Supersymmetry in light of colliders and cosmology

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Outline

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4. B Physics
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7. Preferred Parameter Space
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Introduction

New physics appears as a necessity:

- cosmological problems: dark matter, dark energy
- hierarchy problem in the Standard Model
- unification of interactions

The hope is that LHC will find something new!

- New Physics!

Many theoretical models beyond the SM, within reach of the LHC, already exist in the market.

Supersymmetry

- Supersymmetry (SUSY) is the best motivated and studied candidate for physics beyond the Standard Model.
- It is based on a symmetry between fermions and bosons

Motivation of SUSY in Particle Physics

- Unification of gauge couplings
- Unification with gravity
- Solution of the hierarchy problem
- Candidate for Dark Matter
- Elegant...

MSSM

Minimal Supersymmetric extension of the Standard Model (MSSM): over 100 free parameters!

$\twoheadrightarrow$ phenomenological studies are unfeasible!!

SUSY breaking scenarios

- mSUGRA $\{m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sign}(\mu)\}$
- NUHM $\{$mSUGRA parameters + M_A and $\mu\}$
- AMSB $\{m_0,\ m_{3/2},\ \tan\beta,\ \mathrm{sign}(\mu)\}$
- GMSB $\{\Lambda,\ M_{\mathrm{mess}},\ N_5,\ c_{\mathrm{grav}},\ \tan\beta,\ \mathrm{sign}(\mu)\}$

$\looparrowright$ Get as much information as we can on these parameters!

SUSY Constraints

The most used constraints:

- Collider limits
- Electroweak precision tests
- The anomalous magnetic moment of the muon $(g-2)_\mu$

$$\Delta a_\mu \equiv a_\mu^{SUSY} \equiv a_\mu^{exp} - a_\mu^{SM} = (26 \pm 16) \times 10^{-10}$$

- B Physics
- Cosmological constraints, in particular from WMAP and the relic density

Experimental limits

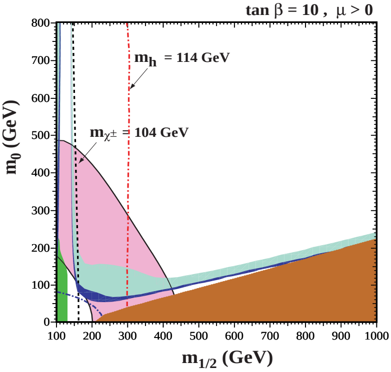
Lower bounds on sparticle masses in GeV:

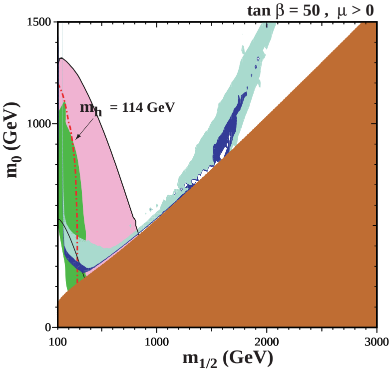
Particle	h^0	χ_1^0	$\tilde{l}_R$	$\tilde{\nu}_{e,\mu}$	$\chi_1^\pm$	$\tilde{t}_1$	$\tilde{g}$	$\tilde{b}_1$	$\tilde{\tau}_1$	$\tilde{q}_R$
Lower bound	111	46	88	43.7	67.7	92.6	195	89	81.9	250

Yao et al. J. Phys. G33 (2006)

Constraining the parameters

mSUGRA





Ellis *et al.*, Phys. Lett. B565, 176 (2003)

B Physics

- A good strategy to find the information on SUSY particles would be
  - to look at where the SM contributions are vanishingly small,
  - to study processes for which QCD corrections are known with high accuracy
  - and branching ratios can be measured in LHC at low luminosity.

$\Rightarrow$ Rare B decays are IDEAL CHOICES for that!

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Constraints from B Physics

- $b \longrightarrow s\gamma$ transition: very sensitive to new physics
  - forbidden at the tree level in SM and can only be induced via loop diagrams,
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  - already measured by BELLE and BABAR
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Effective Hamiltonian

The idea of $B \longrightarrow X_s\gamma$ decay begins with introducing an effective Hamiltonian:

$$\mathcal{H}_{eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{8} C_i(\mu) O_i(\mu)$$

$$\begin{cases}
O_1 = (\bar{s}_L \gamma_\mu T^a c_L)(\bar{c}_L \gamma^\mu T^a b_L) \qquad O_2 = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L) \\
O_3 = (\bar{s}_L \gamma_\mu b_L) \sum_q (\bar{q} \gamma^\mu q) \qquad O_4 = (\bar{s}_L \gamma_\mu T^a b_L) \sum_q (\bar{q} \gamma^\mu T^a q) \\
O_5 = (\bar{s}_L \gamma_{\mu_1} \gamma_{\mu_2} \gamma_{\mu_3} b_L) \sum_q (\bar{q} \gamma^{\mu_1} \gamma^{\mu_2} \gamma^{\mu_3} q) \\
O_6 = (\bar{s}_L \gamma_{\mu_1} \gamma_{\mu_2} \gamma_{\mu_3} T^a b_L) \sum_q (\bar{q} \gamma^{\mu_1} \gamma^{\mu_2} \gamma^{\mu_3} T^a q) \\
O_7 = \frac{e}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} b_R) F_{\mu\nu} \qquad O_8 = \frac{g}{16\pi^2} m_b (\bar{s}_L \sigma^{\mu\nu} T^a b_R) G^a_{\mu\nu}
\end{cases}$$

Wilson Coefficients

$$C_i^{eff}(\mu) = C_i^{(0)eff}(\mu) + \frac{\alpha_s(\mu)}{4\pi} C_i^{(1)eff}(\mu) + \cdots$$

The effective coefficients evolve according to their RGE:

$$\mu \frac{d}{d\mu} C_i^{eff}(\mu) = C_j^{eff}(\mu) \gamma_{ji}^{eff}(\mu)$$

driven by the anomalous dimension matrix $\hat{\gamma}^{eff}(\mu)$:

$$\hat{\gamma}^{eff}(\mu) = \frac{\alpha_s(\mu)}{4\pi} \hat{\gamma}^{(0)eff} + \frac{\alpha_s^2(\mu)}{(4\pi)^2} \hat{\gamma}^{(1)eff} + \ldots$$

Isospin Asymmetry

$$\Delta_{0-} \equiv \frac{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) - \Gamma(B^- \to K^{*-}\gamma)}{\Gamma(\bar{B}^0 \to \bar{K}^{*0}\gamma) + \Gamma(B^- \to K^{*-}\gamma)}$$

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$$\Delta_{0-} = \mathrm{Re}(b_d - b_u)\,.$$

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$$b_q = \frac{12\pi^2 f_B\, Q_q}{m_b\, T_1^{B\to K^*} a_7^c} \left(\frac{f_{K^*}^{\perp}}{m_b} K_1 + \frac{f_{K^*} m_{K^*}}{6\lambda_B m_B} K_2 \right)$$

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$$a_7^c = C_7 + \frac{\alpha_s(\mu) C_F}{4\pi} \Big(C_1(\mu) G_1(s_p) + C_8(\mu) G_8 \Big) + \frac{\alpha_s(\mu_h) C_F}{4\pi} \Big(C_1(\mu_h) H_1(s_p) + C_8(\mu_h) H_8 \Big)$$

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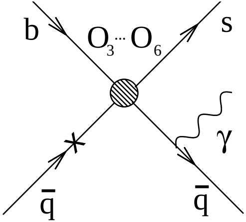
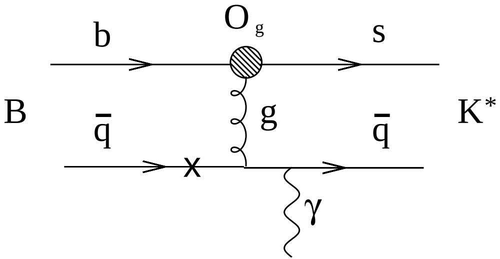
In the Standard Model: $\Delta_{0-} \simeq 8\%$

Kagan and Neubert, Phys. Lett. B 539, 227 (2002)
Bosch and Buchalla, Nucl. Phys. B 621, 459 (2002)

Contribution to Isospin Asymmetry



QCD penguin operators



Electro- and chromo-magnetic operators

Supersymmetric contributions

MSSM with minimal flavor violation (MFV)
$\hookrightarrow$ no more flavor/CP violation than in SM

Calculation of the coefficients at $\mu = M_W$:

$$C_i(\mu) = C_i^{W^\pm}(\mu) + C_i^{H^\pm}(\mu) + C_i^{\chi^\pm}(\mu)$$

Gómez et al. Phys. Rev. D74, 015015 (2006)
Degrassi et al. JHEP 12, 009 (2000)
Ciuchini et al. Nucl. Phys. B 534, 3 (1998)
Ciuchini et al. Nucl. Phys. B 527, 21 (1998)

SuperIso v2.0

A public C–program for calculating isospin asymmetry of $B \to K^*\gamma$ in supersymmetry.

- calculation of isospin asymmetry at NLO and inclusive branching ratio at NNLO,
- automatic calculation in mSUGRA, NUHM, AMSB and GMSB scenarios,
- compatible with the SUSY Les Houches Accord Format,
- modular program, with a well-defined structure.

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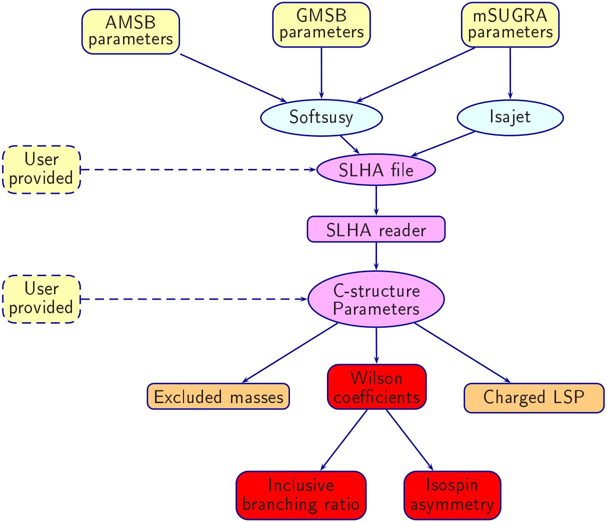
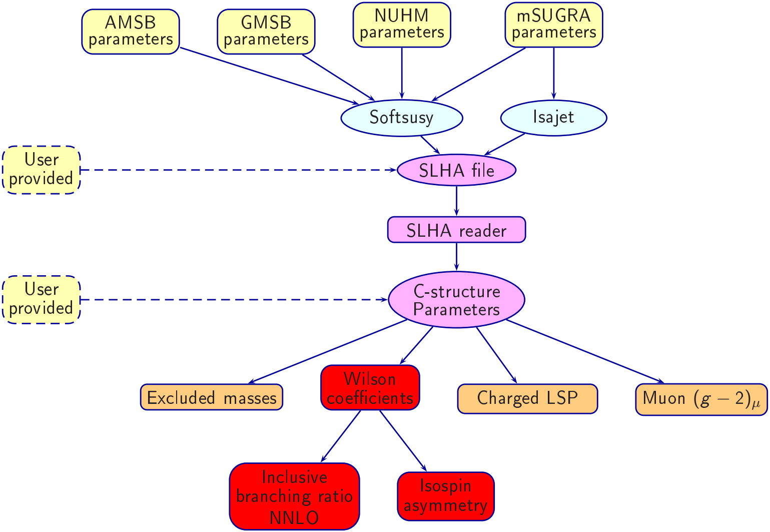
SuperIso v1.0



SuperIso v2.0



SuperIso v2.0

Can be downloaded from:

http://www3.tsl.uu.se/∼nazila/superiso/

Manual:

F. Mahmoudi, arXiv:0710.2067

available online on Comput. Phys. Commun.

For more information:

M. Ahmady & F. Mahmoudi, Phys. Rev. D75 (2007)

F. Mahmoudi, JHEP 0712, 026 (2007)

Experimental data

BABAR

$$\Delta_{0-} = +0.050 \pm 0.045(stat) \pm 0.028(syst) \pm 0.024(R^{+/0})$$

Aubert et al. (BABAR Collaboration) Phys. Rev. D72 (2005)

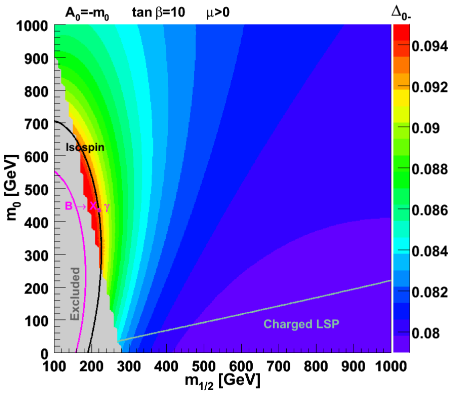
BELLE

$$\Delta_{0+} = +0.012 \pm 0.044(stat) \pm 0.026(syst)$$

Nakao et al. (BELLE Collaboration) Phys. Rev. D69 (2004)

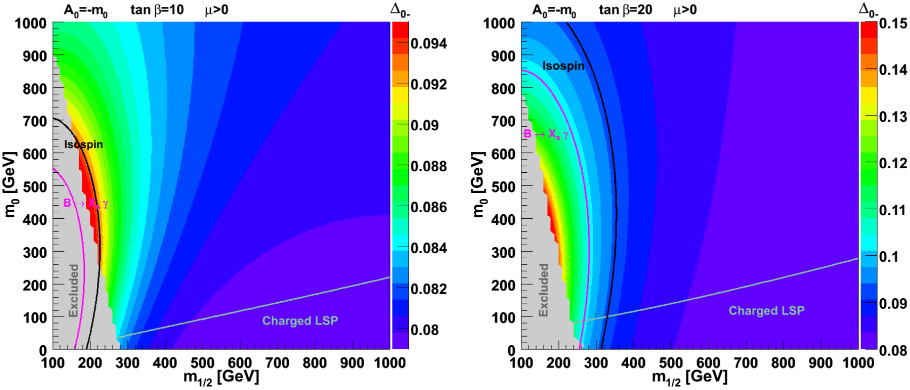
Allowed Region: $-0.018 < \Delta_{0-} < 0.093$

Results: mSUGRA



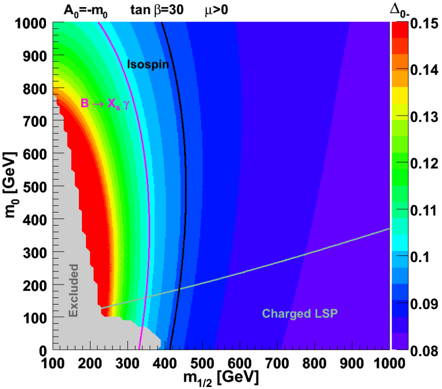
Ahmady & Mahmoudi, Phys. Rev. D75 (2007)

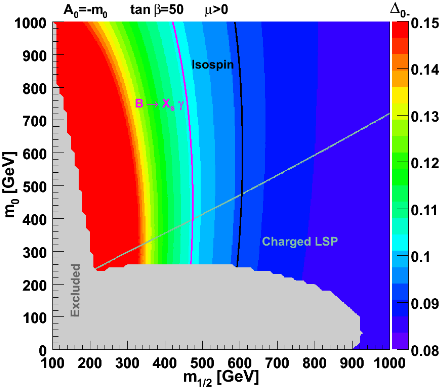
Results: mSUGRA



Ahmady & Mahmoudi, Phys. Rev. D75 (2007)

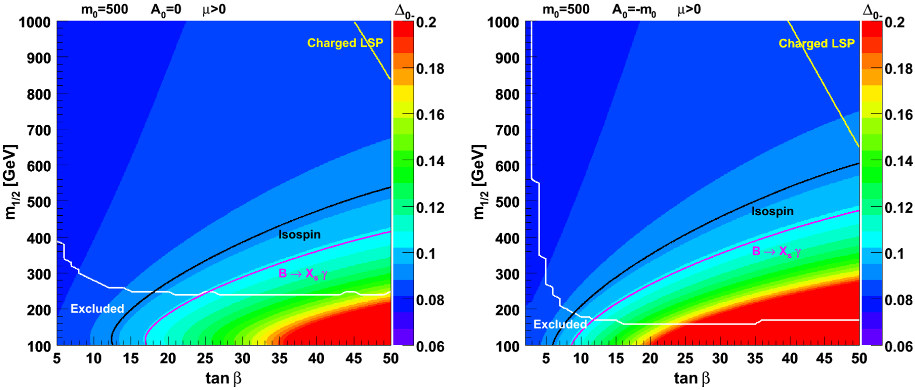
Results: mSUGRA





Ahmady & Mahmoudi, Phys. Rev. D75 (2007)

Results: mSUGRA



Ahmady & Mahmoudi, Phys. Rev. D75 (2007)

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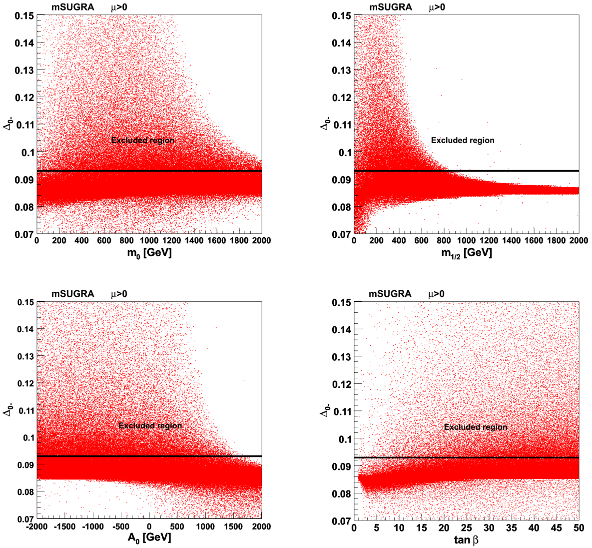
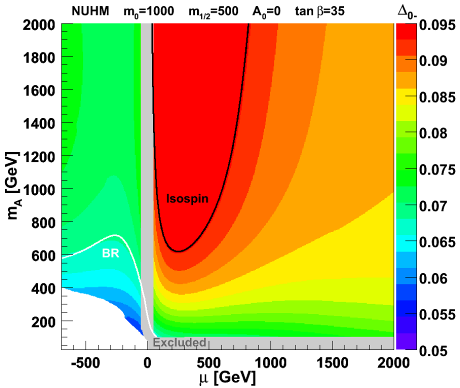


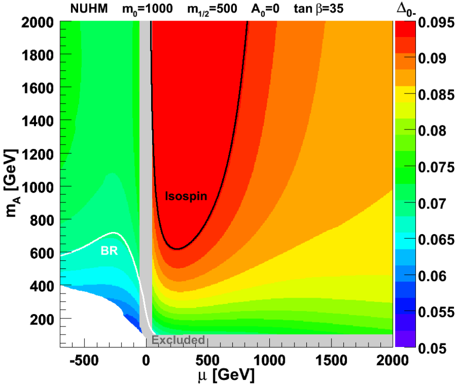
F. Mahmoudi, JHEP 0712, 026 (2007)

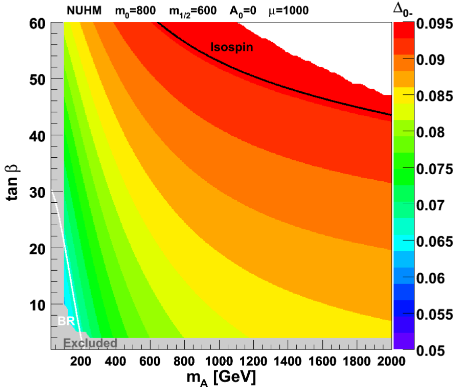
Results: NUHM



F. Mahmoudi, JHEP 0712, 026 (2007)

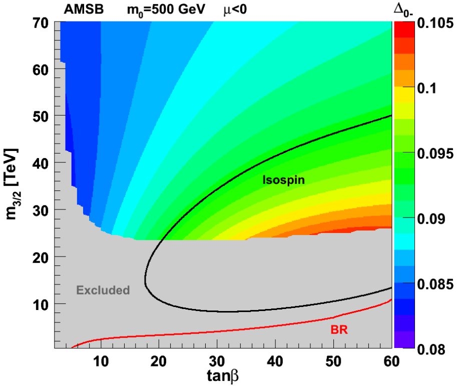
Results: NUHM





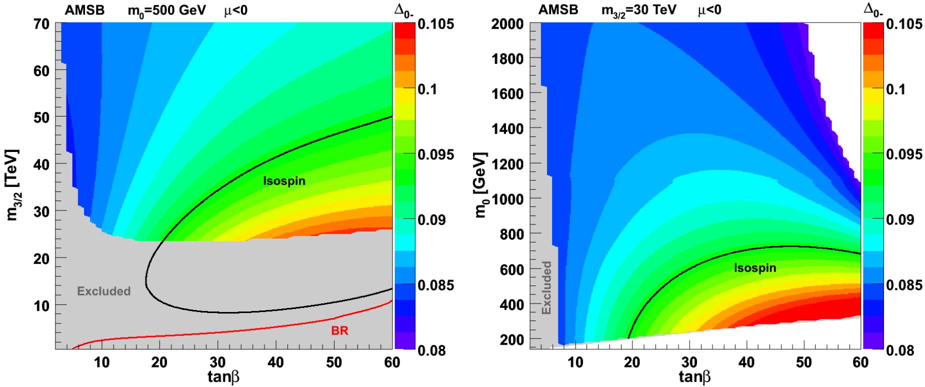
F. Mahmoudi, JHEP 0712, 026 (2007)

Results: AMSB



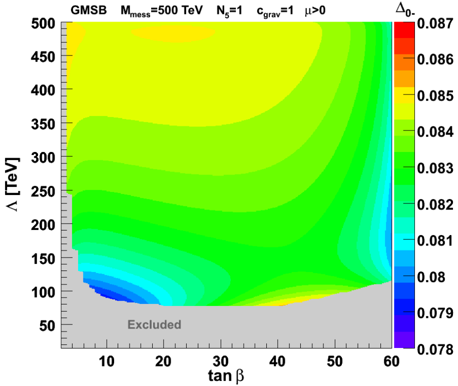
F. Mahmoudi, JHEP 0712, 026 (2007)

Results: AMSB



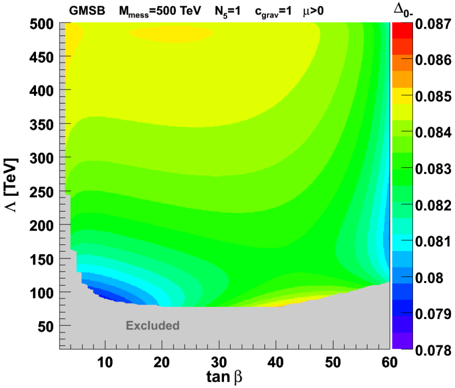
F. Mahmoudi, JHEP 0712, 026 (2007)

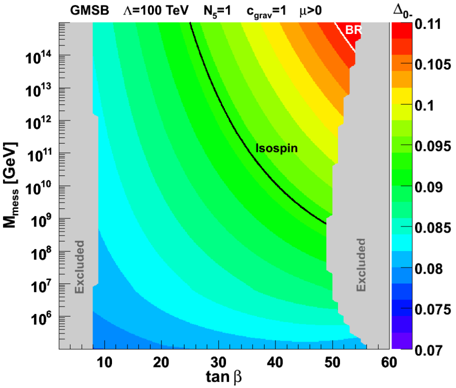
Results: GMSB



F. Mahmoudi, JHEP 0712, 026 (2007)

Results: GMSB





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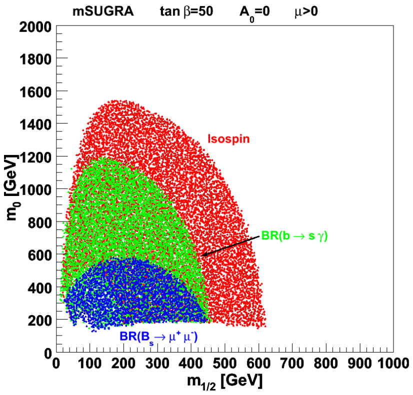

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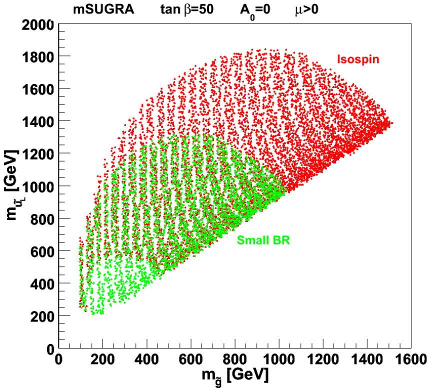
mSUGRA



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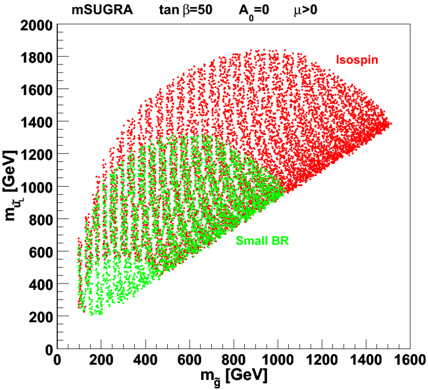
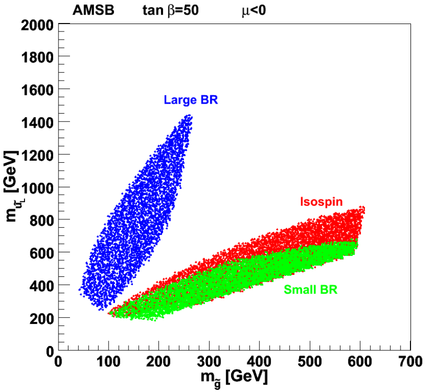


AMSB



F. Mahmoudi, JHEP 0712, 026 (2007)

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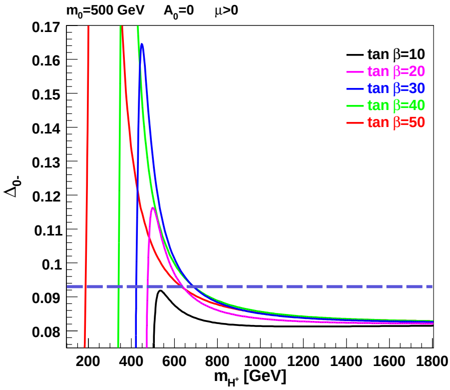

F. Mahmoudi, JHEP 0712, 026 (2007)

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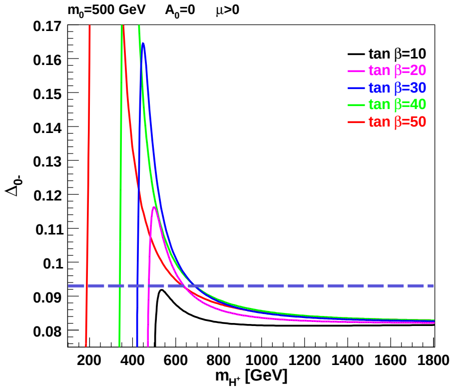
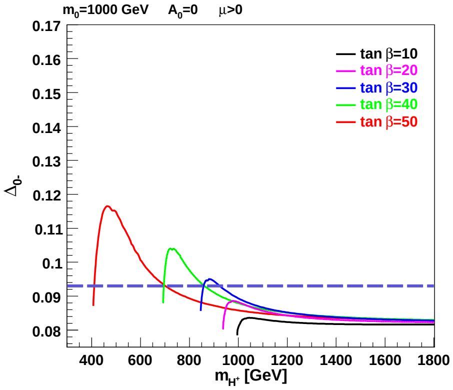




F. Mahmoudi, JHEP 0712, 026 (2007)

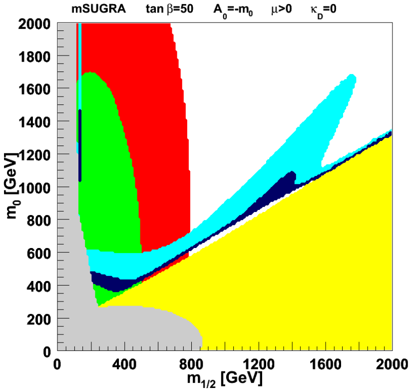
Let's add

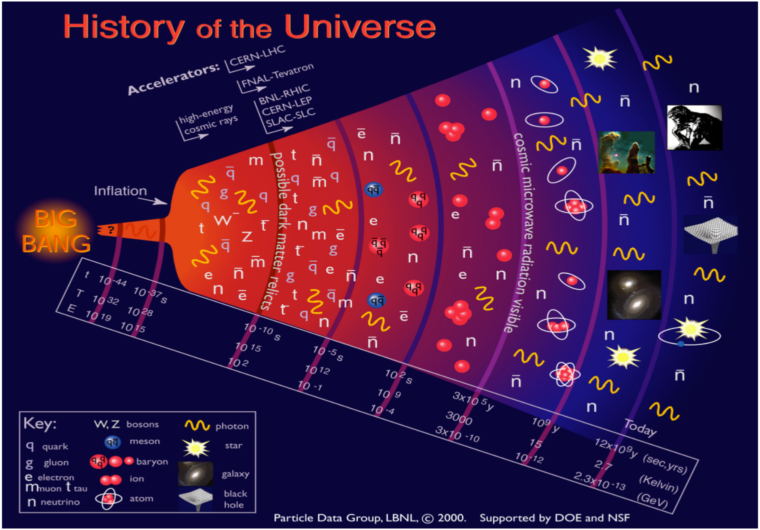
COSMOLOGY

Relic density

The recent observations of the WMAP satellite, combined with other cosmological data impose the dark matter density range at 95% C.L.:

$$0.088 < \Omega_{DM} h^2 < 0.12$$




History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Relic density

In the Standard Model of Cosmology:

- at and before nucleosynthesis time, the expansion is dominated by radiation

$$H^2 = 8\pi G/3 \times \rho_{\text{rad}}$$

- the evolution of the number density of supersymmetric particles follows the equation

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\text{eff}} v \rangle (n^2 - n_{\text{eq}}^2)$$

- solving this equation leads to relic density of SUSY particles in the present Universe

Problem: we have no good constraints on the pre-nucleosynthesis era!

$\Rightarrow$ the expansion rate can be different from what expected in standard cosmology...

Relic density

The expansion rate modification can be parametrized by adding a new density ρ_D: ($T_0 \sim$ nucleosynthesis temperature)

$$H^2 = 8\pi G/3 \times (\rho_{\rm rad} + \rho_D) \text{ with } \rho_D(T) = \rho_D(T_0)(T/T_0)^{n_D}$$

- $n_D = 4$: radiation-like behavior
- $n_D = 6$: behavior of a scalar field dominated by its kinetic term
- $n_D > 6$: extra-dimension effects

We introduce $\kappa_D = \rho_D(T_0)/\rho_{\rm rad}(T_0)$

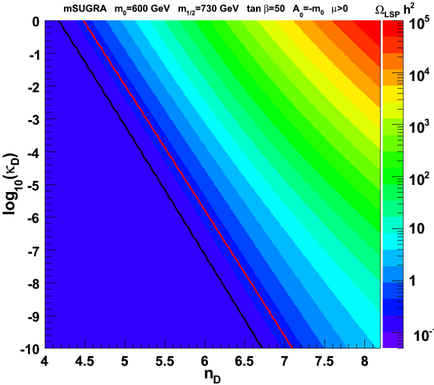
The modified expansion is in agreement with the observations provided

$$n_D > 4 \quad \text{and} \quad \kappa_D < 1$$

Such a modification can drastically change the calculated relic density!

Relic density

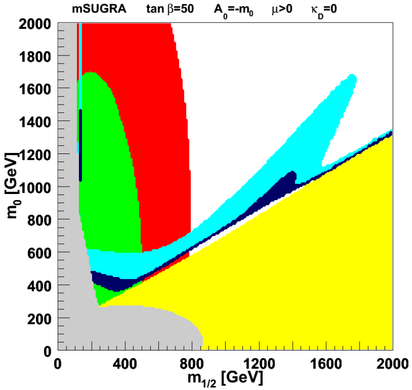
For a mSUGRA test-point with a relic density of $\Omega_{LSP}h^2 = 0.105$ (favored by WMAP) in the usual cosmological model, in the expansion rate modified scenario the computed relic density is changed:



Arbey & Mahmoudi, arXiv:0803.0741

Relic density

Displacement of the WMAP limits in mSUGRA



Large even for a small expansion rate modification!

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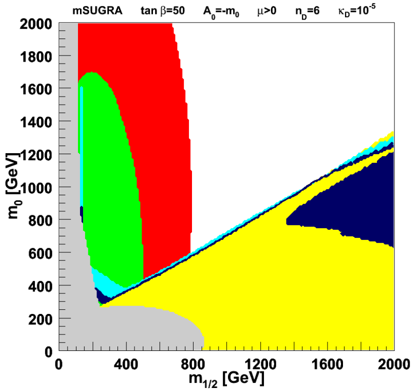

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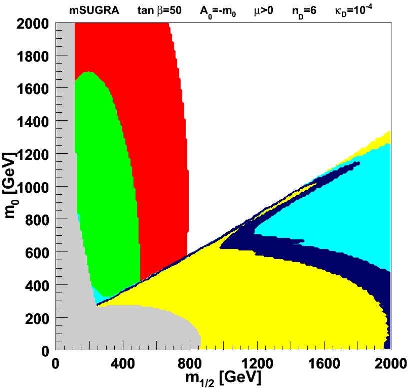

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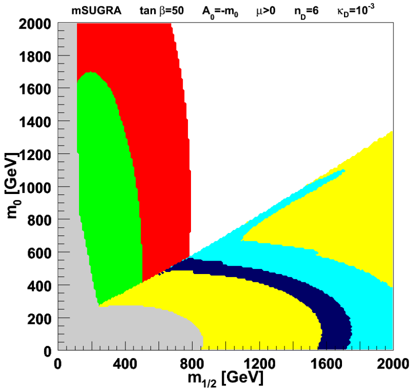

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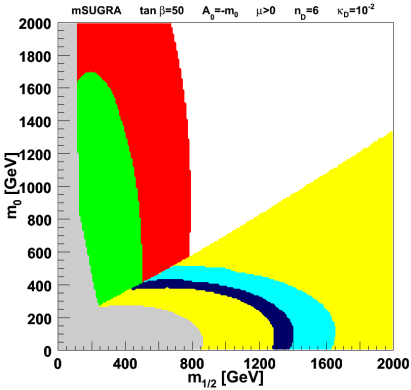

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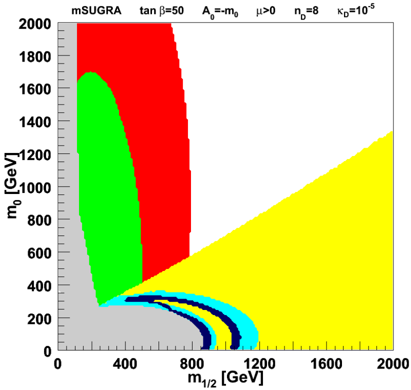

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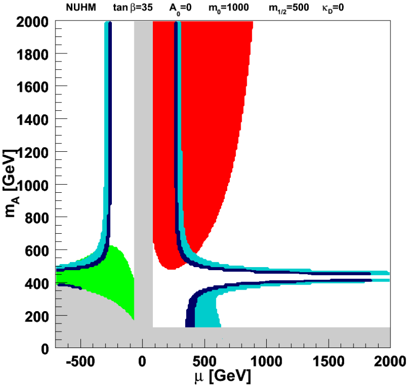
Relic density

Displacement of the WMAP limits in NUHM



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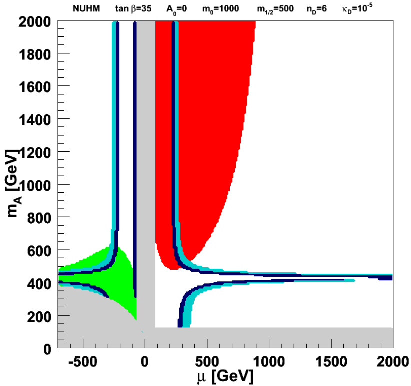

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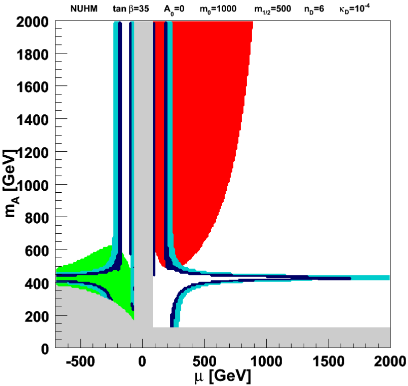

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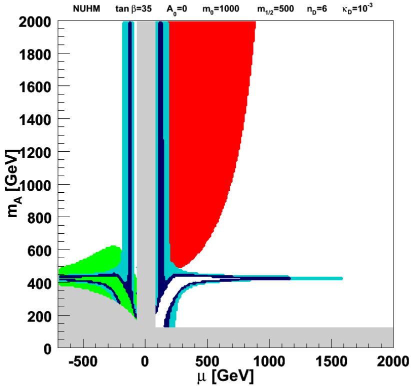

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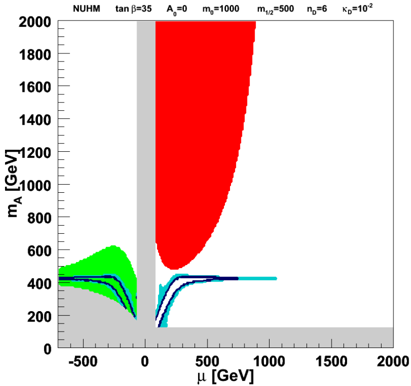

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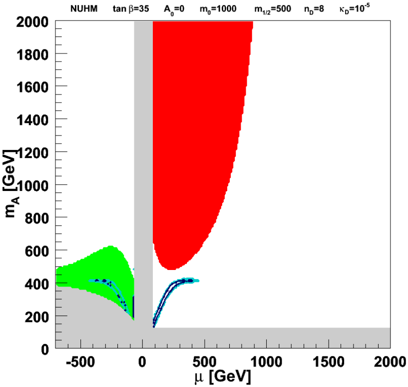

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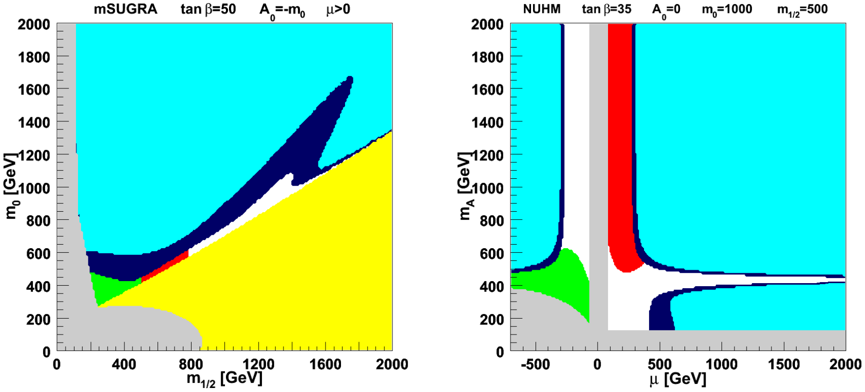
Relic density

Consequence: using the lower limit of the WMAP limit to constrain the relic density is unsafe!

Only the upper limit should be used: $\Omega_{DM} h^2 < 0.12$!



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Conclusion

- Indirect constraints and in particular flavor physics are essential to restrict new physics parameters
- That will become even more interesting when combined with LHC data
- Isospin asymmetry provides new valuable information
- Cosmological data should be taken with a grain of salt
- This kind of analysis should be generalized to more new physics scenarios

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SUPERSYMMETRY!

Backup

Constraints

At 95% C.L.,

- $Br(B \to X_s\gamma)$: $2.07 \times 10^{-4} < \mathcal{B}(b \to s\gamma) < 4.84 \times 10^{-4}$
- Isospin asymmetry: $-0.018 < \Delta_{0-} < 0.093$
- $Br(B_s \to \mu^+\mu^-)$: $\mathcal{B}(B_s \to \mu^+\mu^-) < 0.97 \times 10^{-7}$
- WMAP: $0.088 < \Omega_{DM} h^2 < 0.12$
- Older WMAP: $0.1 < \Omega_{DM} h^2 < 0.3$