Neutralino and Gravitino Dark Matter and the LC

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International Workshop on Future Linear Colliders (LCWS14)
Belgrade, October 5-10, 2014

Motivation

- $\sim$ 27% of the energy density of the Universe is composed of dark matter

  $\rightarrow$ unknown nature
- There is no Standard Model candidate for dark matter
- This is one of the most important motivations for new physics beyond the SM
- The MSSM provides naturally several candidates for dark matter

  $\rightarrow$ lightest neutralino and gravitino are good examples
- LHC has already probed part of the possible solutions
- Future LC will provide a nice complementarity

Constrained SUSY scenarios (CMSSM, mSUGRA,...):

Handful number of free parameters, useful for benchmarking,...

→ Most of the experimental limits are given for constrained MSSM scenarios

However:

- CMSSM is NOT representative of the whole MSSM!
- The available parameter space of CMSSM is very much reduced by the LHC results

General SUSY scenarios: pMSSM

Much richer features, signatures and phenomenology!

- Still a lot of solutions compatible with all present bounds!
- Mass limits are much lower

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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 (+1) free parameters

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

(gravitino mass)

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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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)
- Matrix element calculations (Madgraph)
- Event generation and evaluation of cross-sections (PYTHIA, Prospino)
- Determination of detectability with fast detector simulation (Delphes)

Constraints from:

- LEP and Tevatron direct search limits
- Flavour precision limits, in particular from $\mathrm{BR}(B \to X_s\gamma)$, $\mathrm{BR}(B_s \to \mu^+\mu^-)$, $\mathrm{BR}(B \to \tau\nu)$
- 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

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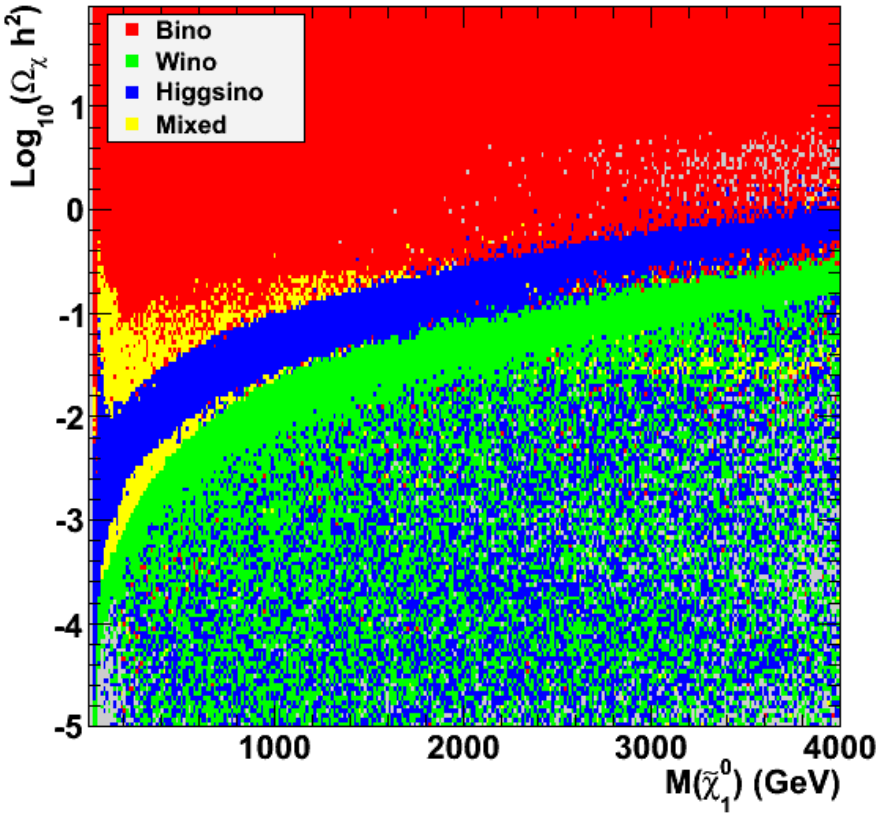
Neutralino states & neutralino relic density

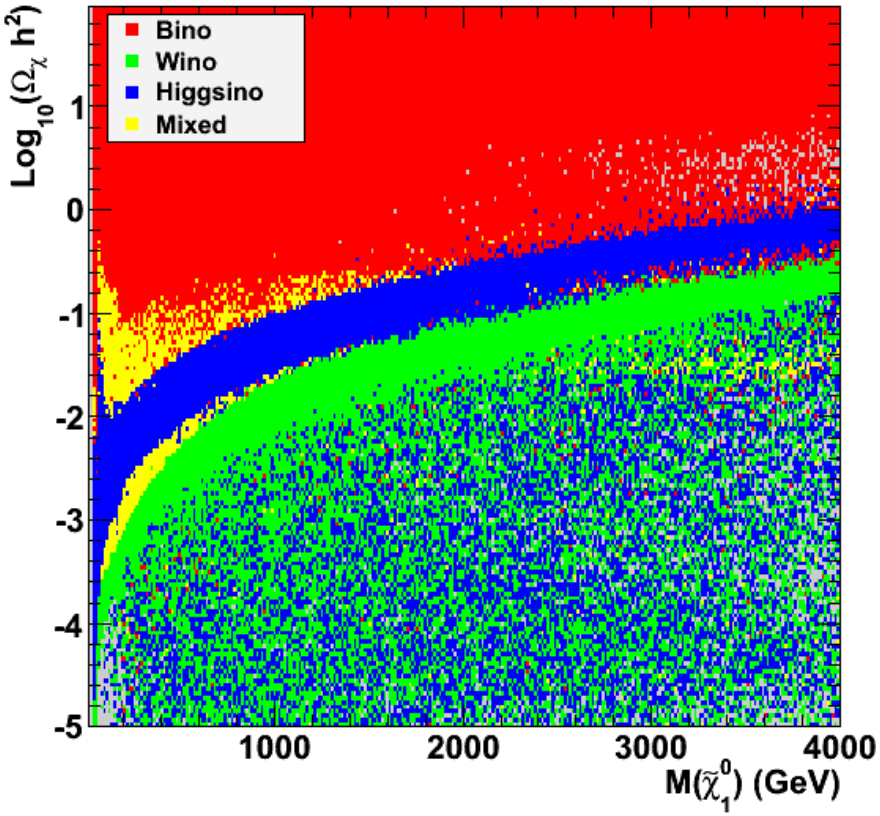


The colours give the nature of the neutralino with the largest fraction in each bin

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

In the following we impose $10^{-5} < \Omega_\chi h^2 < 0.163$

Neutralino states & neutralino relic density



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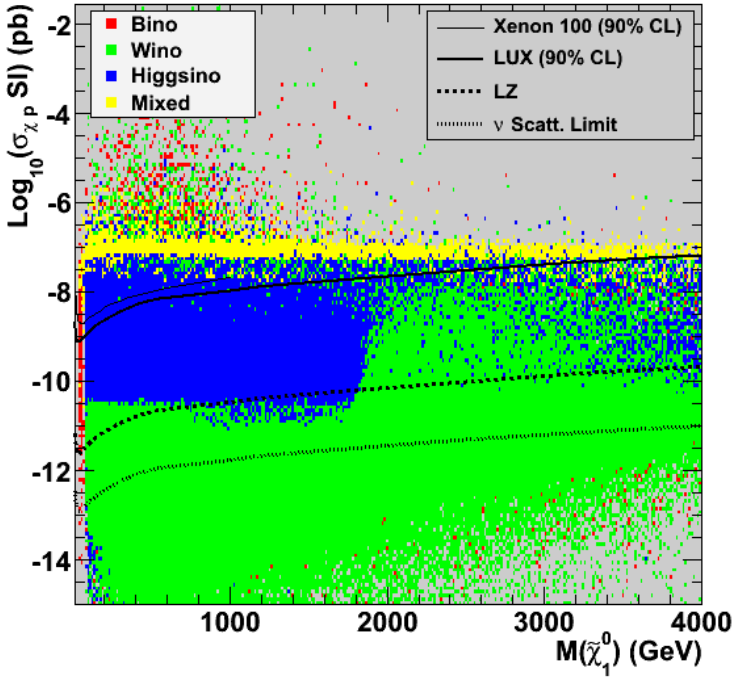

Case of a single component (local) dark matter

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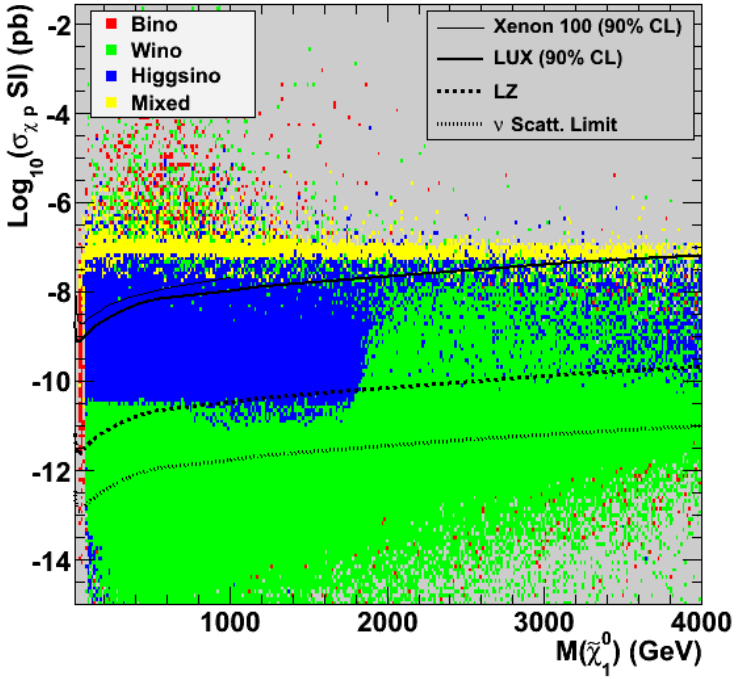

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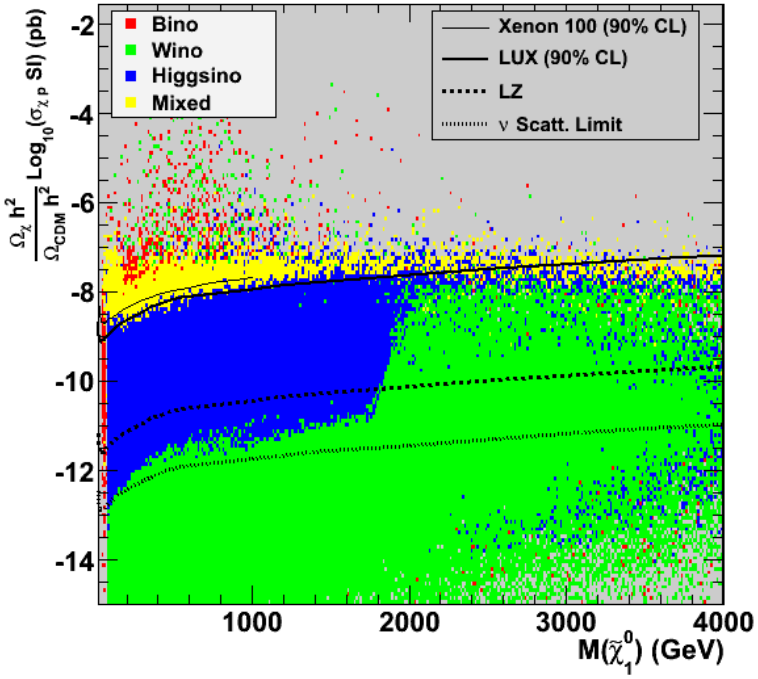
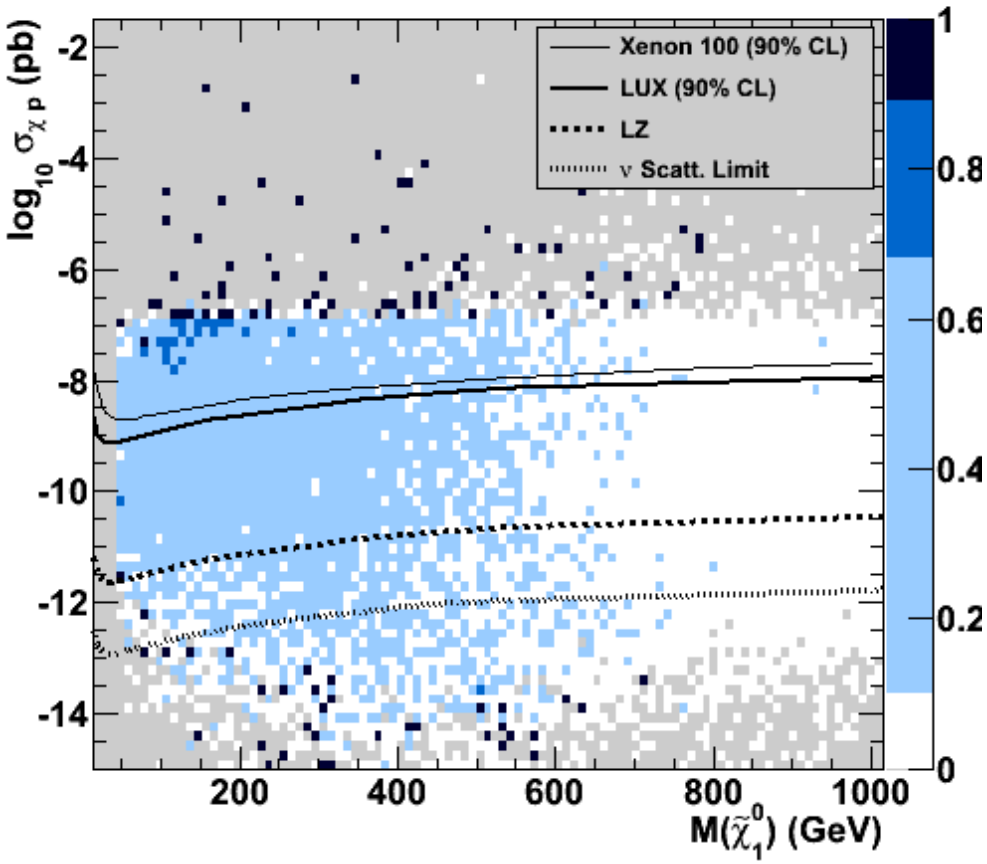


Case of a multiple component (local) dark matter
$\rightarrow$ normalisation by the neutralino relic density

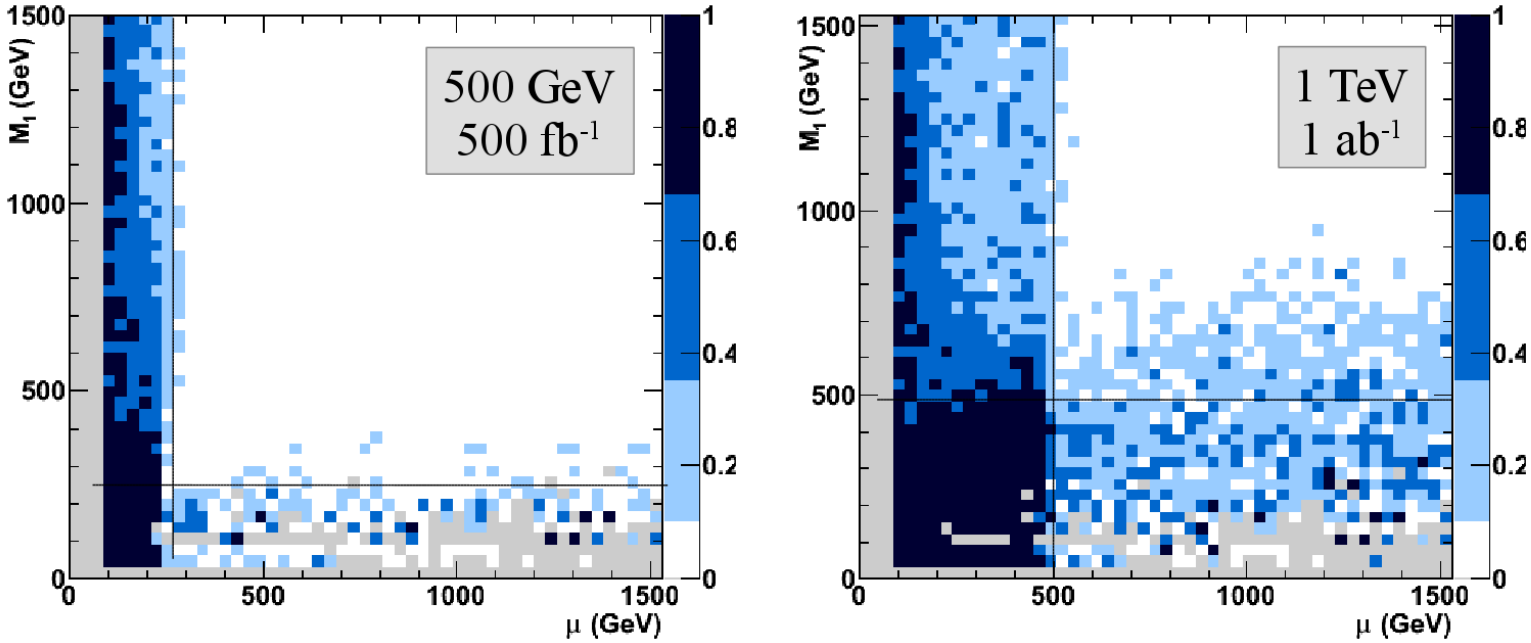
Fraction of accepted pMSSM points excluded by LHC 7+8 TeV SUSY and mono-X searches:



LHC has sensitivities far beyond direct dark matter searches

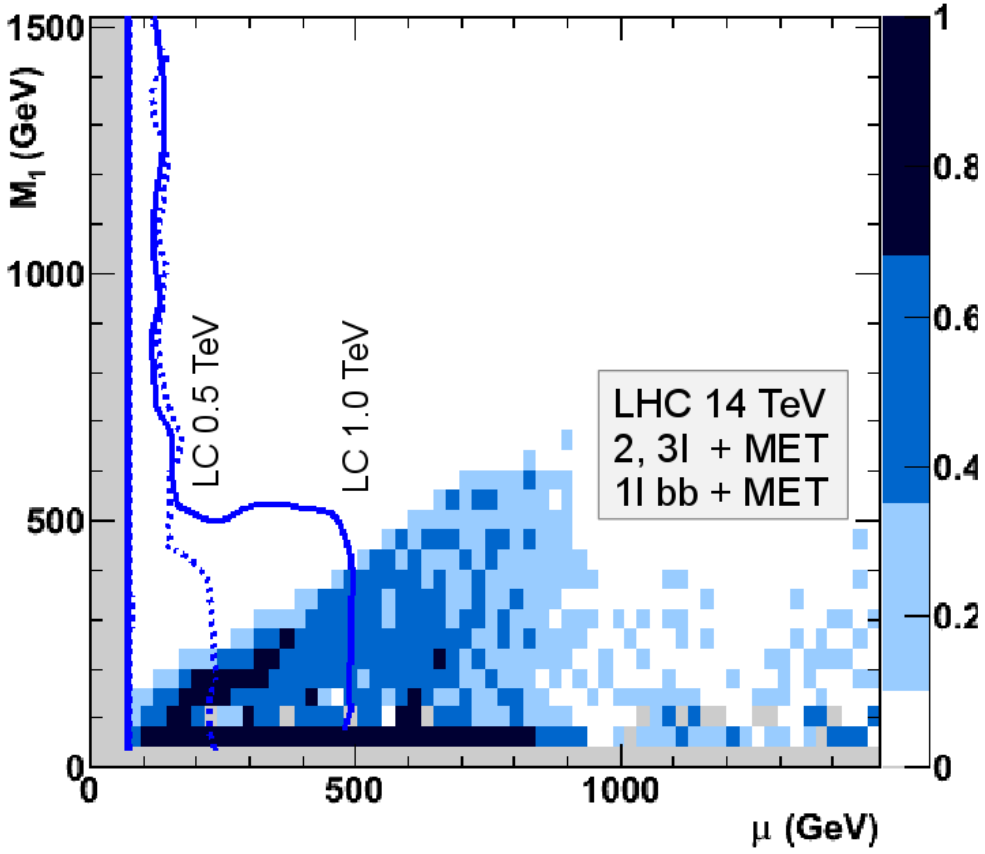
Observability at 0.5 (1.0) TeV as function of M_1 and μ

- requiring at least 50 signal events in sum of $\chi\chi$ channels
- more than 10 (25) GeV of visible energy
- more than 25 (50) GeV of missing energy



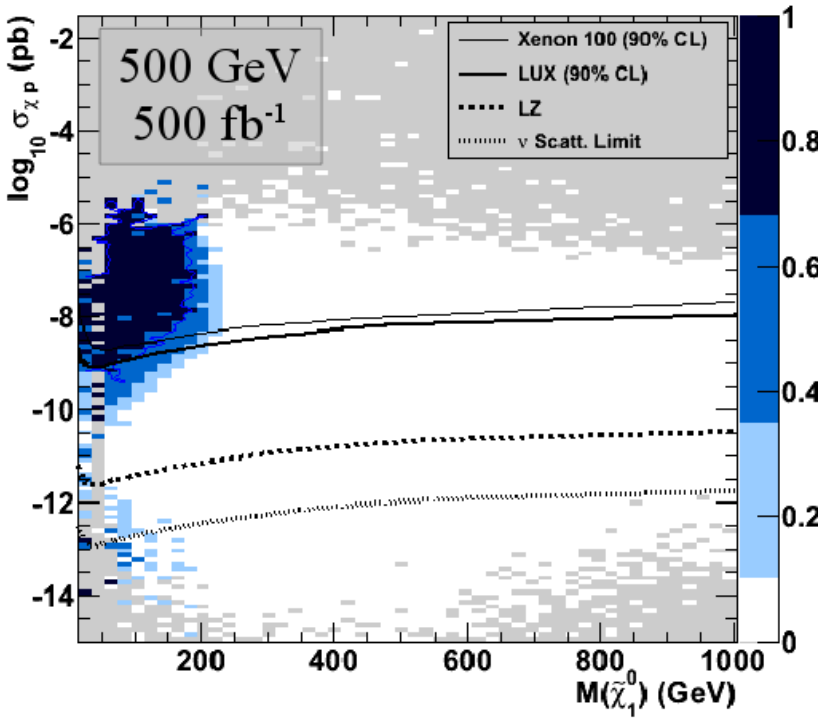
ILC very sensitive in the small μ and M_1 region

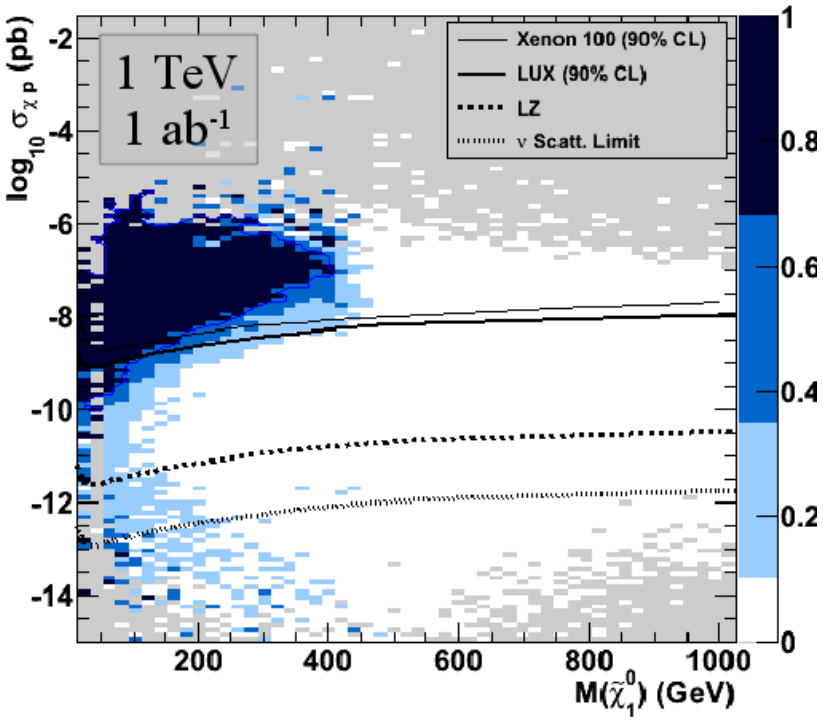
ILC and LHC complementarity in the electroweakino sector



LHC: simple extension of Run 1 analyses without cut optimisation or additional channels

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

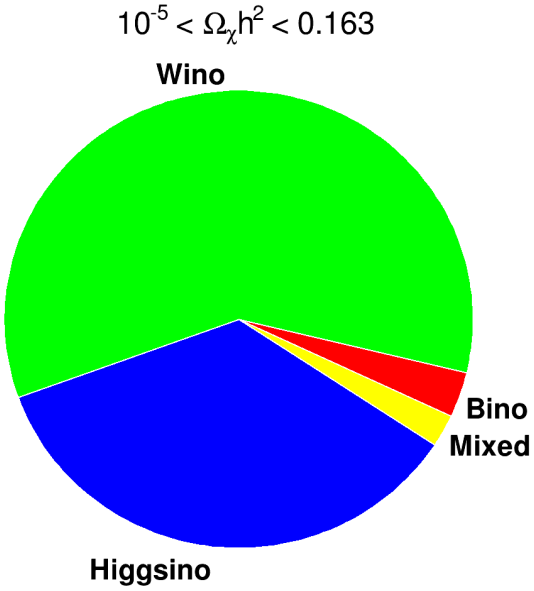
Gravitino Dark Matter

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
  $\rightarrow$ Gravitino produced either through NLSP decay or 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!

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

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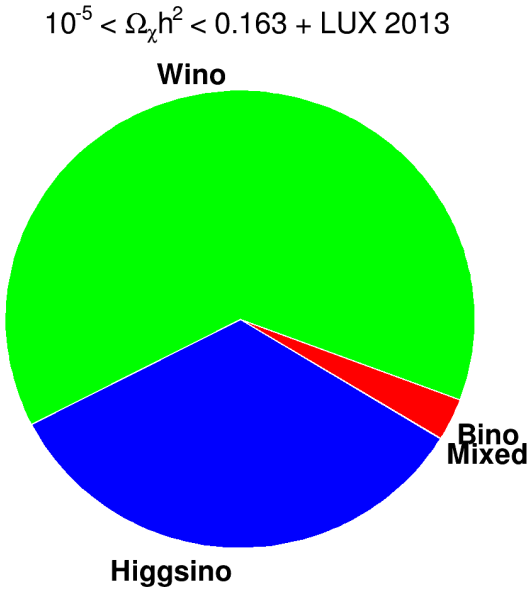

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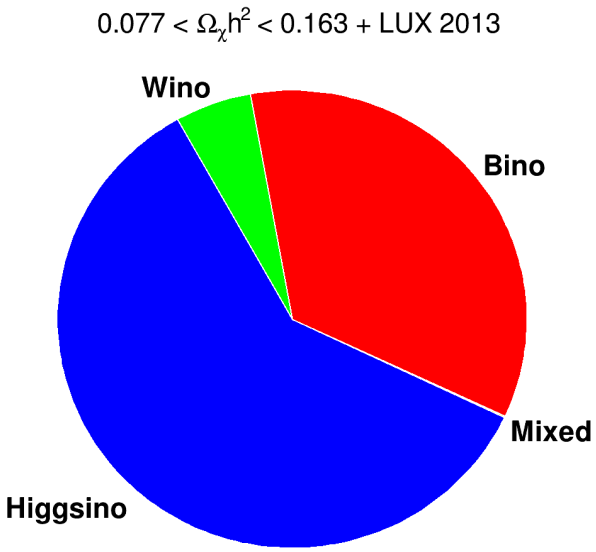

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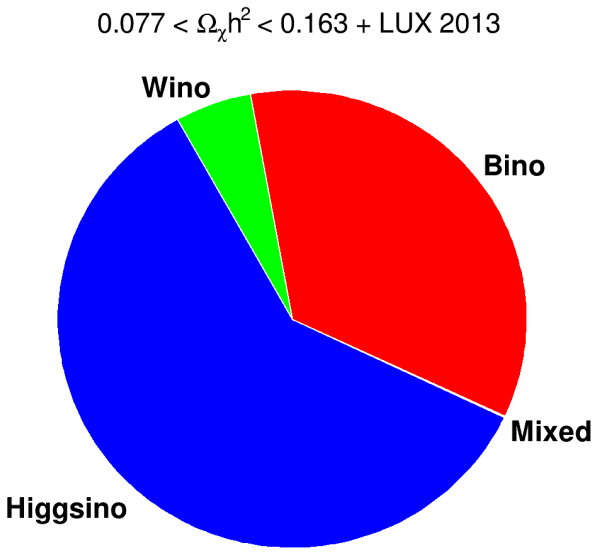

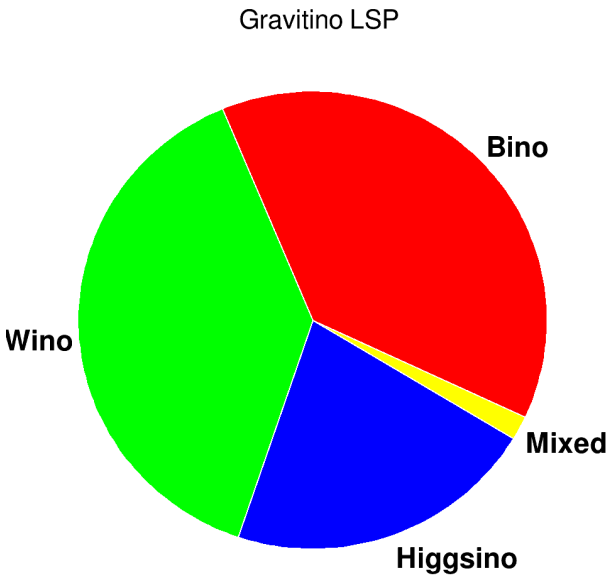

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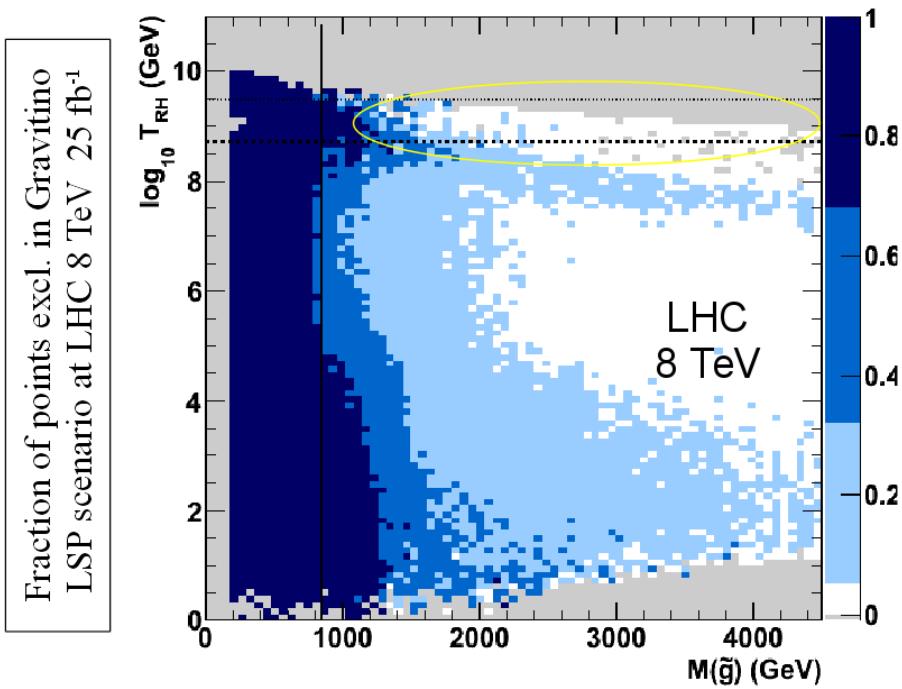
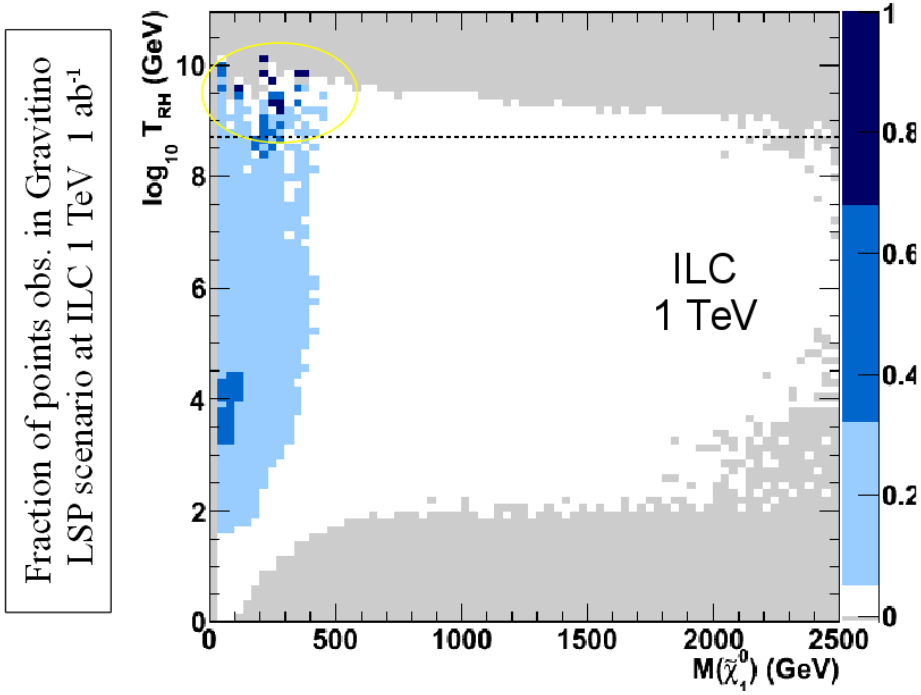
Fraction of excluded points





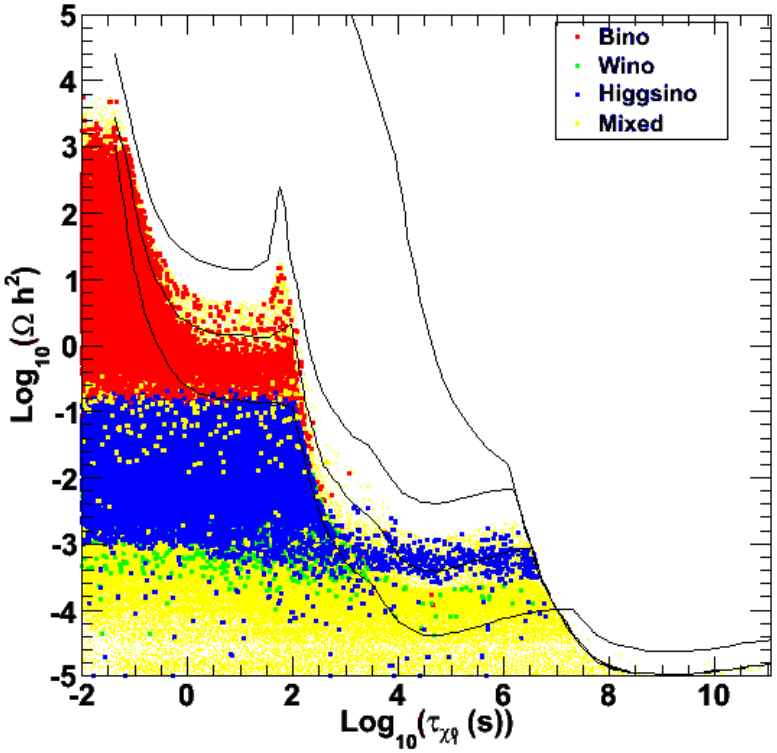
Many scenarios with heavy gluinos remain at high reheating temperatures with light neutralinos → Interesting cases for ILC!

Summary

- Important complementarities between dark matter and L(H)C searches
- Constraints from LHC, DM relic density and direct searches define scenarios to be tested at ILC
- Interesting complementarity of ILC and LHC in the electroweakino sector
- Small μ scenario is where LC has more sensitivity, but it is also more constrained by DM direct searches
- Gravitino DM scenario is less constrained than the neutralino LSP scenario
- Sensitivity of ILC to cosmological parameters such as the reheating temperature in the gravitino LSP scenario

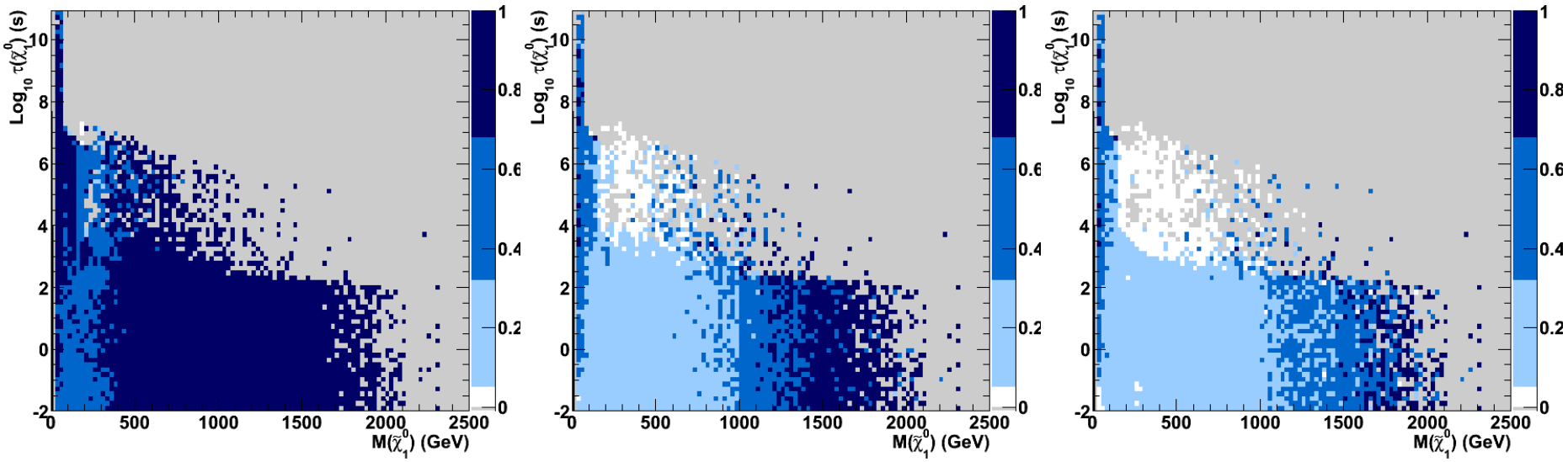
Backup

Constraints from Big-Bang Nucleosynthesis



$\tau_{\tilde{\chi}_1^0}$: neutralino lifetime
Ωh^2: neutralino relic density (in absence of gravitino)
(limits extracted from Jedamzik, hep-ph/060425)

Fraction of points surviving the LHC SUSY and monojet searches



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

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