Combined impact of LHC and dark matter searches for SUSY

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Search for New Physics

Direct searches:

ATLAS and CMS main searches:

- Higgs bosons
- **New Physics (NP)**: SUSY is the main focus of BSM searches

Indirect searches: dark matter sector

- Information on the properties of the DM candidate
  → Constraints on NP parameters

Indirect searches: flavour sector

- Precision flavour physics is sensitive to the presence of new particles in the virtual states
- Probes sectors inaccessible to the direct searches!

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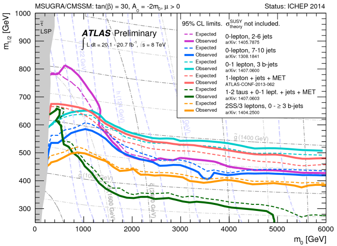
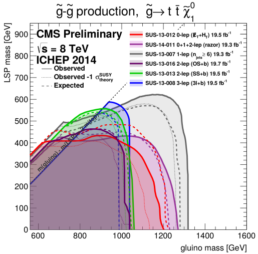
Direct searches

- Discovery of a Higgs boson
- No New Physics signal so far
- Strong limits in the constrained/simplified SUSY scenarios





SUSY masses pushed to larger and larger values!

$$M_{\tilde{g}} \gtrsim 1.3 \text{ TeV}, \qquad M_{\tilde{q}} \gtrsim 2 \text{ TeV}$$

Interpretation of the results

Two important points:

1. What do these limits mean exactly? Is low energy SUSY excluded??

   Most of the experimental limits are given for constrained or simplified MSSM scenarios

   Useful, but NOT representative of the whole MSSM!

   → Reinterpret the results in general MSSM with minimal theoretical assumptions
   → Phenomenological MSSM: an adequate set-up

2. As a result of the current searches: the limits are pushed to larger masses

   This does not provide any conclusive idea!

   The only way to point to a specific SUSY scenario, or falsify SUSY would be to take advantage of **interplays** in particular:

   – Direct searches

     Higgs sector (mass and couplings), other than SUSY searches: Monojet searches

   – Indirect searches

     Dark matter searches (direct DM search results), Flavour physics sector (rare decays)

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Outline

- Direct searches
- Higgs physics
- Dark matter
    - Neutralino dark matter
    - Gravitino dark matter
- Conclusion

Constrained MSSM scenarios

General MSSM

- Many free parameters
- Very difficult to perform systematic studies

A way out: Constrained MSSM scenarios

- Assume universality at GUT scale

  $\rightarrow$ Reduces the number of free parameters to a handful!

- Most well known scenario: CMSSM (or mSUGRA)

  Universal parameters: scalar mass m_0, gaugino mass $m_{1/2}$, trilinear soft coupling A_0 and Higgs parameters (sign of μ and $\tan\beta$)

  $\rightarrow$ Very useful for phenomenology, benchmarking, model discrimination, ...

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Beyond constrained scenarios

Phenomenological MSSM (pMSSM)

- The most general CP/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 (20 with gravitino mass)

10 sfermion masses: $M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$, $M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$, $M_{\tilde{\tau}_L}$, $M_{\tilde{\tau}_R}$, $M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$, $M_{\tilde{q}_{3L}}$, $M_{\tilde{u}_R} = M_{\tilde{c}_R}$, $M_{\tilde{t}_R}$, $M_{\tilde{d}_R} = M_{\tilde{s}_R}$, $M_{\tilde{b}_R}$

3 gaugino masses: M_1, M_2, M_3

3 trilinear couplings: $A_d = A_s = A_b$, $A_u = A_c = A_t$, $A_e = A_\mu = A_\tau$

3 Higgs/Higgsino parameters: M_A, $\tan\beta$, μ

A. Djouadi et al., hep-ph/9901246

In the following, neutralino LSP (or gravitino LSP and neutralino NLSP at the end)

The lightest 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

pMSSM analysis set-up

Complete analysis in pMSSM:

- Calculation of masses, mixings and couplings (SoftSusy, Suspect)
- Computation of low energy observables (**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, ...)
- Calculation of SUSY decay rates (SDECAY)
- Event generation and evaluation of cross-sections (PYTHIA, MadGraph, Prospino)
- Determination of detectability with fast detector simulation (Delphes)

Parameter	Range (in GeV)
$\tan\beta$	[1, 60]
M_A	[50, 5000]
M_1	[-5000, 5000]
M_2	[-5000, 5000]
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	[-5000, 5000]
$M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$	[0, 5000]
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$M_{\tilde{t}_R}$	[0, 5000]
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$M_{\tilde{b}_R}$	[0, 5000]

In collaboration with Alex Arbey and Marco Battaglia

pMSSM scans

Constraints from:

- LEP and Tevatron direct search limits
- Flavour precision limits, in particular from BR($B \to X_s \gamma$), BR($B_s \to \mu^+\mu^-$), BR($B \to \tau\nu$)
- Muon anomalous magnetic moment, $(g-2)_\mu$
- Dark matter relic density

} "**accepted**" points

- Dark matter direct search limits
- Higgs mass limits
- Higgs production and decay rates
- LHC SUSY direct searches
- LHC monojet searches

Statistics:

- more than 200M model points in general analyses
- more than 1B model points for dedicated analyses

Largest statistics in the MSSM so far.

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Direct SUSY and monojet searches at the LHC

Direct SUSY searches:

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

ATLAS-CONF-2013-047

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

ATLAS-CONF-2013-053

chargino and neutralino direct searches (2 or 3 leptons + $\not{E}_T$)

ATLAS-CONF-2013-049, ATLAS-CONF-2013-035

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

ATLAS-CONF-2012-147, ATLAS-CONF-2013-068, CMS PAS EXO-12-048

Usually interpretation in terms of effective operators (WIMP-WIMP-q-$\bar{q}$ or -g-g)

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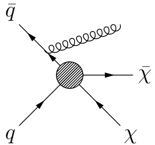

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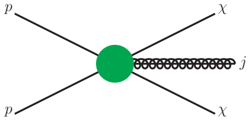
Monojets in the pMSSM

Generic monojets in "simple" DM scenarios:



Monojets in the MSSM:

LHC very sensitive to the strongly interacting particles

→ many SUSY events with monojet signature!

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

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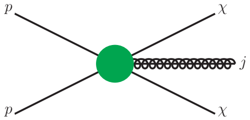

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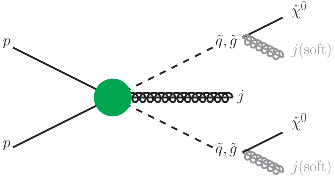

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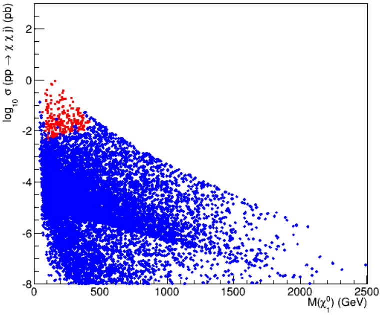
Monojets in the pMSSM

Analysis for the 14 TeV run with 300 fb^{-1}

Production cross-section vs. neutralino mass for

Monojets with neutralinos only:



Red: excluded points
Blue: surviving points

Monojets particularly constraining if all signatures considered!

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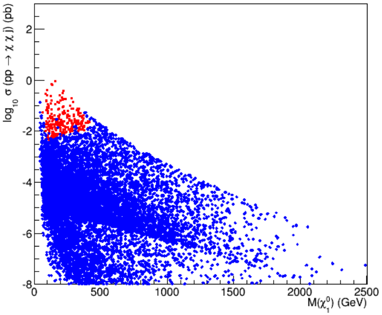
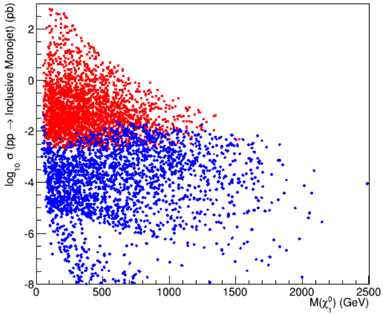


Other monojet signatures:



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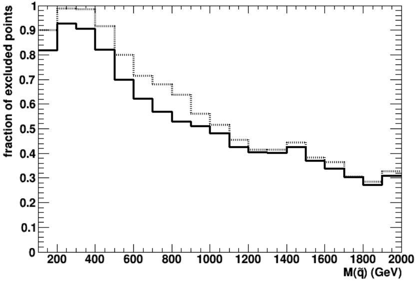
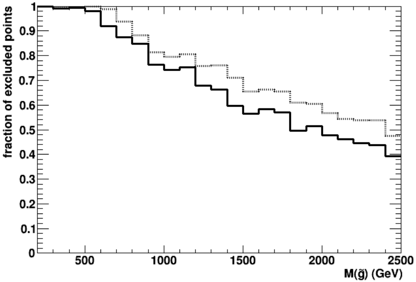
Consequences for SUSY particle masses

Limits on sparticle masses:

Lightest squark mass



Gluino mass



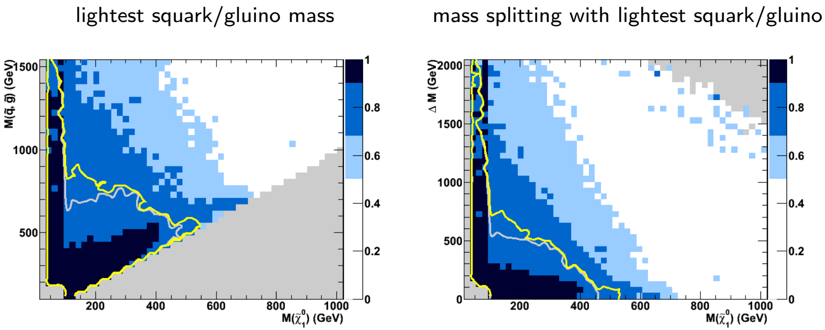
Preliminary

Solid: jets/leptons+MET searches
Dotted: + monojet analyses

squark and gluino masses well below 1 TeV are still allowed!

Complementarity between monojets and direct SUSY searches

Neutralino mass:



A. Arbey, M. Battaglia, FM, Phys. Rev. D89 (2014) 077701

Color scale: fraction of excluded points

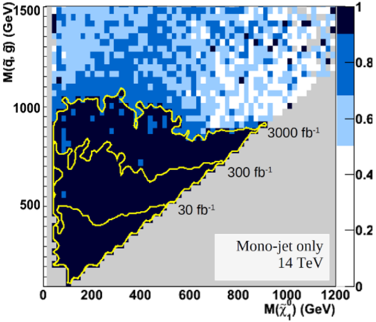
Grey line: 68% C.L. exclusion by jets/leptons+MET searches

Yellow line: + monojet analyses

Monojet searches improve sensitivity by more than 100 GeV in the small mass splitting region!

Prospects from monojet searches at 14 and 100 TeV

Lightest squark/gluino mass vs. neutralino mass



Preliminary

Color scale: fraction of excluded points

Yellow line: 95% exclusion by monojet searches

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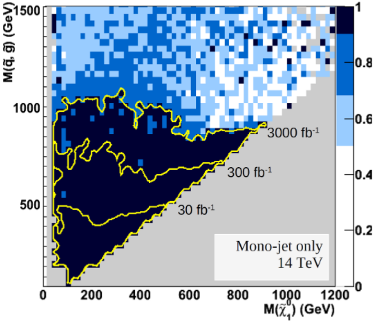

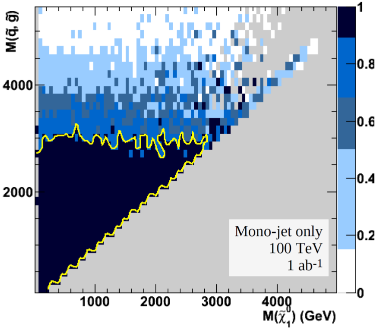

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Higgs sector

Higgs searches

Discovery of a Higgs boson by ATLAS and CMS:

Parameter	Combined value	Experiment
M_H (GeV)	125.09 ± 0.24	ATLAS+CMS
$\mu_{\gamma\gamma}$	1.20 ± 0.30	ATLAS+CMS
μ_{ZZ}	1.10 ± 0.22	ATLAS+CMS
μ_{WW}	0.77 ± 0.21	ATLAS+CMS
$\mu_{b\bar{b}}$	1.12 ± 0.45	ATLAS+CMS+(CDF+D0)
$\mu_{\tau\tau}$	0.94 ± 0.24	ATLAS+CMS

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 of the Higgs mass determination

- In the SM, the Higgs mass is essentially a free parameter
- In the MSSM, the lightest CP-even Higgs particle 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

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

- Important parameters for MSSM Higgs mass:
  - $\tan\beta$ and M_A
  - the SUSY breaking scale $M_S = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$
  - the mixing parameter in the stop sector $X_t = A_t - \mu / \tan\beta$

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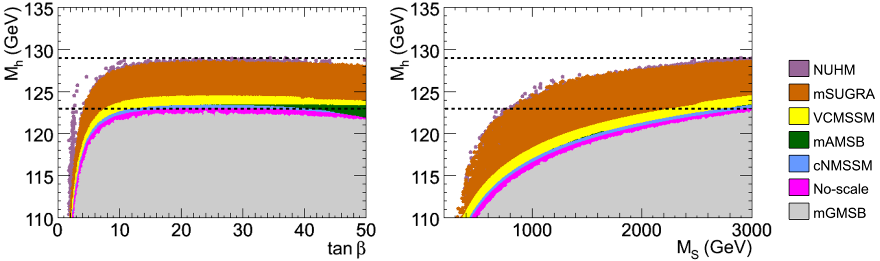
Implications of the Higgs mass determination

Maximal Higgs mass in constrained MSSM scenarios

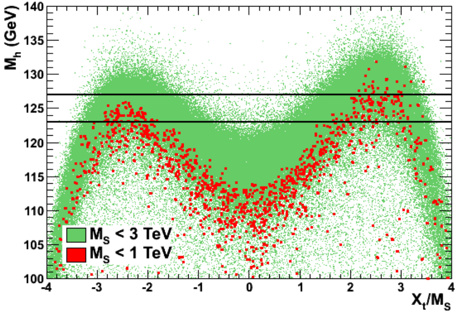


A. Arbey, M. Battaglia, A. Djouadi, FM, JHEP 1209 (2012) 107

Several constrained models are excluded or about to be!

Implications of the Higgs mass determination

Implications in pMSSM:



A. Arbey, M. Battaglia, A. Djouadi, FM, 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

Higgs couplings

Modified couplings with respect to the SM Higgs boson ($\rightarrow$ decoupling limit):

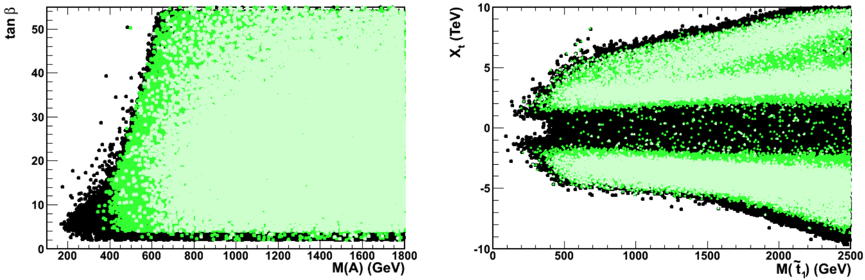
ϕ	$g_{\phi u\bar{u}}$	$g_{\phi d\bar{d}} = g_{\phi\ell\bar{\ell}}$	$g_{\Phi VV}$
h	$\cos\alpha/\sin\beta \rightarrow 1$	$-\sin\alpha/\cos\beta \rightarrow 1$	$\sin(\beta-\alpha) \rightarrow 1$
H	$\sin\alpha/\sin\beta \rightarrow \cot\beta$	$\cos\alpha/\cos\beta \rightarrow \tan\beta$	$\cos(\beta-\alpha)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

where:

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

Higher order corrections to the tree level couplings can be large for light SUSY particles

Consequences of the Higgs rate measurements in pMSSM

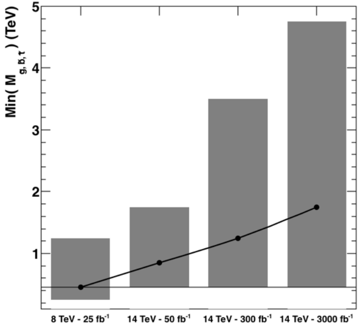


A. Arbey, M. Battaglia, A. Djouadi, FM, Phys. Lett. B720 (2013) 153

Black: all accepted points
Dark green: points compatible at 90% CL with the Higgs rates
Light green: points compatible at 68% CL with the Higgs rates

→ $M_A < 350$ GeV disfavoured by the Higgs signal strengths (→ decoupling regime)
→ Still possible to have $M_{\tilde{t}} < 500$ GeV!
→ $|X_t| < 1.5$ TeV strongly disfavoured

Sensitivity to SUSY mass scales



A. Arbey, M. Battaglia, FM, arXiv:1504.05091

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!

Dark matter sector

Dark Matter Searches

Different types of dark matter searches:

- direct production of LSP's at the LHC
- DM annihilations: DM + DM $\rightarrow$ SM + SM + ...
  - indirect detection: protons, gammas, anti-protons, positrons, ...
  - dark matter relic density

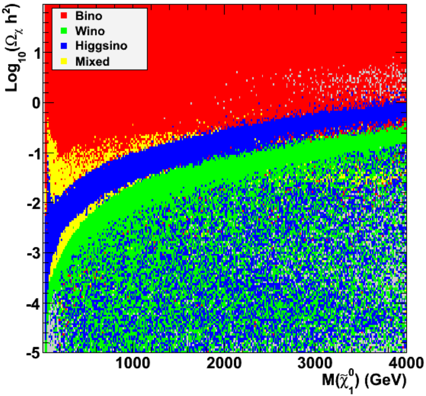
  Possible enhancements of the annihilation cross-sections through Higgs resonances
- DM scattering with matter: DM + matter $\rightarrow$ DM + matter

  $\rightarrow$ direct detection experiments

  Neutralino scattering cross-section sensitive to neutral Higgs bosons

Dark matter direct detection experiments probe the Higgs sector of the MSSM!

Neutralino states & neutralino relic density

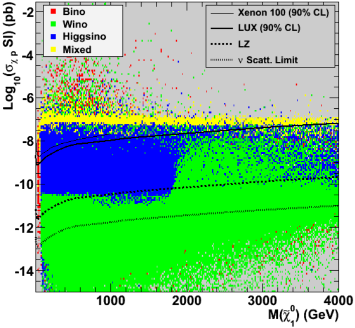


The colours give the nature of the neutralino with the largest fraction in each bin

A. Arbey, M. Battaglia, FM, arXiv:1504.05091

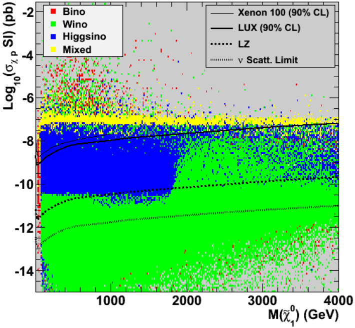
Relic density "naturally" obtained for a Higgsino of 1.3 TeV or a Wino of 2.7 TeV

Neutralino states & neutralino DM direct detection



Case of a single component (local) dark matter

Neutralino states & neutralino DM direct detection



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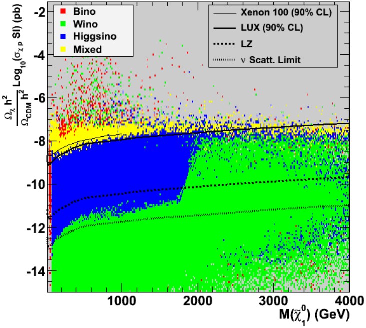
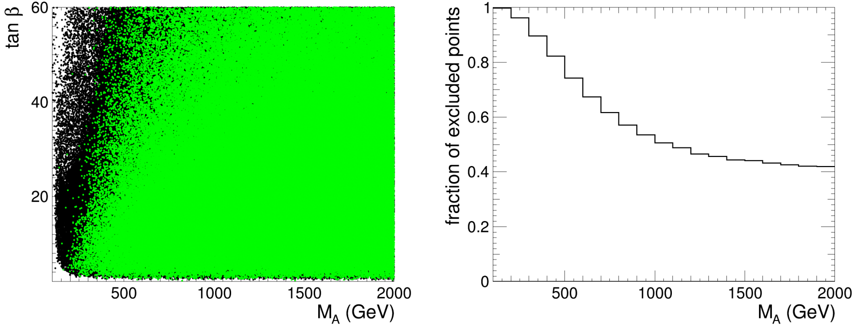


Case of a multiple component (local) dark matter
→ normalisation by the neutralino relic density

Dark matter direct detection constraints

pMSSM points facing LUX limits

Preliminary



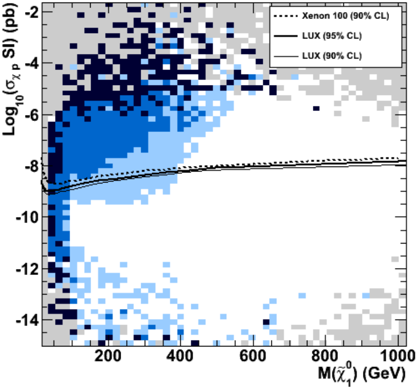
black points: excluded by the LUX limits

Results and sensitivity similar to those from $A/H \to \tau^+\tau^-$ with different couplings/sectors probed.

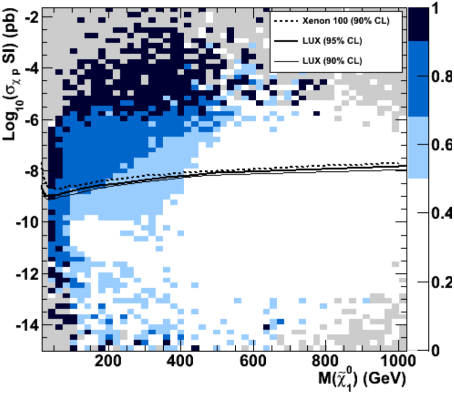
DM direct detection constraints combined with LHC results

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

jets/leptons+MET only



jets/leptons+MET searches and monojet



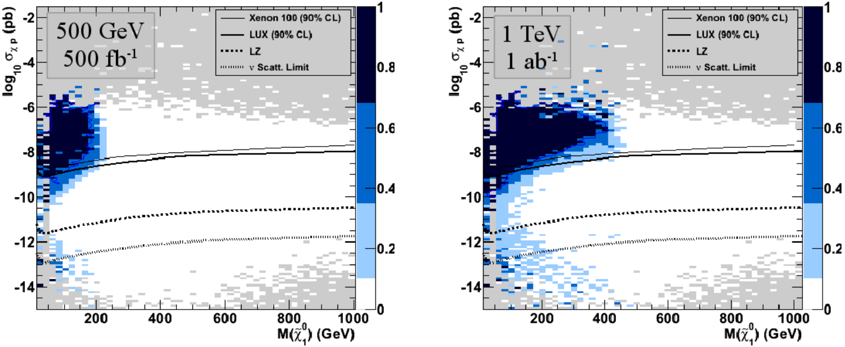
A. Arbey, M. Battaglia, FM, Phys. Rev. D89 (2014) 077701

Colour scale: fraction of excluded points

Nice complementarity between LHC and DM direct detection results!

DM direct detection constraints combined with the future linear collider prospects

Fraction of pMSSM points observable at ILC



DM direct searches compete in excluding the region of full ILC sensitivity

Still opportunities left but limited

However interpretation of DM searches affected by assumptions and uncertainties

Gravitino Dark Matter

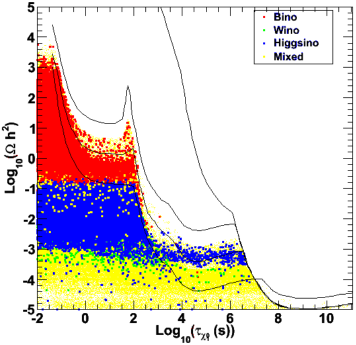
Study restricted to neutralino NLSP case for comparison with neutralino LSP scenario

- Gravitino LSP, single component of dark matter
- Neutralino NLSP short-lived with respect to cosmology
  → Gravitino produced either through NLSP decay or reheating after inflation
  → Neutralino lifetime constrained by Big-Bang Nucleosynthesis
- Neutralino NLSP long-lived with respect to collider physics
  → Same collider constraints as for neutralino LSP scenario
- DM composed exclusively of gravitinos
  → Constraints from direct and indirect detection relaxed
  (gravitino very elusive!)
  → 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!

Gravitino dark matter and BBN constraints

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



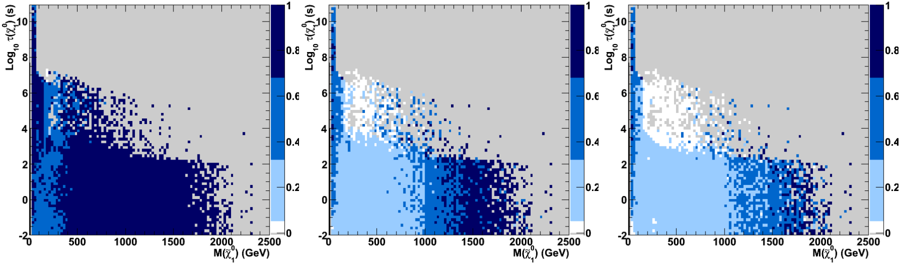
A. Arbey, M. Battaglia, L. Covi, J. Hasenkamp, FM, 1504.XXXXX

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

Gravitino dark matter at the LHC

Fraction of points surviving the LHC SUSY and monojet searches:

Preliminary



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

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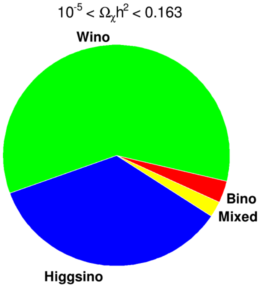
In the gravitino LSP scenario, LHC will probe neutralino masses up to $\sim$1.5 TeV

Neutralino LSP vs. Gravitino LSP

Fraction of neutralino states after dark matter constraints:

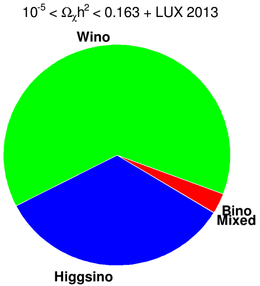


Dark matter constraints strongly affect the neutralino composition

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

Neutralino LSP vs. Gravitino LSP

Fraction of neutralino states after dark matter constraints:



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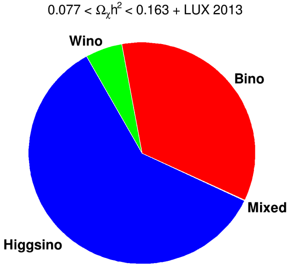

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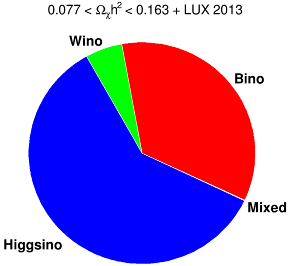
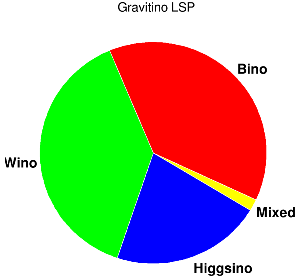
Neutralino LSP vs. Gravitino LSP

Fraction of neutralino states after dark matter constraints:





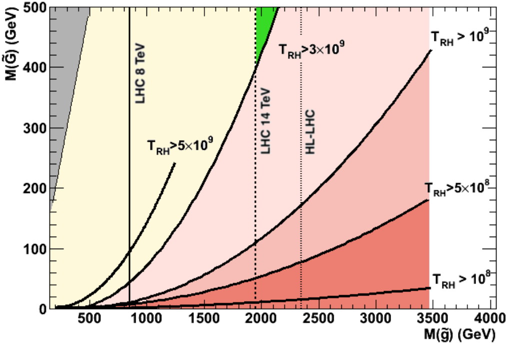
Dark matter constraints strongly affect the neutralino composition

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

Gravitino, gluino and leptogenesis

Leptogenesis models provide lower limits for the reheating temperature: thermal leptogenesis (3×10^9 GeV), flavoured leptogenesis (5×10^8 GeV)

In addition, reheating temperature necessary to accommodate the observed dark matter density is directly related to gluino and gravitino masses



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→ Leptogenesis scenarios set upper limits on the gluino mass

Conclusions

After the first LHC run:

- Simplest NP scenarios already ruled out...
- NP should be subtle!

→ **It is essential to combine LHC results with indirect constraints, and in particular DM search results!**

- We need to go beyond the lamp-post scenarios
- pMSSM seems to be an adequate set-up
- Monojet searches are complementary to the usual SUSY searches

→ **Low energy MSSM is still alive!**

In the next run:

– if no signal, the only way to falsify SUSY would be through the interplay

- between different search channels
- between different sectors

– if new signal:

again the interplay would be extremely useful for model discrimination