Dark matter direct detection in the MSSM with heavy scalars

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Outline

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Introduction

Standard Model (EW sector)

The Standard Model (SM) has been proposed to describe the interactions of quarks and leptons. Yang-Mills theory with gauge symmetry $SU(2)_L \times U(1)_Y$. Quarks and leptons interact via the exchange of vector bosons Z and $W^{\pm}$.
The gauge symmetry $SU(2)_L \times U(1)_Y$ is spontaneously broken via the Higgs mechanism. This mechanism generates masses for the SM fermions and for the vector bosons Z and $W^{\pm}$.

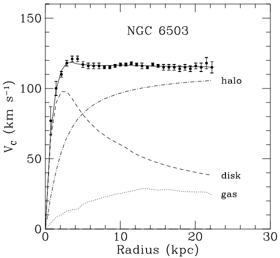
The SM is one of the best tested theories in particle physics.
It has been validate in colliders like LEP, SLC and Tevatron.
The model is minimal, perturbative, unitary and renormalizable.

However, the SM should be taken as an effective theory:

- Hierarchy problem
- No gauge coupling unification
- Dark matter problem

Introduction

Galactic Rotation Curves



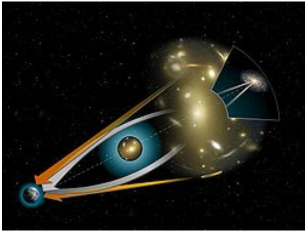
Normally, for $r > r_{vis}$ one would expect

$$v(r) = \sqrt{\frac{GM(r)}{r}}$$

instead

$$v(r) \approx \text{const}$$

Gravitational Lensing



Light bends differently than predicted from GR, if only luminous matter is taken into account.

And also:

- Primordial Nucleosynthesis
- Large Scale Structure

Cosmic Microwave Background

Blackbody radiation, ALMOST homogeneous. Small inhomogeneities due to DM structures during matter-radiation decoupling in the early universe. Only one cosmological model manages (so far!!!) to explain (almost) all observations: ΛCDM

- GR with non-vanishing Cosmological Constant
- Cold Dark Matter

WMAP 5-year results give

$$\Omega_{DM} h^2 = 0.1131 \pm 0.0034$$

whereas

$$\Omega_b h^2 - = 0.02267 \pm 0.00058$$

Minimal Supersymmetric Standard Model (MSSM)

Low scale supersymmetry has now 3 main phenomenological motivations

- ✔ Hierarchy problem
- ✔ Gauge coupling unification
- ✔ A candidate for dark matter

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drawbacks of the model

- ✘ Potentially > 100 free parameters
  mainly arising from scalar sector
- ✘ Quite light Higgs boson mass
  $m_h \lesssim 135$ GeV, tension with LEP searches
- ✘ New sources of FCNC
- ✘ New sources of CP violation
  43 new phases introduced
- ✘ Fast proton decay from 5D operators

➜ Of course, none of these drawbacks are insurmountable
The solution of these 'problems' has been the program for the last years. . .

Outline

Heavy scalars

For SUSY to provide solutions to the unification and DM problems,
only gauginos and higgsinos (SUSY fermions) need to be light.

see e.g: Arkani-Hamed and Dimopoulos

Even with very heavy SUSY scalars (squarks, sleptons and Higgses), it is possible to conserve

- ✔ Gauge coupling unification

Squarks and sleptons sit in complete irreducible representation of $SU(5)$ and the removal of a complete irreducible representation of $SU(5)$ does not affect the prediction of M_{GUT}.
The decoupling of one Higgs doublet will not spoil the unification.

- ✔ A candidate for cold dark matter

Imposing R-parity ensures stability of the LSP, making the lightest neutralino a good candidate for dark matter.

- ✘ Of course, the heavier the scalars are, the more fine tuning we will have to introduce

- ✔ All the last drawbacks can be solved if scalars are heavy

Heavy scalars

In addition to Standard Model particles, the low energy spectrum contains the SUSY fermions

- gauginos: bino ($\tilde{B}$), wino ($\tilde{W}$), gluino ($\tilde{g}$)
- higgsinos: $\tilde{H}_u$, $\tilde{H}_d$

They mix to produce charginos ($\chi^{\pm}_{1,2}$) and neutralinos ($\chi^{0}_{1...4}$), and the gluino.

All the SUSY scalars (squarks, sleptons, Higgses) are assumed to be at a common scale M_S.

➜ Only one Higgs doublet should remain at the electroweak scale
in order to have a proper electroweak symmetry breaking.

✘ The case $M_S \gg 10^5$ GeV, known as Split SUSY, corresponds to an extreme scenario where the solution to the hierarchy problem is lost,
✔ The case $M_S \sim 10^4$ GeV implies just a more important fine tuning.

Anyway, the phenomenology will be pretty similar, because the scalars are decoupled from the low-energy theory.
The scalars will not be accessible at the next generation colliders (LHC, ILC).

Low-energy effective theory

Beside kinetic terms, the most general renormalizable Lagrangian R-parity conserving is

$$\begin{aligned}\mathcal{L} \supset\ & m_H^2 H^\dagger H - \frac{\lambda}{2}\left(H^\dagger H\right)^2 - \Big[h^u_{ij}\,\bar{q}_j\, u_i \epsilon H^* + h^d_{ij}\,\bar{q}_j\, d_i H + h^e_{ij}\,\bar{\ell}_j\, e_i H \\ & + \frac{M_3}{2}\tilde{g}^A \tilde{g}^A + \frac{M_2}{2}\tilde{W}^a \tilde{W}^a + \frac{M_1}{2}\tilde{B}\tilde{B} + \mu\,\tilde{H}_u^T \epsilon\, \tilde{H}_d \\ & + \frac{H^\dagger}{\sqrt{2}}\left(\tilde{g}_u\,\sigma^a\,\tilde{W}^a + \tilde{g}'_u\,\tilde{B}\right)\tilde{H}_u + \frac{H^T\epsilon}{\sqrt{2}}\left(-\tilde{g}_d\,\sigma^a\,\tilde{W}^a + \tilde{g}'_d\,\tilde{B}\right)\tilde{H}_d + \text{c.c.}\Big]\end{aligned}$$

Standard Model like-Higgs boson

$$H = -\cos\beta\,\epsilon\, H_d^* + \sin\beta\, H_u$$

$\tan\beta$ can be interpreted as a Higgs mixing angle.

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Matching conditions at the scale M_S

- Higgs-higgsino-gaugino couplings: $\tilde{g}_u(M_S) = g(M_S)\sin\beta$ $\quad \tilde{g}_d(M_S) = g(M_S)\cos\beta$

  $\tilde{g}'_u(M_S) = g'(M_S)\sin\beta$ $\quad \tilde{g}'_d(M_S) = g'(M_S)\cos\beta$

- Higgs quartic coupling: $\lambda(M_S) = \frac{1}{4}\left[g^2(M_S) + g'^2(M_S)\right]\cos^2 2\beta$
- Yukawa couplings: $h^u_{ij}(M_S) = \lambda^{u*}_{ij}(M_S)\sin\beta,$ $\quad h^{d,e}_{ij}(M_S) = \lambda^{d,e*}_{ij}(M_S)\cos\beta$

Higgs boson mass

Tree level Higgs mass

$$m_H^2(Q) = 2\,\lambda(Q)\,v^2 = \frac{\lambda(Q)}{\sqrt{2}\,G_F}$$

$v \sim 174$ GeV is the Higgs boson vacuum expectation value

One-loop Higgs mass

$$M_H = m_H(Q)\left[1 + \delta^{SM}(Q) + \delta^{\chi}(Q)\right]$$

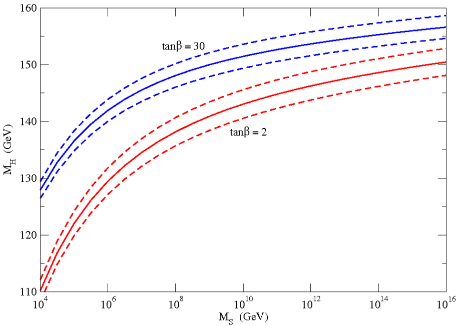
- Standard Model correction:

$\delta^{SM}(Q)$ dominated by top quark loops $\propto M_t^4$

- Neutralino-chargino correction:

$$\delta^{\chi} = \frac{1}{2}\left[\frac{T_H^{\chi}}{\sqrt{2}\,m_H^2\,v} - \frac{\Pi_{HH}^{\chi}(m_H^2)}{m_H^2} + \frac{\Pi_{WW}^{\chi}(0)}{m_W^2}\right]$$

T_H^{χ}, Π_{HH}^{χ} and Π_{WW}^{χ} are the tadpoles and the self-energies of the Higgs and the W boson.



The radiative corrections to the Higgs mass are enhanced by a large logarithm $\log \frac{M_S}{M_{EW}}$

$$110 \text{ GeV} \lesssim M_H \lesssim 160 \text{ GeV}$$

Chargino, neutralino & gluino masses

- Chargino mass matrix:

$$M_\pm = \begin{pmatrix} M_2 & \tilde{g}_u v \\ \tilde{g}_d v & \mu \end{pmatrix}$$

- Neutralino mass matrix:

$$M_0 = \begin{pmatrix} M_1 & 0 & -\tilde{g}'_d v/\sqrt{2} & \tilde{g}'_u v/\sqrt{2} \\ 0 & M_2 & \tilde{g}_d v/\sqrt{2} & -\tilde{g}_u v/\sqrt{2} \\ -\tilde{g}'_d v/\sqrt{2} & \tilde{g}_d v/\sqrt{2} & 0 & -\mu \\ \tilde{g}'_u v/\sqrt{2} & -\tilde{g}_u v/\sqrt{2} & -\mu & 0 \end{pmatrix}$$

The lightest neutralino χ_1^0 is a natural candidate for cold dark matter!

- One-loop gluino mass: $M_{\tilde{g}} = M_3(Q)\left[1 + \frac{\alpha_S}{4\pi}\left(12 + 9\log\frac{Q^2}{M_3^2}\right)\right]$

Structure of the gaugino masses

Since the number of input parameters of the model is rather small, one can relax the assumption of a universal gaugino mass at the GUT scale and still have a predictive model.

- Gravity-mediated SUSY-breaking scenario in which the gaugino masses arise from a dimension–5 operator:

$$\mathcal{L} \sim \frac{\langle F_\Phi \rangle_{ab}}{M_p} \lambda^a \lambda^b$$

$\lambda_{1,2,3}$: gaugino fields
F_Φ: auxiliary component of a chiral superfield Φ which couples to the SUSY field strength.
In the context of $SU(5)$ grand unification the SUSY-breaking F_Φ is a singlet, but in general it can belong to an $SU(5)$ irreducible representation of the product of two adjoints:

$$(\mathbf{24} \otimes \mathbf{24})_{\rm sym} = \mathbf{1} \oplus \mathbf{24} \oplus \mathbf{75} \oplus \mathbf{200}$$

Structure of the gaugino masses

F_Φ	M_1		M_2		M_3	
1	1	1.0	1	2.0	1	7.8
24	1	1.0	3	6.3	−2	15.2
75	5	1.0	−3	−1.2	−1	−1.5
200	10	2.4	2	1.0	1	1.9

Relative gaugino masses at M_{GUT} (M_Z)
for different non-universal gaugino masses cases,with $M_S = 10^4$ GeV.

Spectrum determination

We have implemented a subroutine for the MSSM with heavy scalars
and we integrated it into the program SuSpect — A. Djouadi, J.L Kneur and G. Moultaka

- Inputs
  - M_S — Soft SUSY-breaking sfermion mass parameter
  - $M_1, M_2, M_3\,(M_{GUT})$ — Gaugino mass parameters
  - $\mu\,(M_Z)$ — Higgsino mass parameter
  - $\tan\beta\,(M_S)$ — Higgs mixing angle
  - SM inputs: $\alpha(M_Z)$, $\alpha_S(M_Z)$, G_F, M_Z, M_t, $m_b(m_b)$ and M_τ.

  M_1, M_2, M_3 and μ are parameters in the regularization scheme $\overline{\mathrm{DR}}$

- Evolution of the 15 parameters:

  $g_1, g_2, g_3, h^t, h^b, h^\tau, \mu$ defined at M_Z
  $\tilde{g}_u, \tilde{g}_d, \tilde{g}'_u, \tilde{g}'_d, \lambda$ defined at M_S
  M_1, M_2, M_3 defined at M_{GUT}.

  Using the one-loop Split-SUSY RGE between M_Z and M_S and the one-loop MSSM RGE between M_S and M_{GUT}, it is possible to evolve all parameters down to the EW scale.

  The large logarithmic corrections $\propto \log(M_{EWSB}/M_S)$ are resumed by means of RGEs

- Threshold corrections implemented

NB, A. Djouadi, P. Slavich 07

Dark matter calculations

- Dark matter relic density calculation with a modified version of micrOMEGAs

✔ RGEs and 1-loop corrections implemented

✔ Modification in CalcHEP $\chi - \chi - H$ couplings

➜ DM relic density

➜ Neutralino-nucleon scattering cross-sections

Outline

Collider constraints

- Chargino production $\sigma(e^+e^- \to \chi_1^+\chi_1^-) > 50$ fb

Direct bound from LEP2 at $\sqrt{s} \sim 208$ GeV
$e^+e^- \to \chi_1^+\chi_1^-$ implies $m_{\chi_1^\pm} \gtrsim 103$ GeV if $m_{\chi_1^\pm} - m_{\chi_1^0} <$ few GeV then $m_{\chi_1^\pm} \gtrsim 92$ GeV

- Invisible Z boson decay $\Gamma(Z \to \chi_1^0\chi_1^0) > 2$ MeV

Using the ratio $M_1 : M_2$ at M_Z, it is possible to translate the $m_{\chi_1^\pm}$ bound into a $m_{\chi_1^0}$ bound.
If χ_1^0 is very light, it can contribute to the invisible decay $Z \to \chi_1^0\chi_1^0$

- Neutralino production $\sigma(e^+e^- \to \chi_1^0\chi_i^0) > 50$ fb

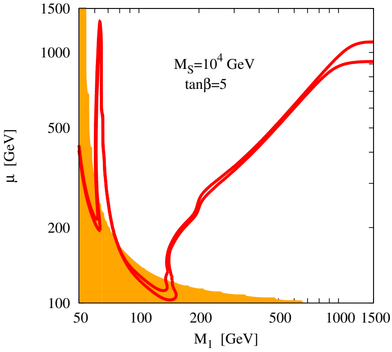
Direct bound from LEP2 at $\sqrt{s} \sim 208$ GeV
$e^+e^- \to \chi_1^0\chi_2^0$ $e^+e^- \to \chi_1^0\chi_3^0$

For $\mathcal{L} \sim 100$ fb^{-1}, cross sections smaller than 50 fb correspond to less than 5 events

Dark matter constraints

Dark matter relic density has been measured by WMAP: $\Omega_{DM}\,h^2 = 0.109 \pm 0.062$, at 68% CL.

Scenario **1**



✘ $\mu \gg \mathbf{M_1}$: χ^0_1 is bino-like
σ_{ann} too small and $\Omega\,h^2$ too big

✘ $\mathbf{M_1} \gg \mu$: χ^0_1 is higgsino-like
σ_{ann} too big and $\Omega\,h^2$ too small
coannihilation with χ^0_2 and $\chi^\pm_1$

✔ Higgs boson funnel: $m_{\chi^0_1} \sim \frac{1}{2} M_H$
LSP annihilation very effective via the exchange of a real Higgs boson

✔ Mixing region for $M_1 \sim \mu$
LSP is a higgsino-bino mixing
$\chi^0_1\chi^0_1 \to W^+W^-,\ ZZ,\ HZ,\ HH$
➜ Threshold $\chi^0_1\chi^0_1 \to t\,\bar{t}$

✔ Coannihilation with χ^0_2 and $\chi^\pm_1$
For $m_{\chi^0_1} \gtrsim 1$ TeV, and $M_1 \gg \mu$
annihilation cross section can be enhanced by coannihilation

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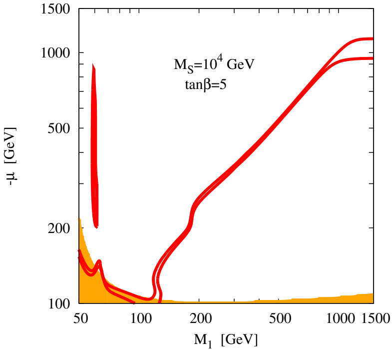


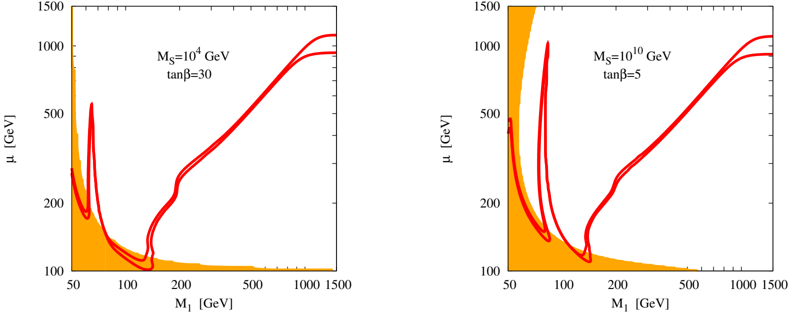
Usually $\mu > 0$ for $b \to s\gamma$ and $(g-2)_\mu$
Because of heavy scalars $\to$
No contribution to these processes!

✘ For $\mu < 0$
$\chi_1^0 - \chi_1^0 - H$ coupling could be suppressed:
$C_{\chi_1^0 \chi_1^0 H} \propto \frac{M_1 + \mu \sin 2\beta}{M_1^2 - \mu^2}$

The Higgs funnel is narrower and lower for $\mu < 0$.

Dark matter constraints

Scenario **1**



$\tan\beta = 30$

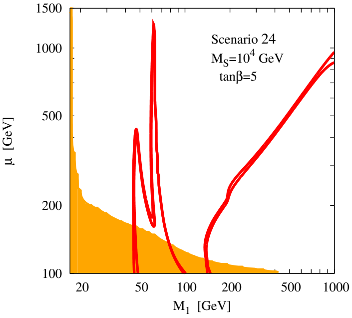
Near the Higgs peak
the coupling $\chi_1^0 - \chi_1^0 - H$ decreases
with increasing $\tan\beta$
$C_{\chi\chi H} \propto \sin 2\beta$
LSP shifted to the $\tilde{H}_d^0$ component

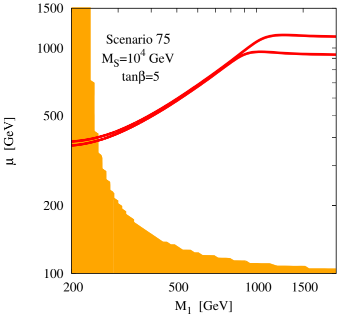
$M_S = 10^{10}$ GeV

The Higgs peak is shifted
$M_1 \sim M_H/2 \sim 75$ GeV
$\chi_1^0\chi_1^0 \to H \to WW^* \to Wf\bar{f}$

Note that variations over M_S and $\tan\beta$ are primarily reflected in the Higgs peak, whereas the mixed region is almost insensitive.

Dark matter constraints: Non-universality





Scenario **24**

$\mathbf{M_1 : M_2 = 1.0 : 6.3}$

✔ Z boson funnel: $\chi_1^0\chi_1^0 \to Z \to f\bar{f}$

Invisible decay $Z \to \chi_1^0\chi_1^0$ should be taken into account!

Scenario **75**

$\mathbf{M_1 : M_2 = 1. : -1.2}$

✔ Coannihilation between χ_1^0, χ_2^0 & $\chi_1^\pm$: very important effects!

➜ $M_1, \mu < 1$ TeV: LSP bino-like

➜ $\mu \sim 1$ TeV: LSP higgsino-like

Outline

Dark matter detection

- ➜ Production at colliders LHC, ILC, CLIC
- ➜ Direct detection Xenon, CDMS, Dama/Libra(?)
- ➜ Indirect detection:

  γ from annihilation in galactic center or halo Fermi

  e^+ from annihilation in galactic center or halo Pamela, Atic

  $\bar{p}$ from annihilation in galactic center or halo Pamela, Atic

  ν from annihilation in massive bodies Icecube

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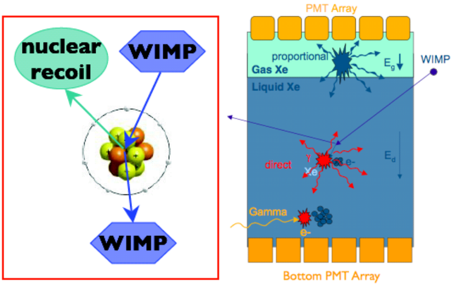
Dark matter direct detection

Direct detection experiments are designed to detect **dark matter particles** by their **elastic collision with target nuclei**, placed in a detector on the Earth.

XENON 100 **kg**



Background

- Gamma rays
- Betas

✔ can be removed by comparing scintillation in liquid xenon and ionisation in gas xenon.

- Neutrons

✘ give the same signal as WIMPs.
It can be removed by shielding with lead protections.

➜ The collaboration expects *negligible* background

Dark matter direct detection

Recoil rates

$$\frac{dN}{dE_r} = \frac{\sigma_{\chi-p} \cdot \rho_0}{2\, M_r^2\, m_\chi} F(E_r)^2 \int_{v_{\min}(E_r)}^{v_{\rm esc}} \frac{f(v)}{v}\, dv$$

Reduced mass $M_r = \frac{m_\chi\, m_N}{m_\chi + m_N}$

N: number of scatterings $(\mathrm{s}^{-1}\mathrm{kg}^{-1})$
E_r: nuclear recoil energy ~few keV
m_χ: WIMP mass
$\sigma_{\chi-p}$: WIMP-proton scattering cross-section
➜ Assume pure spin-independent coupling

ρ_0: local WIMP density $0.38\ \mathrm{GeV\ cm^{-3}}$
F: nuclear form factor Woods-Saxon
$f(v)$: WIMP local vel. distribution M.B.

$$f(v) = \frac{1}{\sqrt{\pi}} \frac{v}{1.05\, v_0^2} \left[e^{-(v-1.05\, v_0)^2/v_0^2} - e^{-(v+1.05\, v_0)^2/v_0^2} \right]$$

Xenon100:

7 energy bins [4, 30] keV
$M = 100$ kg of Xenon
$T = 3$ years of data acquisition

Discrimination method: χ^2

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{N_i^{\rm tot} - N_i^{\rm bkg}}{\sigma_i} \right)^2$$

Gaussian error: $\sigma = \sqrt{\frac{N_i^{\rm tot}}{M \cdot T}}$

Dark matter direct detection

Recoil rates

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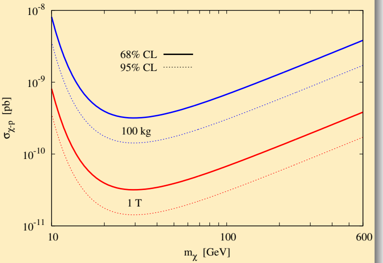
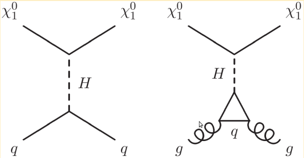
Sensitivity curves for Xenon



The sensitivity curves correspond to the regions where Xenon could detect at least one event, with a stated probability.

Dark matter direct detection & Heavy scalars

Neutralino–nucleus spin-independent interaction

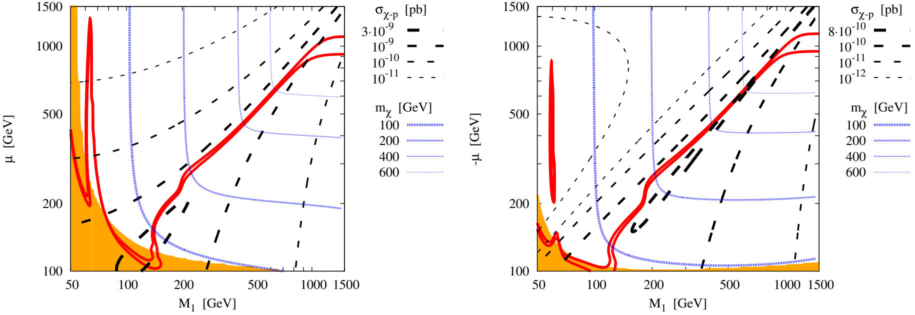


$$C_{\chi_1^0\chi_1^0 H} \propto N_{13}(\tilde{g}_d N_{12} - \tilde{g}'_d N_{11}) - N_{14}(\tilde{g}_u N_{12} - \tilde{g}'_u N_{11})$$

- ✔ The coupling is enhanced for a temperate gaugino-higgsino LSP.
- ✘ Pure gaugino-like or pure higgsino-like LSP $\rightarrow C_{\chi\chi H}$ vanish
- ✘ Plethora of diagrams involving squarks propagators $(\tilde{u}, \tilde{d})$ suppressed by $1/M_S^2$
- ✘ t-channel Z-boson exchange doesn't contribute to the spin-independent cross-section. Axial-vector interaction

Dark matter direct detection & Heavy scalars

Scenario **1**



$M_S = 10^4$ GeV & $\tan\beta = 5$

✔ Scattering cross-section reaches high values, up to $\sim 4 \cdot 10^{-9}$ pb

✔ $C_{\chi\chi H}$ stays high even for elevated M_1 and μ values when LSP is a higgsino-gaugino mixing

✘ Higgs-pole: the bino-like nature of the LSP doesn't enhance the scattering cross-section

✘ $\mu < 0 \quad \rightarrow \quad$ suppression near $M_1 \sim -\mu \sin 2\beta$

Dark matter direct detection & Heavy scalars

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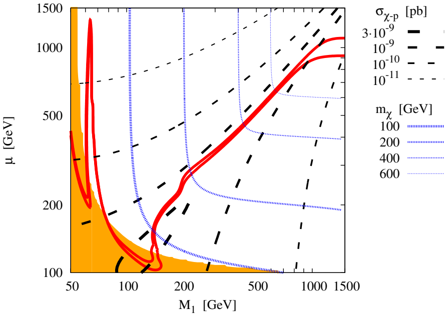
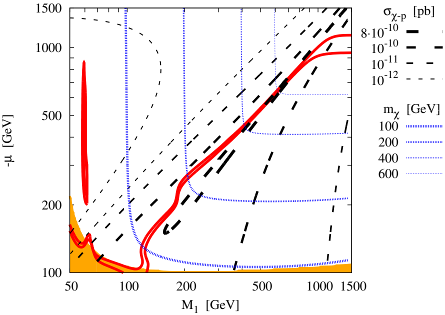




$M_S = 10^4$ GeV & $\tan\beta = 5$

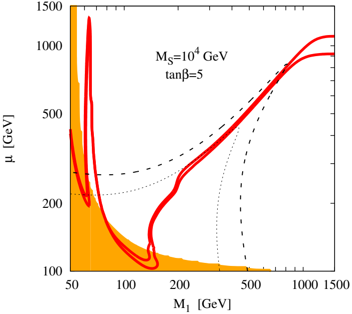
✘ A raising of $M_S \to$ increase of $M_H \to$ decrease of $\sigma_{\chi-p} \propto \frac{1}{M_H^4}$

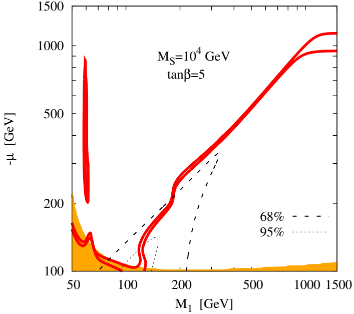
✘ A raising of $\tan\beta \to$ slight increase of $M_H\ldots$
$\to$ the LSP becomes more quickly a pure bino- or higgsino-like state

➜ Best scenario for dark matter direct detection: not very high M_S and low $\tan\beta$

Dark matter direct detection & Heavy scalars

Scenario **1**





$M_S = 10^4$ GeV & $\tan\beta = 5$

➜ Exclusion lines for Xenon100 after 3 years of data acquisition

➜ Ability to test and exclude different regions of the model

✔ In the absence of signal, a sizeable fraction of the parameter space could be excluded!

✘ Only the Higgs peak could not be probed

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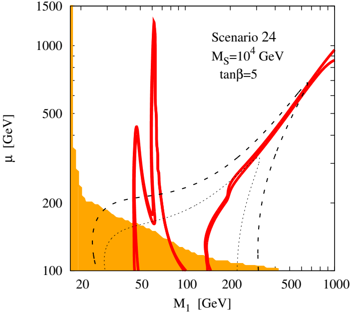
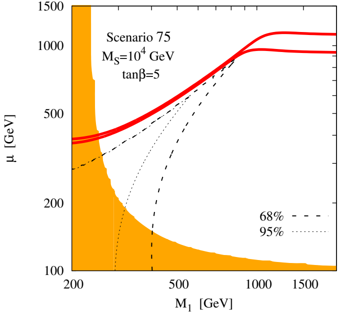


Scenario **24** (M_1 : M_2 ~ 1.0 : 6.3)



Scenario **75** (M_1 : M_2 ~ 1.0 : −1.2)

$M_S = 10^4$ GeV & $\tan\beta = 5$

✘ Neither $Z-$ nor $H-$pole can be detected

✔ Spin-dependent direct detection could explore $Z-$funnel!

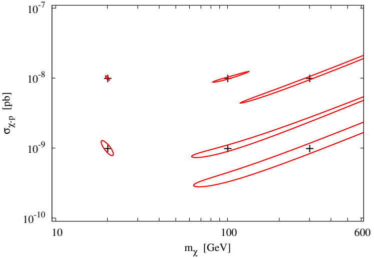
✔ Maximal sensitivity for $m_\chi \sim 30$ GeV

✘ Scenario **75** escapes from detection; DM relic density generated by coann. with $\chi_1^\pm$ and χ_2^0

Outline

Reconstruction prospects: Model independent

➜ Let's suppose that Xenon100 detects some signal!



Ability of Xenon to determine:
the mass and the scattering cross-section
in a microscopically model independent approach

$$\frac{dN}{dE_r} = \frac{\sigma_{\chi-p}\cdot\rho_0}{2\,M_r^2\,m_\chi}\,F(E_r)^2\int_{v_{\min}(E_r)}^{v_{\rm esc}}\frac{f(v)}{v}\,dv$$

✔ Good reconstruction for $\lesssim$ 50 GeV LSP and high scattering cross-section

✘ Dramatic increase of the errors for heavier LSP

➜ However, it could be improved: particular model!

A.M. Green, 07 - 08
NB, A. Goudelis, Y. Mambrini, C. Muñoz, 08

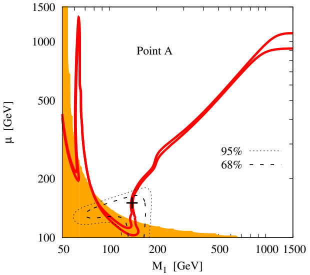
Reconstruction prospects: Benchmark A

Benchmark **A**: Scenario **1**
$M_1 = 138$ GeV, $\mu = +143$ GeV
$m_\chi = 93.6$ GeV, $\sigma_{\chi-p} = 3.2 \cdot 10^{-9}$ pb
LSP: Higgsino-bino mixing

Even if the reconstructed region is large,
the combination with collider and cosmological constraints
allows to drastically shrink the latter

Relative errors: ($\tan\beta$ and M_S fixed)
$\Delta M_1 \sim 3\%$ $\Delta\mu \sim 30\%$
$\Delta m_\chi \sim 20\%$ $\Delta\sigma_{\chi-p} \sim 15\%$

However, the variation of $\tan\beta$ or M_S has a limited impact
in the reconstruction

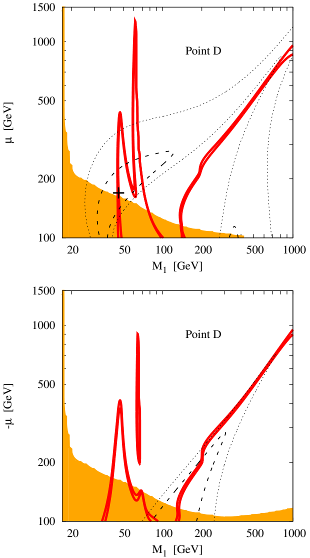


Reconstruction prospects: Benchmark D

Benchmark **D**: Scenario **24**
$M_1 = 45$ GeV, $\mu = +165$ GeV
$m_\chi = 39.0$ GeV, $\sigma_{\chi-p} = 2.9 \cdot 10^{-10}$ pb
very light bino-like LSP

4 parts corresponding to the left and right bands
of the $Z-$ and $H-$peaks
$160 \lesssim M_1 \lesssim 255$ GeV $\quad 45 \lesssim \mu \lesssim 68$ GeV

The signal is also compatible with $\mu < 0$
$\sigma_{\chi-p} \sim 4.7 \cdot 10^{-10}$ pb $\quad 92 \lesssim m_{\chi-p} \lesssim 170$ GeV



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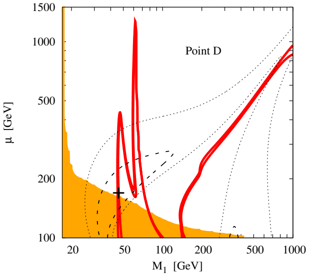
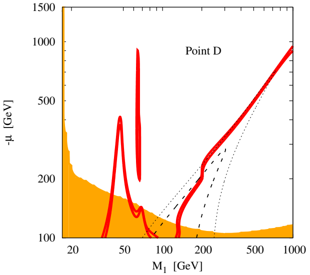
Xenon cannot examine with a high-precision level such a benchmark with a so low scattering cross-section.
However, it can provide very valuables hints on the nature of the WIMP dark matter





Outline

Conclusions

- The MSSM, in the case where the scalars are heavy, is a more predictive scenario.
- We still have
  - ✔ gauge coupling unification,
  - ✔ a good candidate for dark matter.

But we require a large fine-tuning for the Higgs boson.

- We have studied in detail the dark matter constraint
  - ✔ Higgs pole,
  - ✔ 'temperate'gaugino-higgsino LSP region,
  - ✔ Z boson pole (for some scenarios with non-universality)
  - ✔ coannihilation with other neutralinos and charginos

- Dark matter direct detection prospects in Xenon100
  - ✔ sizable fraction of the parameter space could be tested,
  - ✔ maximal sensibility for LSP mixed gaugino-higgsino.

- Reconstruction
  - ✔ In some cases is possible to reconstruct both mass and scattering-cross section,
  - ✔ or at least put strong constraints on the nature of the LSP...
  - ➜ Complementarity with other detection modes!

Outline

Introduction

Hierarchy problem

When calculating quantum corrections to the Higgs boson, there appears quadratic divergences of Λ, the UV cut-off scale.

$$M_H^2 = m_H^2 + \frac{N_f\, \lambda_f^2}{8\,\pi^2}\left[-\Lambda^2 + 6\, m_f^2\, \log\frac{\Lambda}{m_f} - 2\, m_f^2\right] + \mathcal{O}\left(\frac{1}{\Lambda^2}\right)$$

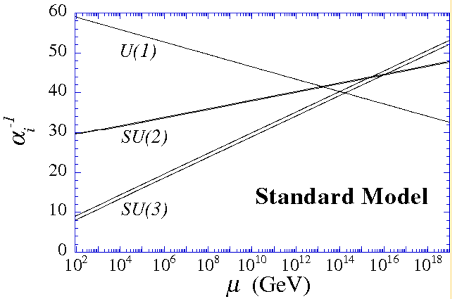
The Higgs boson should be at the EW scale in order to have a proper symmetry breaking
But, the Higgs mass is proportional to Λ^2
and we would like a cut-off Λ of the order of $M_{GUT} \sim 10^{16}$ GeV.

➜ It is the hierarchy problem

Introduction

Gauge coupling unification

The gauge groups $SU(3)_C \times SU(2)_L \times U(1)_Y$ could be subgroups of a bigger symmetry $SU(5)$ or $SO(10)$, broken at a high scale.



➜ There is no unification of gauge coupling constants

Minimal Supersymmetric Standard Model (MSSM)

Low scale supersymmetry has now 3 main phenomenological motivations

- ✔ Hierarchy problem
- ✔ Gauge coupling unification
- ✔ A candidate for dark matter

drawbacks of the model

- ✘ Potentially > 100 free parameters mainly arising from scalar sector
- ✘ Quite light Higgs boson mass $m_h \lesssim 135$ GeV, tension with LEP searches
- ✘ New sources of FCNC
- ✘ New sources of CP violation 43 new phases introduced
- ✘ Fast proton decay from 5D operators

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✘ Potentially > 100 free parameters

Apart from the Standard Model parameters
➜ 62 new free real parameters + 43 new phases
mainly arising from sfermion soft breaking & trilinear couplings.

✘ Difficult to construct a predictive theory. . .

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✘ Quite light Higgs boson mass

At tree level ➜ $M_h < |\cos 2\beta| M_Z \leq M_Z$ already excluded by LEP

nevertheless, including quantum corrections (mainly top + stops loops)

➜ $M_h \lesssim 140$ GeV

LEP gives a lower bound $M_h \gtrsim 114.4$ GeV

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✘ New sources of Flavor Changing Neutral Currents (FCNC)

FCNC in both Standard Model and in the MSSM are generated at loop level.
In general, MSSM generates excessive FCNC, incompatible with experimental measurements.

✘ Severe bounds in flavour structure of soft breaking terms…

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✘ New sources of CP violation

The MSSM introduces 43 new phases.

The electron and neutron electric dipole moments induced at one-loop by gaugino-sfermion exchange are typically a couple of orders of magnitude above the limits

➜ Supersymmetric CP problem

✘ Stringent constraints in CP structure…

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✘ Fast proton decay from dimension-five operators

The MSSM could contain non-renormalizable dimension-5 operators $qq\tilde{q}\tilde{l}$ leading to fast proton decay: $p \to K^+ \bar{\nu}$

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➜ Of course, none of these drawbacks is insurmountable
The solution of these ‘problems’ has been the program for the last 20 years…

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The non-observation of superpartners implies that SUSY is not an exact symmetry:
residual contribution to the Higgs mass, proportional to the mass differences between the SM particles (M_{SM}) and the new SUSY particles