

Phenomenological aspects of the UMSSM

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G. Bélanger, JDS and A. Pukhov, JCAP 1112 (2011) 014, [arXiv:1110.2414]

JDS, PhD thesis : [arXiv:1312.0257]

G. Bélanger, JDS et al., in progress

Outline

- 1 Introduction
- 2 The model
- 3 RH sneutrino DM candidate
- 4 Low $\tan \beta$ region
- 5 Conclusions

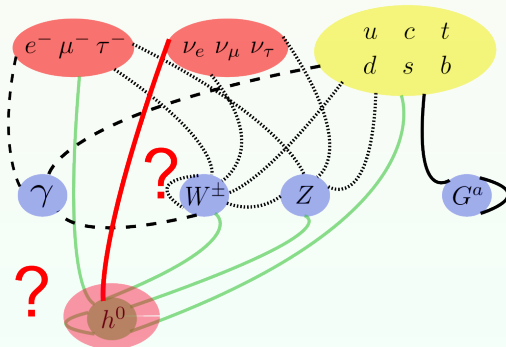
Introduction

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Drawbacks of the Standard Models

✱ Particle Physics (SM)

- ✱ **Hierarchy problem** between EW (~ 100 GeV) and Planck ($\sim 10^{19}$ GeV) scales
Quadratic divergences to the Higgs boson mass squared
- ✱ **Grand Unification** (GUT)
- ✱ **Neutrino sector** (Dirac, Majorana ??)
- ✱ ...

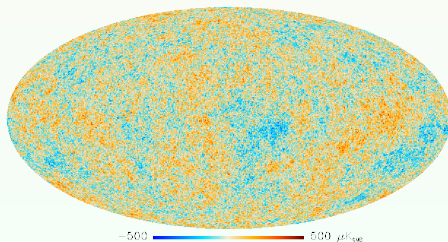


SM interactions, at tree-level

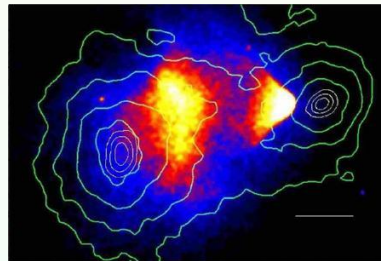
Drawbacks of the Standard Models

★ Cosmology (Λ CDM)

- ★ Simple cosmological model which fits even the most accurate measurements (Planck satellite)
- ★ But needs **Dark Energy** and **Dark Matter** (DM, other evidence : rotation curves of galaxies, galaxy clusters, ...)



P.A.R. Ade et al., [arXiv:1303.5062]



D. Clowe et al., [astro-ph/0608407]

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- ✧ DM made of particles $\neq$ SM particles :
 - ✗ baryons : BBN, CMB, ...
 - ✗ **charged leptons** : we would have seen DM (overproduction of γ , ...)
 - ✗ **neutrinos** : too light $\Rightarrow$ low relic density + HDM

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$\Rightarrow$ Example of DM candidate which gives the right abundance :
Weakly Interacting Massive Particle (WIMP)

✓ Candidates can be found beyond the Standard Model
Here : **Supersymmetry (SUSY)**

Supersymmetry

- ✳ **Fermions $\Leftrightarrow$ bosons $\Rightarrow$ solution to the Hierarchy problem**
- ✳ **Unification at GUT scale**
- ✳ **LSP/DM (supersymmetry breaking, R-Parity)**

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

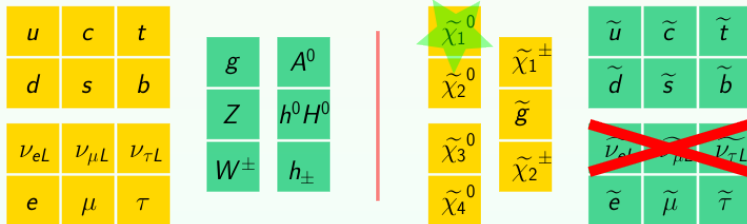
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$\Rightarrow$ **DM candidates in supersymmetric models**

- ★ Examples with the Minimal Supersymmetric Standard Model (MSSM) :



Drawbacks of the MSSM

★ The μ -problem :

MSSM superpotential, $\mathcal{W}_{\text{MSSM}} \supset \mu H_u H_d$, μ SUSY preserving :
 natural values are $\mu = 0$ (chargino mass) or very large, e.g. $\mu \sim M_{\text{Pl}}$, but :
 minimization condition of the MSSM potential $\Rightarrow$

$$\sin 2\beta = \frac{2b}{m_{H_u}^2 + m_{H_d}^2 + 2|\mu|^2},$$

$$M_Z^2 = \frac{|m_{H_d}^2 - m_{H_u}^2|}{\sqrt{1 - \sin^2 2\beta}} - m_{H_u}^2 - m_{H_d}^2 - 2|\mu|^2$$

No fine-tuned cancellation to obtain the expected Z boson mass needs $b, m_{H_u}^2, m_{H_d}^2$
 and $\mu \sim (10 - 100) \times M_Z^2$:

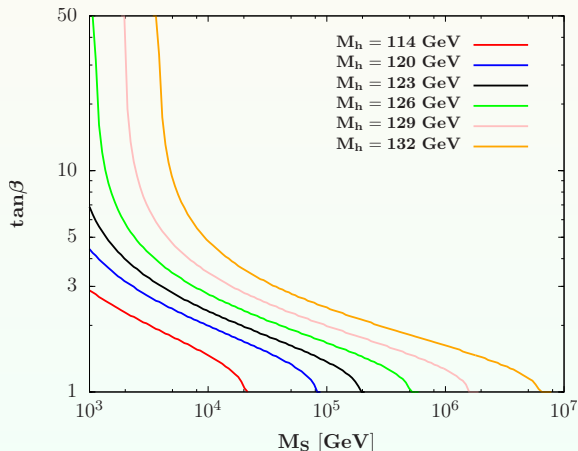
✓ SUSY breaking parameters $b, m_{H_u}^2$ and $m_{H_d}^2$

✗ μ

$\Rightarrow$ MSSM does not account for EW scale μ term

Drawbacks of the MSSM

- * **The μ -problem**
- * **Very small $\tan\beta$, i.e. $\approx 1 \Rightarrow$ tricky :**
TeV-scale SUSY-breaking parameter M_S + SM-like Higgs boson ≈ 125 GeV
 $\Rightarrow$ Higgs boson mass of 125 GeV requires **large $\tan\beta$**



A. Djouadi, J. Quevillon, [[arXiv:1304.1787](https://arxiv.org/abs/1304.1787)]

Possible solutions

- ✳ **Generating an effective μ term** thanks to a Yukawa coupling λ between H_u, H_d and a new scalar field S

$$\mathcal{W}_{\text{MSSM}} \rightarrow \mathcal{W}_{\text{MSSM}}|_{\mu=0} + \lambda S H_u H_d$$

- ✳ **Avoiding very small λ** (new $U(1)_{\text{PQ}}$ global symmetry $\rightarrow$ axion searches), the NMSSM looks in its simplest form like

$$\mathcal{W}_{\text{NMSSM}} = \mathcal{W}_{\text{MSSM}}|_{\mu=0} + \lambda S H_u H_d + \frac{1}{3} \kappa S^3$$

- ✳ In the NMSSM (**U. Ellwanger, C. Hugonie and A. M. Teixeira, [arXiv:0910.1785]**), $m_h \approx 125$ GeV can be achieved with $\tan \beta \approx 2$

NMSSM has drawbacks that can be debated ($\mathcal{W}_{\text{NMSSM}}$ invariant under a discrete $\mathbb{Z}_3$ symmetry $\rightarrow$ domain walls, **S. A. Abel, S. Sarkar and P. L. White, [arXiv:hep-ph/9506359]**)
 $\rightarrow$ variants of the NMSSM

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 $\rightarrow$ variants of the NMSSM

- ✱ **Promoting the new $U(1)_{\text{PQ}}$ global symmetry to a new Abelian gauge symmetry**

The model

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E₆ inspired model

- ✳ Models with extended gauge symmetries are well motivated within the context of Beyond the Standard model (GUT scale models, extra-dimension motivations, superstring models, strong dynamics models, little Higgs models,...)
- ✳ One of the most analysed U(1) extension originates from a string-inspired E₆ grand unified gauge group (P. Langacker and J. Wang, [arXiv:hep-ph/9804428], S.F. King, S. Moretti and R. Nevzorov, [arXiv:hep-ph/0510419],...)
 $E_6 \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\chi \times U(1)_\psi$

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$$E_6 \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\chi \times U(1)_\psi$$

- Low energy gauge symmetry considered : $SU(3)_c \times SU(2)_L \times U(1)_Y \times U'(1)$

$$\text{Coupling constants : } g_3, g_2, g_Y \text{ and } g'_1 = \sqrt{\frac{5}{3}} g_Y$$

- U'(1) charge :

$$Q' = \cos \theta_{E_6} Q'_\chi + \sin \theta_{E_6} Q'_\psi, \quad \theta_{E_6} \in [-\pi/2, \pi/2]$$

- MSSM fields + RH (s)neutrinos + new gauge boson (gaugino) + new singlet (singlino) + $\mathcal{O}(\text{TeV})$ s = UMSSM

	Q'_Q	Q'_u	Q'_d	Q'_L	Q'_ν	Q'_e	Q'_{H_u}	Q'_{H_d}	Q'_S	
$\sqrt{40} Q'_\chi$	-1	-1	3	3	-5	-1	2	-2	0	$\Rightarrow \theta_{E_6} = 0$
$\sqrt{24} Q'_\psi$	1	1	1	1	1	1	-2	-2	4	$\Rightarrow \theta_{E_6} = \pi/2$

Content

* Superpotential :

$$\mathcal{W}_{\text{UMSSM}} = \mathcal{W}_{\text{MSSM}}|_{\mu=0} + \lambda \mathbf{S} \mathbf{H}_u \mathbf{H}_d + \tilde{\nu}_R^* \mathbf{y}_\nu \tilde{\mathbf{L}} \mathbf{H}_u + \mathcal{O}(\text{TeV})$$

* As the NMSSM, this model solves the μ -problem : $\mu = \lambda \frac{v_s}{\sqrt{2}}$

* Higgs sector : MSSM fields + 1 singlet $\Rightarrow$ 3 CP-even Higgs bosons $h_i, i \in \{1, 2, 3\}$

New D-terms for the SM-like Higgs boson :

$$m_{h_1}^2 \leq M_Z^2 \cos^2 2\beta + \frac{1}{2} \lambda^2 v^2 \sin^2 2\beta + \mathbf{g}_1'^2 v^2 (\mathcal{Q}'_{H_d} \cos^2 \beta + \mathcal{Q}'_{H_u} \sin^2 \beta)^2 + \Delta m_h^2$$

* Gauge sector : Physical abelian gauge bosons : $\mathbf{Z}_1$ and $\mathbf{Z}_2$, mixing between the $\mathbf{Z}$ of the SM and the $\mathbf{Z}'$, α_Z is the mixing angle $\Rightarrow \tan \beta$ constrained

$$\mathbf{Z}_1 = \cos \alpha_Z \mathbf{Z} + \sin \alpha_Z \mathbf{Z}'$$

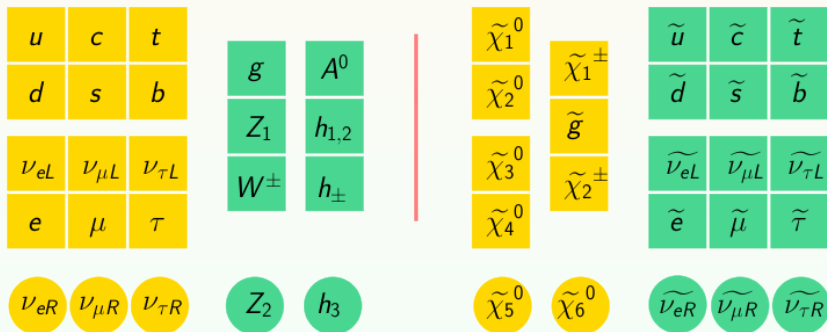
$$\mathbf{Z}_2 = -\sin \alpha_Z \mathbf{Z} + \cos \alpha_Z \mathbf{Z}'$$

$$\cos^2 \beta = \frac{1}{\mathcal{Q}'_{H_d} + \mathcal{Q}'_{H_u}} \left(\frac{\sin 2\alpha_Z (M_{Z_1}^2 - M_{Z_2}^2)}{v^2 \mathbf{g}_1' \sqrt{\mathbf{g}_Y^2 + \mathbf{g}_2^2}} + \mathcal{Q}'_{H_u} \right)$$

* Gauginos sector : 6 neutralinos in the basis $(\tilde{\mathbf{B}}, \tilde{\mathbf{W}}^3, \tilde{\mathbf{H}}_d^0, \tilde{\mathbf{H}}_u^0, \tilde{\mathbf{S}}, \tilde{\mathbf{B}}')$

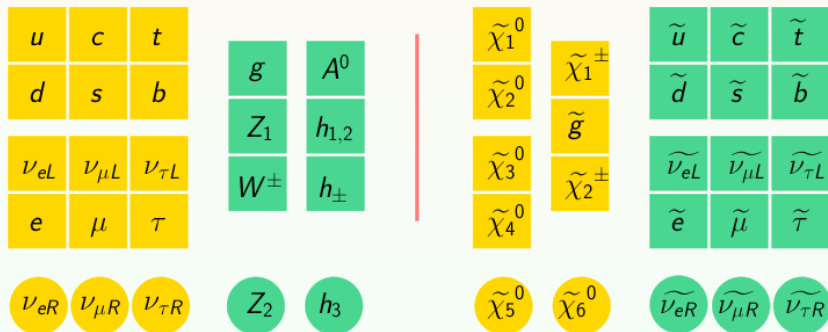
Content

* To sum up :



Content

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* Right-Handed (RH) sneutrinos : are they viable DM candidates?

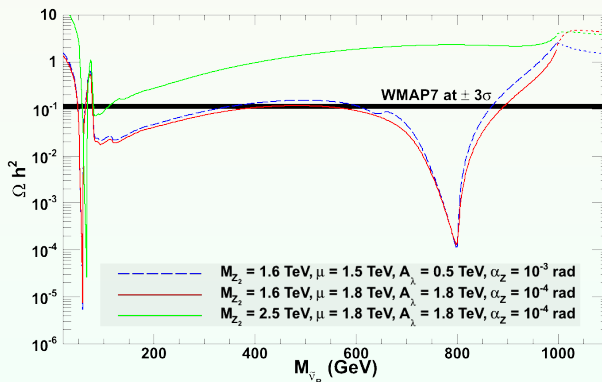
RH sneutrino DM candidate

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WIMP annihilation

Parameter space regions with $\Omega_{\text{WIMP}} h^2 \approx 0.1 \Rightarrow$ need to increase the annihilation cross section : interesting WIMP mass from 50 GeV to TeV-scale :

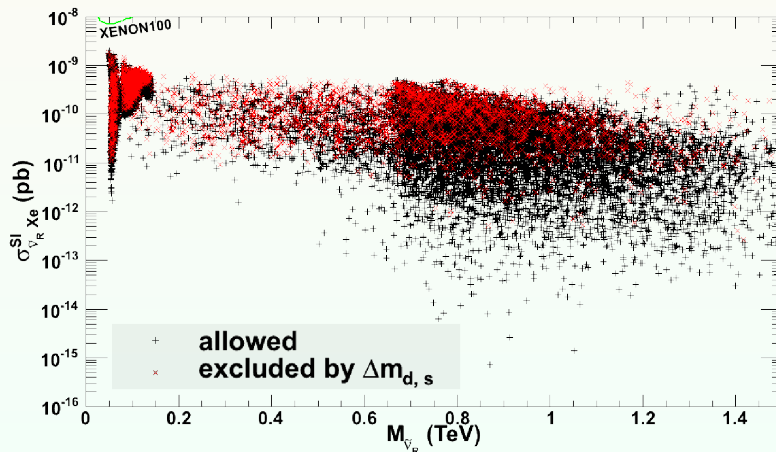
- * WIMP mass near $m_{h_1}/2$
- * WIMP mass near $M_{Z_2}/2$ (also $m_{h_i}/2$)
- * WIMP mass near $m_{h_i}/2$ or above W pair threshold
- * Coannihilation processes (mainly higgsino-like)



Scattering on nucleons

For some $U'(1)$ models we can have a good suppression of the gauge boson or/and Higgs boson contribution

here $U(1)_\psi \Rightarrow \theta_{E_6} = \pi/2$

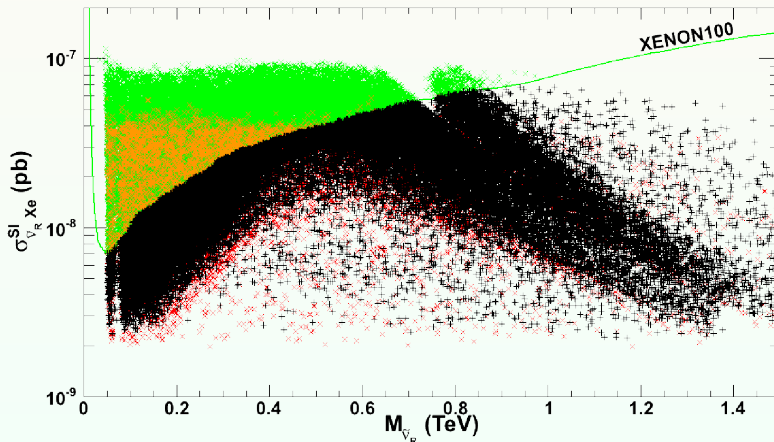


Scattering on nucleons

For other models, huge constraints on the parameter space appear

here $U(1)_\eta \Rightarrow \tan \theta_{E_6} = -\sqrt{5/3}$

OK, $\Delta m_{d,s}$, XENON100, both

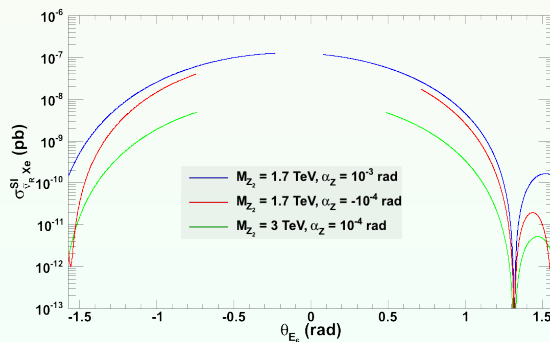


Scattering on nucleons

Abelian gauge boson contribution to direct detection cross section :

$$\sigma_{\tilde{\nu}_R N}^{Z_1, Z_2} = \frac{\mu_{\tilde{\nu}_R N}^2}{\pi} (g_1' Q_\nu')^2 [(y(1 - 4s_W^2) + y')Z + (-y + 2y')(A - Z)]^2$$

$$y = \frac{g_Y \sin \alpha_Z \cos \alpha_Z}{4 \sin \theta_W} \left(\frac{1}{M_{Z_2}^2} - \frac{1}{M_{Z_1}^2} \right), \quad y' = -\frac{g_1'}{2} Q_V^d \left(\frac{\sin^2 \alpha_Z}{M_{Z_1}^2} + \frac{\cos^2 \alpha_Z}{M_{Z_2}^2} \right)$$



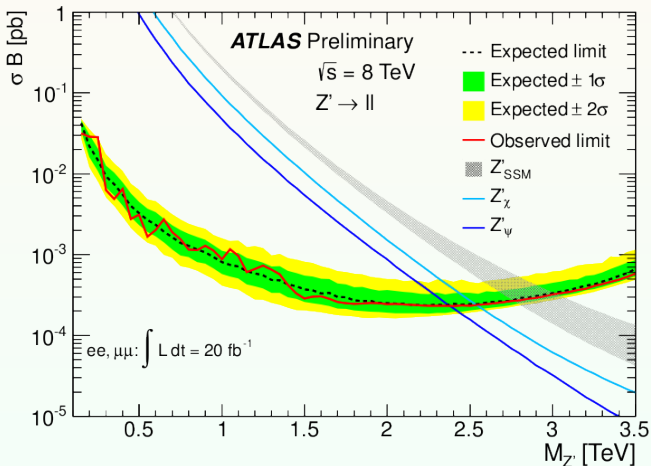
$\Rightarrow$ stringent constraints for small $|\theta_{E6}|$ because of Q_V^d term

Low $\tan \beta$ region

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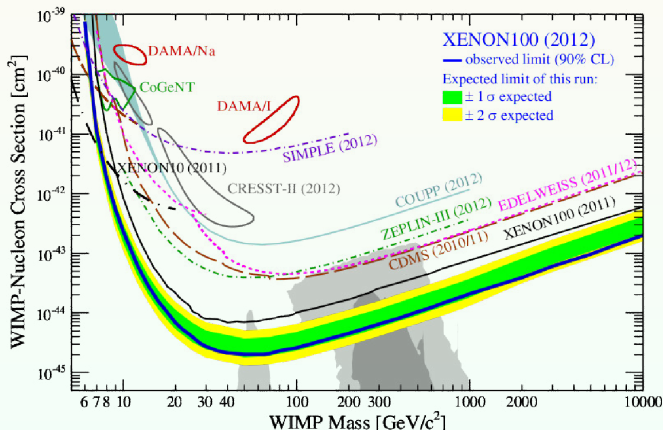
Constraints - Z'

✱ Z' heavy $\Rightarrow$ heavy singlet-like Higgs boson $\Rightarrow$ h_2 mostly doublet-like



Constraints - DM

- DM observables for either neutralino or RH sneutrino DM candidate :
 - $\Omega_{\text{LSP}} h^2 < 0.1221$ (2σ Planck+WP+highL+BAO upper bound)
 - SI WIMP-nucleon cross section limits from XENON100 (a posteriori)



E. Aprile et al., XENON100 Collaboration, [arXiv:1207.5988]

Constraints - Higgs + low energy observables

- Theoretical uncertainties (see **B. C. Allanach, A. Djouadi, J. L. Kneur, W. Porod, P. Slavich, [arXiv:hep-ph/0406166]**)
 $\rightarrow m_{h_1} \in [120.63, 130.63] \text{ GeV}$
- Higgs boson signal strengths and low energy observables (a posteriori)
 $\Rightarrow$ Modification of the `NMSSMTools` code : `UMSSMTools`
 Limits on signal strengths using **G. Bélanger, B. Dumont, U. Ellwanger, J. F. Gunion, S. Kraml, [arXiv:1306.2941]** : $\chi_i^2 \lesssim 6$ with $h_1 \rightarrow i$, $i \in \gamma\gamma, VV^*, b\bar{b}, \tau^+\tau^-$

Observable	Value
$\mathcal{B}(B^\pm \rightarrow \tau^\pm \nu_\tau)$	$(0.99 \pm 0.25) \times 10^{-4}$ UTfit
$\mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-)$	$(2.95^{+0.74}_{-0.67}) \times 10^{-9}$ LHCb + CMS
ΔM_s	$17.719 \pm 0.043 \text{ ps}^{-1}$ HFAG
ΔM_d	$0.507 \pm 0.004 \text{ ps}^{-1}$ HFAG
$\mathcal{B}(\bar{B}^0 \rightarrow X_s \gamma)$	$(3.55 \pm 0.24 \pm 0.09) \times 10^{-4}$ HFAG

Scan

Scanning the parameter space :

★ Nuisance parameters :

★ $m_t = 175.5 \pm 1$ GeV **PDG 2012**

★ Quark content of the nucleon (from **G. Bélanger, F. Boudjema, A. Pukhov, A. Semenov, [arXiv:1305.0237]**)

Parameter	Value
m_u/m_d	0.46 ± 0.05
m_s/m_d	27.5 ± 0.3
$\sigma_{\pi N}$	34 ± 2 MeV
σ_S	42 ± 5 MeV

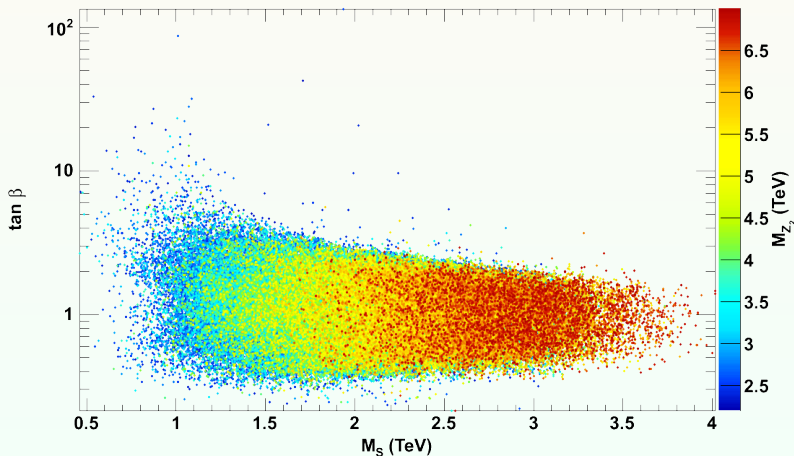
★ UMSSM parameters :

Parameter	Range	Parameter	Range
$m_{\tilde{\nu}_R}$	[0.05, 2] TeV	A_λ	[0, 4] TeV
M_{Z_2}	[2.2, 7] TeV	A_t, A_b, A_τ	[-4, 4] TeV
α_Z	$[-10^{-3}, 10^{-3}]$ rad	$m_{\tilde{Q}_3}, m_{\tilde{u}_3}, m_{\tilde{d}_3}, m_{\tilde{L}_3}, m_{\tilde{e}_3}$	[0, 3] TeV
θ_{E_6}	$[-\pi/2, \pi/2]$ rad	μ, M_1, M'_1	[0.1, 2] TeV

First and second generation sfermion soft mass terms at 3 TeV

$\tan \beta$

- * $\tan \beta \approx 1 + \text{TeV-scale } M_S \Rightarrow$ expected m_{h_1} :
large contribution from pure UMSSM as well as one-loop stop terms

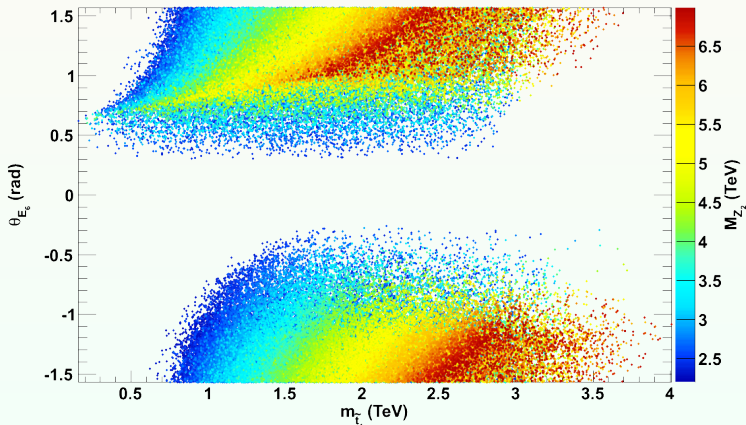


Sfermion masses

- ★ Important UMSSM contribution to sfermion masses (dependent on θ_{E_6}) :

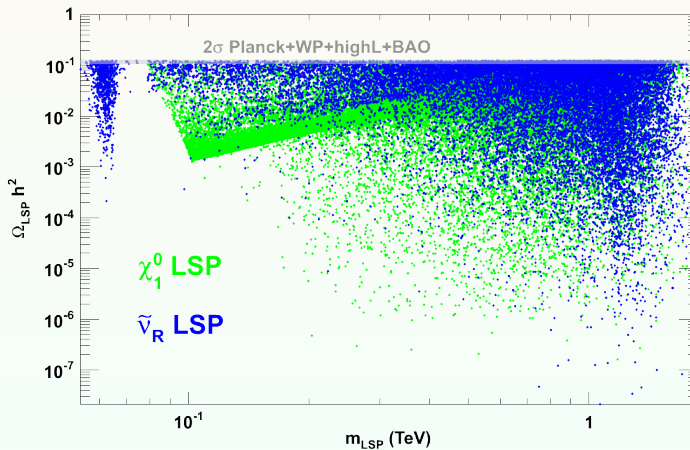
$$\Delta_f = \frac{1}{2} g_1'^2 Q_f' (Q_{H_d}' v_d^2 + Q_{H_u}' v_u^2 + Q_S' v_s^2)$$

⇒ Condition on neutral LSP put strong constraints on θ_{E_6}



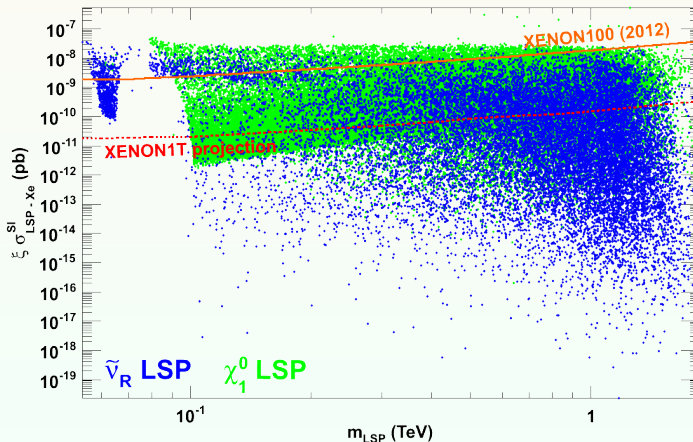
LSP abundance

- * $\tilde{B}$, $\tilde{H}$ and $\tilde{\nu}_R$ LSP with the experimentally allowed abundance



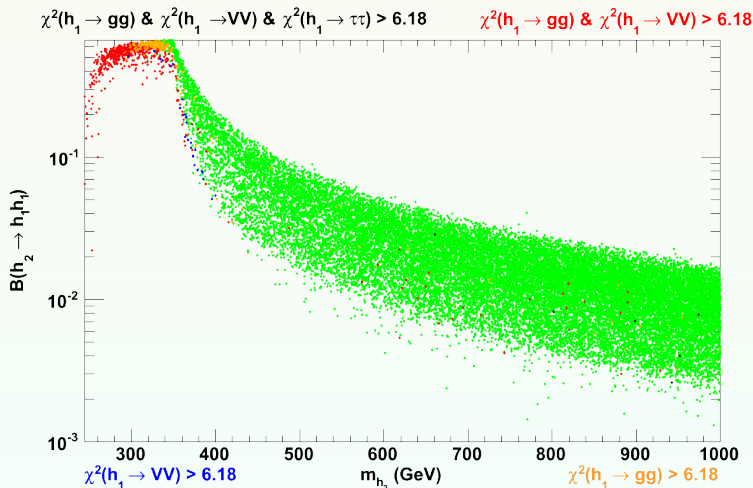
Direct detection

- * $\tilde{B}, \tilde{H}$ and $\tilde{\nu}_R$ LSP with the wanted abundance
- * DM direct detection experiments can probe entirely some regions, especially for $\tilde{\nu}_R$ LSP



h_1 signal strength and h_2 bounds

- h_1 signal strength mostly compatible with current limits, but also useful to exclude “light” h_2 ($\lesssim 300$ GeV) ; large branching ratio into SM-like Higgs boson for such h_2



Conclusions

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- ✱ RH sneutrinos are viable DM candidates in the UMSSM
- ✱ New D-terms in the UMSSM $\Rightarrow$ low $\tan\beta$ values still allowed for TeV-scale M_S
 $\Rightarrow$ sfermion sector impacted
- ✱ χ_1^0 or $\tilde{\nu}_R$ LSP that does not overclose the Universe exclude a large region of the parameter space
- ✱ Viable or excluded regions depend strongly on θ_{E_6}
- ✱ XENON1T would probe entirely some scenarios
- ✱ Study of the SM-like Higgs boson puts bounds on the second CP-even Higgs boson : $m_{h_2} \lesssim 300$ GeV excluded in the UMSSM

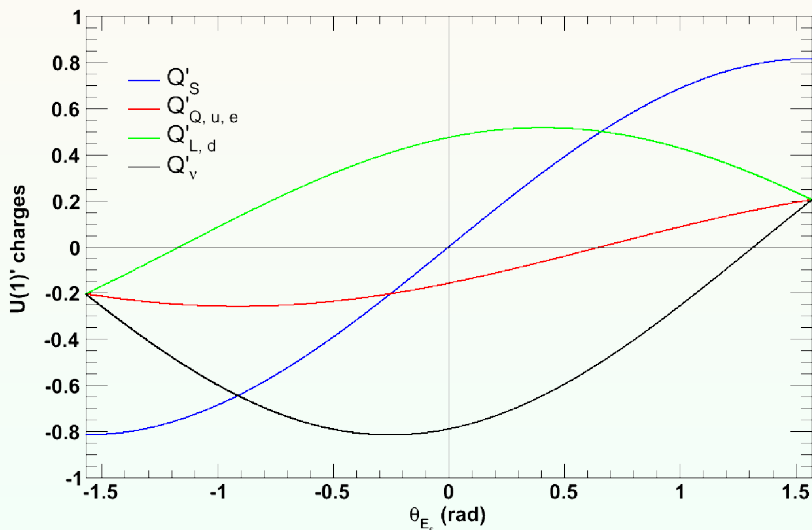
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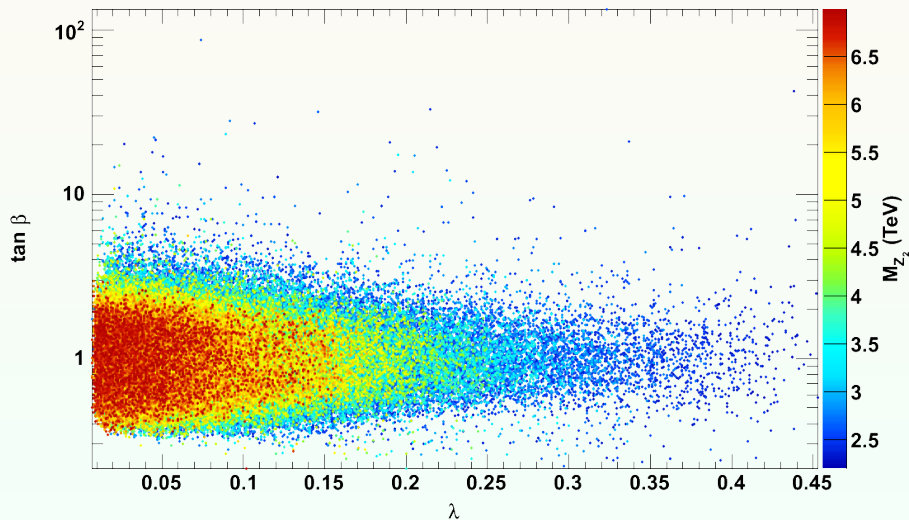
Thanks for your attention !

BACKUP

BACKUP



BACKUP



BACKUP

New contribution from the Z' to $\Delta\rho$: $\Delta\rho < 2 \times 10^{-3} \rightarrow -6.5 \times 10^{-4} \lesssim \alpha_Z \lesssim 6.9 \times 10^{-4}$

