problem.
- There is no reason to reduce low-energy SUSY to its
simplest examples: mSUGRA,CMSSM, mGMSB.

- Most theories of fermion masses generate flavor-dependent soft terms (ex: inverted hierarchy/natural SUSY)
- low-scale SUSY breaking dynamics deform MSSM couplings
- Variety of string/F-theory spectra ; the mechanism and the scale of SUSY is THE big unknown: (mini) split or even high-energy SUSY possible in string theory..

THANK YOU

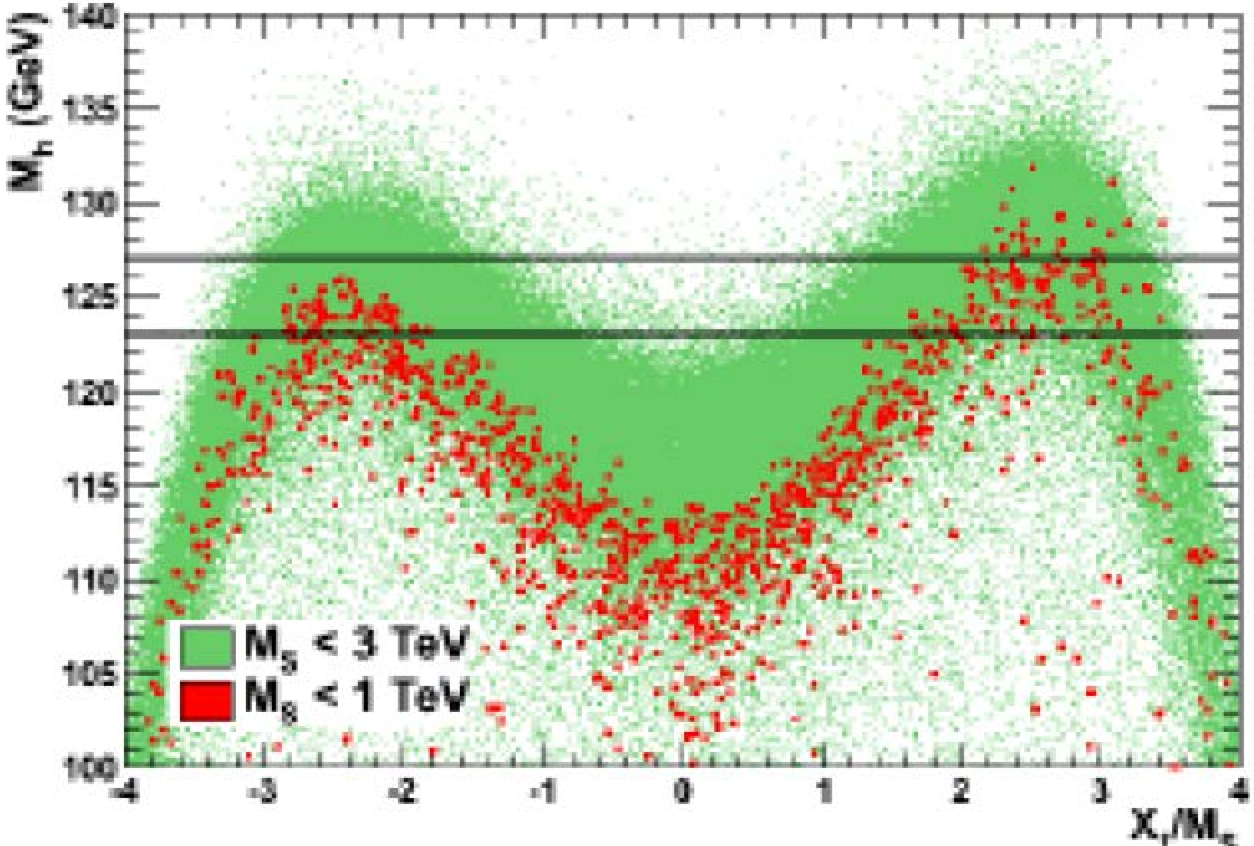
Backup slides

Quantum corrections to the Higgs mass in SM are quadratically divergent



In a microscopic theory (GUT,quantum gravity), the cutoff is a physical mass scale: M_GUT, M_P. It is then difficult to understand why

$$m_h^2 = (m_h^0)^2 + \frac{3\Lambda^2}{8\pi^2 v^2}(4m_t^2 - 4M_W^2 - 2M_Z^2 - m_h^2) \sim v^2$$



From A.Arbey et al, 2011

Higgs boson mass versus X_t/M_{SUSY} ,where describes the mass mixing in the stop sector and X_t is the scalar masses in CMSSM.

M_{SUSY} maximal stop mixing is needed; difficult to obtain from usual boundary conditions at M_P

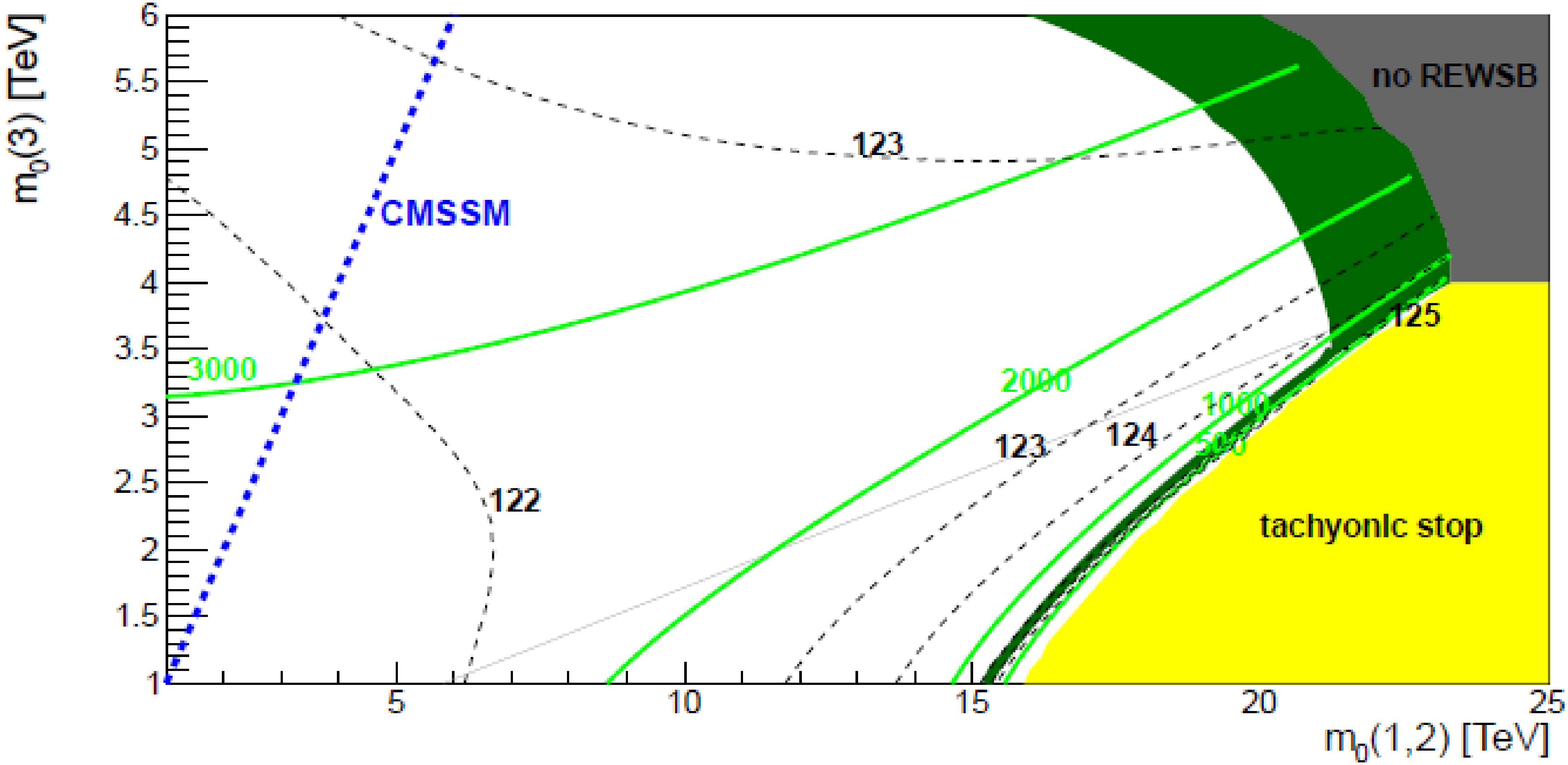


Figure 5: The same as in Figure 3 but for $M_{1/2} = 1.5$ TeV and $A_0 = 0$.

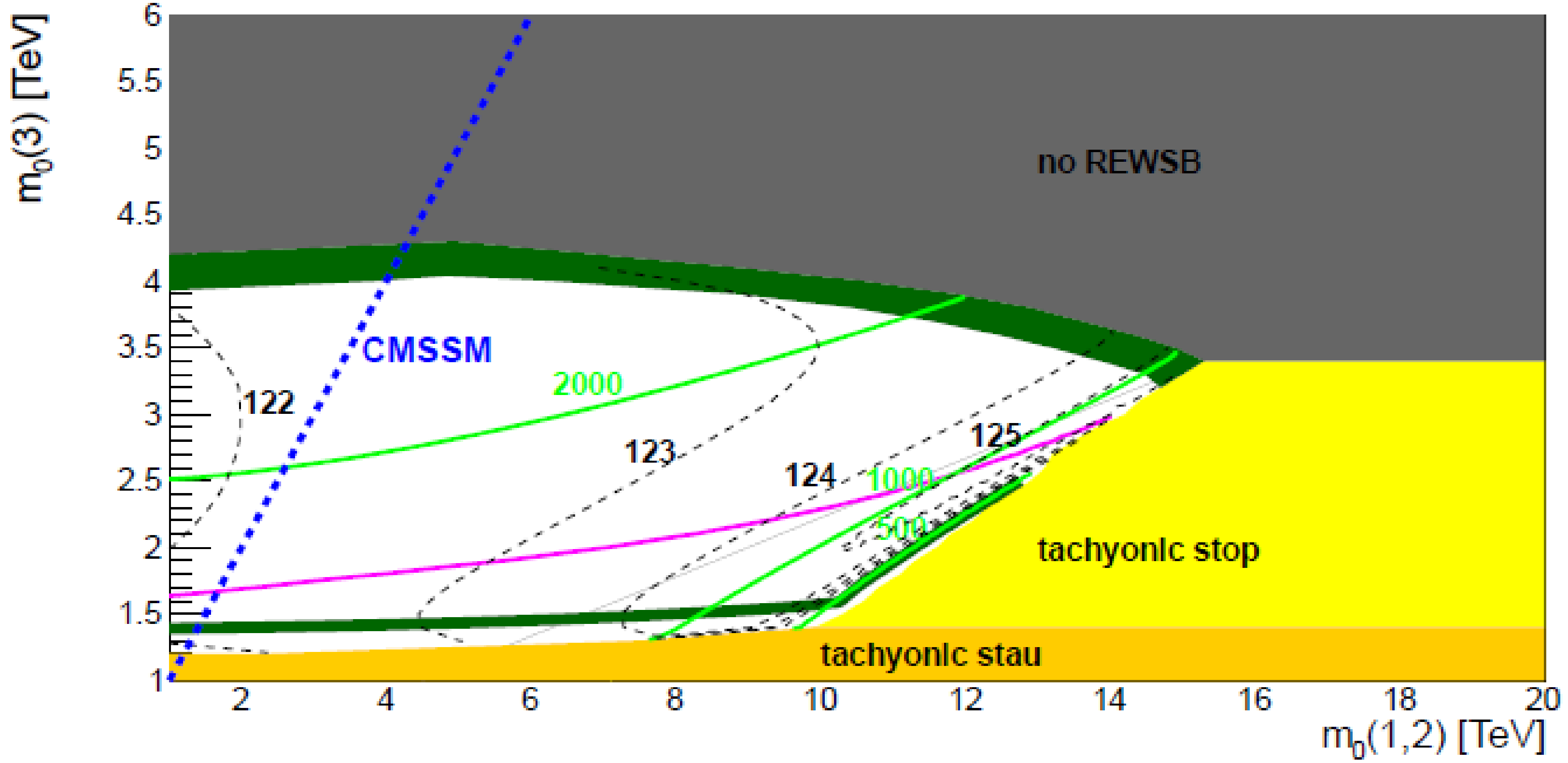
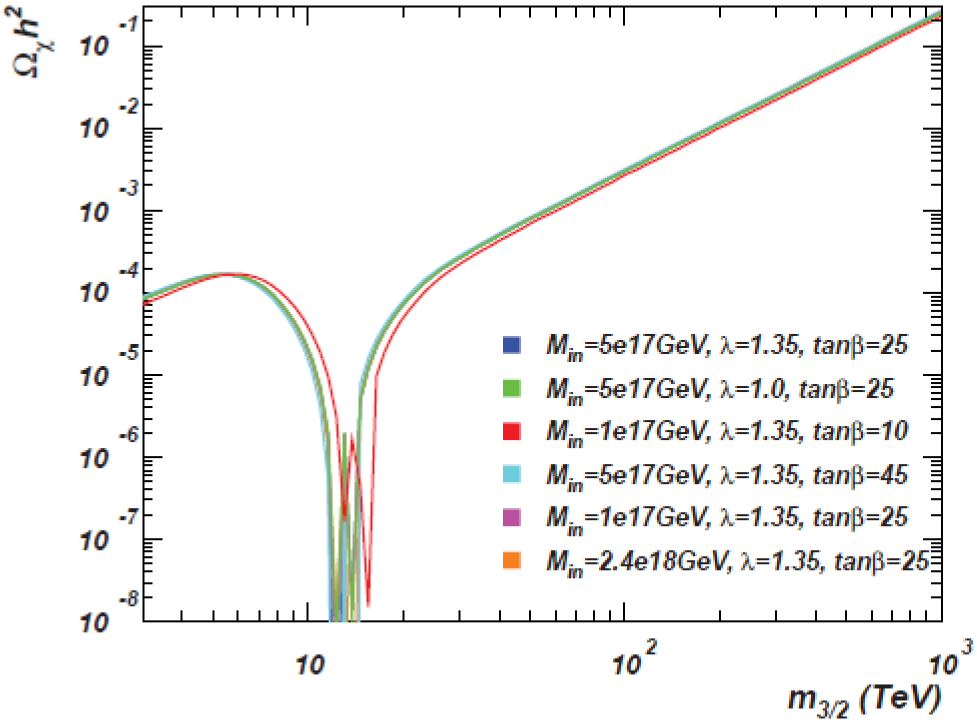


Figure 7: The same as in Figure 3 but for $\tan\beta = 50$ and $m_{H_d} = 1.6 m_0(3)$. The region below the purple line is excluded by $\mathrm{BR}(B_s \to \mu^+\mu^-)$ at 95% C.L. The orange region is excluded because it predicts a tachyonic stau.



E.D.,A.Linde,Y.Mambrini,
K.Olive, A.Mustafayev

Relic density versus gravitino mass in mini-split models (from« strong moduli stabilization »). There is an upper bound $m_{3/2} < 10^3 TeV$ on the gravitino mass.