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Neutralinos in the U(1) extended supersymmetric model

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Motivation

What is the origin of mass?

- in the SM: one Higgs doublet => the hierarchy problem
- in SUSY the hierarchy stabilised

  in superpotential $W = \mu H_u H_d$

  > but negative LEP search results => little fine-tuning

  > and why μ of order EW scale => the μ problem
- 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.

but broken Z_3 symmetry => cosmological domain-wall problem

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

  axion eaten-up by a massive Z' gauge boson

  USSM = a subset of E_6SSM of King, Moretti, Nevzorov

Kinetic term mixing

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

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

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

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

gaugino masses:

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

Higgs sector

Two iso-doublets H_u , H_d and one scalar S

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

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

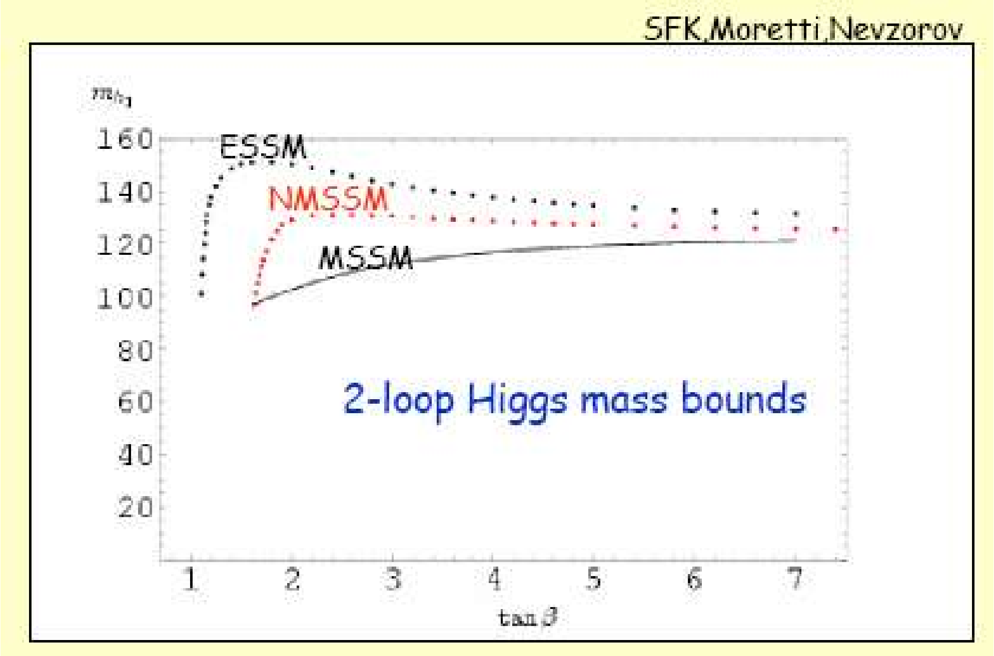
$$\mu = \lambda \frac{v_s}{\sqrt{2}} \quad \text{and} \quad \mu_\lambda = \lambda \frac{v}{\sqrt{2}}$$

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

Higgs sector

The USSM Higgs h_1 mass bound

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



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:

$$\mathcal{M}_6 = \begin{pmatrix} \mathcal{M}_4 & X \\ X^T & \mathcal{M}_2 \end{pmatrix} = \left(\begin{array}{cccc|cc} M_1 & 0 & -m_Z\, c_\beta\, s_W & m_Z\, s_\beta\, s_W & 0 & M_k \\ 0 & M_2 & m_Z\, c_\beta\, c_W & -m_Z\, s_\beta\, c_W & 0 & 0 \\ -m_Z\, c_\beta\, s_W & m_Z\, c_\beta\, c_W & 0 & -\mu & -\mu_\lambda\, s_\beta & Q_1' m_v\, c_\beta \\ m_Z\, s_\beta\, s_W & -m_Z\, s_\beta\, c_W & -\mu & 0 & -\mu_\lambda\, c_\beta & Q_2' m_v\, s_\beta \\ \hline 0 & 0 & -\mu_\lambda\, s_\beta & -\mu_\lambda\, c_\beta & 0 & Q_S' m_s \\ M_k & 0 & Q_1' m_v\, c_\beta & Q_2' m_v\, s_\beta & Q_S' m_s & M_1' \end{array}\right)$$

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

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

Diagonalizing M_6

For small mixing between $\tilde{B}, \tilde{W}^3, \tilde{H}^0_d, \tilde{H}^0_u$ 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'

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

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

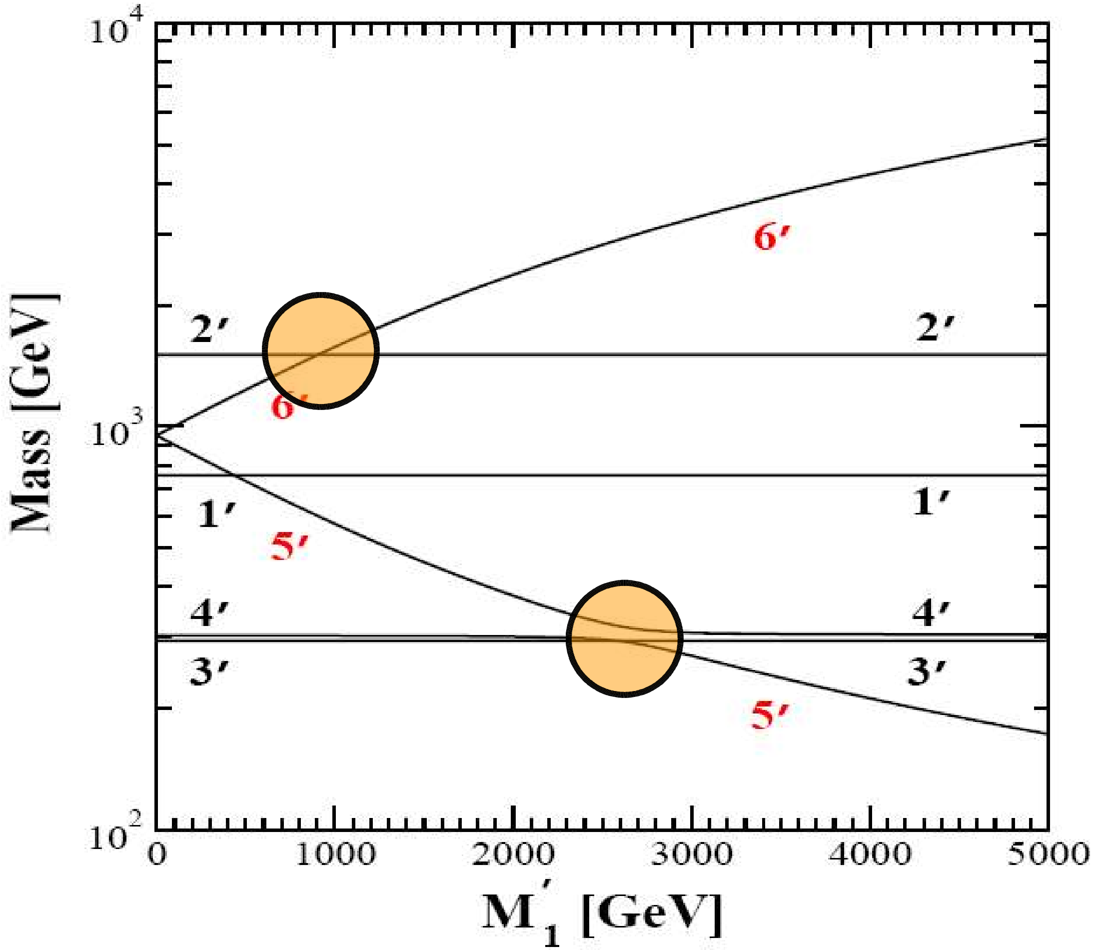
We take a scenario with

$M_2 = 1.5$ TeV, $m_s = 1.2$ TeV

$\mu = 0.3$ TeV and $M_k = 0$

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

$\tan\beta = 5$



Neutralino production in e+e-

$e^+e^- \to \tilde{\chi}^0_i \tilde{\chi}^0_j \quad [i,j = 1\text{–}6$ via s-channel Z, Z' and t-,u-channel selectron

Z exchange:

$$M^2_{ZZ'} = \begin{pmatrix} m^2_Z & \Delta^2_Z \\ \Delta^2_Z & m^2_{Z'} \end{pmatrix}$$

$$m^2_Z = \frac{1}{4} g^2_Z v^2$$
$$m^2_{Z'} = g^2_X v^2 \left(Q'^2_1 c^2_\beta + Q'^2_2 s^2_\beta\right) + g^2_X v^2_S Q'^2_S$$
$$\Delta^2_Z = \frac{1}{2} g_Z g_X v^2 \left(Q'_1 c^2_\beta - Q'_2 s^2_\beta\right)$$

Z, Z' => mass eigenstates Z_1, Z_2 with mixing angle $\theta_{ZZ'}$

$$\langle \tilde{\chi}^0_{iL} | Z_1 | \tilde{\chi}^0_{jL} \rangle = -g_Z \mathcal{Z}_{ij} \cos\theta_{ZZ'} - g_X \mathcal{Z}'_{ij} \sin\theta_{ZZ'}$$
$$\langle \tilde{\chi}^0_{iL} | Z_2 | \tilde{\chi}^0_{jL} \rangle = +g_Z \mathcal{Z}_{ij} \sin\theta_{ZZ'} - g_X \mathcal{Z}'_{ij} \cos\theta_{ZZ'}$$

$$\mathcal{Z}_{ij} = \frac{1}{2}\left(N_{i3} N^*_{j3} - N_{i4} N^*_{j4}\right)$$
$$\mathcal{Z}'_{ij} = Q'_1 N_{i3} N^*_{j3} + Q'_2 N_{i4} N^*_{j4} + Q'_S N_{i5} N^*_{j5}$$

selectron exchange:

$$\langle \tilde{\chi}^0_{iR} | \tilde{f}_L | f_L \rangle = -\sqrt{2}\left[g_2 (I^f_3 N^*_{i2} + (e_f - I^f_3) N^*_{i1} t_W) + g_X Q'_{f_L} N^*_{i6}\right]$$
$$\langle \tilde{\chi}^0_{iL} | \tilde{f}_R | f_R \rangle = +\sqrt{2}\left[g_2\, e_f\, t_W N_{i1} + g_X\, Q'_{f_R} N_{i6}\right]$$

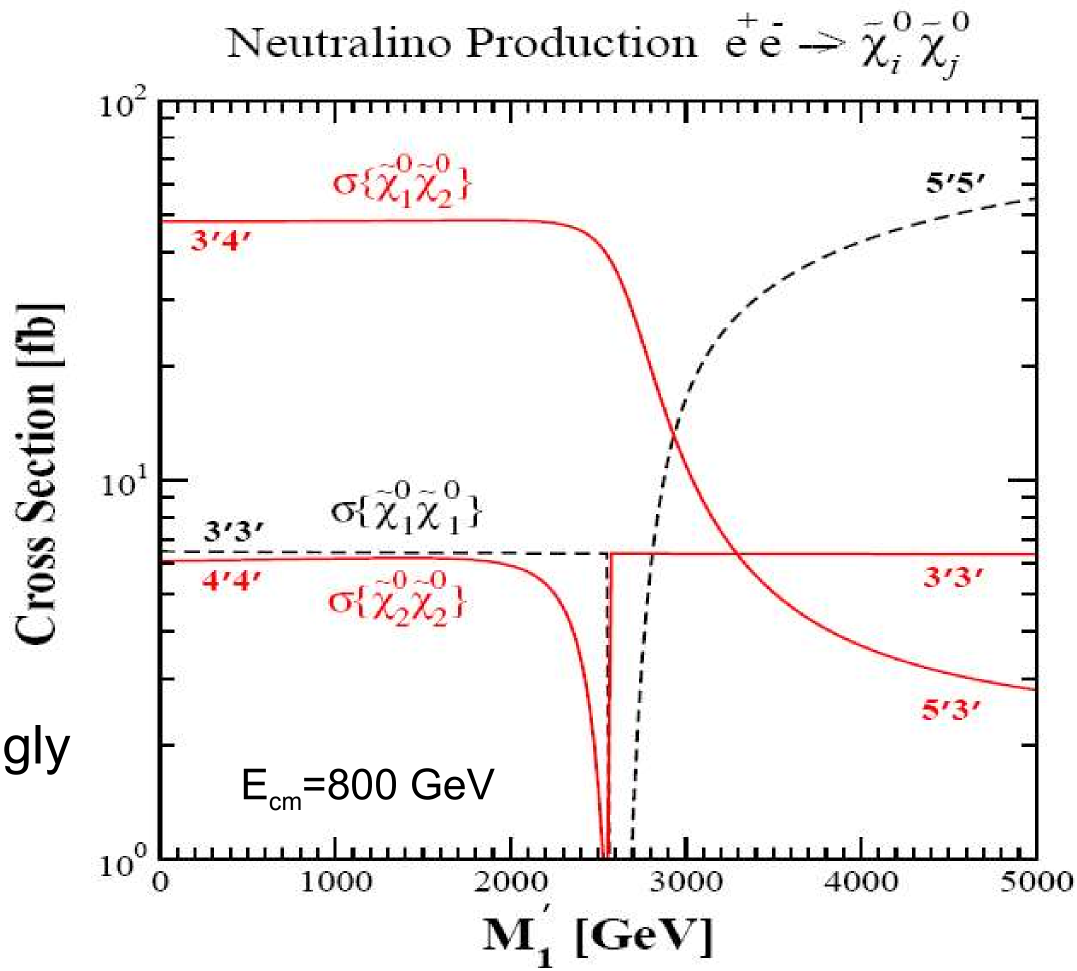
Neutralino production in e+e-

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}

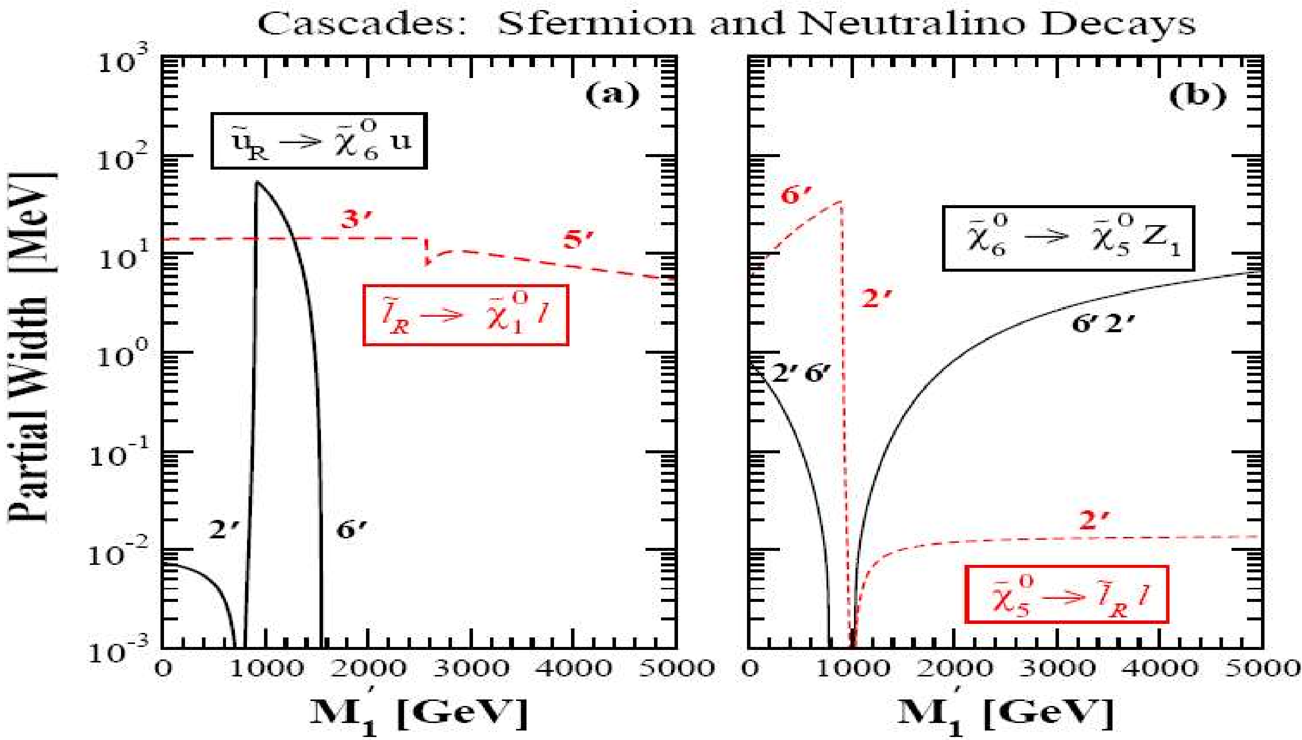
although masses of $\tilde{\chi}_1^0\tilde{\chi}_2^0$ are as in MSSM

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

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

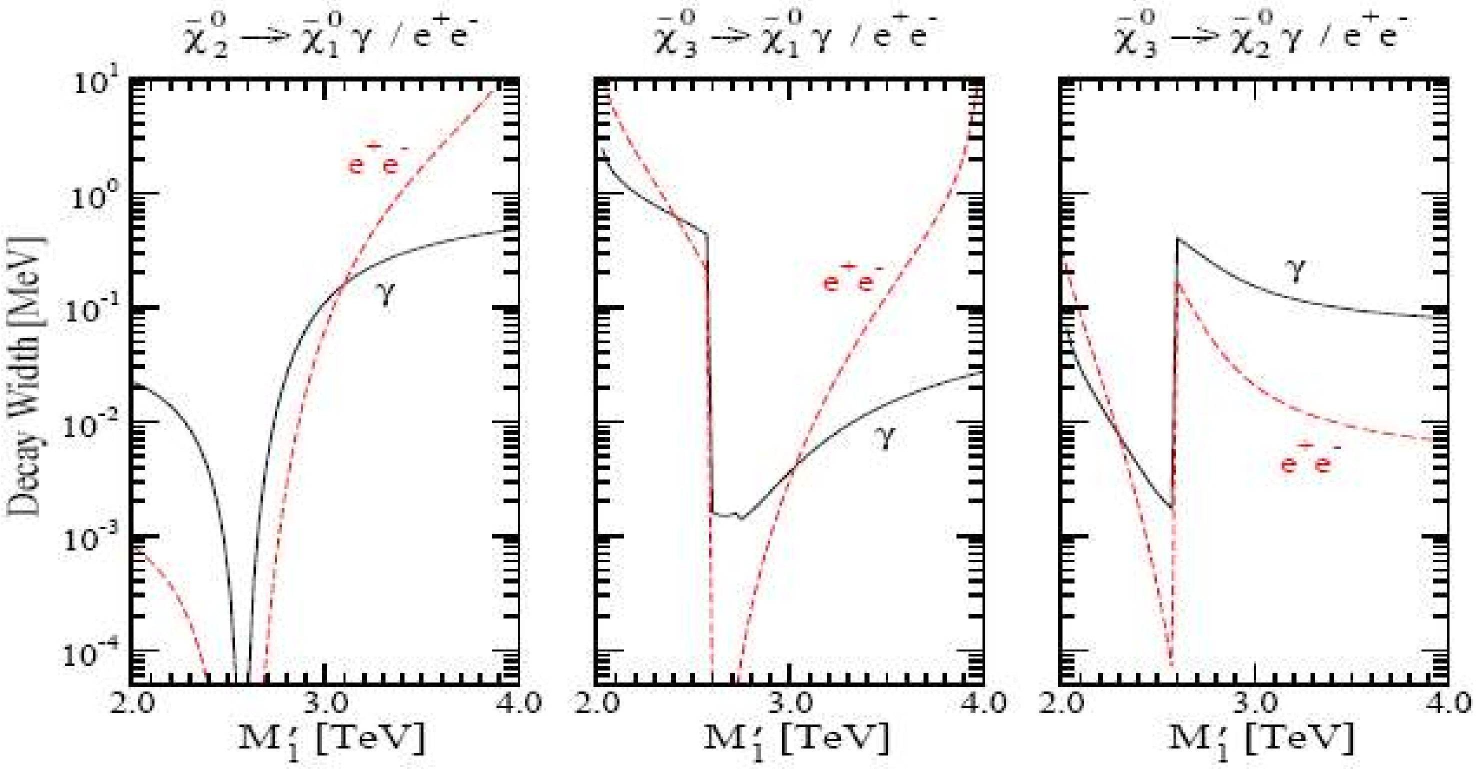
but

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



Summary

- USSM – a well motivated and interesting scenario
- new states: scalar Higgs, Z' and two neutralinos

- Here exploratory studies of the neutralino sector

  - neutralino sector quite complicated
  - in a weakly coupled regime under good theoretical control
  - production and decay processes analysed
  - phenomenology at e+e- and LHC quite different
  - a systematic survey needs more detailed analyses
  - cosmological implications => work in progress Jarecka, King, JK,..