# *Electroweak Symmetry Breaking with Extra Dimensions*

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High Energy Physics in the LHC Era, Paris

# *OUTLINE*

- Introduction
- Supersymmetry breaking:
  - In the hidden brane
  - Scherk-Schwarz breaking
- EWSB from Scherk-Schwarz
- Gauge-Higgs unification

# *Introduction*

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- Supersymmetry and electroweak breakings (e.g. the Higgs mass) remain as the main unknown ingredients in (supersymmetric theories of) particle physics
- They are intimately inter-related since it is known that supersymmetry breaking is required to trigger EWSB in the MSSM: the phenomenology of the MSSM (as we will hopefully observe at LHC) should depend on the way supersymmetry is broken

# *Introduction*

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- 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
- Extra dimensions provide new mechanisms to break SUSY, to trigger ELECTROWEAK breaking and to solve the supersymmetric flavor problem

# *Introduction*

- For instance, if vectors propagate in the bulk of the extra dimensions (and feel supersymmetry breaking) and quarks and leptons are localized on a supersymmetry preserving 3-brane, supersymmetry breaking is GAUGINO MEDIATED to the observable sector :

  SUPERSYMMETRY BREAKING IS FLAVOR BLIND

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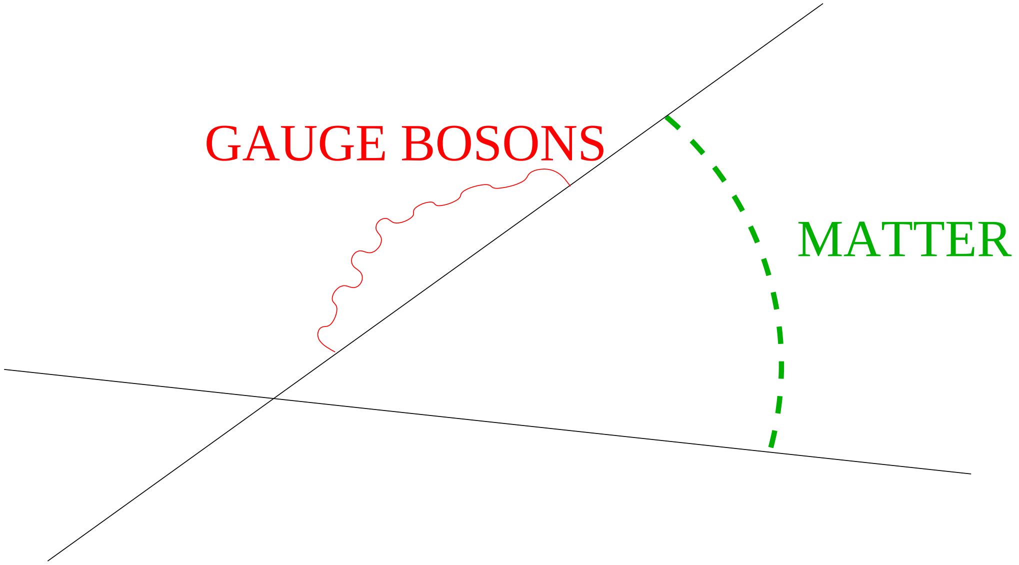
L. Randall, R. Sundrum, hep-ph/9810155

# *Introduction*

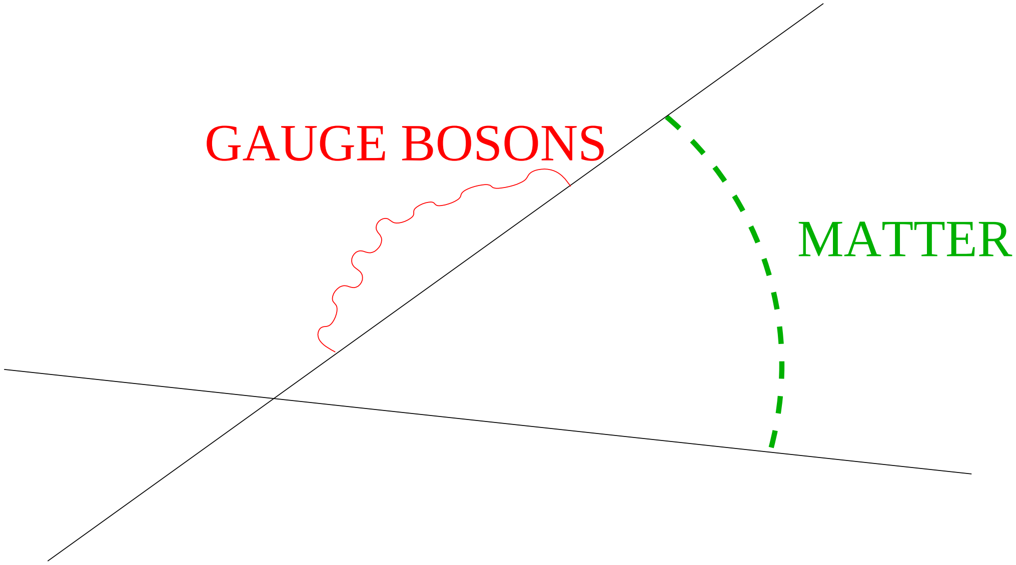
This asymmetry by which matter fields are localized on 3-branes and the gauge sector propagates in the bulk of extra dimensions typically appears in INTERSECTING BRANE constructions
[see Derendinger's talk]

# *Introduction*



INTERSECTING BRANES

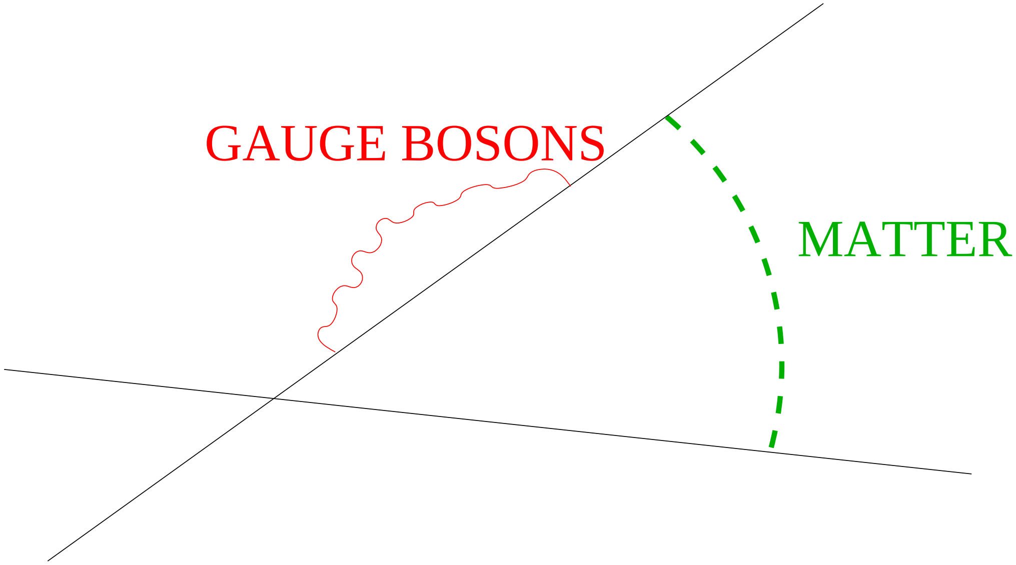
# *Introduction*



INTERSECTING BRANES

Gauge bosons are open string with ends on the same stack of branes: they propagate on the extra dimensions of the brane

# *Introduction*

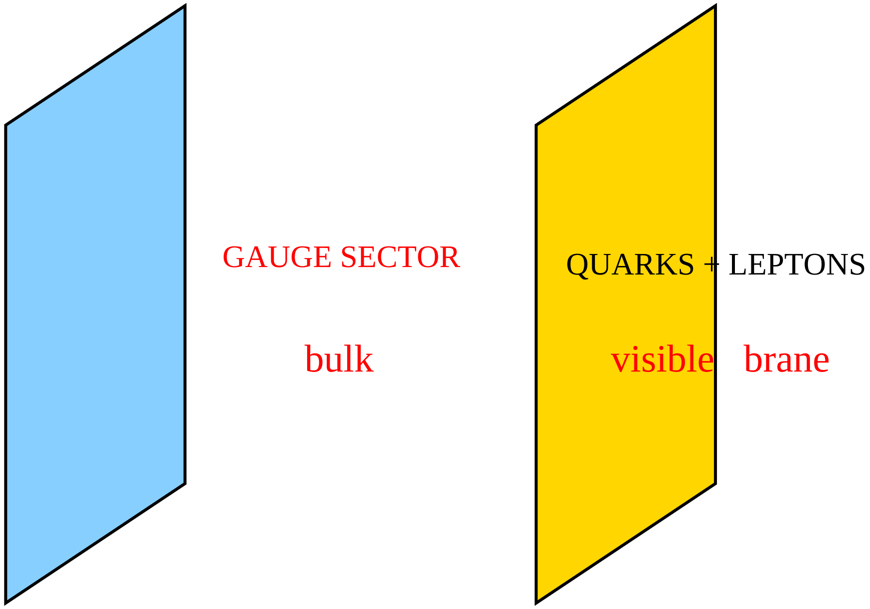


INTERSECTING BRANES

Quarks and leptons are open strings with ends on different branes: they propagate on their intersection

# *Introduction*

From here on we will consider (for simplicity) only a large ($\sim$ TeV scale) extra dimension compactified on an interval or orbifold $S^1/\mathbb{Z}_2$



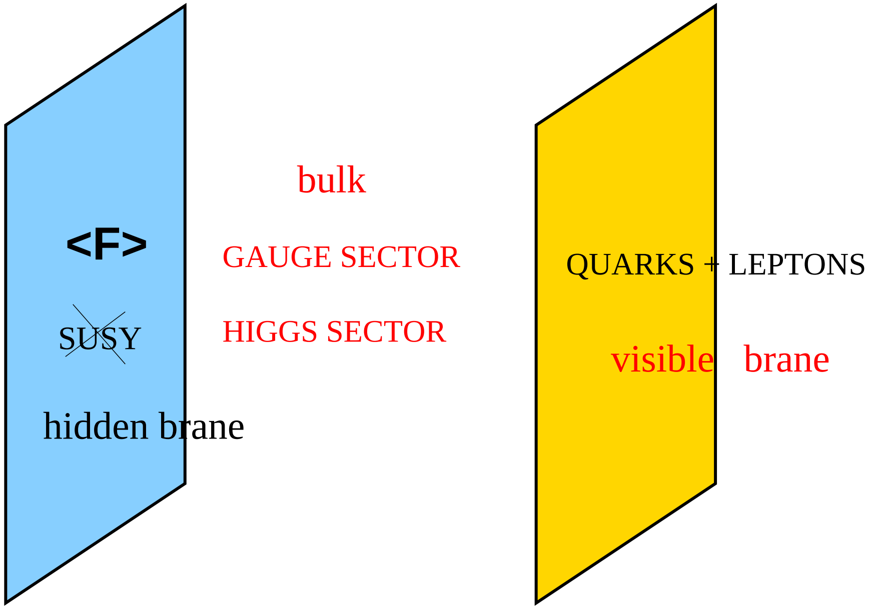
Other possible extra dimensions are small and not detectable at LHC

# *Supersymmetry breaking*

There are two general mechanisms of supersymmetry breaking which are consistent with the previous picture depending on the way supersymmetry is broken

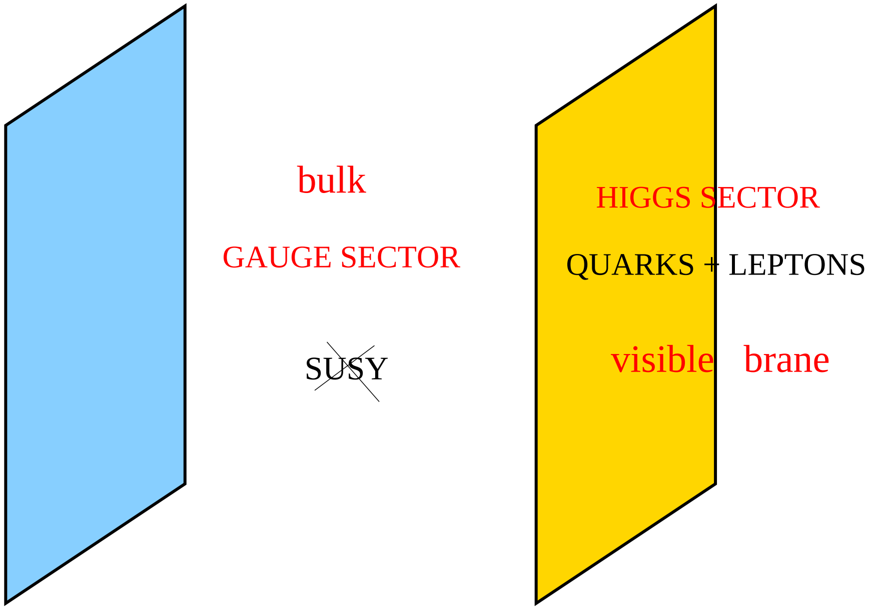
# *Supersymmetry breaking*

Supersymmetry is broken on the hidden brane



# *Supersymmetry breaking*

Supersymmetry is broken in the bulk [Scherk-Schwarz (SS) breaking]


bulk

GAUGE SECTOR

$\cancel{\text{SUSY}}$

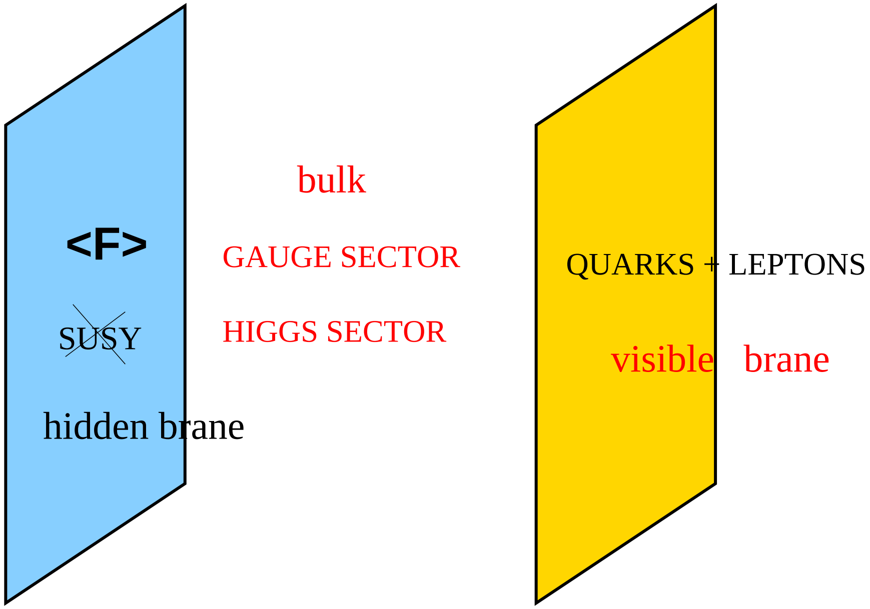
HIGGS SECTOR

QUARKS + LEPTONS

visible brane

# *In the hidden brane*

- Supersymmetry is broken in the hidden brane



bulk

**<F>**

GAUGE SECTOR

QUARKS + LEPTONS

~~SUSY~~

HIGGS SECTOR

visible brane

hidden brane

by a superfield $\varphi$ whose $F$-component acquires a non-vanishing VEV

# *In the hidden brane*

Supersymmetry breaking is transmitted from the hidden sector to the bulk by higher dimensional operators induced by heavy modes (mass $\Lambda$) of the fundamental theory [a]

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[a] E.A. Mirabelli, M.E. Peskin, hep-th/9712214; Z. Chacko, M. Luty, A. Nelson, E. Ponton, hep-ph/9911323

# In the hidden brane

$$\int d^2\theta \varphi W^\alpha W_\alpha \Rightarrow M_{1/2} \sim F/\Lambda \sim 1 \text{ TeV}$$

$$\int d^4\theta \varphi^\dagger \mathcal{H}_u \mathcal{H}_d \Rightarrow \mu \sim F/\Lambda$$

$$\int d^4\theta \varphi^\dagger \varphi(\mathcal{H}_u^\dagger \mathcal{H}_u, \mathcal{H}_d^\dagger \mathcal{H}_d, \mathcal{H}_u H_d)$$

$$\Downarrow$$

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

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[†] E.A. Mirabelli, M.E. Peskin, hep-th/9712214; Z. Chacko, M. Luty, A. Nelson, E. Ponton, hep-ph/9911323

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# *In the hidden brane*

- Electroweak symmetry breaking can proceed depending on the detailed values of the generated parameters $B\mu, m_{H_u}^2, m_{H_d}^2$
- A precise calculation of them requires knowledge of the fundamental theory beyond $\Lambda$
- This theory is not predictive! (unless one knows the underlying theory)

# *In the hidden brane*

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

# *In the hidden brane*

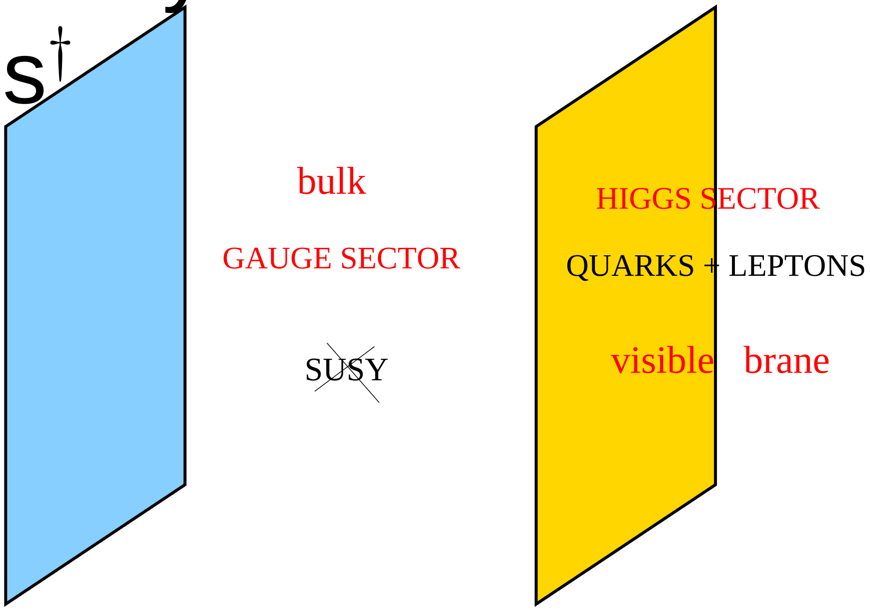
The extra dimension is taken (although this is not compelling) $\sim M_{GUT}$ (not at reach at LHC!) $\Rightarrow$ The theory is not distinguishable from a 4D theory (as the MSSM)

# *In the hidden brane*

A predictive theory of supersymmetry breaking that is distinguishable at LHC from a 4D theory is the SCHERK-SCHWARZ theory

# *Scherk-Schwarz breaking*

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


bulk

GAUGE SECTOR

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HIGGS SECTOR

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visible brane

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

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- It affects fields transforming as $SU(2)_R$

$$\mathbb{V} = (A_\mu, \lambda_1, \lambda_2, \Sigma)$$

$$\mathbb{H} = (H_1, H_2, \Psi)$$

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$$\mathbb{V} = (A_\mu, \lambda_1, \lambda_2, \Sigma)$$

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- It can be interpreted as spontaneous breaking when the radion superfield $\mathcal{T}$ acquires an $F$-term $F \sim \omega$

# *Scherk-Schwarz breaking*

- After SS breaking the gauginos (and the gravitino) get a common mass:
  $M_{1/2} = \omega/R$

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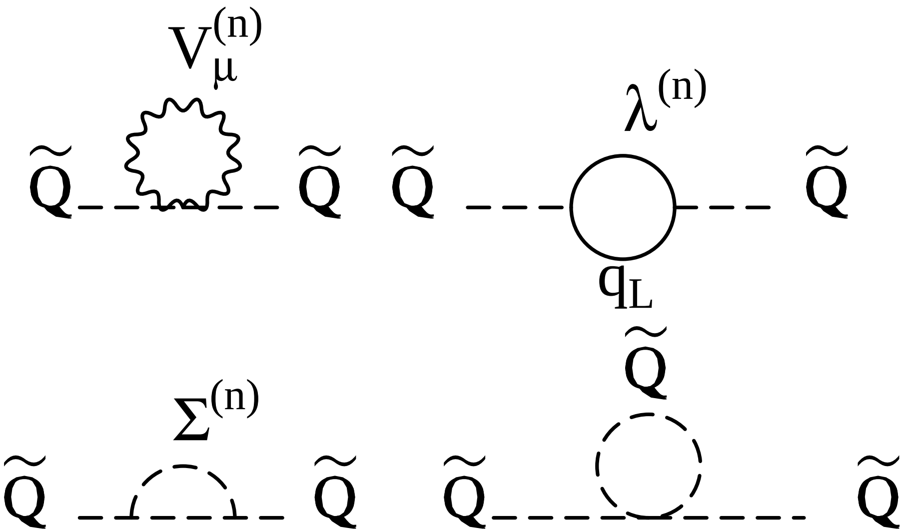

# *Scherk-Schwarz breaking*

- Since the top is localized its effects on the Higgs mass are at two-loop
- There are two competing radiative effects on the Higgs mass:
  - 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*

- In order to implement EWSB the Higgs squared mass at the origin is to be tachyonic
- A detailed analysis of the two-loop effective potential for $\omega = 1/2$ however shows that[†]

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

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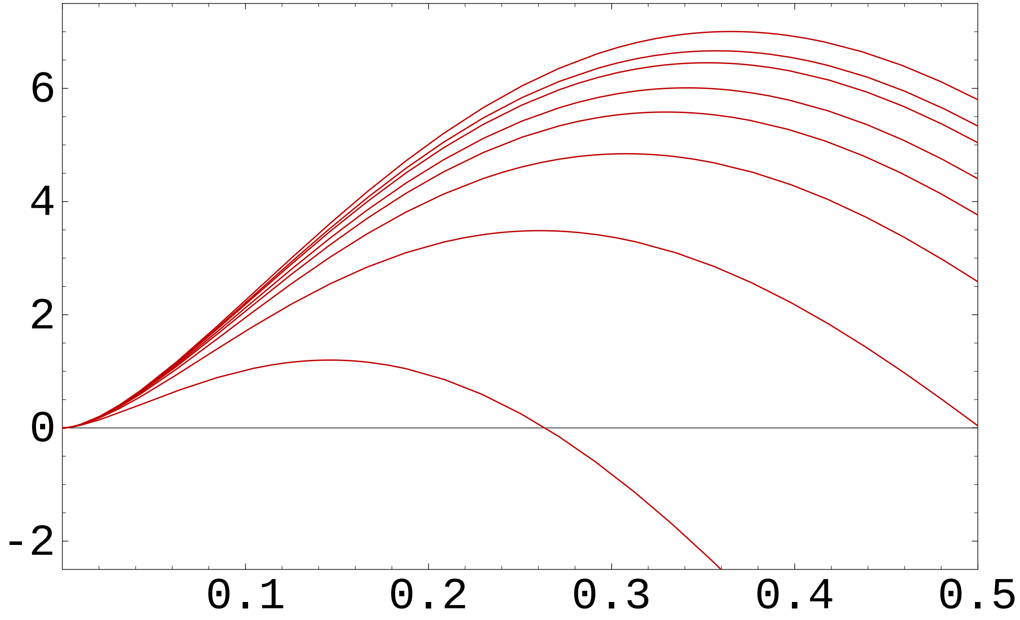
[†] R. Barbieri et al., hep-ph/0205280

# Scherk-Schwarz breaking

For arbitrary values of $\omega$ a similar result[†]



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

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[†] G. Gersdorff, D. Diego, M. Quiros, hep-ph/0605024

# *Scherk-Schwarz breaking*

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

$$\boxed{m^2_{h,rad} > 0 \Rightarrow \text{no EWSB}}$$

- If they are propagating in the bulk the tree-level Higgs squared masses are either zero or $\sim 1/R^2$ and again no EWSB occurs

# Scherk-Schwarz breaking

- A WAY OUT is if tree-level masses are tachyonic $(m_h)^2 < 0$ and in absolute value at the weak scale
- This can happen if Higgses are quasi-localized by a localizing mass $M \geq 1/R$

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

---

G. Gersdorff, D. Diego, M. Quiros, hep-ph/0505244

# *Scherk-Schwarz breaking*

- In that case the scales of supersymmetry breaking and the weak scale are decoupled!!
- An alternative possibility is of course to delocalize the top sector[†]
  [see Barbieri's talk]

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[†] R. Barbieri et al., hep-ph/0011311; N. Arkani Hamed et al., hep-ph/0102090; A. Delgado, M. Quiros, hep-ph/0103058

# *EWSB*

- Higgses propagate (quasi-localized) in the bulk in two hypermultiplets $(\mathcal{H}, \bar{\mathcal{H}}^c)^a$ transforming as a doublet of $SU(2)_H$
- There is a bulk mass term (consistent with $N=2$ supersymmetry)

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

and $\vec{p}$ is a unit vector in space $su(2)_H$

# EWSB

- 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

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

# *EWSB*

- Supersymmetry $(SU(2)_R)$ is broken by the SS parameter $\omega$

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

- $SU(2)_H$ is also broken by the SS mechanism: the parameter $\tilde{\omega}$

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

- Supersymmetric parameters are also

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

# EWSB

- 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 $y = 0$

$$\sqrt{c_0 M}\exp(-c_0 M R y) H_{u,d}(x) + \mathcal{O}(\epsilon)$$

- There are also two heavy modes localizing at $y = \pi$

# *EWSB*

- The soft mass terms are

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

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

- 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

# *EWSB*

- 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 $s_0 \simeq 0.1$
- This (10%) $\mu$-problem is less acute than the MSSM one just because there is a low supersymmetry breaking scale

# *EWSB*

- Electroweak gauginos provide

$$\Delta_G^{(1)} m^2_{H_{u,d}} = \frac{3g^2 + g'^2}{8\pi^4} M_c^2 \sum_{k=1}^{\infty} \frac{\sin(\pi k \omega)^2}{k^3}$$

- The top-stop sector provide

$$\Delta_Y^{(2)} m^2_{H_u} = -\frac{3y_t^2}{4\pi^2} m^2_{\tilde{t}} \log \frac{\omega M_c}{m_{\tilde{t}}}$$

$$\Delta_Y^{(2)} m^2_{H_d} \simeq 0$$

# *EWSB*

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- EWSB occurs in a very peculiar and interesting way
- The tree-level masses $m^2_{H_{u,d}}$ are negative for values of $\tilde{\omega} > 1/4$
- There can be an approximate cancellation between the tree-level and one-loop contributions to the Higgs masses

$$m^2_{H_{u,d}} + \Delta^{(1)}_G m^2_{H_{u,d}} \simeq 0$$

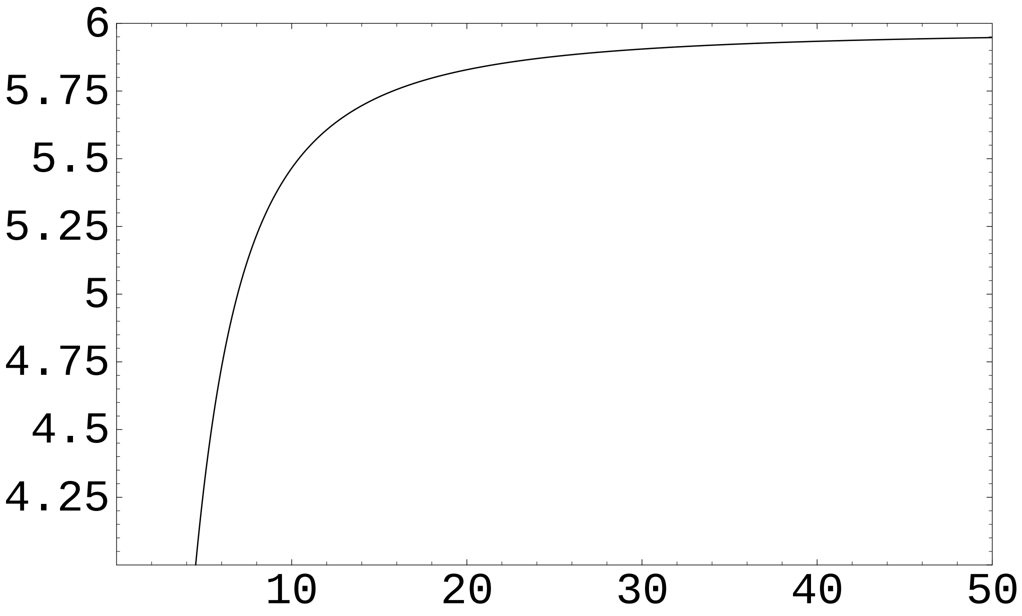
# *EWSB*

- EWSB occurs in a very peculiar and interesting way
- The tree-level masses $m^2_{H_{u,d}}$ are negative for values of $\tilde{\omega} > 1/4$
- The negative two-loop corrections $\Delta^{(2)}_Y m^2_{H_u}$ will easily trigger EWSB!

$$m^2_{H_u} < 0; \; m^2_{H_d} > 0$$

# *Supersymmetric spectrum*

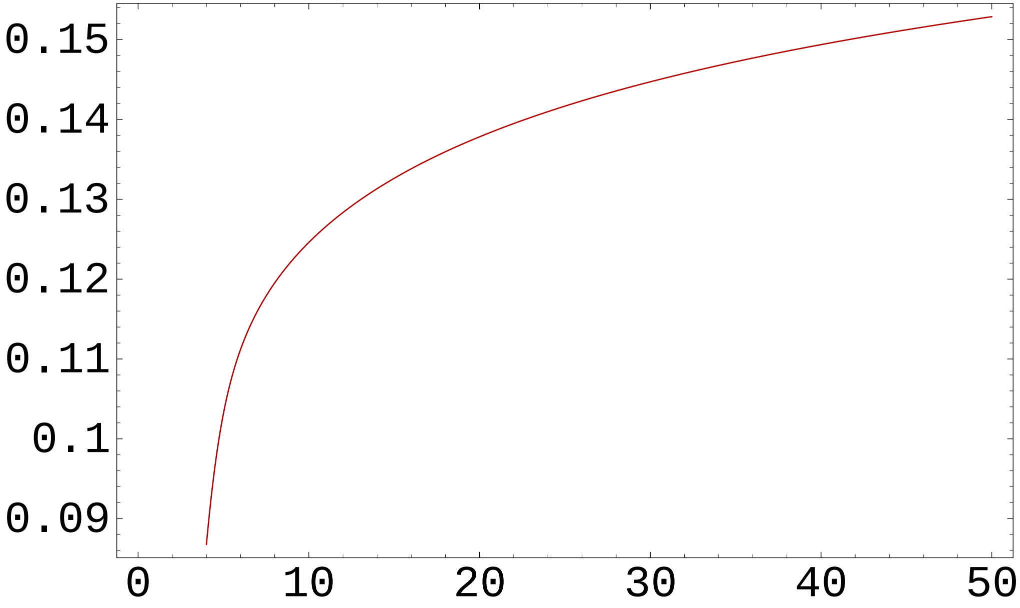
The minimization conditions provide predictions of $\tan\beta$ and $\mu$ as functions of $M_c$



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

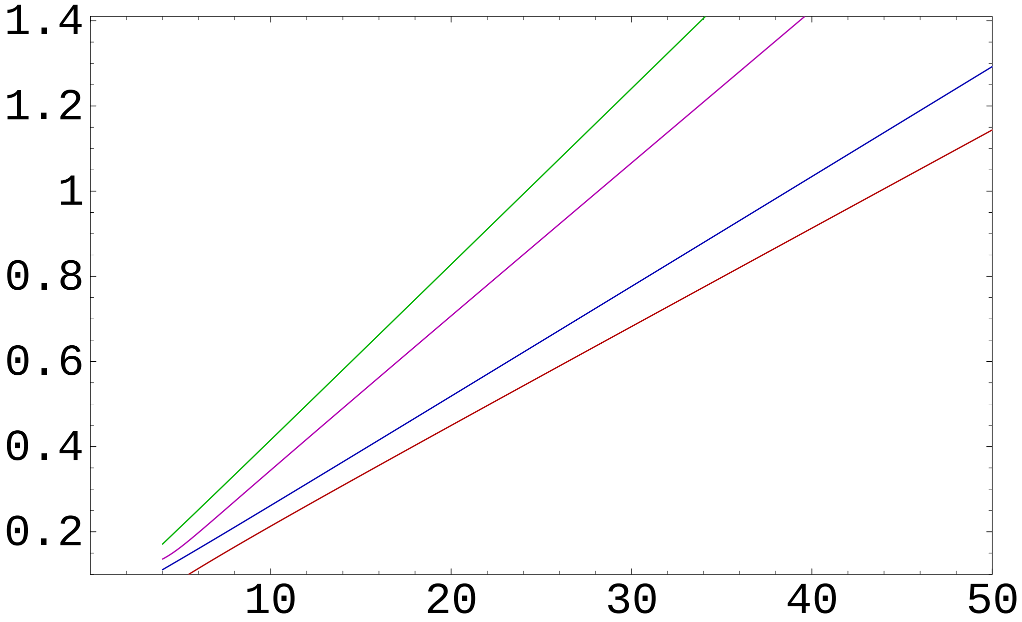
# *Supersymmetric spectrum*

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



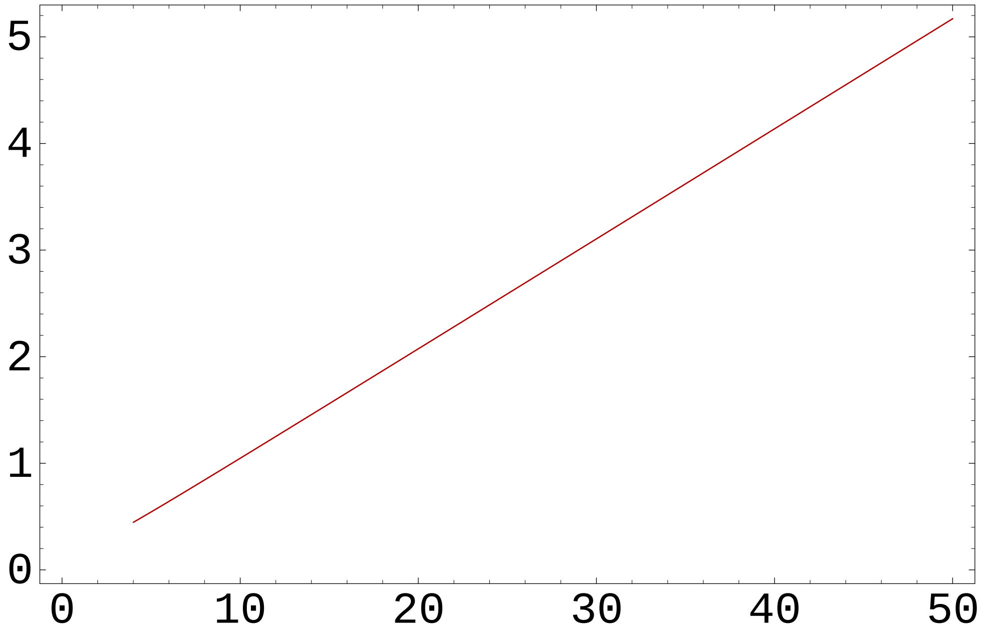
SM-like Higgs mass $m_h$ in TeV

# *Supersymmetric spectrum*



From top to bottom: slepton$_L$ $m_{\tilde{\ell}_L}$ (green line), heavy neutral Higgs $m_H \simeq m_A$ (magenta line), slepton$_R$ $m_{\tilde{e}_R}$ (blue line) and neutralinos $m_{\tilde{\chi}^0} \simeq \mu$ (red line)

# *Supersymmetric spectrum*



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

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

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

# *Supersymmetric spectrum*

A very general prediction of these models (that can falsify them) are the approximate ratios:

$$\tilde{m}^2_{Q_L} \simeq \tilde{m}^2_{U_R} \simeq \tilde{m}^2_{D_R}$$

$$\frac{\tilde{m}^2_Q}{\tilde{m}^2_L} = \frac{16}{9}\frac{\alpha_3}{\alpha_2}$$

$$\frac{\tilde{m}^2_Q}{\tilde{m}^2_E} = \frac{20}{9}\frac{\alpha_3}{\alpha_1}$$

# *Conclusion: SS breaking*

- Models are of "no-scale" type and then no AMSB occurs
- Gauginos are the heaviest supersymmetric particles ($\sim$ TeV)
- Squarks and sleptons acquire radiative masses from gluinos and electroweak gauginos, respectively
- Charged and neutral Higgsinos are almost degenerate up to $\sim$ GeV
- The LSP is a neutralino which is a good candidate to Dark Matter

# *Gauge-Higgs unification*

- Supersymmetry is not the only symmetry that can protect the Higgs mass
- In the presence of compact extra dimensions of length $\sim$1/TeV a gauge symmetry in the higher dimensional theory can provide a non-supersymmetric solution to the hierarchy problem
- The Higgses should be identified with the zero modes of the extra dimensional components of the higher-dimensional gauge bosons.

# *Gauge-Higgs unification*

- For $\delta$ extra dimensions there are $\delta$ bosons

$$H_i(x) = A_i^{(0)}(x),\ i = 1, \ldots \delta$$

transforming in the adjoint representation of the higher-dimensional gauge group

- If

$$\langle H_i \rangle \neq 0$$

the SM is spontaneously broken (Hosotani mechanism)

# *Gauge-Higgs unification*

- $H_i$ is massless at tree-level from gauge invariance
- The masslessness of $H_i$ should hold at any order in perturbation theory if the extra dimensions were infinitely large
- However for compact extra dimensions one expect radiative corrections to generate finite masses $\sim 1/R$
- A quadratically divergent counterterm is forbidden for the same reason

# Gauge-Higgs unification

- The SM Higgs is not in the adjoint representation of the gauge group so we need to:
- Enlarge the gauge group to $\mathcal{G}$ broken to $\mathcal{G}_{SM}$ by the orbifold action

$$\mathcal{G} \longrightarrow \mathcal{G}_{SM}$$

- Such that the Higgses $H_i$ are $SU(2)$ doublets with the correct hypercharge assignment

# *Gauge-Higgs unification*

- A minimal scenario based on $\mathcal{G} = U(3)_c \times U(3)_W$ was constructed where[†]

$$SU(3)_W \longrightarrow SU(2) \times U(1)$$

with $\mathbf{8} = \mathbf{3_0} + \mathbf{1_0} + \mathbf{2_3} + \mathbf{\bar{2}_{-3}}$

- The SM gauge and Higgs fields are identified as

$$A_\mu = \mathbf{3}_\mu + \mathbf{1}_\mu ; \;\; H_i = \mathbf{2_i} + \mathbf{\bar{2}_i}$$

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[†] I. Antoniadis, K. Banakli and M. Quiros, hep-th/0108005

# *Gauge-Higgs unification*

- Unification at a multi-TeV string scale is consistent with

$$\sin^2\theta_W \simeq \frac{1}{4}$$

- One-loop radiative masses in the bulk are given by

$$m_H^2 = \frac{3g^2}{32\pi^4 R^2}\zeta(3)\left[3C_2(\mathcal{G}) - 4\sum_{f(R)} C_R\right]$$

# *Gauge-Higgs unification*

- Fermions induce tachyonic masses and can thus trigger EWSB as in theories with Higgs mechanism
- Although Higgs masses at the branes are not protected by the corresponding 4D gauge invariance they are protected by a shift symmetry: a remnant after orbifold compactification of the higher dimensional gauge invariance
- This protection holds at any order in perturbation theory

# *Conclusion: GHU*

- Gauge-Higgs unification is a very nice and genuine higher-dimensional mechanism to implement EWSB
- The main problems of gauge-Higgs unifications are
    - Having a large enough Higgs mass $\Rightarrow$ theories with six or more dimensions
    - Masss spectrum for the SM fermions $\Rightarrow$ requires introduction of massive bulk fermions