Probing the supersymmetric inflaton and dark matter link

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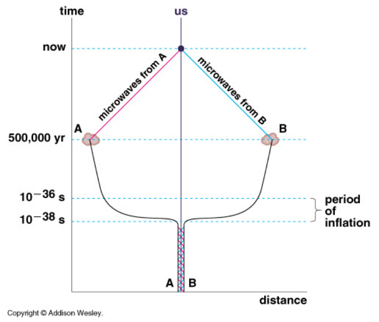
In collaboration with C. Bœhm, A. Mazumdar and E. Pukartas,
arXiv:1205.2815

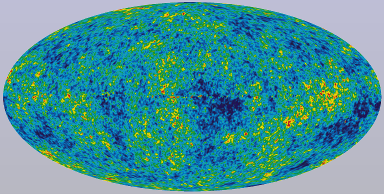
Outline

Motivations

Motivations

- **Inflation motivations**
  - Flatness problem (fine-tuning problem on Ω_k)
  - Horizon problem
  - Monopole problem (topological defect not seen)



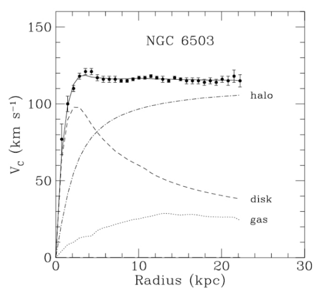


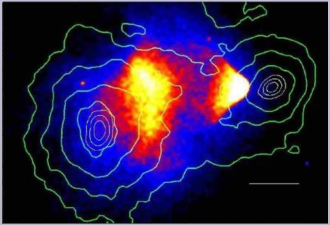
WMAP7

$\Rightarrow$ Cosmic inflation (fast expansion phase in the early universe) embedded in Grand Unified Theories (GUT)

Motivations

- **Inflation motivations**
- **Dark matter (DM) motivations**
  - Galaxy scale : rotation curves of galaxies
  - Galaxy clusters scale : example of the bullet cluster
  - Cosmological scale (CMB), large scale structures, ...





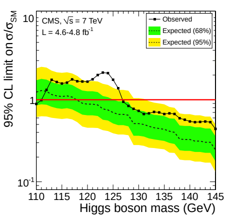
K. G. Begeman, A. H. Broeils and R. H. Sanders, 1991, MNRAS, 249, 523
A direct empirical proof of the existence of dark matter, D. Clowe et al., Astrophys. J. 648 L109-L113, 2006

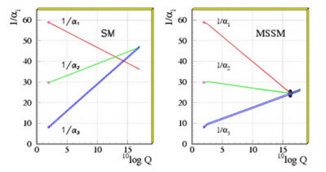
$\Rightarrow \Omega_b h^2 = 0.0226 \pm 0.0005$ and $\Omega_{DM} h^2 = 0.1123 \pm 0.0035$
DM has to be stable and weakly charged under the standard model gauge group

Motivations

- **Inflation motivations**
- **Dark matter (DM) motivations**
- **Supersymmetry motivations**
  - Hierarchy problem on Higgs boson mass
  - Unification at GUT scale

    $\Rightarrow$ cosmic inflation embedded in supersymmetric models
  - LSP/DM (supersymmetry breaking, R-Parity)





The lightest supersymmetric particle (LSP) is stable, at TeV scale, and can be weakly charged under the SM gauge group

$\Rightarrow$ DM candidates in supersymmetric models

Models chosen

Models chosen

- **NUHM2**
  - Supersymmetric model with gravity-mediated supersymmetry breaking based on the MSSM
  - Most popular : mSUGRA, universal scalar masses is assumed, free parameters :

$$m_0,\ m_{1/2},\ A_0,\ \tan\beta \text{ and } \mathrm{sign}(\mu)$$

  - Drawbacks : $m_h \sim 125$ GeV not easy, LSP mostly bino
  - We considered a non-universal scalar masses model, with $m_0^2 \neq m_{H_u}^2 \neq m_{H_d}^2$ (see H. Baer et al [hep-ph/0504001], J. R. Ellis et al [hep-ph/0210205])
  - $\Rightarrow$ Easier to reach Higgs boson mass range not excluded yet by ALTAS and CMS ($m_h \in [115.5, 127]$ GeV), increase DM annihilation rates with higgsino LSP
  - EWSB relations :

$$m_{H_d}^2(1+\tan^2\beta) = M_A^2\tan^2\beta - \mu^2(\tan^2\beta + 1 - \Delta_\mu^{(H_u)}) - (c_{H_d} + c_{H_u} + 2c_\mu)\tan^2\beta$$
$$-\Delta_A\tan^2\beta - \frac{1}{2}M_Z^2(1-\tan^2\beta) - \Delta_\mu^{(H_d)} \text{ and}$$
$$m_{H_u}^2(1+\tan^2\beta) = M_A^2 - \mu^2(\tan^2\beta + 1 + \Delta_\mu^{(H_u)}) - (c_{H_d} + c_{H_u} + 2c_\mu)$$
$$-\Delta_A + \frac{1}{2}M_Z^2(1-\tan^2\beta) + \Delta_\mu^{(H_d)}$$

  - NUHM2 free parameter :

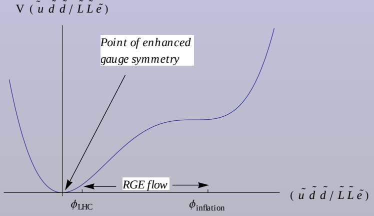
$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mu \text{ and } M_A$$

Models chosen

- NUHM2
- $\widetilde{L}\widetilde{L}\widetilde{e}$ and $\widetilde{u}\widetilde{d}\widetilde{d}$
  - Inflaton, scalar field whose flat direction potential (with a non-negligible slope) leads to the end of the inflation phase
  - Charged under the visible sector of the particle physics model considered, i.e. NUHM2
  - supersymmetric scalar potential :

$$V = \sum_i |F_i|^2 + \frac{1}{2}\sum_a g_a^2 D^a D^a,$$

$$F_i \equiv \frac{\partial W}{\partial \phi_i}, \quad D^a = \phi^\dagger T^a \phi,$$



  - $\Rightarrow$ $\widetilde{L}\widetilde{L}\widetilde{e}$ and $\widetilde{u}\widetilde{d}\widetilde{d}$ D-terms can be such candidates
  - Lifted by higher order superpotential terms $W \supset \frac{\lambda}{6}\frac{\Phi^6}{M_P^3}$, Φ scalar component : $\phi = \frac{\widetilde{u}+\widetilde{d}+\widetilde{d}}{\sqrt{3}}, \quad \phi = \frac{\widetilde{L}+\widetilde{L}+\widetilde{e}}{\sqrt{3}}$ (see R. Allahverdi et al, [hep-ph/0610134], [hep-ph/0605035])

$$V(\phi) = \frac{1}{2}m_\phi^2\,\phi^2 - A\frac{\lambda\phi^6}{6\,M_P^3} + \lambda^2\frac{\phi^{10}}{M_P^6}$$

$$\phi_{\text{inflation}}^4 \simeq \frac{m_\phi M_P^3}{\lambda\sqrt{10}}, \; V''(\phi_{\text{inflation}}) = 0$$

Models chosen

- **NUHM2**
- **$\widetilde{L}\widetilde{L}\widetilde{e}$ and $\widetilde{u}\widetilde{d}\widetilde{d}$**
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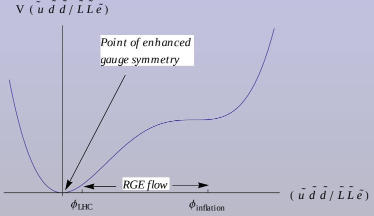


- $\phi = \frac{\widetilde{u}+\widetilde{d}+\widetilde{d}}{\sqrt{3}}, \quad \phi = \frac{\widetilde{L}+\widetilde{L}+\widetilde{e}}{\sqrt{3}}$
- $V(\phi) = \frac{1}{2} m_\phi^2\, \phi^2 - A \frac{\lambda \phi^6}{6\, M_P^3} + \lambda^2 \frac{\phi^{10}}{M_P^6}$

  $\phi^4_{\mathrm{inflation}} \simeq \frac{m_\phi M_P^3}{\lambda \sqrt{10}}, V''(\phi_{\mathrm{inflation}}) = 0$
- $\widetilde{u}\widetilde{d}\widetilde{d}$ RGEs

$$\hat{\mu}\frac{dm_\phi^2}{d\hat{\mu}} = -\frac{1}{6\pi^2}(4M_3^2 g_3^2 + \frac{2}{5} M_1^2 g_1^2),$$
$$\hat{\mu}\frac{dA}{d\hat{\mu}} = -\frac{1}{4\pi^2}(\frac{16}{3} M_3 g_3^2 + \frac{8}{5} M_1 g_1^2)$$

- $\widetilde{L}\widetilde{L}\widetilde{e}$ RGEs

$$\hat{\mu}\frac{dm_\phi^2}{d\hat{\mu}} = -\frac{1}{6\pi^2}(\frac{3}{2} M_2^2 g_2^2 + \frac{9}{10} M_1^2 g_1^2),$$
$$\hat{\mu}\frac{dA}{d\hat{\mu}} = -\frac{1}{4\pi^2}(\frac{3}{2} M_2 g_2^2 + \frac{9}{5} M_1 g_1^2)$$

Constraints and methods

Constraints and methods

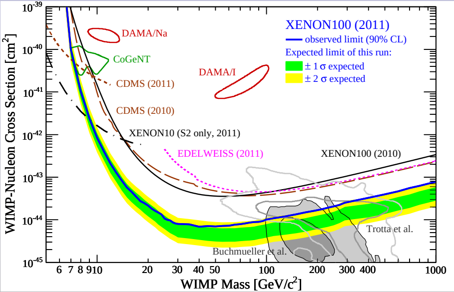
Constraints

- On inflation, explain the observed temperature anisotropy in the CMB with :
  - The amplitude of density perturbations $\delta_H = \frac{8}{\sqrt{5}\pi} \frac{m_\phi M_P}{\phi_0^2} \frac{1}{\Delta^2} \sin^2[\mathcal{N}_{COBE}\sqrt{\Delta^2}]$,
  $\Delta^2 \equiv 900\alpha^2 \mathcal{N}_{COBE}^{-2} \left(\frac{M_P}{\phi_0}\right)^4$, $\quad \mathcal{N}_{COBE} \sim 50$
  - The scalar spectral index n_s of the corresponding power spectrum
  $n_s = 1 - 4\sqrt{\Delta^2}\ \cot[\mathcal{N}_{COBE}\sqrt{\Delta^2}]$,

Constraints and methods

Constraints

- On inflation, explain the observed temperature anisotropy in the CMB
- On our CDM candidate, χ_1^0 :
  - Dark matter relic density with $\Omega_{\text{WIMP}} h^2 = 0.1123 \pm 0.0035$ E. Komatsu et al, [arXiv :1001.4538 [astro-ph.CO]])
  - Spin independent direct detection cross section



Constraints and methods

Constraints

- On inflation, explain the observed temperature anisotropy in the CMB
- On our CDM candidate, χ_1^0
- On NUHM2 model in general :
  - $m_h \in [115.5, 127]$ GeV
  - B-physics : $BR(b \to s\gamma)$, $BR(B_s \to \mu^+\mu^-)$ and $BR(B^+ \to \tau^+\bar{\nu}_\tau)$
  - Electroweak observables : $(g_\mu - 2)$, $\Delta\rho$, $Z \to$ invisible, $\sigma_{e^+e^- \to \chi_1^0\chi_{2,3}^0} \times Br(\chi_{2,3}^0 \to Z\chi_1^0)$

In our study, SUSY contributions are not large so that both $(g_\mu - 2)$ and $BR(B^+ \to \tau^+\bar{\nu}_\tau)$ are well below the measured value

The other electroweak observables apply mainly for light LSP, not the case in this study

Constraints and methods

Methods

- Benchmark points on $(m_0, m_{1/2})$ plane, focus on specific m_h values
- Scanning the parameter space : Markov Chain Monte Carlo method

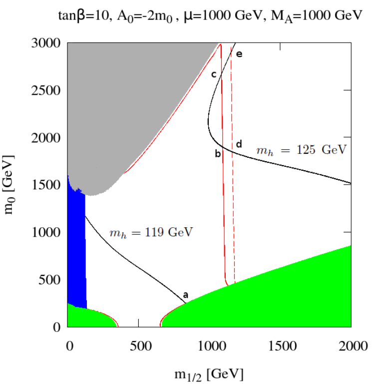
Constraint	Value/Range	Tolerance	Likelihood
m_h (GeV)	[115.5, 127]	1	$\mathcal{L}_1(m_h, 115.5, 127, 1)$
$\Omega_{\chi_1^0} h^2$	[0.1088, 0.1158]	0.0035	$\mathcal{L}_1(\Omega_{\chi_1^0} h^2, 0.1088, 0.1158, 0.0035)$
Relaxing constraint on $\Omega_{\chi_1^0} h^2$	[0.01123, 0.1123]	0.0035	$\mathcal{L}_1(\Omega_{\chi_1^0} h^2, 0.01123, 0.1123, 0.0035)$
$BR(b \to s\gamma) \times 10^4$	3.55	exp : 0.24, 0.09 th : 0.23	$\mathcal{L}_2(10^4 BR(b \to s\gamma), 3.55, \sqrt{0.24^2 + 0.09^2 + 0.23^2})$
$(g_\mu - 2) \times 10^{10}$	28.7	8	$\mathcal{L}_3(10^{10}(g_\mu - 2), 28.7, 8)$
$BR(B_s \to \mu^+\mu^-) \times 10^9$	4.5	0.045	$\mathcal{L}_3(10^9 BR(B_s \to \mu^+\mu^-), 4.5, 0.045)$
$\Delta\rho$	0.002	0.0001	$\mathcal{L}_3(\Delta\rho, 0.002, 0.0001)$
$R_{B^+\to\tau^+\bar{\nu}_\tau}(\frac{NUHM2}{SM})$	2.219	0.5	$\mathcal{L}_3(R_{B^+\to\tau^+\bar{\nu}_\tau}, 2.219, 0.5)$
$Z \to \chi_1^0\chi_1^0$ (MeV)	1.7	0.3	$\mathcal{L}_3(Z \to \chi_1^0\chi_1^0, 1.7, 0.3)$
$\sigma_{e^+e^-\to\chi_1^0\chi_{2,3}^0} \times Br(\chi_{2,3}^0 \to Z\chi_1^0)$ (pb)	1	0.01	$\mathcal{L}_3(\sigma_{e^+e^-\to\chi_1^0\chi_{2,3}^0} \times Br(\chi_{2,3}^0 \to Z\chi_1^0), 1, 0.01)$

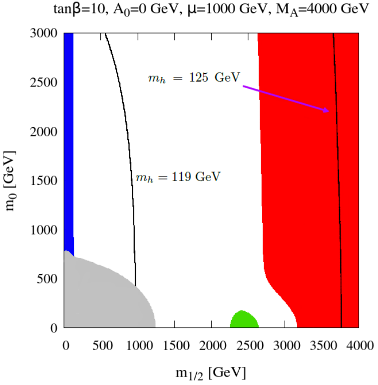
Parameter	Range	Parameter	Range
m_0	]0, 4] TeV	$\tan\beta$	[2, 60]
$m_{1/2}$	]0, 4] TeV	μ	]0, 3] TeV
A_0	[-6, 6] TeV	M_A	]0, 4] TeV

Probing NUHM2

Probing NUHM2

- Hard to accommodate the correct LSP relic density with Higgs boson mass constraint for bino-like LSP (whose mass is close to $M_A/2$)

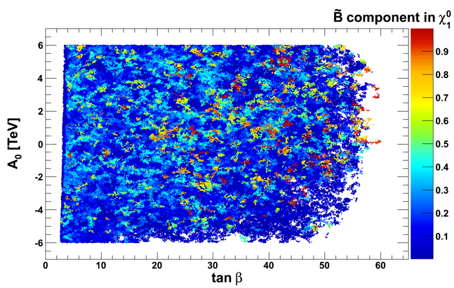


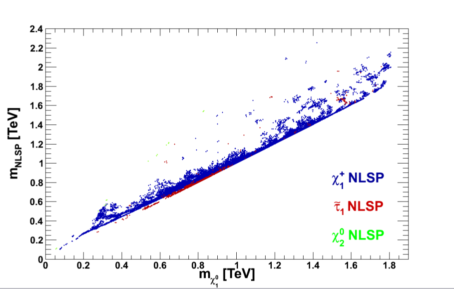


- $\Omega_{\chi_1^0}h^2$, χ_1^+ below LEP2 limits, $\tilde{\tau}_1$ LSP, tachyonic $\tilde{t}$

Probing NUHM2

- Hard to accommodate the correct LSP relic density with Higgs boson mass constraint for bino-like LSP (whose mass is close to $M_A/2$)
- Get mainly higgsino-like LSP, degeneracy between $\chi^0_{1,2}$ and $\chi^\pm_1$





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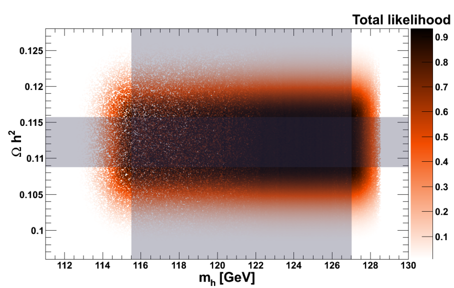
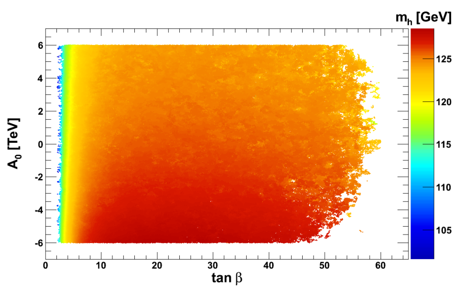
- m_h preferably above 122 GeV, constraining $(A_0, \tan(\text{beta}))$ plane





Probing NUHM2

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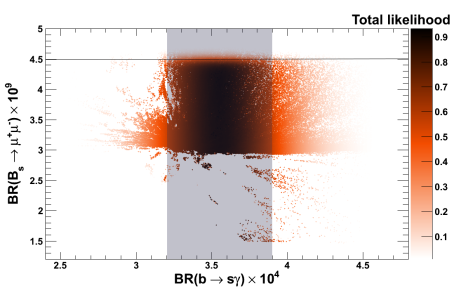
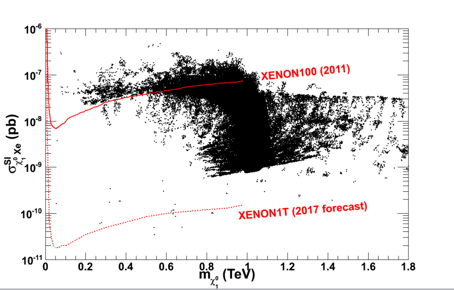
- Get mainly higgsino-like LSP, degeneracy between $\chi^0_{1,2}$ and $\chi^\pm_1$
- m_h preferably above 122 GeV, constraining $(A_0, \tan(\text{beta}))$ plane
- NUHM2 scenarios within LHCb and XENON1T experiments sensitivity

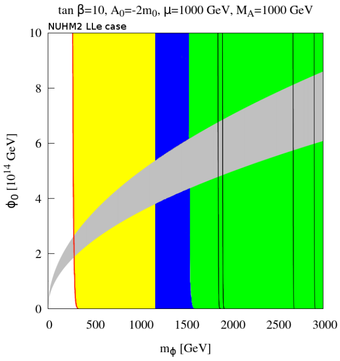


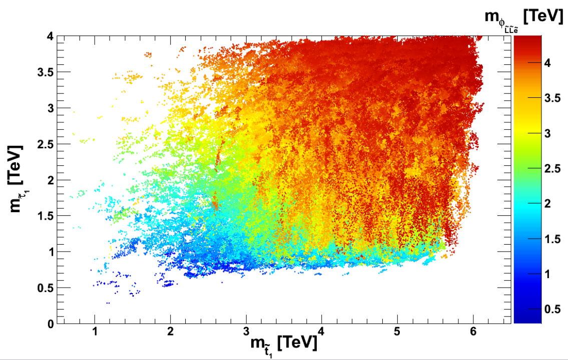


Probing $\widetilde{L}\widetilde{L}\widetilde{e}$ and $\widetilde{u}\widetilde{d}\widetilde{d}$

Probing $\tilde{L}\tilde{L}\tilde{e}$ and $\tilde{u}\tilde{d}\tilde{d}$

- With δ_H and n_s constraints $\Rightarrow$ inflation scale linked to low (LHC) scale
- Keys on inflaton mass if we discover lightest stop/stau at LHC
- $\Omega_{\chi_1^0}h^2$ with $m_h = 119$ GeV, χ_1^+ below LEP2 limits, $\Omega_{\chi_1^0}h^2$ with $m_h = 125$ GeV, satisfy δ_H and n_s constraints





Conclusions

Conclusions

- We searched NUHM2 parameter space regions compatible with DM relic density, Higgs boson mass and inflationary potential required to match CMB
- Sparticle and Higgs searches at LHC combined with Planck satellite measurements could give us huge constraints on inflaton mass
- B-physics constraints will constrain more and more the model since all scenarios are within the LHCb sensitivity
- Probing these scenarios would be possible with forthcoming XENON1T experiment

BACKUP

BACKUP

Likelihood method

- **For the Higgs mass and relic density, we define the likelihood as a function $\mathcal{L}_1$ which decays exponentially at the edges of the $[x_{min}, x_{max}]$ range, according to**

$$\mathcal{L}_1(x, x_{min}, x_{max}, \sigma) = e^{-\frac{(x-x_{min})^2}{2\sigma^2}} \text{ if } x < x_{min},$$
$$= e^{-\frac{(x-x_{max})^2}{2\sigma^2}} \text{ if } x > x_{max}$$
$$= 1 \text{ for } x \in [x_{min}, x_{max}].$$

with σ = variance and x the observable which corresponds in that case to either the Higgs mass or the LSP relic density.

- **For an observable with a preferred value μ and error σ, we use a Gaussian distribution $\mathcal{L}_2$:**

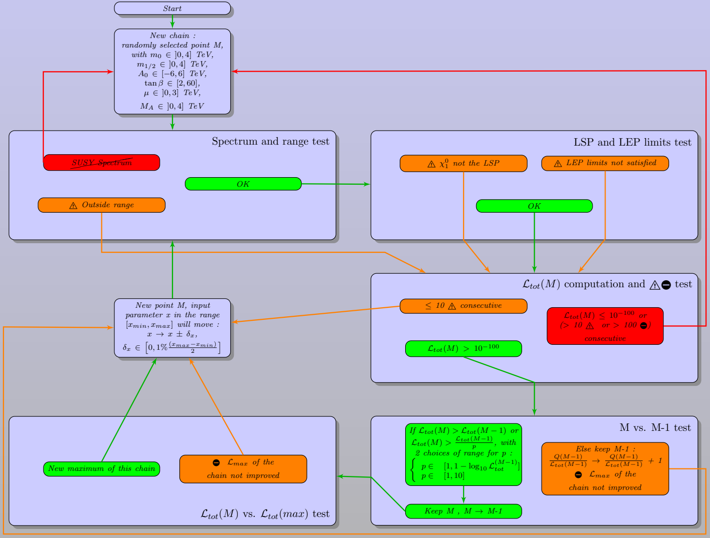
$$\mathcal{L}_2(x, \mu, \sigma) = e^{-\frac{(x-\mu)^2}{2\sigma^2}}.$$

- **For an observable with a lower or upper bound (set experimentally), we will take the function $\mathcal{L}_3$ with a positive or negative variance σ :**

$$\mathcal{L}_3(x, \mu, \sigma) = \frac{1}{1 + e^{-\frac{x-\mu}{\sigma}}}.$$

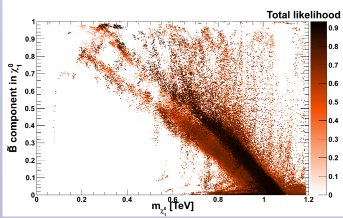
BACKUP

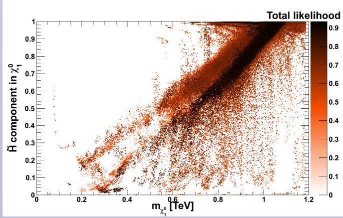
MCMC method

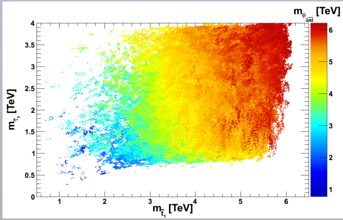


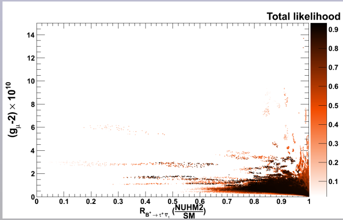
BACKUP

More informations on results :



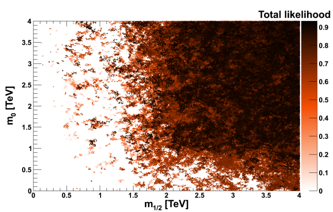


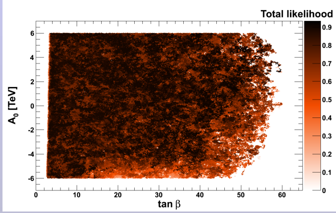


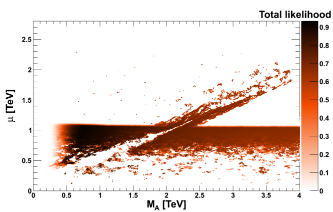


BACKUP

Scan with $\Omega_{\chi_1^0}h^2$ constaint :







Relaxing $\Omega_{\chi_1^0}h^2$ constaint $\Rightarrow$ lower μ allowed