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

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1 Motivations

2 Neutralino DM in the (N)MSSM

3 U(1) extensions of the MSSM
   - 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, ...

Success of the Standard Models

\* Particle Physics (SM)

Les Houches Workshop 2013, courtesy of F. Boudjema
Success of the Standard Models

- Particle Physics (SM)
- Cosmology ($\Lambda$CDM)

- Simple cosmological model which fits even the most accurate measurements (Planck satellite)

Temperature fluctuations of the CMB
P. A. R. Ade et al., arXiv:1303.5062

Temperature angular power spectrum
Motivations  Success of the Standard Models

Success of the Standard Models

- **Particle Physics (SM)**
- **Cosmology ($\Lambda$CDM)**

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

$\Lambda$CDM after Planck measurements

Success of the Standard Models

- **Particle Physics (SM)**
- **Cosmology ($\Lambda$CDM)**
  - Simple models of inflation are still valid

![Graph showing constraints on inflationary models from Planck satellite.](image.png)

Constraints on inflationary models from Planck satellite
Drawbacks of the Standard Models

醒目 Particle Physics (SM)

醒目 Hierarchy problem between EW (\(\sim 100 \text{ GeV}\)) and Planck (\(\sim 10^{19} \text{ GeV}\)) scales

Quadratic divergences to the Higgs boson mass squared
**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)

![Graph showing the evolution of SM gauge couplings](image)

**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
- Neutrino sector (Dirac, Majorana ? ?), ...

![Diagram](image)
Drawbacks of the Standard Models

- **Particle Physics (SM)**
- **Cosmology (ΛCDM)**
  - DM made of particles \(\neq\) SM particles:
    - baryons: BBN, CMB, ...
    - charged leptons: we would have seen DM (overproduction of \(\gamma\), ...)
    - neutrinos: too light \(\Rightarrow\) low relic density + HDM

\(\Rightarrow\) Example of DM candidate which gives the right abundance:

*Weakly Interacting Massive Particle (WIMP)*
**Drawbacks of the Standard Models**

- **Particle Physics (SM)**
- **Cosmology (ΛCDM)**
  - DM made of particles ≠ SM particles:
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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)**
Fermions $\Leftrightarrow$ bosons $\Rightarrow$ solution to the Hierarchy problem

New particles : cancellation of the quadratic term in

$$\Delta m^2_{h^0}\bigg|_{\text{SM}} = \frac{y_f^2}{16\pi^2} \left(-2\Lambda^2 + 6m_f^2 \ln \frac{\Lambda}{m_f} + \ldots\right)$$

with that of

$$\Delta m^2_{h^0}\bigg|_{\text{SUSY}} = \frac{\lambda_s}{16\pi^2} \left(\Lambda^2 - 2m_s^2 \ln \frac{\Lambda}{m_s} + \ldots\right)$$
Fermions \Leftrightarrow \text{bosons} \Rightarrow \text{solution to the Hierarchy problem}

New particles: cancellation of the quadratic term in

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\Delta m^2_{h^0}^\text{SM} = \frac{y_f^2}{16\pi^2} \left( -2\Lambda^2 + 6m_f^2 \ln \frac{\Lambda}{m_f} + \ldots \right)
\]

\[
\Delta m^2_{h^0}^\text{SUSY} = \frac{\lambda_s}{16\pi^2} \left( \Lambda^2 - 2m_s^2 \ln \frac{\Lambda}{m_s} + \ldots \right)
\]

Not yet observed \Rightarrow \text{SUSY breaking}

Minimal Supersymmetric Standard Model (MSSM):
Motivations

Supersymmetry

- Fermions $\leftrightarrow$ bosons $\Rightarrow$ solution to the Hierarchy problem
- Unification at GUT scale

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:**

\[
\begin{array}{ccc}
    u & c & t \\
    d & s & b \\
    \nu_{eL} & \nu_{\mu L} & \nu_{\tau L} \\
    e & \mu & \tau \\
    g & A^0 & \chi_1^0 \\
    Z & h^0 H^0 & \chi_2^0 \\
    W^\pm & h_\pm & \chi_3^0 \\
    \tilde{u} & \tilde{c} & \tilde{t} \\
    \tilde{d} & \tilde{s} & \tilde{b} \\
    \tilde{\nu}_{eL} & \tilde{\nu}_{\mu L} & \tilde{\nu}_{\tau L} \\
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\end{array}
\]
**Supersymmetry**

- Fermions $\Leftrightarrow$ bosons $\Rightarrow$ solution to the Hierarchy problem
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- Examples:

\[
\begin{array}{cccc}
\nu_e & \nu_{\mu} & \nu_{\tau} & e \\
\nu_{\mu} & \nu_{\tau} & \nu_e & \mu \\
\mu & \tau & \nu_{\tau} & \tau \\
\end{array}
\quad
\begin{array}{cccc}
g & A^0 & \chi_1^0 & \tilde{u} \\
Z & h^0 H^0 & \chi_2^0 & \tilde{c} \\
W^\pm & h_\pm & \chi_3^0 & \tilde{t} \\
& & \chi_4^0 & \tilde{d} \\
\end{array}
\]

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Motivations

Supersymmetry

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

_constraints on SUSY/DM

- DM relic abundance
- Direct detection of DM
- Indirect detection of DM (search for anomalous features in cosmic rays like $\gamma, \nu, e^+, \bar{p}$)

- “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 $\bar{p}$ spectrum less exploited $\Rightarrow$ Set constraints
Supersymmetry

癯 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
  \( \mathcal{B}(\bar{B}^0 \rightarrow X_s \gamma), \mathcal{B}(B_s^0 \rightarrow \mu^+ \mu^-), \mathcal{B}(B^\pm \rightarrow \tau^\pm \nu_\tau), \Delta M_{d,s}, \delta a_\mu, \Delta \rho, \ldots \)
Supersymmetry

Motivations

Supersymmetry

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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:
    \[ m_0, m_{1/2}, A_0, \tan \beta \text{ and } \text{sign}(\mu) \]
  - Drawbacks: \( m_{h0} \sim 125 \text{ GeV} \) not easy
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:
  \[ m_0, m_{1/2}, A_0, \tan \beta \text{ and sign}(\mu) \]
- Drawbacks: \( m_{h0} \sim 125 \) GeV not easy
- We considered a non-universal scalar masses model, with \( m_0^2 \neq m_H^2 \neq m_{H_d}^2 \) (H. Baer et al [hep-ph/0504001], J. R. Ellis et al [hep-ph/0210205])
  - Easier to reach \( m_{h0} = 125 \) GeV, increase DM annihilation rates with higgsino LSP

 NUHM2 free parameter:

\[ m_0, m_{1/2}, A_0, \tan \beta, \mu \text{ and } m_{A_0} \]
Neutralino DM in the (N)MSSM

Supersymmetric inflaton

- **NUHM2**
- **£££ and ëëë**

- 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

\[
V(\tilde{u} \tilde{d} \tilde{d} / \tilde{L} \tilde{L} \tilde{e})
\]

- \( \Rightarrow \) £££ and ëëë D-terms can be such candidates (R. Allahverdi et al, [hep-ph/0610134], [hep-ph/0605035])

\begin{align*}
V \left( \tilde{u} \tilde{d} \tilde{d} / \tilde{L} \tilde{L} \tilde{e} \right)
& \Rightarrow \text{Point of enhanced gauge symmetry} \\
& \phi_{\text{LHC}} \quad \phi_{\text{inflation}}
\end{align*}
Method and constraints

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

- On $\tilde{L}\tilde{L}\tilde{e}$ and $\tilde{u}\tilde{d}\tilde{d}$, explain the observed temperature anisotropy in the CMB with:
  - The amplitude of density perturbations $\delta_H = \frac{8}{\sqrt{5}\pi} \frac{m_0}{\phi_0^2} \frac{1}{\Delta^2} \sin^2[\mathcal{N}_{\text{COBE}} \sqrt{\Delta^2}]$, where
    $$\Delta^2 = 900 \alpha^2 \mathcal{N}_{\text{COBE}} \left(\frac{M_P}{\phi_0}\right)^4, \quad \mathcal{N}_{\text{COBE}} \sim 50$$
  - The scalar spectral index $n_s$ of the corresponding power spectrum $n_s = 1 - 4\sqrt{\Delta^2} \cot[\mathcal{N}_{\text{COBE}} \sqrt{\Delta^2}]$.

- On NUHM2 model in general:
  
<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$m_{h^0}$ (GeV)</td>
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<td>$\Omega_{\chi_1^0} h^2$</td>
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<tr>
<td>$\mathcal{B}(\bar{B}^0 \to X_s \gamma) \times 10^4$</td>
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<td>$\delta_a \mu \times 10^{10}$</td>
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<td>$\mathcal{B}(B_s^0 \to \mu^+ \mu^-) \times 10^9$</td>
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<td>$\Delta \rho$</td>
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<tr>
<td>$R_{B \pm \to \tau^\pm \nu_\tau} (\text{NUHM2 over SM})$</td>
<td>2.219</td>
</tr>
<tr>
<td>$Z \to \chi_1^0 \chi_1^0$ (MeV)</td>
<td>1.7</td>
</tr>
<tr>
<td>$\sigma_{e^+e^- \to \chi_1^0 \chi_2^0, 3}$</td>
<td>1</td>
</tr>
<tr>
<td>$\mathcal{B}(\chi_{2,3}^0 \to Z\chi_1^0)$ (pb)</td>
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Method and constraints

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On NUHM2 model in general:

- Compute total likelihood of a point $M$ in NUHM2 parameter space:
  
  \[ \text{if } L^M_{\text{tot}} > \frac{L^m_{\text{tot}}}{p}, \text{ with } p \in [1, 1 - \ln L^m_{\text{tot}}] \Rightarrow \text{keep } M \]
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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- NUHM2 scenarios within LHCb and XENON1T experiments sensitivity
- 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 $\gamma$-rays: Fermi-LAT analysis of the diffuse $\gamma$-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
DM ID limits on the LSP-NLSP mass degeneracy

⇒ 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 $\Delta m$ values?
Results

* Higgsino and mainly wino DM probed

⇒ assume regeneration mechanism
Results

- Higgsino and mainly wino DM probed ⇒ 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

- Higgsino and mainly wino DM probed ⇒ assume regeneration mechanism
- ID constrains scenarios with $\Delta m \lesssim 20$ GeV, DM relic density being regenerated at 100%
- If $m_{\chi^0_1} < 500$ 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
Neutralino DM in the (N)MSSM

NMSSM and SUSY searches @ LHC

Adding a singlet of SM gauge symmetry to solve the $\mu$ problem of the MSSM

$$\mathcal{W}_{\text{MSSM}} = \bar{u}_R^* y_u Q_H - \bar{d}_R^* y_d Q_H - \bar{e}_R^* y_e L_H + \mu H_u H_d$$

$$\Rightarrow \mathcal{W}_{\text{NMSSM}} = \mathcal{W}_{\text{MSSM}} |_{\mu=0} + \lambda S H_u H_d + \frac{1}{3} \kappa S^3$$

2 CP-odd Higgs boson ($a_1, a_2$), 3 CP-even Higgs boson ($h_1, h_2, h_3$)

$$m_{h_1}^2 \mid_{\text{tree}} \lesssim M_Z \cos^2 2\beta + \frac{\lambda^2}{2} v^2$$

$$\Rightarrow$$ less fine tuned $m_{h_1} \sim 125$ GeV

5 neutralinos $\chi_i^0$ in the basis ($B, \tilde{W}^3, \tilde{H}^0_d, \tilde{H}^0_u, S$)
Adding a singlet of SM gauge symmetry to solve the $\mu$ problem of the MSSM

$$\mathcal{V}_{\text{MSSM}} = \bar{u}_R^* y_u \tilde{Q}_H u - \bar{d}_R^* y_d \tilde{Q}_H d - \bar{e}_R^* y_e \tilde{L}_H e + \mu H_u H_d$$

$$\Rightarrow \mathcal{V}_{\text{NMSSM}} = \mathcal{V}_{\text{MSSM}}|_{\mu=0} + \lambda S H_u H_d + \frac{1}{3} \kappa S^3$$

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5 neutralinos $\chi^0_i$ in the basis ($\tilde{B}, \tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}$)

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 ($\tilde{B}$ or $\tilde{S}$) scenarios (mostly light $a_1$ and/or $h_1$)
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 $\tilde{q} \rightarrow q\chi^0_1$ and $\tilde{g} \rightarrow q\bar{q}\chi^0_1$ 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
- $\tilde{q} \rightarrow q + (\chi^0_2 \rightarrow \chi^0_1 + (f\bar{f} \text{ or } a_1 \text{ or } h_1))$
Results

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

![Graph showing exclusion limits for neutralino dark matter in the (N)MSSM and SUSY searches @ LHC](image-url)
Results

- Reduced acceptance into jets + missing $E_T$ search channels and more jets for $\tilde{S}$ LSP
- $\tilde{q} \rightarrow q + (\chi^0_2 \rightarrow \chi^0_1 + (f\bar{f} \text{ or } a_1 \text{ or } h_1))$
- 300 GeV squarks allowed when ($\tilde{S}$-like LSP):
U(1) extensions of the MSSM

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Sneutrinos

- Neutrino oscillations indicative of massive neutrinos $\Rightarrow$ possibility to add right-handed (RH) neutrino fields
  - $\Rightarrow$ Extensions of the MSSM with RH (s)neutrino can provide DM candidate
- 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 symmetry $\Rightarrow$ the UMSSM
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 $g'_1 = \sqrt{\frac{5}{3}}g_Y$

- $U'(1)$ stems from string-inspired $E_6$:
  - $E_6 \rightarrow SU(3)_c \times SU(2)_L \times U(1)_Y \times U(1)_\chi \times U(1)_\psi \Rightarrow U'(1)$ charge:
    $$Q' = \cos \theta_{E_6} Q'_\chi + \sin \theta_{E_6} Q'_\psi, \quad \theta_{E_6} \in [-\pi/2, \pi/2]$$

- Superpotential:
  $$\mathcal{W}_{UMSSM} = \mathcal{W}_{MSSM}|_{\mu=0} + \lambda S H_u H_d + \tilde{\nu}_R^* y_\nu \tilde{L} H_u + \mathcal{O}(\text{TeV}s)$$

- As the NMSSM, this model solves the $\mu$ problem: $\mu = \lambda \frac{v_s}{\sqrt{2}}$

- New D-terms for $m_{h_1}$
The model

- **Gauge sector**: Physical abelian gauge bosons: $Z_1$ and $Z_2$, mixing between the $Z$ of the SM and the $Z'$, $\alpha_Z$ is the mixing angle $\Rightarrow \tan \beta$ constrained

- **Gauginos sector**: 6 neutralinos in the basis $(\tilde{B}, \tilde{W}_3, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}, \tilde{B}')$

- To sum up:

![Diagram showing the particle content of the model](image-url)

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

\[
\begin{align*}
M_{Z_2} &= 1.6 \text{ TeV}, \mu = 1.5 \text{ TeV}, A_\lambda = 0.5 \text{ TeV}, \alpha_Z = 10^{-3} \text{ rad} \\
M_{Z_2} &= 1.6 \text{ TeV}, \mu = 1.8 \text{ TeV}, A_\lambda = 1.8 \text{ TeV}, \alpha_Z = 10^{-4} \text{ rad} \\
M_{Z_2} &= 2.5 \text{ TeV}, \mu = 1.8 \text{ TeV}, A_\lambda = 1.8 \text{ TeV}, \alpha_Z = 10^{-4} \text{ rad}
\end{align*}
\]
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 $U(1)_\eta \Rightarrow \tan \theta_{E6} = -\sqrt{5/3}$

OK, $\Delta m_{d,s}$, XENON100, both
Scattering on nucleons

Abelian gauge boson contribution to direct detection cross section:

\[ \sigma_{\tilde{\nu}R^2N}^{Z_1,Z_2} = \frac{\mu_{\tilde{\nu}R}^2}{\pi} (g_1' Q_{\nu}')^2 \left[ (y(1 - 4s_W^2) + y')Z + (-y + 2y')(A - Z) \right]^2 \]

with

\[ y = \frac{g_Y \sin \alpha_Z \cos \alpha_Z}{4 \sin \theta_W} \left( \frac{1}{M_{Z_2}^2} - \frac{1}{M_{Z_1}^2} \right), \quad y' = -\frac{g_1'}{2} Q_{\nu}' \left( \frac{\sin^2 \alpha_Z}{M_{Z_1}^2} + \frac{\cos^2 \alpha_Z}{M_{Z_2}^2} \right) \]

⇒ stringent constraints for small \( |\theta_{E_6}| \) because of \( Q_{\nu}' \)

term
Need for an update

\[ \Omega h^2 \]

- $M_{Z_2} = 1.6$ TeV, $\mu = 1.5$ TeV, $A_\lambda = 0.5$ TeV, $\alpha_Z = 10^{-3} \text{ rad}$
- $M_{Z_2} = 1.6$ TeV, $\mu = 1.8$ TeV, $A_\lambda = 1.8$ TeV, $\alpha_Z = 10^{1} \text{ rad}$
- $M_{Z_2} = 2.5$ TeV, $\mu = 1.8$ TeV, $A_\lambda = 1.8$ TeV, $\alpha_Z = 10^{1} \text{ rad}$

WMAP7 constraint
Need for an update

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

![Graph showing ATLAS Preliminary results for $\sqrt{s} = 8$ TeV, $Z' \rightarrow \ell \ell$. The graph displays expected limits, observed limits, and various signal models such as $Z'_{SSM}$, $Z'_\chi$, and $Z'_{\psi}$. The expected limits are shown in green for $\pm 1\sigma$ and yellow for $\pm 2\sigma$. The observed limit is indicated by a red line. The integral is given as $ee, \mu\mu: \int L \, dt = 20 \, fb^{-1}$.](image-url)
Need for an update

Updates:
- New limits on $M_{Z_2}$
- DM observables (Planck satellite, update on XENON100 results)
- Higgs boson mass measurements
Need for an update

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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
Results

- Decrease of the upper bound on $|\alpha_Z|$
- $\Delta \rho$: main new constraint for low energy observables
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- $\Delta \rho$: main new constraint for low energy observables
- Constraints from $2\sigma$ signal strength ellipses derived in G. Bélanger et al, arXiv:1306.2941
Conclusions

1 Motivations

2 Neutralino DM in the (N)MSSM

3 U(1) extensions of the MSSM
   - G. Bélanger, JDS et al., in preparation

4 Conclusions
Conclusions

- Discovery (Higgs boson), bounds (exotic particles, DM)
  \[\Rightarrow\] extensions of the SM and especially SUSY are now better probed

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

Thanks!

Jonathan Da Silva (LAPTh)
Conclusions

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- If sparticle discovery ⇒ informations on inflaton candidates
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Thanks!
MCMC procedure

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
  - $\Delta$ Outside range

Step 3: LSP and LEP limits test
- $\Delta \chi^0_1$ not the LSP
- LEP limits not satisfied
  - OK
MCMC procedure

Step 6

$L_{tot}^M$ vs. $L_{tot}^{\max}$ test

Step 7

Iteration

New point $M'$, input parameter $x'$ is shifted from the previous point:

$x' = x \pm \delta_x,$

$\delta_x \in \left[0, 1\% \frac{L_{\max} - L_{\min}}{2}\right]$

Step 4

$L_{tot}^M$ computation and $\Delta \propto \infty$ test

$\leq 10 \Delta$ consecutive

$\frac{L_{tot}^M}{L_{tot}^M} \leq 10^{-100}$ or ($> 10 \Delta$ or $> 100 \propto$)

consecutive

Step 5

$M$ vs. $m$ test

If $L_{tot}^M > \frac{L_{tot}^m}{P}$, with $p \in [1, 1 - \ln L_{tot}^m]$:

keep $M$

New maximum of this chain

$\bullet$ $L_{max}^M$ of the chain not improved

Else keep $m$:

$\bullet$ $L_{max}^M$ of the chain not improved
Models: $\tilde{L}\tilde{L}\tilde{e}$ and $\tilde{u}\tilde{d}\tilde{d}$

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

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

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

\[ \phi_{\text{inflation}}^4 \approx \frac{m_{\phi} M_P^3}{\lambda \sqrt{10}}, \quad V''(\phi_{\text{inflation}}) = 0 \]

$\tilde{u}\tilde{d}\tilde{d}$ RGEs

\[ \hat{\mu} \frac{d m_{\phi}^2}{d \hat{\mu}} = - \frac{1}{6 \pi^2} (4 M_3^2 g_3^2 + \frac{2}{5} M_1^2 g_1^2) \]

\[ \hat{\mu} \frac{d A}{d \hat{\mu}} = - \frac{1}{4 \pi^2} (\frac{16}{3} M_3 g_3^2 + \frac{8}{5} M_1 g_1^2) \]

$\tilde{L}\tilde{L}\tilde{e}$ RGEs

\[ \hat{\mu} \frac{d m_{\phi}^2}{d \hat{\mu}} = - \frac{1}{6 \pi^2} (\frac{3}{2} M_2^2 g_2^2 + \frac{9}{10} M_1^2 g_1^2) \]

\[ \hat{\mu} \frac{d A}{d \hat{\mu}} = - \frac{1}{4 \pi^2} (\frac{3}{2} M_2 g_2^2 + \frac{9}{5} M_1 g_1^2) \]
**ID constraints from $\bar{p}$ $W^\pm$ production leads also to abundant $\bar{p}$ production (after hadronization)**

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

$$\sigma_{DM \ DM \rightarrow W^+W^-}$$
$$m_{DM}$$

DM halo profile (here Einasto profile)

$\bar{p}$ propagation parameters in the galactic halo:

<table>
<thead>
<tr>
<th>Model</th>
<th>$\delta$</th>
<th>$\kappa_0$ [kpc$^2$/Myr]</th>
<th>$V_{\text{conv}}$ [km/s]</th>
<th>L [kpc]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIN</td>
<td>0.85</td>
<td>0.0016</td>
<td>13.5</td>
<td>1</td>
</tr>
<tr>
<td>MED</td>
<td>0.70</td>
<td>0.0112</td>
<td>12</td>
<td>4</td>
</tr>
<tr>
<td>MAX</td>
<td>0.46</td>
<td>0.0765</td>
<td>5</td>
<td>15</td>
</tr>
</tbody>
</table>

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


"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: $-0.1 < p < +0.1$
ID constraints from $\bar{p}$

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

We consider diffuse $\gamma$-ray constraints from dwarf spheroidal galaxies and $\bar{p}$ constraints using ‘MED’ propagation parameters + marginalized background
Generic bounds on DM annihilation into $W^\pm$
Higgs boson contribution to the direct detection cross section for $\tilde{\nu}_R$:

$$g_{\tilde{\nu}_R\tilde{\nu}_R^*} h_i = -g_1' Q'_{\nu} \left[ v_d Q'_{Hd} Z_{hi1} + v_u Q'_{Hu} Z_{hi2} + v_s Q'_{S} Z_{hi3} \right]$$

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