Supersymmetric Dark Matter

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Neutrinos at the forefront of elementary particle physics and astrophysics

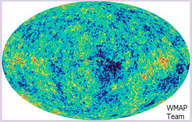
Lyon, October 24, 2012

Different scales involved

- Galactic scale
  - Galaxy Rotation Curves
  - Galaxy Collisions

- Cluster Scale
  - X-Ray Observations
  - Weak Lensing
  - Bullet Cluster

- Cosmological Scale
  - Cosmic Microwave Background
  - Supernovae of type Ia
  - Baryon Acoustic Oscillations
  - ...



Dark Matter Candidates

- **Baryonic Dark Matter**
- **Massive neutrinos**
- **Weakly Interacting Massive Particles (WIMPs)**
  In particular, supersymmetric models provide WIMP candidates!
- **Other particles/fields**: axions, dark fluid, ...
  Exotic and non-baryonic particles
- **Modified Gravitation Laws**
  MOND, TeVeS, Scalar-tensor theories, ...

Minimal Supersymmetric Model (MSSM)

Supersymmetry is based on an additional symmetry between fermions and bosons

SM particle	spin	Superpartner	spin
quarks	$1/2$	squarks	0
leptons	$1/2$	sleptons	0
gauge bosons	1	gauginos	$1/2$
Higgs bosons	0	higgsinos	$1/2$

gauginos + higgsinos mix to 2 charginos + 4 neutralinos

2 Higgs doublets $\rightarrow$ 5 physical Higgs bosons:

- neutral states: scalar h, H; pseudoscalar A
- charged states: H^+, H^-

Minimal Supersymmetric extension of the Standard Model (MSSM)

- More than 100 free parameters
- Very difficult to perform systematic studies

Constrained MSSM scenarios

Minimal Supersymmetric extension of the Standard Model (MSSM)

- More than 100 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 β)

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

  $\rightarrow$ But not representative of the whole MSSM!

Implication in pMSSM

Going beyond constrained scenarios

- Constrained MSSM: useful for benchmarking, model discrimination,...
- However the mass patterns could be more complicated in general
  $\rightarrow$ The signatures and results can be very different!

Phenomenological MSSM (pMSSM)

- 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

10 sfermion masses, 3 gaugino masses, 3 trilinear couplings,
3 Higgs/Higgsino

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

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

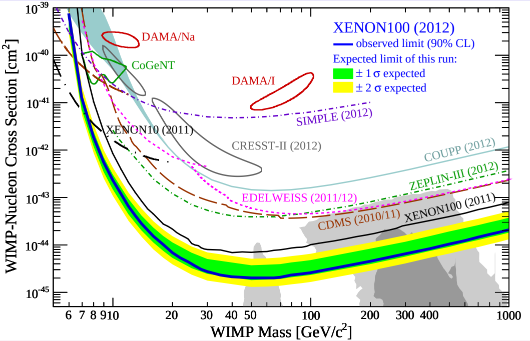
  Possible enhancements of the annihilation cross-sections through Higgs resonances
- DM scattering with matter: DM + matter $\rightarrow$ DM + matter

  $\rightarrow$ **direct detection experiments**

  Neutralino scattering cross-section sensitive to neutral Higgs bosons

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

Present situation:



XENON, arXiv:1207.5988

- DAMA, CoGeNT, CRESST claim for a possible WIMP discovery
- SIMPLE, COUPP, ZEPLIN, CDMS, EDELWEISS and XENON give exclusion limits

$\rightarrow$ **Unclear situation, but the sensitivity is improving!**

Flat scans over the pMSSM with 19 parameters.

Using many codes: `SuperIso Relic`, `SoftSusy`, `FeynHiggs`, `Hdecay`, `Sdecay`, `Higgsbounds`, `Micromegas`, `Prospino`, `Pythia` and `Delphes`, with `SuperIso` as the central core.

$2.16 \times 10^{-4} < \mathrm{BR}(B \to X_s\gamma) < 4.93 \times 10^{-4}$
$\mathrm{BR}(B_s \to \mu^+\mu^-) < 5.0 \times 10^{-9}$
$0.56 < \mathrm{R}(B \to \tau\nu) < 2.70$
$4.7 \times 10^{-2} < \mathrm{BR}(D_s \to \tau\nu) < 6.1 \times 10^{-2}$
$2.9 \times 10^{-3} < \mathrm{BR}(B \to D^0\tau\nu) < 14.2 \times 10^{-3}$
$0.985 < \mathrm{R}_{\mu 23}(K \to \mu\nu) < 1.013$
$-2.4 \times 10^{-9} < \delta a_\mu < 4.5 \times 10^{-9}$
+ sparticle mass lower bounds
+ Higgs search limits 123 GeV $< M_h <$ 129 GeV
+ LHC SUSY direct search constraints
+ **neutralino LSP = dark matter**
+ WMAP (relic) cold dark matter density

Particle	Limits	Conditions
$\tilde{\chi}_2^0$	62.4	$\tan\beta < 40$
$\tilde{\chi}_3^0$	99.9	$\tan\beta < 40$
$\tilde{\chi}_4^0$	116	$\tan\beta < 40$
$\tilde{\chi}_1^\pm$	92.4	$m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} < 4$ GeV
	103.5	$m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} > 4$ GeV
$\tilde{e}_R$	73	
$\tilde{e}_L$	107	
$\tilde{\tau}_1$	81.9	$m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} > 15$ GeV
$\tilde{u}_R$	100	$m_{\tilde{u}_R} - m_{\tilde{\chi}_1^0} > 10$ GeV
$\tilde{u}_L$	100	$m_{\tilde{u}_L} - m_{\tilde{\chi}_1^0} > 10$ GeV
$\tilde{t}_1$	95.7	$m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0} > 10$ GeV
$\tilde{d}_R$	100	$m_{\tilde{d}_R} - m_{\tilde{\chi}_1^0} > 10$ GeV
$\tilde{d}_L$	100	$m_{\tilde{d}_L} - m_{\tilde{\chi}_1^0} > 10$ GeV
$\tilde{b}_1$	248	$m_{\tilde{\chi}_1^0} < 70$ GeV, $m_{\tilde{b}_1} - m_{\tilde{\chi}_1^0} > 30$ GeV
	220	$m_{\tilde{\chi}_1^0} < 80$ GeV, $m_{\tilde{b}_1} - m_{\tilde{\chi}_1^0} > 30$ GeV
	210	$m_{\tilde{\chi}_1^0} < 100$ GeV, $m_{\tilde{b}_1} - m_{\tilde{\chi}_1^0} > 30$ GeV
	200	$m_{\tilde{\chi}_1^0} < 105$ GeV, $m_{\tilde{b}_1} - m_{\tilde{\chi}_1^0} > 30$ GeV
	100	$m_{\tilde{b}_1} - m_{\tilde{\chi}_1^0} > 5$ GeV
$\tilde{g}$	195	

Details about the scans and results can be found in:

A. Arbey, M. Battaglia, F. Mahmoudi, Eur.Phys.J. C72 (2012) 1847

A. Arbey, M. Battaglia, F. Mahmoudi, Eur.Phys.J. C72 (2012) 1906

General scans in pMSSM: more than 60M generated points

Parameter	Range
$\tan\beta$	[1, 60]
M_A	[50, 2000]
M_1	[-2500, 2500]
M_2	[-2500, 2500]
M_3	[50, 2500]
$A_d = A_s = A_b$	[-10000, 10000]
$A_u = A_c = A_t$	[-10000, 10000]
$A_e = A_\mu = A_\tau$	[-10000, 10000]
μ	[-3000, 3000]
$M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$	[50, 2500]
$M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$	[50, 2500]
$M_{\tilde{\tau}_L}$	[50, 2500]
$M_{\tilde{\tau}_R}$	[50, 2500]
$M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$	[50, 2500]
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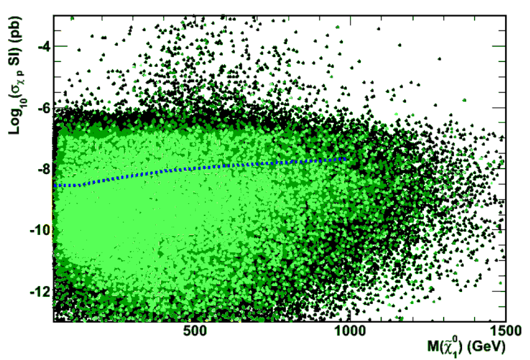
$M_{\tilde{t}_R}$	[50, 2500]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[50, 2500]
$M_{\tilde{b}_R}$	[50, 2500]

pMSSM points and XENON dark matter exclusion limit



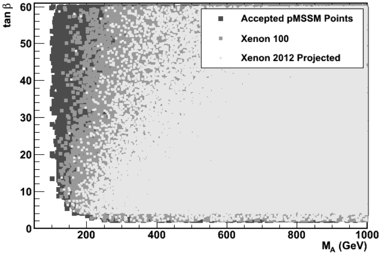
A. Arbey, M. Battaglia, A. Djouadi, F. Mahmoudi, to appear

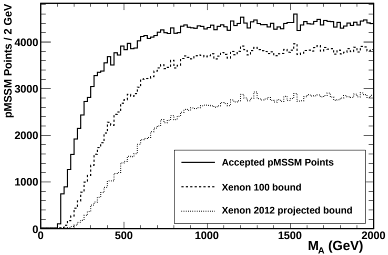
Black: valid points passing the relic density, flavour physics, LHC SUSY search, LEP and Tevatron constraints

Dark green: points also compatible at 90% C.L. with the LHC Higgs search results
Light green: points also compatible at 68% C.L. with the LHC Higgs search results

Dotted blue line: 2012 XENON-100 limit at 95% C.L.

28% of the valid points are excluded by XENON-100 pMSSM points and XENON dark matter exclusion limit



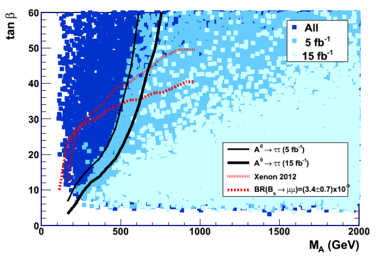


A. Arbey, M. Battaglia, F. Mahmoudi, Eur.Phys.J. C72 (2012) 1906

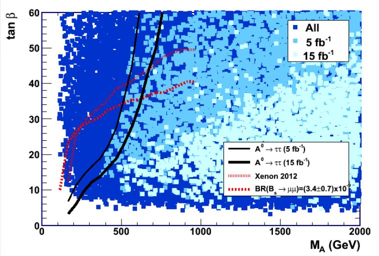
Strong constraints on the CP-odd Higgs mass!

Constraints from flavour physics, dark matter direct detection, SUSY and Higgs searches

Without Higgs decay rate constraints



With Higgs decay rate constraints



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Once putting everything together the allowed region is really squeezed!

Low mass neutralino of mass ~ 10 GeV?

Not possible in constrained MSSM...

General scans in pMSSM $\longrightarrow$ Low-mass neutralino scans

Parameter	Range
$\tan\beta$	[1, 60]
M_A	[50, 2000]
M_1	[-2500, 2500]
M_2	[-2500, 2500]
M_3	[50, 2500]
$A_d = A_s = A_b$	[-10000, 10000]
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$M_{\tilde{t}_R}$	[50, 2500]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[50, 2500]
$M_{\tilde{b}_R}$	[50, 2500]

$\longrightarrow$

Parameter	Range
$\tan\beta$	[1, 60]
M_A	[50, 2000]
M_1	[-300, 300]
M_2	[-650, 650]
M_3	[0, 2500]
$A_d = A_s = A_b$	[-10000, 10000]
$A_u = A_c = A_t$	[-10000, 10000]
$A_e = A_\mu = A_\tau$	[-10000, 10000]
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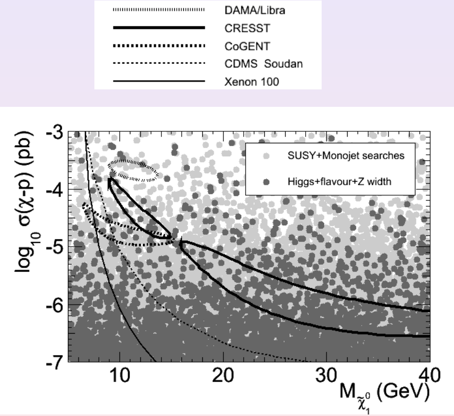
$M_{\tilde{t}_R}$	[0, 2500]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[0, 2500]
$M_{\tilde{b}_R}$	[0, 2500]

Low mass neutralino scans: more than **one billion** generated points



Selection	pMSSM points
Valid points with light χ_1^0, large $\sigma(\chi - p)$	1 M

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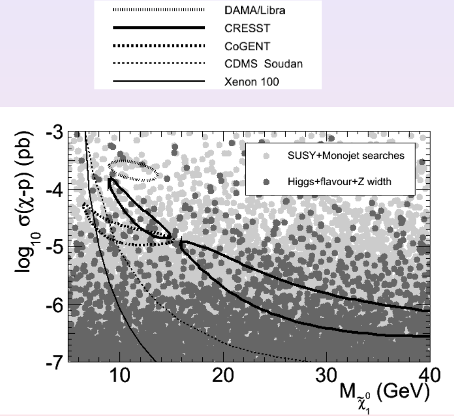
Light neutralinos and dark matter direct detection

Low mass neutralino scans: more than **one billion** generated points



Selection	pMSSM points
Valid points with light χ_1^0, large $\sigma(\chi - p)$	1 M
Monojet searches	280 k

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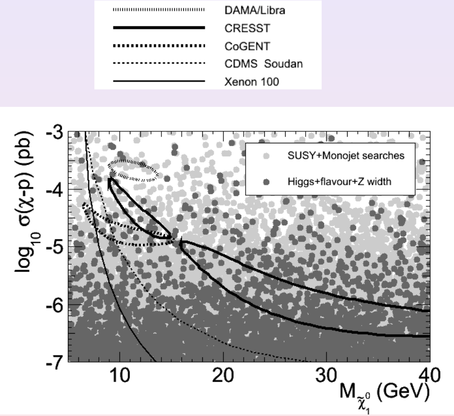

Selection	pMSSM points
Valid points with light χ_1^0, large $\sigma(\chi - p)$	1 M
Monojet searches	280 k
SUSY searches	90 k

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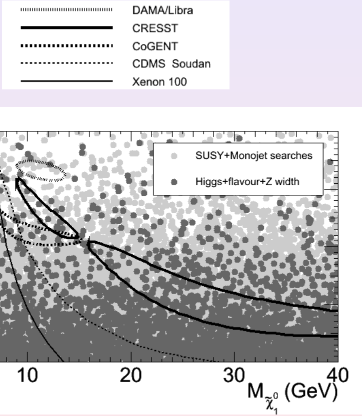

Selection	pMSSM points
Valid points with light χ_1^0, large $\sigma(\chi - p)$	1 M
Monojet searches	280 k
SUSY searches	90 k
LEP searches	50 k

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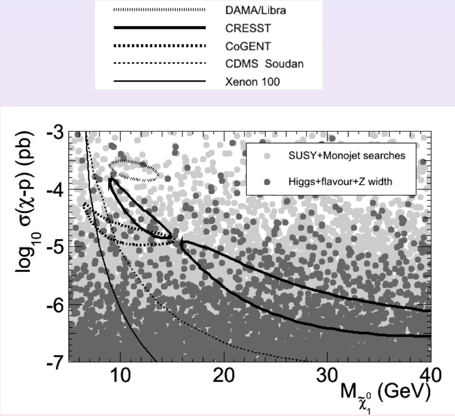

Selection	pMSSM points
Valid points with light χ_1^0, large $\sigma(\chi-p)$	1 M
Monojet searches	280 k
SUSY searches	90 k
LEP searches	50 k
Flavour physics	20 k

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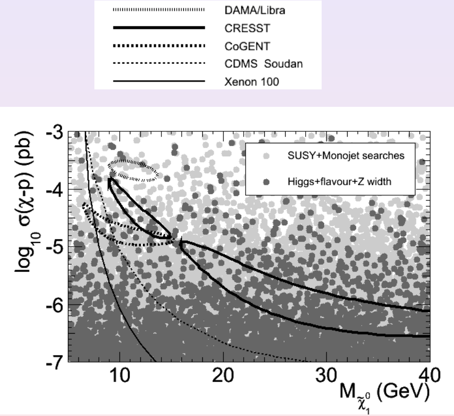
Low mass neutralino scans: more than **one billion** generated points



Selection	pMSSM points
Valid points with light χ^0_1, large $\sigma(\chi - p)$	1 M
Monojet searches	280 k
SUSY searches	90 k
LEP searches	50 k
Flavour physics	20 k
Higgs searches	10 k

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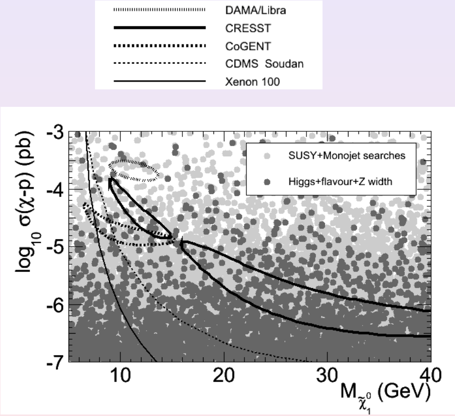
Low mass neutralino scans: more than **one billion** generated points



Selection	pMSSM points
Valid points with light χ_1^0, large $\sigma(\chi - p)$	1 M
Monojet searches	280 k
SUSY searches	90 k
LEP searches	50 k
Flavour physics	20 k
Higgs searches	10 k
Upper WMAP limit	20

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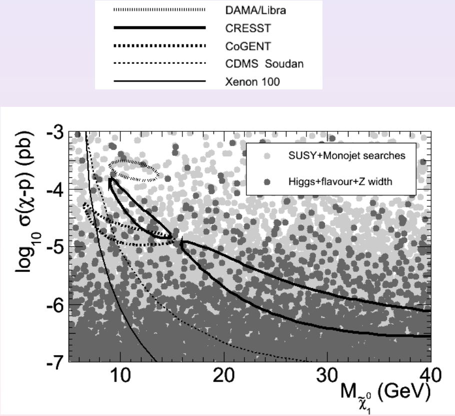
Low mass neutralino scans: more than **one billion** generated points



Selection	pMSSM points
Valid points with light χ_1^0, large $\sigma(\chi - p)$	1 M
Monojet searches	280 k
SUSY searches	90 k
LEP searches	50 k
Flavour physics	20 k
Higgs searches	10 k
Upper WMAP limit	20
Lower WMAP limit	5

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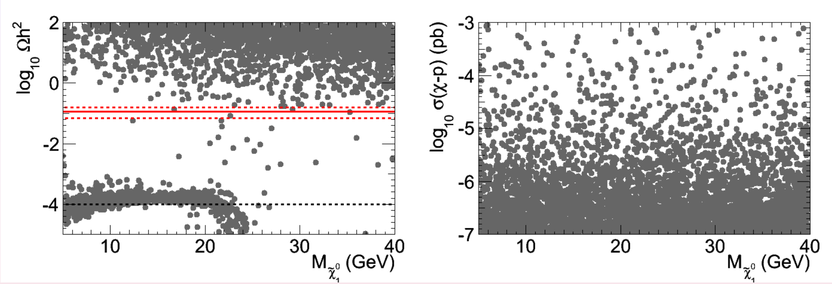
How to reconcile relic density and direct dark matter detection when $M_{\tilde{\chi}^0} < 40$ GeV?



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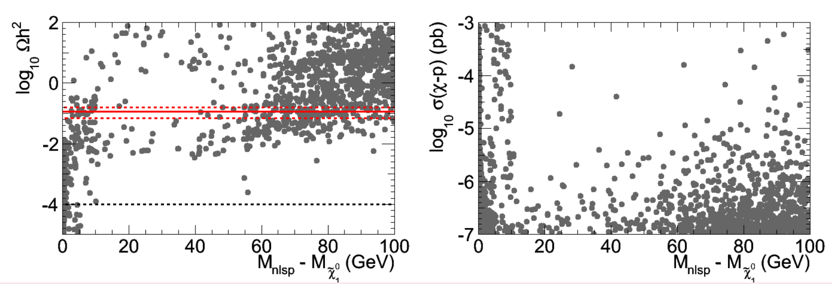

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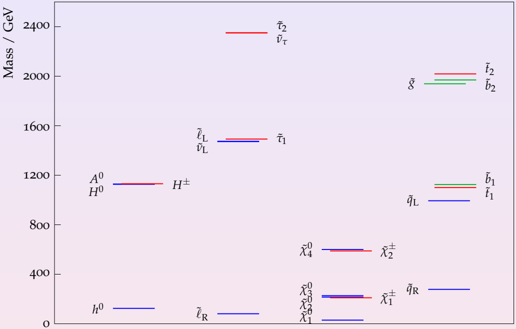
Three main different classes of points can survive the constraints:

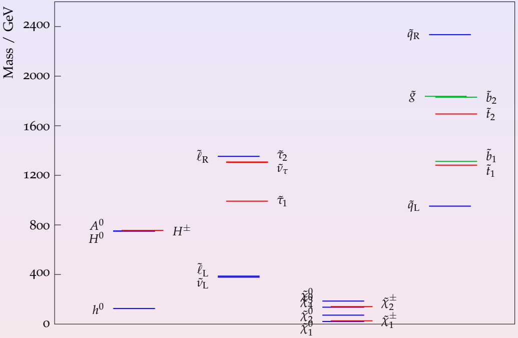
- a slepton with a mass close to LEP limit
($M_{\tilde{\chi}^0} \sim 20 - 40$ GeV)
- compressed spectrum in the neutralino/chargino sector
($M_{\tilde{\chi}^0} \sim 10 - 40$ GeV, $\sigma \sim 10^{-6}$ pb)
- one squark quasi-degenerate with the neutralino
($M_{\tilde{\chi}^0} \lesssim 10 - 20$ GeV, $\sigma \sim 10^{-4}$ pb)

Slepton with a mass at the LEP limit



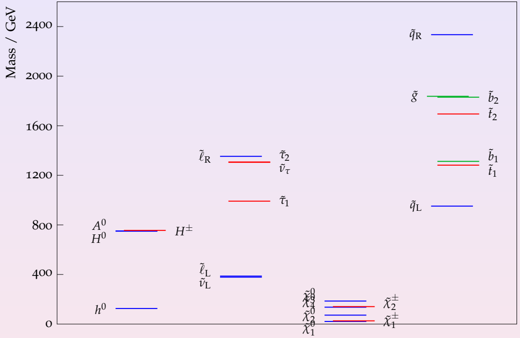
A relatively standard scenario, but the neutralino mass has to be larger (around 30 GeV) to give a large scattering cross-section.

Compressed spectrum in the neutralino/chargino sector



This scenario may be very interesting...

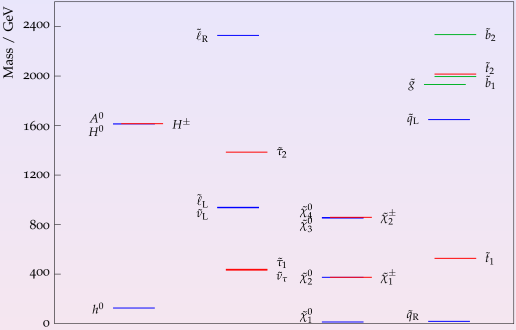
Compressed spectrum in the neutralino/chargino sector



This scenario may be very interesting...

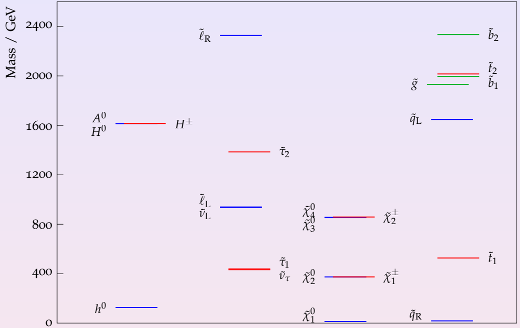
Unfortunately $\sigma(e^+e^- \to \chi_1^0\chi_2^0)$ is in general too large and ruled out by the LEP limits!

One squark quasi-degenerate with the neutralino



These spectra can fulfill all the constraints and have simultaneously a neutralino mass under 15 GeV and a large scattering cross-section!

One squark quasi-degenerate with the neutralino

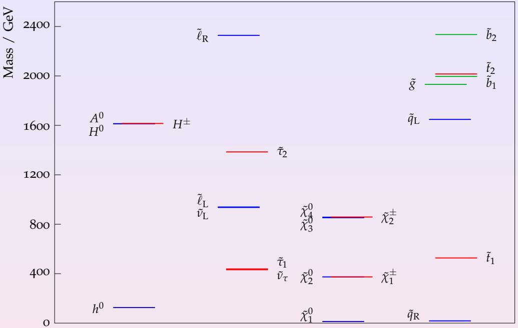


These spectra can fulfill all the constraints and have simultaneously a neutralino mass under 15 GeV and a large scattering cross-section!

Two problems however: $\Gamma(Z \to \tilde{q}\bar{\tilde{q}})$ is very large and $BR(h^0 \to \tilde{q}\bar{\tilde{q}})$ is the dominant Higgs BR... for the first and second generations!

Light neutralinos and dark matter direct detection

One squark quasi-degenerate with the neutralino



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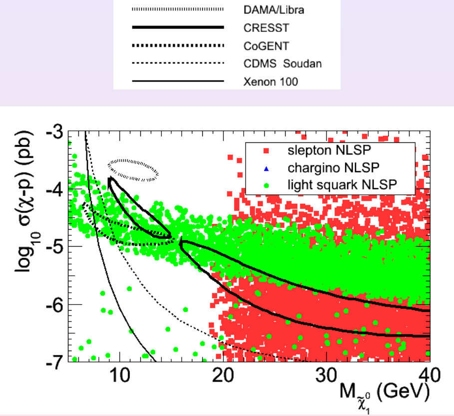
Two problems however: $\Gamma(Z \to \tilde{q}\bar{\tilde{q}})$ is very large and $BR(h^0 \to \tilde{q}\bar{\tilde{q}})$ is the dominant Higgs BR... for the first and second generations!

$\rightarrow$ A light sbottom can pass all these constraints!

Using dedicated scans:



Loose relic density constraint
$10^{-4} < \Omega_\chi h^2 < 0.155$

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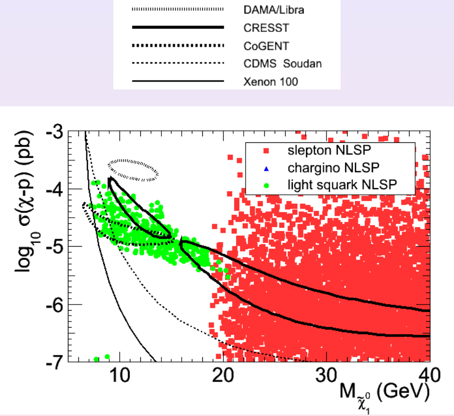
Using dedicated scans:



Tight relic density constraint
$0.068 < \Omega_\chi h^2 < 0.155$

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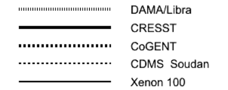
Relic density and direct detection constraints

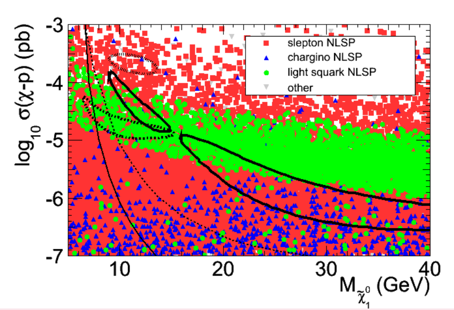
The relic density constraint rules out many models, but alternative cosmology can make them survive, e.g. if:

- 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
- ...

Also, the direct detection scattering cross-section can be enhanced or decreased if the local density and velocity of dark matter are very different from the usually assumed values.

Using dedicated scans:





Relaxing the relic density constraint

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Conclusions and perspectives

pMSSM provides interesting candidates for dark matter!

pMSSM light neutralino can be compatible with all constraints!

Three different scenarios

- A sbottom quasi-degenerate with the neutralino
- Slepton with a mass close to the LEP limit
- Compressed spectrum in the gaugino sector

Next steps

- Characterise more these scenarios in terms of the ATLAS and CMS MET analyses
- Go to alternative scenarios (gravitino dark matter, beyond MSSM, ...)