Dark Matter in the USSM

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Outline

- Motivation
- Models with extra U(1)
- DM phenomenology
  - Relic abundance
  - Direct searches
- Collider connection
- Summary

Based on collaboration with S. King and J. Roberts

JHEP 0901:066,2009 [arXiv:08112204]

Motivation

Known properties of dark matter

- WIMP - a weakly interacting, massive, neutral and stable particle
- the measured density 0.1099 +- 0.0062

Many models provide candidates for WIMP's

SUSY – most attractive framework

- stabilises the Higgs mass
- gives radiative EW symmetry breaking
- predicts unification of gauge couplings
- provides a dark matter candidate

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

But all is not well

Problems of minimal SUSY

- Cosmological 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
- μ problem : why in $W \ni \mu H_d H_u$ is of order EW scale

Motivation to go beyond MSSM

Promote μ to a vev of some scalar field S: $\mu = \lambda\langle S\rangle$

- NMSSM: invoke Z_3 to avoid massless axion

$$W \ni \lambda S H_d H_u + \kappa S^3$$

Nilles ea,
Frere ea
Derendinger ea
Ellis ea,
Ellwanger ea,
…

- U(1)-extended SUSY: promote Z_3 to the gauge symmetry

Cvetic ea,
Suematsu ea,
Ma
Erler ea

Extra U(1) SUSY

- SM fields charged under new $U(1)_X$
- new fermions are needed to cancel anomalies
- elegant solution: identify $U(1)_X$ as a subgroup of E_6 and cancel anomalies by assuming matter in complete 27 representations

- requiring zero $U(1)_X$ charges of RH neutrino specifies the theory uniquely as the E_6SSM of King, Moretti and Nevzorov hep-ph/0510419

- many extra fields -- per family

	Q	u^c	d^c	L	e^c	N^c	S	H_u	H_d	D	$\overline{D}$
$\sqrt{\frac{5}{3}}Q_i^Y$	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	1	0	0	$\frac{1}{2}$	$-\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{3}$
$\sqrt{40}Q_i^N$	1	1	2	2	1	0	5	-2	-3	-2	-3

- + a pair of extra

H'	$\overline{H'}$
$-\frac{1}{2}$	$\frac{1}{2}$
2	-2

for gauge coupling unification

Sketch of the E_6SSM

$$E_6 \to SO(10) \times U(1)_\psi \qquad SO(10) \to SU(5) \times U(1)_\chi$$

Right handed neutrinos are neutral under: $U(1)_N = \frac{\sqrt{15}}{4} U(1)_\psi + \frac{1}{4} U(1)_\chi$

M_{String} — $E_8 \times E_8 \to E_6$

M_{GUT} — $E_6 \to SU(5) \times U(1)_N$

$$27_i \to (10, 1)_i + (5^*, 2)_i + (5^*, -3)_i + (5, -2)_i + (1, 5)_i + (1, 0)_i$$

$27', \overline{27}'$

- $(10,1)_i + (5^*,2)_i$: Quarks, leptons
- $(5^*,-3)_i + (5,-2)_i$: Exotics and Higgs
- $(1,5)_i$: S
- $(1,0)_i$: RHν
- $27', \overline{27}'$: H',H'-bar — Incomplete multiplets (required for unification)

Right handed neutrino masses

~ TeV — $U(1)_N$ broken, Z'/exotics mass, <S> VEV → μ term

M_{SUSY} — SUSY broken

M_Z — $SU(2)_L \times U(1)_Y$ broken

Slide from S.F.King

E_6SSM

- E_6SSM superpotential

$$
\begin{aligned}
W_{E_6} &= W_0 + W_1 + W_2\,, \\
W_0 &= \lambda_{ijk} S_i (H_{dj} H_{uk}) + \kappa_{ijk} S_i (D_j \overline{D}_k) + h^N_{ijk} N^c_i (H_{uj} L_k) + h^U_{ijk} u^c_i (H_{uj} Q_k) \\
&\quad + h^D_{ijk} d^c_i (H_{dj} Q_k) + h^E_{ijk} e^c_i (H_{dj} L_k)\,, \\
W_1 &= g^Q_{ijk} D_i (Q_j Q_k) + g^q_{ijk} \overline{D}_i d^c_j u^c_k\,, \\
W_2 &= g^N_{ijk} N^c_i D_j d^c_k + g^E_{ijk} e^c_i D_j u^c_k + g^D_{ijk} (Q_i L_j) \overline{D}_k\,.
\end{aligned}
$$

- to avoid B and flavor changing processes postulate a Z_{2H} symmetry: only one family of Higgses develops vev's – other Higgses inert

- Z_{2H} must be approximate – to avoid a rapid proton decay postulate a generalised R-parity

USSM

- many extra fields make the detailed studies difficult

preliminary results see J.P Hall, S.F King 0905.2696 [hep-ph]

- we define USSM = SU(3)xSU(2)x$U_Y(1)$ x $U_X(1)$ as a LE subset of E_6SSM assuming extra states and exotics heavy

Suematsu Yanagida
de Carlos Espinosa
Cvetic et al
Barger ea,
King ea,
Cohen Pierce

- particle content of USSM

	Q	u^c	d^c	L	e^c	N^c	S	H_2	H_1
$\sqrt{\frac{5}{3}}Q_i^Y$	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	1	0	0	$\frac{1}{2}$	$-\frac{1}{2}$
$\sqrt{40}Q_i^X$	1	1	2	2	1	0	5	-2	-3

Phenomenology of the USSM

Features:

- extra superpotential term:

$$W_{USSM} = W_{MSSM}(\mu = 0) + \lambda \hat{S}\hat{H}_d\hat{H}_u$$

- extra soft terms:

$$\mathcal{L}_{soft} \ni m_S^2|S|^2 + (\lambda A_\lambda S H_d H_u + h.c.)$$

- new particles in the low-energy spectrum
  - a gauge boson Z' (that mixes a little with Z)
  - extra Higgs (usually H_3, dominantly singlet with mass ~ Z')

    additional contribution to light Higgs -- less fine-tuning
  - two new neutralinos: a singlino and a bino'

Phenomenology quite significantly different from MSSM

USSM - the neutralino sector

The neutralino mass matrix in the inretaction base

$$\mathcal{M}_6 = \begin{pmatrix} \mathcal{M}_4 & X \\ X^T & \mathcal{M}_2 \end{pmatrix} = \begin{array}{c} \begin{array}{cccc|cc} \tilde{B} & \tilde{W}_3 & \tilde{H}_d & \tilde{H}_u & \tilde{S} & \tilde{B}' \end{array} \\ \left(\begin{array}{cccc|cc} M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W & 0 & 0 \\ 0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W & 0 & 0 \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu & -\mu_\lambda s_\beta & Q'_1 g'_1 v c_\beta \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 & -\mu_\lambda c_\beta & Q'_2 g'_1 v s_\beta \\ \hline 0 & 0 & -\mu_\lambda s_\beta & -\mu_\lambda c_\beta & 0 & Q'_S g'_1 v_S \\ 0 & 0 & Q'_1 g'_1 v c_\beta & Q'_2 g'_1 v s_\beta & Q'_S g'_1 v_S & M'_1 \end{array}\right) \end{array}$$

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

Important features:

- since Z' mass $\gtrsim$ 1TeV, sets the scale of v_S

  new sector weakly coupled to MSSM neutralinos

  Choi, Haber, JK, Zerwas

- no singlino mass term:
  - mini see-saw structure for singlino/bino'
  - never have a dominantly bino' LSP

USSM – relic abundance DM

Neutralino mass matrix

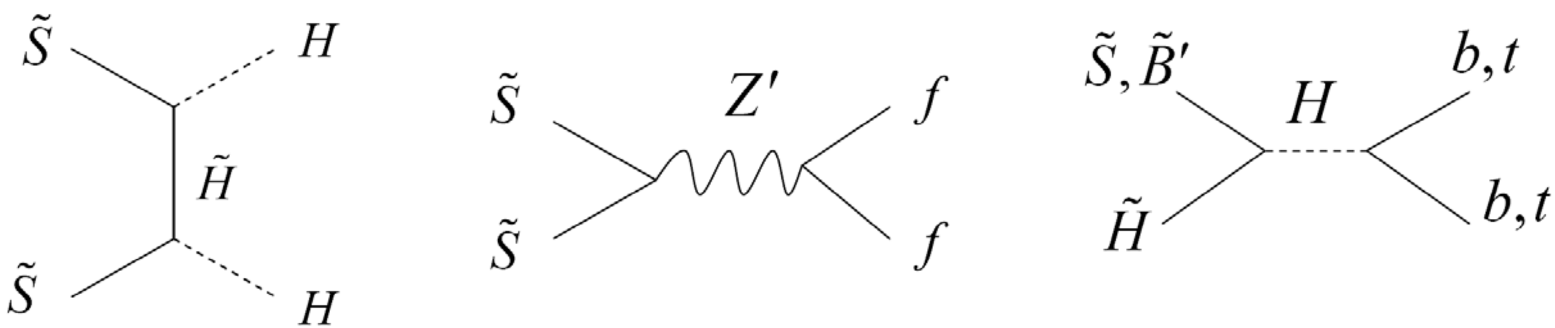
$$\begin{array}{c} \tilde{B} \quad \tilde{W}_3 \quad \tilde{H}_d \quad \tilde{H}_u \quad \tilde{S} \quad \tilde{B}' \\ \begin{pmatrix} M_1 & & & & & \\ & M_2 & & & & \\ & & 0 & -\lambda s & & \\ & & -\lambda s & 0 & & \\ & & & & 0 & \sim M_{Z'} \\ & & & & \sim M_{Z'} & M_1' \end{pmatrix} \end{array}$$

$$\chi_1 = N_1\tilde{B} + N_2\tilde{W} + N_3\tilde{H}_d + N_4\tilde{H}_u + \underbrace{N_5\tilde{S} + N_6\tilde{B}'}_{\text{New}}$$

$$M_1' \to \infty \quad \longrightarrow \quad M_{\tilde{S}} \approx \frac{M_{Z'}^2}{M_1'} \to 0$$

mini-see-saw gives singlino LSP as $M_1' \to \infty$

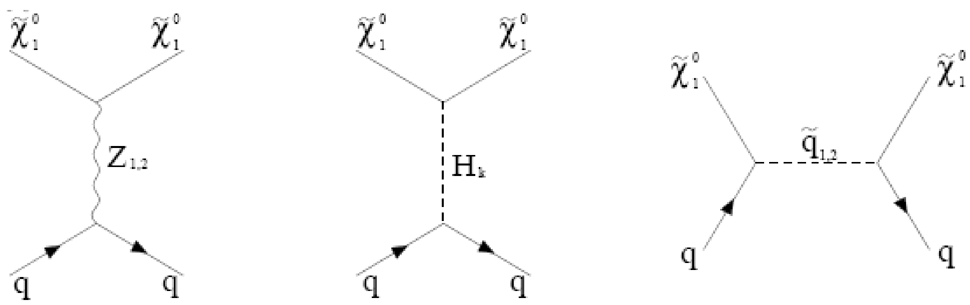
LSP has new annihilation channels via Z' or $\lambda S H_d H_u$



We implement USSM into MicrOmegas

De Carlos Espinosa
Cvetic ea
Barger ea

USSM – direct searches



Different interplay of diagrams for spin dependent and spin independent parts

$$\mathcal{L}_{\rm eff} = A_q \left(\bar{\chi}_1 \gamma^\mu \gamma_5 \chi_1\right)\left(\bar{q}\gamma_\mu\gamma_5 q\right) + B_q \left(\bar{\chi}_1 \chi_1\right)\left(\bar{q} q\right)$$

$$\frac{g_2^2}{16}\sum_{i=1,2}\frac{\left|B_q^{iL}\right|^2+\left|B_q^{iR}\right|^2}{m_{\tilde{q}_i}^2-(m_{\tilde{\chi}^0}-m_q)^2}-\frac{G_F}{\sqrt{2}}\left[|N_{13}|^2-|N_{14}|^2\right] I_q^3$$
$$-\frac{g_1'^2}{4m_{Z'}^2}\left[Q_1|N_{13}|^2+Q_2|N_{14}|^2+Q_s|N_{15}|^2\right]\left(Q_Q+Q_{\bar{q}}\right)$$

$$-\frac{g_2^2}{8}\sum_{i=1,2}\frac{\mathrm{Re}(B_q^{iL}B_q^{iR*})}{m_{\tilde{q}_i}^2-(m_{\tilde{\chi}^0}-m_q)^2}$$
$$-\frac{h_q}{2\sqrt{2}}\sum_{k=1}^{3}\frac{\mathrm{Re}(G_k)+\mathrm{Re}(G'_k)+\mathrm{Re}(G''_k)}{m_{H_k}^2}\begin{cases}\mathcal{O}'_{1k} & \text{for } q=d\\ \mathcal{O}'_{2k} & \text{for } q=u\end{cases}$$

$$\begin{aligned} G_k &= g_2\,(N_{12}-t_W\,N_{11})(N_{14}\,\mathcal{O}'_{2k}-N_{13}\,\mathcal{O}'_{1k})\\ G'_k &= -2\,g'_1\,N_{16}\,(Q_1\,N_{13}\,\mathcal{O}'_{1k}+Q_2\,N_{14}\,\mathcal{O}'_{2k}+Q_S\,N_{15}\,\mathcal{O}'_{3k})\\ G''_k &= \sqrt{2}\lambda\,[N_{15}\,(N_{13}\,\mathcal{O}'_{2k}+N_{14}\,\mathcal{O}'_{1k})+N_{13}N_{14}\mathcal{O}'_{3k}\,] \end{aligned}$$

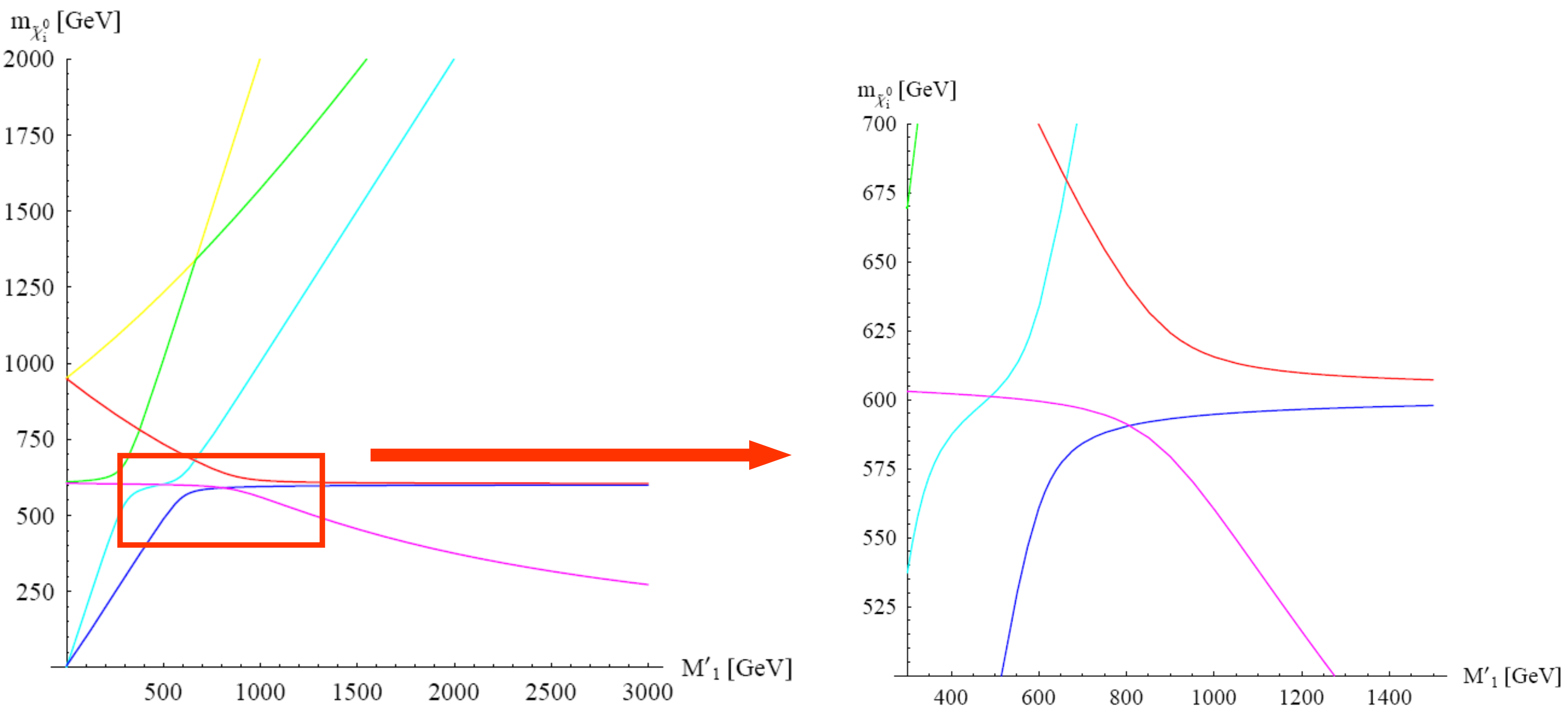
Choi ea, Jarecka

Phenomenology: parameters

- gauge coupling unification $g_X = g_Y\, ,\, g_2$
- v_S set by Z' mass $M_{Z'} \sim g_X Q_S v_S = 950\ \text{GeV}$
- λ set by required $\mu = \lambda v_S/\sqrt{2} = 600\ \text{GeV}$
- A_λ set by mass of pseudoscalar $M_A = 500\ \text{GeV}$
- $\tan\beta = 5$
- universal scalar masses and trilinear couplings $M_{\tilde{f}} = 800\ \text{GeV}$

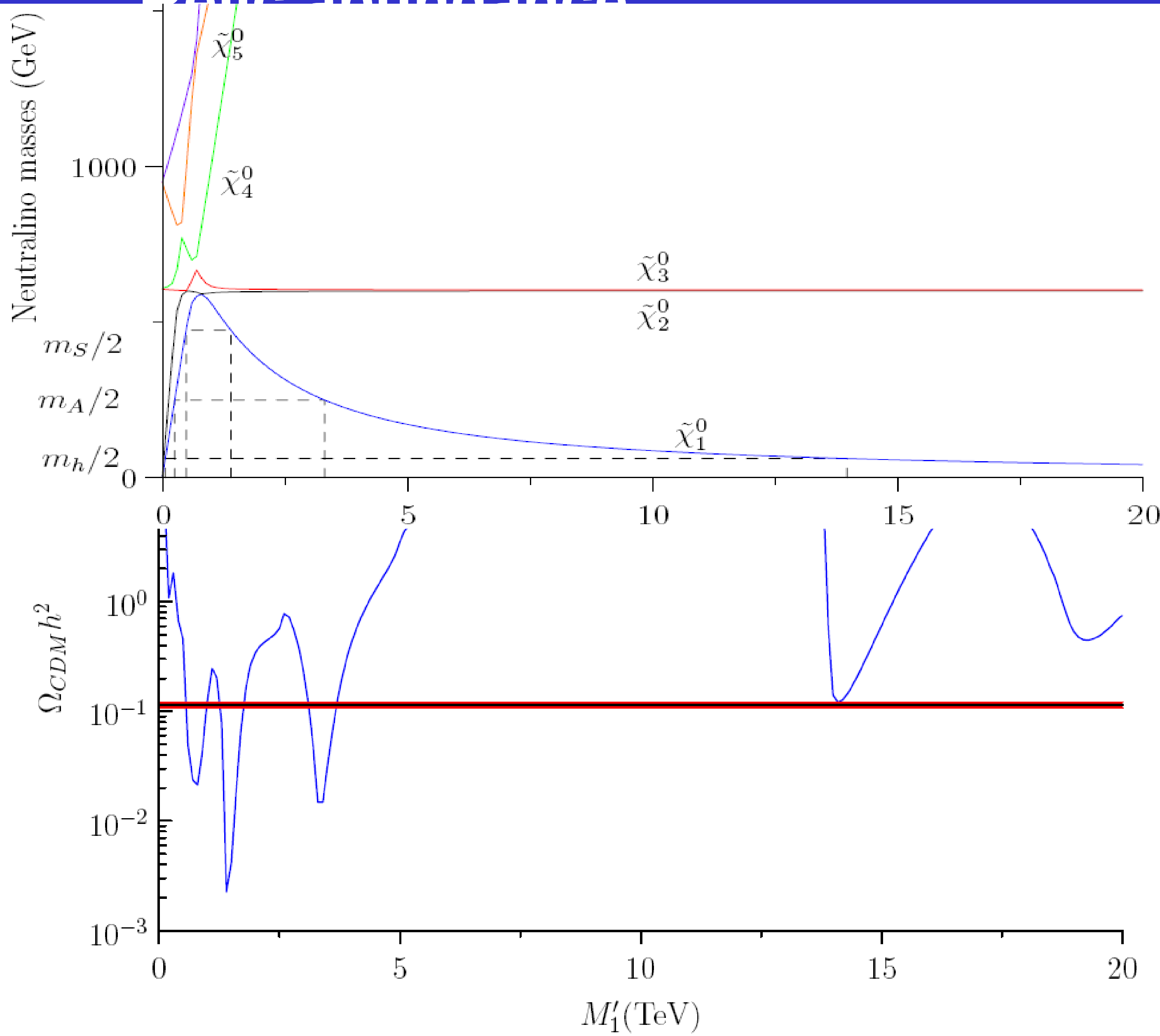
Analyse as a function of $M_1' = M_1 \sim M_2/2$

Neutralino mass spectrum



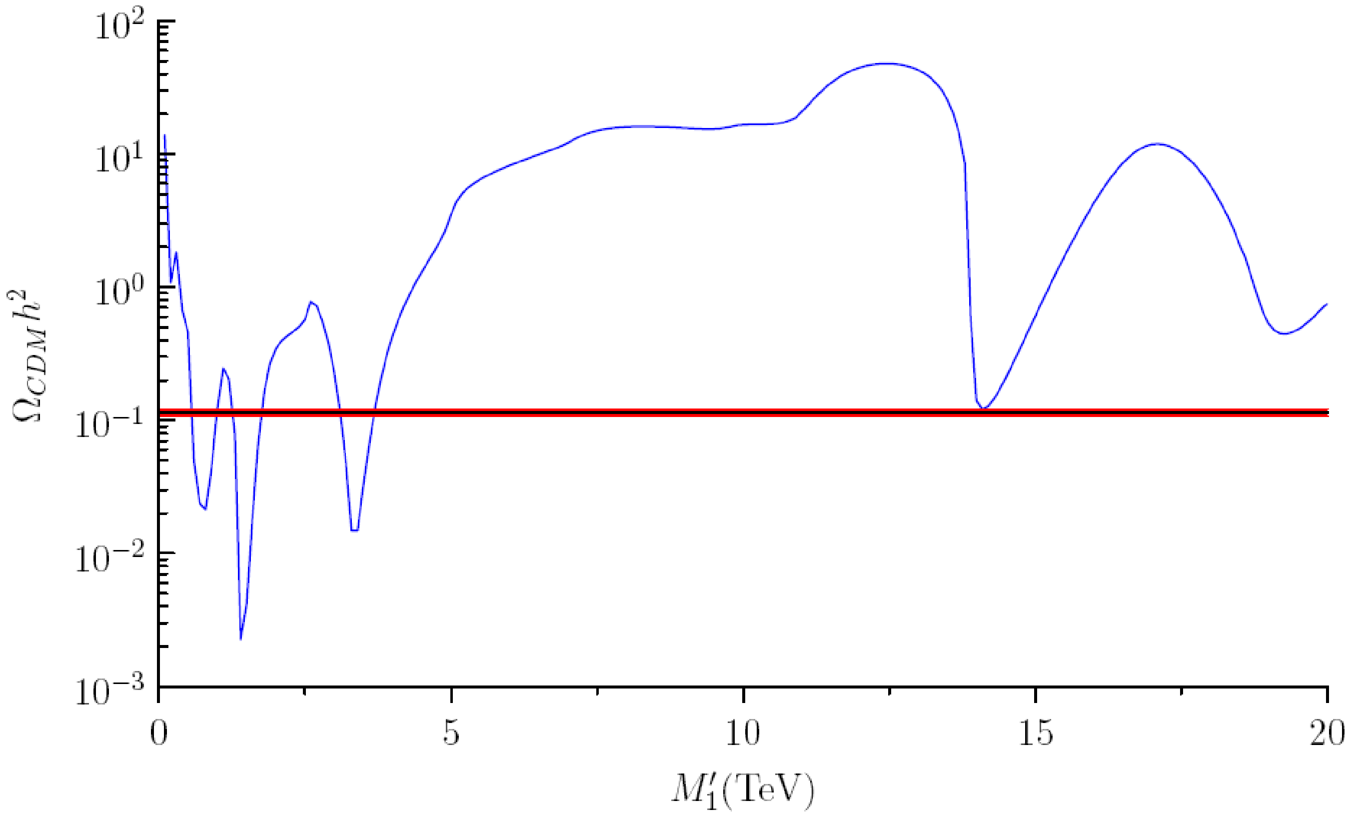
Relic abundance

As M_1' changes



Relic abundance

As M_1' changes



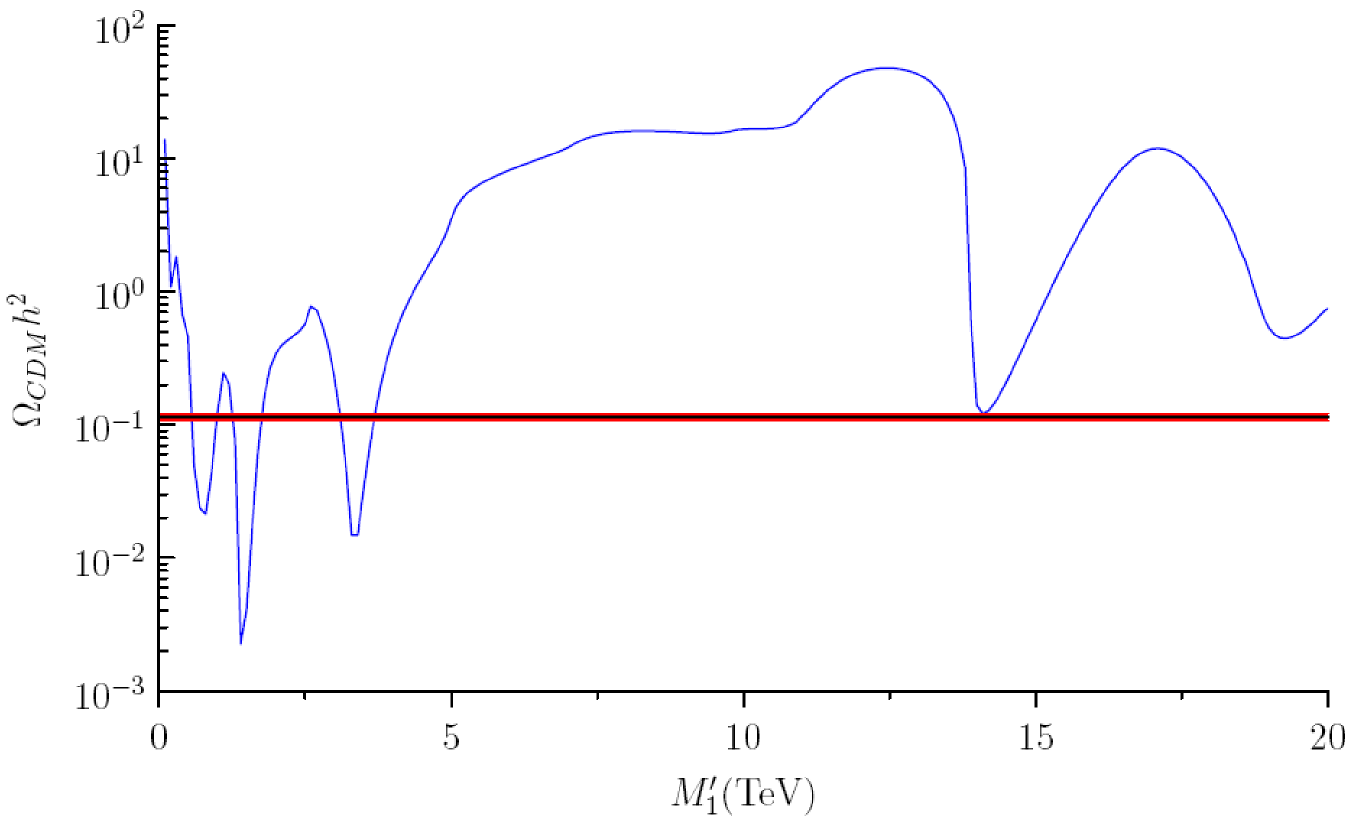
s-channel

Z_2 resonances

Relic abundance

s-channel
H_2 , A
resonances

As M_1' changes



s-channel
Z_2 resonances

Relic abundance

s-channel
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s-channel
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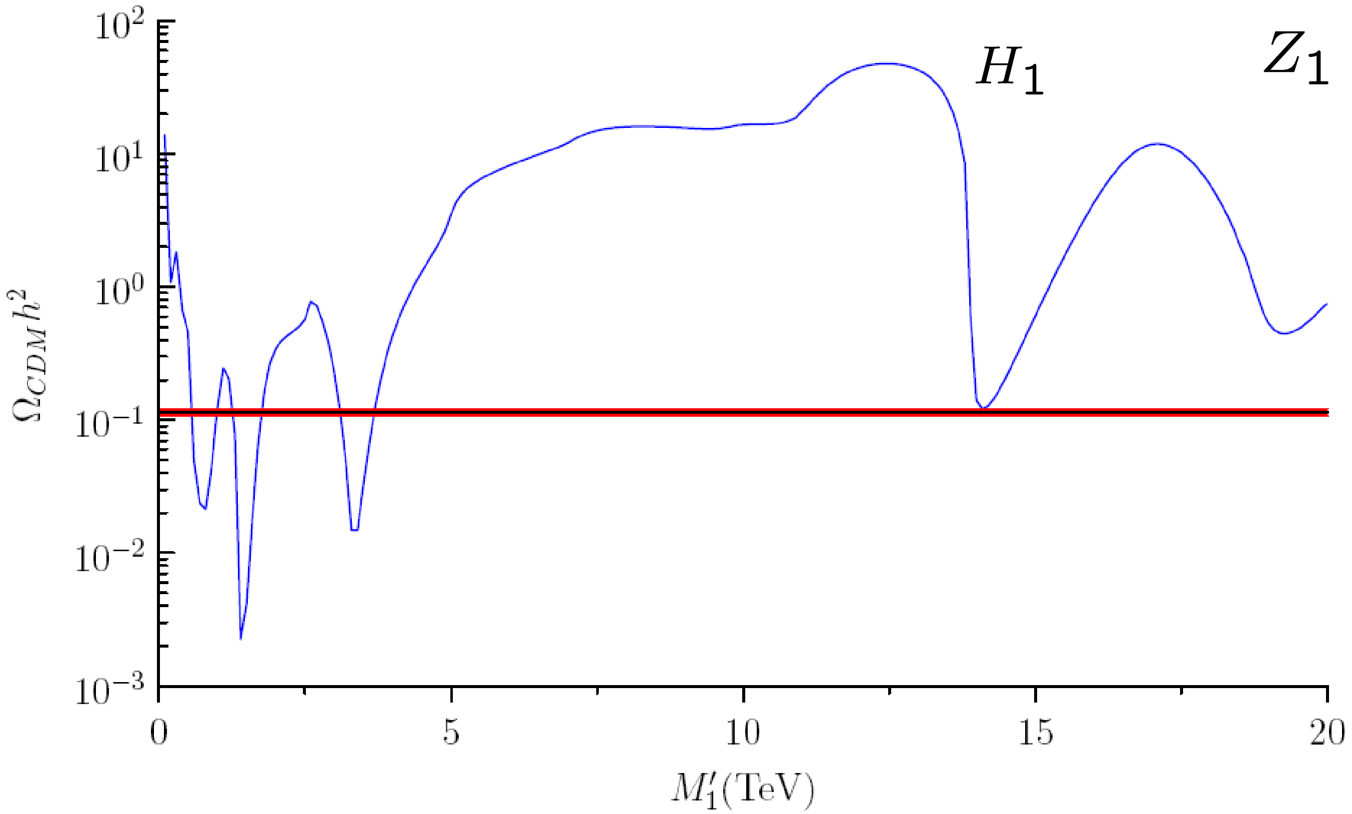
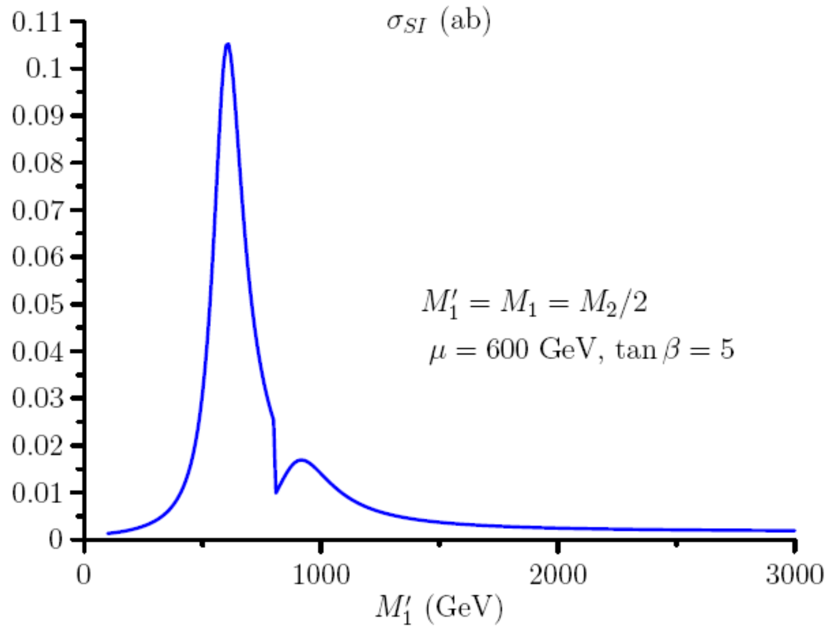
As M_1' changes

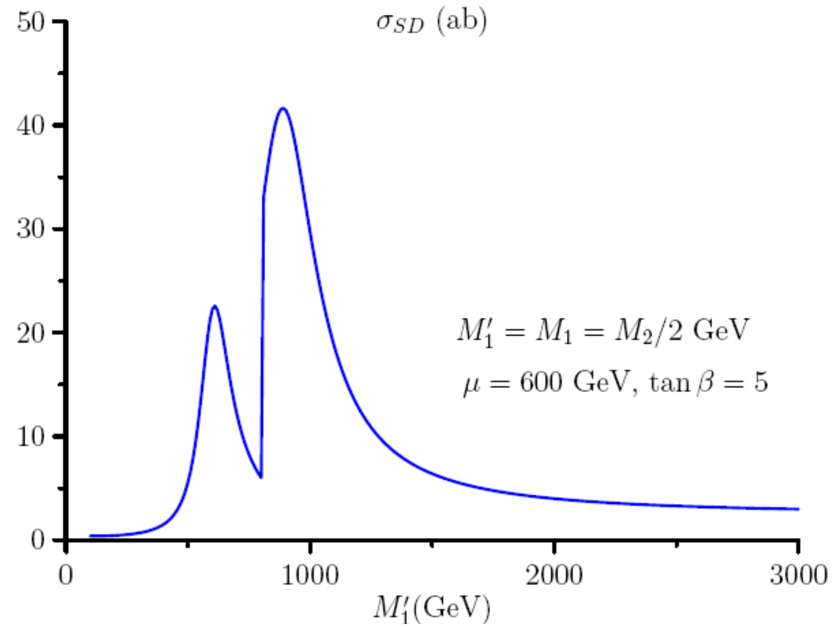


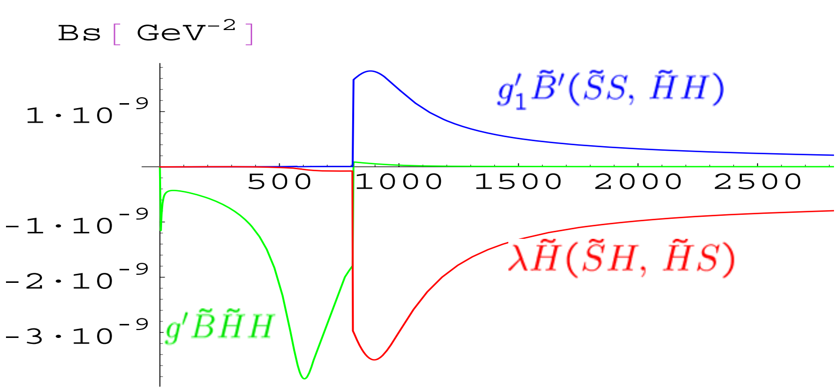
s-channel
Z_2 resonances

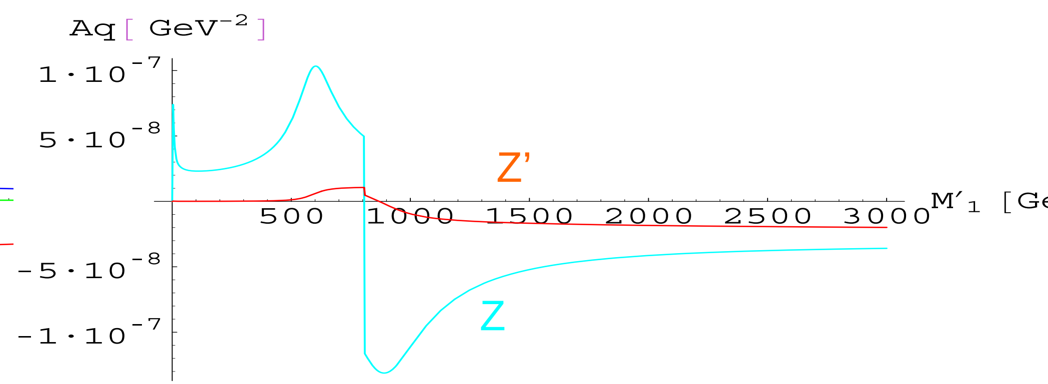
Direct searches

Elastic scattering on a nucleon









Collider connection

Choi, Haber, JK, Zerwas

- neutralino production cross sections at e+e-
  the presence of Z' affects the production cross sections

- neutralino decays $\tilde{u}_R \to u\tilde{\chi}_5^0 \to u[\ell\tilde{\ell}_R] \to u\ell\ell\tilde{\chi}_1^0$
  but branching fractions modified

- new neutralino decay chains
  longer $\tilde{u}_R \to u\tilde{\chi}_6^0 \to u[Z_1\tilde{\chi}_5^0] \to uZ_1[\ell\tilde{\ell}_R] \to uZ_1\ell\ell\tilde{\chi}_1^0$
  or shorter because of $\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 Z$

- in transition zones radiative $\tilde{\chi}_i^0 \to \tilde{\chi}_1^0\gamma$ decays might dominate

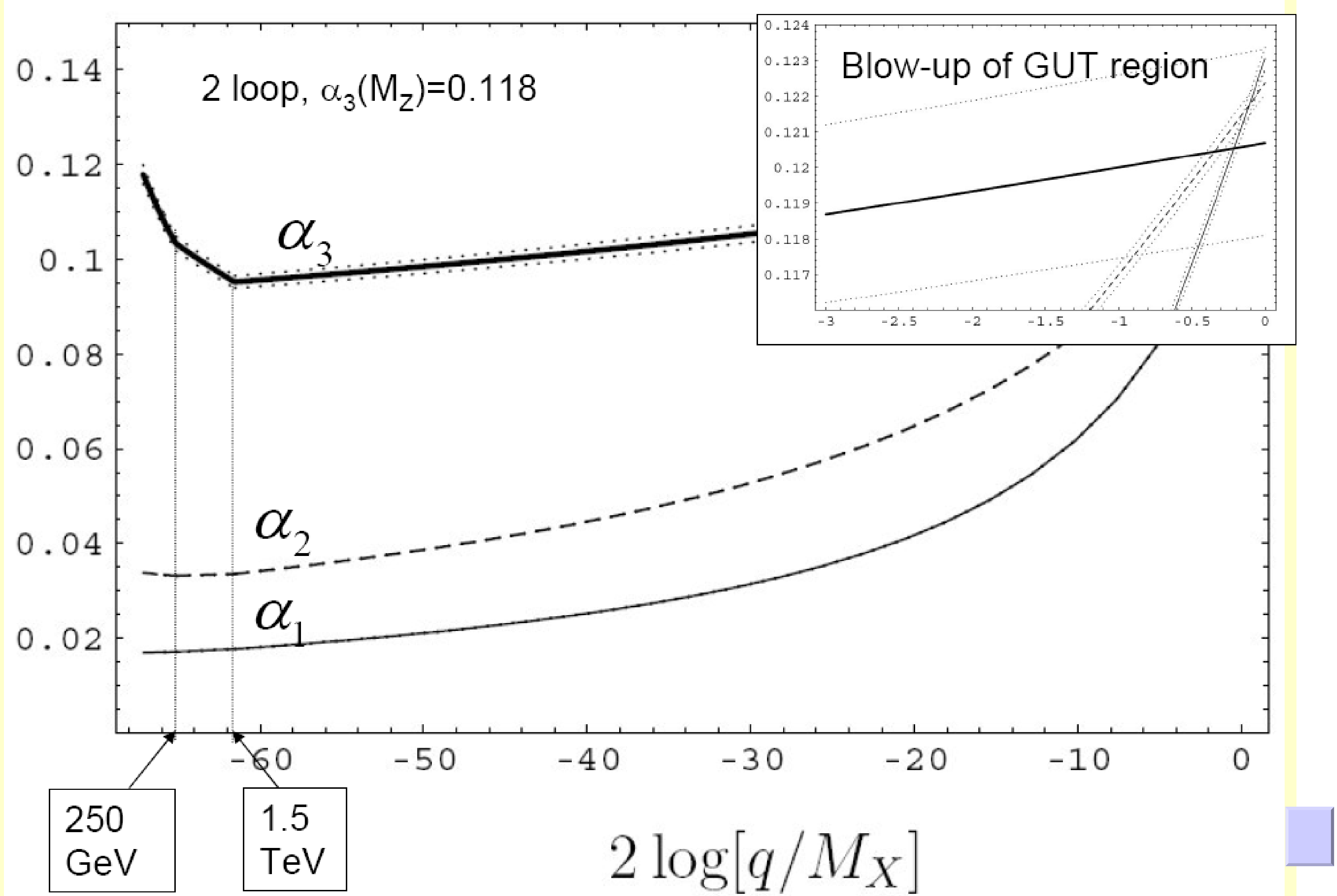
- new decay modes of Higgses, etc.

Summary

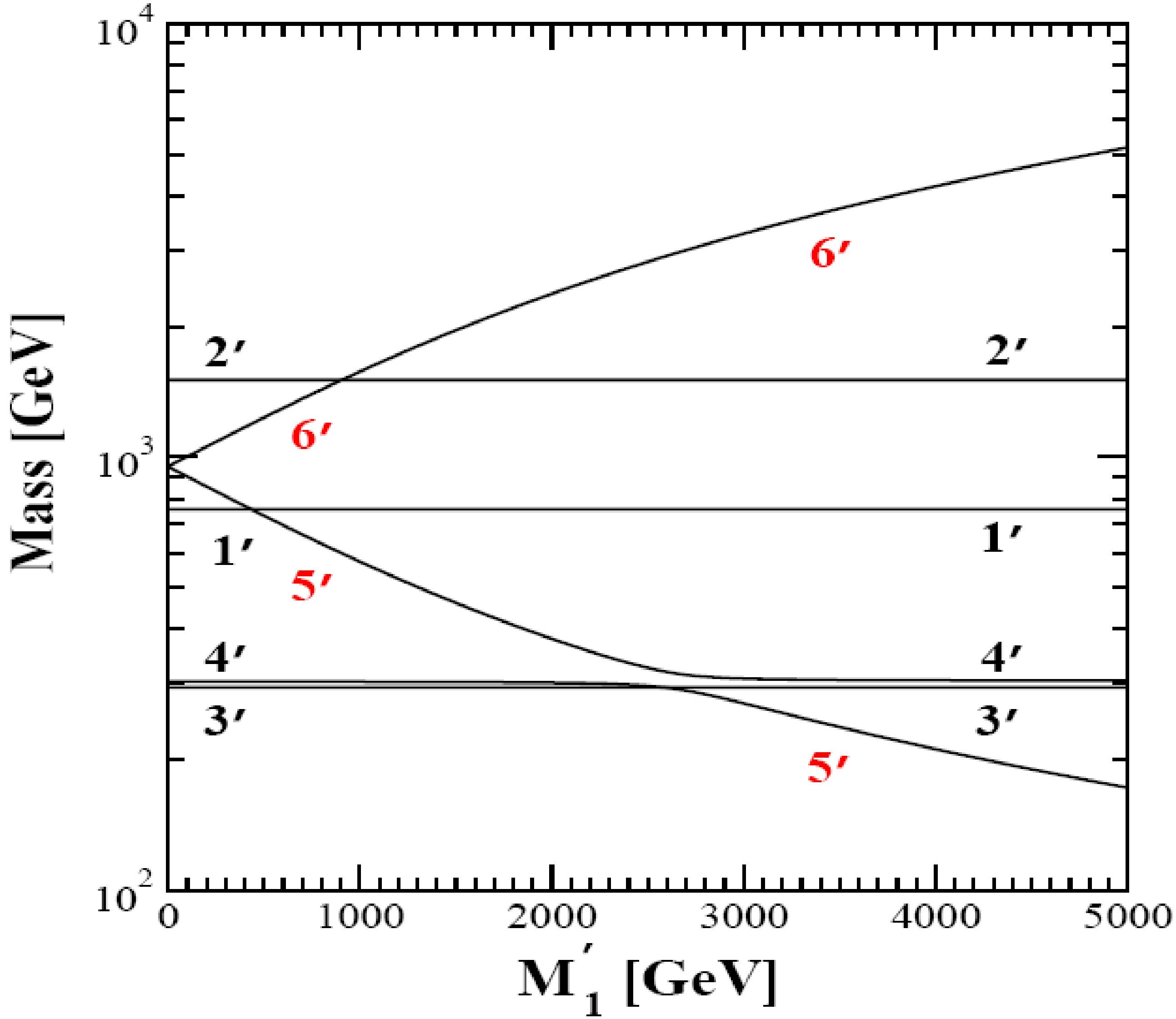
- USSM – an elegant solution to the mu problem
- new states: scalar Higgs, Z' and two neutralinos
    - relaxed bounds on lightest Higgs mass
    - neutralino sector quite complicated
    - in a weakly coupled regime under good theoretical control
- with extra U(1) gaugino heavy
    - lightest neutralino can be singlino-dominated
    - phenomenology at e+e- and LHC quite different
    - candidate for CDM with different nature from MSSM or NMSSM
    - more options, but still needs tuning to match WMAP
    - can be distinguished by studying neutralino and Higgs sectors at colliders
- Next step towards full E_6SSM: add inert Higgses, higgsinos, singlinos etc.

Backup slides

Unification in the E_6SSM



Scenario A: $M_1' \neq M_1$



Scenario A: $M_1' \neq M_1$

DM abundance

As M_1' increases

LSP aquires a significant $\tilde{S}, \tilde{B}'$ component

s-channel A, H_2 resonances

s-channel resonances