XLVIth Rencontres de Moriond,
Electroweak Interactions
and Unified Theories
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Neutralino dark matter with a light Higgs

(based on D. Das, A. G., Y. Mambrini, JCAP 1012:018,2010 [arXiv:1007.4812])

Andreas Goudelis

Deutsches Elektronen-Synchrotron
(DESY) - Hamburg

Outline

1) Introduction and motivation

2) The model

3) Relic density and indirect detection

4) Direct detection constraints (and subtleties!)

5) Conclusions and outlook

Introductory stuff

Relic density:

→ As a rule of thumb, SUSY models tend to give too much dark matter. Some efficient mechanism is needed to reduce the amount of neutralinos! Possibilities:

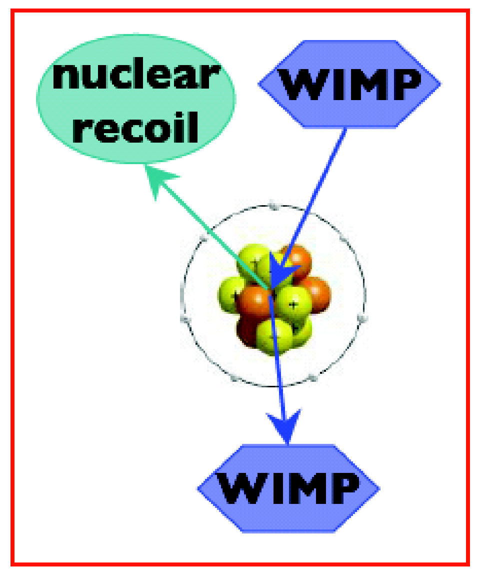
→ **Coannihilation** with NLSP.

→ Neutralino being an appropriate gaugino – higgsino **admixture**.

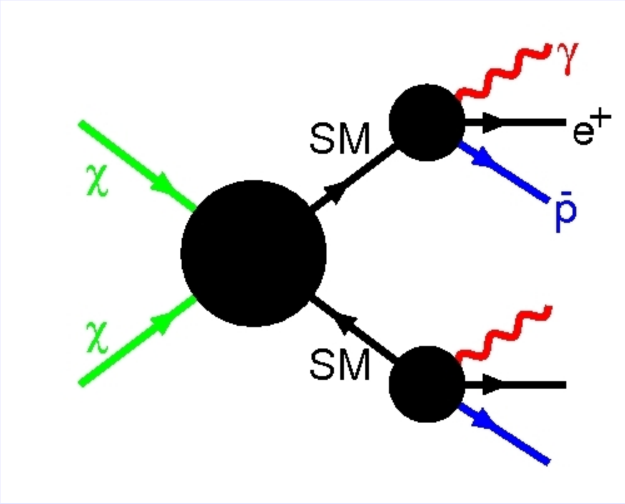
→ LSP and sfermions being sufficiently light → **sfermion exchange**.

→ **Resonances**.

Direct detection:



Indirect detection:



Every channel is different:

→ γ's travel in straight lines, most significant uncertainty comes from "halo profile" (Fermi experiment).

→ Antimatter propagates! Most important factor: the propagation model, treatment à la Annecy (AMS-02 experiment).

Motivation - the little hierarchy problem in the MSSM

In the MSSM, one tree-level relation is:

$$m_{h,H}^2 = \frac{1}{2}\left[m_Z^2 + m_A^2 \mp \sqrt{(m_A^2 - m_Z^2)^2 + 4m_A^2 m_Z^2 \sin^2 2\beta}\right]$$

⟶ So the Higgs mass is lower than the Z mass!

⟶ However, LEP 2 set a bound at 114.4 GeV for m_h in the SM.

⟶ Radiative corrections can help, but require either heavy stops or substantial LR stop mixing.

⟶ But stops cannot be very heavy, and large mixing not always obvious!

⟶ On the other hand, **the SM limit does not strictly apply to the MSSM**.

$$\sigma(e^+e^- \to hZ) = \sin^2(\beta - \alpha)\sigma_{SM}(e^+e^- \to hZ)$$

⟶ To render the LEP 2 limit less restrictive, 2 solutions:

1) Consider **new contributions** to the Higgs mass to satisfy the standard limit:
Beyond the MSSM (NMSSM, USSM, ESSM, μνSSM, BMSSM, MSSM5, MSSM6 ....)

2) Depart from mSUGRA/CMSSM (or, eventually, the MSSM) and **reduce couplings**: LHS

The model

$\longrightarrow$ The idea: One might *need not* severely uplift the lightest Higgs mass.

$\longrightarrow$ This turns out to be impossible in CMSSM/mSUGRA models.

$\longrightarrow$ It is possible, however, in slightly extended frameworks. One such example are non-universal Higgs mass models.

$\longrightarrow$ Is it possible to satisfy WMAP having *A* pole annihilation as the dominant mechanism? (*motivation to be clarified in the following!*)

Seven GUT-scale parameters describe the setup:

$$m_{1/2},\ A_0,\ \mathrm{sign}(\mu),\ \tan\beta,\ m_0,\ m^2_{H_u}(M_{GUT}),\ m^2_{H_d}(M_{GUT})$$

with low-energy quantities being derived through RGE evolution.

Constraints:

$\longrightarrow$ Higgs mass constraint at 93 GeV for LHS (+ the 114 GeV limit starts being valid for the heavier Higgs).

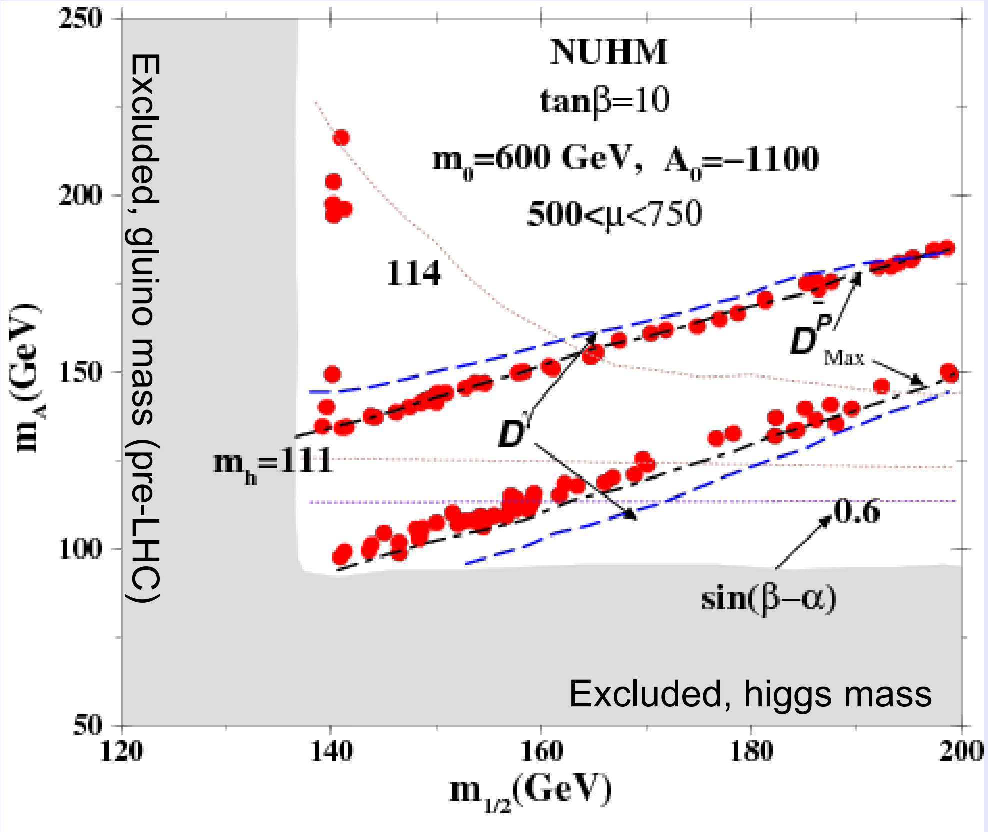
$\longrightarrow$ $b \longrightarrow s\gamma$: Generally μ and A_t should be of opposite sign for diagram cancellation.

$\longrightarrow$ $B_s \longrightarrow \mu^+\mu^-$: We stick to moderate $\tan\beta$ values, hence not that restrictive.

$\longrightarrow$ Relic density constraint.

$\longrightarrow$ Not included: LHC constraints on gluino mass.

Quite light neutralino scenario



Relic density:

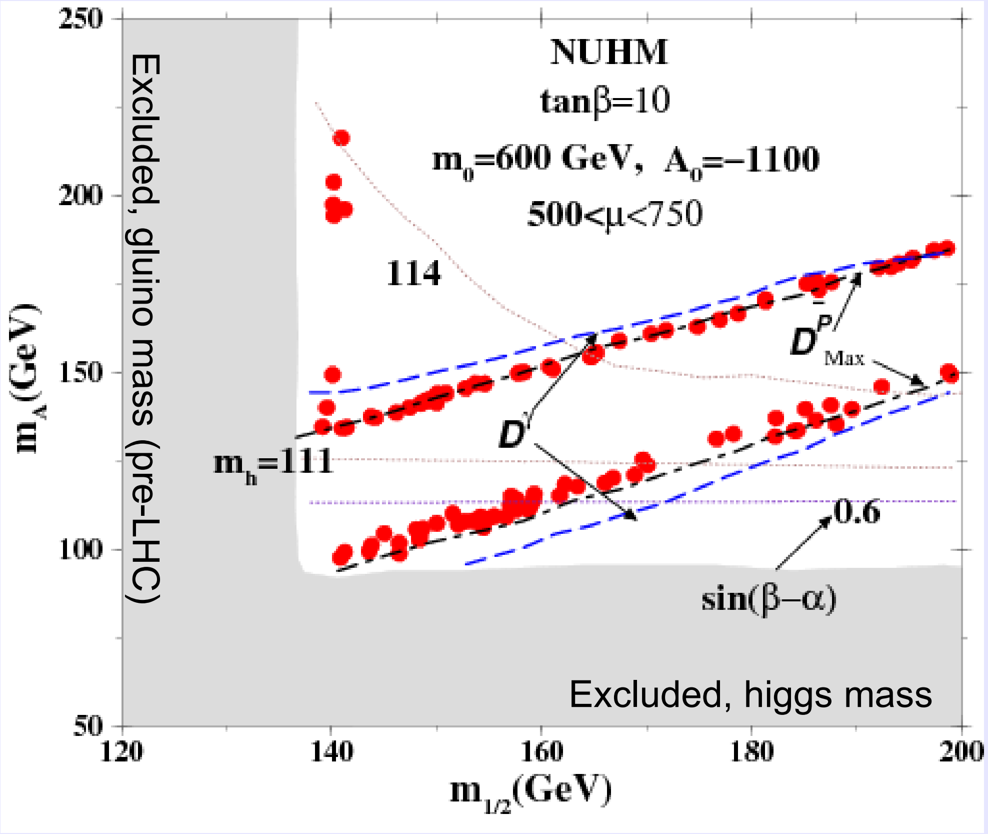
2 regions yielding the correct relic density
→ *h* – funnel region at low $m_{1/2}$.
→ *A* – funnel region in most of the parameter space.

→ Resonant annihilation is the largely dominant process all over the viable parameter space.

Indirect detection (Fermi, AMS-02):

→ We look at intermediate latitudes, hence small profile dependence for gammas.
→ In principle quite good prospects in both channels.
→ At the *A* pole cross-sections at present times are quite large (typical thermal): small velocity dependence.
→ Sharp contrast with the *h* pole, where $\langle \sigma v \rangle \longrightarrow 0$ as v $\longrightarrow 0$.
→ For MIN and MED propagation models all points are invisible.

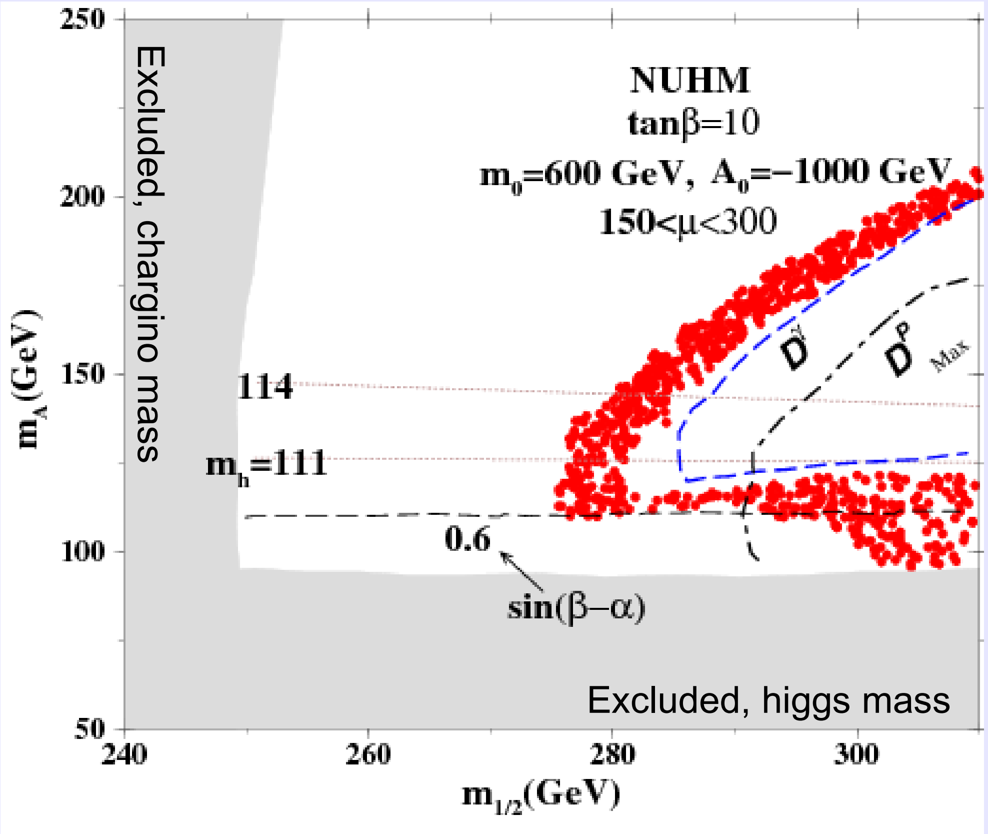
Quite light neutralino scenario



Most probably excluded by LHC constraints on gluino mass!

(But sufficiently instructive for our purposes!)

A bit heavier neutralino scenario



Relic density:

⟶ Once again, we are overall near the *A* pole.
⟶ Smaller μ values in this scenario, hence the neutralino acquires a significant higgsino component.
⟶ Notice that LHS points are further away from the *A* resonance, exactly due to this further enhancement in the couplings to Higgses.

Indirect detection:

⟶ Once again $\langle \sigma v \rangle$ remains quite stable at present times, i.e. thermal.
⟶ In the MIN and MED models, the entire viable parameter space is again invisible.
⟶ LHS seems to evade detection in antiprotons. Not so clear why!

Direct detection – going into some detail

The SI scattering cross-section among a neutralino and a nucleus is given by:

$$\sigma^{SI} = \frac{4m_r^2}{\pi}\left[Zf_p + (A-Z)f_n\right]^2$$

Where:

$$\frac{f_{p,(n)}}{m_{p,(n)}} = \sum_{q=u,d,s} f_{Tq}^{(p,(n))}\frac{\alpha_q}{m_q} + \frac{2}{27} f_{TG}^{(p,(n))} \sum_{c,b,t} \frac{\alpha_q}{m_q}$$

Finally:

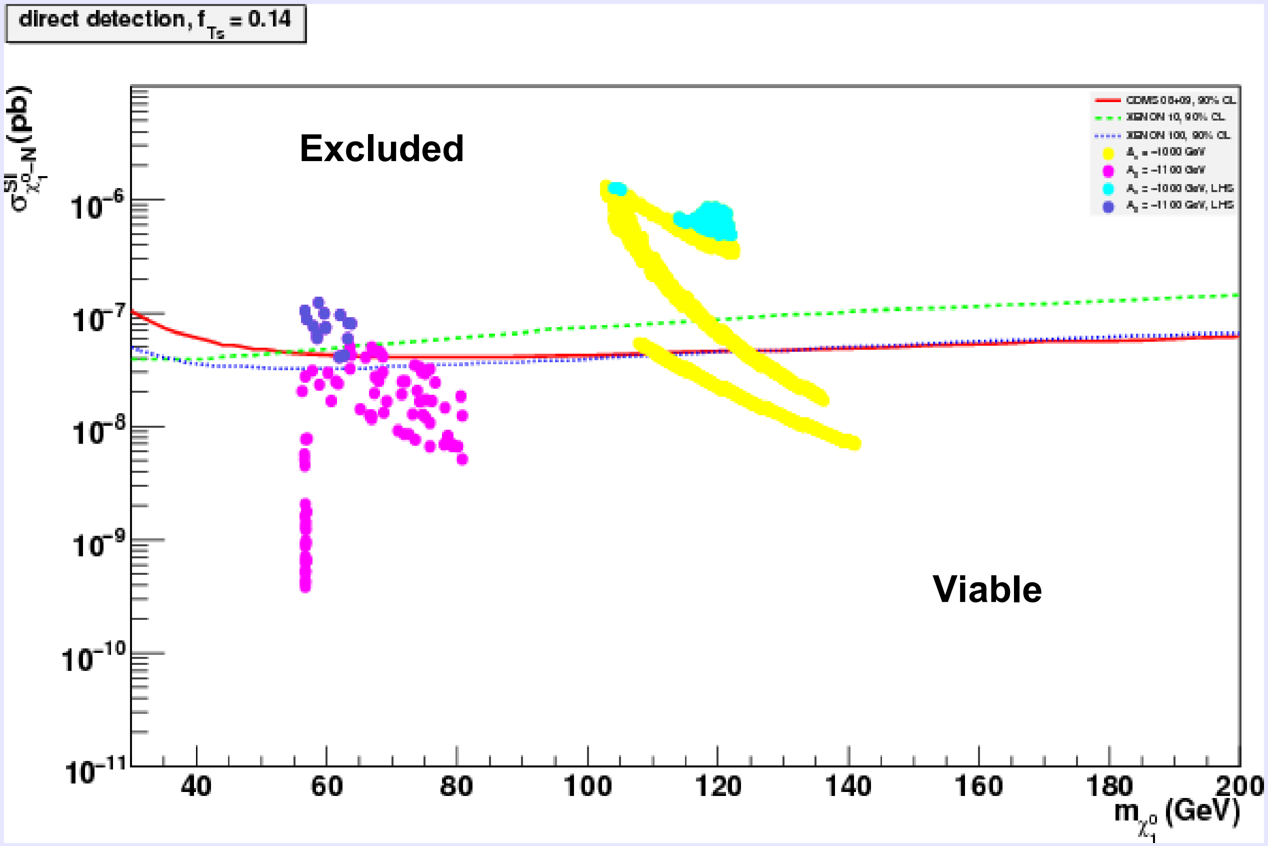
$$m_{p,(n)} \boxed{f_{Tq}^{(p,(n))}} = \langle p,(n)|m_q \bar{q} q|p,(n)\rangle \equiv m_q B_q$$

→This quantity for the *s*-quark is related to the so-called "pion nucleon sigma term", a quantity which is **not** well-constrained (cf. Ellis, Olive, Savage, [arXiv:0801.3656]).

→ DarkSUSY uses an f_{T_s} value of 0.14, while recent lattice simulations seem to favor a much smaller value, around 0.02 (Cao et al, [arXiv:1006.4811], Ohki et al [arXiv:0806.4744]). Results even compatible with zero.

All in all: the SI cross-section in our scenarios is driven by t-channel *h* exchange, which couples strongly to the *s*-quark. The "nucleon composition" in *s* is poorly known. What is the impact of this uncertainty? Well...

Direct detection – first results



The model has in general large scattering cross-sections, primarily due to two reasons:

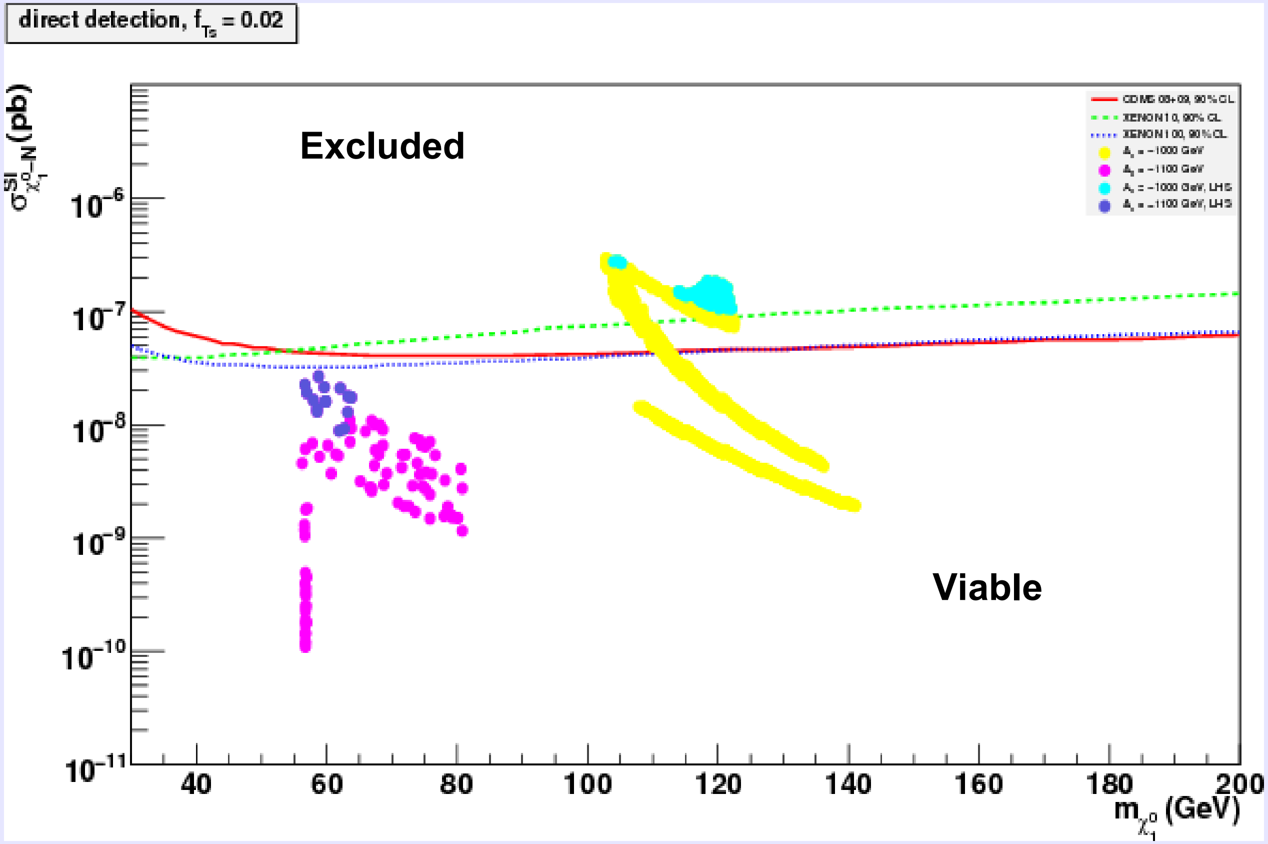
1) Light Higgses

2) The neutralino has a significant higgsino component, which enhances the couplings to the Higgs bosons (especially true for LHS scenarios).

→ So, direct detection seems to impose a "fatal" constraint on our NUHM model, all LHS seem excluded!

However...

Direct detection – fun with f_{Ts} !



1[st] scenario: becomes entirely viable.
2[nd] scenario: excluded by at most a factor 4.

→ It is possible to further reduce f_{T_s}, setting its value to zero. A factor ~3 is gained.

→ An additional factor ~3 can be gained by playing with astrophysics and nuclear form factors.

→ This is no longer playing around with MSSM parameters, the benchmarks have not changed. We're just dealing with NPQCD uncertainties.

So, assessing whether some model is excluded or not is a more complicated business than at first sight... All of the uncertainties should be taken into account.

Conclusions

→ Light Higgs scenarios provide an interesting solution to the little hierarchy problem of the MSSM. No major extension of the model is required (although it is possible!) and they are generally testable at the LHC.

→ In SUSY models the mechanisms through which the correct relic density can be obtained are more or less known: Usually resonances or coupling enhancement due to neutralino composition.

→ Interesting interplay among relic density constraint and indirect detection! Each viable region has its own behavior at zero velocity (*A*-funnel, FP **vs** *h*-funnel, coannihilation)!

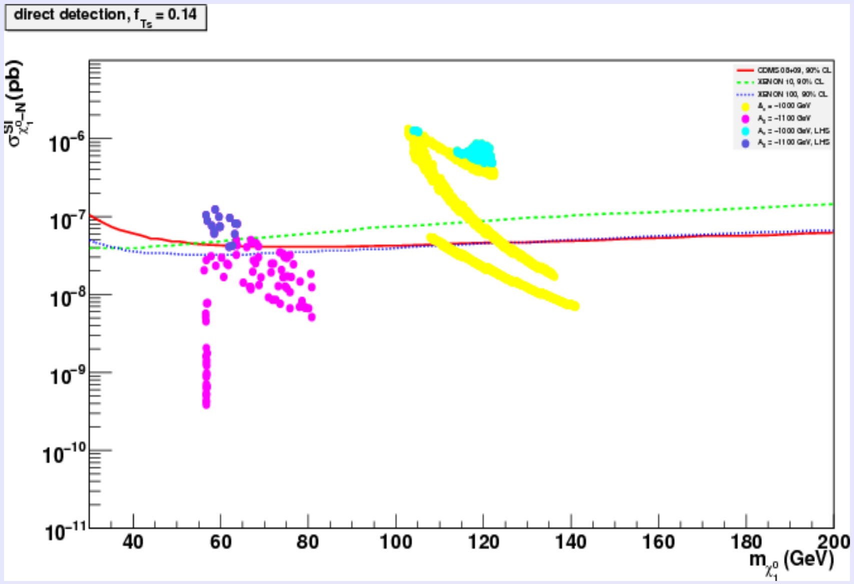
→ Direct detection can also be tricky! One must keep in mind that both experimental limits and theorists' calculations can bare significant uncertainties!

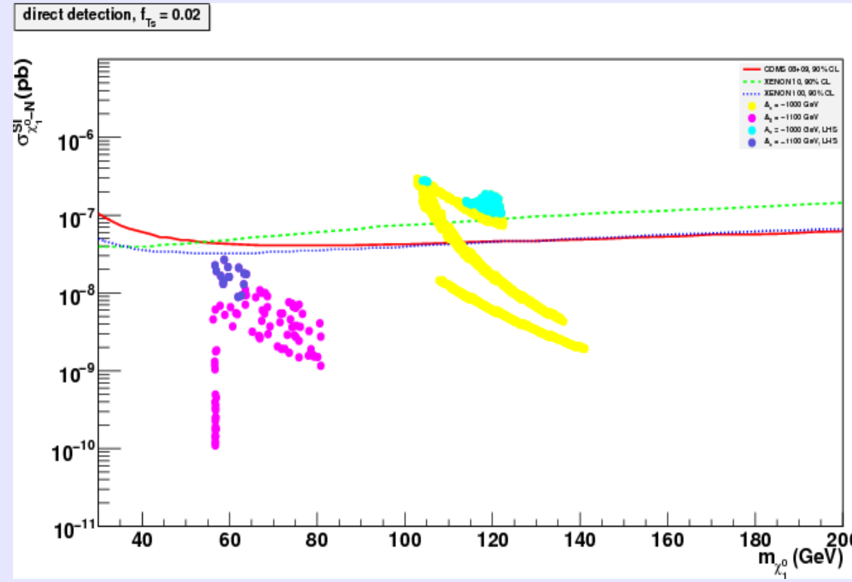
→ Fortunately, significant progress has been made in recent years to quantify such uncertainties in DM calculations: Hadronic issues, multi-body final states, loop corrections, considering alternative velocity distributions...

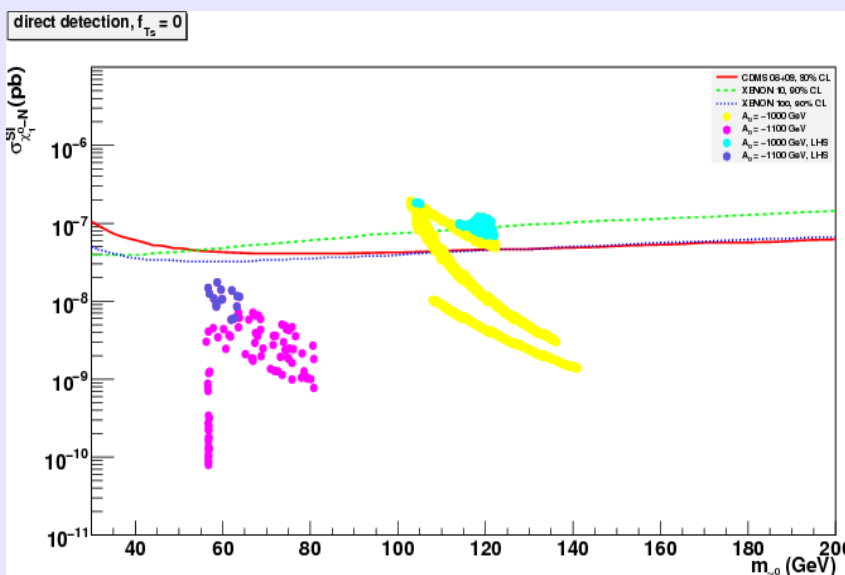
→ In any case, these are uncertainties that should at least be kept in mind when calculating stuff for dark matter!

Backups

NUHM direct detection: result for zero f_{Ts}







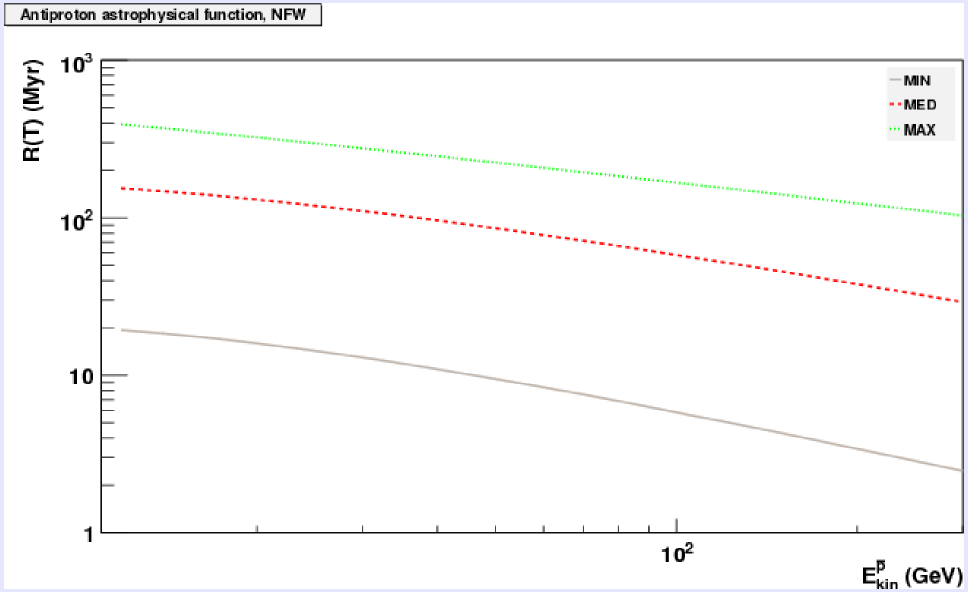
Antiproton flux: formulae and “halo function”

The antiproton flux at solar position is:

$$\Phi_{\odot}^{\bar{p}}(E_{\rm kin}) = \frac{c\,\beta}{4\pi}\frac{\langle\sigma v\rangle}{2}\left(\frac{\rho(\vec{x}_\odot)}{m_\chi}\right)^2 \frac{dN}{dE}(E_{\rm kin}) \boxed{\int_{DZ}\left(\frac{\rho(\vec{x}_s)}{\rho(\vec{x}_\odot)}\right)^2 G_{\bar{p}}^{\odot}(\vec{x}_s)\, d^3x}$$

where the Green's function is

$$G_{\bar{p}}^{\odot}(r,z) = \frac{e^{-k_v\, z}}{2\pi\, K\, L}\sum_{n=0}^{\infty} c_n^{-1}\, K_0\left(r\sqrt{k_n^2+k_v^2}\right)\sin(k_n\, L)\,\sin(k_n\,(L-z))$$



Fluxes and clumps: Examples

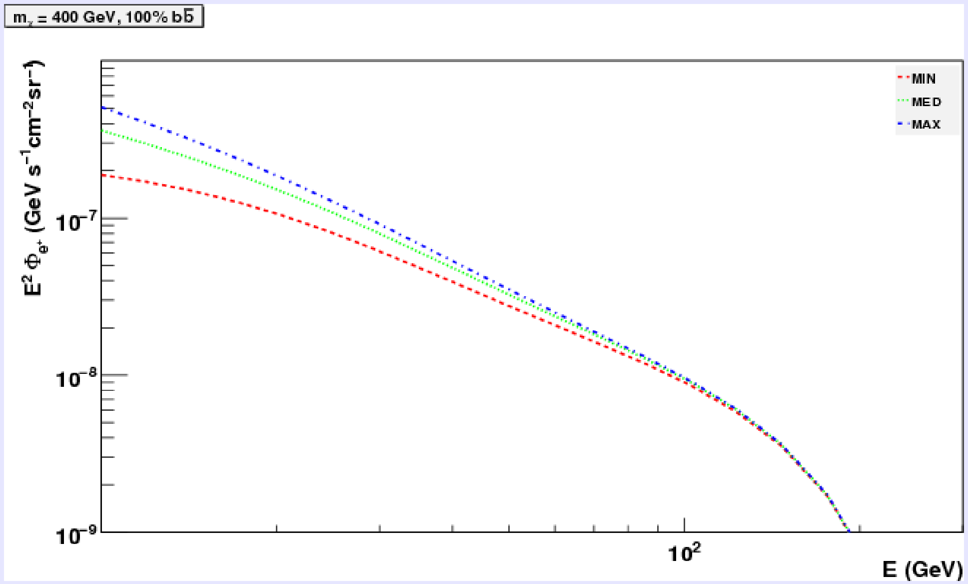
Effective boost factor à la Lavalle et al:

$$B_{\text{eff}} \equiv \frac{\langle \phi \rangle}{\phi_{\text{sm}}} = (1-f)^2 + f B_c \frac{\mathcal{I}_1}{\mathcal{I}_2}$$

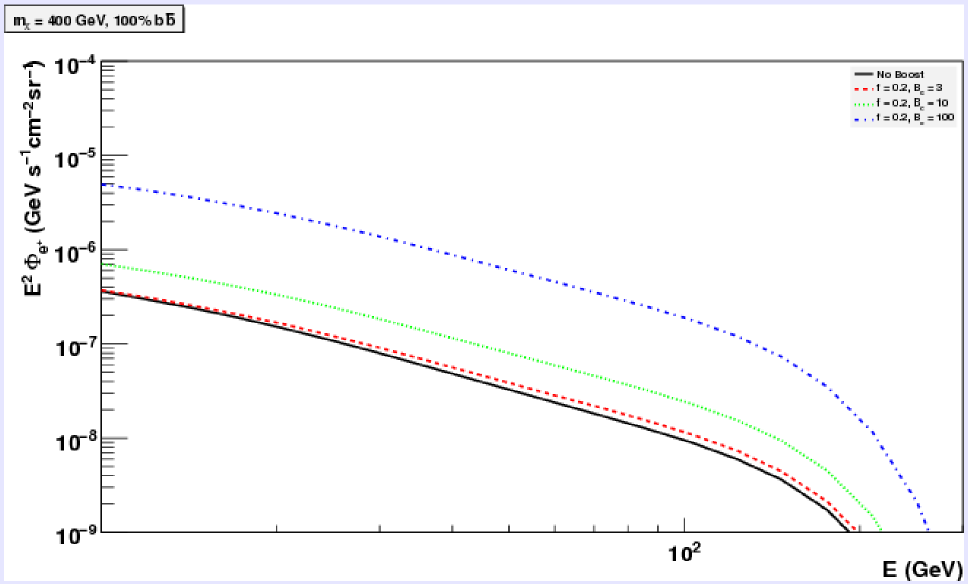
where

$$\mathcal{I}_n = \int_{\text{DM halo}} G(\vec{x}, E) \left(\frac{\rho_{\text{sm}}(\vec{x})}{\rho_0} \right)^n d^3\vec{x}$$

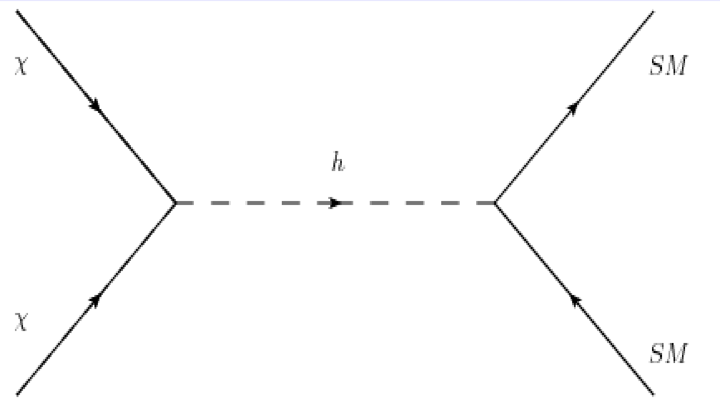
No clumps, just propagation models



Clumps in the MED model



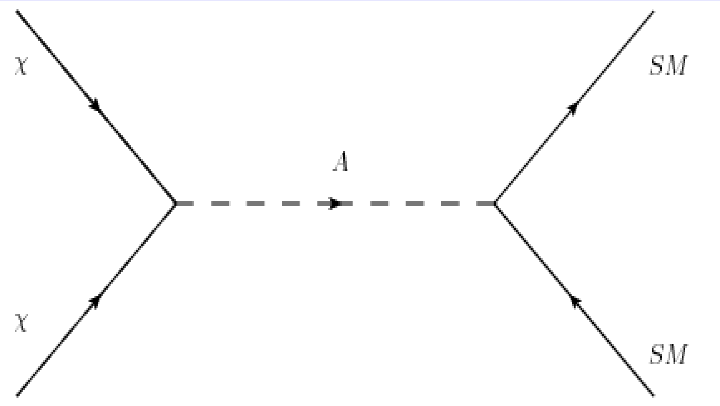
Why is the h pole visible and the A pole invisible?



$$i\mathcal{M} = u(p,s)A\bar{v}(p,s)\frac{i}{p^2 - m_h^2 + im_h\Gamma}\bar{u}(k,s)Bv(k,s)$$

$$|\mathcal{M}|^2 = \frac{A^2B^2(4m_\chi^2 - s)(s - 4m_f^2)}{m_h^4 + (\Gamma^2 - 2s)m_h^2 + s^2}$$

vs ***vs***



$$i\mathcal{M} = u(p,s)A\gamma_5\bar{v}(p,s)\frac{i}{p^2 - m_h^2 + im_h\Gamma}\bar{u}(k,s)B\gamma_5 v(k,s)$$

$$|\mathcal{M}|^2 = \frac{A^2B^2s^2}{m_h^4 + (\Gamma^2 - 2s)m_h^2 + s^2}$$