A CDM Candidate in Supersymmetric Extra U(1) Models

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Introduction (Why do we consider extra U(1) models ?)

- Recent astrophysical observations show the existence of cold dark matter (CDM).

$$0.0945 \le \Omega_{CDM}h^2 \le 0.1287$$
(at 2σ, WMAP 1st year)

- There is no candidate for CDM in the standard model (SM). The SM should be extended.
- Supersymmetry (SUSY) is the most promising candidate, which has a theoretical motivation for the gauge hierarchy problem. It indicates various interesting phenomenological features, *i.e.*
  - gauge coupling unification,
  - radiative symmetry breaking (heavy top quark),
  - new (neutral) particles, *etc.*

MSSM

- The SM is minimally extended into a SUSY model ⇒ Minimal SUSY SM (MSSM).

supersymmetric mass term and no relation to SUSY

$$W_{MSSM} = h_U\bar{U}\hat{Q}\hat{H}_2 + h_D\bar{D}\hat{Q}\hat{H}_1 + h_E\bar{E}\hat{L}\hat{H}_1 + \mu\hat{H}_1\hat{H}_2$$

$$-\mathcal{L}_{SUSY} = \sum_\varphi m_\varphi^2|\varphi|^2 + \left(\frac{1}{2}M_{\tilde{g}}\bar{\lambda}_g\lambda_g + \frac{1}{2}M_{\tilde{W}}\bar{\lambda}_W\lambda_W + \frac{1}{2}M_{\tilde{Y}}\bar{\lambda}_Y\lambda_Y + \text{h.c.}\right) - \left(A_U h_U\bar{\tilde{U}}\tilde{Q}H_2 + A_D h_D\bar{\tilde{D}}\tilde{Q}H_1 + A_E h_E\bar{\tilde{E}}\tilde{L}H_1 + B\mu H_1H_2 + \text{h.c.}\right)$$

- R-Parity guarantees proton stability and also makes the lightest SUSY particle stable.

⇒ $\tilde{\phi}_\ell$: a candidate of CDM

$$\Phi \to R_p\Phi \qquad R_p = (-1)^{3B+L+2S}$$

SM particles ψ_{SM} $R_p = +1$; SUSY particles $R_p = -1$ ⇒ $\tilde{\phi}_\ell \not\to \psi_{SM}\psi_{SM}$

Motivation for extending the MSSM

- If SUSY parameters are suitably taken, there is no serious contradiction with experiments.

However,

- Although there are parameter regions which can explain the observed CDM abundance, they are not wide and restricted.
- The MSSM cannot solve the gauge hierarchy problem completely and there remains the famous μproblem. "Why does μ take a weak scale?"

Thus,

- It seems worth studying various extensions of the MSSM from a viewpoint of CDM.
- Different features from the MSSM may be checked through the LHC experiments.

extend by Introducing U(1)' to MSSM at a TeV range

forbidden by $Q_x(S) \neq 0$

Extra U(1) models

MSSM + { $U(1)'$, singlet chiral superfield $\hat{S}$ }

- Extra U(1) models can solve the μ problem in an elegant way.
- Models are defined by

new interactions

$$D_\mu = \partial_\mu + ig_2\frac{\tau^a}{2}W_\mu^a + ig_1\frac{Y(f)}{2}B_\mu + ig_x\frac{Q_x(f)}{2}Z'_\mu$$

$$W_{MSSM} : \mu\hat{H}_1\hat{H}_2 \Rightarrow \lambda\hat{S}\hat{H}_1\hat{H}_2$$

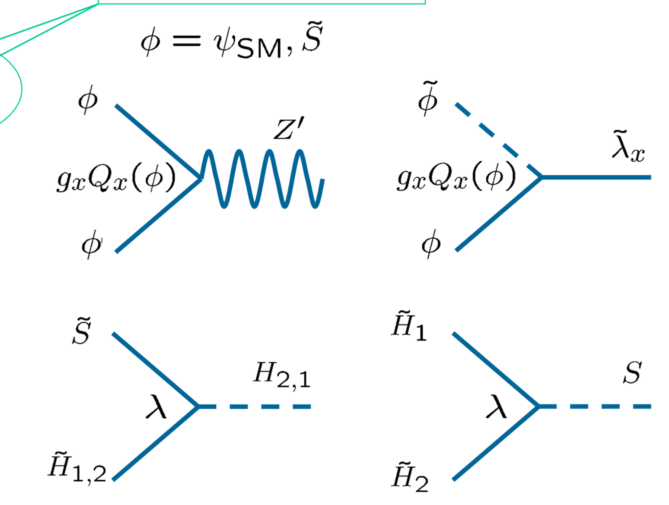
$$-\mathcal{L}_{SUSY} : B\mu H_1H_2 \Rightarrow A_\lambda\lambda SH_1H_2$$

$m_S^2|S|^2$, $\frac{1}{2}M_{\tilde{x}}\bar{\lambda}_x\lambda_x$ are added

- Symmetry breaking is fixed by

$$\langle S\rangle = u, \quad \langle H_1\rangle = \begin{pmatrix} v_1 \\ 0 \end{pmatrix}, \quad \langle H_2\rangle = \begin{pmatrix} 0 \\ v_2 \end{pmatrix}.$$

MSSM sector $\{ v_1^2 + v_2^2 = v^2,\ \tan\beta = v_2/v_1 \}$ $\langle S\rangle \Rightarrow \{ \mu = \lambda u,\ U(1)'$ gauge boson mass $\}$



Interactions for neutralinos can be affected through these new interactions.

Extended neutral sectors in extra U(1) models

(a) A neutral gauge boson Z'

Mass matrix of neutral gauge bosons (Z, Z')

$$\begin{pmatrix} m_Z^2 & \frac{g_x\sqrt{g_2^2+g_1^2}}{2}v^2(Q_1\cos^2\beta - Q_2\sin^2\beta) \\ \frac{g_x\sqrt{g_2^2+g_1^2}}{2}v^2(Q_1\cos^2\beta - Q_2\sin^2\beta) & g_x^2v^2(Q_1^2\cos^2\beta + Q_2^2\sin^2\beta + Q_S^2\frac{u^2}{v^2}) \end{pmatrix}$$

with $m_Z^2 = \frac{g_2^2+g_1^2}{2}v^2$

Mass eigenvalues (Z_1, Z_2)

$$m_{Z_1}^2 \simeq m_Z^2 - m_Z^2\frac{g_x\tan 2\xi}{\sqrt{g_2^2+g_1^2}}(Q_1\cos^2\beta - Q_2\sin^2\beta),$$

$$m_{Z_2}^2 \simeq \frac{g_x^2}{2}(Q_1^2v_1^2 + Q_2^2v_2^2 + Q_S^2u^2) + m_Z^2\frac{g_x\tan 2\xi}{\sqrt{g_2^2+g_1^2}}(Q_1\cos^2\beta - Q_2\sin^2\beta)$$

$Z - Z'$ mixing

$$\tan 2\xi = \frac{2g_x\sqrt{g_2^2+g_1^2}(Q_1\cos^2\beta - Q_2\sin^2\beta)}{g_x^2(Q_1^2\cos^2\beta + Q_2^2\sin^2\beta + Q_S^2u^2/v^2) - (g_2^2+g_1^2)}.$$

phenomenologically interesting

Z' phenomenology

$\xi < 10^{-3} \Rightarrow$ { (1) $u >> v$ — heavy Z_2; (2) $\tan\beta = \sqrt{Q_1/Q_2}$ — light Z_2 }

(b) Neutral Higgs scalars

There exist three CP-even and one CP-odd neutral scalars.

$$H_1 = \begin{pmatrix} v_1 + h_1^0 + iP_1 \\ h_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} h_2^+ \\ v_2 + h_2^0 + iP_2 \end{pmatrix}, \quad S = u + h_S^0 + iP_S.$$

CP-even neutral scalar mass matrix (h_1^0, h_2^0, h_S^0)

$$\begin{pmatrix} \frac{1}{2}(g_2^2+g_1^2+g_x^2Q_1^2)v_1^2 + A_\lambda\lambda u\tan\beta & -\frac{1}{2}(g_2^2+g_1^2-g^2(1,2))v_1v_2 - A_\lambda\lambda u & \frac{1}{2}g^2(1,S)v_1u - A_\lambda\lambda v_2 \\ -\frac{1}{2}(g_2^2+g_1^2-g^2(1,2))v_1v_2 - A_\lambda\lambda u & \frac{1}{2}(g_2^2+g_1^2+g_x^2Q_2^2)v_2^2 + A_\lambda\lambda u\cot\beta & \frac{1}{2}g^2(2,S)v_2u - A_\lambda\lambda v_1 \\ \frac{1}{2}g^2(1,S)v_1u - A_\lambda\lambda v_2 & \frac{1}{2}g^2(2,S)v_2u - A_\lambda\lambda v_1 & \frac{1}{2}g_x^2Q_S^2u^2 + A_\lambda\lambda\frac{v_1v_2}{u} \end{pmatrix}$$

The lightest one can be heavier than that of the MSSM.

$$m_{h_0}^2 \le m_Z^2\left[\cos^2 2\beta + \frac{2\lambda^2}{g_2^2+g_1^2}\sin^2 2\beta + \frac{g_x^2}{g_2^2+g_1^2}(Q_1\cos^2\beta + Q_2\sin^2\beta)^2\right] + \Delta m_1^2$$

new contributions

The present Higgs mass bound cannot exclude small values of $\tan\beta$ such as $\tan\beta \simeq 2$.

(c) Neutralinos

Neutralino sector has 6 components.

Mass matrix $(\tilde{\lambda}_x, \tilde{\lambda}_W, \tilde{\lambda}_B, \tilde{H}_1, \tilde{H}_2, \tilde{S})$ — MSSM contents

$$\begin{pmatrix} M_x & 0 & 0 & \frac{g_xQ_1}{\sqrt{2}}v\cos\beta & \frac{g_xQ_2}{\sqrt{2}}v\sin\beta & \frac{g_xQ_S}{\sqrt{2}}u \\ 0 & M_2 & 0 & m_Zc_W\cos\beta & -m_Zc_W\sin\beta & 0 \\ 0 & 0 & M_1 & -m_Zs_W\cos\beta & m_Zs_W\sin\beta & 0 \\ \frac{g_xQ_1}{\sqrt{2}}v\cos\beta & m_Zc_W\cos\beta & -m_Zs_W\cos\beta & 0 & \lambda u & \lambda v\sin\beta \\ \frac{g_xQ_2}{\sqrt{2}}v\sin\beta & -m_Zc_W\sin\beta & m_Zs_W\sin\beta & \lambda u & 0 & \lambda v\cos\beta \\ \frac{g_xQ_S}{\sqrt{2}}u & 0 & 0 & \lambda v\sin\beta & \lambda v\cos\beta & 0 \end{pmatrix}$$

The lightest neutralino (LN)

$$\tilde{\chi}_\ell^0 = N_{\ell 1}\tilde{\lambda}_x + N_{\ell 2}\tilde{\lambda}_W + N_{\ell 3}\tilde{\lambda}_B + N_{\ell 4}\tilde{H}_1 + N_{\ell 5}\tilde{H}_2 + N_{\ell 6}\tilde{S}$$

$M_x >> \frac{g_xQ_S}{\sqrt{2}}u$ See-saw mechanism

The LN can be dominated by a singlino $(\tilde{S})$.

$|N_{\ell 6}|^2 > 0.5$ $\quad m_{\tilde{S}} \simeq \frac{g_x^2Q_S^2}{2M_{\tilde{x}}}u^2$ ⇒ light neutralino?

Different features from the MSSM can be expected.

CDM in extra U(1) models

- Composition of the LN can be modified from the MSSM. In particular, the singlino dominated LN can be allowed for large values of M_x.
- New interactions can contribute to annihilation of the LN. If the LN is dominated by the singlino, new interactions can contribute most effectively.

relevant components: $\tilde{H}_{1,2}$, $\tilde{S}$

$\tilde{\chi}_\ell^0$, $g_xQ_x(f)$, Z', $\tilde{\chi}_\ell^0$; $Q_1 + Q_2 + Q_S = 0$ ⇒ $Q_S > Q_{1,2}$ ($Q_1Q_2 > 0$)

$\tilde{\chi}_\ell^0$, λ, S, $H_{2,1}$, $\tilde{\chi}_\ell^0$; $u > v$ ⇒ $m_S^2 > m_{H_{1,2}}^2$

The LN with large values of $N_{\ell 6}$ is expected to obtain crucial effects by these.

Annihilation cross section

- In most regions the LN is rather light and then allowed annihilation modes are $\tilde{\chi}_\ell^0\tilde{\chi}_\ell^0 \to f\bar{f}$ (f : SM fermions).
- Compared with the MSSM, there are additional contributions to these modes

$$\sigma_{\tilde{\chi}_\ell^0\tilde{\chi}_\ell^0 \to f\bar{f}} \cdot v = a + bv^2 + \ldots$$

Important processes for the singlino dominated LN

$a \Rightarrow \left| \ldots O(m_f^2) + \ldots O(m_f^2) + \cdots \right|^2$

$b \Rightarrow \left| \ldots O(1) + \ldots O(m_f^2) + \cdots \right|^2$ pole enhancement

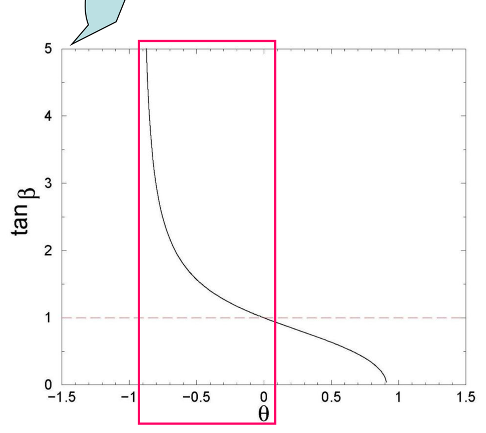
$O(m_f^2)$ suppression due to the final state mass

B.de Carlos and J.R.Espinosa, Phys. Lett. B407 (1997) 12
D.Suematsu, Phys. ReV. D73 (2006) 035010

Analyses and results

- Extra U(1) models are defined by the following parameters:
  - Gauge sector (unification relation)
    $g_3,\ g_2,\ g_1,\ g_x,\ Q_x(\phi) \Rightarrow g_{gut},\ Q_x(\phi)$
  - SUSY breaking sector (universality condition)
    $M_3,\ M_2,\ M_1,\ M_x,\ m_\phi,\ A_y$
    $\Rightarrow M_2,\ M_x,\ m_0,\ A$ ⇒ $m_{3/2}$
  - Symmetry breaking sector
    $\tan\beta,\ u,\ \lambda\left(\equiv\frac{\mu}{u}\right)$
- Additional restrictions for the parameter space.
  - (i) We assume that U(1)' is derived from E_6 as
    $E_6 \supset SO(10)\times U(1)_\psi \supset SU(5)\times U(1)_\psi \times U(1)_\chi$
    $Q_x = Q_\psi\cos\theta - Q_\chi\sin\theta$
    U(1)' charges are fixed by one parameter θ.
  - (ii) In order to satisfy the constraint from Z' phenomenology, we assume $\tan\beta = \sqrt{Q_1/Q_2}$.
- Remaining parameters are
  $\theta,\ M_2,\ M_x,\ m_{3/2},\ u,\ \lambda.$

allowed regions of θ

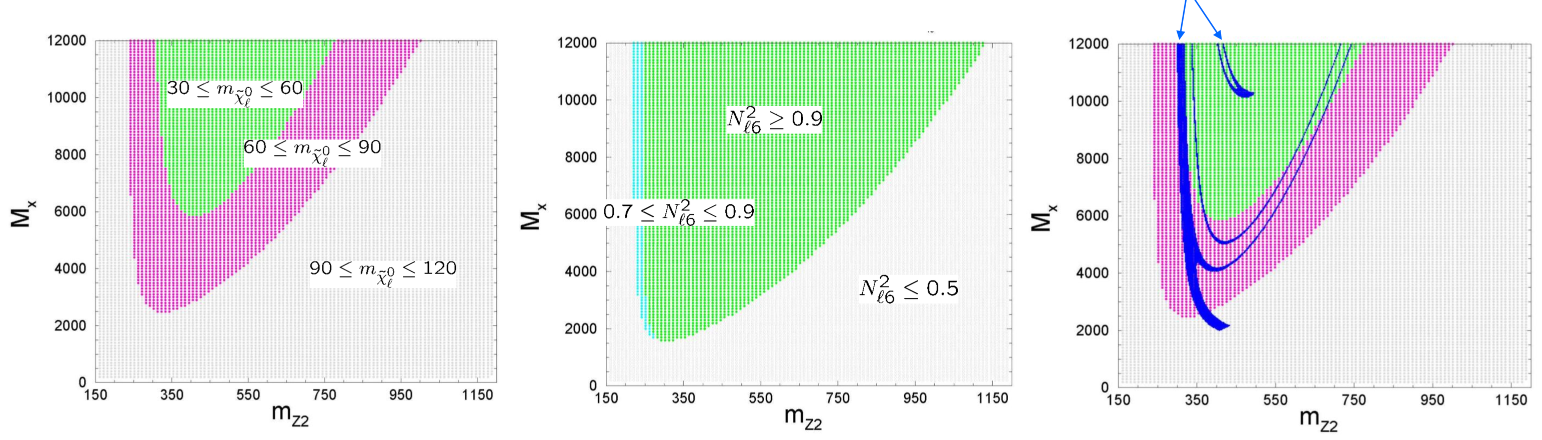


- We focus our study into the case $M_x \gg M_2$ where the singlino dominated LN is expected.
- We assume $m_{3/2} = 1$TeV throughout the study.

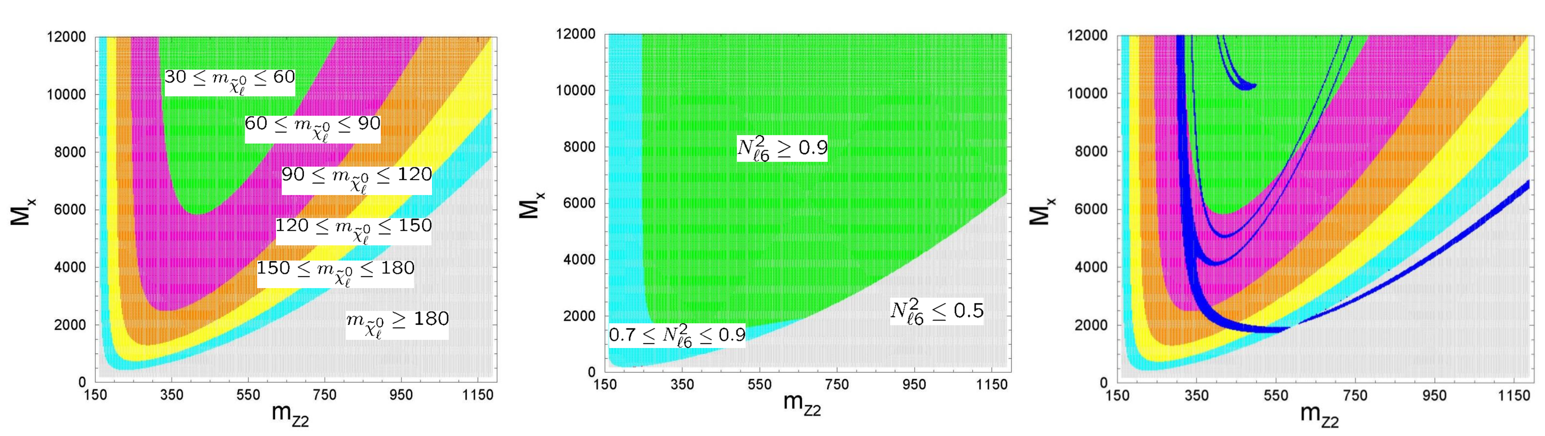
(1) Mass eigenvalues and composition of the LN

$\mu = 700$ GeV is assumed.

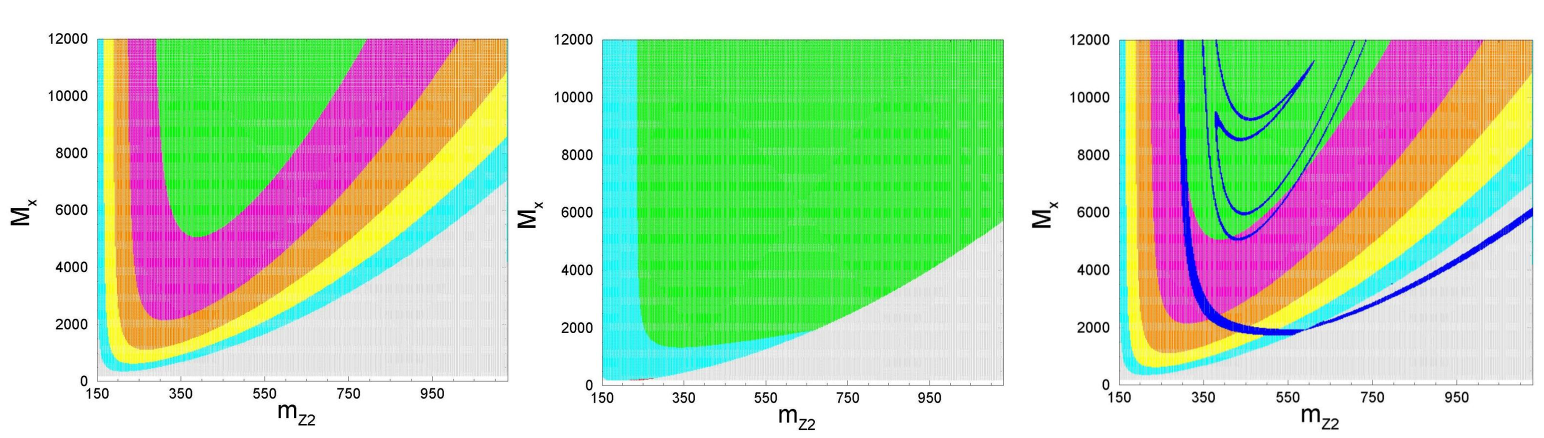
(i) $\theta = -0.253$ $\quad M_2 = 600$ GeV



(ii) $\theta = -0.253$ $\quad M_2 = 1200$ GeV



(iii) $\theta = -0.4$ $\quad M_2 = 1200$ GeV



The light LN is allowed if it is singlino dominated.

(2) WMAP allowed regions

WMAP constraint (blue strips)

Phenomenological constraints

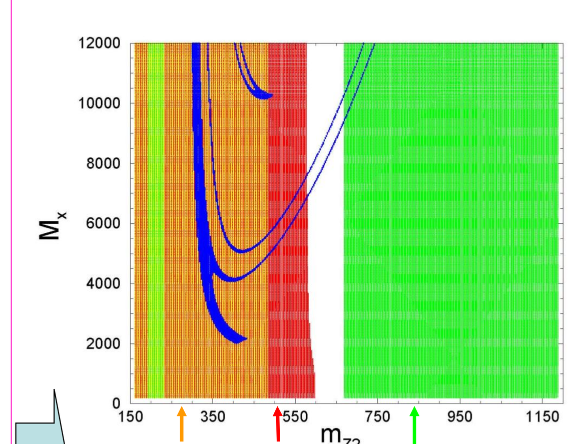
We should impose other constraints which exclude various regions.

- (a) perturbative bounds for λ
  $\lambda \le 0.75$
- (b) neutral Higgs mass bounds
  $m_{h^0} \ge 114$ GeV
- (c) mass bounds for Z_2
  $\sigma(p\bar{p} \to Z_2X)B(Z_2 \to e^+e^-, \mu^+\mu^-) < 0.04$ pb
- chargino mass bounds
  $m_{\tilde{\chi}}^\pm \ge 104$ GeV
- sfermion mass bounds
  $m_{\tilde{f}} \ge 250$ GeV
- ……

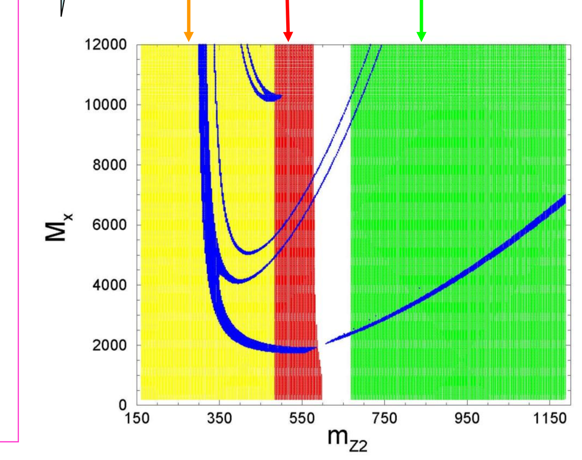
U(1)' D-term contribution should be taken into account

(3) Allowed regions

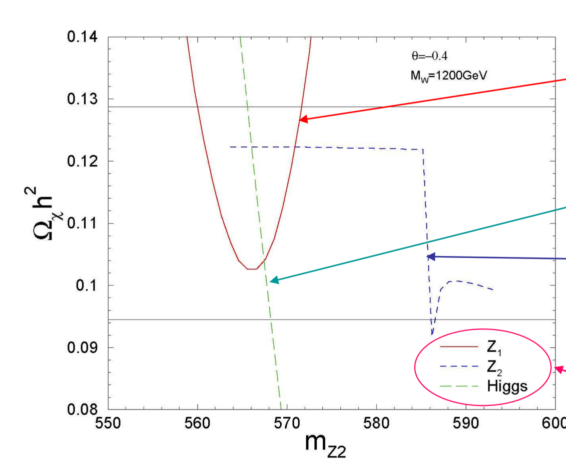
Blue strips in the white regions are phenomenologically allowed.

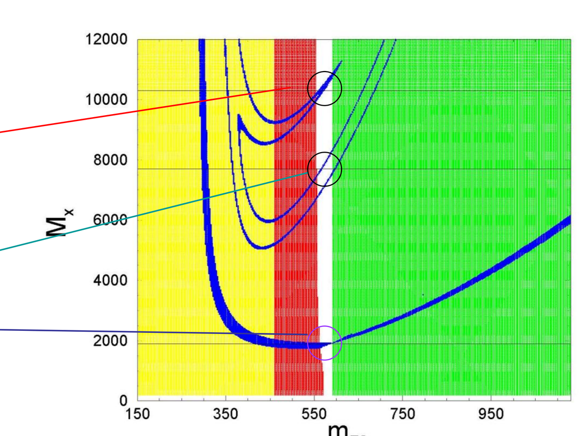


(a) (c) (b) excluded regions



What kind of process plays an important role in each solution?
For fixed M_x values :





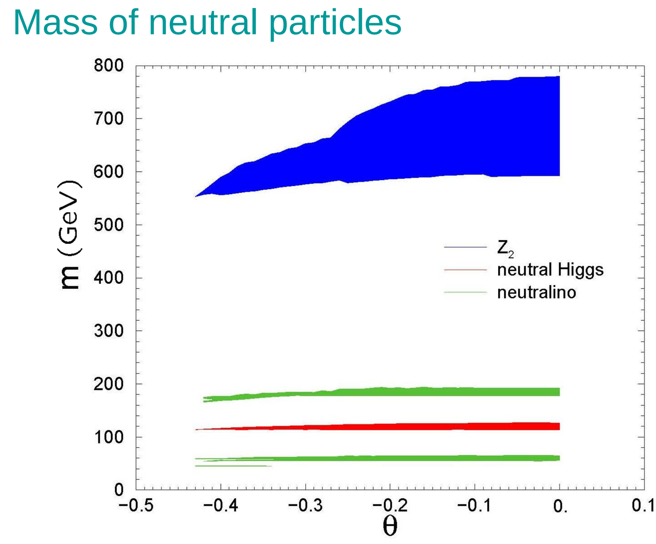
The exchange of these particles are taken into account for each case.

(4) Predictions of the models

- Present models may be distinguished from other extensions of the MSSM through the detection of neutral particles.
- These aspects may be checked in the LHC.
- We use the parameter setting :

300 GeV $\le u \le$ 2300 GeV
200GeV $\le M_{\tilde{x}} \le$ 12 TeV
200 GeV $\le M_2, \mu \le$ 1300 GeV

Mass of neutral particles



Dilepton decay of Z_2 at LHC ($\sqrt{s} = 14$ TeV) $(e^+e^-, \mu^+\mu^-)$