Light neutralino dark matter, XENON100 and LHC results

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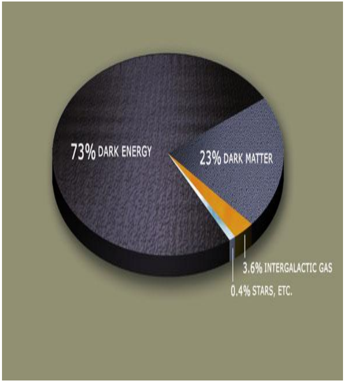
This talk is based on

- L. Calibbi, T. Ota, Y. T., JHEP **1107** (2011) 013; J. Phys. Conf. Ser. **375** (2012) 012041
- P. Grothaus, M. Lindner, Y. T., JHEP **1307** (2013) 094
- L. Calibbi, J. Lindert, T. Ota, Y. T., JHEP **1310** (2013) 132
- work in progress

Outline

1. Introduction
   - Dark matter
   - Relic Density
   - XENON 100 (LUX)
   - LHC
2. MSSM
   - non-universal gaugino mass
   - fine-tuning
   - parameters & constraints
   - computing method
3. Results & discussions
4. Conclusion

Dark matter

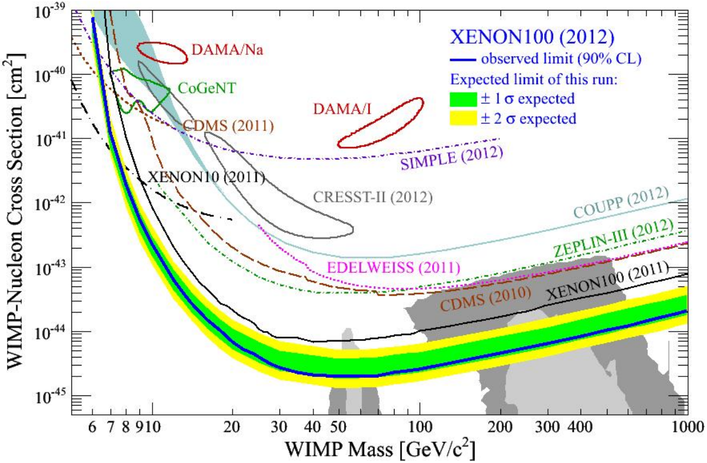


Matter distribution (today)

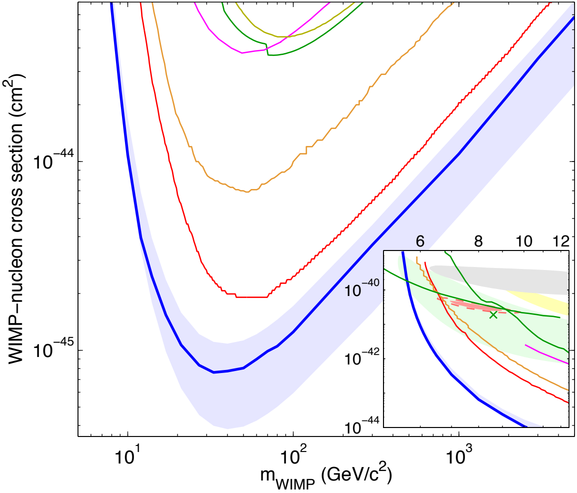
- exist!
- $\Omega h^2 \in [0.089, 0.136]$ (WMAP)
- no electric charge (dark)
- non-baryonic (Big Bang nucleosynthesis)
- cold (?)
- WIMP is good candidate (WIMP "miracle")
- thermal production leads "right" relic density ($\Omega h^2 \sim \langle \sigma v \rangle^{-1}$).

  $m_\chi \sim 0.1 - 1$ TeV.

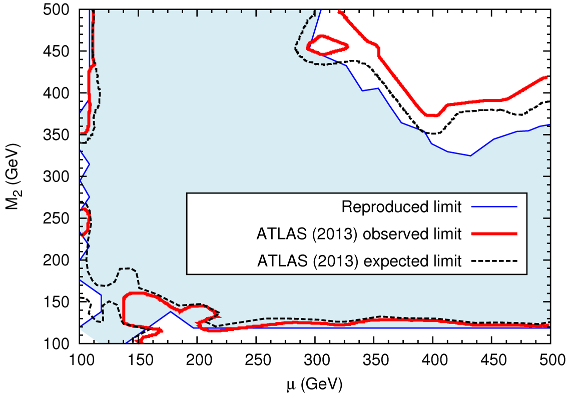
XENON 100 (2012) data [E. April *et al.* [XENON100 Collaboration], arXiv:1207.5988]



LUX (2013) data [D. S. Akerib *et al.* [LUX Collaboration], arXiv:1310.8214]



ATLAS excluded region in M_2 vs. μ parameter [ATLAS, ATLAS-CONF-2013-028][1]



$$m_{\tilde{\tau}_1} = 95\ \mathrm{GeV}, m_{\tilde{\chi}_1^0} = 50\ \mathrm{GeV}, \tan\beta = 50.$$

[1] see also CMS [CMS-PAS-SUS-13-006]

We use phenomenological MSSM (pMSSM) with soft SUSY breaking terms:

$$\tan\beta\,,\ M_1\,,\ M_2\,,\ M_3\,,\ M_A\,,\ \mu\,,\ m_{\widetilde{\ell}_L}\,,\ m_{\widetilde{\ell}_R}\,,\ m_{\widetilde{q}_{1,2}}\,,\ m_{\widetilde{q}_3}\,,\ a_0\,.$$

Assumption:

- LSP as neutralino:
  $\widetilde{\chi}_1^0 = N_{11}\widetilde{B} + N_{12}\widetilde{W}^0 + N_{13}\widetilde{H}_d^0 + N_{14}\widetilde{H}_u^0$.
  $\widetilde{B}$ bino; $\widetilde{W}^0$ wino; $\widetilde{H}_d^0$ down-tye higgsino; $\widetilde{H}_u^0$ up-type higgsino.
  The neutralino mass matrix:

$$\begin{pmatrix} M_1 & 0 & -M_Z s\theta_W c\beta & M_Z s\theta_W s\beta \\ 0 & M_2 & M_Z c\theta_W c\beta & -M_Z c\theta_W s\beta \\ -M_Z s\theta_W c\beta & M_Z c\theta_W c\beta & 0 & -\mu \\ M_Z s\theta_W s\beta & -M_Z c\theta_W s\beta & -\mu & 0 \end{pmatrix}$$

$s\theta_W \equiv \sin\theta_W,\ s\beta \equiv \sin\beta,\ c\theta_W \equiv \cos\theta_W,\ c\beta \equiv \cos\beta.$

Assumptions:

- non-universal gaugino mass: $M_1 \neq M_2 \neq M_3$ (No GUT relation[2]).
  - $\Rightarrow$ PDG mass bound does not hold: $m_\chi \not> 46\ \mathrm{GeV}$
- slepton masses: $m_{\tilde{\ell}_L} \neq m_{\tilde{\ell}_R}$
- squark masses: $m_{\tilde{q}_{1,2}} \neq m_{\tilde{q}_3}$
- A-terms: $A_t = a_0 Y_t m_{\tilde{q}_3}$, $A_b = a_0 Y_b m_{\tilde{q}_3}$, $A_\tau = a_0 Y_\tau \sqrt{m_{\tilde{\ell}_L} m_{\tilde{\ell}_R}}$.

[2] $M_1 = \frac{5}{3} \tan^2 \theta_W M_2$

Fine-tuning definition [Barbieri, Giudice ('88)]

$$\Delta p_i \equiv \left| \frac{p_i}{M_Z^2} \frac{\partial M_Z^2(p_i)}{\partial p_i} \right| = \left| \frac{\partial \ln M_Z^2(p_i)}{\partial \ln p_i} \right| \quad .$$

parameters p_i determine the Z-mass; μ, the two Higgs masses $m_{H_u}^2$, $m_{H_d}^2$ and the bilinear coupling b.

$$\Delta_{\rm tot} \equiv \sqrt{\sum_{p_i=\mu^2, b, m_{H_u}^2, m_{H_d}^2} \{\Delta p_i\}^2}$$

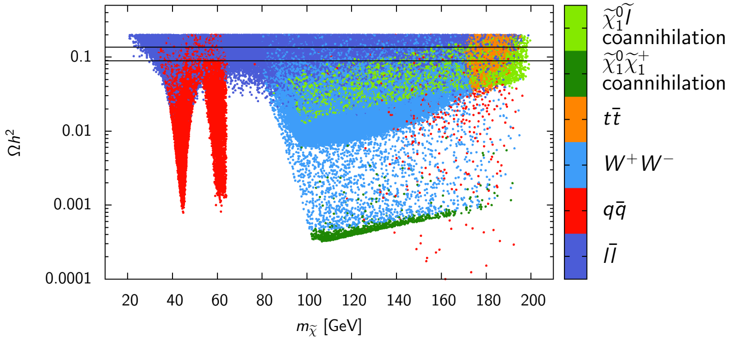
- Scan range of parameters:

$M_1 \in [10, 200]$ GeV, $M_2 \in [100, 2000]$ GeV, $M_3 \in [100, 4000]$ GeV,
$m_A \in [90, 4000]$ GeV, $\pm\mu \in [90, 2000]$ GeV, $a_0 \in [-4.0, 4.0]$,
$m_{\tilde{q}_{1,2}} \in [400, 4000]$ GeV, $m_{\tilde{q}_3} \in [200, 4000]$ GeV, $\tan\beta \in [2, 65]$,
$m_{\tilde{\ell}_L} \in [100, 4000]$ GeV, $m_{\tilde{\ell}_R} \in [60, 4000]$ GeV.

- Experimental constraints
  - $\Omega h^2 \in [0.089, 0.136]$
  - $m_h \in (121.0, 129.0)$ GeV; $m_{\tilde{q}_{1,2}} > 1000$ GeV; $m_{\tilde{g}} > 800$ GeV
  - $\mathrm{Br}(b \to s\gamma) \in [2.89, 4.21] \times 10^{-4}$
  - $\mathrm{Br}(B_s \to \mu^+\mu^-) < 4.5 \times 10^{-9}$
  - $0.52 < R_{B\tau\nu} < 2.61$
  - $0.985 < R_{l23} < 1.013$ $(K \to \mu\nu)$
  - $(g-2)_\mu \in [0.34, 4.81] \times 10^{-9}$
  - $\Gamma(Z \to \tilde{\chi}_1\tilde{\chi}_1) < 3$ MeV; $\sigma(e^-e^+ \to \tilde{\chi}_1, \tilde{\chi}_{2,3}) < 100$ fb; $\Delta\rho < 0.002$

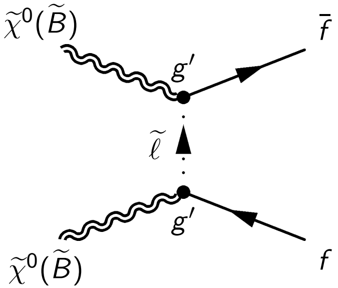
Computing Method:

1. SUSY parameters are randomly chosen.
2. make SUSY Les Houches Accord file.
3. SUSY spectra calculations by `SuSpect`, check consistency. If not go to 1.
4. Low energy observables by `SuperIso`.
5. Relic density, Spin Independent cross sections by `micrOMEGAs`.
6. save data, go to 1.

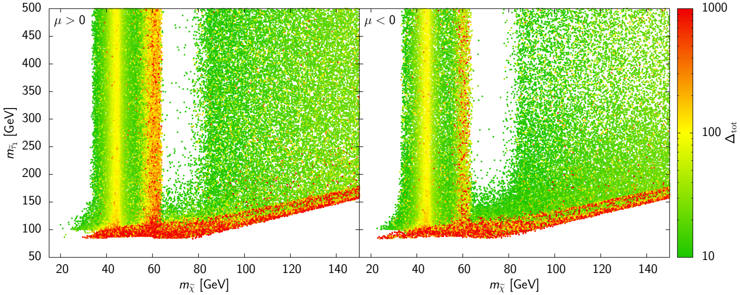


The relic density and the different (co)annihilation mechanisms presented for negative μ. All experimental constraints are applied. $\Omega h^2 \in [0.089, 0.136]$.

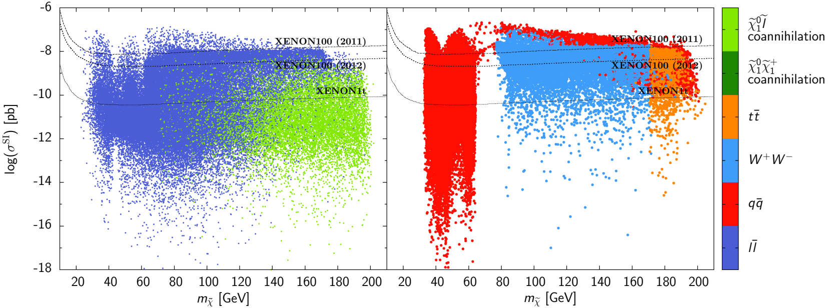
Slepton mediation [Vásquez, Bélanger, Bœhm, PRD 84]



- Neutralinos are annihilated by Slepton.
- $\widetilde{\tau}_1$ is responsible.
- $m_{\widetilde{\tau}_1} > 80.5$ GeV

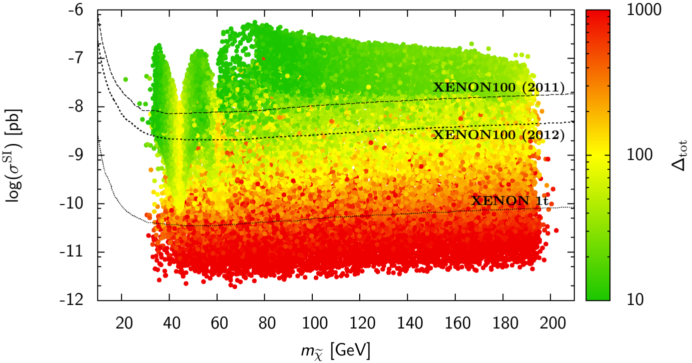


stau mass vs neutralino mass, and their level of fine-tuning:
Left: $\mu > 0$ and Right: $\mu < 0$.

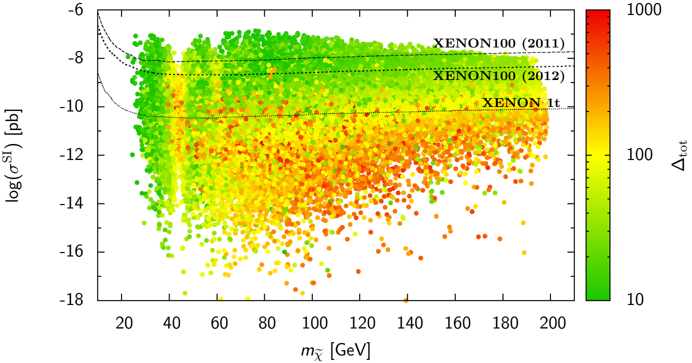


Dominant contribution to the neutralino annihilation in the $m_{\widetilde{\chi}} - \sigma^{\rm SI}$ plane ($\mu < 0$).

Fine-tuning and spin indep. cross section [pb $= 10^{-36}$ cm^2].
$\mu > 0$ with $g-2$ constraint:



Fine-tuning and spin indep. cross section [pb $= 10^{-36}$ cm^2].
$\mu < 0$ with $g - 2$ constraint:



Why $\mu < 0$ makes cross section smaller?

$$\sigma^{\rm SI} \propto \left[\frac{F_h I_h}{m_h^2} + \frac{F_H I_H}{m_H^2}\right]^2$$

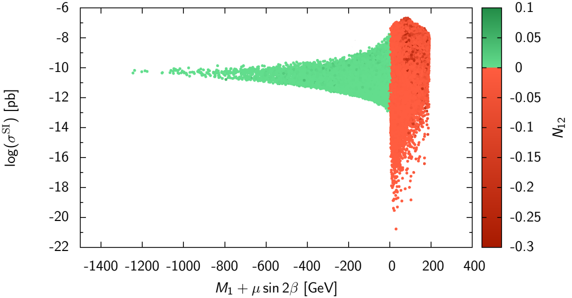
where $I_{h.H}$ are functions of matrix elements and

$$F_h \equiv (-N_{11}\sin\theta_W + N_{12}\cos\theta_W)(N_{13}\sin\alpha + N_{14}\cos\alpha)$$
$$F_H \equiv (-N_{11}\sin\theta_W + N_{12}\cos\theta_W)(N_{13}\cos\alpha - N_{14}\sin\alpha)$$

If we use approximation (Neutralino as bino.) $[\alpha \sim \beta + \pi/2]$

$$N_{11} \simeq 1; \qquad N_{12} \simeq 0$$
$$N_{13} \simeq -M_Z \sin\theta_W \frac{M_1\cos\beta + \mu\sin\beta}{M_1^2 - \mu^2}$$
$$N_{14} \simeq M_Z \sin\theta_W \frac{M_1\sin\beta + \mu\cos\beta}{M_1^2 - \mu^2}$$

$$\sigma^{\mathrm{SI}} \propto \left(\frac{I_H}{m_H^2} \mu \cos 2\beta + \frac{I_h}{m_h^2} (M_1 + \mu \sin 2\beta) \right)^2$$



$\log \sigma^{\mathrm{SI}}$ vs $M_1 + \mu \sin 2\beta$ and the wino component (N_{12}).

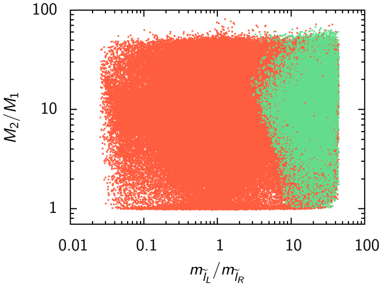
Can we fulfill $(g-2)_\mu$ with $\mu < 0$?

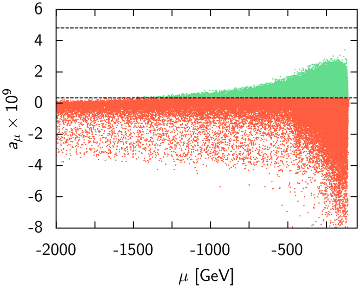
$$a_\mu(\widetilde{W}-\widetilde{H},\widetilde{\nu}_\mu) = \frac{g^2}{8\pi^2}\frac{m_\mu^2 M_2 \mu \tan\beta}{m_{\widetilde{\nu}}^4} F_a\left(\frac{M_2^2}{m_{\widetilde{\nu}}^2},\frac{\mu^2}{m_{\widetilde{\nu}}^2}\right)$$

$$a_\mu(\widetilde{B},\widetilde{\mu}_L-\widetilde{\mu}_R) = \frac{g'^2}{8\pi^2}\frac{m_\mu^2 M_1 \mu \tan\beta}{M_1^3} F_b\left(\frac{m_{\widetilde{\mu}_L}^2}{M_1^2},\frac{m_{\widetilde{\mu}_R}^2}{M_1^2}\right)$$

$$a_\mu(\widetilde{B}-\widetilde{H},\widetilde{\mu}_R) = -\frac{g'^2}{8\pi^2}\frac{m_\mu^2 M_1 \mu \tan\beta}{m_{\widetilde{\mu}_R}^4} F_b\left(\frac{M_1^2}{m_{\widetilde{\mu}_R}^2},\frac{\mu^2}{m_{\widetilde{\mu}_R}^2}\right)$$

F_a and F_b are positive functions. To get positive pull for $\mu < 0$, Bino-higgsino-loop ($a_\mu(\widetilde{B}-\widetilde{H},\widetilde{\mu}_R)$) must be dominant.





The green area satisfies $(g-2)_\mu$ constraint. What we need $m_{\tilde{l}_L} \gg m_{\tilde{l}_R}$. $|\mu| \ll 1.5$ TeV.

LHC phenomenology: production and decays

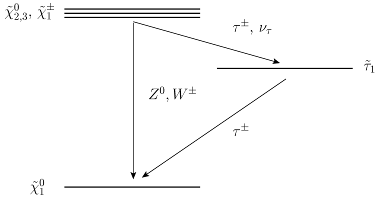
If at least 4 states – $\widetilde{\tau}_1$, $\widetilde{\chi}_2^0$, $\widetilde{\chi}_3^0$, $\widetilde{\chi}_1^\pm$ – are $\mathcal{O}(100)$ GeV.

- Productions (electroweak Drell-Yan):

$$pp \to \widetilde{\tau}_1^+ \, \widetilde{\tau}_1^- + X, \quad pp \to \widetilde{\chi}_i^0 \, \widetilde{\chi}_j^0 + X \,,$$
$$pp \to \widetilde{\chi}_i^0 \, \widetilde{\chi}_1^\pm + X, \quad pp \to \widetilde{\chi}_1^+ \, \widetilde{\chi}_1^- + X \,,$$

  with $i, j = 2, 3$.

- Decays:

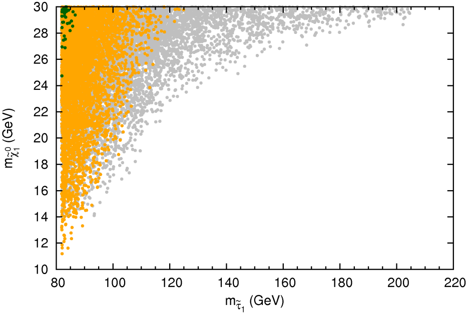


If $m_{\widetilde{\chi}_1^\pm} \simeq m_{\widetilde{\chi}_{2,3}^0} > m_{\widetilde{\tau}_1} > m_{\widetilde{\chi}_1^0}$

$$pp \to \widetilde{\chi}_{2,3}^0 \widetilde{\chi}_{2,3}^0 \to 4\tau + \not{E}_T$$
$$pp \to \widetilde{\chi}_{2,3}^0 \widetilde{\chi}_1^\pm \to 3\tau + \not{E}_T$$

LHC can observe multi-tau signals.

Summary of the LHC searches in $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ plane.



- the gray points fulfill the flavour and relic density constraints
- the orange points correspond to $\mathrm{BR}(h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0) < 20\%$
- the dark-green points evade the ATLAS multi-tau limit

- `Herwig++` for event samples
- `Prospino 2` for NLO K-factors
- `Delphes 3` for fast detector simulation
- Cuts of two Atlas SR applied ($S^{95}_{SR1} < 5.6$, $S^{95}_{SR2} < 10.4$)

$m_{\tilde{\chi}_1^0} \gtrsim 24\ \mathrm{GeV}.$

Conclusions

- We have studied non-universal gaugino mass scenario and have taken into account cosmology, XENON 100 (2011) [LUX] bound, new LHC results (also other collider constraints) and flavour physics.
- Our dark matter candidate is the lightest neutralino (LSP).
- We show that MSSM can not fit DAMA, CoGeNT, CRESST regions due to LHC results on $B_s \to \mu^+\mu^-$ and pseudo-Higgs research.
- Using slepton annihilation mechanism we are able to avoid the XENON 100 (2011) [LUX] limit.
- Positive μ-term is disfavoured by means of fine-tuning; $\mu < 0$ is preferred.

Conclusions

- Negative μ-term case the spin indep. cross section goes down. $M_1 + \mu \sin 2\beta \approx 0$ ("blind spot").
- Even for negative μ-term we are able to satisfy the constraint of the muon anomalous magnetic moment.
- LHC puts the lower bound for the neutralino mass $\gtrsim$ 24 GeV.

Backup

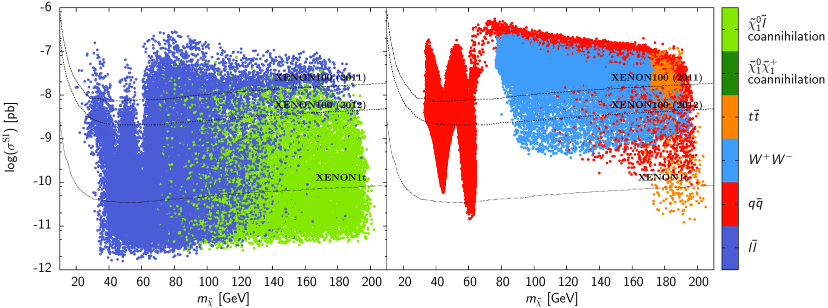
Fine-tunings:

$$\Delta\mu^2 = \frac{4\mu^2}{m_Z^2}\left(1+\frac{m_A^2+m_Z^2}{m_A^2}\tan^2 2\beta\right) \ ,$$

$$\Delta b = \left(1+\frac{m_A^2}{m_Z^2}\right)\tan^2 2\beta \ ,$$

$$\Delta m_{H_u}^2 = \left|\frac{1}{2}\cos 2\beta + \frac{m_A^2}{m_Z^2}\cos^2 2\beta - \frac{\mu^2}{m_Z^2}\right| \times\left(1-\frac{1}{\cos 2\beta}+\frac{m_A^2+m_Z^2}{m_A^2}\tan^2 2\beta\right) \ ,$$

$$\Delta m_{H_d}^2 = \left|-\frac{1}{2}\cos 2\beta + \frac{m_A^2}{m_Z^2}\sin^2 2\beta - \frac{\mu^2}{m_Z^2}\right| \times\left(1+\frac{1}{\cos 2\beta}+\frac{m_A^2+m_Z^2}{m_A^2}\tan^2 2\beta\right) \ .$$



Dominant contribution to the neutralino annihilation in the $m_{\widetilde\chi} - \sigma^{\rm SI}$ plane ($\mu > 0$).

$$\sigma^{\rm SI} \simeq \frac{8G_F^2}{\pi} M_Z^2 m_{\rm red}^2 \left[\frac{F_h I_h}{m_h^2} + \frac{F_H I_H}{m_H^2} \right]^2 \quad ,$$

G_F is Fermi constant, $m_{\rm red}$ is neutralino-nucleon reduced mass. The functions $F_{h,H}$ and $I_{h,H}$ are

$$\begin{aligned} F_h &\equiv (-N_{11}\sin\theta_W + N_{12}\cos\theta_W)(N_{13}\sin\alpha + N_{14}\cos\alpha) \\ F_H &\equiv (-N_{11}\sin\theta_W + N_{12}\cos\theta_W)(N_{13}\cos\alpha - N_{14}\sin\alpha) \\ I_{h,H} &\equiv \sum_q k_q^{h,H} m_q \langle N|\bar{q}q|N\rangle \end{aligned}$$

α is the mixing angle of the mass eigenstates (h and H).

The coefficients $k_q^{h,H}$:

$$k^h_{u\text{-type}} = \cos\alpha/\sin\beta \quad , \qquad k^h_{d\text{-type}} = -\sin\alpha/\cos\beta \quad ,$$
$$k^H_{u\text{-type}} = -\sin\alpha/\sin\beta \quad , \qquad k^H_{d\text{-type}} = -\cos\alpha/\cos\beta \quad ,$$

$$\begin{aligned} N_{12} &\simeq -M_Z^2\cos\theta_W\sin\theta_W\frac{M_1+\mu\sin 2\beta}{(M_1-M_2)(M_1^2-\mu^2)} \\ N_{13} &\simeq -M_Z\sin\theta_W\frac{M_1\cos\beta+\mu\sin\beta}{M_1^2-\mu^2} \\ N_{14} &\simeq M_Z\sin\theta_W\frac{M_1\sin\beta+\mu\cos\beta}{M_1^2-\mu^2} \end{aligned}$$

Using unitary condition we get

$$\sigma^{\rm SI} \simeq \frac{8G_F^2}{\pi} \quad m_{\rm red}^2\frac{M_Z^4\sin^2\theta_W}{(M_1^2-\mu^2)^2}\left(\frac{I_H}{m_H^2}\mu\cos 2\beta+\frac{I_h}{m_h^2}(M_1+\mu\sin 2\beta)\right)^2 \times (N_{11}\sin\theta_W - N_{12}\cos\theta_W)^2$$

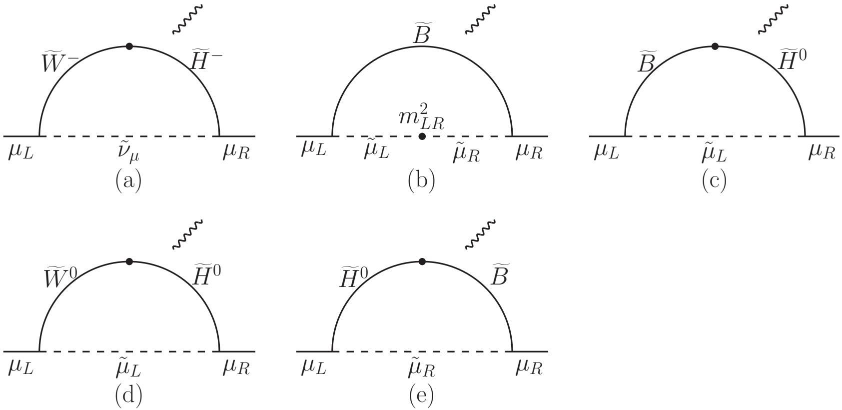
$$
\begin{aligned}
(a)\ a_\mu(\tilde{W}\text{-}\tilde{H},\tilde{\nu}_\mu) &= \frac{g^2}{8\pi^2}\frac{m_\mu^2 M_2 \mu \tan\beta}{m_{\tilde{\nu}}^4}\ F_a\left(\frac{M_2^2}{m_{\tilde{\nu}}^2},\frac{\mu^2}{m_{\tilde{\nu}}^2}\right)\\
(b)\ a_\mu(\tilde{B},\tilde{\mu}_L\text{-}\tilde{\mu}_R) &= \frac{g'^2}{8\pi^2}\frac{m_\mu^2 \mu \tan\beta}{M_1^3}\ F_b\left(\frac{m_{\tilde{\mu}_L}^2}{M_1^2},\frac{m_{\tilde{\mu}_R}^2}{M_1^2}\right)\\
(c)\ a_\mu(\tilde{B}\text{-}\tilde{H},\tilde{\mu}_L) &= \frac{g'^2}{16\pi^2}\frac{m_\mu^2 M_1 \mu \tan\beta}{m_{\tilde{\mu}_L}^4}\ F_b\left(\frac{M_1^2}{m_{\tilde{\mu}_L}^2},\frac{\mu^2}{m_{\tilde{\mu}_L}^2}\right)\\
(d)\ a_\mu(\tilde{W}\text{-}\tilde{H},\tilde{\mu}_L) &= -\frac{g^2}{16\pi^2}\frac{m_\mu^2 M_2 \mu \tan\beta}{m_{\tilde{\mu}_L}^4}\ F_b\left(\frac{M_2^2}{m_{\tilde{\mu}_L}^2},\frac{\mu^2}{m_{\tilde{\mu}_L}^2}\right)\\
(e)\ a_\mu(\tilde{B}\text{-}\tilde{H},\tilde{\mu}_R) &= -\frac{g'^2}{8\pi^2}\frac{m_\mu^2 M_1 \mu \tan\beta}{m_{\tilde{\mu}_R}^4}\ F_b\left(\frac{M_1^2}{m_{\tilde{\mu}_R}^2},\frac{\mu^2}{m_{\tilde{\mu}_R}^2}\right)
\end{aligned}
$$

The positive defined functions $F_a(x,y)$ and $F_b(x,y)$:

$$F_a(x,y) \equiv -\frac{G_3(x) - G_3(y)}{x-y} \qquad F_b(x,y) \equiv -\frac{G_4(x) - G_4(y)}{x-y}$$

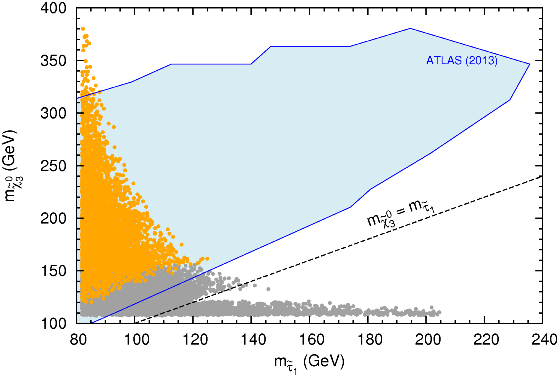
which are symmetric under exchange of the two arguments.

$$\begin{aligned} G_3(x) &= \frac{1}{2(x-1)^3}\left[(x-1)(x-3) + 2\ln x\right] \\ G_4(x) &= \frac{1}{2(x-1)^3}\left[(x-1)(x+1) - 2x\ln x\right] \end{aligned}$$



$\widetilde{W}^-$
$\widetilde{H}^-$
μ_L
$\tilde{\nu}_\mu$
μ_R
(a)
$\widetilde{B}$
m^2_{LR}
μ_L
$\tilde{\mu}_L$
$\tilde{\mu}_R$
μ_R
(b)
$\widetilde{B}$
$\widetilde{H}^0$
μ_L
$\tilde{\mu}_L$
μ_R
(c)
$\widetilde{W}^0$
$\widetilde{H}^0$
μ_L
$\tilde{\mu}_L$
μ_R
(d)
$\widetilde{H}^0$
$\widetilde{B}$
μ_L
$\tilde{\mu}_R$
μ_R
(e)

Excluded region (ATLAS) in $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ plane.



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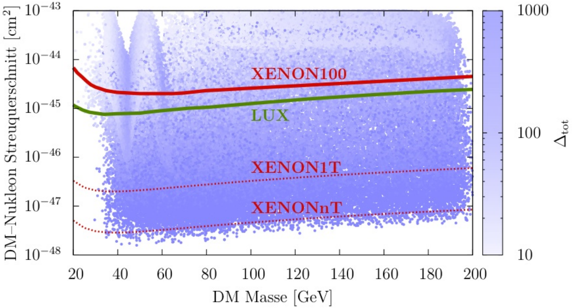

XENON100
LUX
XENON1T
XENONnT
DM–Nukleon Streuquerschnitt [cm²]
DM Masse [GeV]
Δtot
1000
100
10
20 40 60 80 100 120 140 160 180 200
10−43 10−44 10−45 10−46 10−47 10−48