

Neutralino DM in the USSM: an update



Outline

- Motivation
- USSM model
- DM phenomenology
 - Relic abundance
 - Direct searches
- Collider connection
- Summary

Based on collaboration with S. King and J. Roberts
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

Here we consider SUSY

- 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
Erlar 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_6 SSM of King, Moretti and Nevzorov [hep-ph/0510419](https://arxiv.org/abs/hep-ph/0510419)

	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

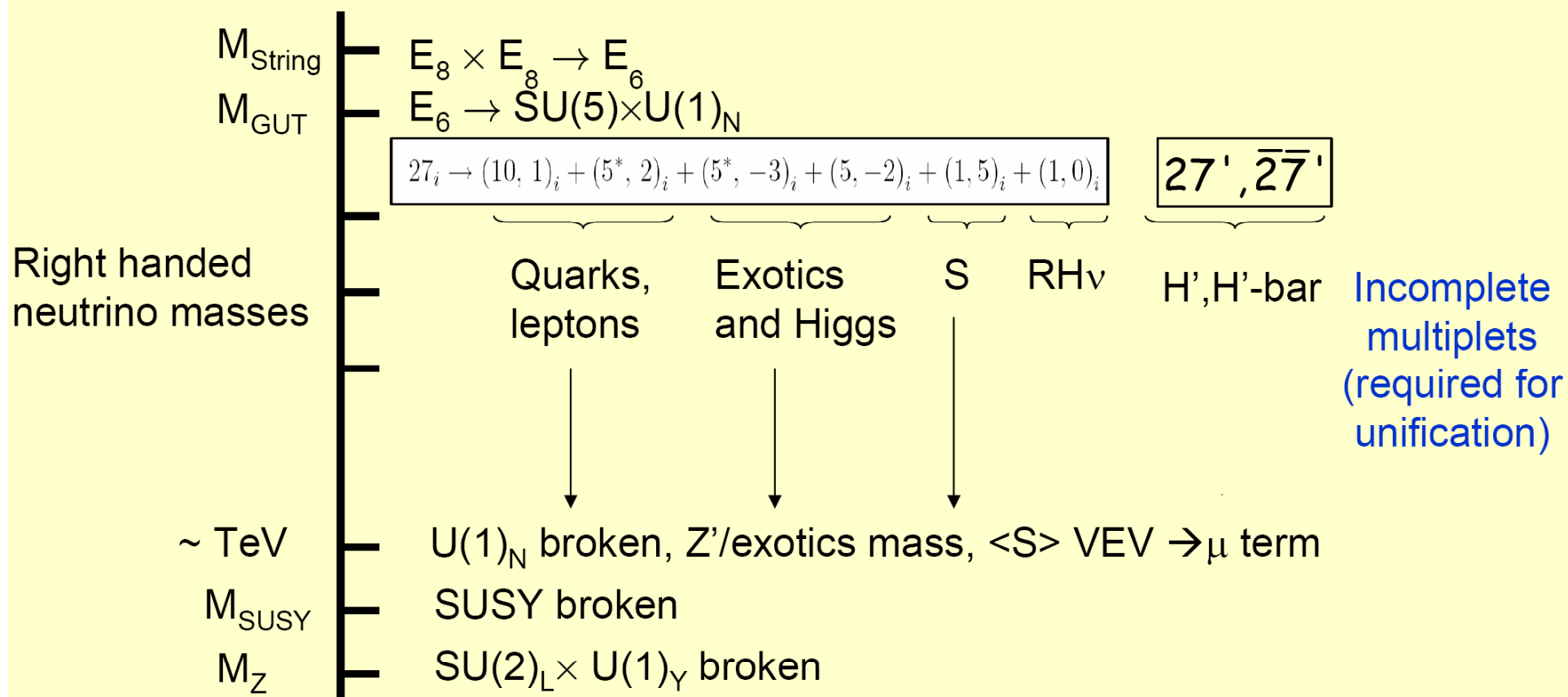
Ma
Barger ea,
Kang ea

Sketch of the E_6 SSM

$$E_6 \rightarrow SO(10) \times U(1)_\psi \quad SO(10) \rightarrow SU(5) \times U(1)_\chi$$

Right handed neutrinos

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



Slide from S.F.King

Extra U(1) SUSY

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Ma
Barger ea,
Kang ea

- many extra fields make the detailed studies difficult
- we define USSM = $SU(3) \times SU(2) \times U_Y(1) \times U_X(1)$ as a LE subset of E_6 SSM assuming extra states and exotics heavy

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

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 $\sim Z'$)
 - two new neutralinos: a singlino and a bino'

Phenomenology changes quite significantly

USSM - the neutralino sector

The neutralino mass matrix in the initial base

$$\mathcal{M}_\theta = \begin{pmatrix} \mathcal{M}_4 & X \\ X^T & \mathcal{M}_2 \end{pmatrix} = \begin{pmatrix} \tilde{B} & \tilde{W}_3 & \tilde{H}_d & \tilde{H}_u & \tilde{S} & \tilde{B}' \\ \hline M_1 & 0 & -M_Z c_\beta s_W & M_Z s_\beta s_W & 0 & 0 \\ 0 & M_2 & M_Z c_\beta c_W & -M_Z s_\beta c_W & 0 & 0 \\ -M_Z c_\beta s_W & M_Z c_\beta c_W & 0 & -\mu & -\mu_\lambda s_\beta & Q'_1 g'_1 v c_\beta \\ M_Z s_\beta s_W & -M_Z s_\beta c_W & -\mu & 0 & -\mu_\lambda c_\beta & Q'_2 g'_1 v s_\beta \\ \hline 0 & 0 & -\mu_\lambda s_\beta & -\mu_\lambda c_\beta & 0 & Q'_5 g'_1 v s \\ 0 & 0 & Q'_1 g'_1 v c_\beta & Q'_2 g'_1 v s_\beta & Q'_5 g'_1 v s & M'_1 \end{pmatrix}$$

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

Important features:

- since Z' mass $\diamond 1\text{TeV}$, 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

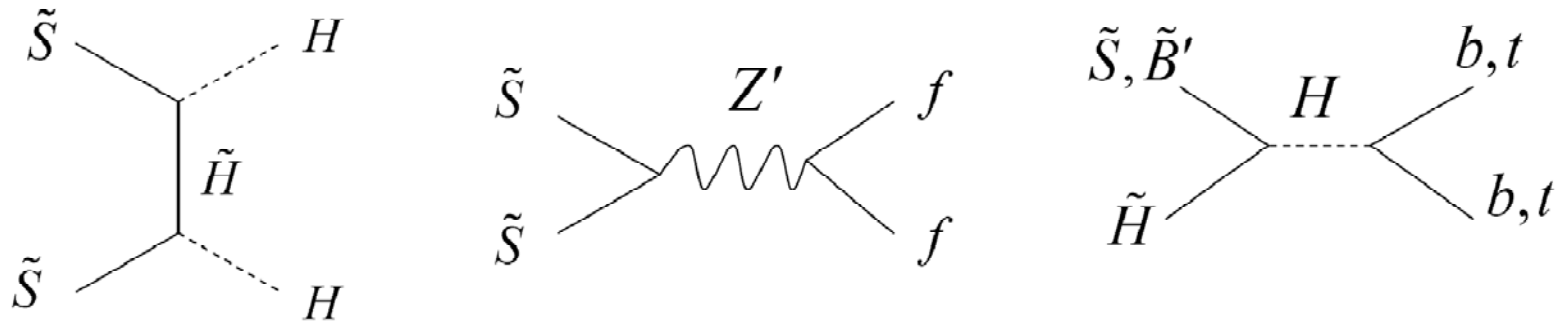
Neutralino mass matrix

$$\begin{pmatrix} \tilde{B} & \tilde{W}_3 & \tilde{H}_d & \tilde{H}_u & \tilde{S} & \tilde{B}' \\ M_1 & & & & & \\ & M_2 & & & & \\ & & 0 & -\lambda s & & \\ & & -\lambda s & 0 & & \\ & & & & 0 & \sim M_{Z'} \\ & & & & \sim M_{Z'} & M_1' \end{pmatrix} \chi_1 = N_1 \tilde{B} + N_2 \tilde{W} + N_3 \tilde{H}_d + N_4 \tilde{H}_u + \underbrace{N_5 \tilde{S} + N_6 \tilde{B}'}_{\text{New}}$$

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

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

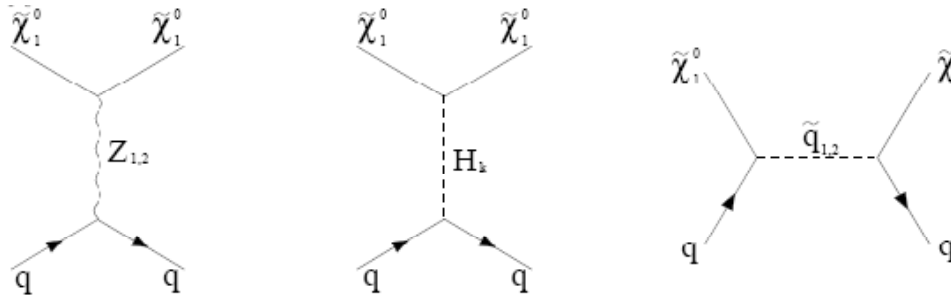
LSP has new annihilation channels via Z' or $\lambda S H_d H_u$



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

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

$$16 \sum_{i=1,2} \frac{g_2^2}{m_{\tilde{q}_i}^2 - (m_{\tilde{\chi}_0} - m_q)^2} - \frac{G_F}{\sqrt{2}} [|N_{13}|^2 - |N_{14}|^2] I_q^3 - \frac{g_1^2}{4m_{Z'}^2} [Q_1 |N_{13}|^2 + Q_2 |N_{14}|^2 + Q_s |N_{15}|^2] (Q_Q + Q_{\bar{q}})$$

$$-\frac{g_2^2}{8} \sum_{i=1,2} \frac{\text{Re}(B_q^{iL} B_q^{iR*})}{m_{\tilde{q}_i}^2 - (m_{\tilde{\chi}_0} - m_q)^2} - \frac{h_q}{2\sqrt{2}} \sum_{k=1}^3 \frac{\text{Re}(G_k) + \text{Re}(G'_k) + \text{Re}(G''_k)}{m_{H_k}^2} \begin{cases} \mathcal{O}'_{1k} & \text{for } q = d \\ \mathcal{O}'_{2k} & \text{for } q = u \end{cases}$$

$$G_k = g_2 (N_{12} - t_W N_{11})(N_{14} \mathcal{O}'_{2k} - N_{13} \mathcal{O}'_{1k})$$

$$G'_k = -2 g_1 N_{16} (Q_1 N_{13} \mathcal{O}'_{1k} + Q_2 N_{14} \mathcal{O}'_{2k} + Q_s N_{15} \mathcal{O}'_{3k})$$

$$G''_k = \sqrt{2} \lambda [N_{15} (N_{13} \mathcal{O}'_{2k} + N_{14} \mathcal{O}'_{1k}) + N_{13} N_{14} \mathcal{O}'_{3k}]$$

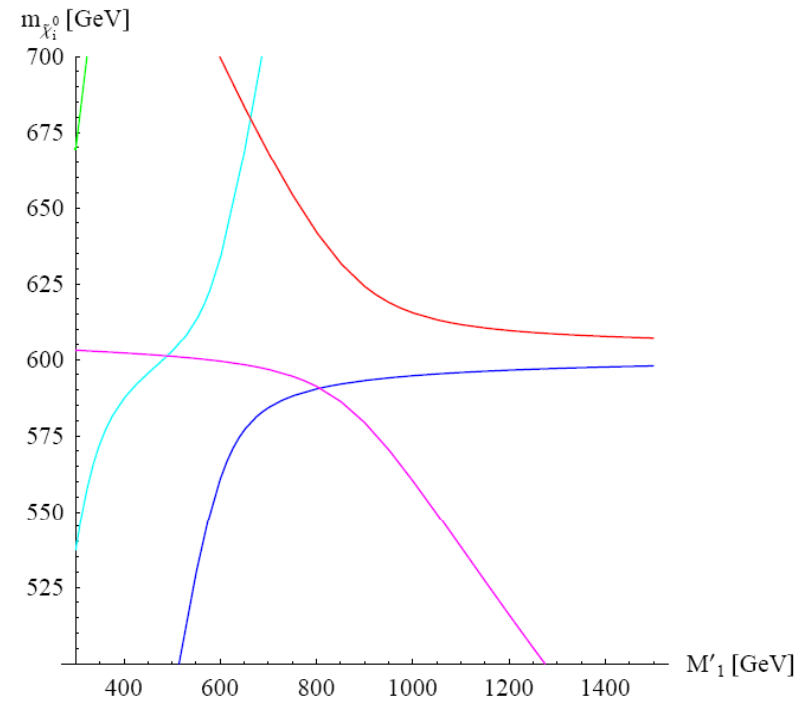
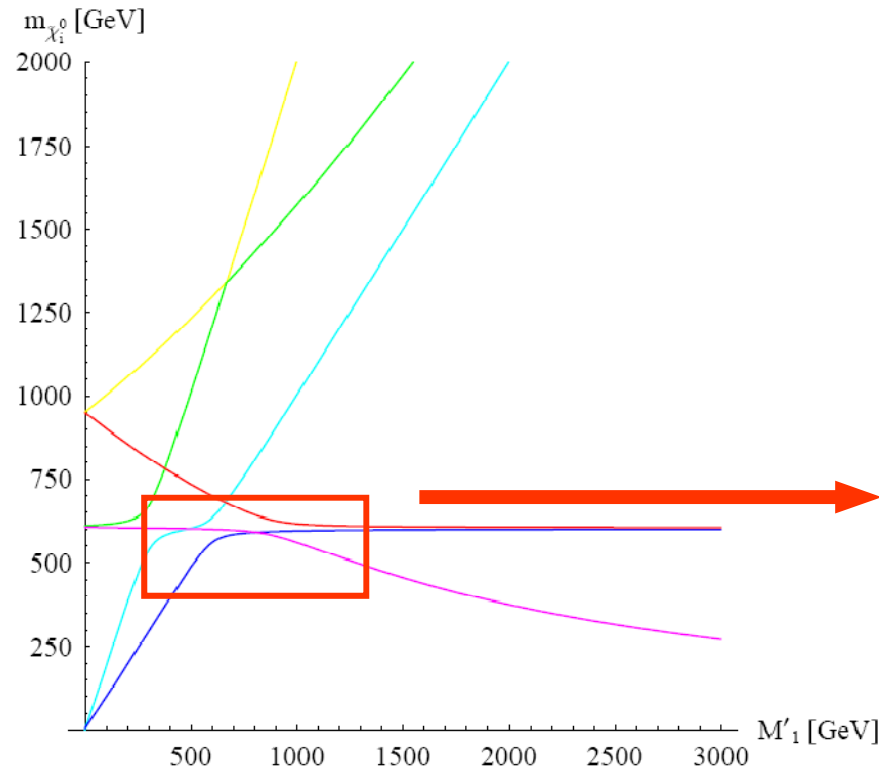
Choi ea,
Jarecka

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 $M_{\tilde{f}} = 800 \text{ GeV}, M_A = 500 \text{ GeV}$

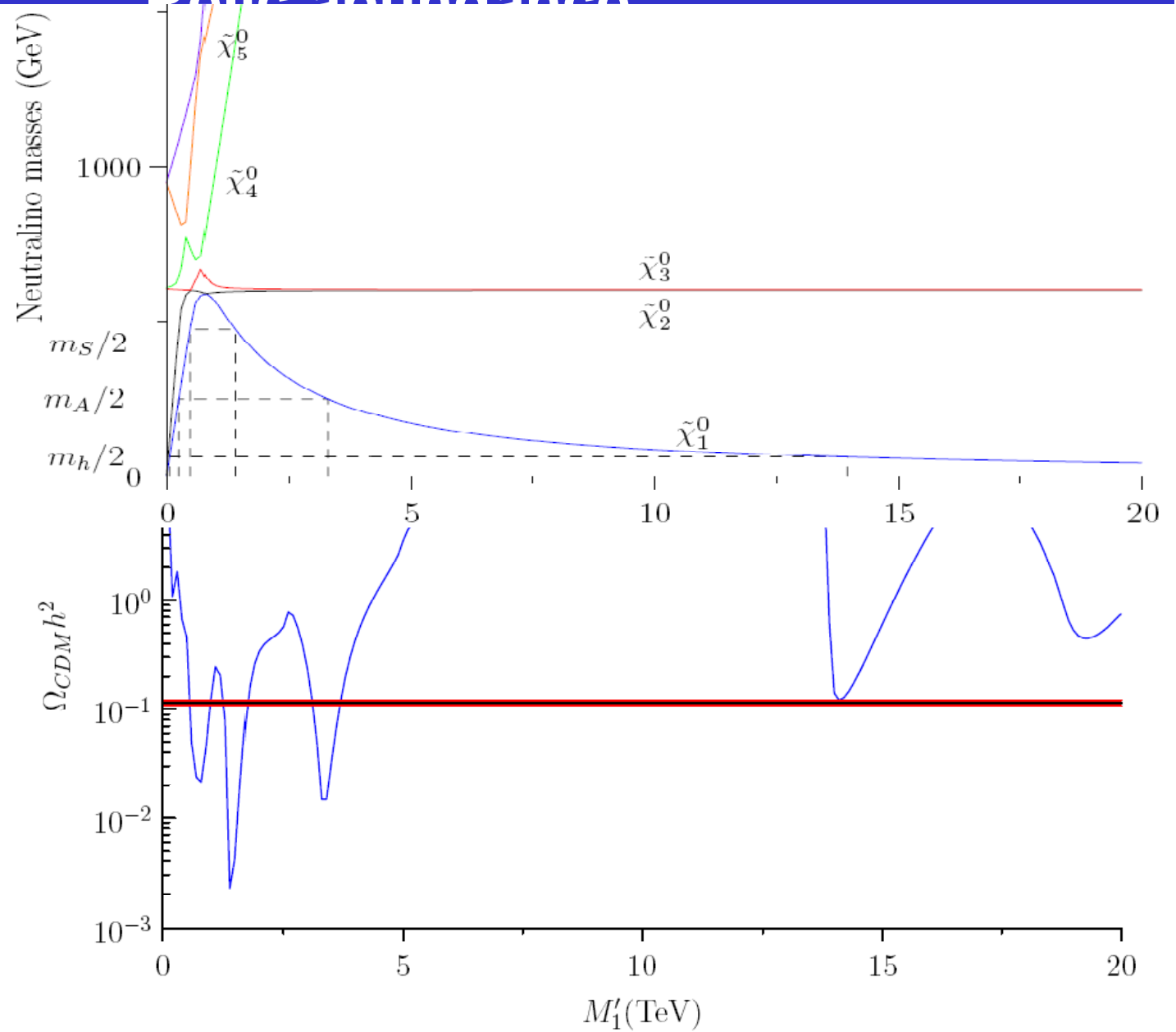
as a function of $M'_1 = M_1 \sim M_2/2$

Neutralino mass spectrum



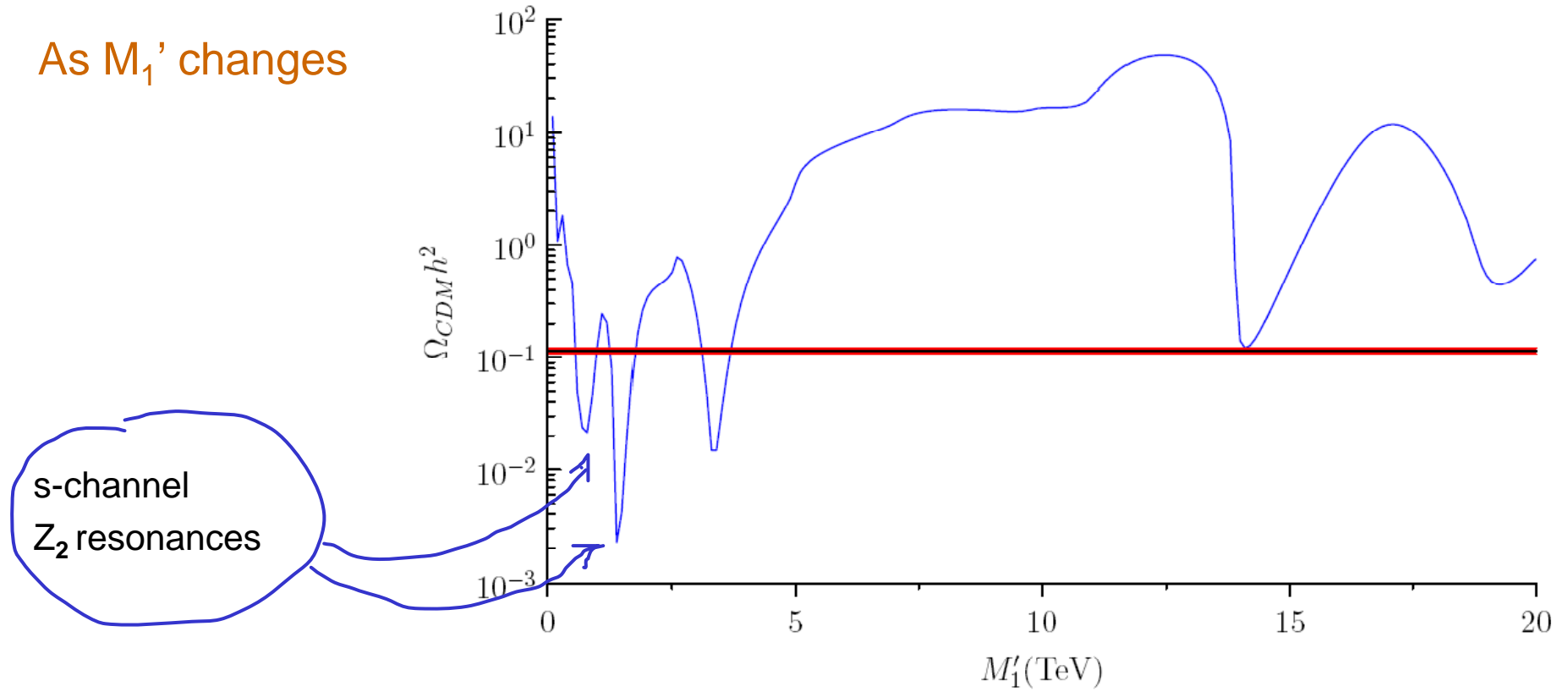
Pole abundance

As M_1' changes



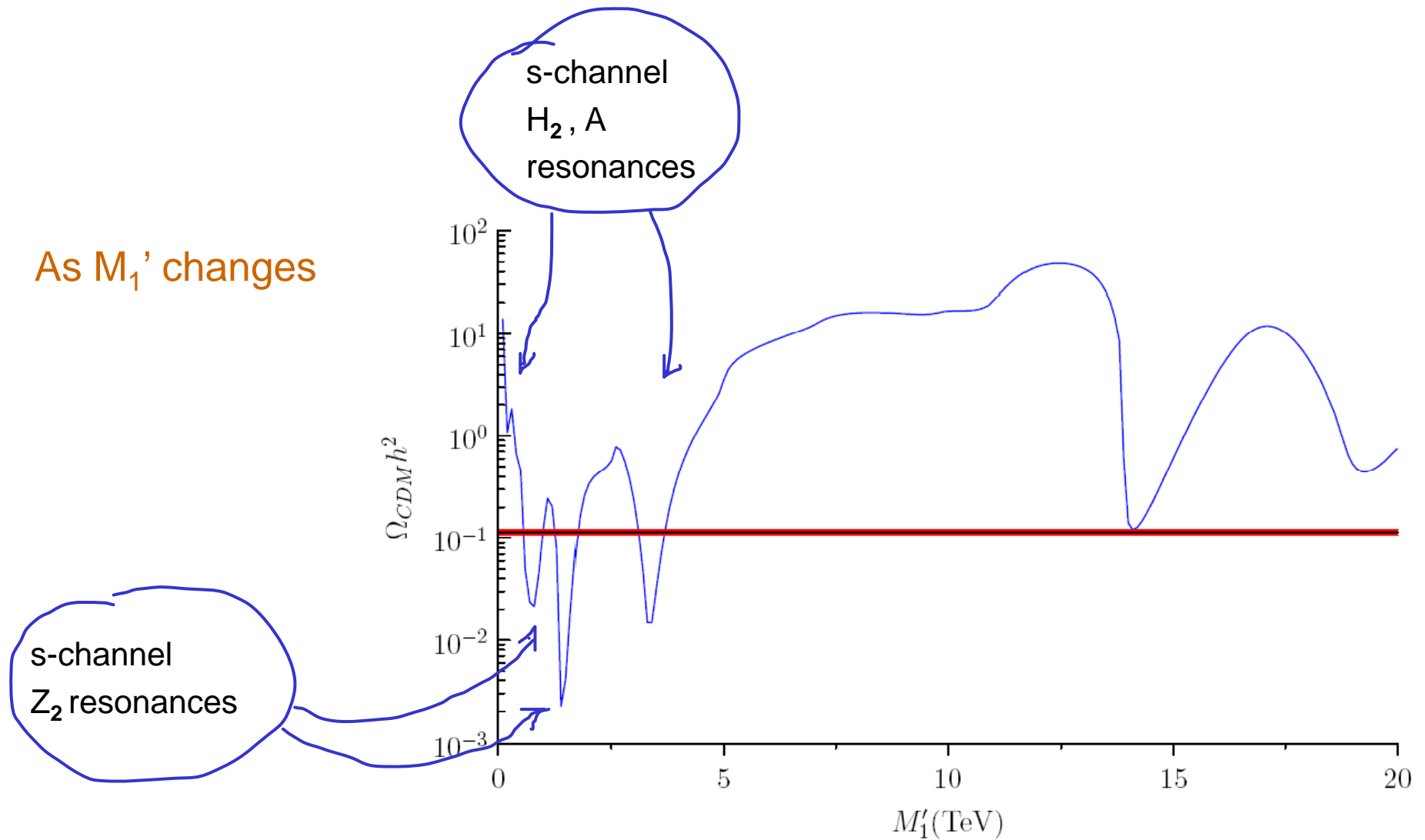
Relic abundance

As M_1' changes



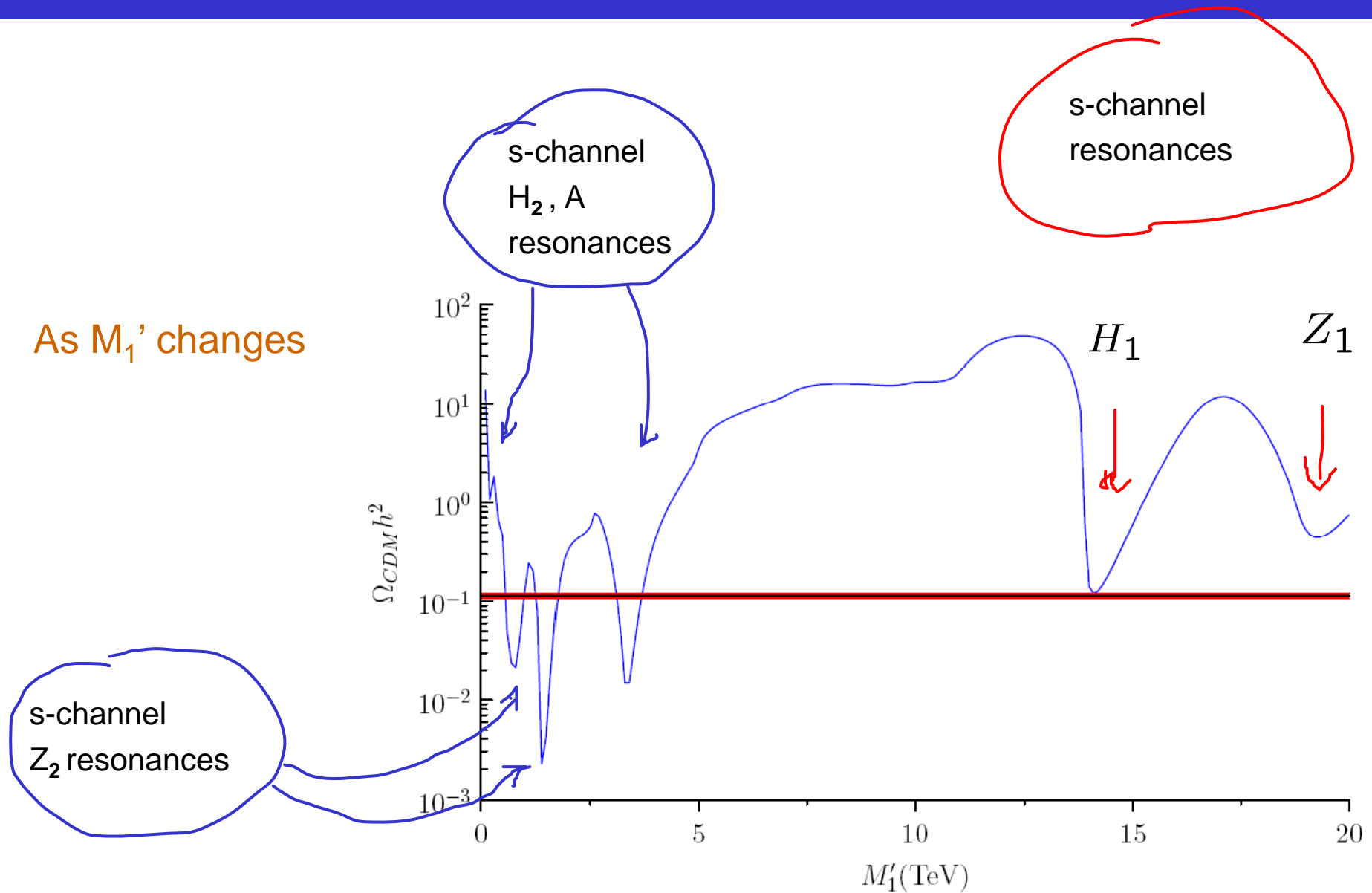
Relic abundance

As M_1' changes



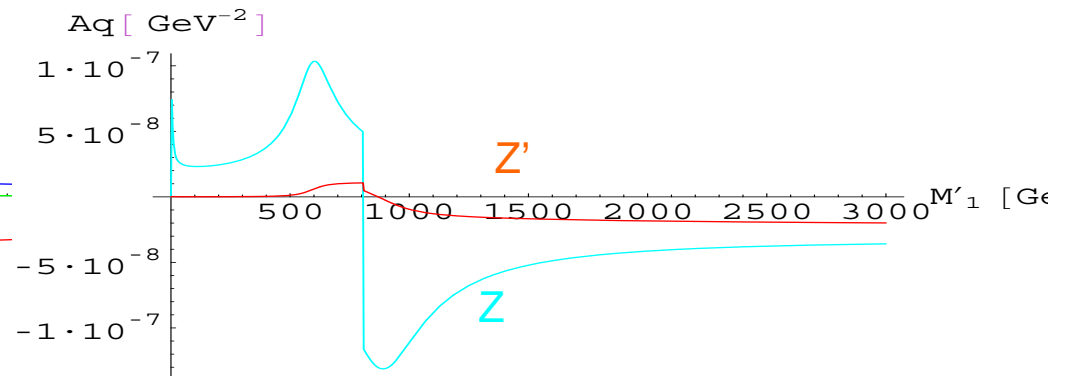
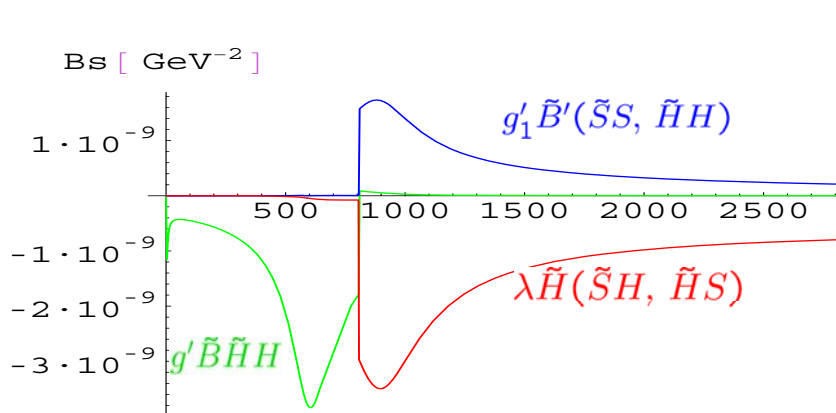
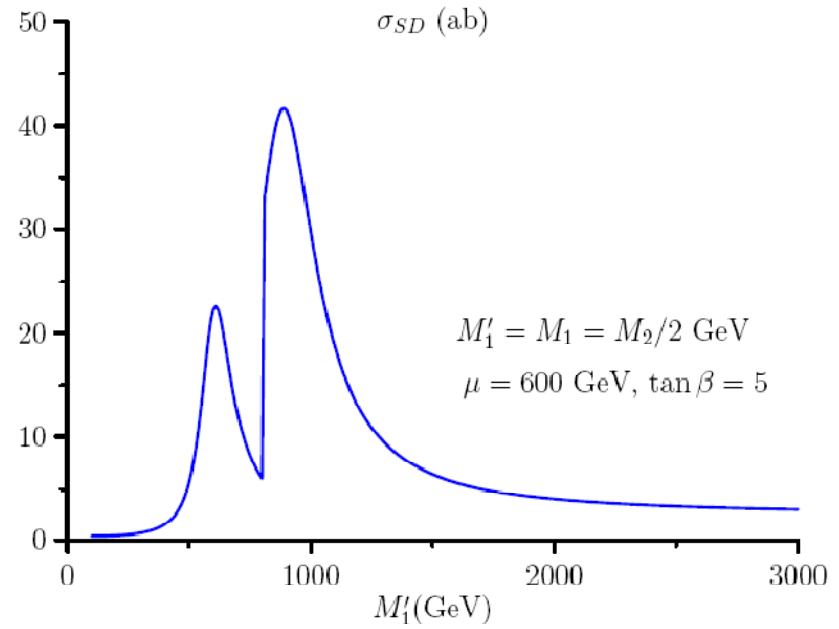
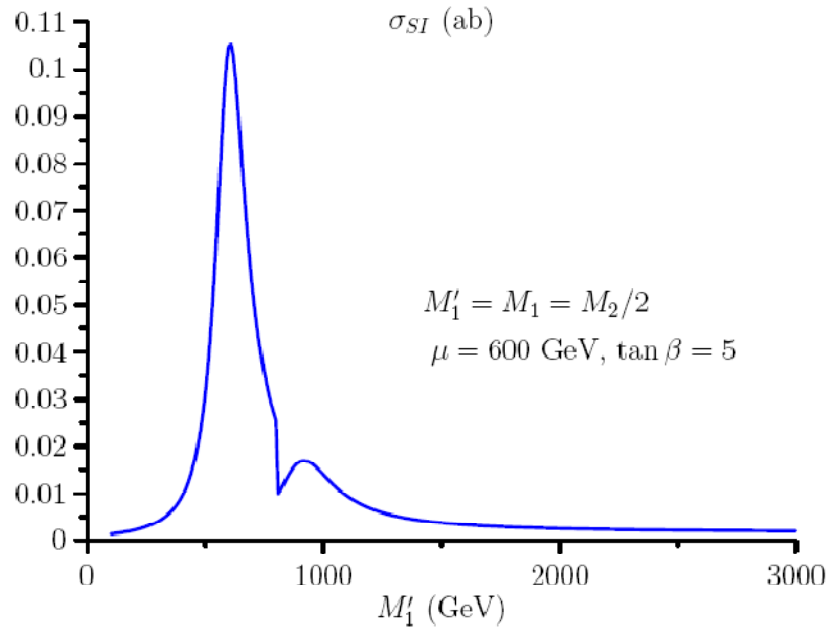
Relic abundance

As M_1' changes



Direct searches

Elastic scattering on a nucleon



Collider connection

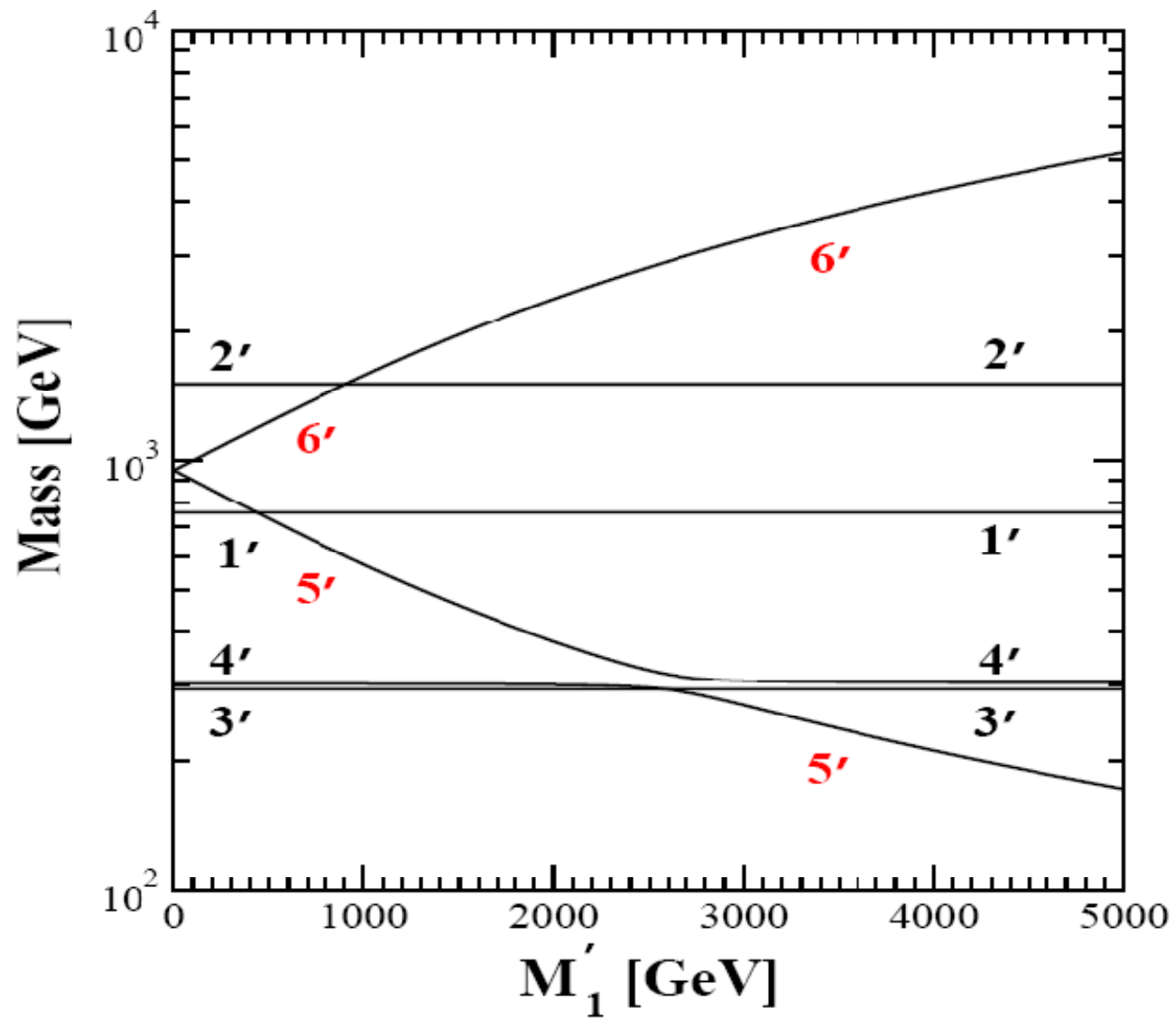
- neutralino production cross sections at e+e-
the presence of Z' affects the production cross sections
- neutralino decays $\tilde{u}_R \rightarrow u\tilde{\chi}_5^0 \rightarrow u[l\tilde{\ell}_R] \rightarrow ull\tilde{\chi}_1^0$
but branching fractions modified
- new neutralino decay chains
longer $\tilde{u}_R \rightarrow u\tilde{\chi}_6^0 \rightarrow u[Z_1\tilde{\chi}_5^0] \rightarrow uZ_1[l\tilde{\ell}_R] \rightarrow uZ_1ll\tilde{\chi}_1^0$
or shorter because of $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 Z$
- in transition zones radiative $\tilde{\chi}_i^0 \rightarrow \tilde{\chi}_1^0 \gamma$ 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_6 SSM: add more singlet superfields, exotics,



Scenario A: $M_1' \odot M_1$

DM abundance

s-channel
A, H_2
resonances

s-channel
resonances

As M_1' increases

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

