



# Dark Matter in the MSSM

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LPC Clermont-Ferrand & CERN

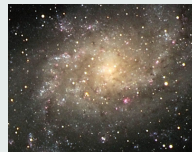
New Perspectives in Dark matter

Lyon, October 22 - 25, 2013

## Different scales involved

- Galactic scale

- Galaxy Rotation Curves
- Galaxy Collisions



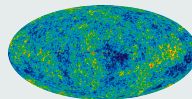
- Cluster Scale

- X-Ray Observations
- Weak Lensing
- Bullet Cluster



- Cosmological Scale

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



- **Baryonic Dark Matter**  
Black holes, dwarves, gases, ...
- **Other particles/fields:** axions, dark fluids, ...  
Exotic and non-baryonic particles
- **Modified Gravitation Laws**  
MOND, TeVeS, Scalar-tensor theories, ...
- **Weakly Interacting Massive Particles (WIMPs)**  
Massive neutrinos, Kaluza-Klein particles, ...  
Supersymmetric candidates: neutralinos, axinos, gravitinos, sneutrinos, ...

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Different types of dark matter searches:

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

Possible enhancements of the annihilation cross-sections through Higgs resonances

- DM **direct detection**:  $\text{DM} + \text{matter} \rightarrow \text{DM} + \text{matter}$

Neutralino scattering cross-section sensitive to neutral Higgs bosons

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

- Neutralino dark matter
- Interplay with collider physics
- Very light neutralino dark matter
- Conclusions

# Neutralino dark matter

Supersymmetry: symmetry relating bosons and fermions ( $\rightarrow$  Lie superalgebra)

## Minimal Supersymmetric extension of the Standard Model (MSSM)

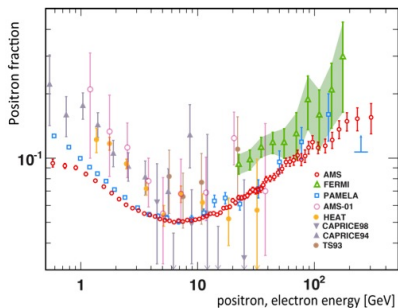
- Includes super partners of the SM particles:  
squarks, sleptons, gauginos and higgsinos  
gauginos + higgsinos mix to 2 charginos + 4 neutralinos  
2 Higgs doublets (coupling  $\mu$ , ratio of vev's =  $\tan \beta$ )  
 $\rightarrow$  5 physical Higgs bosons
- Supersymmetry must be broken
- How SUSY is broken is irrelevant for phenomenology
- This is the mediation mechanism and the associated scale of SUSY breaking which is important
- Lightest SUSY particle (LSP) is stable if  $R$ -parity is conserved  
$$R = (-1)^{2S-L+3B} \quad S = \text{spin}, L = \text{lepton nb}, B = \text{baryon nb}$$
$$R = +1 \text{ for SM particles and } R = -1 \text{ for sparticles}$$



FERMI-LAT: large excess in the  $\gamma$  spectrum at  $\sim 130$  GeV

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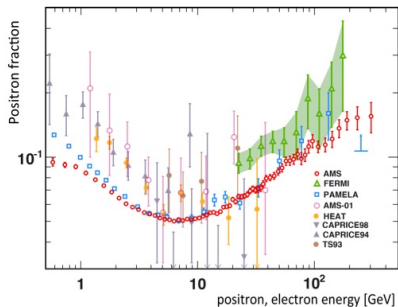
AMS-2, FERMI, PAMELA: large excess in the positron spectrum for  $E_{e^+} \gtrsim 10$  GeV



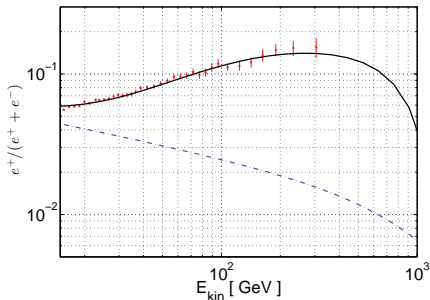
[AMS-2 website](#)

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AMS-2 website

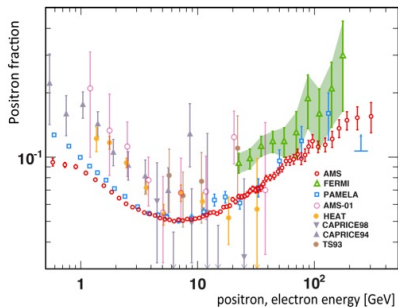


A. De Simone, A. Riotto, W. Xue, JCAP 1305 (2013) 003

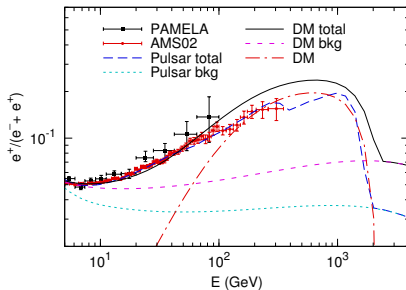
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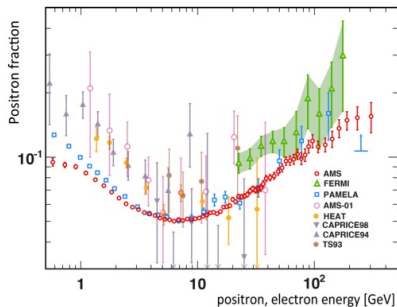
P.-F. Yin et al., Phys. Rev. D88 (2013) 023001

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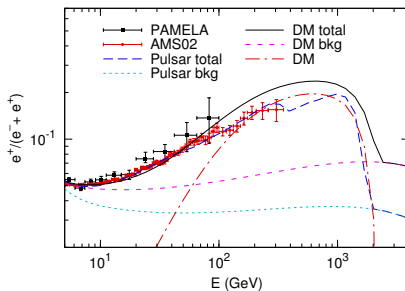
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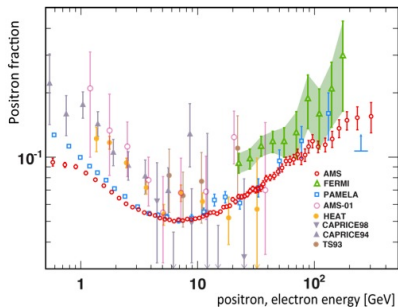
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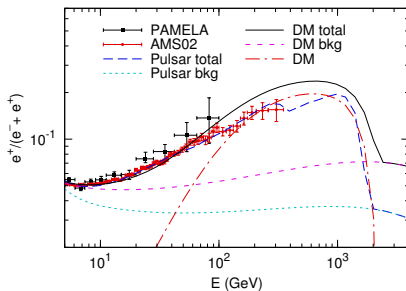
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But also with astrophysical sources (e.g. pulsars)...  $\rightarrow$  **large astrophysical uncertainties**

In the following, we will NOT try to explain these excesses!



In the Standard Model of Cosmology:

- before and at nucleosynthesis time, the expansion is dominated by radiation

$$H^2 = 8\pi G/3 \times \rho_{\text{rad}}$$

- the evolution of the number density of supersymmetric particles follows the Boltzmann equation

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{\text{eff}} v \rangle (n^2 - n_{\text{eq}}^2)$$

$n$ : number density of relic particles

$\langle \sigma_{\text{eff}} v \rangle$ : thermal average of effective (co-)annihilation cross sections to SM particles

Solving the system of equations leads to the relic density of the LSP

To be compared to the very constraining Planck interval:

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



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Caveat about the relic density constraints:

The relic density constraint is strong and can rule 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
- ...

In the following, we generally use a looser constraint:

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

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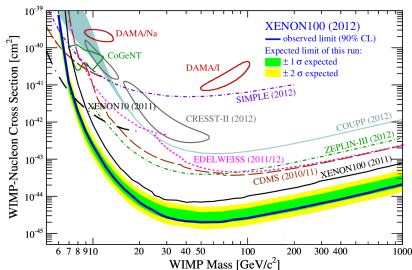
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## Present situation:



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!

Lyon – October 22nd, 2013



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### 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
  - 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  $\mu$  and  $\tan \beta$ )

→ Very useful for phenomenology, benchmarking, model discrimination, ...

→ But not representative of the whole MSSM!

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Many constrained scenarios are phenomenologically very attractive

But Higgs discovery now challenges many scenarios!



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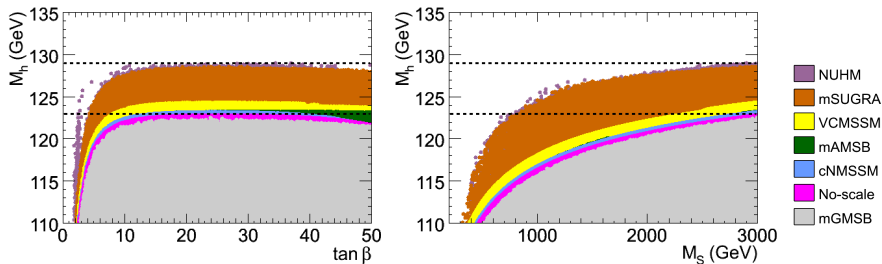
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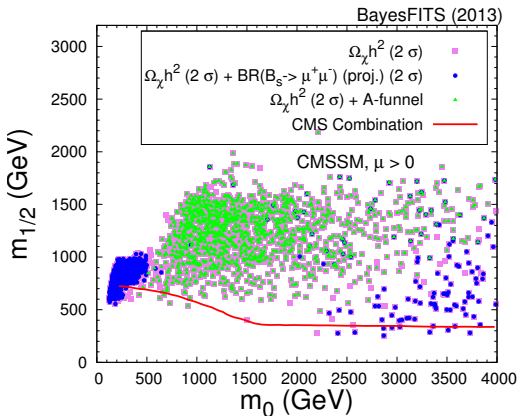
## Maximal Higgs mass in constrained MSSM scenarios



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

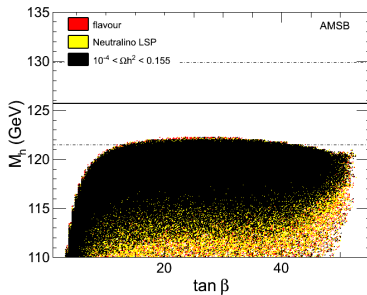
Several constrained models are excluded or about to be!  
But CMSSM is still surviving!

Dark matter and LHC constraints:



CMSSM: very challenging situation!

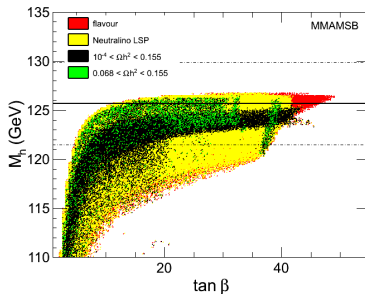
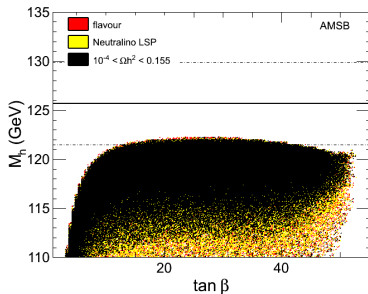
## AMSB vs. Higgs mass



Minimal AMSB scenario very challenged...

A. Arbey, A. Deandrea, FM, A. Tarhini, Phys. Rev. D87 (2013) 115020

## AMSB vs. Higgs mass



Minimal AMSB scenario very challenged...

but less minimal scenarios like Mixed Moduli AMSB provide interesting candidates

A. Arbey, A. Deandrea, FM, A. Tarhini, Phys. Rev. D87 (2013) 115020

## 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

→ 19 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:  $M_A$ ,  $\tan \beta$ ,  $\mu$

A. Djouadi, J.-L. Kneur, G. Moultaka, hep-ph/0211331

## Scan ranges and Tools

Parameter	Range (in GeV)
$\tan \beta$	[1, 60]
$M_A$	[0, 2000]
$M_1$	[-2500, 2500]
$M_2$	[-2500, 2500]
$M_3$	[0, 2500]
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- 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, Higgs, 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)

## Constraints from:

- LEP and Tevatron direct search limits
- Flavour precision limits, in particular from  $\text{BR}(B \rightarrow X_s \gamma)$ ,  $\text{BR}(B_s \rightarrow \mu^+ \mu^-)$ ,  $\text{BR}(B \rightarrow \tau \nu)$
- Muon anomalous magnetic moment,  $(g - 2)_\mu$
- Dark matter relic density (neutralino LSP)
- Dark matter direct search limits
- Dark matter indirect detection limits
- LHC SUSY direct search limits
- Higgs mass limits
- Higgs production and decay rates
- LHC monojet limits

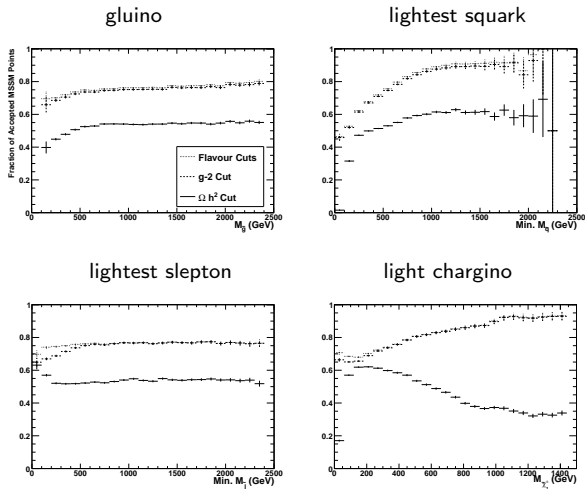
## Statistics:

- more than 100M model points in general analyses
- more than 1B model points for dedicated analyses

Largest statistics in the MSSM so far.

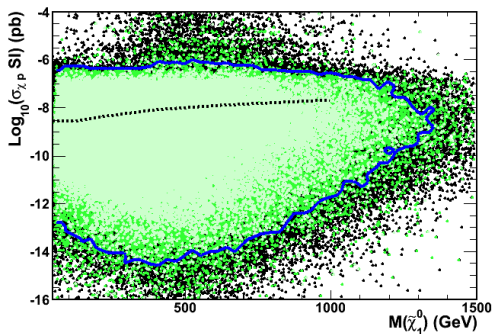


## Effect of constraints and fraction of accepted points:



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

## pMSSM points and XENON dark matter exclusion limit



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

Black: all valid points

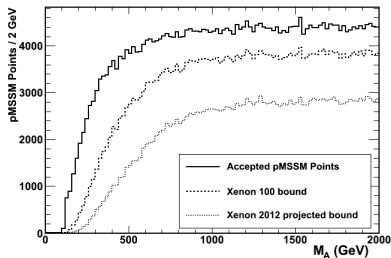
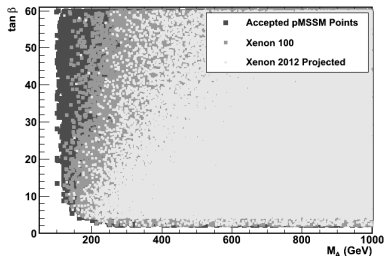
Dark green: points compatible at 90% C.L. with the LHC Higgs search results

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

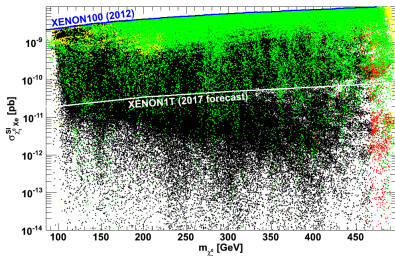
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A. Arbey, M. Battaglia, FM, Eur.Phys.J. C72 (2012) 1906

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

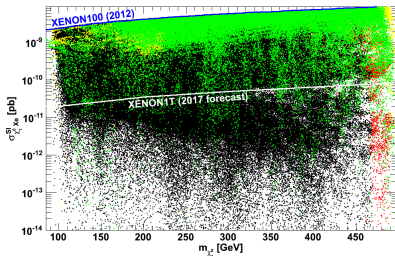
## Direct detection



- Green points: astrophysically allowed
- Black points: excluded by both Pamela and Fermi-LAT
- Red points: excluded by Pamela
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Interesting complementarity between direct and indirect detections

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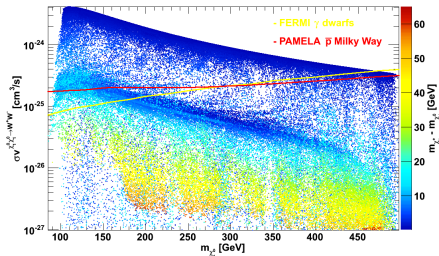


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Interesting complementarity between direct and indirect detections

Indirect detection constraints are stronger for light neutralino and small splitting with the next to lightest SUSY particle

## Indirect detection



G. Belanger, C. Boehm, M. Cirelli, J. Da Silva, A. Pukhov, JCAP 1211 (2012) 028

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

## Low mass neutralino of $\sim 10$ GeV?

Not possible in constrained MSSM...

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

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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:  $(\sigma v)_{\text{tot}} < 10^{-26} \text{ cm}^3/\text{s}$  with  $M_{\tilde{\chi}_1^0} < 50 \text{ GeV}$   
and  $(\sigma v)_{bbg} < 2 \times 10^{-27} \text{ cm}^3/\text{s}$  with  $M_{\tilde{\chi}_1^0} < 50 \text{ GeV}$
- Direct detection:  $10^{-7} < \sigma_{p-\chi}^{\text{SI}} < 10^{-2} \text{ pb}$  with  $M_{\tilde{\chi}_1^0} < 50 \text{ GeV}$   
(close to the CDMS contour and XENON limit)

## Collider searches

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



### Z decay widths

- $\Gamma(Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) < 3 \text{ MeV}$
- $\Gamma(Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) + \Gamma(Z \rightarrow \tilde{b}_1 \tilde{b}_1) < 5 \text{ MeV}$
- $0.21497 < R_b < 0.21761$

### Flavour physics and Precision tests

- $2.63 \times 10^{-4} < \text{BR}(B \rightarrow X_s \gamma) < 4.23 \times 10^{-4}$
- $1.28 \times 10^{-9} < \text{BR}(B_s \rightarrow \mu^+ \mu^-)_{\text{untag}} < 4.52 \times 10^{-9}$
- $0.40 \times 10^{-4} < \text{BR}(B_u \rightarrow \tau \nu) < 1.88 \times 10^{-4}$
- $4.7 \times 10^{-2} < \text{BR}(D_s \rightarrow \tau \nu) < 6.1 \times 10^{-2}$
- $2.9 \times 10^{-3} < \text{BR}(B \rightarrow D^0 \tau \nu) < 14.2 \times 10^{-3}$
- $0.985 < R_{\mu 23} < 1.013$
- 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:

$$\mu_{XX} = \frac{\sigma(pp \rightarrow h) \text{BR}(h \rightarrow XX)}{\sigma(pp \rightarrow h)_{\text{SM}} \text{BR}(h \rightarrow XX)_{\text{SM}}}$$

LHC results:

Parameter	Combined value	Experiment
$M_H$ (GeV)	$125.7 \pm 0.4$	ATLAS+CMS
$\mu_{\gamma\gamma}$	$1.20 \pm 0.30$	ATLAS+CMS
$\mu_{ZZ}$	$1.10 \pm 0.22$	ATLAS+CMS
$\mu_{WW}$	$0.77 \pm 0.21$	ATLAS+CMS
$\mu_{b\bar{b}}$	$1.12 \pm 0.45$	ATLAS+CMS+(CDF+D0)
$\mu_{\tau\tau}$	$1.01 \pm 0.36$	ATLAS+CMS

$\chi^2$  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  $\sigma(e^+e^- \rightarrow \chi_1^0\chi_2^0)$  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**!

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

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

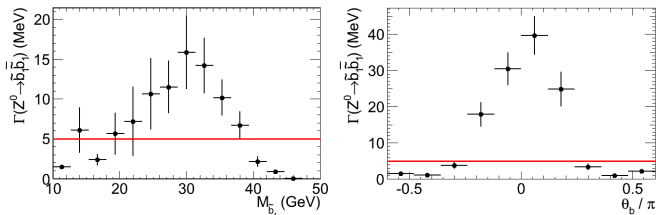
Also, to pass the LEP  $\Gamma(Z \rightarrow \text{invisible})$  constraint,  $\Gamma(Z \rightarrow \tilde{\chi}_1\tilde{\chi}_1)$  needs to be suppressed

Main features:

- right-handed  $\tilde{b}_1$  to respect  $\Gamma(Z \rightarrow \tilde{b}_1\tilde{b}_1)$  constraints
- bino-like  $\tilde{\chi}_1$  to respect  $\Gamma(Z \rightarrow \tilde{\chi}_1\tilde{\chi}_1)$  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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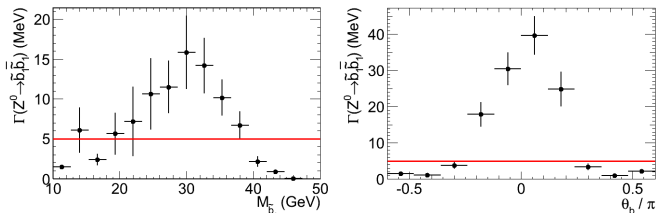
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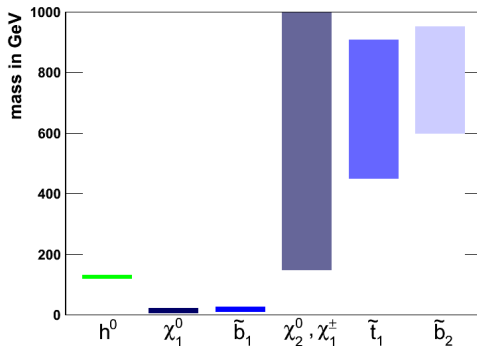
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## Typical spectra

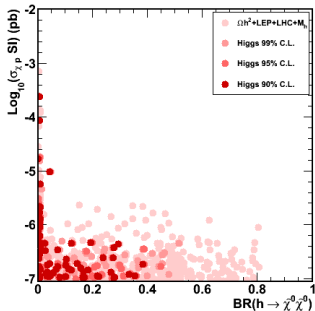
- Light bino-like neutralino of mass  $\sim 10$  GeV
- Light right-handed sbottom of mass  $\sim 15$  GeV



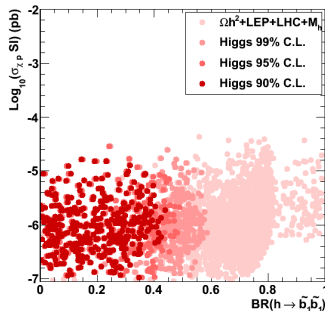
A. Arbey, M. Battaglia, FM, arXiv:1308.2153

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

Invisible  $h$  decay



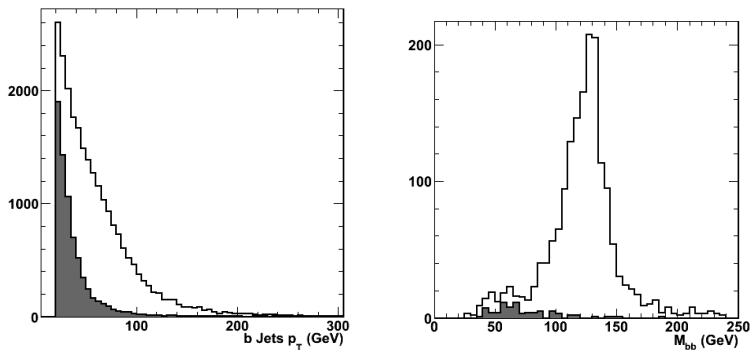
$h \rightarrow \tilde{b}_1 \tilde{b}_1^*$  decay



A. Arbey, M. Battaglia, FM, arXiv:1308.2153

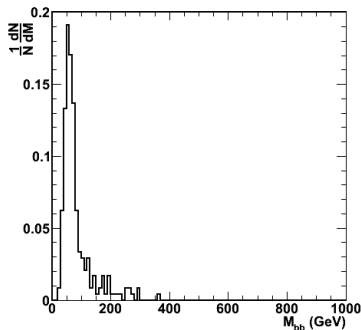
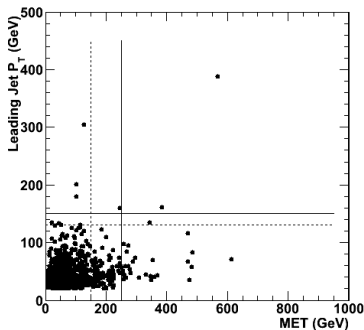
Invisible and sbottom branching fractions restrained to less than 50% at 95% C.L.

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



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

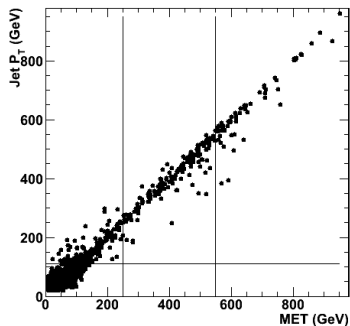
- Large production cross section for  $pp \rightarrow \tilde{b}_1 \tilde{b}_1$
- but small jet  $p_T$  and low MET ( $\epsilon \sim 2 \times 10^{-5}$ ) (PYTHIA 8 + DELPHES 3)  
→ escapes detection in SUSY searches



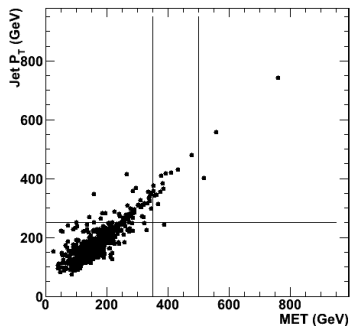
Based on cuts of ATLAS-CONF-2013-053 compared to kinematics of  $pp \rightarrow \tilde{b}_1 \tilde{b}_1$  events

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

→ very low efficiency for these searches too!



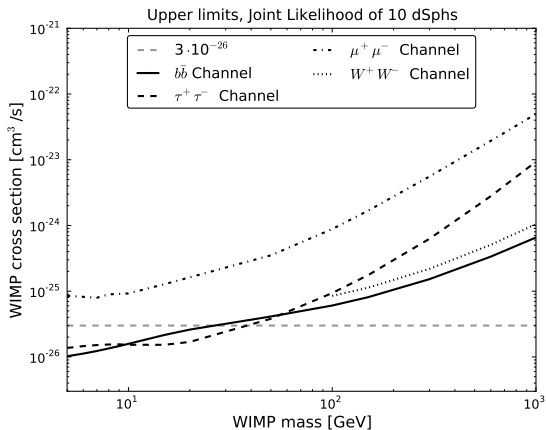
Jet  $p_T$  vs. MET for Monojet



Jet  $p_T$  vs. MET for MonoZ/W

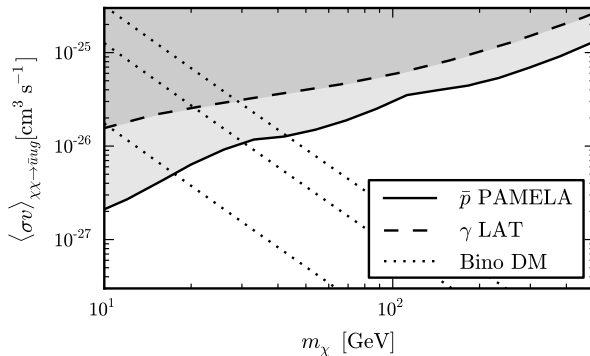
Based on ATLAS cuts of arXiv:1209.4625 and ATLAS-CONF-2013-073

## FERMI-LAT (gamma) on annihilation cross-sections



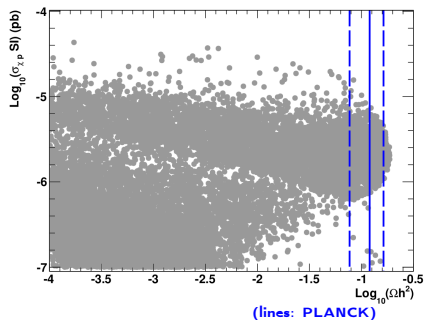
FERMI-LAT Collaboration, Phys. Rev.Lett. 107 (2011) 241302

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

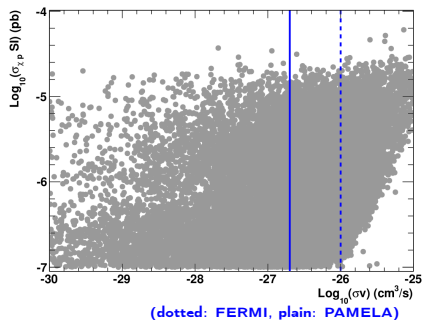


M. Asano, T. Bringmann, C. Weniger, Phys.Lett. B709 (2012) 128

Direct detection vs. relic density



Direct detection vs. indirect detection

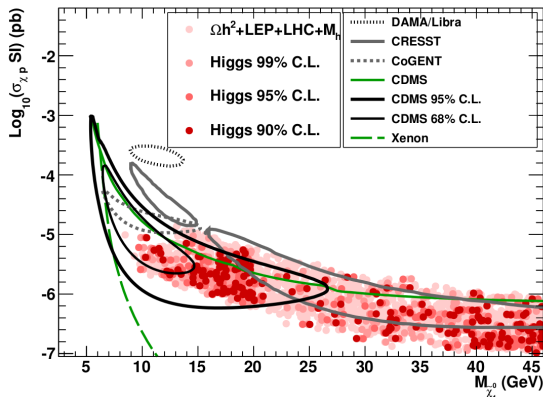


Largest (direct detection) scattering cross sections correspond to

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



Direct detection:

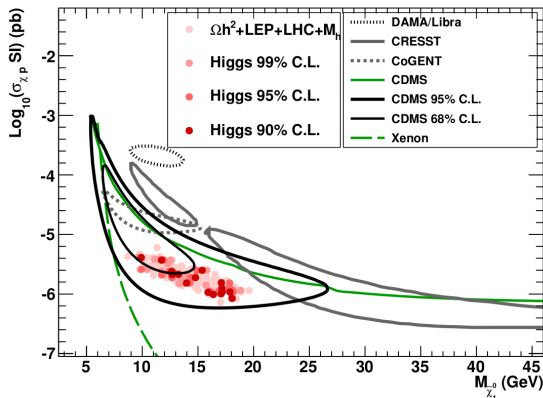


A. Arbey, M. Battaglia, FM, [arXiv:1308.2153](https://arxiv.org/abs/1308.2153)

Loose relic density constraint

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

Direct detection:

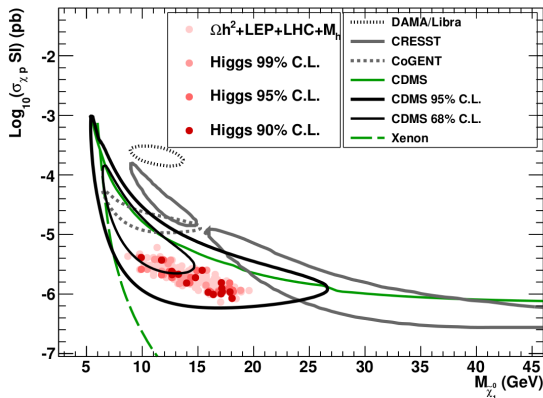


A. Arbey, M. Battaglia, FM, [arXiv:1308.2153](https://arxiv.org/abs/1308.2153)

Tight relic density constraint

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

Direct detection:



A. Arbey, M. Battaglia, FM, [arXiv:1308.2153](https://arxiv.org/abs/1308.2153)

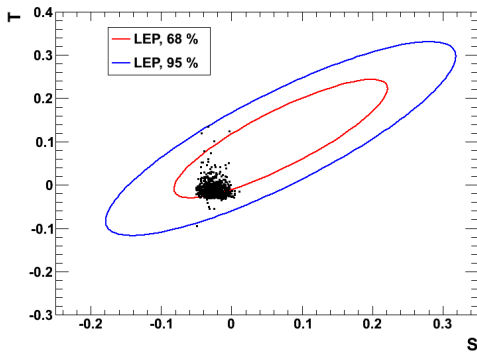
Tight relic density constraint  
 $0.076 < \Omega_\chi h^2 < 0.163$

**Light sbottom scenario satisfies all the present constraints!**

- The MSSM 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  
→ **light neutralino and sbottom scenario**
- Beyond neutralino dark matter, possibility of gravitino, axino, (right-handed) sneutrino DM

Backup

Type	Constraint
Higgs mass constraint Higgs signal strengths	$M_h \in [121, 129] \text{ GeV}$ ATLAS+CMS
Z decay widths	$\Gamma(Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) < 3 \text{ MeV}$ $\Gamma(Z \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0) + \Gamma(Z \rightarrow \tilde{b}_1 \tilde{b}_1) < 5 \text{ MeV}$ $0.21497 < R_b < 0.21761$
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	$2.63 \times 10^{-4} < \text{BR}(B \rightarrow X_s \gamma) < 4.23 \times 10^{-4}$ $1.28 \times 10^{-9} < \text{BR}(B_s \rightarrow \mu^+ \mu^-)_{\text{untag}} < 4.52 \times 10^{-9}$ $0.40 \times 10^{-4} < \text{BR}(B_u \rightarrow \tau \nu) < 1.88 \times 10^{-4}$ $4.7 \times 10^{-2} < \text{BR}(D_s \rightarrow \tau \nu) < 6.1 \times 10^{-2}$ $2.9 \times 10^{-3} < \text{BR}(B \rightarrow D^0 \tau \nu) < 14.2 \times 10^{-3}$ $0.985 < R_{\mu 23} < 1.013$
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	$\sigma v_{\text{tot}} < 10^{-26} \text{ cm}^3/\text{s}$ with $M_{\tilde{\chi}_1^0} < 50 \text{ GeV}$ $\sigma v_{b\bar{b}g} < 2 \times 10^{-27} \text{ cm}^3/\text{s}$ with $M_{\tilde{\chi}_1^0} < 50 \text{ GeV}$
Dark matter direct detection	$10^{-7} < \sigma_{p-\chi}^{\text{SI}} < 10^{-2} \text{ pb}$ with $M_{\tilde{\chi}_1^0} < 50 \text{ GeV}$ (close to the CDMS contour and XENON limit)
LHC searches	Higgs searches SUSY searches $pp \rightarrow \chi\chi + \text{jets}, \gamma \text{ and } Z/W \text{ searches}$



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