THE MSSM FROM SS BREAKING

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- Tree-level masses
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- Supersymmetric spectrum
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Based on work done in collaboration with D. Diego and G.v. Gersdorff

Introduction

- The origin of supersymmetry breaking remains as the main unknown ingredient in supersymmetric theories
- Supersymmetry breaking is known to be required to trigger EWSB in the MSSM
- The phenomenology of the MSSM depends to a large extent on the way supersymmetry is broken

Introduction

- Extra dimensions provide new mechanisms to break symmetries: supersymmetry can be broken non-locally by the Scherk-Schwarz (finite) mechanism
- In models with SS supersymmetry breaking (no-scale models) anomaly mediation will alway be subdominant
- If vectors propagate in the bulk and quarks and leptons are localized on a supersymmetry preserving 3-brane, the SS supersymmetry breaking is GAUGINO MEDIATED: flavor violating interactions suppressed [L. Randall, R. Sundrum, hep-ph/9810155]

Introduction

- This asymmetry where matter fields are localized on 3-branes and the gauge sector propagates in the bulk of extra dimensions typically appears in INTERSECTING BRANE constructions
- Gauge bosons are open string with ends on the same stack of branes: they propagate on the extra dimensions of the brane
- Quarks and leptons are open strings with ends on different branes: they propagate on their intersection

Introduction

- The phenomenology of such models depends to a large extent on the Higgs sector
- Since the top is localized the stop mass is generated at one-loop and EWSB should proceed at two-loop
- There are competing effects
  - The one-loop gauge contribution is positive

$$\Delta_G^{(1)} m_h^2 > 0$$

  - The two-loop top contribution is negative

$$\Delta_Y^{(2)} m_h^2 < 0$$

Introduction

- The two-loop effective potential was analyzed in detail [R. Barbieri et al., hep-ph/0205280] who concluded that EWSB does NOT take place

$$\boxed{\Delta_G^{(1)} m_h^2 + \Delta_Y^{(2)} m_h^2 > 0}$$

- If the Higgs superfields $\mathcal{H}_{u,d}$ are strictly localized in one boundary their supersymmetry breaking masses are equal to zero and the previous criticism applies

Introduction

- Higgses have to propagate in the bulk in two hypermultiplets

$$\mathbb{H}^a = (\mathcal{H}, \bar{\mathcal{H}}^c)^a$$

transforming as a doublet of $SU(2)_H$

- If the Higgses are strictly delocalized one of them (the SM-like) is massless and the other is very massive ($\sim 1/R^2$). Still the previous criticism applies for the light Higgs.
- A way out is if Higgses are quasi-localized by a localizing mass M and tree-level masses are tachyonic (and equal)

Introduction

- Localization is controlled by the parameter

$$\epsilon = e^{-\pi MR}$$

- For $\epsilon \to 1$ Higgses are strictly delocalized
- For $\epsilon \to 0$ Higgses are strictly localized
- For $MR > 1$ ($\epsilon \ll 1$) the tree-level masses $(m_h^0)^2 \sim M^2\epsilon^2$ are comparable in size to radiatively generated masses

Introduction

- In a wide range of the parameter space the soft tree-level masses are tachyonic

$$(m_h^0)^2 < 0$$

- If so they can compensate (or cancel) the positive contribution from the gauge sector and (negative) two-loop corrections can trigger EWSB

$$\Downarrow$$

TREE-LEVEL ASSISTED RADIATIVE BREAKING

The Higgs sector

The bulk Lagrangian is ($N = 1$ superfields)

$$\int d^4\theta \, \frac{\mathcal{T} + \bar{\mathcal{T}}}{2} \{ \bar{\mathcal{H}} \exp(T_a V^a) \, \mathcal{H} + \mathcal{H}^c \exp(-T_a V^a) \, \bar{\mathcal{H}}^c \}$$

$$- \int d^2\theta \, \{ \mathcal{H}^c (\partial_y - \mathcal{M}\mathcal{T}) \mathcal{H} + h.c. \}$$

where the localizing mass term is

$$\mathcal{M} = M \, \vec{p} \cdot \vec{\sigma} \, .$$

and $\vec{p}$ is a bulk unit vector in space $su(2)_H$ [$\mathcal{T}$ is radion superfield]

The Higgs sector

- The boundary Lagrangian is

$$\int d^2\theta \, \frac{1}{2} \left(\mathcal{H}^c[1 + \vec{s}_f \cdot \vec{\sigma}]\mathcal{H} + h.c.\right)\Big|_{y=0,\pi}$$

  and $\vec{s}_f$ is again a unit vector in $su(2)$

- The boundary conditions are obtained from the variational principle. In superfield language they are

$$(1 + \vec{s}_f \cdot \vec{\sigma})\mathcal{H} = 0$$

$$\mathcal{H}^c(1 - \vec{s}_f \cdot \vec{\sigma}) = 0$$

The Higgs sector

Mass eigenvalues and eigenfunctions depend on the following parameters

- The SS parameter that breaks supersymmetry

$$\mathcal{T} = R + 2\,\omega\,\theta^2$$

- The angles between $\vec{p}$ and $\vec{s}_f$

$$c_f = \vec{s}_f \cdot \vec{p}\,(f = 0, \pi)$$

- The angle between $\vec{s}_0$ and $\vec{s}_\pi$

$$\cos(2\pi\tilde{\omega}) = \vec{s}_0 \cdot \vec{s}_\pi$$

The Higgs sector

- By assuming that $Mc_0 > 0$, for

$$\epsilon \equiv \exp(-\pi c_0 M R) \ll 1$$

there are two 4D modes whose wavefunctions localize towards the boundary at $y = 0$

$$H^1(x,y) = \sqrt{c_0 M}\, \exp(-c_0 M R y) H_u(x) + \mathcal{O}(\epsilon)$$

$$H_2^c(x,y) = \sqrt{c_0 M}\, \exp(-c_0 M R y) H_d(x) + \mathcal{O}(\epsilon)$$

- There are also two modes localizing at $y = \pi$ which can be made heavy

Tree level masses

- The tree-level mass lagrangian is as in the MSSM

$$-(\mu^2 + m_{H_u}^2)\,|H_u|^2 - (\mu^2 + m_{H_d}^2)\,|H_d|^2$$

$$+m_3^2\,(H_u \cdot H_d + h.c.)$$

- The quartic potential is

$$V_{\rm quartic} = \frac{g^2 + g'^2}{8}(|H_u|^2 - |H_d|^2)^2 + \mathcal{O}(\epsilon^2)$$

after integrating out the adjoint chiral multiplet Σ

Tree level masses

- The soft mass terms are

$$m_{H_u}^2 = m_{H_d}^2 = 4M^2 \sin^2(\pi\omega)(1 - \tan^2(\pi\tilde{\omega}))\, \epsilon^2$$

$$m_3^2 = 4M^2 \sin(2\pi\omega) \tan(\pi\tilde{\omega})\, \epsilon^2$$

- Even if $M \gg m_Z$, if $\epsilon \ll 1$ it is possible that $M^2\epsilon^2 \sim m_Z^2$ and help for EWSB
- Notice that [To EWSB]

$$m_{H_u}^2 = m_{H_d}^2$$

so that even if they are negative they wouldn't trigger EWSB with stable D-flat directions

Tree level masses

- The Higgsino Dirac mass is

$$\mu^2 = s_0^2 M^2 + \mathcal{O}(s_0^2 \epsilon^2)$$

- It is required that $s_0 \sim m_Z/M$ for EWSB
- For $M \sim M_c \equiv 1/R \sim$ few TeV the parameter $s_0 = 0.1 - 0.01$
- This (10-1%) μ-problem: why

$$\mu \ll M$$

is less acute than the MSSM one: why

$$\mu \ll \Lambda$$

EWSB

- SUSY breaking will predominantly be mediated by one-loop gaugino loops
- Squark masses will be dominated by the contribution from the gluinos

$$\Delta m_{\tilde{t}}^2 = \frac{2\, g_3^2}{3\pi^4}\, M_c^2\, f(\omega),\;\; f(\omega) \equiv \sum_{k=1}^{\infty} \frac{\sin(\pi k \omega)^2}{k^3}$$

- Electroweak gauginos provide

$$\Delta_G^{(1)} m_{H_{u,d}}^2 = \frac{3g^2 + g'^2}{8\pi^4}\, M_c^2 f(\omega)$$

EWSB

- Furthermore there is a sizable two-loop contribution to the Higgs soft mass terms coming from top-stop loops with the one-loop generated squark masses
- This contribution can be estimated in the large logarithm approximation by just plugging the one-loop squark masses in the one-loop effective potential generated by the top-stop sector

$$\Delta_Y^{(2)} m_{H_u}^2 = \frac{3y_t^2}{8\pi^2} \Delta m_{\tilde{t}}^2 \log \frac{\Delta m_{\tilde{t}}^2}{Q^2}\bigg|_{Q=\omega M_c}$$

EWSB

- EWSB occurs in a very peculiar and interesting way [Back to tree-level]
- The tree-level mass $m_{H_u}^2$ is negative for values of $\tilde{\omega} > 1/4$
- There can be a (total or partial) cancellation between the tree-level and one-loop contributions to the Higgs masses

$$m_{H_u}^2 + \Delta_G^{(1)} m_{H_u}^2 \simeq 0$$

- The negative two-loop corrections $\Delta_Y^{(2)} m_{H_u}^2$ will easily trigger EWSB [To fine tuning]

Fine-tuning

- Due to the smallness of the SUSY breaking scale and the extreme softness of the SS mechanism the fine-tuning is much smaller than in the MSSM
- The Z mass from the minimization conditions of the potential in the limit $1 \ll \tan^2\beta \ll m_t^2/m_b^2$

$$\frac{m_Z^2}{2} = -(\mu^2 + m_{H_u}^2 + \Delta_G^{(1)} m_{H_u}^2 + \Delta_Y^{(2)} m_{H_u}^2)$$

- Consider the fundamental parameters $M_i = \mu, m_{H_u}, M_c$

Fine-tuning

- In terms of these fundamental parameters

$$m_Z^2 = -2\mu^2 - 2m_{H_u}^2 - \kappa M_c^2$$

where typically $\kappa \sim 10^{-3}$

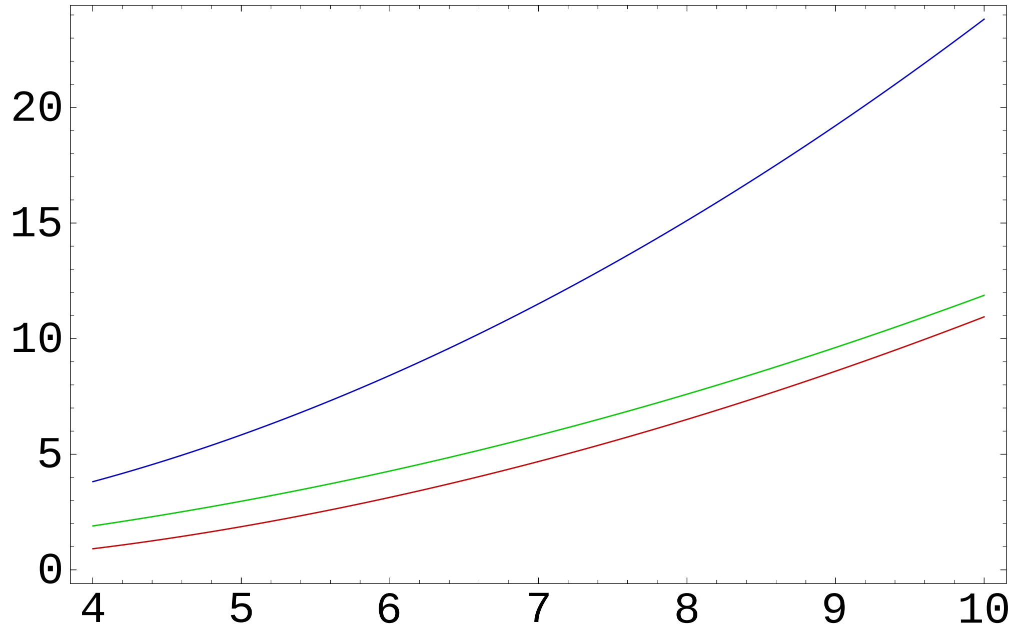
- Consider the sensitivity parameters

$$\Delta_{M_i} = \left| \frac{M_i^2}{m_Z^2} \frac{\partial m_Z^2}{\partial M_i^2} \right|$$

- The sensitivity with respect to M_c can be translated in sensitivity with respect to the gluino mass $M_{\tilde{g}} = \omega M_c$

Fine tuning

[Back to EWSB]



Sensitivity parameters as functions of M_c in TeV ($\omega = 0.45$, $\tilde{\omega} = 0.35$, $M = 1.65 M_c$). From top to bottom $\Delta_{m_{H_u}}$ (blue line), Δ_{M_c} (green line) and Δ_μ (red line)

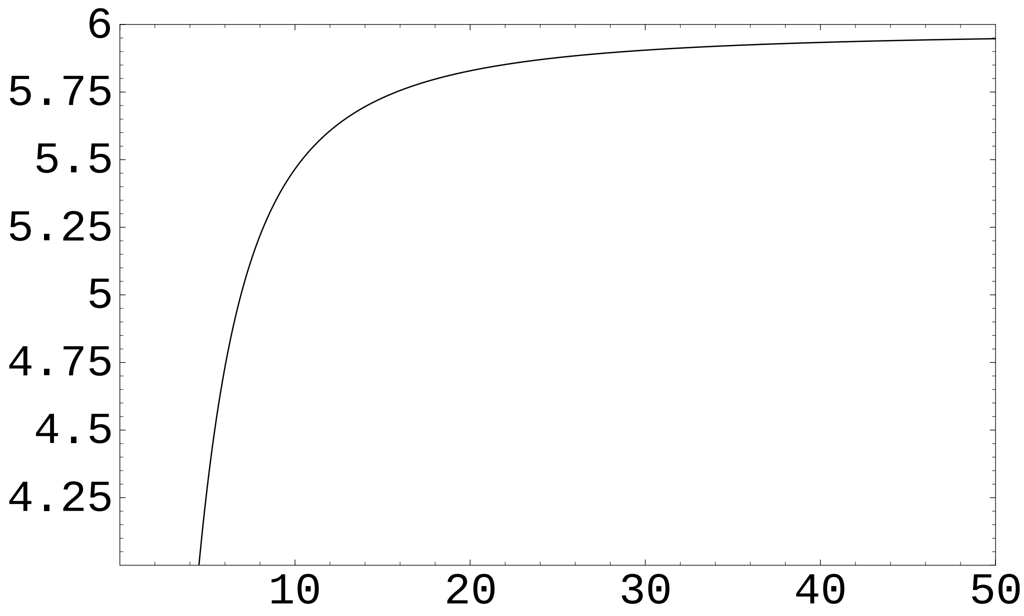
Fine-tuning

- The largest sensitivity appears to be with respect to the parameter m_{H_u}.
- In fact for $M_c = 6.6$ TeV ($M_{\tilde{g}} \sim 3$ TeV) the required amount of fine-tuning is $\sim 10\%$ while for larger values of M_c the fine-tuning naturally increases quadratically.
- In the MSSM the Z mass squared is proportional to $M_{\tilde{g}}^2$ but with a much larger coefficient $\mathcal{O}(1)$ due to large logarithms $\log m_Z/m_{\mathrm{GUT}}$

10% $\Leftrightarrow M_{\tilde{g}} \sim 100$ GeV

Supersymmetric spectrum

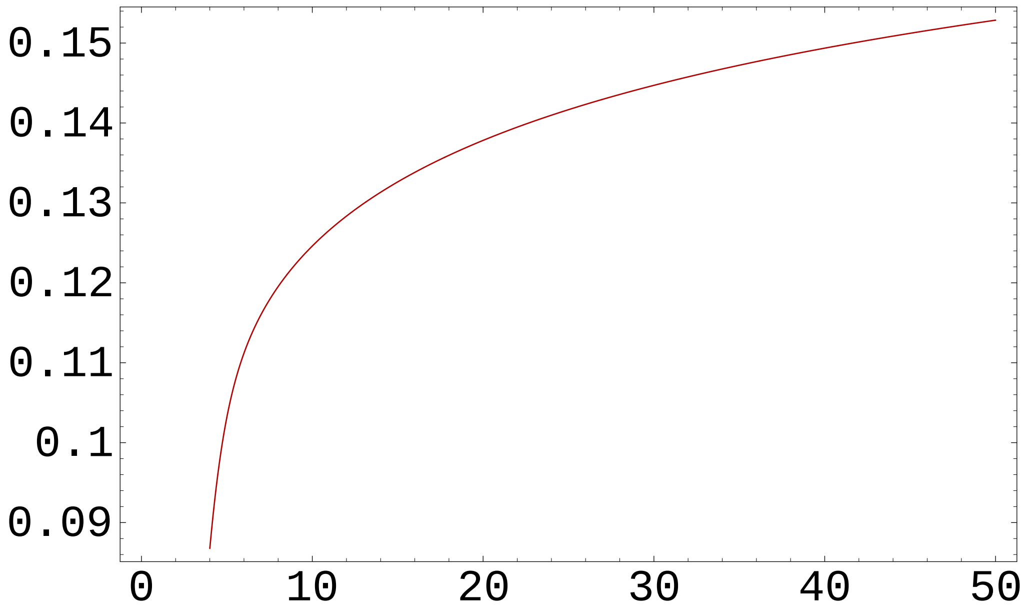
The minimization conditions provide predictions of $\tan\beta$ and μ as functions of M_c



Prediction of $\tan\beta$ for the case $\omega = 0.45$, $\tilde{\omega} = 0.35$, $M = 1.65 M_c$ as a function of the compactification scale M_c in TeV

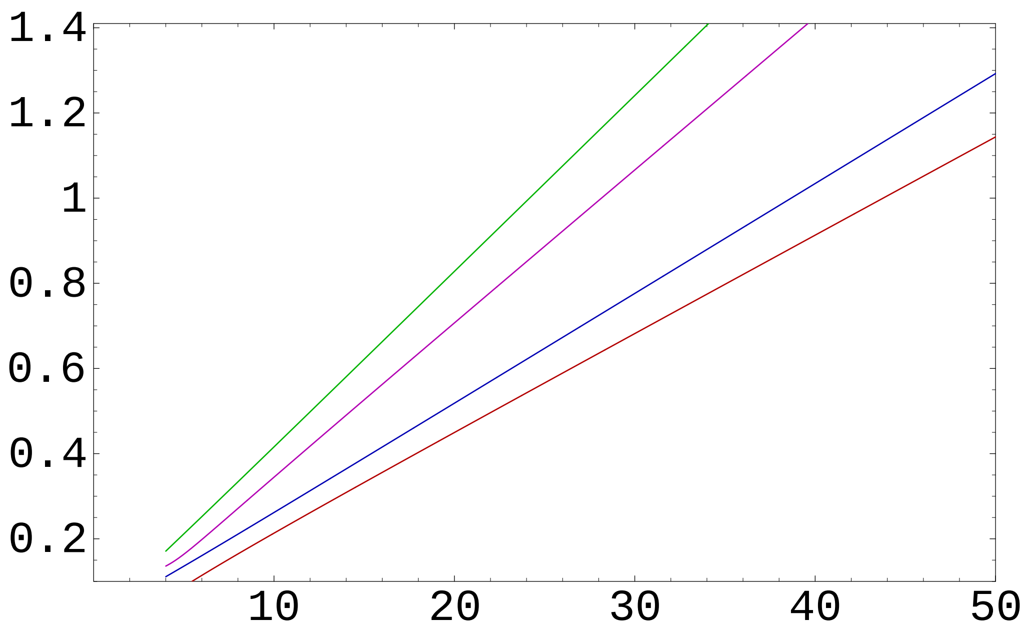
Supersymmetric spectrum

Experimental bound $m_{h^0} > 114.5$ GeV for
$M_c > 6.5$ TeV



SM-like Higgs mass m_h. All masses are in TeV

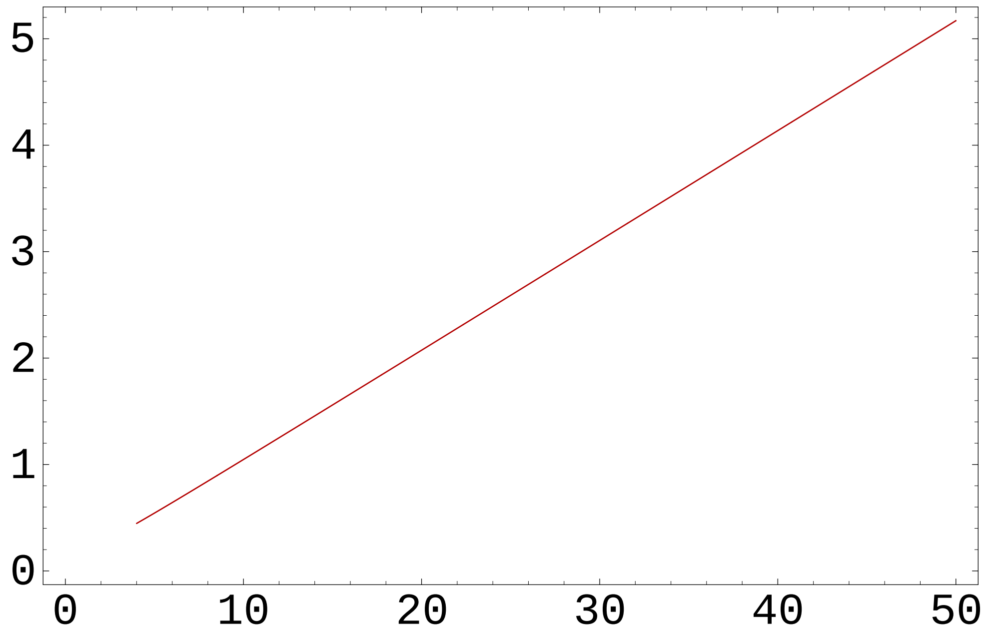
Supersymmetric spectrum



From top to bottom: left-handed sleptons $m_{\tilde{\ell}_L}$ (green line), heavy neutral Higgs $m_H \simeq m_A$ (magenta line), right-handed sleptons $m_{\tilde{e}_R}$ (blue line) and neutralinos $m_{\tilde{\chi}^0} \simeq \mu$ (red line). All masses are in TeV

Supersymmetric spectrum

[To DM]



The squark masses $m_{\tilde{q}}$. All masses are in TeV

$$(m_{\tilde{q}_L},\, m_{\tilde{u}_R},\, m_{\tilde{d}_R},\, m_{\tilde{\ell}_L},\, m_{\tilde{e}_R}) \simeq$$

$$(0.110,\, 0.103,\, 0.102,\, 0.042,\, 0.025) \sin \pi\omega M_c$$

Supersymmetric spectrum

- To complete the supersymmetric spectrum gauginos have a mass given by

$$M_{1/2} = \omega M_c$$

- Higgsinos, charginos and neutralinos, have a mass approximately equal to μ
- They are quasi-degenerate in mass

$$\frac{\Delta m_{\tilde{\chi}}}{m_W} \equiv \frac{m_{\tilde{\chi}^\pm} - m_{\tilde{\chi}^0}}{m_W} \simeq (0.35 + 0.65 \sin 2\beta) \frac{m_W}{M_{1/2}}$$

- For $M_c \sim 10$ TeV, $\Delta m_{\tilde{\chi}} \sim 1$ GeV

Dark Matter

- Neutralino is the LSP and the lightest neutralino is the candidate to Cold Dark Matter
- The recent WMAP results

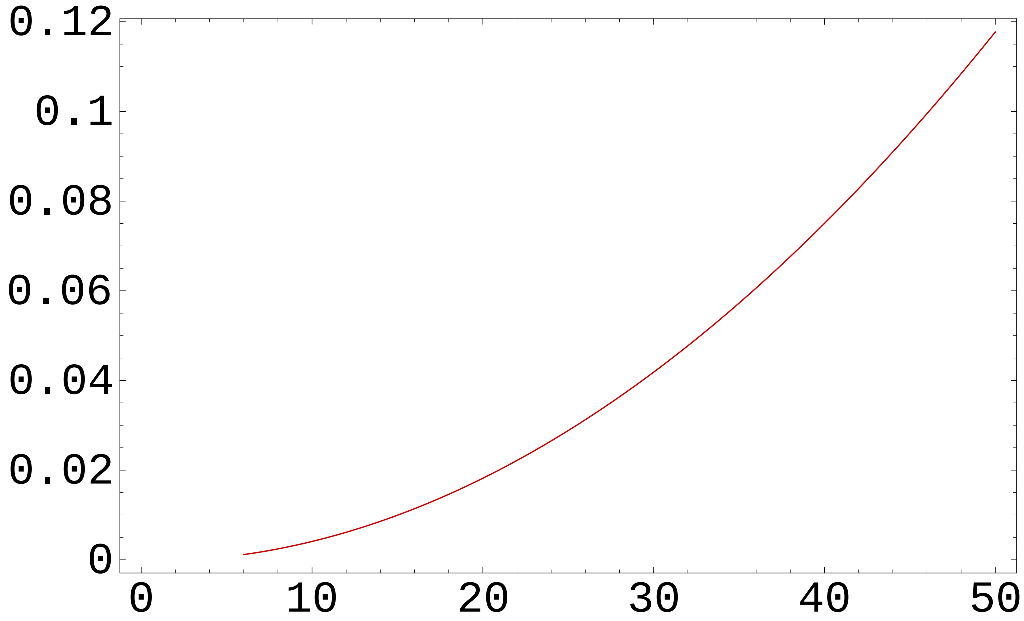
$$0.114 < \Omega_{\tilde{\chi}^0} h^2 < 0.134$$

- In the considered class of models

$$\Omega_{\tilde{\chi}^0} h^2 \simeq 0.09 \, (\mu / TeV)^2$$

Dark Matter

[Back to fine tuning]



$\Omega_{\tilde{\chi}^0} h^2$ as a function of M_c in TeV

WMAP$\Rightarrow$ $M_{\tilde{g}} \sim 20$ TeV

Conclusions

The main features of these models are:

- Matter is localized in a 3-brane and the MSSM Higgses are quasi-localized
- Supersymmetry is broken by the Scherk-Schwarz mechanism
- Models are of "no-scale" type and then no anomaly mediated supersymmetry breaking occurs at tree-level
- No quadratic or linear sensitivity on the cutoff Λ of Higgs masses

Conclusions

- Gauginos are the heaviest supersymmetric particles (they are in the TeV or multi-TeV region)
- Supersymmetry breaking is mediated by gauginos to the observable sector and flavor-changing neutral currents are naturally suppressed
- Squarks and sleptons acquire radiative masses from gluinos and electroweak gauginos, respectively
- EWSB is triggered by tachyonic tree-level masses and two-loop radiative corrections

Conclusions

- The fine-tuning problems of the MSSM can almost entirely be avoided. (For instance in our model a gluino around 3 TeV mass require a modest 10% fine-tuning)
- Higgsinos are the lightest supersymmetric particles (with a mass in the sub-TeV region). Charged and neutral Higgsinos are almost degenerate with mass splittings ~ 1 GeV
- The LSP is a neutralino which is a good candidate to Dark Matter