Constraining the MSSM with LHC and Dark Matter searches

Alexandre Arbey

Lyon U. & CERN TH

Thanks to M. Battaglia, L. Covi, A. Djouadi, N. Mahmoudi, G. Robbins

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At the LHC

- SUSY and exotic searches
- Higgs boson searches and measurements
- flavour physics

In low energy experiments

- B-factories
- Muon $g-2$
- Electric dipole moments
- ...

In space

- Relic density
- Direct detection
- Indirect detection
- ...

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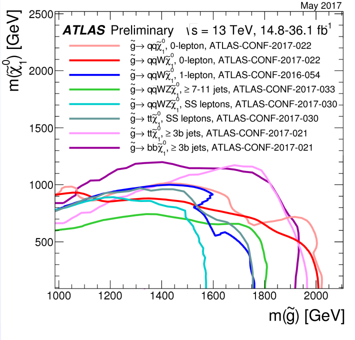
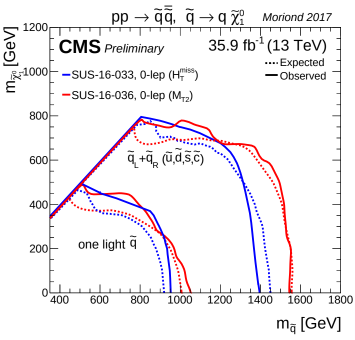
ATLAS and CMS set very strong constraints on the MSSM strongly interacting sector





$$M_{\tilde{g}} \gtrsim 2 \text{ TeV}, \qquad M_{\tilde{q}} \gtrsim 1.5 \text{ TeV}$$

Squarks and gluinos are getting heavier and heavier...

But we already found the first Higgs boson, no need to be pessimistic!

Minimal Supersymmetric extension of the Standard Model (MSSM)

- More than 100 free parameters
- Very difficult to perform systematic studies
- Not all parameters are relevant for a specific analysis

Need for more simple scenarios...

Constrained MSSM scenarios

- Suppose a SUSY breaking mechanism

  $\rightarrow$ Strongly reduces the number of free parameters!

- Most studied scenario: CMSSM (or mSUGRA)

Very much challenged...

Simplified MSSM scenarios

- Only 2 or 3 parameters are varied, the rest being considered as decoupled

Useful to present the results, but not very realistic...

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Phenomenological MSSM (pMSSM)

The most general MSSM scenario with R-parity, CP conservation and minimal flavour violation

$\rightarrow$ 19 independent parameters (20 with gravitino mass)

In the following, we consider the lightest neutralino or the gravitino as dark matter

The neutralino can be

- bino-like ($|M_1| \ll |M_2|, |\mu|$)
- wino-like ($|M_2| \ll |M_1|, |\mu|$)
- higgsino-like ($|\mu| \ll |M_1|, |M_2|$)
- or a mixed state

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Random scans of the 19 (20) pMSSM parameters with neutralino (gravitino) dark matter

Parameter	Range (in GeV)
M_A	[50, 2000]
M_1	[-3000, 3000]
M_2	[-3000, 3000]
M_3	[50, 5000]
$A_d = A_s = A_b$	[-15000, 15000]
$A_u = A_c = A_t$	[-15000, 15000]
$A_e = A_\mu = A_\tau$	[-15000, 15000]
μ	[-3000, 3000]
$M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$	[0, 5000]
$M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$	[0, 5000]
$M_{\tilde{\tau}_L}$	[0, 5000]
$M_{\tilde{\tau}_R}$	[0, 5000]
$M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$	[0, 5000]
$M_{\tilde{q}_{3L}}$	[0, 5000]
$M_{\tilde{u}_R} = M_{\tilde{c}_R}$	[0, 5000]
$M_{\tilde{t}_R}$	[0, 5000]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[0, 5000]
$M_{\tilde{b}_R}$	[0, 5000]
$\tan\beta$	[1, 60]
$(M_{\rm gravitino}$	$< M_{\tilde{\chi}^0_1})$

- Calculation of masses, mixings and couplings (SoftSusy, Suspect)
- Computation of low energy observables and Z widths (SuperIso)
- Computation of dark matter observables (SuperIso Relic, Micromegas)
- Determination of SUSY and Higgs mass limits (SuperIso, HiggsBounds)
- Calculation of Higgs cross-sections and decay rates (HDECAY, Higlu, FeynHiggs, SusHi)
- Calculation of SUSY decay rates (SDECAY)
- Event generation and evaluation of cross-sections (PYTHIA, Prospino, MadGraph)
- Implementation of ATLAS and/or CMS SUSY and monoX search results
- Determination of detectability with fast detector simulation (Delphes)

Neutralino dark matter

Different ways of searching for dark matter:

- **Direct production** of LSPs at the LHC
  $\rightarrow$ neutralinos present in most of the SUSY search channels
  $\rightarrow$ monojet searches specifically designed for invisible particle searches

- **DM annihilations**: DM + DM $\rightarrow$ SM + SM + ...
  - indirect detection: protons, gammas, anti-protons, positrons, ...
  - dark matter relic density: also dependent on co-annihilations

  Annihilation cross-sections can be enhanced through Higgs resonances

- **DM scattering** with matter: DM + matter $\rightarrow$ DM + matter
  $\rightarrow$ direct detection experiments

  Neutralino scattering cross-section sensitive to neutral Higgs bosons

- **Invisible Higgs decays** to LSPs
  $\rightarrow$ very much dependent on the nature of the LSP

In the Standard Model of Cosmology:

- before and at nucleosynthesis time, the expansion is dominated by radiation

$$H^2 = 8\pi G/3 \times \rho_{\mathrm{rad}}$$

- the evolution of the number density of supersymmetric particles follows the Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\mathrm{eff}} v \rangle (n^2 - n_{\mathrm{eq}}^2)$$

n: number density of relic particles
$\langle \sigma_{\mathrm{eff}} v \rangle$: thermal average of effective (co-)annihilation cross sections to SM particles

Solving the system of equations leads to the relic density of the LSP

To be compared to the very constraining Planck interval:

$$0.077 < \Omega_\chi h^2 < 0.160$$

Using this constraint has very strong consequences on the MSSM parameter space and only specific and small regions are selected!

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Caveat about the relic density constraints:

The relic density constraint is strong and can rule out many models, but changing the underlying hypotheses can make them survive, e.g. if:

- the neutralino is not the only component of dark matter
- neutralinos are produced non-thermally (e.g. by the decay of an inflaton)
- dark energy accelerated the expansion of the Universe before the freeze-out
- additional entropy were generated in the early Universe
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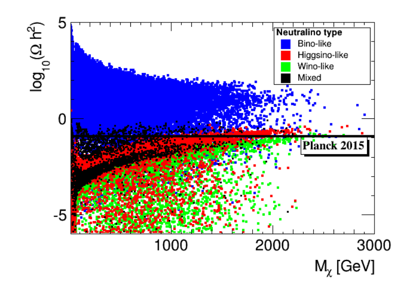
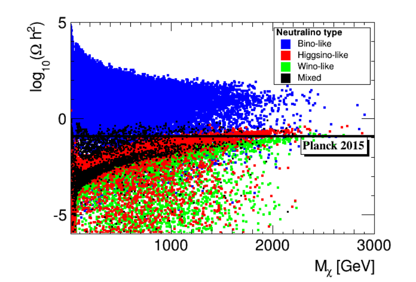


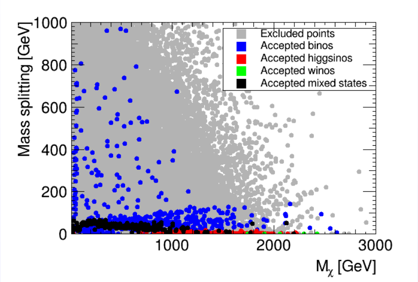
AA, M. Boudaud, F. Mahmoudi, G. Robbins, arXiv:1707.00426

Relic density "naturally" obtained for a Higgsino of 1.3 TeV or a Wino of 2.7 TeV

Neutralino relic density

imposing $0.077 < \Omega_\chi h^2 < 0.160$





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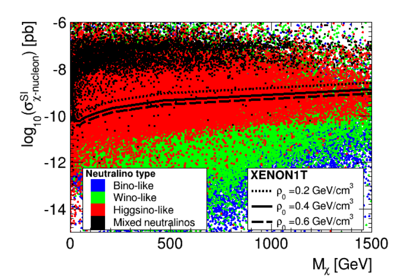
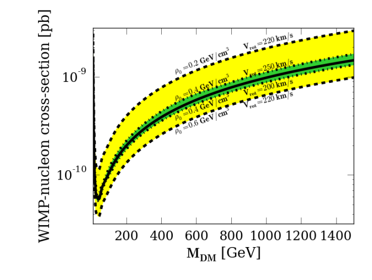
Relic density “naturally” obtained for a Higgsino of 1.3 TeV or a Wino of 2.7 TeV

The lower bound of the relic density tends to select more compressed scenarios with co-annihilations





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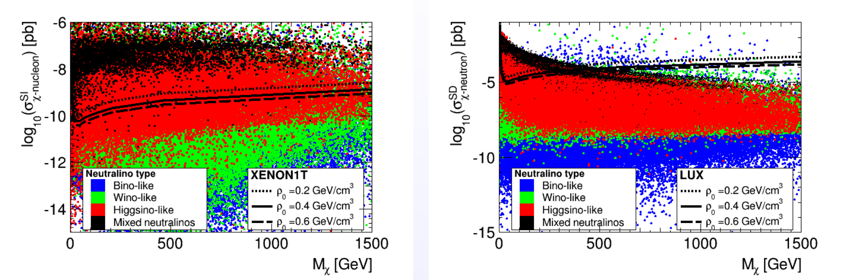
Upper limits on the WIMP-nucleon scattering cross sections

Limits affected by the local dark matter density and velocity



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Upper limits on the WIMP-nucleon scattering cross sections

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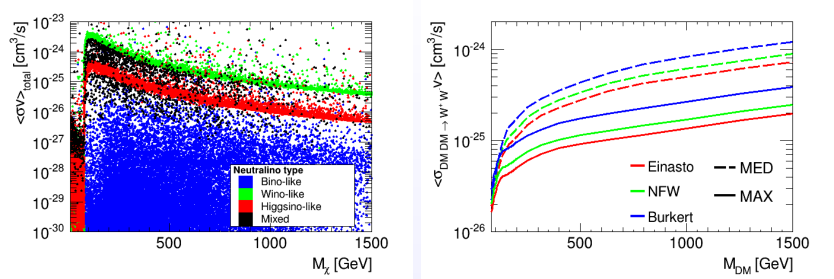
Higgsino-like neutralinos more stongly probed

Strong constraints on the $(M_A, \tan\beta)$ parameter plane

Complementary to $H/A \to \tau^+\tau^-$ and $B_s \to \mu^+\mu^-$ searches



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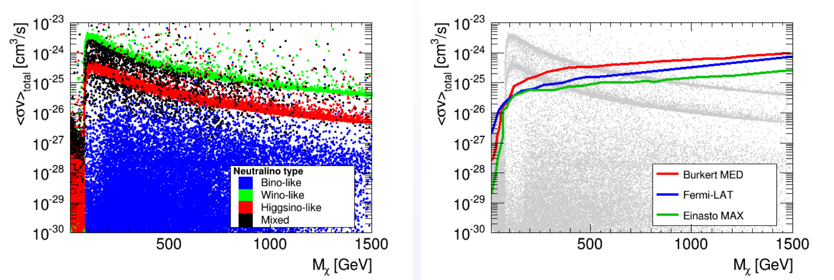
Upper limits on annihilation cross sections

AMS-02: anti-proton fluxes
$\rightarrow$ largely affected by propagation model (factor $\sim$ 10) and galaxy profile (factor $\sim$ 2)

Fermi-LAT: gamma rays from dwarf spheroidal galaxies
$\rightarrow$ affected by galaxy profile



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AMS-02: anti-proton fluxes
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Fermi-LAT: gamma rays from dwarf spheroidal galaxies
→ affected by galaxy profile

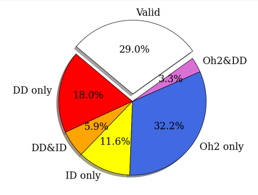
Wino-like neutralinos more stongly probed

→ complementary to direct detection!

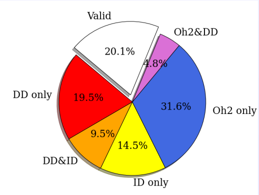
Three Dark Matter benchmark cases

- CONSERVATIVE: AMS-02 antiprotons with Burkert profile and MED propagation model + local density of 0.2 GeV/cm^3
- STANDARD: Fermi-LAT gamma rays with NFW profile + local density of 0.4 GeV/cm^3
- STRINGENT: AMS-02 antiprotons with NFW profile and MAX propagation model + local density of 0.6 GeV/cm^3

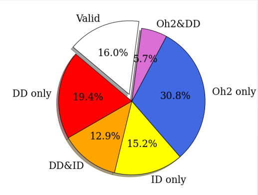
Exclusion by dark matter observables



CONSERVATIVE



STANDARD



STRINGENT

Direct SUSY and monojet searches at the LHC

In our study, we implement the following LHC searches for which we generate events with MadGraph/Pythia and simulate the detector with Delphes:

- **Direct SUSY searches (8 and 13 TeV)**:

  squark and gluino direct searches (jets + $\not{E}_T$)

  stop and sbottom direct searches (t, b-jets (+ leptons) + $\not{E}_T$)

  chargino and neutralino direct searches (leptons (+ b-jets) + $\not{E}_T$)

- **Monojet searches**: search for 1 hard jet + $\not{E}_T$

- **Other Mono-X searches**: mono-$W/Z/\gamma$, mono-top, mono-Higgs, ... searches

$\rightarrow$ Mono-X search results need to be reinterpreted in the MSSM!

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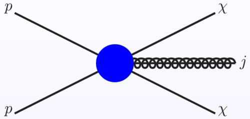

Monojets in the MSSM:

AA, M. Battaglia, F. Mahmoudi, Phys. Rev. D94 (2016) 055015

LHC very sensitive to the strongly interacting particles

→ larger monojet cross sections in the MSSM

→ particularly relevant when small mass splitting between squark/gluino and neutralino

→ monojet searches in the MSSM do not probe the dark matter sector...

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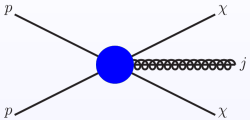

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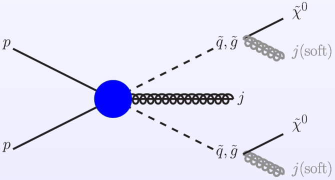

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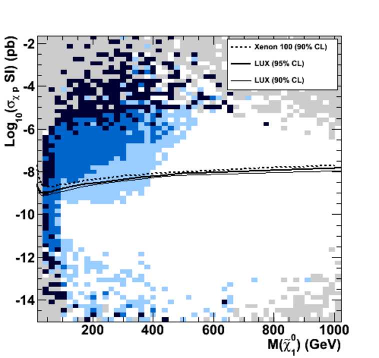
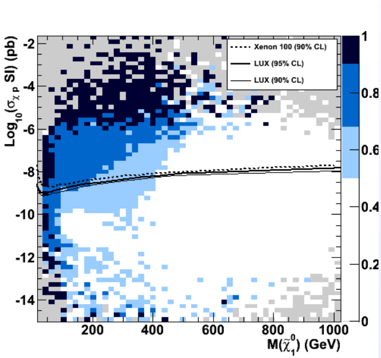
In the dark matter direct detection scattering cross section vs. neutralino mass plane:

jets/leptons+MET only



jets/leptons+MET searches and monojet



Colour scale: fraction of excluded points

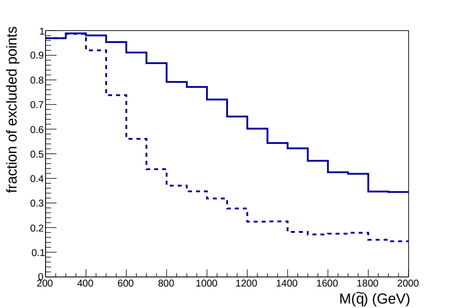
AA, M. Battaglia, F. Mahmoudi, Phys. Rev. D89 (2014) 077701

In contrast with simplified models, in the MSSM monojet searches probe different regions than direct detection

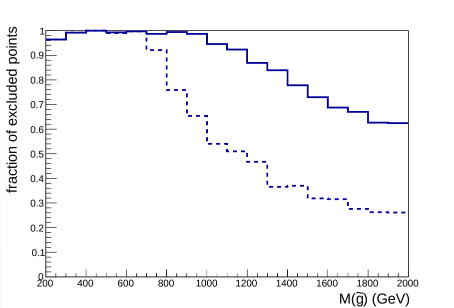
DM direct detection and LHC searches are complementary!

Fraction of excluded points as a function of the

lightest squark mass



gluino mass



Dotted: 8 TeV only
Solid: 8+13 TeV

Squark and gluino masses below ∼1 TeV are still allowed in pMSSM!

- Contrary to the SM Higgs, the MSSM light CP-even Higgs is bounded from above: $M_h^{max} \approx M_Z |\cos 2\beta| +$ radiative corrections $\lesssim 110 - 135$ GeV

- Imposing M_h places very strong constraints on the MSSM parameters through their contributions to the radiative corrections

$$M_h^2 \approx M_Z^2 \cos^2 2\beta \left[1 - \frac{M_Z^2}{{M_A}^2} \sin^2 2\beta\right] + \frac{3 m_t^4}{2\pi^2 v^2} \left[\log \frac{{M_S}^2}{m_t^2} + \frac{{X_t}^2}{{M_S}^2}\left(1 - \frac{{X_t}^2}{12 {M_S}^2}\right)\right]$$

with M_S the averaged stop mass and X_t the stop mixing parameter

- Modified couplings with respect to the SM Higgs boson (→ decoupling limit):

ϕ	$g_{\phi u\bar{u}}$	$g_{\phi d\bar{d}} = g_{\phi \ell\bar{\ell}}$	$g_{\Phi VV}$
h	$\cos\alpha / \sin\beta \to 1$	$-\sin\alpha / \cos\beta \to 1$	$\sin(\beta - \alpha) \to 1$
H	$\sin\alpha / \sin\beta \to \cot\beta$	$\cos\alpha / \cos\beta \to \tan\beta$	$\cos(\beta - \alpha) \to 0$
A	$\cot\beta$	$\tan\beta$	0

$$\text{where } \alpha = \frac{1}{2} \arctan\left(\tan(2\beta) \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2}\right)$$

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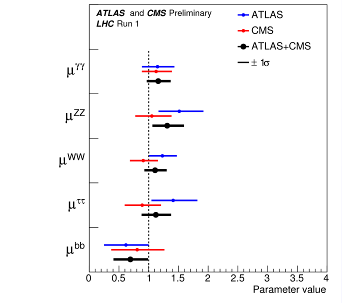
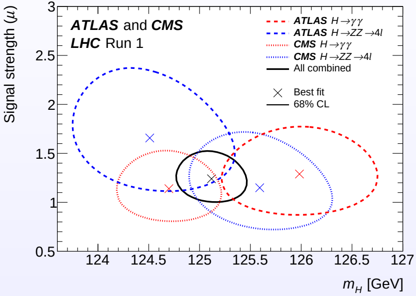
ATLAS and CMS measurements:





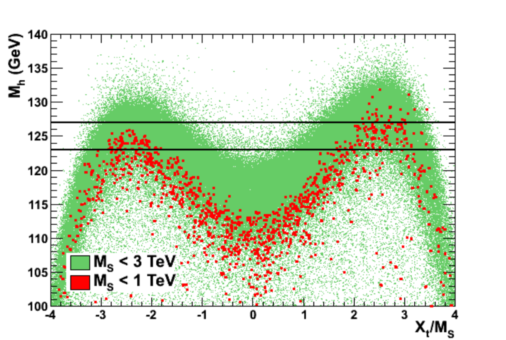
ATLAS, CMS Collaborations, Phys. Rev. Lett. 114, 191803 (2015)

Signal strength defined as:

$$\mu_{XX} = \frac{\sigma(pp \to h)\,\mathrm{BR}(h \to XX)}{\sigma(pp \to h)_{\mathrm{SM}}\,\mathrm{BR}(h \to XX)_{\mathrm{SM}}}$$

$\to$ The results are compatible with the SM Higgs

Implications in pMSSM:

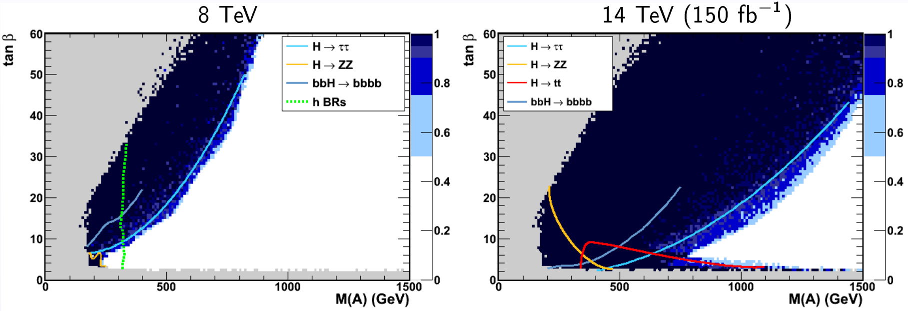


AA, M. Battaglia, A. Djouadi, F. Mahmoudi, J. Quevillon, Phys. Lett. B708 (2012) 162

$M_h \sim 125$ GeV is easily satisfied in pMSSM

No mixing cases ($X_t \approx 0$) excluded for small M_S

Complementary channels: $H \to \tau\tau, ZZ, bb, tt, hZ, hh$



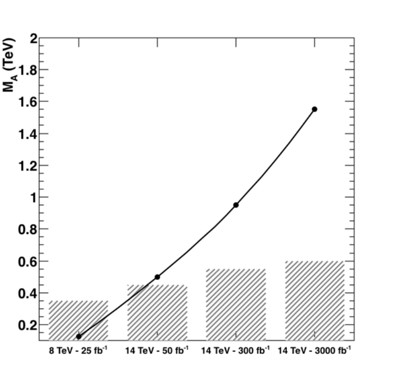
AA, M. Battaglia, F. Mahmoudi, Phys. Rev. D88 (2013) 015007

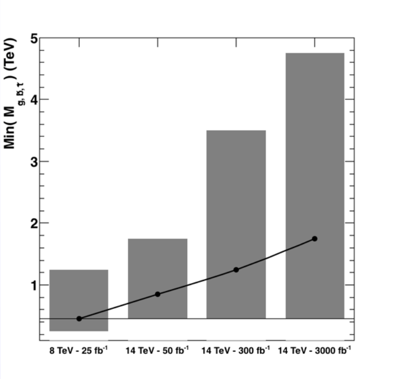
lines: limits corresponding to an exclusion of 99.9% of the points
Grey points: excluded by dark matter, flavour physics and Higgs mass constraints
Colour scale: fraction of excluded points

→ Some points inside the $H \to \tau\tau$ excluded region still survive

→ Other channels ($H \to ZZ$, $H \to t\bar{t}$, ...) will help probing the small $\tan\beta$ region

Sensitivity to the mass of the CP-odd A boson



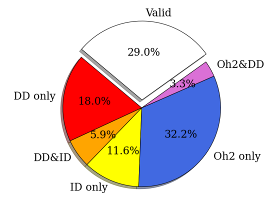


AA, M. Battaglia, F. Mahmoudi, Ann. Phys. 528 (2016) 179

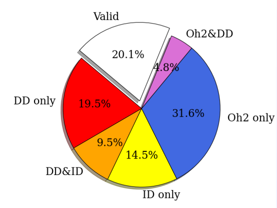
continuous line: 95% C.L. exclusion bounds by the LHC direct searches
gray bars: indirect constraints from the Higgs signal strength measurements

Higgs searches complementary to the direct searches!

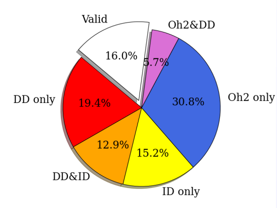
Exclusion by dark matter observables only (Higgs mass pre-imposed)



CONSERVATIVE

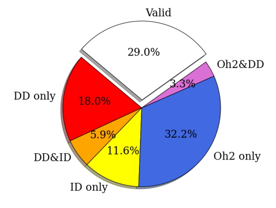


STANDARD



STRINGENT

Exclusion by dark matter observables only (Higgs mass pre-imposed)



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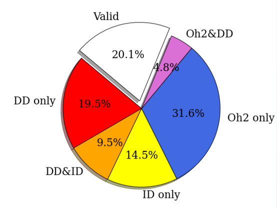

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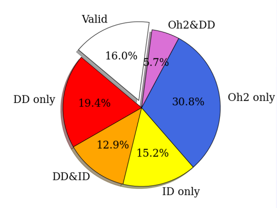
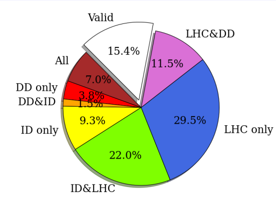
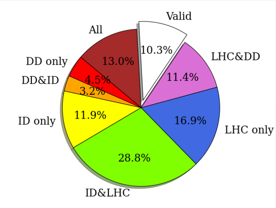
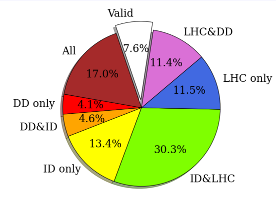


STRINGENT

Exclusion by dark matter observables and LHC searches

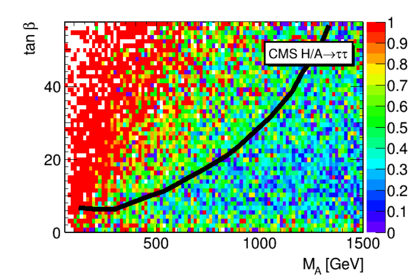






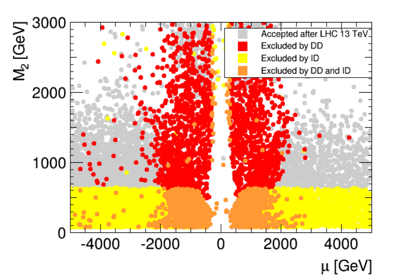
Interesting complementary between DM searches and LHC!

Direct detection and Heavy Higgs searches



Fraction of points excluded by DD

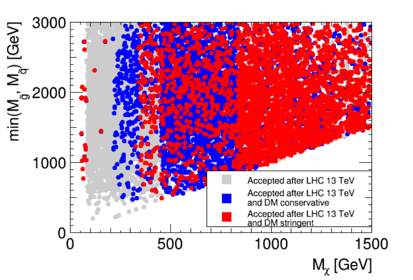
Direct and indirect detection and LHC



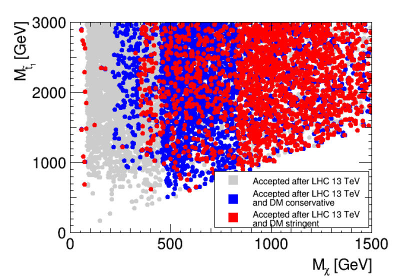
AA, M. Boudaud, F. Mahmoudi, G. Robbins, arXiv:1707.00426

Interesting interplay in the Higgs and Higgsino sectors!

Gluino/squark mass vs. Neutralino mass



Stop 1 mass vs. Neutralino mass

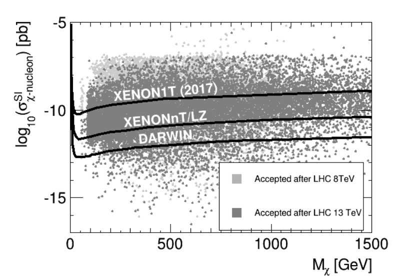


AA, M. Boudaud, F. Mahmoudi, G. Robbins, arXiv:1707.00426

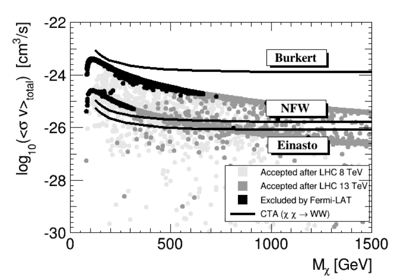
Interplay also interesting in the squark and gluino sectors!

Perspectives

Future of direct detection



Future of indirect detection



AA, M. Boudaud, F. Mahmoudi, G. Robbins, arXiv:1707.00426

Strong improvements expected!

Direct detection will be limited after DARWIN by the neutrino background

Indirect detection will be limited by our knowledge of the dark matter profile

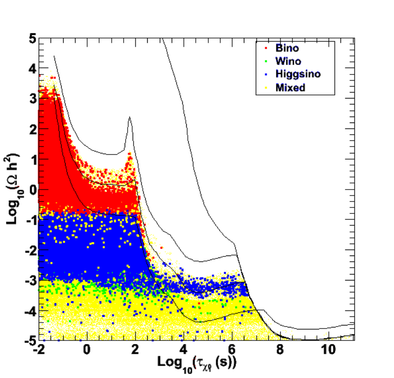
Gravitino dark matter

Set-up of our study:

- Gravitino LSP, single component of dark matter
- Neutralino NLSP (for a fair comparison with the neutralino LSP scenario)
  $\rightarrow$ Gravitino produced either through NLSP decay or during reheating
  $\rightarrow$ Neutralino lifetime constrained by Big-Bang Nucleosynthesis
- Neutralino NLSP long-lived with respect to collider physics
  $\rightarrow$ Same collider constraints as for neutralino LSP scenario
- DM composed exclusively of gravitinos
  $\rightarrow$ Constraints from direct and indirect detection relaxed (gravitino very elusive!)
  $\rightarrow$ Constraints from relic density strongly relaxed (in particular because of gravitino production during reheating)

Gravitino LSP scenario much less constrained than the neutralino LSP scenario!

Constraints from Big-Bang Nucleosynthesis
(limits extracted from Jedamzik, hep-ph/060425)

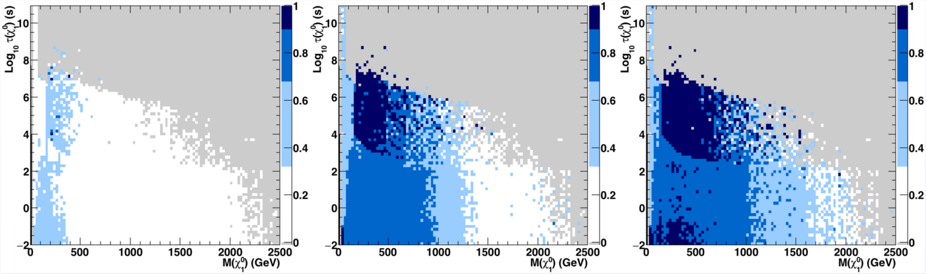


AA, M. Battaglia, L. Covi, J. Hasenkamp, F. Mahmoudi, Phys. Rev. D92 (2015) 115008

$\tau_{\tilde{\chi}_1^0}$: neutralino lifetime
Ωh^2: neutralino relic density (in absence of gravitino)

BBN imposes strong constraints on the neutralino lifetime

Fraction of points excluded by the LHC SUSY and monojet searches

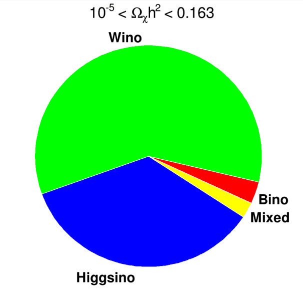


8 TeV, 25 fb^{-1} | 14 TeV, 300 fb^{-1} | 14 TeV, 3000 fb^{-1}

AA, M. Battaglia, L. Covi, J. Hasenkamp, F. Mahmoudi, Phys. Rev. D92 (2015) 115008

In the gravitino LSP scenario, LHC will probe neutralino masses up to ∼1.5 TeV

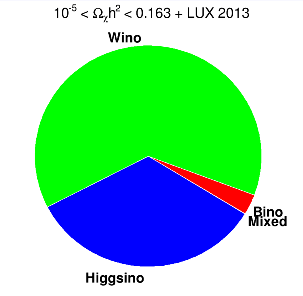
Fraction of neutralino states after dark matter constraints



Dark matter constraints strongly affect the neutralino composition

Gravitino LSP with neutralino NLSP opens up different scenarios lifting the DM constraints and establishing an almost equal share of bino, wino and higgsino NLSP

Fraction of neutralino states after dark matter constraints



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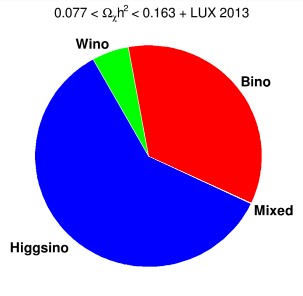

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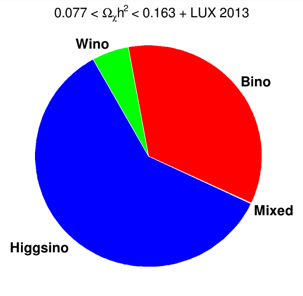
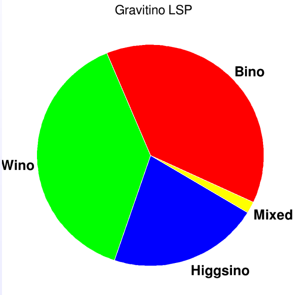


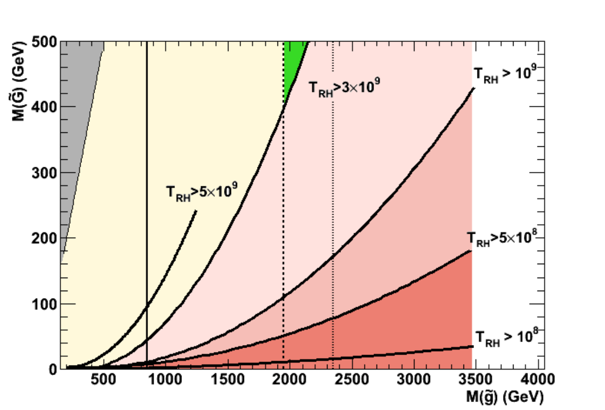


Dark matter constraints strongly affect the neutralino composition

Gravitino LSP with neutralino NLSP opens up different scenarios lifting the DM constraints and establishing an almost equal share of bino, wino and higgsino NLSP

Production of gravitino after inflation related to reheat temperature and gaugino masses

→ LHC gluino searches and DM density measurements probe the reheating temperature



Interesting interplay between cosmology and collider physics!

Conclusions

- The pMSSM provides viable candidates for dark matter
- Dark matter searches are powerful probes for Supersymmetry
- Dark matter observables are subject to uncertainties that have to be considered
- Monojet searches are complementary to the usual SUSY searches at the LHC
- The interplay between LHC and dark matter constraints has to be fully exploited
- Gravitino DM scenario less constrained than the neutralino LSP scenario
- Still plenty of room for SUSY and New Physics!