Phenomenological aspects of the UMSSM

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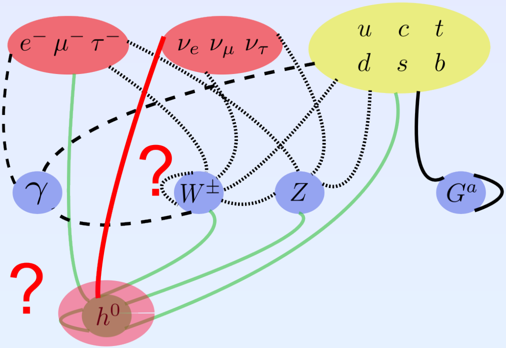
G. Bélanger, JDS and A. Pukhov, JCAP 1112 (2011) 014, [arXiv:1110.2414]
JDS, PhD thesis : [arXiv:1312.0257]
G. Bélanger, JDS et al., in progress

Outline

Introduction

Drawbacks of the Standard Models

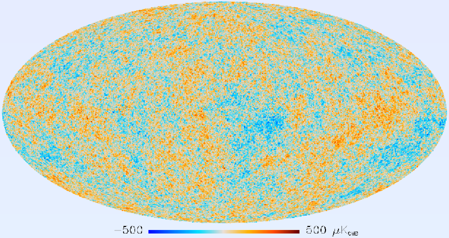
- **Particle Physics (SM)**
  - **Hierarchy problem** between EW ($\sim$ 100 GeV) and higher scales (Planck $\sim 10^{19}$ GeV, inflation $\sim 10^{16}$ GeV with BICEP2 measurements, [arXiv:1403.3985] ??)
  - **Grand Unification** (GUT)
  - **Neutrino sector** (Dirac, Majorana ??)
  - ...



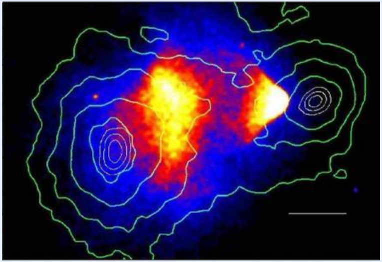
SM interactions, at tree-level

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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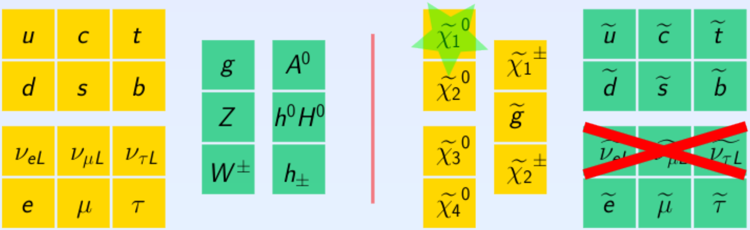
  ## ⇒ DM candidates in supersymmetric models

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



Drawbacks of the MSSM

✷ **The μ-problem :**

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

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

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

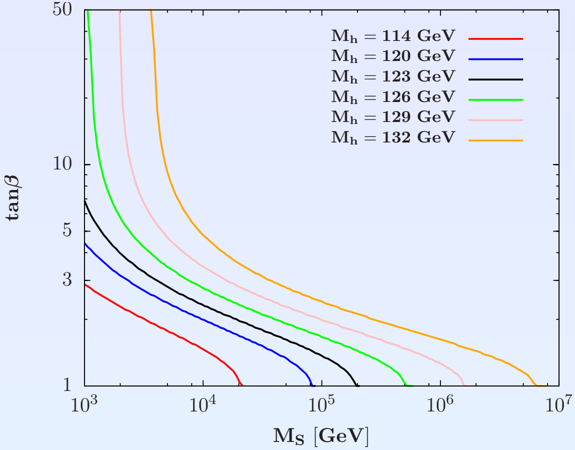
No fine-tuned cancellation to obtain the expected Z boson mass needs $\mathsf{b}, \mathsf{m}_{\mathsf{H_u}}^2, \mathsf{m}_{\mathsf{H_d}}^2$ and $\mu \sim (10 - 100) \times \mathsf{M_Z^2}$:

- ✔ **SUSY breaking parameters $\mathsf{b}, \mathsf{m}_{\mathsf{H_u}}^2$ and $\mathsf{m}_{\mathsf{H_d}}^2$**
- ✘ 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 $\approx$ 125 GeV
  $\Rightarrow$ 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 H_u, H_d and a new scalar field S

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

- Avoiding very small λ (new $U(1)_{PQ}$ global symmetry $\to$ 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 $\to$ domain walls, S. A. Abel, S. Sarkar and P. L. White, [arXiv:hep-ph/9506359])

$\to$ variants of the NMSSM

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- **Promoting the new $U(1)_{PQ}$ 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],...)**
  $E_6 \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\chi \times U(1)_\psi$

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  $E_6 \to SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\chi \times U(1)_\psi$
- 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	$\Rightarrow \theta_{E_6} = 0$
$\sqrt{24}\mathcal{Q}'_\psi$	1	1	1	1	1	1	-2	-2	4	$\Rightarrow \theta_{E_6} = \pi/2$

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**

$$Z_1 = \cos\alpha_Z Z + \sin\alpha_Z Z'$$

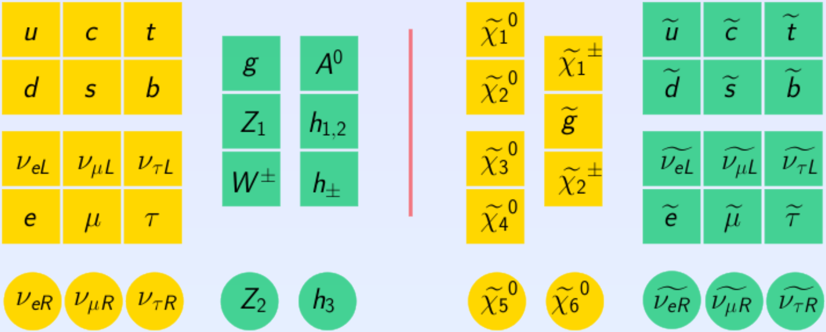
$$Z_2 = -\sin\alpha_Z Z + \cos\alpha_Z Z'$$

$$\cos^2\beta = \frac{1}{\mathcal{Q}'_{H_d} + \mathcal{Q}'_{H_u}} \left(\frac{\sin 2\alpha_Z (M_{Z_1}^2 - M_{Z_2}^2)}{v^2 g_1' \sqrt{g_Y^2 + g_2^2}} + \mathcal{Q}'_{H_u} \right)$$

- **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

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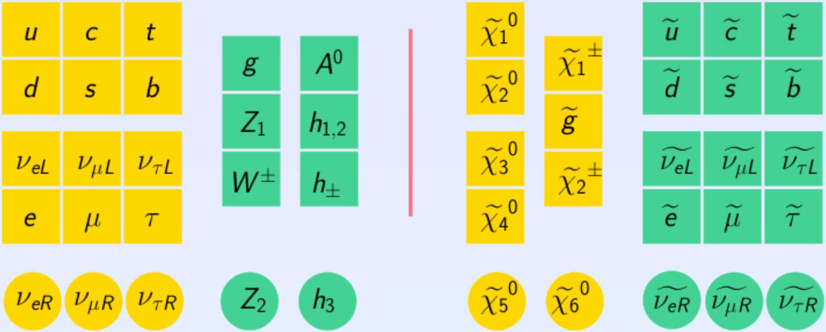


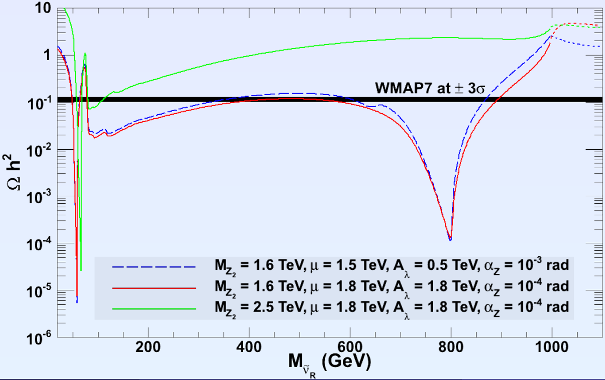
- **Right-Handed (RH) sneutrinos : are they viable DM candidates ?**

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 $\boxed{\text{from 50 GeV to TeV-scale}}$:

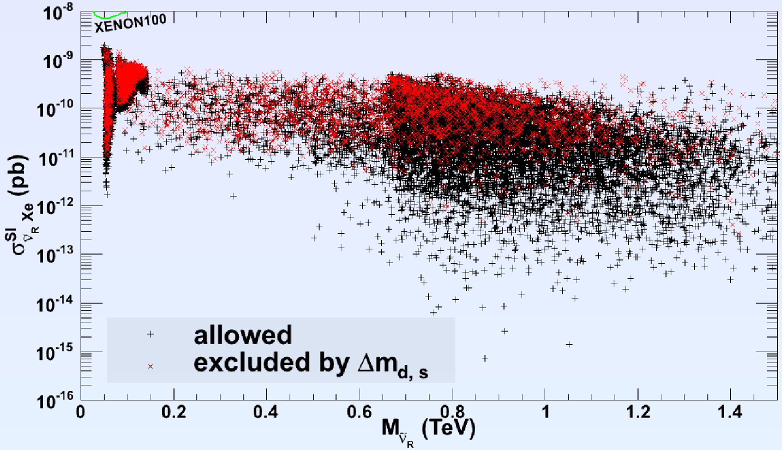
- ✷ WIMP mass near $m_{h_1}/2$
- ✷ WIMP mass near $M_{Z_2}/2$ (also $m_{h_i}/2$)
- ✷ WIMP mass near $m_{h_i}/2$ or above W pair threshold
- ✷ Coannihilation processes (mainly higgsino-like)



Scattering on nucleons

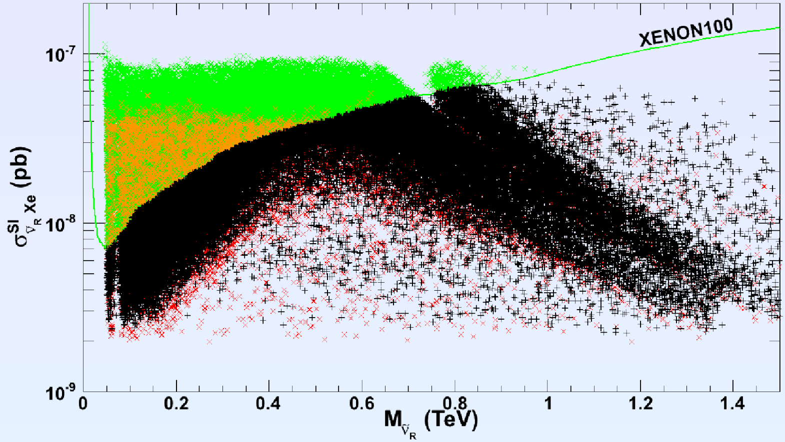
For some $U'(1)$ models we can have a good suppression of the gauge boson or/and Higgs boson contribution

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

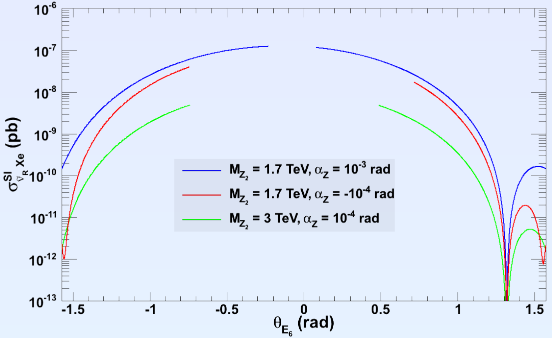


Scattering on nucleons

Abelian gauge boson contribution to direct detection cross section :

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

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

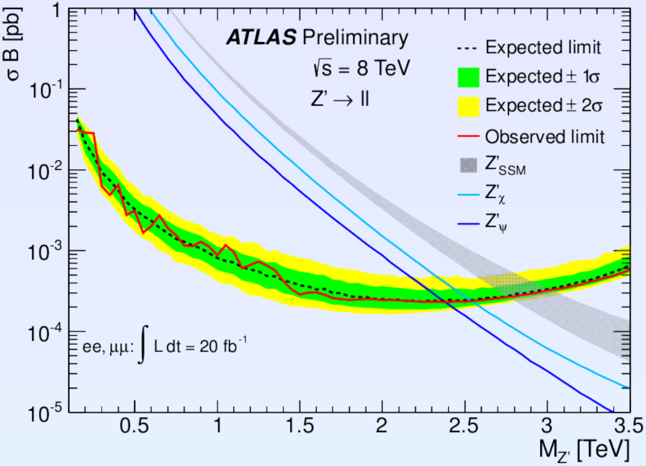


$\Rightarrow$ **stringent constraints for small $|\theta_{E_6}|$ because of Q'^d_V term**

Low $\tan\beta$ region

Constraints - Z'

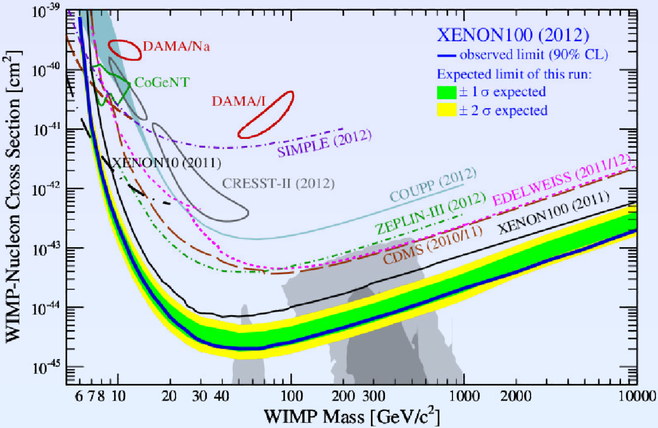
- Z' heavy $\Rightarrow$ heavy singlet-like Higgs boson $\Rightarrow$ h_2 mostly doublet-like



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])**
  $\rightarrow m_{h_1} \in [120.63, 130.63]$ **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] : $\chi_i^2 \lesssim 6$ **with** $h_1 \rightarrow i, \quad i \in \gamma\gamma, VV^*, b\bar{b}, \tau^+\tau^-$

Observable	Value
$\mathscr{B}(B^\pm \rightarrow \tau^\pm \nu_\tau)$	$(0.99 \pm 0.25)\times 10^{-4}$ UTfit
$\mathscr{B}(B_s^0 \rightarrow \mu^+\mu^-)$	$(2.95\,^{+0.74}_{-0.67})\times 10^{-9}$ LHCb + CMS
ΔM_s	17.719 ± 0.043 ps^{-1} HFAG
ΔM_d	0.507 ± 0.004 ps^{-1} HFAG
$\mathscr{B}(\bar{B}^0 \rightarrow X_s\gamma)$	$(3.55 \pm 0.24 \pm 0.09)\times 10^{-4}$ 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 ± 0.05
m_s/m_d	27.5 ± 0.3
$\sigma_{\pi N}$	34 ± 2 MeV
σ_s	42 ± 5 MeV

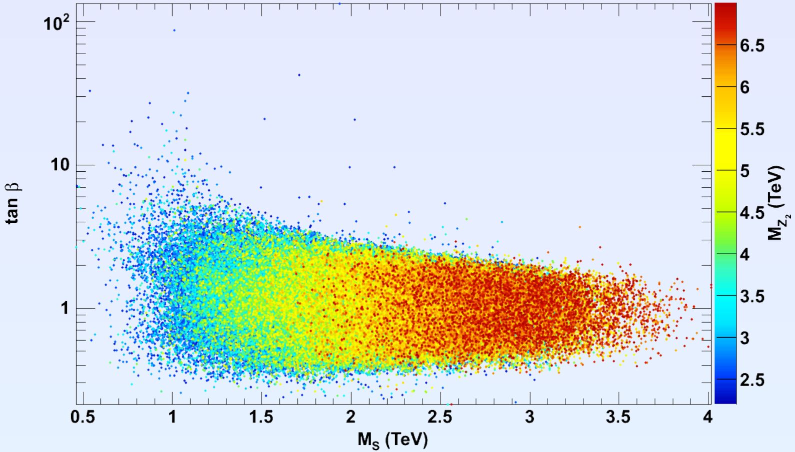
- **UMSSM parameters :**

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

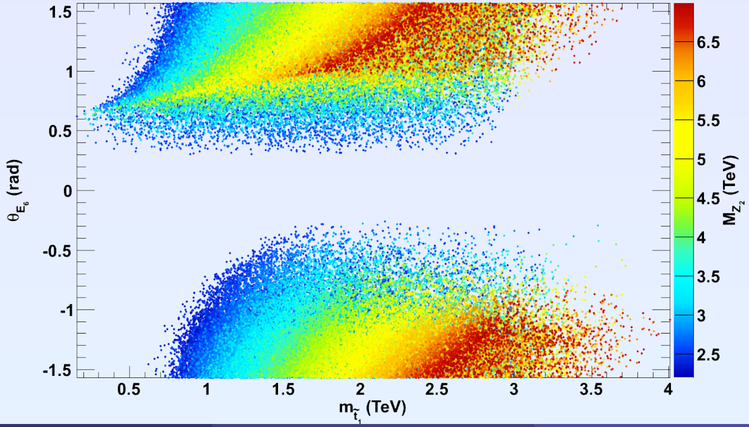
$\tan\beta$

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



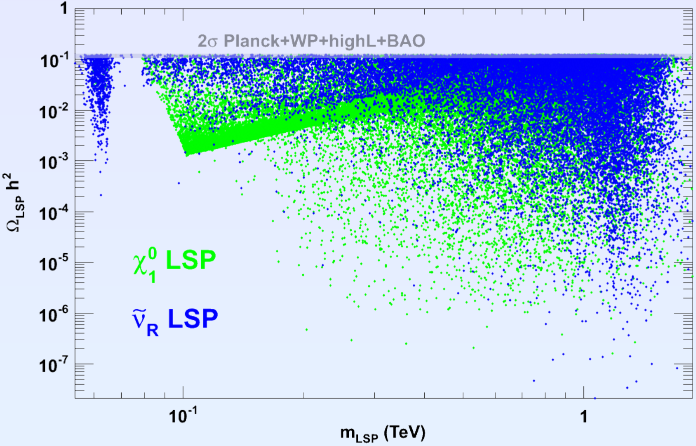
Sfermion masses

- **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}**



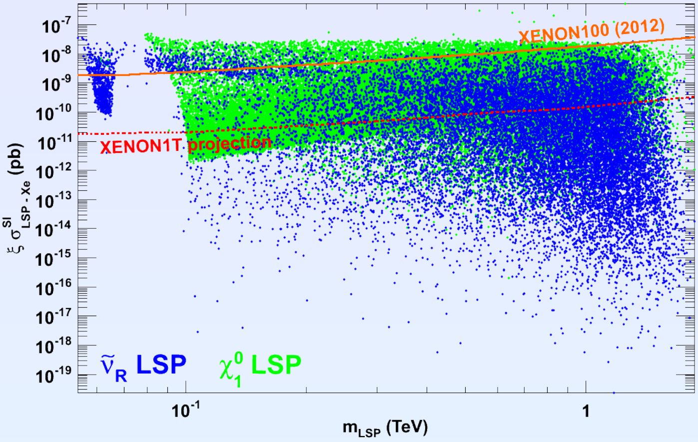
LSP abundance

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



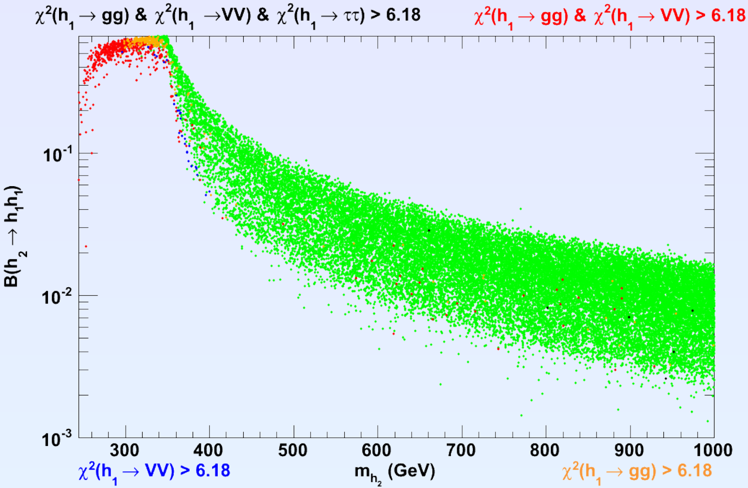
Direct detection

- $\widetilde{B}, \widetilde{H}$ 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

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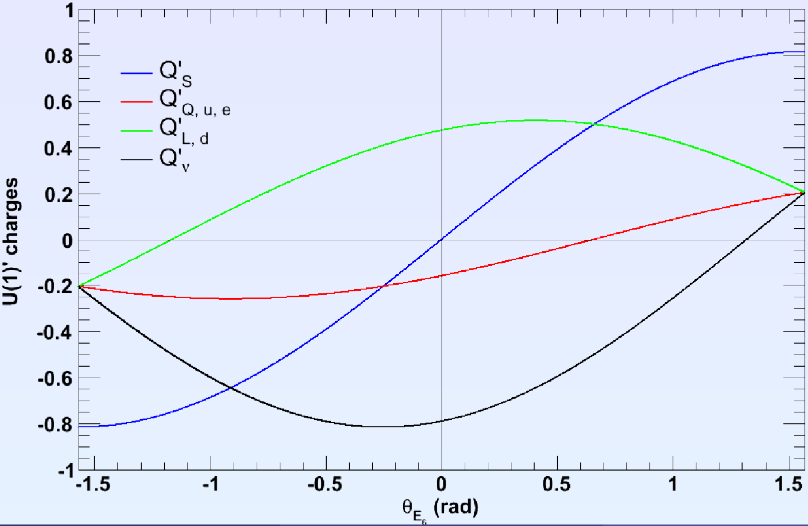
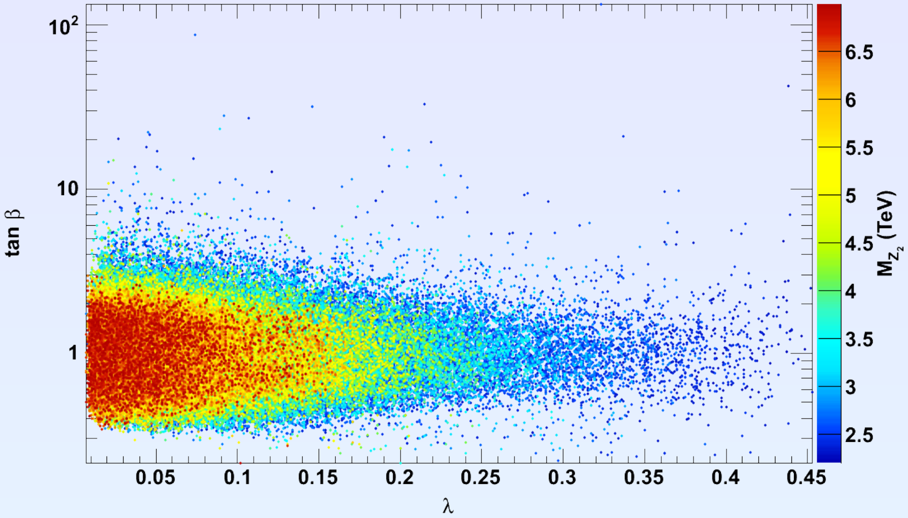


Q'S
Q'Q, u, e
Q'L, d
Q'ν
U(1)' charges
θE6 (rad)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.5
-1
-0.5
0
0.5
1
1.5

BACKUP



10^2
10
1
tan β
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
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 $\Delta\rho$: $\Delta\rho < 2 \times 10^{-3} \rightarrow -6.5 \times 10^{-4} \lesssim \alpha_Z \lesssim 6.9 \times 10^{-4}$