The Well-Tempered Neutralino

Antonio Delgado
CERN

- Motivation: DM in the MSSM
- The well-tempered Bino/Higgsino
- The well-tempered Bino/Wino
- Conclusions

Work done in collaboration with:
N. Arkani-Hamed & G.F. Giudice

Motivation

- After WMAP data it is well established that there is a component of dark matter in the universe:

$$\Omega_{DM}h^2 \simeq 0.12$$

- It is well known that neutral stable weak interacting particle with mass O(100 GeV) is able to reproduce that value
- The MSSM has a natural candidate for that the lightest neutralino, one sneutrino or the gravitino.

- The sneutrino is not favoured because it annihilates to fast.
- The gravitino only interacts gravitationally so it has to be very light not to overclose the universe.
- The lightest neutralino is normally an admixture of bino, wino and higgsino and is quite easy for it to reproduce Ω_{dm}.

- That was the situation before LEP-II but:

$$M_{\chi^\pm} > 94 \text{ GeV}$$

- So either we live in a tuned part of the parameter space where there are cancelations between the different entries.

- Or soft-masses for gauginos and higgsinos are much larger than mixings.

- Lets study the case for pure states.

- Mass for neutralinos

$$\begin{pmatrix} M_1 & 0 & g'v_1 & g'v_2 \\ 0 & M_2 & gv_1 & gv_2 \\ g'v_1 & gv_1 & 0 & -\mu \\ g'v_2 & gv_2 & -\mu & 0 \end{pmatrix}$$

- Mass for charginos

$$\begin{pmatrix} M_2 & \sqrt{2}gv_2 \\ \sqrt{2}gv_2 & \mu \end{pmatrix}$$

- In the case of LSP Bino since it is a singlet the main co-annihilation cross-section is with sleptons or squarks:

$$\langle \sigma_{\tilde{B}} v \rangle = \frac{3g^4 \tan^4 \theta_W r(1+r^2)}{2\pi m_{\tilde{e}_R}^2 x (1+r)^4}, \quad x \equiv \frac{M_1}{T}, \quad r \equiv \frac{M_1^2}{m_{\tilde{e}_R}^2}$$

$$\Omega_{\tilde{B}} h^2 = 1.3 \times 10^{-2} \left(\frac{m_{\tilde{e}_R}}{100 \text{ GeV}} \right)^2 \frac{(1+r)^4}{r(1+r^2)} \left(1 + 0.07 \log \frac{\sqrt{r} 100 \text{ GeV}}{m_{\tilde{e}_R}} \right)$$

- In the case the LSP is a Higgsino the co-annihilation goes into gauge bosons:

$$\langle \sigma_{eff} v \rangle = \frac{g^4}{512\pi\mu^2}\left(21 + 3\tan^2\theta_W + 11\tan^4\theta_W\right)$$

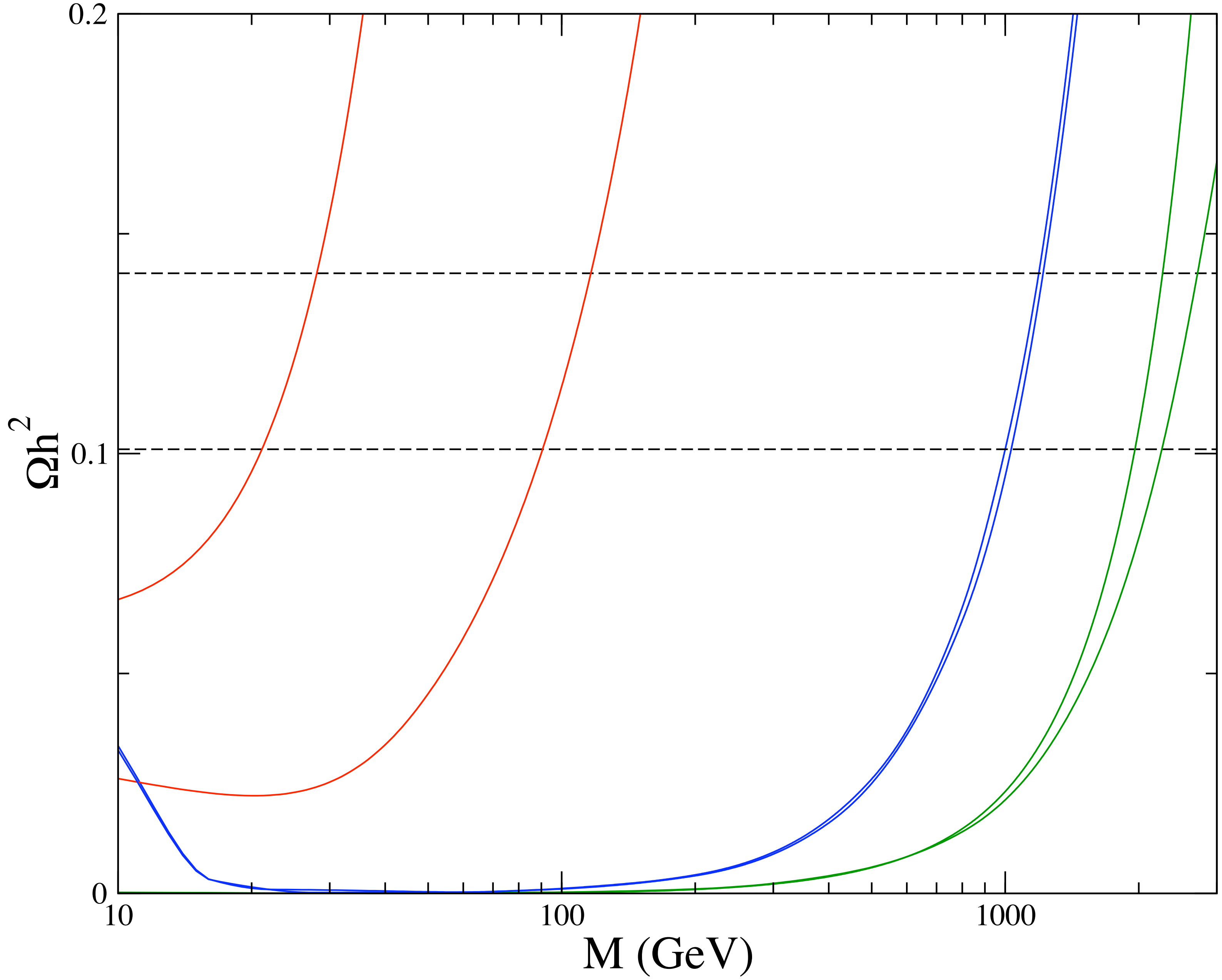
$$\Omega_{\tilde{H}} h^2 = 0.10 \left(\frac{\mu}{1\ \mathrm{TeV}}\right)^2$$

- Finally for the case when the LSP is a Wino the co-annihilation is also through gauge bosons:

$$\langle \sigma_{eff} v \rangle = \frac{3g^4}{16\pi M_2^2}$$

$$\Omega_{\tilde{W}} h^2 = 0.13 \left(\frac{M_2}{2.5 \text{ TeV}} \right)^2$$

- We can plot the previous formulae:



- As can be seen from the previous figure we have the following two conclusions for pure states:
  - ✦ Either we live with a fine-tuned bino almost rulled-out
  - ✦ Or we have a situation untestable at LHC
- A possible way-out is to consider mixings that will allow for a faster decay of the bino

The well-tempered Bino/ Higgsino

- Lets integrate out the wino:

$$\mathcal{M} = \begin{pmatrix} M_1 & -\frac{s_\beta + c_\beta}{\sqrt{2}} s_W M_Z & \frac{s_\beta - c_\beta}{\sqrt{2}} s_W M_Z \\ -\frac{s_\beta + c_\beta}{\sqrt{2}} s_W M_Z & \mu & 0 \\ \frac{s_\beta - c_\beta}{\sqrt{2}} s_W M_Z & 0 & -\mu \end{pmatrix}$$

$$-\frac{M_W^2}{2M_2} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 + s_{2\beta} & c_{2\beta} \\ 0 & c_{2\beta} & 1 - s_{2\beta} \end{pmatrix} + \mathcal{O}\left(\frac{1}{M_2^2}\right)$$

- The **eigenvalues** are given by:

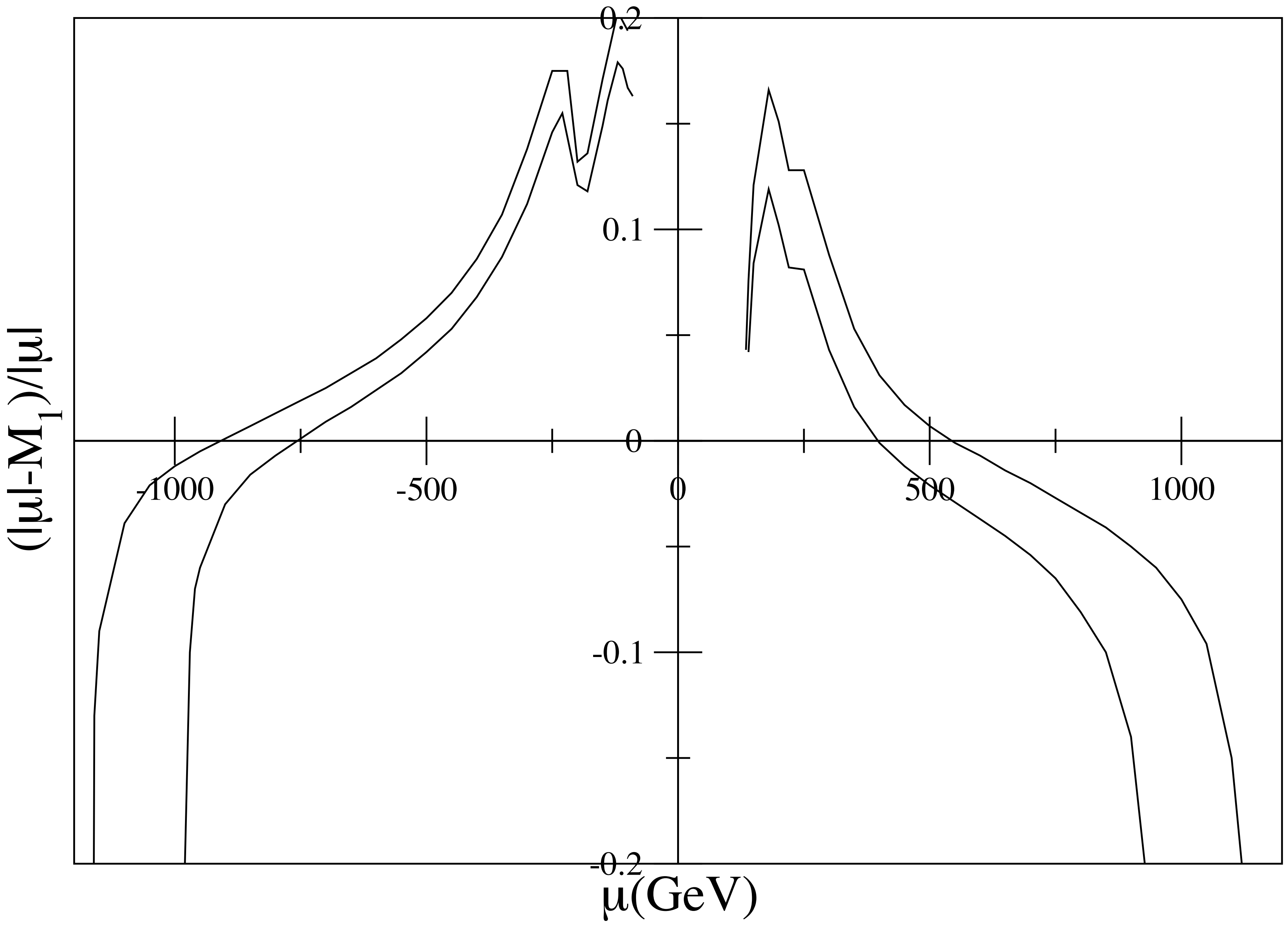
$$M_1 + \theta_\pm^2\,(M_1 \mp \mu)\,, \qquad \pm\,\mu - \theta_\pm^2\,(M_1 \mp \mu)\,, \qquad \mp\,\mu$$

$$\theta_\pm = \frac{(s_\beta \pm c_\beta) s_W M_Z}{\sqrt{2}(\mu \mp M_1)}$$

- And the **mixings**:

$$N = \begin{pmatrix} 1 - \frac{\theta_+^2}{2} - \frac{\theta_-^2}{2} & \theta_+ & \theta_- \\ -\theta_+ & 1 - \frac{\theta_+^2}{2} & -\theta_+\theta_- \frac{(M_1+\mu)}{2\mu} \\ -\theta_- & \theta_+\theta_- \frac{(M_1-\mu)}{2\mu} & 1 - \frac{\theta_-^2}{2} \end{pmatrix}$$

- The relic density is dominated by the co-annihilation of the three neutral states and the charged one into gauge bosons:



The well-tempered Bino/Wino

- Lets integrate out the higgsino:

$$\mathcal{M} = \begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix} - s_{2\beta}\frac{M_Z^2}{\mu}\begin{pmatrix} s_W^2 & -s_W c_W \\ -s_W c_W & c_W^2 \end{pmatrix} + \mathcal{O}\left(\frac{1}{\mu^2}\right)$$

- The eigenvalues:

$$m_{\chi_1} = M_1\left[1 - \Delta\left(t_W\theta + \theta^2 + t_W\delta\right)\right]$$

$$m_{\chi_2} = M_1\left[1 + \Delta\left(1 - \frac{\theta}{t_W} + \theta^2 - \frac{\delta}{t_W}\right)\right]$$

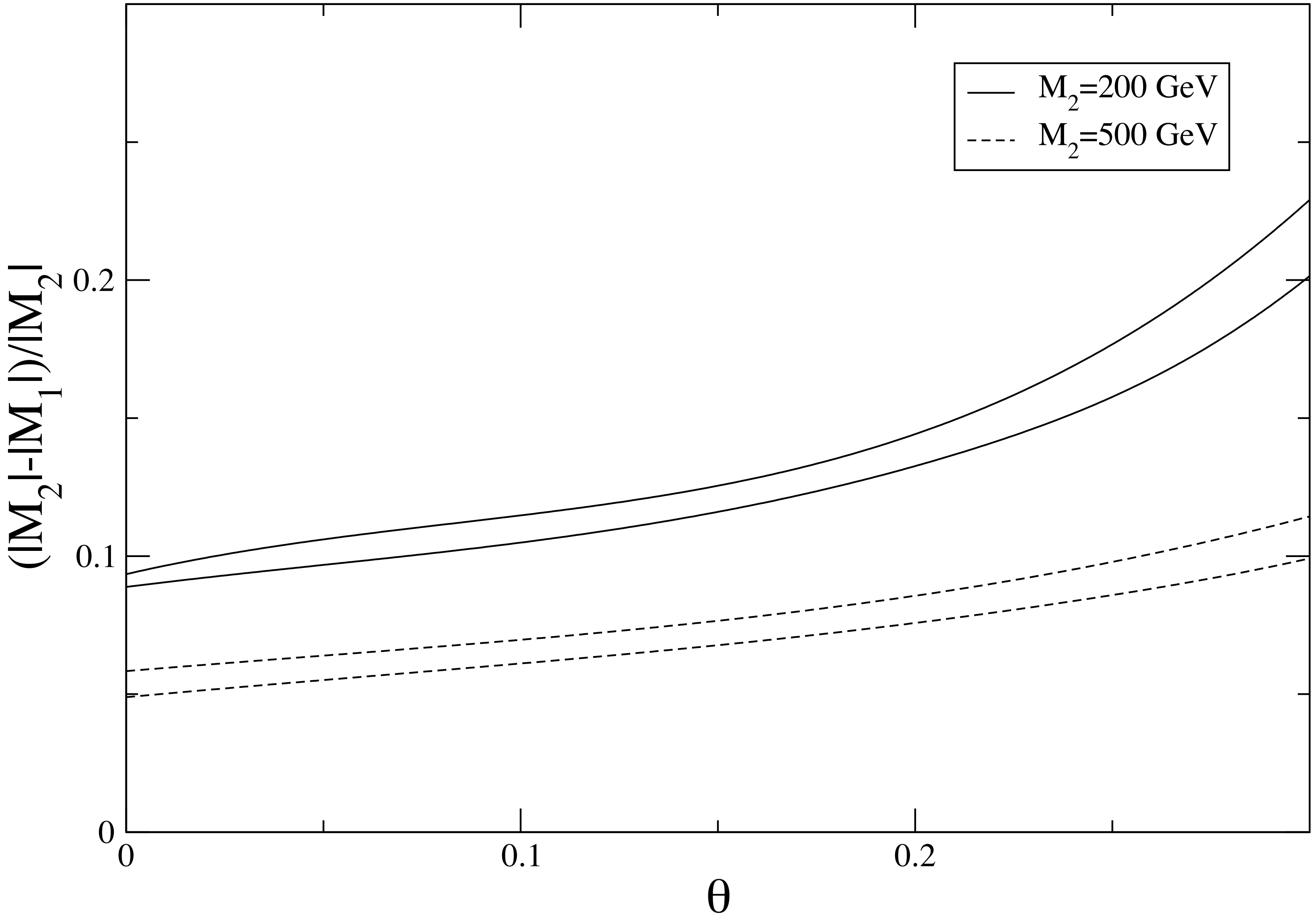
$$m_{\chi^+} = M_1\left[1 + \Delta\left(1 - \frac{\theta}{t_W} - \frac{\delta}{t_W}\right)\right]$$

- And mixing:

$$-N_{12} = \theta + \left(\frac{1}{t_W} - t_W\right)\theta^2 + \delta$$

$$\theta \equiv \frac{s_{2W}\, s_{2\beta} M_Z^2}{2\mu\Delta M_1}, \qquad \delta \equiv \frac{s_{2W} M_Z^2}{2\mu^2\Delta}, \qquad \Delta \equiv \frac{M_2 - M_1}{M_1}$$

- The relic density is dominated by the co-annihilation of the two neutral states and the charged one into gauge bosons:



- We can try to make a connection with UV soft term supposing $\mu > M_1, M_2$.

- If we integrate-out the Higgsinos we have the following RGEs:

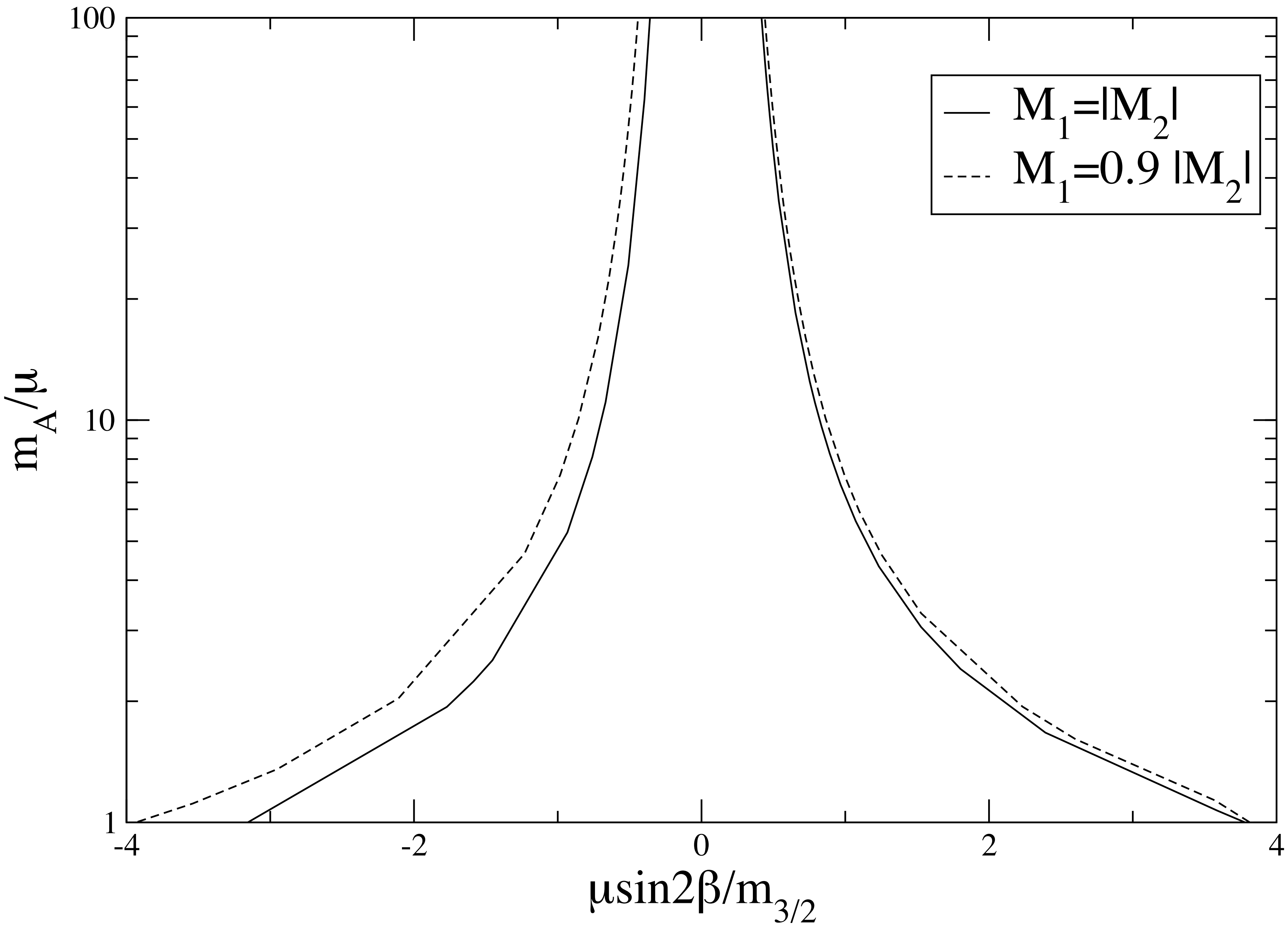
$$M_1 = \quad M_1(m_A^2)\left[1 + \tfrac{\alpha}{8\pi c_W^2}\left(11\log\tfrac{\tilde{m}_q^2}{m_A^2} + 9\log\tfrac{\tilde{m}_\ell^2}{m_A^2} + \log\tfrac{\mu^2}{m_A^2}\right)\right] + \tfrac{\alpha}{8\pi c_W^2}\mu s_{2\beta} f\left(\tfrac{\mu^2}{m_A^2}\right)$$

$$M_2 = \quad M_2(m_A^2)\left[1 + \tfrac{\alpha}{8\pi s_W^2}\left(9\log\tfrac{\tilde{m}_q^2}{m_A^2} + 3\log\tfrac{\tilde{m}_\ell^2}{m_A^2} + \log\tfrac{\mu^2}{m_A^2} - 12\log\tfrac{M_2^2}{m_A^2}\right)\right] + \tfrac{\alpha}{8\pi s_W^2}\mu s_{2\beta} f\left(\tfrac{\mu^2}{m_A^2}\right)$$

$$f(x) = \frac{2\log x}{1-x}$$

- If we supposed AMSB boundary conditions:

$$M_1(m_A) = \frac{11\alpha(m_A)}{4\pi c_W^2} m_{3/2}, \;\; M_2(m_A) = \frac{\alpha(m_A)}{4\pi s_W^2} m_{3/2}$$



Conclusions

- Although DM is considered one of the main successes of the MSSM, after LEP-II is no longer true that it can be achieved in a natural way for LHC.
- Either the Bino tends to overclose the universe or Higgsinos and Winos are to massive to be seen.
- The well-tempered solutions present different situations where observable DM candidate exists.
- The Bino-Wino has an interesting realization.