Light neutralino in the MSSM

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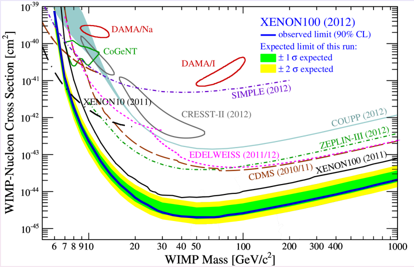
GDR Terascale Meeting

Present situation:

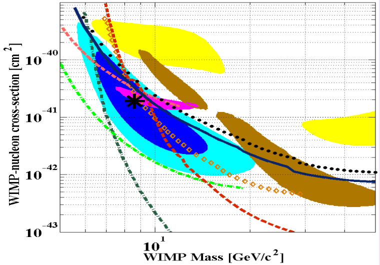


XENON, arXiv:1207.5988

- Possible WIMP discovery from DAMA, CoGeNT, CRESST
- SIMPLE, COUPP, ZEPLIN, EDELWEISS and XENON give exclusion limits

Hints for Dark matter particles in direct detection?

Present situation:



CDMS, arXiv:1304.4279

- Possible WIMP discovery from DAMA, CoGeNT, CRESST and more recently CDMS
- SIMPLE, COUPP, ZEPLIN, EDELWEISS and XENON give exclusion limits

→ **Possibility of reconciliation for DM of about 10 GeV!**

We consider the 19-parameter pMSSM

Can we find light neutralino of ~ 10 GeV?

- 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, DarkSUSY)
- 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)
- Determination of detectability with fast detector simulation (Delphes)
- Test of vacuum stability (Vevacious)

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]
μ	[-3000, 3000]
$M_{\tilde{e}_L} = M_{\tilde{\mu}_L}$	[0, 2500]
$M_{\tilde{e}_R} = M_{\tilde{\mu}_R}$	[0, 2500]
$M_{\tilde{\tau}_L}$	[0, 2500]
$M_{\tilde{\tau}_R}$	[0, 2500]
$M_{\tilde{q}_{1L}} = M_{\tilde{q}_{2L}}$	[0, 2500]
$M_{\tilde{q}_{3L}}$	[0, 2500]
$M_{\tilde{u}_R} = M_{\tilde{c}_R}$	[0, 2500]
$M_{\tilde{t}_R}$	[0, 2500]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[0, 2500]
$M_{\tilde{b}_R}$	[0, 2500]

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$M_{\tilde{b}_R}$	[0, 2500]

Type	Constraint
Higgs mass constraint Higgs signal strengths	$M_h \in [121, 129]$ GeV ATLAS+CMS
Z decay widths	$\Gamma(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) < 3$ MeV $\Gamma(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) + \Gamma(Z \to \tilde{b}_1 \tilde{b}_1) < 5$ MeV $0.21497 < R_b < 0.21761$
LEP and Tevatron SUSY searches	PDG limits + specific analysis of the $\tilde{\chi}^+ \tilde{\chi}^- / \tilde{\chi}_2^0 \tilde{\chi}_1^0$ channels
Oblique parameters S, T, U	LEP limits
Vacuum stability	stable or long-lived scalar potential minimum
Flavour physics	$2.63 \times 10^{-4} < \mathrm{BR}(B \to X_s \gamma) < 4.23 \times 10^{-4}$ $1.28 \times 10^{-9} < \mathrm{BR}(B_s \to \mu^+ \mu^-)_{\rm untag} < 4.52 \times 10^{-9}$ $0.40 \times 10^{-4} < \mathrm{BR}(B_u \to \tau \nu) < 1.88 \times 10^{-4}$ $4.7 \times 10^{-2} < \mathrm{BR}(D_s \to \tau \nu) < 6.1 \times 10^{-2}$ $2.9 \times 10^{-3} < \mathrm{BR}(B \to D^0 \tau \nu) < 14.2 \times 10^{-3}$ $0.985 < R_{\mu 23} < 1.013$
Muon anomalous magnetic moment	$-2.4 \times 10^{-9} < \delta a_\mu < 4.5 \times 10^{-9}$
Loose relic density Tight relic density	$10^{-4} < \Omega_\chi h^2 < 0.163$ $0.076 < \Omega_\chi h^2 < 0.163$
Dark matter annihilation cross-section	$\sigma v_{\rm tot} < 10^{-26}$ cm^3/s with $M_{\tilde{\chi}_1^0} < 50$ GeV $\sigma v_{bbg} < 2 \times 10^{-27}$ cm^3/s with $M_{\tilde{\chi}_1^0} < 50$ GeV
Dark matter direct detection	$10^{-7} < \sigma^{\rm SI}_{p-\chi} < 10^{-2}$ pb with $M_{\tilde{\chi}_1^0} < 50$ GeV (close to the CDMS contour and XENON limit)
LHC searches	Higgs searches SUSY searches monojet, monophoton and mono-Z/W searches

Signal strength is defined as:

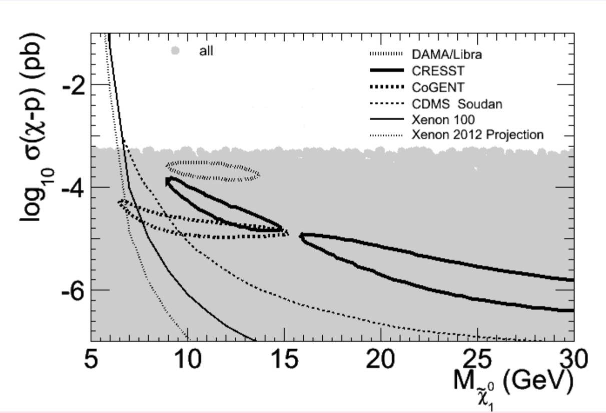
$$\mu_{XX} = \frac{\sigma(pp \to h)\,\mathrm{BR}(h \to XX)}{\sigma(pp \to h)_{\mathrm{SM}}\,\mathrm{BR}(h \to XX)_{\mathrm{SM}}}$$

LHC results:

Parameter	Combined value	Experiment
M_H (GeV)	125.7 ± 0.4	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)
$\mu_{\tau\tau}$	1.01 ± 0.36	ATLAS+CMS

χ^2 analysis of the Higgs constraints (mass + signal strengths)

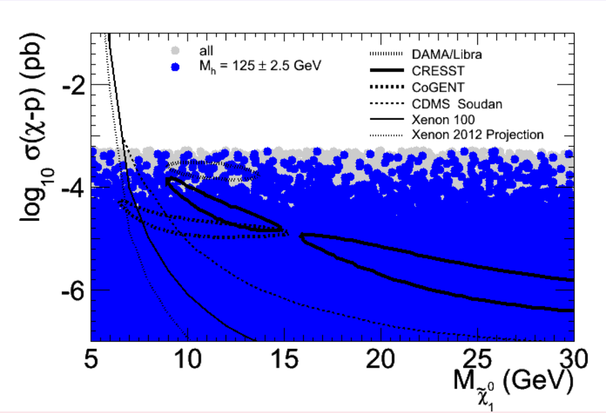
Low mass neutralino scans: more than **one billion** generated points



All
$\sim$ 1M points

AA, M. Battaglia, F. Mahmoudi, Eur.Phys.J. C72 (2012) 2169

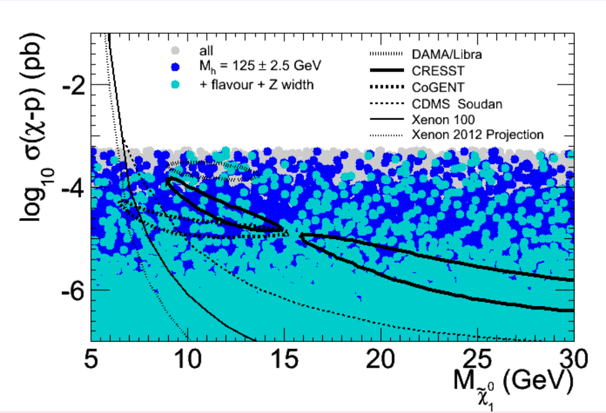
Low mass neutralino scans: more than **one billion** generated points



+Higgs mass
$\sim$ 100k points (10%)

AA, M. Battaglia, F. Mahmoudi, Eur.Phys.J. C72 (2012) 2169

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

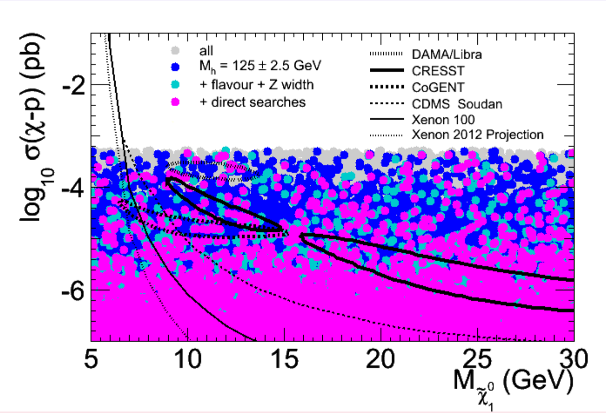


+Flavour + Z widths
$\sim$ 10k points (1%)

AA, M. Battaglia, F. Mahmoudi, Eur.Phys.J. C72 (2012) 2169

Light neutralinos and dark matter direct detection

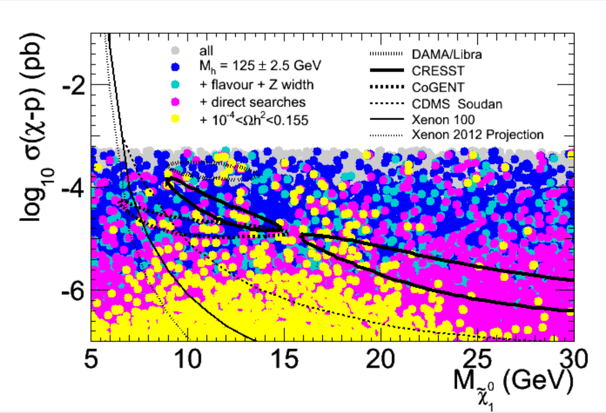
Low mass neutralino scans: more than **one billion** generated points



+Direct searches
$\sim$ 5k points (0.5%)

AA, M. Battaglia, F. Mahmoudi, Eur.Phys.J. C72 (2012) 2169

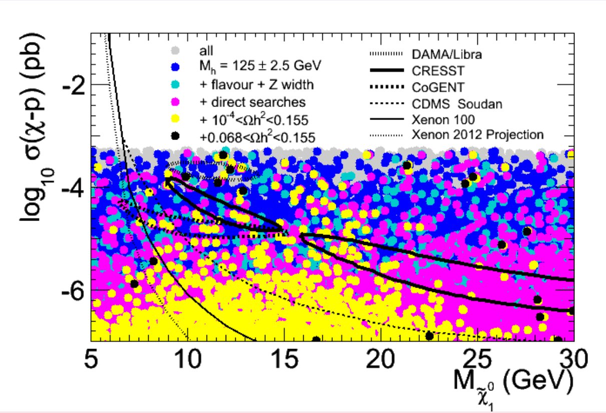
Low mass neutralino scans: more than **one billion** generated points



+Loose relic density
$\sim$ 1k points (0.1%)

AA, M. Battaglia, F. Mahmoudi, Eur.Phys.J. C72 (2012) 2169

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



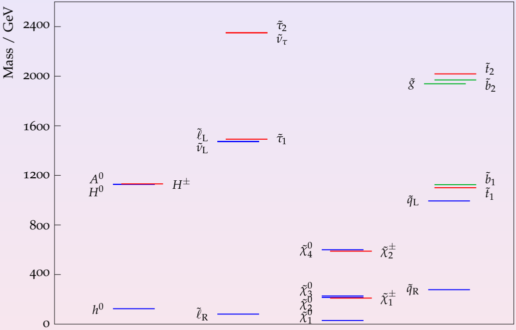
+Tight relic density
$\sim$ 18 points (0.002%)

AA, M. Battaglia, F. Mahmoudi, Eur.Phys.J. C72 (2012) 2169

Three main classes of points can survive the constraints:

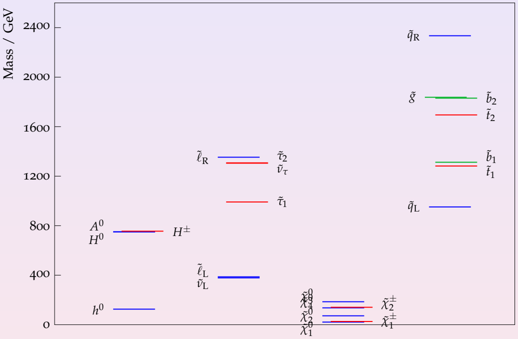
- a slepton with a mass close to LEP limit
  ($M_{\tilde{\chi}^0} \sim 20 - 40$ GeV)
- compressed spectrum in the neutralino/chargino sector
  ($M_{\tilde{\chi}^0} \sim 10 - 40$ GeV, $\sigma \sim 10^{-6}$ pb)
- one squark quasi-degenerate with the neutralino
  ($M_{\tilde{\chi}^0} \lesssim 10 - 20$ GeV,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

Slepton with a mass at the LEP limit



A relatively standard scenario, but the neutralino mass has to be larger ($\sim 20 - 30$ GeV) to give a large scattering cross-section.

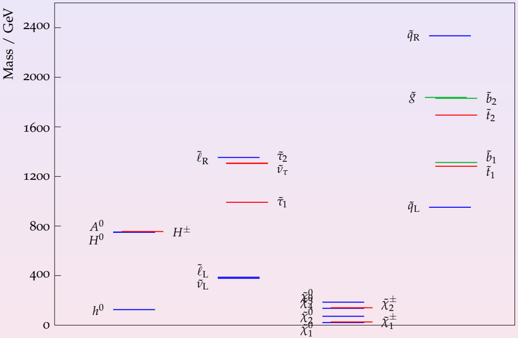
Compressed spectrum in the neutralino/chargino sector



This scenario may be very interesting...

Unfortunately $\sigma(e^+e^- \to \chi_1^0\chi_2^0)$ is in general too large with respect to the LEP limits!

Compressed spectrum in the neutralino/chargino sector



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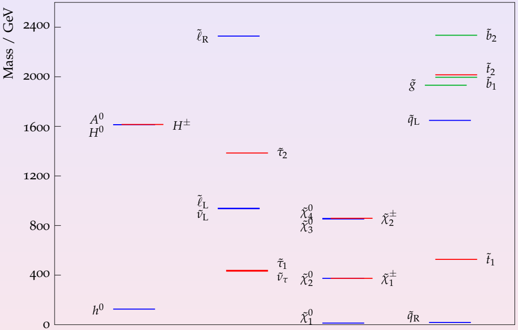
One squark quasi-degenerate with the neutralino



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

Light sbottom scenario

One important issue: $\Gamma(Z \to \tilde{q}\bar{\tilde{q}})$ is in general too large large

But for sbottom quark, thanks to the sbottom mixing, $\Gamma(Z \to \tilde{b}_1\bar{\tilde{b}}_1)$ can be suppressed and be compatible with the LEP results

In addition $\Gamma(Z \to \tilde{\chi}^0_1\tilde{\chi}^0_1)$ needs to be suppressed

Needed features:

- bino-like $\tilde{\chi}^0_1$ to respect $\Gamma(Z \to \tilde{\chi}^0_1\tilde{\chi}^0_1)$ and other LEP constraints
- right-handed $\tilde{b}_1$ to respect $\Gamma(Z \to \tilde{b}_1\bar{\tilde{b}}_1)$ constraints
- small mass splitting $(M_{\tilde{b}_1} - M_{\tilde{\chi}^0_1})$ to get an adequate relic density

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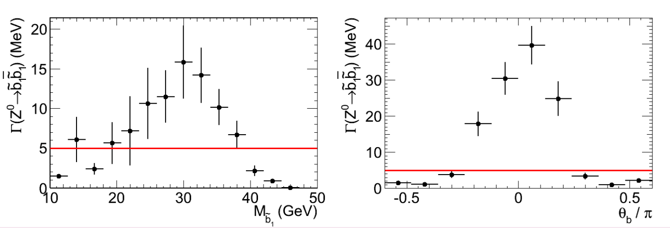

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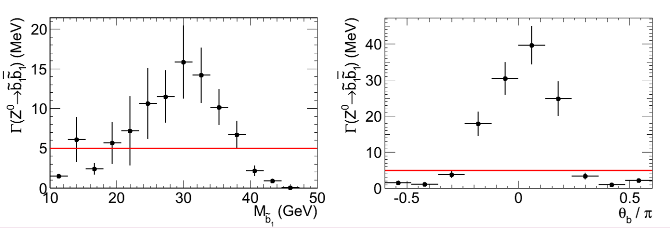

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Needed features:

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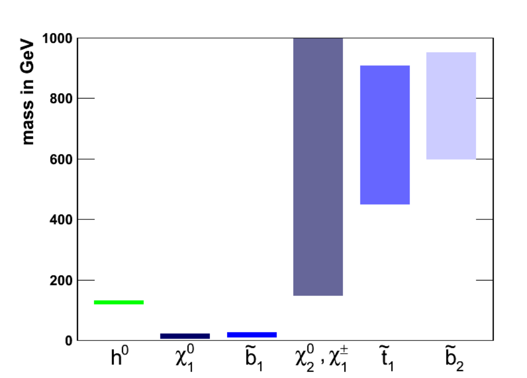
- small mass splitting $(M_{\tilde{b}_1} - M_{\tilde{\chi}_1^0})$ to get an adequate relic density

- Light bino-like neutralino of mass $\sim$ 10 GeV
- Light right-handed sbottom of mass $\sim$ 15 GeV



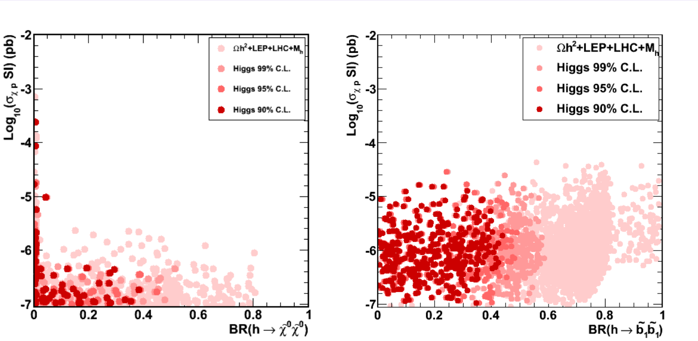
AA, M. Battaglia, F. Mahmoudi, arXiv:1308.2153

Other SUSY particle masses irrelevant for this scenario

Considering all light neutralino scenarios:

Invisible h decay

$h \to \tilde{b}_1 \bar{\tilde{b}}_1$ decay



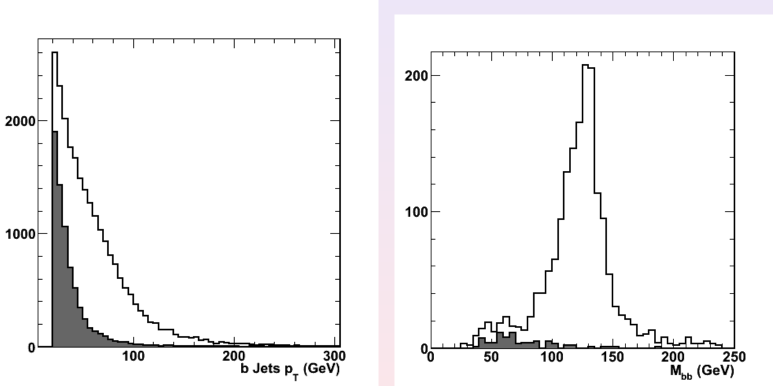
AA, M. Battaglia, F. Mahmoudi, arXiv:1308.2153

Scattering cross section can be enhanced for bino-like neutralinos

Higgs decay to two sbottoms can be also suppressed

Can we find the Higgs decay to two sbottoms at the LHC (if any...)?

WH events simulated with PYTHIA 8, fast simulation with DELPHES 3

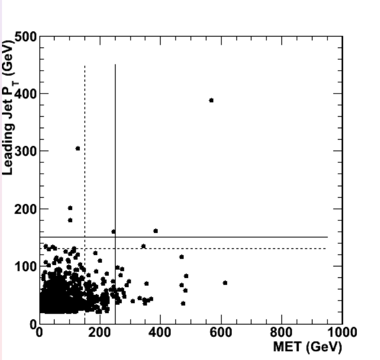


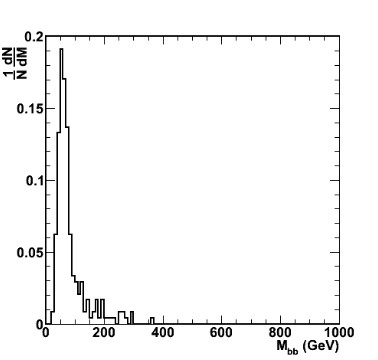
Comparison of $h \to b\bar{b}$ (open histograms) and $h \to \tilde{b}_1\tilde{b}_1$ (shaded histograms)

Can LHC direct searches probe the light neutralino and sbottom scenario?

- Large production cross $pp \to \tilde{b}_1 \tilde{b}_1$
- but small jet p_T and low MET ($\epsilon \sim 2 \times 10^{-5}$) (PYTHIA 8 + DELPHES 3)

$\to$ escapes detection in SUSY searches



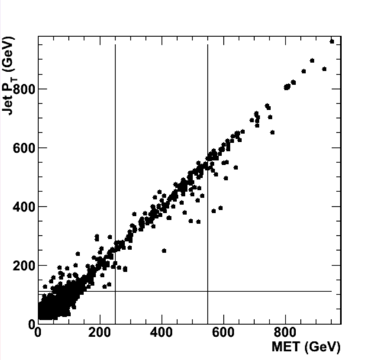


Based on cuts of ATLAS-CONF-2013-053 compared to kinematics of $pp \to \tilde{b}_1 \tilde{b}_1$ events

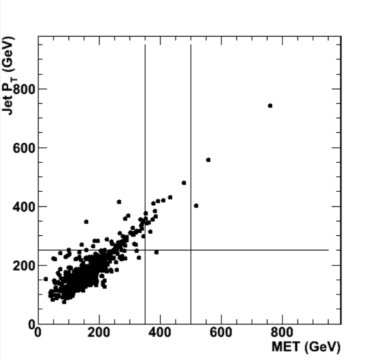
And monoX searches?

Monojet, monophoton and monoZ/W samples generated with MadGraph 5, PYTHIA 8 and simulated with DELPHES 3

$\rightarrow$ very low efficiency for these searches too!



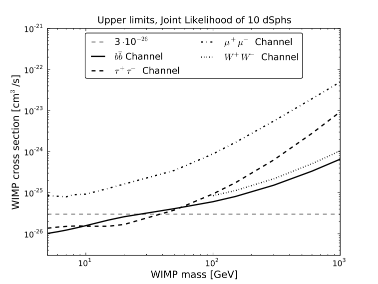
Jet p_T vs. MET for Monojet



Jet p_T vs. MET for MonoZ/W

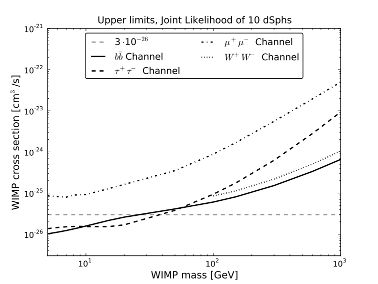
Based on ATLAS cuts of arXiv:1209.4625 and ATLAS-CONF-2013-073

Constraints from FERMI-LAT (gamma) on annihilation cross-sections



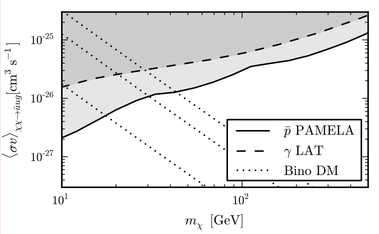
FERMI-LAT Collaboration, Phys. Rev. Lett. 107 (2011) 241302

Constraints from FERMI-LAT (gamma) on annihilation cross-sections



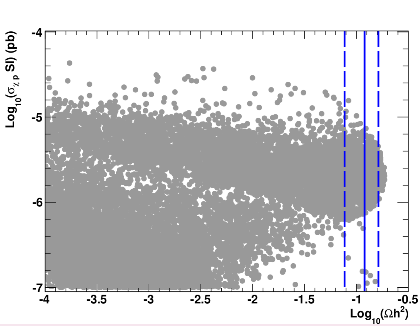
FERMI-LAT Collaboration, Phys. Rev. Lett. 107 (2011) 241302

Constraints on gluon-strahlung annihilation cross-sections from PAMELA (antiproton) and FERMI-LAT (gamma)



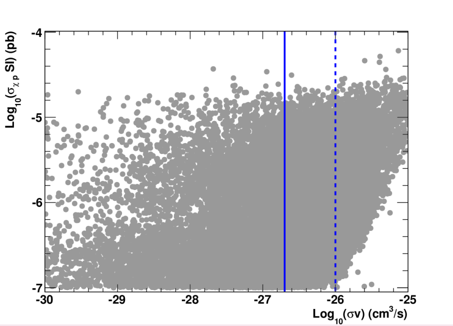
M. Asano, T. Bringmann, C. Weniger, Phys. Lett. B709 (2012) 128

Direct detection vs. relic density



(lines: PLANCK)

Direct detection vs. indirect detection

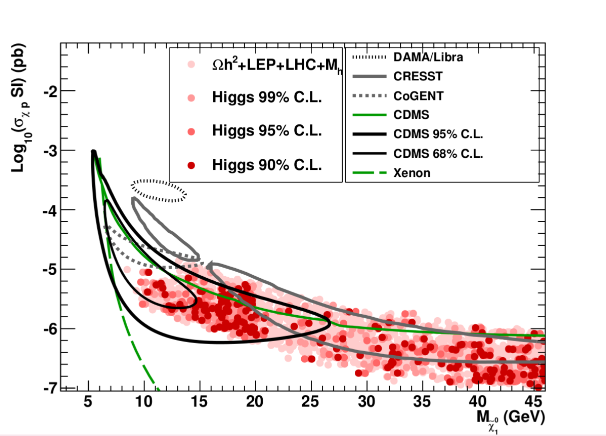


(dotted: FERMI, plain: PAMELA)

Largest (direct detection) scattering cross sections correspond to

- smallest relic density
- largest (indirect detection) annihilation cross sections

Summary plots

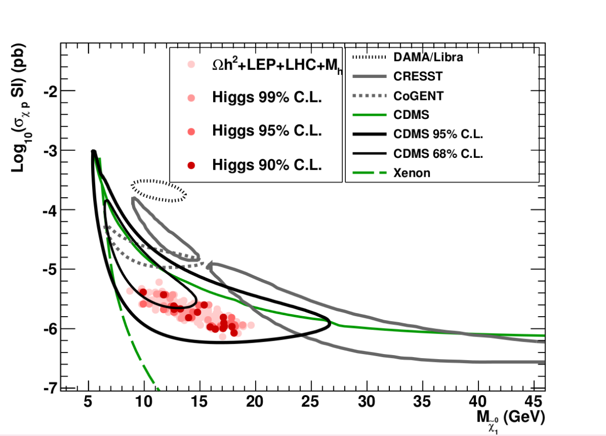


AA, M. Battaglia, F. Mahmoudi, arXiv:1308.2153

Loose relic density constraint

$10^{-4} < \Omega_\chi h^2 < 0.163$

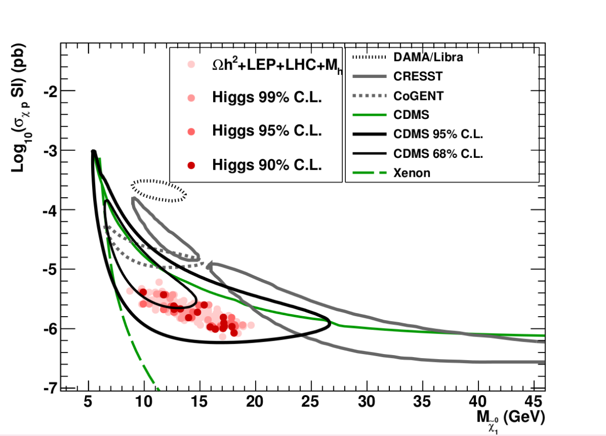
Summary plots



AA, M. Battaglia, F. Mahmoudi, arXiv:1308.2153

Tight relic density constraint

$0.076 < \Omega_\chi h^2 < 0.163$



AA, M. Battaglia, F. Mahmoudi, arXiv:1308.2153

Tight relic density constraint

$$0.076 < \Omega_\chi h^2 < 0.163$$

Light sbottom scenario satisfies all the present constraints!

Conclusion

- Dark matter searches are powerful probes for Supersymmetry
- The pMSSM provides interesting candidates for dark matter
- pMSSM very light neutralinos can be compatible with all constraints

  $\rightarrow$ **sbottom miracle!**
- Interplay between dark matter, Higgs and flavour sectors can help closing the windows

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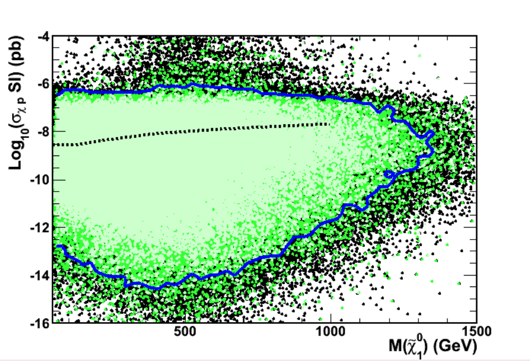
Stay tuned for the next direct detection results!

Backup

XENON dark matter exclusion limit in the pMSSM



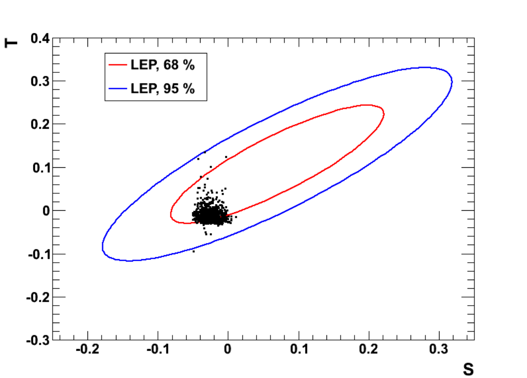
AA, M. Battaglia, A. Djouadi, F. Mahmoudi, Phys.Lett. B720 (2013) 153

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

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

In the following, we focus on the region where $M_{\tilde{\chi}^0_1} < 50 GeV$

S, T, U constraints



Points consistent with all other constraints also consistent with S, T, U