Neutralino Dark Matter and the 125 GeV Higgs boson measured at the LHC

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(Based on work done in collaboration with A. Bottino and N. Fornengo)
LHC Integrated luminosity 2010-2012

- 2010: 0.04 fb\(^{-1}\)
  - \(\sqrt{s} = 7\) TeV
  - Commissioning
- 2011: 6.1 fb\(^{-1}\)
  - \(\sqrt{s} = 7\) TeV
  - ... exploring the limits
- 2012: 23 fb\(^{-1}\)
  - \(\sqrt{s} = 8\) TeV
  - ... production
We have entered the LHC era!

After the discovery of the Higgs boson what next?  
No direct evidence of physics beyond the standard model until now
What are the consequences for Dark Matter searches?
On the other hand, searching for susy dark matter is not for the faint of heart...
Hot issues in the Dark Matter business today

• DAMA and CoGeNT modulations
• CoGeNT and CRESST spectral “excesses”
• 3-event “excess” in CDMS-Si
• Constraints from XENON, CDMS (Ge –low)
• KIMS bound on WIMP-Iodine cross section
• A SM-like Higgs with $m_H \sim 125$ GeV: can it be relevant for DM searches?
• Light neutralinos in effective MSSM: are they still viable?
The WIMP low-mass region of direct detection experiments is getting ever more crowded...

Upper bounds:

- CDMS-Si (2008+2013)
- CDMS-Si (2013)
- CDMS-Ge (low threshold)
- CDMS-Ge (high threshold)
- Edelweiss
- XENON100
- XENON10 (S2 only)

Possible signal regions:

- DAMA/LIBRA
- CoGeNT
- CRESST
- CDMS-Si

(Updated to May 2013)

Interestingly, all signal regions qualitatively in the same ball-park

But at face value they are inconsistent to some of the upper bounds
Effective MSSM scheme (effMSSM) - Independent parameters

- $M_1$ U(1) gaugino soft breaking term
- $M_2$ SU(2) gaugino soft breaking term
- $M_3$ SU(3) gaugino soft breaking term
- $\mu$ Higgs mixing mass parameter
- $\tan \beta$ ratio of two Higgs v.e.v.'s
- $m_A$ mass of CP odd neutral Higgs boson (the extended Higgs sector of MSSM includes also the neutral scalars $h, H$, and the charged scalars $H^\pm$)
- $m_{\tilde{q}}$ soft mass for squarks of the first two families
- $m_{\tilde{t}}$ soft mass for squarks of 3° family
- $m_{\tilde{l}}$ soft mass common to all sleptons
- A common dimensionless trilinear parameter for the third family ($A_{\tilde{b}} = A_{\tilde{t}} \equiv A_{\tilde{q}}; A_{\tilde{\tau}} \equiv A_{\tilde{l}}$)
- $R \equiv M_1 / M_2$

SUGRA $\rightarrow R = 0.5$
Can the neutralino be light?

Lower limits on the neutralino mass from accelerators

- **Indirect** limits from chargino production \((e^+e^- \rightarrow \chi^+\chi^-)\):
  \[ m_{\chi^\pm} \gtrsim 100 \text{ GeV} \Rightarrow m_{\chi} \gtrsim 50 \text{ GeV} \quad \text{if} \quad R \equiv \frac{M_1}{M_2} = \frac{5}{3} \tan^2 \theta_w \]

- **Direct** limits from \(e^+e^- \rightarrow \chi^i_0\chi^j_0\) \((\chi^1_0 \equiv \chi, m_{\chi^1_0} < m_{\chi^2_0} < m_{\chi^3_0} < m_{\chi^4_0})\):
  - Invisible width of the Z boson (upper limit on number \(N_{\nu}\) of neutrino families)
  - Missing energy + photon(s) or \(f\bar{f}\) from \(\chi^i_0 > 1 \rightarrow \chi^1_0\) decay

- **Direct** limits from \(\tilde{t} \rightarrow c\chi\) and \(\tilde{b} \rightarrow b\chi\) at Tevatron
  \[ \dagger \text{small production cross sections} \]
  \[ \ddagger \text{light squark masses (} \lesssim 100 \text{ GeV) required} \]

⇒ No absolute **direct** lower bounds on \(m_\chi\)
Neutralino - nucleon cross section

(A.Bottino, F.Donato, N.Fornengo and S.Scopel, PRD69,037302 (2004) )

Color code:
● $\Omega \chi h^2 < 0.095$
× $\Omega \chi h^2 > 0.095$

Tight correlation between relic abundance and $\chi$-nucleon cross section:

$$\Omega \chi h^2 \leq (\Omega_{CDM} h^2)_{max}$$

$$\sigma_{\text{scalar}}^{(\text{nucleon})} \sim \frac{10^{-40} cm^2}{(\Omega_{CDM} h^2)_{max}} \frac{GeV^2}{m_\chi [1-m_\chi^2/m_h^2]^{1/2}} \text{ for } m_\chi \lesssim 20 \text{ GeV}$$

The elastic cross section is bounded from below

→ “funnel” at low mass

DAMA/NaI modulation region, likelihood function values distant more than 4 σ from the null result (absence on modulation) hypothesis, Riv. N. Cim. 26 n. 1 (2003) 1-73, astro-ph/0307403

Light relic neutralinos have (roughly) the right mass and cross section to explain DAMA/LIBRA, CoGeNT, CDMS II, CDMS-Si and CRESST
Production of susy particles @ LHC & Tevatron

\[ pp, p\bar{p} \rightarrow \tilde{q}\tilde{q}, \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g} \]

- Cross sections calculated to NLO, typically in pb range at LHC
- Masses depend on how SUSY is broken, but otherwise, cross section is model-independent
- Production cross section at LHC increases dramatically relative to Tevatron, especially for squark/gluino

[Prospino]
The fate of a squark...

direct decay to a neutralino:
(early discovery channel, easy to see if kinematically accessible (acoplanar jets+missing energy)

“sequential” chain through sleptons:

“branched” chain through gauge and Higgs bosons:
LHC bounds constrain gluino and squark masses

squarks of first two families

heavy stop ($m_{\text{stop}} > m_t + m_\chi$)

ATLAS, PRL109,2011803(2012)

light stop ($m_{\text{stop}} < m_t + m_\chi$)

ATLAS, CERN-PH-EP-2012-211

(“simplified model”, valid for decoupled gluino, $M_3 >> m_{\text{squark}}$)

sbottom

CMS Coll., CMS PAS SUS-12-028

CMS Coll., CMS PAS SUS-12-028
In light of the stringent bounds from the LHC in the following we will assume that $M_3$ (gluino mass) and $m_q$ (soft mass for the first two families) are heavy.

N.B. bounds on sbottom and stop are less constraining because the top and bottom flavours are scarce in the proton.

For the lower bound on the slepton masses we used the LEP values $m_{slep}on > 80$-$100$ GeV (depending on flavour). These lower bounds actually depend on the condition that $m_{slep}on - m_{\chi} > O(3$-$15)$ GeV. If these conditions are not met, it has been claimed by C. Boehm et al., (arXiv:1303.5386) that the slepton lower bound can decrease to about 40 GeV. Indeed this may have relevant implications for the neutralino phenomenology (but what about monojet+missing energy bounds?)
Bounds on Electro-Weak production of neutralinos and charginos

N.B. if squarks of the first two families and gluinos are heavy only the first diagram contributes

τ-dominated scenario, compatible with next-to-lightest neutralinos and lightest chargino of higgsino type

$|\mu| > 280$ GeV
Implications of Higgs discovery

**H→γγ**

Selected diphoton sample

![Graph showing events vs. photon mass](image)

**H→WW**

**ATLAS Preliminary**

\[ \sqrt{s} = 8 \text{ TeV}, \int L dt = 20.7 \text{ fb}^{-1} \]

![Graph showing events vs. mass](image)

**H→ZZ**

![Graph showing events vs. mass](image)

**H→bb**

![Graph showing events vs. mass](image)
The Higgs mass after Moriond 2013

A. Whitbeck, Moriond QCD 2013  T. Adye, Moriond QCD 2013
Signal strengths: $\sigma(pp \rightarrow H \rightarrow X)_{\text{MSSM}} / \sigma(pp \rightarrow H \rightarrow X)_{\text{SM}}$

- Overall agreement with the Standard Model
- Excess in $H \rightarrow \gamma \gamma$?
We used FeynHiggs to calculate the Higgs spectrum and couplings @ two loops

After the Higgs discovery the SUSY parameter space is restricted because:

• one of the two the Higgs boson masses is constrained to have mass $\sim 125$ GeV and to be Standard-Model like
• the other Higgs boson must be either heavier or lighter. In the latter case it must be very weakly coupled to the Z boson (to evade LEP limits)
• So there are two possibilities: $H_{125} = H$ or $H_{125} = h$

In light of this we single out two scenarios:

• Scenario I: $H_{125} = H$ (heavy Higgs scalar)
• Scenario II: $H_{125} = h$ (light Higgs scalar)
Scenario I

maximal mixing
\(\mu = -200 \text{ GeV}\)
\(M_{SUSY} = 1 \text{ TeV}\)
\(H^+ \quad (-----)\)
\(H \quad (-----)\)
\(h \quad (-----)\)

Scenario II

\(m_h \sim m_A \sim m_H \sim 125 \text{ GeV}\)
\(m_h \sim 125 \text{ GeV} < m_A \sim m_H\)
Constraints from signal strengths (abridged...)

- Experimentally slight excess in $pp\to H\to\gamma\gamma$ while decays to fermions (b and $\tau$) may possibly be slightly too low.
- A general fit performed in P. Bechtle, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein, L. Zeune, arXiv:1211.1955 disfavours production cross sections very different from the standard model ones, so $pp\to H\to\gamma\gamma$ is driven by the decay branching ratios.
- Branching ratios to b and $\tau$ fermions are correlated (both down-type), obviously $H\to bb$ dominates.
- $H\to bb$ and $H\to\gamma\gamma$ are anticorrelated (a small relative decrease in the dominant channel implies a much higher relative increase in subdominant ones and the other way around).
- So in order to boost $H\to\gamma\gamma$ need to suppress $H\to bb$. The corresponding coupling:

\[
\frac{g_{H bb}}{g_{H_{SM} bb}} = \frac{1}{1 + \Delta b} \left( -\frac{\sin \alpha_{\text{eff}}}{\cos \beta} + \Delta b \frac{\cos \alpha_{\text{eff}}}{\sin \beta} \right)
\]

is suppressed if the correction $\Delta b$ is large and positive.
- Another mechanism (discussed in M. Carena et al., JHEP 1207 (2012) 175, [arXiv:205.5842]; JHEP 1203 (2012) 014, [arXiv:1112.3336]) is through light sleptons (light squarks modify also the gluon fusion rate, with a compensating effect between the production cross section and the decay branching ratio) $\to$ modify $\alpha_{\text{eff}}$. 

Constraints from signal strengths (abridged...)

Through a sbottom/gluino or a stop/higgsino loop the bottom quark couples to the “wrong” Higgs doublet through the effective lagrangian:

\[ h_b H_1^0 b \bar{b} + \Delta h_b H_2^0 b \bar{b} \]

so the relation between Yukawa coupling and mass is modified:

\[ h_b \to \frac{m_b}{v} \frac{1}{1 + \Delta_b} \tan \beta \quad \left( \Delta_b = \frac{\Delta h_b}{h_b} \tan \beta \right) \]

\[ \Delta_b = \frac{2 \alpha_s}{3 \pi} M_3 \mu \tan \beta I(m_{\tilde{b}_1}, m_{\tilde{b}_2}, M_3) + \frac{h_t^2}{16 \pi^2} \mu A_t \tan \beta I(m_{\tilde{t}_1}, m_{\tilde{t}_2}, \mu) \]

\[ I(a, b, c) = \frac{1}{(a^2 - b^2)(b^2 - c^2)(a^2 - c^2)} \left( a^2 b^2 \log \frac{a^2}{b^2} + b^2 c^2 \log \frac{b^2}{c^2} + c^2 a^2 \log \frac{c^2}{a^2} \right) \]

→ to get a large $\Delta_b$ need large $\mu$
Actually, the $H \rightarrow \tau\tau$ channel strongly constrains the low $m_A$ scenario.

Upper bound on production cross section converted into a constraint on $\tan\beta$ vs $m_A$ in the $m_h^{\text{max}}$ scenario:

$\mu=200$ GeV, $X_t=2000$ GeV, $M_2=200$ GeV, $M_3=800$, $M_{\text{SUSY}}=1000$ GeV

To get the limit in a scenario different from $m_h^{\text{max}}$ (in particular with large $\mu$) need to recalculate the production cross section and compare it directly to the corresponding upper bound.
Latest bound on $H \rightarrow \tau\tau$ much more constraining ($\tan\beta < 5$ at low $m_A$)

This bound is particularly severe for low-mass relic neutralinos because a large value of $\tan\beta$ is instrumental in enhancing the annihilation cross section (keeping the relic density in the observational range) and the neutralino-nucleon cross section (explaining DAMA, CoGeNT, CDMS-Si, CRESST)

However, CMS does not provide the corresponding upper bound on the production cross section.

Since this bound is particularly important, to estimate it we adopted inverse engineering...
We reproduced the 2011 CMS limit in the $m_h^\text{max}$ scenario by calculating $\sigma(\Phi\rightarrow\tau\tau)$ with $m_A$ and $\tan\beta$ taken from the CMS upper bound curve.

We then estimated the new bound on $\sigma(\Phi\rightarrow\tau\tau)$ by repeating the exercise with $m_A$ and $\tan\beta$ taken from the 2012 CMS constraint curve → the limit on the cross section can now be compared to the theoretical expectation in scenarios which are different from $m_h^\text{max}$.

N.B. don’t know how to combine 7 TeV and 8 TeV data, since the 2012 CMS data combine 4.9 fb$^{-1}$ at 7 TeV and 12.1 fb$^{-1}$ at 8 TeV we adopted the 8 TeV curve.
In Scenario I the charged Higgs is light and the decay $t \rightarrow H^+b$ is kinematically allowed


• Again, the bound on $\tan \beta$ is given in the $m_h^{\text{max}}$ scenario, need to recalculate it for an arbitrary choice of parameters
• N.B. also a lower bound on $\tan \beta$, parameter space shrinks at small $m_A$!
As before we recalculate the branching ratio $t \to H^+b$ in the $m_h^\text{max}$ scenario and compare it to the limit published by ATLAS (N.B. now there are two curves, one for the upper bound on $\tan\beta$ and the other for the lower bound).

\[ \Gamma^{\text{tree}}(t \to b H^+) = \frac{g^2}{64\pi M_W^2} |V_{tb}|^2 m_t^3 \lambda^{1/2} (1, q_{H^+}, q_b) \times \left[ (1 - q_{H^+} + q_b) \left( \cot^2 \beta + q_b \tan^2 \beta \right) + 4 q_b \right] \]

\[ q_{b,H^+} = \frac{m_{b,H^+}^2}{m_t^2}, \quad r_{b,t} = \frac{m_{b,t}^2}{M_{H^+}^2} \]

\[ \lambda(1, x, y) = 1 + x^2 + y^2 - 2(x + y + xy) \]
The $B_s \rightarrow \mu\mu$ decay

First evidence for the decay $B_s \rightarrow \mu\mu$: $1.1 \times 10^{-9} < \text{BR}(B_s \rightarrow \mu\mu) < 6.4 \times 10^{-9}$

Compatible with SM expectation: $\text{BR}(B_s \rightarrow \mu\mu) \sim 3 \times 10^{-9}$

Important constraint whenever $m_A$ is light and $\tan\beta$ is large, as in the light neutralino model, since $\text{BR}(B_s \rightarrow \mu\mu) \propto \tan\beta^6/m_A^4$

Dominant term:

$$BR^{(8)}(B_s \rightarrow \mu^+\mu^-) \approx 5.8 \times 10^{-8} \left( \frac{14 A m_t m_{\tilde{q}}}{m_{\tilde{q}}^2 + m_t^2} \right)^2 \left( \frac{m_{\chi^\pm}}{110 \text{ GeV}} \right)^2 \left( \frac{90 \text{ GeV}}{m_A} \right)^4 \left( \frac{\tan\beta}{35} \right)^6$$

To pass the constraint need:

• chargino of higgsino type to be light $\rightarrow$ small $\mu$ or

• trilinear coupling $A$ to be small (leading to stop-quark degeneracy) and respecting the hierarchy:

$$|\mu| \ll |A| \ll \frac{m_{\tilde{q}}}{m_t} \tan\beta$$

or

• small $\tan\beta$

B-meson decays are sensitive to susy particles (charged Higgs, \(\tan \beta\) and susy corrections to the Higgs coupling)

\[ \mathbf{B} \rightarrow \tau \nu \]

Red points: \(m_\chi < 10\ \text{GeV}\)

Allowed interval for \(R_{B\tau\nu}\) based on world average (BaBar+Belle) for \(\text{BR}(B \rightarrow \tau \nu)\)

b→sγ decay

N.B. In Scenario I $m_A$ is light so also $m_{H^\pm} \approx m_A^2 + m_W^2$ is light

Then the loop with a top quark and a charged Higgs must be canceled by the loop with a stop and a chargino → need a light chargino of higgsino type, i.e. $|\mu|$ should be small. However this is not possible because otherwise pp→H→γγ is too small

Tension in Scenario I between pp→H→γγ and b→sγ
Muon g-2

\[ 3.1 \times 10^{-10} \leq \Delta a_\mu \equiv a_\mu^{\text{exp}} - a_\mu^{\text{theory}} \leq 47.9 \times 10^{-10} \]

\[ a_\mu \equiv \frac{g_\mu - 2}{2} \]

Largest uncertainty is in the determination of the Standard Model hadronic contribution

Large for light sleptons, dominant SUSY contributions proportional to $\mu \tan\beta$

$\Rightarrow$ light sleptons and large $|\mu|$ lead to large muon g-2
Scenario I: parameter scan

$H_{125} = H$ (heavy scalar)

Optimized parameter scan with:

$123 \text{ GeV} \leq m_{H_{125}} \leq 129 \text{ GeV}$

(include $\sim 2 \text{ GeV}$ theoretical uncertainty)

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<th>Scenario I</th>
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Scenario I: signal strengths

\[ R_{\gamma\gamma} = \frac{\sigma(p + p \rightarrow H_{125}) BR(H_{125} \rightarrow \gamma + \gamma)}{\sigma_{SM}(p + p \rightarrow H_{125}) BR_{SM}(H_{125} \rightarrow \gamma + \gamma)} \]

same for \( R_{ZZ}, R_{WW} \) and \( R_{\tau\tau} \)

CMS+ATLAS 2 σ experimental ranges (Moriond 2013):

\[
\begin{align*}
0.61 &< R_{\gamma\gamma} < 1.57 \\
0.75 &< R_{ZZ} < 1.47 \\
0.44 &< R_{WW} < 1.24 \\
0.21 &< R_{\tau\tau} < 1.90,
\end{align*}
\]

Scenario I: experimental constraints

Tension with g-2 and b→sγ

Scenario I: relic abundance

\[0.11 < \Omega h^2 < 0.13\]
(Planck, arXiv:1303.5076)

Scenario I: fractional contributions to the annihilation cross section at freeze out of different channels

\[ \Omega \chi h^2 = \frac{x_f}{g_*(x_f)^{1/2}} \frac{9.9 \cdot 10^{-28} \text{ cm}^3\text{s}^{-1}}{\langle \sigma v \rangle_{\text{int}}} \]

\[ x_f \equiv \frac{m_\chi}{T_f} \]

\[ \langle \sigma v \rangle_{\text{int}} = \int_{x_f}^{x_0} \langle \sigma v \rangle dx \]

\( T_f = \) freeze-out temperature

\( g_*(x_f) = \) # of relativistic degrees of freedom at \( T_f \)

- \( \chi \chi \to \text{slepton} \to ff \)
- \( x \chi \chi \to \text{higgs} \to ff \)
- \( o \chi \chi \to Z \to ff \)

Scenario I: fractional contributions to the annihilation cross section at zero temperature of different final states

- $\chi\chi \rightarrow \tau\tau$
- $\chi\chi \rightarrow bb$

Scenario II: parameter scan

\( H_{125} = h \) (light scalar)

Optimized parameter scan with:

\[
123 \text{ GeV} \leq m_{H_{125}} \leq 129 \text{ GeV}
\]

(include \( \sim 2 \) GeV theoretical uncertainty)

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Scenario II: signal strengths

\[ R_{\gamma\gamma} = \frac{\sigma(p + p \to H_{125}) BR(H_{125} \to \gamma + \gamma)}{\sigma_{SM}(p + p \to H_{125}) BR_{SM}(H_{125} \to \gamma + \gamma)} \]

same for \( R_{ZZ}, R_{WW} \) and \( R_{\tau\tau} \)

CMS+ATLAS 2 \( \sigma \) experimental ranges (Moriond 2013):

\[ 0.61 < R_{\gamma\gamma} < 1.57 \]
\[ 0.75 < R_{ZZ} < 1.47 \]
\[ 0.44 < R_{WW} < 1.24 \]
\[ 0.21 < R_{\tau\tau} < 1.90, \]

Scenario I: experimental constraints

The configurations plotted in this Scenario satisfy all constraints

Scenario II: relic abundance

$0.11 < \Omega h^2 < 0.13$
(Planck, arXiv:1303.5076)

Scenario II: fractional contributions to the annihilation cross section at freeze out of different channels

$$\Omega \chi h^2 = \frac{x_f}{g_\star(x_f)^{1/2}} \frac{9.9 \cdot 10^{-28}}{\langle \sigma_{\text{ann}} v \rangle_{\text{int}}}$$

$$x_f \equiv m_\chi / T_f$$

$$\langle \sigma_{\text{ann}} v \rangle_{\text{int}} = \int_{x_f}^{x_0} \langle \sigma_{\text{ann}} v \rangle dx$$

$T_f$=freeze-out temperature

$g_\star(x_f)$=# of relativistic degrees of freedom at $T_f$

- $\chi\chi \rightarrow$ slepton $\rightarrow$ ff
- $\chi\chi \rightarrow$ higgs $\rightarrow$ ff
- $\chi\chi \rightarrow Z \rightarrow$ ff
- $\chi\chi \rightarrow WW$
- $\chi\chi \rightarrow ZZ$
- $\chi\chi \rightarrow Zh$
- $\chi\chi \rightarrow hh$

Scenario I: fractional contributions to the annihilation cross section at zero temperature of different final states

- $\chi\chi \rightarrow \tau\tau$
- $\chi\chi \rightarrow bb$
- $\chi\chi \rightarrow WW$
- $\chi\chi \rightarrow ZZ$
- $\chi\chi \rightarrow Zh$

Direct detection

The local density $\rho_\chi$ is rescaled with the coefficient $\xi$ defined as:

$$\xi = \min \left\{ 1, \frac{\Omega_\chi h^2}{(\Omega_{CDM} h^2)_{min}} \right\}$$

and $(\Omega_{CDM} h^2)_{CDM} = 0.11$ (Planck 2013)

Due to rescaling the cross section is suppressed whenever the relic density is low, i.e. whenever the annihilation cross section $<\sigma v>$ is large (for instance, can easily see a dip corresponding to resonant annihilation $\chi\chi \rightarrow Z \rightarrow ff$)

Top-of-atmosphere antiproton flux in the first energy bin of PAMELA ($T_p=0.28$ GeV)

- Scenario I
- Scenario II

Low expected signals in large parts of the configuration space because the dominant annihilation channel is a leptonic one ($\tau\tau$).

More sizeable expected signals only for resonant $\chi\chi \rightarrow A \rightarrow bb$ ($m_\chi \sim m_A/2$) and for $m_\chi > m_W$ when the $\chi\chi \rightarrow WW$ channel opens up.

Top-of-atmosphere antiproton flux: two examples of high flux

Contribution to the Isotropic Gamma-Ray Background (IGRB) produced by galactic dark matter annihilation at high latitudes

Scenario I

\[ \Phi_\gamma(E_\gamma, \psi) = \frac{1}{4\pi} \left( \frac{\sigma_{\text{ann}} v}{m_\chi^2} \right) \frac{dN_\gamma}{dE_\gamma} \frac{1}{2} I(\psi) \]

Integration along the line of sight:

\[ I(\psi) = \int_{\text{l.o.s.}} \rho^2(r(\lambda, \psi)) \, d\lambda(\psi) \]

\( \psi = \text{angle between l.o.s. and source} \)

Conclusions

- There are now 4 direct detection experiments (DAMA, CoGeNT, CRESST, CDMS-Si) that claim some kind of excess over the background. They all point to approximately the same WIMP mass ($10 < m_{w} < 20$) and cross section ($10^{-39} \text{ cm}^2 < \sigma_{W,\text{nucleon}} < 10^{-41} \text{ cm}^2$).
- Relic neutralinos in an effective MSSM without unification of gaugino masses can explain these excesses, requiring low $|\mu|$ and $m_{A}$ and large $\tan\beta$ (to enhance both the annihilation cross section and direct detection at low neutralino mass).
- The 2011-2012 runs of the Large Hadron Collider have led to very stringent lower bounds (~TeV range) on the gluino mass and on the masses of squarks of the first two families. Limits on sbottoms and stops are less stringent (in the range of a few hundreds GeV).
- The discovery of the Higgs particle at $m_{h} \sim 125$ GeV with production cross sections compatible to the standard model have constrained the available parameter space further, in particular implying large $|\mu|$. The CMS bound on $pp \rightarrow h,H,A \rightarrow \tau\tau$ is particularly stringent on $\tan\beta$ (<5) at low $m_{A}$. The combination of these limits is in tension with an explanation of direct detection excesses in terms of relic neutralinos in a minimal MSSM.
- Relic neutralinos with $m_{\chi} > 40$ GeV remain viable DM candidates, possibly detectable with indirect methods.