

Phenomenological aspects of the UMSSM

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G. Bélanger, JDS and A. Pukhov, JCAP 1112 (2011) 014, [[arXiv:1110.2414](https://arxiv.org/abs/1110.2414)]

JDS, PhD thesis : [[arXiv:1312.0257](https://arxiv.org/abs/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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2 The model

3 RH sneutrino DM candidate

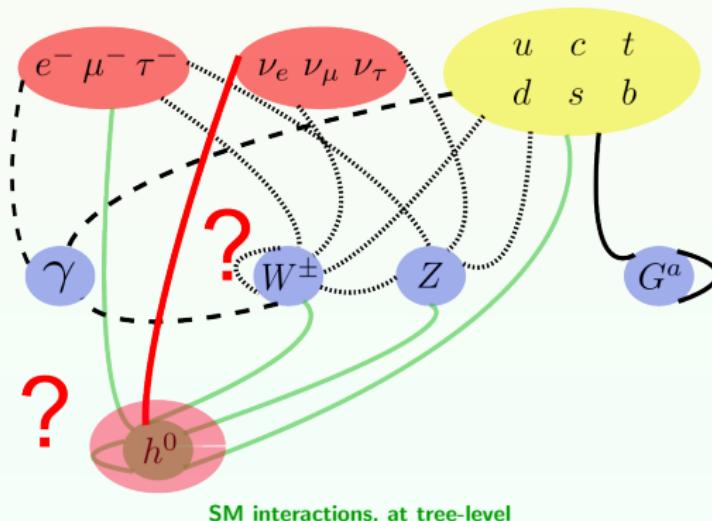
4 Low $\tan \beta$ region

5 Conclusions

Drawbacks of the Standard Models

* Particle Physics (SM)

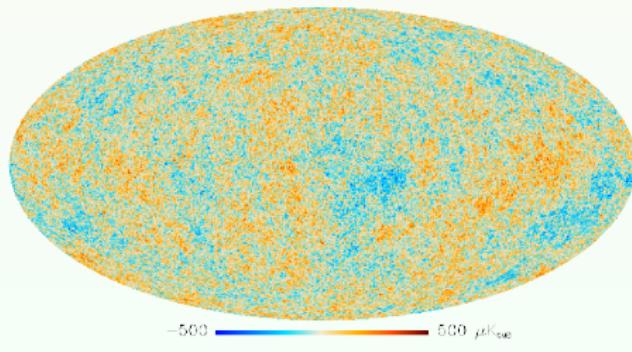
- * **Hierarchy problem** between EW (~ 100 GeV) and Planck ($\sim 10^{19}$ GeV) scales
Quadratic divergences to the Higgs boson mass squared
- * **Grand Unification (GUT)**
- * **Neutrino sector** (Dirac, Majorana ??)
- * ...



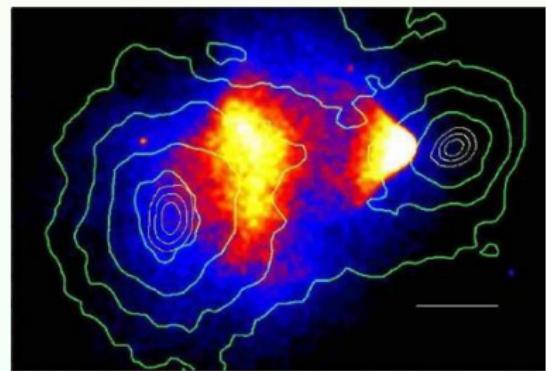
Drawbacks of the Standard Models

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

\Rightarrow DM candidates in supersymmetric models

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

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

g	A^0
Z	$h^0 H^0$
W^\pm	h_\pm

\tilde{u}	\tilde{c}	\tilde{t}
\tilde{d}	\tilde{s}	\tilde{b}
$\tilde{\nu}_{eL}$	$\tilde{\nu}_{\mu L}$	$\tilde{\nu}_{\tau L}$
\tilde{e}	$\tilde{\mu}$	$\tilde{\tau}$

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 $\mu \sim (10 - 100) \times M_Z^2$:

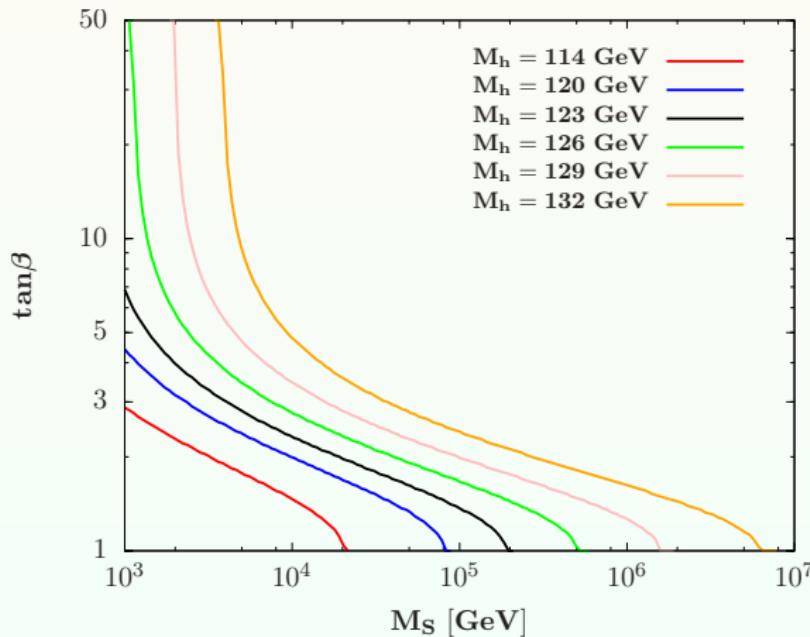
✓ SUSY breaking parameters $b, m_{H_u}^2$ and $m_{H_d}^2$

✗ 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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- ★ 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 : $SU(3)_c \times SU(2)_L \times U(1)_Y \times U'(1)$
 Coupling constants : g_3, g_2, g_Y 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) + $\mathcal{O}(\text{TeV}) = \text{UMSSM}$

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
$\sqrt{24} Q'_\psi$	1	1	1	1	1	1	-2	-2	4

$\Rightarrow \theta_{E_6} = 0$ $\Rightarrow \theta_{E_6} = \pi/2$

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

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

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

$$\cos^2 \beta = \frac{1}{Q'_{H_d} + Q'_{H_u}} \left(\frac{\sin 2\alpha_Z (M_{Z_1}^2 - M_{Z_2}^2)}{v^2 g'_1 \sqrt{g_Y^2 + g_2^2}} + Q'_{H_u} \right)$$

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

Content

* To sum up :

u	c	t
d	s	b
ν_{eL}	$\nu_{\mu L}$	$\nu_{\tau L}$

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}
$\widetilde{\nu_{eL}}$	$\widetilde{\nu_{\mu L}}$	$\widetilde{\nu_{\tau L}}$

$\widetilde{\nu_{eR}}$ $\widetilde{\nu_{\mu R}}$ $\widetilde{\nu_{\tau R}}$

Content

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u	c	t
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ν_{eL}	$\nu_{\mu L}$	$\nu_{\tau L}$

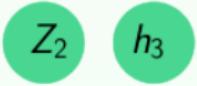
e	μ	τ
-----	-------	--------

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

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

\tilde{u}	\tilde{c}	\tilde{t}
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\widetilde{e}	$\widetilde{\mu}$	$\widetilde{\tau}$
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* Right-Handed (RH) sneutrinos : are they viable DM candidates ?

RH sneutrino DM candidate

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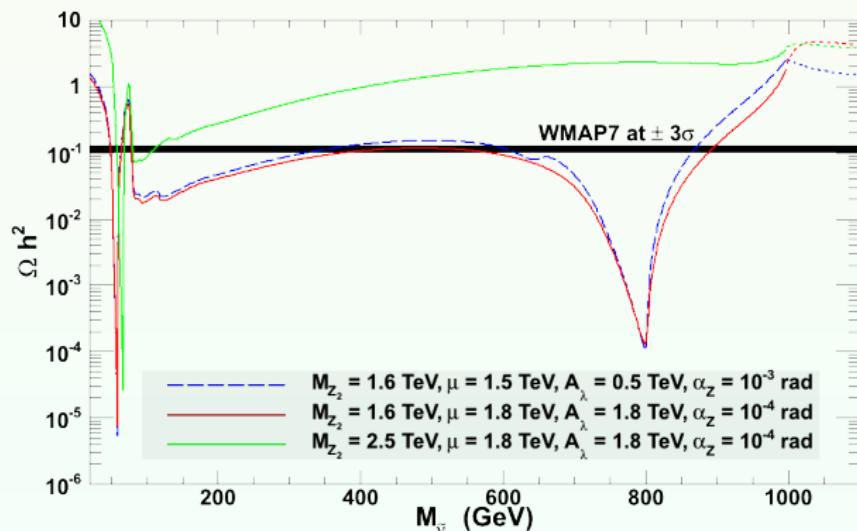
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WIMP annihilation

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 :

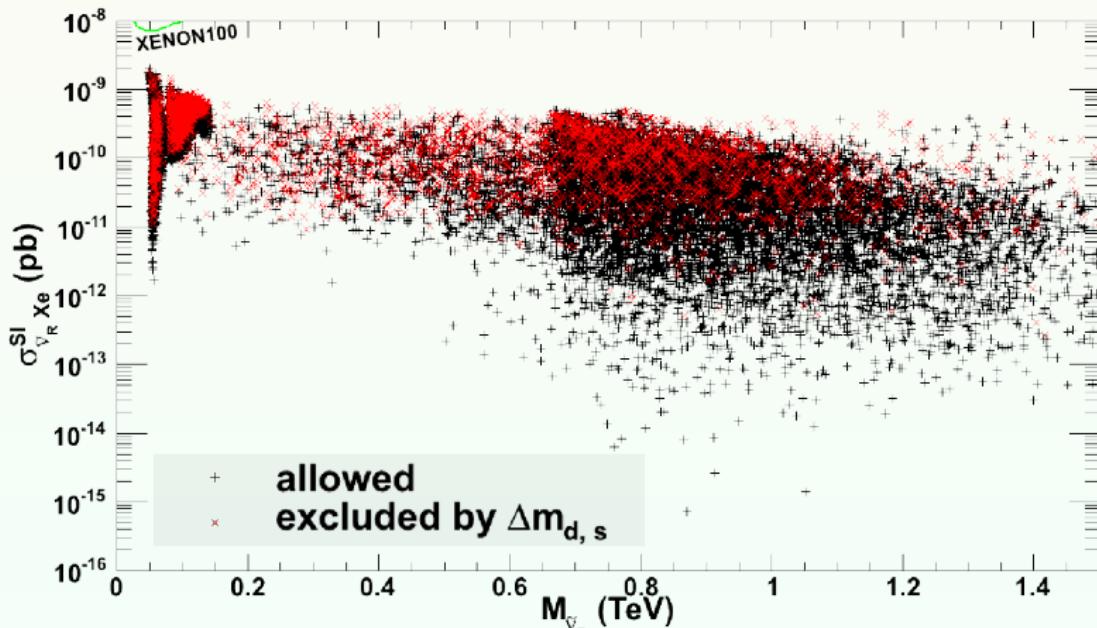
- * WIMP mass near $m_{h_1}/2$
- * WIMP mass near $M_{Z_2}/2$ (also $m_{h_1}/2$)
- * WIMP mass near $m_{h_1}/2$ or above W pair threshold
- * Coannihilation processes (mainly higgsino-like)



Scattering on nucleons

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

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

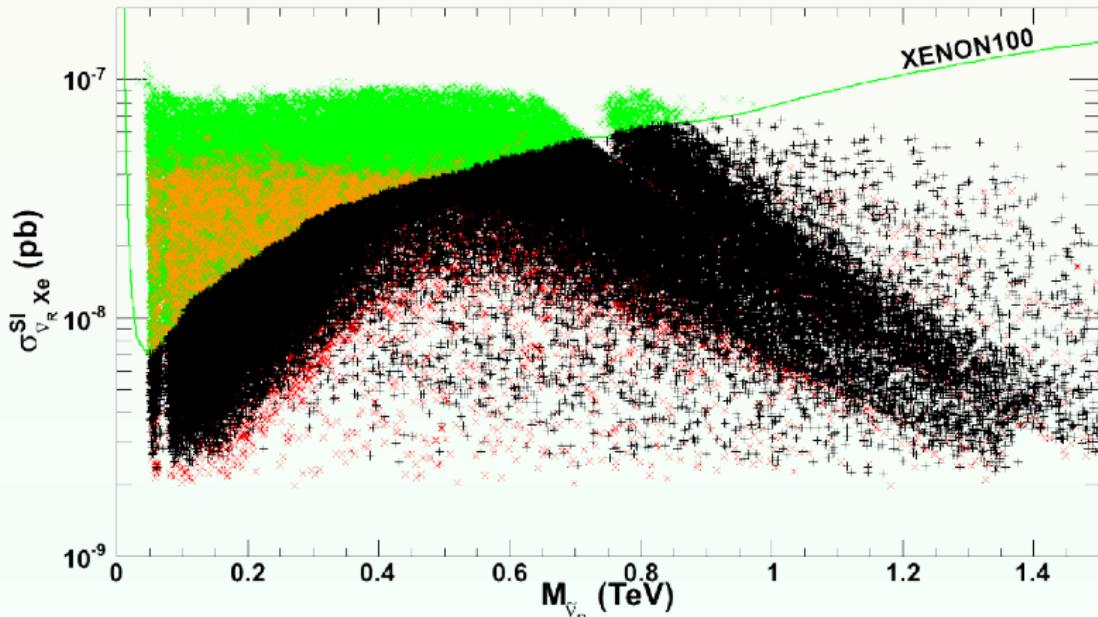


Scattering on nucleons

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

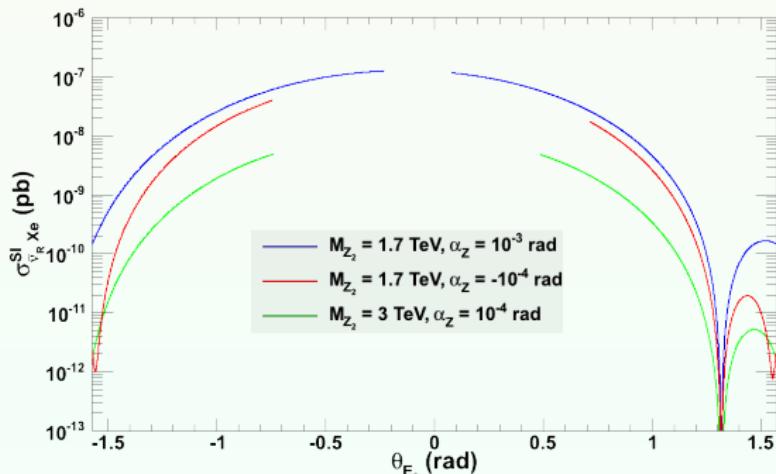


Scattering on nucleons

Abelian gauge boson contribution to direct detection cross section :

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

$$y = \frac{g_Y \sin \alpha_Z \cos \alpha_Z}{4 \sin \theta_W} \left(\frac{1}{M_{Z_2}^2} - \frac{1}{M_{Z_1}^2} \right), \quad y' = -\frac{g'_1 Q_V'^d}{2} \left(\frac{\sin^2 \alpha_Z}{M_{Z_1}^2} + \frac{\cos^2 \alpha_Z}{M_{Z_2}^2} \right)$$



⇒ stringent constraints for small $|\theta_{E_6}|$ because of $Q_V'^d$ term

Low $\tan \beta$ region

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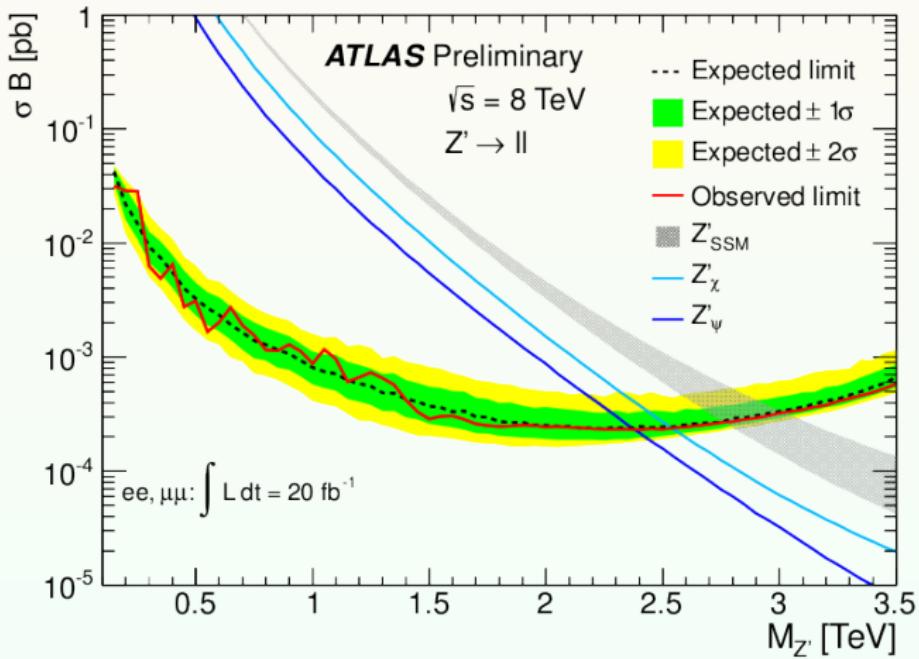
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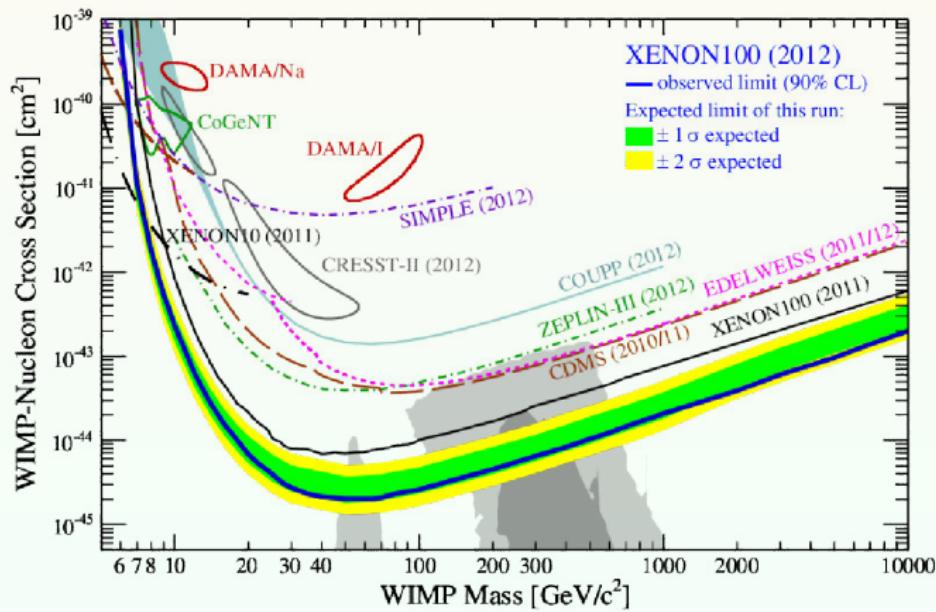
Constraints - Z'

- * 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]** : $\chi^2_i \lesssim 6$ 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

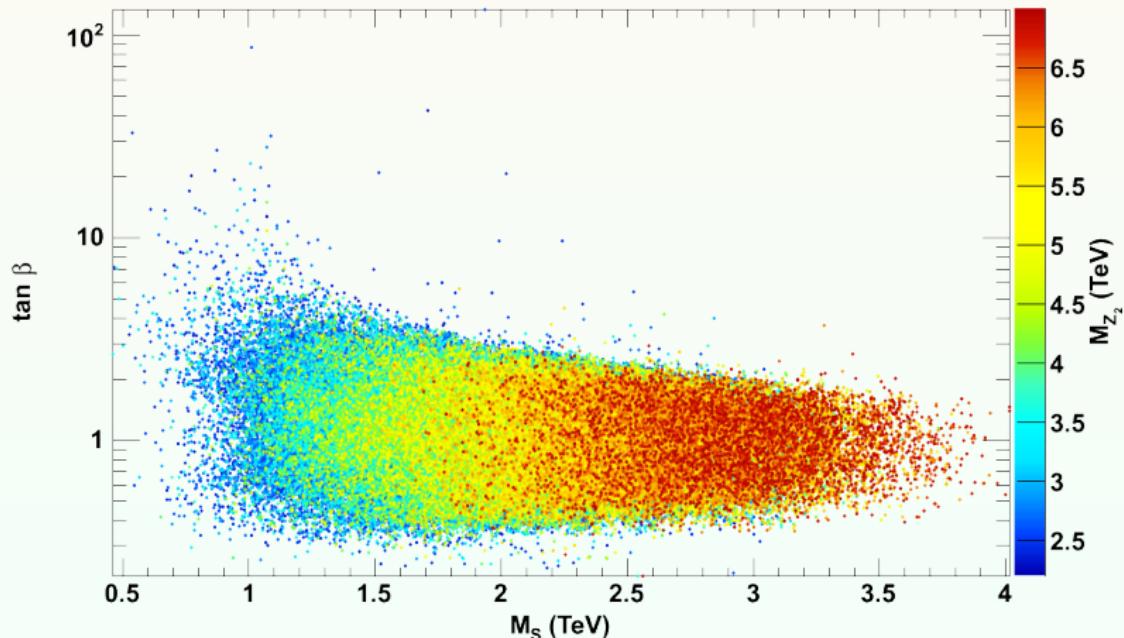
- ★ UMSSM parameters :

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

$\tan \beta$

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

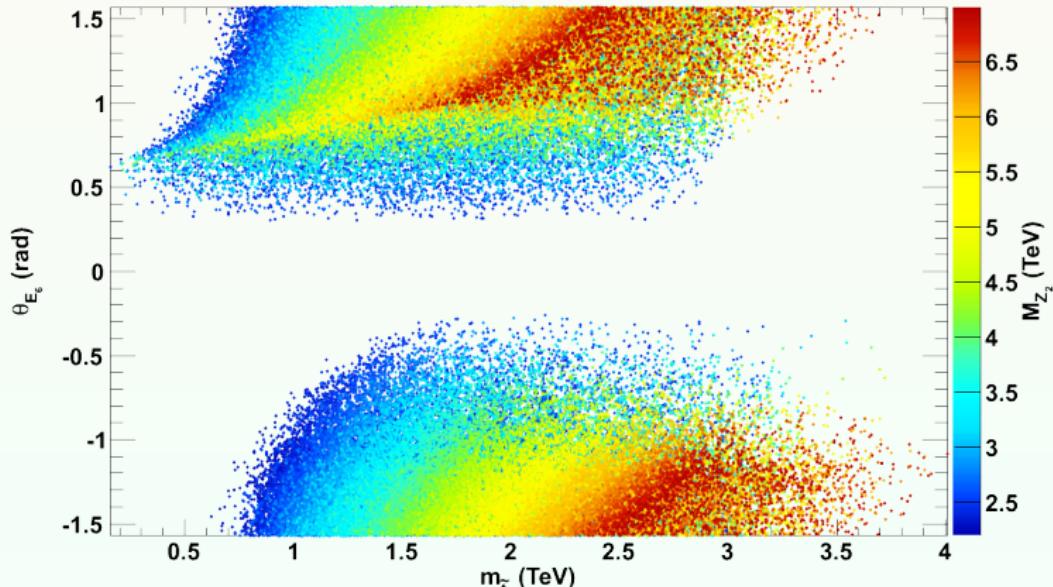


Sfermion masses

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

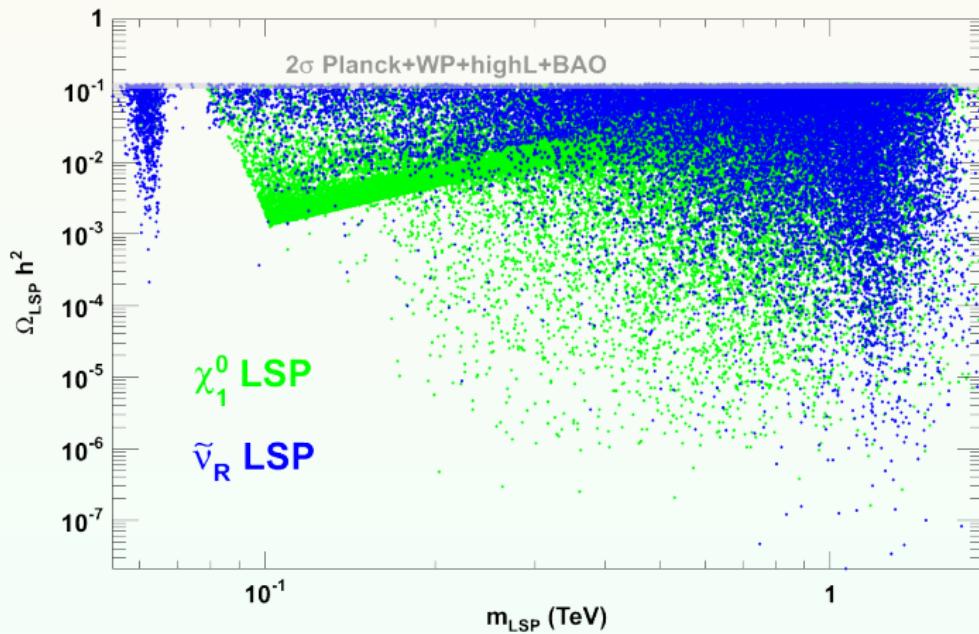
$$\Delta_f = \frac{1}{2} g_1'^2 Q'_f (Q'_{H_d} v_d^2 + Q'_{H_u} v_u^2 + Q'_S v_s^2)$$

\Rightarrow Condition on neutral LSP put strong constraints on θ_{E_6}



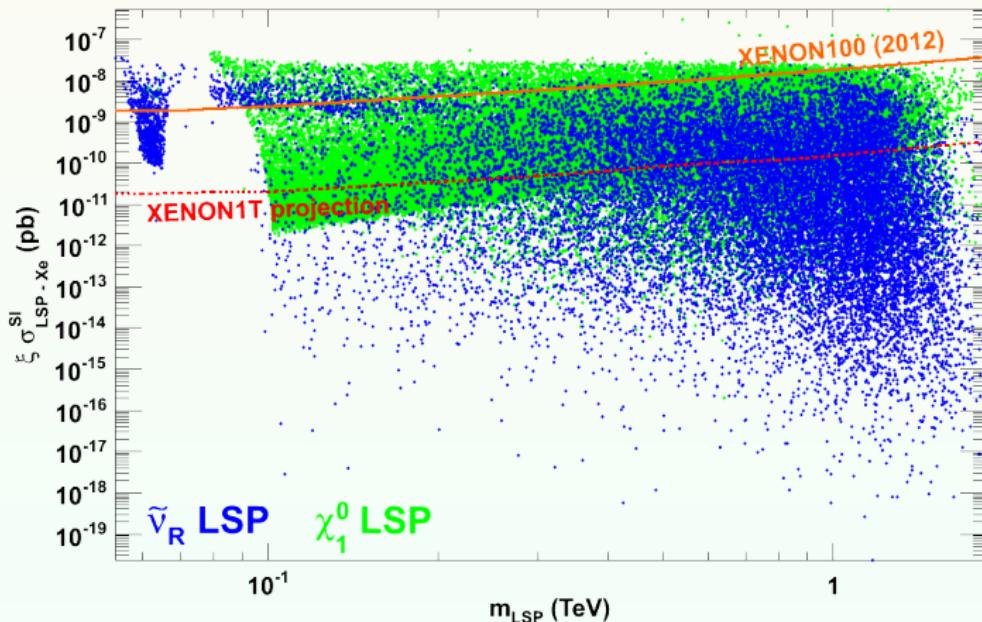
LSP abundance

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



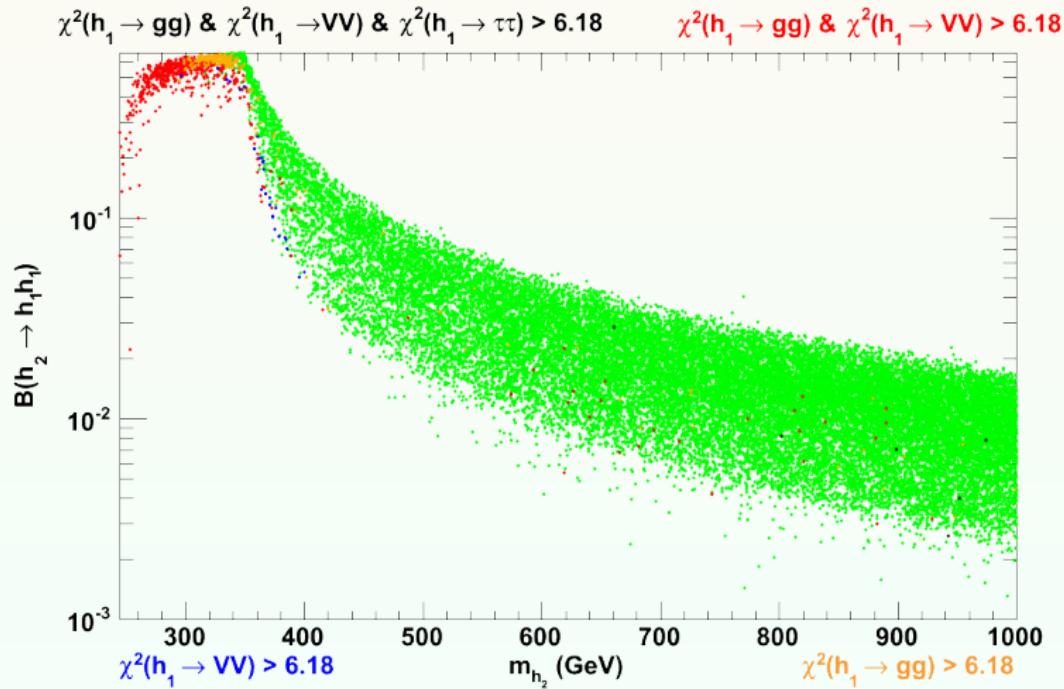
Direct detection

- \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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Conclusions

- ★ 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

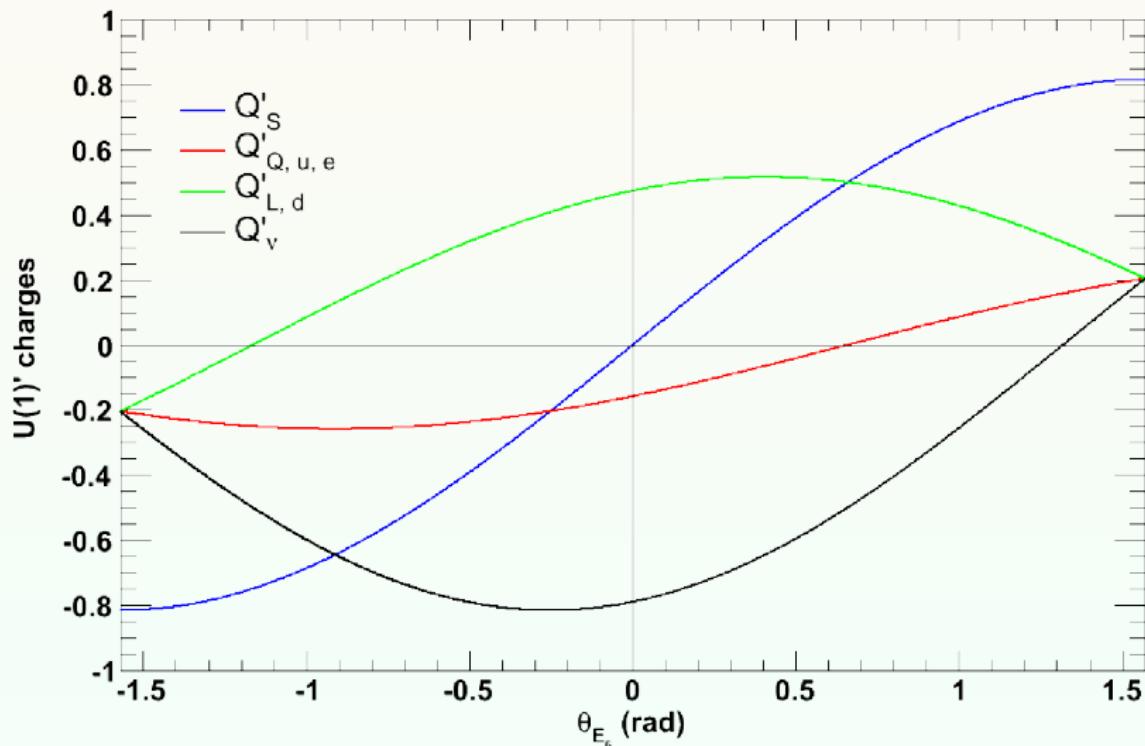
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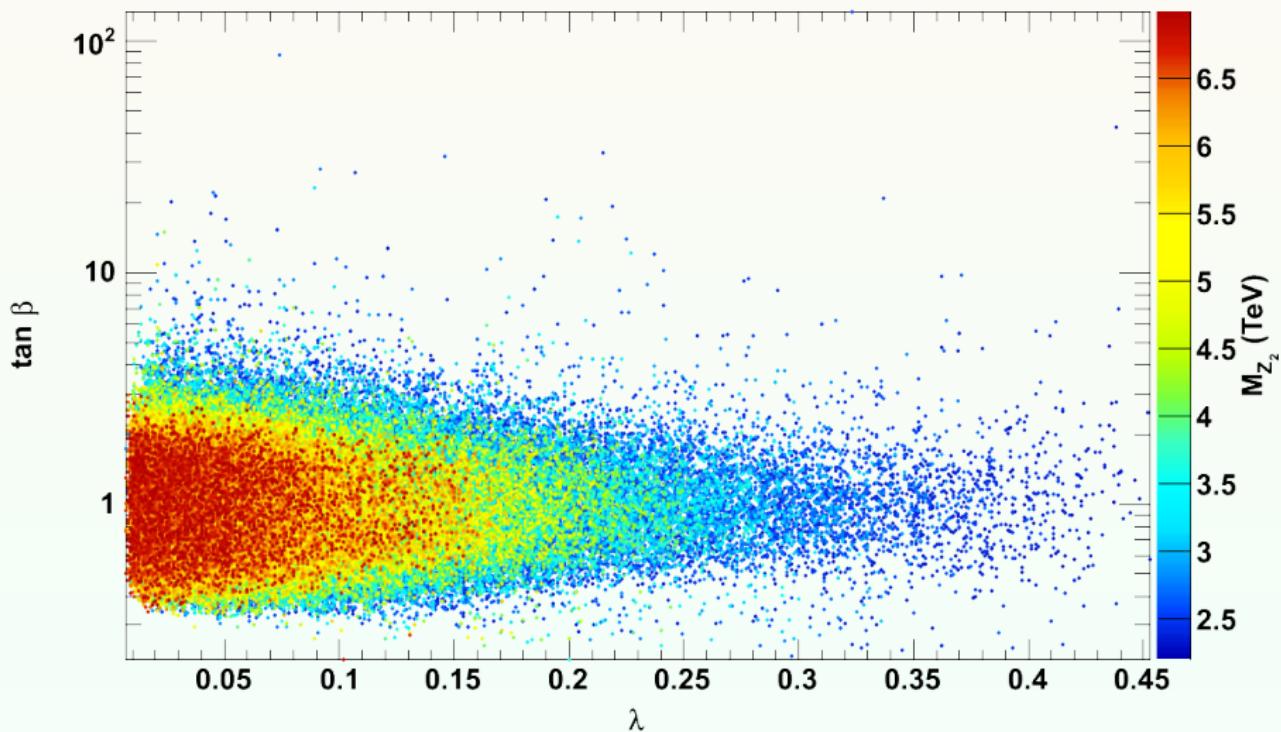
Thanks for your attention !

BACKUP

BACKUP



BACKUP



BACKUP

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

