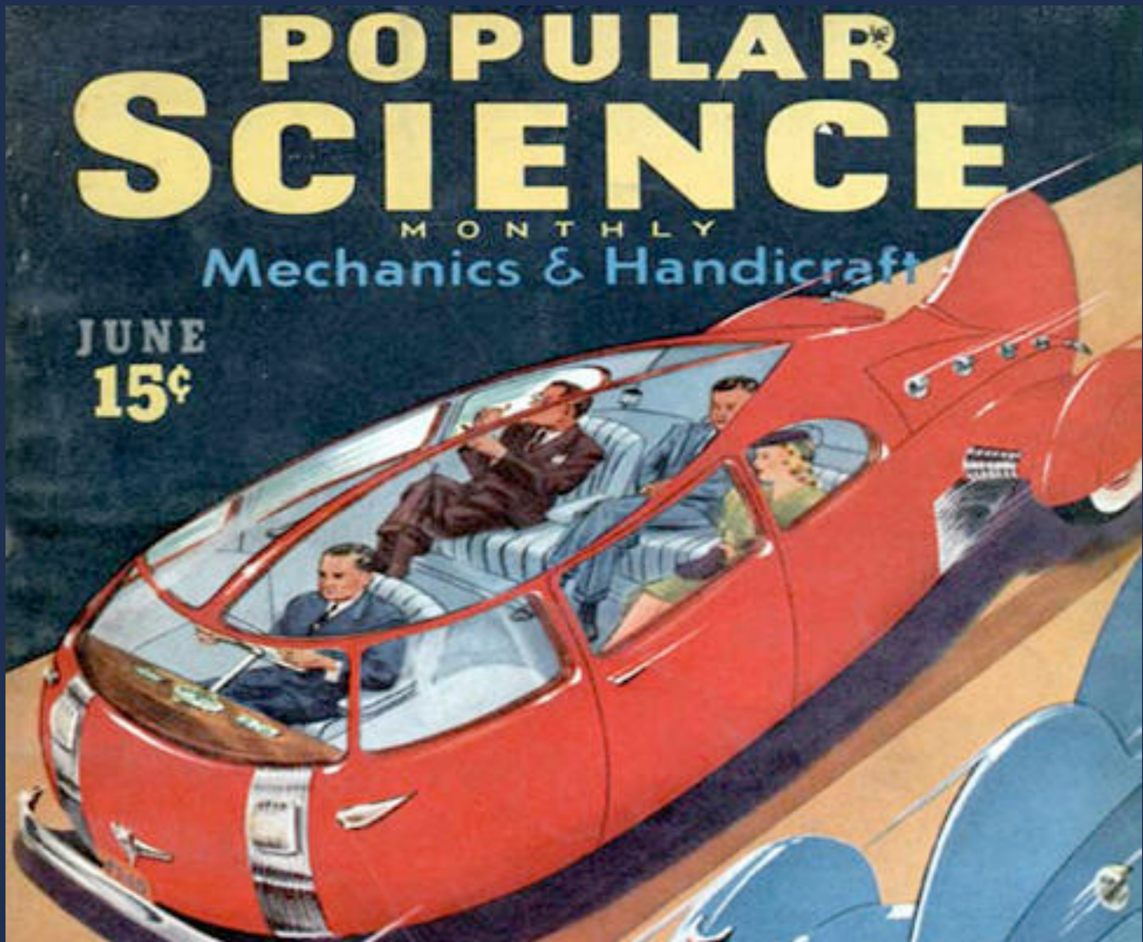
It is the year 2012...

... where's my ~~flying car?~~

SUSY



David G. Cerdeño

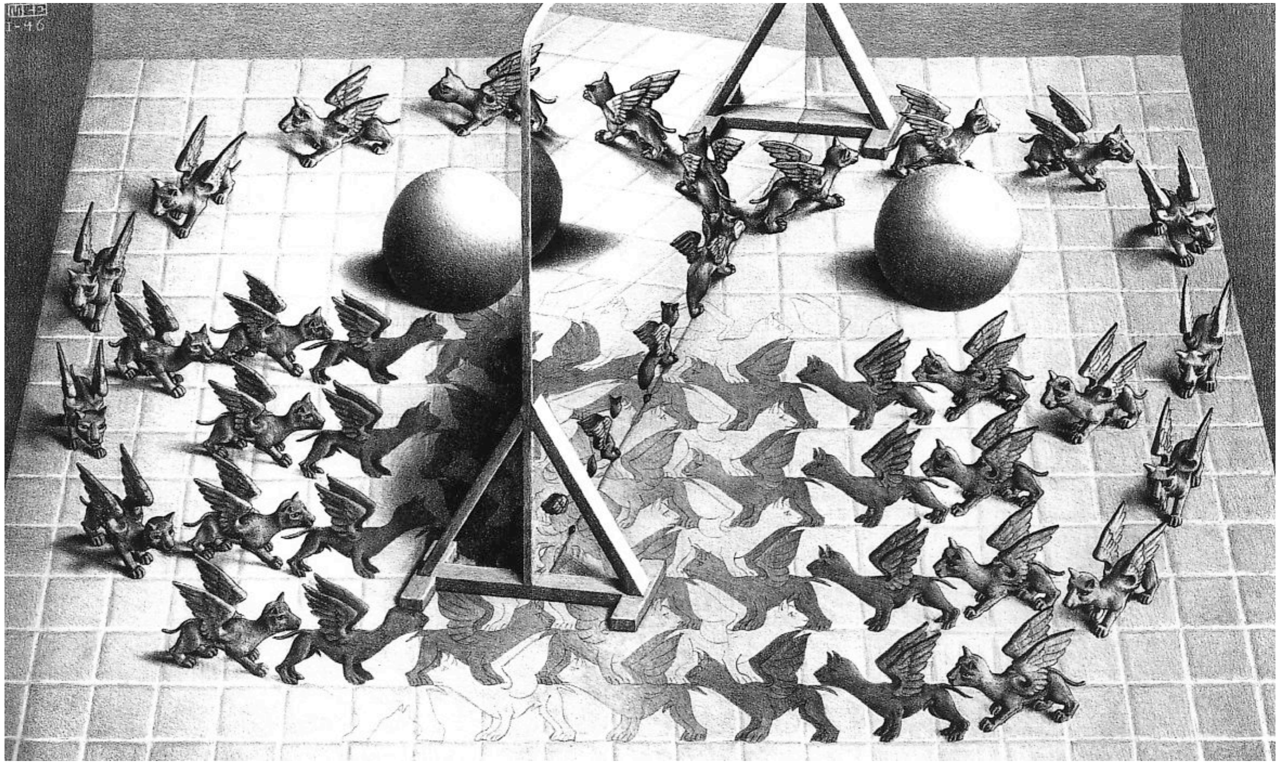
Outline

• SUSY...	SUSY parameter space Simplifying assumptions ... and extended models
• ...NOT BEEN FOUND YET...	Direct SUSY searches Higgs searches Low-energy observables
• ...BUT IS STILL ALIVE...	Parameter space of SUSY models Implications for dark matter

Conclusions

- Supersymmetry is more than just the CMSSM (and the experimental bounds have to be applied for each individual model)
- LHC searches + Higgs mass “measurement (+ dark matter requirements) impose very stringent constraints on the parameter space of SUSY models
- mh~125 GeV seems to imply a heavy spectrum with maximal stop mixing
- Potential conflicts with low energy observables (g-2) and rare decays
- Implications for dark matter Dark matter

Supersymmetric models



New symmetry relating particles with different spin statistics

The more general symmetry of the S matrix

The best approach to solve the naturalness problems of the Standard Model

Supersymmetric models contain a relatively large number of free parameters unless simplifying hypothesis are made on the origin of these or they are related to more fundamental theories

EW SUSY

Effective MSSM

All parameters defined at low scale – inputs are all the new terms in the Lagrangian and Superpotential (the Yukawas are normally fit to reproduce experimental values)

Gaugino mass parameters	$M_1,\ M_2,\ M_3$
Slepton soft masses	$m^2_{L_{ij}},\ m^2_{E_{ij}}$
Squark soft masses	$m^2_{Q_{ij}},\ m^2_{U_{ij}},\ m^2_{D_{ij}}$
Trilinear parameters	$A_E^{i,j}, A_U^{i,j}, A_D^{i,j}$

Parameters describing the Higgs sector

$$\tan\beta \equiv \frac{\langle H_u\rangle}{\langle H_d\rangle}$$

$\mu,\ m_A$

12something parameters

$$L_{soft,1} = \frac{1}{2}\left(M_1\tilde{B}\tilde{B} + M_2\tilde{W}_a\tilde{W}^a + M_3\tilde{g}_\alpha\tilde{g}^\alpha\right) + h.c.$$

$$\begin{aligned} L_{soft,2} = & -M^2_{H_1}H^*_{1a}H^a_1 - M^2_{H_2}H^*_{2a}H^a_2 - M^2_{\tilde{L},ij}\tilde{L}^*_{ia}\tilde{L}^a_j - M^2_{\tilde{E},ij}\tilde{E}^*_i\tilde{E}_j \\ & -M^2_{\tilde{Q},ij}\tilde{Q}^*_{ia}\tilde{Q}^a_j - M^2_{\tilde{U},ij}\tilde{U}^*_i\tilde{U}_j - M^2_{\tilde{D},ij}\tilde{D}^*_i\tilde{D}_j \end{aligned}$$

$$\begin{aligned} L_{soft,3} = & -\epsilon_{ab}\left(A^L_{ij}\tilde{L}^a_i H^b_1\tilde{E}^*_j + A^D_{ij}\tilde{Q}^a_i H^b_1\tilde{D}^*_j + A^U_{ij}\tilde{Q}^b_i H^a_2\tilde{U}^*_j - B\mu H^a_1 H^b_2\right) \\ & +h.c. \end{aligned}$$

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$$\tan\beta \equiv \frac{\langle H_u \rangle}{\langle H_d \rangle}$$

$\mu,\ m_A$

12something parameters

Simplifying assumptions

Universality of soft masses in order to avoid FCNC

Gaugino mass parameters $M_1,\ M_2,\ M_3$

Slepton soft masses $m^2_{L_{1,3}},\ m^2_{E_{1,3}}$

Squark soft masses $m^2_{Q_{1,3}},\ m^2_{U_{1,3}},\ m^2_{D_{1,3}}$

Trilinear parameters A_E, A_U, A_D

Parameters describing the Higgs sector

$$\tan\beta \equiv \frac{\langle H_u \rangle}{\langle H_d \rangle}$$

$\mu,\ m_A$

19 parameters (pMSSM)

Supersymmetric models contain a relatively large number of free parameters unless simplifying hypothesis are made on the origin of these or they are related to more fundamental theories

EW SUSY

Extended scenarios are also well-motivated (and have a larger number of parameters)

Next-to-MSSM

- Addition of a new superfield, ***S***, singlet under the SM gauge group

$$\mathrm{NMSSM} \quad = \quad \mathrm{MSSM} + \hat{S} \begin{cases} 2 \text{ extra Higgs (CP} - \text{even, CP} - \text{odd)} \\ 1 \text{ additional Neutralino} \end{cases}$$

- New terms in the superpotential

$$W = Y_u\, H_2\, Q\, u + Y_d\, H_1\, Q\, d + Y_e\, H_1\, L\, e - \lambda\, S\, H_1 H_2 + \frac{1}{3}\kappa S^3$$

- New terms in the Lagrangian

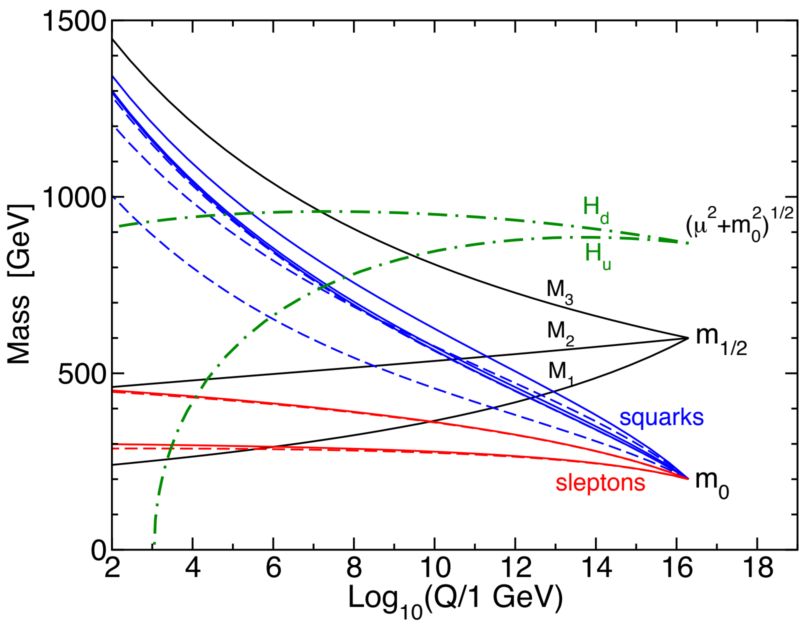
$$-\mathcal{L}_{\mathrm{soft}}^{\mathrm{Higgs}} = m_{H_i}^2\, H_i^* H_i + m_S^2\, S^* S + (-\lambda A_\lambda\, S H_1 H_2 + \frac{1}{3}\kappa A_\kappa S^3 + \mathrm{H.c.})$$

Supersymmetric models contain a relatively large number of free parameters unless simplifying hypothesis are made on the origin of these or they are related to more fundamental theories

EW SUSY GUT Scale String Scale

Parameters are defined at a high scale (normally GUT-scale) and Renormalization Group Equations are used to determine the low-energy parameters

Gaugino mass parameters	$M_1,\ M_2,\ M_3$
Slepton soft masses	$m^2_{L_{ij}},\ m^2_{E_{ij}}$
Squark soft masses	$m^2_{Q_{ij}},\ m^2_{U_{ij}},\ m^2_{D_{ij}}$
Trilinear parameters	$A_E^{i,j}, A_U^{i,j}, A_D^{i,j}$
Higgs mass parameters	$m^2_{H_d},\ m^2_{H_u}$
	$\tan\beta \equiv \frac{\langle H_u \rangle}{\langle H_d \rangle}$



Impose conditions for REWSB

$$\mu^2 = \frac{-m^2_{H_u}\tan^2\beta + m^2_{H_d}}{\tan^2\beta - 1} - \frac{1}{2}M_Z^2 \,,$$

Supersymmetric models contain a relatively large number of free parameters unless simplifying hypothesis are made on the origin of these or they are related to more fundamental theories

EW SUSY GUT Scale
String Scale

Gravity-mediated models

Constrained MSSM: Universal choice of parameters (4-parameters)

$$M,\ m,\ A,\ \tan\beta,\ sign(\mu)$$

Non-universal models, e.g., non-universal Higgs model (NUHM) (6 parameters)

$$M,\ m,\ A,\ \tan\beta,\ sign(\mu)\ \ m^2_{H_d},\ m^2_{H_u}$$

Gauge-mediated scenarios

Anomaly-mediated scenarios

...

Supersymmetric models contain a relatively large number of free parameters unless simplifying hypothesis are made on the origin of these or they are related to more fundamental theories

EW SUSY

GUT Scale
String Scale

String Motivated
Supergarvity models

The soft parameters are understood as originating from a Supergravity theory (assuming a SUGRA-breaking mechanism)

$$M_1,\ M_2,\ M_3$$
$$m^2_{L_{ij}},\ m^2_{E_{ij}}$$
$$m^2_{Q_{ij}},\ m^2_{U_{ij}},\ m^2_{D_{ij}}$$
$$A_E^{i,j}, A_U^{i,j}, A_D^{i,j}$$
$$m^2_{H_d},\ m^2_{H_u}$$

Given in terms of

Kähler potential superpotential

$$G(\phi_M,\phi_M^*) = K(\phi_M,\phi_M^*) + \log|W(\phi_M)|^2$$

$$f_a(\phi_M)$$

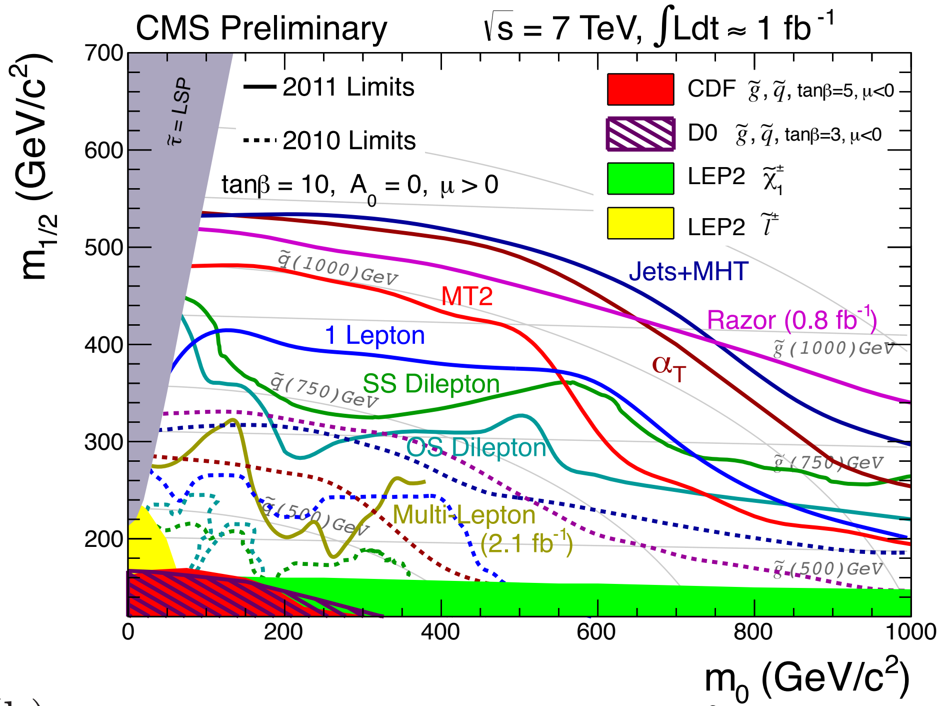
Gauge kinetic function

More fundamental models

Less parameters (related to the geometry and size of the compact space)

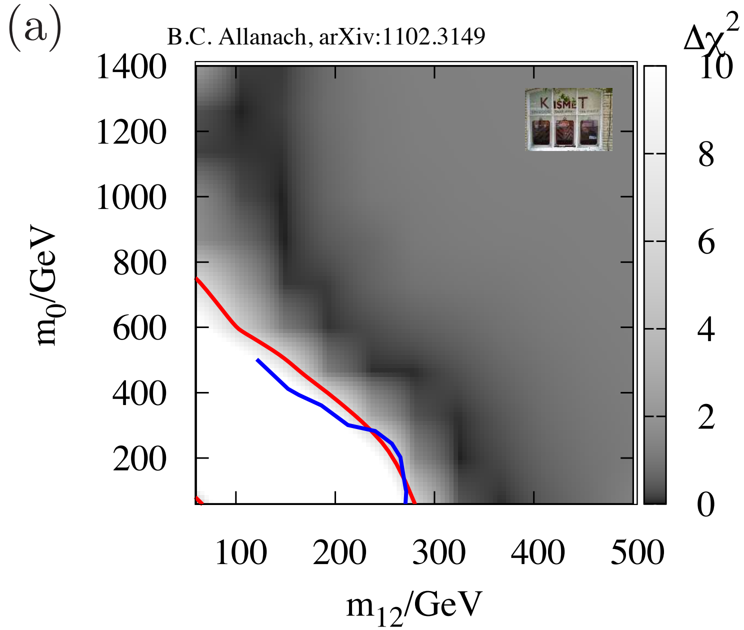
Justification for some universality principles (e.g., we can recover the CMSSM or NUHM)

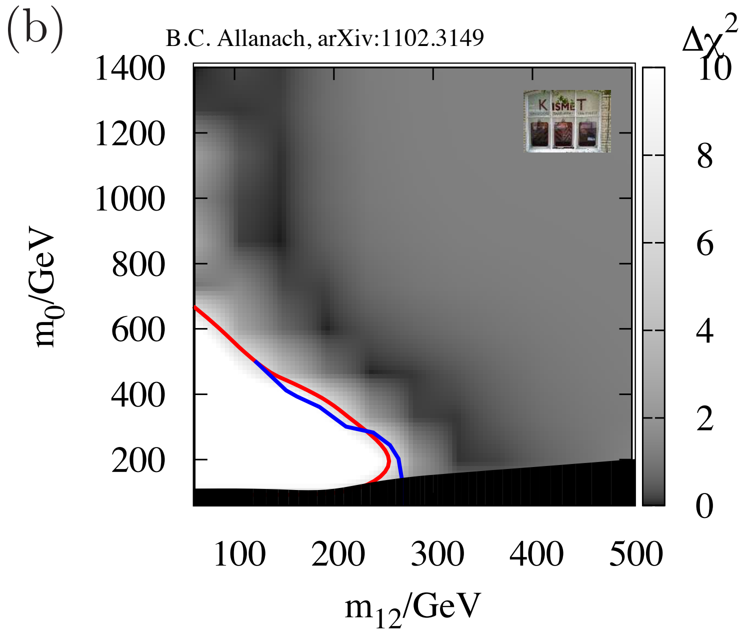
So when we see this plot....



... we should understand that this is not valid for all SUSY models

Although within the CMSSM some of these bounds are not too sensitive to the actual values of A and tanb



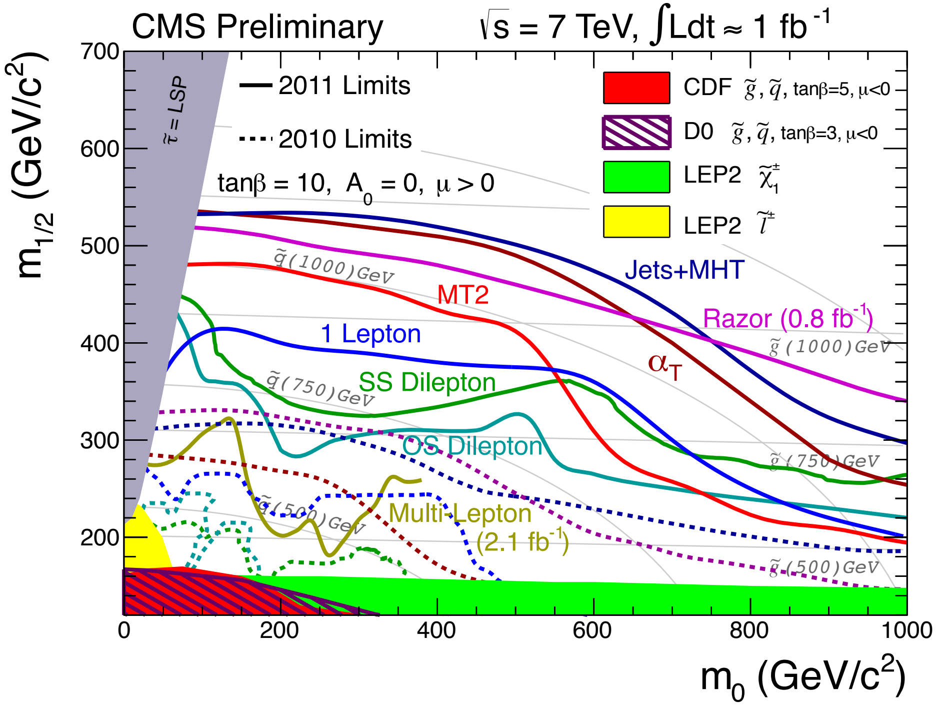


Allanach 2011

So when we see this plot....

... we should understand that this is not valid for all SUSY models

... the bounds on the parameter space of different scenarios might show more profound differences



The **HIGGS BOSON** is the theoretical particle of the Higgs mechanism, which physicists believe will reveal how all matter in the universe get its mass. Many scientists hope that the Large Hadron Collider in Geneva, Switzerland will detect the elusive Higgs Boson when it begins colliding particles at 99.99% the speed of light.

Wool felt with gravel fill for maximum mass.

Higgs in the MSSM

The lightest CP-even Higgs receives important loop corrections to its mass coming from top-stop loops

$$m_h^2 \simeq M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{16\pi^2 v^2}\left(\log\frac{m_{\tilde{t}}^2}{m_t^2} + \frac{X_t^2}{m_{\tilde{t}}^2}\left(1 - \frac{X_t^2}{12 m_{\tilde{t}}^2}\right)\right)$$

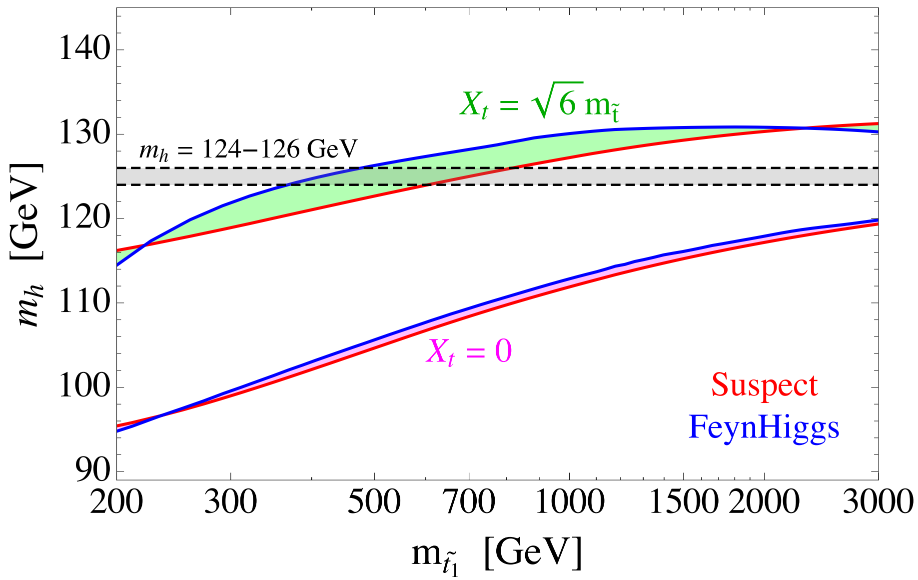
$$\begin{aligned} v^2 &= v_1^2 + v_2^2 \\ m_{\tilde{t}} &= (m_{\tilde{t}_L} m_{\tilde{t}_R})^{1/2} \\ X_t &= A_t - \mu\cot\beta \end{aligned}$$

Maximising the 1-loop expression leads to

$$|X_t| \simeq \sqrt{6} m_{\tilde{t}}$$

Which, in terms of the trilinear parameter translates into

$$A/m \simeq \pm 2$$



Hall, Pinner, Ruderman 2012

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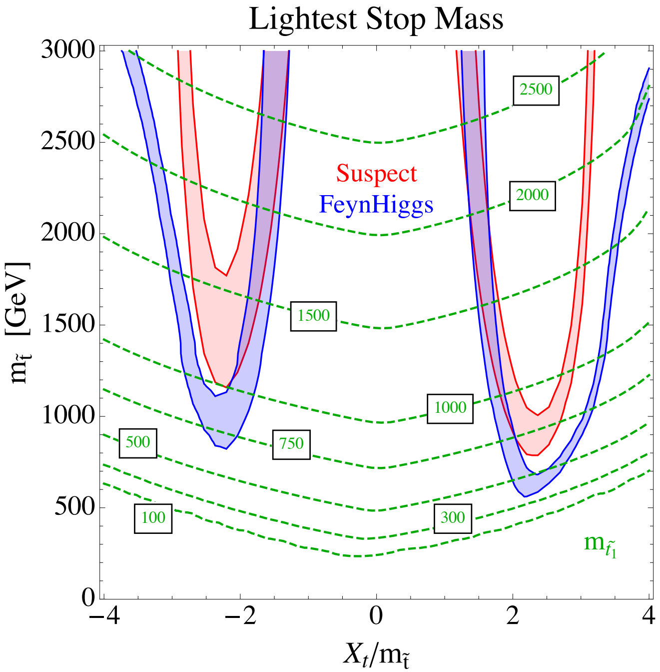

Hall, Pinner, Ruderman 2012

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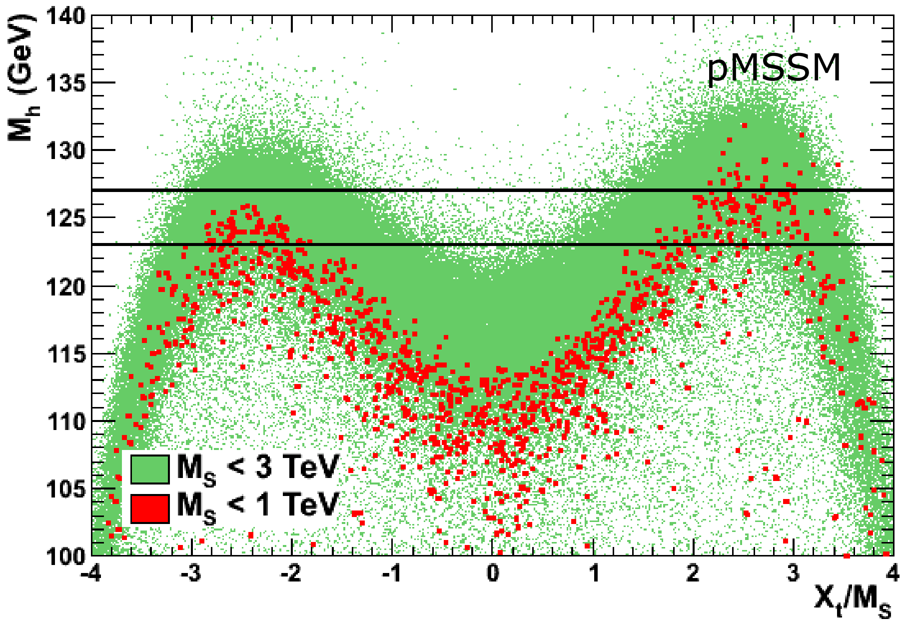
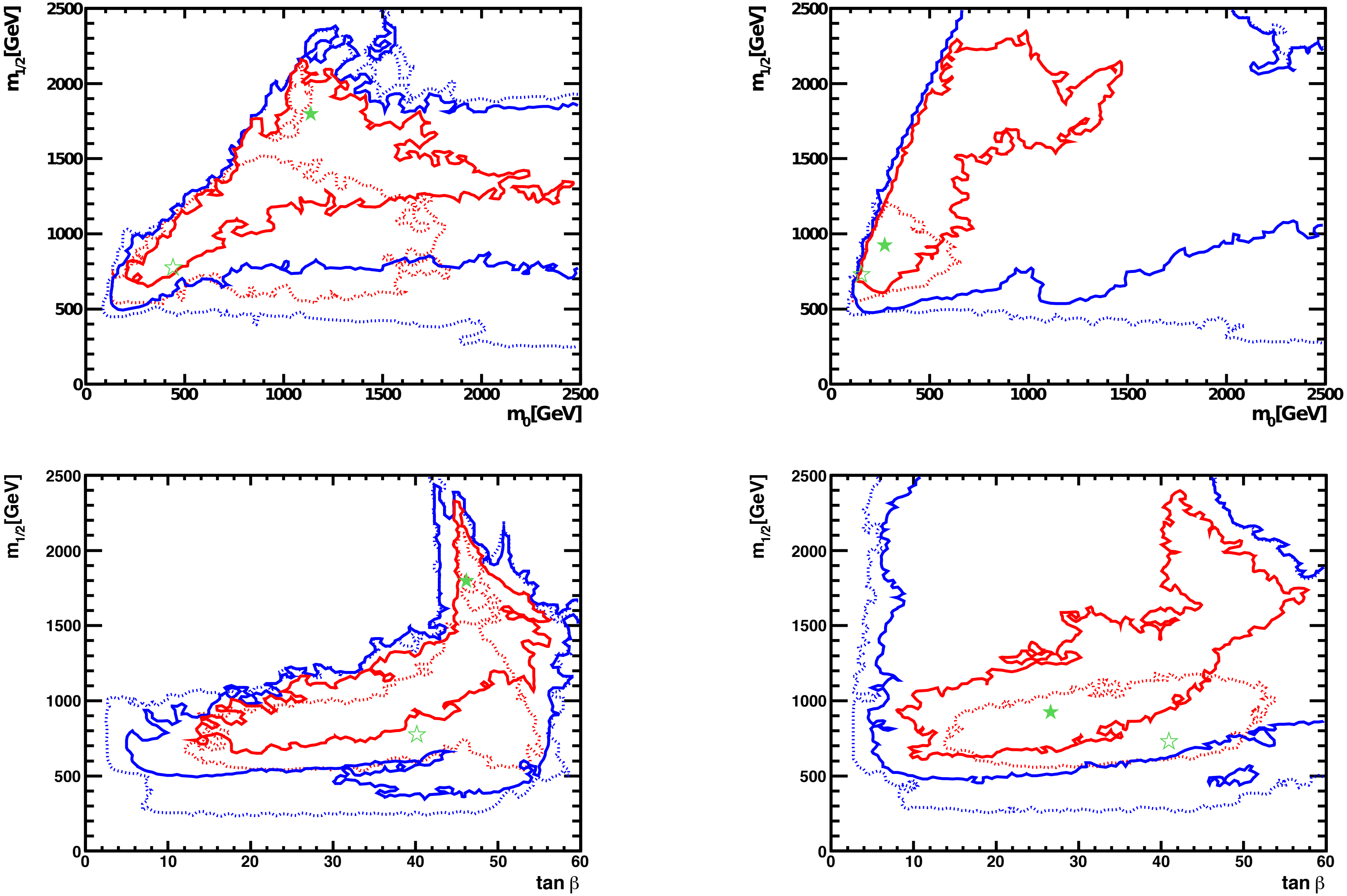


Arbey, Battaglia, Djouadi, Mahmoudi, Quevillon 2012

CMSSM **NUHM**

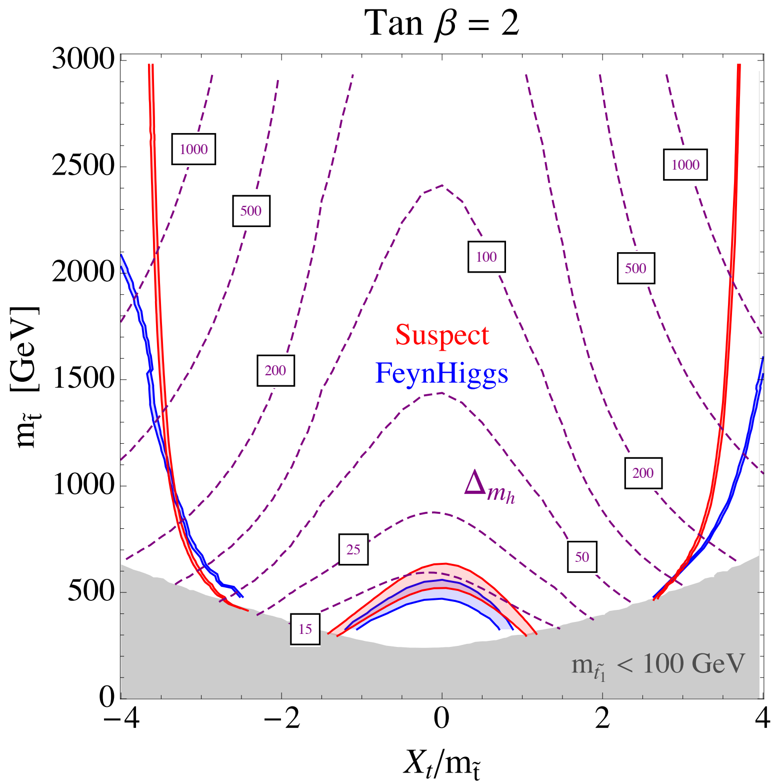


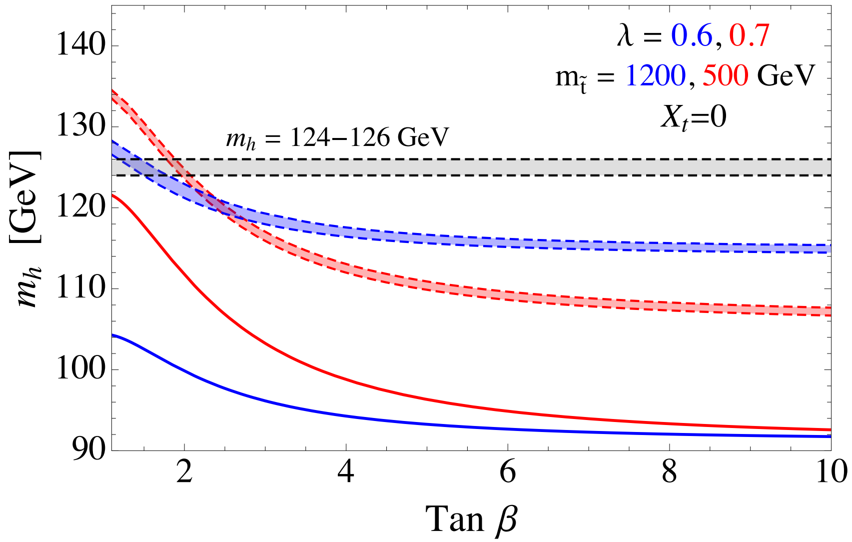
Imposing the Higgs mass constraint implies heavier spectra

Buchmuller et al. 2012

In the Next-to MSSM maximal stop mixing is not needed

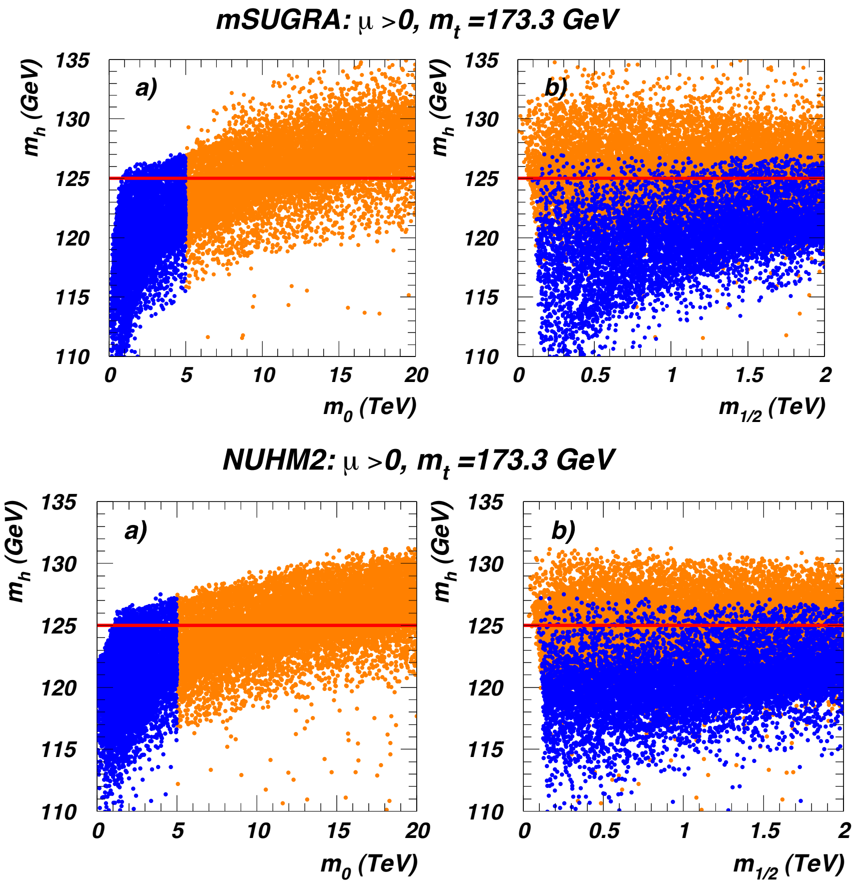
$$m_h^2 \;=\; M_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \delta_t^2$$



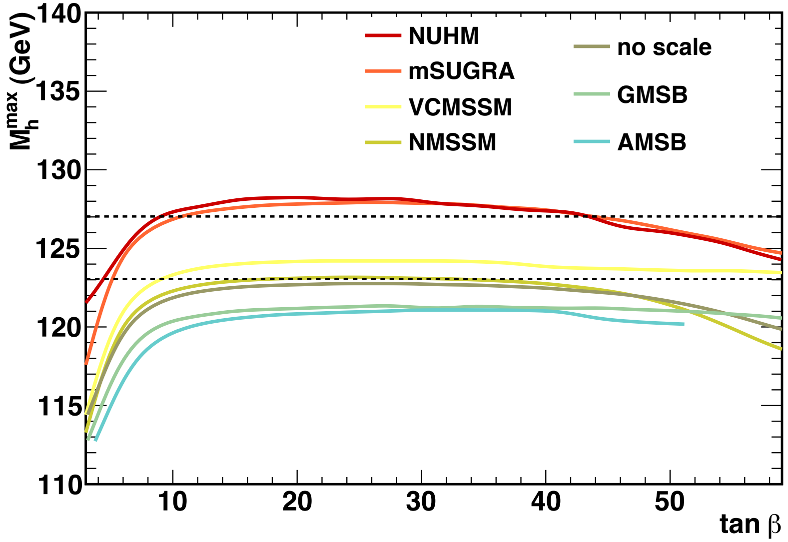


Hall, Pinner, Ruderman 2012

In principle, lighter spectra are also possible



Baer, Barger, Mustafayev 2012



Arbey, Battaglia, Djouadi, Mahmoudi, Quevillon 2012

Tensions with low energy observables

Experimental bounds in low-energy observables, when combined with LHC constraints (or when trying to fit the Higgs mass “measurement”) lead to some tension in the parameter space of SUSY models.

$$\mathrm{BR}(B_s \to \mu^+\mu^-) < 4.5 \times 10^{-9}$$

$$2.85 \times 10^{-4} \leq \mathrm{BR}(b \to s\gamma) \leq 4.25 \times 10^{-4}$$

$$10.1 \times 10^{-10} < a_\mu^{SUSY} < 42.1 \times 10^{-10}$$

$$2.9 \times 10^{-10} < a_\mu^{SUSY} < 36.1 \times 10^{-10}$$

Muon anomalous magnetic moment

The SUSY contribution to the muon (g-2) decreases if the spectrum is heavy

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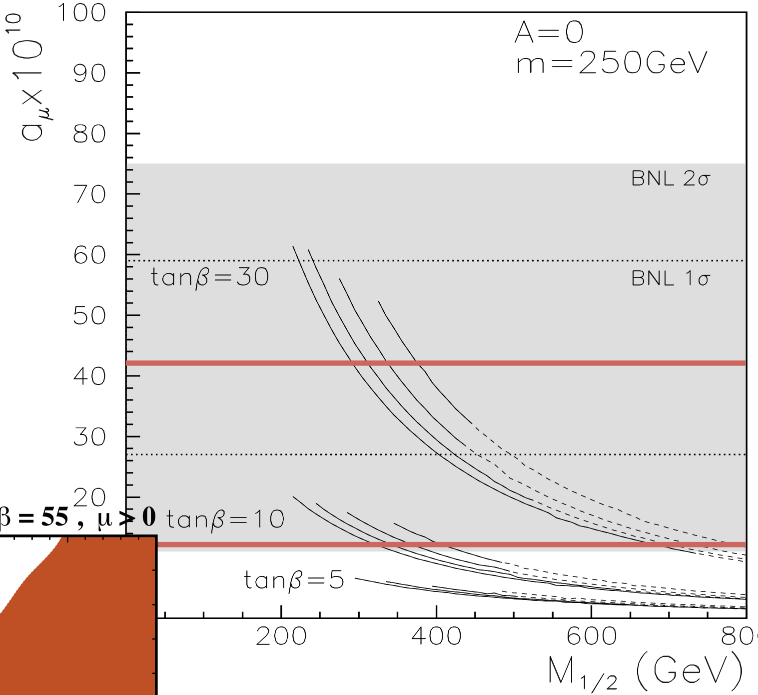
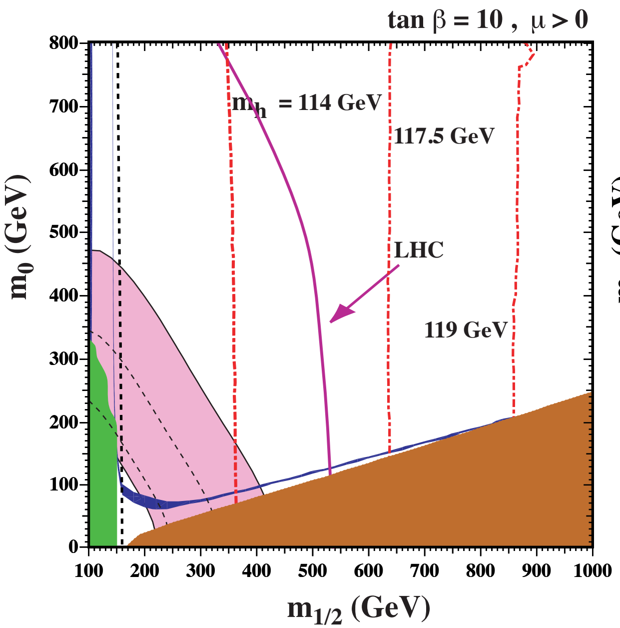
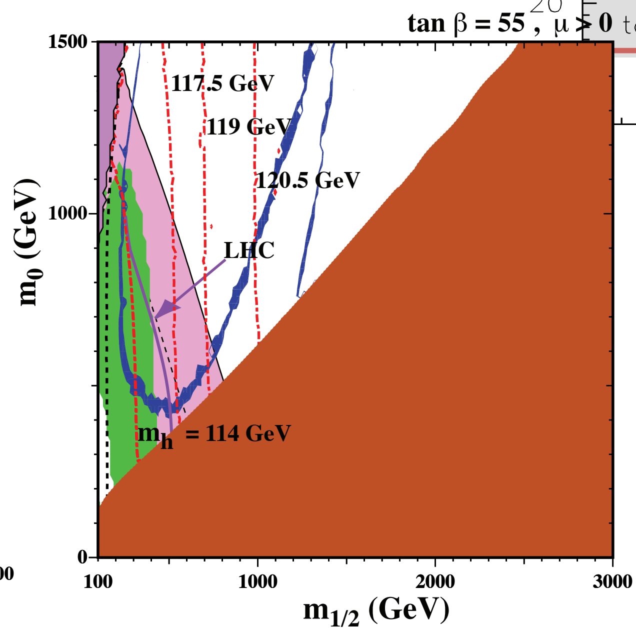


LHC lower bounds on SUSY masses imply some tension for specific models





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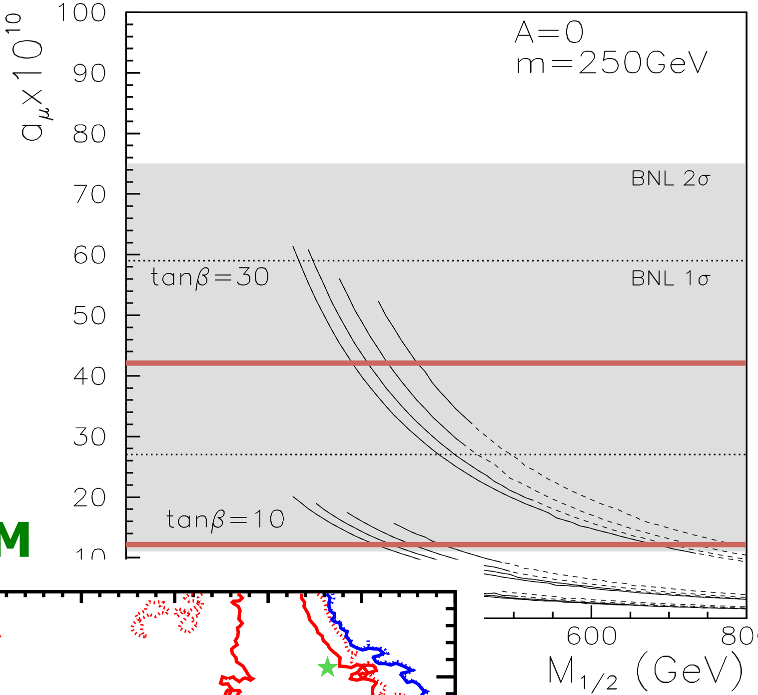

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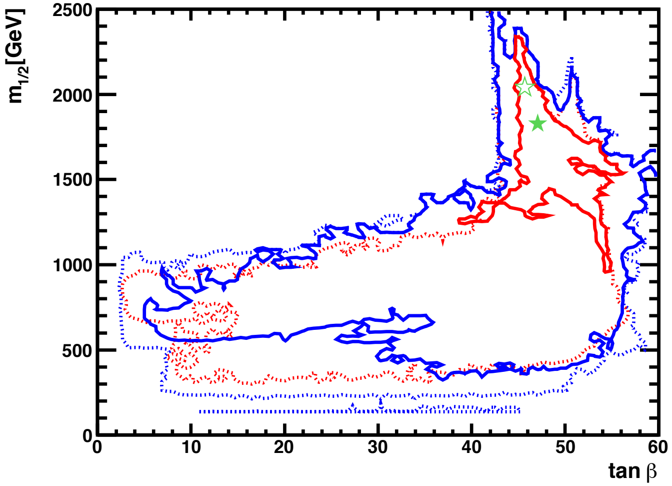
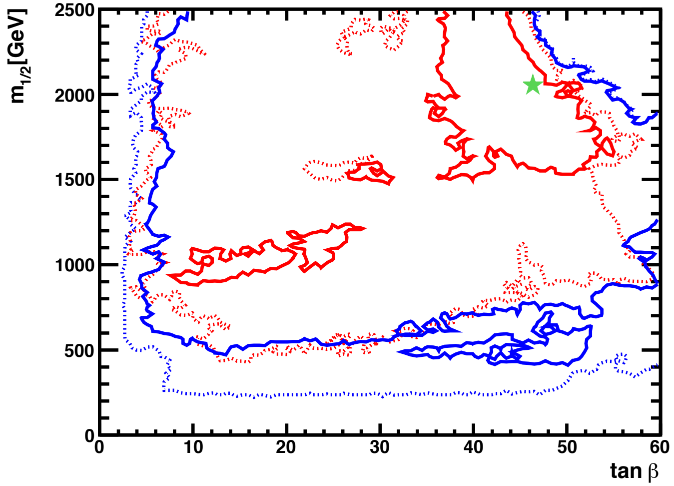
CMSSM



NUHM



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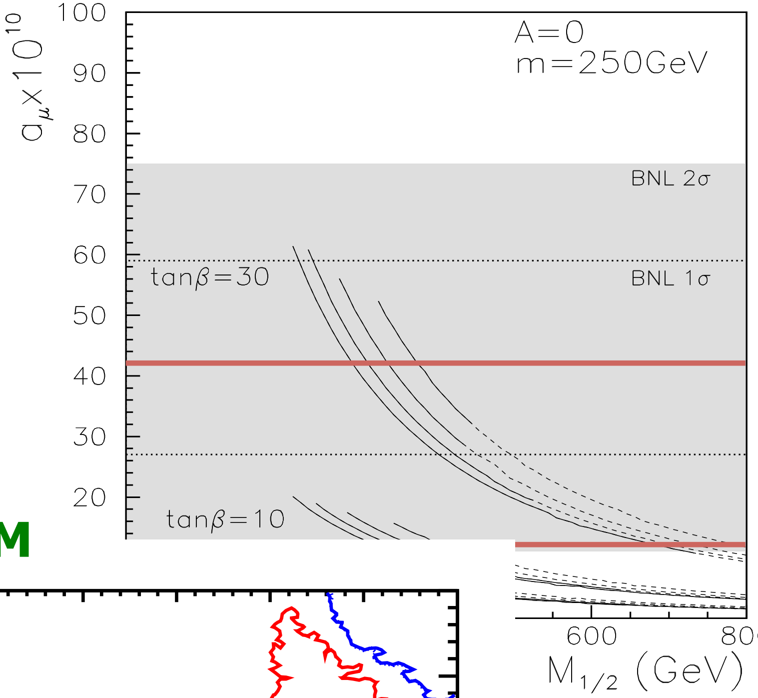

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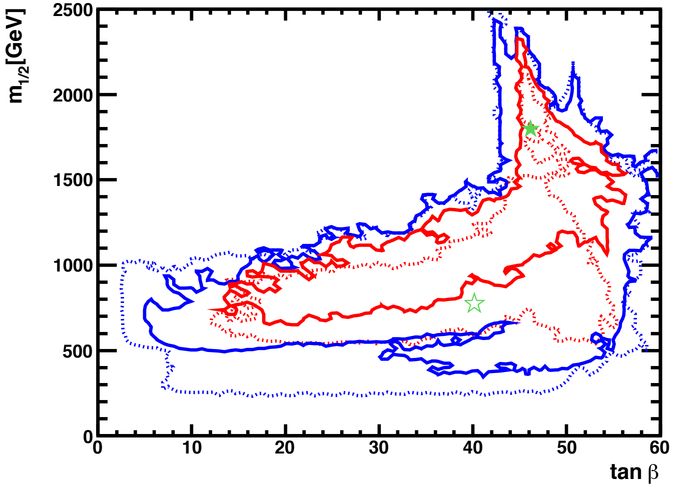

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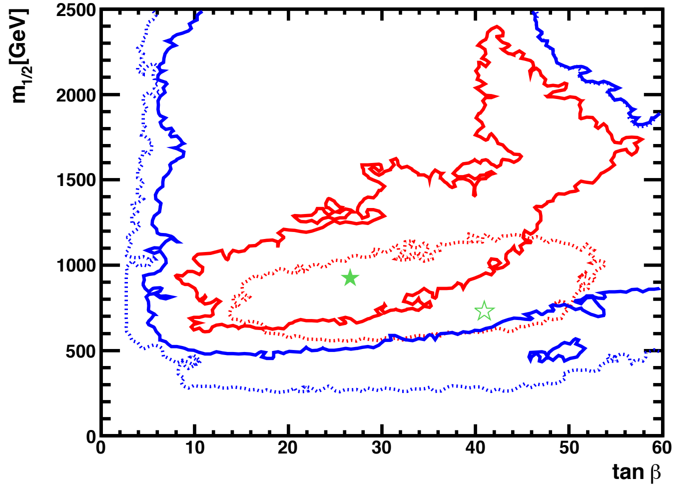

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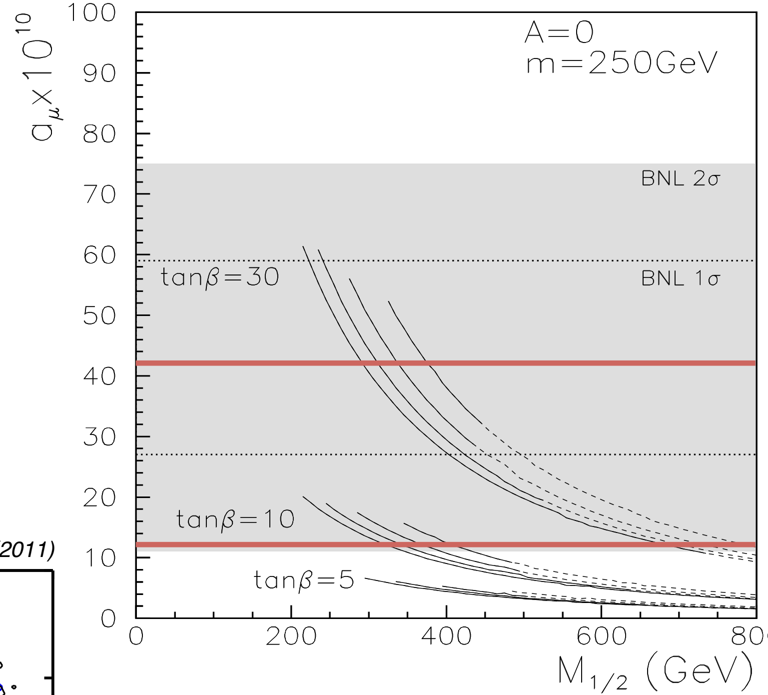
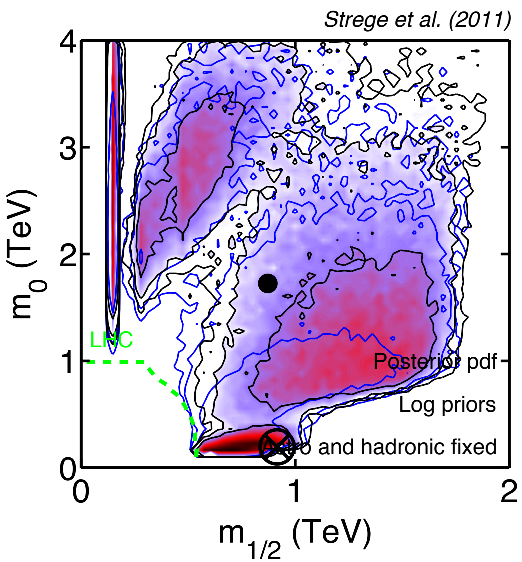
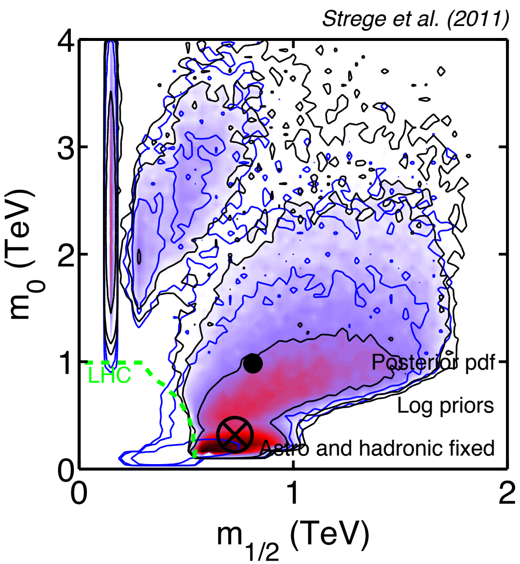


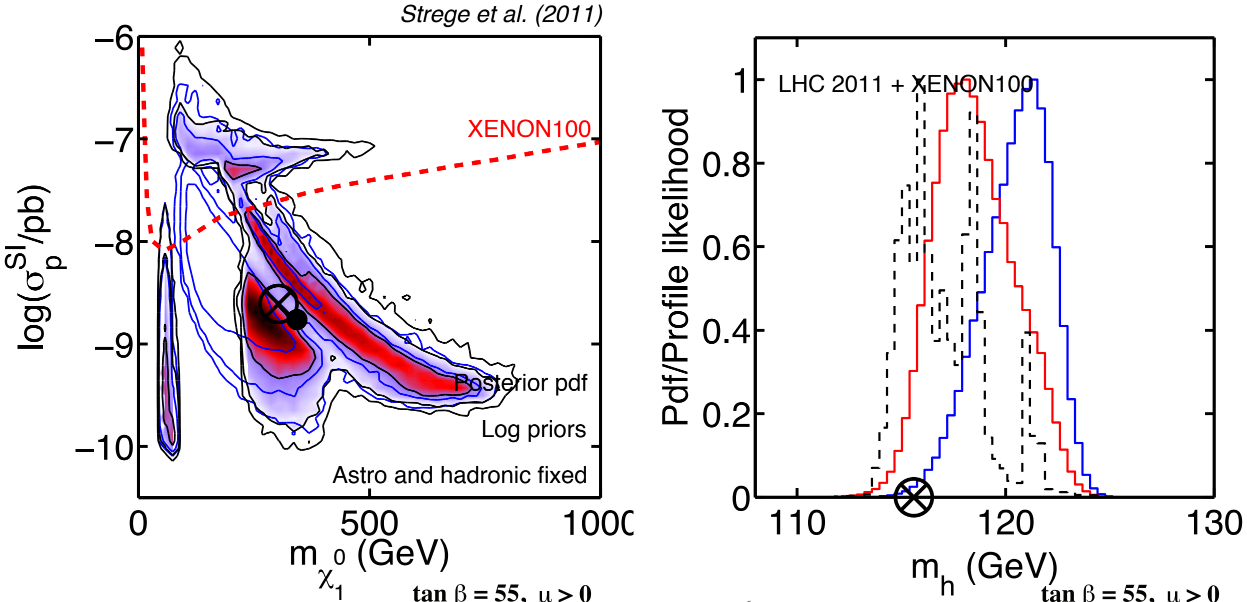
IF DM relic density is also imposed only a few regions of the parameter space survive... Heavier points are also disfavoured





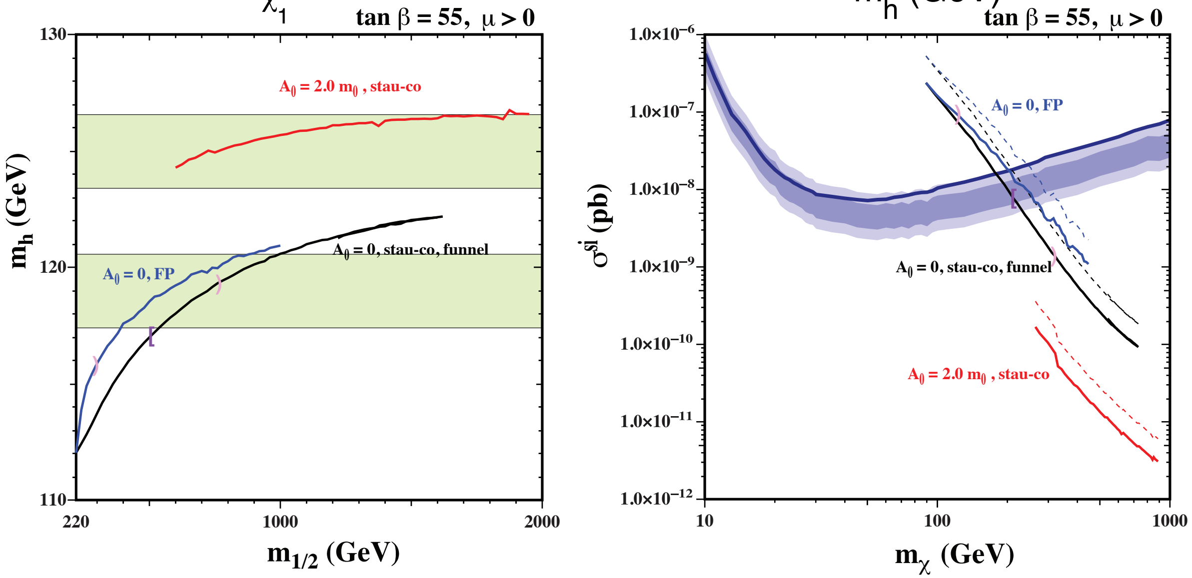
Implications for dark matter

LHC constraints INDIRECTLY lead to constraints on the DM model



A lower bound in the neutralino mass is found that excludes some regions with large scattering cross-section IN THE CMSSM

Bertone et al. 2012



If mh~125 GeV is imposed, the scattering cross section for neutralinos is generally beyond the reach ofdirect DM detection IN THE CMSSM

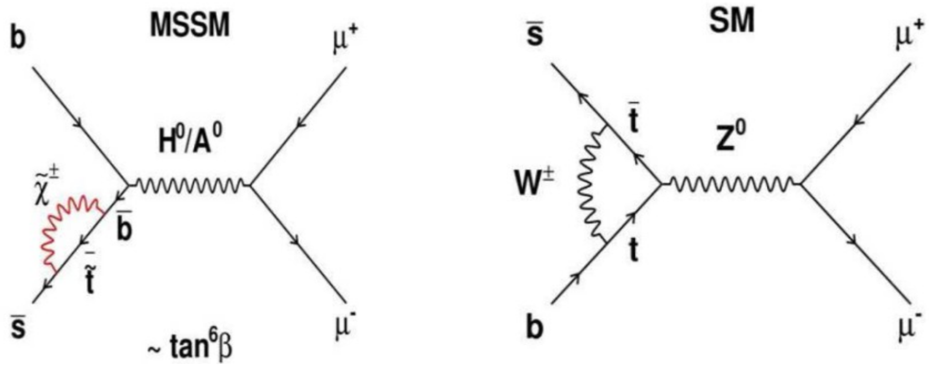
Ellis, Olive 2012

Constraints from rare decays

LHCb has obtained an unprecedented upper bound on the rare decay of Bs into muons

$$\mathrm{BR}(B_s \to \mu^+\mu^-) < 4.5 \times 10^{-9}$$

$\mathrm{BR}(B_s \to \mu\mu)_{SM} = (3.2 \pm 0.2) \times 10^{-9}$



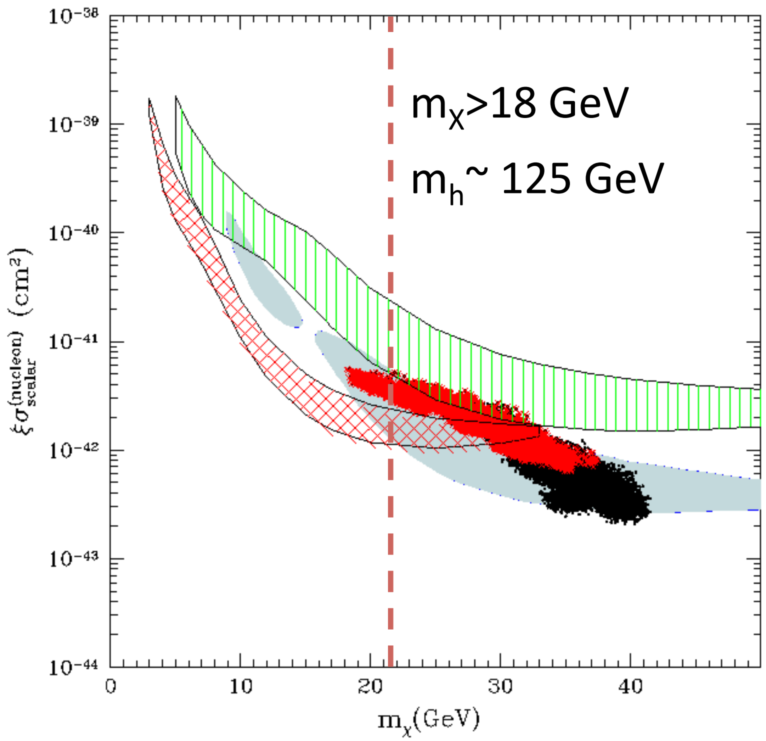
$$\mathrm{B}(B_s^0 \to \mu^+\mu^-) \propto \frac{\tan^6\beta}{m_A^4}\left(\frac{\mu A_t}{m_{\tilde{t}_L}^2}\right)^2$$

This constrains regions with small pseudoscalar mass and large tanb, but also those in which the stop mixing is sizable. This affects:

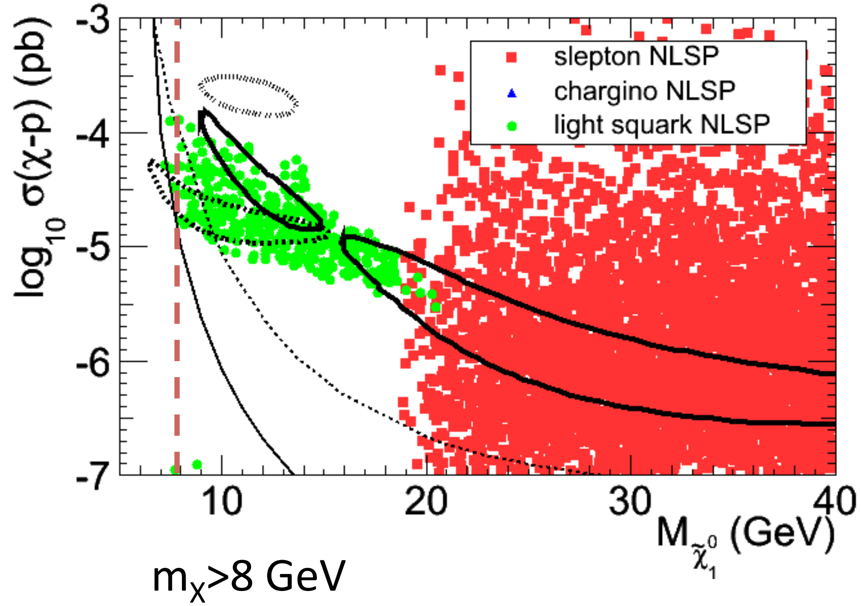
- Regions with heavy Higgs mass (typically maximal stop mixing – normally large tanb)
- Models for very light neutralino dark matter (small m_A, large tanb)

Constraints from rare decays

- Models for very light neutralino dark matter (small m_A, large tanb)



Bottino, Fornengo, Scopel 2011



Arbey, Battaglia, Mahmoudi 2012

No more annihilation mediated by the pseudoscalar – now the relic density is obtained by light-squark exchange

Constraints from rare decays

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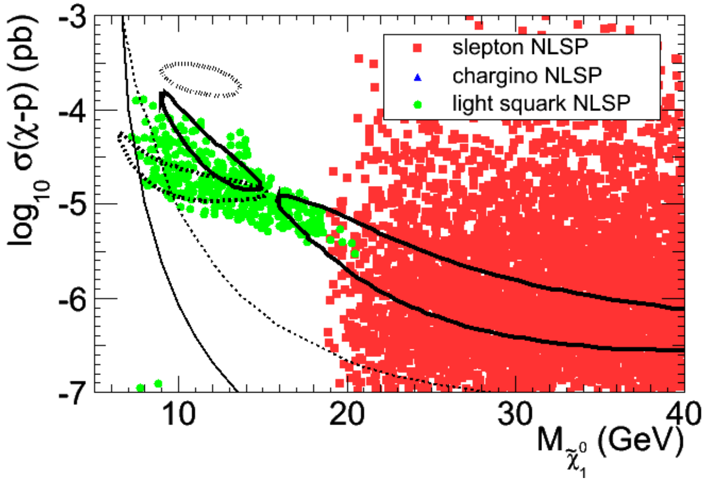
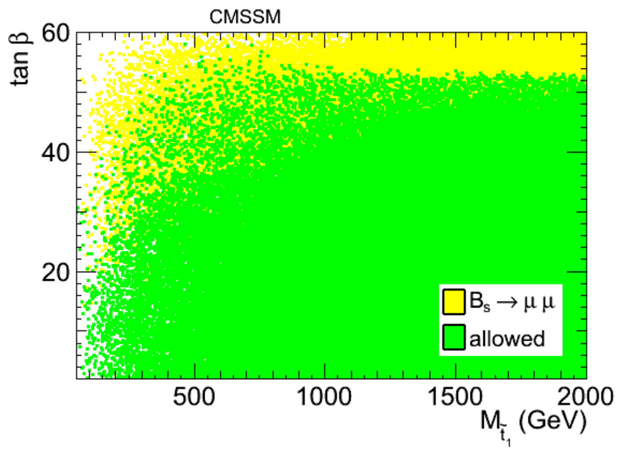
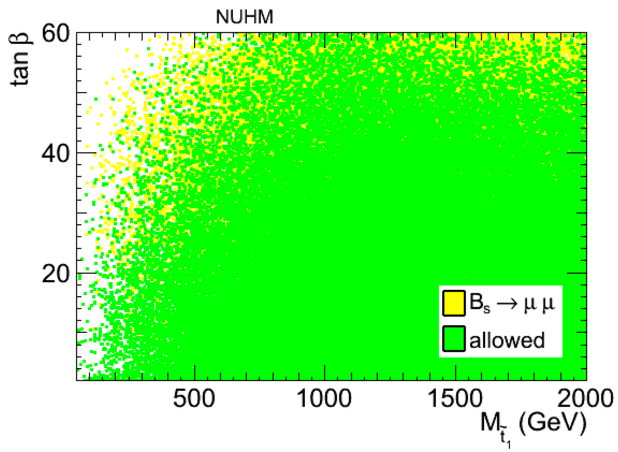
$\mathrm{BR}(B_s \to \mu\mu)_{SM} = (3.2 \pm 0.2) \times 10^{-9}$



Arbey, Battaglia, Mahmoudi 2012





A specific string-motivated scenario

Let us consider an F-theory construction in which SUSY breaking is transmitted solely by the moduli fields (having no contribution from the dilaton)

$$G = -2\log(t_b^{3/2} - t^{3/2}) + \log|W|^2$$

$$f = T\ ;\ K_\alpha = \frac{t^{1-\xi_\alpha}}{t_b}$$

Fields live on a 7-brane

$$\begin{aligned} m_{\tilde{f}}^2 &= \frac{1}{2}|M|^2\,, \\ m_H^2 &= \frac{1}{2}|M|^2(1-\frac{3}{2}\rho_H)\,, \\ A &= -\frac{1}{2}M(3 - \rho_H)\,, \\ B &= -M(1-\rho_H)\,, \end{aligned}$$

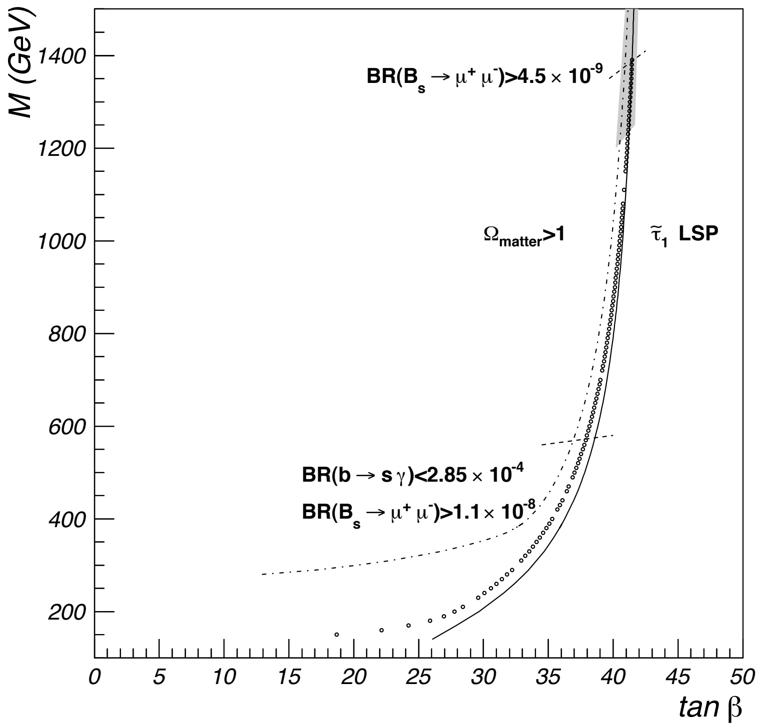
In the case of vanishing fluxes one recovers a special case of the CMSSM, for non-vanishing fluxes, the NUHM

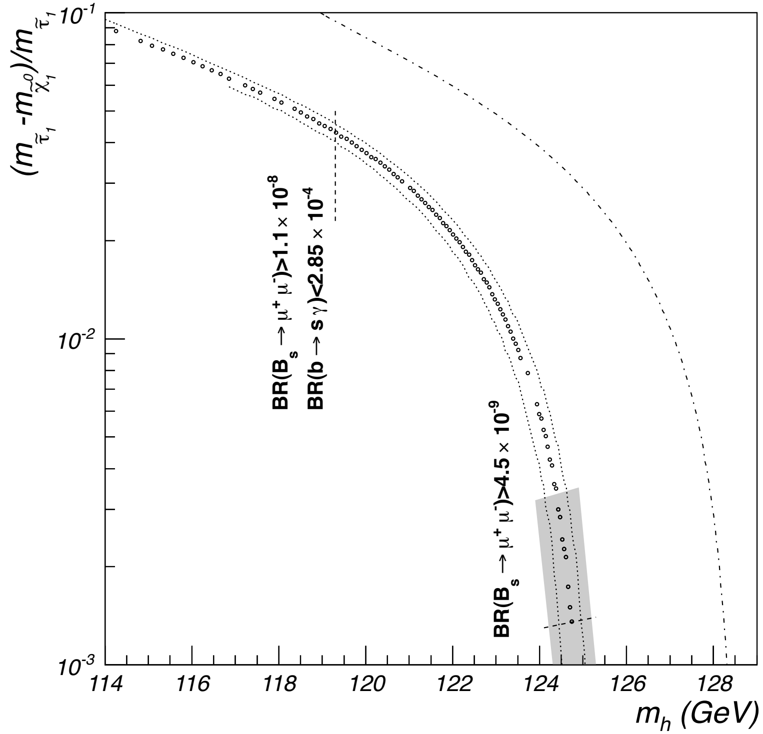
$$M = \sqrt{2}m = -(2/3)A = -B$$

Two parameter model (M, ρ_H)
"Similar" to the CMSSM (actually a special case)
tanb is NOT an input, it is derived in order to fulfil the boundary condition for B

A specific string-motivated scenario

Can we reproduce LHC constraints + DM relic density?





Imposing the relic density constraint forces us to stay in the coannihilation region with large values of tanb

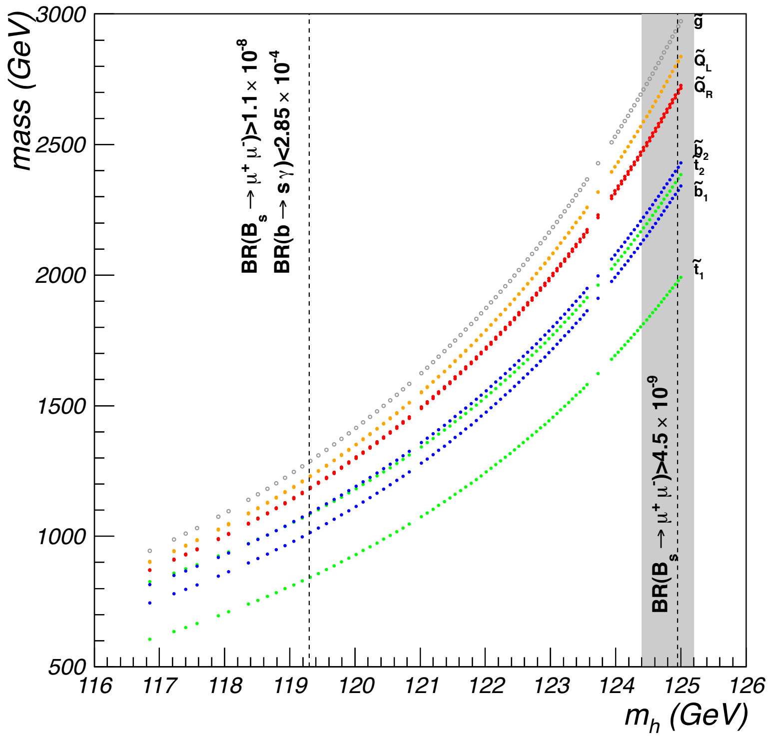
The conditions for maximal stop mixing are fulfilled and the Higgs can have a sizable mass

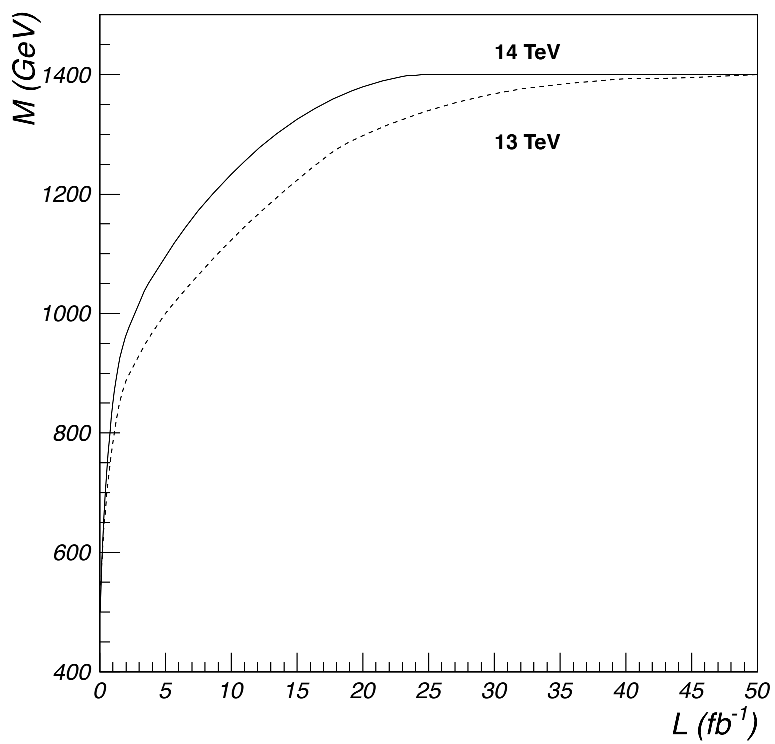
$\rho_H = \mathbf{0.16}$

$$A = -3/\sqrt{2}m \simeq -2m$$

A specific string-motivated scenario

Can we reproduce LHC constraints + DM relic density?





Rare decay constraints only leave the region with the largest possible mass spectrum

That could only be explored with the LHC in a 13-14 TeV configuration.

Conclusions

- Supersymmetry is more than just the CMSSM (and the experimental bounds have to be applied for each individual model)
- LHC searches + Higgs mass "measurement (+ dark matter requirements) impose very stringent constraints on the parameter space of SUSY models
- mh~125 GeV seems to imply a heavy spectrum with maximal stop mixing
- Potential conflicts with low energy observables (g-2) and rare decays
- Implications for dark matter Dark matter