Supersymmetric Dark Matter candidates in light of constraints from collider and astroparticle observables

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Outline

1. **Motivations**
2. **Neutralino DM in the (N)MSSM**
    - C. Bœhm, JDS, A. Mazumdar and E. Pukartas, Phys. Rev. D87 (2013) 023529, arXiv :1205.2815
    - G. Bélanger, C. Bœhm, M. Cirelli, JDS and A. Pukhov, JCAP 1211 (2012) 028, arXiv :1208.5009
    - D. A. Vasquez, G. Bélanger, C. Bœhm, JDS, P. Richardson and C. Wymant, Phys. Rev. D86 (2012) 035023, arXiv :1203.3446
3. **U(1) extensions of the MSSM**
    - G. Bélanger, JDS and A. Pukhov, JCAP 1112 (2011) 014, arXiv :1110.2414
    - G. Bélanger, JDS et al., in preparation
4. **Conclusions**

Motivations

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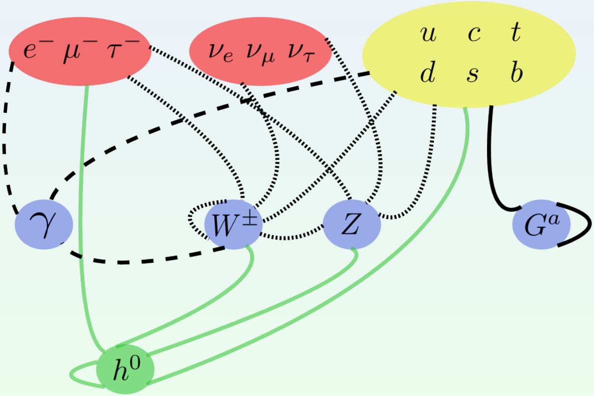
4. Conclusions

Success of the Standard Models

- **Particle Physics (SM)**
  - **All particles discovered since 1 year - 1 day**

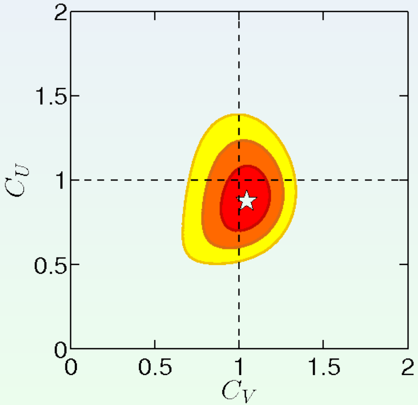


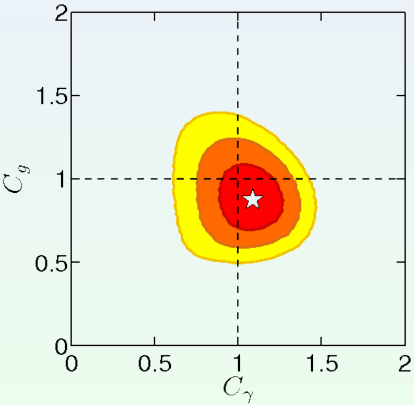
SM interactions, at tree-level

Success of the Standard Models

✶ Particle Physics (SM)

- All particles discovered since 1 year - 1 day
- With the expected properties, ...





Reduced Higgs couplings, G. Bélanger, B. Dumont, U. Ellwanger, J. F. Gunion and S. Kraml, arXiv :1306.2941

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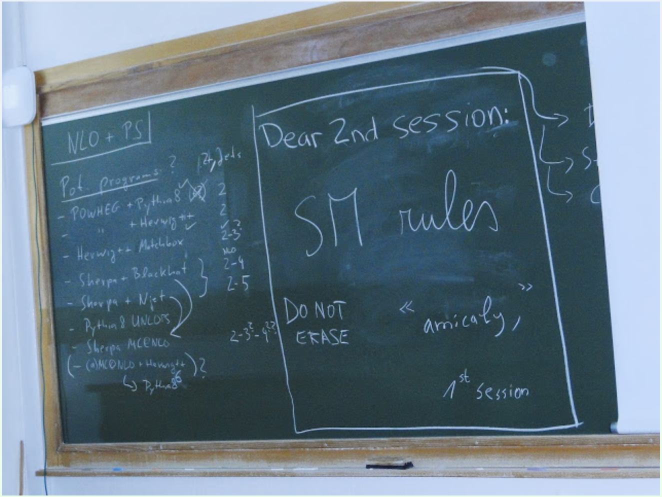
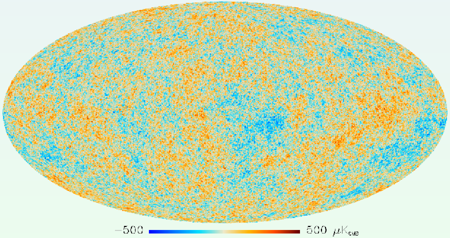
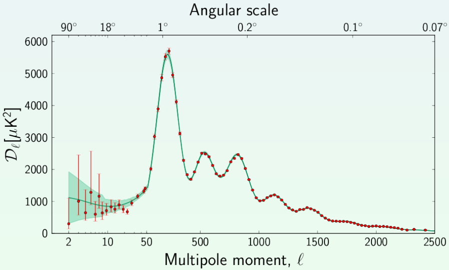


Les Houches Workshop 2013, courtesy of F. Boudjema

Success of the Standard Models

- **Particle Physics (SM)**
- **Cosmology (ΛCDM)**
  - **Simple cosmological model which fits even the most accurate measurements (Planck satellite)**





Temperature fluctuations of the CMB

Temperature angular power spectrum

P. A. R. Ade et al., arXiv :1303.5062

Success of the Standard Models

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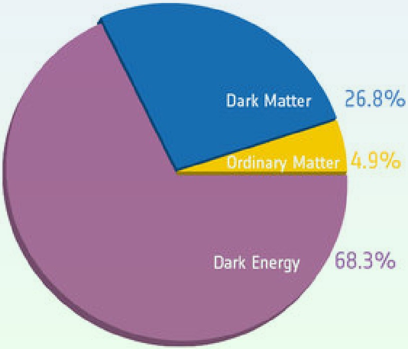
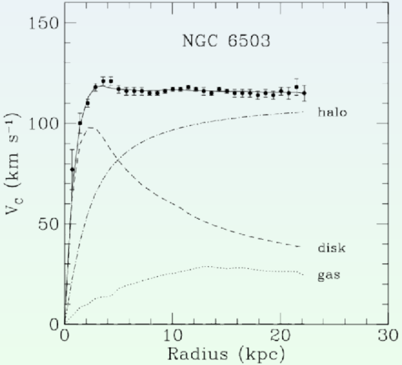
- **Cosmology (ΛCDM)**
  - **Needs Dark Energy and Dark Matter (DM, other evidence : rotation curves of galaxies, bullet cluster, ...)**





ΛCDM after Planck measurements

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

Success of the Standard Models

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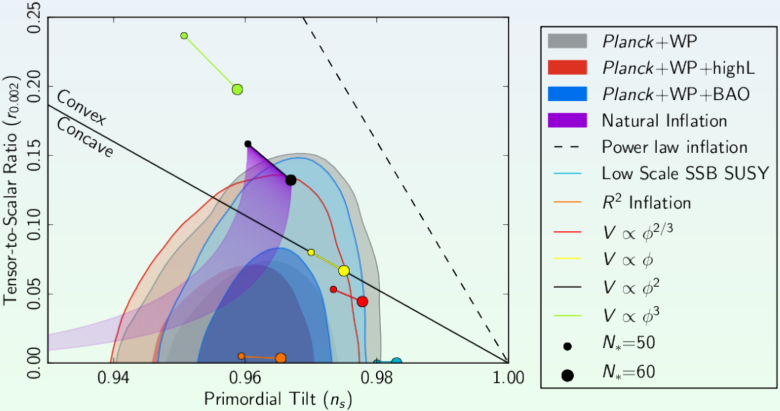
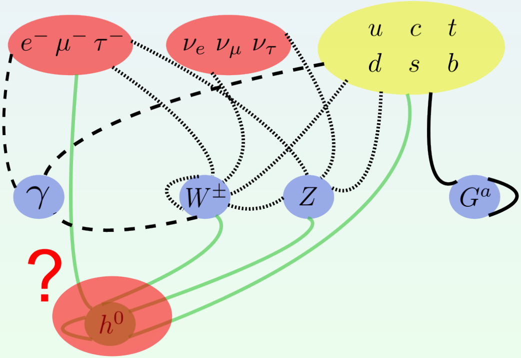
  - **Simple models of inflation are still valid**



Constraints on inflationary models from Planck satellite

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**



Drawbacks of the Standard Models

Particle Physics (SM)

- Hierarchy problem between EW (∼ 100 GeV) and Planck (∼ 10^{19} GeV) scales
  Quadratic divergences to the Higgs boson mass squared
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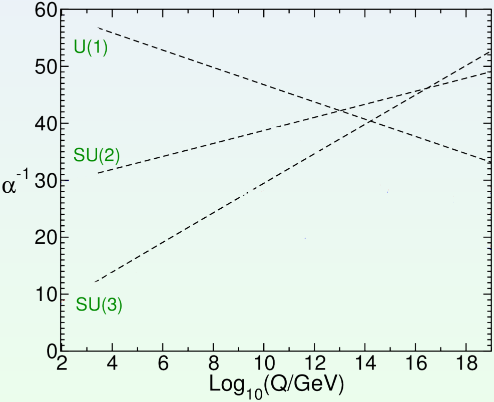

Evolution of SM gauge couplings, Stephen P. Martin, arXiv :hep-ph/9709356

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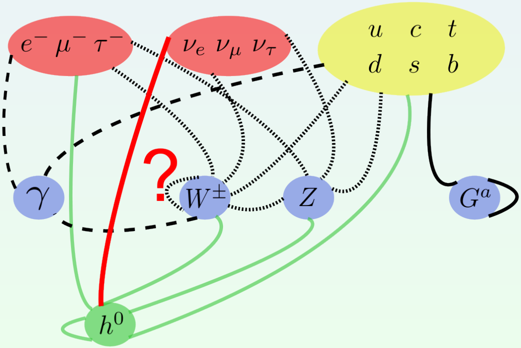
Particle Physics (SM)

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



Drawbacks of the Standard Models

- ✶ **Particle Physics (SM)**
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  - **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**

$\Rightarrow$ Example of DM candidate which gives the right abundance :
Weakly Interacting Massive Particle (WIMP)

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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 ⇔ bosons ⇒ solution to the Hierarchy problem**

New particles : cancellation of the quadratic term in
$\Delta m^2_{h^0}\Big|_{SM} = \frac{y_f^2}{16\pi^2}\left(-2\Lambda^2 + 6m_f^2 \ln\frac{\Lambda}{m_f} + \ldots\right)$ **with that of**
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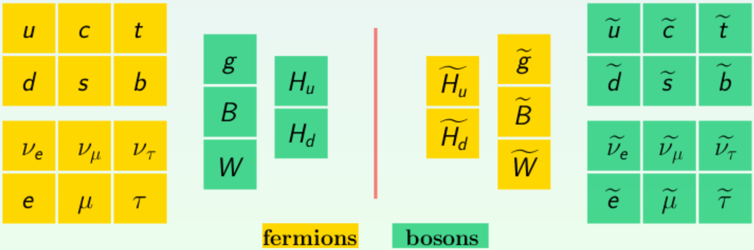
Not yet observed ⇒ SUSY breaking
Minimal Supersymmetric Standard Model (MSSM) :



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- **Fermions ⇔ bosons ⇒ solution to the Hierarchy problem**
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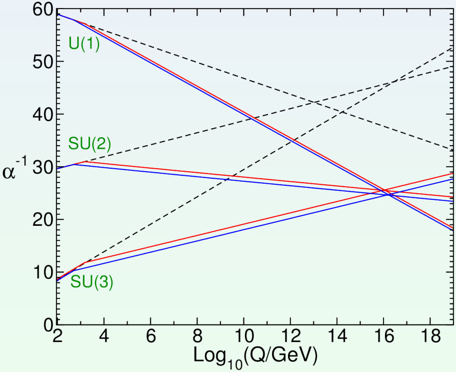


Gauge coupling unification, Stephen P. Martin, arXiv :hep-ph/9709356

Supersymmetry

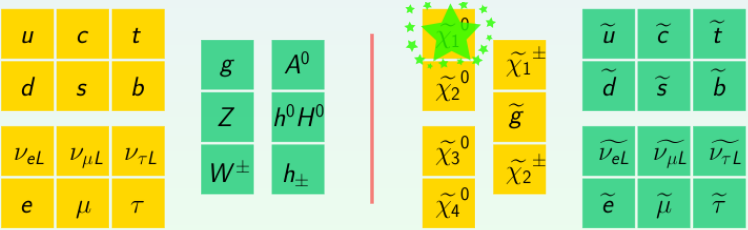
- Fermions ⇔ bosons ⇒ solution to the Hierarchy problem
- Unification at GUT scale
- LSP/DM (R-Parity)

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

⇒ DM candidates in supersymmetric models

Supersymmetry

- **Fermions ⇔ bosons ⇒ solution to the Hierarchy problem**
- **Unification at GUT scale**
- **LSP/DM (supersymmetry breaking, R-Parity)**
- **Examples :**



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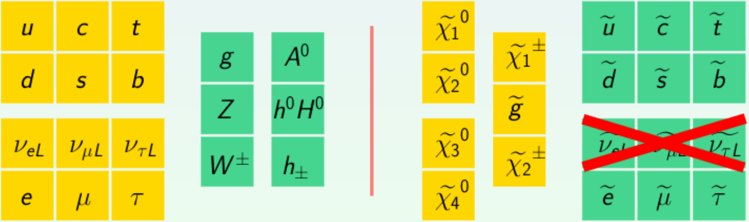
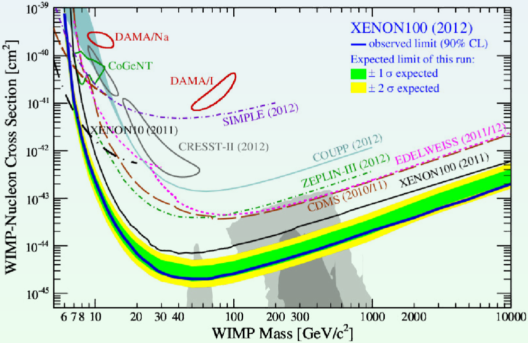


Supersymmetry

- **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

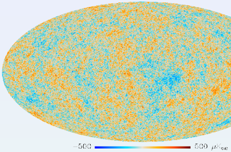
Supersymmetry

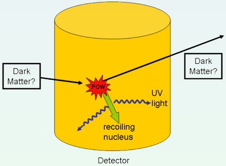
- Constraints on SUSY/DM
  - DM relic abundance
  - Direct detection of DM
  - Indirect detection of DM (search for anomalous features in cosmic rays like $\gamma, \nu, \mathrm{e}^+, \bar{\mathrm{p}}$)
    - ✘ "Background drawback" : ID depends on the current knowledge of astrophysical sources
    - ✔ Remove carefully known (modelled) background
    - ✔ Clear features not mimicked by astrophysical sources
    - A huge number of data validates the modelling of astrophysical background sources in the GeV-TeV range :
absence of anomalies in the $\bar{\mathrm{p}}$ spectrum less exploited ⇒ **Set constraints**

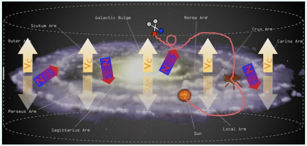
Supersymmetry

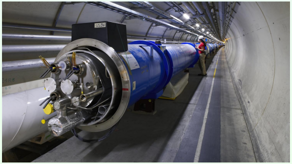
- **Constraints on SUSY/DM**
  - **DM relic abundance**
  - **Direct detection of DM**
  - **Indirect detection of DM**
  - **Collider constraints**
    - **LEP ⇒ charged sparticles**
    - **LHC ⇒ coloured sparticles**
    - **Low energy observables** $\mathscr{B}(\bar{\mathbf{B}}^{\mathbf{0}} \to \mathbf{X_s}\gamma), \mathscr{B}(\mathbf{B_s^0} \to \mu^+\mu^-), \mathscr{B}(\mathbf{B}^{\pm} \to \tau^{\pm}\nu_\tau),$ $\mathbf{\Delta M_{d,s}}, \delta\mathbf{a}_\mu, \mathbf{\Delta}\rho,$ **...**

Supersymmetry









Neutralino DM in the (N)MSSM

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Supersymmetric inflaton

- **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 :**

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

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

Supersymmetric inflaton

✴ NUHM2 (Non-Universal Higgs Masses type 2)

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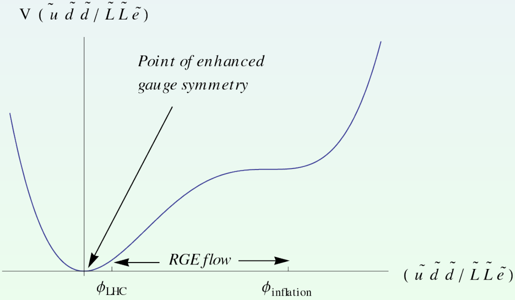
  - ✘ Drawbacks : $m_{h^0} \sim 125$ GeV not easy
- We considered a non-universal scalar masses model, with $m_0^2 \neq m_{H_u}^2 \neq m_{H_d}^2$ (H. Baer et al [hep-ph/0504001], J. R. Ellis et al [hep-ph/0210205])
  - ✔ Easier to reach $m_{h^0} = 125$ GeV, increase DM annihilation rates with higgsino LSP
- NUHM2 free parameter :

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

Supersymmetric inflaton

- **NUHM2**
- **$\widetilde{L}\widetilde{L}\widetilde{e}$ and $\widetilde{u}\widetilde{d}\widetilde{d}$**
  - **Inflaton, scalar field whose flat direction potential (with a non-negligible slope) leads to the end of the inflation phase**
  - **Charged under the visible sector of the particle physics model considered, i.e. NUHM2**
  - **$\Rightarrow$ $\widetilde{L}\widetilde{L}\widetilde{e}$ and $\widetilde{u}\widetilde{d}\widetilde{d}$ D-terms can be such candidates (R. Allahverdi et al, [hep-ph/0610134], [hep-ph/0605035])**



Method and constraints

Constraints imposed on a scan made using Markov Chain Monte Carlo method :

- **On $\widetilde{\mathbf{L}}\widetilde{\mathbf{L}}\widetilde{\mathbf{e}}$ and $\widetilde{\mathbf{u}}\widetilde{\mathbf{d}}\widetilde{\mathbf{d}}$, explain the observed temperature anisotropy in the CMB with :**
  - **The amplitude of density perturbations** $\delta_{\mathbf{H}} = \frac{8}{\sqrt{5}\pi}\frac{m_\phi M_{\mathrm{P}}}{\phi_0^2}\frac{1}{\Delta^2}\sin^2[\mathcal{N}_{\mathbf{COBE}}\sqrt{\Delta^2}]$,

    $\Delta^2 \equiv 900\alpha^2\mathcal{N}_{\mathbf{COBE}}^{-2}\left(\frac{M_{\mathrm{P}}}{\phi_0}\right)^4, \quad \mathcal{N}_{\mathbf{COBE}} \sim 50$
  - **The scalar spectral index** n_s **of the corresponding power spectrum**
    $n_s = 1 - 4\sqrt{\Delta^2}\cot[\mathcal{N}_{\mathbf{COBE}}\sqrt{\Delta^2}]$,
- **On NUHM2 model in general :**

Constraint	Value/Range
m_{h^0} (GeV)	[115.5, 127]
$\Omega_{\chi_1^0}h^2$	[0.1088, 0.1158]
$\mathscr{B}(\bar{B}^0 \to X_s\gamma) \times 10^4$	3.55
$\delta a_\mu \times 10^{10}$	28.7
$\mathscr{B}(B_s^0 \to \mu^+\mu^-) \times 10^9$	4.5
$\Delta\rho$	0.002
$R_{B^\pm\to\tau^\pm\nu_\tau}(\frac{\mathrm{NUHM2}}{\mathrm{SM}})$	2.219
$Z \to \chi_1^0\chi_1^0$ (MeV)	1.7
$\sigma_{e^+e^-\to\chi_1^0\chi_{2,3}^0}$ $\times\mathscr{B}(\chi_{2,3}^0 \to Z\chi_1^0)$ (pb)	1

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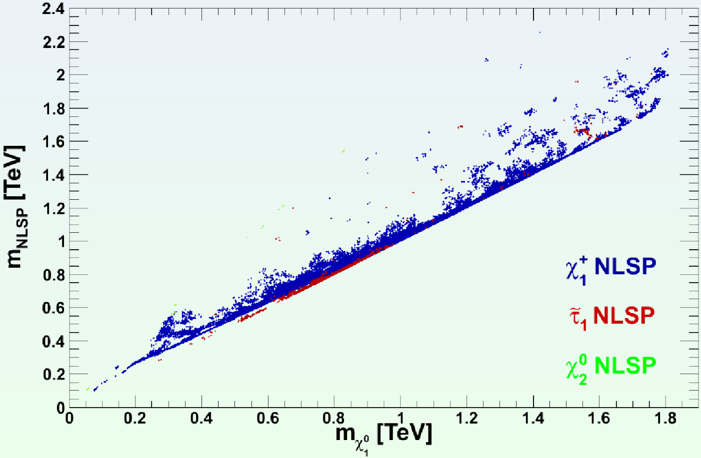
- **Compute total likelihood of a point M in NUHM2 parameter space :**
  if $\mathcal{L}_{\rm tot}^{\mathbf{M}} > \frac{\mathcal{L}_{\rm tot}^{\mathbf{m}}}{\mathbf{p}}$**, with** $\mathbf{p} \in [1, 1 - \ln \mathcal{L}_{\rm tot}^{\mathbf{m}}] \Rightarrow$ **keep M**

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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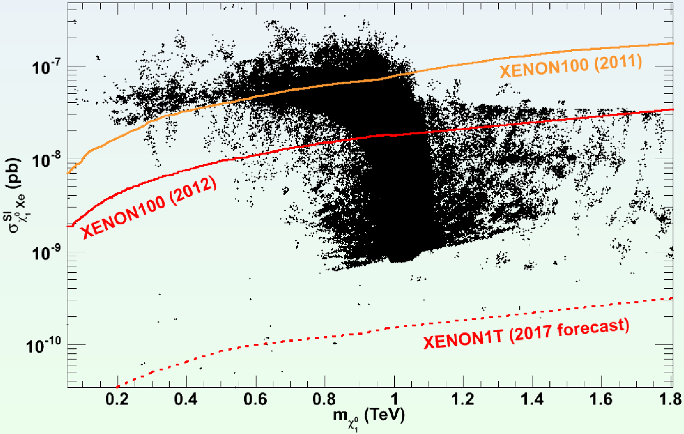

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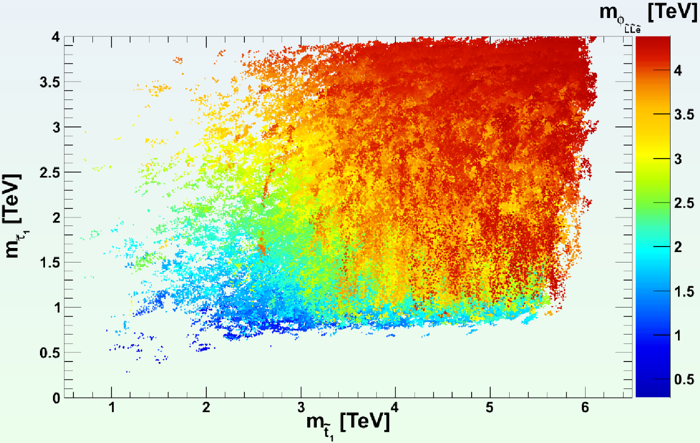
- **Informations on inflaton mass if we discover lightest stop/stau at LHC**



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**

- **From γ-rays :** FERMI-LAT **analysis of the diffuse γ-ray emission from dwarf spheroidal galaxies (Ackermann et al, Phys. Rev. Lett. 107 (2011) 241302)**
- **From $\bar{p}$: derived bounds from** PAMELA **antiprotons data using several approaches**

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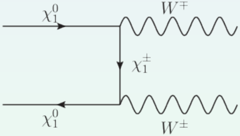
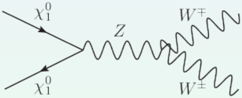
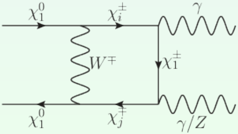
⇒ A "simplified" version of the pMSSM (phenomenological MSSM)

Aim : dominant neutralino DM annihilation channels into gauge bosons







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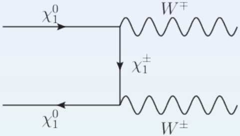
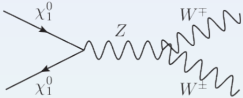
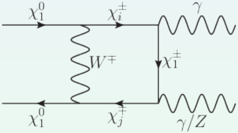
$\Rightarrow$ **A "simplified" version of the pMSSM**

Aim : dominant neutralino DM annihilation channels into gauge bosons



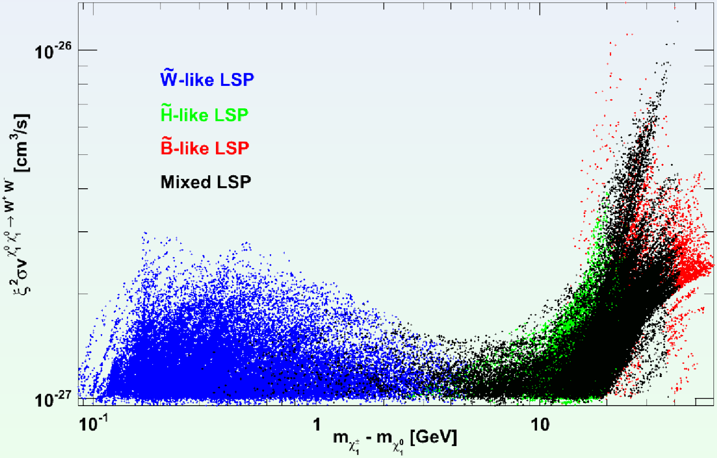




- **All sfermion masses + CP-odd Higgs boson are set to 2 TeV (except for the third generation of squarks, to get $m_{h^0} \sim 125$ GeV), light chargino/neutralino ($m_{\chi_1^0} < 500$ GeV) such that the mass splitting $\Delta m = m_{\chi_1^{\pm}} - m_{\chi_1^0}$ is small**
- **MCMC scan**
- **How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

Results

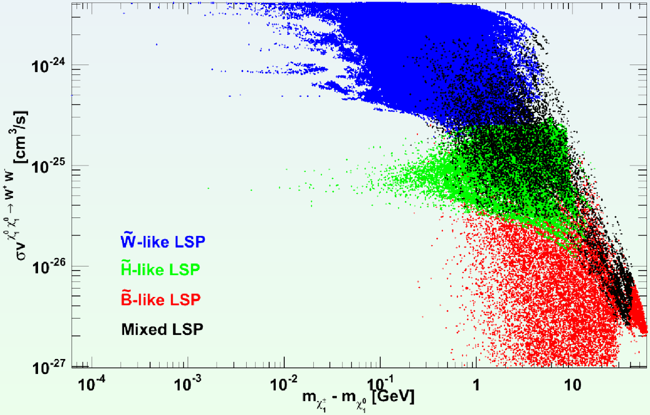
- ✶ **Higgsino and mainly wino DM probed**



$\Rightarrow$ **assume regeneration mechanism**

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**



Results

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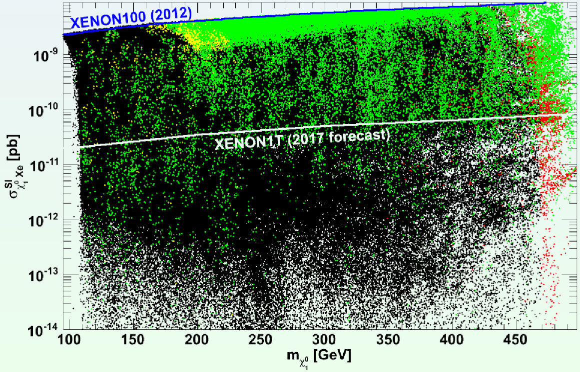
- **ID constrains scenarios with $\Delta m \lesssim 20$ GeV, DM relic density being regenerated at 100%**
- **If $m_{\chi_1^0} < 500$ GeV and $\Delta m < 0.25$ GeV wino DM ruled out**
- **No explanation of the "130 GeV line" in this simplified pMSSM**
- **ID constraints really competitive with direct detection experiments**



OK
Fermi-LAT
Pamela
both

NMSSM and SUSY searches @ LHC

- Adding a singlet of SM gauge symmetry to solve the μ problem of the MSSM
- $\mathcal{W}_{\mathrm{MSSM}} = \tilde{u}_R^* y_u \widetilde{Q} H_u - \tilde{d}_R^* y_d \widetilde{Q} H_d - \tilde{e}_R^* y_e \widetilde{L} H_d + \mu H_u H_d$
  $\Rightarrow \mathcal{W}_{\mathrm{NMSSM}} = \mathcal{W}_{\mathrm{MSSM}}|_{\mu=0} + \lambda S H_u H_d + \frac{1}{3}\kappa S^3$
- 2 CP-odd Higgs boson (a_1, a_2), 3 CP-even Higgs boson (h_1, h_2, h_3)
  $m_{h_1}^2|_{\mathrm{tree}} \lesssim M_Z^2 \cos^2 2\beta + \frac{\lambda^2}{2} v^2$
  $\Rightarrow$ less fine tuned $m_{h_1} \sim 125$ GeV
- 5 neutralinos χ_i^0 in the basis $(\widetilde{B}, \widetilde{W}^3, \widetilde{H}_d^0, \widetilde{H}_u^0, \widetilde{S})$

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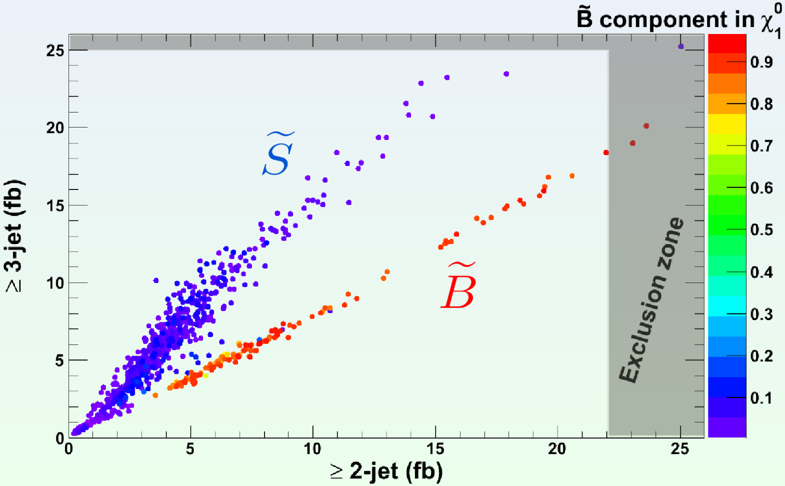
- **Using results of a previous work (D. Albornoz Vasquez et al., arXiv :1107.1614, arXiv :1201.6150) with constraints on DM, *B* and Higgs physics to define the relevant NMSSM parameter space**
- **Motivated by hints of a signal in direct detection experiments (DAMA/Libra, arXiv :1002.1028 ; CoGeNT, arXiv :1201.6150)**
  $\Rightarrow$ **light DM ($\widetilde{B}$ or $\widetilde{S}$) scenarios (mostly light a_1 and/or h_1)**

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
  ⇒ what about the NMSSM ?
- **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 $\tilde{q} \rightarrow q\chi_1^0$ and $\tilde{g} \rightarrow q\bar{q}\chi_1^0$ 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**
    ⇒ Are ATLAS limits so constraining ?

Results

- **Reduced acceptance into jets + missing E_T search channels and more jets for $\tilde{S}$ LSP**
- $\tilde{q} \to q + (\chi_2^0 \to \chi_1^0 + (f\bar{f} \text{ or } a_1 \text{ or } h_1))$



Results

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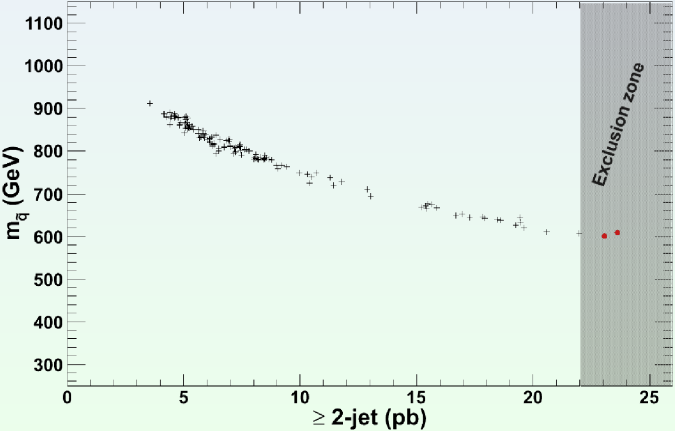
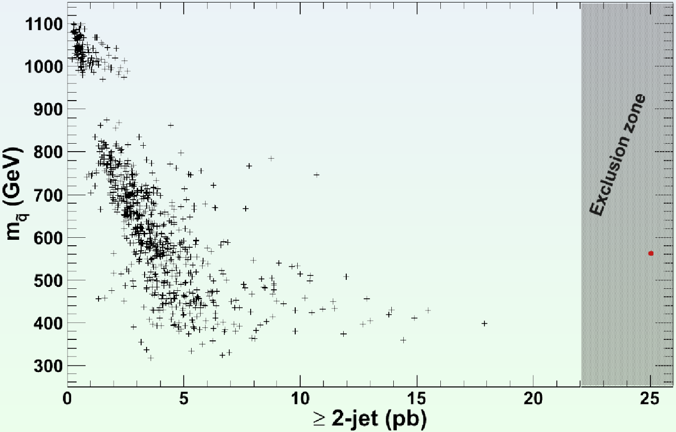
- $\tilde{q} \to q + (\chi_2^0 \to \chi_1^0 + (f\bar{f}$ or a_1 or $h_1))$
- Usual exclusion ($\tilde{B}$-like LSP) :



Results

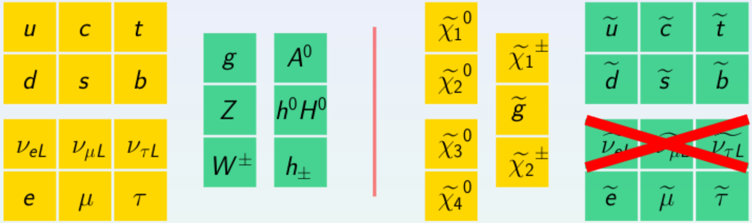
- **Reduced acceptance into jets + missing E_T search channels and more jets for $\widetilde{S}$ LSP**
- $\tilde{q} \rightarrow q + (\chi_2^0 \rightarrow \chi_1^0 + (f\bar{f} \text{ or } a_1 \text{ or } h_1))$
- **300 GeV squarks allowed when ($\tilde{S}$-like LSP) :**



U(1) extensions of the MSSM

1. Motivations
2. Neutralino DM in the (N)MSSM
    - C. Bœhm, JDS, A. Mazumdar and E. Pukartas, Phys. Rev. D87 (2013) 023529, arXiv :1205.2815
    - G. Bélanger, C. Bœhm, M. Cirelli, JDS and A. Pukhov, JCAP 1211 (2012) 028, arXiv :1208.5009
    - D. A. Vasquez, G. Bélanger, C. Bœhm, JDS, P. Richardson and C. Wymant, Phys. Rev. D86 (2012) 035023, arXiv :1203.3446
3. **U(1) extensions of the MSSM**
    - **G. Bélanger, JDS and A. Pukhov, JCAP 1112 (2011) 014, arXiv :1110.2414**
    - **G. Bélanger, JDS et al., in preparation**
4. Conclusions

Sneutrinos



- **Neutrino oscillations indicative of massive neutrinos ⇒ possibility to add right-handed (RH) neutrino fields**

  ⇒ Extensions of the MSSM with RH (s)neutrino can provide DM candidate

- **Here RH neutrino mass generated by introducing Dirac mass terms**
  ⇒ supersymmetric partner can be at the TeV scale

- **This candidate couples to new vector, scalar field by adding a new abelian gauge symmetry ⇒ the UMSSM**

The model

- Symmetry group : $\mathbf{SU(3)_c \times SU(2)_L \times U(1)_Y \times U'(1)}$
  Coupling constants : g_3, g_2, g_Y and $g_1' = \sqrt{\frac{5}{3}} g_Y$
- $\mathbf{U'(1)}$ stems from string-inspired $\mathbf{E_6}$:
  $\mathbf{E_6 \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\chi \times U(1)_\psi \Rightarrow U'(1)}$ charge :

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

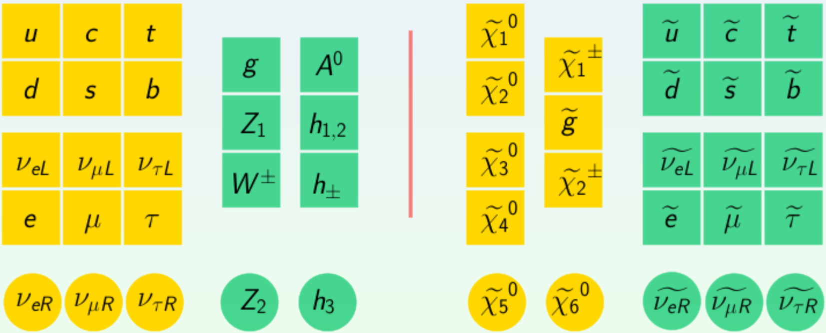
- Superpotential :

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

- As the NMSSM, this model solves the μ problem : $\mu = \lambda \frac{v_s}{\sqrt{2}}$
- New D-terms for m_{h_1}

The model

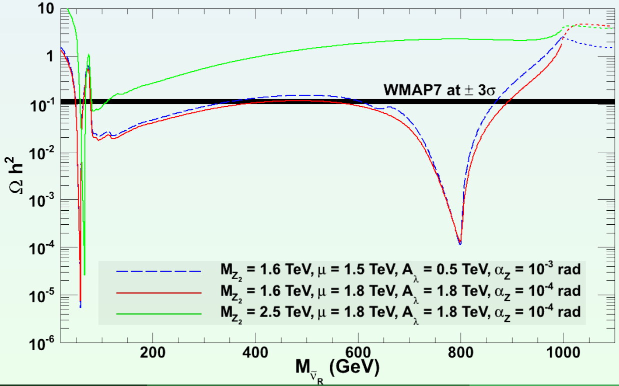
- **Gauge sector : Physical abelian gauge bosons : $\mathbf{Z_1}$ and $\mathbf{Z_2}$, mixing between the Z of the SM and the $\mathbf{Z'}$, $\alpha_{\mathbf{Z}}$ is the mixing angle $\Rightarrow$ $\tan\beta$ constrained**
- **Gauginos sector : 6 neutralinos in the basis $(\widetilde{\mathbf{B}}, \widetilde{\mathbf{W}}^3, \widetilde{\mathbf{H}}^0_{\mathbf{d}}, \widetilde{\mathbf{H}}^0_{\mathbf{u}}, \widetilde{\mathbf{S}}, \widetilde{\mathbf{B'}})$**
- **To sum up :**



WIMP annihilation

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

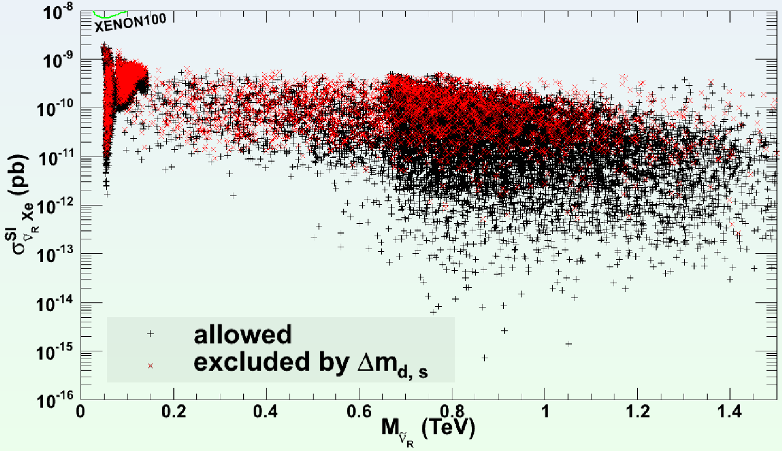
- **WIMP mass near $m_{h_1}/2$**
- **WIMP mass near $M_{Z_2}/2$ (also $m_{h_i}/2$)**
- **WIMP mass near $m_{h_i}/2$ or above W pair threshold**
- **Coannihilation processes (mainly higgsino-like)**



Scattering on nucleons

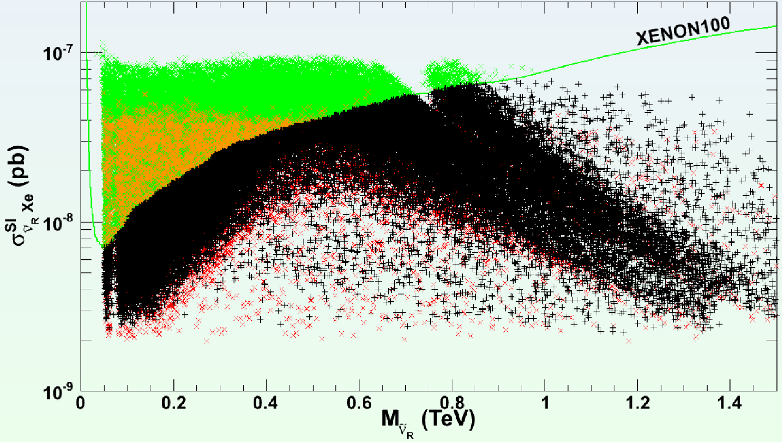
For some $U'(1)$ models we can have a good suppression of the gauge boson or/and Higgs boson contribution

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



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

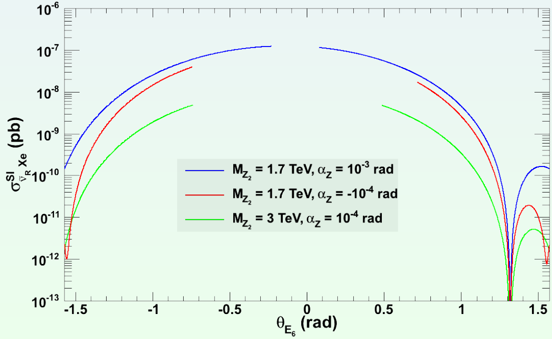


Scattering on nucleons

Abelian gauge boson contribution to direct detection cross section :

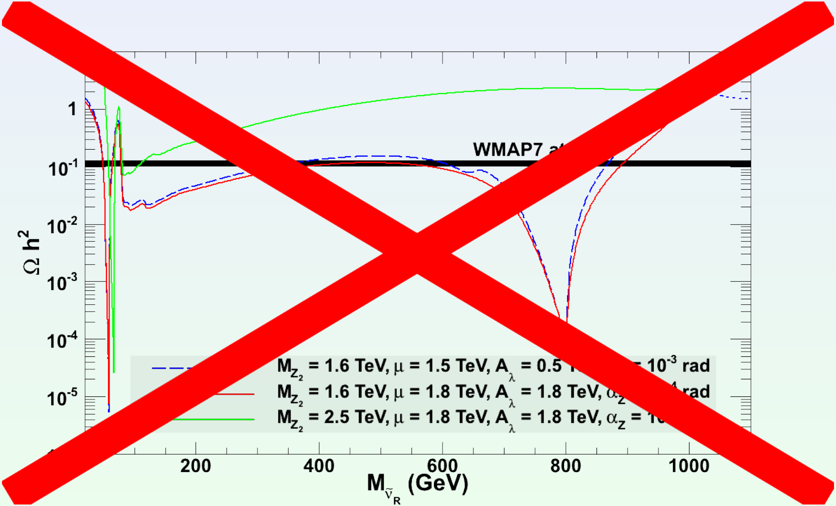
$$\sigma^{Z_1,Z_2}_{\tilde{\nu}_R N} = \frac{\mu^2_{\tilde{\nu}_R N}}{\pi}(g'_1 \mathcal{Q}'_\nu)^2[(y(1-4s^2_W)+y')Z+(-y+2y')(A-Z)]^2$$

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



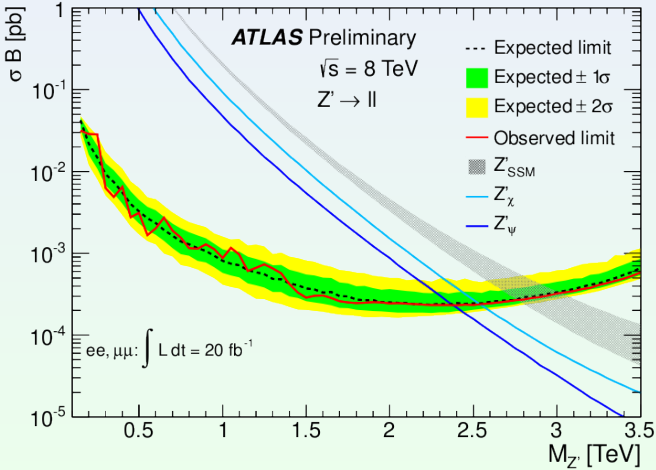
⇒ **stringent constraints for small $|\theta_{E_6}|$ because of Q'^d_V term**

Need for an update



Need for an update

- **Updates :**
  - **New limits on M_{Z_2}**



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    - **DM observables (Planck satellite, update on XENON100 results)**
    - **Higgs boson mass measurements**

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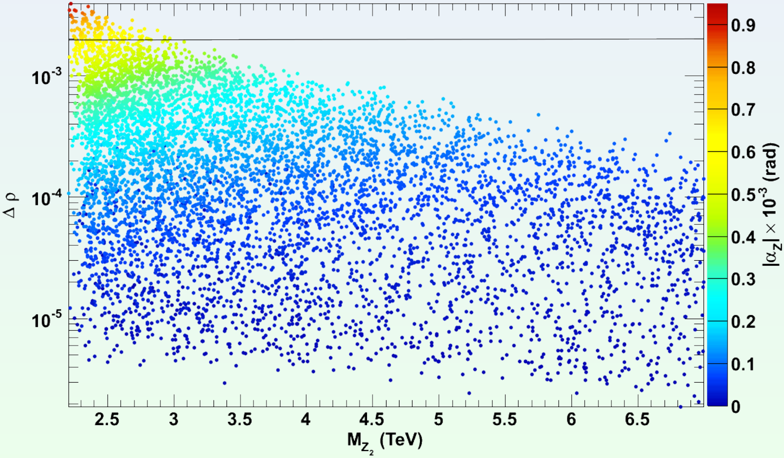
  - **DM observables (Planck satellite, update on XENON100 results)**
  - **Higgs boson mass measurements**
- **New inputs :**
  - **Higgs boson signal strengths + more low energy observables**
    ⇒ Modification of the `NMSSMTools` **code :** `UMSSMTools`
  - **Also neutralino as DM candidate**
  - **Relax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

Results

- Decrease of the upper bound on $|\alpha_Z|$
- $\Delta\rho$: main new constraint for low energy observables



Results

- **Decrease of the upper bound on $|\alpha_Z|$**
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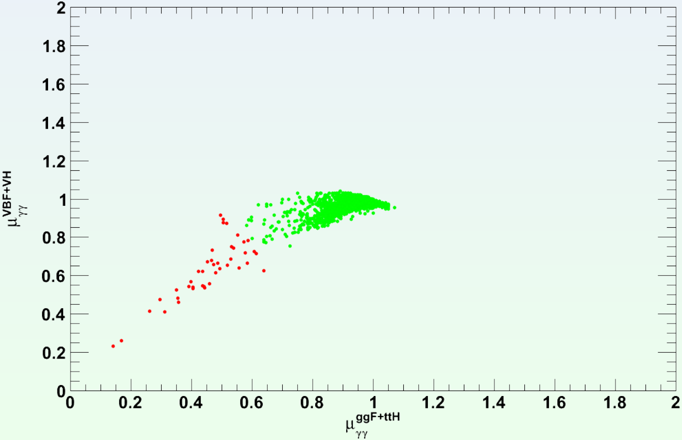
- **Constraints from 2σ signal strength ellipses derived in G. Bélanger et al, arXiv :1306.2941**



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- **Caveat on the use of limits on simplified models**

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- **More general work in this model is in progress**
- **Implement the UMSSM model in the public version of the `micrOMEGAs` code**

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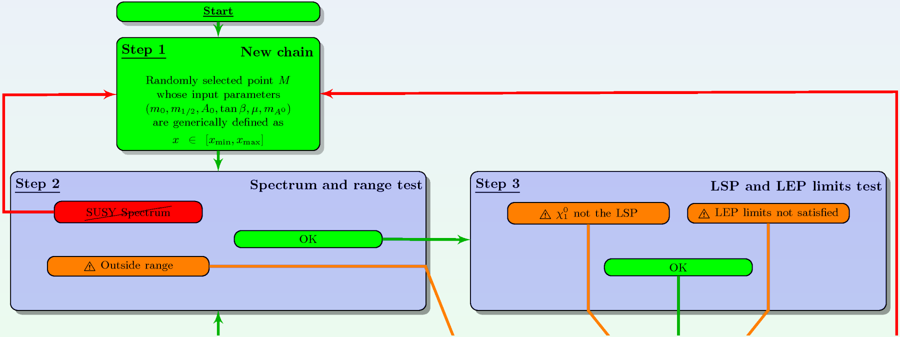
Thanks !

BACKUP

BACKUP

MCMC procedure



Start

Step 1 **New chain**

Randomly selected point M whose input parameters $(m_0, m_{1/2}, A_0, \tan\beta, \mu, m_{A^0})$ are generically defined as $x \in [x_{\min}, x_{\max}]$

Step 2 **Spectrum and range test**

~~SUSY Spectrum~~

OK

⚠ Outside range

Step 3 **LSP and LEP limits test**

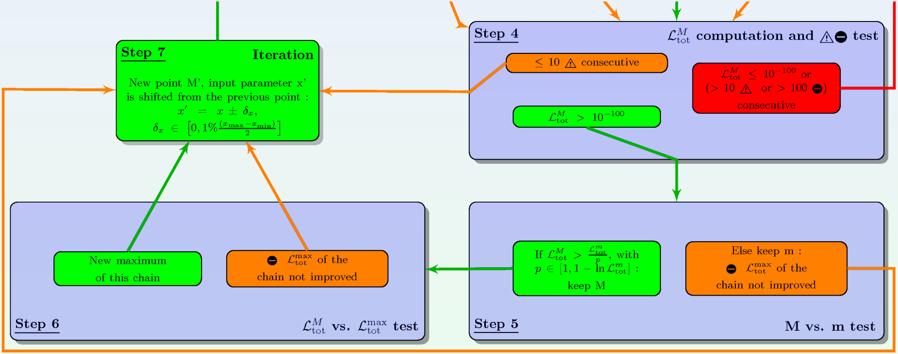
⚠ χ_1^0 not the LSP

⚠ LEP limits not satisfied

OK

BACKUP

MCMC procedure



Step 7 **Iteration**

New point M', input parameter x' is shifted from the previous point : $x' = x \pm \delta_x$, $\delta_x \in \left[0, 1\% \frac{(x_{\rm max} - x_{\rm min})}{2}\right]$

Step 4 $\mathcal{L}^M_{\rm tot}$ **computation and ⚠⛔ test**

≤ 10 ⚠ consecutive

$\mathcal{L}^M_{\rm tot} \leq 10^{-100}$ or (> 10 ⚠ or > 100 ⛔) consecutive

$\mathcal{L}^M_{\rm tot} > 10^{-100}$

Step 5 **M vs. m test**

If $\mathcal{L}^M_{\rm tot} > \frac{\mathcal{L}^m_{\rm tot}}{p}$, with $p \in [1, 1 - \ln \mathcal{L}^m_{\rm tot}]$: keep M

Else keep m : ⛔ $\mathcal{L}^{\rm max}_{\rm tot}$ of the chain not improved

Step 6 $\mathcal{L}^M_{\rm tot}$ **vs.** $\mathcal{L}^{\rm max}_{\rm tot}$ **test**

New maximum of this chain

⛔ $\mathcal{L}^{\rm max}_{\rm tot}$ of the chain not improved

BACKUP

Models : $\widetilde{\mathsf{L}}\widetilde{\mathsf{L}}\widetilde{\mathsf{e}}$ and $\widetilde{\mathsf{u}}\widetilde{\mathsf{d}}\widetilde{\mathsf{d}}$

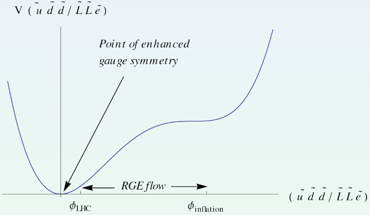
Inflaton, scalar field whose flat direction potential (with a non-negligible slope) leads to the end of the inflation phase

Charged under the visible sector of the particle physics model considered, i.e. NUHM2

$$\phi = \frac{\tilde{u}+\tilde{d}+\tilde{d}}{\sqrt{3}}, \quad \phi = \frac{\tilde{L}+\tilde{L}+\tilde{e}}{\sqrt{3}}$$

$$V(\phi) = \frac{1}{2} m_\phi^2\, \phi^2 - A\frac{\lambda\phi^6}{6\, M_P^3} + \lambda^2 \frac{\phi^{10}}{M_P^6}$$

$$\phi^4_{\text{inflation}} \simeq \frac{m_\phi M_P^3}{\lambda\sqrt{10}}, V''(\phi_{\text{inflation}}) = 0$$



$\widetilde{\mathsf{u}}\widetilde{\mathsf{d}}\widetilde{\mathsf{d}}$ RGEs

$$\hat{\mu}\frac{dm_\phi^2}{d\hat{\mu}} = -\frac{1}{6\pi^2}(4M_3^2 g_3^2 + \frac{2}{5}M_1^2 g_1^2),$$
$$\hat{\mu}\frac{dA}{d\hat{\mu}} = -\frac{1}{4\pi^2}(\frac{16}{3}M_3 g_3^2 + \frac{8}{5}M_1 g_1^2)$$

$\widetilde{\mathsf{L}}\widetilde{\mathsf{L}}\widetilde{\mathsf{e}}$ RGEs

$$\hat{\mu}\frac{dm_\phi^2}{d\hat{\mu}} = -\frac{1}{6\pi^2}(\frac{3}{2}M_2^2 g_2^2 + \frac{9}{10}M_1^2 g_1^2),$$
$$\hat{\mu}\frac{dA}{d\hat{\mu}} = -\frac{1}{4\pi^2}(\frac{3}{2}M_2 g_2^2 + \frac{9}{5}M_1 g_1^2)$$

BACKUP

ID constraints from $\bar{p}$ $W^{\pm}$ production leads also to abundant $\bar{p}$ production (after hadronization)

⇒ $\bar{p}$ flux produced by DM annihilation determined by :

- $\sigma_{\mathrm{DM\ DM}\ \to\ W^+W^-}$
- m_{DM}
- DM halo profile (here Einasto profile)
- $\bar{p}$ propagation parameters in the galactic halo :

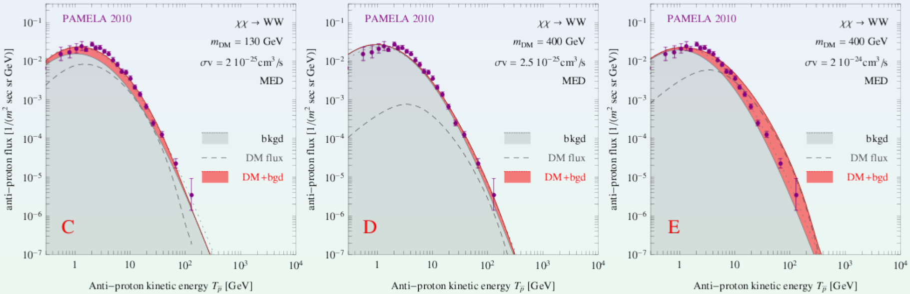
Model	δ	$\mathcal{K}_0$ [kpc^2/Myr]	V_{conv} [km/s]	L [kpc]
MIN	0.85	0.0016	13.5	1
MED	0.70	0.0112	12	4
MAX	0.46	0.0765	5	15

⇒ We compare the sum of the astrophysical background flux and predicted $\bar{p}$ flux originating from DM with the PAMELA data, 2 methods :

- "Aggressive" procedure : fixed background (standard flux from T. Bringmann and P. Salati, Phys. Rev. D 75 (2007) 083006)
- "Conservative" procedure : marginalized background, namely standard description of the background spectrum multiplied by $A\,(T/T_0)^p$ with :
  - $T = \bar{p}$ kinetic energy
  - $T_0 = 30$ GeV : pivot energy
  - normalisation of the background spectrum : $0.6 < A < 1.4$
  - spectral index : $-0.1 < p < +0.1$

BACKUP

ID constraints from $\bar{\mathrm{p}}$

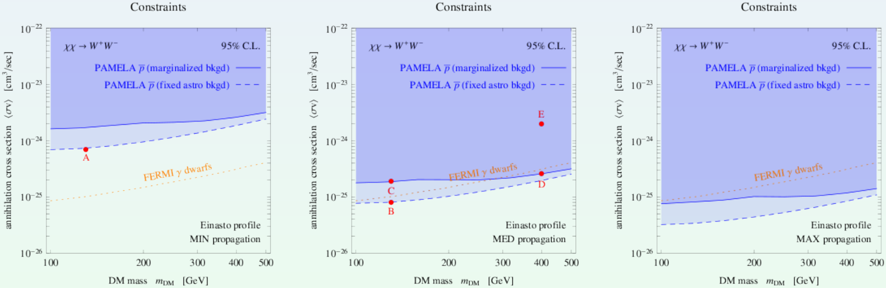


"Conservative" procedure approximately independent of $m_{\rm DM}$: $\bar{\mathrm{p}}$ flux from heavy DM negligible at low energy, where PAMELA set very small error bars

We consider diffuse γ-ray constraints from dwarf spheroidal galaxies and $\bar{\mathrm{p}}$ constraints using 'MED' propagation parameters + marginalized background

BACKUP

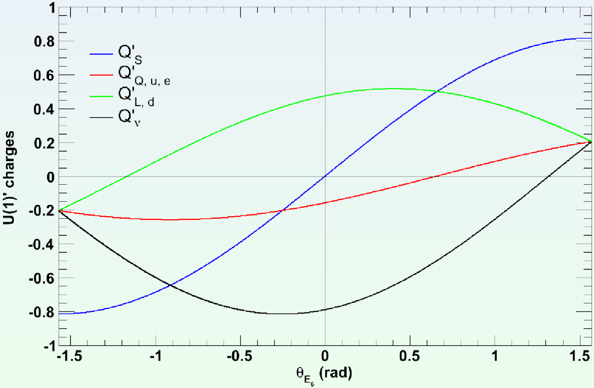
Generic bounds on DM annihilation into $W^{\pm}$



BACKUP

Higgs boson contribution to the direct detection cross section for $\tilde{\nu}_R$:

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



⇒ **increase of the cross section for $\theta_{E_6} < 0$ because of $\mathcal{Q}'_\nu$**