Study of some supersymmetric dark matter models

Jonathan Da Silva

Particle Physics group, University of Manchester, United Kingdom

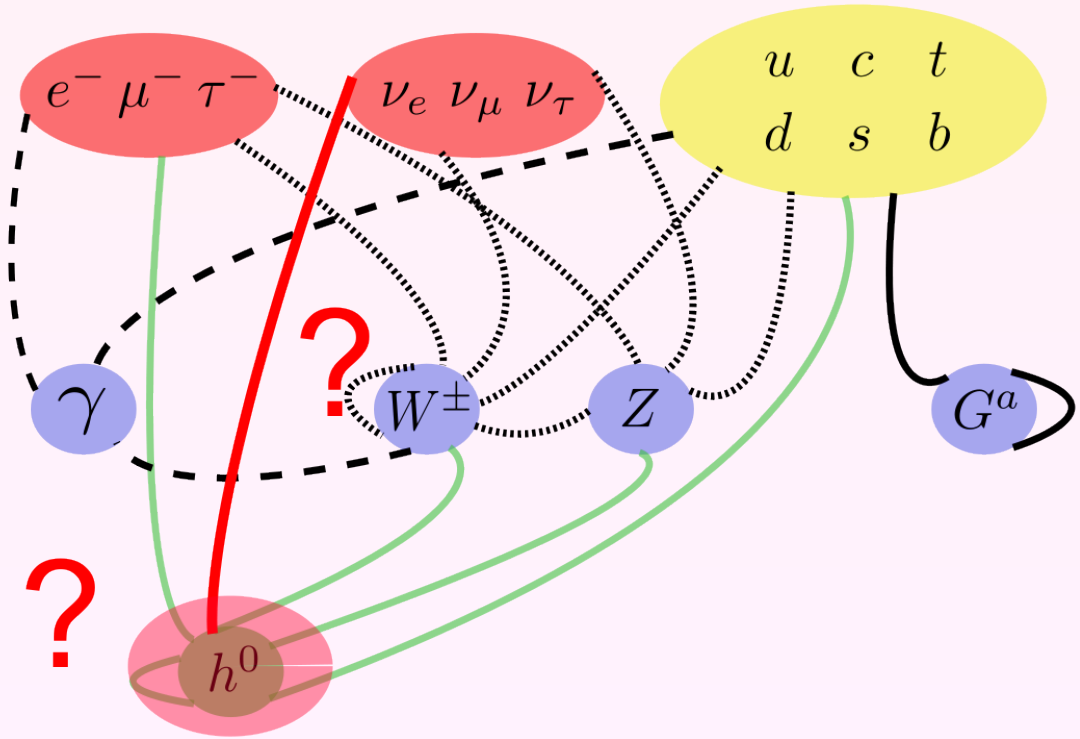
MCnet meeting, University of Manchester, October 29, 2013

Based on work done at LAPTh during my PhD under the supervision of Geneviève Bélanger :
G. Bélanger, JDS and A. Pukhov, JCAP 1112 (2011) 014, [arXiv:1110.2414],
D. A. Vasquez, G. Bélanger, C. Bœhm, JDS, P. Richardson and C. Wymant, Phys. Rev. D86 (2012) 035023, [arXiv:1203.3446],
G. Bélanger, C. Bœhm, M. Cirelli, JDS and A. Pukhov, JCAP 1211 (2012) 028, [arXiv:1208.5009],
C. Bœhm, JDS, A. Mazumdar and E. Pukartas, Phys. Rev. D87 (2013) 023529, [arXiv:1205.2815]

Outline

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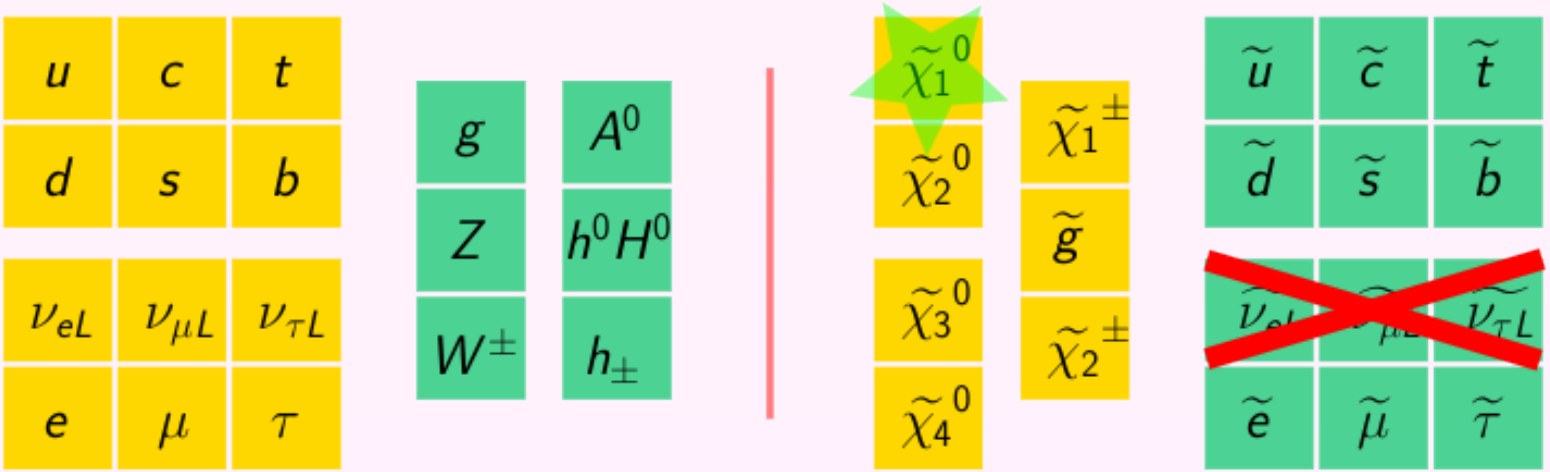
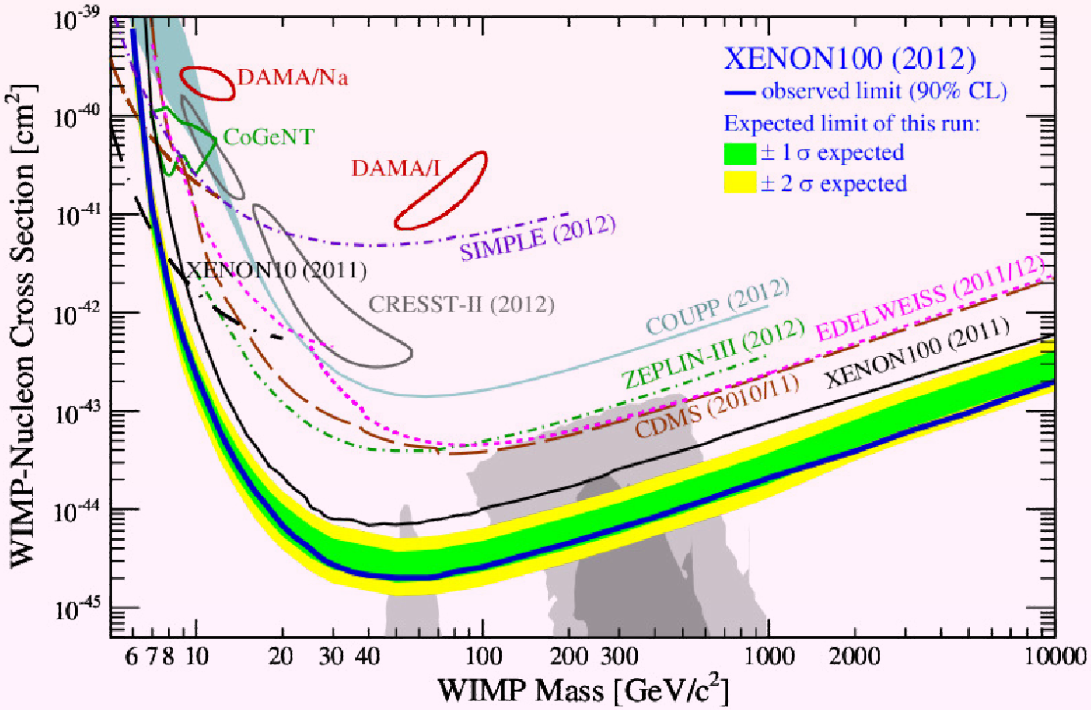
  $\Rightarrow$ **DM candidates in supersymmetric models**
- **Examples :**



Supersymmetry

- **Constraints on SUSY/DM**
  - **DM relic abundance**
  - **Direct detection of DM**



E. Aprile et al., XENON100 Collaboration, Phys. Rev. Lett. 109:181301, [arXiv:1207.5988]

Supersymmetry

- **Constraints on SUSY/DM**
  - **DM relic abundance**
  - **Direct detection of DM**
  - **Indirect detection (ID) of DM (search for anomalous features in cosmic rays like $\gamma, \nu, \mathrm{e}^+, \bar{\mathrm{p}}$)**
  - **Collider constraints**
    - **LEP $\Rightarrow$ charged sparticles**
    - **LHC $\Rightarrow$ coloured sparticles**
    - **Low energy observables**
      $\mathscr{B}(\bar{\mathrm{B}}^0 \to \mathrm{X_s}\gamma), \mathscr{B}(\mathrm{B_s^0} \to \mu^+\mu^-), \mathscr{B}(\mathrm{B}^\pm \to \tau^\pm\nu_\tau)$,
      $\Delta \mathrm{M_{d,s}}, \delta \mathrm{a}_\mu, \Delta\rho$, **...**

Neutralino DM in the (N)MSSM

NUHM2

NUHM2 (Non-Universal Higgs Masses type 2)

- Supersymmetric model with gravity-mediated supersymmetry breaking based on the MSSM
- Most popular : mSUGRA/CMSSM, universal scalar masses is assumed, free parameters :

$$\mathbf{m_0},\ \mathbf{m_{1/2}},\ \mathbf{A_0},\ \tan\beta \text{ and } \mathbf{sign}(\mu)$$

  - ✘ Drawbacks : $\mathbf{m_{h^0}} \sim 125$ GeV not easy

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- We considered a non-universal scalar masses model, with $m_0^2 \neq m_{H_u}^2 \neq m_{H_d}^2$
  - ✔ Easier to reach $m_{h^0} = 125$ GeV, increase DM annihilation rates with higgsino LSP
- NUHM2 free parameter :

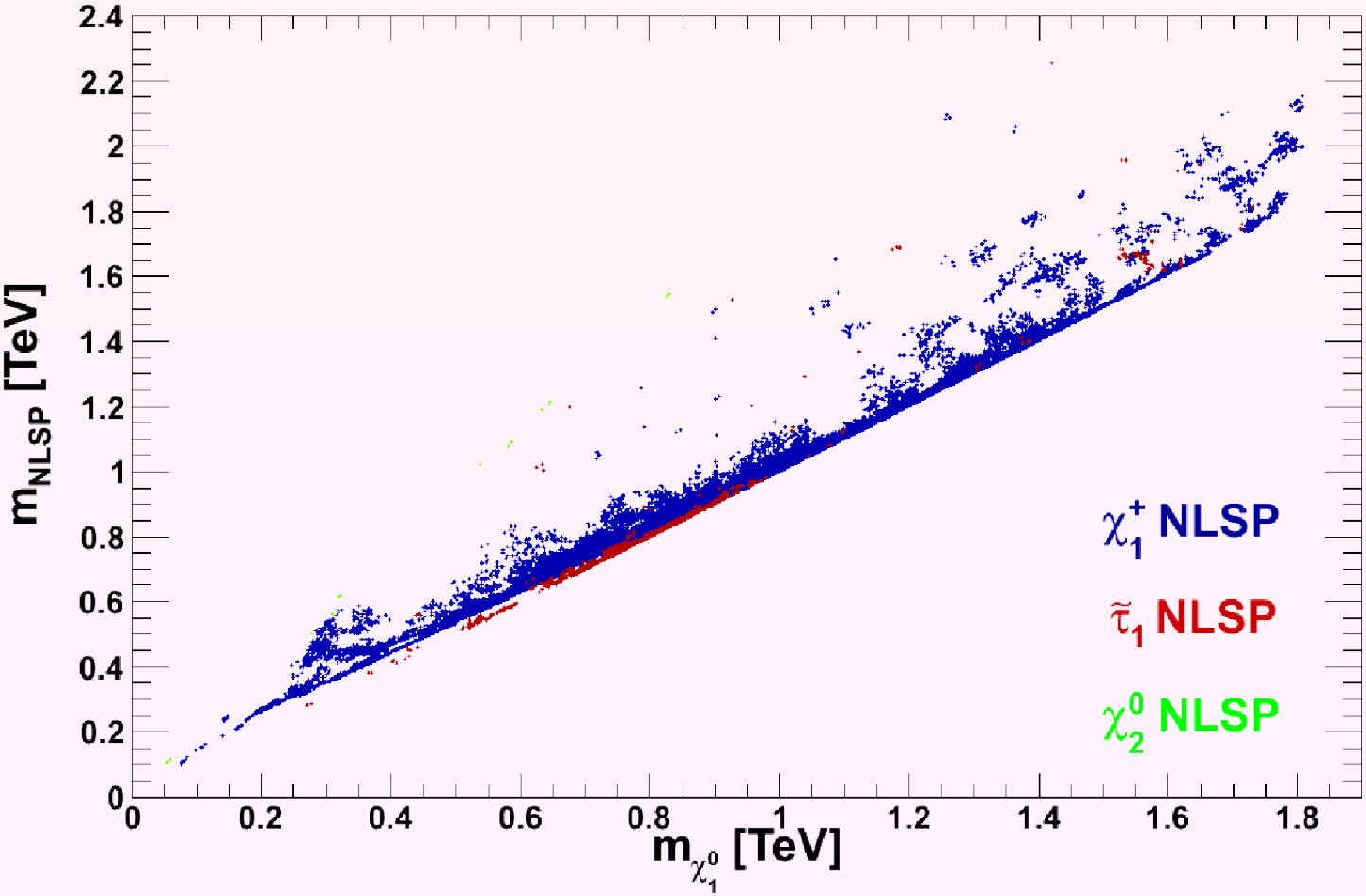
$$m_0,\ m_{1/2},\ A_0,\ \tan\beta,\ \mu \text{ and } m_{A^0}$$

- Higgs boson mass + DM relic density + B-Physics constaints imposed on a scan done using Markov Chain Monte Carlo method

C. Bœhm, JDS, A. Mazumdar and E. Pukartas, Phys. Rev. D87 (2013) 023529, [arXiv:1205.2815]

Results

- Hard to find bino-like LSP + correct LSP relic density (mass mainly close to $m_{A^0}/2$)
- Get mainly higgsino-like LSP, degeneracy between $\chi^0_{1,2}$ and $\chi^\pm_1$



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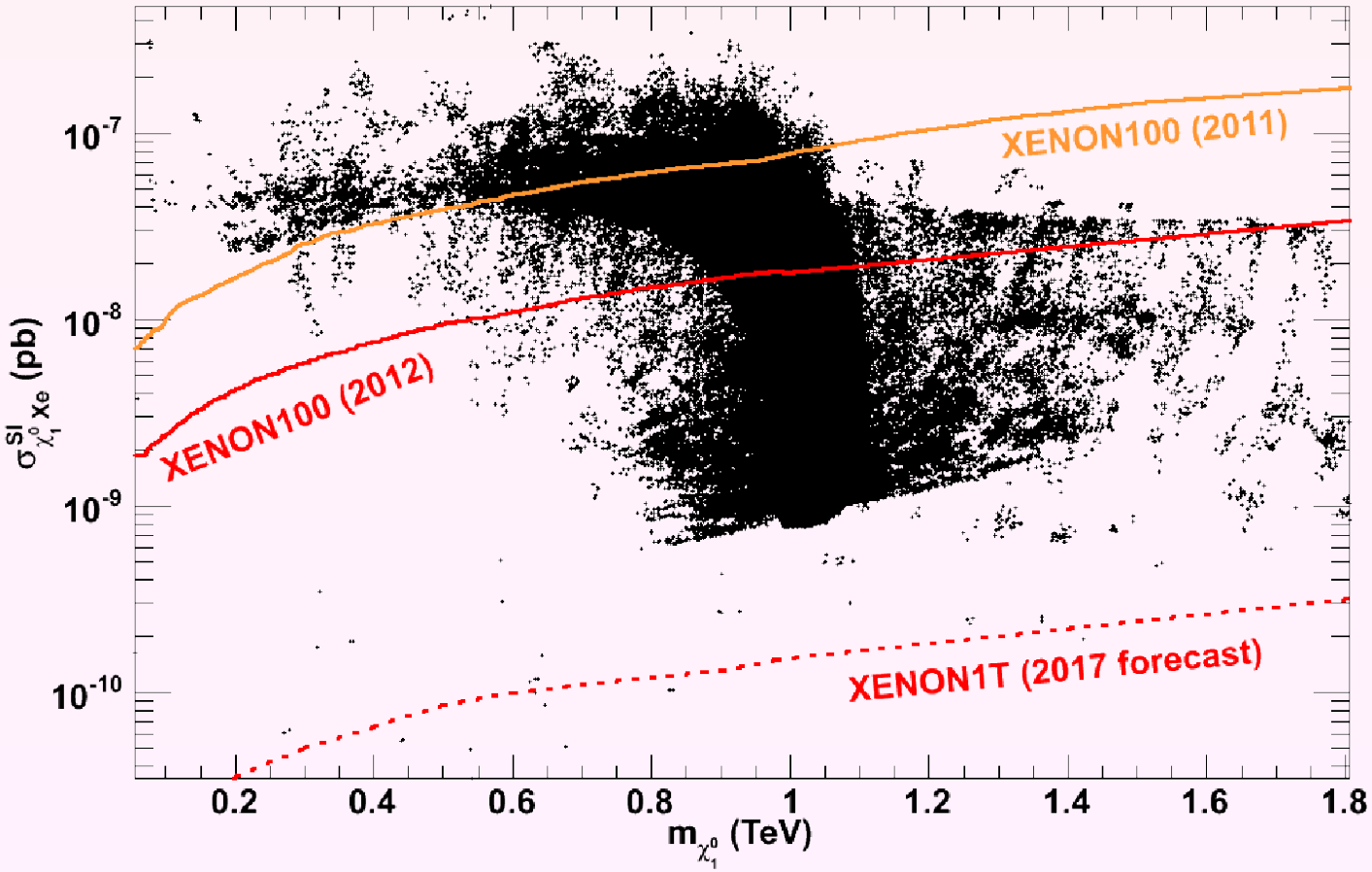
- NUHM2 scenarios within LHCb and XENON1T experiments sensitivity



DM ID limits on the LSP-NLSP mass degeneracy

Possibility to set stringent constraints on DM properties by looking at DM annihilation into $W^{\pm}$, when LSP and NLSP are mass degenerate (difficult at the LHC), using Fermi-LAT **AND** Pamela **data**

DM ID limits on the LSP-NLSP mass degeneracy

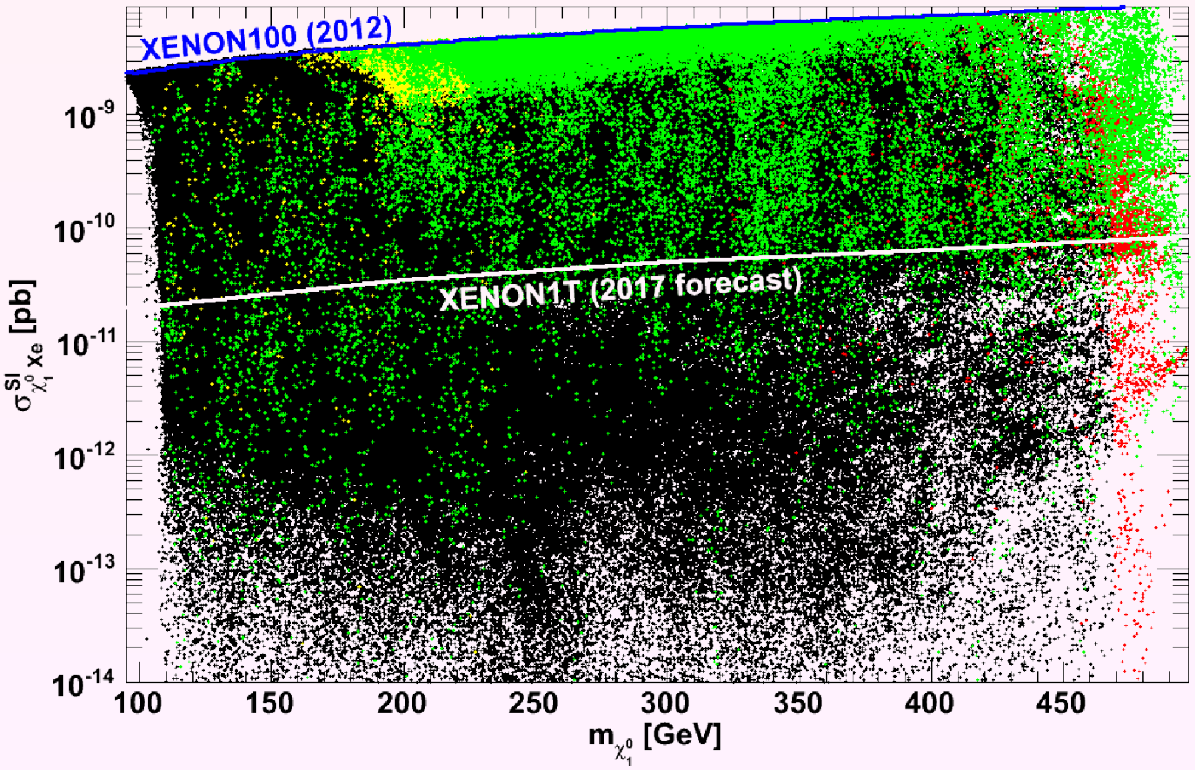
Possibility to set stringent constraints on DM properties by looking at DM annihilation into $W^{\pm}$, when LSP and NLSP are mass degenerate (difficult at the LHC), using Fermi-LAT AND Pamela data
$\Rightarrow$ A "simplified" version of the pMSSM (phenomenological MSSM)
Aim : dominant neutralino DM annihilation channels into gauge bosons

- **All sfermion masses + CP-odd Higgs boson are set to 2 TeV (except for the third generation of squarks, to get $m_{h^0} \sim 125$ GeV), light chargino/neutralino ($m_{\chi_1^0} < 500$ GeV) such that the mass splitting $\Delta m = m_{\chi_1^{\pm}} - m_{\chi_1^0}$ is small**
- **MCMC scan**
- **How powerful are the $\bar{p}/\gamma$-ray limits on excluding parts of pMSSM parameter space and Δm values ?**

G. Bélanger, C. Bœhm, M. Cirelli, JDS and A. Pukhov, JCAP 1211 (2012) 028, [arXiv:1208.5009]

Results

- Higgsino and mainly wino DM probed $\Rightarrow$ assume regeneration mechanism
- ID constrains scenarios with $\Delta m \lesssim 20$ GeV, DM relic density being regenerated at 100%
- If $m_{\chi_1^0} < 500$ GeV and $\Delta m < 0.25$ GeV wino DM ruled out
- ID constraints really competitive with direct detection experiments



OK
Fermi-LAT
Pamela
both

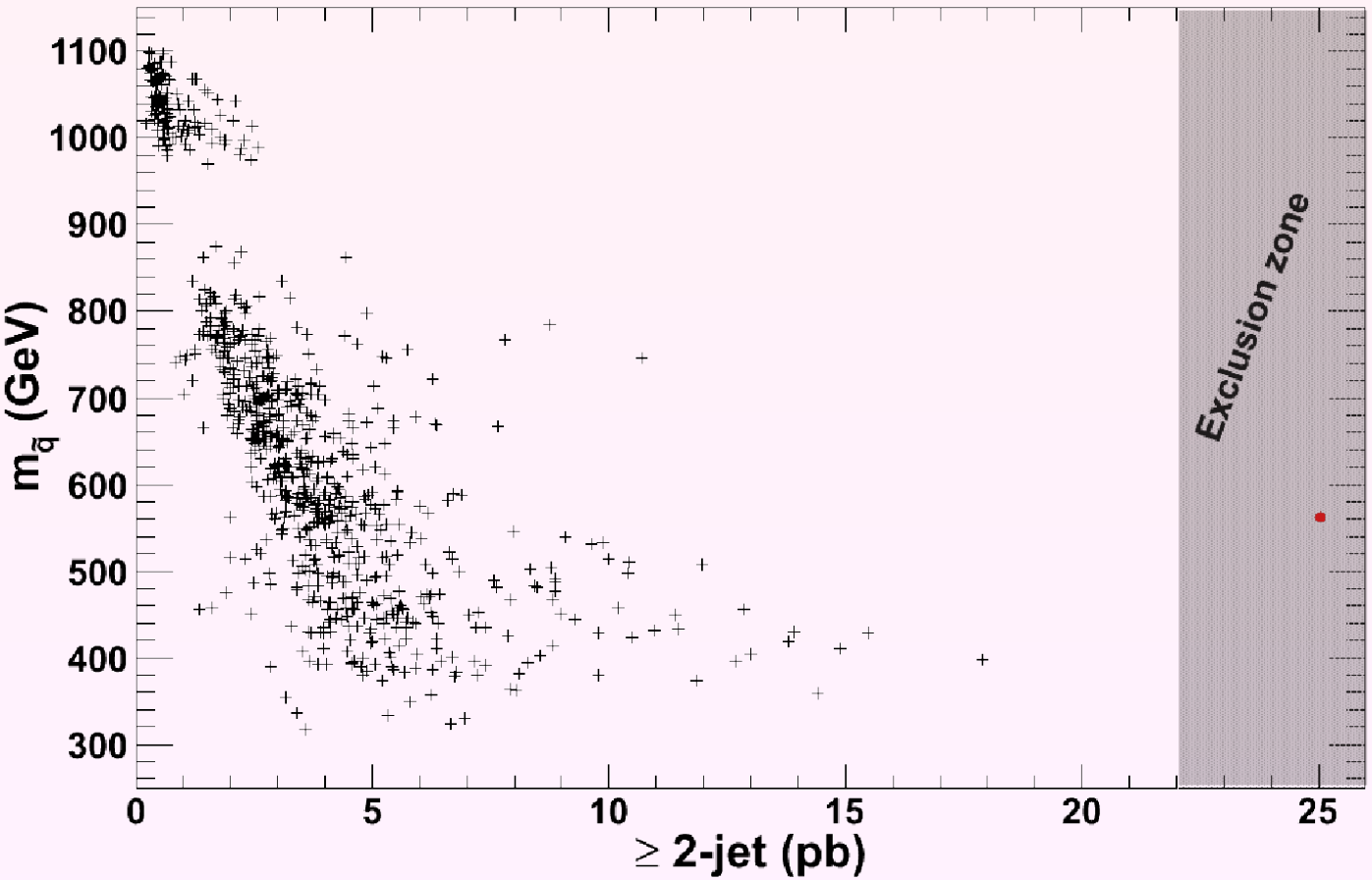
NMSSM and SUSY searches @ LHC

- Searches for exotic particles are now reaching a high level of exclusion that allow to reject a wide class of models
  but limits obtained assuming simplified models of New Physics
  $\Rightarrow$ what about the NMSSM ?
- $\mathcal{W}_{\mathrm{NMSSM}} = \mathcal{W}_{\mathrm{MSSM}}|_{\mu=0} + \lambda \mathbf{S H_u H_d} + \frac{1}{3}\kappa \mathbf{S^3}$
- Example of the exclusion limit coming from the ATLAS 1.04 fb^{-1} search for squarks and gluinos via jets and missing E_T
- In general exclude squarks lighter than 0.6 - 1 TeV and gluinos below 0.5 TeV in the constrained MSSM via $\tilde{q} \to q\chi_1^0$ and $\tilde{g} \to q\bar{q}\chi_1^0$ decays
  - Applying SUSY searches@LHC with ATLAS's 1.04 fb^{-1} 0-lepton jets + missing E_T search using Herwig++ 2.5.1 and RIVET 1.5.2
    $\Rightarrow$ Are ATLAS limits so constraining ?

D. A. Vasquez, G. Bélanger, C. Bœhm, JDS, P. Richardson and C. Wymant, Phys. Rev. D86 (2012) 035023, [arXiv:1203.3446]

Results

- Reduced acceptance into jets + missing E_T search channels and more jets for $\widetilde{S}$ LSP
- $\tilde{q} \rightarrow q + (\chi_2^0 \rightarrow \chi_1^0 + (f\bar{f}$ or a_1 or $h_1))$
- 300 GeV squarks allowed when $\tilde{S}$-like LSP :



U(1) extensions of the MSSM

The model

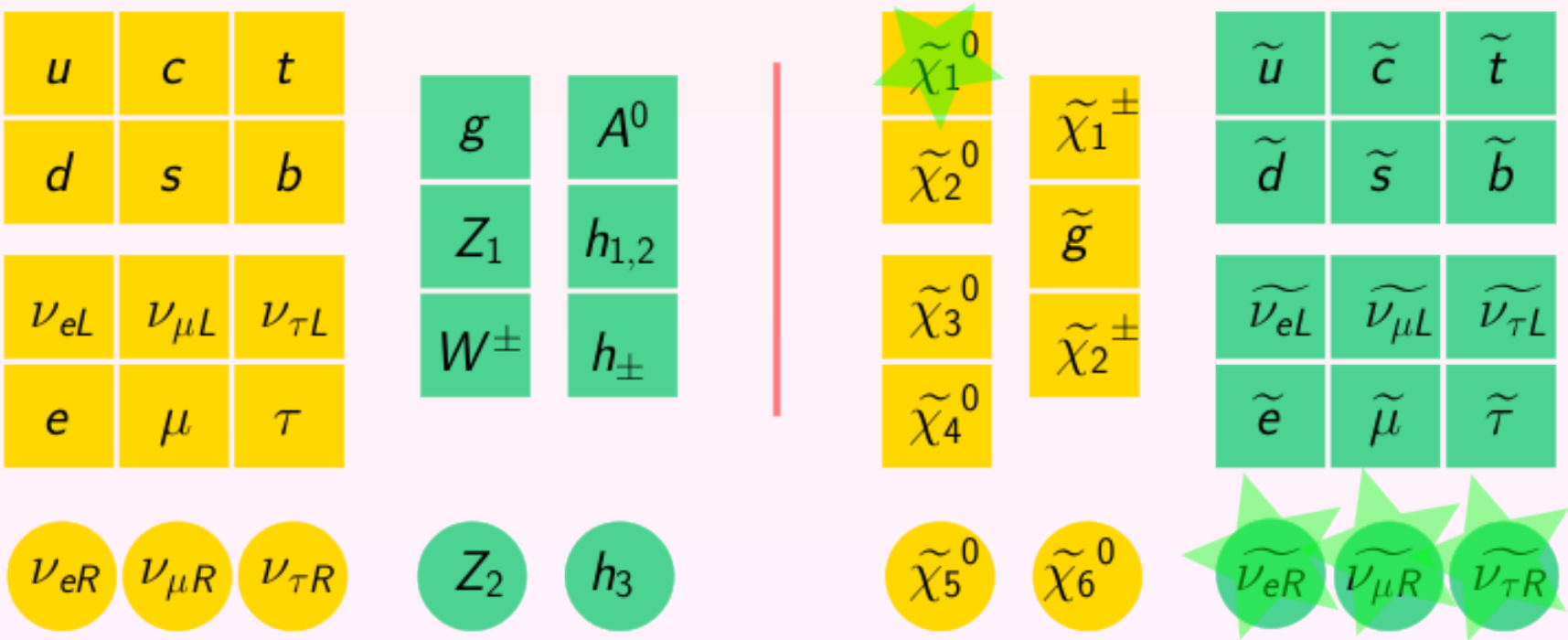
- **Symmetry group : $SU(3)_c \times SU(2)_L \times U(1)_Y \times U'(1)$**
  Coupling constants : g_3, g_2, g_Y and $g'_1 = \sqrt{\frac{5}{3}} g_Y$

- $\mathcal{W}_{UMSSM} = \mathcal{W}_{MSSM}|_{\mu=0} + \lambda S H_u H_d + \tilde{\nu}^*_R y_\nu \widetilde{L} H_u + \mathcal{O}(TeVs)$
- **New D-terms for m_{h_1}**
- **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**
- **Gauginos sector : 6 neutralinos in the basis $(\widetilde{B}, \widetilde{W}^3, \widetilde{H}^0_d, \widetilde{H}^0_u, \widetilde{S}, \widetilde{B'})$**

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

The model

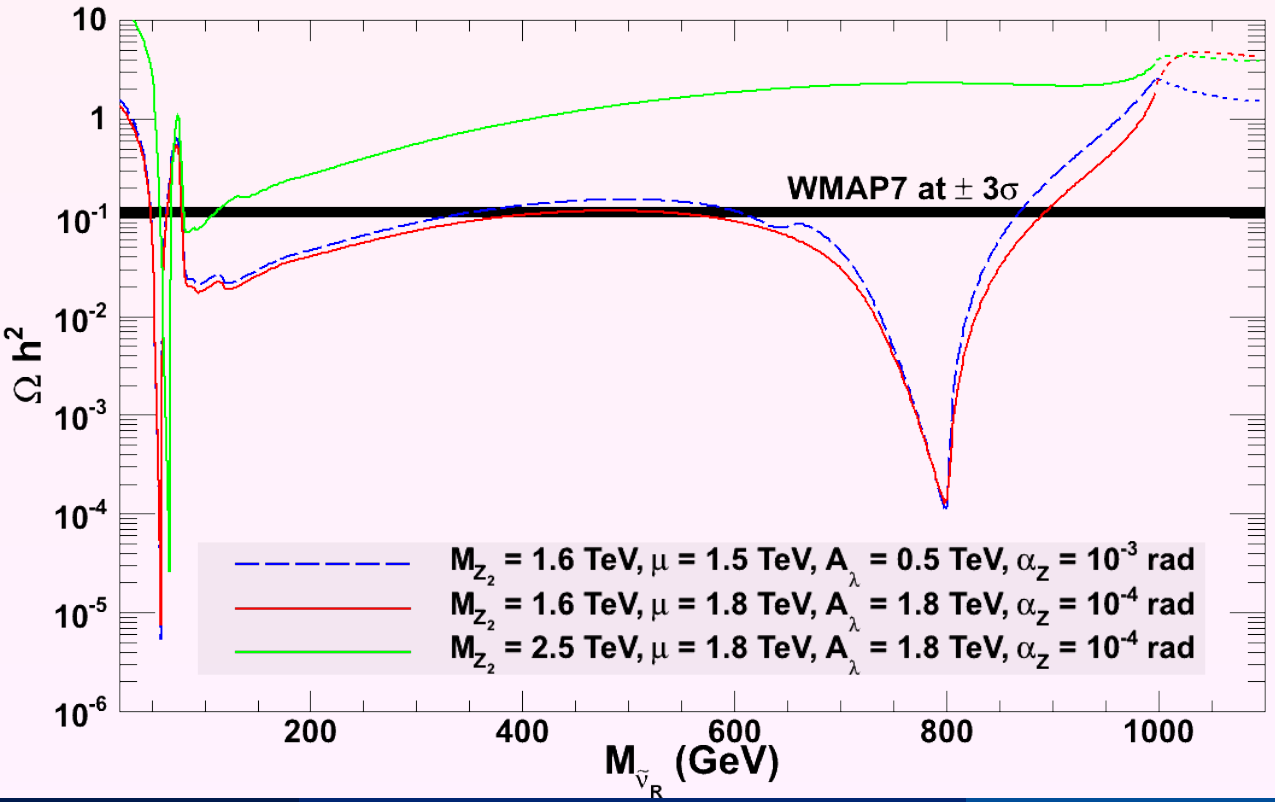
- **To sum up :**



RH sneutrino annihilation

Parameter space regions with $\Omega_{WIMP} h^2 \approx 0.1 \Rightarrow$ 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)**

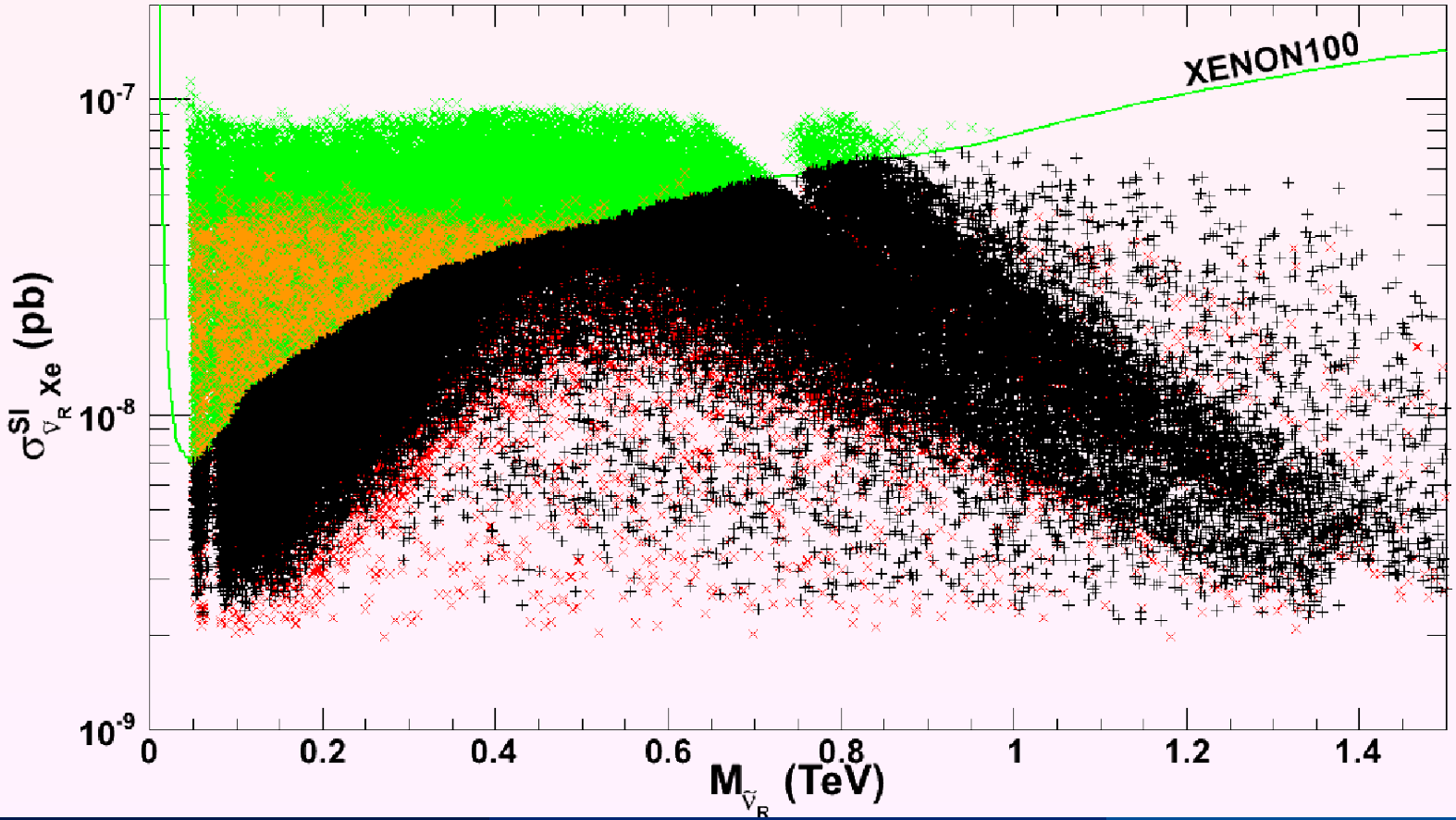


Scattering on nucleons

For some $U'(1)$ models we can have a good suppression of the gauge boson or/and Higgs boson contribution... for other models, huge constraints on the parameter space

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

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



Need for an update

- **Updates :**
  - **New limits on M_{Z_2}**
  - **DM observables (Planck satellite, update on XENON100 results)**
  - **Higgs boson mass measurements**
- **New inputs :**
  - **Higgs boson signal strengths + more low energy observables**
    $\Rightarrow$ Modification of the `NMSSMTools` code : `UMSSMTools`
  - **Also neutralino as DM candidate**
  - **Relax relic abundance constraint**
  - **Third generation of sfermions allowed to be light**

$\Rightarrow$ In progress

Conclusions

- Discovery (Higgs boson), bounds (exotic particles, DM)
  $\Rightarrow$ extensions of the SM and especially SUSY are now better probed
- Indirect detection of DM can be a competitive tool
- Caveat on the use of limits on simplified models
- UMSSM has another viable DM candidate, the RH sneutrino
- More general work in this model is in progress
- Implement the UMSSM model in the public version of the `micrOMEGAs` code