Constraints on supersymmetry, from flavor physics and cosmology

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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.

SUSY Constraints

The most used constraints:

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

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

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

Direct constraints

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)

Indirect constraints

SUSY models can be divided into two categories:

- R-parity conserving models
- R-parity violating models

R-parity conserving models can also be divided according to how SUSY breaks:

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

In these models, SUSY effects always appear in loops

$\rightarrow$ difficult to detect unless the SM process is absent or loop-mediated.
$\rightarrow$ Good places to look for: $B-\bar{B}$ mixing, $b \rightarrow s\gamma$, ...

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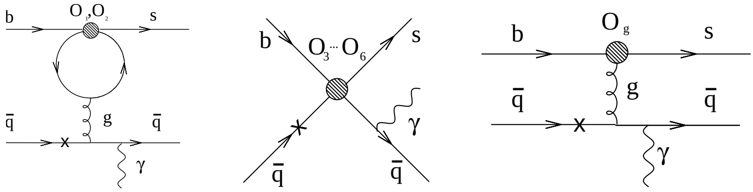
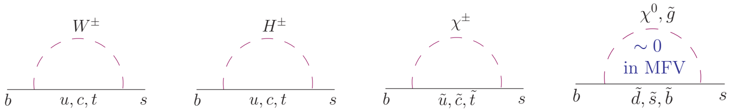
$b \to s\gamma$ transitions



Contributing loops:



$b \to s\gamma$ transitions

- Charged Higgs loop always adds constructively to the SM penguin
- Chargino loops can add constructively or destructively
  - if constructive, great enhancement in the BR($b \to s\gamma$)
    - BR is the interesting observable
  - if destructive, other interesting observables
    - CP asymmetry

$$A_{CP} = \frac{BR(\bar{B} \to X_s\gamma) - BR(B \to X_s\gamma)}{BR(\bar{B} \to X_s\gamma) + BR(B \to X_s\gamma)}$$

    - **Isospin asymmetry**

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

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Effective Hamiltonian

The calculation of $b \to s\gamma$ observables 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

Two main steps:

- Calculating $C_i^{eff}(\mu)$ at scale $\mu \sim M_W$ by requiring matching between the effective and full theories

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

- Evolving the $C_i^{eff}(\mu)$ to scale $\mu \sim m_b$ using the RGE:

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

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

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

Inclusive Branching ratio

$$\mathcal{B}[\bar{B} \to X_s \gamma]_{E_\gamma > E_0} = \mathcal{B}[\bar{B} \to X_c e \bar{\nu}]_{\rm exp} \left| \frac{V_{ts}^* V_{tb}}{V_{cb}} \right|^2 \frac{6\alpha_{\rm em}}{\pi C} \left[P(E_0) + N(E_0) \right]$$

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$$C = \left| \frac{V_{ub}}{V_{cb}} \right|^2 \frac{\Gamma[\bar{B} \to X_c e\bar{\nu}]}{\Gamma[\bar{B} \to X_u e\bar{\nu}]}$$

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$$\begin{aligned} P(E_0) &= P^{(0)}(\mu_b) + \alpha_s(\mu_b) \left[P_1^{(1)}(\mu_b) + P_2^{(1)}(E_0, \mu_b) \right] \\ &+ \alpha_s^2(\mu_b) \left[P_1^{(2)}(\mu_b) + P_2^{(2)}(E_0, \mu_b) + P_3^{(2)}(E_0, \mu_b) \right] + \mathcal{O}\left(\alpha_s^3(\mu_b) \right) \end{aligned}$$

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$$\begin{aligned} P^{(0)}(\mu_b) &= \left(C_7^{(0)\rm eff}(\mu_b) \right)^2 \\ P_1^{(1)}(\mu_b) &= 2 C_7^{(0)\rm eff}(\mu_b) C_7^{(1)\rm eff}(\mu_b) \\ P_1^{(2)}(\mu_b) &= \left(C_7^{(1)\rm eff}(\mu_b) \right)^2 + 2 C_7^{(0)\rm eff}(\mu_b) C_7^{(2)\rm eff}(\mu_b) \end{aligned}$$

Misiak and Steinhauser, hep-ph/0609241

Inclusive Branching ratio

- Theoretical values for the SM:
  NLO (Gambino & Misiak '02): $\mathcal{B}[\bar{B} \to X_s\gamma] = (3.60 \pm 0.30) \times 10^{-4}$

  NNLO (Misiak & Steihauser '07): $\mathcal{B}[\bar{B} \to X_s\gamma] = (3.15 \pm 0.23) \times 10^{-4}$
  or (Becher & Neubert '07): $\mathcal{B}[\bar{B} \to X_s\gamma] = (2.98 \pm 0.26) \times 10^{-4}$
  or (Gambino & Giordano '08): $\mathcal{B}[\bar{B} \to X_s\gamma] = (3.30 \pm 0.24) \times 10^{-4}$

- Experimental values:
  PDG 2002: $\mathcal{B}[\bar{B} \to X_s\gamma] = (3.30 \pm 0.40) \times 10^{-4}$

  HFAG 2008: $\mathcal{B}[\bar{B} \to X_s\gamma] = (3.52 \pm 0.25) \times 10^{-4}$

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Big changes in both the theoretical and experimental values of the branching ratio!

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

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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)

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

SuperIso v2.1

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,
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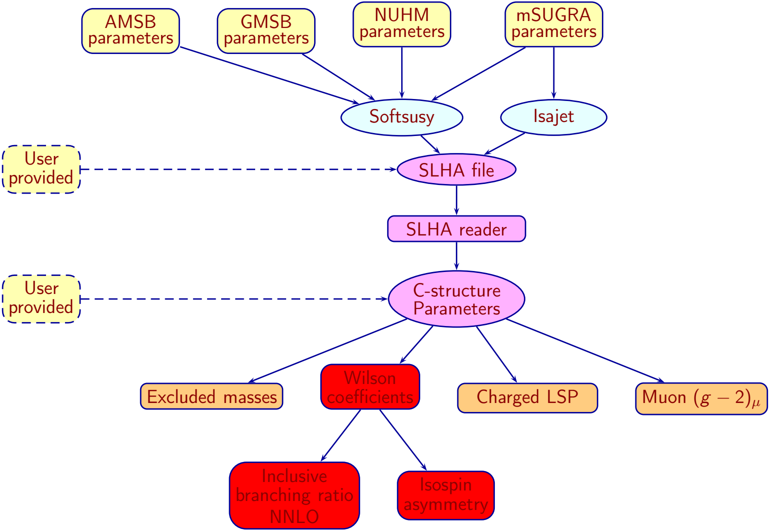


SuperIso v2.1

Can be downloaded from:

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

Manual:

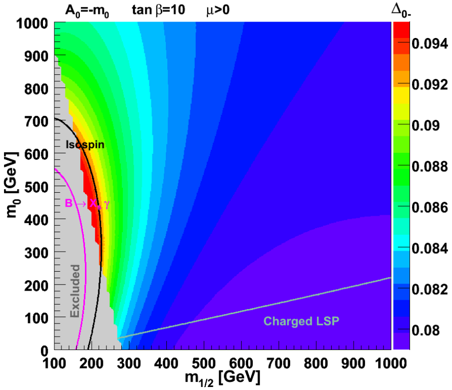
F. Mahmoudi, arXiv:0710.2067, Comput. Phys. Commun. 178, 745 (2008)

For more information:

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

F. Mahmoudi, JHEP 0712, 026 (2007)

Results: mSUGRA



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

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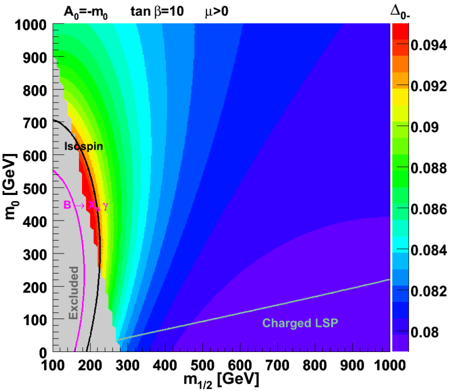

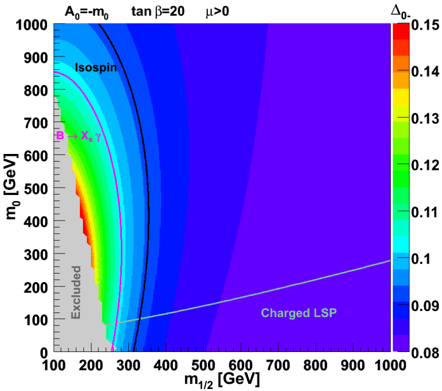

Ahmady & Mahmoudi, Phys. Rev. D75 (2007)

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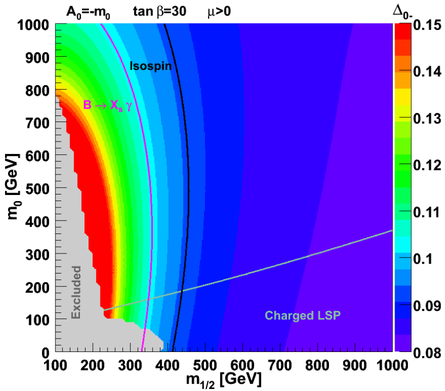

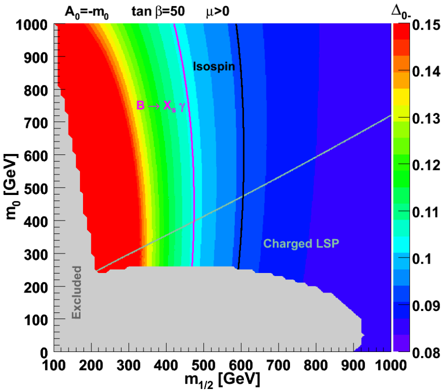

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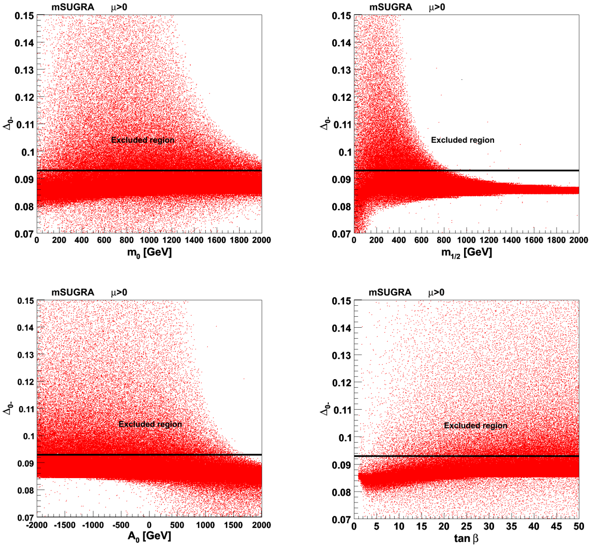
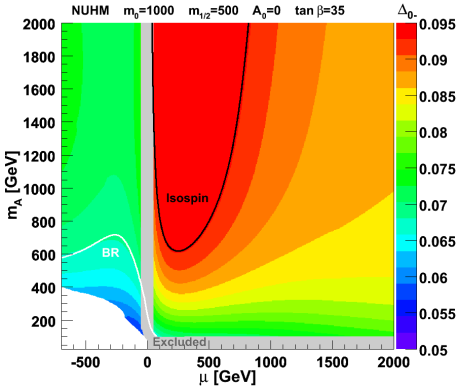


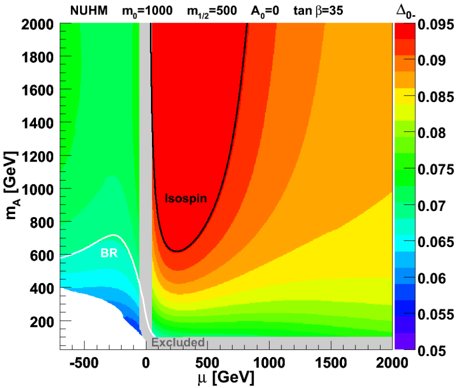
F. Mahmoudi, JHEP 0712, 026 (2007)

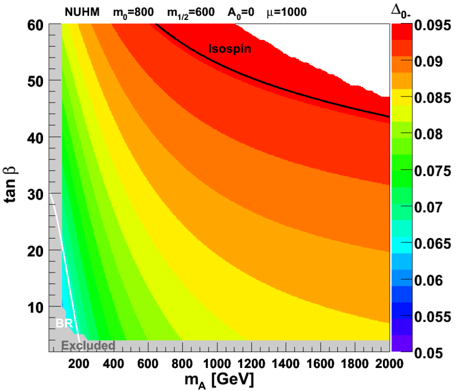
Results: NUHM



F. Mahmoudi, JHEP 0712, 026 (2007)

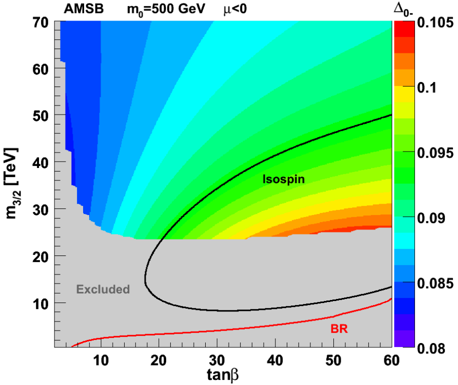
Results: NUHM





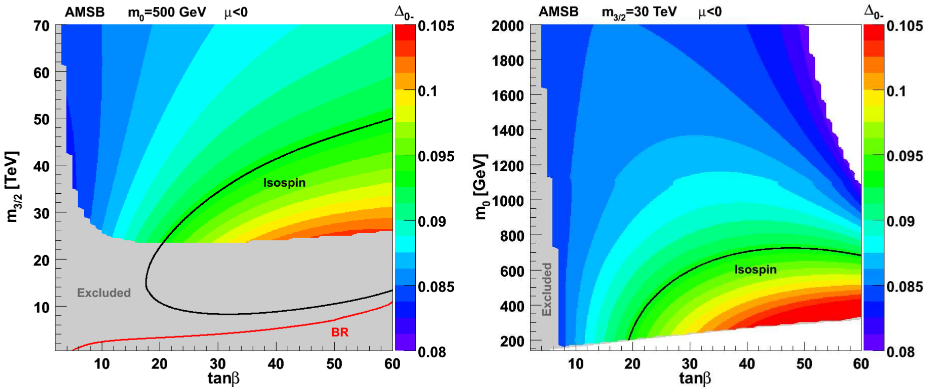
F. Mahmoudi, JHEP 0712, 026 (2007)

Results: AMSB



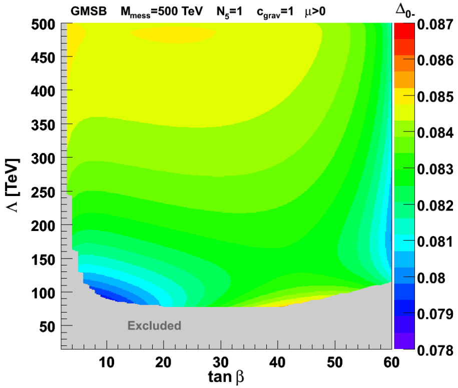
F. Mahmoudi, JHEP 0712, 026 (2007)

Results: AMSB



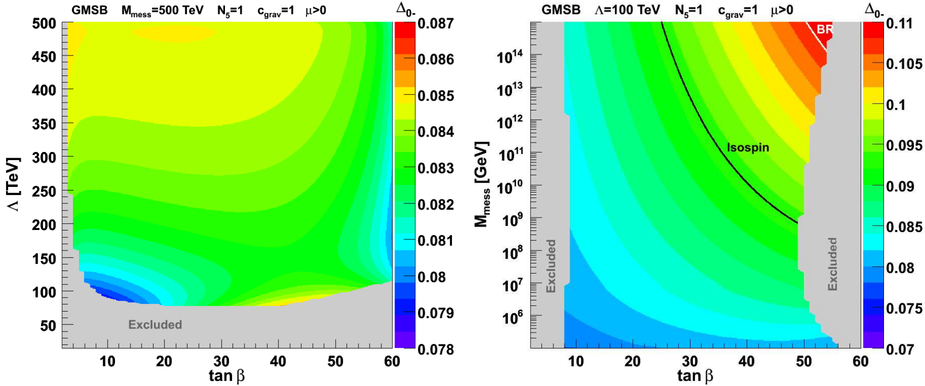
F. Mahmoudi, JHEP 0712, 026 (2007)

Results: GMSB



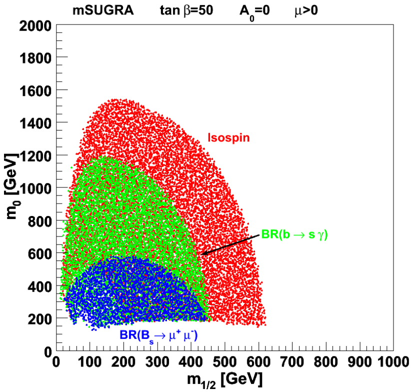
F. Mahmoudi, JHEP 0712, 026 (2007)

Results: GMSB



F. Mahmoudi, JHEP 0712, 026 (2007)

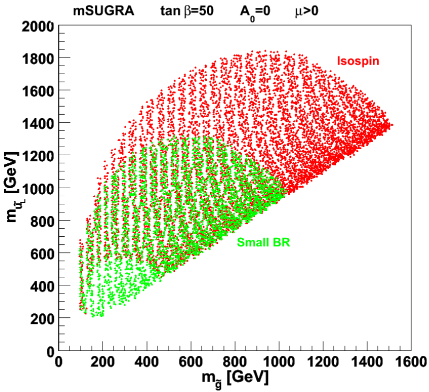
Results



F. Mahmoudi, JHEP 0712, 026 (2007)

Results

mSUGRA



F. Mahmoudi, JHEP 0712, 026 (2007)

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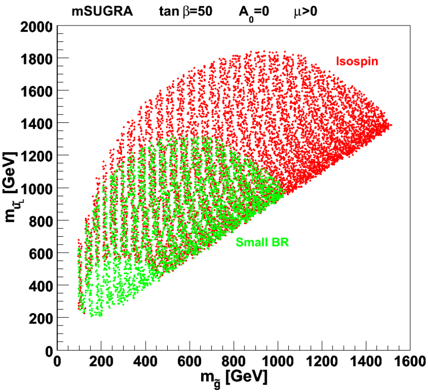
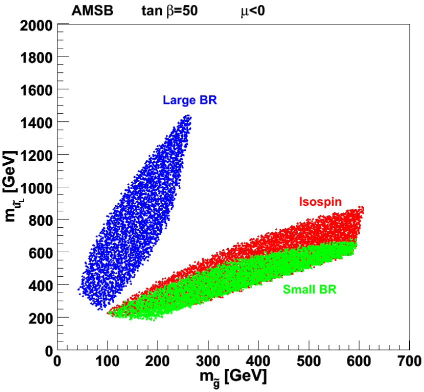


AMSB



F. Mahmoudi, JHEP 0712, 026 (2007)

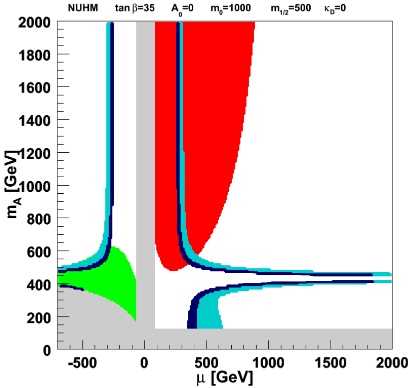
Let's add

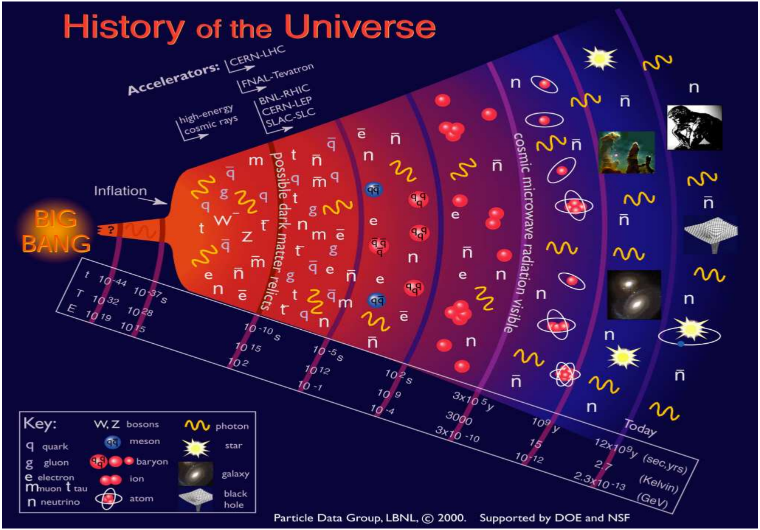
COSMOLOGY

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

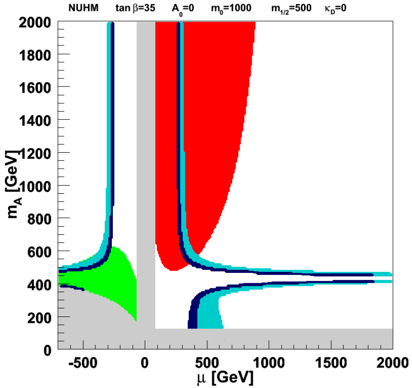
The modified expansion is in agreement with the observations provided

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

Such a modification can drastically change the calculated relic density!

Relic density

Displacement of the WMAP limits in NUHM



Large even for a small expansion rate modification!

Arbey & Mahmoudi, arXiv:0803.0741

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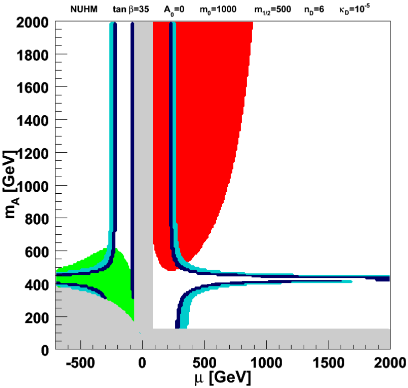
Displacement of the WMAP limits in NUHM



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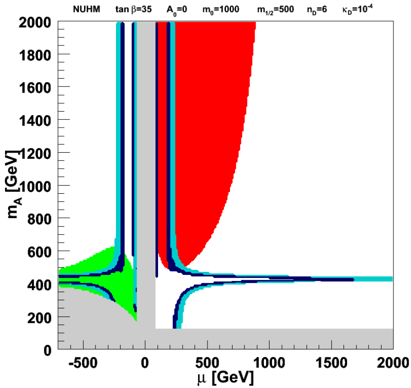

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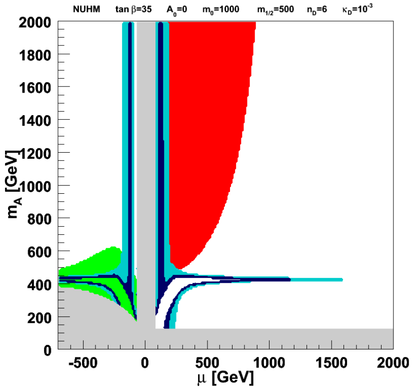

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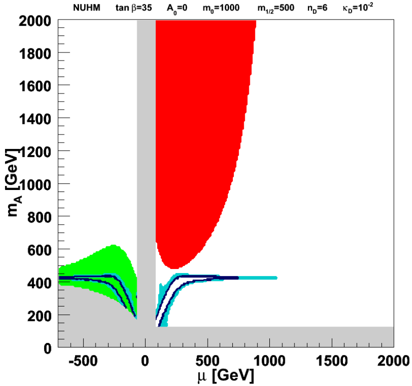

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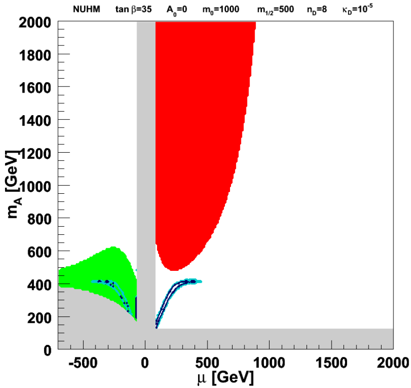


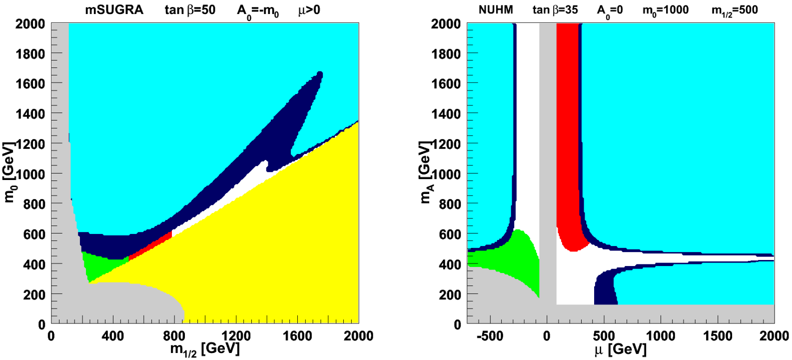
Large even for a small expansion rate modification!

Arbey & Mahmoudi, arXiv:0803.0741

Relic density

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

→ The lower limit should be disregarded: $\Omega_{DM} h^2 < 0.12$!



Arbey & Mahmoudi, arXiv:0803.0741

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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Backup

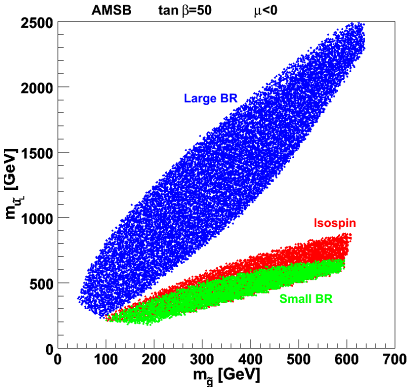
Constraints

At 95% C.L.,

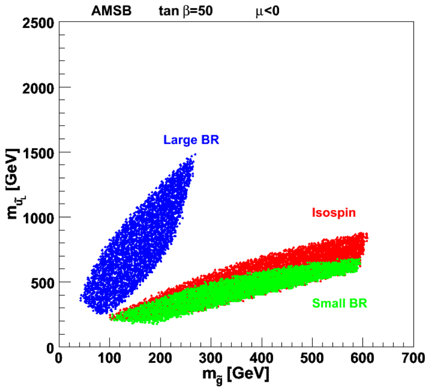
- $Br(B \to X_s\gamma)$: $2.07 \times 10^{-4} < \mathcal{B}(b \to s\gamma) < 4.84 \times 10^{-4}$
- Isospin asymmetry: $-0.018 < \Delta_{0-} < 0.093$
- $Br(B_s \to \mu^+\mu^-)$: $\mathcal{B}(B_s \to \mu^+\mu^-) < 0.97 \times 10^{-7}$
- WMAP: $0.088 < \Omega_{DM}h^2 < 0.12$
- Older WMAP: $0.1 < \Omega_{DM}h^2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

NLO vs. NNLO

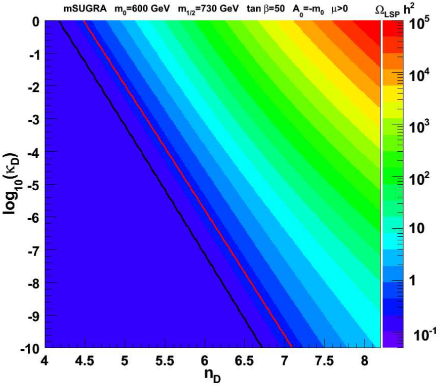
NLO



NNLO



For a mSUGRA test-point with a relic density of $\Omega_{\rm LSP} h^2 = 0.105$ (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