Supersymmetry breaking

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pedagogical introduction
effective theory approach

apologies to the experts
references only at the end

models and stringy viewpoint
in plenary and parallel talks

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Why supersymmetry?

- a possibility within LRQFT
- fits with superstrings/M-theory
- hierarchy problem: $\frac{M_{weak}}{M_P} \sim 10^{-15}$
- vacuum energy: $\frac{\Lambda_{cosm}}{M_P} \sim 10^{-30}$
- unification of coupling constants
- nice fit to EW precision tests

but:

- no SUSY particle found (yet)
- no light Higgs found (yet)
- flavour problems: B, L, FCNC, CP
- hierarchy only partially solved
- no insight on vacuum energy

SUSY BREAKING crucial
open problem to clarify the puzzle
(theoretically/experimentally)

$N=1$, 4D global SUSY

V^a	vector multiplets	$\begin{pmatrix} A^a_\mu \\ \lambda^a \end{pmatrix}$	$h=\pm 1$ $h=\pm 1/2$	(D^a)
ϕ^i	chiral multiplets	$\begin{pmatrix} \psi^i \\ \varphi^i \end{pmatrix}$	$h=\pm 1/2$ $h=0$	(F^i)

The MSSM

gauge group $SU(3)\times SU(2)\times U(1)$

gauginos $(\widetilde{g}, \widetilde{W}, \widetilde{B})$

3 families, 2 Higgs doublets

squarks $(\widetilde{q})$, sleptons $(\widetilde{l})$, higgsinos $(\widetilde{H}_{1,2})$

R-parity conserving superpotential

$$w = Q h^U U^c H_2 + Q h^D D^c H_1 + L h^E E^c H_1 + \mu H_1 H_2$$

Explicit soft SUSY breaking

$$-\mathcal{L}_{soft} = \varphi^\dagger m^2 \varphi + (\tfrac{1}{2} M_A \lambda_A \lambda_A + m_3^2 H_1 H_2 + \tilde{q} A^U \widetilde{u}^c H_2 + \tilde{q} A^D \widetilde{d}^c H_1 + \tilde{l} A^E \widetilde{e}^c H_1 + h.c.)$$

MSSM vs. Standard Model

ameliorates hierarchy $(M_{weak} \sim \Delta m_{SUSY})$

but:

why $\frac{\Delta m_{SUSY}}{M_P} \sim 10^{-15}$ and $\mu \sim \Delta m_{SUSY}$?

irrelevant improvement on vacuum energy

typically $\Lambda_{cosm} \sim \sqrt{\Delta m_{SUSY} M_P} \quad (< M_P)$

B, L problem solved by R-parity but

new severe flavour problem (FCNC,CP)

need universality or equivalent conditions

move to spontaneous SUSY

Plan of the lecture:

1. $N = 1$ 4D global
2. $N = 1$ 4D local
3. extra dimensions

1. Global $\mathrm{N}=1$ 4D SUSY

$$Q_\alpha|0\rangle \neq 0 \quad \Leftrightarrow \quad \langle \delta_\eta \chi \rangle \neq 0 \quad (\chi = \psi^i, \lambda^a)$$

$$\delta_\eta \psi^i = \ldots + \sqrt{2}\eta F^i \quad \delta_\eta \lambda^a = \ldots + \eta D^a$$

SUSY $\Leftrightarrow$ $\langle F^i \rangle \neq 0$ and/or $\langle D^a \rangle \neq 0$

(2-derivative) effective Lagrangian

$$\mathcal{L} = \left[W(\phi) + \tfrac{1}{4} f_{ab}(\phi) \mathcal{W}^a \mathcal{W}^b \right]_F + h.c.$$
$$+ \left[K(\phi^\dagger, e^V \phi) + \xi_a V^a \right]_D$$

Renormalizable case:

$$f_{ab}(\phi) = \frac{\delta_{ab}}{g_a^2} \quad K(\phi^\dagger, \phi) = \phi^\dagger \phi$$
$W(\phi) =$ degree-3 polynomial

Generic case:

$dim > 4$ interactions with scale $\Lambda < M_P$
(gravitation consistently neglected)

Auxiliary fields:

$$F^i = -K^{i\bar{\jmath}}\overline{W}_{\bar{\jmath}}$$
$$+\tfrac{1}{2}K^{i\bar{\jmath}}K_{\bar{\jmath}lm}\psi^l\psi^m + \tfrac{1}{4}K^{i\bar{\jmath}}\overline{f}_{ab\bar{\jmath}}\overline{\lambda}^a\overline{\lambda}^b$$

$$D^a = -Ref^{ab}[\xi_b + K_i(T_b\varphi)^i]$$
$$-[\tfrac{i}{2\sqrt{2}}Ref^{ab}f_{bci}\psi^i\lambda^c + h.c.]$$

Scalar potential:

$$V_{global} = ||F||^2 + ||D||^2 \geq 0$$

SUSY-breaking scale:

$$\Lambda^4_{SUSY} = \langle ||F||^2 + ||D||^2 \rangle$$

Goldstino:

$$\widetilde{G} \propto \langle F_i \rangle \psi^i + \langle D_a \rangle \lambda^a$$

Classical mass formulae:

$$Str\mathcal{M}^2 = -2\overline{F}^{\bar{\jmath}}(R_{\bar{\jmath}i} + S_{\bar{\jmath}i})F^i \; + \text{Dterms}$$
$$R_{\bar{\jmath}i} = \partial_{\bar{\jmath}}\partial_i \log\det(K_{\overline{m}n})$$
$$S_{\bar{\jmath}i} = \partial_{\bar{\jmath}}\partial_i \log\det(Ref_{ab})$$

Realistic models ?

no reliable model with MSSM fields only

an interesting failure: $W \ni \Lambda^2_{SUSY}\sqrt{H_1 H_2}$

(requires $\Lambda \sim \Lambda_{SUSY} \sim M_{weak}$)

need at least a 'goldstino' multiplet

simplest choice: $T \equiv (z, \chi, F^z)$

gauge singlet chiral multiplet

SUSY mass splittings:

$$(\Delta m^2_{SUSY})_{IJ} \sim \gamma_{IJ} \cdot \frac{\Lambda^4_{SUSY}}{\Lambda^2}$$

$\gamma_{IJ} = \mathcal{O}(1)$ effective T-I-J coupling

no viable model with $dim \leq 4$ couplings

only $dim > 4$ couplings between

goldstino and MSSM multiplets

to obtain a realistic spectrum

(classical or quantum origin)

Examples of SUSY masses

$$\left[\gamma_{ij}\frac{|T|^2\phi_i^\dagger\phi_j}{\Lambda^2}\right]_D \quad \Rightarrow \quad (m^2)_{ij} \sim \gamma_{ij}\frac{\Lambda_{SUSY}^4}{\Lambda^2}$$

$$\left[\beta\frac{T\mathcal{W}^A\mathcal{W}^A}{\Lambda}\right]_F \quad \Rightarrow \quad M_A \sim \beta\frac{\Lambda_{SUSY}^2}{\Lambda}$$

$$\left[\beta'\frac{T^\dagger H_1 H_2}{\Lambda}\right]_D \quad \Rightarrow \quad \mu \sim \beta'\frac{\Lambda_{SUSY}^2}{\Lambda}$$

$$\left[\beta''\frac{|T|^2 H_1 H_2}{\Lambda^2}\right]_D \quad \Rightarrow \quad m_3^2 \sim \beta''\frac{\Lambda_{SUSY}^4}{\Lambda^2}$$

$$\left[\gamma'_{ij}\frac{T\phi_i\phi_j H}{\Lambda}\right]_F \quad \Rightarrow \quad A_{ij} \sim \gamma'_{ij}\frac{\Lambda_{SUSY}^2}{\Lambda}$$

how can the special $\gamma_{ij}, \gamma'_{ij}$ needed to avoid the SUSY flavor problem arise?

must know more about the symmetries of the underlying microscopic theory

SUSY breaking dynamics not essential

transmission mechanism may be enough

Gauge mediation

observable sector	$\overset{\text{gauge}}{\longleftrightarrow}$	messenger sector	$\overset{\text{superpotential}}{\longleftrightarrow}$	hidden sector
MSSM		$\Phi(5) + \Phi^c(\overline{5})$		T

$$w = kT\Phi\Phi^c + \ldots \qquad \langle z \rangle \neq 0 \quad \langle F^z \rangle \neq 0$$

$$\mathcal{M}^2 = k^2 \langle z \rangle^2 > \Delta m_{SUSY}^2 = k \langle F^z \rangle$$

gaugino ($1l$) and scalar ($2l$) masses:

$$M \sim \frac{\alpha}{4\pi} \frac{\langle F^z \rangle}{\langle z \rangle} \qquad m^2 \sim \left(\frac{\alpha}{4\pi} \frac{\langle F^z \rangle}{\langle z \rangle} \right)^2$$

SM gauge interactions $\Rightarrow$ universality

effective theory:

$$\Lambda \sim \frac{4\pi \langle z \rangle}{\alpha} \quad \text{and} \quad \Lambda_{SUSY}^2 \sim \langle F^z \rangle$$

$\Lambda_{SUSY} \geq \mathcal{O}(10)$TeV for realistic spectrum

μ, m_3^2 not generated by gauge interactions require rather contrived modifications

Dynamical SUSY breaking

global $N = 1$ 4D interesting laboratory
for non-perturbative SUSY breaking

controllable models of DSB do exist

simplest example: the 3-2 model

gauge group $G = SU(3) \times SU(2)$
$Q(3,2)$ $\overline{U}(\overline{3},1)$ $\overline{D}(\overline{3},1)$ $L(1,2)$

$$w = w_{cl} + w_{np}$$

$w_{cl} = \lambda Q\overline{U}L$ no TL flat directions
non-anomalous $U(1) \times U(1)_R$ symmetry

$$w_{np} = \frac{\Lambda_3^7}{(Q\overline{U})(Q\overline{D})} \qquad (\Lambda_3 \gg \Lambda_2)$$

spontaneously broken SUSY!

generic (Λ_3, Λ_2) can also be studied
supersymmetry is always broken

. . . but we should not forget gravity . . .

2. Local $\mathrm{N}=1$ 4D SUGRA

consistent + realistic breaking $\Rightarrow$
local supersymmetry $\equiv$ supergravity

The minimal framework:

MSSM multiplets (V^a, ϕ^i) + goldstino multiplet (T)

+ gravitational multiplet $\begin{pmatrix} e_\mu^\alpha \\ \psi_\mu \end{pmatrix}$ $\begin{matrix} h = \pm 2 \\ h = \pm 3/2 \end{matrix}$

gravitino = gauge fermion of SUGRA

A crucial difference with global SUSY:

$$V_{sugra} = ||F||^2 + ||D||^2 - ||H||^2$$

matter + gauge − gravitational

$$\Lambda^4_{SUSY} = \langle ||F||^2 + ||D||^2 \rangle > M^4_{weak}$$

$$\Lambda_{cosm} = \langle V_{sugra} \rangle^{1/4} < M^2_{weak}/M_P$$

dictated by phenomenology

$\Downarrow$

gravitational effects crucial
for vacuum selection

The superHiggs effect (flat space)

$\psi_\mu(\pm 3/2) \oplus \tilde{G}(\pm 1/2)$ massive gravitino

$$\Lambda_{cosm} = \langle V \rangle^{1/4} \simeq 0 \;\&\; ||H||^2 = 3 m_{3/2}^2 M_P^2$$
$$\Downarrow$$
$$\Lambda_{SUSY}^4 = 3 m_{3/2}^2 M_P^2$$

one-to-one correspondence $m_{3/2}^2 \leftrightarrow \Lambda_{SUSY}$

Two flat ($M_P \to \infty$) limits:

1. $m_{3/2}$ fixed, $\Lambda_{SUSY} \to \infty$

explicitly broken SUSY
with $\mathcal{O}(m_{3/2})$ soft terms
and decoupled goldstino

2. Λ_{SUSY} fixed, $m_{3/2} \to 0$

spontaneously broken SUSY
interacting goldstino multiplet
with effective couplings
$\lambda_G \sim \Delta m_{SUSY}^2 / \Lambda_{SUSY}^2$

Gravitino mass vs. phenomenology

$m_{3/2}$ (Λ_{SUSY}) model-dependent parameter
even after choosing $\Delta m_{SUSY} \sim M_{weak}$

heavy		light		very light
$\mathcal{O}(M_{weak})$	$\gg$	$m_{3/2}$	$\gg$	$\mathcal{O}(M_{weak}^2/M_P)$
$\mathcal{O}(M_{weak}/M_P)$	$\ll$	λ_G	$\ll$	$\mathcal{O}(1)$
$\mathcal{O}(\sqrt{M_{weak}M_P})$	$\gg$	Λ_{SUSY}	$\gg$	$\mathcal{O}(M_{weak})$
$\mathcal{O}(M_P)$	$\gg$	Λ	$\gg$	$\mathcal{O}(M_{weak})$

heavy gravitino phenomenology

MSSM + soft terms with cutoff $\Lambda \sim M_P$

- $\odot$ MSSM LSP stable (dark matter)
- $\odot$ fits nicely with grand unification

light gravitino phenomenology

MSSM + goldstino multiplet with $\Lambda \ll M_P$

- $\odot$ MSSM LSP $\rightarrow$ particle + (goldstino)

very light gravitino ($\Lambda \sim M_{weak}$):

- $\odot$ unsuppressed (s)goldstino interactions
- $\odot$ avoid Higgs bound $m_h < 130$ GeV

Basic formalism of 4D SUGRA

(neglecting gauge superfields for simplicity)

defining (dimensionless) function:

$$G(\phi^\dagger, \phi) = \frac{K(\phi^\dagger,\phi)}{M_P^2} + \log\left|\frac{w(\phi)}{M_P^3}\right|^2$$

natural SUGRA units: $M_P \equiv 1$

classical scalar potential:

$$V_{sugra} = V_F + V_D + V_H$$

$V_D =$ similar to global case

$$V_F + V_H = e^G (G_i G^{i\bar{\jmath}} G_{\bar{\jmath}} - 3)$$

4D Minkowski $\Leftrightarrow \langle V_{sugra} \rangle = 0$

auxiliary fields (SUSY breaking):

$$F_i \propto G_i \propto w_i + w K_i$$

$D_a =$ similar to global case

field-dependent gravitino mass:

$$m_{3/2}^2 = e^G = |w|^2 e^K$$

coupling to gauge superfields can also be included

will be omitted to keep the discussion simple

Generic problems of 4D SUGRA

hierarchy:

why $m_{3/2} \ll M_P$?

vacuum energy:

why $\langle ||F||^2 + ||D||^2 \rangle \simeq \langle ||H||^2 \rangle$?

cannot be addressed in global SUSY

simplest example: Polonyi model

$$K = |T|^2 \qquad\qquad w = m^2 (T + \beta)$$

fine-tune $\beta = (2 - \sqrt{3}) M_P \Rightarrow \Lambda_{cosm} = 0$

set $m^2 \sim M_{weak} M_P \Rightarrow m_{3/2} \sim M_{weak}$

flavour:

effective goldstino couplings to MSSM

as in any effective theory approach

$\Downarrow$

generic $N = 1$ 4D SUGRA unsatisfactory

too flexible an effective theory

more insight from symmetries/dynamics?

look first at some special supergravities simplest no-scale model:

$$K = -3\log(T+\overline{T})$$

$SU(1,1)/U(1)$ Kähler invariance (T-duality)

$$T \to \frac{aT-ib}{icT+d} \qquad (ad-bc=1)$$

if $w(T) \to (icT+d)^3 w[(aT-ib)/(ict+d)]$

compatible with vector of $N>1$ SUGRA
e.g. $N=2$ prepotential $F=(X^1)^3/X^0$

$$w = k \neq 0 \text{ (T-independent)}$$

admissible $N>1$ ($N=2$) gauging

$$w = m_0 \;\; (-im_1 T) \;\; +3n^1T^2 \;\; (+in^0T^3)$$

Notes:

⊙ K, w may depend on $\phi \neq T$, above formulae when ϕ at their (SUSY) VEVs

⊙ w can have non-perturbative origin (gaugino condensation and/or other)

⊙ equivalences by field redefinitions

special properties of the model:

$V \equiv 0$ classical flat potential

$F^z \neq 0 \quad (\forall z)$ broken SUSY

$m^2_{3/2} = \frac{|k|^2}{(z+\overline{z})^3}$ sliding Λ_{SUSY}

when coupled to MSSM fields:

⊙ may allow for universal SUSY masses
$\Delta K = (T+\overline{T})^{-n}|C|^2 \Rightarrow \widetilde{m}^2_C = (n-1)m^2_{3/2}$

⊙ may allow for dynamical hierarchy
gauge vs. Yukawa renorm. effects
$\Rightarrow$ effective infrared fixed point of
$V_{eff}[m_{3/2}(T), H]$
if $Veff \sim \mathcal{O}(m^4_{3/2} \log \ldots)$ [not $\mathcal{O}(m^2_{3/2} M^2_P)$]

problems at this 4D level:

⊙ unexplained origin of K and w
(chirality $\Rightarrow$ no realistic $N > 1$ 4D model)

⊙ no control over UV quantum corrections

help from extra dimensions?

3. Extra dimensions

present activity on SUSY breaking mostly theories with extra dimensions:

- ⊙ effective $D > 4$ supergravities
- ⊙ $D = 10$ superstrings with branes
- ⊙ $D = 11$ supergravity from M-theory

$D > 4$ SUSY-breaking models
later in plenary and parallel talks

for simplicity, discuss here a toy model:
minimal 5D supergravity on S^1/Z_2
(as effective non-renormalizable theory)

⊙ learn some qualitative lessons: Scherk-Schwarz mechanism and its 'non-local' character, effective theory ambiguities, equivalence with 'gaugino condensation', no-scale models from extra dimensions

⊙ comments: extensions to more complicated/realistic models, open problems

Preamble: free massless 5D scalar

$$\mathcal{L} = (\partial^M \phi^\dagger)(\partial_M \phi) \quad x^M \equiv (x^\mu, y) \quad \text{(flat)}$$

symmetry: $\phi' = e^{-i\beta}\phi \quad \beta \in \mathbf{R}$ (constant)

circle compactification: $\quad y \equiv y + 2\pi R \ (\forall y)$

Strict periodicity conditions:

$$\phi(x, y + 2\pi R) = \phi(x, y)$$

$$\phi(x, y) \propto \sum_n \varphi_n(x) e^{\frac{iny}{R}}$$

$$(\partial^y \phi^\dagger)(\partial_y \phi) \quad \Rightarrow \quad \text{4D masses}$$

$$m_n^2 = \frac{n^2}{R^2} \quad (n \in \mathbf{Z})$$

standard Kaluza-Klein spectrum

Twisted periodicity conditions:

$$\phi(x, y + 2\pi R) = e^{-i\beta}\phi(x, y) \quad (\beta = \text{twist})$$

$$\phi(x, y) \propto e^{\frac{-i\beta y}{2\pi R}} \sum_n \varphi_n(x) e^{\frac{iny}{R}}$$

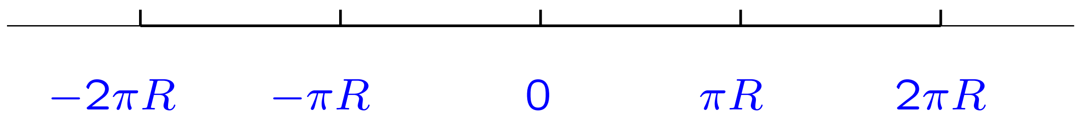
$$m_n^2 = \left(\frac{n}{R} - \frac{\beta}{2\pi R}\right)^2 \quad (n \in \mathbf{Z})$$

shifted Kaluza-Klein spectrum

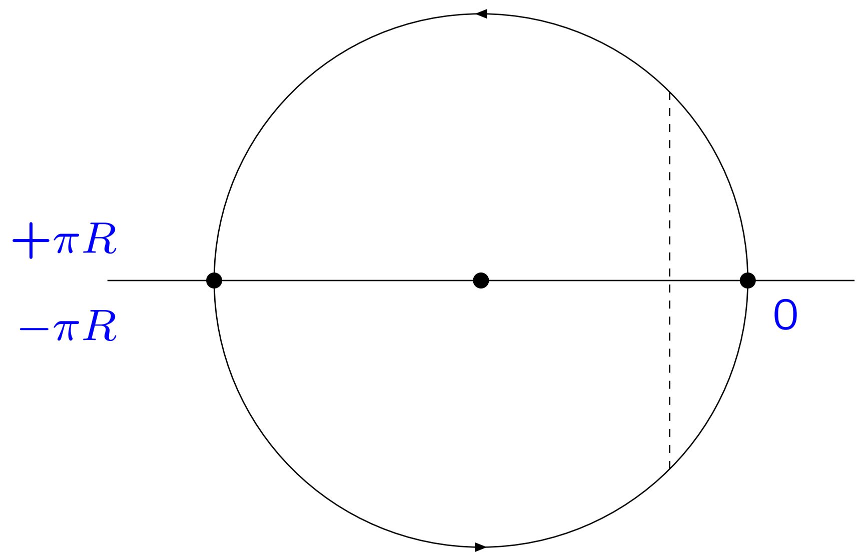
A useful case study

structure of induced mass terms in
5D theory on S^1/Z_2 ($S^1 \equiv R/T$)

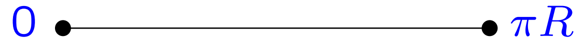
$$x^M \equiv (x^\mu\,,\, y)$$



T: $y \equiv y + 2\pi R$



Z_2: $y \equiv -y$



Work on covering space S^1 . . .

(interacting) 5D massless spinor $\Psi(x^\mu, y)$

$$\Psi = \begin{pmatrix} \psi_1 \\ \psi_2 \end{pmatrix} \quad \Psi(-y) = Z\Psi(y) \quad Z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

two 4D Weyl spinors, ψ_1=even and ψ_2=odd

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_{int}$$

$$\mathcal{L}_0 = i\overline{\Psi}^T \overline{\sigma}^\mu \partial_\mu \Psi - \frac{1}{2}\left(i\Psi^T \hat{\sigma}^2 \partial_y \Psi + \text{h.c.}\right)$$

invariant under Z_2 and a global $SU(2)$:

$$\Psi'(y) = U\Psi(y) \qquad U \in SU(2)$$

twist $\quad (U_\beta Z U_\beta = Z)$:

$$\Psi(y + 2\pi R) = U_\beta \Psi(y)$$

not restrictive to take:

$$U_\beta = \exp(i\beta\hat{\sigma}^2) \qquad (0 < \beta < \pi)$$

physics fully determined by:

lagrangian $\mathcal{L}(\Psi, \partial\Psi)$ + twist β

e.g.: $\quad m_n = \frac{n}{R} - \frac{\beta}{2\pi R} \quad (n \in \mathbf{Z})$

universal shift in the spectrum

move to a basis of periodic fields
by a local field redefinition:

$$\Psi(y) = V(y)\,\widetilde{\Psi}(y) \qquad \widetilde{\Psi}(y+2\pi R) = \widetilde{\Psi}(y)$$

$V(y+2\pi R) = U_\beta V(y)$ twist condition

$V(y) \in SU(2)$ to preserve can. kin. terms

$V_{11,22}$ even, $V_{12,21}$ odd to preserve Z_2 parities

important: no unique solution for V(y)

equivalent 5D theory with periodic fields:

$$\mathcal{L}(\Psi,\partial\Psi) =$$
$$\mathcal{L}(\widetilde{\Psi},\partial\widetilde{\Psi}) + \{-\tfrac{i}{2}[m_1(y)+im_2(y)]\widetilde{\psi}_1\widetilde{\psi}_1 +$$
$$\tfrac{i}{2}[m_1(y)-im_2(y)]\widetilde{\psi}_2\widetilde{\psi}_2 + im_3(y)\widetilde{\psi}_1\widetilde{\psi}_2 + h.c.\}$$

$m(y) \equiv m_a(y)\hat{\sigma}^a = -iV^\dagger(y)\partial_y V(y)$ (Maurer-Cartan)

conditions on $V(y) \Rightarrow$ conditions on $m(y)$

$$m(y+2\pi R) = m(y) \qquad m_a(y) \in \mathbf{R}$$
$$m_{1,2}(-y) = m_{1,2}(y) \qquad m_3(-y) = -m_3(y)$$

where is the information on the twist β ?

$$\cos\beta = \frac{1}{2} tr\, P \left\{ \exp\left[i \int_y^{y+2\pi R} dy' m(y') \right] \right\}$$

Comments:

$\odot$ mass terms of 3 kinds, however not the most general ones allowed by 4D Lorentz (3 real vs. 3 complex parameters)

$\odot$ equivalent theories via field redefinitions

periodic fields with mass terms

$\Updownarrow$

twisted fields and no mass terms

equivalence valid also with interactions

(some additional terms for derivative interactions)

$\odot$ to exploit the equivalence the other way:

$$V(y) = V(0) P\{\exp[i \textstyle\int_0^y dy' m(y')]\}$$

$\odot$ mass profiles $m(y')$ for periodic fields have no absolute physical meaning what matters is just the twist β

$\Downarrow$

$m_{1,2}(y)$ can be localized at fixed points

Example:

'ordinary' field redefinition:

$$V^O(y) = \exp\left(i\beta\hat{\sigma}^2 \frac{y}{2\pi R}\right)$$

$$m_1^O(y) = m_3^O(y) = 0 \qquad m_2^O(y) = \frac{\beta}{2\pi R}$$

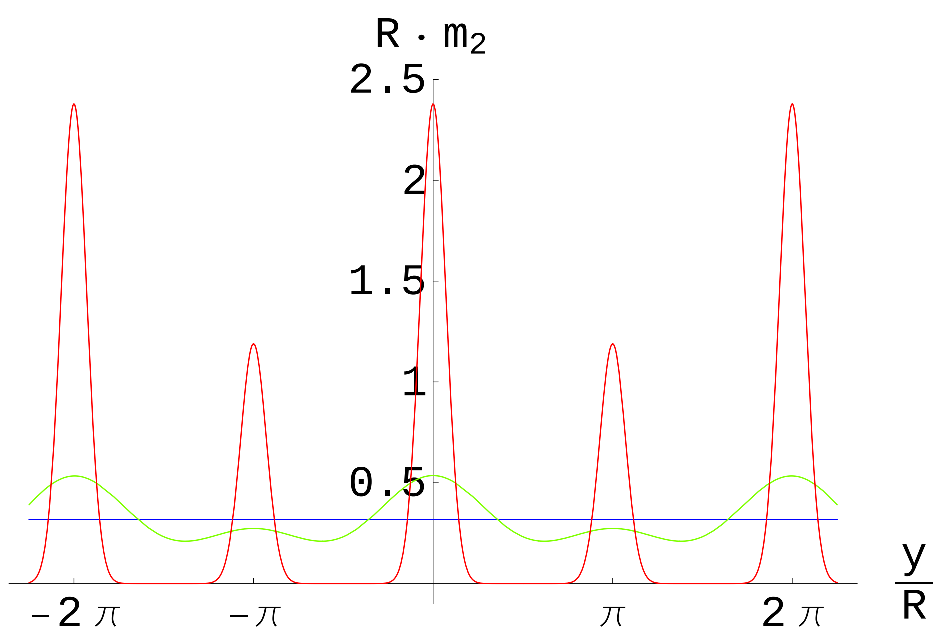
familiar constant mass profile

but 'generalized' choices are possible, e.g.:

$$m_1^G(y) = m_3^G(y) = 0 \qquad m_2^G(y) \neq 0$$

as long as

$$\int_y^{y+2\pi R} dy'\, m_2^G(y') = \int_y^{y+2\pi R} dy'\, m_2^O(y') = \beta$$



Two representative and equivalent choices for $m_2^G(y)$

with the equivalent constant profile $m_2^O(y) = 1/(\pi R)$

A 'special' choice is the 'singular' limit

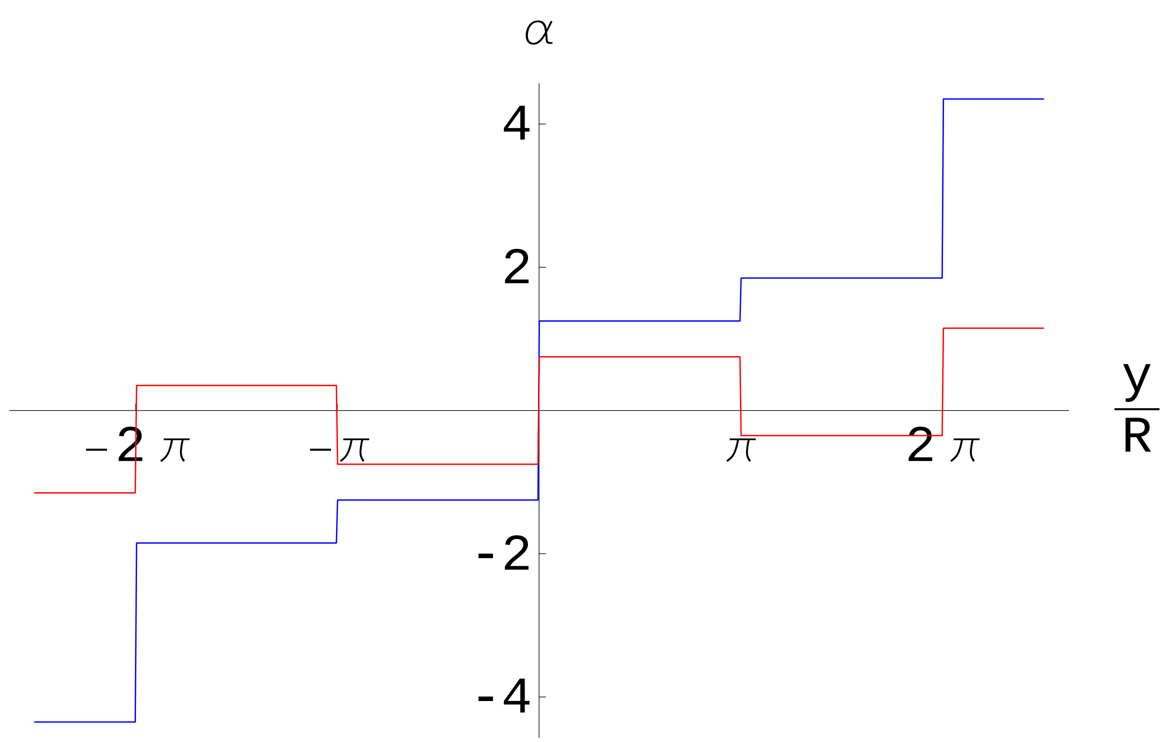
[to be handled with some care (regularization)]

$$m_2^S(y) = [\delta_0 \delta(y) + \delta_\pi \delta(y - \pi R)]_{per}$$

$$\delta_0 + \delta_\pi = \beta \qquad V^S(y) = \exp\left[i\alpha(y)\hat{\sigma}^2\right]$$

$$\alpha(y) = \frac{\delta_0 - \delta_\pi}{4}\epsilon(y) + \frac{\delta_0 + \delta_\pi}{4}\eta(y)$$

$\epsilon(y) =$ periodic sign $\qquad\qquad \eta(y) =$ 'staircase'



The function $\alpha(y)$ for two representative parameter choices:

$\delta_0 = 2.5,\ \delta_\pi = 0.6$ and $\delta_0 = 1.5,\ \delta_\pi = -1.1$

Another instructive example:

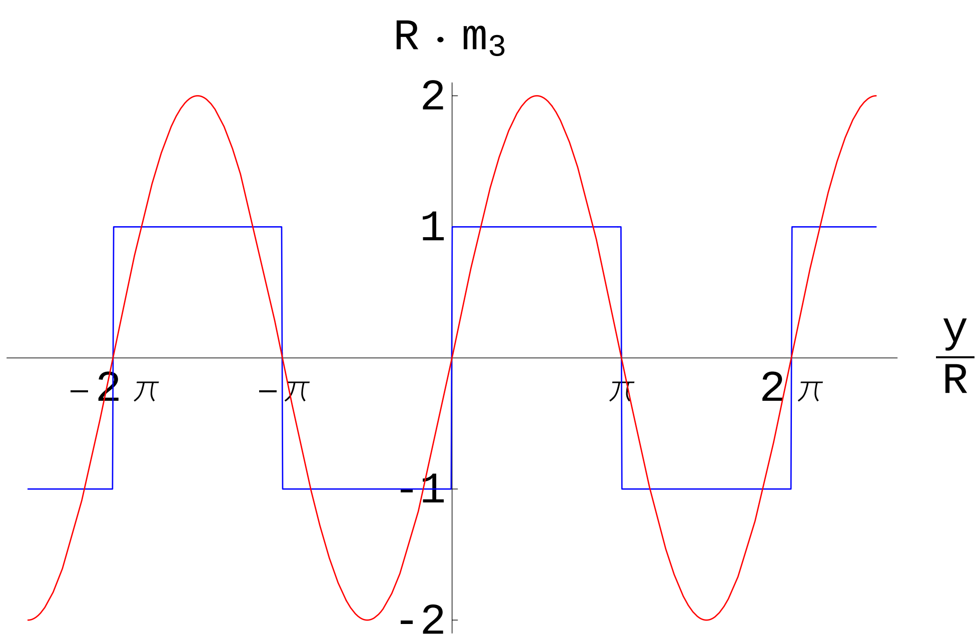
$$m_1(y) = m_2(y) = 0 \qquad m_3(y) \neq 0$$

real odd periodic function of y

$$\int_y^{y+2\pi R} dy'\, m_3(y') = 0 \quad \Rightarrow \quad \beta = 0$$

Such mass profile can be completely removed by a suitable field redefinition

NO TWIST



Two representative and equivalent choices for $m_3(y)$:

$m_3(y) = (2\sin y)/R$ and $m_3(y) = \epsilon(y)/R$.

The super-Higgs effect (flat case)

of minimal 5D supergravity
all we need for our discussion is:

$(e_M^A\,,\,\Psi_M\,,\,B_M)$ (SUGRA multiplet)

$$\kappa\mathcal{L} = i\epsilon^{MNOPQ}\overline{\Psi}_M \Sigma_{NO} D_P \Psi_Q + \ldots$$

$$\delta\Psi_M = \frac{2}{\kappa} D_M \eta + \ldots$$

$\eta =$ local 5D SUSY parameter

$$D_M \Psi = \left(\partial_M + \frac{1}{2}\omega_{MAB}\Sigma^{AB}\right)\Psi$$

flat background

$$\langle G_{MN}\rangle = \eta_{MN} \qquad \langle \Psi_M \rangle = \langle B_M \rangle = 0$$

solution of the 5D equations of motion

S^1/Z_2 compactification (no twist):

$$\Psi_M = \begin{pmatrix} \psi_{1M} \\ \psi_{2M} \end{pmatrix} \quad (M = \mu, 5) \quad \text{5D gravitino}$$

$$Z = \hat{\sigma}^3 \text{ for } \Psi_\mu \qquad Z = -\hat{\sigma}^3 \text{ for } \Psi_5$$

even: $E_\mu^\alpha, E_5^{\hat{5}}, B_5$ odd: $E_\mu^5, E_5^\alpha, B_\mu$

$\Downarrow$

dilaton and axion zero modes

often ignored in phenomenological studies

Effective no-scale theory of zero modes:

$$T = E_5^5 + i\sqrt{\tfrac{2}{3}} B_5$$

The spectrum:

$$M_{(0)} = 0 \qquad (E_\mu^\alpha, \psi_\mu^1; \psi_5^2, E_5^{\hat{5}}, B_5)$$

$$M_{(n)} = \frac{n}{R} \ (n \neq 0) \quad (2, 3/2, 3/2, 1)$$

effective $N=1$ 4D no-scale SUGRA from minimal 5D SUGRA on S^1/Z_2

$$E_M^A = \begin{pmatrix} \phi^{-1/2}\hat{e}_\mu^a & \phi A_\mu \\ 0 & \phi \end{pmatrix} \qquad B_M = \begin{pmatrix} B_\mu \\ B \end{pmatrix}$$

$$\Psi_M \longrightarrow \psi_\mu^1, \psi_\mu^2, \psi_5^1, \psi_5^2$$

odd fields $(A_\mu, B_\mu, \psi_\mu^2, \psi_5^1) \Rightarrow$ no zero mode

even fields recombine into $(\hat{e}_\mu^a, \psi_\mu)$ and (z, χ), where $\chi \propto \psi_5^2$ and

$$z \equiv \phi + i\sqrt{\tfrac{2}{3}}B$$

$$\hat{e}_4^{-1}\mathcal{L} = -\tfrac{1}{2}R(\hat{e}) - \tfrac{3}{4}\phi^{-2}\hat{g}^{\mu\nu}(\partial_\mu\phi)(\partial_\nu\phi)$$
$$-\tfrac{1}{2}\phi^{-2}\hat{g}^{\mu\nu}(\partial_\mu B)(\partial_\nu B) + \ldots$$
$$\Downarrow$$
$$K_{\overline{T}T}\hat{g}^{\mu\nu}(\partial_\mu\bar{z})(\partial_\nu z)$$
$$\Downarrow$$
$$K = -3\log(T+\overline{T}) + \ldots$$

Twisted S^1/Z_2 compactifications:

can be discussed as the case study

$$\Psi_M(y+2\pi R) = U_\beta \Psi_M(y)$$
$$\Psi_M(y) = V(y)\,\widetilde{\Psi}_M(y), \ldots$$

can look at derivative terms only
in 5D lagrangian and transformation laws

can redefine also local SUSY parameter

$$\eta = \binom{\eta_1}{\eta_2} \quad \eta(y) = V(y)\,\tilde{\eta}(y)$$

show that SUSY breaking is spontaneous
$\beta \neq 0 \Rightarrow$ unitary gauge where $\widetilde{\Psi}_5$ disappears

can have localized gravitino masses
'brane-induced' SUSY breaking
and interpret $\delta_{0,\pi}$ as remnants of some
non-perturbative localized dynamics

non-locality of SUSY order parameter
improves the ultraviolet behaviour
of symmetry-breaking quantities
e.g. finite $\mathcal{O}(\frac{1}{R^4})$ 1-loop vacuum energy
missed by dimensional reduction

(non-decoupling of heavy KK modes)

An intriguing analogy: gaugino condensation in M-theory

- $\odot$ localized gravitino mass terms (P_0, P_π)
  - $\odot$ vanishing classical vacuum energy
  - $\odot$ radius R = classical flat direction
  - $\odot$ non-local order parameter $P_0 + P_\pi$ (unbroken SUSY for $P_0 = -P_\pi \neq 0$)
- $\odot$ goldstinos = y-components of gravitinos
  - $\odot$ effective 4D theory of no-scale type

In M-theory:

$\langle G_{11abc} \rangle \Rightarrow m_2(y)$ localized at $y = 0, \pi R$

however, also some differences:
warped background, additional moduli

strong hints for an equivalence
further work needed to prove it

Final comments

there are many $D > 4$ SUGRA and string models generalizing our toy example

some advanced topics of interest:

$\odot$ couplings of broken $D > 4$ SUGRA to bulk and localized multiplets: transmission mechanisms in $D > 4$ at classical and/or quantum level

$\odot$ problem of radion stabilization (more generally, of moduli stabilization)

$\odot$ spontaneous breaking in warped spaces, e.g. RS: $ds^2 = e^{a(y)} \eta_{\mu\nu} dx^\mu dx^\nu + dy^2$

$\odot$ spontaneously broken SUGRA in dS_4

$\odot$ cosmological solutions in $D > 4$

we'll hear a lot on this at the Workshop!

References

In a spirit of an introductory lecture, I refer here only to some review papers, where references to the original literature can be found, or to papers that were used in preparing this presentation

Effective 4D $N = 1$ global SUSY

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4D no-scale

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