The MSSM from extra dimensions

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Johns Hopkins 30th Workshop GGI, Florence June 8, 2006

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Introduction

- The origin of supersymmetry breaking remains as the main unknown ingredient in supersymmetric theories
- On the one hand, supersymmetry breaking is known to be required to trigger EWSB in the MSSM: the phenomenology of the MSSM depends on the way supersymmetry is broken
- On the other hand, a generic problem of supersymmetric theories is: why do squark masses conserve flavor? Generically in 4D $\Rightarrow$ Gauge mediated and/or anomaly mediated SUSY breaking

Introduction

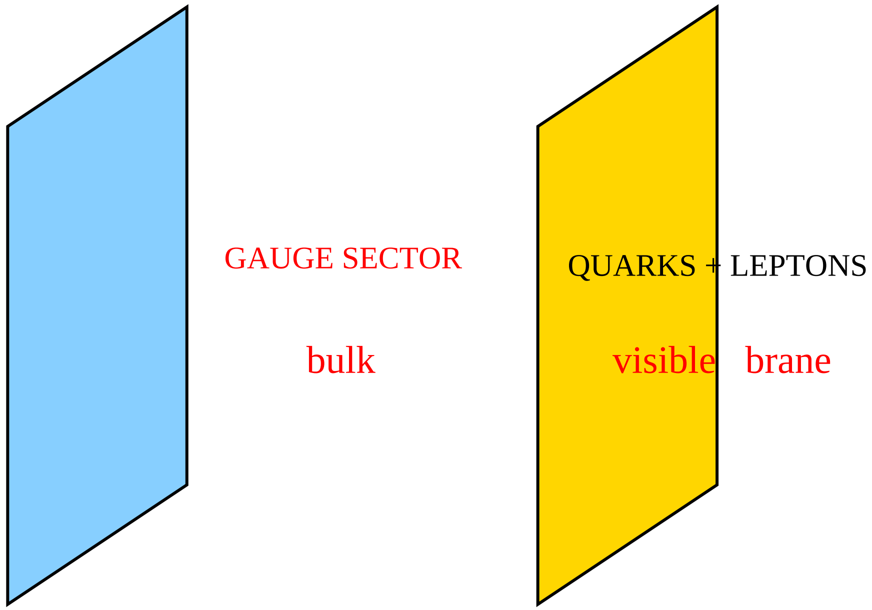
- Extra dimensions provide new mechanisms to break supersymmetry and to solve the supersymmetric flavor problem
- If vectors propagate in the bulk (and feel supersymmetry breaking) and quarks and leptons are localized on a supersymmetry preserving 3-brane, supersymmetry breaking to the observable sector is GAUGINO MEDIATED: flavor violating interactions suppressed [L. Randall, R. Sundrum, hep-ph/9810155]

Introduction

- This asymmetry by which 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

Supersymmetry breaking

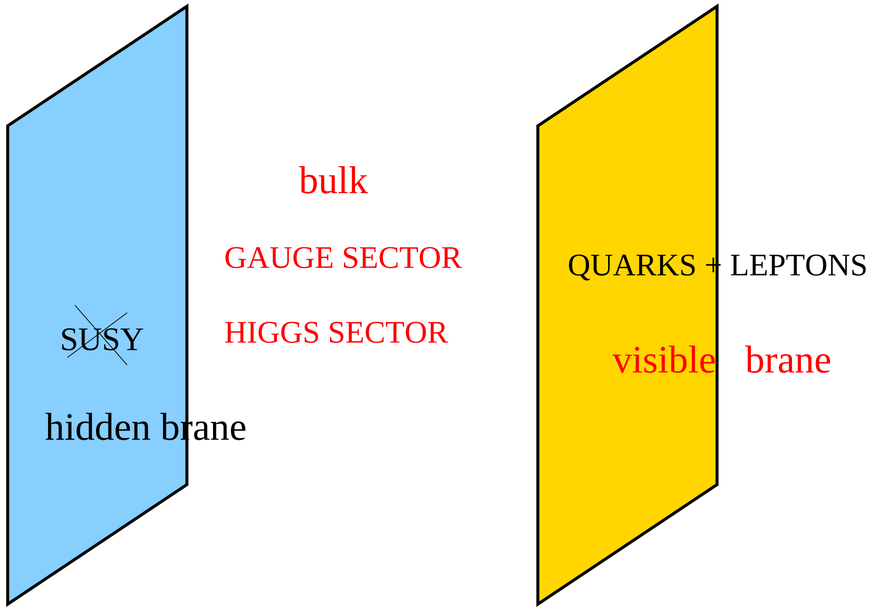
- From here on we will restrict ourselves to a 5D theory where the extra dimension has been compactified on an orbifold $S^1/\mathbb{Z}_2$



- There are two general mechanisms of supersymmetry breaking which are consistent with the previous picture

In the hidden brane

- Supersymmetry is broken in the hidden brane



by a superfield φ whose F-component acquires a non-vanishing VEV [E.A. Mirabelli, M.E. Peskin, hep-th/9712214; Z. Chacko, M. Luty, A. Nelson, E. Ponton, hep-ph/9911323]

In the hidden brane

- Supersymmetry breaking is transmitted from the hidden sector to the bulk by higher dimensional operators induced by heavy modes (mass Λ) of the fundamental theory
- $\int d^2\theta \varphi W W \Rightarrow M_{1/2} \sim F/\Lambda \sim 1$ TeV
- $\int d^4\theta \varphi^\dagger \mathcal{H}_u \mathcal{H}_d \Rightarrow \mu \sim F/\Lambda$
    - $\int d^4\theta \varphi^\dagger \varphi (\mathcal{H}_u^\dagger \mathcal{H}_u, \mathcal{H}_d^\dagger \mathcal{H}_d, \mathcal{H}_u H_d)$

$$\Downarrow$$

$$B\mu, m_{H_u}^2, m_{H_d}^2 \sim F^2/\Lambda^2$$

In the hidden brane

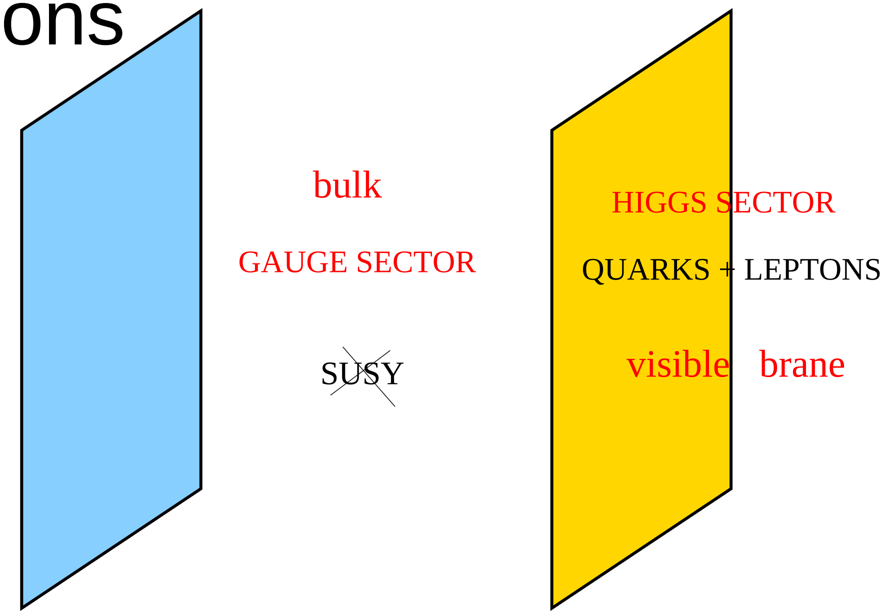
- Electroweak symmetry breaking can proceed depending on the detailed values of the generated parameters $B\mu, m^2_{H_u}, m^2_{H_d}$
- A precise calculation of them requires knowledge of the fundamental theory beyond Λ
- In this approach the extra dimension is used to hide the sequestered sector by the factor

$$e^{-\pi\Lambda R}$$

and to propagate supersymmetry breaking from gauginos to squarks and sleptons in a finite way

Scherk-Schwarz breaking

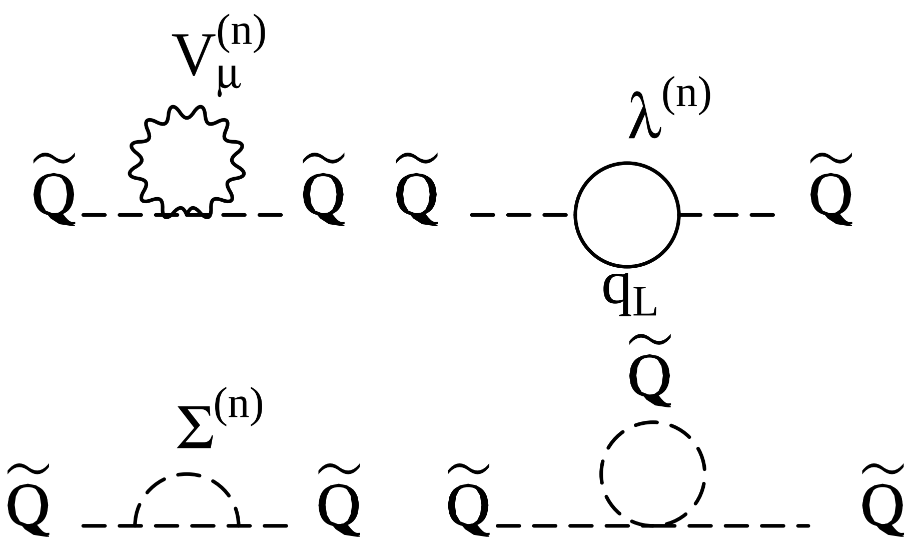
- Scherk-Schwarz supersymmetry breaking is a genuine mechanism for breaking globally supersymmetry in theories with extra dimensions



[I. Antoniadis, S. Dimopoulos, A. Pomarol, M.Quiros, NPB 544 (1999) 503; A. Delgado, A. Pomarol, M.Quiros, PRD 60 (1999)095008]

Scherk-Schwarz breaking

- After SS breaking the gauginos (and the gravitino) get a common mass: $M_{1/2} = \omega / R$
- Squarks and sleptons acquire one-loop finite masses $\sim$ $(\text{loop factor})\; g^2/R^2$



Scherk-Schwarz breaking

- 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 two competing effects
  - The one-loop gauge contribution is positive

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

  - The two-loop top contribution is negative

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

Scherk-Schwarz breaking

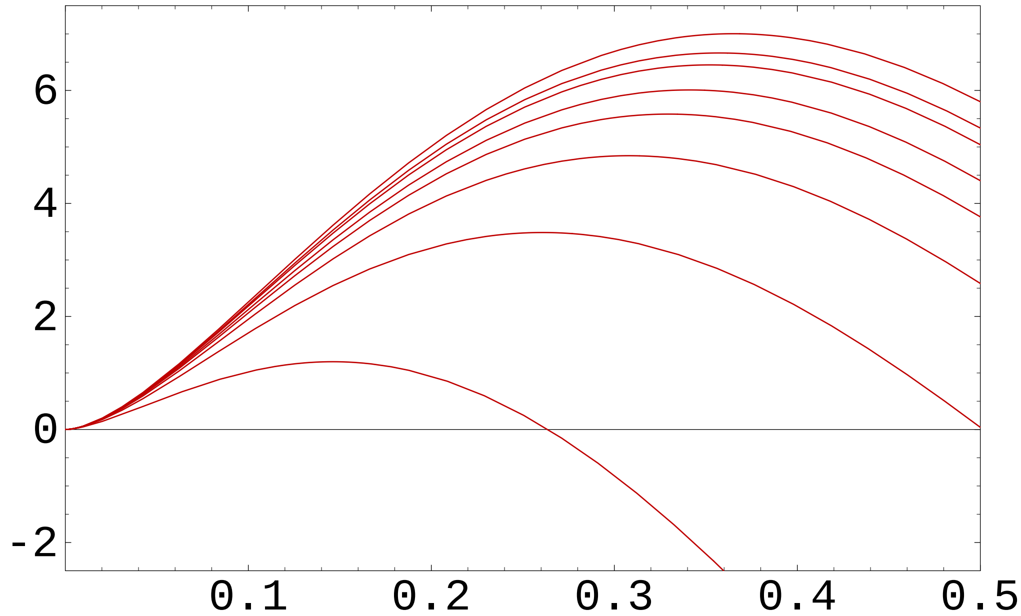
- A detailed analysis of the two-loop effective potential for $\omega = 1/2$ [R. Barbieri et al., hep-ph/0205280] shows however that

$$\boxed{m^2_{h,rad} = \Delta^{(1)}_G m^2_h + \Delta^{(2)}_Y m^2_h > 0}$$

- If the Higgs superfields $\mathcal{H}_{u,d}$ are strictly localized in one boundary their supersymmetry breaking masses are equal to zero: no EWSB
- If they are propagating in the bulk the Higgs squared masses are either zero or $\sim 1/R^2$ and again no EWSB occurs

Scherk-Schwarz breaking

- For arbitrary value of ω a similar result follows [G. Gersdorff, D. Diego, M. Quiros, hep-ph/0605024]



Plot of $10^4 m^2_{h,rad}$ as a function of ω for $\tan\beta =$1 (bottom curve), 1.5, 2, 2.5, 3, 4, 5, 15

Scherk-Schwarz breaking

- A way out is if Higgses are quasi-localized by a localizing mass M and tree-level masses are tachyonic $(m_H)^2 < 0$ [G. Gersdorff, D. Diego, M. Quiros, hep-ph/0505244] [a] and in absolute value at the weak scale

$$\epsilon = e^{-\pi M R} \ll 1, |m_H^0| \sim M\epsilon \sim m_Z$$

so that the scales of supersymmetry breaking and the weak scale are decoupled

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[a] Another possibility (contradicts original requirement of localized matter) is to delocalize the top sector [R. Barbieri et al., hep-ph/0011311; N. Arkani Hamed et al., hep-ph/0102090; A. Delgado, M. Quiros, hep-ph/0103058]

The model

- Higgses have to propagate (quasi-localized) in the bulk in two hypermultiplets

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

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

- Supersymmetry $(SU(2)_R)$ is broken by the SS parameter ω
- $SU(2)_H$ is also broken by the Scherk-Schwarz mechanism, the parameter $\tilde{\omega}$
- By assuming $\epsilon \ll 1$ there are two 4D modes whose wavefunctions localize towards the boundary at $y = 0$ and two other heavy modes localized at $y = \pi R$

The model

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 model

- 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 $su(2)_H$

- 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 model

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 model

- 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

The model

- 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 multiplet Σ

The model

- 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

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

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

The model

- 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 just because there is a low supersymmetry breaking scale

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

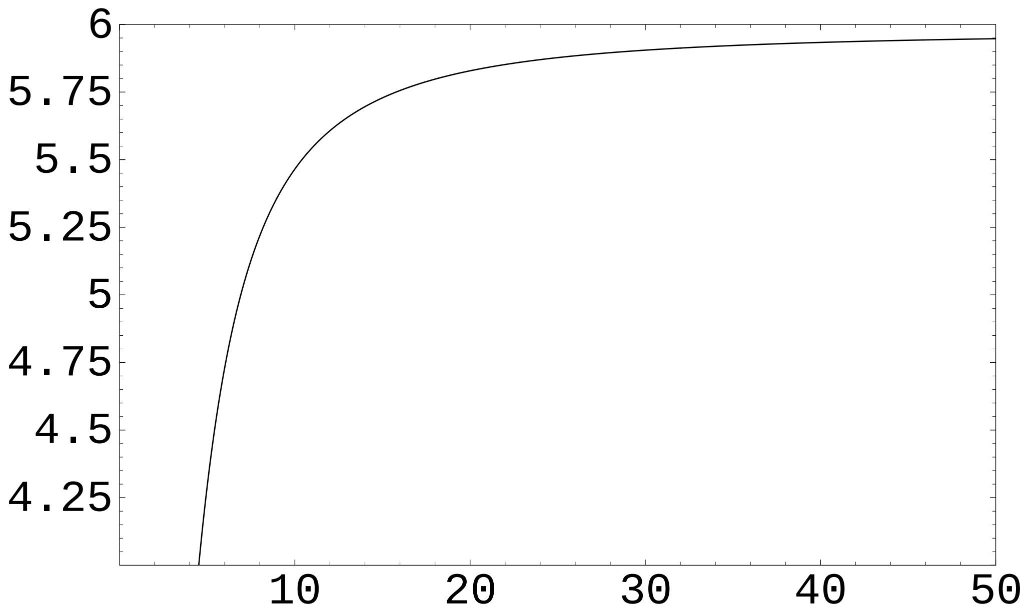
- EWSB occurs in a very peculiar and interesting way
- The tree-level mass $m^2_{H_u}$ is negative for values of $\tilde{\omega} > 1/4$
- There can be a (total or partial) cancellation between the tree-level and one-loop contributions to the Higgs masses

$$m^2_{H_u} + \Delta^{(1)}_G m^2_{H_u} \simeq 0$$

- The negative two-loop corrections $\Delta^{(2)}_Y m^2_{H_u}$ will easily trigger EWSB

Supersymmetric spectrum

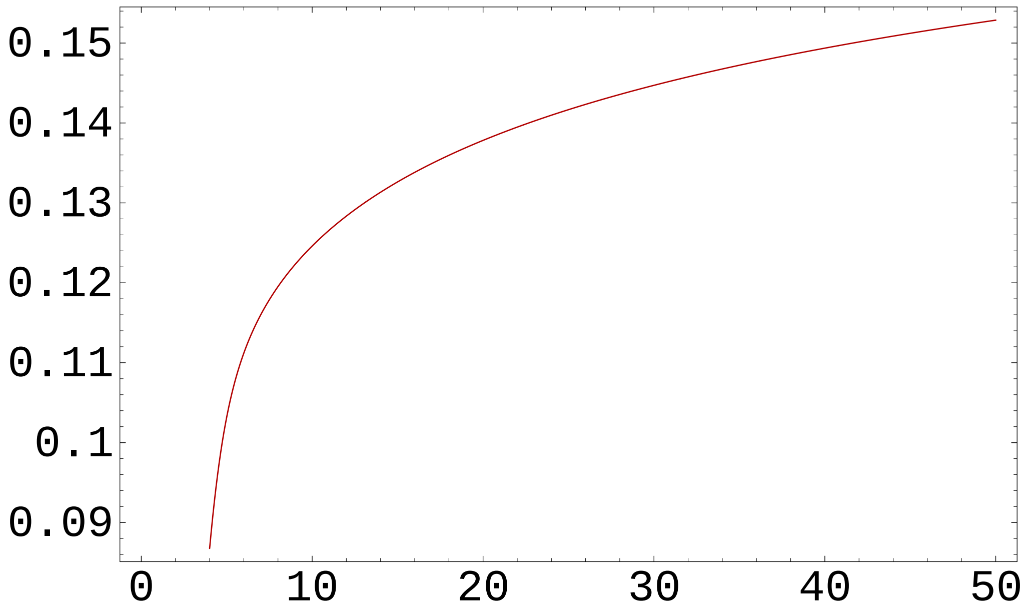
The minimization conditions provide predictions of $\tan\beta$ and μ as functions of M_c



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

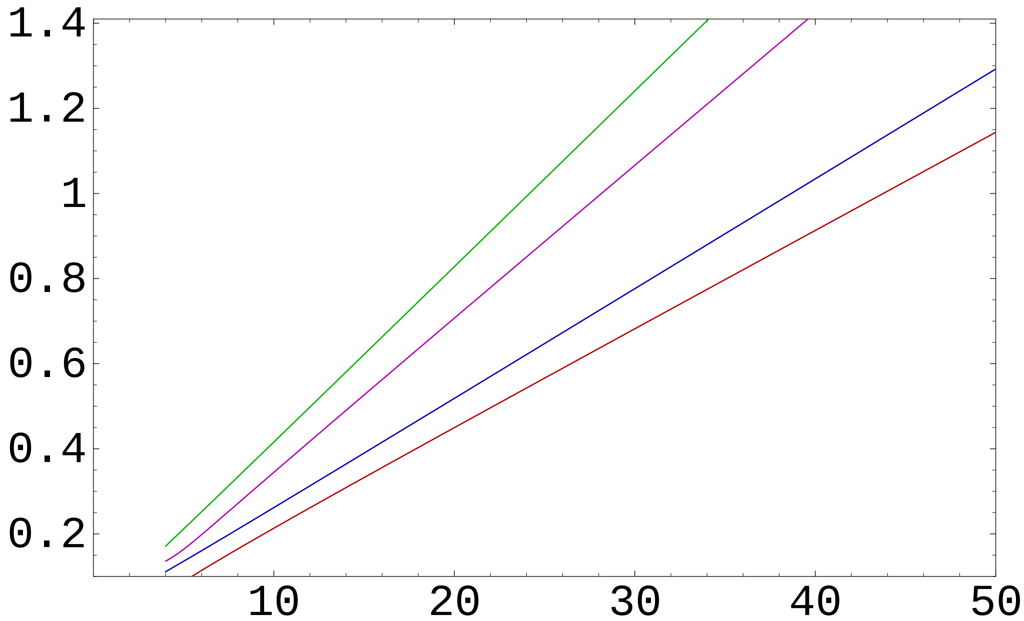
Supersymmetric spectrum

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



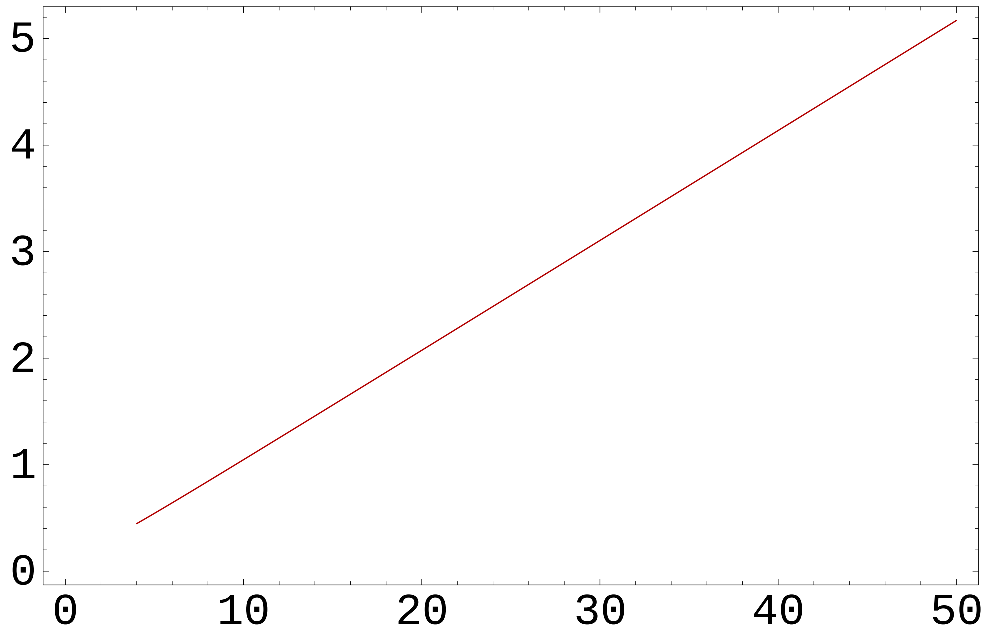
SM-like Higgs mass m_h. All masses are in TeV

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)

Supersymmetric spectrum



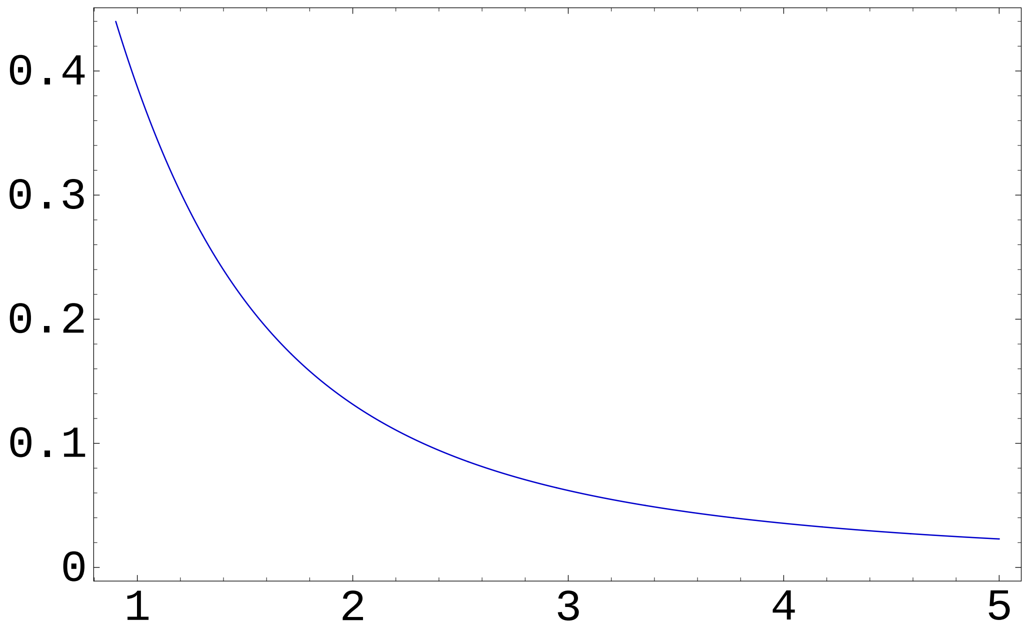
The squark masses $m_{\tilde{q}}$

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

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

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



Fine-tuning as function of $M_{\tilde{g}}$ in TeV

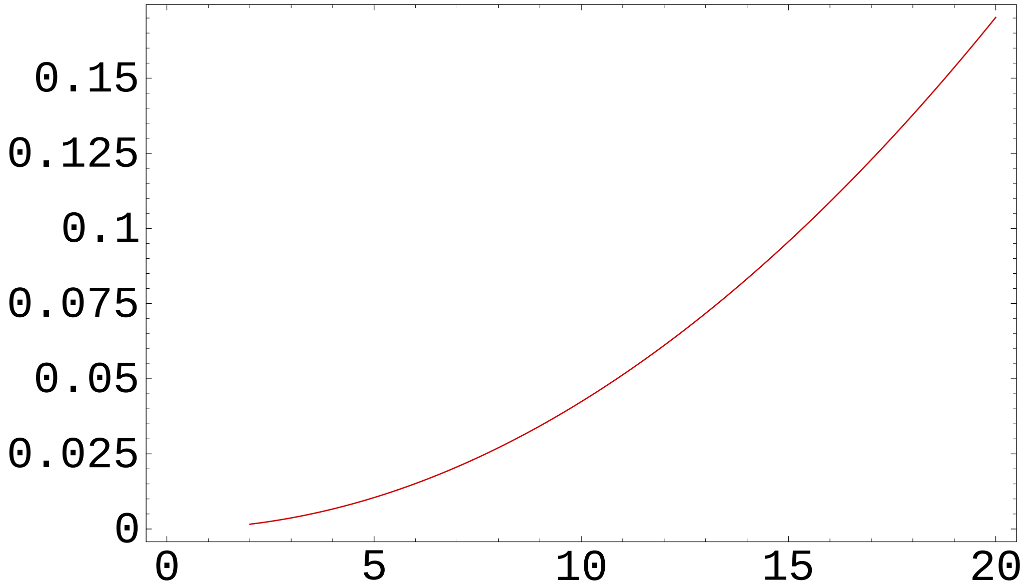
Fine-tuning

- In fact for $M_{\tilde{g}} \sim 3$ TeV the required amount of fine-tuning is $\sim 10\%$ while for larger values of $M_{\tilde{g}}$ 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 $\log m_Z/m_{\mathrm{GUT}}$

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

Dark Matter

- Neutralino is the LSP and the lightest neutralino is the candidate to CDM



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

WMAP $\Rightarrow M_{\tilde{g}} \sim 15$ TeV

Conclusions

The main features of these models are:

- Models are of "no-scale" type and then no anomaly mediated supersymmetry breaking occurs
- No one-loop quadratic or linear sensitivity on the cutoff Λ of Higgs masses
- Gauginos are the heaviest supersymmetric particles (they are in the TeV or multi-TeV region)
- EWSB is triggered by tachyonic tree-level masses and two-loop radiative corrections

Conclusions

- Squarks and sleptons acquire radiative masses from gluinos and electroweak gauginos, respectively
- Charged and neutral Higgsinos are almost degenerate with mass splittings ~ 1 GeV
- Fine-tuning of MSSM alleviated
- The LSP is a neutralino which is a good candidate to Dark Matter