Phenomenological aspects of the UMSSM

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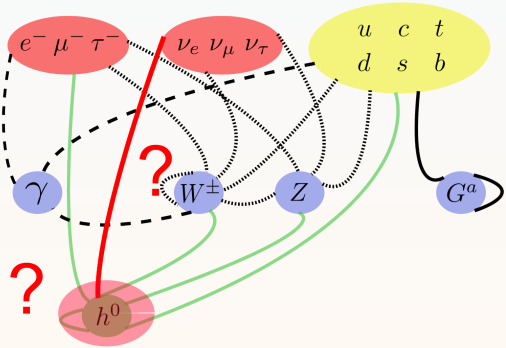
G. Bélanger, JDS and A. Pukhov, JCAP 1112 (2011) 014, [arXiv:1110.2414]
JDS, PhD thesis : [arXiv:1312.0257]
G. Bélanger, JDS et al., in progress

Outline

Introduction

Drawbacks of the Standard Models

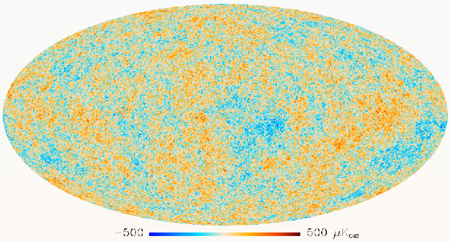
- **Particle Physics (SM)**
  - **Hierarchy problem** between EW ($\sim$ 100 GeV) and Planck ($\sim 10^{19}$ GeV) scales
    Quadratic divergences to the Higgs boson mass squared
  - **Grand Unification** (GUT)
  - **Neutrino sector** (Dirac, Majorana ? ?)
  - ...



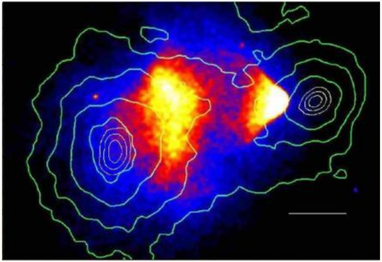
SM interactions, at tree-level

Drawbacks of the Standard Models

- **Cosmology (ΛCDM)**
  - 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]

Drawbacks of the Standard Models

Cosmology (ΛCDM)

- 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, ...)
- 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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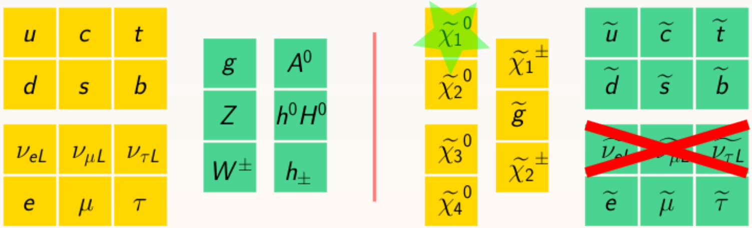
  $\Rightarrow$ DM candidates in supersymmetric models

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



Drawbacks of the MSSM

✷ **The μ-problem :**

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

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

$$M^2_Z = \frac{|m^2_{H_d} - m^2_{H_u}|}{\sqrt{1 - \sin^2 2\beta}} - m^2_{H_u} - m^2_{H_d} - 2|\mu|^2$$

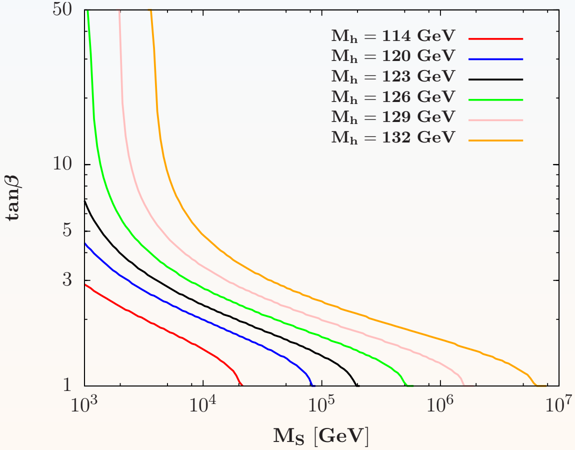
No fine-tuned cancellation to obtain the expected Z boson mass needs $b, m^2_{H_u}, m^2_{H_d}$ and $\mu \sim (10 - 100) \times M^2_Z$:

- ✔ **SUSY breaking parameters $b, m^2_{H_u}$ and $m^2_{H_d}$**
- ✘ μ

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

Drawbacks of the MSSM

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



A. Djouadi, J. Quevillon, [arXiv:1304.1787]

Possible solutions

- Generating an effective μ term thanks to a Yukawa coupling λ between $\mathbf{H_u}, \mathbf{H_d}$ and a new scalar field S

$$\mathcal{W}_{\mathsf{MSSM}} \to \mathcal{W}_{\mathsf{MSSM}}|_{\mu=0} + \lambda \mathbf{S H_u H_d}$$

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

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

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

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

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

The model

E_6 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 E_6 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],...)
  $E_6 \to SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\chi \times U(1)_\psi$

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$E_6 \to SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\chi \times U(1)_\psi$
- Low energy gauge symmetry considered : $SU(3)_c \times SU(2)_L \times U(1)_Y \times U'(1)$
Coupling constants : g_3, g_2, g_Y and $g'_1 = \sqrt{\frac{5}{3}} g_Y$
- $U'(1)$ charge :

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

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

	$\mathcal{Q}'_Q$	$\mathcal{Q}'_u$	$\mathcal{Q}'_d$	$\mathcal{Q}'_L$	$\mathcal{Q}'_\nu$	$\mathcal{Q}'_e$	$\mathcal{Q}'_{H_u}$	$\mathcal{Q}'_{H_d}$	$\mathcal{Q}'_S$
$\sqrt{40}\mathcal{Q}'_\chi$	-1	-1	3	3	-5	-1	2	-2	0
$\sqrt{24}\mathcal{Q}'_\psi$	1	1	1	1	1	1	-2	-2	4

Content

- **Superpotential :**

$$\mathcal{W}_{\mathbf{UMSSM}} = \mathcal{W}_{\mathbf{MSSM}}|_{\mu=0} + \lambda \mathbf{S H_u H_d} + \tilde{\nu}_{\mathbf{R}}^{*} \mathbf{y}_{\nu} \widetilde{\mathbf{L}} \mathbf{H_u} + \mathcal{O}(\mathbf{TeVs})$$

- **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 :
  $m_{h_1}^2 \leq M_Z^2 \cos^2 2\beta + \frac{1}{2}\lambda^2 v^2 \sin^2 2\beta + g_1'^2 v^2 (\mathcal{Q}'_{H_d} \cos^2\beta + \mathcal{Q}'_{H_u} \sin^2\beta)^2 + \Delta m_h^2$

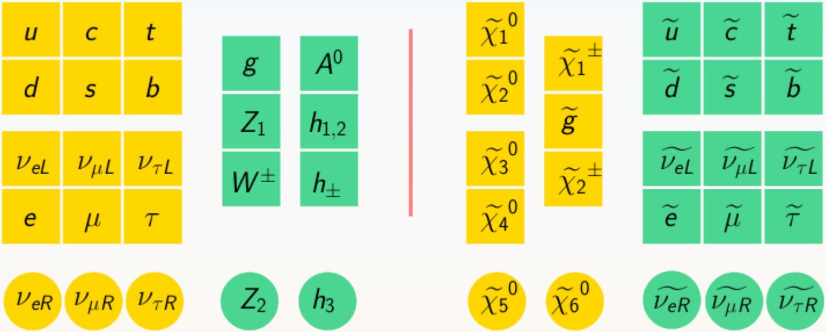
- **Gauge sector : Physical abelian gauge bosons : Z_1 and Z_2, mixing between the Z of the SM and the Z', α_Z is the mixing angle $\Rightarrow$ $\tan\beta$ constrained**

$$\mathbf{Z_1} = \cos\alpha_Z \mathbf{Z} + \sin\alpha_Z \mathbf{Z'},$$
$$\mathbf{Z_2} = -\sin\alpha_Z \mathbf{Z} + \cos\alpha_Z \mathbf{Z'},$$

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

Content

✷ **To sum up :**



Content

- **To sum up :**

u	c	t
d	s	b
ν_{eL}	$\nu_{\mu L}$	$\nu_{\tau L}$
e	μ	τ
ν_{eR}	$\nu_{\mu R}$	$\nu_{\tau R}$

g	A^0
Z_1	$h_{1,2}$
$W^\pm$	$h_\pm$
Z_2	h_3

$\tilde{\chi}_1^0$	$\tilde{\chi}_1^\pm$
$\tilde{\chi}_2^0$	$\tilde{g}$
$\tilde{\chi}_3^0$	$\tilde{\chi}_2^\pm$
$\tilde{\chi}_4^0$	
$\tilde{\chi}_5^0$	$\tilde{\chi}_6^0$

$\tilde{u}$	$\tilde{c}$	$\tilde{t}$
$\tilde{d}$	$\tilde{s}$	$\tilde{b}$
$\widetilde{\nu_{eL}}$	$\widetilde{\nu_{\mu L}}$	$\widetilde{\nu_{\tau L}}$
$\tilde{e}$	$\tilde{\mu}$	$\tilde{\tau}$
$\widetilde{\nu_{eR}}$	$\widetilde{\nu_{\mu R}}$	$\widetilde{\nu_{\tau R}}$

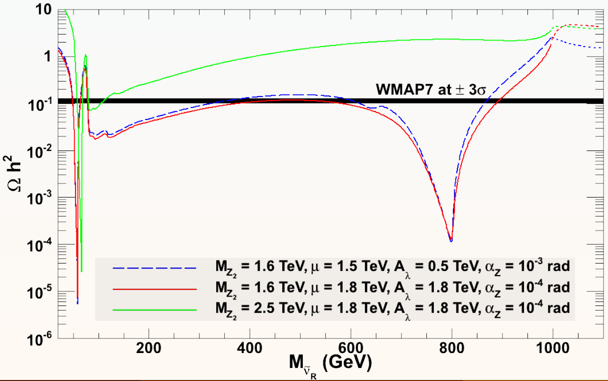
- **Right-Handed (RH) sneutrinos : are they viable DM candidates ?**

RH sneutrino DM candidate

WIMP annihilation

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

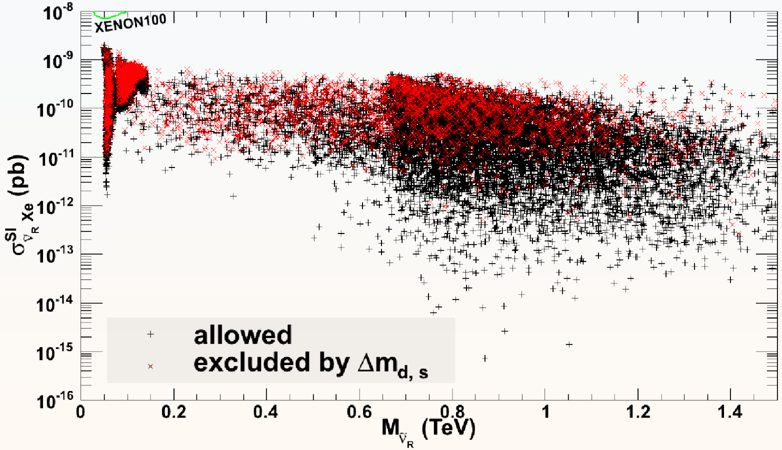
- WIMP mass near $m_{h_1}/2$
- WIMP mass near $M_{Z_2}/2$ (also $m_{h_i}/2$)
- WIMP mass near $m_{h_i}/2$ or above W pair threshold
- Coannihilation processes (mainly higgsino-like)



Scattering on nucleons

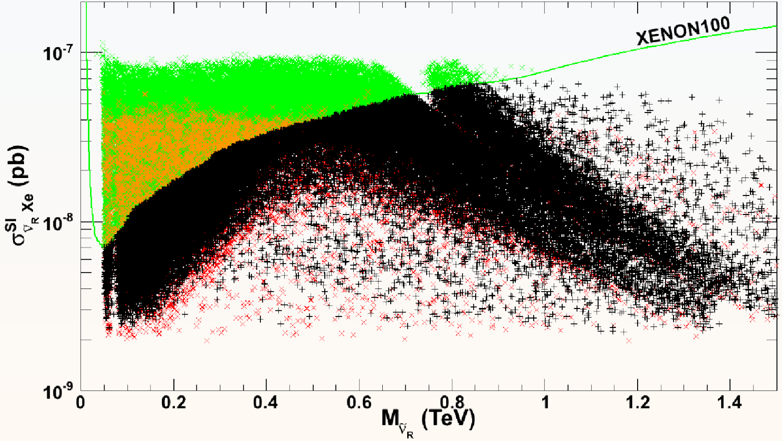
For some $U'(1)$ models we can have a good suppression of the gauge boson or/and Higgs boson contribution

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



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**

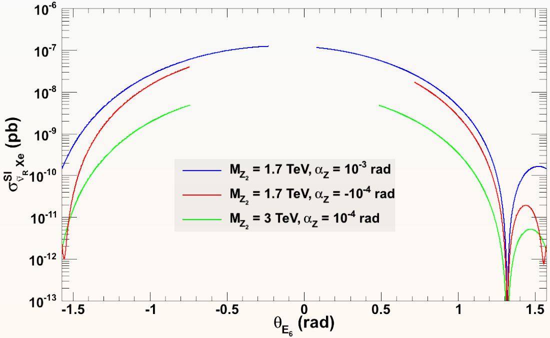


Scattering on nucleons

Abelian gauge boson contribution to direct detection cross section :

$$\sigma^{Z_1,Z_2}_{\tilde{\nu}_R N} = \frac{\mu^2_{\tilde{\nu}_R N}}{\pi}(g'_1 \mathcal{Q}'_\nu)^2[(y(1-4s^2_W)+y')Z+(-y+2y')(A-Z)]^2$$

$$\text{with } y = \frac{g_Y \sin\alpha_Z \cos\alpha_Z}{4\sin\theta_W}\left(\frac{1}{M^2_{Z_2}}-\frac{1}{M^2_{Z_1}}\right),\ y' = -\frac{g'_1}{2}Q'^d_V\left(\frac{\sin^2\alpha_Z}{M^2_{Z_1}}+\frac{\cos^2\alpha_Z}{M^2_{Z_2}}\right)$$

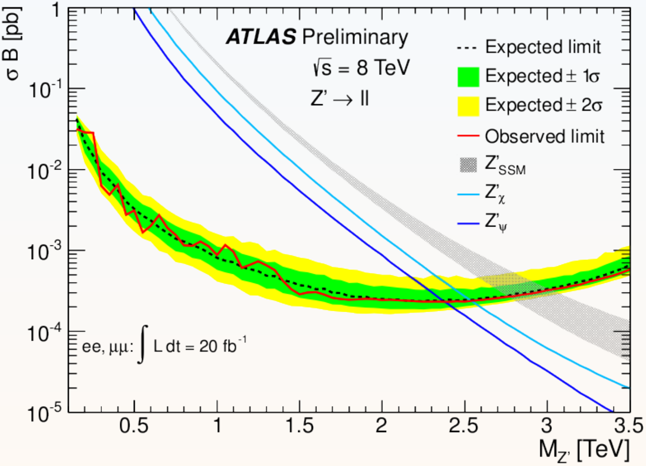


$\Rightarrow$ **stringent constraints for small $|\theta_{E_6}|$ because of Q'^d_V term**

Low $\tan\beta$ region

Constraints - Z'

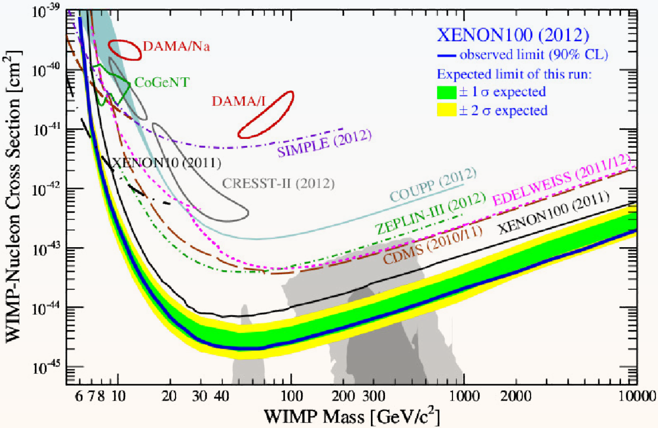
- Z' heavy $\Rightarrow$ heavy singlet-like Higgs boson $\Rightarrow$ h_2 mostly doublet-like



ATLAS Collaboration, http://cds.cern.ch/record/1525524

Constraints - DM

- DM observables for either neutralino or RH sneutrino DM candidate :
  - $\Omega_{\rm LSP}h^2 < 0.1221$ (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])**
  $\rightarrow \mathbf{m_{h_1}} \in [120.63, 130.63]$ **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] : $\chi^2_i \lesssim 6$ **with** $h_1 \rightarrow i, \quad i \in \gamma\gamma, VV^*, b\bar{b}, \tau^+\tau^-$

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

Scan

Scanning the parameter space :

- **Nuisance parameters :**
  - $\mathbf{m_t} = 175.5 \pm 1$ **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 $\pm$ 0.05
m_s/m_d	27.5 $\pm$ 0.3
$\sigma_{\pi N}$	34 $\pm$ 2 MeV
σ_s	42 $\pm$ 5 MeV

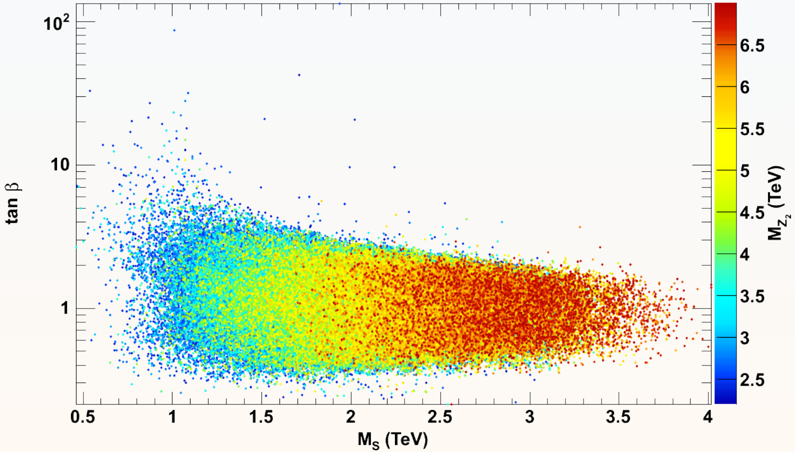
- **UMSSM parameters :**

Parameter	Range	Parameter	Range
$\mathbf{m_{\tilde{\nu}_R}}$	[0.05, 2] TeV	$\mathbf{A_\lambda}$	[0, 4] TeV
$\mathbf{M_{Z_2}}$	[2.2, 7] TeV	$\mathbf{A_t}, \mathbf{A_b}, \mathbf{A_\tau}$	[-4, 4] TeV
$\alpha_\mathbf{Z}$	[-10^{-3}, 10^{-3}] rad	$\mathbf{m_{\tilde{Q}_3}}, \mathbf{m_{\tilde{u}_3}}, \mathbf{m_{\tilde{d}_3}}, \mathbf{m_{\tilde{L}_3}}, \mathbf{m_{\tilde{e}_3}}$	[0, 3] TeV
$\theta_{\mathbf{E_6}}$	[-$\pi/2$, $\pi/2$] rad	$\mu, \mathbf{M_1}, \mathbf{M_1'}$	[0.1, 2] TeV

First and second generation sfermion soft mass terms at 3 TeV

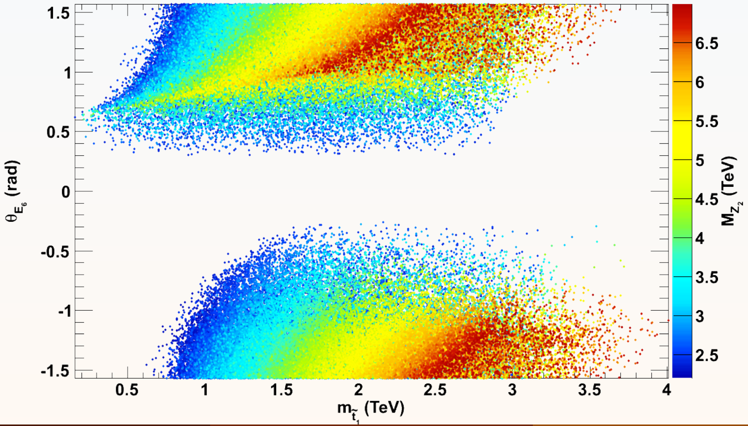
tan β

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



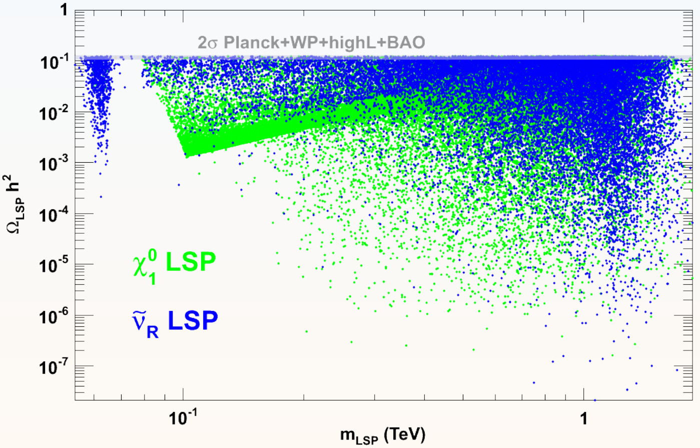
Sfermion masses

- **Important UMSSM contribution to sfermion masses (dependent on θ_{E_6}) :**
  $\Delta_f = \frac{1}{2} {g'_1}^2 \mathcal{Q}'_f (\mathcal{Q}'_{H_d} v_d^2 + \mathcal{Q}'_{H_u} v_u^2 + \mathcal{Q}'_S v_s^2)$
  $\Rightarrow$ **Condition on neutral LSP put strong constraints on θ_{E_6}**



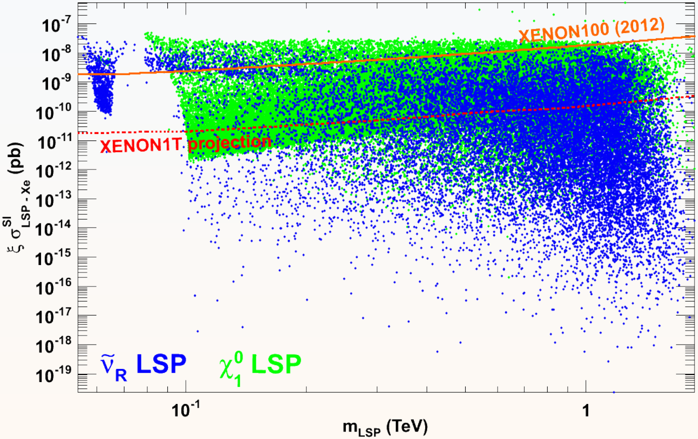
LSP abundance

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



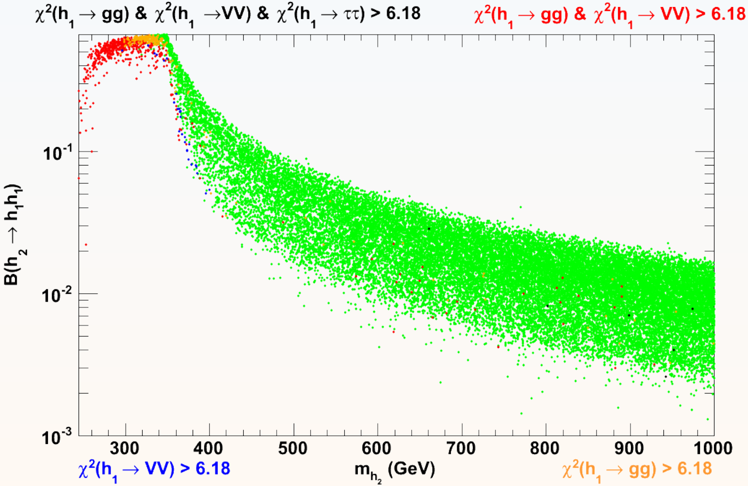
Direct detection

- $\widetilde{\mathrm{B}}, \widetilde{\mathrm{H}}$ and $\tilde{\nu}_{\mathrm{R}}$ LSP with the wanted abundance
- DM direct detection experiments can probe entirely some regions, especially for $\tilde{\nu}_{\mathrm{R}}$ 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^0_1 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

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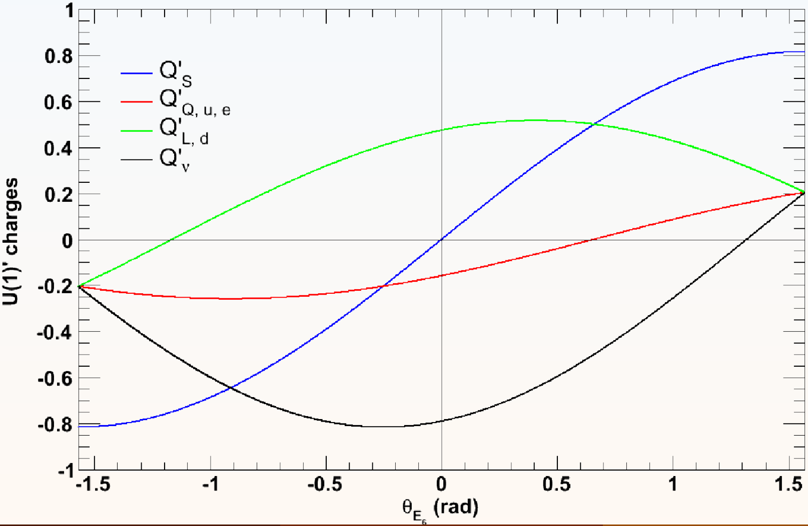
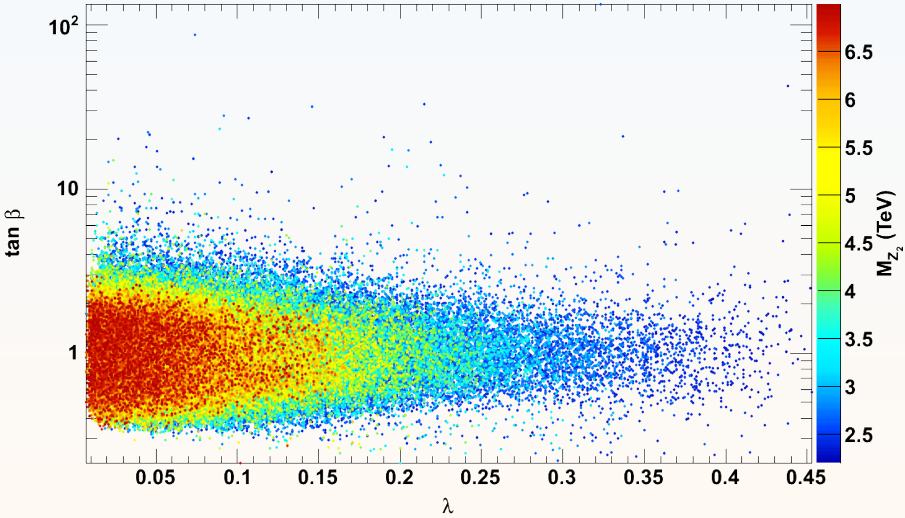


Q'S
Q'Q, u, e
Q'L, d
Q'ν
U(1)' charges
θE6 (rad)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.5
-1
-0.5
0
0.5
1
1.5

BACKUP



10^2
10
1
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
tan β
λ
6.5
6
5.5
5
4.5
4
3.5
3
2.5
M_{Z_2} (TeV)

BACKUP

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