Dark matter and MSSM

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In collaboration with M. Battaglia & F. Mahmoudi

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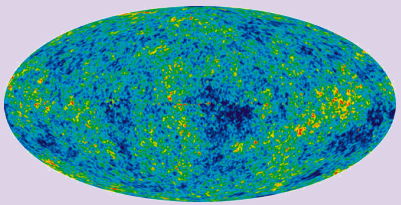
Dark Matter Problem

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, ...

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!

Outline

- Neutralino dark matter
- Very light neutralino dark matter
- Collider physics constraints
  - LHC direct SUSY searches
  - LHC Higgs results
  - Interplay of collider and dark matter results
- Conclusions

Neutralino dark matter

Minimal Supersymmetric Model (MSSM)

From N. Mahmoudi's yesterday talk!

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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^-

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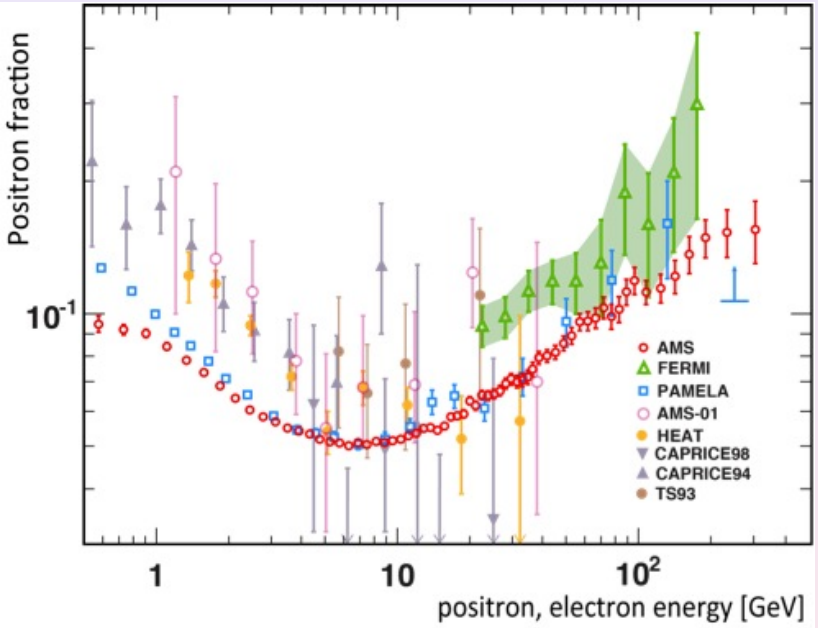
Dark matter indirect detection

FERMI-LAT: large excess in the γ spectrum at ~ 130 GeV

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



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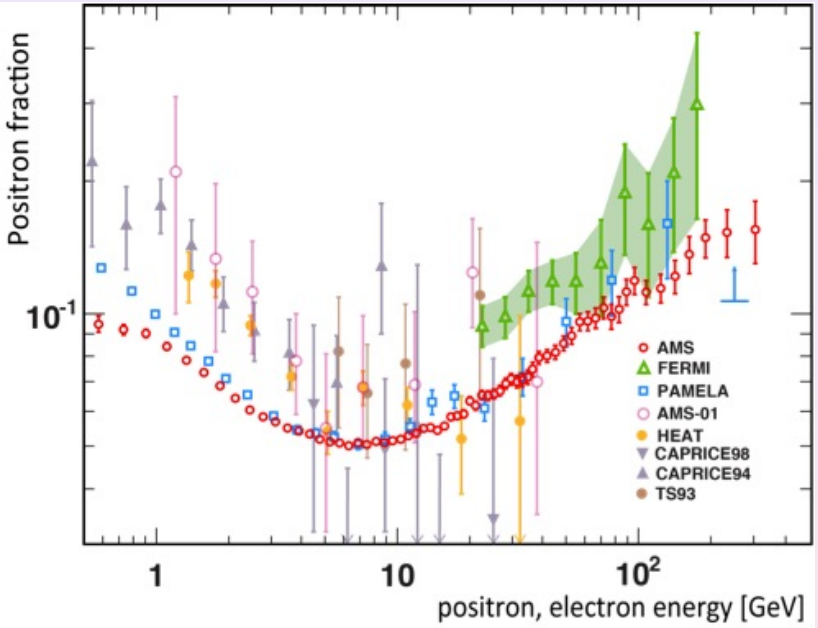

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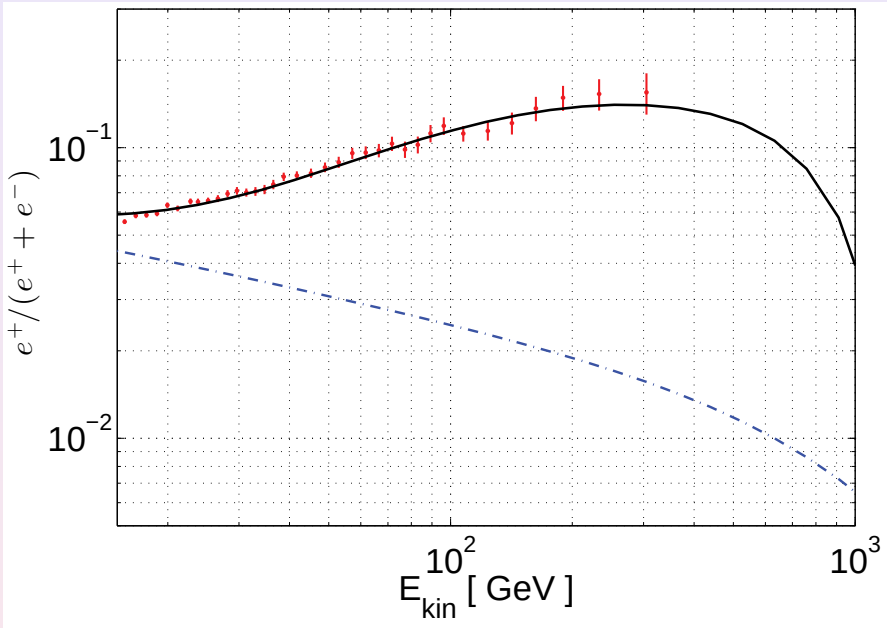

De Simonea, Riotto, Xue, arXiv:1304.1336

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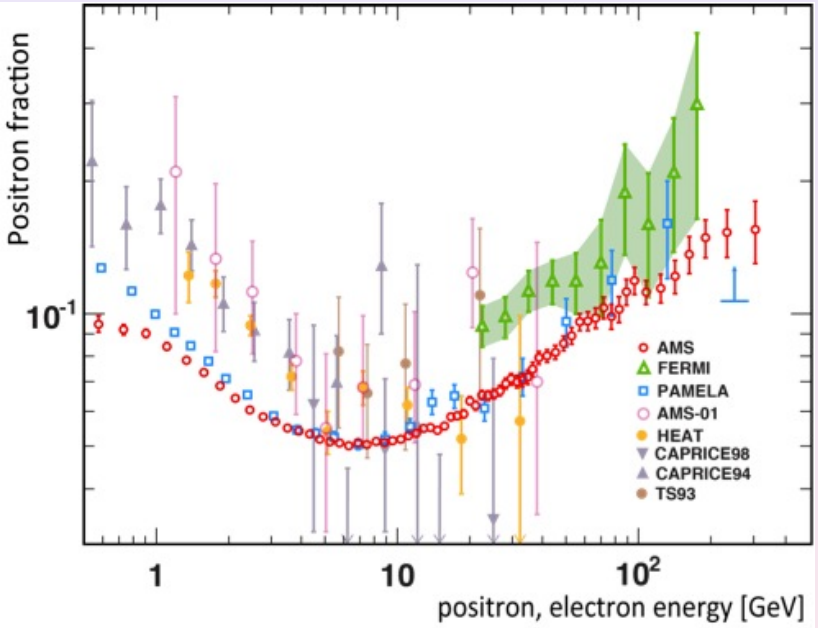

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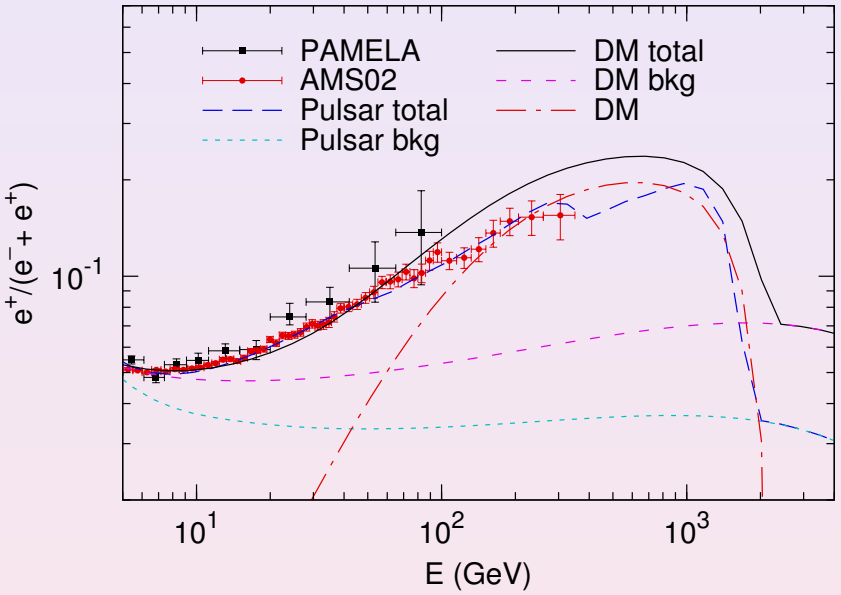

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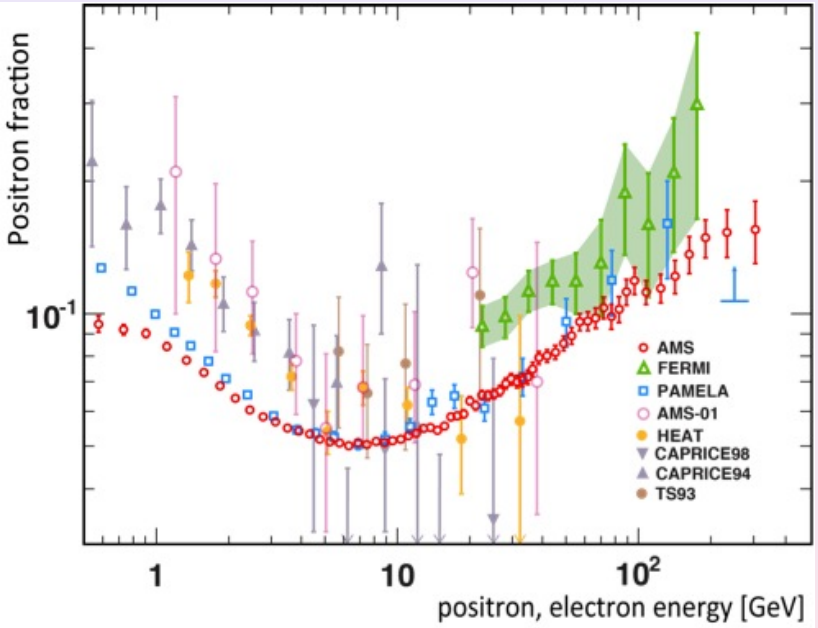

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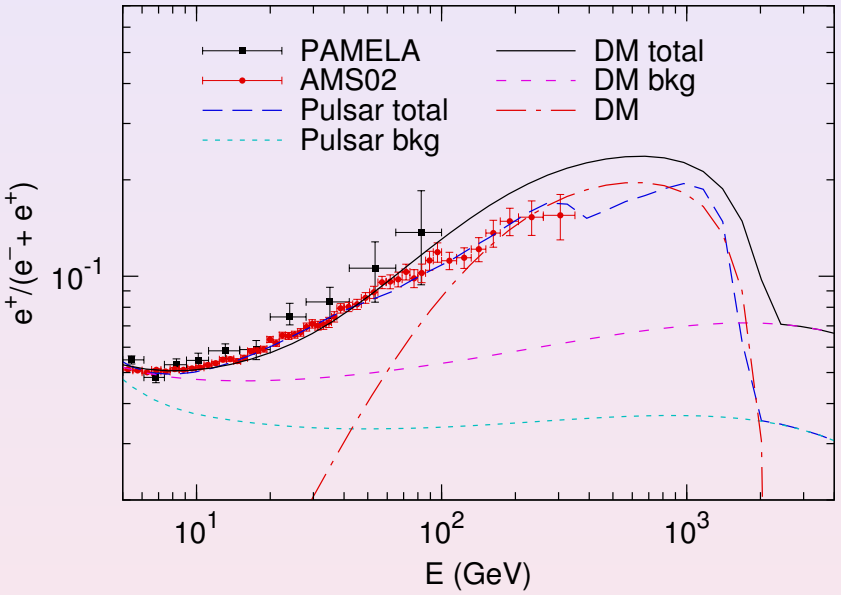

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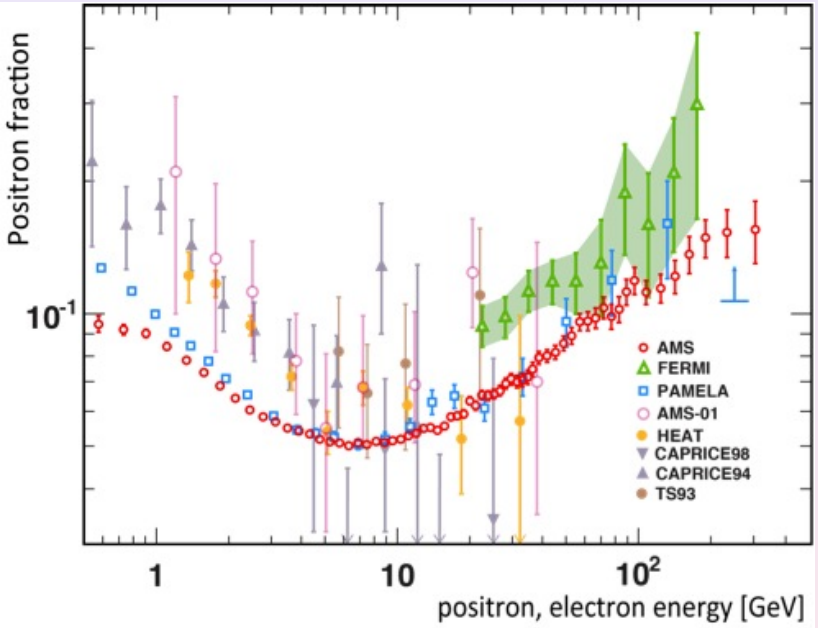

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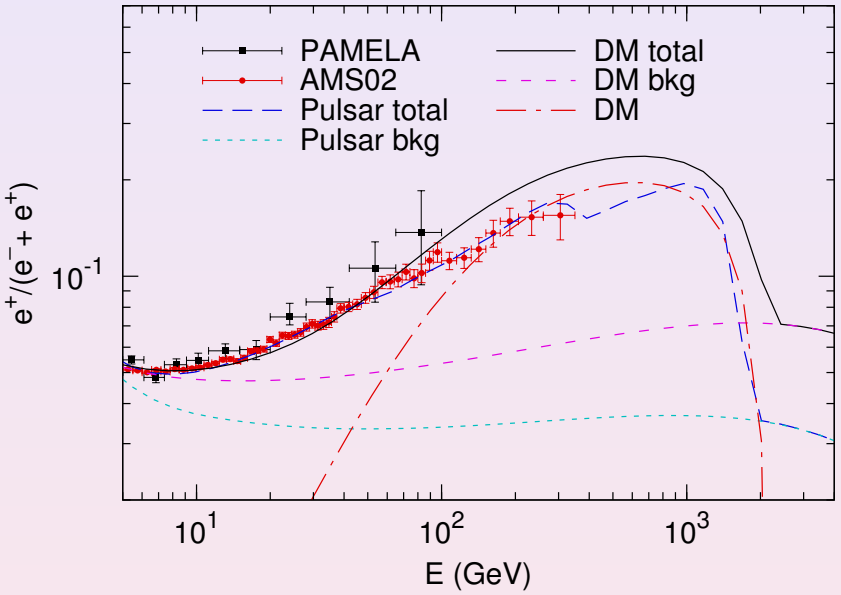

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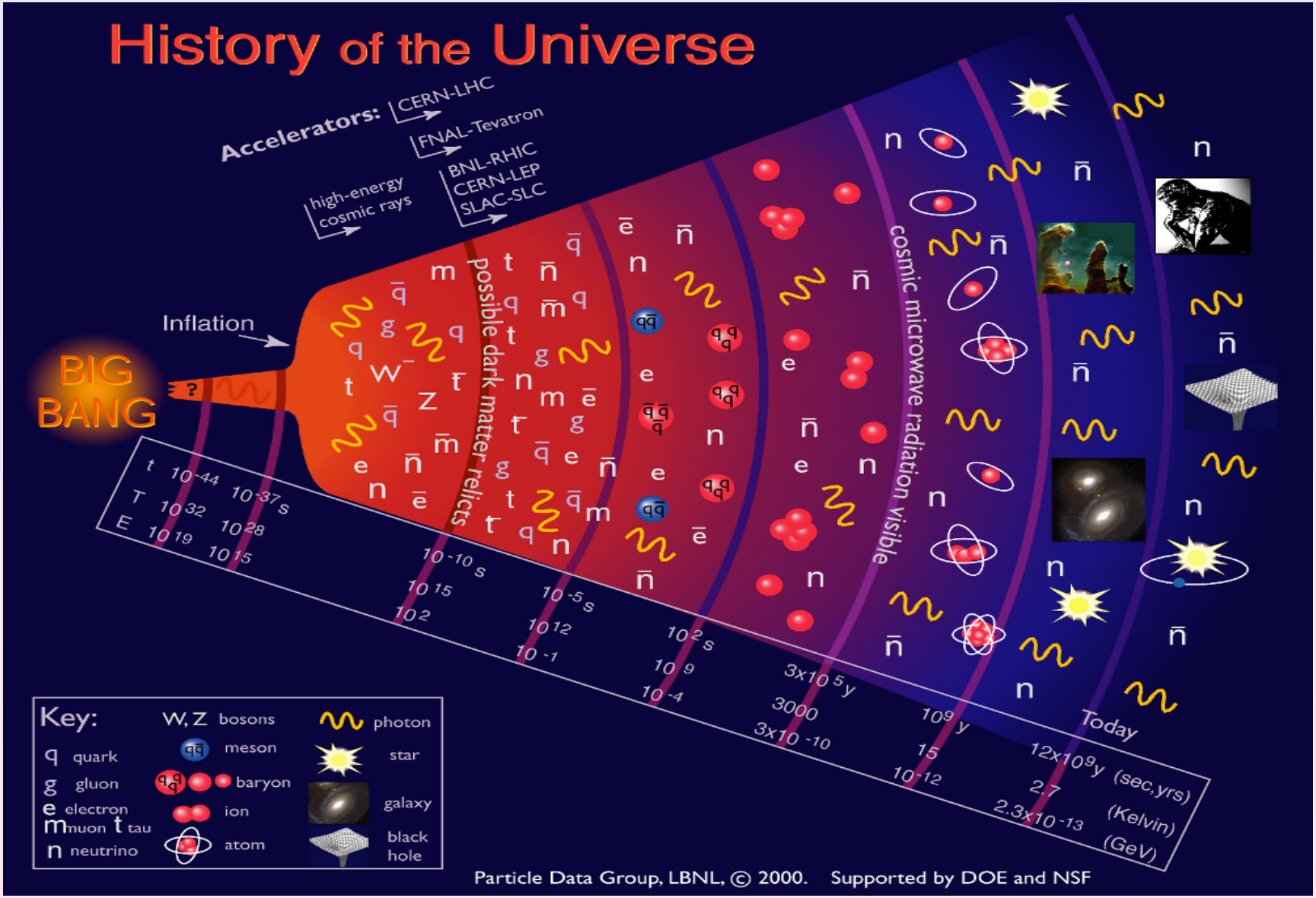
In our study, because of the astrophysical uncertainties, we do NOT impose indirect detection constraints

Dark matter relic density



Dark matter relic density

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 WMAP interval:

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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
- ...

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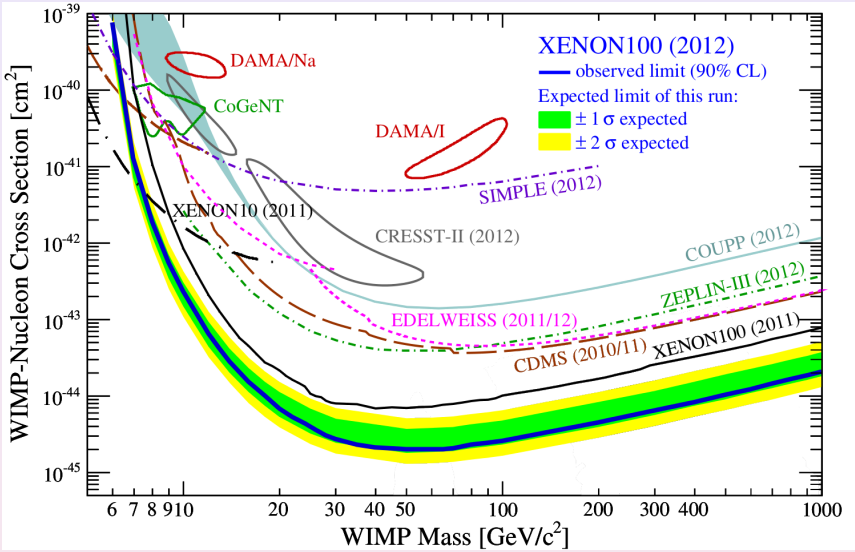
Dark matter direct detection

Present situation:



XENON, arXiv:1207.5988

- DAMA, CoGeNT, CRESST and now CDMS claim for a possible WIMP discovery
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→ **Unclear situation, but the sensitivity is improving!**

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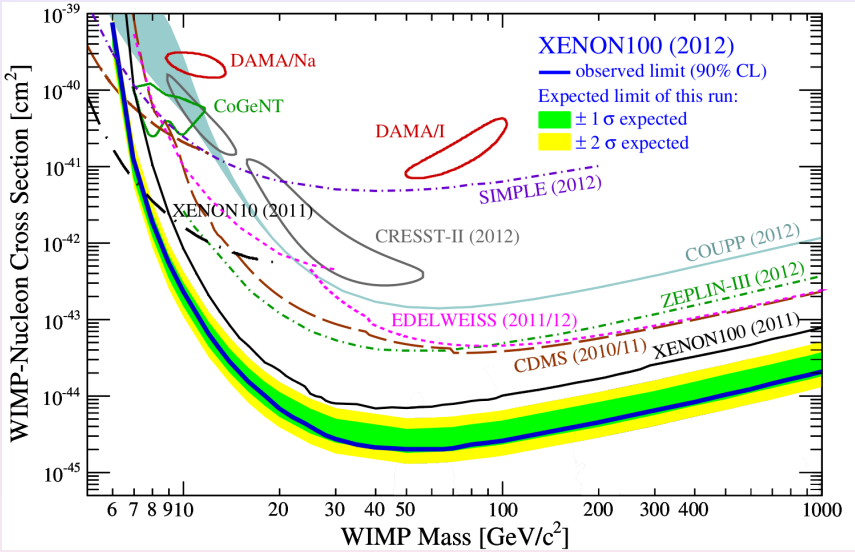

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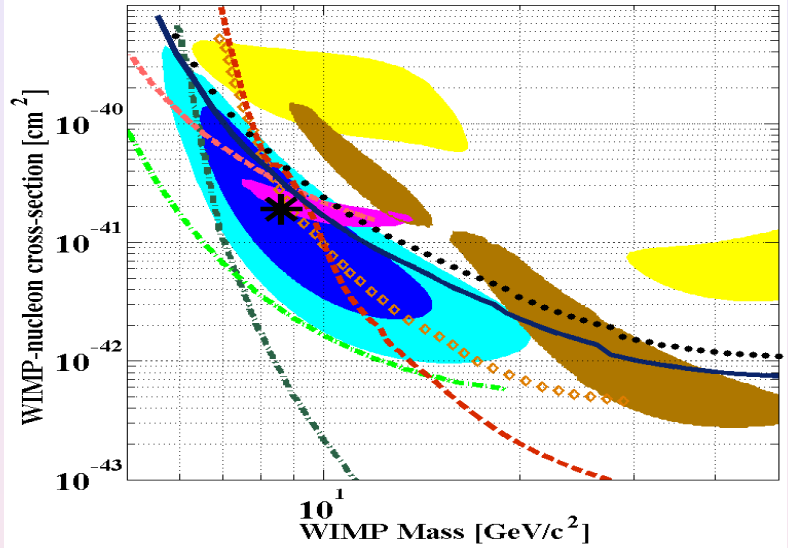

CDMS, arXiv:1304.4279

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Supersymmetric framework

Phenomenological MSSM (pMSSM)

Rather general MSSM model with 19 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

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

We consider the lightest neutralino as DM, which can be

- bino-like ($|M_1| \ll |M_2|, |\mu|$)
- wino-like ($|M_2| \ll |M_1|, |\mu|$)
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$\rightarrow$ Different couplings and properties

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pMSSM scans

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

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pMSSM scans

Constraints from:

- LEP and Tevatron direct search limits
- Flavour precision limits, in particular from BR($B \to X_s\gamma$), BR($B_s \to \mu^+\mu^-$), BR($B \to \tau\nu$)
- Muon anomalous magnetic moment, $(g-2)_\mu$
- Dark matter relic density (neutralino LSP)
- Dark matter direct search limits
- LHC SUSY direct search limits
- Higgs mass limits
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Statistics:

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

Largest statistics in the MSSM so far.

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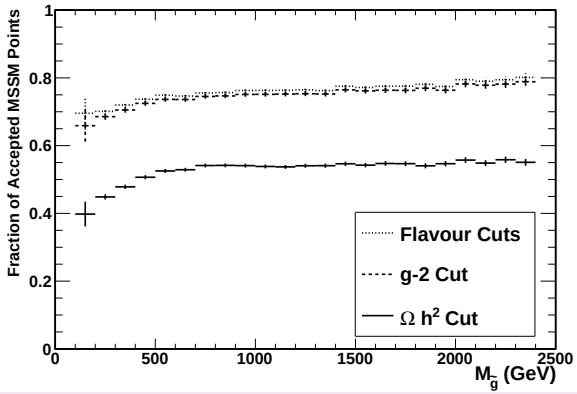
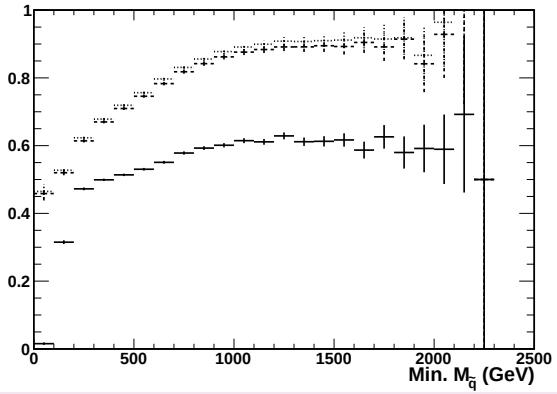
Relic density and pMSSM

Effect of constraints and fraction of accepted points:

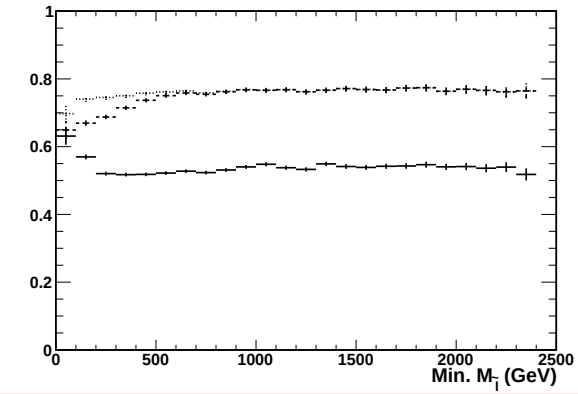
gluino



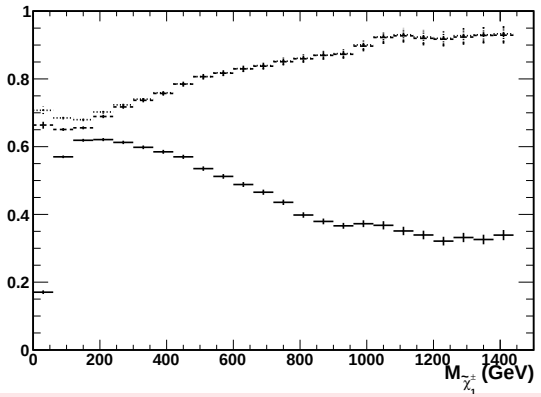
lightest squark



lightest slepton



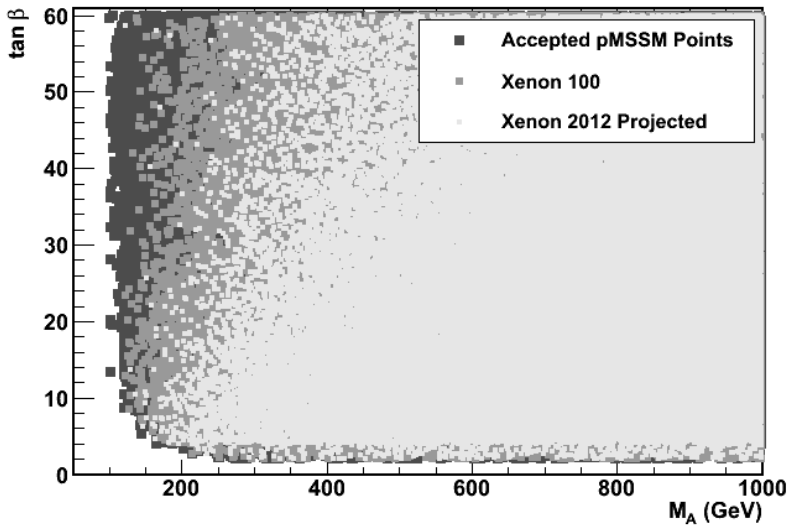
light chargino

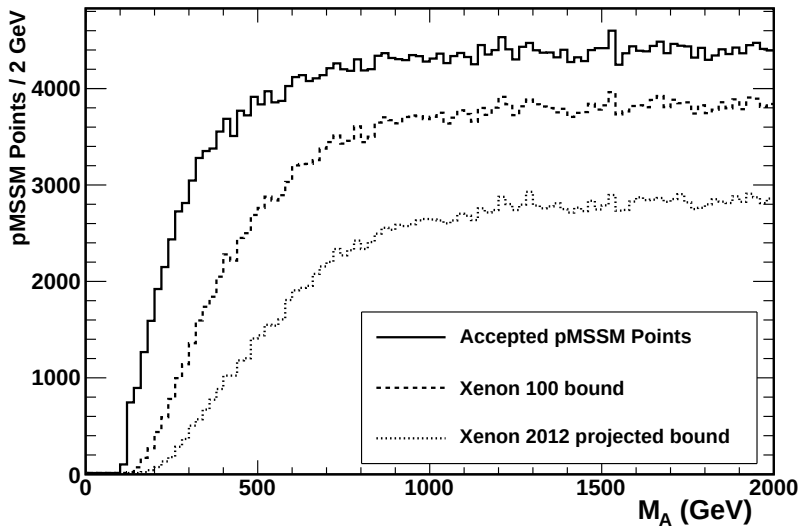


AA, M. Battaglia, F. Mahmoudi, Eur.Phys.J. C72 (2012) 1847

Neutralinos and dark matter direct detection

pMSSM points and XENON dark matter exclusion limit



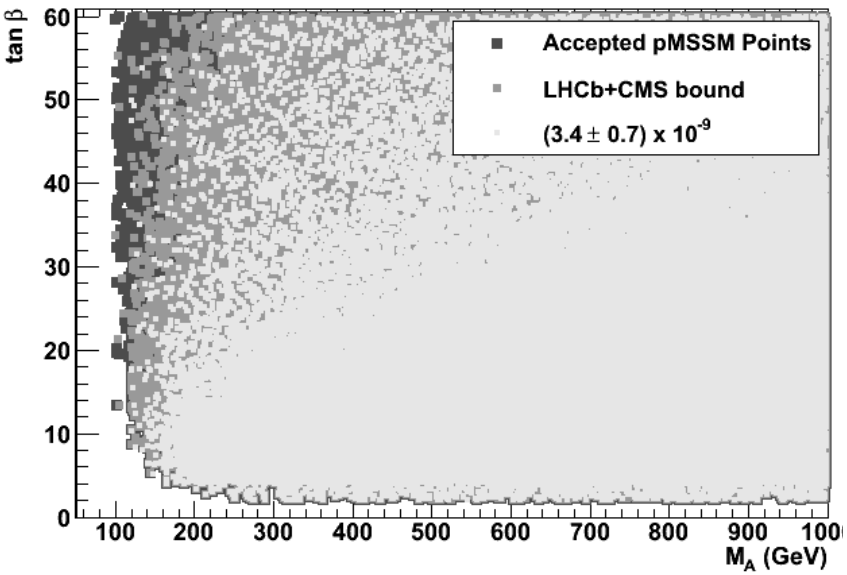


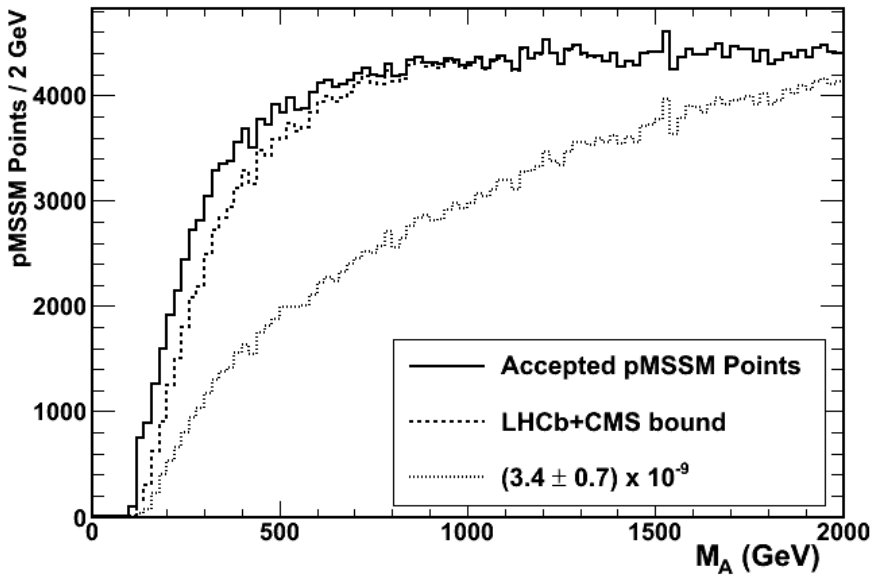
AA, M. Battaglia, F. Mahmoudi, Eur.Phys.J. C72 (2012) 1906

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

Sensitivity to M_A from BR($B_s \to \mu^+\mu^-$)

For comparison: BR($B_s \to \mu^+\mu^-$) constraint





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

Very light neutralino dark matter

Light neutralinos in the pMSSM

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

pMSSM study

Low mass neutralino of ~ 10 GeV?

Not possible in constrained MSSM...

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

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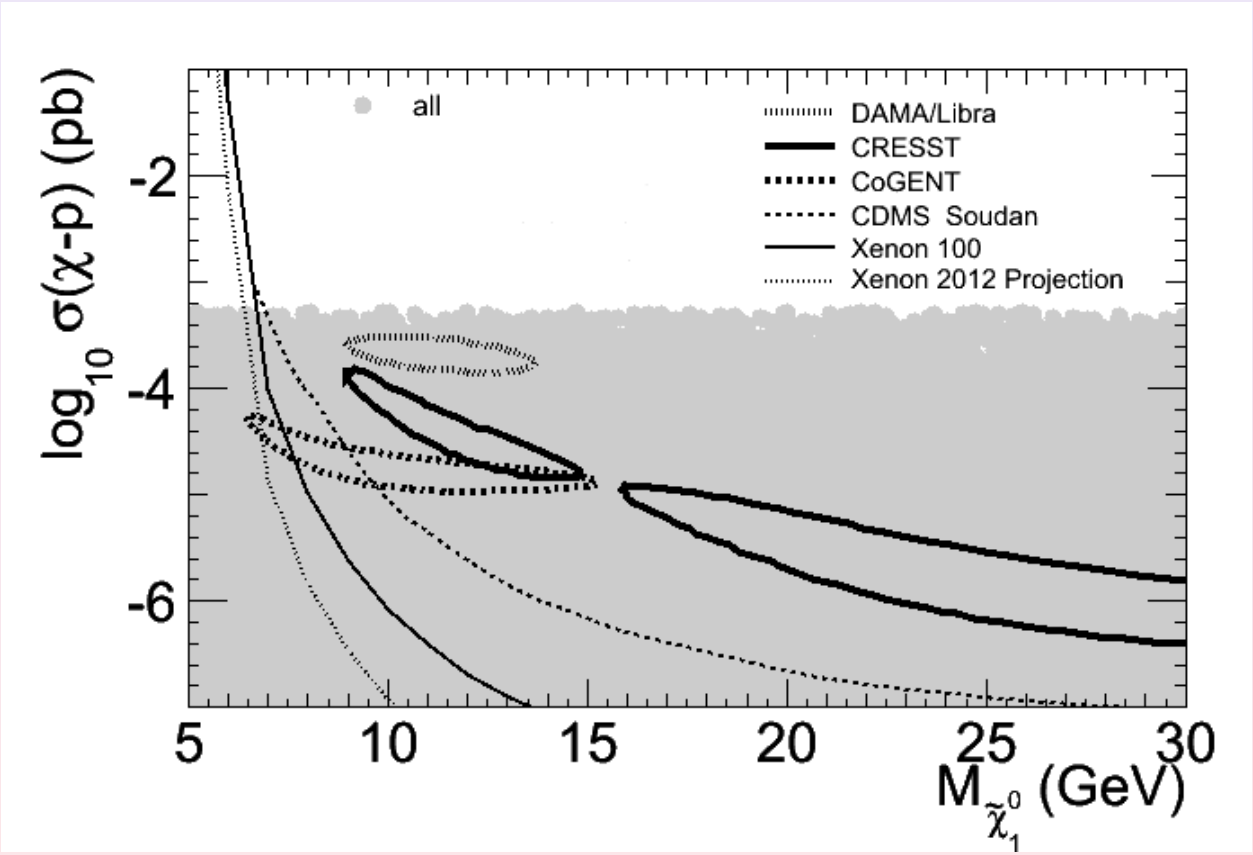
Light neutralinos and dark matter direct detection

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



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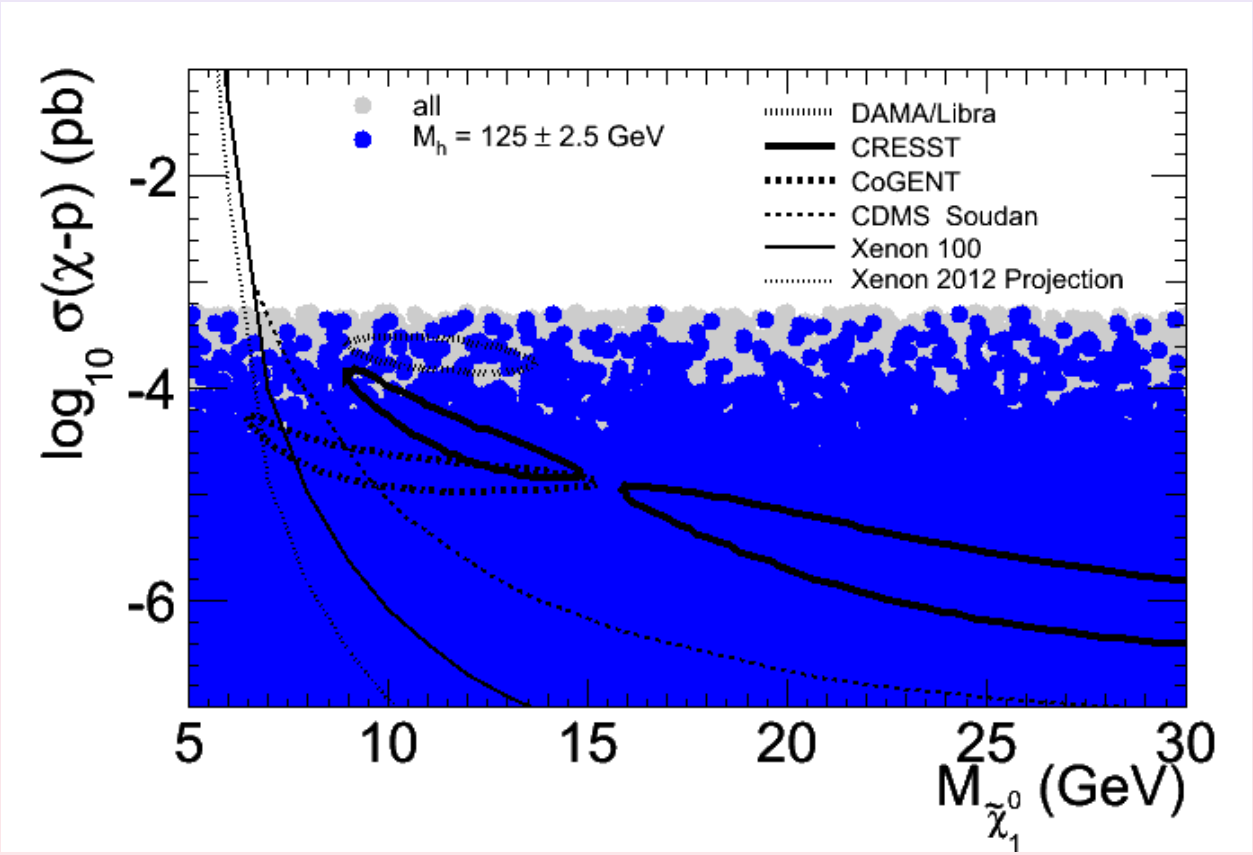
AA, M. Battaglia, F. Mahmoudi, Eur.Phys.J. C72 (2012) 2169

Light neutralinos and dark matter direct detection

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



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

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Light neutralinos and dark matter direct detection

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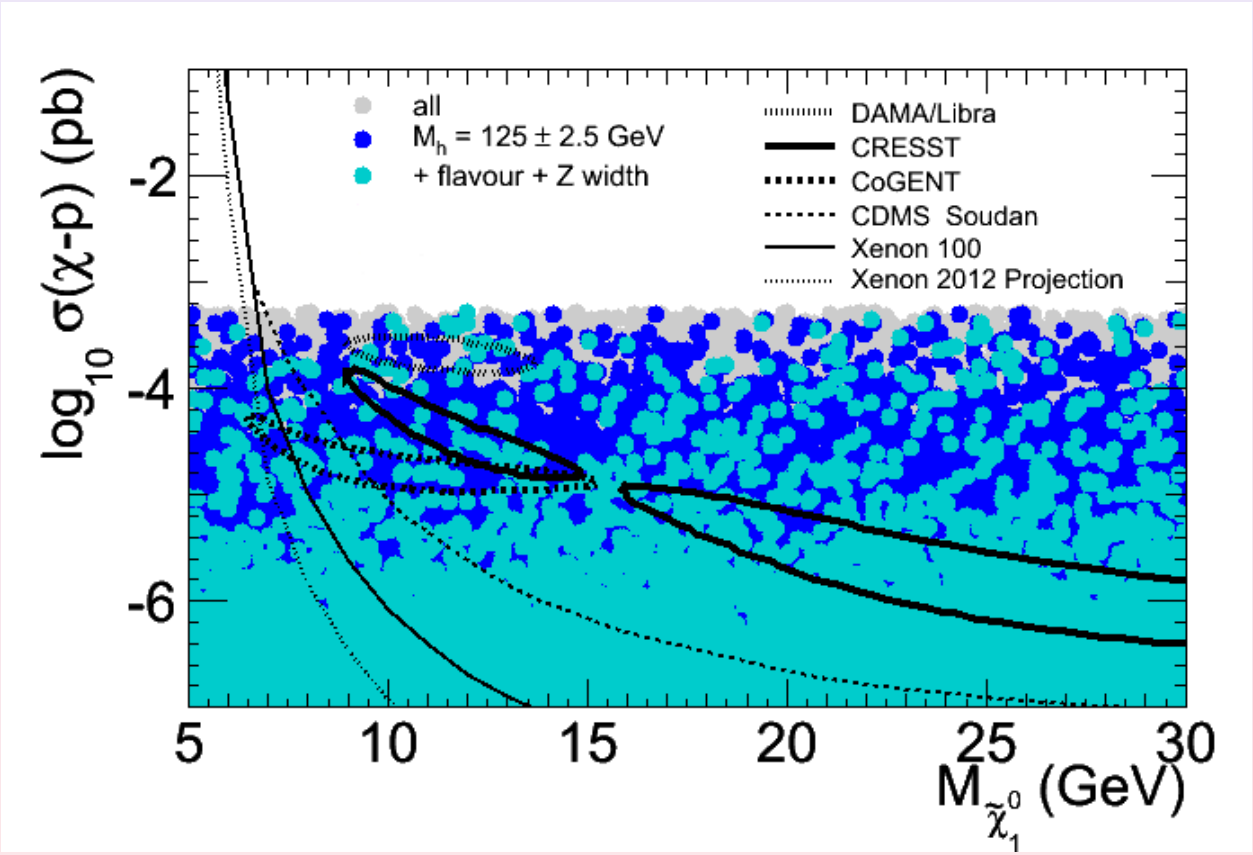

+Flavour + Z widths
$\sim$ 10k points (1%)

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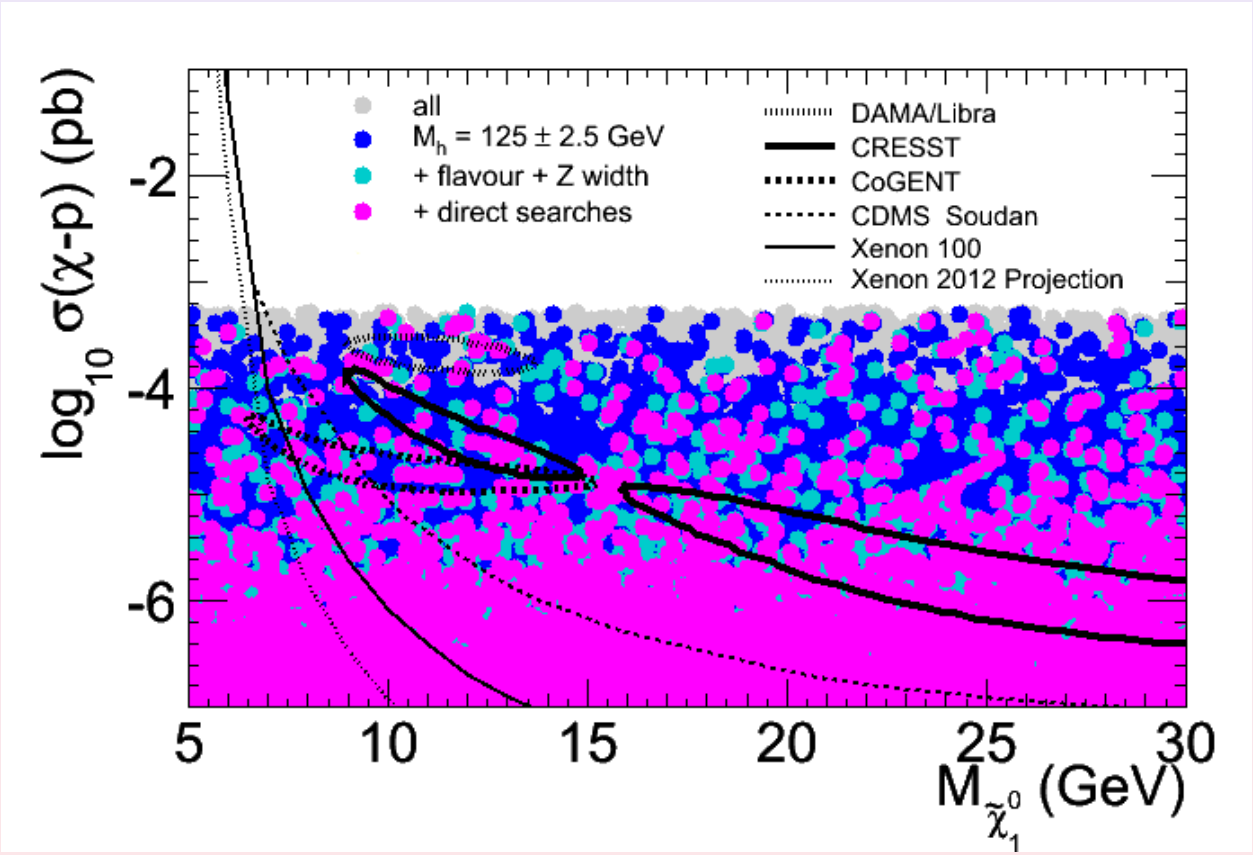

+Direct searches + Monojets
$\sim$ 5k points (0.5%)

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Light neutralinos and dark matter direct detection

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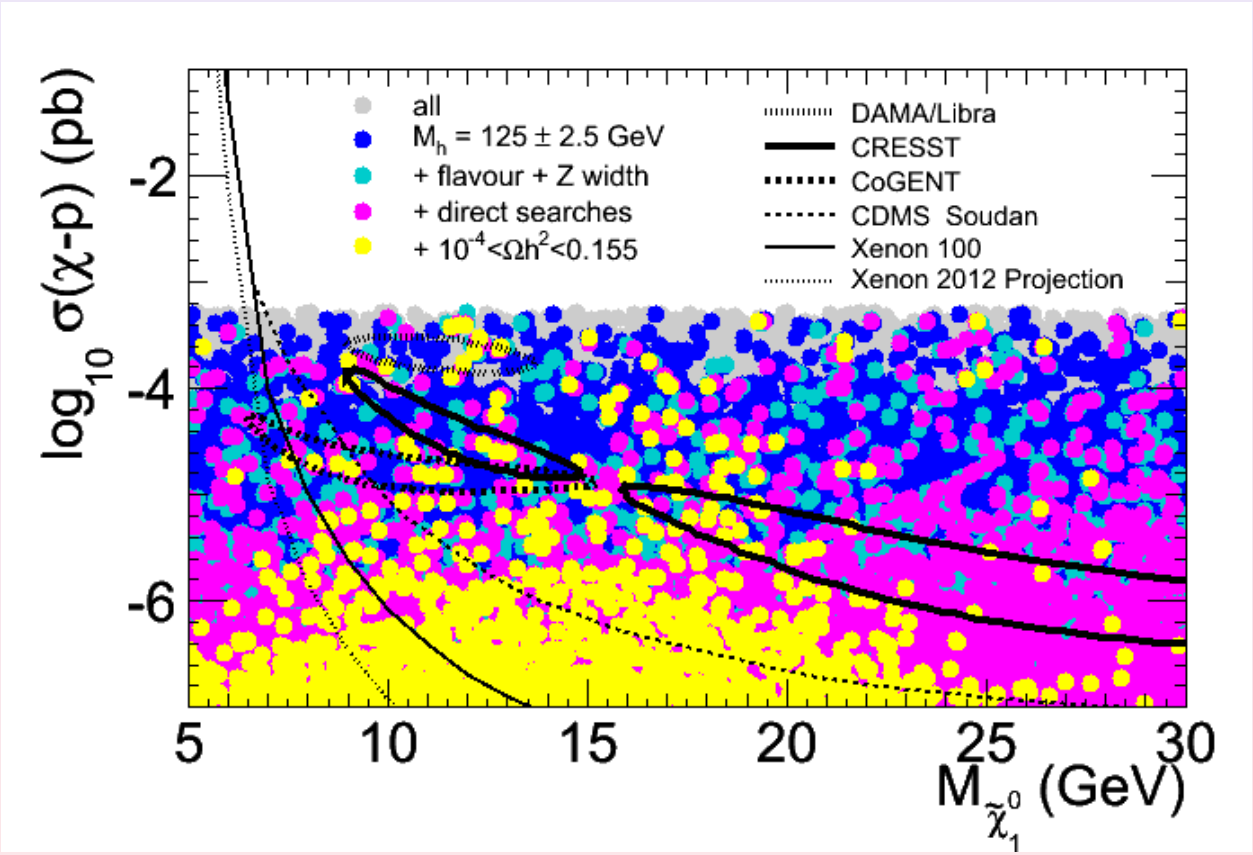

+Loose relic density
$\sim$ 1k points (0.1%)

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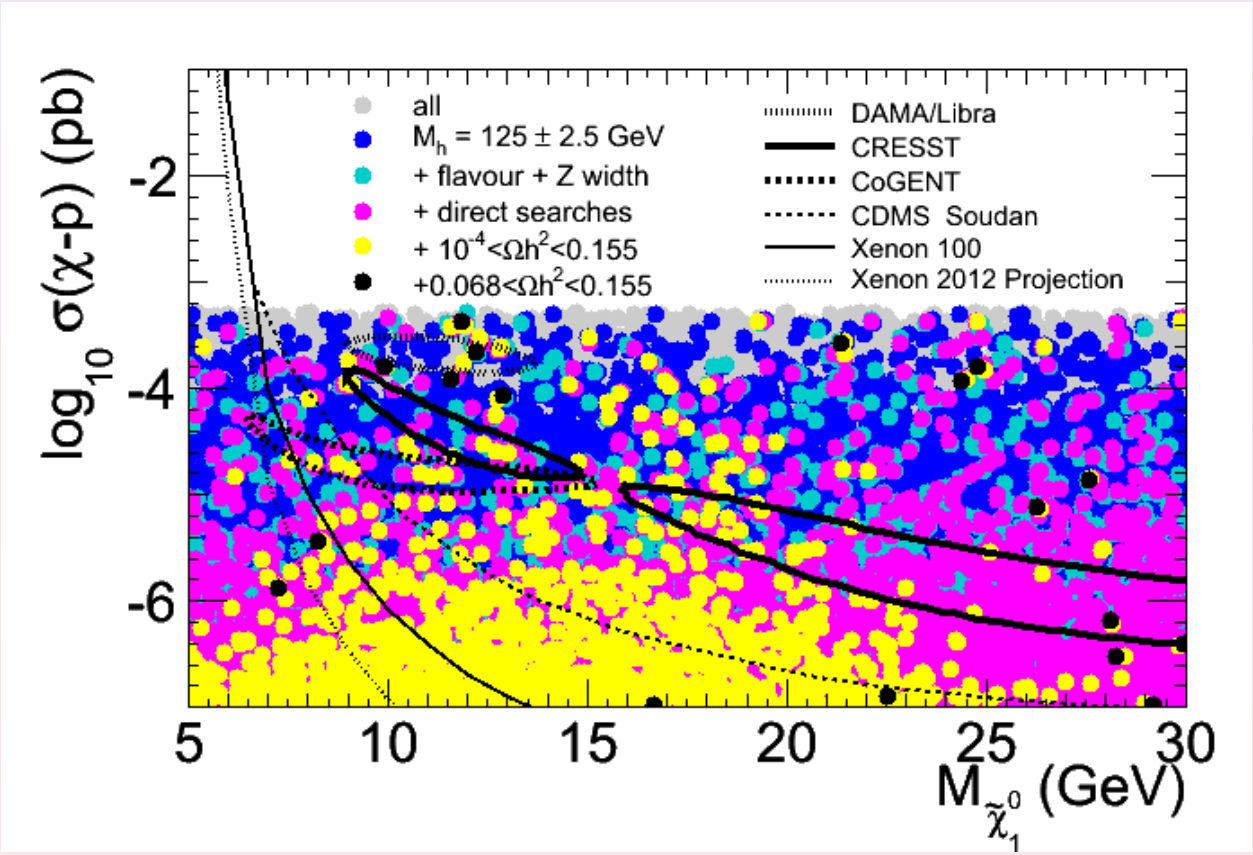
Light neutralinos and dark matter direct detection

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



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

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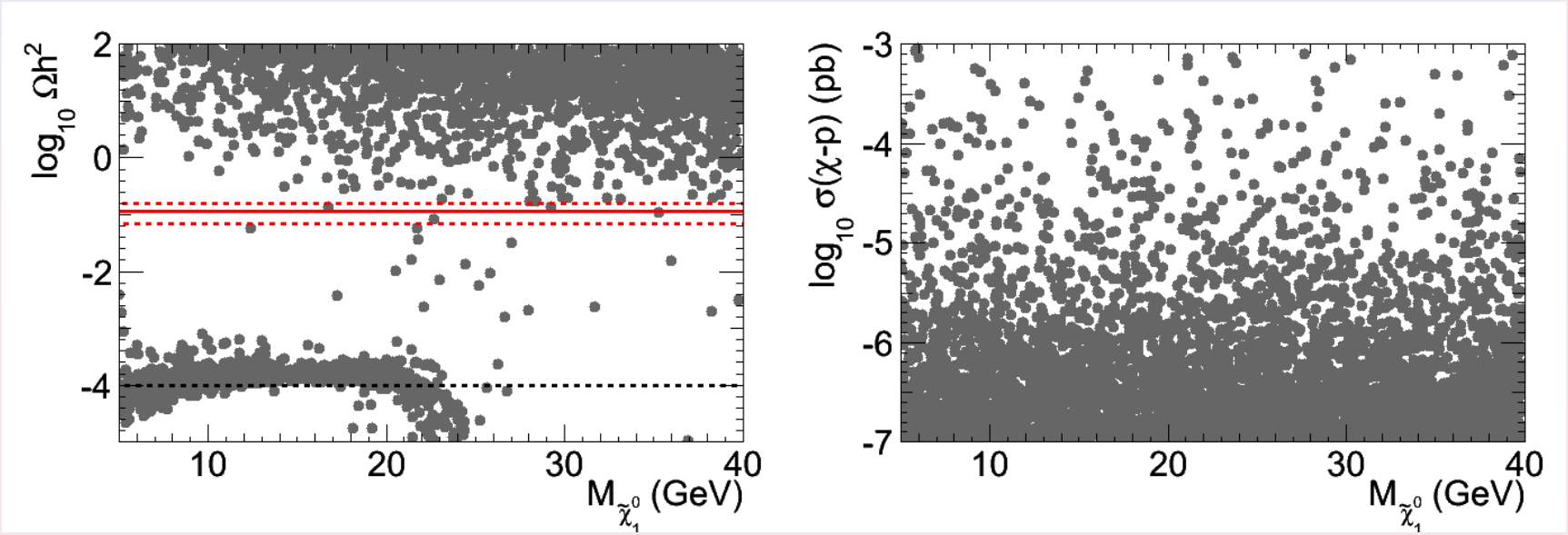
Light neutralinos and dark matter direct detection

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



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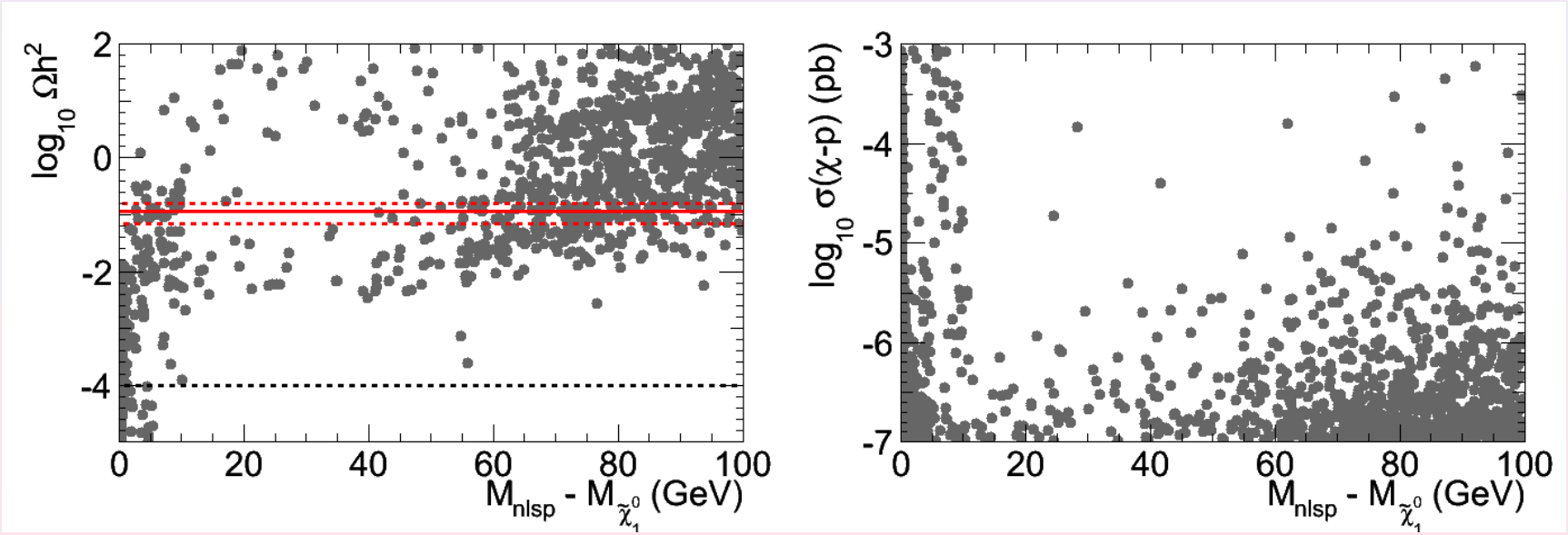

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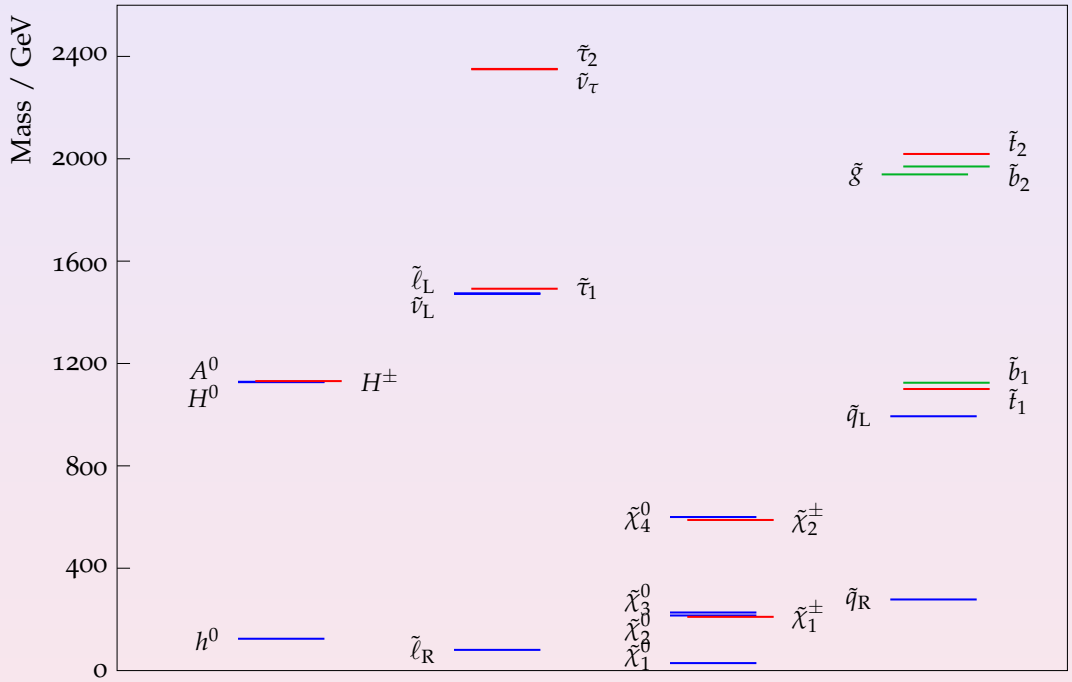
Light neutralinos and dark matter direct detection

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)

Light neutralinos and dark matter direct detection

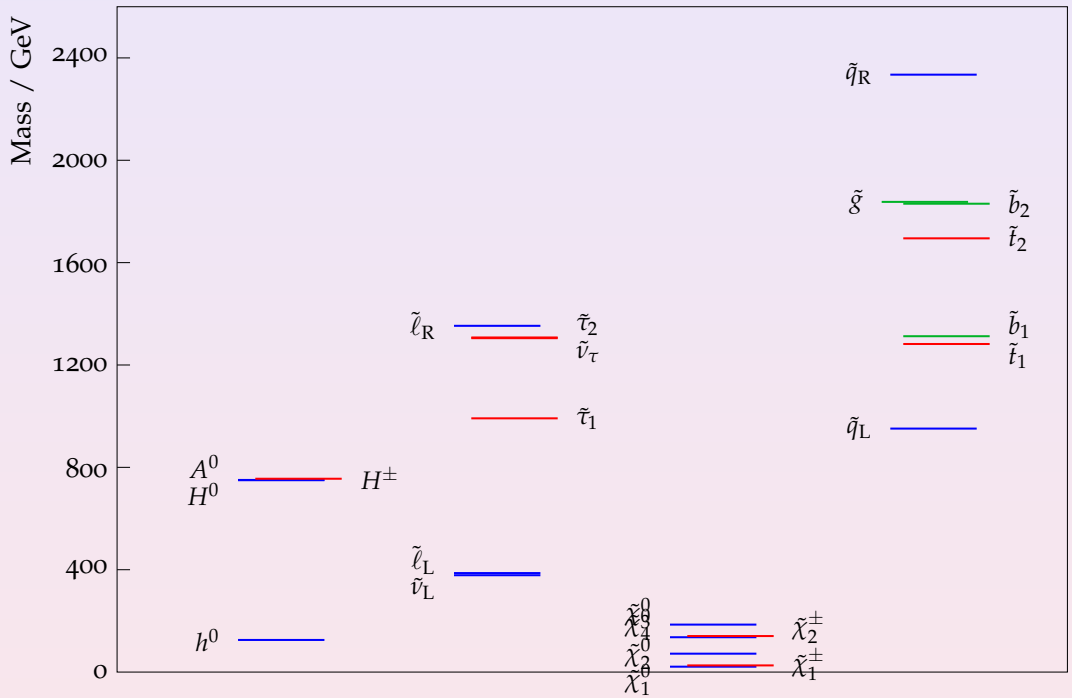
Slepton with a mass at the LEP limit



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

Light neutralinos and dark matter direct detection

Compressed spectrum in the neutralino/chargino sector

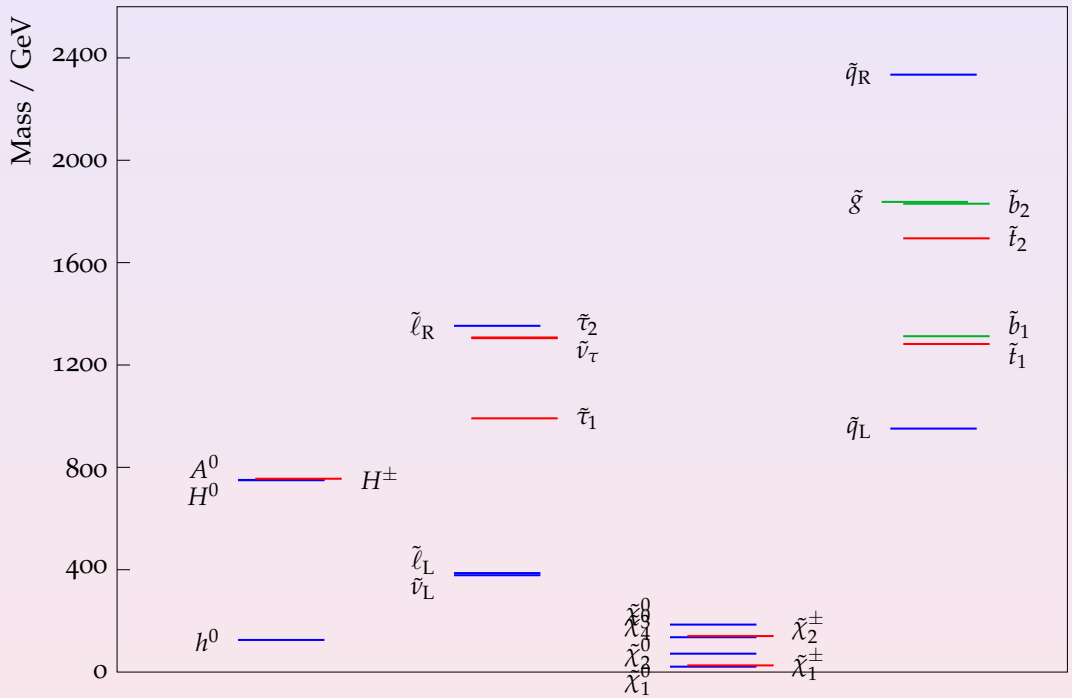


This scenario may be very interesting...

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

Light neutralinos and dark matter direct detection

Compressed spectrum in the neutralino/chargino sector



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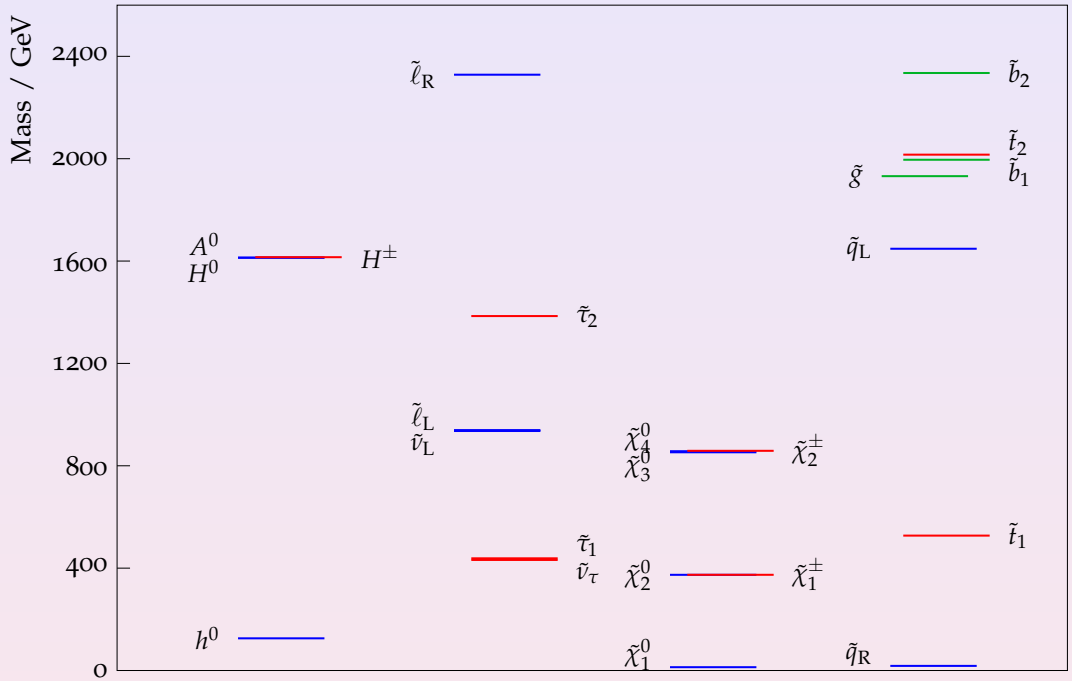
Light neutralinos and dark matter direct detection

One squark quasi-degenerate with the neutralino



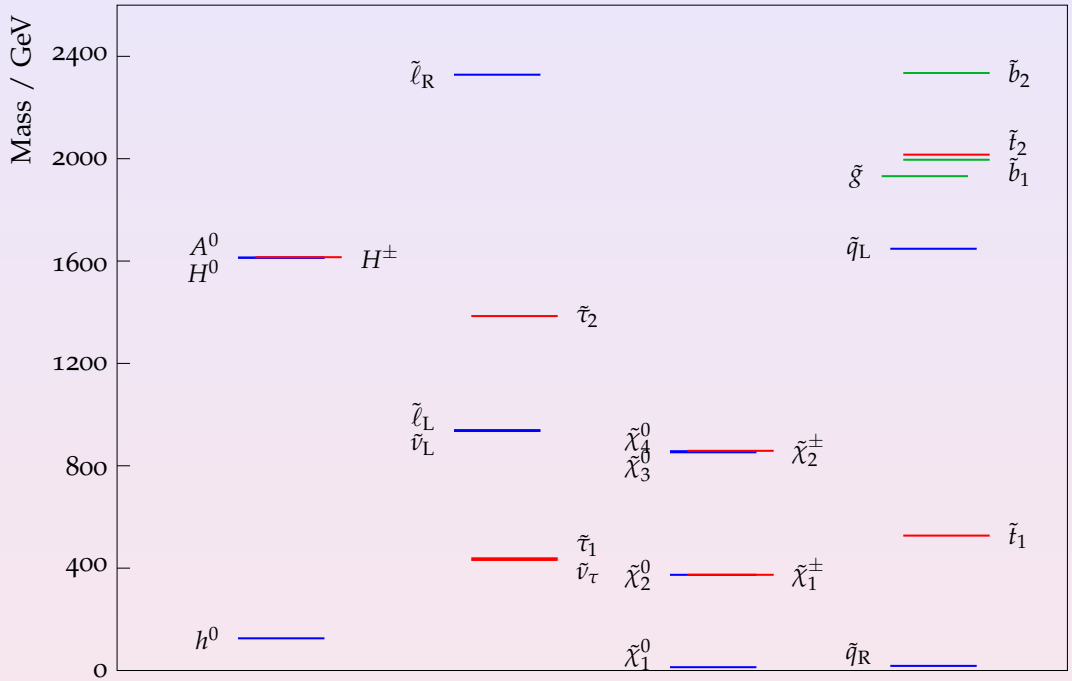
These spectra can fulfill all the constraints and have simultaneously a neutralino mass below 15 GeV and a large scattering cross-section!

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!

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

Light neutralinos and dark matter direct detection

One squark quasi-degenerate with the neutralino



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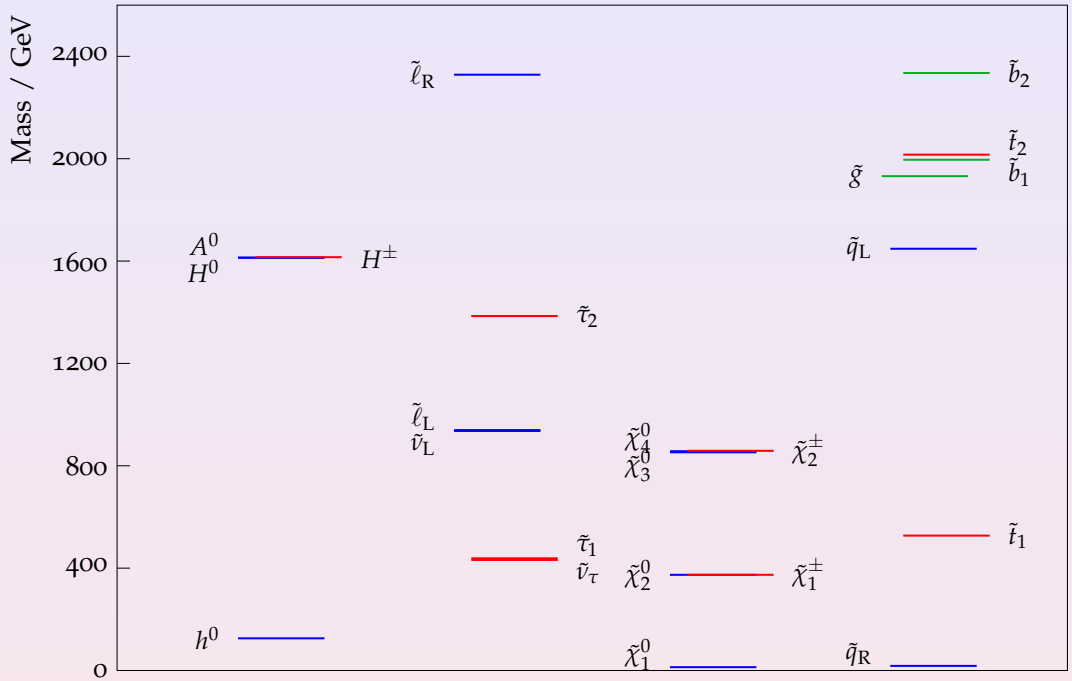

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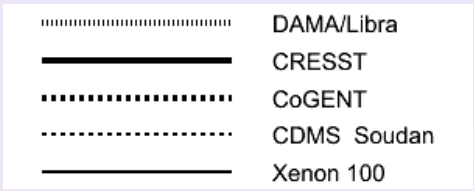
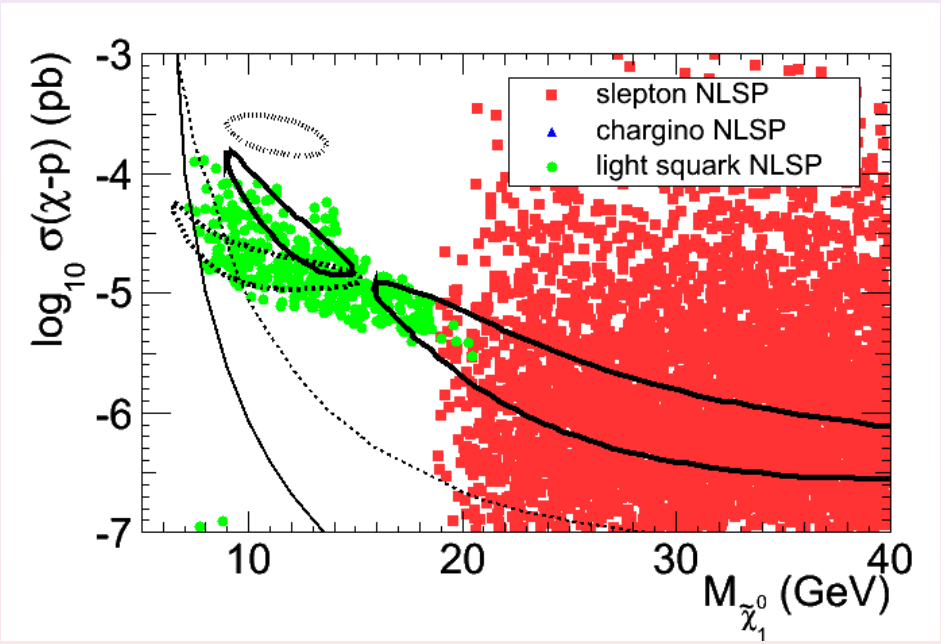
Light neutralinos and dark matter direct detection

Using dedicated scans:





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

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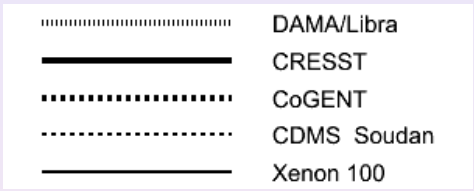
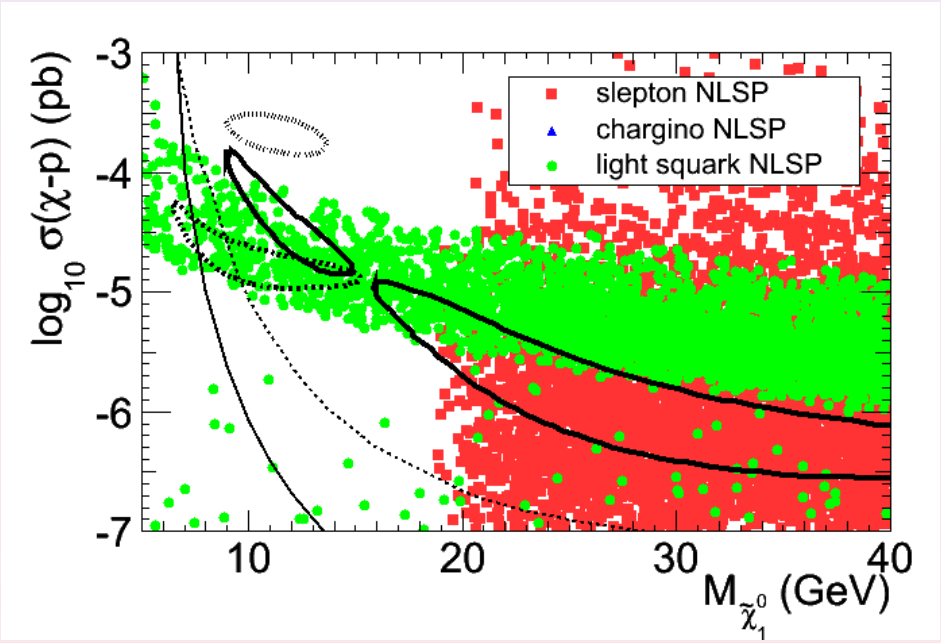
Light neutralinos and dark matter direct detection

Using dedicated scans:





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

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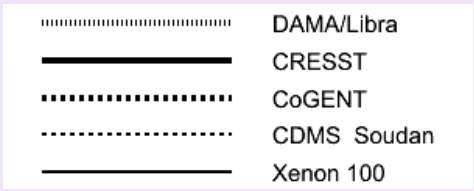
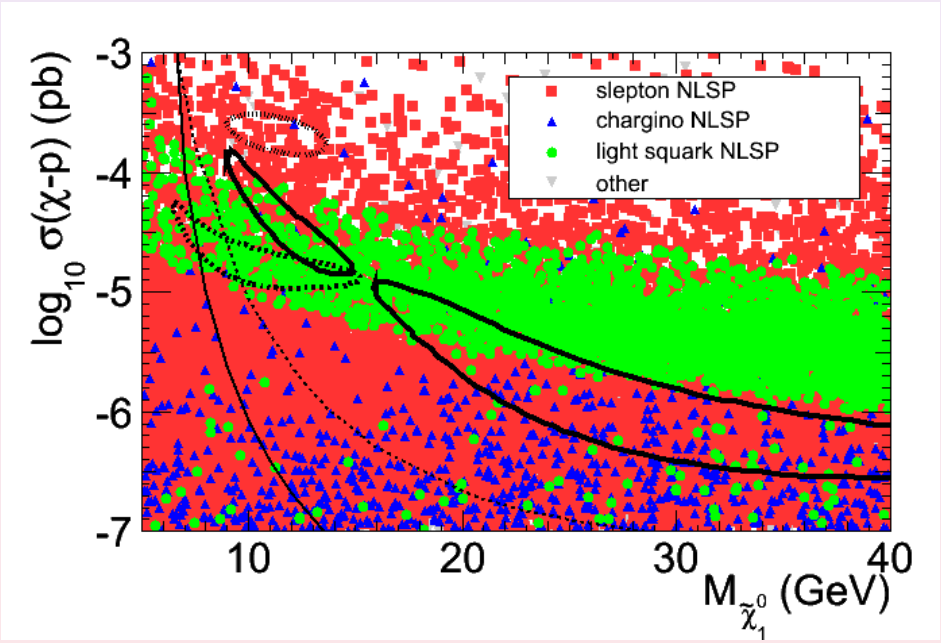
Light neutralinos and dark matter direct detection

Using dedicated scans:





Relaxing the relic density constraint

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Interplay with collider physics

pMSSM scans

Constraints from:

- LEP and Tevatron direct search limits
- Flavour precision limits, in particular from BR($B \to X_s\gamma$), BR($B_s \to \mu^+\mu^-$), BR($B \to \tau\nu$)
- Muon anomalous magnetic moment, $(g-2)_\mu$
- Dark matter relic density (neutralino LSP)
- Dark matter direct search 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.

pMSSM scans

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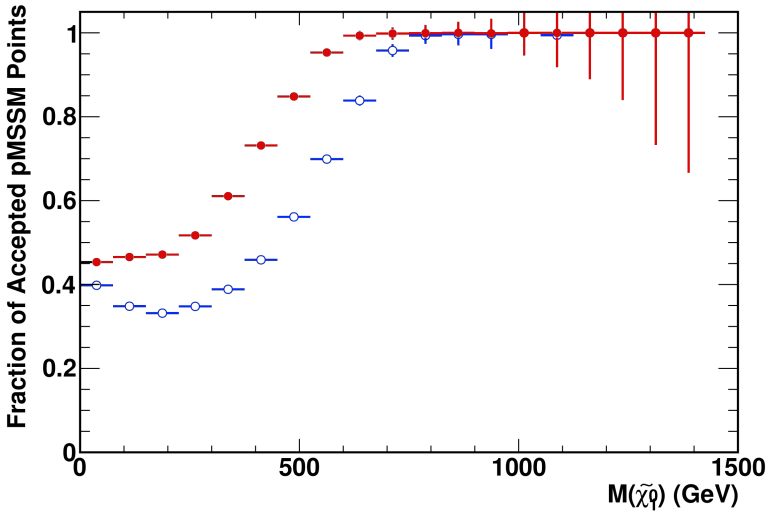
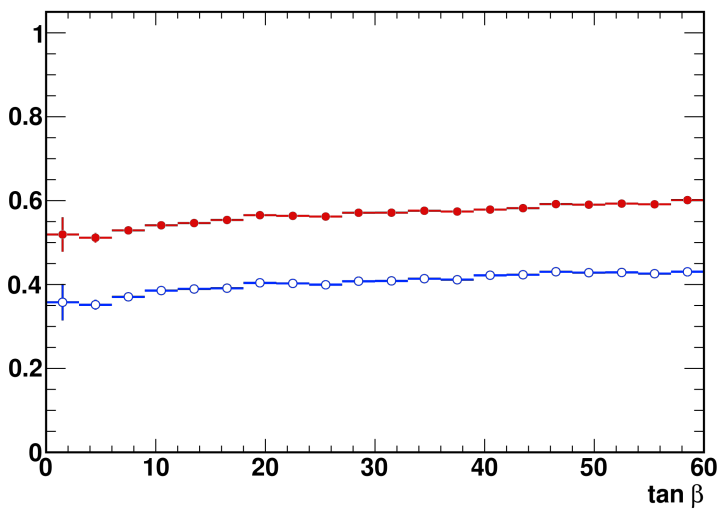
Consequences of SUSY searches in pMSSM

Weakly Interacting Sparticle Spectra of Allowed pMSSM Points

lightest neutralino



$\tan\beta$



Red: 1 fb^{-1}
Blue: 15 fb^{-1}

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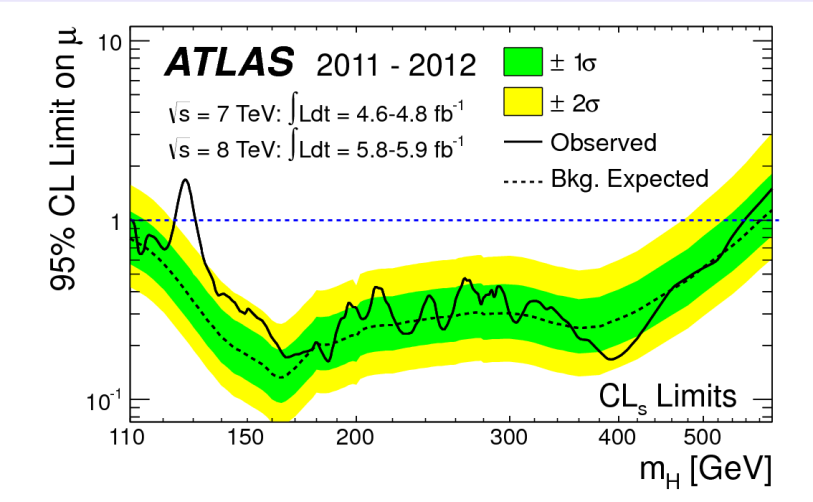
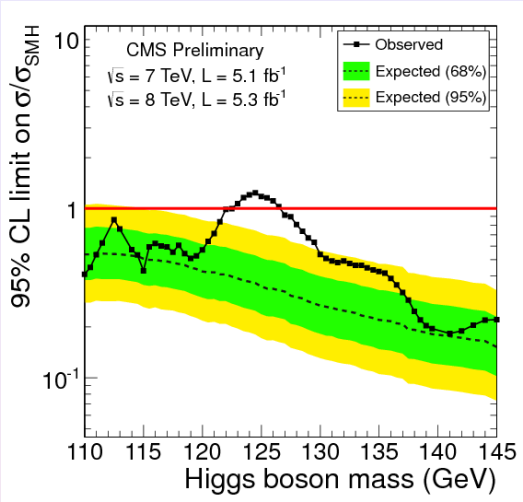
The domain of neutralino masses above 500 GeV is relatively unaffected by the present LHC data

Higgs sector



ATLAS-CONF-2012-091



CMS PAS HIG-2012-015

Parameter	Combined value	Experiment
M_H (GeV)	125.7 ± 2.1	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

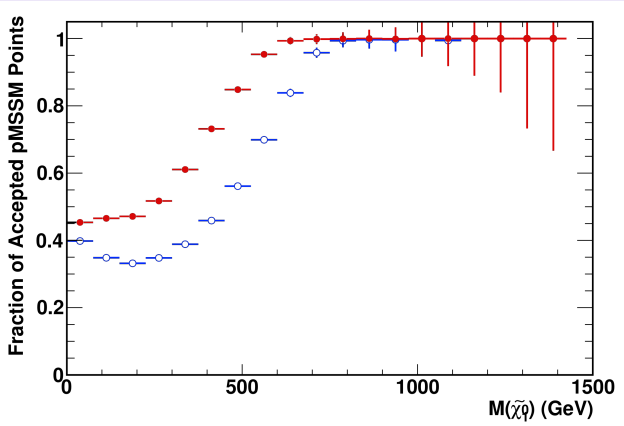
$$\mu_{XX} = \frac{\sigma(pp \to h)\,\mathrm{BR}(h \to XX)}{\sigma(pp \to h)_{\mathrm{SM}}\,\mathrm{BR}(h \to XX)_{\mathrm{SM}}}$$

$\to$ diphoton decay mode $\Rightarrow$ massive neutral boson with spin $\neq 1$
$\to$ compatible with the SM Higgs
$\to$ still too early for conclusive information from couplings/rates

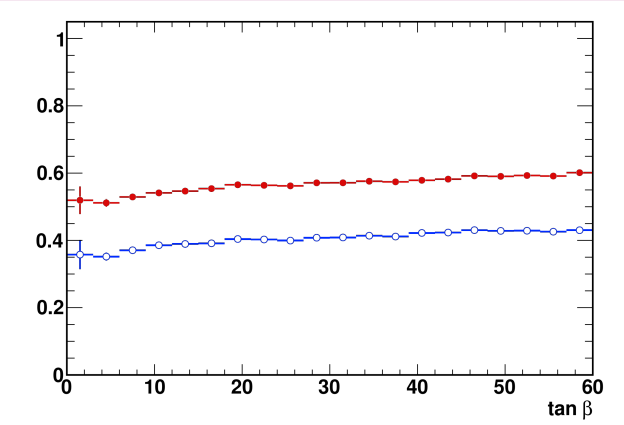
Consequences of a 126 GeV Higgs

Impact on the lightest neutralino mass

With $M_h > 111$ GeV



Impact on $\tan\beta$



AA, M. Battaglia, F. Mahmoudi, Eur.Phys.J. C72 (2012) 1847
AA, M. Battaglia, F. Mahmoudi, Eur.Phys.J. C72 (2012) 1906

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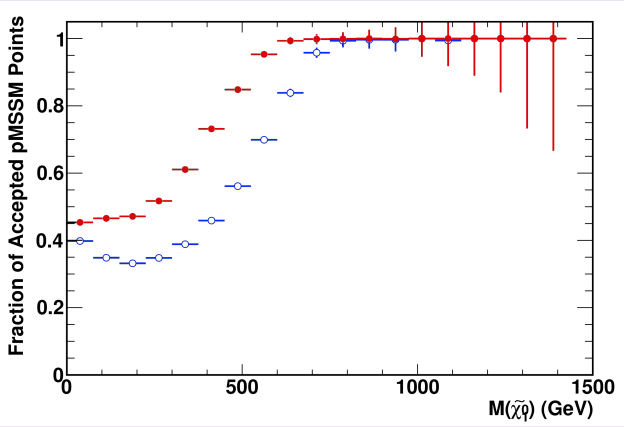
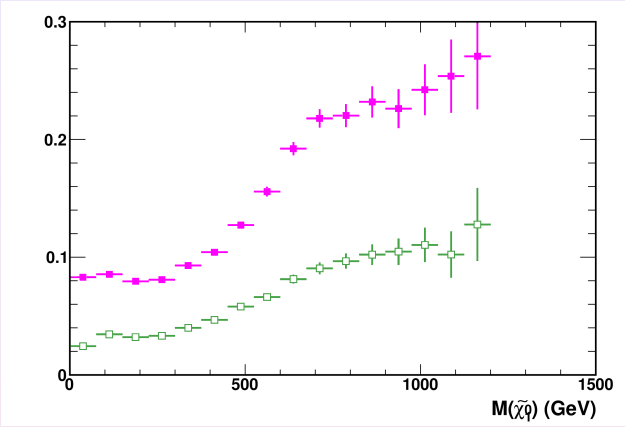
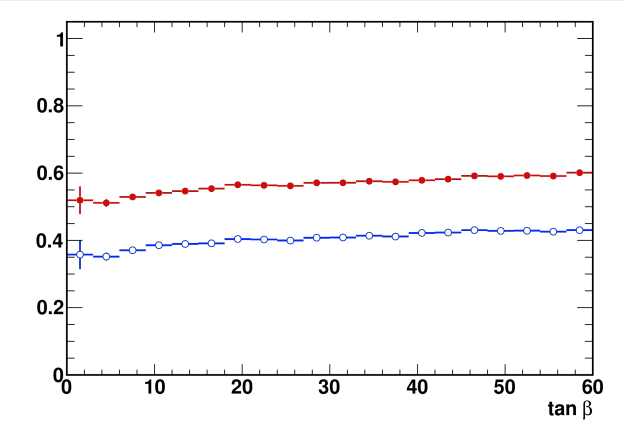
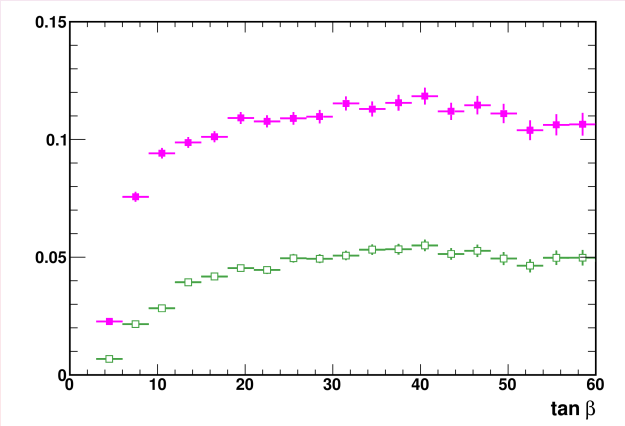


With $123 < M_h < 127$ GeV



Impact on $\tan\beta$





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

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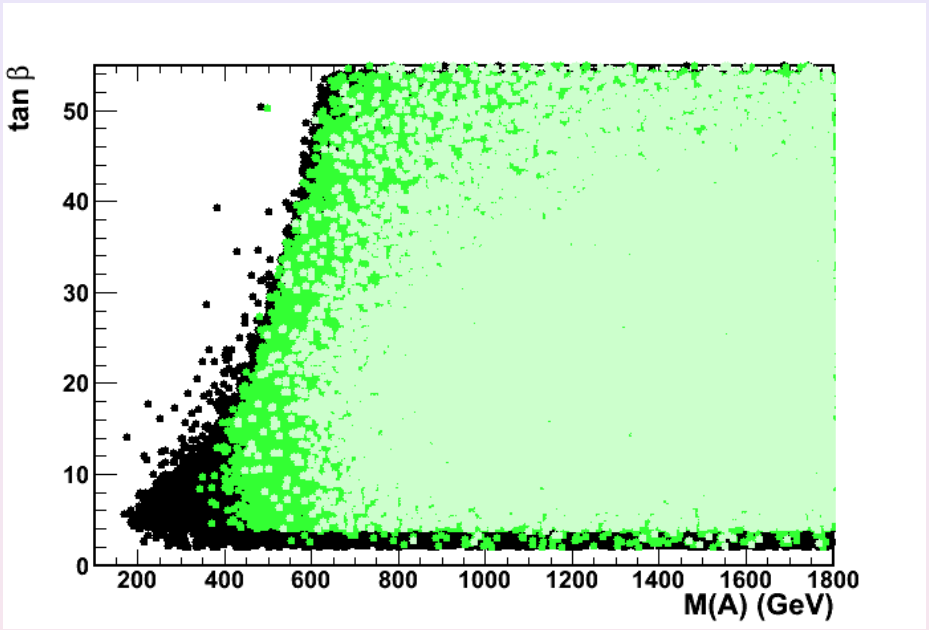
Consequences of the Higgs rate measurements in pMSSM

Consequences of the cross-section and decay rate measurements



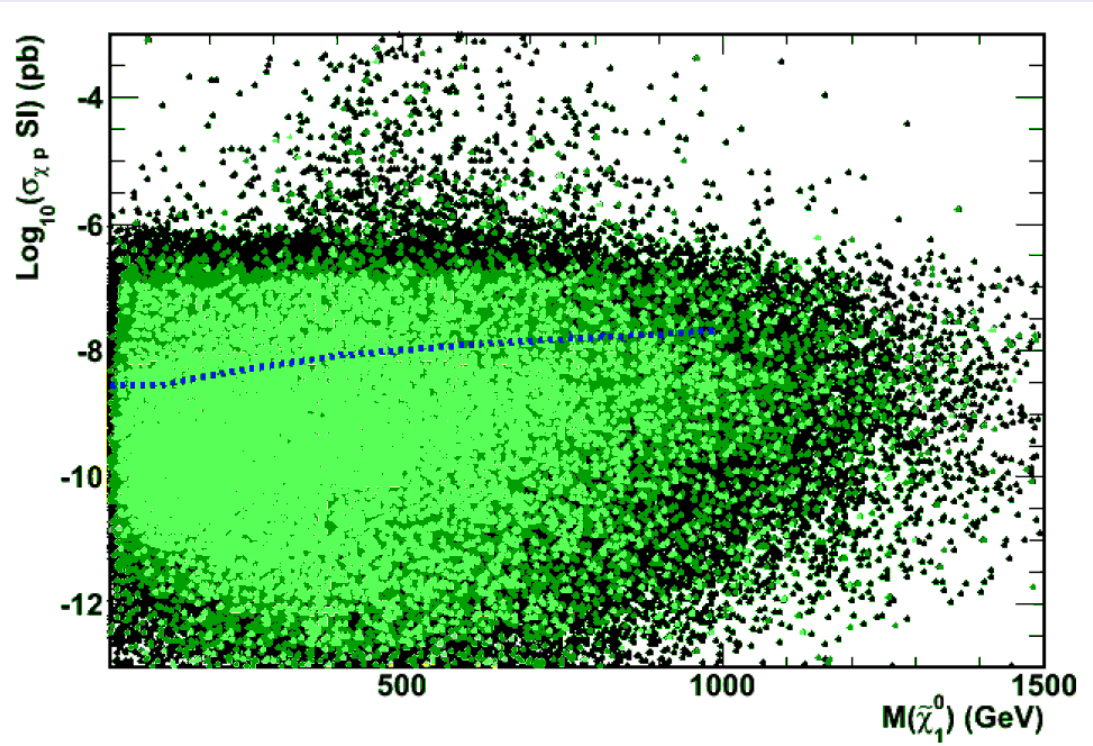
AA, M. Battaglia, A. Djouadi, F. Mahmoudi, Phys.Lett. B720 (2013) 153

$\rightarrow$ $M_A < 400$ GeV disfavoured by the Higgs signal strengths
$\rightarrow$ Same parameter area as probed by direct detection!

Black: all accepted points
Dark green: points compatible at 90% CL with the Higgs rates
Light green: points compatible at 68% CL with the Higgs rates

Dark Matter direct detection and pMSSM

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

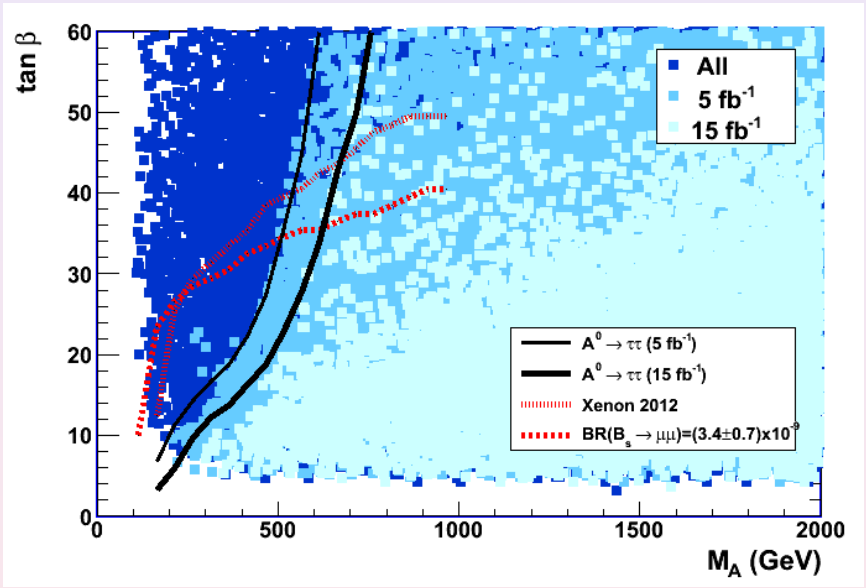
Dotted line: 2012 XENON-100 limit at 95% C.L.

28% of the valid points are excluded by XENON-100

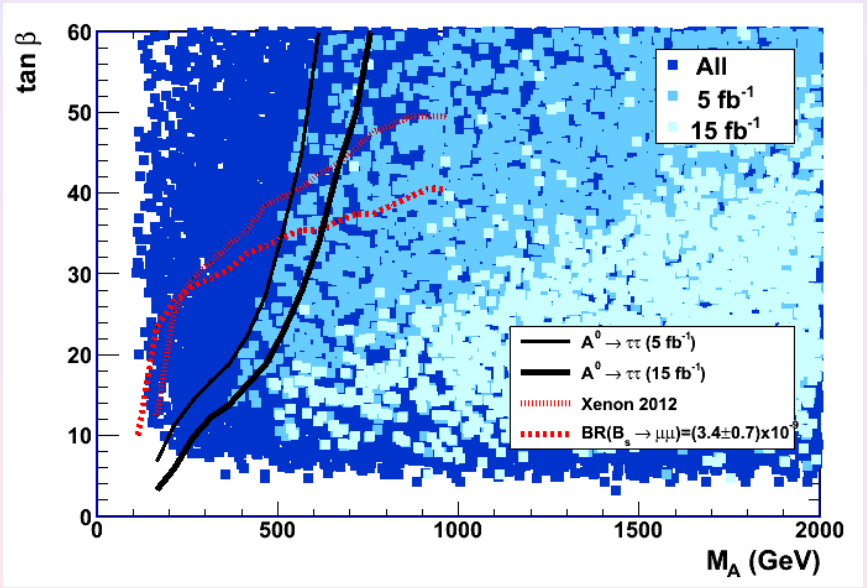
Interplay: Summary plots

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!

Conclusion

- Low energy SUSY is still alive!
- The pMSSM provides interesting candidates for dark matter
- pMSSM very light neutralinos can be compatible with all constraints
  $\rightarrow$ *sbottom miracle*
- Direct detection constraints sensitive to M_A and $\tan\beta$
- Interplay between dark matter, Higgs and flavour sectors can help to close the window

Backup

Backup

Constraints

$2.16 \times 10^{-4} < \mathrm{BR}(B \to X_s\gamma) < 4.93 \times 10^{-4}$
$\mathrm{BR}(B_s \to \mu^+\mu^-) < 5.0 \times 10^{-8}$
$0.56 < \mathrm{R}(B \to \tau\nu) < 2.70$
$4.7 \times 10^{-2} < \mathrm{BR}(D_s \to \tau\nu) < 6.1 \times 10^{-2}$
$2.9 \times 10^{-3} < \mathrm{BR}(B \to D^0\tau\nu) < 14.2 \times 10^{-3}$
$0.985 < \mathrm{R}_{\mu 23}(K \to \mu\nu) < 1.013$
$-2.4 \times 10^{-9} < \delta a_\mu < 4.5 \times 10^{-9}$
$10^{-4} < \Omega_\chi h^2 < 0.155$
+ sparticle mass upper bounds
+ Higgs search limits