ElectroWeak Symmetry Breaking

(and Supersymmetry Breaking)

by a compact extra-dimension

R.B., SUSY 2002

A specific proposal for $G_F^{1/2} \to R$

No connection with gravity (a priori)

ph/0011311 B, Hall, Nomura

th/0203039 B, Contino, Creminelli, Rattazzi, Scrucca

ph/0205280 B, Marandella, Papucci

Motivation

Standard Model

$(\mu, \lambda) \longleftrightarrow (m_H, G_F^{-1}(\Lambda^2))$

MSSM

$\lambda = g^2 +$ rad. corr. $\Rightarrow m_H$ light

$G_F^{-1}(m_i, \lg \Lambda)$

Where are the superpartners and/or the Higgs?

Not at LEP. A problem?

A fine-tuning dependent answer

Are there theories without such ambiguity?

The proposal

B, Hall, Nomura

[Concentrate on

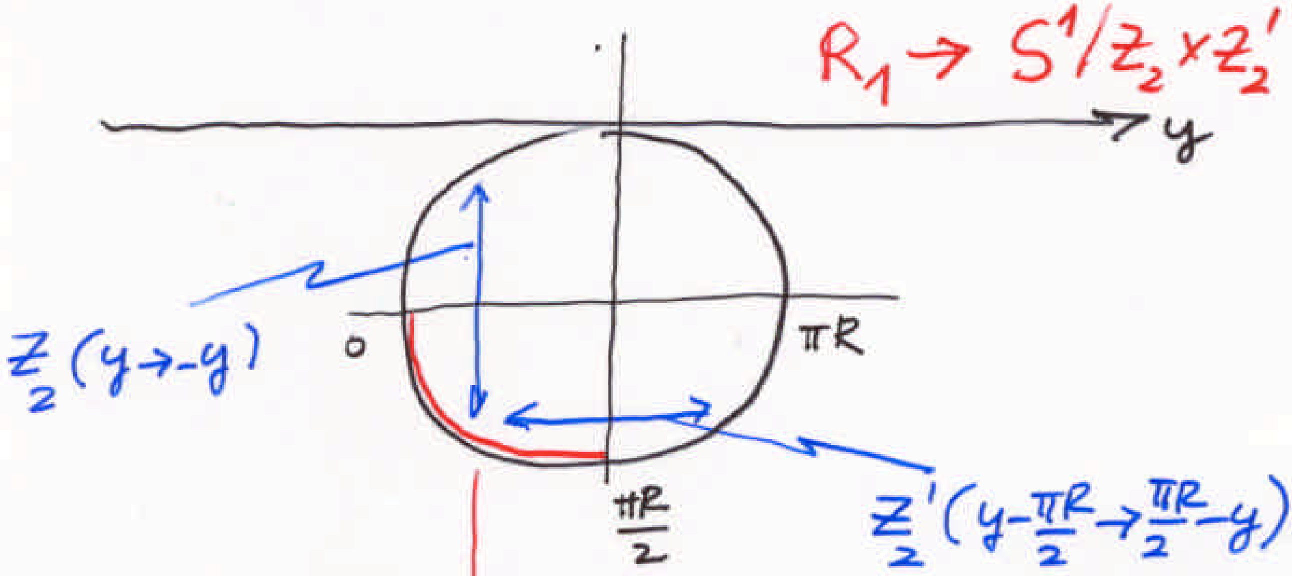
$$|\delta m_h^2(\text{top loop})| = \frac{3}{\sqrt{2}\pi^2} G_F m_t^2 \Lambda^2 = 0.1\,\Lambda^2$$
$$\gtrsim (1\,\text{TeV})^2 \quad \text{for } \Lambda \gtrsim 3\,\text{TeV} \;]$$

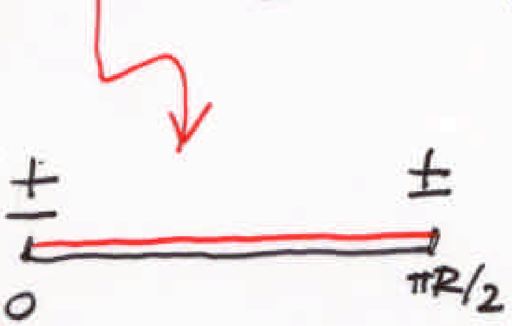
1. Insist on susy and promote $Q = (t,b)_L$ and t^c to 5D-fields

$$\psi(x) \to \psi(x,\underline{y})$$

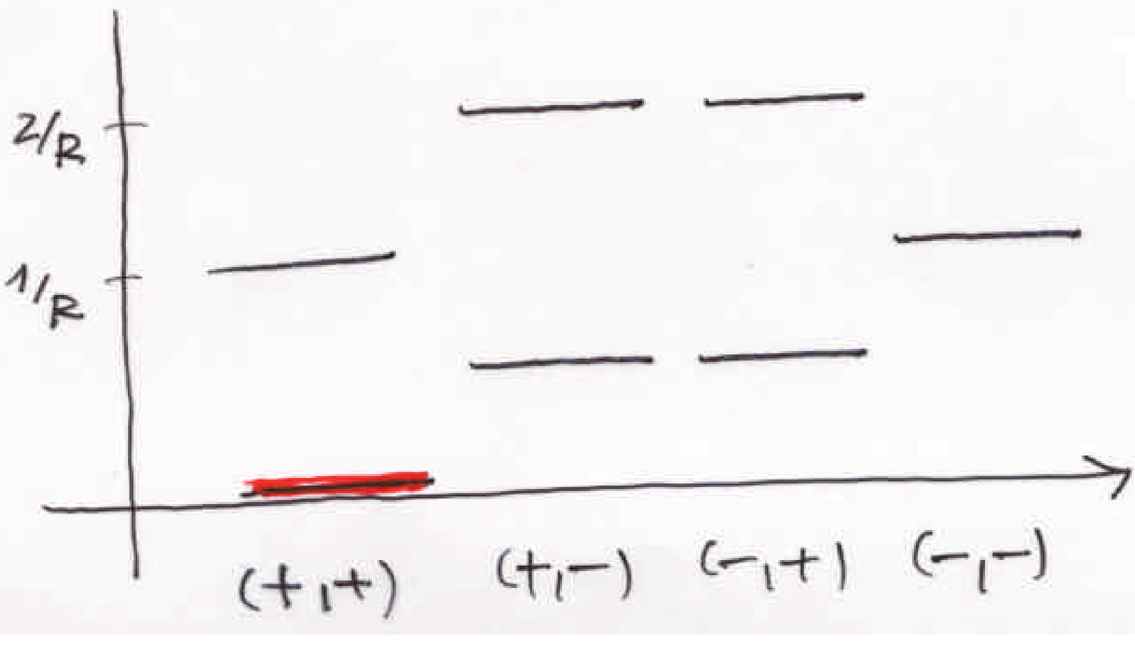
$$\begin{tikzcd} f \arrow[r] \arrow[d] & f^c \arrow[d, "\text{SUSY}"] \\ \tilde{f} \arrow[r, "4D \to 5D"'] & \tilde{f}^c \end{tikzcd}$$

2. Use proper boundary conditions to "get rid" of unwanted states

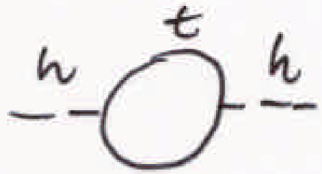




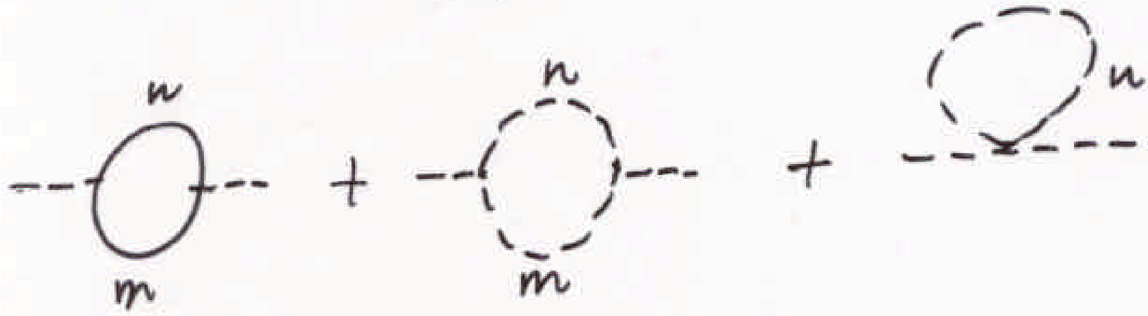
$f(+,+)$
$\tilde{f}(+,-)$
$\tilde{f}^c(-,+)$
$f^c(-,-)$



With a Yukawa coupling $\lambda_t QTH$
localized at $y=0$ (one of the boundaries)



$$\Downarrow$$



$$\Downarrow$$

$$\delta m_h^2 = -\frac{63\,\zeta(3)}{64\pi^4}\,\lambda_t^2\,\frac{1}{R^2} = 0.1\,\frac{1}{R^2}$$

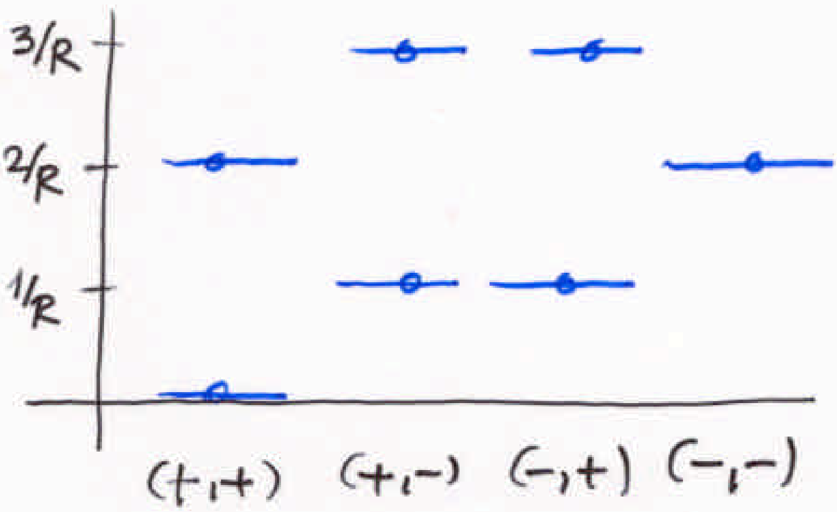
finite because supersymmetry
only broken by boundary conditions,
i.e. locally unbroken (see below)

Extend to full theory

1. Treat all SM fields on same footing : $\varphi(x) \to \varphi(x,y$

2. Keep SU_{321} , supersymmetry and 5D Poincaré

$\Rightarrow$



Matter multiplets : $f(+,+)$, $\tilde{f}(+,-)$, $\hat{f}^c(-,+)$, $f^c(-,-)$

Gauge multiplets : $A_\mu(+,+)$, $\lambda_1(+,-)$, $\lambda_2(-,+)$, $\Sigma + iA_5(-,-)$

Higgs multiplet : $h(+,+)$, $\hat{h}(+,-)$, $\tilde{h}^c(-,+)$, $h^c(-,-)$

$\Rightarrow$ SM fields only as massless states.

$\frac{1}{R}$ as only parameter so far (other than g_s, g, g' and λ_t)

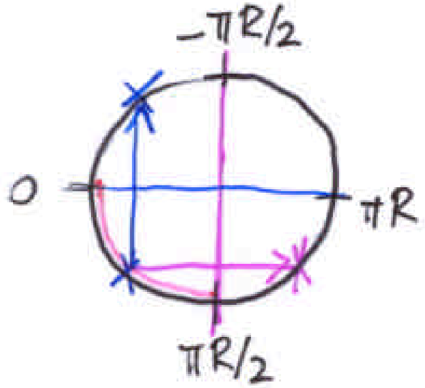
$\partial_\mu + i g A_\mu$

MODEL 1 ($\theta=0$)

3. Can one get the SM spectrum only as zero modes?

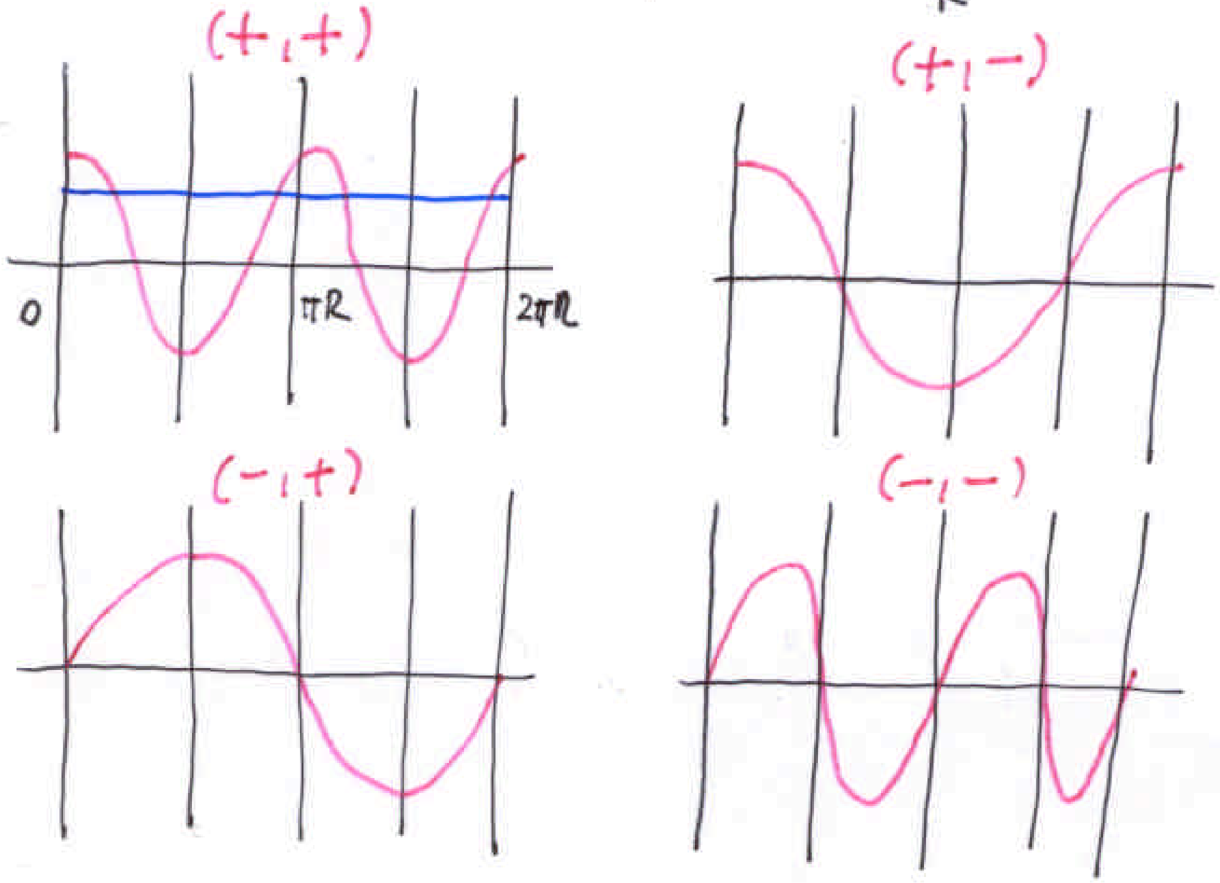
Yes, in a unique way

$\mathbb{R}^1/Z_2\times Z_2'$



$$(+,+):\ \cos\frac{2ny}{R}$$
$$(+,-):\ \cos\frac{(2n+1)y}{R}$$
$$(-,+):\ \sin\frac{(2n+1)}{R}y$$
$$(-,-):\ \sin\frac{(2n+2)}{R}y$$

$n=0,1,2,\dots$



Which symmetries after projection?

1. Residual local susy in 5D

$$\xi_D = \begin{pmatrix} \xi_1(x,y) \\ \xi_2(x,y) \end{pmatrix} \begin{matrix} (+,-) \\ (-,+) \end{matrix}$$

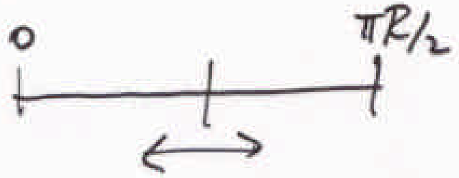
[No connection between λ and "Hp".

crucial for calculability

2. Continuous $U(1)_R$ (even after EWSB)

Hence no A-term, no $m\lambda\lambda$

3. local y-parity



$$\varphi(y) = \underbrace{(-)^{n}}_{Z_2 \text{ or } Z_2'} \varphi(\pi R/2 - y)$$

forbids mass terms for hypermultiplets

(but see below)

Which symmetries after projection?

local susy with parameters

$$\xi_D = \begin{pmatrix} \xi_1(x,y) \\ \xi_2(x,y) \end{pmatrix} \begin{matrix} (+,-) \\ (-,+) \end{matrix}$$

[No connection between Λ and M_{Pl}]

crucial for calculability

Which Lagrangian?

$$\mathcal{L} = \underbrace{\mathcal{L}_5}_{N=1 \text{ in } 5D} + \delta(y)\,\underbrace{\mathcal{L}_4}_{N=1 \text{ in } 4D} + \delta(y-\tfrac{\pi R}{2})\,\underbrace{\mathcal{L}_4'}_{N=1' \text{ in } 4D}$$

①

$$\xi_D(y=0) = \begin{pmatrix} \xi_1(x) \\ 0 \end{pmatrix} \Rightarrow \overset{\hat{M}}{\begin{pmatrix} \psi_M \\ \varphi_M \end{pmatrix}} \quad \overset{\hat{H}}{\begin{pmatrix} \tilde{h} \\ h \end{pmatrix}}$$

$$\mathcal{L}_4 = \dots + \lambda_t \hat{Q}\hat{U}\hat{H}$$

$$\xi_D(y=\tfrac{\pi R}{2}) = \begin{pmatrix} 0 \\ \xi_2(x) \end{pmatrix} \Rightarrow \overset{\hat{M}'}{\begin{pmatrix} \psi_M \\ \varphi_M^{c+} \end{pmatrix}} \quad \overset{\hat{H}_c'}{\begin{pmatrix} \tilde{h}^c \\ h^+ \end{pmatrix}}$$

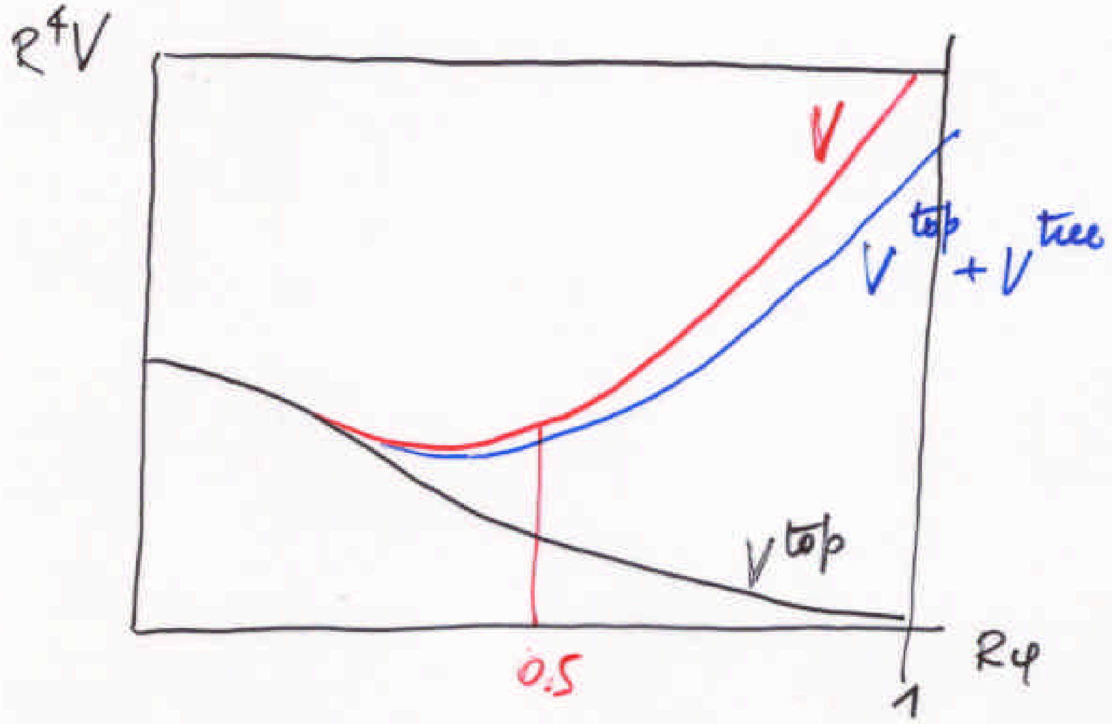
only one Higgs field as in the SM

②

$$\mathcal{L}_4' = \dots + \lambda_b \hat{Q}'\hat{D}'H_c' + \lambda_e \hat{L}'\hat{E}'H_c'$$

$$V^{top} = \frac{6N_c}{\pi^6 R^4} \sum_{k=0}^{\infty} \frac{\cos\left[(2k+1)\pi R m_t(\varphi)\right]}{(2k+1)^5}$$

$$V = \frac{g^2+g'^2}{8}\varphi^4 + V^{top} + \delta V^{gauge}$$



$$\frac{1}{R} = \left(\frac{\pi^6}{18}\right)^{1/4} (M_Z v)^{1/2} \left[1 + O(1\%)\right] = 341 \text{ GeV}$$

$\hookrightarrow$ 366 GeV from δV^g

$$m_H = \sqrt{2} M_Z \left(1 - \frac{1}{4}\cos(\pi R m_t)\right) = (127 \pm 2) \text{ GeV}$$

not the MSSM!

$$\frac{1}{(\pi R M)^2}$$

$\delta m_t = 5$ GeV

± 8 GeV from higher orders

Where is the cut off?

$\delta(y)\, \lambda_t H Q U \qquad [\lambda_t] = m^{-3/2}$

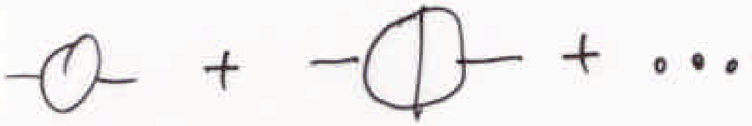
$\Lambda \equiv$ scale at which perturbation theory breaks down

Two estimates:

1. naive dimensional analysis, adapted to 5D:

$$y_t = \frac{\lambda_t}{(2\pi R)^{3/2}} \simeq \frac{1}{16\pi^2}\left(\frac{24\pi^3}{2\pi R\Lambda}\right)^{3/2} \simeq 8.3\,(R\Lambda)^{-3/2}$$

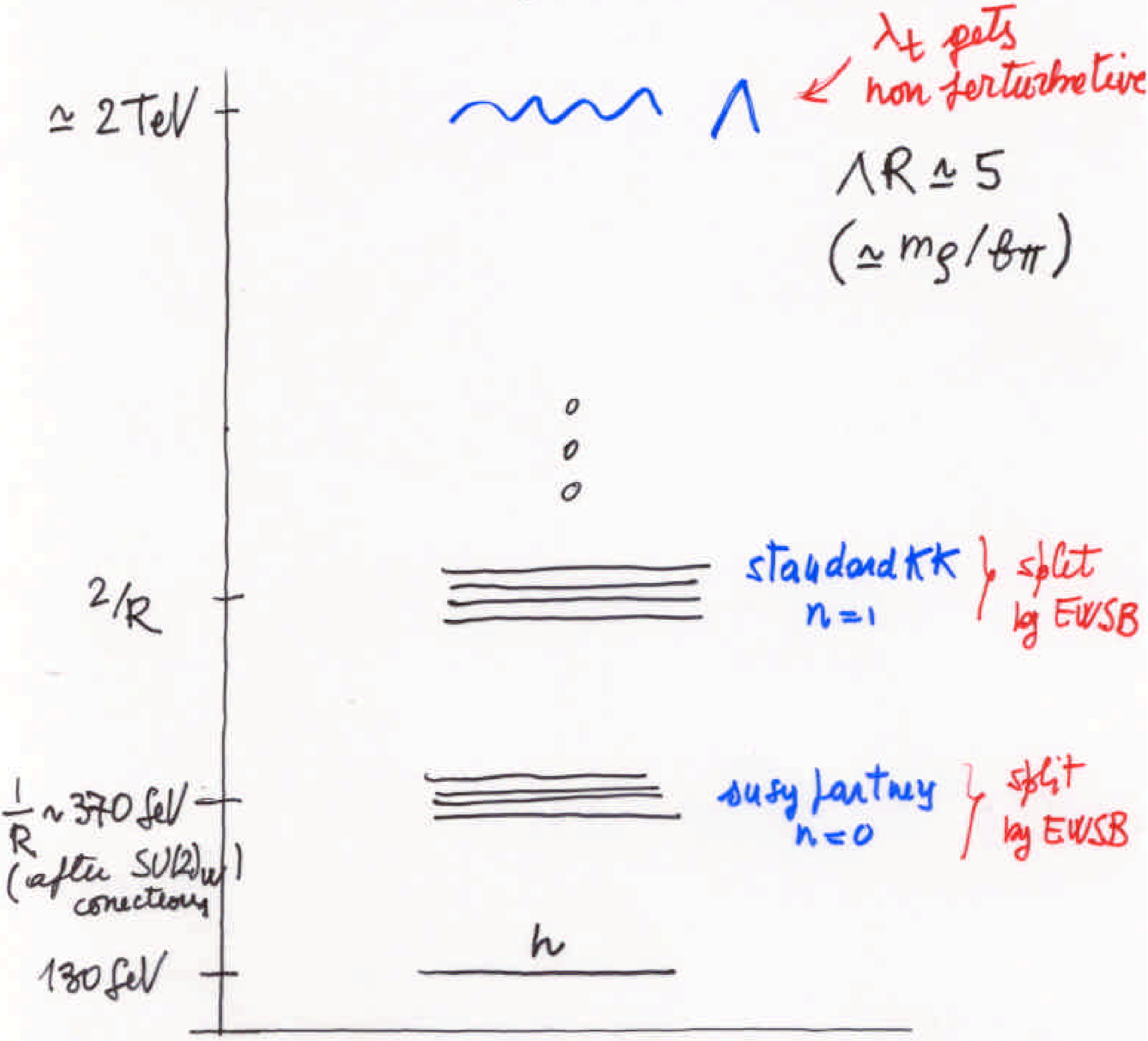
2. Counting states in 4D



$$\frac{(\sqrt{2}\,y_t)^2}{16\pi^2} N_{KK}^3 \simeq \frac{2 y_t^2}{16\pi^2}(\Lambda R)^3 \simeq 1 \Rightarrow y_t = 8.9\,(R\Lambda)^{-3/2}$$

Matching to $y_t(m_t)$ $\Rightarrow$ $\boxed{\Lambda R \simeq 5}$

Summary (so far)



Problems of consistency? $S_1/Z_2\times Z_2'$

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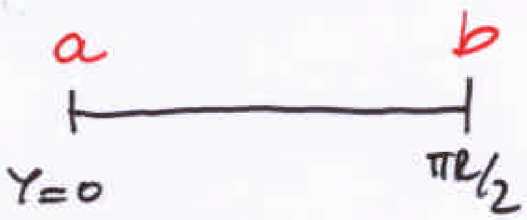
1. Anomalies? Scrucca, Serone, Silvestrini, Zwirner

Yes, in general, localized on branes



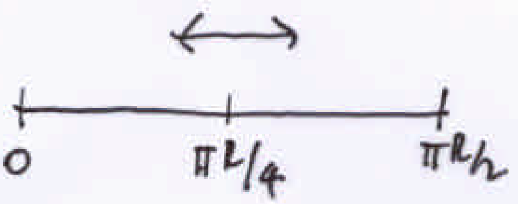
(normalized to $\mathrm{Tr}(Q^a Q^b Q^c)$)

$a+b=0$ $\Longleftrightarrow$ No anomaly in zero mode sector

$a=-b\neq 0$: Can is be cancelled by a CS term in 5D

From the Higgs hypermultiplet (with no massless higgsino) $\propto \mathrm{Tr}(Y^3)\left(\delta(y)-\delta(y-\frac{\pi R}{2})\right)$

$\Rightarrow$



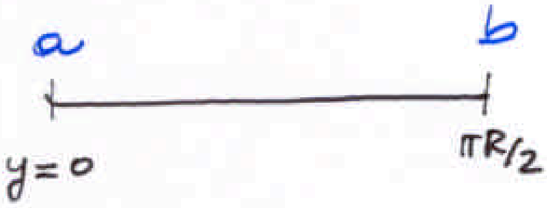
broken

Mass terms for hypermultiplets not forbidden, although small from rad. corr.

$\psi\,\partial_y \psi^c + M(y)\,\psi\psi^c$ with $M(y)$ $(-,-)$

2. Fayet Iliopoulos term? $S_1/Z_2\times Z_2'$

Ghilencea, Groot Nibbelink, Nilles



$$\delta \mathcal{L}_{FI} = a\,\delta(y)(D-\partial_y\Sigma) + b\,\delta(y-\tfrac{\pi R}{2})(-D-\partial_y\Sigma)$$

$a+b=0 \iff$ No breaking of supersymmetry, nor of the gauge symmetry; consistency with supergravity (unlike in 4D)

$\left(\int d^4\theta\,(\partial_y V-\varphi-\varphi^\dagger)\right)$

From the Higgs hypermultiplet $a=-b\neq 0$ for the hypercharge FI

$$\xi\,(\delta_y-\delta_{y-\pi R_n})\,D_Y$$

↑ An extraparameter, equivalent to a mass term $M_i \propto Y_i$ for the i-th hypermultiplet, although small from rad. corr.

Spectrum and phenomenology (after EWSB)

- Include uncertainty from brane-localized op.s
- Neglect hypermultiplet masses ($m_i \simeq 0$)

$1/R$	360 ± 70 GeV
h	130 ± 10
$\tilde{t}_1, \tilde{u}_1$	210 ± 20
$\chi^\pm, \chi^0, \tilde{g}, \tilde{q}, \tilde{\ell}$	360 ± 70
$\tilde{t}_2, \tilde{u}_2$	540 ± 30
A_1, q_1, ℓ_1, h_1	720 ± 140

$\Rightarrow$ $\tilde{t}_1, \tilde{u}_1$ stable (or quasi-stable)

$$T^+ = \tilde{t}_1 \bar{d} \quad , \quad T^0 = \tilde{t}_1 \bar{u}$$

μ-like, $\frac{dE}{dx}$, ToF

missing E_T

$$\chi^\pm, \chi^0, \tilde{g}, \tilde{q}, \tilde{\ell} \rightarrow T\text{'s} + \dots$$

KK_1 ($A_\mu^1, \dots$) at $2/R$

with suppressed coupling to standard fermions

(Some) possible criticisms

1. Cutoff too low? $\Lambda R \simeq 5$

No, by inspection of $\mathcal{L}_{eff}$ $(m_\rho / f_\pi \simeq 4)$

2. $M_1 \simeq 0 \Rightarrow$ many fine-tunings?

$M_1^{(0)} = 0$ sufficiently stable in the cut-off theory

$M_1 \neq 0$ not needed for consistency with data

3. Really unique?

$M_1 \neq 0$ possible - Can raise $1/R$ to TeV

(and ΛR) still without a fine tuned G_F.

Light fragments of the spectrum always present.

4. Consistent with standard Unification?

Not in any obvious way. $\Leftarrow$

Determine m_h and $1/R$

If $$V = -0{,}1\,\frac{\lambda_t^2}{R^2}|h|^2 + \frac{g^2+g'^2}{8}|h|^4$$

$$\Rightarrow \quad m_H = m_Z\,, \quad 1/R \simeq 2{,}3\, m_Z$$

However

$$V_{1\,loop}^{top} = \frac{1}{2}\,\mathrm{Tr}\int\frac{d^4p}{(2\pi)^4}\sum_n \lg\frac{p^2+m_{Bn}^2(h)}{p^2+m_{Fn}^2(h)}$$

$$= \frac{1}{R^4}\,f(\underline{\lambda_t h R}) = -0{,}1\,\frac{\lambda_t^2 h^2}{R^2} + \ldots \Leftarrow$$

From

$$V = V_{1\,loop}^{top} + \frac{g^2+g'^2}{8}|h|^4$$

$$\Rightarrow \quad m_H = \sqrt{2}\,M_Z\left(1-\frac{1}{4}\cos(\pi R m_t)\right) = (127\pm 2)\,GeV$$

$$\frac{1}{R} = (341\pm 4)\,GeV$$