DARK MATTER, NEW PHYSICS AND COSMOLOGY IN THE LIGHT OF LHC

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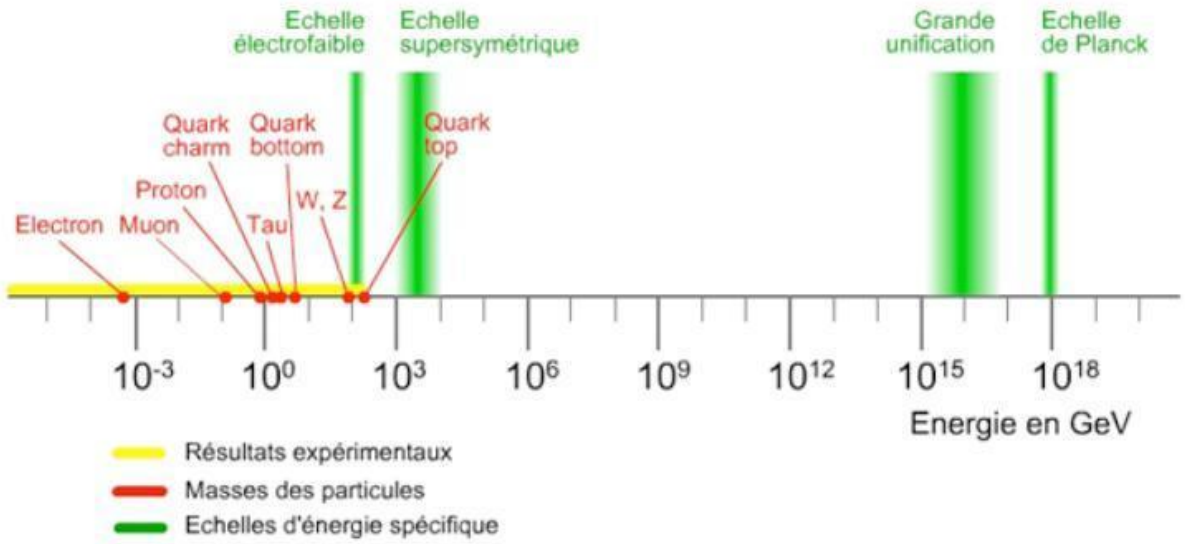
Outline

Introduction

- The energy scales



- SUSY : extension of SM to the TeV scale.
  LHC : Machine at the TeV scale which describes new physics.

Definition

- SUSY : symmetry relates bosons and fermions.
- Q generator of SUSY algebra :
  $\bar{Q}|boson\rangle = |fermion\rangle$ & $Q|fermion\rangle = |boson\rangle$
- generators create a new state called superpartner, it corresponds to a supersymmetric particle.

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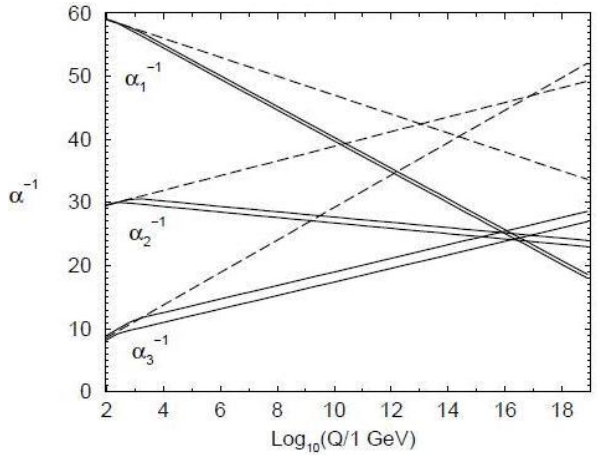
- generators create a new state called superpartner, it corresponds to a supersymmetric particle.
- SUSY algebra contains anti-commutators because of fermionic generators. (super Poincaré algebra)

$$\begin{aligned}
\{Q_\alpha, \bar{Q}_{\dot{\alpha}}\} &= 2\sigma^{\mu}_{\alpha,\dot{\alpha}} P_\mu \\
\{Q_\alpha, Q_\beta\} &= \{\bar{Q}_{\dot{\alpha}}, \bar{Q}_{\dot{\beta}}\} = 0 \\
[Q_\alpha, P^\mu] &= [\bar{Q}_{\dot{\beta}}, P^\mu] = 0 \\
[Q_\alpha, M_{\mu\nu}] &= [\bar{Q}_{\dot{\beta}}, M_{\mu\nu}] = 0
\end{aligned}$$

Motivations in particle physique

- Unification of gauge couplings :



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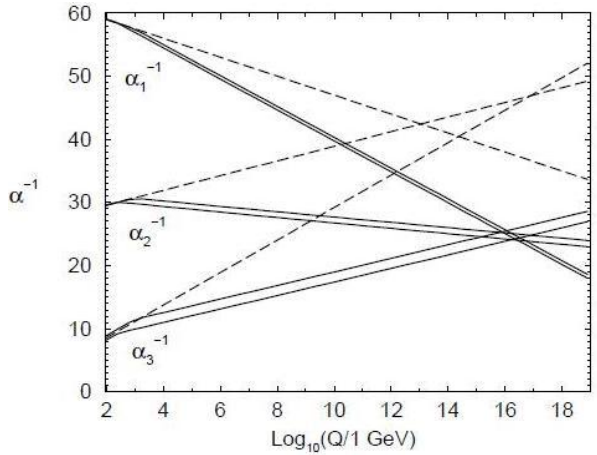
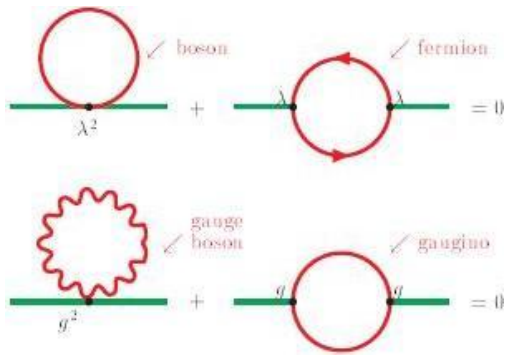


- Solution of the hierarchy problem :



Description of gravity

- The graviton, hypothetic particle mediates the gravity, have a spin 2 and the others bosons (photon, gluons, W et Z) have a spin 1 $\Rightarrow$ they correspond to different representations of Poincaré Algebra.
- **Supersymmetric Transformations** $\Rightarrow$
  spin 2 $\rightarrow$ spin 3/2 $\rightarrow$ spin 1 $\rightarrow$ spin 1/2 $\rightarrow$ spin 0.

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- Infinitesimal Transformations $\delta_\epsilon = \epsilon^\alpha Q_\alpha$, $\bar{\delta}_{\bar{\epsilon}} = \bar{Q}_{\dot{\alpha}} \bar{\epsilon}^{\dot{\alpha}}$, $\Rightarrow$
  $\{\delta_\epsilon, \bar{\delta}_{\bar{\epsilon}}\} = 2(\epsilon \sigma^\mu \bar{\epsilon}) P_\mu$
- Local coordinate transformation $\epsilon = \epsilon(x) \Rightarrow$ Supergravity (*local version of SUSY*).

Field content

- The content of MSSM

Superfield	*Bosons*	*Fermions*	$SU_c(3)$	$SU_L(2)$	$U_Y(1)$
Gauge					
G^a	*gluon* g^a	*gluino* $\tilde{g}^a$	8	1	0
V^k	*Weak* $W^k(W^{\pm}, Z)$	*wino, zino* $\tilde{w}^k(\tilde{w}^{\pm}, \tilde{z})$	1	3	0
V'	*Hypercharge* $B(\gamma)$	*bino* $\tilde{b}(\tilde{\gamma})$	1	1	0
Matter					
L_i	sleptons $\tilde{L}_i = (\tilde{\nu}, \tilde{e})_L$	leptons $L_i = (\nu, e)_L$	1	2	−1
E_i	$\tilde{E}_i = \tilde{e}_R$	$E_i = e_R$	1	1	2
Q_i	squarks $\tilde{Q}_i = (\tilde{u}, \tilde{d})_L$	quarks $Q_i = (u, d)_L$	3	2	1/3
U_i	$\tilde{U}_i = \tilde{u}_R$	$U_i = u_R^c$	3^*	1	−4/3
D_i	$\tilde{D}_i = \tilde{d}_R$	$D_i = d_R^c$	3^*	1	2/3
Higgs					
H_1	Higgses H_1	higgsinos $\tilde{H}_1$	1	2	−1
H_2	H_2	$\tilde{H}_2$	1	2	1

Lagrangian of MSSM

- $$\mathcal{L} = \mathcal{L}_{SUSY} + \mathcal{L}_{Breaking} = \mathcal{L}_{Gauge} + \mathcal{L}_{Yukawa} + \mathcal{L}_{Breaking}$$
- superpotentiel which reproduces Yukawa interaction in SM

$$W = \epsilon_{ij}(y^U_{ab} Q^j_a U^c_b H^i_2 + y^D_{ab} Q^j_a D^c_b H^i_1 + y^L_{ab} L^j_a E^c_b H^i_1 + \mu H^i_1 H^j_2)$$

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- such as SM but : fields $\rightarrow$ superfields.
  Difference : term which describes the Higgs mixing (absent in SM because we have 1 Higgs doublet).

R-parity

- R-parity symmetry

$$R = (-1)^{3(B-L)+2S}$$

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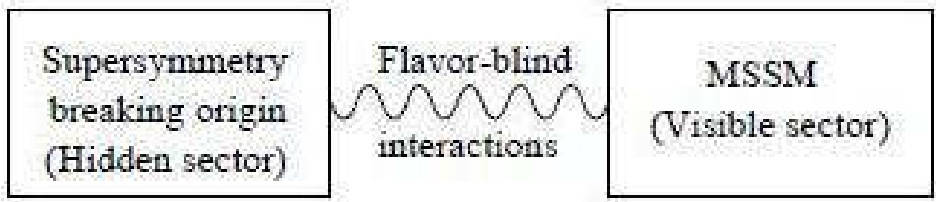
- Consequences of R-parity conservation :
  1. Superparticles are created by pairs.
  2. The **LSP** is absolutely stable.
  3. The **LSP** is an excellent candidate for dark matter, and it is in general a *neutralino*.

Breaking mechanisms

- The breaking occurs in a hidden sector and the ordinary matter will be in the visible sector



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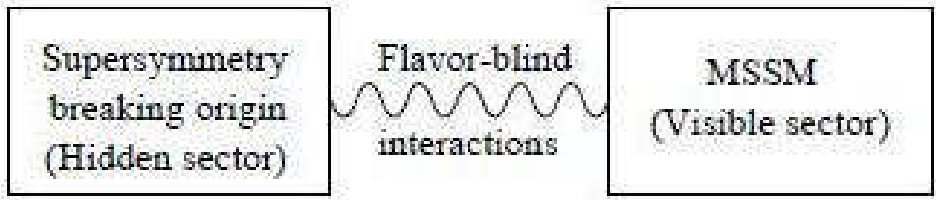

- 4 important mechanisms for generating the SUSY breaking :
  - Gravity mediation (SUGRA) ;
  - Gauge mediation ;
  - Anomaly mediation ;
  - Gaugino mediation.

Soft terms for breaking SUSY

- universality hypothesis $\Rightarrow$ only 5 parameters which define the mass scale :

$$\mu, m_0, m_{1/2}, \text{ A et B} \leftrightarrow \tan\beta = \frac{v_2}{v_1}$$

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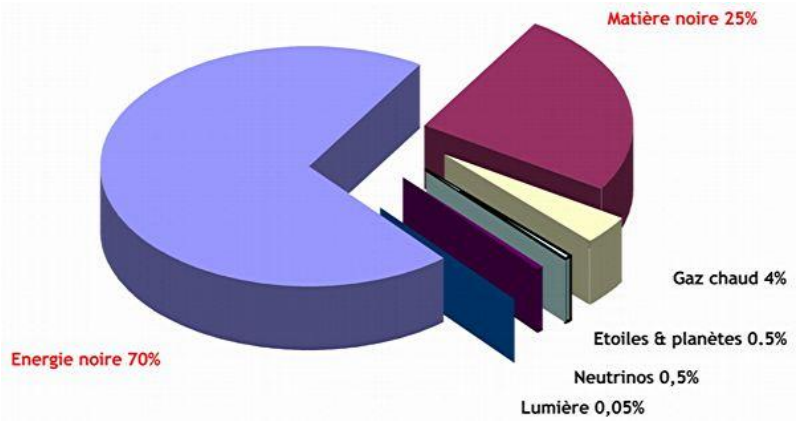
$$\begin{aligned} -\mathcal{L}_{Breaking} &= m_0^2 \sum_i |\varphi_i|^2 \\ &+ \left(\frac{1}{2} m_{1/2} \sum_\alpha \tilde{\lambda}_\alpha \tilde{\lambda}_\alpha + B[\mu H_1 H_2] \right. \\ &\left. + A[y^U_{ab} \tilde{Q}_a \tilde{U}^c_b H_2 + y^D_{ab} \tilde{Q}_a \tilde{D}^c_b H_1 + y^L_{ab} \tilde{L}_a \tilde{E}^c_b H_1] + h.c. \right. \end{aligned}$$

(1)

General Description

- existence of DM : direct and indirect detection (rotation curves of galaxies ...)



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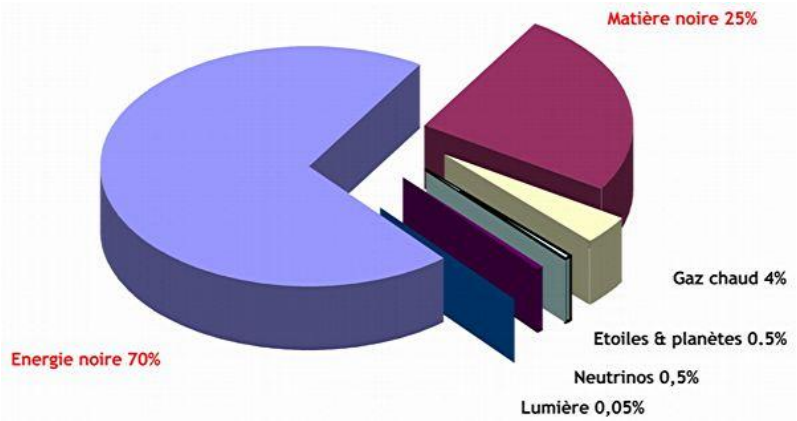

- Types of non-baryonic DM : Cold DM formed by WIMP, Hot DM formed by relativistic light particles (neutrinos) and Warm DM sterile neutrino is a good candidate.

CDM & WIMP

- For WIMP : no candidates in SM, SUSY offers an excellent candidate : the neutralino (**LSP**).

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- The evolution of density number $n_\chi(t)$ is described by the Boltzmann equation :

$$\frac{dn_\chi}{dt} + 3Hn_\chi = - < \sigma_a v > [(n_\chi)^2 - (n_\chi^{eq})^2]$$

- The relic density is proportionally inverse to the cross section $\Omega_\chi h^2 \sim \frac{1}{<\sigma_a v>}$.

LSP

- Gravity mediation : LSP is the lightest *neutralino* $\tilde{\chi}_1^0$.
- Gauge mediation : LSP is the *gravitino* $\tilde{G}$ that is produced by the decay from **NLSP**.($\tilde{\chi}_1^0 \to \gamma\tilde{G}, h\tilde{G}, Z\tilde{G}$ or $\tilde{l}_R \to \tau\tilde{G}$).
- Anomaly mediation : LSP is $\tilde{\chi}_1^0$ (decaying from NLSP) or $\tilde{\nu}_L$ (decaying from chargino $\tilde{\chi}^+ \to \tilde{\nu}l$).

SUPERISO

- SuperIso is a public C program that is :
  - dedicated to the flavour physics observable calculations
  - aimed to provide everyone the possibility to do the calculations in different models
  - based on the most precise calculations publicly available in the literature

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- Models : SM, 2HDM, MSSM (mSUGRA, AMSB, NUHM, GMSB), NextMSSM.

SUPERISO RELIC

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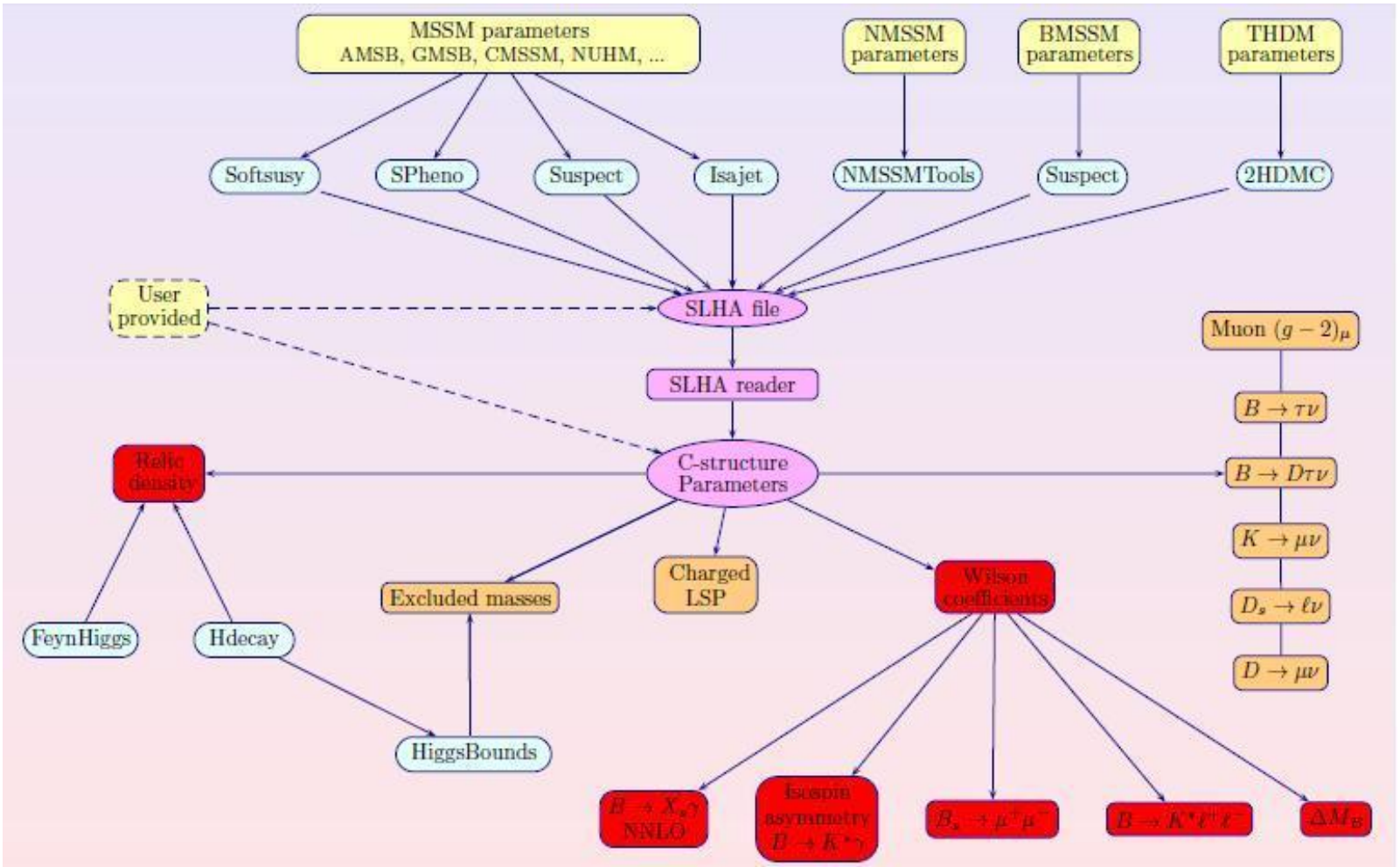
- Concept of the code consists of :
  - Automatized computation of flavour observables and relic density in SUSY
  - Flexible particle physics model implementation (mSUGRA, NUHM, AMSB, ...)
  - Flexible cosmological model implementation (dark energy, dark entropy, ...)
  - Publicly available on http ://superiso.in2p3.fr/relic

SUPERISO RELIC

- Structure of the code consists of :
  - Generation of a SLHA file with Isajet, Softsusy, Spheno or Suspect
  - Initialization of the variables using the SLHA file
  - Generation of additional Higgs sector variables with FeynHiggs or Hdecay
  - Calculation of W_{eff} with Fortran functions
  - Calculation of $< \sigma_{eff} v >$ with C functions
  - Solving of the Boltzmann equation with C functions
  - Computation of the other SuperIso observables

How it works ?


MSSM parameters
AMSB, GMSB, CMSSM, NUHM, ...
NMSSM parameters
BMSSM parameters
THDM parameters
Softsusy
SPheno
Suspect
Isajet
NMSSMTools
Suspect
2HDMC
User provided
SLHA file
Muon $(g-2)_\mu$
SLHA reader
$B \to \tau\nu$
Relic density
C-structure Parameters
$B \to D\tau\nu$
$K \to \mu\nu$
Excluded masses
Charged LSP
Wilson coefficients
$D_s \to \ell\nu$
FeynHiggs
Hdecay
$D \to \mu\nu$
HiggsBounds
$\bar{B} \to X_s\gamma$ NNLO
Isospin asymmetry $B \to K^*\gamma$
$B_s \to \mu^+\mu^-$
$B \to K^*\ell^+\ell^-$
ΔM_B

Observables

1. CHARGED LSP
2. EXCLUDED MASS
3. DARK MATTER
4. BRANCHING RATIO $\bar{B} \to X_s\gamma$
5. ISOSPIN ASYMMETRY $B \to K^*\gamma$
6. MUON ANOMALOUS MAGNETIC MOMENT
7. BRANCHING RATIO $B_s \to \mu^+\mu^-$
8. BRANCHING RATIO $B_u \to \tau\nu_\tau$
9. BRANCHING RATIO $B \to D\tau\nu_\tau$

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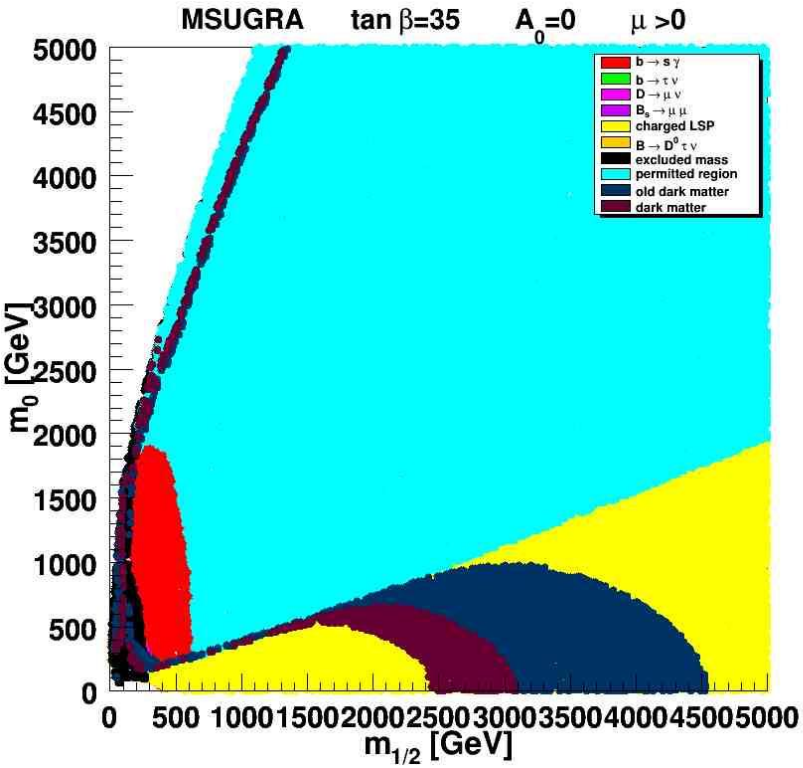
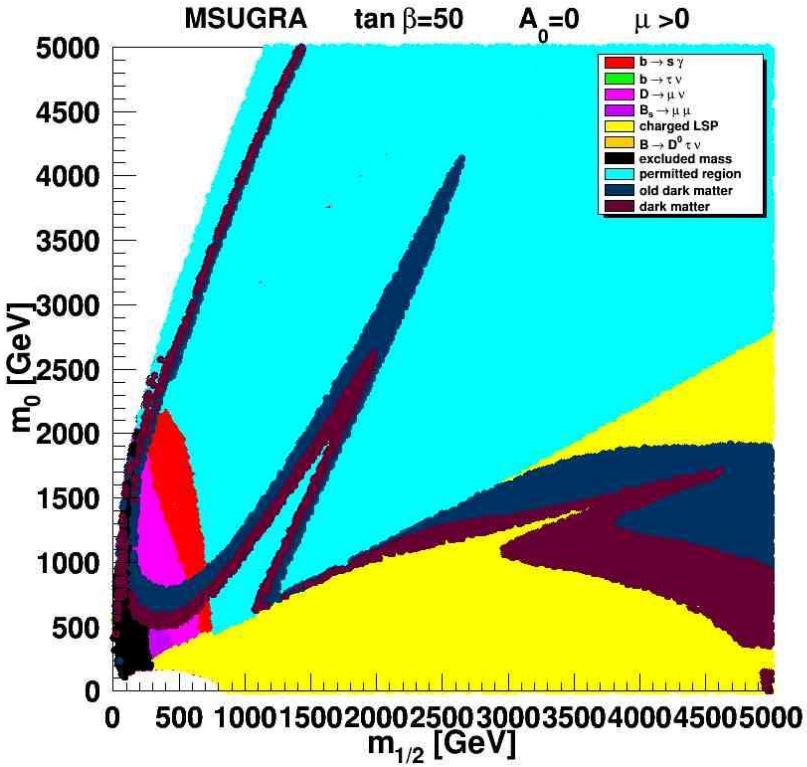
- Important model in particle physics needs only 4 input parameters (m_0, $m_{1/2}$, tanβ and A_0) and a (μ) sign to determine the phenomenology at low energy.
- ISAJET, SOFTSUSY, SPHENO and SUSPECT are 4 generators of spectra $\Rightarrow$ numericaly calculation of RGE, deduction of particle masses and mixing matrices $\Rightarrow$ calculation of decay widths, branching ratio, cross section of production...

mSUGRA results (SOFTSUSY)





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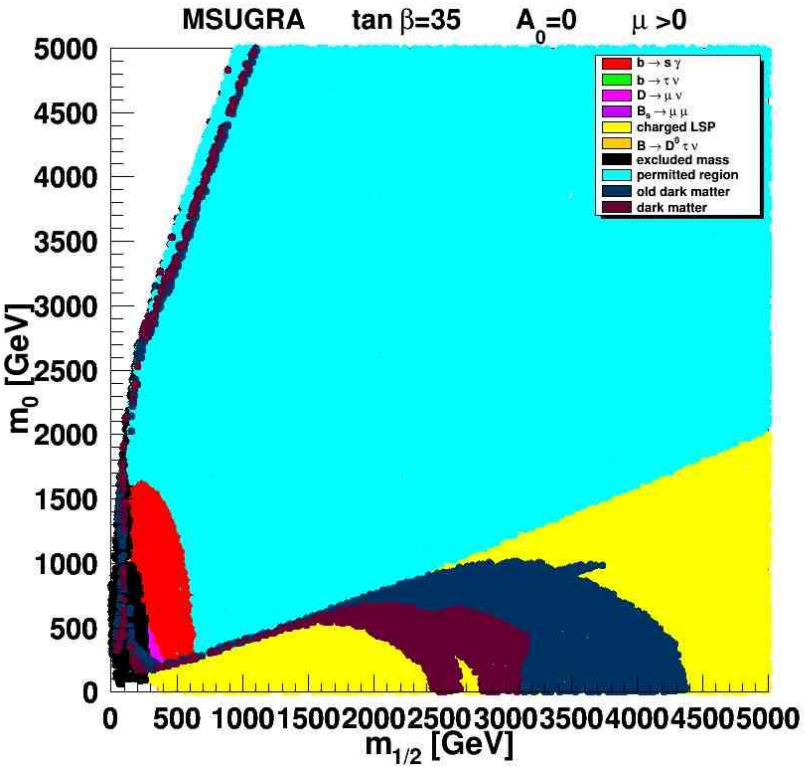
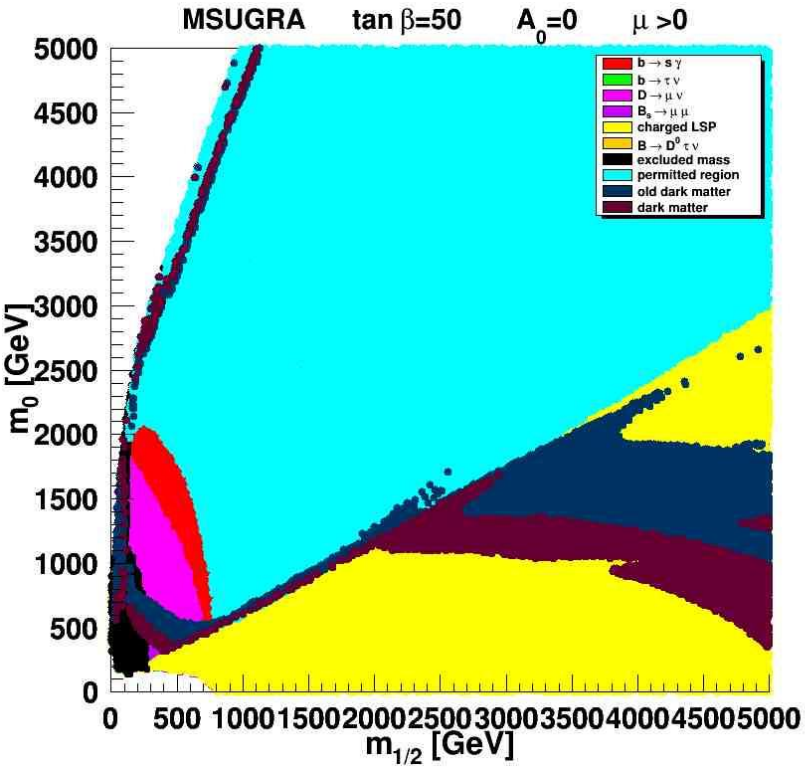
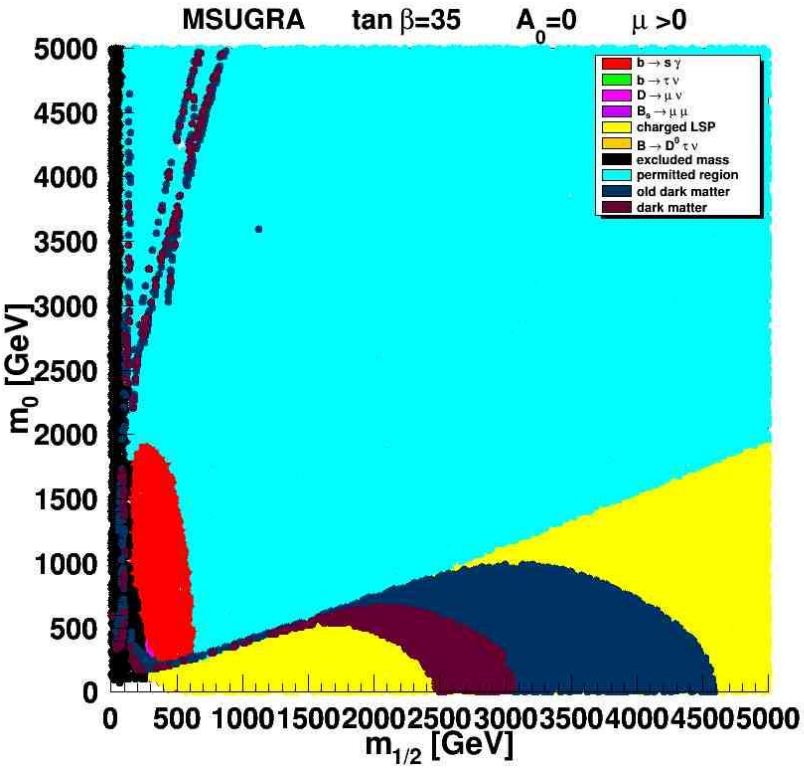
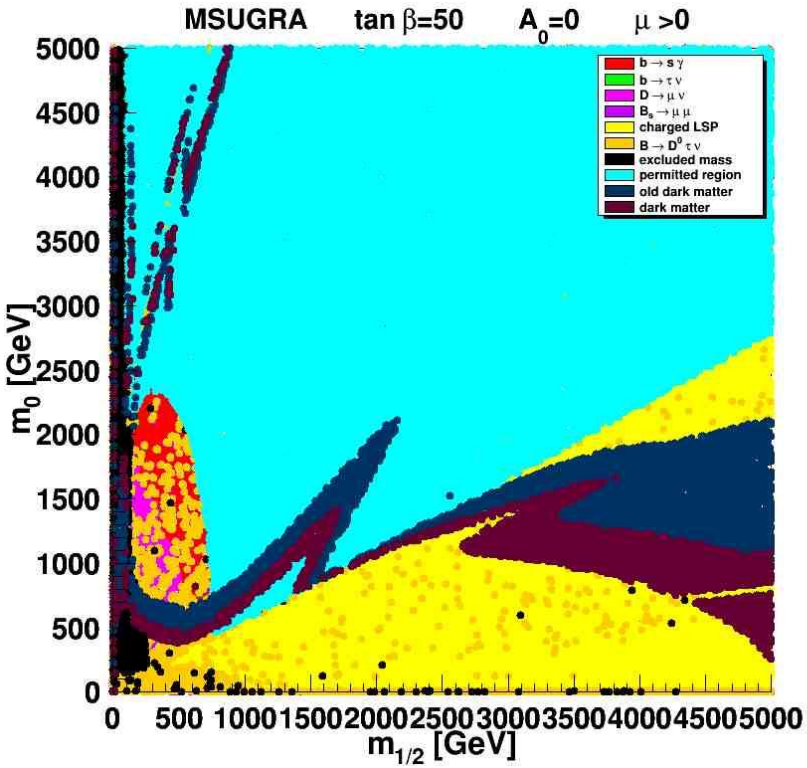


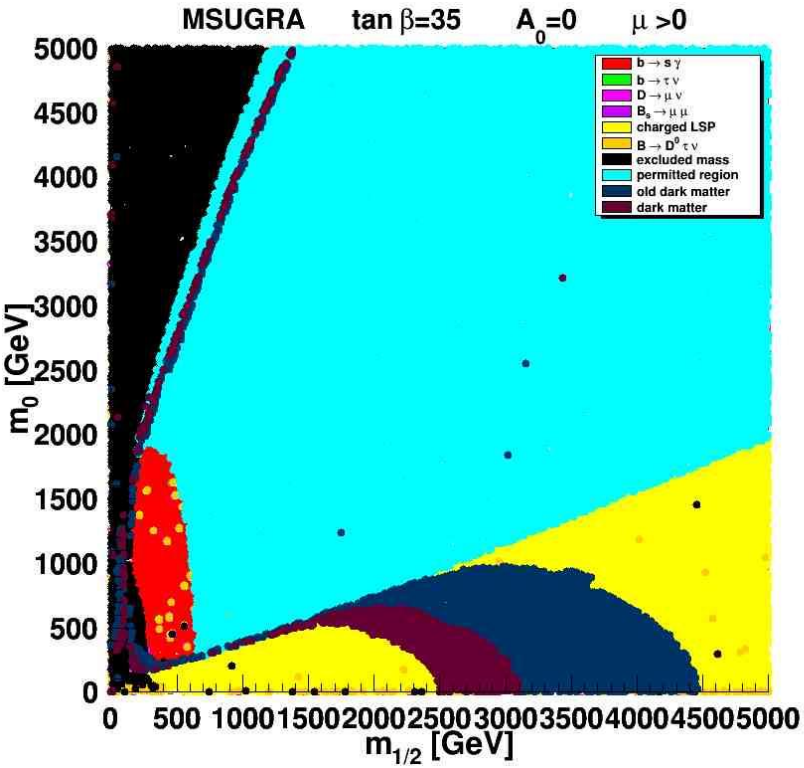


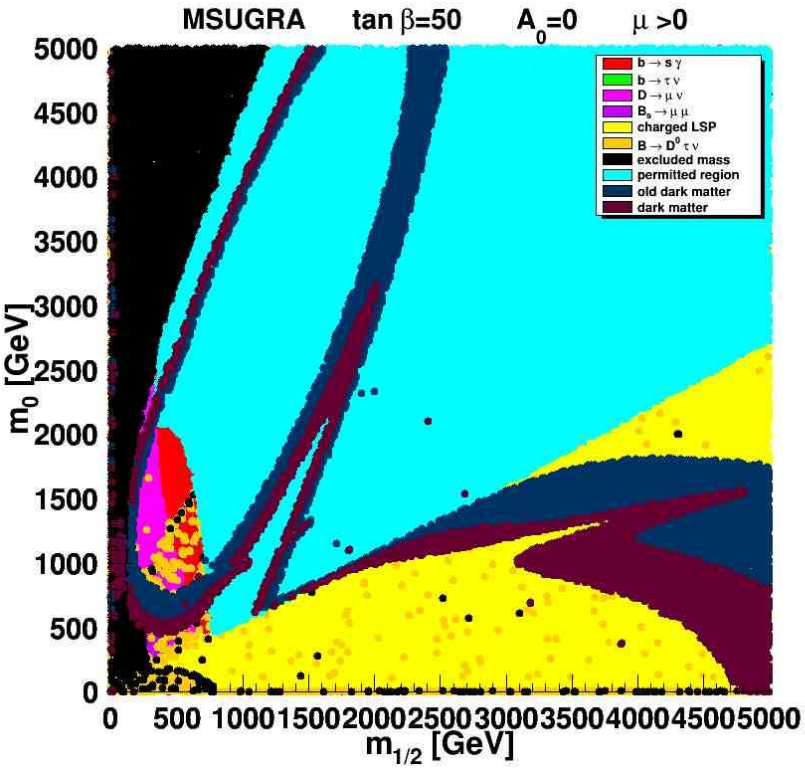
mSUGRA results (SPHENO)



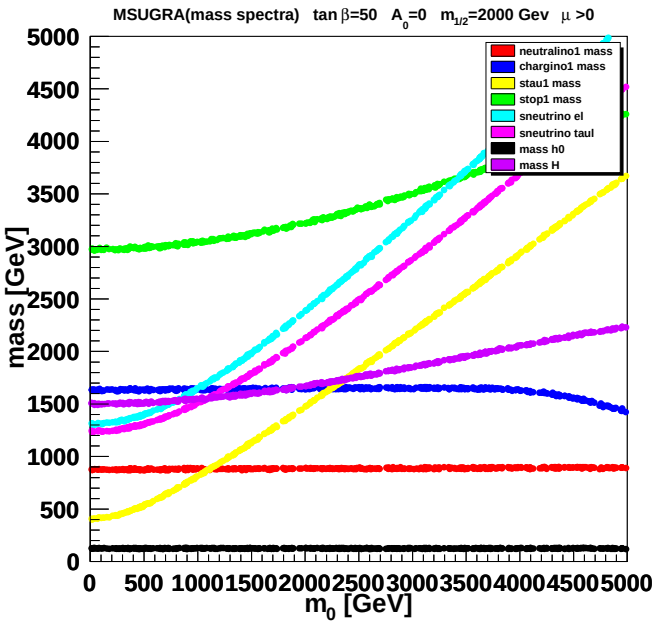


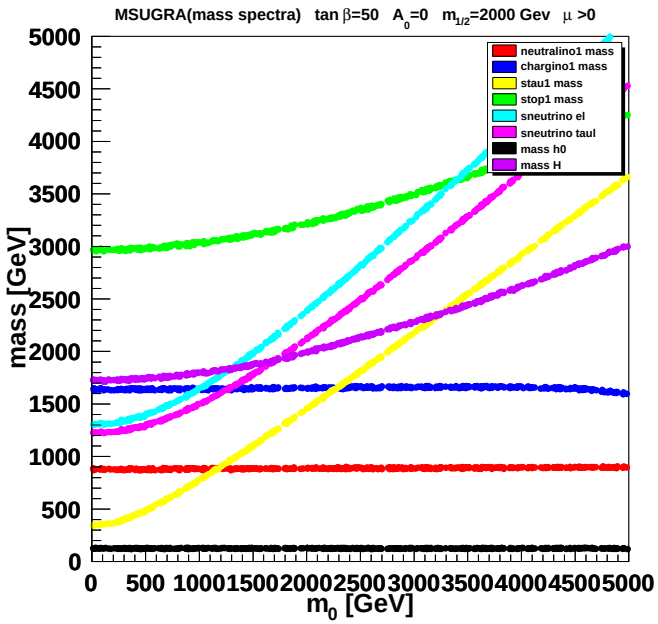
mSUGRA results (SUSPECT)





Mass spectra in mSUGRA





The mass spectra of mSUGRA model : (at left) SOFTSUSY, (at right) ISAJET

- The neutralino is the candidate of dark matter in mSUGRA.

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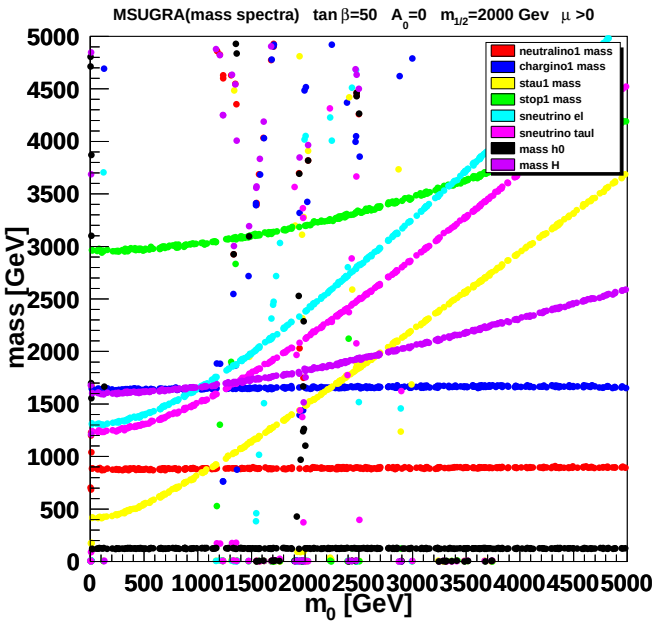

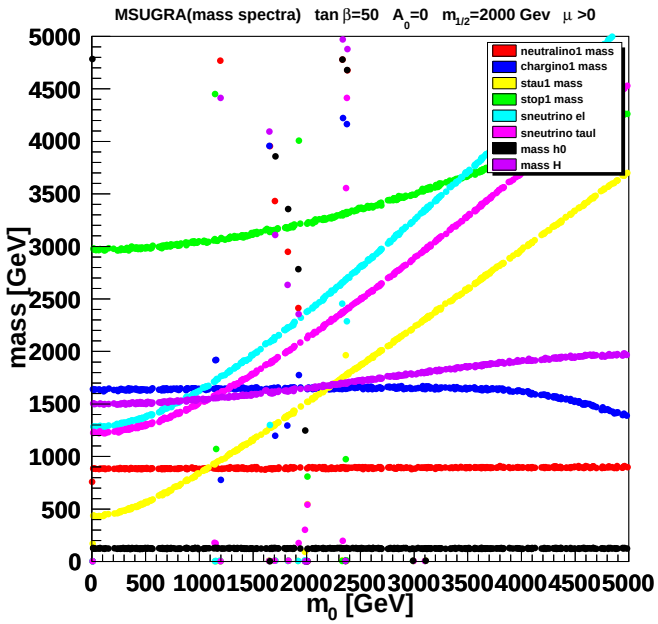

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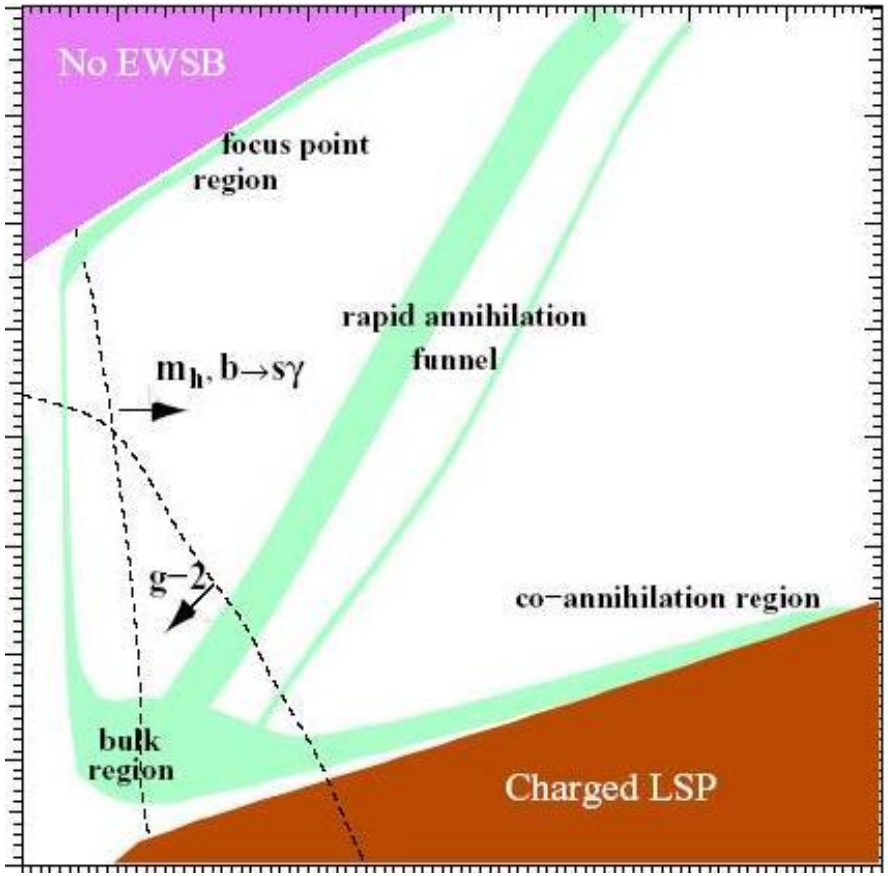
Favoured regions

- 4 favoured regions of parameters space :



Discussion of results

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- A-funnel region :resonnance situation $m_{A^0} \approx m_{H^0} \approx 2m_{\chi_1^0}$, s-channel Higgs exchange $\chi_1^0\chi_1^0 \to A^0 \to b\bar{b}$ or $\tau\bar{\tau}$.

AMSB

- AMSB (Anomaly Mediated Supersymmetry Breaking) is a predictive framework for SUSY breaking in which the breaking of scale invariance mediates between hidden and visible sectors, and the sparticules acquire their masses due to this mediation.

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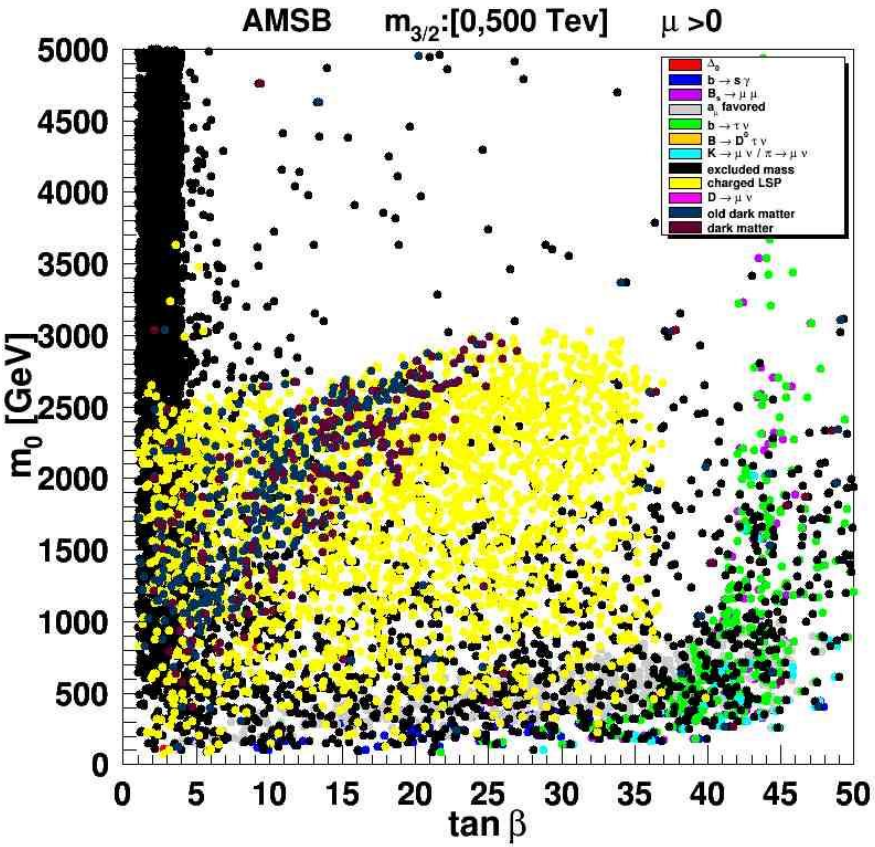
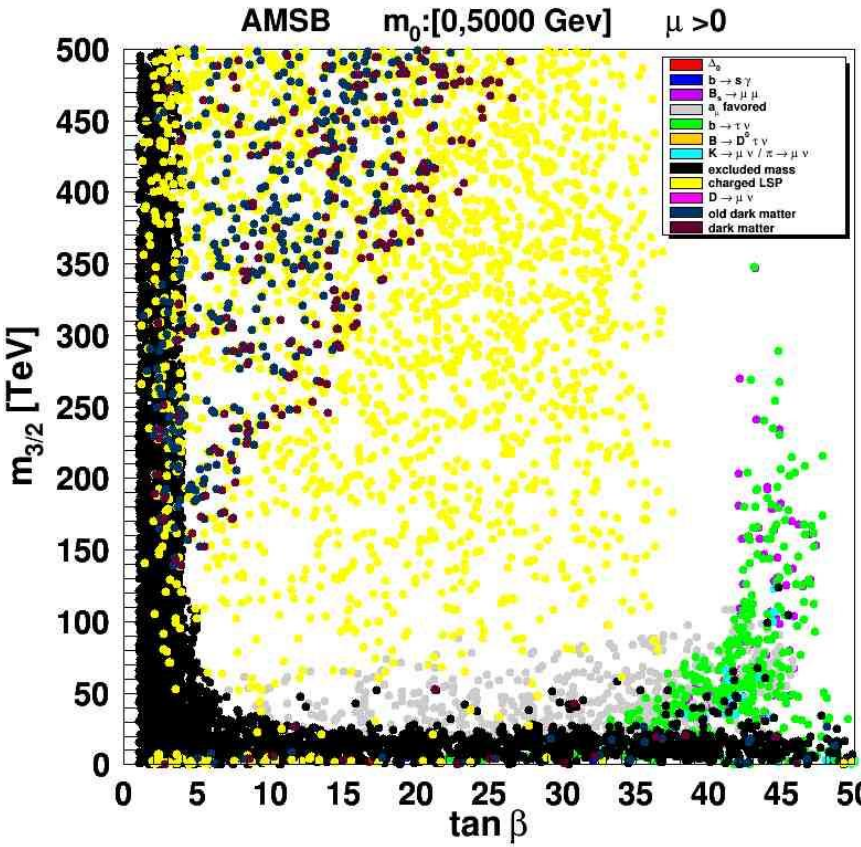
- This model suffer of the problem of negative square masses of sleptons (tachyonic state) and the zones where the problem doesn't appear are reduced.
- The parameters of this model are :

$$m_0, m_{3/2}, tan\beta, sign(\mu).$$

AMSB results





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- $\Rightarrow$ MM-AMSB and HC-AMSB.

MM-AMSB

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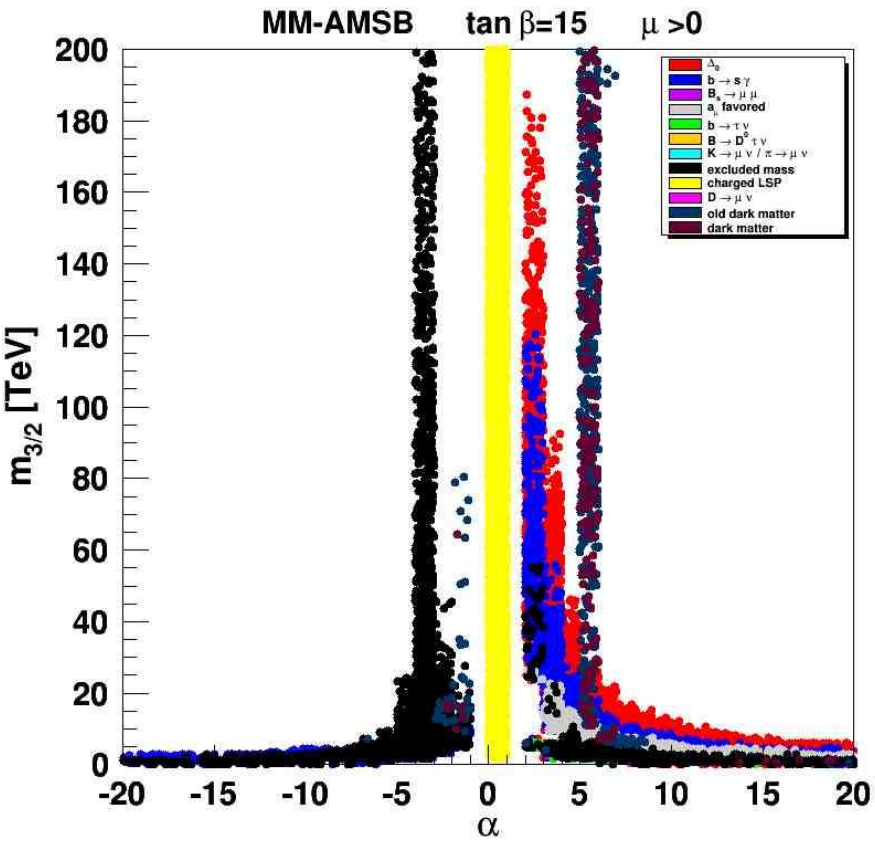
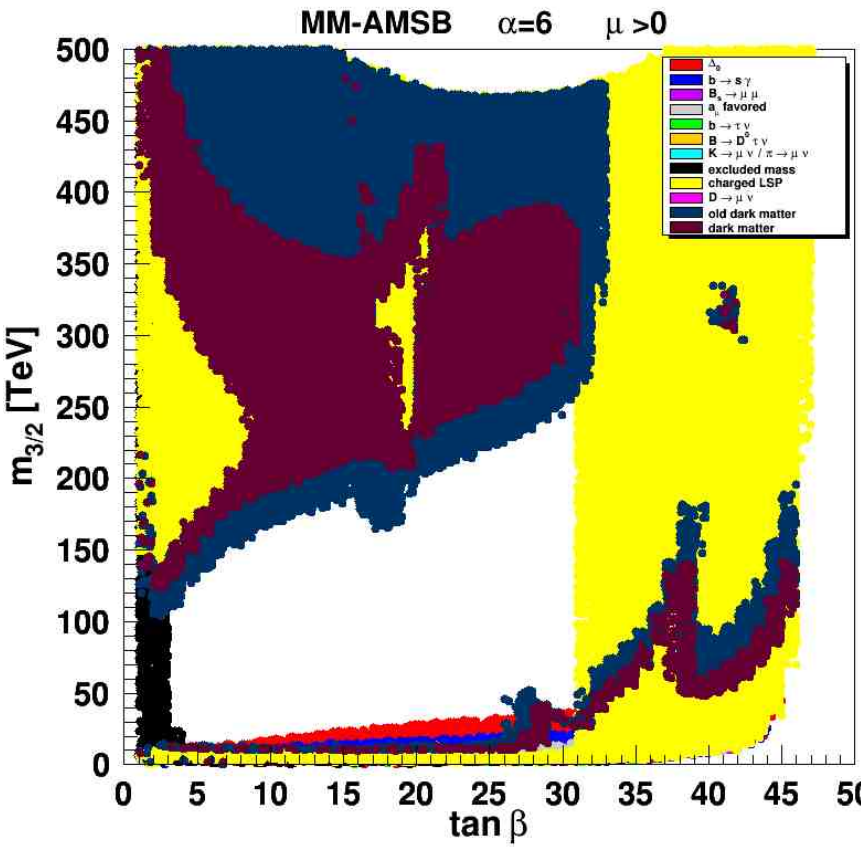
- α : relative contribution of anomaly mediation and garvity mediation (moduli) for soft terms.
- n_i :modular weights of visible sector of matter fields.
- l_a : the gauge kinetic function.
- I added this model in SuperIso taking n_i=0 and l_a=1.

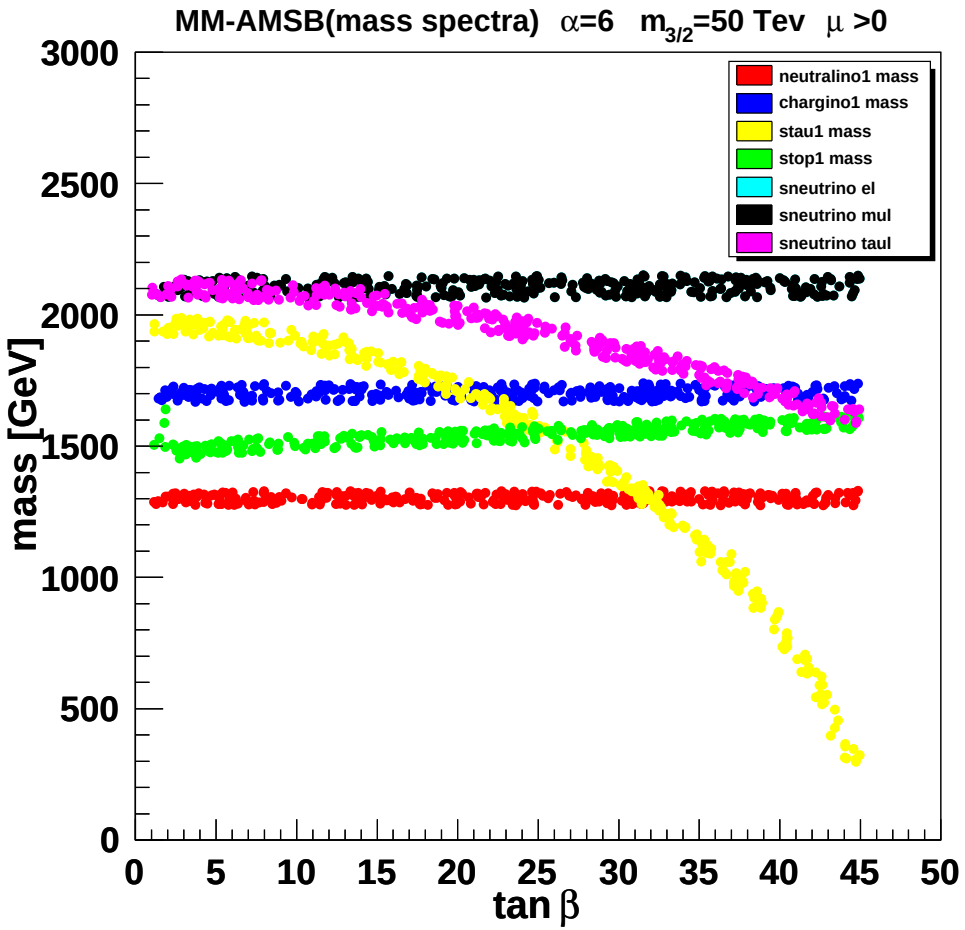
MM-AMSB results





Parameters space in the MM-AMSB model with zero modular weights and $\mu > 0$, in the planes $(m_{3/2},\alpha)$ at left and $(m_{3/2},tan\beta)$ at right

Mass spectra for MM-AMSB



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- LSP must be created by pairs (conservation of R-parity) $\Rightarrow$ more difficult for detection at LHC in the near futur.
- Decay from NLSP which is the stop, $\tilde{t}_1 \rightarrow c\chi_1^0$ or $\tilde{t}_1 \rightarrow bW\chi_1^0$

.

Can axino be a candidate for DM ? !

- The stau can decay into an *axino* plus a particle from SM : $\tilde{\tau} \rightarrow \tilde{a} + \text{SM}$, $n_{\tilde{\tau}} \sim n_{\tilde{a}}$ and $\rho_{\tilde{\tau}} = m_{\tilde{\tau}} n_{\tilde{\tau}}$. And, $\rho_{\tilde{a}} = m_{\tilde{a}} n_{\tilde{a}} = m_{\tilde{a}} n_{\tilde{\tau}} = \frac{m_{\tilde{a}}}{m_{\tilde{\tau}}} \rho_{\tilde{\tau}}$. $m_{\tilde{a}} \sim 0.1$ Gev and $m_{\tilde{\tau}} \sim 1000$ GeV so $\rho_{\tilde{a}} \sim 10^{-4} \rho_{\tilde{\tau}}$. But $\Omega_M = \frac{\rho_M^0}{\rho^c} \Rightarrow \Omega_{\tilde{a}} \sim 10^{-4} \Omega_{\tilde{\tau}}$.

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- This new value of $\Omega \Rightarrow$ (where axino is DM) is also excluded by other constraints of flavour physics !
- The axino can't be a candidate for DM in MM-AMSB.

HC-AMSB

- HC-AMSB (HyperCharged Anomaly Mediation) is a scenario motivated by the string theory which explain an extension of AMSB.
- SUSY breaking is localized at the bottom of a strongly warped hidden region, geometrically separated from the visible region where the MSSM resides.

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- Depending on its size, the bino mass M_1 can lead to a small perturbation to the spectrum of anomaly mediation.

HC-AMSB

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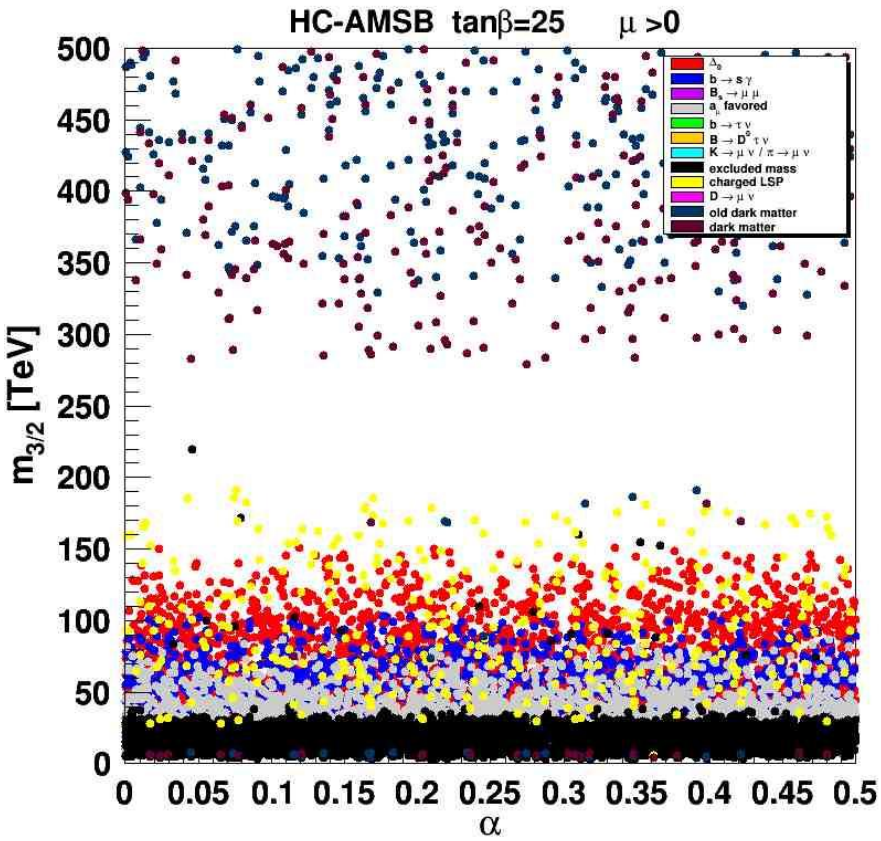
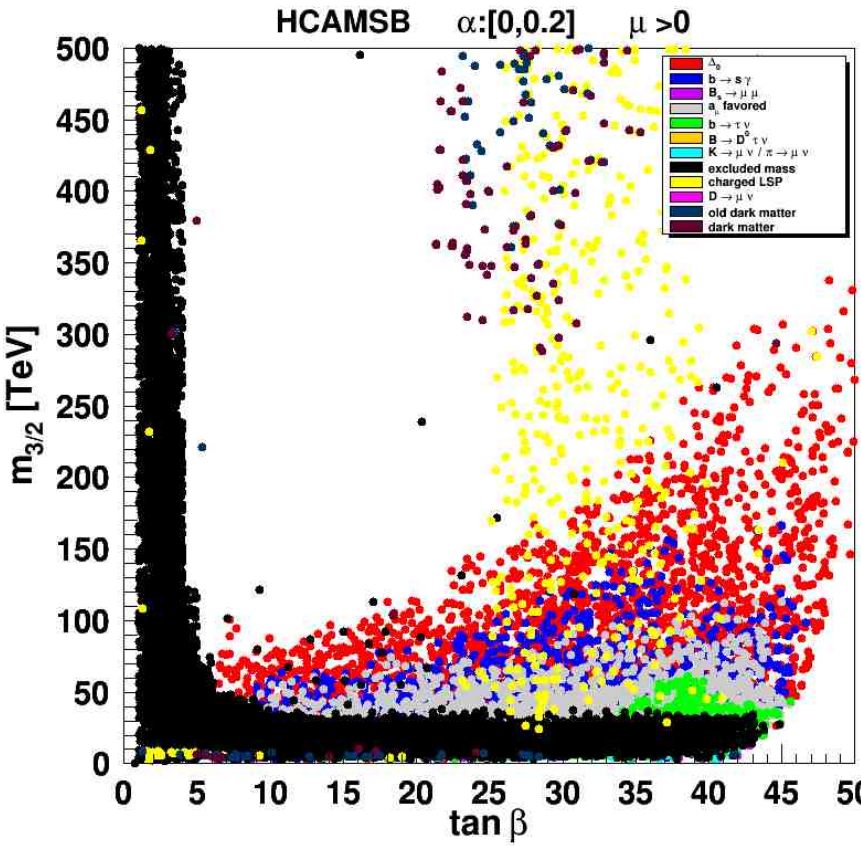
- α is a dimensionless quantity which represents the size of hypercharge contribution to soft terms relatives to the AMSB contribution.

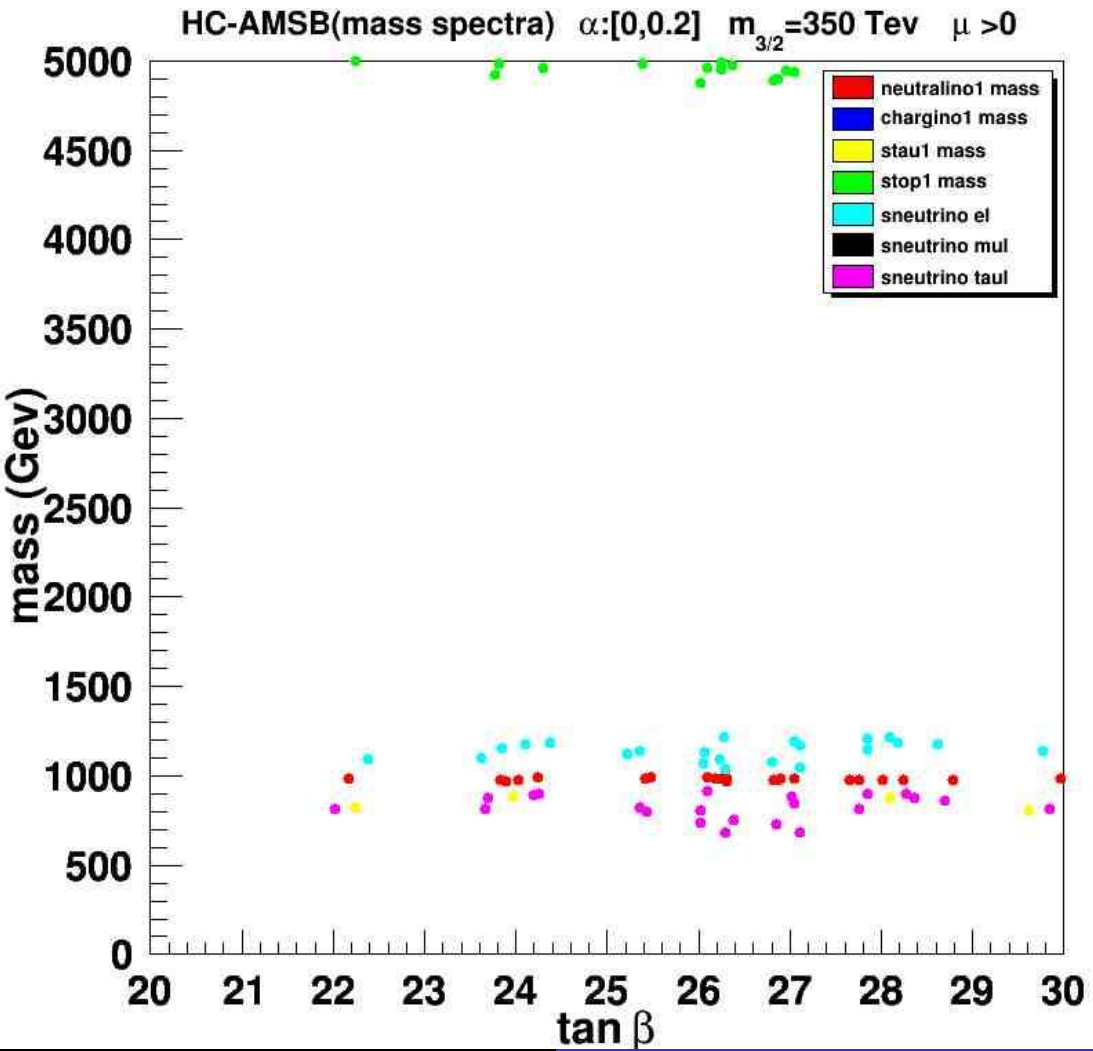
HC-AMSB results





The parameters of space in the HC-AMSB model with $\alpha \in [0,0.2]$ and $\mu > 0$, in the planes $(m_{3/2},\alpha)$ at left and $(m_{3/2},tan\beta)$ at right.

Mass spectra for HC-AMSB



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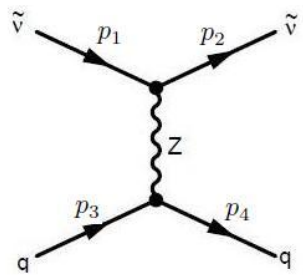
- The diagram which corresponds to the interaction of sneutrinos with the nucleus via t-channel is :



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- mSUGRA : the neutralino is the LSP , while AMSB does'nt offer any allowed regions for the dark matter.
- MM-AMSB, as in mSUGRA, the neutralino is the LSP, but in HC-AMSB, it is the sneutrino tau that is the lightest and it is excluded by the direct detection of its interaction with the nucleus.

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- Addition of non-thermal production of relic particles.
- Implementation of an alternative entropy modification.
- Inclusion of a BBN code to test the cosmological modifications.