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Dark matter in the U(1) extended supersymmetric model

Jan Kalinowski

FACULTY OF PHYSICS
WARSAW UNIVERSITY

based on works in collab. with

S.Y. Choi, H.E. Haber and P.M. Zerwas, Nucl.Phys.B in press
D. Jarecka, S.F. King and J. Roberts, work in progress

Dark matter

Three categories of evidence for dark matter:

Rotation curves of galaxies
Cosmic microwave background
Gravitational lensing

Known properties of dark matter

weakly interacting, massive, neutral and stable particle

the measured density $\Omega_{CDM}h^2 = 0.106 \pm 0.008$

Many candidates for WIMP's

most preferred neutralinos – mixtures of neutral spatrners of gauge bosons and Higgs

SUSY

SUSY has a problem

- Bino DM: generally gives $\Omega_{CDM}h^2 \gg \Omega_{CDM}^{WMAP}h^2$
- Wino/Higgsino DM: generally gives $\Omega_{CDM}h^2 \ll \Omega_{CDM}^{WMAP}h^2$
- only small parts of the "octopus" in the cMSSM left

MSSM has a μ problem: why in $W = \mu H_u H_d$ is of order EW scale

- NMSSM promote μ to vev of some scalar field S

$$W = \lambda S H_u H_d + \tfrac{1}{3} k S^3$$

required to avoid a massless axion due to global PQ symmetry which broken at weak scale.

Nilles ea,
Frere ea
Derendinger ea
Ellwanger ea,
…

but broken Z_3 symmetry => cosmological domain-wall problem

- promote PQ to the U(1) gauge symmetry: U(1)-extended SUSY

Cvetic ea,
Suematsu ea,
…

Kinetic term mixing in USSM

$\mathrm{U}(1)_Y \times \mathrm{U}(1)_X$ gauge kinetic term for B^Y and B^X

$$\mathcal{L}_{\rm gauge} = -\frac{1}{4}Y^{\mu\nu}Y_{\mu\nu} - \frac{1}{4}X^{\mu\nu}X_{\mu\nu} - \frac{\sin\chi}{2}Y^{\mu\nu}X_{\mu\nu}$$

Holdom
Del Aguila ea
Dienes ea

can be converted to canonical form

$$\begin{pmatrix} \hat{W}_Y \\ \hat{W}_X \end{pmatrix} = \begin{pmatrix} 1 & -\tan\chi \\ 0 & 1/\cos\chi \end{pmatrix} \begin{pmatrix} \hat{W}_B \\ \hat{W}_{B'} \end{pmatrix}$$

the U(1) part of the covariant derivative => effective Q_x charge

$$D_\mu = \partial_\mu + ig_Y Y B_\mu + i\left(-g_Y Y\tan\chi + \frac{g_X}{\cos\chi}Q\right)B'_\mu$$
$$= \partial_\mu + ig_Y Y B_\mu + ig_X Q' B'_\mu$$

gaugino masses:

$$\mathcal{L}_{\tilde{g}\,\rm mass} = -\frac{1}{2}M_Y\tilde{Y}\tilde{Y} - \frac{1}{2}M_X\tilde{X}\tilde{X} - M_{YX}\tilde{Y}\tilde{X} + \rm h.c.$$
$$= -\frac{1}{2}M_1\tilde{B}\tilde{B} - \frac{1}{2}M'_1\tilde{B}'\tilde{B}' - M_k\tilde{B}\tilde{B}' + \rm h.c.$$

$$M'_1 \equiv \frac{M_X}{\cos^2\chi} - \frac{2\sin\chi}{\cos^2\chi}M_{YX} + M_Y\tan^2\chi$$

Higgs sector

Two iso-doublets H_u , H_d and one scalar S

$$\hat{W} = \hat{W}_Y + \lambda \hat{S} \left(\hat{H}_u \hat{H}_d\right)$$

After spontaneous EW + $U(1)_X$ symmetry breaking by

$$\langle H_u \rangle = \frac{\sin\beta}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad \langle H_d \rangle = \frac{\cos\beta}{\sqrt{2}} \begin{pmatrix} v \\ 0 \end{pmatrix}, \quad \langle S \rangle = \frac{1}{\sqrt{2}} v_s$$

the doublet higgsino mass and higgsino-singlino mass terms are generated

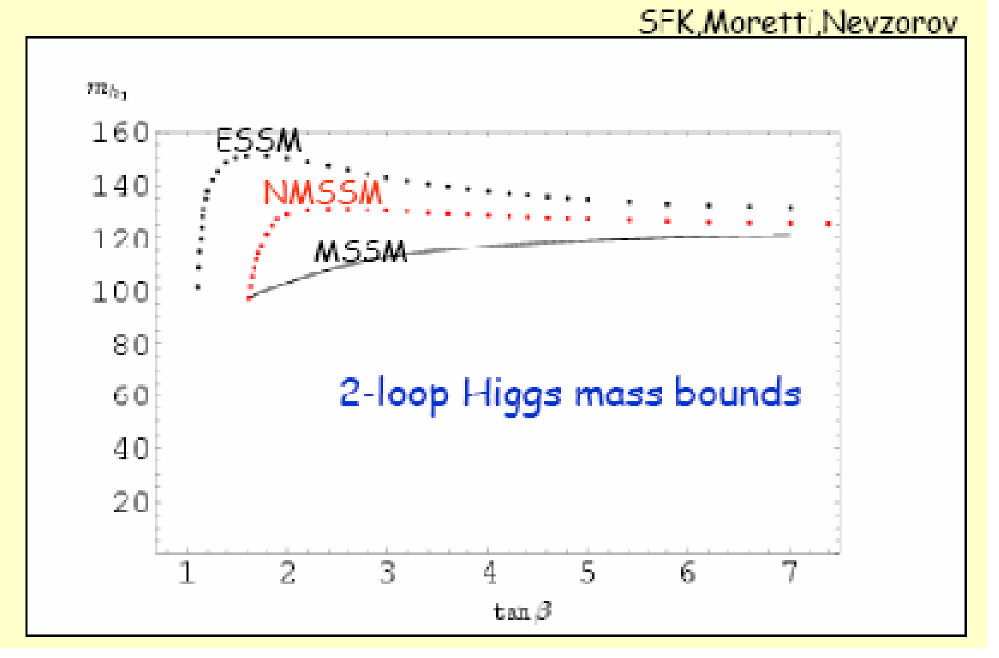
$$\mu = \lambda \frac{v_s}{\sqrt{2}} \quad \text{and} \quad \mu_\lambda = \lambda \frac{v}{\sqrt{2}}$$

physical Higgs bosons: three neutral scalars
two charged
one neutral pseudoscalar

Higgs sector

The USSM Higgs h_1 mass bound

$$m_{h_1}^2 \le \frac{\lambda^2}{2} v^2 \sin^2 2\beta + M_Z^2 \cos^2 2\beta + \tfrac{1}{4} M_Z^2 \left(1 + \tfrac{1}{4}\cos 2\beta\right)^2 + \Delta \le \left(160\ GeV\right)^2$$



hep-ph/0510419, hep-ph/0511256

Neutralino sector

In the $\tilde{B}, \tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{S}, \tilde{B}'$ basis, the neutralino mass matrix:

$$\mathcal{M}_6 = \left(\begin{array}{cccc|cc} M_1 & 0 & -m_Z\, c_\beta\, s_W & m_Z\, s_\beta\, s_W & 0 & M_k \\ 0 & M_2 & m_Z\, c_\beta\, c_W & -m_Z\, s_\beta\, c_W & 0 & 0 \\ -m_Z\, c_\beta\, s_W & m_Z\, c_\beta\, c_W & 0 & -\mu & -\mu_\lambda\, s_\beta & Q_1' m_v\, c_\beta \\ m_Z\, s_\beta\, s_W & -m_Z\, s_\beta\, c_W & -\mu & 0 & -\mu_\lambda\, c_\beta & Q_2' m_v\, s_\beta \\ \hline 0 & 0 & -\mu_\lambda\, s_\beta & -\mu_\lambda\, c_\beta & 0 & Q_S' m_s \\ M_k & 0 & Q_1' m_v\, c_\beta & Q_2' m_v\, s_\beta & Q_S' m_s & M_1' \end{array}\right)$$

where $m_v = g_X\, v$ and $m_s = g_X\, v_s$

and the $U(1)_X$ charges $Q_1 = -\frac{3}{2\sqrt{10}}\,, \quad Q_2 = -\frac{2}{2\sqrt{10}}\,, \quad Q_S = \frac{5}{2\sqrt{10}}$

Note a see-saw type 2x2 block in $\tilde{S}, \tilde{B}'$ subspace:

for large M_1' singlino may become very light

Suematsu
Hesselbach ea,
Moortgat-Pick ea,
Barger ea,
King ea,

Scenario with non-universal $M_1,\ M_1'$: Suematsu, hep-ph/0511299

Diagonalizing M_6

For small mixing between

Choi, Haber, K, Zerwas

$\tilde{B}, \tilde{W}^3, \tilde{H}_d^0, \tilde{H}_u^0$ and $\tilde{S}, \tilde{B}'$

- diagonalize first 4x4 and 2x2 blocks

$$\mathcal{M}_6 \to \left(\begin{array}{cccc|cc} \tilde{m}_{1'} & & & & 0 & M_k \\ & \tilde{m}_{2'} & & & 0 & 0 \\ & & \tilde{m}_{3'} & & +\mu_\lambda c_- & Q'_- m_v \\ & & & \tilde{m}_{4'} & -\mu_\lambda c_+ & Q'_+ m_v \\ \hline 0 & 0 & +\mu_\lambda c_- & -\mu_\lambda c_+ & \tilde{m}_{5'} & \\ M_k & 0 & Q'_- m_v & Q'_+ m_v & & \tilde{m}_{6'} \end{array}\right)$$

- perform block-diagonalization

$$V^6 \approx \begin{pmatrix} 1\!\!1_{4\times 4} - \frac{1}{2}\Omega\Omega^T & \Omega \\ -\Omega^T & 1\!\!1_{2\times 2} - \frac{1}{2}\Omega^T\Omega \end{pmatrix} \begin{pmatrix} V^4 & 0 \\ 0 & V^2 \end{pmatrix}$$

- eigenvalues only shifted

$$\Omega_{i'j'} = \frac{(V^4 X V^{2T})_{i'j'}}{\tilde{m}_{i'} - \tilde{m}_{j'}}$$

$$m_{i'} = \tilde{m}_{i'} + \sum_{j'=5'}^{6'} \frac{(V^4 X V^{2T})^2_{i'j'}}{\tilde{m}_{i'} - \tilde{m}_{j'}} \qquad [i' = 1', .., 4']$$

$$m_{j'} = \tilde{m}_{j'} - \sum_{i'=1'}^{4'} \frac{(V^4 X V^{2T})^2_{i'j'}}{\tilde{m}_{i'} - \tilde{m}_{j'}} \qquad [j' = 5', 6']$$

Illustrative example

Evolution of the neutralino mass spectrum as a function of M_1'

$$\text{from}: \quad M_1' \ll v \ll \mu \ll M_1, M_2, v_s$$
$$\text{to}: \quad v \ll \mu \ll M_1, M_2, v_s \ll M_1'$$

We take a scenario with

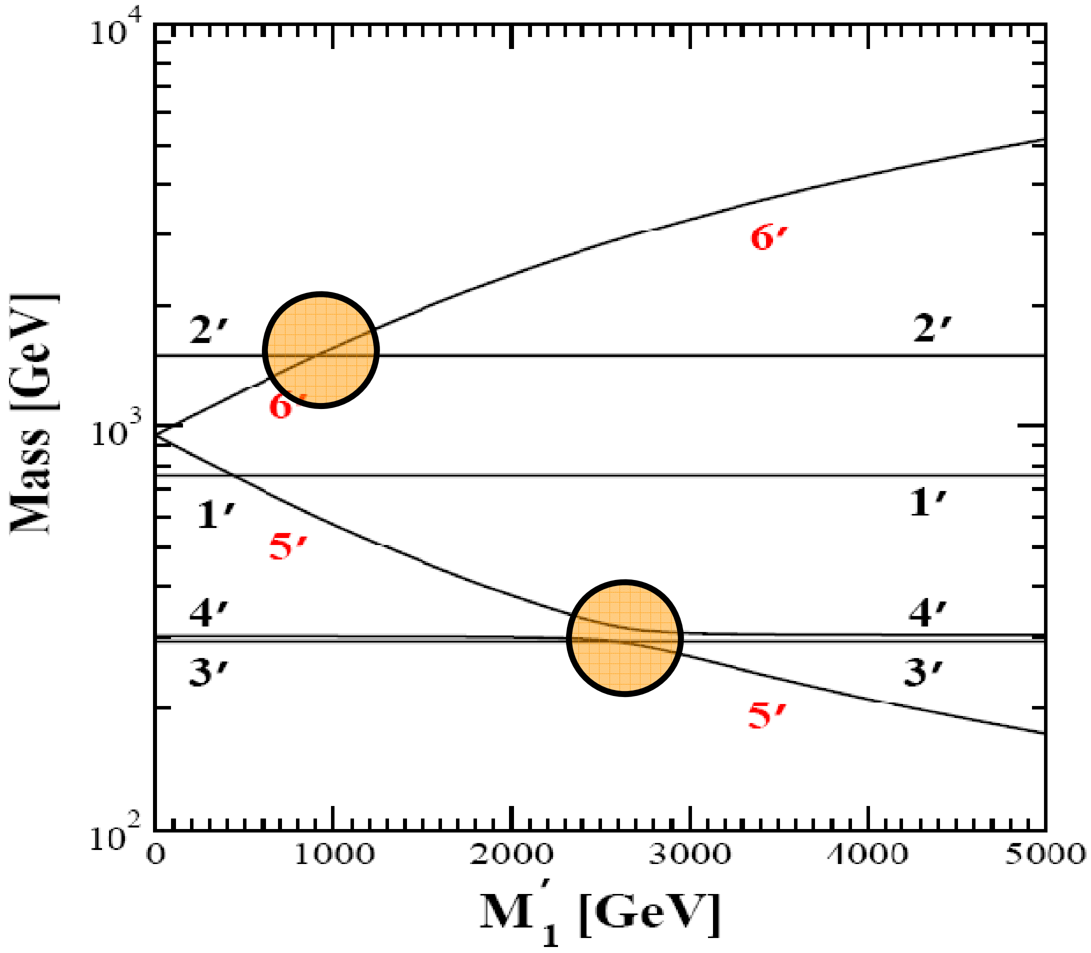
$M_2 = 1.5 \text{ TeV}, \, m_s = 1.2 \text{ TeV}$

$\mu = 0.3 \text{ TeV and } M_k = 0$

$M_1 = (5/3)\tan^2\theta_W M_2$

$\tan\beta = 5$

$M_A = 500 \text{ GeV}$



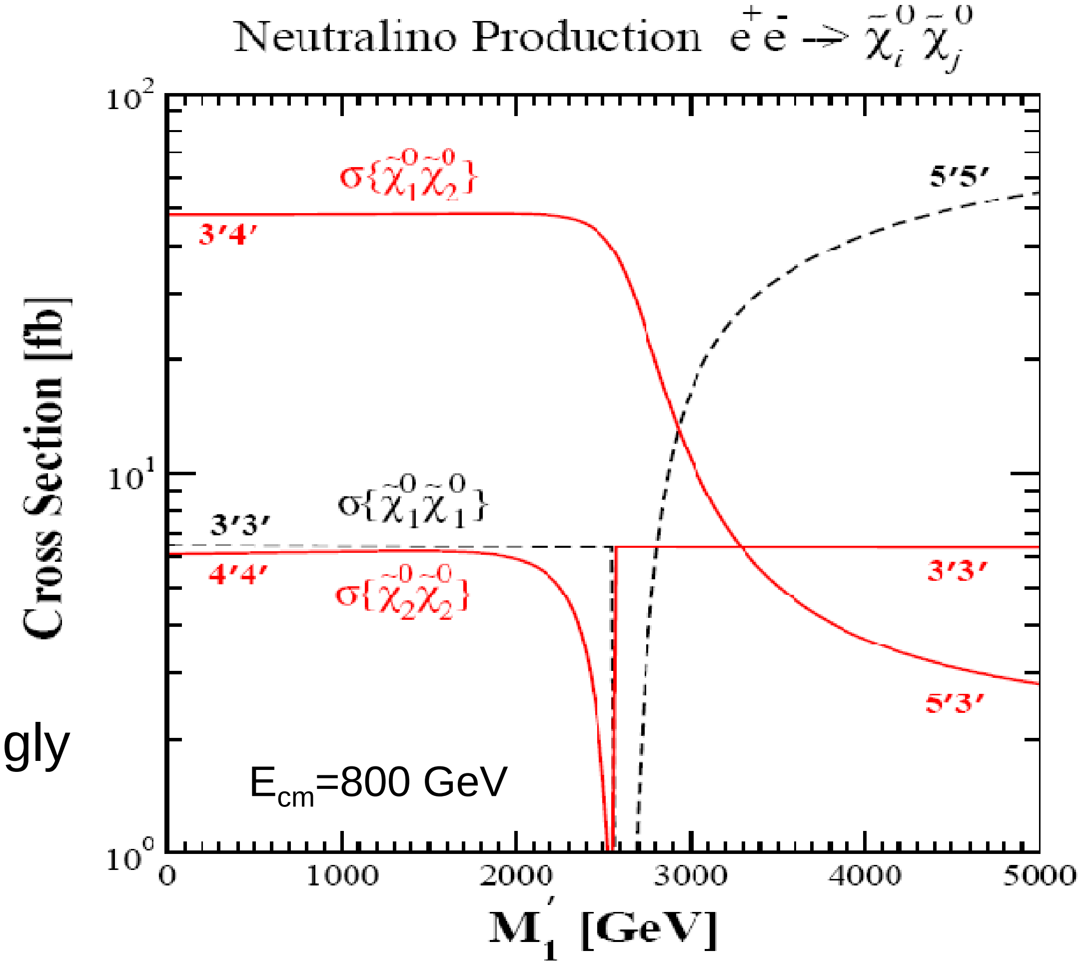
Neutralino production in e+e-

in our scenario

$$M_{Z_2} = 949 \text{ GeV}$$

$$\theta_{ZZ'} = 3.3 \times 10^{-3}$$

$$m_{\tilde{e}_{R,L}} = 701 \; GeV$$



The presence of ~1 TeV Z_2 strongly affects cross sections
e.g. for M_1'=0

Cross Section [fb]	$\sigma\{\tilde{\chi}_1^0\tilde{\chi}_1^0\}$	$\sigma\{\tilde{\chi}_1^0\tilde{\chi}_2^0\}$	$\sigma\{\tilde{\chi}_2^0\tilde{\chi}_2^0\}$
USSM	6.5	48.0	6.1
MSSM	1.7×10^{-3}	67.1	8.5×10^{-3}

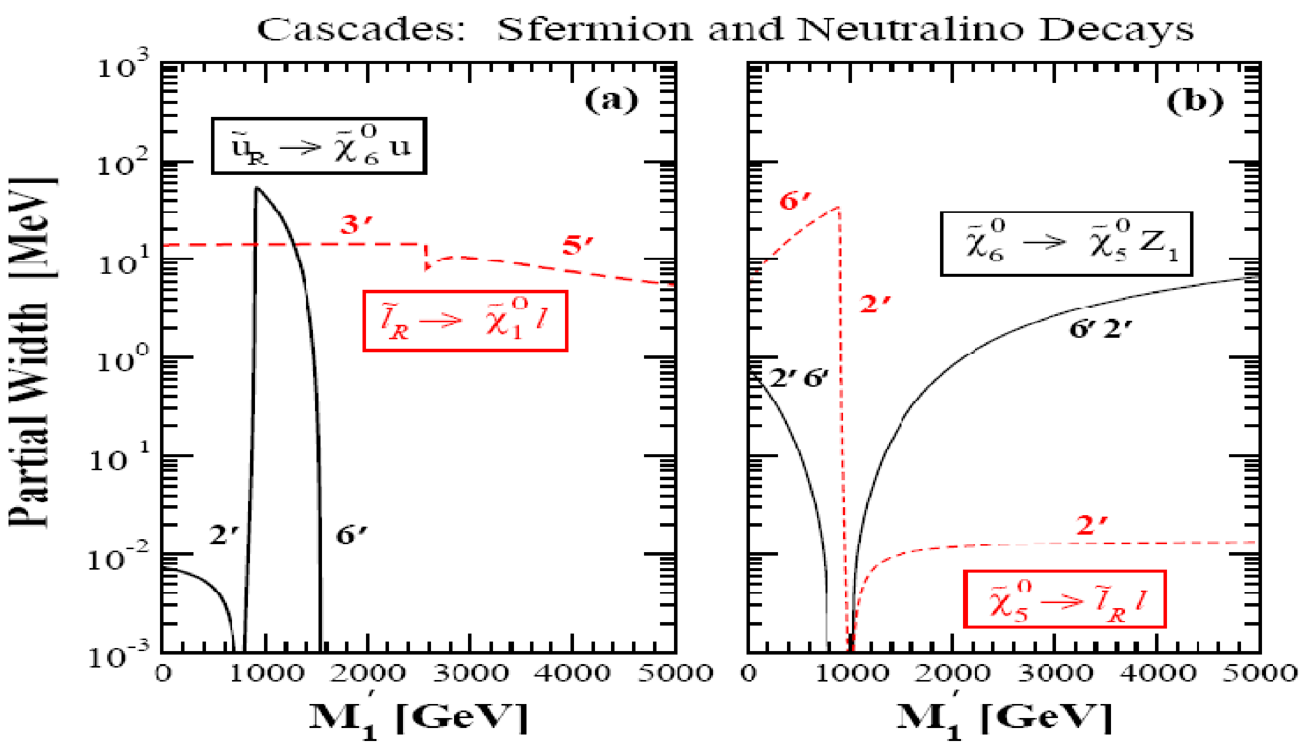
although masses of $\tilde{\chi}_1^0\tilde{\chi}_2^0$ are as in MSSM

Neutralino decays

Phenomenology changes significantly: only selected examples

- Cascade decays - c.f. LHC celebrated case

$$\tilde{u}_R \to u\tilde{\chi}_6^0 \to u[Z_1\tilde{\chi}_5^0] \to uZ_1[\ell\tilde{\ell}_R] \to uZ_1\ell\ell\tilde{\chi}_1^0$$



- also possible

$$\tilde{u}_R \to u\tilde{\chi}_5^0 \to u[\ell\tilde{\ell}_R] \to u\ell\ell\tilde{\chi}_1^0$$

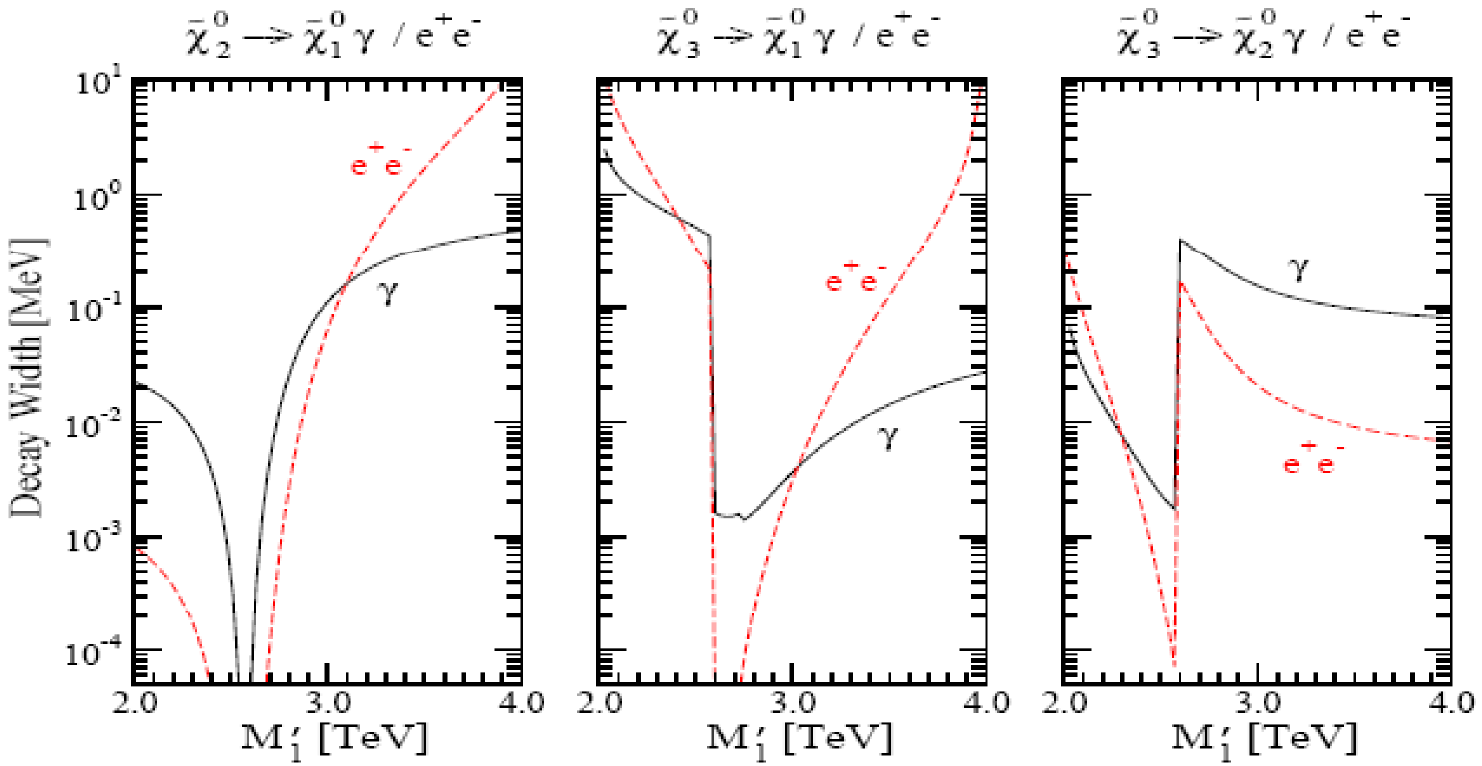
but

Decay Width [MeV]	$\Gamma[\tilde{u}_R \to \tilde{\chi}_i^0 u]$
USSM	130.0
MSSM	3294.6

Neutralino decays

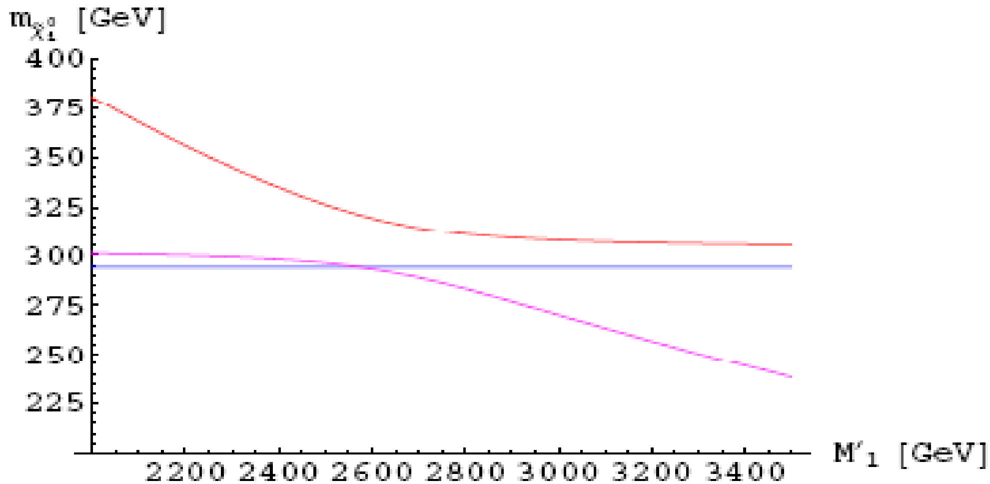
- Radiative decays - important in cross-over zones

e.g. near M'_1=2.6 TeV 4'-5' zone



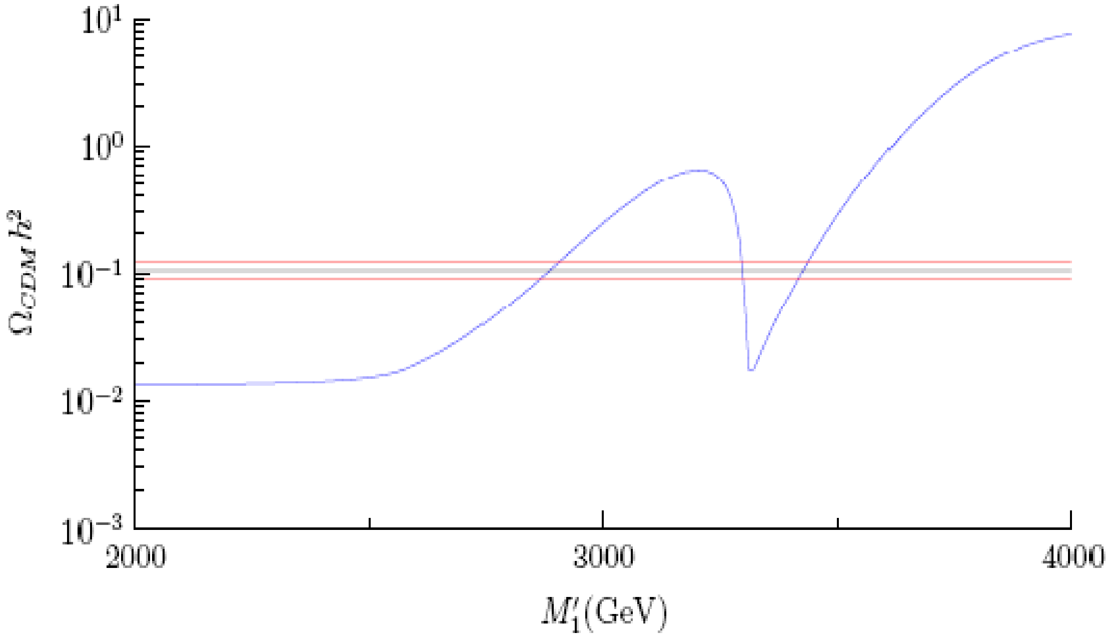
DM relic density

Depends on the nature
of the lightest neutralino

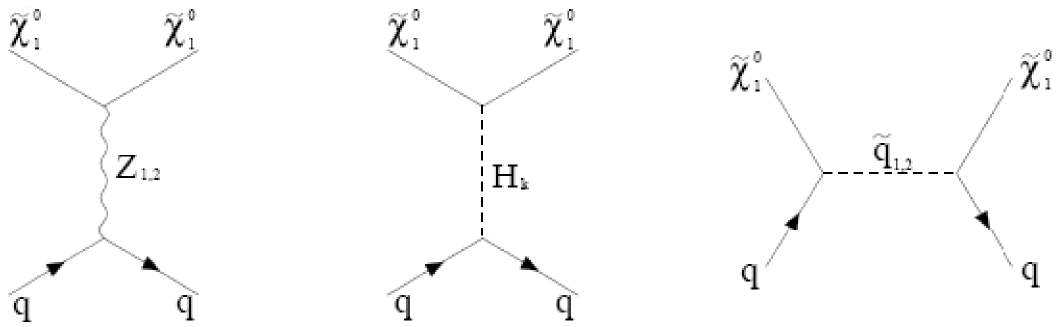


With increasing M_1' it changes
from higgsino to singlino,
so we can try to guess…

also Higgs funnel crossed

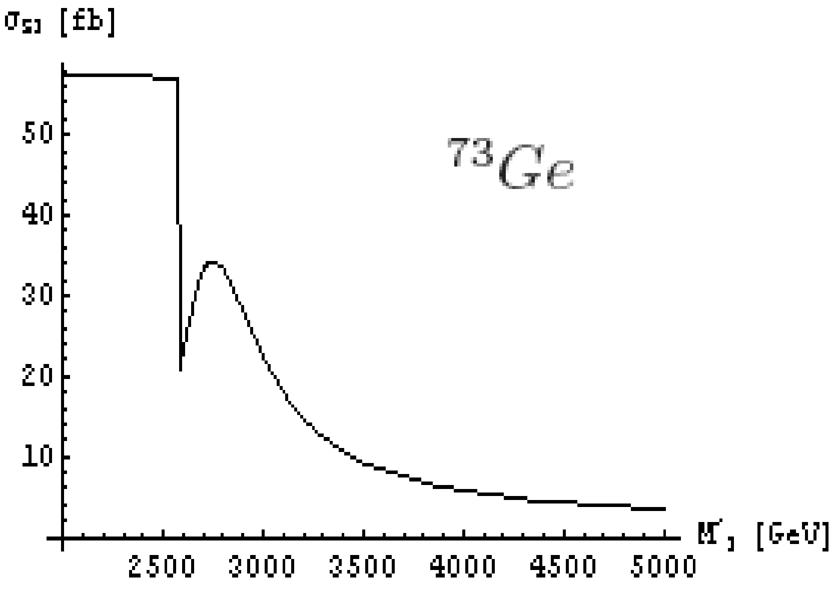


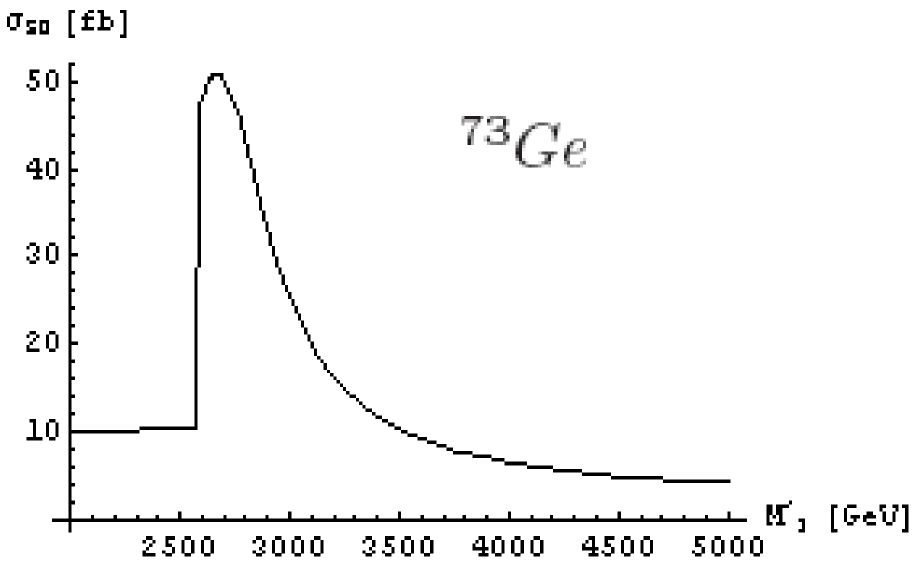
Direct DM searches



More difficult to guess.
Different interplay of diagrams
for spin independent
and spin dependent parts

Choi ea,
Jarecka





Summary

- USSM – an elegant solution to the mu problem
- new states: scalar Higgs, Z’ and two neutralinos

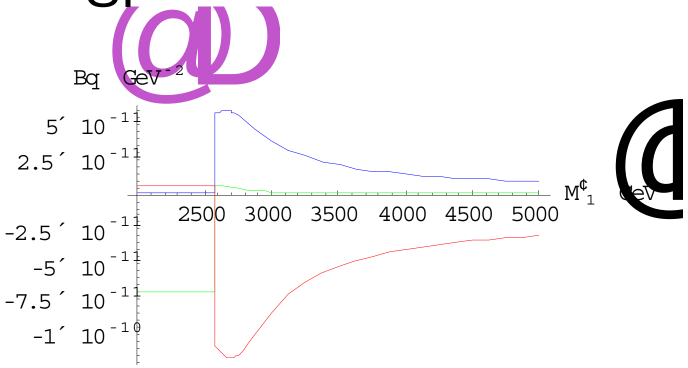
  - relaxed bounds on lightest Higgs mass
  - neutralino sector quite complicated
  - in a weakly coupled regime under good theoretical control

- with extra U(1) gaugino heavy

  - lightest neutralino can be singlino-dominated
  - phenomenology at e+e- and LHC quite different
  - candidate for CDM with different nature from MSSM or NMSSM
  - can be distinguished by studying neutralino and Higgs sectors

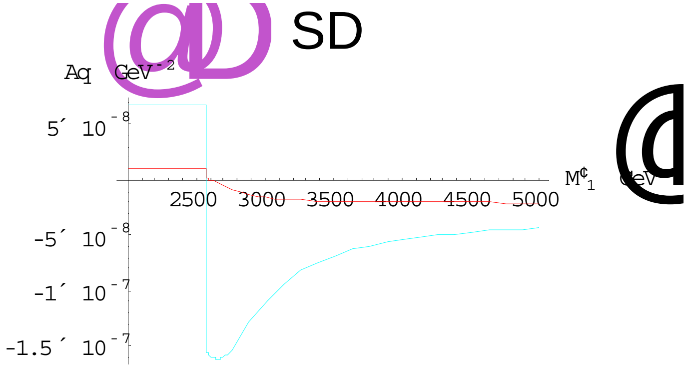
  - interesting phenomenoology – deserves dedicated studies

SI

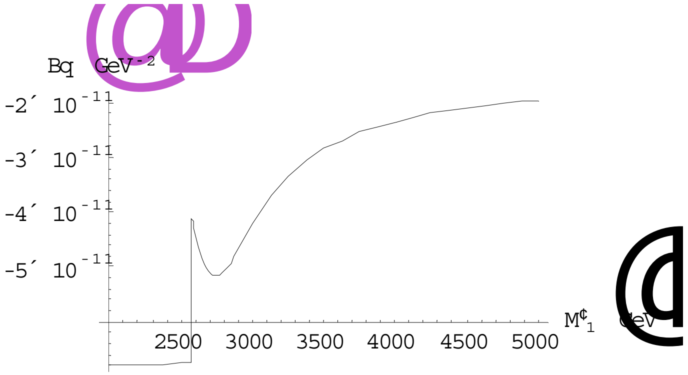

Bq GeV-2
5´ 10-11
2.5´ 10-11
-2.5´ 10-11
-5´ 10-11
-7.5´ 10-11
-1´ 10-10
2500 3000 3500 4000 4500 5000
M¢1 GeV

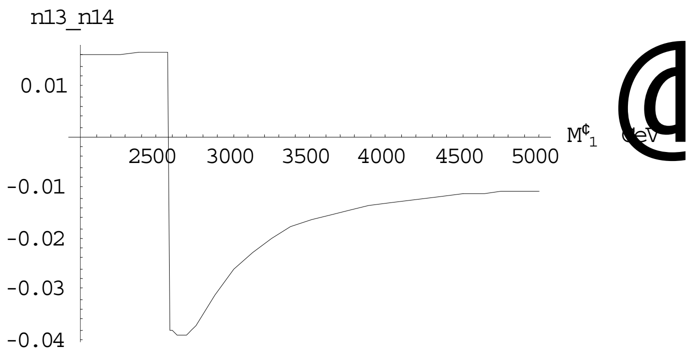
g g’ λ

SD


Aq GeV-2
5´ 10-8
-5´ 10-8
-1´ 10-7
-1.5´ 10-7
2500 3000 3500 4000 4500 5000
M¢1 GeV

Z Z’


Bq GeV-2
-2´ 10-11
-3´ 10-11
-4´ 10-11
-5´ 10-11
2500 3000 3500 4000 4500 5000
M¢1 GeV


n13_n14
0.01
-0.01
-0.02
-0.03
-0.04
2500 3000 3500 4000 4500 5000
M¢1 GeV