Dark matter and Higgs boson properties in extensions of the MSSM

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G. Bélanger, JDS and A. Pukhov, JCAP 1112 014 (2011)

D. Albornoz Vasquez, G. Bélanger, C. Bœhm, JDS, P. Richardson and C. Wymant, arXiv:1203.3446 [hep-ph], submitted to Physical Review D

Outline

1. Motivations
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   - WIMP annihilation
   - Scattering on nucleons
3. Global scan
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4. Higgs in the UMSSM
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Motivations

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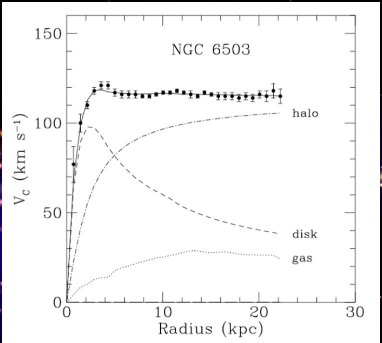
Need of dark matter (DM)

Since 1933 and Zwicky observations, we accumulated evidences for DM existence :

- Galaxy scale : rotation curves of galaxies



K. G. Begeman, A. H. Broeils and R. H. Sanders, 1991, MNRAS, 249, 523

Circular velocity $v(r) = \sqrt{\frac{GM(r)}{r}}$ expected to fall in $\frac{1}{\sqrt{r}}$, observed approximately constant (! ?)

$\Rightarrow$ need of a halo with $M(r) \propto r$

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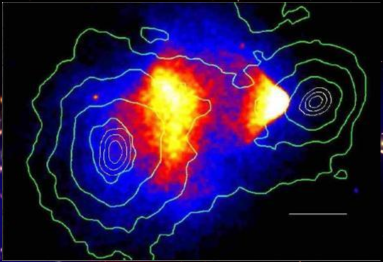
- Galaxy clusters scale : example of the bullet cluster



A direct empirical proof of the existence of dark matter, D. Clowe et al., Astrophys. J. 648 L109-L113, 2006

Study of X-rays and gravitational lensing effect of this cluster : discrepancy between baryonic matter and gravitational potential

$\Rightarrow$ non-negligible non-colliding component of clusters

Need of dark matter (DM)

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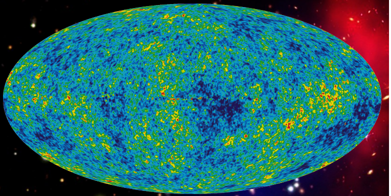
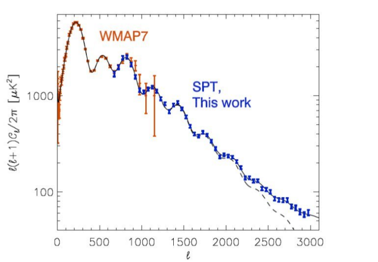
- Galaxy clusters scale : example of the bullet cluster
- Cosmological scale : the Cosmic Microwave background (CMB)



WMAP7



SPT

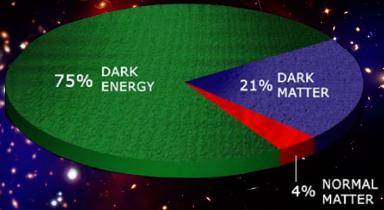
To match a cosmological model with the CMB power spectrum

$$\Rightarrow \Omega_b h^2 = 0.0226 \pm 0.0005 \text{ and } \Omega_{DM} h^2 = 0.1123 \pm 0.0035$$

Need of dark matter (DM)

Since 1933 and Zwicky observations, we accumulated evidences for DM existence :

- Galaxy scale : rotation curves of galaxies
- Galaxy clusters scale : example of the bullet cluster
- Cosmological scale : the Cosmic Microwave background (CMB)
- Large scale structures, ...



DM has to be stable and weakly charged under the standard model gauge group (otherwise we should have seen it)

Conservation of DM structures ⇒ warm vs. cold DM

here we choose CDM

Need of supersymmetry

- **Hierarchy problem**

No symmetry protects higgs mass :

$$\Delta m_H^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda^2 + \dots$$

Supersymmetry, symmetry between fermions and bosons (thanks to Poincaré group extension) plays this role by adding one-loop corrections :

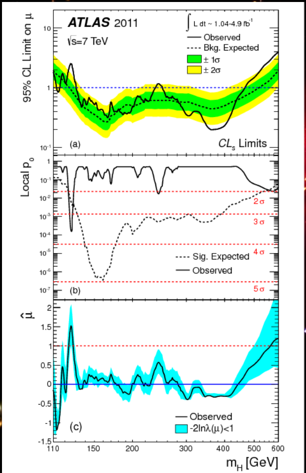
$$\Delta m_H^2 = \frac{|\lambda_S|^2}{16\pi^2}\Lambda^2 + \dots$$

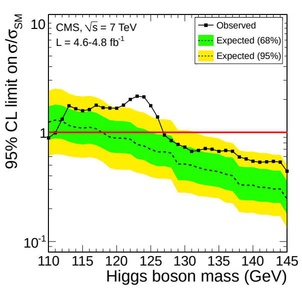
$\Rightarrow$ Cancellation of quadratic divergence

Need of supersymmetry

Hierarchy problem

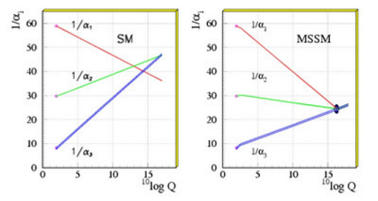
Hint of Higgs boson ?





Need of supersymmetry

- Hierarchy problem
- Gauge coupling unification



Modification of RGEs in the supersymmetry framework

u	c	t
d	s	b
ν_e	ν_μ	ν_τ
e	μ	τ

g	H_u
B	H_d
W	

$\widetilde{H}_u$	$\widetilde{g}$
$\widetilde{H}_d$	$\widetilde{B}$
	$\widetilde{W}$

$\widetilde{u}$	$\widetilde{c}$	$\widetilde{t}$
$\widetilde{d}$	$\widetilde{s}$	$\widetilde{b}$
$\widetilde{\nu}_e$	$\widetilde{\nu}_\mu$	$\widetilde{\nu}_\tau$
$\widetilde{e}$	$\widetilde{\mu}$	$\widetilde{\tau}$

fermions bosons

$\Rightarrow$ Supersymmetry allows unification at GUT scale

Need of supersymmetry

- Hierarchy problem
- Gauge coupling unification
- LSP/DM

No supersymmetric particles seen at the same mass as their standard partners
$\Rightarrow$ supersymmetry is broken, new particles (at least) at TeV scale

Supersymmetric terms give us proton decay
$\Rightarrow$ need of R-Parity to forbid them $P_R = (-1)^{3(B-L)+2s}$

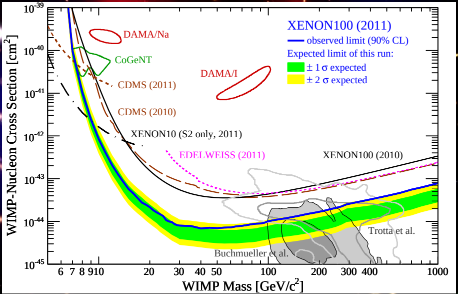
$\Rightarrow$ Result : the lightest supersymmetric particle (LSP) is stable

This LSP, stable, at TeV scale, can be weakly charged under the SM gauge group

$\Rightarrow$ DM candidates in supersymmetric models

Some candidates

- Assuming R-parity, 2 CDM (WIMPs) candidates in the MSSM :
  - Lightest neutralino : a lot of studies ⇒ good DM candidate
  - Left-handed (LH) sneutrino : too high coupling with Z^0 ⇒ don't satisfy experimental constraints on spin independent direct detection ⇒ bad DM candidate



- Others SUSY candidates to DM : Gravitino, axino, ...

Sneutrino

- Neutrino oscillations indicative of massive neutrinos $\Rightarrow$ possibility to add a right-handed (RH) neutrino field

  $\Rightarrow$ Extensions of the MSSM with RH (s)neutrino can provide DM candidate

- Different mechanisms appear to obtain sneutrino DM :
  - Mixing between LH and RH sneutrinos
  - Sneutrino in inverse see-saw mechanism models
  - RH sneutrino extension in the NMSSM
  - ...

- Here RH neutrino mass generated by introducing Dirac mass terms $\Rightarrow$ supersymmetric partner can be at the TeV scale

- **This candidate couples to new vector, scalar field by adding a new abelian gauge group, it's the UMSSM**

The UMSSM

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Contents

- Extending the SM gauge group is well-motivated in superstrings and grand unified theories M. Cvetič and P. Langacker, Phys. Rev. D 54, 3570 (1996)
- Symmetry group : $SU(3)_c \times SU(2)_L \times U(1)_Y \times U'(1)$

  Coupling constants : g_3, g_2, g_Y and $g'_1 = g_1 = \sqrt{\frac{5}{3}} g_Y$
- $U'(1)$ stems from the breaking of E_6 :

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

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

- As the NMSSM, this model solves the μ problem, since it's related to the v.e.v of the singlet responsible of the breaking of the new abelian gauge group
- Superpotential :

$$\begin{aligned} W_{MSSM} &= \bar{u} y_u Q H_u - \bar{d} y_d Q H_d - \bar{e} y_e L H_d + \mu H_u H_d \\ W_{UMSSM} &= W_{MSSM}|_{\mu=0} + \lambda S H_u H_d + \bar{\nu} y_\nu L H_u + o(TeV) \end{aligned}$$

Q' choice	Q	$\bar{u}$	$\bar{d}$	L	$\bar{e}$	$\bar{\nu}$	H_u	H_d	S
$\sqrt{40}Q_\chi$	-1	-1	3	3	-1	-5	2	-2	0
$\sqrt{24}Q_\psi$	1	1	1	1	1	1	-2	-2	4

Contents

Some differences with the MSSM :

- Gauge sector : Physical abelian gauge bosons : Z_1 and Z_2, mixing between the Z^0 of the SM and the Z', α_Z is the mixing angle

$$M^2_{Z_1,Z_2} = \frac{1}{2}\left(M^2_{Z^0} + M^2_{Z'} \mp \sqrt{\left(M^2_{Z^0} + M^2_{Z'}\right)^2 + 4\Delta^4_Z}\right)$$

$$\sin 2\alpha_Z = \frac{2\Delta^2_Z}{M^2_{Z_2} - M^2_{Z_1}}$$

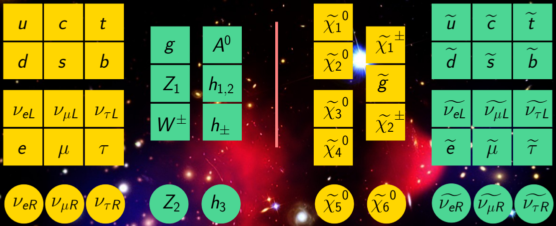
- Higgs sector : 1 CP odd higgs A^0, 5 CP even higgs : $h^\pm$, h_1, h_2 and h_3 singlet-like higgs (h_2 or h_3) mass near Z_2 mass including pure UMSSM terms + radiative corrections

$\Rightarrow$ m_{h_1} above LEP limits

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

Contents

To sum up :



Relevant free parameters :

- WIMP mass $M_{\tilde{\nu}_R}$
- Higgs sector $\Rightarrow$ μ, A_λ
- Gauge sector : M_{Z_2} and α_Z $\Rightarrow$ t_β constrained
- Gaugino sector : M_1, M'_1 and again μ (higgsino NLSP)
- θ_{E_6}
- Soft terms at 2 TeV $\Rightarrow$ no sfermion coannihilation

Constraints

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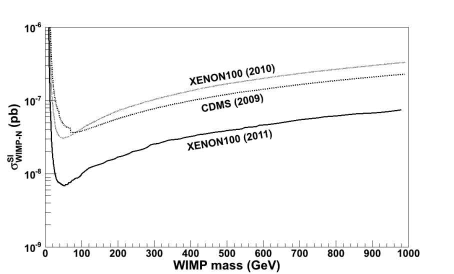
Constraints

- On our CDM candidate
  - Relic density at 3σ with $\Omega_{\text{WIMP}} h^2 = 0.1123 \pm 0.0035$
  - Spin independent direct detection cross section



Constraints

- On our CDM candidate
- On different sectors of the model
  - Higgs mass constraints from LEP and LHC : 114.4 GeV $< m_{h_1} <$ 144 GeV

    in this talk only 123 GeV $< m_{h_1} <$ 127 GeV
  - New Z boson mass constraints from ATLAS :

Q' choice	Q_ψ	Q_N	Q_η	Q_I	Q_S	Q_χ
M_{Z_2} (TeV)	1.49	1.52	1.54	1.56	1.60	1.64

  - Z^0 properties $\Rightarrow |\alpha_Z| \lesssim 10^{-3}$ ($M_W = \cos\theta_W M_{Z^0}$, not M_{Z_1} !)
  - LEP constraints on sparticles masses (especially charginos)
  - $B^0_{d,s} - \bar{B}^0_{d,s}$ mesons physics constraints : $\Delta M_{d,s}$ mass differences with one-loop supersymmetric contribution with charginos and charged higgs
    $\Rightarrow$ supersymmetry can increase the difference that appears between observed and standard model expected values :

$$\Delta m_s = 17.77 \pm 0.12\ \mathrm{ps}^{-1} (\mathrm{CDF}),\ \Delta m_s^{SM} = 20.5 \pm 3.1\ \mathrm{ps}^{-1}$$

$$\Delta m_d = 0.507 \pm 0.004\ \mathrm{ps}^{-1} (\mathrm{HFAG}),\ \Delta m_d^{SM} = 0.59 \pm 0.19\ \mathrm{ps}^{-1}$$

$$\Delta m_s = 17.63 \pm 0.11\ \mathrm{ps}^{-1} (\mathrm{LHCb})$$

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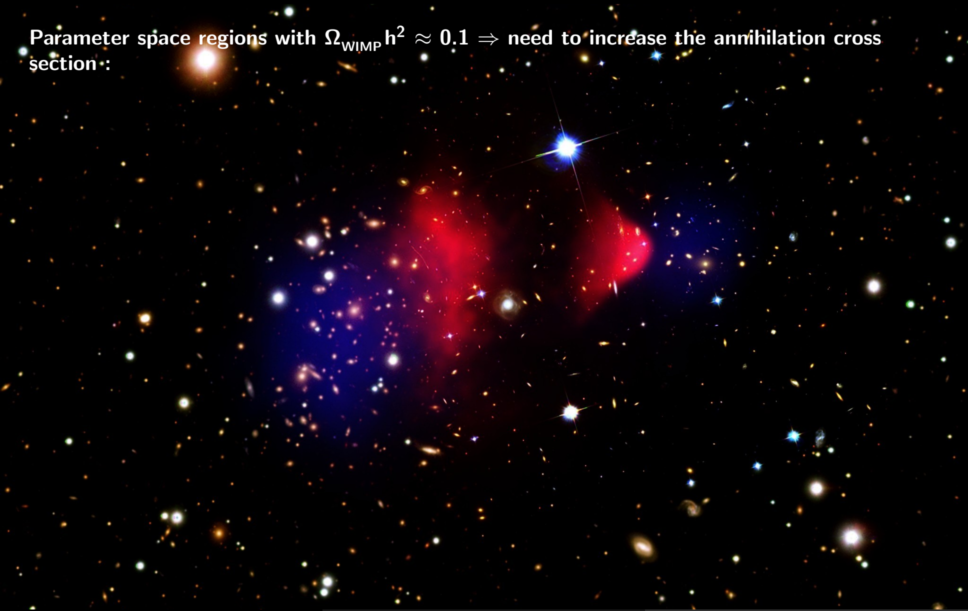
Parameter space regions with $\Omega_{\mathrm{WIMP}} h^2 \approx 0.1 \Rightarrow$ need to increase the annihilation cross section :



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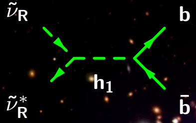

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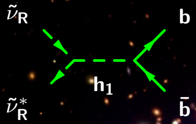
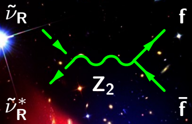


- WIMP mass near $M_{Z_2}/2$ (also $m_{h_i}/2$)



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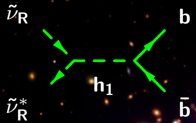

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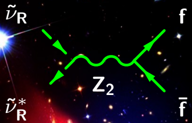
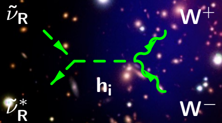
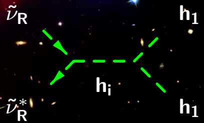


- WIMP mass near $m_{h_i}/2$ or above W pair threshold





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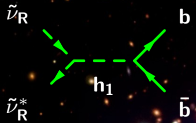

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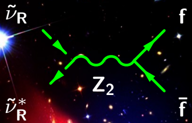

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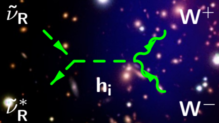
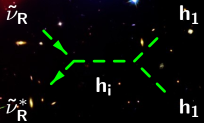
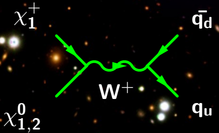
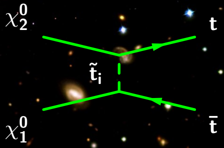




- Coannihilation processes (mainly higgsino-like)





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- WIMP mass near $m_{h_1}/2$
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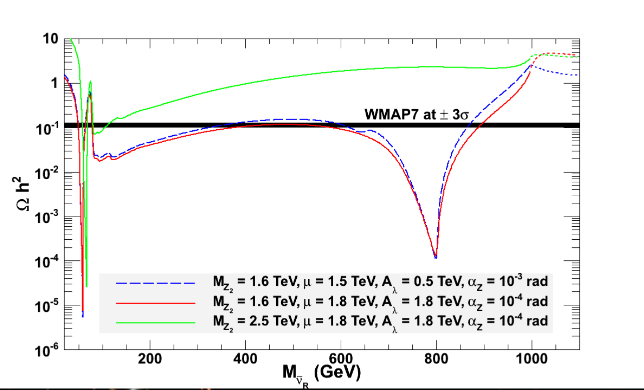

Scattering on nucleons

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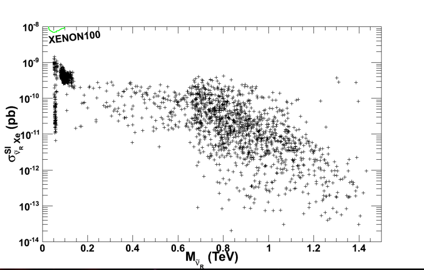
Scattering on nucleons

- **Mainly abelian gauge bosons contribution, h_1 for LSP mass $\lesssim 200$ GeV**



$\Rightarrow$ for some $U'(1)$ models we can have a good suppression of the gauge boson or/and higgs part

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

Scattering on nucleons

- Mainly abelian gauge bosons contribution, h_1 for LSP mass $\lesssim 200$ GeV

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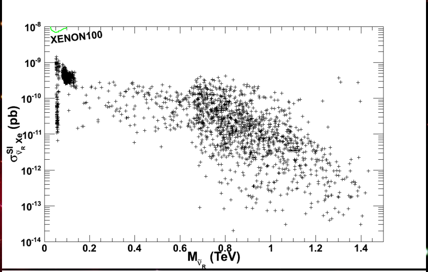
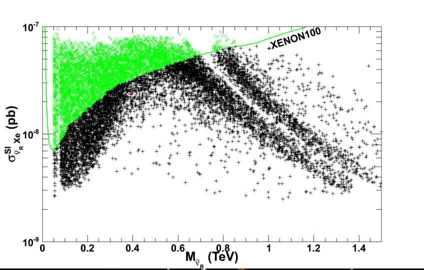
here $U(1)_\psi \Rightarrow \theta_{E_6} = \pi/2$



$\Rightarrow$ for other models, huge constraints on the parameter space appear
here $U(1)_\eta \Rightarrow \tan\theta_{E_6} = -\sqrt{5/3}$

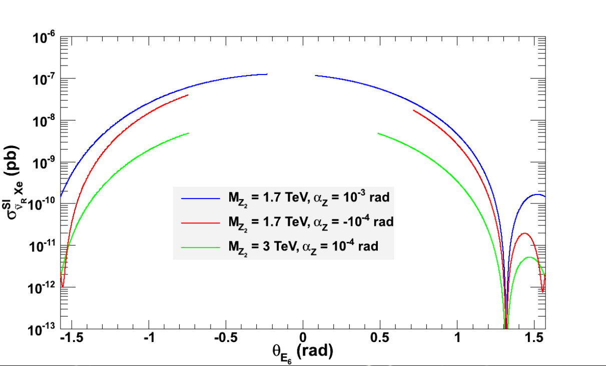


Scattering on nucleons

Abelian gauge boson contribution to direct detection :

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

$$\text{with } y = \frac{g' \sin\alpha_Z \cos\alpha_Z}{4\sin\theta_W}\left(\frac{1}{M^2_{Z_2}}-\frac{1}{M^2_{Z_1}}\right),\ y' = -\frac{g_1'}{2} Q_V'^d \left(\frac{\sin^2\alpha_Z}{M^2_{Z_1}}+\frac{\cos^2\alpha_Z}{M^2_{Z_2}}\right)$$

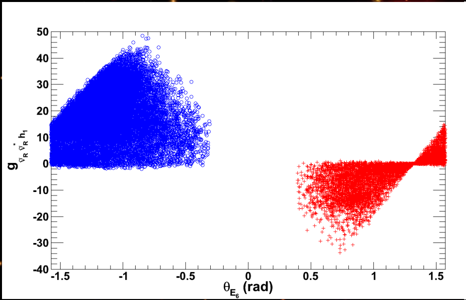


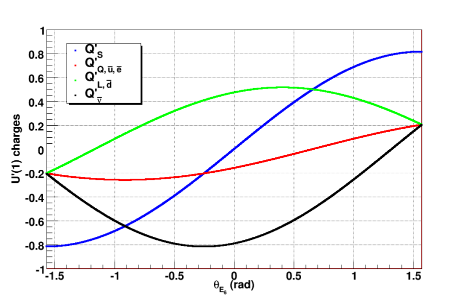
$\Rightarrow$ **stringent constraints for small $|\theta_{E_6}|$ because of $Q_V'^d$ term**

Scattering on nucleons

Higgs-CDM contribution :

$$g_{\tilde{\nu}_R \tilde{\nu}_R^* h_i} = -{g'_1}^2 Q'_{\bar{\nu}} \left[v_d Q'_{H_d} Z_{hi1} + v_u Q'_{H_u} Z_{hi2} + v_s Q'_S Z_{hi3} \right]$$





$\Rightarrow$ increase of the cross section for $\theta_{E_6} < 0$ because of $Q'_{\bar{\nu}}$

Global scan

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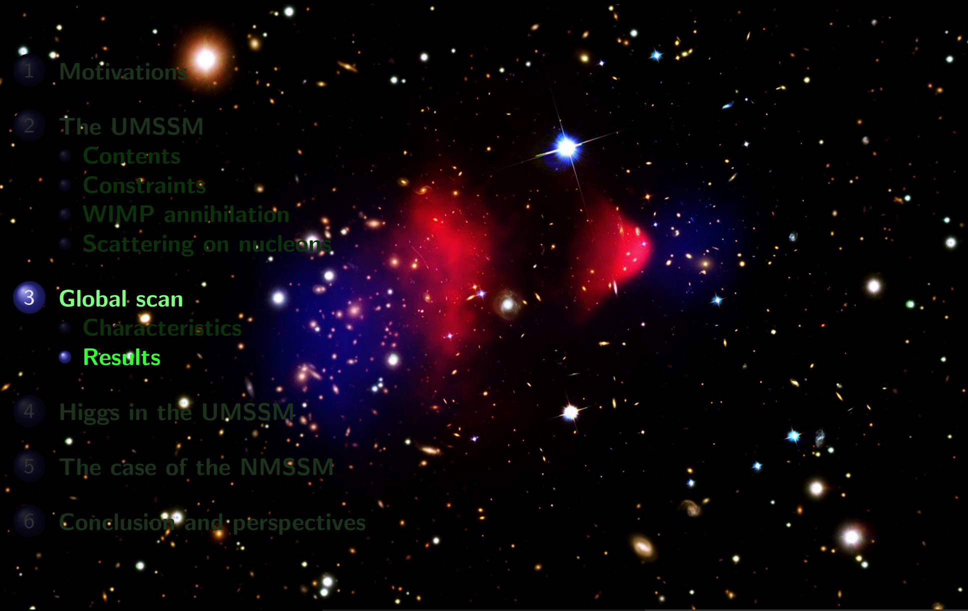
Characteristics

Fixed parameters				Free parameters	
Soft terms				Name	Domain of variation
m_{Q_i}	2 TeV	m_{L_i}	2 TeV	$M_{\tilde{\nu}_R}$	[0, 1.5] TeV
$m_{\bar{u}_i}$	2 TeV	$m_{\bar{d}_i}$	2 TeV	M_{Z_2}	[1.3, 3] TeV
$m_{\bar{e}_i}$	2 TeV	$m_{\bar{\nu}_j}$	2 TeV	μ	[0.1, 2] TeV
$i \in \{1,2,3\}$, $j \in \{1,2\}$				A_λ	[0, 2] TeV
Trilinear couplings + M_K				θ_{E_6}	[-$\pi/2$, $\pi/2$] rad
A_t	1 TeV	A_b	0 TeV	α_Z	[-3.10^{-3}, 3.10^{-3}] rad
A_c	0 TeV	A_s	0 TeV	M_1	[0.1, 2] TeV
A_u	0 TeV	A_d	0 TeV	M_1'	[0.1, 2] TeV
A_l	0 TeV	M_K	1 eV	$M_2 = 2M_1$ et $M_3 = 6M_1$	

Results



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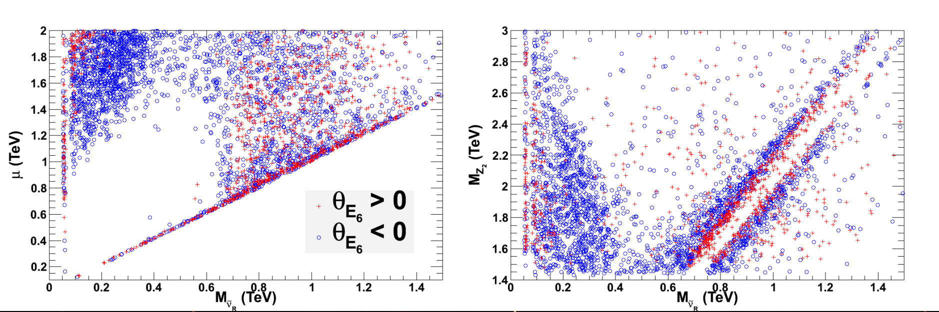
Results

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



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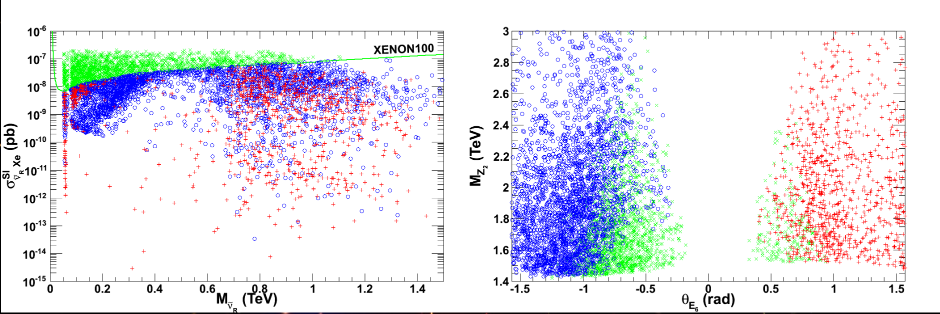
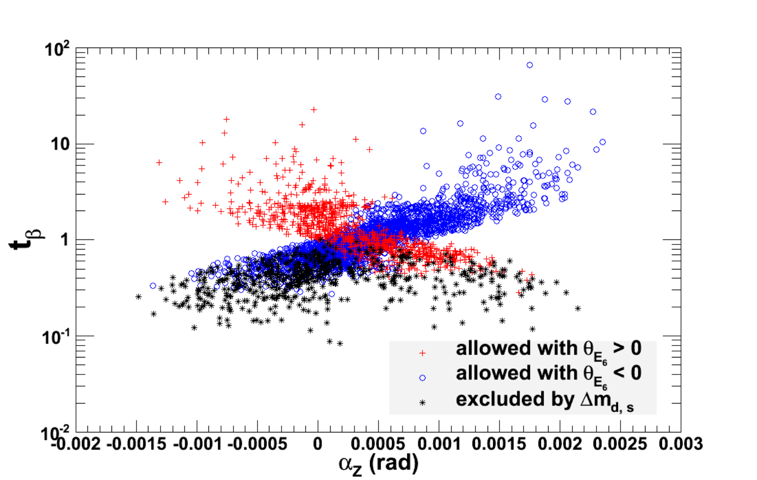


Lower is $|\theta_{E_6}|$, higher are Z_2 processes in direct detection cross section $\Rightarrow$ huge constraint

Results

Large SUSY corrections proportional to $\frac{1}{t_\beta^4}$ $\Rightarrow$ small values of t_β very constrained by ΔM_s :



Higgs in the UMSSM

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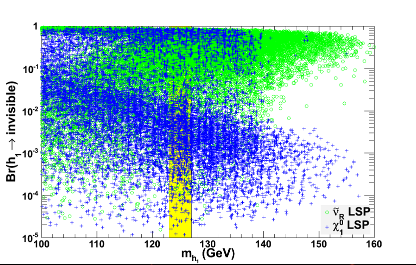
Higgs in the UMSSM

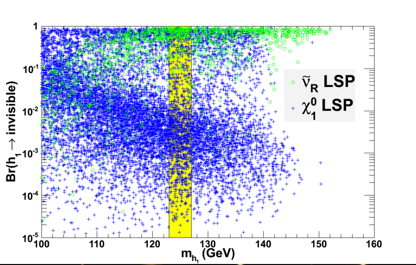
Small invisible width even for light DM $\rightarrow$

$$R_{ggXX} = \frac{\sigma(gg \rightarrow h)_{BSM} BR(h \rightarrow XX)_{BSM}}{\sigma(gg \rightarrow h)_{SM} BR(h \rightarrow XX)_{SM}}$$

, for UMSSM and $X = \gamma \rightarrow \sim 1$ (work in progress)

ψ η





The case of the NMSSM

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The case of the NMSSM

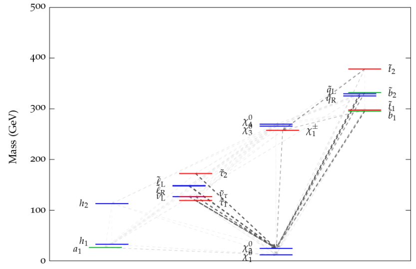
- NMSSM superpotential :

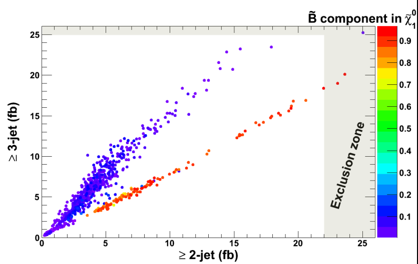
$$W_{NMSSM} = W_{MSSM}(\mu = 0) + \lambda S H_u H_d + \frac{1}{3}\kappa S^3 \quad (1)$$

- 2 CP-odd, 5 CP-even Higgs
- Doublet-singlet mixing much more important than in the UMSSM for a Higgs $\sim$ 125 GeV (large λ)
- Mixing leads to reduced Br($H \to b\bar{b}$) and total width, increasing Br($H \to \gamma\gamma$)
- 5 neutralinos, lightest can be mostly singlino
- Input parameters at EW scale
- Implication of excess in the $\gamma\gamma$ channel at $\sim$ 125 GeV (Ellwanger, 1012.1201, 1112.3548)
- In this talk light neutralino (direct detection motivation) : D. Albornoz Vasquez, et al., 1107.1614, 1201.6150
- $\rightarrow$ satisfy WMAP for χ_1^0 near $m_{h_1,A_1}/2$

The case of the NMSSM

- SUSY searches@LHC
- Jets + $\not{E}_T$ ATLAS 1fb^{-1} using Herwig++ and Rivet
- In general exclude squarks lighter than 0.6 - 1 TeV and gluinos below 0.5 TeV
- $\rightarrow$ reduced acceptance into Jets + $\not{E}_T$ search channels for singlino LSP

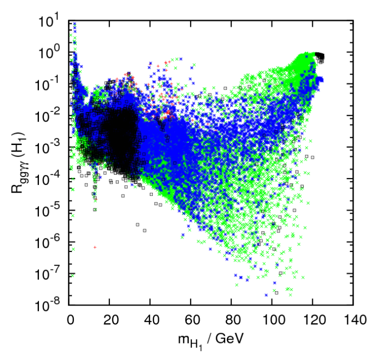


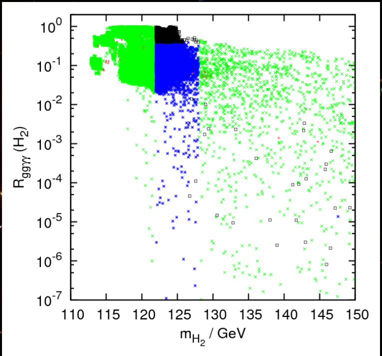


- $\tilde{q} \rightarrow q + (\chi_2^0 \rightarrow \chi_1^0 + (f\bar{f} \text{ or } A_1 \text{ or } h_1))$
- More jets for $\tilde{S}$ LSP

The case of the NMSSM

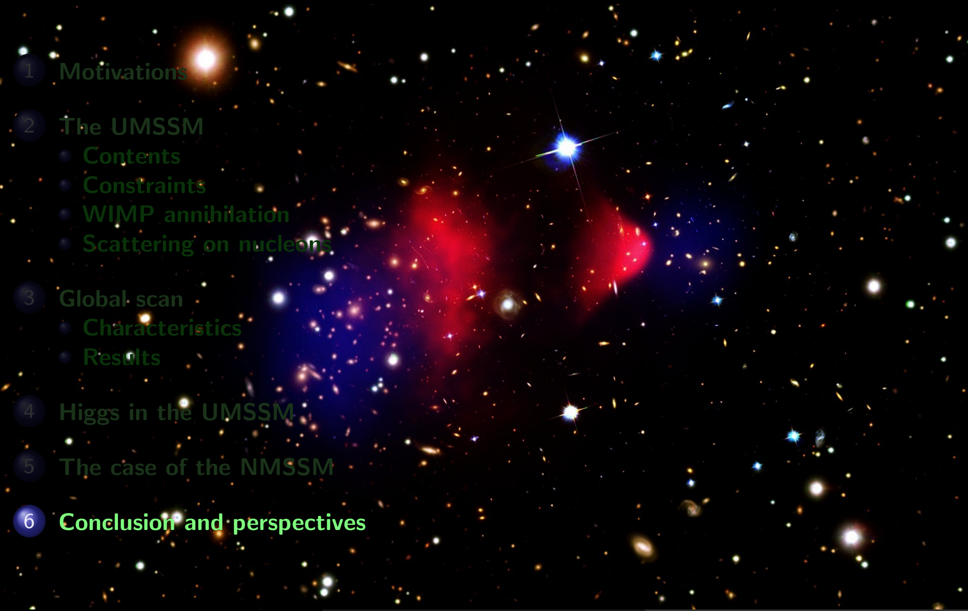
- $R_{gg\gamma\gamma}$:





- MSSM-like Higgses, with possible strong suppression (invisible modes)
- $\rightarrow$ Relaxing LSP mass constraint give us $R_{gg\gamma\gamma} > 1$

Conclusion and perspectives



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Conclusion and perspectives

- RH sneutrino is a viable dark matter candidate in the UMSSM
  it respects experimental limits in the case of some annihilation processes :
  - Resonance (h_1, Z_2 and singlet-like higgs)
  - Coannihilation (neutralinos, charginos, others sfermions)
  - Annihilation into W pairs generally with exchange of h_1
- Direct detection experiments strongly constrain the model as well as ΔM_s
- Results for $R_{gg\gamma\gamma}$ soon

- NMSSM : excess in the $\gamma\gamma$ channel not easy for light LSP, possible in the context of general NMSSM
- Jets + $\cancel{E}_T$ searches can be evaded for singlino DM

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Thanks for your attention !