Beyond the MSSM

Modifications to Higgs mass and Higgsino-LSP

Kingman Cheung, SY Choi, Jeonghyeon Song 2009

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Motivations

Dine, Seiberg, Thomas 2007 (BMSSM)

- The most popular SUSY model is the minimal one called MSSM. (Just like our SM is in fact the minimal SM). Heavier degrees of freedom are often integrated out and their effects are presented as higher dimensional operators.
- In SUSY, it is even so, because the communication of SUSY breaking from hidden sectors to visible sector is largely unknown. It involves unknown dynamics at a high scale M.

- If this scale M is not as high as Planck scale, it may induce some low energy effects, which can be studied via some higher dimensional operators suppressed by M.
- The least suppressed effective operator was suggested to be, in the superpotential (Dine, Seiberg, Thomas)

$$\lambda \frac{(H_u H_d)^2}{M}$$

- This term will raise the Higgs boson mass and modifies the Higgsino properties.
- It will then affect the dark matter properties of Higgsino LSP.

An example of underlying theory

(Dine, Seiberg, Thomas)

- Existence of a heavy singlet field, similar in structure to NMSSM

$$W = \mu H_u H_d + \frac{1}{M_S} S^2 + \lambda_S S H_u H_d$$

- If $S \gg \mu$, one can integrate out the S using

$$S = -\frac{\lambda_S}{M_S}(H_u H_d)$$

- Resulting in the following

$$W = \mu H_u H_d - \frac{\lambda_S^2}{2M_S}(H_u H_d)^2$$

The operator

The MSSM superpotential with the dim-5 operator is

$$W = W_{\rm mssm} + W_{\rm dim-5}$$

where

$$\begin{aligned} W_{\rm mssm} &= \epsilon_{ab}\left(Y_u Q^a H_u^b U^c - Y_d Q^a H_d^b D_c - Y_e L^a H_d^b E^c + \mu H_u^a H_d^b\right) \\ W_{\rm dim-5} &= \frac{\lambda}{M}\left(\epsilon_{ab} H_u^a H_d^b\right)^2 \end{aligned}$$

Effects on Higgs Boson Mass

- The Higgs potential receives the F-term contribution from the new term in the superpotential, and from the corresponding SUSY-breaking term:

$$\delta V_H = 2\epsilon_1 (H_u H_d)(H_u^\dagger H_u + H_d^\dagger H_d) + \epsilon_2 (H_u H_d)^2 + h.c.$$

where

$$\epsilon_1 \equiv \frac{\mu^* \lambda}{M}, \qquad \epsilon_2 \equiv -\frac{M_{\rm SUSY}\lambda}{M}$$

- The BMSSM correction to the Higgs boson mass is

$$\delta m_h^2 = v^2 \left(\epsilon_{2r} + 2\epsilon_{1r} \sin 2\beta + \frac{2\epsilon_{1r}(m_A^2 + m_Z^2)\sin 2\beta - \epsilon_{2r}(m_A^2 - m_Z^2)\cos^2 2\beta}{\sqrt{(m_A^2 - m_Z^2)^2 + 4 m_A^2 m_Z^2 \sin^2 2\beta}} \right)$$

$$\simeq 8v^2 \frac{m_A^2}{m_A^2 - m_Z^2} \frac{\epsilon_{1r}}{\tan\beta} + \mathcal{O}\left(\frac{\epsilon}{\tan^2\beta}\right)$$

- BMSSM correction to the heavier Higgs mass is

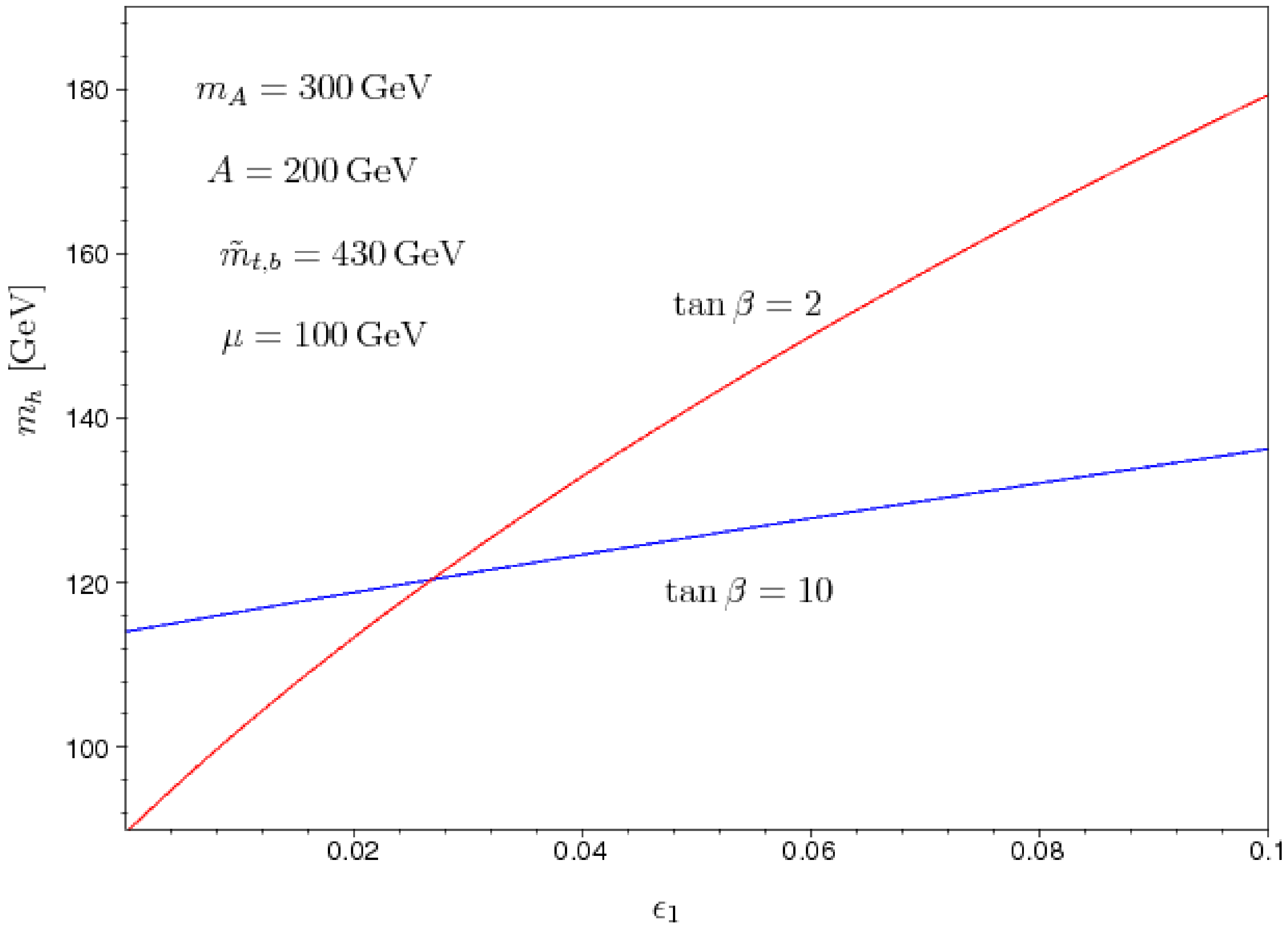
$$\delta m_H^2 = 2v^2 \left(\epsilon_{2r} + 2\epsilon_{1r} \sin 2\beta - \frac{2\epsilon_{1r}(m_A^2 + m_Z^2) \sin 2\beta - \epsilon_{2r}(m_A^2 - m_Z^2) \cos^2 2\beta}{\sqrt{(m_A^2 - m_Z^2)^2 + 4m_A^2 m_Z^2 \sin^2 2\beta}} \right)$$

$$\simeq 4v^2 \epsilon_{2r} - \frac{16 m_Z^2}{m_A^2 - m_Z^2} v^2 \frac{\epsilon_{1r}}{\tan\beta} + \mathcal{O}\left(\frac{\epsilon}{\tan^2\beta} \right)$$

- to the charged Higgs mass

$$\delta m_{H^\pm}^2 = 2\epsilon_{2r} v^2$$

Effects on Higgs boson mass



Effects on Higgsinos

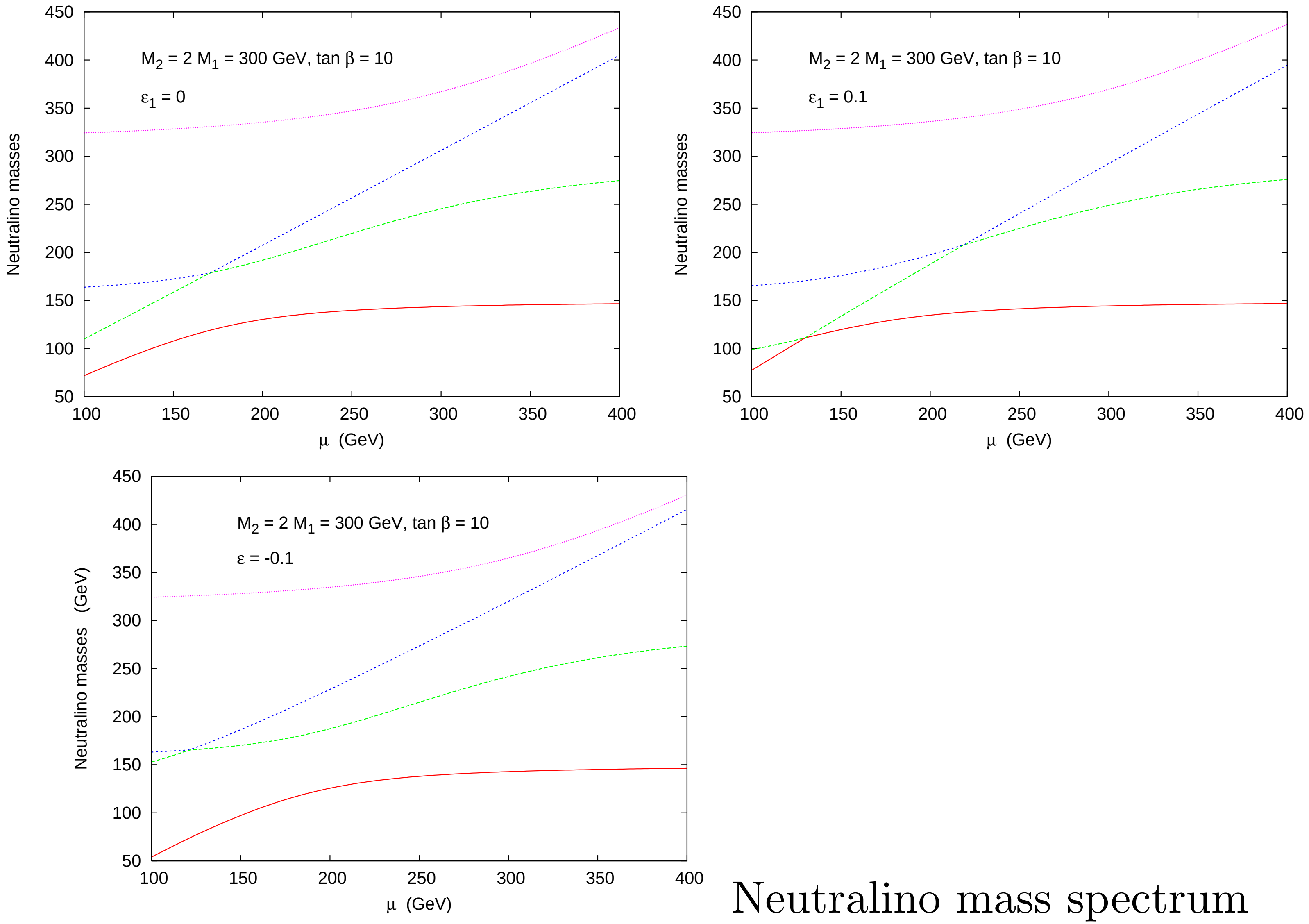
$$\mathcal{L} = -\mu\left(\widetilde{H}_u^+\widetilde{H}_d^- - \widetilde{H}_u^0\widetilde{H}_d^0\right) - \frac{\lambda}{M}\Big[2\left(H_u^+H_d^- - H_u^0H_d^0\right)\left(\widetilde{H}_u^+\widetilde{H}_d^- - \widetilde{H}_u^0\widetilde{H}_d^0\right) + 2\Big(H_u^+\widetilde{H}_d^- - H_u^0\widetilde{H}_d^0\Big)\left(\widetilde{H}_u^+H_d^- - \widetilde{H}_u^0H_d^0\right) + \left(\widetilde{H}_u^+H_d^- - \widetilde{H}_u^0H_d^0\right)^2 + \left(H_u^+\widetilde{H}_d^- - H_u^0\widetilde{H}_d^0\right)^2\Big] + H.c.$$

Modifications to the neutralino mass matrix $M_{\widetilde{N}}$, in the basis of $(\widetilde{B},\ \widetilde{W}^3,\ \widetilde{H}_d^0,\ \widetilde{H}_u^0)$, are

$$M_{\widetilde{N}} = \begin{pmatrix} M_1 & 0 & -m_Z s_W c_\beta & m_Z s_W s_\beta \\ 0 & M_2 & m_Z c_W c_\beta & -m_Z c_W s_\beta \\ -m_Z s_W c_\beta & m_Z c_W c_\beta & \frac{\lambda}{M} v^2 s_\beta^2 & -\mu + \frac{2\lambda}{M} v^2 c_\beta s_\beta \\ m_Z s_W s_\beta & -m_Z c_W s_\beta & -\mu + \frac{2\lambda}{M} v^2 c_\beta s_\beta & \frac{\lambda}{M} v^2 c_\beta^2 \end{pmatrix},$$

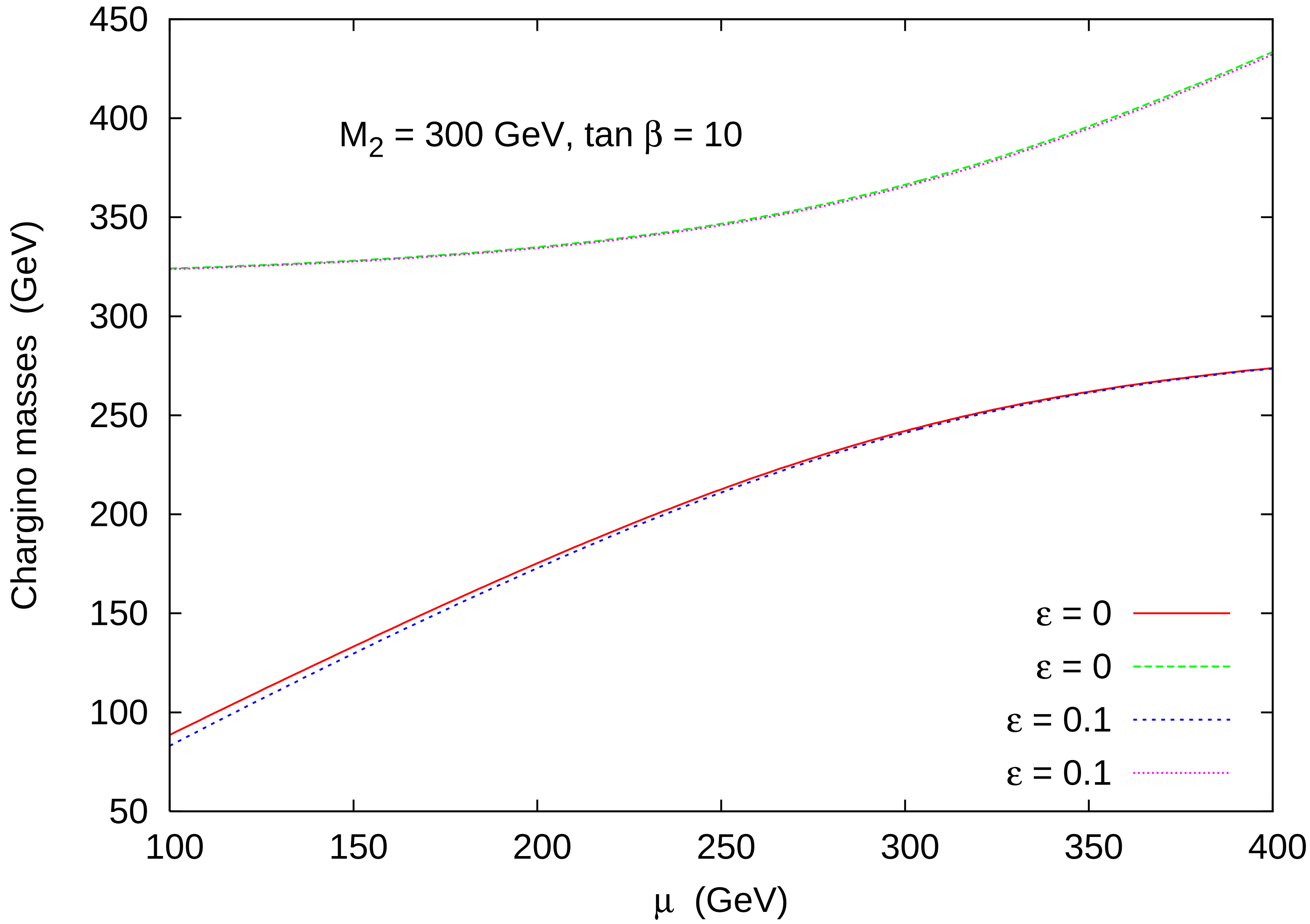
while those for chargino mass matrix are

$$M_{\widetilde{C}} = \begin{pmatrix} M_2 & \sqrt{2} m_W s_\beta \\ \sqrt{2} m_W c_\beta & \mu - \frac{\lambda}{M} v^2 c_\beta s_\beta \end{pmatrix},$$



Neutralino mass spectrum

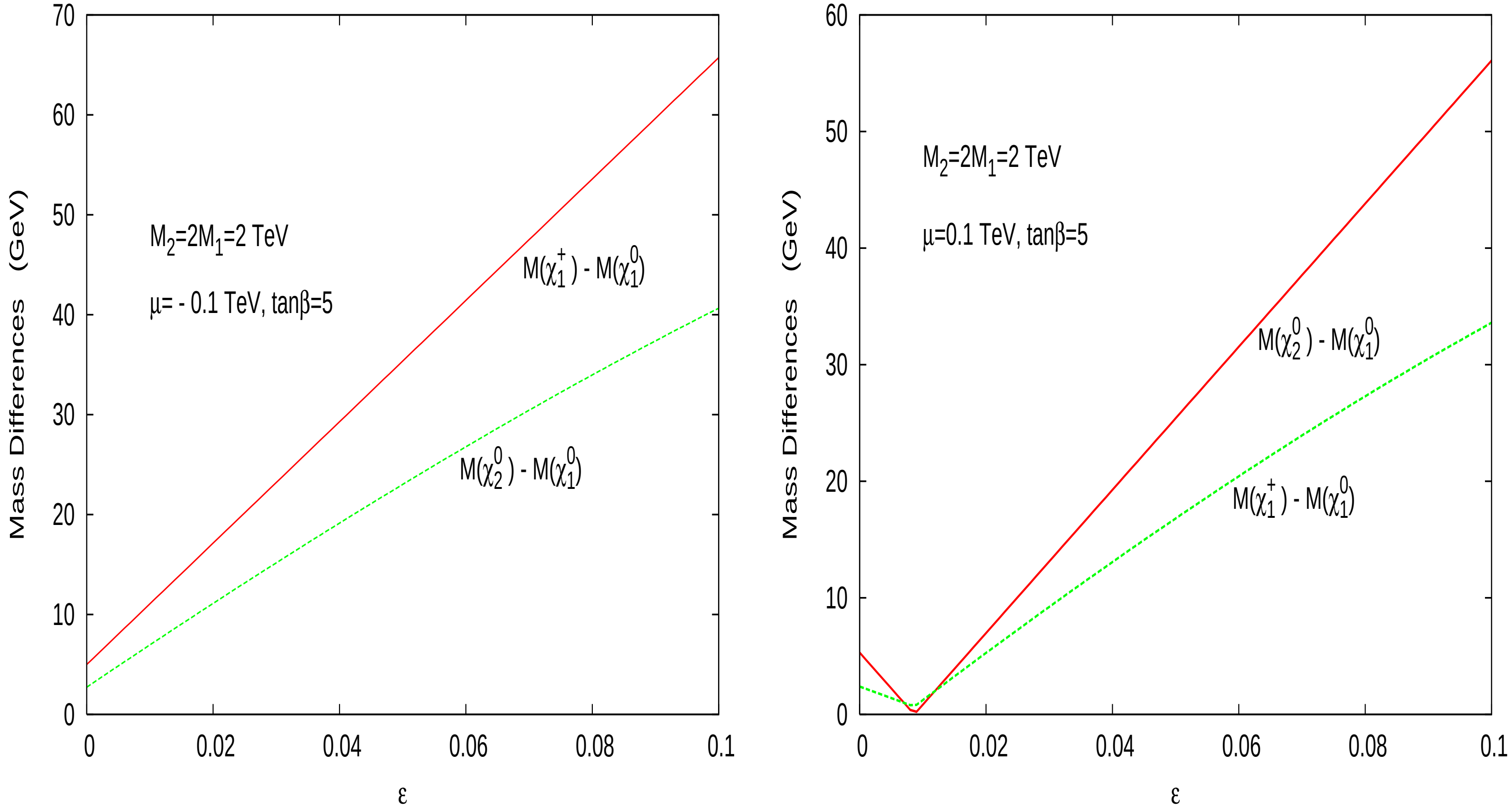
Chargino mass spectrum



Mass Splittings

- In the Higgsino LSP scenario ($\mu \ll M_{1,2}$), there is a high degree of mass degeneracy among $\widetilde{\chi}_1^0$, $\widetilde{\chi}_2^0$, and $\widetilde{\chi}_1^\pm$.
- Experimentally, it is a very difficult challenge to detect the soft leptons or jets in the neutralino and chargino decays.
- Even including the radiative corrections the mass splitting is less a GeV.
- The BMSSM corrections are very sizable. Thus, the experimental detection is easier in the sense that the decay products are more energetic.

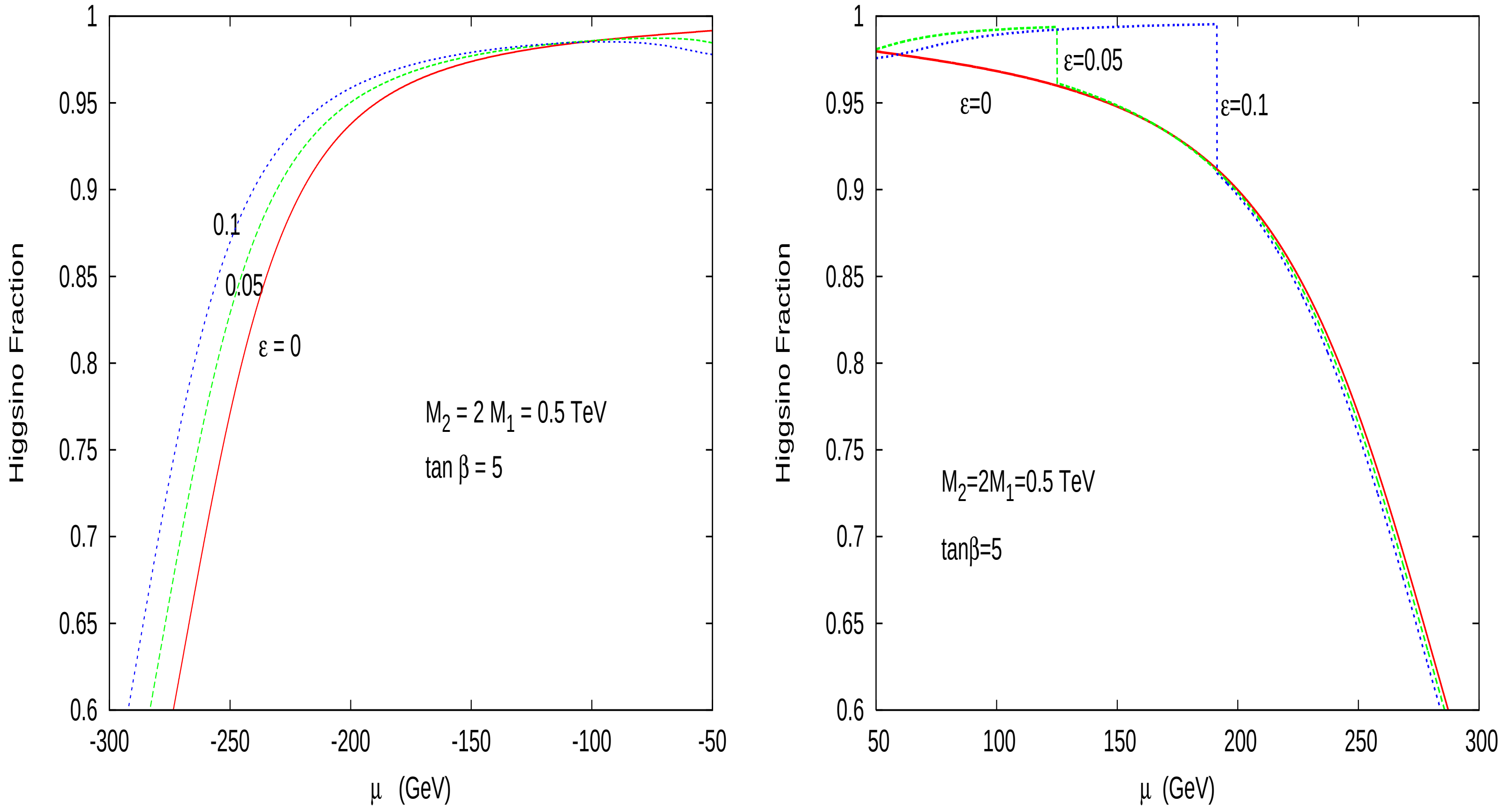
Neutralino chargino mass splittings



Collider Detection

- For the LSP mass around 100 GeV the mass difference between $\widetilde{\chi}_1^0$ and $\widetilde{\chi}_2^0$ is of order $20 - 40$ GeV for $\epsilon = 0.05 - 0.1$,
- The mass difference between $\widetilde{\chi}_1^{\pm}$ and $\widetilde{\chi}_1^0$ is even larger, of order $35 - 65$ GeV for $\epsilon = 0.05 - 0.1$.
- In the pure-Higgsino case ($|\mu| \ll M_1$), the mass differences due to the BMSSM effects are of the order of $|\mu|\epsilon$.
- The decay products of chargino and the second neutralino is hard enough for detection.

Higgsino Fraction



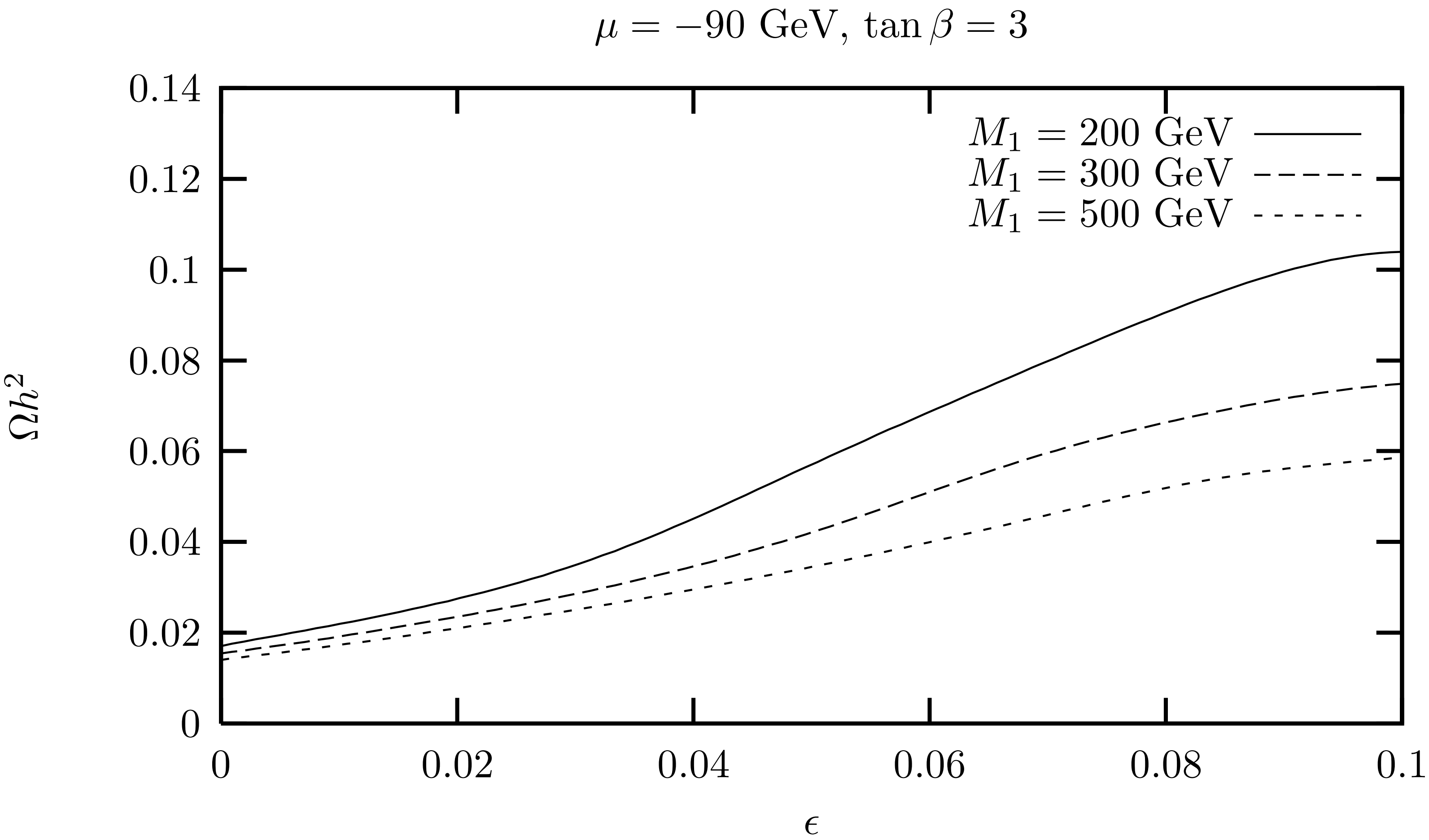
Effects on Higgsino Dark Matter

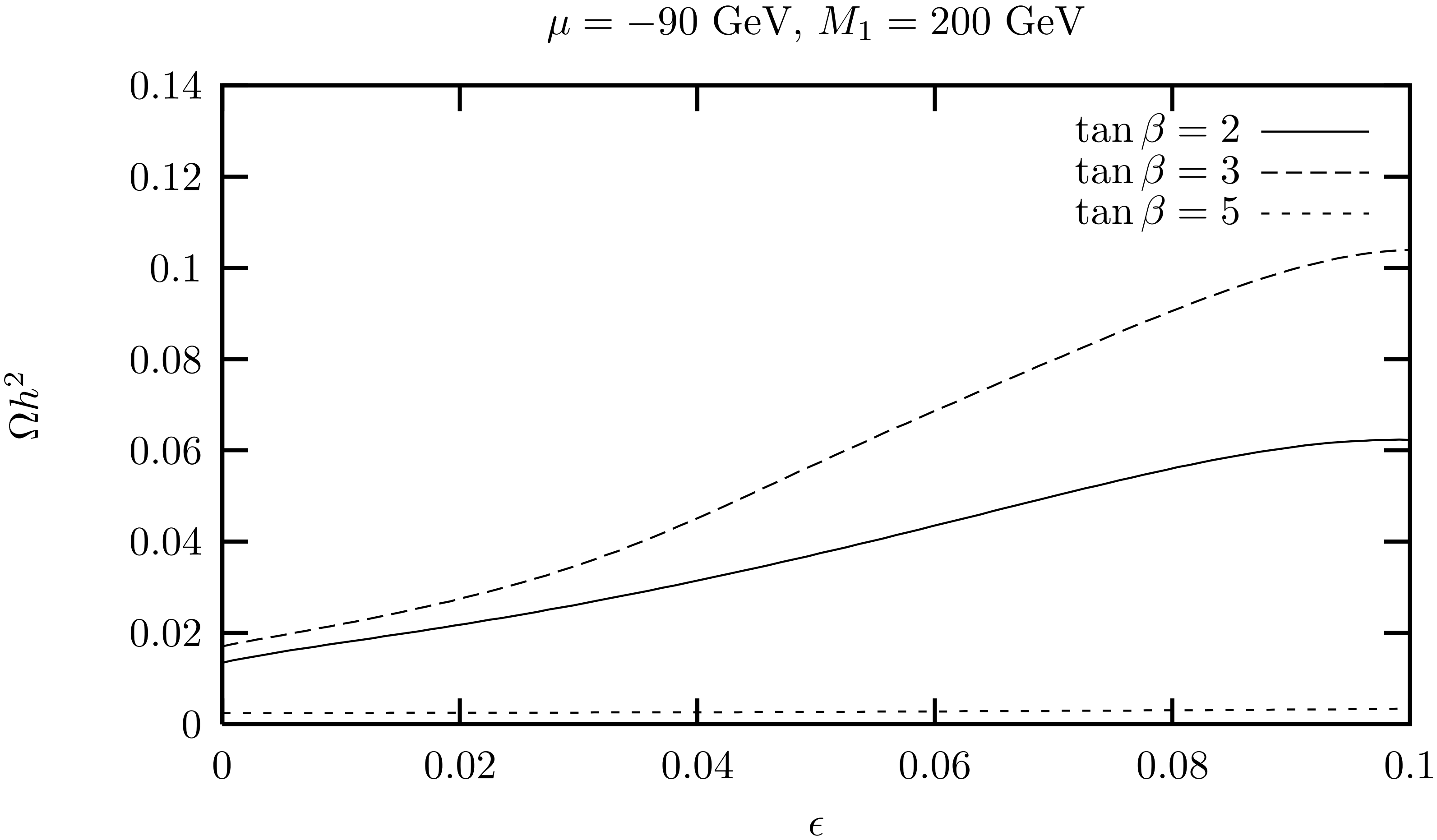
- Since the mass differences of $\Delta M_{\widetilde{\chi}_2^0 - \widetilde{\chi}_1^0}$ and $\Delta M_{\widetilde{\chi}_1^\pm - \widetilde{\chi}_1^0}$ due to the BMSSM corrections increases significantly, the effect of coannihilation will be reduced substantially.

- We use
$$\Omega_{\rm CDM} h^2 \approx \frac{0.1 \text{ pb}}{\langle \sigma_{\rm eff} v \rangle}$$

- With coannihilation the σv is
$$\langle \sigma_{\rm eff} v \rangle = \frac{\sigma_{\widetilde{\chi}_1^0 \widetilde{\chi}_1^0} \, v_{\widetilde{\chi}_1^0 \widetilde{\chi}_1^0} + 2\, \sigma_{\widetilde{\chi}_1^0 \widetilde{\chi}_1^\pm} \, v_{\widetilde{\chi}_1^0 \widetilde{\chi}_1^\pm} \left(1 + \frac{\Delta m_+}{m_{\widetilde{\chi}_1^0}} \right)^{3/2} e^{-\Delta m_+ / T}}{\left[1 + 2 \left(1 + \frac{\Delta m_+}{M_{\widetilde{\chi}_1^0}} \right)^{3/2} e^{-\Delta m_+/T} \right]^2} \, .$$

- For $\sigma_{\widetilde{\chi}_1^0 \widetilde{\chi}_1^0}$ we have considered $\widetilde{\chi}_1^0 \widetilde{\chi}_1^0 \to hh, Z^0 h, Z^0 Z^0, W^+ W^-, f \bar{f}$.
For $\sigma_{\widetilde{\chi}_1^0 \widetilde{\chi}_1^\pm}$ we include $\widetilde{\chi}_1^0 \widetilde{\chi}_1^- \to W^- h^0, W^- Z^0, W^- \gamma, f \bar{f}'$


$\mu = -90$ GeV, $\tan\beta = 3$
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
Ωh^2
0
0.02
0.04
0.06
0.08
0.1
ϵ
$M_1 = 200$ GeV
$M_1 = 300$ GeV
$M_1 = 500$ GeV


$\mu = -90$ GeV, $M_1 = 200$ GeV
$\tan\beta = 2$
$\tan\beta = 3$
$\tan\beta = 5$
Ωh^2
ϵ
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
0.02
0.04
0.06
0.08
0.1

Spin-independent Scattering Cross Section

- Higgsino dark matter is not flavored because of large direct detection rate. Mainly due to the Higgs exchange diagrams.
- Since the Higgs mass increases with ϵ, the scattering cross section decreases substantially.
- It is brought to be under the CDMS limit ($4 - 5 \times 10^{-44}$ cm^2, shown by a simple estimate.

Summary Figure

$\mu = -90$ GeV, $\tan\beta = 3$, $M_1 = 300$ GeV