Dark Matter Detection in BMSSM effective theory

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N.Bernal, A.G., JCAP 1003:007,2010 [arXiv:0912.3905]

Outline

Motivation

As nice as it might be, the MSSM is not without issues! A notorious relation is:

$$m^2_{h,H} = \frac{1}{2}\left[m_Z^2 + m_A^2 \mp \sqrt{(m_A^2 - m_Z^2)^2 + 4m_A^2 m_Z^2 \sin^2 2\beta}\right]$$

It turns out that, even including RC, there are two possibilities to pass the LEP constraints:

- Large stop masses $\mapsto$ Naturalness issues...
- Large stop mixing $\mapsto$ Not always easy to obtain...

The idea:

- It is known that going beyond the MSSM (BMSSM) one can introduce effects uplifting the lightest higgs mass, already at tree-level (NMSSM, UMSSM etc...).
- Parametrize such new physics in terms of effective operators, organized in increasing powers of $1/M$ suppression, M being the new physics scale (O(TeV)).
- (Dine, Seiberg, Thomas, '07): Add dim-5 operators in the pure Higgs sector to strictly address the little hierarchy problem.

The model - Some formalism

It turns out that through appropriate field definition, ∃ only 2 relevant operators:

$$\mathcal{W}^{\text{Higgs}}_{\text{MSSM-5}} = \int d^2\theta \left(\mu H_u H_d + \underbrace{\frac{\lambda_1}{M}(H_u H_d)^2}_{\text{SUSY}} \right) + \underbrace{\int d^2\theta \mathcal{Z} \frac{\lambda_2}{M}(H_u H_d)^2}_{\not{\text{SUSY}}}$$

yielding corrections to the Higgs potential, as:

$$\begin{aligned} \delta\mathcal{L} &= 2\epsilon_1 H_u H_d (H_u^\dagger H_u + H_d^\dagger H_d) + \epsilon_2 (H_u H_d)^2 + \text{h.c.} \\ &+ \frac{\epsilon_1}{\mu^*} \Big[2(H_u H_d)(\widetilde{H}_u \widetilde{H}_d) + 2(\widetilde{H}_u H_d)(H_u \widetilde{H}_d) \\ &+ (H_u \widetilde{H}_d)(H_u \widetilde{H}_d) + (\widetilde{H}_u H_d)(\widetilde{H}_u H_d) \Big] + \text{h.c.} \end{aligned}$$

and 2 relevant new parameters:

$$\epsilon_1 = \frac{\mu^* \lambda_1}{M}, \quad \epsilon_2 = -\frac{m_{\text{SUSY}} \lambda_2}{M}$$

Vacuum stability imposes (Blum, Delaunay, Hochberg, '09):

$$|\epsilon_1| \lesssim 0.1, |\epsilon_2| \lesssim 0.05$$

Some consequences

- Uplift of the tree-level prediction of the Higgs mass.
  (Dine, Seiberg, Thomas, '07 and Berg, Edsjo, Gondolo, Lundstrom, Sjors, '09)
  $\Longrightarrow$ Regions excluded in the plain MSSM framework re-enter the game!
- Consequences on electroweak baryogenesis, mainly thanks to light stop possibility.
  (Bernal, Blum, Losada, Nir '09)
- Consequences on Dark Matter:
  ↬ Existing regions previously excluded by Higgs constraint become viable.
  ↬ New regions appear. (more in the following)
  (Berg et al, '09 and Bernal et al, '09)
- We consider two benchmarks, already explored for relic density and baryogenesis in (Bernal, Blum, Losada, Nir '09)

Our questions:

↬ Are the new viable regions detectable?
↬ How is detection modified wrt the MSSM?

Benchmarks: mSUGRA - like, Light Stops Heavy Sleptons

mSUGRA - like

↬ Begin with a set of mSUGRA GUT-scale parameters:

- $\tan\beta$: Ratio of the Higgs vev's
- A_0: Universal trilinear coupling
- sign(μ): Sign of the higgsino mass parameter
- $m_{1/2}$: Universal gaugino mass
- m_0: Universal scalar mass (Higgses and sfermions)

↬ Fix: $\tan\beta = (3, 10)$, $A_0 = 0$, $\mu > 0$ and vary $m_{1/2}, m_0$
↬ Evolve down to the EW scale (SUSPECT).
↬ Take into account NR operators' effects at low energy (!!! NOT generalized mSUGRA !!!).

Light Stops, Heavy Sleptons

↬ Start with a set of low-energy parameters:

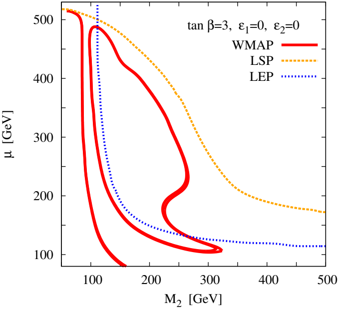
- $\tan\beta$: ratio of the Higgs vevs
- μ: higgsino mass parameter
- m_A: pseudoscalar Higgs mass parameter
- $X_t = A_t - \mu\cot\beta$: Trilinear coupling for stops
- M_2: Wino mass parameter, $M_1 \sim M_2/2$
- m_U: right stop mass parameter
- m_Q: 3rd generation left squarks mass parameter
- $m_{\tilde{f}}$: mass for sleptons, 1st and 2nd generation squarks and right sbottom

↬ Fix: $\tan\beta = (3, 10)$, $m_U = 210$ GeV, $m_Q = m_A = m_{\tilde{f}} = 500$ GeV and vary μ, M_1
↬ Include directly the effect of NR operators.

Light Stops Heavy Sleptons: Relic Density

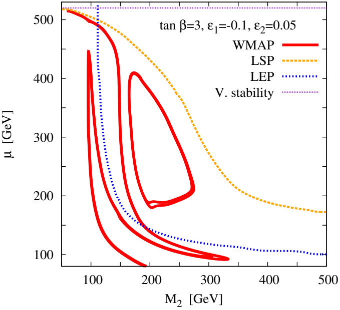
MSSM (Excluded)

Bernal, Blum, Nir, Losada, '09



BMSSM (OK)

Bernal, Blum, Nir, Losada, '09



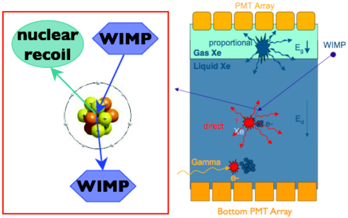
↬ Regions where DM relic density constraint is fulfilled are quite particular, each with its own characteristics:

- Coannihilation with $\tilde{\tau}$ (mSUGRA-like) or $\tilde{t}$ (here)
- Higgs/Z poles

↬ Constraints coming from requirement for neutralino LSP, LEP chargino searches, vacuum stability.

Direct Detection - Principles

Schematically



Dark Matter is detected through its collisions with target nuclei of a (typically large) ground-based detector.
⟼ Our choice: The XENON experiment (running, upgrades to come)
⟼ We consider zero backgrounds.

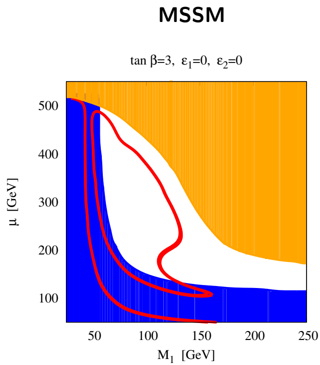
Event Rate

$$\frac{dN}{dE_r} = \frac{\sigma_{\chi-N} \cdot \rho_0}{2\, M_r^2\, m_\chi} F(E_r)^2 \int_{v_{\min}(E_r)}^{v_{esc}} \frac{f(v)}{v}\, dv$$

Where:

- N: Number of scatterings $(\mathrm{s}^{-1}\mathrm{kg}^{-1})$
- E_r: Nuclear recoil energy (∼few keV)
- m_χ: WIMP mass
- $M_r = \frac{m_\chi\, m_N}{m_\chi + m_N}$: WIMP - Nucleus Reduced Mass
- $\sigma_{\chi-N}$: WIMP-Nucleus cross-section (Spin-independent coupling)
- ρ_0: Local WIMP density (0.385 GeV cm^{-3})
- $f(v)$: WIMP local velocity distribution (Maxwell-Boltzmann)
- F: Nuclear form factor (Woods-Saxon)

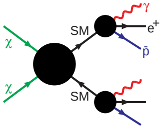
Direct Detection: Light stops, heavy sleptons - Low tan β



- Detection best for low (M_1, μ) values: light neutralino!
- Significant scattering CS enhancement for $M_1 \simeq \mu$: neutralino is mixed bino-higgsino state, so $\chi_1^0 - \chi_1^0 - h$ couplings are maximised.
- Detection deteriorates due to NR operators.
- However, good parameter space coverage: We see slightly less than in MSSM, but cosmologically relevant and not excluded by LEP!

γ-ray detection - Principles

Schematically



DM annihilation into SM particles in the galactic halo. Look for γ-rays as primary or secondary products of WIMP annihilations. Possible to look at different places, the most standard: GC.

Our choices:

$\longmapsto$ γ-rays: Fermi satelite (running!)

$\longmapsto$ Background as seen from HESS measurements (diffuse + PS at SgrA*).

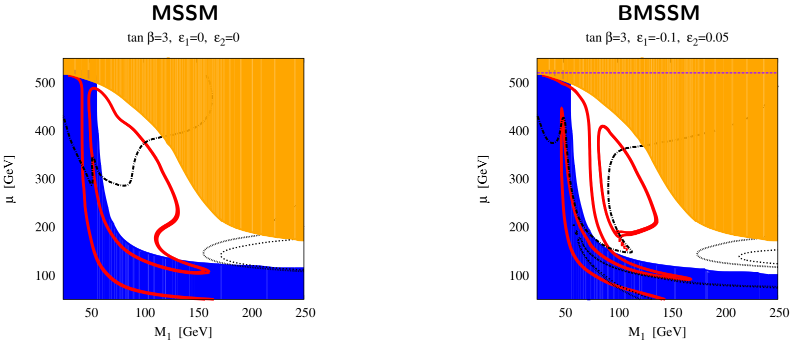
Event Rate

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma, \psi) = \frac{\langle \sigma v \rangle}{8\,\pi\, m_\chi^2} \sum_i \frac{dN_\gamma^i}{dE_\gamma} Br_i \int_{\text{los}} \rho(r)^2\, dl$$

Where:

- Br_i: Annihilation Fraction into i-th SM particle
- dN_γ^i/dE_γ: Functions describing SM particles' decays into γ-rays (PYTHIA)
- $\langle \sigma v \rangle$: Total thermally averaged WIMP self-annihilation cross-section
- $\rho(r)$: Distribution of DM in the galaxy (NFW, Einasto, NFW$_c$).

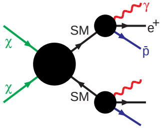
γ-rays from the GC: Light stops, heavy sleptons - Low tan β



- Detection best for low (M_1, μ) values: lighter LSP.
- Once again, some thresholds appear: Annihilation into Z, W pair-production.
- For $M_1 > \mu$: Significant higgsino component: GOOD, couples to Z! BUT wrong relic density...
- Higgs Funnel unexplorable...
- NR operators: Increase in $\chi\chi A$ coupling $\rightarrow$ annihilation into fermion pairs.
- hZ channel gets closed (REMEMBER: h heavier!).

Antimatter detection - Principles

Schematically



DM annihilation into SM particles in the galactic halo. The main detected particles: e^+ and antiprotons as primary or secondary products of WIMP annihilations.

⟼ Each channel is different!!!

Our choices:

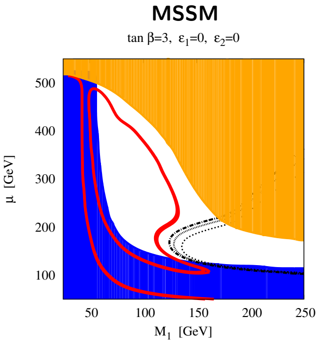
⟼ AMS-02 satelite (oncoming).

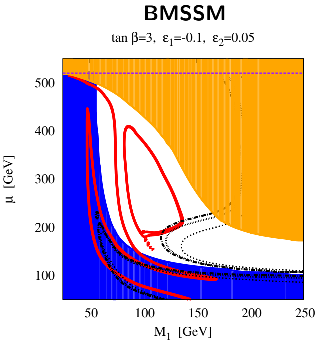
⟼ Backgrounds: Fermi*PAMELA for positrons, Conventional for antiprotons.

Event Rate

- Antimatter doesn't simply traverse the galaxy, it interacts with the ISM.
- Process described by a diffusion-convection-reacceleration equation.
- Many different treatments exist, from fully numerical to fully analytical.
- Our choice: Semi-analytical 2D diffusion equation solution as in (Baltz, Edsjo, '98 and Lavalle, Pochon, Salati, Taillet, '06)

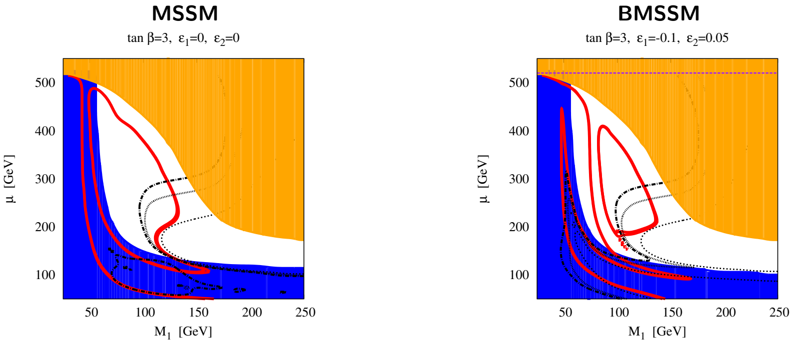
Positrons: Light stops, heavy sleptons - Low tan β





↬ Much worse perspectives, PAMELA excess burries all signals.
↬ Adds practically nothing to other channels.
↬ Some small hope in the region where the LSP carries a significant higgsino component, due to the rise in the coupling with Z's.
↬ Astrophysical boosts quite constrained (~ 10).

Antiprotons: Light stops, heavy sleptons - Low tan β



- Much better than positrons. Better than γ in that astro not taken optimistic.
- Halo substructure effects could improve some more (though not too much).
- Low bkg modelization confirmed by PAMELA.
- One of the best indirect channels?

Discussion

A lot of plots where shown! What should one keep from the previous???

- Adding of just 2 dim-5 operators allows for the reopening of important regions yielding the correct relic density, absent in the relevant scenarios of the MSSM.
- Effective FT techniques: Powerful (because general) but require caution!
- An example caveat in the analysis: RGE flow.
- Important constraints coming equally from vacuum stability.
- Interesting interplay with experimental perspectives: DM detection gets challenged.

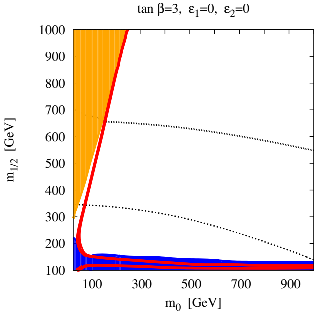
Perhaps also:

- The analysis presented here can be significantly ameliorated. An example: look AROUND (and not AT) the GC. Other places are also possible.
- Antiprotons seem quite promissing, due to low bkg!
- Especially after the CDMS-II results, everyone waits XENON!
- Importance of multi-messenger approach: Different PS parts seen at different experiments (example: $\tan\beta$).

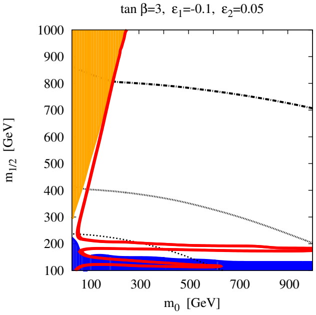
!!! Discussion Time !!!

Direct Detection: Correlated Stop-Slepton masses - Low tan β

MSSM



BMSSM

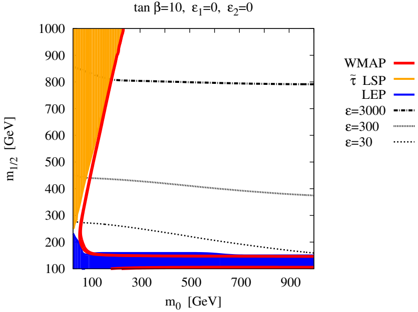


- As $(m_0, m_{1/2})$ increase, so do squark propagators' and χ_1^0's mass.
- For low $m_{1/2}$, $\chi_1^0 - \chi_1^0 - h/H$ couplings are maximized.
- (Not seen here): Best detection for low tan β values.
- NR operators: Increase of m_h, detection worse.

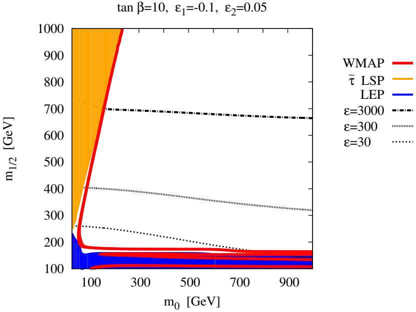
But at least, not excluded!

Direct Detection: Correlated Stop-Slepton masses - Higher tan β

MSSM

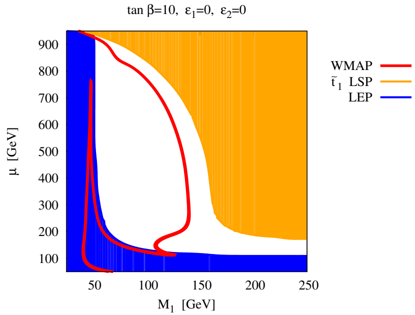


BMSSM

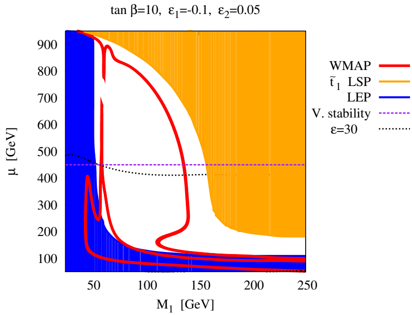


Direct Detection: Light stops, heavy sleptons - Higher tan β

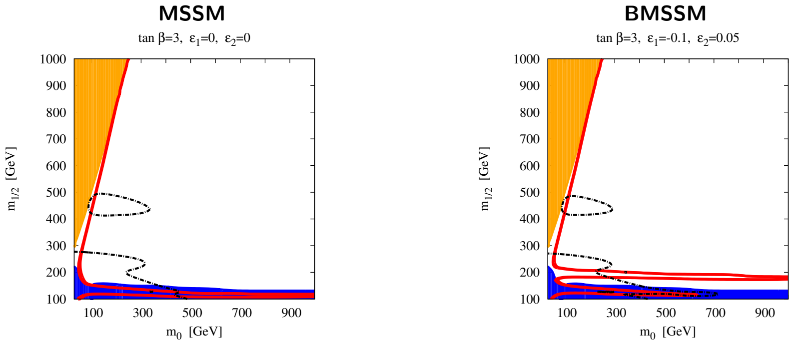
MSSM



BMSSM



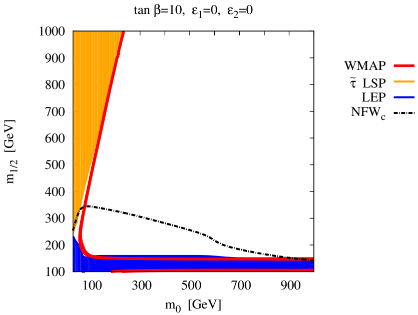
γ-rays from the GC: Correlated Stop-Slepton masses - Low $\tan\beta$



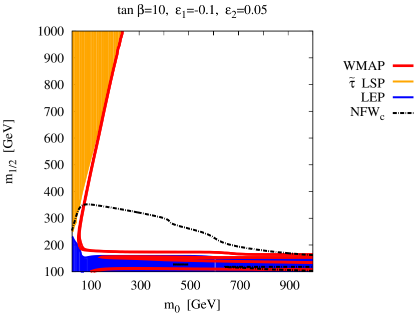
- Detection best for low $(m_0, m_{1/2})$ values: squark masses.
- Appearence of thresholds: annihilation into real Z, real W pair production, real $t\bar{t}$ pair production.
- Total self-annihilation CS augments with $\tan\beta$ (but thresholds vanish).
- Very small effect by NR operators (roughly LSP mass).
- Only NFW$_c$ allows detection.

γ-rays from the GC: Correlated Stop-Slepton masses - Higher tan β

MSSM

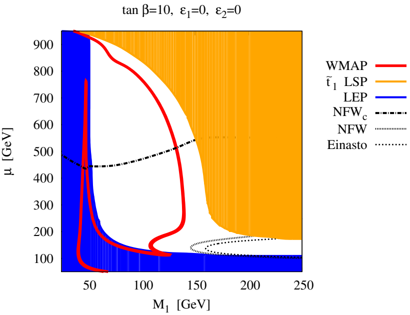


BMSSM

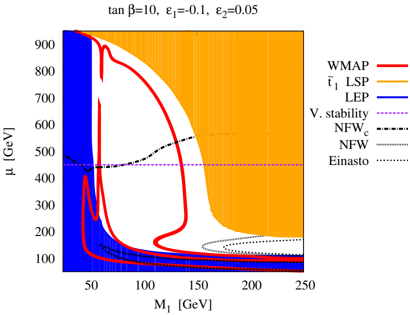


γ-rays from the GC: Light stops, heavy sleptons - Higher tan β

MSSM

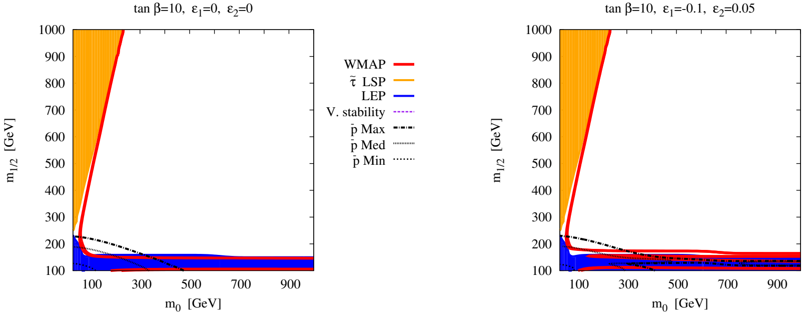


BMSSM



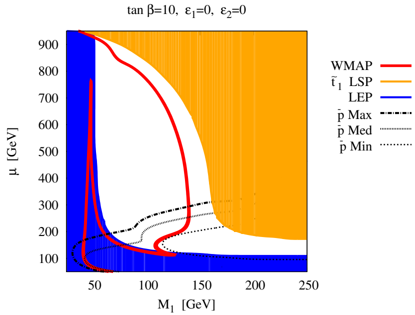
Antiprotons: Correlated Stop-Slepton masses - Higher tan β

MSSM **BMSSM**

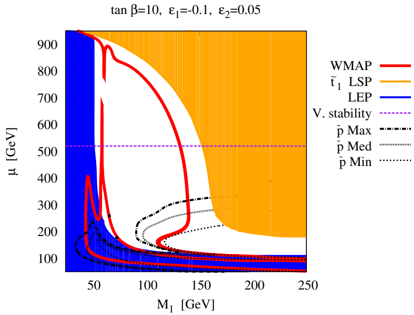


Antiprotons: Light stops, heavy sleptons - Higher tan β

MSSM

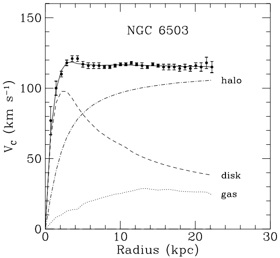


BMSSM



Why Dark Matter?

Galactic Rotation Curves



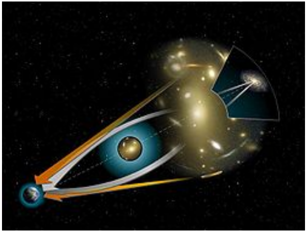
Normally, for $r > r_{\text{vis}}$ one would expect

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

instead

$$v(r) \approx \text{const}$$

Gravitational Lensing



Light bends differently than predicted from GR, if only luminous matter is taken into account.

And also:

- Primordial Nucleosynthesis
- Large Scale Structure

Cosmic Microwave Background

Blackbody radiation, ALMOST homogeneous. Small inhomogeneities due to DM structures during matter-radiation decoupling in the early universe. Only one cosmological model manages (so far!!!) to explain (almost) all observations: ΛCDM

- GR with non-vanishing Cosmological Constant
- Cold Dark Matter

WMAP 5-year results give

$$\Omega_{\text{DM}} h^2 = 0.1131 \pm 0.0034$$

whereas

$$\Omega_b h^2 = 0.02267 \pm 0.00058$$

So, what about radiative corrections?

The most important contributions come from the top/stop sector:

$$\delta_{m_h} \sim \frac{12}{16\pi}\left[\ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t}\right) + \frac{|X_t|^2}{m^2_{\tilde{t}_1} - m^2_{\tilde{t}_2}} \ln\left(\frac{m^2_{\tilde{t}_1}}{m^2_{\tilde{t}_2}}\right) + \frac{1}{2}\left(\frac{|X_t|^2}{m^2_{\tilde{t}_1} - m^2_{\tilde{t}_2}}\right)^2 \left(2 - \frac{m^2_{\tilde{t}_1} + m^2_{\tilde{t}_2}}{m^2_{\tilde{t}_1} - m^2_{\tilde{t}_2}} \ln\left(\frac{m^2_{\tilde{t}_1}}{m^2_{\tilde{t}_2}}\right)\right)\right]$$

where: $X_t = A_t - \mu \cot\beta$.

↬ So, either heavy stops, or strong LR stop mixing.
↬ But in principle, superpatners should be light and large LR mixing is not always obvious!

$\mapsto$ MSSM litlle hierarchy problem.

The moral lesson:

Experimental constraints on the lightest Higgs mass can be overcome, but restricting oneself to rather particular areas of the parameter space.

Corrections to the Higgs mass

We place ourselves in the regime where the NR operators can be treated as perturbations. This means:

$$m_h^2 \approx (m_h^{\text{tree}})^2 + \delta_{\text{loop}} m_h^2 + \delta_\epsilon m_h^2$$

with

$$\delta_\epsilon m_h^2 = 2v^2 \left(\epsilon_2 - 2\epsilon_1 \sin(2\beta) - \frac{2\epsilon_1 (m_A^2 + m_Z^2) \sin(2\beta) + \epsilon_2 (m_A^2 - m_Z^2) \cos^2(2\beta)}{\sqrt{(m_A^2 - m_Z^2)^2 + 4 m_A^2 m_Z^2 sin^2(2\beta)}} \right)$$

which can be $O(10^1)$GeV.

↬ For $\epsilon_1 \lesssim -0.1$ and small $\tan\beta$ we can fulfill the LEP constraints even with light and unmixed stops!
↬ This, in short, means evading the little hierarchy problem.
↬ Corrections important in the low $\tan\beta$ regime. As it augments, we fall back to the MSSM.
↬ (Not seen here) Contributions also to neutralino/chargino masses and couplings.