Neutralino dark matter and MSSM

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Different types of dark matter searches:

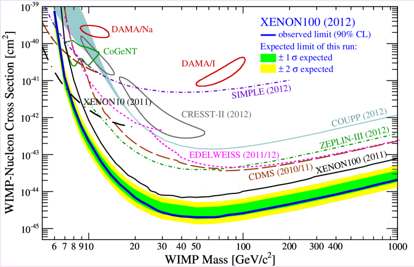
- direct production of WIMPs at the LHC
- DM annihilations: DM + DM $\rightarrow$ SM + SM + ...
  - **indirect detection**: protons, gammas, anti-protons, positrons, ...
  - dark matter **relic density**

  Possible enhancements of the annihilation cross-sections through Higgs resonances
- DM **direct detection**: DM + matter $\rightarrow$ DM + matter

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

→ **Unclear situation, but the sensitivity is improving!**

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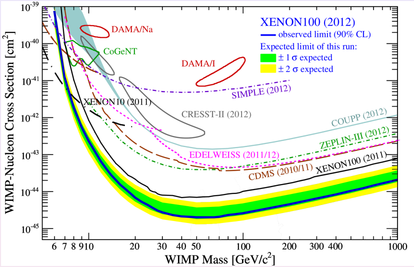

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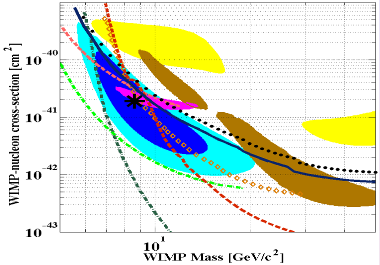

CDMS, arXiv:1304.4279

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→ **Unclear situation, but the sensitivity is improving!**

We consider the 19-parameter pMSSM with neutralino dark matter

Parameter	Range (in GeV)
$\tan\beta$	[1, 60]
M_A	[0, 2000]
M_1	[-2500, 2500]
M_2	[-2500, 2500]
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]
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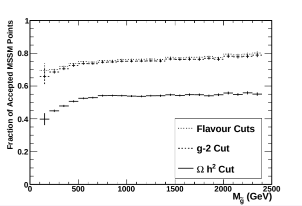
$M_{\tilde{u}_R} = M_{\tilde{c}_R}$	[0, 2500]
$M_{\tilde{t}_R}$	[0, 2500]
$M_{\tilde{d}_R} = M_{\tilde{s}_R}$	[0, 2500]
$M_{\tilde{b}_R}$	[0, 2500]

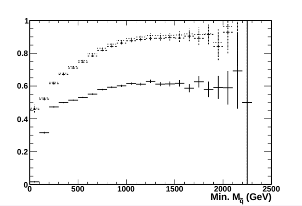
- Calculation of masses, mixings and couplings (SoftSusy, Suspect)
- Computation of low energy observables and Z widths (**SuperIso**)
- Computation of dark matter observables (**SuperIso Relic**, Micromegas, DarkSUSY)
- Determination of SUSY and Higgs mass limits (**SuperIso**, HiggsBounds)
- Calculation 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)

Effect of constraints and fraction of accepted points:

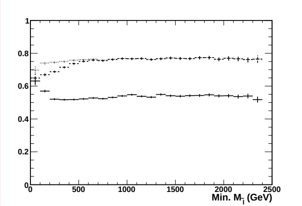
gluino



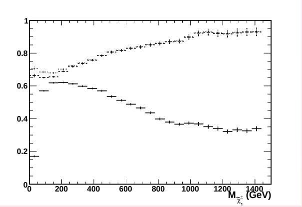
lightest squark



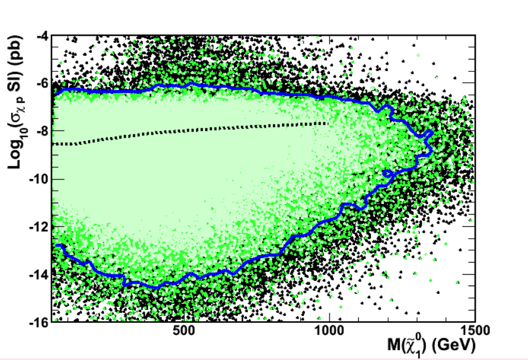
lightest slepton



light chargino



AA, M. Battaglia, F. Mahmoudi, Eur.Phys.J. C72 (2012) 1847 pMSSM points and XENON dark matter exclusion limit

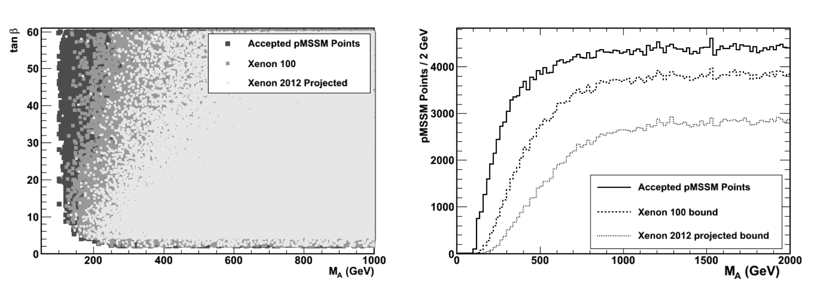


AA, M. Battaglia, A. Djouadi, F. Mahmoudi, Phys.Lett. B720 (2013) 153

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.

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



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

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

Can the pMSSM provide solutions compatible with CoGeNT/CRESST/DAMA/CDMS data?

Low mass neutralino of ~ 10 GeV?

Not possible in constrained MSSM...

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

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$\tan\beta$	[1, 60]
M_A	[50, 2000]
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M_2	[-2500, 2500]
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$\longrightarrow$

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Dark matter

- Loose relic density: $10^{-4} < \Omega_\chi h^2 < 0.163$
- Tight relic density: $0.076 < \Omega_\chi h^2 < 0.163$
- Indirect detection: $(\sigma v)_{\rm tot} < 10^{-26}$ cm^3/s with $M_{\tilde\chi^0_1} < 50$ GeV and $(\sigma v)_{bbg} < 2 \times 10^{-27}$ cm^3/s with $M_{\tilde\chi^0_1} < 50$ GeV
- Direct detection: $10^{-7} < \sigma^{\rm SI}_{p-\chi} < 10^{-2}$ pb with $M_{\tilde\chi^0_1} < 50$ GeV (close to the CDMS contour and XENON limit)

Collider searches

- LEP and Tevatron mass limits
- LEP searches for $\tilde\chi^+\tilde\chi^- / \tilde\chi^0_2\tilde\chi^0_1$
- LHC SUSY searches (sbottom, stop, neutralino/chargino)
- LHC monoX searches ($pp \to \chi\chi +$ jets, γ and Z/W)
- Higgs searches (mass and signal strengths)

Constraints

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
- $0.21497 < R_b < 0.21761$

Flavour physics and Precision tests

- $2.63 \times 10^{-4} < \mathrm{BR}(B \to X_s \gamma) < 4.23 \times 10^{-4}$
- $1.28 \times 10^{-9} < \mathrm{BR}(B_s \to \mu^+ \mu^-)_{\mathrm{untag}} < 4.52 \times 10^{-9}$
- $0.40 \times 10^{-4} < \mathrm{BR}(B_u \to \tau \nu) < 1.88 \times 10^{-4}$
- $4.7 \times 10^{-2} < \mathrm{BR}(D_s \to \tau \nu) < 6.1 \times 10^{-2}$
- $2.9 \times 10^{-3} < \mathrm{BR}(B \to D^0 \tau \nu) < 14.2 \times 10^{-3}$
- $0.985 < R_{\mu 23} < 1.013$
- Muon anomalous magnetic moment: $-2.4 \times 10^{-9} < \delta a_\mu < 4.5 \times 10^{-9}$

Other constraints

- Oblique parameters S, T, U
- Vacuum stability: stable or long-lived one-loop scalar potential minimum

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)

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)

  Relatively standard scenario, but neutralino mass far from interesting region

- compressed spectrum in the neutralino/chargino sector
  ($M_{\tilde{\chi}^0} \sim 10 - 40$ GeV, $\sigma \sim 10^{-6}$ pb)

  Scenario of interest...
  Unfortunately $\sigma(e^+e^- \to \chi_1^0\chi_2^0)$ in general too large with respect to LEP limits!

- one squark quasi-degenerate with the neutralino
  ($M_{\tilde{\chi}^0} \lesssim 10 - 20$ GeV, $\sigma \sim 10^{-5}$ pb)

  These spectra can fulfill all the constraints and have simultaneously a neutralino mass below 15 GeV and a large scattering cross-section, if the squark is a **sbottom**!

Solutions

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

Due to the sbottom mixing, $\Gamma(Z \to \tilde{b}_1 \bar{\tilde{b}}_1)$ can be suppressed and pass the LEP constraint

Also, to pass the LEP $\Gamma(Z \to \text{invisible})$ constraint, $\Gamma(Z \to \tilde{\chi}_1 \tilde{\chi}_1)$ needs to be suppressed

Main features:

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

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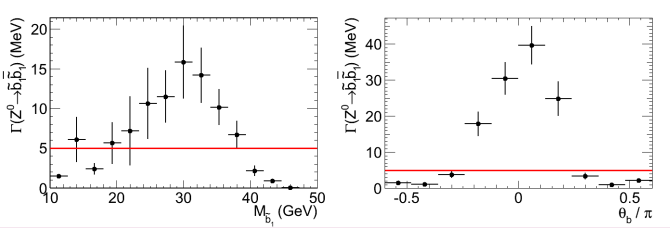

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Light sbottom scenario

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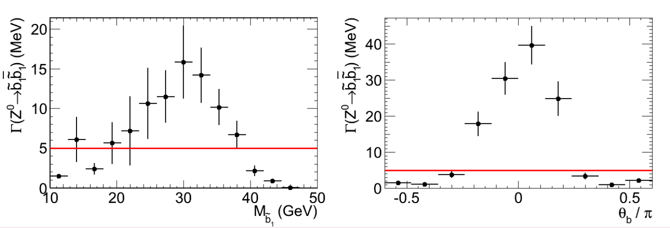

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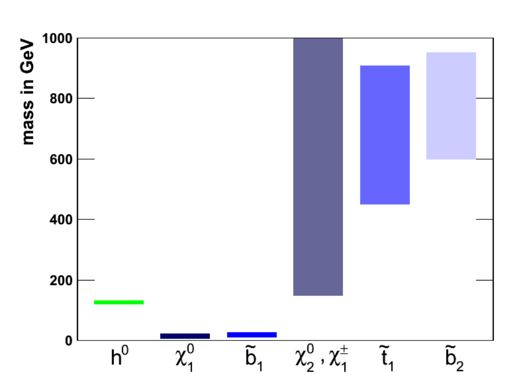
- small mass splitting $(M_{\tilde{b}_1} - M_{\tilde{\chi}_1})$ to get an adequate relic density

- Light bino-like neutralino of mass ~ 10 GeV
- Light right-handed sbottom of mass ~ 15 GeV

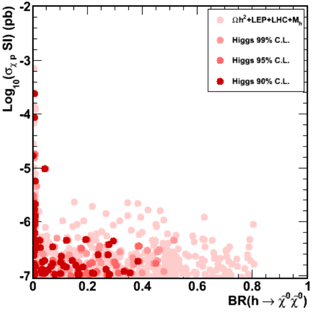


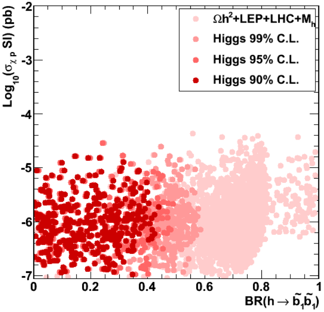
AA, M. Battaglia, F. Mahmoudi, arXiv:1308.2153

The masses of the other SUSY particles are irrelevant for this scenario

Invisible h decay

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



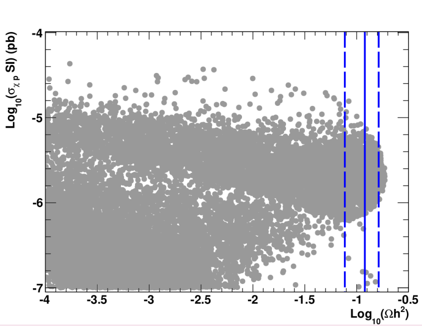


AA, M. Battaglia, F. Mahmoudi, arXiv:1308.2153

Invisible and sbottom branching fractions restrained to less than 50% at 95% C.L.

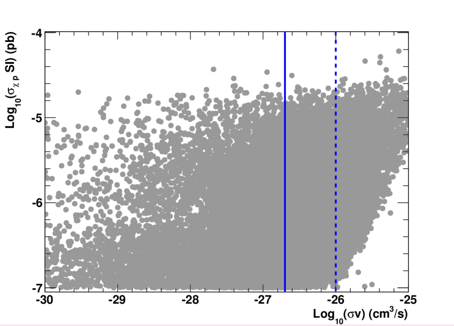
Relic density, direct and indirect detections

Direct detection vs. relic density



(lines: PLANCK)

Direct detection vs. indirect detection



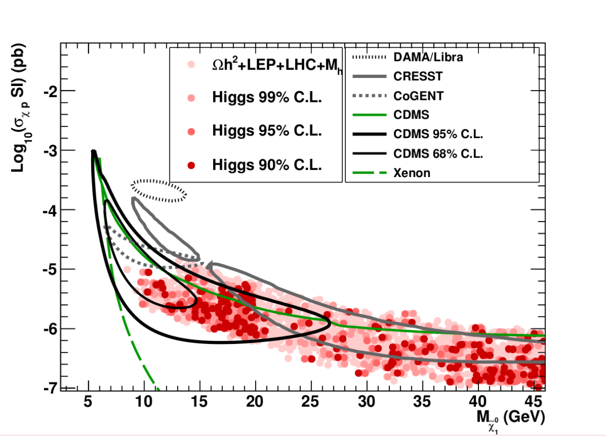
(dotted: FERMI, plain: PAMELA)

Largest (direct detection) scattering cross sections correspond to

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

Dark matter direct detection

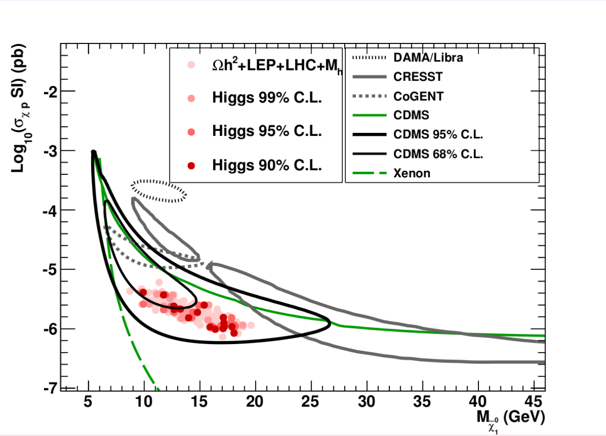
Direct detection:



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

Loose relic density constraint
$$10^{-4} < \Omega_\chi h^2 < 0.163$$

Direct detection:



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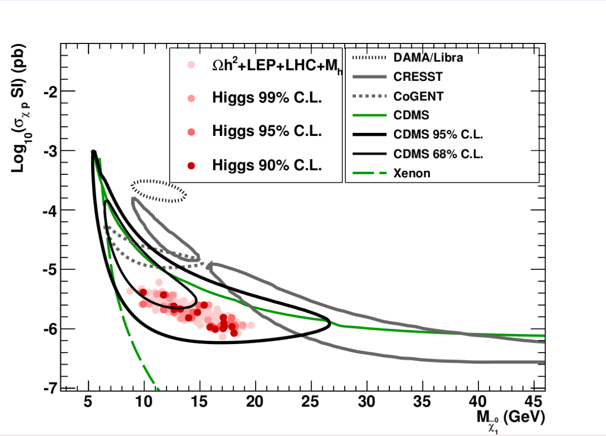
Tight relic density constraint

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

Direct detection:



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Tight relic density constraint

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

Light sbottom scenario satisfies all the present constraints!

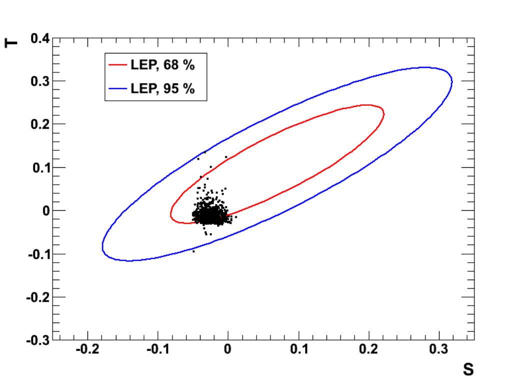
- The pMSSM provides viable candidates for dark matter
- Dark matter searches are powerful probes for Supersymmetry
- Direct detection constraints sensitive to the MSSM Higgs sector
- Interplay between dark matter, Higgs and flavour sectors can help closing the windows
- pMSSM very light neutralinos can be compatible with all constraints

  $\rightarrow$ **light neutralino and sbottom scenario**

Backup

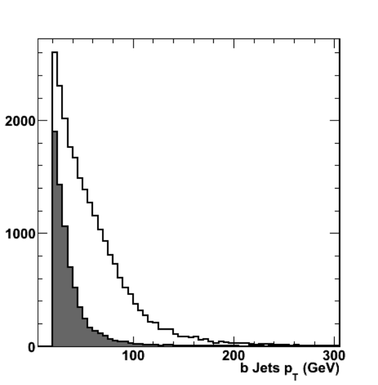
Constraints

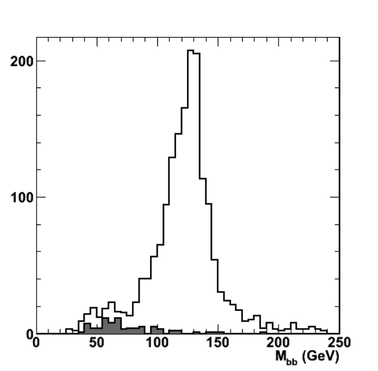
Type	Constraint
Higgs mass constraint Higgs signal strengths	$M_h \in [121, 129]$ GeV ATLAS+CMS
Z decay widths	$\Gamma(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) < 3$ MeV $\Gamma(Z \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) + \Gamma(Z \to \tilde{b}_1 \tilde{b}_1) < 5$ MeV $0.21497 < R_b < 0.21761$
LEP and 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 $pp \to \chi\chi +$ jets, γ and Z/W searches



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

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

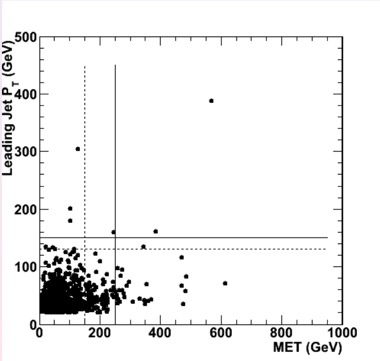


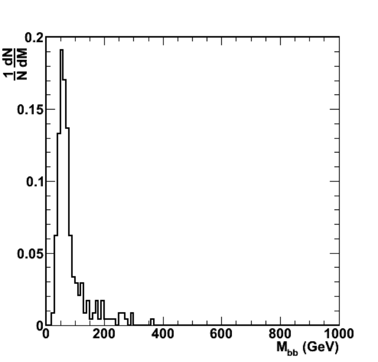


Comparison of $h \to b\bar{b}$ (open histograms) and $h \to \tilde{b}_1\tilde{b}_1$ (shaded histograms)

- 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)

$\rightarrow$ escapes detection in SUSY searches

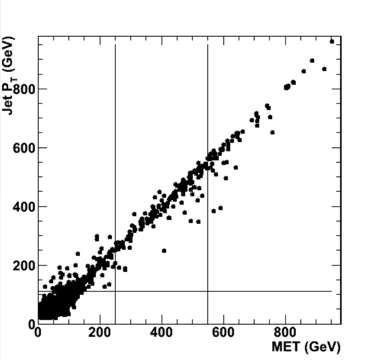




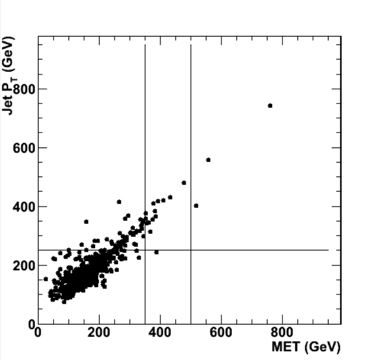
Based on cuts of ATLAS-CONF-2013-053 compared to kinematics of $pp \to \tilde{b}_1 \tilde{b}_1$ events

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

→ very low efficiency for these searches too!



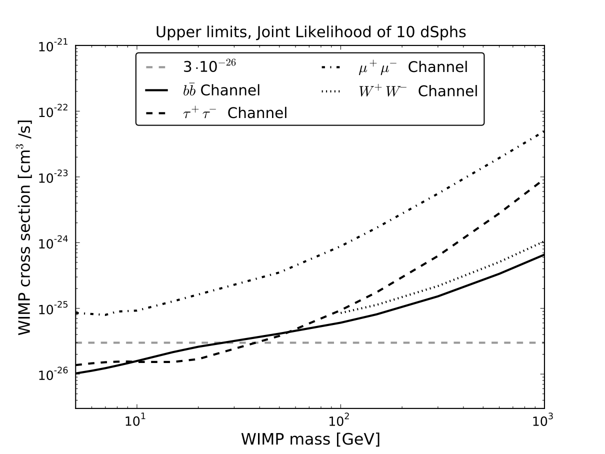
Jet p_T vs. MET for Monojet



Jet p_T vs. MET for MonoZ/W

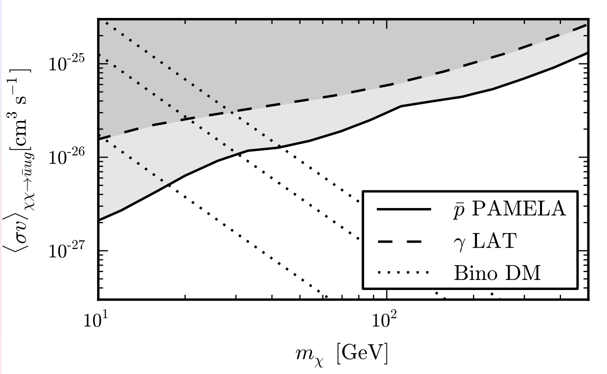
Based on ATLAS cuts of arXiv:1209.4625 and ATLAS-CONF-2013-073

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