Dark matter and LHC: complementarities and limitations

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Based on arXiv:1707.00426

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Objectives

- We study the **complementarities between dark matter searches and collider constraints** on the pMSSM
- We focus on the consequences of the related **astrophysical uncertainties**

pMSSM: phenomenological MSSM

- The most general CP and R-parity conserving MSSM
- Minimal Flavour Violation at the TeV scale
- The first two sfermion generations are degenerate
- The three trilinear couplings are general for the 3 generations

$\rightarrow$ 19 free parameters

Method

pMSSM points generation

- **20 million points** were randomly generated with **SOFTSUSY**, using the ranges in the table aside for the 19 pMSSM parameters.

  400 000 remained after imposing that the neutralino 1 is the LSP and the Higgs mass lies between 122 and 128 GeV.

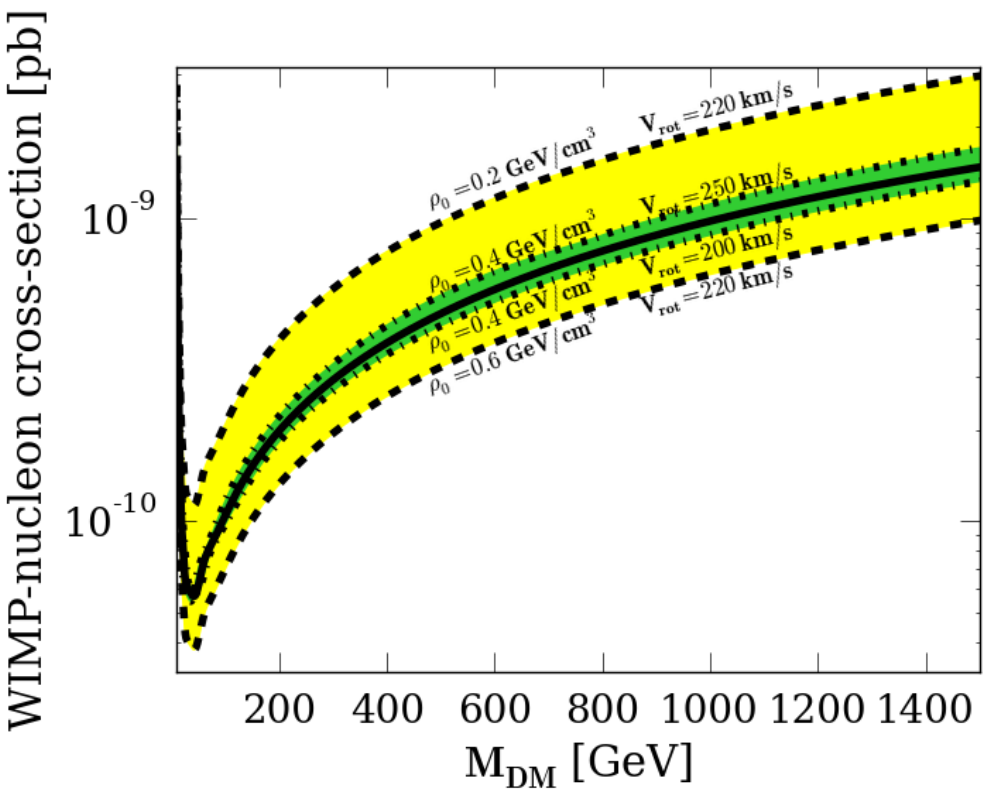
- For each point, we computed :
  - the neutralino relic density (**SuperIso Relic**)
  - Annihilation and scattering cross-sections (**micrOMEGAs**)
  - Higgs production cross-sections (**SusHi**)
  - Higgs branching ratios (**Hdecay**)
  - Other quantities for LHC analysis (**MadGraph, PYTHIA, Delphes...**)

Parameter	Range (in GeV)
$\tan\beta$	[1, 60]
M_A	[50, 2000]
M_1	[-3000, 3000]
M_2	[-3000, 3000]
M_3	[50, 3000]
$A_d = A_s = A_b$	[-10000, 10000]
$A_u = A_c = A_t$	[-10000, 10000]
$A_e = A_\mu = A_\tau$	[-10000, 10000]
μ	[-3000, 3000]
$M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$	[0, 3000]
$M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$	[0, 3000]
$M_{\tilde{\tau}_L}$	[0, 3000]
$M_{\tilde{\tau}_R}$	[0, 3000]
$M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$	[0, 3000]
$M_{\tilde{q}_{3L}}$	[0, 3000]
$M_{\tilde{u}_R} = M_{\tilde{c}_R}$	[0, 3000]
$M_{\tilde{t}_R}$	[0, 3000]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[0, 3000]
$M_{\tilde{b}_R}$	[0, 3000]

Direct detection

We used the **XENON1T** upper limit on the WIMP-nucleon SI cross section and assessed its astrophysical uncertainties related to:

- the **local DM density** $\rho_0 = 0.2 - 0.6$ GeV/cm^3
- the **DM velocity distribution**, whose main parameter in the standard halo model is the disc rotation velocity $v_{rot} = 200 - 250$ km/s

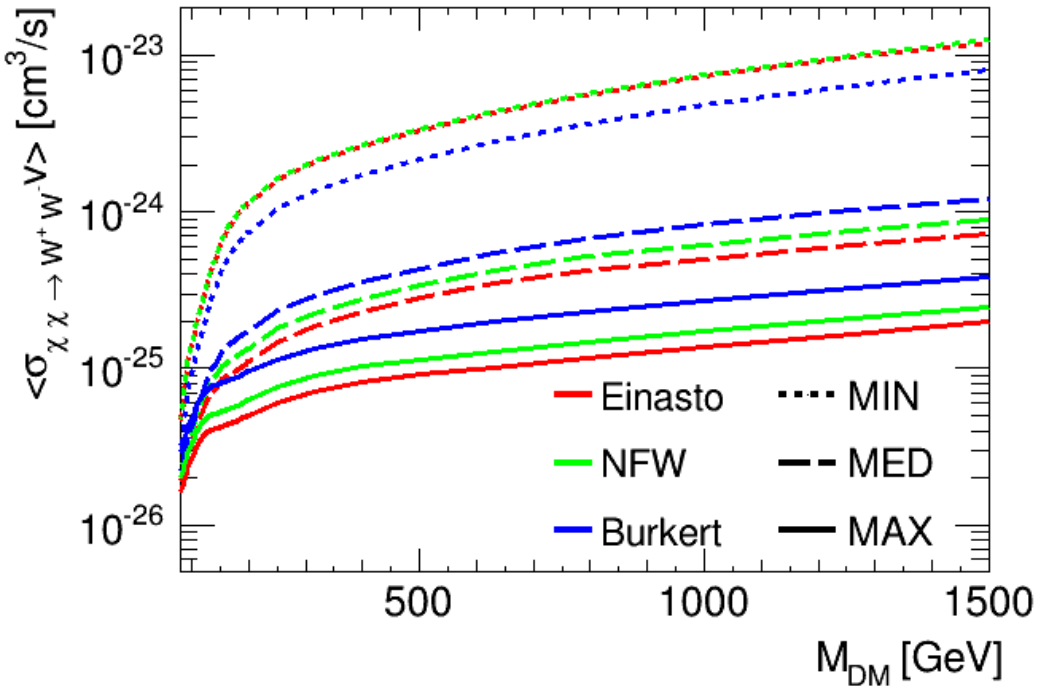


$\Rightarrow$ The local density uncertainties have the largest impact

Indirect detection

We used the **AMS-02** antiproton data, following the procedure described in [arXiv:1412.5696] for:

- 3 different halo density profiles Burkert, Einasto and NFW
- the 3 benchmark sets of parameters for cosmic ray progagation MIN, MED and MAX



The weakest limit is given by NFW MIN
The strongest limit is given by Einasto MAX

We also performed a combined analysis of the 19 confirmed dwarf galaxies oberved by **Fermi-LAT**, for comparison

LHC 13 TeV

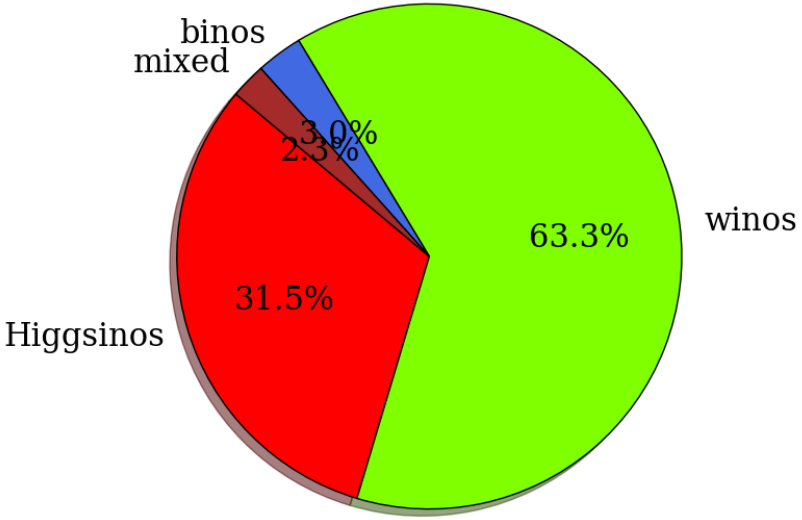
Our analysis of the LHC run 2 takes into account:

- SUSY direct searches
- Monojet searches
- Light Higgs signal strength constraints
- Heavy Higgs decay constraints $H/A \to \tau\tau$

Pre-imposed constraints:

- **light Higgs mass** constraint,
- **flavour physics**,
- **LEP** and **Tevatron** constraints
- **the upper bound of the relic density from Planck 2015 measurements**.

Neutralino types



Fractions of neutralino 1 types in our scan after imposing the light Higgs mass limit, LEP and flavour constraints, and relic density upper bound

The upper bound of the relic density excluded 94% of the binos in our original sample of points

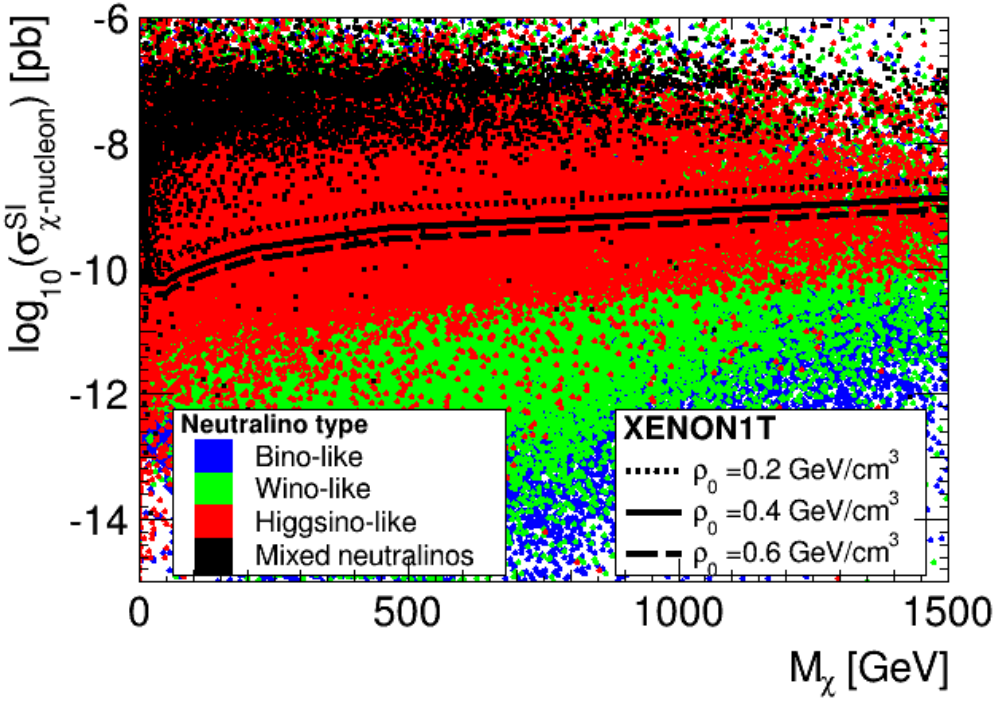
Neutralino 1 types:

bino-like: $|M_1| \ll |M_2|, |\mu|$
wino-like: $|M_2| \ll |M_1|, |\mu|$
Higgsino-like: $|\mu| \ll |M_1|, |M_2|$
mixed-state otherwise.

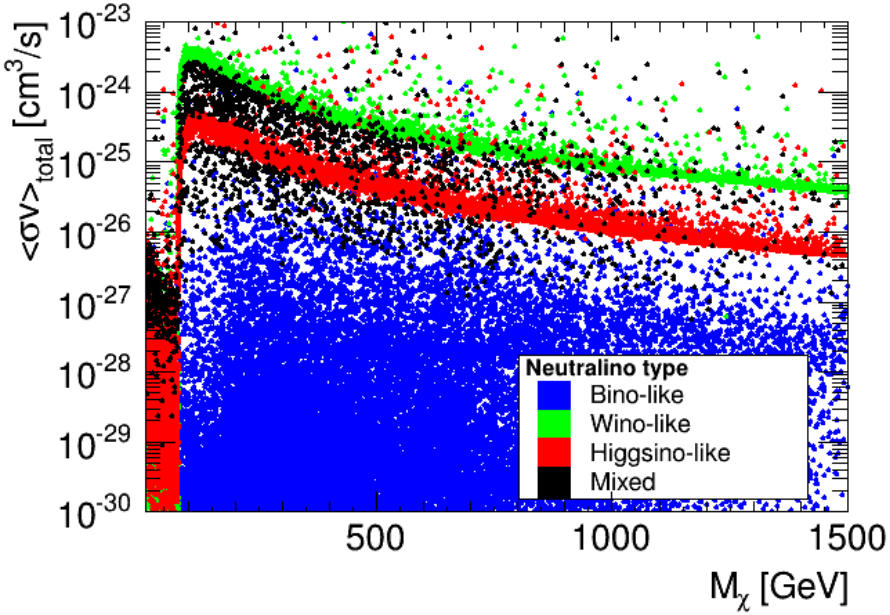
Results

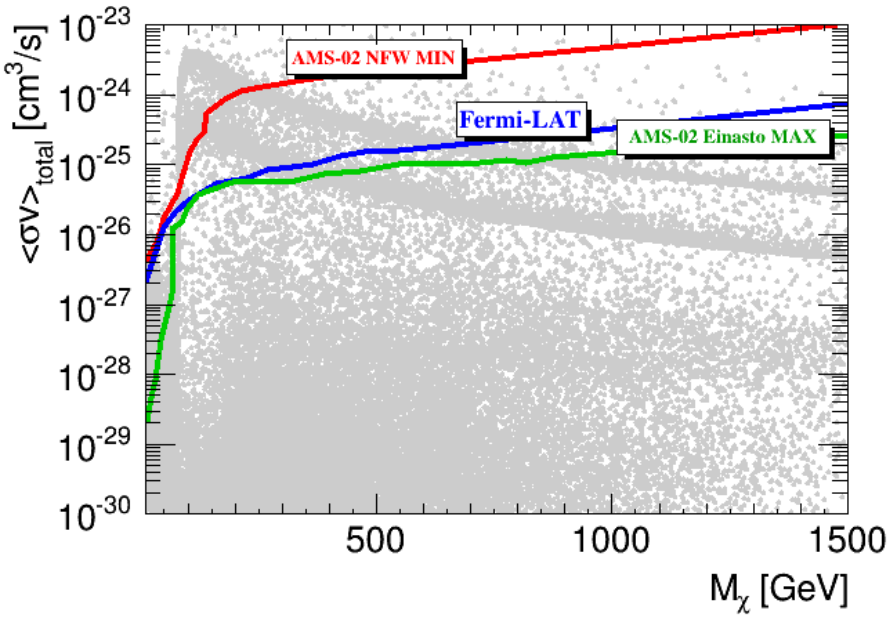
Direct detection

- Mixed-state neutralinos are almost all excluded
- Next, Higgsinos are the most excluded
- Depending on the local density, DD can exclude 23 to 37% of our points, but those uncertainties do not affect the type of excluded neutralinos



Indirect detection

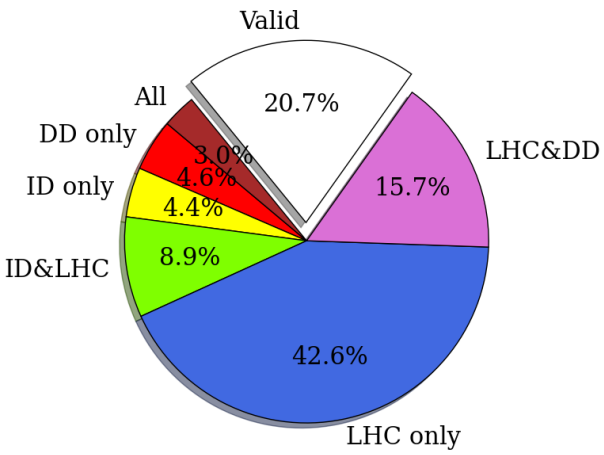




Winos annihilate mostly into W^+W^-
Higgsinos into W^+W^- and ZZ

- AMS-02 NFW MIN eliminates winos with $90 \lesssim M_\chi \lesssim 250$ GeV
- Fermi-LAT eliminates winos with $90 \lesssim M_\chi \lesssim 700$ GeV and a significant fraction of Higgsinos
- AMS-02 Einasto MAX goes even further in mass and also eliminates masses $\lesssim 80$ GeV

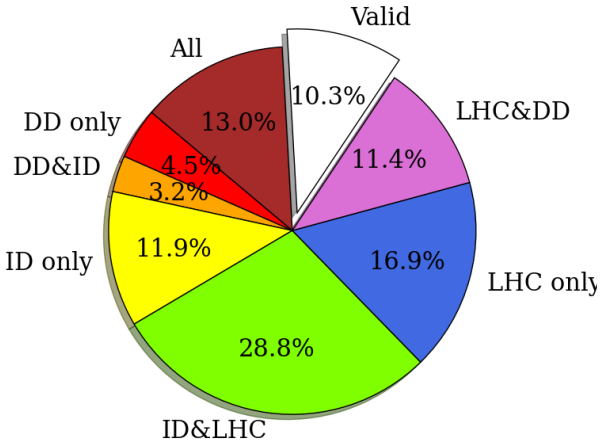
Combination with LHC 13 TeV constraints



CONSERVATIVE

(AMS-02 NFW MIN

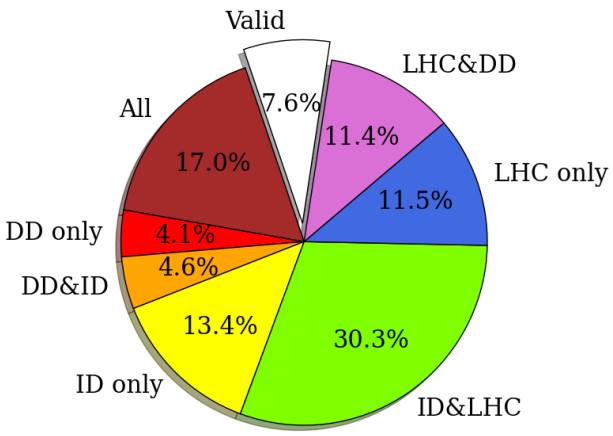
$\rho_0 = 0.2\ GeV/cm^3$ *)*



STANDARD

(Fermi-LAT

$\rho_0 = 0.4\ GeV/cm^3$ *)*



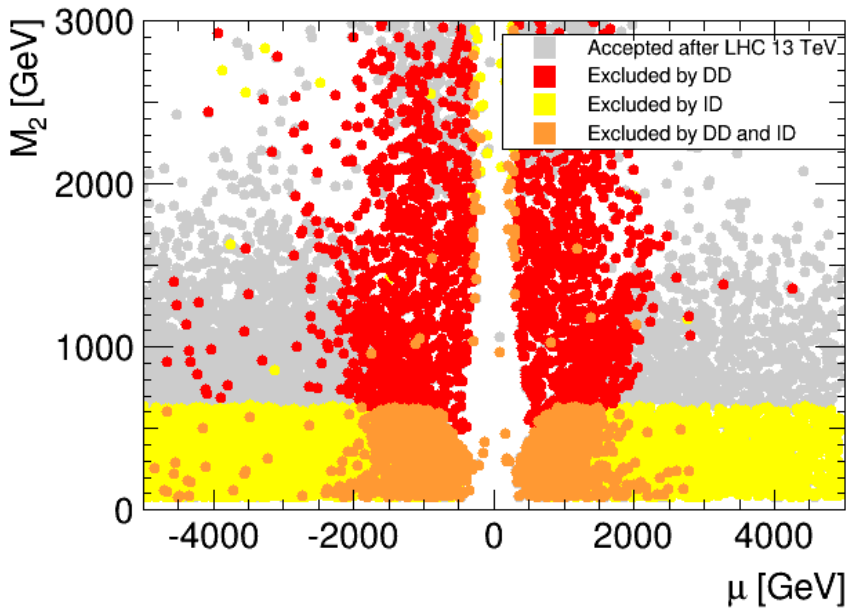
STRINGENT

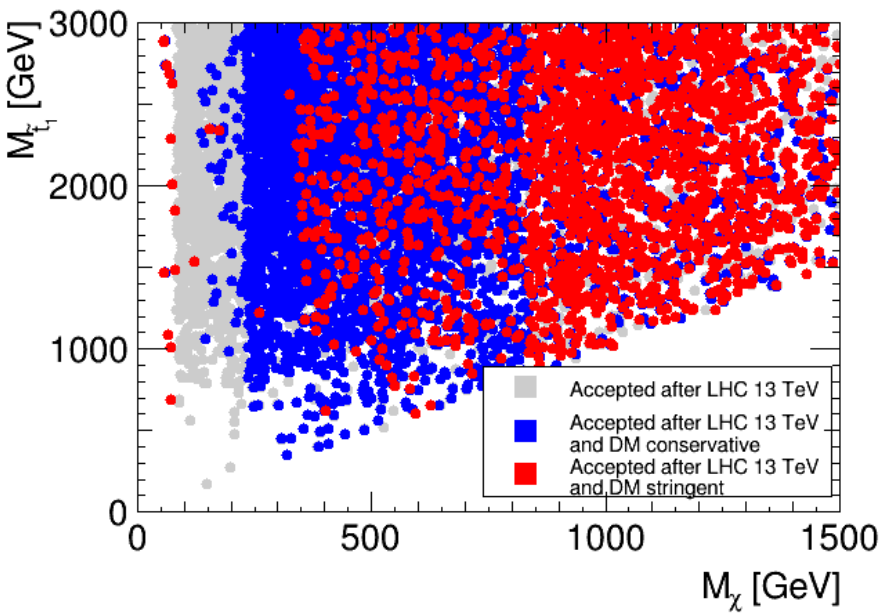
(AMS-02 Einasto MAX

$\rho_0 = 0.6\ GeV/cm^3$ *)*

- LHC 13 TeV excludes 70% of our points
- Direct detection excludes 5-9% of our points in addition to LHC
- Indirect detection can exclude between 4 and 18% of the points in addition to LHC. This fraction depends strongly on the chosen astrophysical parameters

Complementarities between LHC and DM constraints



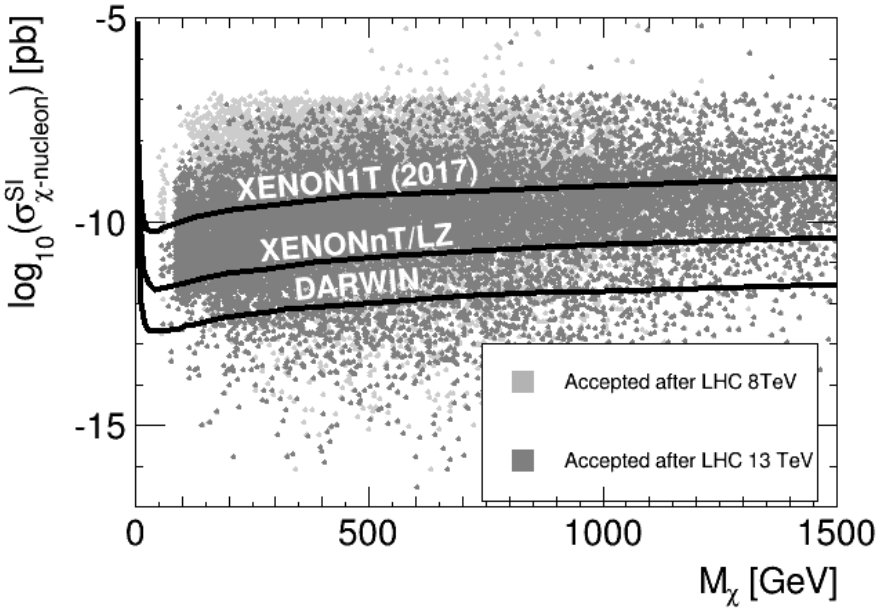


Light Higgs signal strength and EWino searches exclude small $|\mu|$ values. Direct and indirect detection bring strong complementary constraints.

A few points with very light stop mass were remaining after LHC constraints. They are all excluded by indirect detection, even in the conservative case

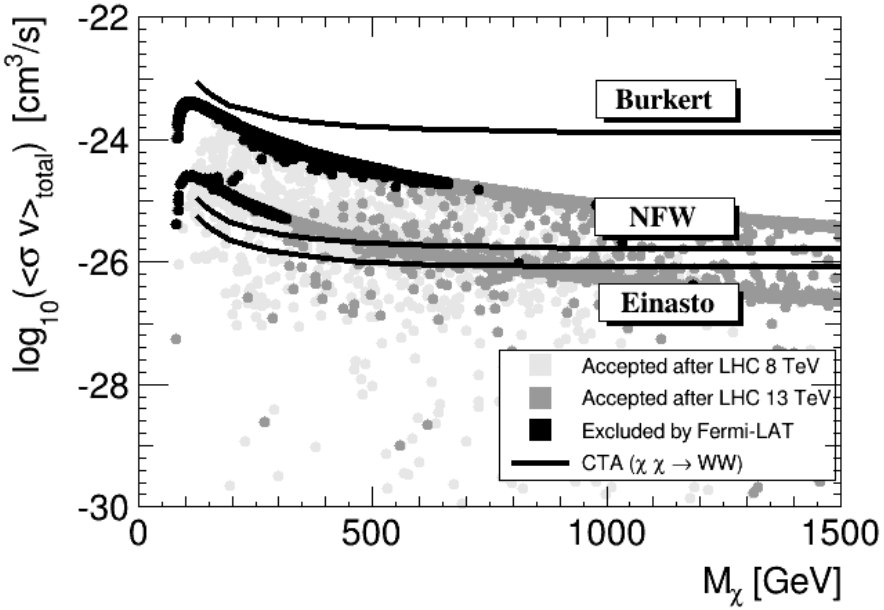
Prospects

Direct detection



In the next years, limits will be dramatically lowered with experiments such as XENONnT and LZ.
The neutrino background will be reached with DARWIN, leaving a few winos beyond this limit.

Indirect detection



Those remaining winos could be probed by CTA before 2030.
However, these limits are highly dependent of the DM halo profile.

Conclusions

- Each type of DM constraints seems to probe a privileged neutralino type: binos for the relic density upper bound, Higgsinos for direct detection and winos for indirect detection
- Combined with collider constraints, DM searches can probe between **80% and 92%** of the points in our sample, depending on the chosen astrophysical parameters
- Direct detection excludes a relatively small but robust number of points which are not excluded by LHC constraints.
- On the opposite, indirect detection can probe a larger fraction of points, but is very sensitive to astrophysical uncertainties.
- **Indirect detection could be a crucial asset in the future** to probe the pMSSM parameter space even further, but as long as the problem of the uncertainties on cosmic ray propagation and on the DM halo profile is not resolved, its study will not bring solid constraints.

Backups

LHC analyses

Analysis	Target	8 TeV	13 TeV
2-6 jets + MET	$\tilde{g}$, $\tilde{q}$	20 fb^{-1}	13.3 fb^{-1} , 36.1 fb^{-1}
7-11 jets +MET	$\tilde{g}$, $\tilde{q}$	20 fb^{-1}	18.2 fb^{-1} , 36.1 fb^{-1}
2-6 jets + 1 lepton + MET	$\tilde{g}$, $\tilde{q}$	20 fb^{-1}	14.8 fb^{-1}
2, 3 leptons + MET	$\tilde{\chi}_2^0$, $\tilde{\chi}_1^\pm$, $\tilde{\ell}$	20 fb^{-1}	13.3 fb^{-1} , 36.1 fb^{-1}
jets + 0 lepton +MET	$\tilde{t}$	20 fb^{-1}	13.3 fb^{-1} , 36.1 fb^{-1},
jets + 1 lepton + MET	$\tilde{t}$	20 fb^{-1}	13.2 fb^{-1}, 36.1 fb^{-1}
b-jets + 2 leptons + MET	$\tilde{t}$	20 fb^{-1}	13.3 fb^{-1} , 36.1 fb^{-1}
2 b-jets + MET	$\tilde{b}$, $\tilde{t}$	20 fb^{-1}	3.2 fb^{-1} 36.1 fb^{-1},
Monojet	MET	20.3 fb^{-1}	3.2 fb^{-1}
mono-Z, W	MET	20.3 fb^{-1}	3.2 fb^{-1}

List of ATLAS searches implemented in this analysis.

Light Higgs and flavour constraints

Channel	Experimental value
$h \to \gamma\gamma$	1.14 ± 0.19
$h \to WW$	1.09 ± 0.18
$h \to ZZ$	1.29 ± 0.26
$h \to bb$	0.70 ± 0.29
$h \to \tau\tau$	1.11 ± 0.24

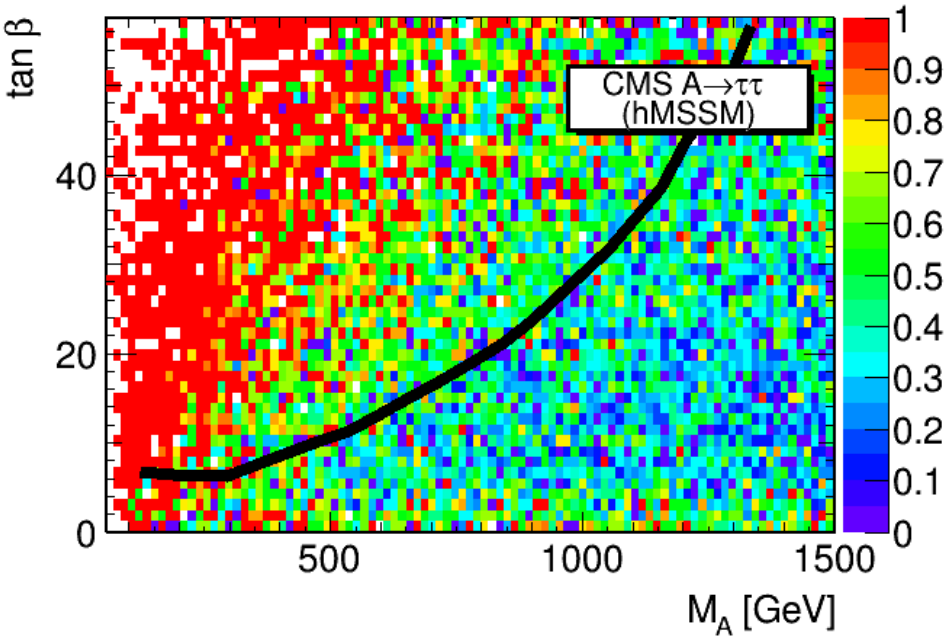
List of the Higgs signal strengths used in this analysis.

Observable	Experiment	SM prediction
$\mathrm{BR}(B_s \to \mu^+\mu^-) \times 10^9$	3.0 ± 0.65	3.54 ± 0.27
$\mathrm{BR}(B \to X_s\gamma) \times 10^4$	3.32 ± 0.15	3.34 ± 0.22
$\mathrm{BR}(B_u \to \tau\nu_\tau) \times 10^4$	1.06 ± 0.19	0.82 ± 0.29

Experimental results and the corresponding SM values for the flavour physics observables used in this work. The experimental data represents the most recent measurements or official combinations.

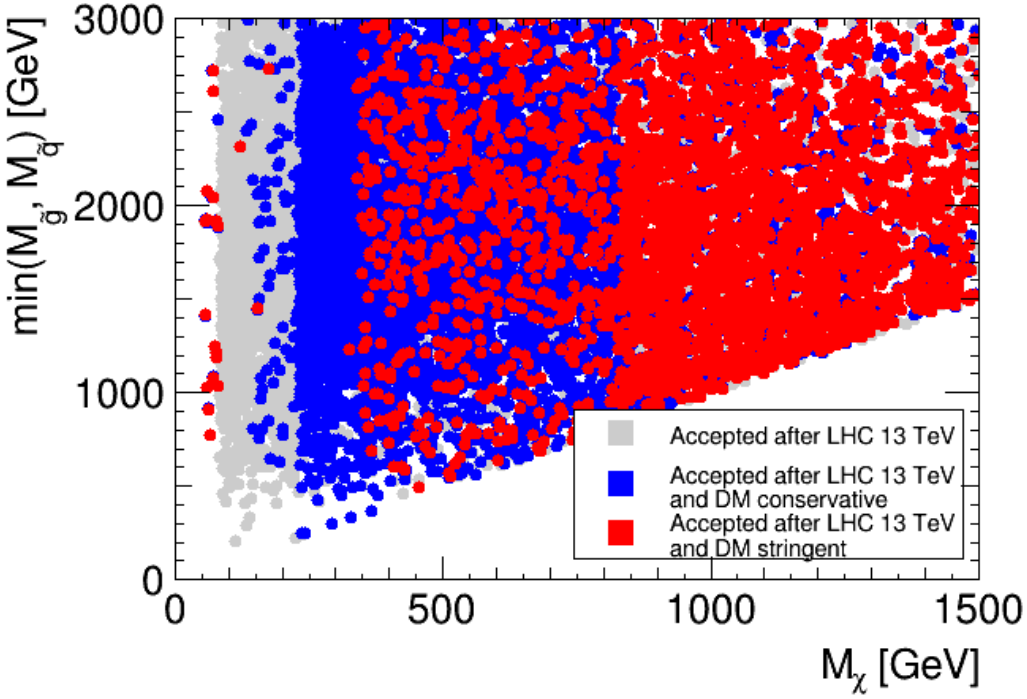
Direct detection and Higgs sector

- Most of the points excluded by direct detection are also excluded by LHC limits on the heavy Higgs sector
- However, direct detection also eliminates points with small tan β and large M_A. Then, it is still worth being considered.

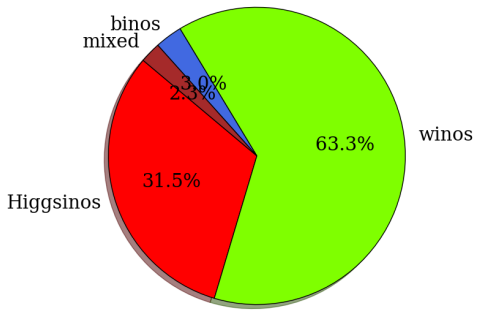


Fraction of points excluded by direct detection

Squark/gluino mass



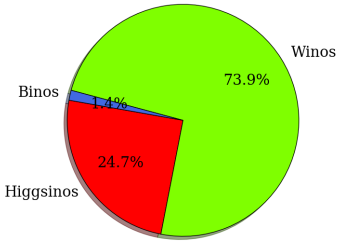
Remaining points

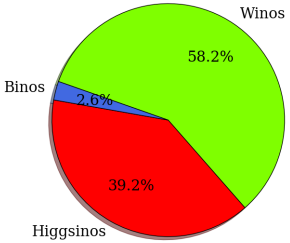


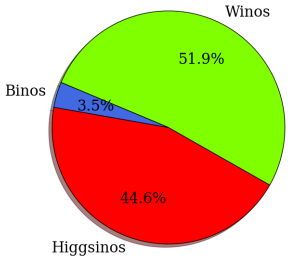
Binos
Higgsinos
Winos

Distribution of points after imposing LEP constraints, light Higgs mass, flavour constraints and relic density upper bound

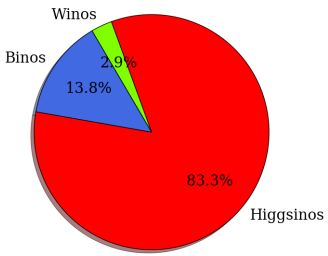
CONSERVATIVE STANDARD STRINGENT

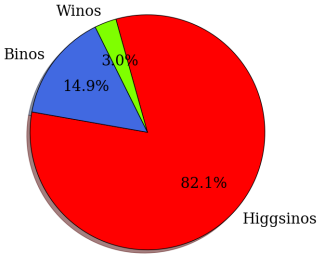


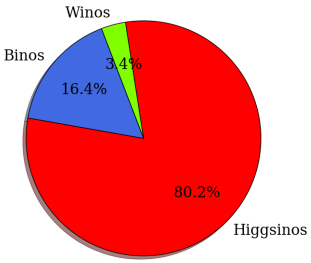




+ LHC 13 TeV, indirect and direct detection







+relic density lower bound